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Selected answers and remarks by **Viktor T. Toth** on

Relativity, Gravitation, Quantum Physics, Fields, Astrophysics, Cosmology

[in informal Am-English]

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Viktor T. Toth

Who's Viktor T. Toth?

Viktor T. Toth is a Canadian Hungarian software developer, author of *Visual C++ Unleashed* and other computer books. He studied at Budapest Un. of Technology & Economics. Dr. Toth is also a gifted and appreciated theoretical physicist, with over two dozen papers ranging on topics in advanced Physics. He lives in Ottawa, ON.

Viktor received his first software development contract in 1979: his task was to simulate the take-off distance of TU-154 aircraft with engine failure at Budapest airport under various weather conditions, to compute tables of maximum take-off weight. Since then, he has worked on many software projects and is thoroughly familiar with the entire software development life cycle.
He authored – or co-authored – studies for large software projects (for instance, he was one of the authors of the Automation Master Plan of the Canadian Patent Office in 1988); he designed and developed the Windows version of Industry Canada's Integrated Spectrum Observation Centre, with over 120000 lines of C++ code. Moreover, he created NORTEC's HELP (Humidification, Engineering and Load sizing Program), an application for professional engineers and salespersons dealing with large-scale building humidification systems.
He also wrote several books on the C++ programming language and the Linux operating system. As part of his scientific research, he independently developed a precision orbit determination program used to analyze the anomalous trajectory of the Pioneer 10 and 11 spacecraft. Also, he is one of the maintainers of Maxima, a preeminent open-source CAS.
Viktor is just as competent with modern software development technologies as with ancient systems. He routinely switches between developing an interactive app for his Android smartphone and maintaining a 30-year-old legacy LISP code for Maxima. He is familiar with formal software project management and development methodologies. Finally, he also has experience designing and debugging hardware.

His papers include: General Relativistic Observables of the GRAIL mission; Numerical simulation code for Bose-Einstein self-gravitating condensates; MOG application to Einstein lensing rings; Abell 520, the Bullet Cluster Support for the thermal origin of the Pioneer 10 and 11 spacecrafts anomaly; Acceleration of relativistic reference frames in Minkowski SpaceTime; Support for time-varying behavior of the Pioneer anomaly from the extended Pioneer 10 and 11 Doppler data sets and cosmological observations in a Modified Theory of Gravity (MOG).

A repository of Viktor's answers to questions on some puzzling current-Physics issues can be found at:

https://www.quora.com/profile/Viktor-T-Toth-1

Contents

A foreword to the serious Reader

You can find lots of insight, strong but honest criticism and ideas, rigor, and doubt admissions in these pages about the main current issues from the World of Physics. The effective reading of this PDF document *is* indeed *very far from being easy*. A few themes are discussed and stressed *insistently* in a deceptively informal language, with different emphasis and complementary perspectives as well as frameworks. In its own way, it's a sort of pre-release advanced *seminal* textbook.

You'd better stop and count to ten before bursting in favor or not. Nothing is taken as 'absolutely certain', coherence and consistency are always sought for, ready to an inexorable *experimental falsification* process. Don't look for bizarre hypotheses nor for whimsical fantasies here: these attitudes have no place whatsoever in Physics – let it be Fundamental or not – nor have anything to do with what is meant for *educated* and *sensical* guesswork.

Obviously, you know your current competence level. Thus, you may consider not to bypass pages 382-383 on the *least* background – I dare say, *prerequisites* – to let your reading get deeper. That's why you'll stumble into certain 'aged' models: they always tingle 'under the hood' in active working, even in the most recent literature, and that's why I'm very often in need to refresh them for details, let these be trivial or subtle but, in most cases, crucial before any *big leap*. In a gamble with Natural Reality, one *should expect* things can get messed up – or, at the very best – *try to figure out* how they might. And this will be *seldom* the end of the whole game …

Consolidated literature and computational tools, which I practiced over the years in their early versions, are listed before the final **Appendix** on *Gravitational Waves*. All these tools come from the Web; some updated editions of these (landmark) works are available *for free* in PDF format (yellow highlights) to the interested reader.

So, have a good reading and, above all, insight in some of the current Physics frontiers. Keep yourself ready with a pen, some paper sheets aside and a good CAS for calculations, in view of any new … *temporary* conclusion.

C M

Physics Issues and Answers

1 -

Does $E = mc^2$ mean that anything with Mass has Potential Energy, i.e., is about 'converting' Mass into Energy?

the force that a body feels in a Gravitational Field. As for the *Weak Equivalence Principle*, passive gravitational Mass is *directly proportional* to inertial Mass, so any conversion factor between the two is purely a matter of convention. We usually measure passive gravitational Mass and inertial Mass using the same set of units, so the conversion factor is just 1: *passive gravitational Mass and inertial Mass are the same*.
Active gravitational Mass determines the gravitational force exerted by a massive body. For Newton's 3rd Law to remain in effect, *active and passive gravitational Mass must be the same*.
So, assuming that the Weak Equivalence Principle and Newton's Laws are valid, there is only one Mass so far: the same quantity determines Inertia, behavior in a Gravitational Field, and the magnitude of the Gravitational Field produced. This Mass is a property of an object, and all observers agree on the magnitude of this property, regardless of their own motion. The property is, therefore, *invariant*. This *invariant Mass* is also sometimes called *rest Mass*. The two expressions refer to the same thing: they are synonyms.
Lastly, especially in older textbooks, it was often customary to combine *rest Mass* with *Kinetic Eenergy*, expressed as Mass using the Mass-Energy equivalence relationship $E = mc^2$.
The resulting *relativistic Mass* is *observer-dependent* since the observed velocity of an object depends on the observer's own motion. This concept of relativistic Mass has been the source of a lot of unnecessary confusion, and it is not really helpful, so its use fell No, $E = mc^2$ means exactly what Einstein said it means when he first published this result back in 1905.
The title of the paper was: 'Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?' or 'Does the Inertia of a body depend on its Energy-content?'. The paper answered this question unambiguously: no, $E = mc^2$ does not mean that anything with Mass has Potential Energy. It means, to use Einstein's own words from the aforementioned paper, that *the Mass of a body is a measure of its Energy-content* ('Die Masse eines Körpers ist ein Maß für dessen Energieinhalt').
In short, *Mass* (which determines Inertia) and *Energy-content* are the *same thing*. Which is why $E = mc^2$ is often called the *Mass-Energy Equivalence* relationship. The factor c^2 is just a *conversion factor* between different units but *there is no physical process involved*. [see Issues 148 and 159, P.s 70 and 75]

2 -

Do we need to distinguish *gravitational* vs. *inertial Mass*?

Inertial Mass is the quantity that characterizes the extent to which a body, floating in empty space, resists a force; m is the Mass m that goes into Newton's equation, $\boldsymbol{F} = m\boldsymbol{a}$, which relates force $\boldsymbol{F}$ to acceleration $\boldsymbol{a}$.
Passive gravitational Mass determines out of favor in recent decades.

3 -

What determines how particle systems respond to Gravitation?

Photons have no rest Mass but the quantity that determines how a thing gravitates, or responds to Gravitation, is not rest mass. It is a complex entity called the *Stress Energy-Momentum Tensor* that consists of Energy, Momentum, Pressure, and *Shear Stresses* (it is usually represented by a 4×4 symmetric matrix; it is not a simple number).
Now, it so happens that for most everyday objects, their speeds are small compared to the speed of light, and pressure and stresses are also small compared to relativistic media. So, the Stress-Energy-(linear)Momentum Tensor is dominated by rest-Mass. When it comes to the Sun, the Earth, a lump of metal, a human being …, gravitational behavior is very accurately (but not perfectly!) described using Newtonian Gravity and their respective rest Masses.
But the moment we get to relativistic speeds, this is no longer the case. Entities can no longer be characterized by rest Mass alone; other components of the tensor become equally important.
Specifically, a photon has no rest Mass, but it carries plenty of Energy and has Momentum. Its Stress-Energy-Momentum Tensor is certainly not zero. So, it can be a source of Gravity, it has Inertia, and it responds to Gravity. But its behavior can no longer be described by Newtonian Gravity, as evidenced, among other things, by the fact that Relativity Theory predicts (correctly, as confirmed by observation) *twice* the deflection angle for a photon in a

gravitational field than the deflection of a Newtonian particle would be, moving at the same speed.

4 -

What is really 'Matter'?

'Matter' is a somewhat poetic term, the meaning of which, often depends on context.
Energy is a so-called *constant of the motion*. It is the quantity that is conserved under Time translation in systems that are time-translation invariant. It is one of the manifestations of *Emmy Noether's Theorem*, that *every symmetry or invariance is accompanied by conserved quantities*; Energy is one of these quantities, associated with the *translational* and *rotational symmetries* (*invariances*) in Time.
Mass exists in several form. Inertial Mass is the property that characterizes how a body in *free* space resists a force. Since Einstein's 1905 paper, we know that *Inertial Mass consists of the Energy-content* of that body (Mass-Energy equivalence). The Weak Equivalence Principle (all bodies are affected by Gravity the same way) on the other hand tells us that *inertial Mass* is the same as the so-called *passive gravitational Mass* (which determines how much force a body feels in a gravitational field). Furthermore, Newton's 3rd Law guarantees that the *active* gravitational Mass (i.e., how much gravitational force a body exerts) will also be the same.
This is nice English prose, by the way, but everything is written above can be represented in the form of decent-looking equations, offering unambiguous mathematical definitions.
Now Matter … that's another thing altogether. Unlike Mass and Energy, 'Matter' is usually not a quantifiable term that appears in equations. To any cosmologist, everything is Matter that fills empty space. This includes atoms, light, even ephemeral things like virtual particles, though usually not the Gravitational Field, even though it, too, has Energy and Momentum. To another physicist, Matter may be 'stuff' composed of fermions; 'stuff' made from bosons would be *Radiation*, in this context meant as an alternative to Matter. And to others, depending on context, the definition of Matter may be narrower (e.g., restricted to forms of Matter that are stable on human timescales) or broader. This is simply the usual ambiguity of a spoken language; how a word often has similar but distinct meanings in different professional contexts.

5 -

Can Energy be converted into Mass, and vice-versa?

Energy is a *constant of the motion*, a quantity conserved for systems that are invariant (unchanging) under time translation (i.e., the same Laws of Physics yesterday, today, or tomorrow).
Energy is not 'converted into Mass'. The meaning of the one equation everyone knows, $E = mc^2$, is crystal clearly stated in the title of Einstein's own 1905 paper: the inertia of a body is determined by its Energy-content. In other words, what we call Mass is just the *intrinsic Energy of a body*.
And the Big Bang did not convert Energy into Mass either. The expression, 'Big Bang', references the prevailing model of an expanding Cosmos, that was very hot and very dense early on. General Relativity does predict an initial singularity, but we have no reason to believe that the rules of Relativity Theory apply, unmodified, in this extreme regime. In short, we know nothing about the actual beginning of time (if such a thing even existed). Our firm knowledge begins after the first pico-second or so, and it describes how various fields and particles interacted and evolved, and this also means that Kinetic Energy and various forms of Potential Energy (including *rest Mass*) got converted into one another in a variety of ways, too, even as Energy overall, along with Linear and Angular Momentum, remained *conserved*.

6 -

Can Dark Matter collapse into black-holes?

Dark Matter *can* collapse into black-holes. However, it is a darn good question why the presumed Dark Matter in the present-day Universe doesn't collapse into black-holes on a regular basis. And the reason is… *because it is dark*!
What does 'dark' really mean? It's a bit of a misnomer. Dark Matter *isn't* black. Rather, it is completely *transparent*. Transparent because it does not interact with other known forms of matter. So *matter* particles fly through it *unaffected*, and photons fly through it *unaffected as well*.
Moreover, Dark Matter doesn't interact *with itself* either. Therefore, *Dark Matter particles fly through Dark Matter, too*, *unaffected by anything other than Gravity*. And therein lies the problem!
What happens when normal Matter collapses under its self-Gravity? There is a build-up of *pressure*. Pressure means *heat*. Which means that Gravitational Potential Energy and Kinetic Energy both turn into *waste heat*, which is then either radiated away as light or it is dissipated away in the form of *pressure waves*; yes, *sound* (extremely low

frequency sound, many octaves below the audible range) does play a significant role in structure formation.
But none of this happens for Dark Matter: particles may accelerate towards each other under their mutual Gravity, but then they just fly past (or through!) each other, unaffected, and fly away from each other on the opposite side.
So, unless a Dark Matter cloud happens to collapse *very symmetrically*, at no point will it reach the density to turn into a black-hole. Nor will those Dark Matter particles stay together, which would enable further collapse. That is because their tremendous speed (gained as they fall towards each other) is not dissipated: there is no mechanism to do so. So, they do not stop in the form of a compact object. Rather, they fly through each other and just as quickly as they came together, they fly apart.

7 -

If the singularity inside a black-hole is a *time instant* rather than a *place*, where is all the Mass of the black-hole located?

Two cases should be distinguished.
First, the mathematical solution of a 'finished' black-hole, the end state of gravitational collapse. This solution was first obtained by K. Schwarzschild in 1916. This is what we would see if the collapse began an infinite amount of time in the past. This solution is a *vacuum solution*: there is no matter anywhere.
Now let us take a look at a more realistic case, the collapsing dust sphere. Here, 'dust' is simply a catch-all word to describe any medium that has no, or negligible, pressure, so it can collapse without rebounding. This situation was first developed by Oppenheimer and Snyder in 1939. The outside observer would see a collapsing sphere of dust, but over time, as the radius of the sphere approaches the (yet to form) event horizon, gravitational time dilation makes everything appear increasingly in slow motion. This time dilation is divergent: The actual moment of horizon formation is never seen; it remains forever in the future for the outside observer.
For the infalling observer, the situation is different. The moment of crossing the event horizon will not appear particularly special, but once the horizon is crossed, there is no escape. The observer will find himself inside an ever shrinking 'universe' of dust everywhere, essentially a Big Bang in reverse. The singularity is an unavoidable future moment in time when the density of this 'Universe' becomes divergent and time itself comes to an end.
So, there we have it. In the case of the Schwarzschild solution, it's Vacuum everywhere, but it is a limiting case, a mathematical idealization. In the case of a realistic collapsing object à-la Oppenheimer-Snyder (*Vacuum expectation value*, V. e. v.), the Mass never goes away, the dust sphere is always present, from the point of view of either outside or infalling observers.

8 -

Do neutrinos have Mass? In what sense does it 'oscillate'?

The prevailing wisdom is that neutrinos do have Mass, but it is weirder than we think.
We believe that neutrinos have Mass because neutrinos went missing. We know how many neutrinos are supposed to be produced by nuclear processes in the Sun, and these are readily detectable here on the Earth. However, … we didn't detect nearly as many as we should have.
Now neutrinos (like all fermions) come in 3 flavors: *electron neutrinos*, *muon neutrinos* and *tau neutrinos*. When we learned how to detect muon and tau neutrinos, suddenly the missing neutrinos turned up after all: somehow, they changed from electron neutrinos into muon neutrinos *en route* from the Sun.
How can this be? Well, … this is where things get weird. Remember that in Quantum Physics, a particle does not simultaneously have, e.g., a position and a velocity? That is, when a particle is in a 'position eigenstate', it will not have a velocity (or Momentum), and when it is in a 'Momentum eigenstate', it has no position?
Something similar is going on with neutrinos. Yes, they have Mass, we believe. But not only that, when a neutrino is in a Mass eigenstate, it does not have a well-defined flavor; and when it is in a flavor eigenstate, it does not have a well-defined Mass.
And *en route* from the Sun, a neutrino is in neither eigenstate; rather, it is in a mixed state of various possible *Masses* and *flavors*. So, when the neutrino arrives and interacts with a detector, it may be in a different flavor eigenstate. The probability of its flipping, or 'oscillating' between, e.g., the electron and muon neutrino flavors can be precisely calculated. This is what we observe.
This has consequences. *First*, there is no point assigning a Mass to, e.g., the electron neutrino; when the neutrino is in a definite flavor eigenstate, its Mass is indeterminate; *second*, the actual neutrino Masses and flavor mixing are defined by a 3×3 matrix. It even has a name: it is the *PMNS* (Pontecorvo-Maki-Nakagawa-Sakata) *matrix*, named after the physicists who developed this concept. It has four independent components (the rest are determined by various symmetries of this matrix), three of which are called *mixing angles* and the remaining is a *phase*. Essentially, this matrix determines how the various neutrino Masses relate to each other and how the various neutrino flavors

'mix' in neutrino oscillations; the actual Masses of the neutrinos are still subject to yet another number, an overall common factor. Anyhow, here is our best knowledge of neutrino Masses to date (2023), in the form of experimentally fitted values of this neutrino mixing (row-wise) matrix:

$$\mathbf{U}_{\text{PMNS}} := \begin{pmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & -0.15 \pm 0.03 \\ -035 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & -0.45 \pm 0.06 & 0.77 \pm 0.06 \end{pmatrix} .$$

As to the actual Masses, we know that the sum of the Masses of all neutrino flavors put together cannot be more than about $0.3\ \text{eV}/c^2$ $(\approx 5.348 \cdot 10^{-37}\ \text{kg})$, i.e., less than 10^{-6} of the electron Mass $(\sim 9.109 \cdot 10^{-31}\ \text{kg})$.

9 -

Why wasn't it obvious from the start that *gravitational Mass* and *inertial Mass* are the same quantity? Why would the weak equivalence principle be obvious?

Ancient philosophers certainly didn't believe this to be true. After all, it was 'obvious' that heavy objects, such as a lump of lead, fell much faster than light objects, such as a feather.
It took until Galileo to overturn this ancient wisdom and establish the experimental fact that objects accelerate at the same rate regardless of their size or material composition. But first, it was necessary to devise experiments that minimized the effects of air resistance and friction.
And it was only in the 20th century, with General Relativity, that this principle was elevated to what is essentially an axiom of Relativity Theory.
But obvious it is not. The Weak Equivalence Principle certainly does not apply to the other macroscopic force that we know, electromagnetism: the electric charge (the electrostatic equivalent of the gravitational Mass) is independent of the inertial Mass, and thus the 'Charge-to-Mass ratio' of an object can be anything. Different objects with different Charge-to-Mass ratios respond differently to an Electrostatic Field; acceleration does depend on the size and material composition of an object in that field.
And there are also plenty of examples of speculative but decent, well-reasoned alternate Gravity Theories (aiming to deal with shortcomings of the existing theory) in the scientific literature in which the Weak Equivalence Principle is violated in some way.

10 -

Why is the Higgs Field depicted as an entity that restrains the free motion of some particles (by conferring a degree of Mass) when there does not appear to be any such interference to an object's speed in (free) space?

Because people make clumsy attempts to translate into imprecise, everyday language something that is described precisely and accurately (in the form of testable predictions) by complicated mathematics.
The mathematics, in this case, tells us that there is such a thing as the Higgs Field, which has a *quartic* potential, and its lowest Energy state is not the state free of excitations. The mathematics then proceeds to tell us that this leads to spontaneous symmetry breaking and a *new* lowest Energy Vacuum state, in which the Higgs field has a non-zero *Vacuum expectation value* (V. e. v.). The mathematics, then, tells us that particles that interact with the Higgs Field now end up interacting with this V. e. v., i.e., the Vacuum itself, and that, for all practical intents and purposes, shows up as a Mass term in their equations of motion.
There, this is a more precise plain (?) English summary of what the math actually says. Though far less intuitive, this is a more serious explanation over the 'Higgs field is like molasses, resisting the free motion of some particles' description or its variants that often appear in popular accounts, because while the molasses thing may be more easily visualizable, it is also quite misleading and creates a false sense of understanding.
We strive to make difficult topics in theoretical physics comprehensible to a non-physicist audience, and we dread the idea of telling the public that this or that simply cannot be understood without the requisite mathematical background. Yet unfortunately that is indeed the case. Certain things just cannot be intuited, and this is especially true in the realm of Quantum and Particle Physics.

11 -

Why does Dark Energy not behave gravitationally in the same manner as Dark Matter?

Because it has a different equation of state.

Gravitation is not determined by Mass-Energy density alone. It is determined by a complicated quantity (the so-called Stress-Energy-Momentum Tensor) that considers Mass-Energy, Momentum, Pressure and anisotropic (e.g., shear) Stresses as well.
In our ordinary, everyday world, surrounded by matter that is not particularly dense (by relativistic standards) and not moving very fast, the quantity is dominated by Mass density. So, we are not making a terribly big mistake by using Newtonian Gravity as a useful (and quite accurate) approximation. In Newtonian Gravity, only Mass-Energy counts, and thus Newtonian Gravity does not distinguish between Dark Matter (which has no pressure) and Dark Energy (which has large *negative* pressure).
Now, because Dark Energy is characterized by a huge *negative pressure*, it cannot be ignored! The contribution of pressure to the gravitational field equations is larger in magnitude than the contribution of Mass-Energy density. And it is this large, negative pressure that completely changes the picture, and makes Dark Energy behave as if Gravitation were repulsive.
The 'equation of state' mentioned in the first sentence is simply a relationship between pressure and Energy density. Pressure and Energy density have the same dimensional units, so, their *ratio* is just a plain number, usually denoted by the letter. w .
For Dark Matter, $w = 0$. For most ordinary Matter, $w \approx 0$. For a gas hot enough for its constituent particles to fly around at high relativistic speeds, $w = 1/3$ but, as for Dark Energy, $w = -1$. Both the sign and the magnitude of w should tell us that Dark Energy does behave very differently from other known forms of Matter.

12 -

Why do we need gravitons when Gravity is not a force?

It all boils down to one of the key principles in General Relativity, the 'Weak Equivalence Principle'. The Weak Equivalence Principle basically states that all objects respond to Gravity exactly the same way, regardless of their shape or what they're made of.
This makes Gravity quite different from Electromagnetism. In Electromagnetism, a lump of charged matter responds very differently to an electromagnetic field than a lump of neutral matter. It all boils down to a quantity called the 'Charge-to-Mass ratio': Charge determines the amount of force acting on a particle, its Mass determines the inertial resistance to that force.
But for Gravity, 'charge' really is just *inertial Mass*. So, the gravitational 'Charge-to-Mass ratio' is just Mass divided by Mass, which is always 1, for all forms of Matter (even for massless things like photons, this is true; of course, they do not have Mass, so the definition of 'Charge-to-Mass ratio' becomes a little more abstract and mathematical, but the relationship nonetheless holds).
This has a very direct consequence. If all material particles are accelerated by the same rate, then we can always find an accelerating coordinate system in which those particles are not accelerating at all but are either standing still or moving at uniform velocity. In short, *the effects of Gravity can be canceled out by a geometric transformation*!
This makes Gravity very similar to another force closely related to inertia: the 'centrifugal' force. When we are on a merry-go-round, no actual interaction is pulling your body away from its center. There is no force. What we feel is a pseudo-force, which arises as a result of your motion in a non-inertial reference frame: the rotating reference frame of the merry-go-round. The only actual force is the force acting on your body through the seat in which you sit, keeping us in that rotating reference frame instead of allowing your body to follow an inertial (straight) trajectory.
So, it is strongly tempting to view Gravity the same way: as a pseudo-force, which arises as a consequence of us sitting in a non-inertial reference frame, with the only actual force acting on our body being the force exerted by the floor, preventing us from following an inertial (free-falling) trajectory.
But reality is a tad more nuanced. Unlike the centrifugal (pseudo-)force, the gravitational force has sources: everything with Mass-Energy contributes to the gravitational field. And this gravitational field itself is a material field in a very direct sense of the word: it carries Energy and Momentum and can be detected (as indeed it has been, in the recent gravitational wave observations by LIGO (*L*aser *I*nterferometer *G*ravitational-wave *O*bservatory), but also indirectly, first back in the 1970s, through observing close binary star systems that lose Energy by emitting gravitational waves).
And it's not like other forces cannot be described using the language of geometry. In fact, such a geometric description (through what are called *covariant derivatives*) is part of the standard toolset of Quantum Field Theory and the celebrated *Standard Model* of Particle Physics. The key difference is that the geometry in this case depends on the Charge-to-Mass ratio of the particle experiencing that geometry. In contrast, as mentioned for Gravity, the Charge-to-Mass ratio is the same, just 1, for all objects, so it plays no such role: the geometry is the same, no matter what particle is used to measure it. When you hear the Gravitational Field described as a field that 'couples universally and minimally to matter', that's what it takes for the universal geometric interpretation to be possible.
Ultimately, what it boils down to is what was mentioned moments ago, that Gravity has sources. Why does that matter? We can do Quantum Field Theory just fine in the curved geometry of SpaceTime of General Relativity. There are interesting consequences to be sure (one of the most striking is the realization that the 'particle' concept is not at

all fundamental; two accelerating observers may not agree on what particle content they see) but the theory is consistent, and it also respects *causality*. But when we introduce matter (which is described by Quantum Field Theory) as the source of Gravitation, we run into an insurmountable problem: quantum fields (characterized by things that are not numbers) determine *SpaceTime curvature* (which is characterized by numbers). In short, Einstein's famous Field Equation becomes meaningless: it asks how many apples it takes to make an orange.
This leads us to not read too much into the geometric interpretation, and instead view Gravitation as yet another field, like the Electromagnetic field and consider quantizing it. Even without knowing how the quantized theory works in detail, we know what it would look like in the 'perturbative limit' of Weak Gravitational Fields: it would be expressed in terms of quanta that we call *gravitons*.

This would be the end of the story if we had succeeded in quantizing Gravity. But we have not, despite decades of theoretical efforts. Which leaves other possibilities open. One of them, arguably the ugliest yet most successful approach, is to simply accept the status quo: what if Gravity is not quantized? What if Matter is represented in Einstein's field equations not by its quantum-valued fields but by the corresponding 'expectation values', i.e., ordinary numbers? This is an ugly hack, a kludge, but it works miraculously well: this 'Semi-classical Gravity' accurately describes any conceivable experiment or observation that we can carry out and would fail only in the earliest moments of the Big Bang or in the final instants of existence of a particle falling into a black-hole singularity.
Perhaps we don't need gravitons at all; perhaps, it is true that Gravity is only a *pseudo-force*. Or perhaps it is as real a force as Electromagnetism, but one that can be interpreted as geometry because the underlying field couples to Matter *universally* and *minimally*. The question remains open for now.

"… It is wrong to think that geometrization is something essential. It is only a kind of crutch (Eselsbrücke) for the finding of numerical laws. Whether one links 'geometrical' intuitions with a theory, is a ... private matter." (Einstein to Reichenbach, 1926, as quoted in 'Why Einstein did not believe that General Relativity geometrizes Gravity').

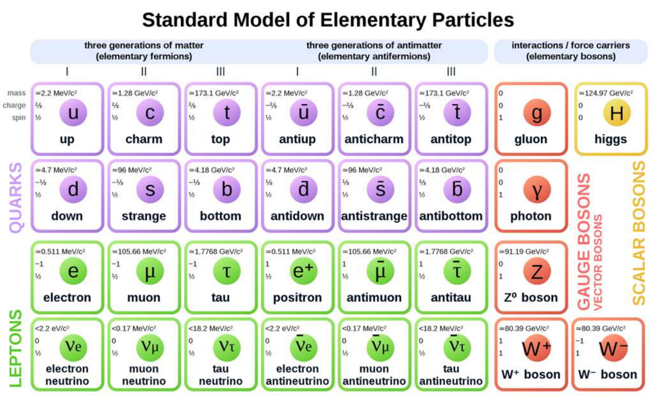
13 -

Why must there be a Quantum Theory of Gravity?

Einstein's Equation for Gravity reads (SI units):

$$\boldsymbol{R}_{\mu\nu} - \frac{R}{2}\boldsymbol{g}_{\mu\nu} - \Lambda \boldsymbol{g}_{\mu\nu} = \frac{8\pi G}{c^4}\boldsymbol{T}_{\mu\nu},$$

where $\boldsymbol{g}_{\mu\nu}$ is the *metric* tensor of SpaceTime manifold, $\boldsymbol{R}_{\mu\nu}$ is the *Ricci Tensor* formed from the metric, R is the (*scalar*) *curvature* of SpaceTime surface, $\Lambda\,(\approx 0)$ is the (negligible) *Cosmological Constant* (or Vacuum Energy-density), G is the *Newtonian gravitational constant*, and $\boldsymbol{T}_{\mu\nu}$ is the *Stress-Energy-Momentum Tensor* of Matter. So, *geometry* is collected in the left-hand side while *physical stuff* $(\text{Matter}+\text{Energy})$ is collected in the right-hand side.
We already know that all 'physical stuff' (the particle and field content of the *Standard Model of Particle Physics*, which includes leptons, quarks, electromagnetism, nuclear interactions and even the Higgs boson) are best described by a Quantum Theory. Which means that the 'true' value of $T_{\mu\nu}$ cannot be a number but a *quantum operator*.



But the left-hand side of Einstein's equation above is a number. So crudely put, we have an equation that says that a number equals something that is not a number. Of course, this is an absurdity. One band-aid solution is to write down the ad-hoc field equation of 'Semi-classical' Gravity, where the *tensor operator* $\boldsymbol{T}_{\mu\nu}$ is replaced by its *expectation value* (i.e., by a *number*):

$$\boldsymbol{R}_{\mu\nu} - \frac{R}{2}\boldsymbol{g}_{\mu\nu} - \Lambda\boldsymbol{g}_{\mu\nu} = \frac{8\pi G}{c^4}\langle T_{\mu\nu}\rangle .$$

In almost all cases, *this equation is more than sufficient*; the only known exceptions would be the *extreme* Gravity regime near a gravitational singularity inside a black-hole, or the earliest instants after the Big Bang. Everywhere else, the semi-classical approximation works fine.
However, if we wish to go beyond band-aids and arrive at a truly *unified theory* that incorporates Gravity along with all other particles and forces, we expect that instead of changing the right-hand side of Einstein's equation to a number, it would be the left-hand side that would be changed to an operator, thus treating SpaceTime itself on a quantum footing. This would be a truly quantum Theory of Gravity. And while we may never be able to detect gravitons directly, a working Quantum Theory of Gravity may be a prerequisite to truly understanding Physics near singularities (be it black-holes or the Big Bang).

14 -

Why can't Quantum Mechanics explain Gravity (at least, so far)?

First of all, one should explain what *known* Physics can do, before explaining where the problems lie.
Contrary to what you may occasionally hear, we can do Quantum Field Theory on the curved SpaceTime background of General Relativity. The theory has some striking consequences, not the least of which is that the notion of a 'particle' becomes observer-dependent, and depending on the circumstances, where some observers see particle content, other observers see nothing (the technical background is that once SpaceTime is curved, there is no privileged flat Minkowski-background, and the so-called 'Fourier decomposition' of a field, which is what gives rise to the field quanta that we recognize as *particles*, is different in different accelerating reference frames).
It is also possible to introduce *quantum matter* as a source of Gravitation, but only in a rather inelegant way. Quantum matter is represented mathematically using quantities that do not behave as numbers. SpaceTime, on the other hand, is characterized by numbers. To make the equations work, quantum matter is represented instead by an average of sorts, the so-called *expectation value*. This allows us to have an equation with numbers on both sides. This is called Semi-classical Gravity. It may be an approximation, a kludge, but Semi-classical Gravity accurately describes all regimes accessible to us through experiment or astronomical observation. This means, unfortunately, that Nature seems to offer no hints as to how we can go beyond this level of description.
What we would like to have is more than an ad hoc semi-classical equation, but a proper Quantum Field Theory of Gravitation, or equivalent. The problem with Gravitation starts with its *coupling constant*, Newton's constant of Gravitation. This is a dimensioned constant, that is, it has units attached. In units preferred by particle physicists, the gravitational constant has units of *length squared* or units of *inverse Mass* squared. It is known that a theory with such a coupling constant is not renormalizable: that is, the usual technique of removing the infinities that arise in a quantum field theory and produce consistently finite results *do not* work for Gravitation.
This is a problem that so far found no satisfactory solution. Semi-classical Gravity works but it is inelegant. For a while, there was hope that, in Gravitation, the unwanted infinities cancel out each other anyway but that has not been the case. Many different approaches have since been tried, ranging from novel approaches to quantizing gravity to not quantizing gravity at all. Ultimately, maybe the real problem is that beyond Semi-classical Gravity, Nature offered no hints so far. Much as we'd like to think that we are smart enough to figure out things on our own, that has never been the case: Physics is dead without data.
Therefore, Quantum Physics so far, fails when it comes to Gravity because a way to measure the quantum effects of Gravity was never found, and thus we're trying to solve a riddle without any clues.

15 -

If Quantum Mechanics is for very small things and General Relativity is for very large things, then what about things in between? Is there a size or situation in which neither paradigms work?

While it is true that Quantum Mechanics is usually observed with very small things, that is not always the case. The correct expression would be 'few degrees of freedom', that is to say, few independent ways for a system to move, rotate, wiggle, etc. .
An electron can move in three spatial directions and has two spin states. It has three spatial degrees of freedom and an additional spin degree of freedom with two discrete values. It is not the physical size of the electron but this, its few degrees of freedom, that makes its behavior manifestly quantum mechanical.
The more the degrees of freedom, the more any quantum behavior gets 'averaged out', so to speak. So, it really boils down to the expected level of accuracy as to when it is okay to forget about Quantum Mechanics and just use Classical Physics.
As to General Relativity, however, it is equally valid in the classical and in the quantum domain. Here is a title from

the noted physicist Robert Wald: 'Quantum Field Theory in Curved SpaceTime and Black-hole Thermodynamics'. The title says it all: it is manifestly possible to do Quantum Field Theory in the curved SpaceTime of General Relativity.

So, what is it, then, that the two being incompatible? They are, but only insofar as the source of Gravitation is concerned. General Relativity tells us that Gravitation (i.e., the curvature of SpaceTime) is sourced by the Stress-Energy-Momentum Tensor of Matter. In General Relativity, this tensor consists of a bunch of ordinary numbers. Not so in Quantum Physics: numbers are replaced usually by mathematical operators, that obey different rules of Mathematics. So, the fundamental equation of General Relativity, Einstein's Field Equation, becomes non-sensical: it equates apples (real numbers) on one side with oranges (non-numbers) on the other side.

The expected resolution of this conundrum would be to turn Gravity into a Quantum Field Theory, but that hasn't worked so far, for deeply technical reasons. Another resolution is a cheap cop-out, a kludge, but one that works surprisingly well: replace the 'quantum' Stress-Energy-Momentum tensor with its so-called 'expectation value', essentially an *average*, which is in the form of numbers. When we do that, we get a theory (it is called Semi-classical Gravity) that works almost flawlessly everywhere except for the earliest instants after the Big Bang and deep inside black-holes, near the singularity.

Everywhere else, we have a healthy synthesis of Quantum Field Theory and General Relativity, offering predictions at any reasonable level of accuracy that we can *replicate* through experiment or astronomical observations.

16 -

When an object quantum tunnels into a black-hole, would just one atom change, or the whole object? Would objects with more Mass or density have a greater chance of turning into black-holes?

It is indeed surmised by some (notably among them, Freeman Dyson (Rev. Mod. Phys. **51** (3), 1979)) that Matter, in particular lumps of Matter greater in Mass than the Planck Mass of about $2 \cdot 10^{-8}$ kg , can collapse into a black-hole through *quantum tunneling*.

The reason why this can happen is that every lump of matter, even something as small as $2 \cdot 10^{-5}$ g , self-gravitates. And although very strong forces (electrostatic, strong nuclear, the pressure arising from the Pauli Exclusion Principle) exist that prevent matter from collapsing upon itself, these forces are, ultimately, finite, and on very short scales, gravity prevails over even the strongest repulsive force. As a result, the collapsed state is of lower Energy, compared to the uncollapsed state.

This is why stars greater than about 2.3 solar Masses can collapse into a black-hole under their own *self-gravity*. For smaller objects, however, the barrier represented by the repulsive forces is too great for Gravity to overcome in a classical collapse process.

But this is where quantum tunneling comes in. It is exceedingly rare for a macroscopic object to show such coherent behavior, but it is not completely excluded. And Dyson actually calculates how long it would take for a macroscopic Mass, on the average, to quantum tunnel into a black-hole state. For a Planck Mass object ($\sim 2.17645 \cdot 10^{-8}$ kg , essentially, a small speck of dust), it's about $10^{10^{26}}$ years , a 10^{38}- digit number.

Such timescales are completely beyond our comprehension or imagination, but in a universe with an eternal future, they exist. And thus, according to Dyson (for what it's worth, a reasonable layman can quite agree) over such incredibly long timescales, small lumps of Matter will spontaneously collapse into black-holes, which then would pretty much instantaneously evaporate in bursts of Hawking Radiation. Ultimately, this seems to me like a mechanism by which any remaining lumps of matter in this incredibly old, dark, dead future universe convert into radiation, which will then redshifted into oblivion by that universe, which still expands at an exponential rate under the influence of a positive cosmological constant This is due to Dark Energy.

So, in answer to the question, it is macroscopic objects (or macroscopic parts of larger objects) that will quantum tunnel into a black-hole state. This is why the process is so incredibly improbable that we end up with double exponents simply trying to express the number of years that it takes for something like that to occur.

It is a mind-boggling thought though ultimately rather depressing: This process would represent the final act in our Universe, as any and all remaining lumps of matter dissipate away as *waste heat*, only to be redshifted to infinite wavelength and vanish, leaving behind a completely empty, featureless void.

17 -

Where is the gravitational 'center' of the Universe, the place where all Matter would collapse to if the Force of Gravity were strong enough to overcome the apparent contemporary expansion?

On cosmological scales, the Universe is considered to be homogeneous, and isotropic on length scales greater than 200 Mpc (Mega-parsecs) or ~ $6.5 \cdot 10^{8}$ light-years. This is (approximately) about $5\,\%$ of the radii of the *visible* Universe. Stated another way, viewed on any scale greater than this, it becomes very difficult to distinguish one 'patch' or 'box' of the Universe from the next.
It gets more complicated though. We can imagine that the visible Universe extends in a bubble around us. The distance from us to the edge of the bubble is going to be roughly the age of the Universe (13.8 Gya $(\cdot 10^{9}$ (i.e., billion) years) times c, the speed of light. Let's keep it simple and call it $\sim 1.4 \cdot 10^{10}$ light-years.
Now, let's imagine that an observer, is as far away as the 5% number mentioned earlier. His bubble is going to extend basically 5% further than ours but he won't be able to see the *back* 5% of our bubble. If we continue to take different bubbles from different spots, we will start collecting an 'ensemble' of *visible* or *Hubbleian Universes*. If we take our entire ensemble and 'glue' them all together without duplicating anything, we will have pasted an infinite number of Hubbleian Universes together and will have an infinitely large super-bubble that is *spatially flat* in any way you look.
And since we are dealing with distances *extremely* much larger $(\ggg)$ than 200 Mpc, it will be very difficult to distinguish one point from another in the material inside the super-bubble. So, to put it bluntly, it can be argued that the Universe *has no center*. There are more sophisticated arguments that rely on attempted descriptions of the Universe pre-Big-Bang. This could be expressed mathematically as a limit from calculus. The limit estimated average ends up with an *indefinite* form $(+\infty - \infty)/2$, i.e., with no decisive result and, unfortunately, no clue (yet) to the solution.

18 -

Can an Electromagnetic Field slow down clocks and deflect light like a Gravitational Field?

Yes, it might.
Perhaps the most significant property of Gravitation is that it is *universal*. It applies to every object the same way, regardless of that object's material composition. Which means that to the extent that it affects clocks, it affects all clocks the same way. There are no exceptions.
Now consider Electromagnetism. Surely, for instance, the presence of a magnetic field will affect a clock made of steel parts. Or surely, a clock made of plastic parts will behave differently if it acquires an electrostatic charge?
But, of course, the thing is, we can always build a clock that is unaffected by Electromagnetism. For instance, we can make a clock from non-magnetizable parts in a shielded enclosure.
This is not something that can be done with Gravity. There are no materials that are neutral to Gravitation or shield Gravitation. This follows from the universality of Gravitation.
Same goes for deflecting light. Sure, an Electromagnetic Field can deflect light. That's what lenses do: it is the electromagnetic properties of the transparent lens material that deflect light. But not all forms of matter deflect (or absorb) light in the same way, and we can always find materials that barely affect light. This is not the case with Gravity: The *gravitational deflection* of light is determined by Mass alone, and material composition is irrelevant.
In the end, it turns out that it is possible to express Electromagnetism using the language of Geometry, just like Gravity. However, when it comes to Gravity, there is only one Geometry: all forms of Matter, all material particles are governed by that one-and-only-one *Geometry*. For Electromagnetism, there is no such unique geometry. The actual geometry depends on the nature (e.g., the Charge-to-Mass ratio) of the object or particle that is used to probe the field.

19 -

When a star collapses into a black-hole, it doesn't spontaneously gain loads of Mass. So, where does the gigantic gravitational pull come from?

It doesn't come from anywhere. At a given distance, the Gravitational Field does not change. For instance, if the Sun were to collapse into a black-hole (it cannot, it's too small for gravitational collapse, but let's ignore that for now), the Earth's orbit would not change because the Sun's gravitational field would remain unchanged.
The difference is that we can get a lot closer to a black-hole. Right now, the Sun's radius is a little less than 700,000 km. That means that even if we wanted to, we cannot get closer to the center of the Sun than about 700,000 km because that's where we hit the Sun's surface. And even if we could somehow burrow under the Sun's surface, the gravitational acceleration would actually decrease, as soon there'd be a lot more Sun above your head than beneath our feet.

But if the Sun were to collapse into a black-hole, its radius would shrink from 700000 km to a little under 3 km. So, we could get more than 200000 times closer to the Sun without any of the Sun being above our heads; all of it would be beneath our feet still.
And when we are 200000 times closer to an object, its gravitational pull is $4 \cdot 10^{10}$ times stronger. That's where the gigantic gravitational pull comes from: because a black-hole is very, very compact, we can get very, very close to it while still being entirely outside of it, thus experiencing the full strength of its Gravitational Field up close.

20 -

Shouldn't gravitons have Mass since they escape a black-hole while light doesn't?

Virtual particles that mediate an interaction should not be confused with *free* particles that constitute Radiation. Light does not escape a black-hole. Similarly, Gravitational Radiation does not escape a black-hole.
But a black-hole can have an electric charge (the simplest charged black-hole solution is the Reissner-Nordström black-hole). Such a black-hole interacts with electrically charged objects through the Electromagnetic Field; i.e., in the *perturbative* Quantum Field Theory description, it exchanges *virtual photons* with those objects. The same way it exchanges *virtual gravitons* (in a putative *perturbative* Gravitational Quantum Field Theory) with other sources of Gravitation.
None of this has anything to do with whether or not gravitons have rest-Mass. Particles with rest Mass are no more capable of escaping a black-hole than massless particles. But this applies to 'real' particles that form radiation. In other words, a black-hole cannot emit light, and no matter what shenanigans happen inside its event horizon, it also won't emit gravitational radiation. Interactions, however, are another matter; virtual particles (which, really, aren't miniature cannonballs but rather, a pretty picture associated with the series expansion of an awful integral that expresses how quantum fields interact with one another) are not subject to the same rules.

21 -

How does SpaceTime tell Matter how to move?

It is not SpaceTime proper (i.e., neither Space nor Time) that tells Matter how to move, but rather, the *Gravitational Field* (the formal 'cause') determines how we measure distances between events in SpaceTime. Because it determines the *measured geometry* (the formal 'effect') of SpaceTime, this field (also known as the 'metrical' field, or simply 'metric') is sometimes considered part of SpaceTime. The metric, together with Space and Time, forms a 'metric manifold' and sometimes it is this metric manifold that is labeled 'SpaceTime'. Such an ambiguous terminology is the source of a lot of confusion.
The metrical field determines how distances are measured. The resulting geometry is no longer (pseudo-)Euclidean, and 'straight' paths are no longer straight lines. Matter follows the straightest paths determined by the metric, the so-called *geodesics*.
If Gravity alters the passing of Time and Gravity is different everywhere in the Universe, then how can there be any standard of Time?
The answer is that indeed, if your clocks are sufficiently accurate, the concept of Standard Time becomes meaningless. This is not a purely theoretical problem, by the way. Present-day atomic clocks are accurate enough to measure very tiny differences in the Earth's Gravitational Field. We are talking differences in altitude measured in tens of centimeters or less! And, of course, gravitational anomalies due to varying density (e.g., caves, mineral deposits, groundwater) can substantially change the rate at which such an ultra-precise clock ticks.
So, two high precision atomic clocks at two different locations on the Earth will not stay in sync, because of these differences in the gravitational potential. And thus, it becomes a question: which one should be 'standard'? What does 'standard time' mean anyway?
It is not sure if there is a sensible answer to that question, other than simply declaring one specific location the standard, and compare all other clocks to it.

22 -

In the context of trying to unify GTR with QM, most people seem to talk about quantizing Gravity, thereby pushing GTR toward the quantum side. Why not do it the other way around?

How many apples does it take to make an orange?
That is basically the dilemma that arises from Einstein's Field Equations. These equations connect Gravitation (represented by the metric of SpaceTime) and all forms of matter (represented by a quantity called the Stress-Energy-Momentum Tensor (see Issue 48, p. 23).

Our best theory of Matter is a Quantum Theory. Which means that the Stress-Energy-Momentum Tensor of Matter is a ‘quantum quantity’, fundamentally different, mathematically speaking, from classical quantities.
So, if classical numbers are apples and quantum quantities are oranges, we have a dilemma: Gravitation is expressed in terms of apples, Matter in terms of oranges, and an equality between the two is just not possible.
The Quantum Theory is ‘superior’ to the Classical Theory in the sense that it can account for things that the Classical Theory cannot, and yet it yields the Classical Theory as a limit. Which is why the obvious route to reconciling Gravitation and our best theory of Matter would be through quantizing Gravitation. That is, turning classical apples into quantum oranges.
Except that it doesn’t work. So far, no one succeeded in creating a viable Quantum Theory of Gravitation. So the obvious question presents itself: why not try the other way around?
Giving up the Quantum Theory is not an option, of course. Its successes are too numerous to count. But there is one thing that we can do: instead of having a quantum quantity in Einstein’s field equations, we can use its ‘average’, its so-called ‘expectation value’.
It actually works. The resulting theory is called Semi-classical Gravity, and it can actually account for all observed phenomena, indeed pretty much all phenomena that we can ever hope to observe using physically realizable instrumentation.
So why don’t we just accept this and move on? Because Semiclassical Gravity is ugly. It looks like a kludge, a cheap cop-out. Instead of explaining how things work, it sweeps the discrepancies under the rug by averaging them away.
That said, until and unless a better theory is found, or unless we find some explicit observational signature of Quantum Gravity, Semi-classical Gravity may remain the best answer that we have.

23 -

What is the Gravity inside a black-hole?

Victor T. Toth calculated that the Gravity of a black-hole is about $2.25 \cdot 10^{9}$ m/s². Calculating the Gravity of a black-hole is tricky business, because Newtonian formulas really fail there.
The Newtonian formula gives finite acceleration (but big) values for small black-holes at the event horizon. For really big supermassive black-holes, the acceleration may be even smaller, small enough for a human to survive.
But that’s not reality. Let us put it in the form of another question. How powerful must your rocket be to be able to hover? And the answer is, at the event horizon your rocket has to be infinitely powerful. Anything less than infinite, and you are doomed to cross the horizon and become trapped. So that, then, is the relativistic answer: contrary to the Newtonian formula, *the gravitational acceleration at the event horizon is infinite*.
Inside the black-hole, things get really weird. Simply put, time and the radial coordinate switch roles here. There is no ‘center’; what you may think of as the central singularity is now a moment in future time, not a location in space. And to the extent that there is acceleration, yes, there is, but it is acceleration in the temporal direction, inevitably taking you toward that singularity. Also, the event horizon is no longer a surface to which you can return, but a moment in past time, to which you cannot return without a time machine.
Eventually (that ‘eventually’ is measured in milliseconds in the case of a stellar sized black-hole but may be hours in the case of a truly large supermassive black-hole) you still end up getting ripped to shreds as different parts of your body experience wildly varying rates of time dilation, and finally, your existence ends with the singularity. Well, that’s what the conventional theory says anyway; how the picture might change in light of Quantum Gravity remains anyone’s guess at our present level of knowledge.

24 -

We consider that Electromagnetic Force is far more powerful than Gravitational Force but one can wonder, on what factors are we comparing to? Gravitational Force may be negligible in case of an atom, but what about black-holes? It reaches infinity there.

The comparison is usually done at the level of elementary particles, specifically the elementary charge carrier, the electron.
If we look at, say, the Earth as a whole, it is electrically neutral but quite massive, so obviously, its gravity dominates.
Yet even though the Earth weighs $6 \cdot 10^{18}$ (6 billion trillion) metric tons, we can suspend a heavy object on a simple string, and the electrostatic forces binding the molecules of that string together are more than sufficient to resist the pull of Gravity. Therefore, comparison on the level of elementary particles makes sense.

25 -

If Space and Time are not separate by a single entity called SpaceTime, why does cosmic inflation only talk about the expansion of Space, but not Time? Was it not SpaceTime that inflated?

Just because SpaceTime is SpaceTime does not mean that Space and Time have to behave the same way.
In fact, it does not mean that space and space must behave the same way. Take Physics here on the surface of the Earth. Clearly, Physics is rather different in the horizontal plane vs. the vertical direction. Yet we do not doubt that 3-dim space is an integral whole, not 'plane-line', which must be split into a horizontal plane and a vertical line.
This even though, e.g., pilots even use different units to measure the horizontal (using nautical miles) vs. the vertical (using meters or feet).
In the case of the Standard Cosmology, the assumption is that there is a reference frame in which the Universe is *spatially homogeneous* and *isotropic* (that is, a symmetry exists between the three spatial directions). The symmetry does not extend into the Time direction, in part because the time direction is qualitatively different from the spatial directions anyway. Under this assumption, we end up with a highly symmetry SpaceTime, in which Space undergoes uniform expansion as a function of Time.
In contrast, and by way of an alternate example, when we look at a ray of light, a high degree of symmetry exists between the spatial direction of its propagation and the time direction; the other two spatial directions are treated differently.
Many other possibilities exist, including those with high degrees of symmetry and those with no symmetries at all. They are all examples of SpaceTime.

26 -

Does a black-hole have any temperature?

In the classical Einstein's theory, black-holes are objects of pure geometry. They absorb everything and emit nothing, and as such, would correspond to a temperature of 0 K.
If we consider Quantum Physics, however, there is *Hawking Radiation*: intuitively (though, it must be admitted, somewhat misleadingly) * described as the creation of particle-antiparticle pairs near** the event horizon, with sometimes the negative Energy particle of the pair falling into the black-hole, with the positive Energy particle escaping to infinity. A distant observer would see this as the black-hole emitting feeble radiation. The radiation would have the standard blackbody spectrum known from Thermodynamics, corresponding to a temperature that is inversely proportional to the black-hole's Mass.
This temperature is very small for astrophysical black-holes. A black-hole with the same Mass as the Sun would have a temperature of about $6 \cdot 10^{-8}$ K . Actual black-holes are even larger (at least about three times as massive as the Sun) so their temperature is less than $2 \cdot 10^{-8}$ K .
The blackbody radiation, therefore, is in the form of radio waves with wavelengths measured in tens of kilometers or longer. The power of this emission is exceedingly tiny and proportional to the inverse square of the black-hole's Mass. For a black-hole as massive as the Sun, it would be about $9 \cdot 10^{-30}$ W (i.e., 9 would be the 29th digit after the decimal point when this value is expressed in watts). Such a tiny emission is, of course, completely undetectable, making it unlikely that we will ever be able to confirm the existence of Hawking Radiation directly.

* This particle-antiparticle pair production picture is nice and intuitive, but also misleading: one must remember that in Quantum Field Theory, fields are supreme, particles are just convenient and intuitive labels attached to terms in a series expansion of an integral, and when it comes to accelerating observers or curved SpaceTime — and spacetime is certainly curved in the vicinity of a black-hole! — two observers won't even agree on the particle content, so what appears as a state populated with particles to one observer may appear as empty vacuum to another.

** But 'near' the event horizon shall come with a huge caveat: as the wavelength of photons produced here is more than an order of magnitude bigger than the size of the black-hole (the radius of a one solar Mass black-hole is about 3 km) 'near' really is 'near' in the sense a football field is 'near' the ball placed somewhere inside it.

27 -

If the Universe is flat, then, how do we have 3 dimensions?

The word 'flat' has several meanings.
Something can be 'flat' as in 'flattened', 2-dim. But this is not the meaning used when the Universe is described as 'spatially flat' in Physical Cosmology.
Something can also be 'flat' if it has no curvature. Our physical Cosmos, to the best of our knowledge, has no such curvature on the largest of scales. That is, the sum of the angles of a triangle formed, e.g., using laser beams over extragalactic distances, would be $180°$. In contrast, a Universe with *positive* spatial curvature would have these angles

sum to *more* than $180°$; whereas a Universe with *negative* spatial curvature would have the angles sum to *less* than $180°$.
The fact that on the largest of scales, little wrinkles in SpaceTime (local changes in the Gravitational Field due to stars and galaxies and whatnot) notwithstanding, there is no curvature, is described by the word 'flat'. Alternatives would be hyperbolic (*negative* curvature) or 'spherical'; again, this is not meant to imply the 2-dim surface of an ordinary sphere, rather its higher dimensional analog, a 3-dim sphere.

28 -

The Law of Conservation of Energy says that 'Energy cannot be created or destroyed. It can only be transformed'. Does that same rules apply to photons?

It's said that 'Matter cannot be created nor destroyed'. Does the same rule hold true for photons?
Many things are 'said' that just aren't true. This is one of them.
The whole point of our best theory of Matter to date, Quantum Field Theory, was that it accounts for the creation and destruction of Matter. There are even names for this: the relevant mathematical operators are called 'creation' and 'annihilation' operators. They exist for all field quanta, including photons, electrons, quarks. They can all be 'created' and 'destroyed' and it happens all the time.
There are certain quantities that cannot be created or destroyed: Energy, (Linear) Momentum, Angular Momentum, Electric Charge, etc. These are so-called Constants of the Motion, related at a very deep level, as we know since the discovery of Amalie Emmy Noether (1882-1935) more than a century ago, to the basic symmetries of the universe. But 'Matter' is not one of these quantities.

29 -

If Dark Energy is getting stronger (accelerated expansion of Universe), where will it get Energy from? Does it violate the laws of Thermodynamics?

No, the laws of Thermodynamics or Energy Conservation are not violated by Dark Energy.
Dark Energy's distinguishing characteristic is its *negative pressure*.
Think what happens to Matter with positive pressure under self-gravity. Gravity does work by causing a cloud of matter (e.g., a cloud of gas) to contract; the cloud, in turn, has increasing pressure and temperature, which is where the work done by gravity goes. If you could somehow 'switch off' Gravity, the cloud would explode as all that Energy, stored in the form of *heat* and *pressure*, is released, converted back into Kinetic Energy.
When pressure is negative, the opposite happens. Gravity causes a cloud of stuff with negative Energy to expand (this sounds weird until we consider a more pedestrian example of similarly weird behavior: bubbles rise in the sea because of Gravity). The work done by Gravity, in the case of Dark Energy, ends up creating more Dark Energy. If that didn't happen, we'd end up losing gravitational Potential Energy without any gain that would balance that loss. So, this is how, in the end, all conservation laws remain satisfied.

30 -

Why do some scientists describe the zero Mass/infinite-density point of a black-hole as a doughnut or ring shaped, inside a black-hole?

First of all, let's forget 'zero Mass/infinite-density point'. A black-hole is fundamentally a 4-dim thing, an object of SpaceTime, not just Space. In particular, the singularity of a Schwarzschild black-hole is not a point in Space but a moment in Time. Observers inside a Schwarzschild event horizon experience a collapsing universe that becomes denser over time everywhere, until the moment in time comes when the density becomes divergent, worldlines terminate, and there is no future anymore. That moment in Time is the singularity, not some point in Space.
But this neat, clean picture is true only in the case of perfect *spherical* symmetry. When a black-hole has *Angular Momentum* (i.e., it *rotates*), *it is not spherically symmetric anymore*. Whereas densities in the *radial* direction become divergent, densities in the *tangential* direction do not. This can be envisioned as a 'ring-shaped' singularity, which is simultaneously true and misleading: true if we wish to, say, plot the shape of the singularity using suitable plotting software, but misleading because the singularity is still a moment in time, not a geometric object floating in space. The thing that changes is how the interior of the black-hole's event horizon approaches that moment in time.
A sensical advice? Let's forget point-like or ring-like, unless you wish to study the 4-dim SpaceTime geometry of a Schwarzschild or a Kerr black-hole. If we want to understand what the singularity is, what matters is not its shape, but rather, that it is a *future* moment in Time (which means the end of Time for anything inside the event horizon), not something floating in space.

31 -

If the Higgs boson in the *False Vacuum* theory is 'true', how would Light, Mass, Matter, Energy, and the Laws of Physics function in the *True Vacuum*?

While it's very difficult to offer a meaningful layperson's description of Physics prior to symmetry-breaking, it should perhaps mention, by way of an answer, that this is actually how the theory is presented.
That is to say, we first write down a theory of massless, interacting fields, including a so-called *Higgs doublet field*, with its symmetry-breaking potential.
Then, we work out the consequences of this *unstable Higgs Field*, how it results in a decay of the Vacuum (it's usually not called a *false* Vacuum, because it has no stability in the Standard Theory) into a new, lower Energy state, which is the Vacuum that we observe (the stable, *true* Vacuum), and how particles interacting with this Vacuum via the now non-zero-Vacuum expectation value of the Higgs field start to behave as massive particles as a result.
So, *true* Vacuum is what we live in today, whereas the *unstable* Vacuum (not called *false* Vacuum because it was never stable, not even briefly) is the Vacuum in which fields with *unbroken symmetries* live.

32 -

Are black-holes just stars vibrating at a frequency outside our visual field?

Looking behind the question, reading between the lines, presumably this question is based on two fundamental misunderstandings concerning black-holes:

a. that we have seen them and don't know what they are;

b. that we observe them only in the optical range of wavelengths.

Neither of these statements holds true. Black-holes, first and foremost, are theoretical predictions. They existed as predictions decades before they were first (indirectly) observed in binary star systems. When they were finally observed (Event Horizon Telescope (EHT) project, April 10, 2019), the observation confirmed what we already suspected based on established theory. We did not need to look for new explanations; we had a readily available, solid theoretical explanation long before any observational facts came to be at our disposal.
Black-holes are observed (or mostly, not observed, for all the obvious reasons) at all frequencies, ranging from radio waves to gamma rays. Suspected black-hole companions in binary star systems do not emit any electromagnetic radiation at any frequency (what is observed is the behavior of the companion star and the behavior of matter falling into the black-hole.) The famous recent image of an actual black-hole (the 'shadow' of the photon sphere of the M87* black-hole obscuring part of its accretion disk) was taken at radio wavelengths, not visible light.
So no, black-holes are not just stars. Black-holes are the end result of *gravitational collapse*, as predicted by Einstein's General Theory of Relativity, as first worked out by Schwarzschild in 1916, as worked out first in detail by Oppenheimer and Snyder in 1939, and as first observed in a binary star system in the early 1970s.

33 -

How do physicists say that Einstein's Theory of Relativity breaks down in the *interior* of a black-hole when it is not possible to make observations of the interior of a black-hole?

We have recognized something important: the fact that scientific inquiry should concern itself with phenomena that can be observed (directly or indirectly). We cannot directly observe the singularity of a black-hole, so, unless what is going on inside the singularity can be indirectly observed, there is no need to hypothesize scientific laws governing said interior.
In fact, General Relativity is a self-consistent theory in this sense; it predicts that we will never observe matter that has fallen through the event horizon and hit the singularity, therefore it is able to postulate that said matter simply ceases to exist (however, as the matter fell into the hole, its own gravitational field was combined with that of the rest of the hole; the field equations predict that such curvature persists even when the matter no longer exists. Thus, to an external observer, the hole now seems more massive than it was before the matter fell in).
However, if one believes that it is possible to indirectly observe the internal state of the singularity, then it becomes necessary to determine the physical laws that describe and govern the evolution of that internal state. In fact, most physicists nowadays believe that black-holes evaporate through Hawking Radiation, and a significant fraction also believe that as the black-hole evaporates, the radiation carries away information about the matter that fell into the hole, so that by the time the hole has evaporated completely, all of the information that originally fell in has been re-emitted in a scrambled form. In order to predict the state of the radiation that comes out, therefore, we need to understand the internal state of the singularity. General Relativity is not up to that task since, as previously stated, its take is that there is a singularity and matter is simply obliterated when it reaches that point. Instead, it's widely believed that a Quantum

Theory of Gravity is required, and that it will show that there is no singularity (in other words, the center of a black-hole is extremely, but *not* infinitely dense).
Saying that General Relativity 'breaks down' is an oversimplified way of saying that not only can we not use GR to understand the singularity, but it can't even be approximately used for that task because it is formulated in terms of real numbers and cannot handle infinite densities that it itself would be forced to predict.

34 -

Are both Hubble expansion and frame dragging much the same thing since in both cases, objects are carried along with SpaceTime?

These two phenomena are very different, but they are similar in one respect: SpaceTime is not dragging anything anywhere, not even in the case of 'frame dragging'.
SpaceTime has no substance, nor it is sticky. Objects cannot be anchored to it. It has no Energy, no Momentum, no ability to do anything to objects. It is not a physical field.
The thing that can affect Matter is the Gravitational Field, also known as. the SpaceTime metric. Unlike SpaceTime itself, the metric is a physical field, which carries Energy and Momentum, and which interacts with other forms of Matter, influencing them.
The Hubble expansion simply references a state of expansion in which Matter is in. Newton's 1^{st} law applies: a state of uniform motion remains a state of uniform motion unless a force changes it. So, if things in this Universe are flying apart, they will continue to fly apart unless a force alters their behavior. No dragging is needed.
The force that can alter their behavior is Gravitation. It can slow down the expansion due to mutual attraction. More curiously, when stuff with *negative* pressure dominates (this would be the infamous Dark Energy), Gravity can also speed up the expansion. But it is not SpaceTime carrying anything anywhere. It is good old Gravity, or if you wish, the geometry of SpaceTime as determined by the SpaceTime metric, i.e., the Gravitational Field. This, by the way, is a so-called 1^{st}- order effect: the Laws of Expansion (the Friedmann Equations) can, in fact, be derived from Newtonian Gravity alone.
But we know, thanks to Einstein, that the Gravitational Field is more complicated than that. In particular, things such as pressure, internal stresses, and the rate of rotation all contribute to the Gravitational Field of an object. These are 2^{nd}- order effects: generally, they are suppressed (compared to the Newtonian part) to the tune of v^2/c^2, where v would be a typical speed (e.g., the circular orbital (scalar) velocity) in the Gravitational Field equation.
What is pictorially (and, as this question demonstrates, most unfortunately misleading) called *frame dragging* is simply the specific contribution to the Gravitational Field by the rotation of the gravitating system.

35 -

Are singularities multi-dimensional?

A singularity in Mathematics is a point or set of points in the domain of a function where the function is ill-behaved (e.g., divergent, not differentiable, etc).
It is precisely in this sense that the word 'singularity' is used in Gravitational Physics, marking points, or sets of points, in SpaceTime where the Gravitational Field (i.e., the SpaceTime metric) is ill-behaved.
There is no general rule regarding the dimensionality of singular point sets. For instance, the simplest black-hole metric, the Schwarzschild metric, has a single singular point in space, extending throughout *all of time*. So technically, it is one-dimensional, as it extends alongside the time dimension.
The singularity of a rotating Kerr black-hole is said to be ring-shaped. If we also consider the time dimension, it would appear as a cylindrical surface in 4-dim SpaceTime, i.e., it would be 2-dim with 1 *spatial* and 1 *temporal* dimension.
It can be argued that, technically, it is possible to conceive of SpaceTimes in which 3- or even 4-dim singularities exist (i.e., an entire extended region of SpaceTime where the metric is ill-behaved), or perhaps even SpaceTimes with singularities that have fractional dimensions. It is unlikely that it is possible to construct a singular set that have more dimensions than the SpaceTime in which it exists but – we are out of our depth here – Topology can get weird with many counterintuitive results, so one should be cautious here and not make definitive statements.

36 -

What is the *minimum amount of Mass* needed to create a black-hole?

A black-hole results when the escape velocity from a massive system becomes *greater* than the speed of light *in vacuo*. Escape velocity can be affected by adjusting the Mass or the radius of the system. Thus, a black-hole isn't so much about having a very large Mass rather about having a *huge density*.

The smallest black-hole would be one whose $1/2$ of the event horizon radius (Schwarzschild radius) equals the *Mass's Compton wavelength*, which is *the smallest size to which a given Mass can be localized*.
Thus, Schwarzschild radius $=$ 2 · Compton wavelength) , i.e., $GM/c^2|_S = \hbar/Mc|_C$. Solving for M, one gets

$$M = (\hbar c/G)^{1/2},$$

where M is the Mass of the black-hole, c is the speed of light *in vacuo*, G is the Newton's classical Gravitational Constant and $\hbar \equiv h/(2\pi)$ is the *reduced* Planck Constant. The MKSA result is

$$M = \left(\frac{(1.0545718 \cdot 10^{-34}\,\mathrm{J\cdot s})(299792458\ \mathrm{m\cdot s^{-1}})}{6.67408 \cdot 10^{-11}\ \mathrm{m^3 \cdot kg^{-1} \cdot s^{-2}}}\right)^{1/2} \approx 2.1765 \cdot 10^{-8}\,\mathrm{kg}\ \ (\equiv 21.765\ \mu\mathrm{g}).$$

37 -

If a black-hole's surface rotated at $v_{\parallel} = 0.99999\,c$, would the centripetal force create a bulge?

While black-holes do not actually have a surface, it is true that they can *rotate* (hence, have *Angular Momentum*).
Such a black-hole (called a *Kerr black-hole*) does deviate from spherical symmetry, however, it is more than a simple flattening. A Kerr black-hole has a very rich geometric structure.
For instance, in the vicinity of a rotating black-hole there is a region called the ergo-sphere: in this region, no particle can be at rest relative to a distant observer, yet it is still possible for a particle to escape this region, as it is not inside the event horizon. The outer boundary of the ergo-sphere is indeed flattened; but the inner boundary, the event horizon, remains spherical.
The singularity itself is also different: instead of being point-like, it is now described as an extended, 'ring' singularity. And it is situated behind an inner, so-called *Cauchy horizon* and may even feature causality violations. The usual interpretation of these more extreme features is that they are probably non-physical, just mathematical artifacts.
A Kerr black-hole 'rotating at $v_{\parallel} = 0.99999\,c$' would be a near extremal Kerr black-hole. In the case of an extremal Kerr black-hole, the horizons would collapse and vanish, exposing the 'naked' singularity. However, it is generally assumed that such black-holes do not exist in Nature, and indeed, as a black-hole's Angular Momentum increases, it becomes increasingly hard to add to this Angular Momentum (e.g., by dropping rotating matter into the black-hole).

38 -

Do photons have Mass according to the Theory of Relativity and Quantum Mechanics?

Neither the Theory of Relativity nor Quantum Mechanics say anything about the photon Mass. Both theories are agnostic in this regard.
The Theory of Relativity does, of course, postulate the existence of an invariant speed, and waves propagating in a massless field in the vacuum travel at this speed. So, if the photon is massless (and it certainly appears to be) it travels at that speed, too, which explains why we call the *invariant* speed the (*Vacuum*) *speed of light*.
But it is the Standard Model of Particle Physics, a specific application of Quantum Field Theory, which proclaims the photon to be massless. One segment of the theory is the electroweak theory, the unification of the weak force and electromagnetism. The unified force has 4 mediating particles, two charged, two uncharged. Without the *symmetry-breaking Higgs mechanism*, all 4 mediating particles would be massless. The Higgs mechanism endows 3 of the 4 particles with Mass: so, for all practical intents and purposes, we can think of the Z^0-boson of the Weak Interaction as a *massive* photon. But the photon of Electromagnetism remains massless, and this is important insofar as the theory's mathematical behavior (its ability to be "renormalized", that is, the fact that unwanted infinities can be removed from the theory using a systematic and mathematically consistent process) is concerned. So, in the Standard Model of Particle Physics, the photon pretty much must remain massless in order for the theory to work as it does.

39 -

Will a black-hole transform into a star again due to Hawking's Radiation?

No, a black-hole would never transform into a star. Hawking Radiation is basically waste heat, radiated away into space. The only question is, will any remnant be left behind after it happens? It seems that there is no fully formed consensus on this question, in part because it becomes critical as to what we mean by 'black-hole'.
A 'fully formed' black-hole is one that comes complete with an existing event horizon, presumably hiding a singularity. Hawking Radiation can reduce the size of this black-hole, until a Planck-scale remnant remains. Will that

last remnant also disappear through evaporation? Will it become a 'naked singularity'? Or something else? Without a working Quantum Theory of Gravity, we do not know for sure, though it is certain that even if there is a remnant, it will be subatomic in size and nothing like a star.

But actual astrophysical black-holes that result from gravitational collapse are not 'fully formed'. Oppenheimer and Snyder, who first described the process of collapse within the context of General Relativity in their landmark 1939 paper, called it 'continued gravitational contraction'; this reflects the fact that to the outside observer, the collapse appears to slow down due to gravitational time dilation, and the formation of the horizon remains forever in the future. Presumably, then, Hawking Radiation would cause the collapsing matter to evaporate before the horizon ever forms, and thus there will never be a horizon or a singularity; at the end of the evaporation process, nothing remains.

We should hasten to add, though, that Hawking Radiation is an incredibly slow process. A black-hole weighing three and a half times the Mass of the Sun would take about $10^6(10^9)^7$ years (1 *million vigintillion* years) to evaporate in full. Actually, more because such a black-hole has a Hawking Temperature measured in nano-K, meaning it's much colder than the Universe surrounding it, so presently, it would actually gain Energy by absorbing minuscule amounts of the Cosmic Microwave Background radiation. The Cosmos would first have to cool to the point where it's colder than the black-hole before evaporation could even begin.

40 -

The *speed of light* is the *universal* speed limit. What sets this limit? Is it the speed of light or is light itself constrained by some other factor?

Richard Feynman was once asked who the world's greatest physicist was. His answer surprised many because Einstein was then all the rage: "From a long view of the history of mankind – seen from, say, ten thousand years from now – there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the Laws of Electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade".

Differential form	Integral form
$\nabla\cdot\mathcal{E} = \dfrac{\rho}{\varepsilon_0}$	$\oiint_S \mathcal{E}\cdot\hat{n}\,dS = \iiint_V \dfrac{\rho}{\varepsilon_0}\,dV$
$\nabla\cdot\boldsymbol{B} = 0$	$\oiint_S \boldsymbol{B}\cdot\hat{n}\,dS = 0$
$\nabla\times\mathcal{E} = -\dfrac{\partial\boldsymbol{B}}{\partial t}$	$\oint_C \mathcal{E}\cdot dl = -\iint_S \dfrac{\partial\boldsymbol{B}}{\partial t}\cdot\hat{n}\,dS$
$\nabla\times\boldsymbol{B} = \dfrac{1}{c^2}\left(\dfrac{\boldsymbol{J}}{\varepsilon_0}+\dfrac{\partial\mathcal{E}}{\partial t}\right)$	$\oint_C \boldsymbol{B}\cdot dl = \dfrac{1}{c^2}\iint_S\left(\dfrac{\boldsymbol{J}}{\varepsilon_0}+\dfrac{\partial\mathcal{E}}{\partial t}\right)\cdot\hat{n}\,dS$

Maxwell's Equations in SI (rationalized MKSA) unit version (*Feynman' form*)

Maxwell's Equations, written above in the *Feynman's form*, i.e., assuming $\mathcal{E}$ and $\boldsymbol{B}$ as the 'true' *fundamental* fields, define the properties of the second Quantum Field called *Electromagnetism* $(c^2 := 1/(\varepsilon_0\mu_9))$.

There are many other ways of writing these equations but, however they are written, they say something noteworthy. For example, the second equation (Gauss' Law of Magnetism) says there can't exist magnetic monopoles, even though the equation above it defines *electric monopoles*, or the force caused by stationary charges. Remarkably, the 4th equation can be solved for the speed of electromagnetic phenomena *in a vacuum*, $c := 2.99792458\cdot10^8$ m/s (present day, agreed-upon *exact* value).

James Clerk Maxwell published his equations way back in 1861-1862. Experimenters were excited! It was immediately apparent that light ought to be an electromagnetic phenomenon because other experimenters, who were at the time independently trying to measure the speed of light, were coming up with velocities not one part in a thousand different!

Note that Maxwell's calculation of c was actually a function of two physical measurements, the *Permittivity*, ε_0, and the *Permeability*, μ_0, of a *Vacuum*, values that are not hard to measure. So, Maxwell's c is perfect and absolutely depending on the accuracy of the other constants, which describe only the nature of the medium, nothing else! To believe anything can go faster than light is to believe that there is something that has a permittivity and permeability *less than Vacuum*. So, in a very fundamental way, we can't get a more accurate measurement for c and for any electromagnetic phenomenon in a Vacuum. Let's remember, Maxwell was talking only about the characteristic of the Electromagnetic Field in a Vacuum. All the Relativity issues came later with Einstein (who said he 'stood on the shoulders of giants' …, i.e., Maxwell's).

It is hard to overestimate the significance of Maxwell's accomplishment. He put together the basic ideas of Faraday, Gauss, Ampère, and other 19th century scientists who were then experimenting with the newly discovered principles of Electricity and Magnetism. They seemed to be related, but nobody was quite sure how. The telegraph had just been invented. The American Civil War had begun. It was the era of wood-fired steam engines and horses and muskets. People worked under whale-oil lamps and candles. But the ideas of Maxwell in the early 1860s were almost miraculous. Interest in his theories among scientists was phenomenal.

Now, is the speed of light absolute? c is determined by the nature of the Vacuum in 'normal Space'. The 'Space' during *cosmic expansion* was not 'normal'. The Space inside a black-hole might not be 'normal'. The Space beyond what we consider the Universe is probably not 'normal'.

Is the Space inside stars and various celestial bodies 'normal'? Would the core of a star, where the density is 10 times the density of depleted $^{235}\mathrm{U}$, be 'normal' Space? We would surmise that nobody yet knows.

41 -

If the Universe expands faster than the speed of light, does Dark Matter expand faster than the speed of light too?

The Universe *is not* expanding at a speed higher than light's *nor* it is expanding at a speed lower than light's. Cosmic expansion *does not* have a speed measured in distance-divided-by-time, so it cannot be compared against the speed of light in a vacuum.

Cosmic expansion is characterized by the Hubble parameter, which tells you how fast systems are moving away *from each other* given their distance. Its value is about $70\ \mathrm{km}/(\mathrm{s}\cdot\mathrm{Mpc})$. Therefore, two systems that are 1 million parsecs apart (1 megaparsec, $1\ \mathrm{Mpc}$, is about $3\cdot 10^6$ light-years) move away from each other, on average, at $7\cdot 10^4\ \mathrm{m/s}$.

Two systems at $10\ \mathrm{Mpc}$ from each other move away from each other, on average, at $700000\ \mathrm{m/s}$. At $100\ \mathrm{Mpc}$, it would be $7\cdot 10^6\ \mathrm{m/s}\ (\equiv 7000\ \mathrm{km/s})$, and so on.

In an *infinite* Universe it means that there are indeed systems far enough away from each other that they are moving away from each other at a speed $\gg c$, e.g., $\sim 233c$. But this is not the 'flat SpaceTime' of Special Relativity. Neither of those two systems exceeds the speed of light *locally*, and they are mutually invisible to each other, hidden by 'effective' event horizons.

Now we know where the misunderstood notion that the *expansion* has a speed coming from: many people imagine the Universe as a bubble of matter expanding into *pre-existing* space. In that case, it would make sense to speak of the speed at which the boundary of this bubble grows.

But this is not how expansion works: there is no bubble of matter and there is no boundary. Matter is everywhere and, on average, the Universe is the same everywhere. Its density decreases over time everywhere. This is harder to imagine, but *this is the way it is*.

As for Dark Matter, it doesn't do anything special. Its dynamical behavior is that of 'dust', matter with negligible pressure. It may consist of particles that remain yet to be discovered, but its behavior is perfectly ordinary dynamics (as far as we know, anyway).

42 -

If the escape velocity of a black-hole is larger than the speed of light, then what would prevent an object falling from infinity into the black-hole to not reach a speed greater than that of light?

That is precisely what happens, but the devil is in the details.

As an object falls towards the event horizon of a black-hole, its speed *increases*. At the event horizon, its speed is the *vacuum speed of light*; and beyond the event horizon, it is actually faster than the vacuum speed of light *outside* the horizon.

Except that we never get to see this. Because another effect associated with the event horizon is *time dilation*, which becomes divergent at the horizon. In practice, it means that, as seen by us, distant observers, instead of speeding up the object appears to *slow down*. We never get to see it reach the horizon, because time dilation stretches that last moment in time to infinity. Indeed, we never even get to see the horizon form. And therefore, we never actually get to observe the object moving faster-than-light; that remains forever in our infinite future (indeed, this is precisely how an event horizon works).

43 -

If Dark Matter does not interact with Electromagnetic Radiation, doesn't this imply that there cannot be things like electrons and protons in Dark Matter and, following that, no quarks, leptons or bosons? What is Dark Matter, then?

Well, yes, exactly. The whole point of Dark Matter is that it is assumed to consist of particles other than the particles of the Standard Model of Particle Physics; specifically, particles that do not interact with Standard Model particles in any meaningful way. Not through Electromagnetism, but not through the weak or strong force either.
Having said that, it is not inconceivable that Dark Matter consists of 'Dark Electrons', 'Dark Quarks' or whatever, interacting with each other by exchanging 'Dark Photons'. In other words, a complete 'shadow' sector that mimics the Standard Model but does not interact with it.
Just to be sure, one should not seriously propose it as a theory, nor can an exact 'dark' replica of the Standard Model work. The role Dark Matter plays in cosmological models is *different* from that of normal Matter, and the fact that Dark Matter *does not interact with itself* is a key element of that model.
But it is not altogether inconceivable that Dark Matter consists of particles that mimic at least some aspects of the Standard Model particles.
Then again, maybe Dark Matter doesn't exist at all, and we're just fooled by what is really a modification of the Theory of Gravitation. Until we have independent confirmation of the existence of Dark Matter, this, too, remains a possibility on the table.

44. -

What is wrong with the question 'What existed before the Big Bang?' It is told that this question doesn't make sense, but nobody has never heard a decent layman's explanation as to why.

The question is perfectly OK. When people say it makes no sense, they don't mean that the question in itself is stupid, but that the question has a premise that there was something like time before the Big Bang.
General Relativity – from which the original Big Bang theory was derived by G. Lemaître in 1927, before it was called the Big Bang Theory – views Time and Space not as two separate things, but as one thing, SpaceTime. So it's natural to then conclude that without Space there is no time (at least, not in the sense that we're used to). In this sense, the question is a bit like 'what is north of the North Pole?'
Even St. Thomas Aquinas (13th century) reasoned that time is part of God's creation, so that to ask what existed before would be impossible to answer. According to St. Thomas, time started with 'In the beginning'.
However, this point of view is not the only one, or even the correct one. The fact is that if we run the clock backwards and extrapolate according to General Relativity, we eventually reach a point just before zero – the first 10^{-42} s, also known as the Planck epoch – where General Relativity intrudes on Quantum Mechanics. The problem is that General Relativity and Quantum Mechanics don't play nicely together, so we actually can't model what happened at that time in Space and Time.
That's when Physics as we know it stops, and we need something new, Physics *but not as we know it*. To go beyond that, we need at least a theory of Quantum Gravity, and we don't have such a theory yet.
So, the actual answer to the question 'What existed before the Big Bang?' is: *We don't know*. We could speculate with 'it is possible that *before the Big Bang* completely lacks meaning' or 'we have several super-fun hypotheses, including a white-hole, the big bounce, the zero-Energy Universe hypotheses and countless others', but the short of it is 'we don't know and we lack the tools for a sensical hypothesis, now'.

45 -

Is the *speed of Gravity* pretty much identical to the *speed of light*? Or, even, does the speed of Gravity have to be equal to the speed of light?

No, the speed of *gravitational radiation* (not 'Gravity'! We also don't talk about the speed of Electrostatics) need not be the same as the speed of *electromagnetic radiation* (e.g., the speed of light) *in a Vacuum*. However, they are the same in Einstein's General Theory of Relativity.
On the other hand, they are also different in entire families of alternative Gravity theories, i.e., theories that are modifications of Einstein's Theory. One broad class of such theories is the class of *bimetric* theories, in which the speed of gravitational radiation is determined by a SpaceTime metric, a SpaceTime geometry that is different from the SpaceTime geometry that governs electromagnetic radiation.
The gravitational-wave event GW170817 (was spectacular, in part, because a burst of a gravitational wave signal was accompanied by bursts of electromagnetic radiation (light, radio-waves, X-rays, etc.) from the same event. The event took place some $1.3 \cdot 10^{8}$ light-years from the Earth, yet both the gravitational radiation and the electromagnetic radiation arrived essentially *simultaneously* (to the extent that the arrival times differed, it had to do with how the

physics of the event unfolded, not travel times).
This event told us that if any differences exist in the propagation speeds of gravitational vs. electromagnetic waves, it is too *small* to be detected even over such an enormous distance.
So, whether they have to or not, it appears the Gravitational Radiation and Electromagnetic Radiation *do travel at the same speed*.

46 -

At what frequency or Energy level would a photon have to be to collapse into a black-hole?

The frequency, or Energy, of a photon, is not an intrinsic property. It depends on the observer.
If you are running towards that photon, its Energy will appear *higher*; if you are running away from that photon, its energy will appear *lower* (E-M Doppler effect).
So, no matter how high the photon's Energy is in some observer reference frame, there are always observer reference frames in which that same photon appears as an ordinary visible light photon or as an even lower Energy, radio frequency photon.
So no, a photon cannot collapse into a black-hole.
Lots of photons, however? Perhaps. There is a whimsical name for a (purely theoretical) self-gravitating structure made purely of electromagnetic radiation: *Kugelblitz*, which is German for *ball lightning* (no, it is not implied that a self-gravitating cloud of electromagnetic radiation is the same as ball lightning). And yes, a Kugelblitz can collapse into a black-hole.
However, that is not a single photon but a *large* number of photons forming a medium called a *photon gas*, at sufficient density to have its own photon sphere (the radius within which closed photon orbits are possible) and thus, possibly, self-sustaining and capable of collapse.

47 -

If the accelerating expansion of the Universe eventually destroy atoms, can it reach the point of ripping virtual particles from each other in essentially same process as *Hawking Radiation* being emitted at an event horizon?

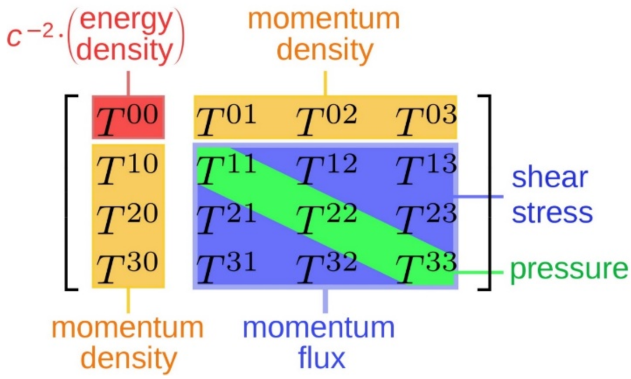
Accelerating expansion applies between gravitationally bound systems, that is, galaxy superclusters. It does not rip gravitationally bound systems apart. It has been written about the hypothetical *Big Rip*, which would be accelerated expansion on steroids, ultimately indeed tearing even atoms apart.
But this would require the presence of something much more sinister than Dark Energy: it would require *Phantom Energy*, stuff with an equation of state so extreme that as it expands under the Force of Gravity (just like Dark Energy, Phantom Energy responds to Gravity as though it was repulsive), causing its Energy density to increase.
We have no reason to believe that this Universe contains any Phantom Energy, and plenty of reasons to believe that it doesn't (in part because its existence would make the whole Universe unstable). But if it existed, its effect is not at all related to Gravitational Vacuum Polarization, that is the mechanism behind Hawking Radiation. It is rather ordinary Gravity that becomes so strong, so extreme, to overwhelm all other forces. The closest thing that one could relate it to would be extreme *tidal* forces, the 'spaghettification' (see Issue 301, P. 138) that may take place near neutron stars or close or inside small black-holes.

48 -

What are tensors, and is Kinetic Energy a tensor?

Think about a *vector* for a moment. In the context of Geometry, a vector is a quantity with a magnitude and a direction. Could we generalize this concept somehow?
Well… think about *pressure*. We are used to thinking of pressure as a simple number, because we usually measure the pressure in *isotropic* media: media that have properties that are not dependent on direction, such as air.
But pressure could depend on direction. In an *anisotropic* medium, pressure in the horizontal direction, for instance, may differ from pressure in the vertical direction. Or pressure in the north direction may not be the same as pressure in the east direction.
Moreover … what is Pressure? Pressure is force-per-unit-area. Any area is *oriented*. The area in question can face northward or eastward, or it can be horizontal or vertical. The orientation of an area element can be characterized by its *normal* vector: a unit vector that is perpendicular to that area element, the length of which is proportional to the size of that area element.
So there we have it: pressure, which is force-per-unit-area, is a number that relates two vector quantities: the force (a vector) and the area element, characterized by another vector.

This relationship can be represented by the mathematical idea of a *rank*-2 *tensor*: a quantity that relates two vectors and yields a number.
In practice, rank-2 tensors can be represented by *matrices* (see below), and the usual rules of matrix multiplication can be used to apply and manipulate them.
No, Kinetic Energy *is not* a tensor. Energy is just a number: it has no direction. In general, however, Energy *can be thought* of as part of a tensor in the 4-dim Geometry of SpaceTime. This tensor, called the *Stress-Energy-Momentum Tensor*, combines the quantities of Energy, Momentum, and the *anisotropic* pressure tensor that has been described above. As a 4-dim tensorial quantity, it can be thought of relating, e.g., the 4-dim velocity (a vector) and the four-dimensional current (a vector too) that together characterize, in 4 dim, a medium interacting with a *potential field*.



The Stress-Energy-(Linear)Momentum Tensor (contravariant representation)

49 -

Are singularities multi-dimensional?

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It is precisely in this sense that the word ‘singularity’ is used in Gravitational Physics, marking points, or sets of points, in SpaceTime where the Gravitational Field (also known as. the SpaceTime metric) is ill-behaved.
There is no general rule regarding the dimensionality of singular point sets. For instance, the simplest black-hole metric, the Schwarzschild metric, has a single singular point in space, extending throughout all of time. So technically, it is 1-dim, as it extends alongside the time dimension.
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Technically, it can be argued, it is possible to conceive of SpaceTimes in which 3- or even 4-dim singularities exist (i.e., an entire extended region of SpaceTime where the metric is ill-behaved), or perhaps even SpaceTimes with singularities that have *fractional dimensions*. It very hard to believe that it is possible to construct a singular set that have more dimensions than the SpaceTime in which it exists, but … Topology can get really weird with many counterintuitive results, so should be extremely cautious here and not make definitive statements …

50 -

If there were *no bosons* and no Gravity, but *only fermions* in the Universe, would the Universe be completely static?

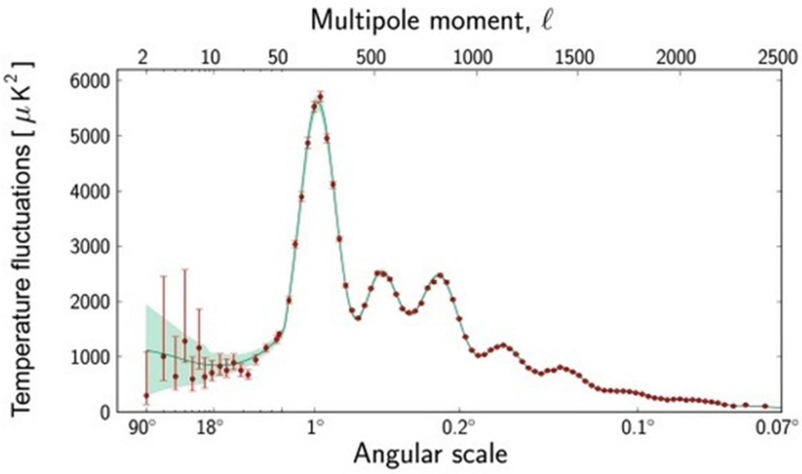
Where does this (often-heard) conjecture come from? Why would a fermions-only Universe be static? Is there some misunderstanding here whose origin, though, is hard to figure out?
Whatever those origins, it is not true that the absence of bosons leads to a static Universe. Even in a Universe with only one type of fermion and no interactions, the fermionic field would have time-dependent solutions, propagating waves, so no, it would not be static.
Nor does a fermion-only theory necessarily mean no interactions. There can be so-called ‘contact’ interactions involving 4 fermions (essentially, two fermions bouncing off each other). It is not obvious how to renormalize such a theory, but there are ways (e.g., making it a higher derivative theory that is finite to all orders, to begin with).
So, there is no principle that states that bosons are required for a Universe to evolve with time or to have interactions. Bosons are seen more naturally as ‘force carriers’, since emitting or absorbing an integral-spin boson makes a fermion remain a fermion or a boson remain a boson, whereas emitting or absorbing a (1/2)-spin fermion changes a fermion

into a boson or vice-versa. But this does not mean that particles cannot interact, e.g., by exchanging pairs of fermions, as indeed high-Energy photons do in photon-photon scattering (e.g., in two-photon physics events like high-eEnergy γ- photons interacting with the γ- photons of the Cosmic Microwave Background).

51 -

We are told that the makeup of the Universe is 73% Dark Energy, 23% Dark Matter and 4% ordinary Matter. How can they be so certain? The Universe may contain more Space and Matter. We may not have discovered it all. Is it right?

No, it is likely to be *wrong*, basically by assuming that these numbers are dreamt up in some sort of philosophical or metaphysical speculation. The numbers may be wrong, but the way they are obtained is a much more rigorous process than your question appears to imply.
Here is one of the most meaningful plots extrapolated from Planck's *power spectrum of Temperature fluctuations* in the Cosmic Microwave Background:



First, … this is hard data. This is a representation of data collected by the *Planck satellite*, a satellite that spent a long time observing the *Cosmic Microwave Background* (CMB) in all sky directions. The CMB exhibits very minute temperature fluctuations, and these are *statistically correlated* across various parts of the sky. The curve that we see here is a representation of that statistical correlation.
Or rather, the data points that we see in this plot are data points derived directly from the observations of the satellite. The curve is a *prediction* based on the known properties of matter, the presumed properties of Dark Matter and Dark Energy vs. Einstein's equations of General Relativity that govern the large-scale behavior of the Cosmos.
The agreement between prediction and the data is striking. And the prediction is very sensitive to the relative ratios of normal Matter, Dark Matter and Dark Energy. If we were to assume, say, 80% Dark Energy or 60% Dark Energy (or no Dark Energy at all) the curve would appear very *different*; the agreement with the data would be *lost*.
Of course, we may still be wrong. Neither Dark Matter nor Dark Energy has ever been detected directly. And it is possible that an alternative theory of Gravity might account for all these and similar observations without Dark Matter or Dark Energy.
But, it should be emphasized, the certainty that we have, the reason why we trust the Standard Cosmological Model is precisely because, most of the times, it offers such exquisite agreement between predictions and data.
Not always. There are still some predictions that are going awry, including the recently much publicized tension between 'local' measurements of the Hubble parameter vs. cosmological measurements. Perhaps these disagreements will go away as we understand the data better. Perhaps they will point the way to an improved theory. Science is not static, not standing still: we continue making new discoveries, both observational and theoretical.
But the reason why we actually trust what we already have is because it is hard-earned knowledge (not speculation) tested against a large body of experimental and observational data.
And of course, it is possible that distant parts of an infinite Universe, far beyond the observable Universe, have very different physical properties that, we may never know. The subject of our study is the part of the Universe that we can, in principle, see. That's what Physics is about: *it's about things we can observe*.

52 -

When a photon is cosmologically *red-shifted*, where does its Energy go?

The Energy of a cosmological photon doesn't go anywhere. Kinetic Energy is *not* an intrinsic property of an object. Its value *depends on the observer*.
Suppose you fire a bullet. It has plenty of Kinetic Energy, right?
But suppose we are flying alongside that bullet in my supersonic airplane and reach out and grab the bullet. As far as we are concerned, the bullet was standing still, motionless relative to my airplane. When we grab it, there is no Kinetic Energy to worry about; the bullet is motionless in our reference frame, so, its Kinetic Energy is 0.
So, where did that Energy go? The answer is: it didn't go anywhere; it was never the same in two different, incompatible reference frames.
The same applies to *cosmological photons*. When we measure those photons, we are *not* in the same reference frame as the medium that emitted that photon. *First*, we are moving relative to that medium, at relativistic speeds; *second*, we are in a different gravitational environment: the average gravitational potential in the present epoch is much less than what it was in the early Universe, that was much denser.
If we stood on the surface of an object that has a strong Gravitational Field (such that its surface gravitational potential is comparable to the average gravitational potential at the time the photon in question was emitted) and that object was moving at a high rate of speed relative to the isotropic reference frame (such that it actually remains motionless relative to the medium where the photon was emitted) the Kinetic Energy of the arriving photon that you measure would be the same as it was when the photon was emitted.
In short, the photon *en route* did not interact with anything: it didn't gain or lose Energy. The difference in Energy arises because the observer's (our) reference frame is *not* the same as the rest frame of reference of the medium where the photon was emitted, *due to cosmic expansion*, the resulting velocity between distant objects, and the resulting change in Gravitational Potential over time.

53 -

Why can't 'Dark Matter' be just ordinary Matter that does not emit light, like the multitudes of rogue (not currently orbiting a star) planets recently discovered?

Because of the Cosmic Microwave Background measurements.
Originally, when it was just 'missing Mass', what we're saying was thought to be a good possibility – it was just non-light emitting ordinary matter. Many people started to look for this. The Massive Compact Halo Object (MACHO) Project was a decade-long campaign to very cleverly use microlensing to try to detect dark, small objects like-black-holes or planets, or really anything that might be *non-luminous ordinary Matter* in compact form. When that search failed, there was talk of 'crystalline' molecular hydrogen that would be transparent and smooth, so not compact. All kinds of ideas were floating around. None of these were ever detected, but astronomers are very clever about constantly coming up with new ideas to try.
All this changed when the CMB was measured. The COBE, WMAP and Planck satellites have measured the CMB to now incredible precision. The key feature is those giant bumps seen in the harmonic power spectrum, the so-called *acoustic peaks*: it can be straightforwardly derived where these bumps come from. Unlike galaxies, which are hugely complex systems, the early Universe can be mostly solved with a pen and paper. Once you specify the ingredients of the Universe, the predictions are mostly a matter of just doing the mathematics. There's not a lot of uncertainty. In teaching Cosmology, it is derived in class where these bumps come from; the calculation is long and complicated but the math is straightforward.
Here's the thing: the ratio of heights of the 1^{st} and the 2^{nd} bump is directly related to the ratio of *non-light interacting* to *light-interacting* Matter. Notice: it wasn't said 'Dark Matter' but 'non-light interacting' Matter.
Today, Dark Matter could be planets or black-holes, ordinary matter that just *doesn't emit light*. But in the early Universe, at 380000 light-years after the Big Bang, there are no planets or stars around. All that Mass would all have been in the form of ionized atoms. And ionized atoms interact quite strongly with light.
The bumps come from *acoustic oscillations*, i.e. the light-interacting (ordinary!) Matter and light sloshing around in the potential well set by the Dark Matter. Since ordinary Matter interacts with light, it gets pulled around by fast-moving light, whereas the Dark Matter doesn't because it doesn't interact with light. This creates a separation between these components that causes the 'ringing', i.e., the acoustic oscillations.
It's a bit like taking a trough of water and pulling a ladle through it. The water gets pulled by the ladle, but the trough doesn't. The result is that waves are set up. These waves are what shows up as bumps in the harmonic power spectrum: the longest wave corresponds to the length of the box (which in the case of the CMB, is 380000 light-years). This longest wave represents the first bump. The CMB measurements indicate that Dark Matter not only has to be non-light emitting, but also non-light interacting.
Using the CMB, we can measure how much non-light interacting stuff there is in the Universe at 380000 light-years.

Using galaxies today, we can measure how much non-light emitting stuff there is around today. And here's the kicker: we measure the exact same amount!
That's either a remarkable coincidence, or it shows that the Dark Matter today is indeed non-light interacting, *not just non-light emitting*. That is, it's not just dark planets or something like that; such objects can absorb and reflect light, even if they don't emit (much).
This is why the CMB is probably the strongest evidence (among a lot of strong evidence) for Dark Matter today.

54 -

Two spheres with the same size are supposed to fall at the same time regardless of their Mass. We all know isn't true for a ball full of helium, that will not fall at all. Isn't it true also for very big Mass differences, even without an atmosphere?

Two spheres of the same size are not supposed to fall at the same rate in an atmosphere.
Two spheres of the same size will experience the same air resistance, i.e., at any given speed, air resistance will produce the same non-conservative force, slowing their downward acceleration.
But the gravitational force that pulls the spheres down depends on their Mass (minus their buoyancy in air). Therefore, a sphere with less Mass will experience the same air resistance but less downward force than a sphere with more Mass; in other words, the sphere with less Mass will fall slower (or not at all, if its buoyancy cancels out its Mass altogether, resulting in *no net downward force*).

55 -

What is the relationship between the laws of Special Relativity and those of Quantum Mechanics?

Schrödinger's first attempt was to formulate a relativistic wave equation for Quantum Mechanics. He failed: the resulting equation predicted nonsensical negative probabilities (the equation later was rediscovered as the Klein-Gordon equation describing a scalar field in Quantum Field Theory). Instead of a relativistic equation, then, Schrödinger proposed a nonrelativistic variant, which is known to this date as the Schrödinger equation.
The first successful Relativistic Quantum Theory was produced by Dirac, in the form of the *Dirac Equation*, which describes a relativistic *half-odd spin* particle such as the electron, and its corresponding antiparticle.
One of the shortcomings of a quantum particle theory, even a relativistic one, is that it does not preclude violations of causality in the form of faster-than-light signaling (that, in certain observer reference frames, would be seen as backwards-in-time signaling). This is one of the motivations for Quantum Field Theory.
Quantum Field Theory is relativistic 'by design', i.e., its equations are invariant under transformations between inertial observer reference frames (in fact, the equations can be written in generally covariant form, that is to say, they remain valid even in the curved background of Gravity in General Relativity). In a Quantum Field Theory, faster-than-light signaling is canceled out exactly, so causality is strictly preserved. The theory's other virtue is that it accounts for particle *creation* and *annihilation*, something that a quantum particle theory *cannot* do.

56 -

Are Universes *white-holes*? Is the cosmic microwave background the white-hole event horizon?

The Universe might indeed be a white-hole (a time-reversed black-hole with a past singularity). The possibility cannot be completely excluded that we are, in fact, observing the interior of a white hole metric from within its event horizon.
But no, that event horizon is not the CMB. For observers inside a white-hole event horizon, the event horizon is part of the future, not the past. World lines of such observers begin at the singularity itself. If the Universe were completely transparent, then we would 'see' this past singularity in every possible sky direction.
But the Universe is not completely transparent, and in the distant past, it was quite opaque. What we see, in every possible sky direction, is this glowing, opaque but incandescent gas, that filled the Universe when it was about 380000 years old, which is when the gas gradually became transparent so its own glow, instead of being reabsorbed by the gas, began to travel in all possible directions unimpeded.
This glow now appears, redshifted by a factor of about 1100, as microwave radiation. This is what we see with radio telescopes. It is not a horizon of any sort; if we had means to see beyond the CMB (e.g., perhaps using some future technique involving neutrino astronomy) we could see the Universe when it was much younger than 380000 years.

57 -

Does Big Bang Theory also explain the origin of Space, Time, and Energy or merely explain how the Universe changed over cosmological time?

What is colloquially referred to as the ‘Big Bang theory’ (though no cosmologist uses that phrase unless she\he were talking at a television show), i.e., the Physics of an expanding Cosmos in accordance with the rules of General Relativity and Quantum Field Theory, describes how the Cosmos evolved from its earliest moments until the present day. It says nothing about why the Cosmos exists, whether it has any origin outside of its existence, or any reason, purpose, or rationale for its existence. Arguably, such questions will remain in the realm of priests or philosophers, not physicists.

58 -

Can General Relativity be modified to describe a Universe with universally *repulsive* Gravity?

Sure. Just change the *coupling constant of Gravitation*, i.e., Newton’s constant $G = 6.674 \cdot 10^{-11}\,\mathrm{m}^3/(\mathrm{kg}\cdot\mathrm{s}^2)$, to a negative number and quickly, you have *repulsive Gravity*.
Presumably, other than Gravity, everything can continue to work exactly as before. Energy conditions are still satisfied, the Standard Model of particle physics still applies, etc. …
Where things might go haywire is in Cosmology. Absent a cosmological constant and spatial curvature, there is no homogeneous and isotropic solution (the Hubble-parameter would be imaginary). So either spatial curvature or the cosmological constant must make up for the negative contribution of the Matter-Energy density (multiplied by Newton’s constant) as a precondition for such a Universe.
And, of course, there will be no self-gravitating systems like galaxies, solar systems, stars, or planets.

Addendum:
In the answer above, only a Classical theory of Gravitation was considered. It is of course true that a spin-2 graviton yields an attractive force, but this is predicated on the assumption that the coupling constant is *positive*, which in turn is based on the notion that a consistent QFT with a negative coupling constant does not exist. This is certainly the case for QED, as *a negative coupling constant means no ground state*. However, since we do not actually have a Quantum Theory of Gravitation, we do not know if this consideration applies to Gravity, and we cannot a priori exclude a *negative* coupling constant, with the consequences described above.

59 -

Is a bowling ball on fabric just a helpful analogy for how gravity works in a 3+1 SpaceTime? If so, what is SpaceTime actually like?

It is actually a very bad analogy that has been misleading laypeople for generations.
The ‘bowling ball on fabric’ analogy suggests two things: that there is, in fact, some external force pulling the bowling ball down, and that as a result, Space (i.e., the fabric) becomes distorted.
In reality, there is no external force, and furthermore, Newtonian Gravity, in the case of weak fields and nonrelativistic speeds, is due almost entirely to *how Time is distorted*, *not Space*. So, the ‘fabric’ doesn’t get bent. Rather, the closer you are to the source of a Gravitational Field, the slower your clock ticks.
This deflects the trajectories of material objects according to the principle of least action: namely that the trajectory between two events (locations in space at a specific moment in time) is such that the time actually measured by a clock traveling with the object is maximized (no, it’s not trivial, nor intuitive, but when we work it out, we get the trajectories that are calculated using Newtonian Gravity, with small relativistic corrections).

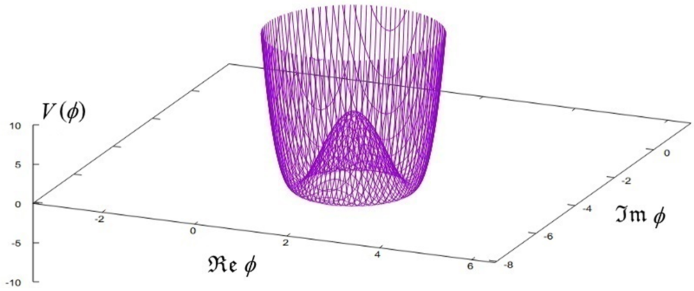
60 -

In the Early Universe, Electromagnetic and Weak forces were combined to form the Electroweak force. But as the Universe started to cool down, the force was separated. The Universe still expands and cools down, so can a similar happen in the future?

This is indeed a definite possibility, as a matter of fact, according to some physicists, a near scary certainty.
The separation of forces to which the question alludes is since the *Higgs* (*scalar*) Field has a *self-interaction potential* with its (infamous) ‘Mexican hat’ behavior: the Potential Energy of the field is in the form

$$V(\phi): \lambda\phi^4 - \mu\phi^2$$

graphically depicted as something like this below:



The ‘false Vacuum’ at the center of the plot (technically not a false Vacuum as it was not even a metastable state) decayed into the ‘true Vacuum’ represented by the lowest Energy state of the Higgs Field (the bottom of the surface, on either side of the center).

So, the question is, is this lowest Energy state of the Higgs field really the ‘true Vacuum’ or is an even lower Energy state possible?

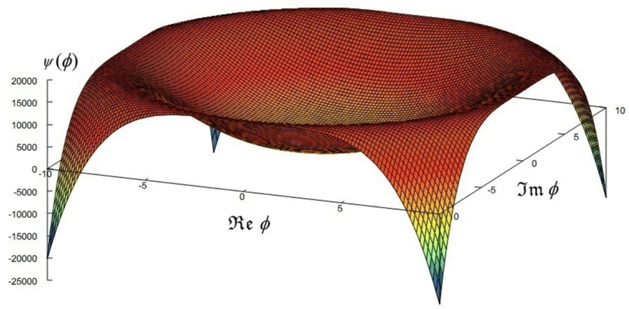
The unpleasant answer is that a lower Energy state (possibly, a state that is not bounded from below at all) is indeed favored by the Standard Model of Particle Physics, given the *observed* values of its parameters.

This is due to *quantum corrections* to higher-order quantum interactions. Therefore, as a result, the quartic term $\lambda\phi^4$ is replaced by something proportional to

$$\psi(\phi) := (\lambda^2 - \kappa^2)\phi^4 ln(\phi/\mu),$$

where μ is an Energy scale term (the *renormalization* scale) and κ is some constant. If $\lambda < \kappa$, this term is *positive* when $\phi < \mu$, but becomes *negative* (and *unbounded* from below) for $\phi > \mu$.

In short, there is a potential barrier, but beyond that potential barrier is an *infinite abyss*, a *never-ending collapse*:



And no matter how large that potential barrier is, given enough time the probability that it will be breached, if nothing else, by *quantum tunneling*, will approach unity.

Is this really in our future? Or is there a new lowest Energy limit due to some high Energy quantum behavior of which we are completely ignorant? Or perhaps this lower Energy state does not exist at all? We do not know. But in its simplest form, the Standard Model does appear to predict that such a collapse will eventually happen. Not now, not tomorrow, perhaps trillions of years or more from now, but the possibility is definitely there.

If that were to happen, even if a new, stable vacuum is reached, physics as we know it would end. Particle masses would change, particle interactions would change. The atoms that we know from the Periodic Table, would cease to exist. The Universe would become literally unrecognizable to us (not that we could actually exist in it to observe it, as our existence would be fundamentally incompatible with the Laws of Physics in this *new* Universe).

As to what might trigger this phase transition, it can be argued that is anyone’s guess. But the ‘silver lining’, if it can be called that, is that we would receive no advance notice. When it happens, we would simply cease to exist. Out of the many different ways to go, vanishing in less than a blink of an eye along with the entire Universe is one of the least painful alternatives, so there.

One slight technical difference between the spontaneous symmetry breaking in the Early Universe and this hypothetical phase transition is that whereas the former indeed happened because the Universe cooled down such that typical kinetic energies became less than the Energy level of the central peak of the ‘Mexican hat’ potential; the future phase transition happens (if it happens) not because of further cooling but because of quantum tunneling or something similar, which allows the Universe to ‘sneak’ through the potential barrier to reach the lower states of Energy on the other side.

61 -

How massive does a black-hole need to be in order to swallow a whole neutron star?

Actually, it is possible for even a very small black-hole to swallow a whole neutron star, depending on how they collide. Anyway, it makes sense to face this question through the *Roche-limit* and compare it to the Schwarzschild radius of the black-hole. The Roche-limit tells us how close a satellite (in this case, a neutron star) can get to a primary system (in this case, the black-hole) before getting ripped apart by tidal gravitational forces.
A neutron star can be treated essentially as a self-gravitating liquid sphere. In this case, the Roche-limit is given by

$$d \approx 2.44\,r\left(\frac{m_{\rm bh}}{m_{\rm ns}}\right)^{1/3},$$

where $m_{\rm bh}$ and $m_{\rm ns}$ are the Masses of the black-hole and the neutron star, respectively, and r is the neutron star radius. Assuming a neutron star of 1.5 solar Masses $(\approx 2.98\cdot 10^{30}\,{\rm kg})$, with a radius of 10 km, this formula tells us that the black-hole has to be at least 19 times as heavy as the Sun for the Roche-limit to fall within its Schwarzschild radius (given by $r_S = 2Gm_{\rm bh}/c^2$).

62 -

If photons are their own anti-matter, how can light get trapped in a black-hole?

What do we think happens *exactly* when a Matter particle and its anti-Matter counterpart meet? They annihilate each other, we say. Not exactly.
We should not forget that, for an isolated system, Total Energy is *conserved*, Linear Momentum is *conserved*, Angular Momentum is *conserved*. So, when a Matter and an anti-Matter particle meet, we get particles that, on the whole, carry the *same* total Energy, Linear Momentum, and Angular Momentum.
When an electron and a positron (anti-electron) meet, they may produce a pair or a triplet of photons. When two photons meet, … well, most of the time, they just fly through each other, but if their total combined Energy exceeds the sum of the rest-Masses of an electron and a positron, they may in fact produce an electron-positron pair. This is called two-photon Physics but such processes happen very seldom.
In any case, none of this makes any difference insofar as the black-hole is concerned. Whether it is in the form of photons, electrons and positrons, or whatever, the only thing that matters on the outside is the *total* Energy (Mass), (Linear) Momentum, and Angular Momentum of the black-hole. Which remains the same no matter what those photons get converted into if they do.

63 -

Does the event horizon of a black-hole actually exist? PBS SpaceTime (a public digital network) stated it is just a *coordinate singularity*.

We can split this question into two separate ones.
Yes, the event horizon is 'just a coordinate singularity'. This is an important statement because for quite some time, many physicists (Einstein included!) were under the impression that the singular behavior of Schwarzschild coordinates at the event horizon means that the Laws of Physics break down there. It took quite a while to understand that this is not the case; that while Schwarzschild coordinates (indeed, *any static* coordinate system) fail at the event horizon, coordinates such as those co-moving with an infalling observer do not, and provide a perfectly reasonable description of SpaceTime at, and beyond, the event horizon.
So, is the event horizon real? Undoubtedly so *in a very specific sense*: it is a *surface of no return*. An observer that crosses the event horizon is committed to fall into the (real) central singularity of the black-hole or at least remain forever trapped behind the horizon (e.g., in the case of a rotating black-hole).
But … is the event horizon really *real*? Maybe not. Because to an observer who sits outside the horizon and never crosses it, the horizon never happens. In this observer's reference frame, the horizon *remains forever in the future*. (This is the geometric interpretation of the coordinate singularity in Schwarzschild coordinates). So, the event horizon just never happens insofar as this observer is concerned.
Worse yet, if Hawking Radiation indeed exists and the black-hole evaporates in finite time, the horizon may never even get to form in the first place. These questions represent the boundaries of our knowledge, subject to much debate even today. So, PBS was not wrong when they told us that the event horizon is just a coordinate singularity, but it unfortunately does not tell us if the event horizon actually exists or not. For that, a better understanding of Quantum Gravity is required.

64 -

If Space is expanding, elastic and pliable, and can be dragged, then, what's it made of? It can't be just void, can it? Is it made of Dark Matter or something else?

In the mainstream theory (that is, General Relativity), contrary to what you may read in some less than well-informed popular accounts, Space is *not* expanding. Space isn't a thing: it is not elastic nor pliable, cannot be dragged, is not made of anything. Nor does it have little markers that would allow us to measure it in any which way.
Rather, it is Matter that is *flying apart*. The distance between distant chunks of Matter changes over time. Matter has *measurable* Momentum. It is affected by Gravity. It slows down when Gravity commands it to do so; it also speeds up when Gravity (in the dominating presence of Dark Energy) tells it to, not unlike a bubble that rises in the sea instead of sinking as a result of Gravity.
The matter that is flying apart includes Ordinary Matter as well as the hypothetical constituents we call 'Dark Matter' and 'Dark Energy', distinguished from each other by their so-called equations of state: Dark Matter behaving like a 'pressureless fluid' (also called 'dust') and Dark Energy behaving as a fluid with enormous *negative pressure*.
What causes confusion sometimes is that the word 'SpaceTime' is often used to refer not just to the combination of 3-dim space and 1-dim time, but also the Gravitational Field, which, in General Relativity, also determines the measurable geometry (distances and angles) in SpaceTime by playing the role of the so-called 'metric'. Unlike Space and Time, this metric is a *physical quantity* that exists on its own right, like Matter. It can be measured. It carries Energy and Momentum from place to place in the form of gravitational influences, or even over great distances in the form of gravitational waves. And it, of course, responds to the expansion of Matter since Matter determines the Gravitational Field by acting as its source, just as the Gravitational Field, in turn, determines how Matter moves; i.e., Matter and the Gravitational Field interact with each other.
In fact, it is this relationship between Matter and the Gravitational field that is expressed in the form of Einstein's Field Equations of Gravitation (see Issue 13, p. 6). The underlying SpaceTime is almost *irrelevant*: one of the key principles of Relativity theory is that it works in any coordinate system, so it does not even matter how we define Space vs. Time in terms of setting up our coordinates. In contrast, Matter and the Gravitational Field have tangible, measurable physical reality independent of any choice of coordinates.

65 -

Do black-holes rotate? Or only the Kerr ones?

A rotating black-hole is a Kerr (or Kerr-Newman, if it also has charge) black-hole. So, saying that 'only the Kerr ones' rotate is like saying that only rotating black-holes rotate.
To be more precise, the Schwarzschild metric describes a spherically symmetric black-hole (no rotation). This can be generalized to the axially symmetric Kerr case, which includes rotation; if the rotation is set to zero, we get back the Schwarzschild solution.
A further generalization is replacing empty SpaceTime with SpaceTime that can contain Electromagnetic Fields; the resulting black-hole can be charged (Reissner-Nordström) or charged-and-rotating (Kerr-Newman).
The infamous 'no hair' theorem basically asserts that under a reasonable set of assumptions, this really is it: a black-hole, in addition to its Mass, Angular Momentum and electric charge, has no other discernible properties (that is, 'no hair').

66 -

Is it wrong to use a purely (modified) Newtonian description of the Cosmos, as opposed to trying to imagine curved SpaceTime?

Some of the things that we see in the Cosmos can be modeled very successfully using Newtonian Dynamics. Other things, unfortunately, cannot.
Let's see one example: *cosmological redshift*. For relatively nearby galaxies, it is not a terribly big mistake to attribute that redshift to a velocity-related Doppler shift: distant galaxies are moving away from us, so, as a result of the Doppler effect, light from these galaxies is shifted toward the red end of the spectrum.
But when we look at really distant galaxies, this neat description no longer applies. In addition to the velocity-related shift in frequency, there is also an additional redshift that is *related to Gravity*. Quite literally, clocks in the distant past were ticking more slowly compared to present-day clocks, because the overall gravitational field was stronger.
So, light reaching us from the distant past will appear *lower* in frequency, i.e., *redder*, than it should be if the World were Newtonian. Long story short, Newtonian Dynamics works very well in many situations. But it is not a perfect description of the physical world around us, and the *stronger* the Gravitational Field, or the *higher* the speeds, the *larger* the deviations from a purely Newtonian Universe.

67 -

We often say that tensors are a generalization of *scalars*, *vectors*, and *matrices*, but aren't tensors themselves actually members of a particular type of vector space? Wouldn't that make vectors the more general concept?

The literature on tensors is a hot mess! Physicists and mathematicians, at least those whose aims are somewhat different, come at the subject from viewpoints so distant that it can be hard to reconcile what we read. We're betraying a personal bias when we say that some physicists have muddied the waters so seriously that it seems almost impossible to extract meaning from many of the descriptions one reads.

However badly physicists have bungled the exposition, they've had a critical hand in formulating the concepts, and it seems to many to be essential to inspect the physical motivations.

Physicists and engineers use tensors to represent quantifiable physical 'situations" (we have to be vague here about what constitutes a situation). There is an immediate problem: we need a coordinate system to do this, and there is no god-given coordinate system available. Any coordinate system we use is almost entirely arbitrary. The axes could be moved in some way, or we might have one coordinate system moving with respect to another, or we might be using rectangular or polar or cylindrical or spherical coordinates or curvilinear coordinates on a surface, etc. . Because of this, we have to worry about what aspects of our representation are artifacts of the coordinate system and what features of the representation are intrinsic to the 'situation' we are trying to represent.

The immediate and sad answer is the numbers we use for coordinates depend entirely on the choice of coordinate system, so that a change in coordinate system brings with it a completely different representation. How then, do we manage to extract what is *intrinsic* from all these different representations?

There is a cheap and dirty mathematical conceit that is of absolutely no help: call two representations equivalent if they represent the same situation. This is an equivalence relation, it partitions the set of representations into equivalence classes, and it an entire equivalence class that describes the situation intrinsically. But this is almost a joke!

But not quite: if we can describe how to move about within each equivalence class and distinguish between different equivalence classes – hopefully in a way subject to calculation – then the joke becomes an effective way to describe our 'situation' regardless of the point of view imposed by a particular representation. The idea is that two different coordinate systems can be described by a (computable) transformation that takes coordinates in one system to coordinates in the other system. So, what we need is that our representations can utilize the coordinate transformations in order to change the representation in such a way that the situation represented does not change, instead the description from the new perspective changes to describe the same thing from, metaphorically, a different angle.

This is the basic concept of what a tensor should do. It should represent some situation, and when the coordinate system we use for the representation is changed, the transformation that describes the coordinate change can be applied in some prescribed way to the tensor so that the new representation still describes the original situation. This is why tensors are, with maddening vagueness, sometimes described as 'quantities whose components transform appropriately', as if this description tells us anything at all about what a tensor is.

Linear Algebra provides good examples of issues involved. If we want to compute with a linear transformation, we have to choose a basis and represent the transformation with a matrix. But if we change the basis, the original matrix no longer represents the same thing; we need a new matrix to describe the same transformation with respect to the new basis. We know exactly how to do this: if the original matrix is $\mathbf{A}$ and if $\mathbf{B}$ represents the transformation that takes the new basis back to the original basis, then the matrix for the same linear transformation in the new basis is $\mathbf{B}^{-1}\mathbf{AB}$. Rewrite how this works on the entries a_{ij} of the matrix $\mathbf{A}$ and you get the kind of formula that describes how tensors transform.

It is a substantial task to make these ideas meaningful and escape from the nightmarish profusion of upper and lower indices, implied summations, and arcane index gymnastics that are the bread and butter of those who calculate with tensors.

But the question at hand is whether tensors are a generalization of vectors. A generalization of a class of objects ought to include all the original objects as particular instances of the generalization, and here we often see a logical error: it is true that all rank-1 tensors are vectors, but it is not true that all vectors are tensors (of any rank), so in this rather simple sense, it is wrong to speak of tensors as generalizing vectors. The problem lies with that elusive condition about 'appropriate transforming', which nowhere appears in the definition of a vector space, but rather is an additional condition that narrows the scope of what is a vector, rather than broadening it as a generalization would have to do. A classic example is the cross product $\boldsymbol{v}\times\boldsymbol{w}$, which, when $\boldsymbol{v}$ and $\boldsymbol{w}$ are *linearly independent*, is a vector that fails to transform properly under a reflection in the plane spanned by $\boldsymbol{v}$ and $\boldsymbol{w}$. We know that some accounts try to wiggle out of this 'anomaly' by depriving the cross product of its birthright and redefining it to be a 'pseudovector', and maybe this terminology is useful for those who, after all, must deal with this unfortunate reality, but this infelicitous renaming of things that already make perfect sense shouldn't distract anyone from what is really going on mathematically.

68 -

Instead of defining a new term 'Momentum', what was the problem to always treat it as the product mass · velocity ?

Momentum is a far more generic concept than the product of Mass and Velocity for point-like Masses. What is the Momentum of an extended object? Well, it would be the integral of the product of its Mass-density ρ times the (vector-valued) velocity field, over the volume V of the object: $\boldsymbol{p} := \iiint_V \rho \boldsymbol{v}(\boldsymbol{r}) d^3\boldsymbol{r}$.

Then there is the issue of *relativistic speeds*, when Momentum is no longer the simple product of Mass and velocity. In the limiting case of photons, there is no Mass at all, yet Momentum still exists.
That leads us to how Momentum is defined, in the first place. Not as Mass times velocity but, in *Lagrangian Physics*, as the vector-valued quantity that is a constant of the motion for systems that are invariant under spatial translations. This quantity turns out to be the product of Mass and velocity if the system in question is a point mass, but *not all* systems are point-Masses.
This definition of Momentum is called the *canonical Momentum*, and it also plays a fundamental role when we transition from Lagrangian to *Hamiltonian Mechanics* by way of a *Legendre Transformation*. Hamiltonian Mechanics, in turn, is the foundation for the procedures of *canonical quantization*, which is the formal route from Classical to Quantum Mechanics and from Classical to Quantum Field Theory.
Surely, a concept this important, this central to Theoretical Physics deserves to have its own name.

69 -

Why did Einstein need two Theories of Relativity?

The theory that Einstein presented in 1905, originally called the Theory of Relativity, is about inertial (nonaccelerating, nonrotating) observer reference frames. This theory works well and resolves the previously noted contradiction between the geometry of Space and Time and the Equations of Maxwell for the Electromagnetic Field.
However, Einstein felt that this theory was incomplete in the sense that it treated accelerating (or rotating) observers as second-class citizens. So, he sought an extension of the theory, to which he referred as the 'General Theory', that would treat both inertial and accelerating observers on the same footing.
There were numerous false starts. There were times when Einstein thought that there is no solution. But eventually by 1915, he managed to find the correct form of this 'General Theory'. The previous 1905 version was included in the new theory as a special case (zero system-acceleration).
Over time, the (mathematically much simpler) 1905 theory therefore became known as the Special Theory of Relativity, whereas the 1915 theory became known as the General Theory of Relativity. But these are really not separate theories; the General Theory includes the Special Theory as a limiting case.

70 -

Large black-holes have a density less than that of a neutron star. So they need not to contain a singularity (only, e.g., neutron stars). Is this correct?

A black-hole doesn't even have a volume, never mind a density.
It is, of course, possible to calculate the volume of a sphere that has the same radius as the Schwarzschild radius of a black-hole. But that calculation is valid only in Euclidean space. In the warped SpaceTime of a black-hole, the interior volume of the event horizon has no sensible mathematical definition.
In any case, the standard black-hole solutions (Schwarzschild, Kerr) are, in fact, *Vacuum solutions*. That is to say, the matter density is *zero* everywhere. The black-hole Mass is a property that is customarily assigned to the singularity itself, though even that does not make much sense, since the singularity is not so much a point as it is a future moment in time, accessible only to particles that have crossed the event horizon.
No, a black-hole, e.g., a Schwarzschild black-hole, is the asymptotic limit, the end stage of gravitational collapse. We get the static black-hole in the *infinite future*, when all infalling matter reached the singularity (or got so close to it that it no longer makes a difference) and only the gravitational field remains.
This gravitational field defines an event horizon but, as we saw, the event horizon has no volume, and it is foolish to try to assign to it a density.
One thing about a black-hole solution that is worth remembering, though, is that until this asymptotic end state (with all matter reaching the singularity, leaving only vacuum) is reached, the interior of the event horizon cannot be static. So no, it cannot contain a static neutron star. A supermassive black-hole may swallow a neutron star whole, but that neutron star unavoidably falls towards the singularity and within a very short amount of time as measured by a clock moving alongside it, it would be first eaten up by *tidal effects* and then end up at the singularity, its existence coming

to an end. This moment is never seen by outside observers though, because to outside observers, the event horizon itself and everything that happens there remains forever in the future. Black-hole Physics is weird. Do not expect naïve intuition to work here.

71 -

How is the *Einstein-Hilbert action* derived?

As a general rule, the Action Principle of a physical theory is *not* derived. Rather, it is *postulated*, serving pretty much as the fundamental axiom of that theory.
By way of example, the Standard Model of Particle Physics is stated by way of presenting its *action* (or *Lagrangian*, short for *Lagrangian density*, which is the integrand of the *action integral*), a page-long equation that brings together all the known fields and interactions apart from Gravity into a more-or-less coherent whole (not trying to disparage a beautiful theory here, just reminding ourselves that it is known to be *incomplete*).
On a much simpler level, Maxwell's Theory of massless Electromagnetism can be presented by *postulating* the Lagrangian density

$$\mathcal{L}_{\rm EM} := -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - A_\mu J^\mu\,,$$

with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.
This is all we need to know, in principle, to derive Maxwell's Equations and everything we know about Classical Electromagnetic Theory.
On the same footing, by *postulating*

$$\mathcal{L}_{\rm EH} := \frac{1}{16\pi G}(R - 2\Lambda)\,,$$

amounts to postulating a Gravitational Theory, notably Einstein's (with a *Cosmological* Constant). Alternate theories of gravitation usually begin by postulating a different, or modified, version of this Lagrangian density; e.g., Jordan-Brans-Dicke Theory, arguably the simplest modified theory of Gravitation, promotes the inverse of G to a scalar field ϕ by way of the Lagrangian (give a look back at equations in Issue 13, p. 6)

$$\mathcal{L}_{\rm JBD} := \frac{\phi}{16\pi G}\left(R - 2\Lambda - \omega\frac{\partial_\mu\phi\,\partial^\mu\phi}{\phi^2}\right).$$

None of these Lagrangians are derived: they are simply stated as *postulates* and their consequences are then explored and compared to observation.

72 -

It's often said that Mass and Energy are equivalent. Would it be more accurate to say that Mass is a specific type of Energy?

There is no need to paraphrase what Einstein very clearly expressed in the title of his 1905 paper in which the Mass-Energy equivalence relationship is first introduced: "Does the Inertia of a body depend upon its Energy-content?"
Einstein answers the question in the *affirmative*. The Inertia (which we recognize as the body's Mass, i.e., its ability to resist an *external* force) is, in fact, directly proportional to the body's Energy-content. So, there really is no need to introduce the separate concept of Mass.
What confuses the issue (slightly) is that the meaning of 'Energy-content' depends on the definition of the body in question. For instance, when you look at the Earth, its Energy-content does not include its Kinetic Energy as it orbits the Sun, or the Gravitational Potential Energy of the Earth-Sun system. However, when you look at the Solar System as a whole, its Energy-content includes both these quantities; a distant object, orbiting the solar system, would follow an orbit that is determined by the sum of all such quantities (of course, great, though the Earth's Kinetic Energy is compared to human scales, it is dwarfed by the rest Mass-Energy of the Earth itself, not to mention the Sun, but, in principle, it's all there).
This discussion, on the other hand, should also make it clear that no matter what kind of Energy we consider, we can always find a body for which it is part of that body's Energy-content. So, Mass is not a 'specific type of Energy': it is the sum of all types of Energies for whatever the definition is of a particular body.

73 -

Everything has a cause. What caused the Big Bang?

The premise of this question is false: *not everything has a cause*.
Inside this Universe, as far as we know, everything has a cause. That is because this is a *causal Universe*, a Universe with a *mathematical structure* such that the present fully and unambiguously *determines the future*. So in this Universe, no matter what happens, you can always look at the past and deduce what made that happen, at least in principle. In short, the cause exists.
But it is easy, trivially easy almost, to construct model universes that are *acausal*, universes in which cause-and-effect does not apply, in which the present either doesn't determine the future, or the future is *ambiguous*, not unique.
And insofar as the existence of this Universe is concerned, there is no corresponding past. The existence of this Universe defines time as we know it. So it is not even meaningful to discuss the cause, in a strict mathematical sense.
So, assuming that this universe actually started with an initial singularity (colloquially called the 'Big Bang'), contrary to common sense, there is no logical expectation for it to have a cause, quite the contrary: rigorous mathematical logic tells us that *no such cause exists*.
Mind you, there is also another misconception lurking behind this question: that it 'all started with a Big Bang'. Perhaps … but that's not what standard Cosmology says. Physical Cosmology extrapolates back from the present (which we observe) to the past (that we deduce) as far as our knowledge of the Laws of Physics permits. We can make a reliable extrapolation back to the point, more or less, when the Universe was about a picosecond old (assuming that it actually did start with a Big Bang). But that initial picosecond? We really have no idea. We don't even know if it was a picosecond or an eternity. This regime is ruled by Laws of Physics (unification of the *Strong Force* and *Quantum Gravity*) about which we only have vague, speculative ideas. The one thing that almost every cosmological physicist seems to agree on, however, is that the naïve prediction of General Relativity, namely that this initial picosecond started with a Big Bang, is almost certainly not correct.
So, to sum up … it may or may not have started with a Big Bang, but even if it did, *the Big Bang needs no cause*.
One caveat: if the Big Bang was not an initial singularity: if it was in fact preceded by a prior state, such as a contracting phase of the Universe in a 'Big Bounce' Cosmology, or a pre-inflationary eternal Cosmos in 'eternal inflation', to name two specific examples: Then yes, it did have a cause. But the standard, run-of-the-mill, General Relativistic Big Bang, otherwise known as the Initial Singularity, has no such cause.

74 -

If the Universe is expanding, then why are Gravity-'locked' planets not affected by the expansion?

This question, like many similar questions, is ultimately premised on the notion that expansion is something that space does, dragging things along.
That is most emphatically *not* the case, even if occasionally even physicists (though typically physicists not working in Physical Cosmology) subscribe to this misconception.
Expansion simply means the very pedestrian idea that things are flying apart (in fact, the basic equations of the expanding Cosmos, the Friedmann Equations, can be derived from Newtonian Physics alone, as can be found in many introductory-level Cosmology textbooks).
If we start with a Universe that is homogeneous (same everywhere) and isotropic (no preferred direction), and the 'stuff' in this Universe begins its existence in a state of flying apart, it will continue to do so either.

a. forever, or

b. until Gravity wins.

That is to say, Gravity slows things down by trying to pull things together. If things were initially not flying fast enough, this means that Gravity eventually wins, the flying apart stops, and the Universe re-collapses. But if initially things are flying apart fast enough, this never happens, and the expansion continues forever.
Things are further complicated by the fact that a medium with *negative pressure*, the so-called 'Dark Energy', can accelerate the process by responding to Gravity as though it were repulsive, not unlike the way a bubble rises in the sea because of Gravity; but let put this aside, as Dark Energy and acceleration are not relevant to this discussion.
It was mentioned *homogeneous* and *isotropic*. But our Universe is *only approximately* homogeneous and isotropic. There were small deviations from perfect homogeneity and isotropy early on. Some regions were *slightly denser* than others. *Slightly denser* means more Mass, more Gravity to slow the expansion. So, these 'perturbations' grew over time. The actual theory, also discussed in Cosmology books, is called the *Newtonian Theory of Small Perturbations*.
If the density of an *overdense* region became large enough, that region *may have stopped* expanding altogether. The matter present within that region became gravitationally bound. This is how clusters of galaxies and within them, galaxies, and within those solar systems, stars and planets had a chance to form. In short, these gravitationally bound structures represent lumps of matter that stopped flying apart because of *self-Gravity*.

75 -

Does the Sun's motion through space create *gravitational waves*? If so, would they still be far too minuscule to detect?

[Compare with final **Appendix**, p.s 9-10]

Technically, the answer is *yes*, but those gravitational waves are *extremely weak*.
Uniform motion does not create gravitational waves, but *accelerating* motion, in particular *orbital* motion, does. But because Gravity is very weak, to begin with, the *power* of the gravitational waves produced by orbital motion is minuscule, unless the orbit is a very, very tight orbit (e.g., the orbits during the final seconds of a black-hole merger, when the two black-holes orbit each other at nearly the speed of light, completing several hundred orbits a second).
The Earth's orbit is not a very tight orbit; it takes a full year for the Earth to circle the Sun once. The corresponding, very *low frequency* gravitational waves produced by the Earth are emitted at a Power $\lesssim 200$ W . This is an absolutely minuscule output that can never be detected in practice.
The Sun's case is even worse. The Sun is much heavier than the Earth, of course, but it orbits the Milky Way very *slowly*; it takes on the order of a 10^8 years to complete 1 orbit. As a result of this motion, the Sun produces gravitational waves at a *Power* of less than $2\,\mathrm{W}$ and at a frequency so low that it would take a detector as large as a cluster of galaxies to detect waves of such a low frequency. For a binary Mass-system $\{m_1, m_1\}$, in which Masses are in *mutual* uniform *circular* revolution, a CM-frame (general-relativistic) calculation from *Einstein's Equations* gives $(a \equiv r, \forall r := \|\boldsymbol{r}\|, \iff e = 0)$:

i. the *Time-change* in orbital radius,

$$\frac{dr}{dt} = -\frac{64G^3}{5c^5}\frac{m_1 m_2(m_1+m_2)}{r^3} ,$$

ii. the *Energy* of a *circular* orbit,

$$E = -\frac{Gm_1 m_2}{2r} ,$$

iii. the *average Power*, as the rate at which Energy changes vs. Time,

$$\langle P\rangle = \frac{dE}{dt} \equiv \frac{dE}{dr}\frac{dr}{dt} = \frac{Gm_1 m_2}{2r^2}\left(-\frac{64}{5}\frac{G^3}{c^5}\frac{m_1 m_2(m_1+m_2)}{r^3}\right)$$
$$= -\frac{32G^4}{5c^5}\frac{m_1^2 m_2^2(m_1+m_2)}{r^5} .$$

The result is a *negative* quantity. This can be interpreted as the rate at which the system *loses* Power because of Gravitational Radiation.
Introducing the values for the Masses of the Earth and the Sun and the average distance between them, we get the approximately $200\,\mathrm{W}$ mentioned above. Similarly, by introducing the values for the Sun's Mass and the estimated Mass of the Milky Way, along with the average distance of the Sun from the center of the Milky Way, yields the figure of less than $2\,\mathrm{W}$.

76 -

How did the Big Bang happen if nothing existed? No God, no heat, no particles, no atoms.

Modern Cosmology does not say 'nothing existed'. The people who say 'nothing existed' are creationists who have never had a class in Physics, Astronomy or Cosmology.
The Big Bang model describes a hot, dense Early Universe that sprang from a very small state that contained the entire Mass-Energy of the entire visible Universe. That's not 'nothing', rather, it is literally the exact opposite of 'nothing'.
Anyone who tells you the Big Bang model says the Universe came from 'nothing' has no idea what they're talking about, and we should completely disregard anything they say about Cosmology. We wouldn't listen to someone in the US who says Jesus was born in 1492 and his parents were Adam and Eve, right? So, why would we listen to someone who is that wrong about Cosmology?

77 -.

If the *Planck Length* were the *minimum* observable – hence, measurable – length, how would it affect General Relativity and Quantum Physics? Would they be compatible?

This is the reason why some people came up with the idea of *doubly-Special Relativity*. The idea is that if the *Planck Length* has physical meaning, we have to ask who is measuring it. In Special Relativity, length depends on the *observer*, so, what is the Planck Length to one observer may not be the Planck Length to another observer. Doubly-Special Relativity attempts to resolve this by introducing, in addition to an invariant speed, also an *invariant length*.
Others argued that this is really not necessary, since even if the Planck Length has physical significance, it is itself not the length of a physical object, so, how it transforms under the Lorentz group has no relevance.

78 -

If the Earth were to shrink in size to maybe the size of a baseball but keep its *same* Mass, would a black-hole be created?

Surprisingly, the answer is a *maybe*, but with a 'caveat'.
The question says, 'keep its same Mass', but there is a problem with that part. The Mass of the Earth in the volume of a baseball: that exceeds neutron star densities by something like 10 orders of magnitude. To compress matter to this extent, insane quantities of Energy would be required. How insane, we don't even know. Much of the physics of neutron stars remains little more than guesswork. What about going 10 orders of magnitude beyond that? That is not something we know how it can be done.
So, … where does this Energy, needed to overcome the *repulsive pressure of Matter*, come from? Are we converting some of the Earth's own matter or is this Energy invested from an external source?
If the latter, that means that in addition to the Earth's own Mass, we are adding humongous quantities of Mass-Energy by the act of compression. Again, this is not something that can be readily calculated, but it is not inconceivable that the Energy required exceeds the Mass-Energy of the Earth itself.
And if it exceeds the Mass-Energy of the Earth by a factor of 3 or so, the resulting amount of Mass-Energy will have a *Schwarzschild radius* that is greater than the radius of a baseball. That means that a black-hole *might* indeed form.
If we are strictly limited to whatever Mass-Energy is present in the Earth, with no external sources, then the answer is no. The Schwarzschild radius of the Earth is about $1/4$ or so the radius of a baseball. And Gravity is of no help here.
Even if we managed to compress all the Earth's matter to the size of a baseball, the resulting configuration of matter won't be stable. Though it would have tremendous surface gravity, rather than collapsing under its own self-gravity, once the mechanism that is used to create this object becomes absent, the object would explode, with a significant portion of its Mass converted to the Kinetic Energy of whatever remains, which would disintegrate and fly apart at nearly the speed of light.

79 -

Why is the *graviton* so important in Quantum Gravity theory and can LHC be used to prove it is an *actual* elementary particle?

The graviton is important because it is pretty much irrelevant how we quantize Gravity; if Gravity is a quantum theory, in the weak field, low Energy perturbative limit we will be dealing with gravitons as the field quanta. So observational evidence of gravitons amounts to confirming the quantum nature of Gravity.
No, the LHC *cannot* be used to detect or study gravitons. No particle accelerator can and, quite likely, no particle accelerator ever will. To give an example why Freeman Dyson once did a neat calculation. The hot Sun emits not just electromagnetic radiation (produced by charged particles bouncing about) but also *thermal gravitational radiation* (produced by massive particles bouncing about). Its thermal gravitational output is estimated at about $8\cdot 10^{7}$ W (for comparison, its light output is something like close to $4\cdot 10^{23}$ W).
So, suppose, said Dyson, that we can use the entire Earth as a detector of gravitons. A perfect detector. So how many atomic transitions will there be, using all the atoms of the entire Earth, due to solar thermal gravitational radiation? Well, … 1 event every 10^{9} years.
That's how weakly interacting gravity is, and that's how utterly impossible it is to detect individual gravitons from any source. The best we can hope for is a yet undiscovered effect that might offer an indirect detection of Quantum Gravitation. But we are not there yet.
Still, it's darn important, because such a detection would be the only way to confirm that Gravity is indeed a *quantum theory* and to distinguish between competing theories of Quantum Gravity.

80 -

Is Physics near its end? The major critical issues are:

a. most of the new theories offer no ways of experimental testing;

b. theories are getting more complicated over the years, but human brain capacity is limited.

In the late 19th century, Physics was near the end. Everything related to motion was beautifully summarized in the form of modern Mechanics, where all the equations of motion could be derived from the simple, elegant Principle of Least action. Thermodynamics was finally understood and, thanks to Statistical Physics, explained in terms of the mechanical behavior of constituent particles. All electromagnetic phenomena received an explanation in the form of a set of elegant *field equations*, which as an added bonus, also explained the behavior of light and Optics. In short, apart from some minor, insignificant loose ends, the great project called Physics was complete: respected scholars advised talented young students to direct their interests elsewhere as Physics was a dead discipline.
As to those pesky little insignificant loose ends: one was the need to reconcile the constant speed of light predicted by Maxwell's equations with the rules of Classical Mechanics. The other, more obscure problem related to the nature of blackbody radiation. Very minor issues indeed, with no practical implications whatsoever. Who would have thought that they would lead within a few short years to a complete upheaval of Physics and a period of theoretical discoveries that probably has no parallel in the course of Human History?
Today, we are actually a lot less close to completing the great project of Physics than we thought we were 120 years ago. The Standard Model of Particle Physics is an amazing achievement, but it has holes in it: massive neutrinos, the hierarchy problem, indeed the very origin of the up to 26 independent dimensionless parameters that define the theory. And even if these issues are resolved, it is widely believed that the underlying Quantum Field Theory loses its validity at very high energies, and something new is needed. Something new that may be related to another great problem, that of unifying Quantum Theory with Gravity at all Energy levels. Cosmology, too, only just became a proper physical science with observational data used to validate theories in the past half century. And it has many issues. Did inflation happen? What about the *Cosmological Constant* problem? And so on.
These are not minor loose ends, like the light speed and blackbody radiation issues were believed to be minor loose ends by some in the 1890s. These are major, major issues that will likely require *new ways of thinking* to be resolved.
It is true that some theories have become very complicated. But the fundamental theories really aren't that complex. A lot of the complication, in many people's opinion, comes from the fact that the way these theories are taught retraces the often-convoluted history of their development. Even so, talented young scholars have no trouble absorbing the accumulated knowledge of prior generations of physicists and make meaningful contributions. The fact that in the somewhat blind search for improved understanding, we sometimes end up with theoretical proposals that are truly overly complicated should not mislead us: theories that are inherently complex tend not to prevail, while those that do prevail are soon expressed in simpler form.
A perfect example is Maxwell's Theory: in its original form it was a horrendous set of 20-some equations, as complicated in appearance as the worst modern theory. This was greatly simplified by Heaviside who wrote down the theory in *vector calculus notation*. Then, in the 20th century, the theory was re-expressed in 4 dimensions and ultimately, using the language of differential forms. Today, we can simply state, 'Let be a 3-times *differentiable vector field* on a Lorentzian 4-manifold and d the *exterior derivative* operΦator. Given $F = d\Phi$, then, $dF = 0$ identically. Furthermore, if the manifold is endowed with a *metric*, we can form the *dual* $G = \star F$ and define the current $J = \star dG$, which is *conserved*, since $\star d \star J = 0$ identically'. There, that's all there is to Electromagnetic Theory: three not terribly long sentences, aren't they?

81 -

What is wrong with Newtonian Gravity? Why is General Relativity better?

First and foremost, Newtonian Gravity is an 'action-at-a-distance' theory. Newton himself was deeply concerned about this. He actually wrote (about his own theory!): "It is inconceivable that inanimate Matter should, without the mediation of something else, which is not material, operate upon, and affect other matter without mutual Contact … That Gravity should be innate, inherent and essential to Matter, so that one body may act upon another at a distance through a Vacuum, without the Mediation of anything else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it. Gravity must be caused by an Agent acting constantly according to certain laws; but whether this Agent be material or immaterial, I have left to the Consideration of my readers".

Second, Newtonian Gravity is not compatible with Special Relativity. This is a mathematical incompatibility: if you plug in the equations of Newtonian Gravity into the framework of Special Relativity, contradictions ensue.

Third, the concept of the Weak Equivalence Principle (namely that all bodies, regardless of their material composition, respond to Gravity the same way) has the important implication that at least in the immediate vicinity of a freefalling object, a simply geometric transformation can 'get rid' of Gravity. This suggests that the theory of Gravitation has geometric origins. That is not the case with Newtonian Gravity, which, in fact, also violates the Weak Equivalence Principle more directly, once the *Mass-Energy equivalence* of Special Relativity is taken into account.

Fourth, Newtonian Gravity is contradicted by observation. Einstein's three classical tests of Gravity included the anomalous perihelion advance of Mercury (already known when General Relativity was born, but up until that point, it had no credible explanation); the bending of light by a gravitating source like the Sun (predicting twice the value that one would get from Newtonian Gravity alone, treating photons as little projectiles; confirmed by Eddington's 1919 solar eclipse expedition); and the *gravitational redshift* of light (unambiguously confirmed only after Einstein's death, in the 1950's). Since then, numerous other tests confirmed Einstein's predictions, including precision satellite navigation or more recently, the discovery of *gravitational waves*.
In short, it was pretty well understood in the Physics community already in the late 19^{th} century that Gravitation needs a proper Field Theory. Once Special Relativity entered the scene, it was well understood that a Relativistic Field Theory was needed. And finally, as Einstein began investigating the notion of generalizing his Relativity Theory to treat accelerating frames on the same level as inertial frames (hence the name, General Relativity, to expand on what was back then known simply as the Theory of Relativity, without the 'Special' adjective), the Weak Equivalence Principle made him realize that such a theory must necessarily be a Theory of Gravitation.

82 -

Why does the Moon's Gravity cause tides to the oceans, but the Sun's gravity doesn't?

They both do but the magnitudes differ. As everybody knows for sure, the Gravitational Force is proportional to the *inverse square of distance*. Tides, however, are also proportional to the *ratio* of the *size* of the object (in this case, the Earth) to the *distance* from the source of Gravitation. Multiply these two effects together and you find that tides are proportional to the *inverse cube of distance*.
The Sun is some $2.7 \cdot 10^7$ times more massive than the Moon but it is also 390 times as far from the Earth as the Moon. Divide $2.7 \cdot 10^7$ by 390^3 and the result is a bit less than 0.46 . So, tides due to the Sun are present, but they are *about half as strong* as the tides due to the Moon.
Therefore, when we see tides, they are dominated by the Moon's pull, but the Sun's contribution can considerably strengthen or weaken tides. Which is precisely what we see in the oceans.

83 -

How can the Universe with an infinite Mass expand instead of collapse due to Gravity?

First, the total Mass of the Universe is not known. True, in the Standard Cosmological Model, we have a Universe that is spatially infinite and homogeneous (same everywhere) so indeed, its Mass would be infinite, but this is by no means a certainty;

second, even in this infinite Universe, the Mass-density (Mass/(unit-volume)) remains *finite*;

third, there is the 'shell theorem', and its relativistic extension, *Birkhoff's Theorem*. The Gravitational Field inside a uniform *spherical* shell of Matter is zero. If the Earth were hollow, you could float weightlessly inside. So even in an infinite Universe, concentric shells of Matter surrounding we will not have a gravitational influence on us. Only *local* deviations from this homogeneous background (e.g., the presence of a nearby star or planet) may be relevant;

fourth, there is the issue of Time: the Universe has a *finite* age. This defines the range within which Matter could have influenced us. Matter outside this 'cosmological horizon' just hasn't been around long enough to exert an influence on us (or us, on that lump of Matter).

84 -

If we are at a certain distance from the center of a neutron star and it turns into a black-hole, does the amount of Gravity *change* for us at that same distance from the center?

If we are outside the neutron star, spherically symmetric collapse into a black-hole will produce no gravitational effects whatsoever.
The overall Gravitational Field will *not* change. There will be *no* gravitational waves either.

This is assuming that all of neutron star collapses to form the black-hole. If some of that material escapes and forms an expanding spherical shell, once you are inside that shell, the Gravitational Field will appear *weaker*. And if the collapse deviates from spherical symmetry, there will be changes and also there will be gravitational waves.
But what about spherically symmetric, complete collapse? Outside the collapsing object, the gravitational field in the vacuum will remain *static*, described by the celebrated *Schwarzschild solution*.

85 -

Did anything exist $13.8 \cdot 10^9$ years before the Big Bang happened?

There are a lot of answers to the question saying things like "No. Time started at the Big Bang". It is a rather secure and understandable position, but it is somewhat misleading. So, let's get a little deeper.
The Big Bang is the process of expansion of the Universe, which appears to have started in a singularity, $13.8 \cdot 10^9$ years ago. The Big Bang is *still* happening, we are *still* in this expansion process.
There is a thing called the Big Bang Theory. It is a scientific theory that describes this *process of expansion*. Scientific theories are hypotheses which developed a great level of merit by accumulating a great deal of empirical evidence and corroboration. That applies to the Big Bang Theory as well. We do have much empirical evidence for the expansion.
Nevertheless, there are two things that are commonly believed to be covered by the Big Bang Theory, which are not:

a. the singularity itself (the absolute zero-time, $t = 0$);

b. the non-existence of a time *prior* to the singularity.

The mathematical model used to describe the process of expansion of the Universe in fact points to a singularity at $t = 0$ and is undefined for $t < 0$. This may be interpreted as the non-existence of time before the singularity (which may actually be the case), but also may be interpreted as a time irrelevant to the development of our Universe (which also makes sense, since *causality breaks at the singularity*).
The fact is that we cannot currently assess any empirical information that corroborates the idea of the physical singularity at $t = 0$ or the nature (or non-existence) of time at $t < 0$. Any statements about these conditions are, at least currently, *unfalsifiable*, hence *unscientific*. Thus, such claims cannot belong to any scientific theory, including the Big Bang's. The bottom line is that, for all we know, we are *not* justified to say that there definitely was no Time before the Big Bang's singularity. We can say, at best, that, according to the model, no Time prior to the singularity has a *causal relationship* with our Universe, which may mean 'no Time at all' or a 'Time with no relevance to the dynamics of our Universe'. Let's see what Stephen Hawking says on the matter in his 'A Brief Story of Time':

Ch. 3:

"This means that even if there were events before the Big Bang, one could not use them to determine what would happen afterward, because predictability would break down at the Big Bang.
Correspondingly, if, as is the case, we know only what has happened since the Big Bang, we could not determine what happened beforehand. As far as we are concerned, events before the Big Bang can have no consequences, so they should not form part of a scientific model of the Universe. We should therefore cut them out of the model and say that Time had a beginning at the Big Bang …".

Ch. 8:

"At the singularity, General Relativity and all other Physical Laws would break down: one couldn't predict what would come out of the singularity. As explained before, this means that one might as well cut the Big Bang*, and any events before it, out of the theory, because they can have no effect on what we observe. SpaceTime would have a boundary – a beginning at the Big Bang.

These excerpts clearly mean that there is nothing we know (or at least that Hawking knew at the time of the writing) that excluded the existence of time before the singularity, but we choose to 'cut them out of the model' because 'events before the Big Bang can have no consequences', since causality breaks at $t = 0$.

They also clearly mean that the Big Bang Theory doesn't state anything about the non-existence of Time before the singularity.

Note: Stephen Hawking used 'Big Bang' and 'singularity' *interchangeably* in his book, although he recognizes that the singularity is a mathematical model and that the singularity is *not* part of the Big Bang Theory ("One might as well cut the Big Bang*, and any events before it, out of the theory").

* That means: the singularity.

So, long story short, the answer to the question is:
We don't know if anything existed $13.8 \cdot 10^9$ years before the Big Bang's singularity, and possibly we will never know, since causality seems to break at the singularity, which would make possible events before it both non-assessable and irrelevant to the dynamics of our Universe.

86 -

If electrons are quanta of the Electron Field, then, what is making that Electron Field? In other words, has there to be something causing the field?

That's a very important and fundamental question. The answer is we simply *don't know* why there is an Electron Quantum Field. All we can say with certainty is that when the Universe came into existence it had several quantum fields in it that permeated every $(3+1)$-dim SpaceTime point in it.

The Electron Quantum Field was one of those. Every electron in our Universe is a local quantized excitation of the same quantum field. That's why all the electrons are exactly *alike* in terms of each of their properties - *Mass*, *Charge* and *spin*.
As the Universe expanded and created new SpaceTime, the quantum fields *continued* to permeate each SpaceTime point. We now know the existence of 25 such quantum fields – 12 for the fermions (6 quarks. 3 leptons, 3 neutrinos) and 13 for the bosons (8 gluons, photon, W^+, W^-, Z^0 and Higgs [see Table in Issue 13, p. 6]).
The existence of the last *bosonic* quantum field was confirmed in 2012 with the discovery of Higgs boson. The last *fermionic* quantum field, for the *top quark*, was confirmed in 1995. These are likely to be the last quantum fields discovered for some time to come.
The existence of all these quantum fields in our Universe at its origin has long puzzled physicists. Some people have speculated that the existence of these quantum fields is vital in a Universe that could possibly support intelligent life.
If these quantum fields did not exist, we won't be here to discuss them! This speculation is known as the Anthropic Principle. It was first proposed by the American theoretical physicist Brandon Carter (1973), in the context of the values of certain fundamental constants of Nature.
Carter was intrigued by the fact that some fundamental constants of Nature such as the *speed of light*, *Planck's constant* and *fine structure constant* have values that are very close to those can support the formation of atoms. If these constants had values even a few percent different from the ones than they do have, atoms *would not* have formed in our Universe. Without atoms, there is no hope for life, let alone intelligent life to emerge.
So he reasoned that the fact these constants have these values is just an accident that enabled intelligent life to emerge. That's how we happen to be in a Universe that supports life. These constants could have any other value in a different universe but in our Universe they have these definite values that are conducive for the emergence of intelligent life. This is the foundation of *Anthropic Principle*.
One immediate consequence of the Anthropic Principle is that there must be a very large number of Universes out there. In most of these universes the Electron Quantum Field or any of the quantum fields do not exist. In any such Universe, there would be *no chance* of even an atom to exist. The collection of all the possible universes is known as the *multiverse*.
This is an interesting speculation, and it has held an important place in the Theoretical Physics for over 40 years. The whole field of String Theory relies on it. But there is absolutely no direct nor indirect evidence to support this idea. Since the total Mass and Energy contained in a Universe is always conserved, the Laws of Physics do not allow any information to be passed between two hypothetical universes.
Perhaps we must accept what we can observe: the Universe is the way it is. We may never know why it has these quantum fields that seem so fine tuned to allow the existence of intelligent life, or why the SpaceTime in our Universe has 3-dim Space and 1-dim Time.

87 -

Why is relativistic *Kinetic* Energy *not* equal to $(1/2)\cdot$(relativistic mass)$\cdot$(relative speed)^2?

It may be helpful to proceed the other way around with the calculations and ask: why is the *non-relativistic* (n-R) Kinetic Energy of a point (rest-)Mass m_0

$$K_{\text{n-R}} = (1/2)\, m_0 v^2\,?$$

We can start with the *relativistic* (R) Kinetic Energy – i.e., *the true general* form of Kinetic Energy –

$$K_R = \frac{m_0 c^2}{(1 - v^2/c^2)^{1/2}} \equiv \gamma m_0 c^2 .$$

When the point-Mass speed is *very small* compared to c, $v \ll c$, we can approximate $\gamma := 1/(1 - v^2/c^2)^{1/2}$ as

$$\frac{1}{(1 - v^2/c^2)^{1/2}} \approx 1 + \frac{1}{2}\frac{v^2}{c^2} ,$$

so that

$$K_R \approx m_0 c^2 \left(1 + \frac{v^2}{2c^2}\right) = m_0 c^2 + \frac{1}{2} m_0 v^2 .$$

There we have it: this *relativistic* (approximate) expression of Kinetic Energy for a 'slowly moving' point-like system is the sum of the *rest-Mass Energy*, $m_0 c^2$, and the well-known *non-relativistic* kinetic term, $(1/2) m_0 v^2$.
The fact that the expression of K_R is not obviously related to the *relativistic Mass*,

$$m \equiv \frac{m_0}{(1 - v^2/c^2)^{1/2}} \quad (\equiv \gamma m_0) ,$$

a *speed-dependent* quantity, is just another demonstration as to why m is not a particularly useful concept in Relativity Theory and why it seems to fade away in the literature of recent decades.

88 -

Is Gravity considered a *local* or a *non-local* phenomenon?

Newtonian Gravity is *non-local*. This was a shortcoming of the Theory that was recognized by Newton himself. As he wrote to Bentley: "That Gravity should be innate inherent and essential to Matter so that one body may act upon another at a distance through a vacuum without the mediation of any thing else by and through which their action or force may be conveyed from one to another is to me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws …".
That 'agent' is the Gravitational Field, *doubling* as the SpaceTime metric, in Einstein's Theory. Instead of one body instantaneously acting on another over a distance, the body affects the Gravitational Field in its own vicinity; these changes that propagate, *no faster than the vacuum speed of light*, until, eventually, there is a resulting change in the Gravitational Field near the other body, to which that body responds. This theory is strictly local: Matter and the Gravitational Field interact *locally* and changes propagate at a *finite* speed *without violating causality*.

89 -

Why can't both General Relativity and Quantum Physics be correct?

Who says they can't be?
We can do Quantum Field Theory just fine on the curved SpaceTime background of General Relativity. There are some striking consequences (e.g., accelerating observers may not even agree on the particles that they see) but the Theory works, it is self-consistent, it makes sense.
We can also make Quantum Fields the source of Gravity, at least in an approximation. This is somewhat inelegant, because we need to take the so-called *expectation values* of these Quantum Fields for them to be compatible with our Classical Gravity Theory but the resulting approximation, called Semi-classical Gravity, works in every conceivable scenario that is accessible to us by way of experiment or astronomical observation.
What we have so far been unable to do in a convincing manner is turning Gravity itself into a Quantum Field Theory. The reasons are deeply technical and have to do with how a tensor field theory with a dimensioned coupling constant is not amenable to *renormalization*, techniques that can otherwise be used to 'tame' a quantum field theory, *removing unwanted infinities* and retaining a theory with genuine predictive power. And so far, we have been unable to come up with a truly credible alternative solution.
There can be various reasons for this. For instance:

1. perhaps *Gravity is not a quantum field at all*, in which case an entirely different approach is needed;

2. perhaps we need a more fundamental theory first, such as Supersymmetric String Theory, which might yield Einstein's Theory in the low-Energy approximation;
3. perhaps we just need to be persistent and continue research, e.g., into loop quantum gravity or other approaches to create a bona fide Quantum Gravity Theory.

The biggest hurdle is that we have *no data*. There are no observable Quantum Gravity phenomena. So, we get no guidance from Nature.
But, at least in our reading of this situation, it is wrong to suggest that there is a fundamental incompatibility or contradiction between Quantum Field Theory and General Relativity. The very fact that QFT works on a curved SpaceTime background should tell us that much. The open questions, namely

a. is Gravity a *quantum field*?

and

b. how is Gravity sourced by Matter?

these are, in a sense, 'practical' questions, not questions that imply incompatibility.

90 -

If stars of several magnitudes our sun collapse to create black-holes why the early Universe of much larger Mass and Energy did not collapse into a black-hole? Was it because the expansion force outweighed Gravity?

Close. There is no 'expansion force'. However, that early Universe was a universe that was in the state of *rapidly flying apart*. Matter just didn't get a chance to coalesce under its *Self-gravity*, because any lump of matter, be it something as small as your fist or as big as the largest galaxy, was flying apart *faster than its own gravitational escape velocity*.
Over time, however, some parts of the Universe were a little denser than other parts, and in these overdense parts, Self-gravity was just a little stronger than elsewhere. This meant Matter flying apart a little more slowly. Over time, some more Momentum was lost in these overdense lumps due to dissipative processes. Eventually, self-Gravitating structures: stars, clusters of stars, galaxies began to form, which lost enough Momentum to stay together under Self-gravity, no longer in a state of flying apart.
But even these lumps didn't just collapse into black-holes right away, because as they became denser and hotter, their internal pressure increased, capable of resisting the force of Gravity. Large stars only collapse under their Self-gravity once these internal pressures are no longer sufficient to hold Matter apart, which usually happens only at the end of the star's life cycle, when its nuclear fuel runs out.

91 -

What exactly are the various 'Planck Constants'?

There are lots of constants in Physics. For example, there is the Mass of the electron, the charge of the electron, the ratio of the Mass of the electron to the Mass of the proton, the wavelength of light emitted by a certain atomic transition, etc. But all of these are constants that are related, in one way of another, to particular kinds of objects in our Universe: they do not apply to everything in the Universe, so, they are not truly fundamental.
There are, in fact, only a few fundamental constants that have units that could be combined to make a length, a time or an Energy unit. Again, by *fundamental*, it is meant constants that apply to the entire Universe in one way or another. In fact, the only known truly *fundamental constants* are:

c - the speed of light. This is not just the speed of light, it is really the *conversion factor* between the time dimension and the 3 space dimensions in our 4-dim SpaceTime. It has units of **distance/time**;

$\hbar$ ($\equiv h/(2\pi)$) - the fundamental constant that sets the scale for all quantum phenomena in the whole Universe. It has units of **action** or **Energy · Time**, i.e., **Mass · Length^2/Time**;

G - the Newtonian Gravitational Constant that is also used in General Relativity. All Matter and all Energy in the Universe attracts all other Energy and Matter in the Universe via the curvature of 4-dim SpaceTime. Again, this applies to the entire contents of the Universe. It has units of **Length^3/(Mass · Time^2)**.

There is one other constant that *seems* to be as fundamental, the *Boltzmann constant*. Boltzmann constant has units of **Energy/(Kelvin degree)** and therefore it is really just the *definition* of $1\,\mathrm{K}$. So, Boltzmann constant k_B is *not* a fully fundamental constant, one which tells us something about the Universe.

To sum up things, there are no other fundamental constants that apply to the entire Universe and all of its contents. Now from the 3 fundamental constants above, we can construct scales of *Length*, *Time* and (*total*) *Energy* as follows:

- PLANCK LENGTH

$$l_P := \left(\frac{G\hbar}{c^3}\right)^{1/2} \approx 1.616 \cdot 10^{-15}\ \mathrm{m}\,;$$

- PLANCK TIME

$$t_P := \left(\frac{G\hbar}{c^5}\right)^{1/2} \approx 5.391 \cdot 10^{-44}\ \mathrm{s}\,;$$

- PLANCK ENERGY

$$E_P := \left(\frac{c^5\hbar}{G}\right)^{1/2} \approx 1.956 \cdot 10^{9}\ \mathrm{J} \equiv 1.221 \cdot 10^{28}\ \mathrm{eV}\,;$$

- PLANCK MASS, m_P, and MASS-DENSITY are deduced from Planck (total) Energy by defining

$$m_P := \frac{E_P}{c^2} \equiv \left(\frac{c\hbar}{G}\right)^{1/2} \approx 2.177 \cdot 10^{-8}\ \mathrm{kg}; \qquad \rho_P := \frac{m_P}{l_P^3} \equiv \frac{c^5}{G^2\hbar} \approx 5.155 \cdot 10^{96}\ \mathrm{kg/m^3}\,;$$

- PLANCK (ABSOLUTE) TEMPERATURE as well, T_P, is deduced from Planck (total) Energy by defining

$$T_P := \frac{E_P}{k_B} \equiv \left(\frac{c^5\hbar}{Gk_B^2}\right)^{1/2} \approx 1.417 \cdot 10^{32}\ \mathrm{K}\,.$$

So, 'fundamentally', the *Planck Scale* is the only scale that applies to everything in the Universe. In other words, these units are the most *natural units* to use for measurements of Distance, Time, Energy and Mass. In fact, theoretical physicists often work in a system of units where $c = 1, \hbar = 1$ and $G = 1$, i.e., exactly the Planck Scale units since all the Planck units would have a numerical value of 1 if $c = 1, \hbar = 1$ and $G = 1$!

In terms of the significance of the Planck Scale, it is thought to be the scale of the strings of String Theory. So strings are *about as long as the Planck Length and vibrate on Planck Time scales*.

If the *Planck Energy* is confined to the volume of cube of size 1 Planck Length it will form a black-hole. In fact, this is thought to be the smallest possible Mass for a black-hole and at these 'Planck' distances, times and energies it is thought that quantum gravitational effects will be very significant.

The *Planck Length* is the smallest distance scale *we can probe with accelerators*. High-Energy accelerators are used to probe small objects, such as the quarks inside protons, so the goal is always to build higher-Energy accelerators. However, if we could build an accelerator that achieved the Planck Energy for a particle like the electron, when the electron interacted with the target, a black-hole would form and it would not help to go to higher energies than that since the black-hole would just get bigger. That is why the Planck Length is the smallest length scale that we could theoretically probe.

The *Planck time* is the time it takes for light to traverse 1 unit of Planck Length 'in Vacuo'.

At about the 1 Planck Time unit after the Big Bang, it is thought that Gravitation separated from the 3 other fundamental forces of Nature (*Strong*, *Weak* and *Electromagnetic*).

There are many speculations about other things that could happen at the Planck Scale. For example, SpaceTime could become a chaotic quantum foam due to the gravitational fluctuations from *quantum fluctuations* at that scale. SpaceTime could become *quantized* (which would cause *violations* of Lorentz invariance at the Planck Scale). But, again, these are speculations: we really do not know what happens at the Planck Scale.

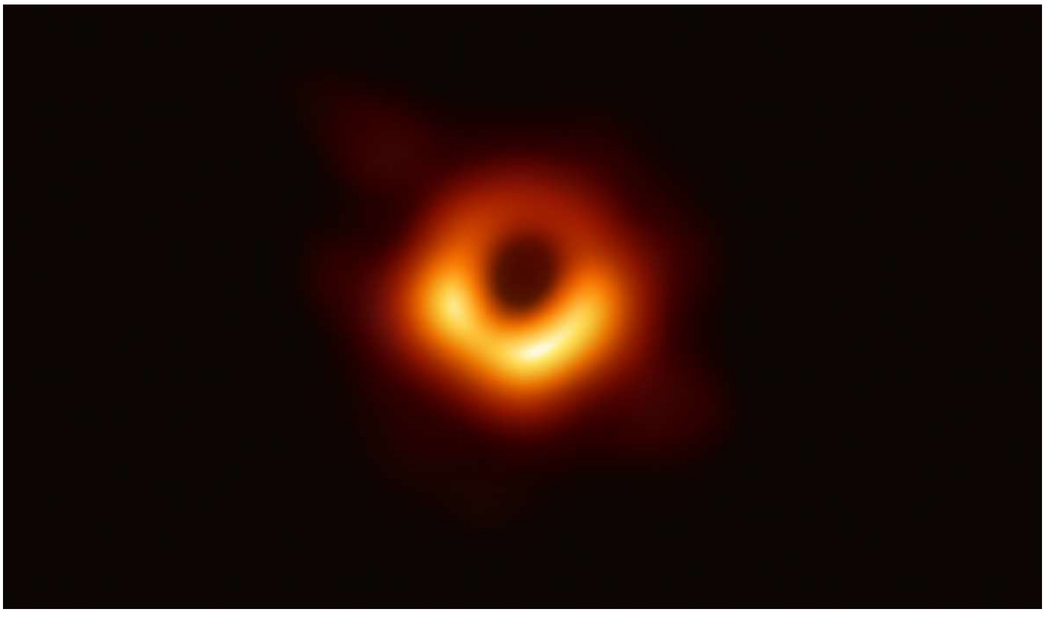
One interesting note, the *Planck Length* and *Planck Time* are far smaller by many orders of magnitude than lengths or times we can measure. However, macroscopic objects have energies far higher than the Planck Energy, but if you divide the Energy of a macroscopic body by the number of particles in the body, the Energy per particle is many orders of magnitude less than the Planck Energy. As an example, the highest-Energy cosmic ray ever detected is estimated to have an Energy of $3 \cdot 10^{20}$ eV, which is 8 orders of magnitude below the Planck Energy. This highest Energy cosmic ray did have the Kinetic Energy equal to that of a 142 g baseball flying at about 100 km/h. To get to a Planck Energy, consider the chemical Energy stored in an car gas tank (57.2 L (liters) of gasoline at $34.2 \cdot 10^6$ J/L is about 1 unit of Planck Energy; also, $1\ \mathrm{L} \equiv 10^{-3}\ \mathrm{m}^3$). In other words, 1 unit of Planck Energy could drive a car a few hundred km!

The *Planck Mass* is approximately 1% of the Mass of a typical mosquito, so the Energy of that tank of gasoline is the 1% Energy-equivalent of a mosquito Mass! The basic reason why the Planck Mass is so large is because the total Gravitational Force in this Universe is *extremely weak*: 1 unit of Plank Mass confined to a *Planck Volume* will turn into a black-hole and because Gravity is so weak, it takes a large amount of Mass for the Gravity to be strong enough to form a black-hole in that volume.

92 -

If black-holes collide spirally, but other systems with barycenter (e.g., Sun-Jupiter) have stable orbits, isn't the Energy exchange by gravitons already proven?

Other systems are technically not stable. E.g., the Sun-Earth system is continuously losing Kinetic Energy due to emitted *gravitational radiation*. However, *the amount of gravitational radiation that this system emits is absolutely minuscule, comparable to the Energy emitted by a couple of light bulbs*. This produces no appreciable, no measurable effect on planetary orbits even over the entire lifetime of the Solar System.
We 'see' in-spiraling black-holes at the very end of the process, when they are already extremely close to each other (a few hundred meters!) and orbiting each other at a speed *comparable to the speed of light*. It's only then that gravitational effects become strong enough to cause a rapid change in orbits, lead to the final hours, minutes, seconds of in-spiral and the strong gravitational wave signal that we detect with LIGO.
None of this has anything to do with gravitons. All the above unfolds in accordance with the predictions of the classical theory of General Relativity. While we generally assume that the Gravitational Field must also be a quantum field and that, therefore, in the *weak field approximation*, it may be represented using quanta that we call 'gravitons', this no more amounts to a detection of gravitons than, say, observing that a lodestone lines up with the Earth's magnetic field amounts to a detection of photons.
Presently, there are no known ways by which gravitons could be detected, using either present-day or conceivable future technology. To illustrate the difficulty, Freeman Dyson once offered a calculation comparing the thermal output of the Sun in the electromagnetic spectrum vs. its thermal output of gravitons. The Sun emits thermal gravitons, too, since it consists of hot, massive particles that wiggle a lot. The fundamentals of the mechanism are the same as the emission of light, just much, much weaker. How much weaker? Suppose we wanted to detect an atomic transition that unambiguously signals that an atom 'captured' a graviton, a quantum of the Gravitational Field, coming from the Sun. Now suppose that we can eliminate all other effects as we turn the entire Earth into a 'perfect' graviton detector. Dyson basically calculated that this detector would catch, on average, 1 solar thermal graviton every 10^9 years. So, barring something revolutionary, or an inventive way to ascertain their existence indirectly (e.g., by cosmological observations) we may never have observational evidence of the existence of gravitons or the quantization of the Gravitational Field.



The first reconstructed image ever of a black-hole (Apr. 10, 2019) in super-massive galaxy Virgo A (or M87* or NGC4486)

93 -

Will we be able to measure the Space part of Universe's curvature in the future to determine if it's finite?

We can measure the *spatial curvature*, Ω_K, of the Universe. For instance, the satellite Planck 2018 results (Planck is a satellite that spent several years making precision observations of the cosmic microwave background) allow us to estimate the spatial curvature as $|\Omega_K| < 0.005$.

What this means is that in the present Universe, the contribution of spatial curvature in the *Friedmann Equations* of Cosmology is at most $0.5\,\%$ *of everything else* but, more likely, it is 0.

We surmise that it is 0 because the relative contribution of spatial curvature increases over time. If it is this small in the present-day Universe, it must have been astonishingly small in the early Universe. Astonishingly small but non-zero numbers (pure numbers, with no units of measurement) tend *not* to exist in Nature. So, it seems much more likely that $|\Omega_K| = 0$ now and always. Which means that *we live in a spatially flat, infinite Universe*.

At least that's what the Standard Cosmological Model says. Other models (including the *inflationary* scenario) may offer different explanations as to why $|\Omega_K|$ is so small.

94 -

Einstein came up with the idea that massive objects bend the 'fabric of SpaceTime' as an explanation for Gravity. So doesn't it follows that there to be some other form of Gravity to make things roll down into the valleys of SpaceTime?

While it is true that Einstein's 'happiest thought' led him to the understanding that Gravitation and the geometry of SpaceTime are intimately related, he was not overly impressed by this geometric interpretation. In fact, he cautioned against reading too much into this 'mental aid'. In his later efforts, where he sought unification of (classical) Electromagnetism and Gravitation, the geometric interpretation did *not* play a prominent role.
In any case, even if we take the geometric interpretation seriously, we must be cautious. Beautiful visualizations of heavy objects sitting at the bottom of rubber sheet are mostly *inconsistent*: they imply something that just is hardly true, that Gravitation bends Space. This is not completely false, however, since a little bit of bending of Space does happen. But that 'little bit', here on the surface of the Earth, for instance, amounts to about 10^{-9}.
The dominant gravitational effect, the Newtonian part of Gravity that we feel and measure in our everyday experience, is not about bending Space. It is due entirely to the '*bending of Time*', i.e., *Gravitational Time dilation*.
So, if we really want a physically correct visualization of how gravity affects SpaceTime geometry, let's forget rubber sheets. Let's think clocks that tick *more slowly* near a *large Mass* than elsewhere.

95 -

If $E = mc^2$, does that mean photon has $E = 0$ because $m \equiv 0$?

This is a common misconception about $E = mc^2$: such an equation *only* works for material particles that are *stationary* or that are moving *extremely slowly* compared to c. Closer to the speed of light (ultra-relativistic regime) and at the speed of light, things change: $E = mc^2$ does *not* work, being incorrect. The *correct* general equation is

$$E = ((pc)^2 + (mc^2)^2)^{1/2},$$

which is the equation used for *any* particle both near and at the speed of light. For photons, which are *massless* particles, the equation above reduces to $E = pc$ because $m \equiv 0$. Using $E = pc$ for Electromagnetic Radiation (hence, for *photons*), we can apply it in the quantum regime (de Broglie) as $E = (\hbar/\lambda\!\!\!^{-})c$, which confirmed *particle-wave duality*.

96 -

Is it possible that the Big Bang could be false? If so, what other theories could also be feasible?

Of course, it is possible that a physical theory is false.
Science is not religion. Though we seek truth (an understanding of Nature) we do not claim to know the absolute truth. Sure, some theories are better tested than others, but ultimately, given that we only ever can make a finite number of observations, exceptions are always possible, unaccounted for by existing theory.
By way of example, we have known since the dawn of civilization that the Sun rises every day in most parts of the

world. Over time, our understanding of why this is so has become more sophisticated, but if our simple scientific theory is that "The Sun rises every day", it can be tested and tested again, and in the several million days since human beings first began to construct settlements and invented primitive forms of record-keeping, the Sun has not failed us once. So, we can be certain that it will rise again tomorrow.
But what if it doesn't? What if there is a hitherto unknown, weird effect in Physics that will manifest itself tomorrow and the Sun won't rise? Extremely unlikely, to be sure, but can we exclude it with absolute certainty? *No*, *we cannot*. And it was to happen, we'd have to go back to the drawing board and *modify* our theory: "The Sun rises every day except on days when condition [...] applies" (fill-in the blank).
What we call the 'Big Bang' is a body of Physics that uses present-day astronomical observations and the known laws of Fundamental Physics (Gravity, Particle Physics, Thermodynamics, etc.) to extrapolate backwards and figure out what the Universe was like in the distant past. Unless our understanding of basic Physics is really off, we can be quite certain that in the distant past the Universe was hot and dense and has been expanding and cooling ever since (this is what 'Big Bang' actually means. The 'primordial atom' or 'initial singularity' stuff we may have read about is nice, but physical cosmologists know that we cannot really go back that far; our theories are not good enough. We can deduce what happened after the first pico-second or so of this supposed initial event, but we don't know what happened in that first pico-second or indeed, if it was a pico-second or an eternity).
But as to the detailed specifics of the model, such as the ratio of normal vs. 'Dark' Matter, the contribution of a Cosmological Constant also known as Dark Energy, the value of spatial curvature, etc., it is almost certain that we don't have those details quite right just yet. The fact that we have not yet been able to find observational evidence of Dark Matter, the tension between various estimates of the rate of expansion, and similar issues are strong hints that *we do not yet have the full picture*.
So, while it is unlikely that the Big Bang model (that is to say, an expanding Universe with a hot and dense past) is grossly wrong, our understanding has a long way to go when it comes to its detailed features.

97 -

If Planck's Length is the *smallest feasible measure of Space*, then, does that mean that the Universe is finite in size?

The Planck Length is *not* the smallest measurement of Space, just as the Planck Mass (approx. $22\,\mu\mathrm{g}$) is *neither* the largest *nor* the smallest measurement of Mass (see Issue 77, P. 33).
While it is technically difficult, a clever experiment involving coherent beams of γ rays, in the scale of the solar system, can, in principle, measure differences in wavelength smaller than 1 Planck Length.
The Planck Length represents a length scale beyond which Perturbative Quantum Field Theory is pretty much likely to fail. It is also generally believed among particle physicists that, despite its successes, the Standard Model of Particle Physics, and the Quantum Field Theory on which it is built fail at this Length scale (and also fail at the Energy scale defined by the Planck Mass).
Whether or not lengths shorter than the Planck Length exist, it says nothing about the size of the Universe. The Standard Cosmological Model, assuming it is valid in the first place, remains just as valid either way, implying a spatially *infinite*, *open* Universe with a *past singularity* but *eternal future*.

98 -

How much of our Universe has fallen into black-holes?

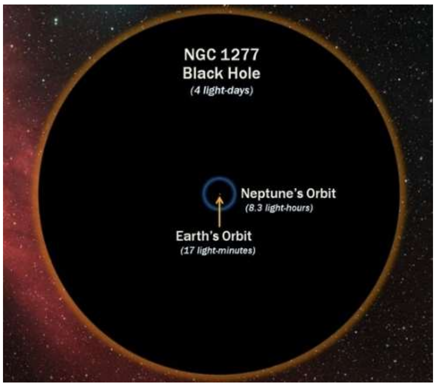
The answer is: *not much at all*. Stellar-Mass black-holes carry 3 to several tens of *solar Masses*, so black-holes of these sizes won't carry a lot of Mass at all, relatively speaking. They can grow larger, but they are small objects with a limited range of gravitational influence. The black-holes that carry the most Mass by far are the *super-massive black-holes* at the center of a galaxy.

Mass

In terms of Mass, supermassive black-holes are absolute monstrosities. The supermassive black-hole *blazar* (blazing quasi-stellar object) named S5 0014+813 has been estimated to be $4 \cdot 10^{10}$ solar Masses – nearing the theoretical limit through which black-holes can acquire Mass through the ordinary *accretion disc* mechanism, which is $5 \cdot 10^{10}$ solar Masses. Although the $4 \cdot 10^{10}$ Mass finding may be overestimated, no doubt that supermassive black-holes carry an astounding amount of Mass.

Size

In terms of size however even supermassive black-holes are very compact. For example, the supermassive black-hole in NGC 1277, for example, is an astounding $1.7 \cdot 10^{10}$ solar Masses – considerably less massive than S5 0014+813, but still very impressive. And yet, this huge black-hole is 'only' 11 times the size of Neptune's orbit (Neptune takes ~ 164.79 terrestrial years to complete a single (quasi-circular) revolution as long as $\sim 2.914 \cdot 10^{10}$ km about the Sun. Compared to Earth's data, Neptune's Mass is 17.2 times and its volume 59.32 times as large).



Supermassive black-holes are not that massive vs. Universe

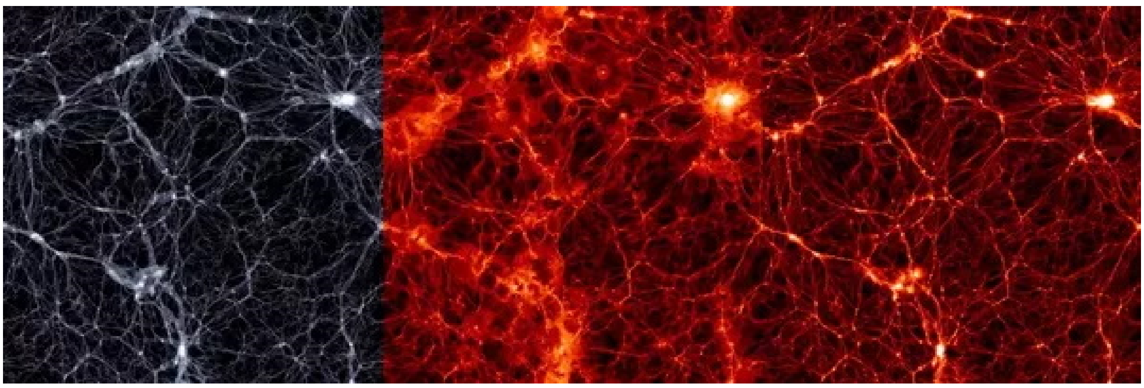
Although supermassive black-holes are very impressive, and – as the name suggests – incredibly massive. And yet most supermassive black-holes only constitute 0.1-0.2 % of the *total Mass* of their host galaxies. The supermassive black-hole NGC 1277 is not only very massive, however; it also constitutes 14% of the total Mass of its host galaxy.
The supermassive black-hole of SAGE0536AGN is another such extreme case with a supermassive black-hole totaling a 'mere' $3.5 \cdot 10^{8}$ solar Masses, but although its host galaxy constitutes $2.5 \cdot 10^{10}$ solar Masses, the supermassive black-hole is still 30 times larger than expected. And yet, this is still only 1.4% of the total Mass of the galaxy.

No-reach

Since supermassive black-holes can acquire a Mass totaling $5 \cdot 10^{10}$ solar Masses through the conventional accretion disc mechanism – that is, by direct gravitational influence on objects that come close to the black-hole – we might expect the supermassive black-hole to be able to consume the Mass of its entire galaxy, and while that may be true in principle (as there isn't thought to be an actual limit a supermassive black-hole can grow), the supermassive black-hole simply doesn't have enough reach. The very point of the $5 \cdot 10^{10}$ solar Mass limit of the accretion disc mechanism is that this is the point at which there will no longer be any gases or stars in close proximity of the black-hole for it to be able to consume. At this point supermassive black-holes can only grow larger through galactic mergers, where it will eventually merge with the supermassive black-hole of its companion host galaxy. This will form a larger galaxy with a larger supermassive black-hole, but this black-hole will still have a severely constricted reach.

Beyond no-reach

While one would think galaxies constitute all the matter in the Universe and the space between galaxies is an empty void, most of the *baryonic matter* in the universe is not located in galaxies;
49% of Dark Matter is in collapsed structures called *haloes* while 23% of *baryonic Matter* (visible Matter) is located in haloes, which includes galaxies and the 'circum-galactic medium'.
45% of the Dark Matter and 46% of the baryons can be found in filaments, which are the tendrils of the cosmic web which galaxies are embedded in. The last 6% of Dark Matter can be found in voids, whereas a surprisingly high 31% of baryonic matter can be found in voids. In other words, 77% of the ordinary Matter in the Universe is *not* located in galaxies, let alone anywhere near any supermassive black-holes.



Above is an image of the filaments of the *Dark Matter Web*, with galaxies tending to form at 'nodes', where filaments of the web connect and Gravity is stronger. Galaxies constitute 23% of the Matter in the Universe, the filaments 46% (69% together) with 31% in voids. As time passes, one could expect more matter to clump together into galaxies, but given the huge distances there is a limit to this, as Gravity is a weak force and Space is expanding.

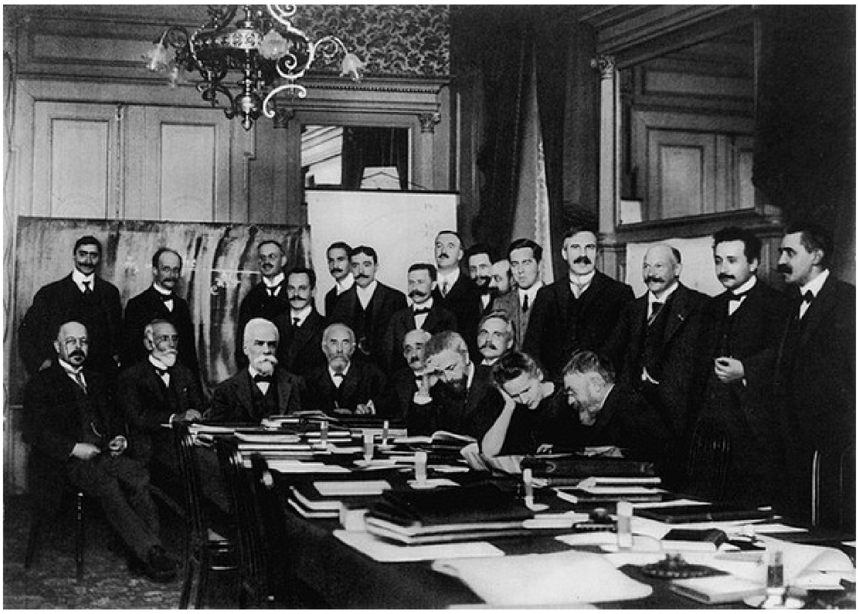
Conclusion

It's really only a tiny fraction of the Universe that will either end up as or in black-holes. This is assuming of course that the Universe won't end up in a Big Crunch where the Universe collapses and ultimately ends as a black-hole singularity; or the Big Bounce scenario, where essentially the same occurs, but it causes a new Universe to emerge (or the same one with a different 'breath') in a presumably endless cycle. In such scenarios, the entire Universe would end up as a black-hole singularity.

99 -

Why did Albert Einstein have so much difficulty accepting Quantum Mechanics?

Let us not rewrite Physics history. Instead, let's begin with a historical photograph:



This picture was taken in 1911. It was a very exclusive meeting, the first in a series, founded by Belgian industrialist Ernest Solvay in that same year. What you see here is the 'crème de la crème', the world's best when it came to the topic of this conference. What was the topic of this first Solvay Conference? It was 'Radiation and Quanta'.
See that fine-looking young gentleman, standing, second from right, with the dark moustache? That's Albert Einstein. One might wonder: what was he doing there?
Einstein, though better known for his theories of Relativity, also happens to be one of the founding fathers of Quantum Physics. His 1905 paper about the *photoelectric effect* – which upended Maxwell's Theory by suggesting that the Electromagnetic Field itself ought to be quantized – was so revolutionary, even a decade later some of his friends were convinced that the paper was wrong and that even great scientists, like Einstein, sometimes make mistakes.
Well, this 'mistake' earned Einstein his one-and-only Nobel prize.
I hope that makes it clear that Einstein had no trouble accepting the notion of Quantum Mechanics.
What Einstein didn't accept was that Quantum Mechanics, or more specifically, its *probabilistic interpretation* known as the Copenhagen interpretation, was the final word on the subject. He believed that Quantum Mechanics, though works well in practice, must be an '*effective theory*', an approximation of a deeper, more elegant theory that does away with probabilities.
This led him on a quest towards a classical *unified* theory. Meanwhile, the world of Physics marched ahead in a different direction, developing Quantum Field Theory, achieving successes that made Einstein's later efforts look quaint and unnecessary. This fruitless quest consumed the last few decades of Einstein's life. Perhaps if Einstein had lived longer and saw the development of *group* theoretical methods, *non-Abelian* Quantum Field Theory and, ultimately, the Standard Model of Particle Physics, his views would have mellowed, and he would have sought a resolution to the question of how we interpret the Quantum World in a different direction. But his life ended in 1955, when all this was still in its infancy.

100 -

What is the Mass of the photon? And how does one calculate its Mass?

In the quantized version of Maxwell's Theory of the Electromagnetic Field, Quantum Electrodynamics (QED), the quantum of that field, the photon, is massless.
It is possible to modify Maxwell's theory, and its quantum version, to endow the photon with Mass. The resulting theory is called Proca or Maxwell-Proca Theory, named after the Romanian physicist Alexandru Proca who first developed this approach in the 1930's.
In Physics, of course, observation trumps any theory. There have been many attempts in the past several decades to either measure the photon Mass or establish upper limits. Current values are typically in the vicinity of 10^{-24} (a trillionth of a trillionth) of the electron Mass or less.
Therefore, it is fair to say that we know with certainty that the photon is either massless or it is so light that its Mass might as well be 0 for all practical intents and purposes.

101 -

Why does travelling at the speed of light makes one age at a different rate to those of their home planet?

It doesn't. Not quite like that anyway. Now it is true that when two travelers move relative to each other, to each the other will appear in slow motion. But that is only part of the story. This simple picture applies only when the travelers are in uniform motion, but that unfortunately also means that after meeting once, they cannot meet for a second time, to compare their respective clocks (either mechanical or biological).
For two travelers to meet more than once, at least one has to change speed and/or direction; basically, turn around.
Given two persons, one traveling at a more or less uniform rate, the other making drastic changes to his velocity (accelerating to near the speed of light; then accelerating again to change direction; then decelerating), when they meet for a second time, they find that the one who accelerated more will have experienced less elapsed (*proper*) time.
As to why this is so, the answer is not exactly intuitive. Rather, it is a mathematical consequence of the basic principle of Relativity, namely if something moves at what we know as the vacuum speed of light, all travelers will measure the same vacuum speed of light regardless of their own motion. This entirely counterintuitive principle follows from the assumption that Maxwell's Theory of Electromagnetism holds for all observers (and it does, as we know from observation.) For this principle to remain valid, we need to redefine how geometry works: Euclidean space and time are replaced by 'Minkowski SpaceTime' with different rules for Geometry. When we work out the math, we can work out how much time clocks measure along different trajectories, and we find what has been described above: that if two clocks follow different trajectories but eventually meet again, the clock that did more accelerating will have measured less time in total.

102 -

Why does wave-particle duality exist? What is *reality*, and why does observation affect the system to be measured? Was Einstein's view of reality correct?

It may be better not to think of Quantum Physics too much in terms of this wave-particle duality business, because it hides something far more fundamental. Namely that at the quantum level, physics is not characterized by numbers, but rather, by non-commuting quantities, which Dirac called q*-numbers*.

This has numerous consequences, not the least of which is that because of the rules of arithmetic that apply to these quantities, not all of them can be simultaneously number-valued. In short, when you observe, say, the linear Momentum of an electron (that is to say, you set up an experiment in which the electron's Momentum interacts with a classical apparatus, forcing the Momentum to be in a so-called *eigenstate*, i.e., be *number-valued*) its position cannot be number-valued: this electron at this time has no classical position. This is important to emphasize: it is not the limitations of our instrumentation or our inability to measure something: we just cannot measure what does not exist.
This is why it is fundamentally wrong to say that measuring the electron's Momentum, say, affects its position and introduces an *uncertainty*. This was, of course, Heisenberg's view but we have come a long way since Heisenberg. Quantum reality is something much more profound: in an experimental configuration in which the electron's linear Momentum interacts with a classical apparatus, the electron has *no classical* position at all.
So, what does it have instead? This electron would have a position characterized by a *q-number*. The q-number does not tell you what the position is; but it can tell you what the probabilities are of measuring specific values of position, that is, the probability of finding the electron in different places.
And when you look at the governing equation of these probabilities, it will typically be a *wave equation*. This wave equation tells us the probability that, given prior measurements (e.g, that prior measurement of the electron's linear Momentum) how the probability of finding the electron evolves from place to place and from time to time. But if there

is, in fact, a measuring apparatus that interacts with the electron's position at some point in space and time, that will constrain the position of the electron to be number-valued then and there. So it will be observed, as always, as a point-like particle with a definite position even though at no other time did it have a classically defined position.
There is, by the way, a fairly revealing classical analogy to all this. Never mind position and Momentum. Think instead about an ordinary sound and two of its properties: the time when it is heard and its frequency. When a sound is a perfect sine wave, its duration is infinite, so the time when it is heard is ill-defined. Conversely, think of a momentary sound like a gunshot. Its timing is very well defined but in the frequency domain, that loud pop is a combination of a myriad frequencies; there is no well-defined pitch. The two quantities are related to each other by a so-called *Fourier Transform*, just like the position and Momentum of an elementary particle are related to each other by a Fourier transform. So when one of the two has a well-defined classical value (i.e., it is represented by a so-called *Dirac delta functional*) the other would be a sine wave of sorts.
Einstein mostly objected to the idea that Quantum Physics is about probabilities as he believed firmly that Physical Reality exists independent of our ability to observe it. Presumably, if he lived longer and had been given a chance to become familiar with Quantum Field Theory (QFT), especially its modern formulations, he would have welcomed it. In particular, he would have liked the idea that in a typical QFT calculation, there are no probabilities. Everything is *exact*, including Conservation Laws, that are exactly satisfied, or the calculation of various cross-sections that an interaction can have. This would have made it a lot clearer that probabilities enter the scene when we introduce the fiction of a classical measuring apparatus, manifested in the form of 'external legs' of a *Feynman diagram*, for instance.
Unfortunately, Einstein died more than 60 years ago, when QFT was still in its infancy and its spectacular successes (in particular, the foundational role it plays in the Standard Model of Particle Physics) were still many years away.

103 -

Are Maxwell Equations are an effect of the constancy of the speed of light in all inertial frames? If so, what is the fundamental cause of that constancy?

Maxwell Equations are NOT an effect of the constancy of the speed of light.
Maxwell equations are, in fact, mathematical identities that apply to any 4-dim vector field that is at least three times differentiable, in conjunction with the definition of what is known as a massless current in the literature.
But these equations only work in SpaceTime with 'Minkowski signature' and are invariant under the set of transformations known as *Conformal Transformations*. Without going into detail, conformal transformations in SpaceTime define an invariant speed (one that is unaffected by the transformation). Indeed, Maxwell's Equations predict that electromagnetic waves in Vacuum *propagate at this speed*.
Furthermore, the speed of propagation of an electromagnetic wave is directly related to the properties of the medium in which it propagates, so arguably, the Vacuum speed of light is a reflection of the properties of the Vacuum. It stands to reason that an observer sees the same Vacuum with the same physical properties regardless of his own motion, since there are no markers or anything in Vacuum that would characterize the observer's speed relative to the Vacuum.
So, ultimately, the source of the existence of an *invariant speed* is inherently related to a fundamental symmetry of SpaceTime under the conformal group of transformations or one of its subgroups (including translations, rotations, and changes in velocity, also known as. 'boosts'). As to 'why' this is so, that is not necessarily a question that Physics can answer.

104 -

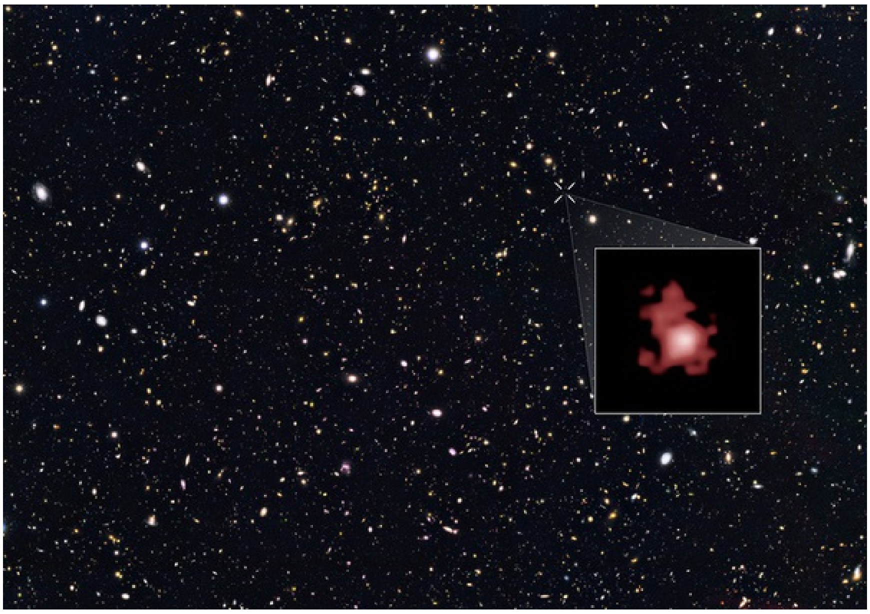
Do we say the Universe is $13.8 \cdot 10^9$ years old just because we can see $13.8 \cdot 10^9$ light-years away with our telescopes? If our telescopes were more powerful, would we say the Universe is that much older?

The answer almost stares we in the face from our own question. The thing is that the telescope is not only a tool that can see far away in the distance but also, because of the finite speed of light, *back in time*.
So, we might ask, how far back in time can we see? Only back until that moment where light exists and can move freely through space.
Beyond that our telescopes can't see, because there's no more light to be seen. That's one of the reasons we know that there must have been a beginning to this Universe.

As a bonus point:

> The objects the telescopes actually see are right now at a far longer distance than $13.8 \cdot 10^9$ light-years away and that is because of the expansion of the Universe! Since the light left its host galaxy some, let's say $13.8 \cdot 10^9$ years ago, the space between our own Milky Way and the galaxy kept expanding.

This means that the galaxy we are seeing is actually $32 \cdot 10^9$ light-years away in this moment, not that the Earth and the galaxy were so far apart initially.



GN-z11, the observed farthest galaxy from the Earth, a $32 \cdot 10^9$ years old image of a galaxy $32 \cdot 10^9$ light-years away!
(Photo courtesy of NASA, ESA, and P. Oesch, Yale Un.)

105 -

Is 1/3 of the Matter of the Universe missing?

If the question refers to Dark Matter, it is closer to $6/7$ of all 'pressureless' Matter. The remaining 1/7 is the normal, 'baryonic' Matter which we are familiar with.
However, there is, or at least used to be, a discrepancy between the amount of normal Matter that we expect from cosmological measurements vs. the amount of normal Matter that we actually see. But it wasn't 1/3, more like half of all normal Matter that was unaccounted for. It appears though that this missing normal Matter is, in fact, accounted for by the inter-galactic medium, i.e., the very tenuous, mostly hydrogen gas that is present in the voids between galaxies.

106 -

If Matter is made up of atoms which are made up of electrons, and electrons are wave functions which are made of fields, how is material like Matter formed?

Matter is made up of atoms. Atoms are made up of electrons and nuclei; atomic nuclei are made up of protons and neutrons, which, in turn are made up of quarks.
These particles are, in fact, all excitations of underlying fields: the electron field, 6 different quark fields, and additional fields such as the Electromagnetic Field, the fields of the Weak and Strong nuclear interactions, and the fields associated with neutrinos, which mediate interactions between the other fields. The Higgs Field is in there, too.
Complex interactions between these fields create those localized packets of Energy, Linear Momentum, Angular Momentum, with *electric charge* and other properties that we recognize as atoms. The same interactions (mostly Electromagnetism) allow these localized things called atoms to interact with one another, forming more complex structures such as molecules, including the highly complex molecules of life.
For clarification, the wavefunction is related by distinct: it is a mathematical construct that describes the state of an entity (a particle, an atom, etc.) and which can be used to make testable predictions about that entity.
And we know all of the above with a great deal of certainty not because of philosophical consensus but because the mathematical theory, which is described here briefly, yields exact, testable predictions that can be verified in the laboratory, but which also form the basis of much of modern technology, from semiconductors to designing drugs.

107 -

When were the photons we see today created in the core of the Sun?

The photons that we see from the Sun were *not* created in the core of the Sun.
The temperature in the core of the Sun is several million degrees. The vast majority of photons created there are hard γ- rays. Fortunately, these photons are immediately reabsorbed by the surrounding material, which is dense, opaque, fully ionized, mostly hydrogen gas.
The heat that is produced in the core of the Sun eventually reaches the surface by a combination of all heat transfer mechanisms (radiation, conduction, convection), though different mechanisms play different roles at various depths.
Ultimately, it is the surface of the Sun, heated to just a tad under 6000 K, and radiating as a near perfect thermodynamic black-body, that produces most of the light that we see. So, the photons that we see were, in fact, emitted by incandescent hot gas at the surface of the Sun, the boundary region between the opaque upper layer and the Sun's transparent atmosphere, approximately 8 minutes before they reached our eyes.

108 -

What is the current rate of Matter destruction in stars and in black-holes? What is the current rate of Mass destruction in stars? How do those two values evolve over the lifespan of the Universe?

If by 'Matter destruction', the question is actually referring to the rate at which atomic matter is converted into electromagnetic radiation (light and heat), the Sun shines at a rate of $3.9 \cdot 10^{26}$ W, which is the equivalent of 4.3 million metric tons of ordinary matter converted into electromagnetic radiation. That is to say, the Sun loses 4.3 million metric tons every second, as it emits 4.3 million metric tons' worth of electromagnetic radiation every second.
It should not be called 'Mass destruction'. It is a rather common misconception that Mass (or worse yet, Matter) is 'converted into Energy' by various processes. But this is not what happens: *Mass is Energy*. When we grab a brick, roughly 99% of the Mass we feel is due to the strong force binding Energy holding quarks together inside protons and neutrons inside that brick's atoms. Only about 1% of the Mass is due to the quark rest Masses (and those rest Masses, in turn, are actually due to the binding Energy between quarks and the Higgs Field's Vacuum expectation value). Einstein's 1905 paper that introduces Mass-Energy equivalence actually says it clearly right in its title: the inertial Mass of an object is its Energy-content.
So, when a chemical or nuclear reaction produces radiated heat, all that happens is that one form of Energy (usually, binding Energy) is converted into another form of Energy (Kinetic Energy of electromagnetic radiation). The radiating object's Energy-content (hence, Mass) is reduced by the corresponding amount. No Mass-Energy is destroyed in the process, it is simply a conversion from one form into another.
Stars, then, do this: convert some of the nuclear binding Energy into *radiated heat*. Over the entire lifespan of a star, only a fraction of a star's Mass is converted into *radiation*, however. As to black-holes, if anything, they do the opposite: they radiate nothing (other than Hawking Radiation, which is minuscule for an astrophysical black-hole) and anything they 'swallow', including any radiation they absorb, adds to the black-hole's overall Mass.
The 'lifespan of the Universe' is a mighty big number. In fact, as far as we know, the future lifespan of our Universe is infinite. So it kind of makes sense, at least for fun, to extrapolate what we know to the extreme distant future. Of course all this gets very speculative at this point since we have no means of validating these extrapolations, they are so far outside what we can actually study or experience.
Still, … we have to remember black-holes and Hawking Radiation. Normally, black-holes form by gravitational collapse, which requires at least three times the Mass of the Sun to overcome the inherent pressure of condensed Matter. But if we wait for an extremely long period of time, gravitational collapse just might happen by quantum tunneling, and smaller objects, even much smaller objects, may collapse into black-holes. In the very distant future Universe, these black-holes would appear isolated, and there would be no measurable cosmic microwave background either, so these new black-holes could freely evaporate through Hawking Radiation. The timespan of evaporation may be very long by our standards but compared to how far in the future this will take place, it might as well just be the blink of an eye. Eventually, Hawking Radiation converts all the original Mass into radiation. This radiation then spreads out and, in an expanding Universe, gets redshifted until it becomes undetectable.
If this picture is true, then eventually in the extreme future, by quantum tunneling through a black-hole state, all ordinary Matter eventually gets converted into electromagnetic radiation, which is then dissipated away in an expanding Cosmos, leaving behind just emptiness.

We are talking about time-spans so great, when expressed in years even exponents need exponents (e.g., $10^{10^{120}}$ years and the like). And going even further beyond these vast timescales, quantum tunneling may do even weirder things, such as allowing the empty, dead vacuum to spawn whole new universes spontaneously.
Either that or, more likely, everything in the last few paragraphs is nonsense. Extrapolating our Science, this far beyond the realm of the known, though it can be fun, is almost certainly an exercise in futility.

109 -

Does light orbit stars and black-holes?

Indeed, light can orbit black-holes in very tight orbits (not stars though; stars are too large in geometric size compared to their Mass, so light cannot get close enough without hitting the surface).
The region where closed photon orbits exist around a black-hole is called the photon sphere (the recently published picture of the ‘shadow’ of the M87* supermassive black-hole does, in fact, show the area blocked by the photon sphere of this black-hole).
However, these orbits are not stable. The slightest perturbation to a photon is sufficient to cause it to either hit the event horizon or escape to infinity after a small number of orbits.

110 -

Is the Time dilation in Interstellar exaggerated?

Very much so. The Physics of Interstellar was grossly exaggerated.
For a stellar-size black-hole, such extreme time dilation is found only within meters of its event horizon. There are no stable orbits there (unless the black-hole is rotating at a near extremal rate) and tidal forces would rip apart a human being quite possibly even on the molecular level, in a form of extreme ‘spaghettification’.
It is possible to survive tidal forces in the vicinity of a supermassive black-hole weighing at least a hundred thousand Suns or so. So, a single human in a spacesuit, orbiting such a (presumably rotating) supermassive black-hole could survive and experience extreme time dilation (but see further comments below).
However, to have an entire solar system survive in an environment of extreme time dilation, and moreover, experience approximately uniform time dilation, would require a supermassive black-hole far bigger than either the fictitious Gargantua or the largest supermassive black-holes observed in reality, by many orders of magnitude bigger, in fact.
And that leads to other contradictions. Such an environment of extreme time dilation will not abruptly end just outside that solar system. Rather, it would extend a great distance, gradually diminishing over a distance measured in light years. So, the idea that there is extreme time dilation between an astronaut on the planet and a relatively nearby spaceship just makes no sense.
An astronaut in an environment of such extreme time dilation would see incoming light from the rest of the universe at an extreme blueshift. Distant stars would appear as brightly burning pinpoints of light, with most of their radiation arriving in the form of UV and x-rays. Even the cosmic microwave background would be catastrophic: at such extreme blueshift, the whole sky would appear to radiate at a temperature of many thousands of degrees, equivalent to placing the astronaut inside an incredibly hot oven.
Furthermore, descending into such a deep gravitational well would release astronomical (pun partially intended) quantities of Kinetic Energy; and conversely, to be able to escape from that gravitational well would require a propulsion system that could, in empty space, accelerate a craft to near the speed of light.

111 -

Geometrically speaking, is the event horizon of a black-hole a sphere or a ring? Can it be oblate or elliptical?

The Schwarzschild solution of a nonrotating black-hole-is obtained as the spherically symmetric, static Vacuum solution of Einstein’s field equations of Gravitation.
Similarly, the *Kerr solution* that describes a *rotating* black-hole is obtained as a static Vacuum solution assuming axial symmetry.
The ‘no hair’ Theorem asserts that the Kerr black-hole is, in fact, the most general static Vacuum solution (if we permit an electrostatic field, we get the Kerr-Newman solution instead).
But we should be careful with the conclusion that this implies that the event horizon is spherical (in the Schwarzschild case) or perhaps an oblate spheroid (in the Kerr case).
Both these characterizations are based on the implied assumption that the event horizon is presently there, a ‘thing’ in space, which has a shape that can be measured or, at least, characterized by its geometric properties.
Yet that is not the case. To an outside observer, the event horizon is not there yet, and never will be. It forever remains in the outside observer’s future. The only kind of observer that can actually experience the horizon is an infalling observer who crosses the horizon. But for this observer, the horizon is not a well-defined shape in space; rather, it becomes a past moment in time. So, it’s kind of like asking if last Thursday afternoon was spherical or oblate.
Having said that, even if we cannot observe the horizon itself, we can imagine, for instance, a swarm of rockets hovering outside the black-hole at a given power level. For the Schwarzschild black-hole, these rockets would form a sphere; the more powerful the rockets, the closer they could hover to the yet-to-be-formed event horizon. And for the Kerr black-hole, they would indeed form an oblate spheroidal shape.

Not elliptical though: an elliptical shape would have to be maintained by rotation; and that rotation, in turn, would produce *gravitational radiation*, causing the black-hole to lose Energy until it settles down to the Kerr (or Schwarzschild) representation.

112 -

How can Schrodinger's cat be in two states, alive and dead? We don't know, but *it is* either live or dead.

This is just hitting the nail on the head! Popular accounts of Quantum Mechanics notwithstanding, Schrödinger's kitty is not simultaneously alive and dead. It is … a tad more nuanced than that.

For starters, this proposed thought experiment was primarily intended to point out the inconsistencies of the strict Copenhagen interpretation of Quantum Mechanics: namely that if we take this probability business seriously and literally, we'd end up with a cat that is both alive and dead at the same time until it is 'observed'.

But … OK, let's step back for a second. Let us look at another experiment first, the famous two-slit experiment. A stream of particles going through a pair of holes and then showing an interference pattern, even if they are fired one particle at a time. From this we conclude that en route, the particles have no classical path: they really are in two places at once until they are 'observed', that is, until they interact with a macroscopic instrument such as a fluorescent screen.

Now let's return to our hapless cat. There is a particle involved here, too: the atom that either splits or it doesn't, producing the signal that breaks the vial that kills (or doesn't kill) the cat with poison. So, we open the box later and we find … either a live cat, in which case we unambiguously conclude that the cat was alive all along, or a dead cat, in which case a competent vet can tell us the time of death (or better yet, just leave a camera in the box, too. Come to think of it, let's just stick with the camera and avoid harming any cats). In any case, unlike the two-slit experiment, here there are no signs whatsoever of the cat being in two states at once. No interference. On the contrary, we can unambiguously reconstruct the cat's history.

"How come?" we ask. Because the cat (or the camera) is a macroscopic instrument. When the atom in the experiment interacts with it, it confines that atom into a so-called *eigenstate*: it will either have split or not. There is no ambiguity here.

Now, if we wanted to be really, really pedantic, then we could point out that even though a cat (or a camera) is a very complex object consisting of an incredibly large number of elementary particles that are not in a coherent state, so a huge number of quantum degrees of freedom, that number is still finite, so it can, in principle, still be in a two-state superposition.

Indeed, a truly classical instrument is in an eigenstate all the time, whereas a cat, or a camera, can only be said to be almost in an eigenstate almost all the time. But that almost is physically indistinguishable from always because of the *very large number of degrees of freedom involved*. Any difference between almost and always in this context becomes a purely philosophical matter: it boils down to the infinitesimally small possibility that because we live in a Quantum Universe, the Classical Reality that we observe *is not* what's actually out there.

113 -

Does Quantum Field Theory really say that particles don't actually exist? If so, how can be explained that basic idea to those of us who grew up learning about protons, neutrons and quarks as actual 'things'?

The fundamental entities in our best theory to date, Quantum Field Theory, are *fields*.

Classical fields can have arbitrary values of *Energy* and *Momentum*. *Quantum* fields are, in a sense, more constrained. We can describe their state as a sum of 'excitations', each of which has a specific frequency, not unlike music can be thought of as a combination of many frequencies. But the Energy levels at each specific frequency cannot be arbitrary. Rather, they come in set units. So, when a quantum field interacts with another quantum field, the result is that its number of excitations *at some given frequency increases or decreases by one*.

This sounds very mathematical of course, but here is the thing: these excitations have physical existence. For starters, they carry *Energy* and *Momentum*, i.e., they can be the means to communicate a physical influence between things.

Moreover, these excitations can, under the right circumstances, be highly localized. That is to say, the quantum field has a high likelihood of interacting with other fields at a specific location, and almost no likelihood of interacting with other fields elsewhere. In this case, the excitation actually behaves almost as though it was a miniature cannonball or some such thing, that is to say, a *particle*.

So, protons, neutrons, quarks are 'things': they carry Energy, they carry Momentum from place to place, and they let other things influence each other through their actions. But they are not, actually, miniature cannonballs. Depending on the circumstances, they can be smeared out, so to speak. Indeed, if we allow for the curved SpaceTime of Gravity or more generally, for accelerated observers in Relativity Theory, two observers may not even agree on what excitations of a quantum field they see, i.e., they won't see the same particle content (but they do see the same field).

But at other times, these 'particles' are confined in space and for all practical intents and purposes, behave as though they were miniature cannonballs after all. For instance, when the electron gun in an old-style CRT display emits electrons, they do follow the route prescribed by Classical Physics for electrically charged particles as they travel towards the screen, influenced by the electric and magnetic fields of the CRT.
On the other hand, when you look at what happens to a ray of light in Diffraction Optics, it is not possible to account for that using the notion of photons as miniature cannon balls. Rather, the field reigns supreme: you need the machinery of Maxwell's Electromagnetic Field, or its *quantized* version, to understand in full what happens, how waves interfere constructively or destructively and how a diffraction pattern forms. Yet, when it comes to the actual detection of light, a photon counter still measures individual photons, even though in such an experiment they decidedly do not behave like miniature cannonballs; rather, they are the unit excitations of the Electromagnetic Field, which can exist even when they have no well-defined position.

114 -

What are the problems that physicists face while searching for the Grand Unified Theory?

The obstacles in the search for a Grand Unified Theory are essentially the shortcomings of the current best theory that we have, the Standard Model of Particle Physics.
The biggest problem of course is that the model does not incorporate Gravity. The direct reason for this is that unlike the other three interactions, Einstein's Classical Theory of Gravitation *cannot* be turned into a *Renormalizable Quantum Field Theory* (renormalizable, in this context, means a theory from which unwanted infinities can be removed by suitable mathematics). In the absence of a quantum theory of Gravity, Einstein's Field Equation is only approximately valid: its left-hand side (*SpaceTime curvature*) is an *ordinary number*, its right-hand side (the stress-Energy-Momentum of Matter) is a *quantum mechanical operator*, so the two cannot possibly be equal. We can replace the right-hand side with its *expectation value*, which would be a number, but this is only an approximation (look back at Issue 13, P. 6).
Beyond the problem of Gravity, the Standard Model has its own shortcomings.
In first place, it is 'ugly'. It is cobbled together, on the basis of observation, from a multitude of fields: three generations of fermions combined into left-handed doublet and right-handed singlet states, 'held together', so to speak, by the rather arbitrary gauge symmetry group $SU_c(3)\times SU_L(2)\times U_Y(1)$, the symmetry of which is broken by a scalar doublet (the Higgs Field) that also interacts with the charged fermions, endowing them with Mass. As such, this model already has 18 parameters that are not predicted by the theory but must be established through observation.
Next, add the problem of neutrino Masses. The standard model predicts massless neutrinos. We now know from neutrino oscillations that neutrinos are not only *massive*, but they behave unlike other fermions: we've never observed *right-handed* neutrinos, and even for the left-handed neutrinos, *flavor* and *Mass eigenstates* don't coincide.
A phenomenological description (the neutrino Mass-matrix) introduces another 6 parameters to the theory, along with a seventh parameter that describes the *CP* (*Charge-Parity*) *symmetry violation* of the neutrino Mass-matrix, but it does not tell us how to introduce neutrino Masses in a manner such that the symmetries and renormalizability of the Standard Model are preserved.
Then, there is the issue of no CP-violation in the Strong Interaction. Why is this the case? One possible explanation involves a new (as yet unobserved) particle called the *axion*. If there is a small strong CP-violation after all (or an axion), that is yet another parameter to the Standard Model, bringing the total to a whopping 26.
Next, the hierarchy problem. Why are the particle Masses what they are? Why are even the heaviest elementary particles so 'light' compared, e.g., to the Planck Mass?
Last, but not least, the Cosmological Constant problem. We now know, from supernova data, that more than 70% of the Universe is 'Dark Energy', also known as the *Cosmological Constant*. The likeliest origin of this component from Quantum Field Theory would be *vacuum fluctuations*. But, depending on what assumptions you calculated it, the computed value for Dark Energy is anywhere between 50-120 orders of magnitude *larger* than what we observe. Some people dubbed this the worst prediction in the history of Particle Physics!
So there is plenty of work to do, and in all likelihood, plenty of groundbreaking discoveries to be made. Perhaps there is a true 'theory of everything' out there, which explains everything in Physics with no tunable parameters, making our Universe the only Universe possible. Perhaps not. But we're a very long way away from knowing, either way.

115 -

Since the ether was discovered in 1925, is the Special Theory of Relativity still valid?

Presumably, this question refers to the ether-drift experiments of Dayton Miller, carried out in 1925 on top of Mt. Wilson. Miller indeed claimed to have detected *ether drift*, though the detected magnitude was much smaller than predicted by any ether theory. Had these detections been confirmed by other experimenters, they would indeed have

challenged Relativity Theory, as Einstein himself acknowledged. However, Miller's results were disputed, and no other credible experiment has been able to replicate his results.
Today, we have technologies that rely heavily on our understanding of electromagnetic waves using Relativity Theory. One example is precision spacecraft navigation, including GPS. If there were any measurable ether drift, these technologies would fail. Essentially, every time we use a GPS device to determine our accurate position here on the Earth using the precise timing of radio signals from a set of satellites, we confirm Relativity Theory at a precision much greater than Miller's.

116 -

Was Albert Einstein troubled by Quantum Physics only because it conflicted with his General Theory of Relativity?

No, on several counts.
First, the conflict between Quantum Physics and General Relativity, to the extent that it can be called a conflict (see below) became apparent only in the years or decades after Einstein's death.
More importantly, Einstein was not troubled by Quantum Physics at all. He was one of the founding fathers of Quantum Physics. His groundbreaking 1905 paper on the *photoelectric effect*, which earned him the Nobel Prize, was so revolutionary, even a decade later friends of him felt the need to apologize: even a genius can make mistakes occasionally, they said. What Einstein proposed was the almost sacrilegious idea at the time of discarding Maxwell's beautiful theory of Electromagnetism in favor of quantizing the Electromagnetic Field itself!
Einstein was more of a spectator than a participant in the development of the 'new' Quantum Theory, the Wave Mechanics of Schrödinger, or the equivalent Matrix Mechanics of Heisenberg but it is unlikely that the theories themselves caused Einstein much hardship. Rather, what Einstein was deeply troubled by was the *probabilistic Copenhagen interpretation* of the Quantum Theory and its reliance on the ill-defined concept of an 'observer'. This conflicted fundamentally with Einstein's world view as a physicist, his belief in the existence of an *observer-independent objective reality*.
It was in this vein that Einstein was trying to construct counterexamples, thought experiments that would purportedly prove that the Quantum Theory is necessarily incomplete, perhaps an approximation of a deeper, more fundamental theory that does away with probabilities and observers. He did not succeed, and the debate never died, though the development of Quantum Field Theory brought a lot of clarity.
And it was only after Quantum Field Theory became a mature discipline, after Einstein's death, that it became clear that the path to a quantum Theory of Gravitation is not as straightforward as it was previously thought. Quantum theories of Gravity are notoriously *non-renormalizable*, meaning that the Theory yields meaningless *infinities* that *cannot* be removed by a consistent mathematical process.
This does not mean that there is a fundamental conflict between General Relativity and the Quantum Theory. For starters, we can do Quantum Field Theory on the curved background of General Relativity just fine. It is when we look at Quantum Matter as a source of Gravitation that a conflict arises: Einstein's Field Equation ends up with incompatible quantities on its two sides (number-valued quantities characterizing SpaceTime vs. operator-valued, 'quantum' quantities characterizing Matter). But even this can be easily (albeit inelegantly) resolved, to a very good approximation, by what is known as Semi-classical Gravity. Herein lies our problem: the approximation is a little too good, meaning that it pretty much covers every conceivable scenario involving observation or measurement. This means that we are not getting useful hints from Nature as to which direction to take in search of a better theory. We are left guessing. And so far, no truly successful theory emerged.
But this is way beyond the state-of-the-art of the 1950s, when Einstein died. So, this was not a motivation for him.

117 -

What is the difference between 'past photos' of event horizons of black-holes and the newly released (2018) 'photo' of a claimed black-hole?

[see Issue 92, p. 42]

The difference between 'past photos' of event horizons and the recently released picture, reconstructed from radio-telescope observations (strictly speaking, not a photo, but a 'bona fide' picture just not taken in the visible part of the spectrum of M87*) is that past photos *do not exist*. This result by the Event-Horizon Telescope collaboration is the first ever successful campaign, a multiyear international effort, to image the immediate vicinity of a black-hole, showing the 'shadow' of its so-called photon sphere. This image was made possible by

- the fact that M87* is a very large black-hole, with a Mass amounting to several billion Suns, and
- that the 'telescope' in question was a set of linked radio-telescopes forming, using what is called *very long baseline interferometry*, a 'virtual' telescope with an effective size as big as the Earth itself.

118 -

How one's own Theory of Gravitation can be created?

A sensical way is just using differential equations, if one wishes to create a 'proper' theory of Gravitation that would be treated with respect by other theoreticians …
For starters, one should identify the problem to solve. Is it, e.g., galaxy rotation curves? The failure to detect Dark Matter\Dark Energy? The Cosmological Constant problem? Something else?
Second, identify the playground. Are you looking for a Classical Theory of Gravitation, presumably an extension of Einstein's Theory of Relativity? If so, does this new theory respect, e.g., Conservation Laws or the Weak Equivalence Principle? Or is the playground Quantum Physics and one is looking for a Quantum (Field) Theory of Gravitation?
Third, one should identify the *constraints*. Existing theory works very well in most scenarios and has been tested exquisitely well in some. Whatever modified theory of Gravitation results, it must reproduce those successes in addition to its own claims.
Now, let's notice that it hasn't been said anything yet about the *mathematical machinery*. That would be putting the cart before the horse: the job defines the tools, not the other way around.
Therefore, a pretty universal tool for the theorist is *variational calculus* and the *Principle of Least Action*. One should learn how to use these tools in the case of 4-dim and in the case of a field theory, understand what an expression like

$$S = \frac{1}{16\pi G}\int (R + 2\Lambda)(-g)^{1/2}\, d^4x$$

means, why the terms are there, what they do and how varying this equation with respect to $g_{\mu\nu}$ leads to *Einstein's Vacuum Field Equations*. Understand what current modified theories do, e.g., scalar-tensor theories, $f(R)$ theories, theories involving unit or arbitrary vector fields, etc. Understand why people tried these approaches and why they were not altogether successful.
Though it's more than half a century old, recommended reading would be Feynman's *Lectures on Gravitation*. That book provides an approach that is different from the usual perspective: instead of presenting Gravitation as a theory of 4-dim geometry, Feynman approaches it from a *particle physicist's perspective*. From it we learn why it is not viable to use anything less than a tensor (or spin-2) theory to describe gravitational phenomena. With that and a bit of grounding in Quantum Field Theory, including *non-Abelian gauge theories*, you may be ready to take the plunge and study Quantum Field Theory on a curved background and think about why Gravitation is special. Also, why it resists attempts to be 'tamed' by way of *renormalization*.

119 -

How is the Universe expanding *faster* than light speed? How does this not disprove c as the universal maximum speed?

We should remember that an expanding Cosmos *is not* flat SpaceTime. Distances and speeds over large distances have no unique, unambiguous definition in curved SpaceTime and comparisons to c must *always* be done locally.
Before thinking about the Cosmos as a whole, let's take, for instance, our own Solar System. One of the more interesting, non-trivial effects of General Relativity is the Shapiro-delay: when a ray of light passes near the Sun, from our perspective here on the Earth, it takes longer to arrive than a naïve calculation would suggest. Why? Because near the Sun, there is *gravitational time dilation*. From our perspective, light rays travel slower than c near the Sun. But if we were floating near the Sun and measured that ray of light as it passed near us, we would find that it moves just at c. Why? Because your own clock that we use to measure speed will also be subject to the same dilation. But this also means that if we looked at that light ray elsewhere alongside its path, from our perspective, it would be faster than c! It's not because that ray of light actually moved faster than c. It is because your clock ticks slower while you are deep inside the Sun's gravitational field that so far-away things will appear sped up.
In short, in General Relativity the speed of distant things is ill-defined and yes, it can appear to be greater than c.
So, let's consider the rate of expansion of the Universe. Let's look at something distant, say, a galaxy from which light took over 13 billion years to arrive. Naïvely, we could say that this galaxy is then about 13 billion light-years from us, or at least was when it emitted the light that we now see. This would indeed qualify as the 'light travel time'.
But wait. Didn't we just say that light rays appear to move more slowly in stronger gravitational fields? The overall gravitational field in the Cosmos was stronger when the Cosmos was *denser*, so this light ray certainly would have appeared to us to move slower than c. So, perhaps that distant galaxy is closer than $13 \cdot 10^9$ light-years?
But there is another way of estimating the distance from that galaxy. We could chop up the path of that light ray into small segments and estimate how that segment expanded between the time when the light ray passed through it and the present. Summing it up (by way of an integral) we get a value that is over $4 \cdot 10^{10}$ light-years.

So, as has been said above, there's no unambiguous definition of distance.
This last distance estimate is popular because it tells us where the galaxy is now relative to us in the so-called co-moving frame. But if one takes that $4 \cdot 10^{10}$ business literally, it means that this distant galaxy must have been moving away from us at roughly three times the vacuum speed of light! How is that possible?
Well, ultimately, it's the same thing as with the Shapiro delay. We are estimating the speed of a *distant object*: the answer we get *depends on our choice of reference frame*. Meanwhile, if we could somehow travel to that galaxy's location, we would notice that it is not moving faster than the speed of light at all. As a matter of fact, just like our Milky Way, it is more or less at rest with respect to the cosmic microwave background as it is seen at its location.
To make a long story short: in the non-flat SpaceTime of General Relativity, the speed of distant things is *ill-defined*. The vacuum speed of light remains *invariant* and, *locally*, no object can travel faster than c. But distant objects can *appear* to move faster, depending on how we define the reference frame in which their speed is expressed.

120 -

If SpaceTime is not a 'real thing', then, what is *frame-dragging*?

Frame-dragging concerns the behavior of the metric of SpaceTime, i.e., the Gravitational Field.
It's convenient to distinguish between SpaceTime (3 spatial directions and 1 temporal direction) vs. the Gravitational Field for two reasons:
first, the Gravitational Field may or may not be the metric of SpaceTime. It is not a question of trying to propose some radical reinterpretation of Einstein's Theory of Gravitation. Rather, this is a reminder that Einstein himself was not particularly fond of his theory's geometric interpretation. So, why we think that the geometric interpretation is appropriate? While other theories (e.g., Electromagnetism) can also be expressed using the language of Differential Geometry (*covariant derivatives*, to be precise), what distinguishes Gravity is that it is universal: the Geometry of Gravitation is 'sensed' by all Matter equally, so, it is the only Geometry insofar as Gravitation is concerned (in contrast, as for Electromagnetism, for instance, a neutral and a charged particle certainly do not experience the same geometry). But, just because we can interpret Gravitation as the (one and only, universal) Geometry of SpaceTime, does not mean that we must nor do we know for certain that a yet-to-be-discovered Quantum Theory of Gravitation will obey the same constraints. In any case, it is certainly possible to develop the Classical Theory of Gravitation from first principles without ever alluding to SpaceTime Geometry, just as a non-linear *Tensor* Field Theory;
second, the metric of SpaceTime is not the same as SpaceTime itself. A manifold may or may not be endowed with a metric (or it may be endowed with multiple metrics). So, we have 3 spatial dimensions and 1 temporal dimension, i.e., a 4-dim manifold; to this, we add a rule that allows us to form inner products of vectors, and we express this rule in the form of a metric. This rule can be expressed as a *tensor-valued field* attached to every point in SpaceTime. And unlike SpaceTime, which only has an ephemeral existence (it cannot be directly observed or measured, only through the spatio-temporal relationship of things within it) the metric is a *physical field*: It carries *Energy* and *Momentum*, it carries information from point to point. In other words, it behaves, in principle, very much like the Electromagnetic Field, with *gravitational radiation* playing the *same* role as light. And frame-dragging is essentially the gravitational equivalent of *magnetic* effects when it comes to, e.g., a *rotating*, *charged body*. Even if a future modification of Gravitation were to discard the geometric interpretation, frame-dragging would remain, as it is a *physical effect* concerning the physical Gravitational Field, not something related to the ephemeral SpaceTime, other than, of course, SpaceTime serving as the playground where all these things are taking place.

121 -

Does Dark Matter have Dark Energy or are they separate entities?

Dark Matter and Dark Energy are *separate* entities, both defined by their respective 'equations-of-state', which are quite distinct.
The 'equation-of-state' connects the *Energy density* and the *pressure* of a substance. The ratio of these two quantities is a simple number that does not depend on the choice of units in which Mass, Length and Time are measured (such a number is called a *dimensionless number*).
Cosmologists like to talk about 'dust', for instance and are not referring to the mysterious substance in the P. Pullman novels, but rather, to *any* substance with *negligible pressure*, characterized by the equation-of-state $w = 0$.
Essentially, any non-relativistic form of Matter qualifies as dust: stars, planets, people, dirt, air, water, all have negligible pressure on the cosmic scale of things.
There are, of course, substances with non-negligible pressure. However, the equations tell us that, in an expanding Universe, such substances get diluted much more rapidly than 'dust'. So, 'dust' remains.
Except that there is just not enough 'dust'. When we account for all the stars, planets, gas, (actual) dust, everything,

we only get about $1/6$ of the amount of 'dust' that is needed for the Universe to work the way it seems to work. So, we just assume that the remaining $5/6$ is there somewhere, in some form unrelated to normal Matter; because we don't see this 'dust', we gave it a name, 'Dark Matter'.
Up until the 1990's, it was generally thought that the Universe contains only 'dust' in various forms. But then it became clear, observing data from distant supernovae, that there must also be a so-called *Cosmological Constant*. Except that it is not necessarily a constant; it could be a substance with gigantic negative pressure, $w = -1$. The curious property of something with such negative pressure is that, in an expanding Universe, it does not get diluted at all. Therefore, over time, it remains the dominant constituent. But what is it? We don't know, but we gave it a name anyway: 'Dark Energy'.
So, that's it. Two phrases, 'Dark Matter' and 'Dark Energy', which are basically there to represent our ignorance. We would not call them 'Dark Matter' or 'Dark Energy' if we knew what they are. But we don't. The only thing we know about them is their respective equations of state.

122 -

Does gravity bend, warp and curve 4-dim SpaceTime within a higher dimensional space, like folding a 2-dim paper in a 3-dim space? If not, then how is this possible in only 3 dim?

No, very specifically no. When it comes to the *theory of manifolds and curvature*, there is an important distinction between *intrinsic curvature* and *extrinsic curvature*.
Extrinsic curvature is what you get when, say, we roll up a sheet of paper to form a cylinder. Notice that you can do so without stretching the sheet of paper. Right angles on the paper remain right angles. Straight lines remain 'straight', in the sense that they remain the geodesics of the cylinder that you form. The angles of a triangle formed from such lines still add up to 180°.
Contrast this with stretching a rubber sheet, e.g., to make it fit on a hemispherical surface. We are now distorting that sheet. Straight lines become curved. Angles change. The angles of a triangle formed from geodesics *no longer* add up to 180°. This is *intrinsic* curvature.
The key difference is that *intrinsic curvature* can be measured *within* the manifold itself. We do not need access to the 3rd dimension to conclude that the angles of a triangle on that 2-dim rubber sheet do not add up to 180° anymore. Measuring *extrinsic curvature*, however, requires access to the *higher-dimensional* space in which the manifold is embedded. In fact, it only makes sense with respect to that higher-dimensional manifold.
Gravitation is represented by the intrinsic curvature of 4-dim SpaceTime. So, it is like stretching that rubber sheet, not like rolling up that sheet of paper. As such, this curvature exists in the manifold without any reference to a higher-dimensional embedding space.

123 -

Is 'Particle Physics' the study of Quantum Field theories?

Well, yes. In fact, the 'Standard Model of Particle Physics' is a non-Abelian Quantum Field Theory.
The basic idea behind a Quantum Field Theory is that fields, such as the Electromagnetic Field, are the fundamental objects. These fields are 'quantized', which means that instead of being characterized by numbers, they are characterized by quantities (often represented by mathematical operators) that do not commute under multiplication, that is, the *order* in which they are multiplied *changes the result*. We find that the state of these fields can be described using *discrete* excitations, or *field quanta*, which manifest themselves in actual experiments as *particles*. So for instance, when we speak of an electron emitting a photon, what the theory actually says is that the Electromagnetic Field and the Electron Field interact, and as the Energy and Momentum of the electron field changes, the Electromagnetic Field *acquires an excitation*.
Why do we do this? Well, there really are two main reasons. *One* is that quantum particle theories may describe well how particles behave but not how particles are created and destroyed in interactions. *The other* is that even particle theories that are designed to be relativistic *can violate causality* by allowing *faster-than-light* and *backward-in-time* interactions, which we do not observe in Nature. In contrast, quantum field theories easily account for the creation and destruction of 'particles' (field excitations) and they elegantly and fully cancel out any interaction that would be faster than light or act backwards in time.
Moreover, as we describe the interaction between fields, nasty mathematical expressions can often be tamed in the form of a summation of successively smaller terms; and, almost magically, these terms can be represented combinatorically by neat diagrams, the so-called *Feynman diagrams*, arrows in which appear to us intuitively as particles! So even though we know that we are talking about an interaction between two fields, it becomes legitimate to speak of a particle A emitting or absorbing a particle B because this would indeed correspond to the first, largest

term in that series of successfully smaller terms in a summation.
Add to this the fact that although the end result is not particularly elegant, using the tools of Quantum Field Theory we were able to construct a framework that successfully describes all the known particle content of the Universe (with several of these particles first predicted by the theory, only to be confirmed by observation later, sometimes many years later) and all the known interactions outside of Gravity, and it is easy to see why the theory prevails; for all its limitations and shortcomings, it is still our most successful theory of Nature by far.

124 -

What does ds^2 mean in the *Schwarzschild solution*?

A 'solution' in General Relativity is in the form of the *Metric of SpaceTime*, also known as the Gravitational Field. The metric determines how distances are calculated. In a flat space, in *rectangular* coordinates, this is easy to do: if the differences in coordinates is the set $\{\Delta x, \Delta y, \Delta z\}$, then the distance can be computed by the Pythagoras' Theorem in 3-dim, i.e., $\Delta r^2 = \Delta x^2 + \Delta y^2 + \Delta z^2$.
In the case of 4-dim SpaceTime, there are two important things to consider:
first, 'distance' combines both 'distance' in Space and 'distance' in Time, using the speed of light 'in vacuo' as a *conversion factor*. Depending on convention (which has no physical meaning), we either have $\Delta s^2 = c^2\Delta t^2 - \Delta r^2$ or $\Delta s^2 = \Delta r^2 - c^2\Delta t^2$;
second, as for General Relativity, there are non-trivial coefficients that vary from point to point. These coefficients together form the *metric of SpaceTime*. Because they vary from point to point, it no longer makes sense to compute distances using finite differences, such as Δy; instead, we move on to infinitesimal quantities, like dy. The result is most easily written in matrix form:

$$ds^2 = (cdt \quad dx \quad dy \quad dz)\begin{pmatrix} g_{tt} & g_{tx} & g_{ty} & g_{tz} \\ g_{xt} & g_{xx} & g_{xy} & g_{xz} \\ g_{yt} & g_{yx} & g_{yy} & g_{yz} \\ g_{zt} & g_{zx} & g_{zy} & g_{zz} \end{pmatrix}\begin{pmatrix} cdt \\ dx \\ dy \\ dz \end{pmatrix}.$$

More generally, the coordinates need not be rectangular-like; the formulation above is valid in any *orthogonal* coordinate system.
In the case of the *Schwarzschild metric*, which is spherically simmetric, spherical coordinates are the most natural choice. In these coordinates, most of the matrix elements of the metric are zero and what remains can be written in a more compact form (e.g., see: WEINBERG, S., *Gravitation and Cosmology*, Eq. (8.2.12), P. 180, JOHN WILEY & SONS):

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right)c^2dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2 d\theta^2 - r^2(sin\,\theta)^2 d\varphi^2 .$$

ds^2 is the square of the 'infinitesimal line-element' and the formula that defines it basically provides the rule by which distances and time intervals can be calculated in SpaceTime, in the presence of a compact gravitating Mass M. Specifically, *finite* distances are calculated by integrating ds over a given path.

125 -

What is the mathematical proof of Einstein's Gravity Equation?

Fundamental equations in Physics *do not* have mathematical proofs. They have to be mathematically consistent, of course (and demonstrations of that consistency would rely on mathematical proofs) but the validity of the equations is determined by observational evidence, not proof.
According to current consolidated epistemology (evolved from Popper, K., & others, Russel, B.), a physical theory is expected to be 'falsifiable', i.e., it is expected to produce predictions that can either *confirmed* or *refuted* by observation. If they are refuted by observation, the theory must be discarded or, at least, modified.
Einstein's Theory of Gravitation has so far been validated by numerous precision tests in the Solar System, in that its predictions were confirmed by observation.
Nonetheless, there is room for possible extensions or modifications of Gravitation, as Einstein's theory does not work on the scale of galaxies and beyond without the need to postulate 'Dark Matter' and 'Dark Energy'. Perhaps these media exist. But it is also possible that they do not, and instead, the theory itself is in need of revision.

But on the scale of the Solar System, Einstein's Theory has been tested in a variety of ways in the past century, and in each case, its predictions were *confirmed*, sometimes with exquisite precision.

126 -

If anti-Matter is basically Time-reversed Matter and white-holes are Time-reversed black-holes, then if we make a 'black'-hole with anti-Matter, will it instead be a 'white'-hole?

Anti-Matter is not 'basically time-reversed matter'. It is true that certain antiparticles can be viewed as time-reversed negative Energy particles, but that does not make anti-Matter time-reversed Matter, it is simply a statement of a symmetry (that is sometimes broken) that we find in Nature.
As for black-holes, they don't care what we make them out of. Matter and anti-Matter both have *positive Energy*. We throw enough matter and anti-Matter together, we get a black-hole; it is irrelevant if it was more Matter, more anti-Matter, or an equal quantity of both.

127 -

What's the mathematical background to understand Special Relativity (SR), General Relativity (GR) and Quantum Mechanics (QM)? Is it possible to cover that with self-study?

To understand SR beyond the high-school level of simplistic Lorentz formulas, it helps if one understands Maxwell's Theory. That means that one is familiar with *Algebra* and *Calculus*, *Ordinary* and *Partial Differential Equations*, *Linear Algebra* and *Vector Fields*.
In addition, GR requires an understanding of *Riemannian Geometry*, *Tensor Algebra* and *Tensor Calculus*. These tools are used in many areas of Theoretical Physics (Quantum Field Theory, mainly), so they are useful to learn in any case.
QM is not terribly complicated in the beginning if you just look at the Schrödinger equation of a single particle in one dimension. But things escalate rather rapidly from there. A good understanding of Quantum Physics does not exist without *Lagrangian* and *Hamiltonian Mechanics*, for which one needs to know the basics of the *Calculus of Variations* and the concept of a *Legendre Transformation*. Knowing about operators, abstract vector spaces and the concept of a *Hilbert Space* can be helpful. Knowing about *Fourier Transforms* is essential to make the transition to Quantum Field Theory. You'll also need a little bit of *Group Theory*, in particular the theory behind *Continuous* (*Lie*) *Groups*.
Sure, it is possible to cover it all with self-study, so long as one doesn't mind going down a few dead ends and making more than a few embarrassing *mistakes* (been there, done that). One must just keep in mind that learning about concepts is not enough; one also needs to convert what has been learnt into an applied skill, by using it to *solve actual problems*, be they exercises in textbooks or actual problems you encounter. One learns the most efficiently when a goal has been set, when there is a problem to solve.

128 -

What is the Potential of a photon? In other words, does a photon have Potential Energy?

Potential Energy is not an intrinsic property of an object. So, it is not meaningful to discuss the Potential Energy of a photon, an electron, or a brick for that matter, without mentioning the environment with which the object interacts. Potential Energy arises from those interactions.
A photon interacts with electric charges, and it interacts with the Gravitational Field. So, when electric charges or the Gravitational Field are present, the interaction has the potential to change the photon's Kinetic Energy. Therefore, there is Potential Energy.
For instance, a photon approaching a gravitating Mass will gain Kinetic Energy; it will appear blue-shifted as a result. This Kinetic Energy comes from the Potential Energy that arises from the interaction between the photon and the Gravitational Field. As the photon gets closer to the gravitating object, the Potential Energy *decreases*, the photon's Kinetic Energy *increases* in such a way that Total Energy is *conserved*.

129 -

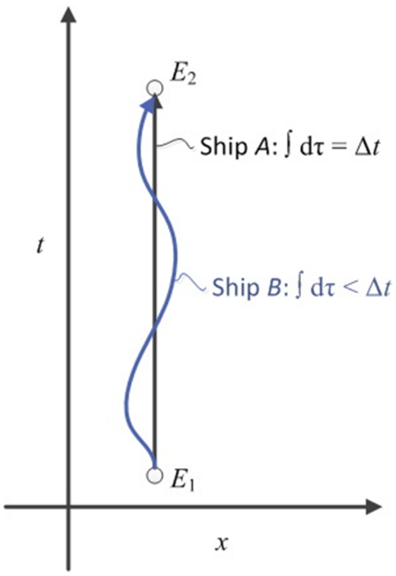
How is Time-dilation consistent?

The reason why this question causes so much confusion is that a rule (the simple *time dilation formula* found in many introductory-level textbooks and even some popular publications) is applied outside the scope within which it is valid (inertial frames of reference in Minkowski SpaceTime).

Let's forget the time dilation formula. A much more useful concept is the concept of *proper time*.

Without going into excessive detail, *proper time* is essentially a measure of the length of the trajectory of an observer in SpaceTime. Unlike coordinate time, which depends on the observer, *proper time* is a relativistic *invariant*; it is not dependent on the choice of coordinate system. Proper time also happens to be exactly the amount of time measured by a clock that moves along that trajectory. So, *proper time* is really a synonym for 'time measured by the traveler'.
In ordinary geometry, the distance between two points is shortest along a straight line. In the pseudo-Euclidean Geometry of Relativity, the *proper Time*, which is a kind of a 'distance', is *longest* along a 'straight' line; straight lines, in Relativity, are the SpaceTime trajectories of inertial (acceleration-free) motion.
So, let's take our twin ships *A* and *B*. Initially, they are at the same location at the same time, which is how they get to synchronize their clocks. Then they depart. Eventually, they meet again, when they can compare their clocks.
Their clocks will have measured the proper time along their respective trajectories. If neither ship accelerated, ever, they can never meet again, so this second comparison of clocks cannot take place. One of them at least has to turn around, and that requires acceleration. So, if they do meet, at least one, possibly both, ships will have accelerated as they changed direction. So, the *proper* time on board one, or maybe both, ships will be less than the *proper* time of an inertial observer who may have sailed by the ships at just the right velocity to be present at both events without accelerating in between.
If both ships did the same amount of accelerating (e.g., if they went on symmetrical 'mirror' trajectories) their clocks will by synchronous. If one ship did more acceleration than the other, its clock will have shown less (*proper*) time elapsed.

Let's illustrate this with a simple diagram. The two ships, *A* and *B*, travel between two events E_1 and E_2 (an *event* is a location in space at a specific moment in time; so, if the two ships met, say, Friday at 8 am at the center of Times Square, in New York City, that would be an event characterized by time, date and geographic location). Ship *A* 'travels' by simply staying put, so, for this ship, only time passes, its location (in its own inertial coordinate system) remains constant. Ship *B*, however, follows a wigglier path, accelerating.



Our intuition tells us that the length of the curvy path of ship *B* is longer. This is of course true in ordinary Euclidean Geometry. In the pseudo-Euclidean Geometry of SpaceTime, the *spacetime* path of ship *B* is actually the shorter one; the straight path is always the longest (has the most *proper time*). So, ship *B* will measure (and experience) less time than ship *A* as it gets from event E_1 to E_2. The important bit, of course, is that the symmetry between the two ships' paths is broken: ship *B* did more accelerating than ship *A*. If ship *A* had followed, e.g., the mirror image of the path of ship *B*, they would both have been doing the same amount of acceleration, so that their clocks would be synchronized when they meet at event E_2.

130 -

Why can we not get a quark by itself?

Let's take a spring. It has two ends. Now, we are asked to give just one end of that spring. Can we do that? Well … let's stretch that spring. If we stretch it beyond the breaking point, what do we end up with? Two springs, right? Both of which still have two ends, right?
That's pretty much how the strong interaction works. Say, two quarks are held together by it. To try to remove one of the quarks, we need to invest energy, just like when stretching a spring. When we invest enough energy, we actually put in the energy to create a new quark-antiquark pair. The new quark will end up taking up the place of our original quark (the one we were trying to remove), and the anti-quark will pair up with the quark we are removing … so, once again, we have a spring with two ends.
Paradoxically, if we want 'free' quarks, we need to look deep inside the nucleon. Again, imagine those springs with heavy balls on their ends. If the springs are completely relaxed, the balls can move around almost freely. It's only when the springs become stretched that the balls become confined. This is the concept of 'asymptotic freedom' when it comes to quarks: unlike other particles, quarks become 'free' when they are bound inside a nucleon.
Conditions similar to the inside of a nucleon may have existed very early in the Universe. In that state, quarks were 'free'. And such a 'quark-gluon plasma' can also be created in large particle accelerators, but this state is unstable; the plasma rapidly cools and decays (the quarks clump up into particles).

131 -

When a physicist says the Universe came from nothing, could this imply Universes are finite?

No ‘bona fide’ physicist should say such a thing, for one very simple reason: the equations of physical Cosmology describe how the Universe works, not where it came from.
We know that the Standard Cosmological Model’s mathematics predicts a so-called *initial singularity* some 13.8 billion years ago. If this prediction is accurate, the moment in time corresponding to the singularity does not exist, and time prior to this moment does not exist either. Say, this moment is $t = 0$. The equations that we have describe the Universe when $t > 0$. They tell us nothing about $t \leq 0$, as these times are not part of the Physical Universe: they do not exist, just like the place one mile north of the North Pole does not exist.
There is an idea, a conjecture if we wish, that the (positive) energy content of Matter in this Universe is balanced exactly by the (negative) Gravitational Potential Energy of the Universe. If this is true, that means that the Total Energy content of the universe is 0. This idea is sometimes whimsically called ‘the ultimate free lunch’.
But that’s really all it is: a whimsical conjecture, nothing more. One immediate problem this idea runs into is the lack of a so-called generally covariant definition of the Energy of the Gravitational Field. Because of this, while it is possible to attribute a meaningful energy content to the Gravitational Field in a specific frame of reference, it is not possible to do so without picking a frame of reference, and even then, not necessarily in a manner that applies to the whole Universe. This is even more fundamental an issue than the question of spatial infiniteness (which, by itself, would not necessarily be an obstacle).
So, while one personally finds the ‘ultimate free lunch’ idea somewhat appealing, do not let any physicist get away with spouting such nonsense, unless they make it absolutely clear that it is just a whimsical notion at present, nothing more, or unless they found some new way to reliably describe mathematically the energy content of the Gravitational Field in extended volumes.
And even the ‘ultimate free lunch’ idea does not say that the Universe ‘came’ from nothing, only that, in terms of its conserved quantities (energy, Linear Momentum, Angular Momentum, electric charge, etc.) it is nothing when these quantities are summed for the entire Universe, *they all sum to* 0.

132 -

The neutrino was thought to be massless. Experiments showed the *opposite*. Might this happen with the photon?

Of course, it could happen with the photon as well. Experimental physicists and astrophysicists are constantly probing the photon Mass and continue to establish ever more stringent upper limits. If you search the literature for ‘experimental limits on photon rest Mass’ or similar phrases, you get tons of hits. However, the two situations are quite different.
There is no a priori technical reason for the neutrino to be massless. It was assumed to be massless because we only observe so-called *left-handed neutrinos*. This ‘handedness’ relates the direction of the neutrino’s spin vector to its velocity vector. For a left-handed neutrino, the spin vector points in the direction opposite from its velocity vector. But here is the thing … if neutrinos are slower than light then, in principle, you could run faster than the neutrino and look back; from your perspective, its velocity vector now points in the opposite direction, but the spin vector doesn’t. So, what is a left-handed neutrino to others is a right-handed neutrino to us. Since we see neutrinos with all kinds of energies coming from all sorts of places, we should see right-handed neutrinos among them. We don’t … which makes sense if only left-handed neutrinos exist and they travel at the speed of light, so we cannot run faster than them and look back. This would have neatly explained the handedness of neutrinos.
Except that neutrino comes in three flavors (electron, muon, tau). And, as we found out, these flavors mix. A neutrino that begins its life as an electron neutrino in the Sun may be detected as a muon neutrino here on the Earth. The easiest mathematical model for this observed phenomenon is in the form of a ‘Mass-mixing matrix’, but the existence of that matrix implies that neutrinos *must be massive*.
Incidentally, we still don’t know just how massive they are, and indeed, one of the three Mass states may, in fact, still be massless! The only things we know from these observations and experiments are rates of neutrino mixing, which allow us to set some limits on the differences between Mass states, but that’s all.
None of this applies to photons. There are no photon flavors. There is no photon handedness. So no indication one way or another that the photon might be massive. Moreover, whereas the theory is somewhat agnostic to neutrino Masses (we can put neutrino Masses into the theory ‘by hand’ and the theory remains sensible) the masslessness of photons is an essential feature of the theory, as this represents the so-called *unbroken* $U(1)$ part of the *Electroweak Symmetry Group*.
Of course, just because our theory needs a massless photon would not stop Nature from endowing them with Mass. In that case, we’d have to search for a better theory. But based on the successes of the theory, and on the very stringent upper limits that exist on the photon rest Mass, we say it is a fairly safe bet that the photon is truly massless.

133 -

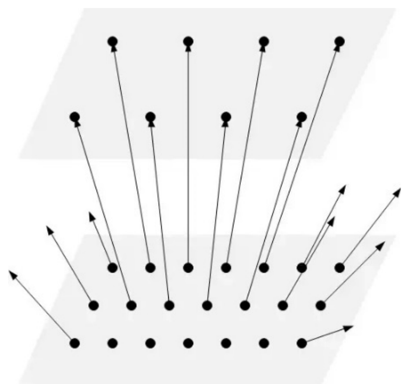
Why do protons consist of 2 *up quarks* and 1 *down quark*?

Quarks are *fundamental* particles. That is a given. We don't know why; there is no reason. We can imagine universes in which the rules are different. Our Universe has quarks. Specifically, our Universe has 6 quarks, but four are just heavy carbon-copies of the first two, which means that they are unstable, decaying into lighter particles. So, that leaves the two: the *up quark* and the *down quark* (see image in Issue 13, P. 6).
These quarks interact with each other through all three *fundamental interactions*: *Electromagnetism*, the *Weak* and the *Strong* interaction. While Electromagnetism wants to push quarks with *like* charges apart, the Strong interaction can stick them together … up to a point.
It can stick two *up* quarks together or two *down* quarks together. Why not three? Well … having two *up* quarks works, because they are both energetically in a ground state, but with opposing spin. Quarks, being *fermions*, cannot be in exactly the same state (Pauli Exclusion Principle). And there are only two spin states. So, if we tried to add a third quark, it would have to be in a higher energy state … and that's just too much for the *strong interaction* to handle. So, 3 up quarks or 3 down quarks won't work.
But why do we need 3 quarks? That's because of the way the Strong interaction works. It has three charges (whimsically labeled after the principal colors *red*, *green* and *blue*), but a stable configuration of quarks has to be 'color neutral': either a quark and an anti-quark of the *same color*, or three quarks, each with a *different color*.
That leaves just two possible combinations of three quarks: *ddu* and *duu*. One of these is electrically *neutral*; the other has $+1$ electric charge. We call the electrically neutral combination the *neutron*, the charged one the *proton*.
Curiously, only one of these is truly *stable*: the *charged* one. The neutral one is ever so slightly heavier, which means that it can actually decay (through the Weak Interaction) into the other, while emitting an electron and an anti-electron neutrino. Fortunately, when a neutron is inside an atom, things change, and the neutron becomes a bit more stable $(\sim 14'$ average life-time$)$. So, we end up with a Periodic Table of Elements.

134 -

How can the Universe be flat but also a sphere at the same time? The shape of the Universe must be spherical if the Big Bang sent all Matter, and Energy alike, in all directions. How can this intuitively contradictory fact be possible?

The problem is that popularizations of the Big Bang as an explosion that took place at some location, sending stuff in all directions, are blatantly wrong. Let's try to unlearn this 'intuitive' but totally *misleading* picture.
Instead, let's imagine an infinite sheet of paper with dots on a grid representing galaxies. Suppose the dots are spaced 1 cm apart. Now, let's imagine another infinite sheet of paper with dots, but this time the dots are 2 cm apart.
Now, let's imagine projecting the dots from the first sheet to the next sheet, so that every dot on the first sheet corresponds to a dot on the second sheet, something like this diagram (only showing a small section of the two sheets, of course):



Clearly, there is a one-to-one correspondence between the dots (this is the same mathematics that shows that there are *as many integers as there are even numbers*: (denumerable) infinity can be weird this way: $2 \cdot \infty$ is still an ∞ of the same *cardinality*. However, the dots are spaced further apart in the second sheet. And we could repeat a process with another sheet on which the dots are even further apart. Yet they are not 'moving in all directions' (we can pick any particular dot and just say that this is your dot and it is where it is, so every other dot is moving away from your dot); rather, it's the space between them that's increasing.
Playing the same thing backward, we could imagine another sheet on which the dots are just half 1 cm apart, or 1 mm, or a fraction of 1 mm. Until we end up with what mathematicians would call a 'degenerate' version of the sheet in which the distance between the dots shrinks all the way to 0.

This 'degenerate' version of the sheet is the *instant of the Big Bang* event. The next instant, no matter how short this 'instant' may be, the sheet is no longer degenerate: the dots are a small but at finite distance apart, say, 10^{-24} mm , and there is an *infinite* number of them on an *infinite*, flat sheet.
$13.8 \cdot 10^{9}$ light-years later, it will still be the same flat sheet, but the dots are now millions of light-years apart and we call them *galaxy clusters*.

135 -

If Gravity travels with speed of light in Vacuo, can it travel slower in a different medium?

Yes, of course Gravity can travel slower in a medium with which it interacts.
The question is, what would that medium be? Gravity interacts very weakly. So even the interior of a neutron star is mostly transparent to a passing gravitational wave. So just as light doesn't slow down much in air, gravitational waves won't slow down much even in that extremely dense medium.
However, ... Gravity also interacts with Gravity. *Gravitational waves*, just like light waves, are subject to the Shapiro delay, which effectively slow down a passing wave as it increases the time for the wave to travel the distance between two points (locally, we'd still measure the wave's velocity as the vacuum speed of light).
Has it been measured? Well ... perhaps, albeit not with great precision even if so. We should remember that we only have one definitive gravitational wave measurement, GW150914, from September 2019. But it appears that coincident with this measurement, there was a gamma ray observation made by the Fermi gamma ray telescope. For the gravitational wave and electromagnetic (γ) radiation to reach us within the same half-second over a distance of $1.3 \cdot 10^{9}$ light-years must mean that the two waves followed similar trajectories with extraordinary accuracy. This would mean that they must have had to respond to the curvature of SpaceTime (due to intervening galaxies and all) the same way, too.
Of course, though likely, it is by no means certain that the Fermi observation was an observation of GW150914, and even if it was, we have not seen any studies that would determine how accurately gravitational waves must mimic the behavior of electromagnetic waves. So, we should restrain from creating a false impression here that this has been rigorously tested: it wasn't.

136 -

Why is the speed of everything relative except for light? Is this is a flaw for Theory of General Relativity?

In 1887, two US physicists, A. A. Michelson and E. W. Morley, performed a precision experiment that conclusively showed that the observed speed of light does not depend on the direction of the light beam relative to the Earth's own motion.
This experiment has been interpreted by many physicists of the time as a call for revising theories of the *electromagnetic aether*, which was thought to be the medium that carried electromagnetic waves. They were trying to invent various schemes under which the aether would have been dragged along by the Earth, and even schemes in which the length of the measuring apparatus changed as a function of its motion through the aether.
Einstein chose a different path. The fact that the speed of light is the same for all observers was a given: it's what observations told us. But instead of endowing the (hypothetical) aether with ever more exotic properties, Einstein dispensed with the aether altogether, and simply questioned our understanding of the *Geometry of SpaceTime and velocity transformations*. The rest is history.
In the language of modern mathematics, Einstein sought *the most general family of transformations* of 4-dim Space-and-Time that would leave the speed of light *invariant*. The most general such group is the so-called *conformal group*. However, it needs to be further restricted if we also want electric charges to be conserved. That leaves us the so-called *Lorentz-Poincaré group of transformations*. As it turns out, this is the most general set of transformations under which *Maxwell's Equations remain unchanged*.
So, in retrospect, even without observational evidence such as the Michelson-Morley experiment, if one accepts Maxwell's Theory to be valid for all *inertial* observers, the *Lorentz-Poincaré group*, necessarily follows. And that is none other than Special Relativity.

Nature is under no obligation to be fair, intuitive or easy to understand: *Nature does not exist for our convenience*. In any case, once we learn the mathematical basics, Relativity Theory is very straightforward and very elegant. Far from being a 'flaw', it is one of the cleanest, fundamental physical theories. And for the past 100 years, every time it was tested, the theory was *confirmed by experiment*, which is why we have very high confidence in its validity.

137 -

If humans found a microscopic primordial black-hole, what would the specifications of its container have to be to keep it safely on the Earth?

We don't want to keep a primordial black-hole on the Earth. Or anywhere near the Earth. Here is why.
Let's start with a 1 metric ton primordial black-hole. Well … our problem is *Hawking Radiation*. This black-hole has an effective temperature of $1.23 \cdot 10^{20}$ K and a lifetime of less than a tenth of 10^{-7} s. In other words, 1 metric ton of Mass is *instantly converted into high-Energy γ Radiation*. That's about a million Hiroshima nukes going off all at once. Not a good day for anyone within a few hundred kilometers.
A smaller black-hole evaporates even faster, so let's not go there. What about a bigger one, say, 1000 metric tons? Well, it has a more respectable lifetime … 84 seconds. But that's still way too short. In 84 seconds, we end up releasing the energy of 10^9 Hiroshima nukes. Not a good day for anyone, anywhere on the planet.
So, let's go even bigger, … say, 10^6 metric tons. OK, that one has a more reasonable lifetime of over 2600 years. But it is still hot as hell. It emits about 360 TW of thermal power. That's an awful lot of heat. It's as hot as the Sun when we are more than 140 km from it. Worse yet, all that heat is released in the form of hard *gamma radiation*. Not a good day for anyone within a few hundred kilometers.
So how about 10^9 metric tons? That one is fairly stable, with a lifetime of well over $2 \cdot 10^{12}$ years. And it emits about 360 MW of waste thermal power … which is not unlike the waste heat, say, from an operating nuclear reactor. This is something we can deal with. But … we now have an object weighing 10^9 metric tons, which is only twice the size of a proton. Its gravity will be comparable to that of the whole Earth at a distance of 3 meters; at 1 meter, it will be almost 7 times the Earth's Gravity. Furthermore, there is no conceivable material that could hold this object … since most of the space between atoms is empty space and this black-hole would not interact with these atoms anyway nor could we keep it in place even if we, say, managed to give it an electric charge and try to control it by Electric or Magnetic fields. It will just fall through towards the center of the Earth as though there was nothing there. Unfortunately, there are lots of things there, which the black-hole would disrupt as it chaotically travels throughout the Earth's interior. After a extremely long time, it would dissipate enough Kinetic Energy to settle down near the center of the Earth, where it will likely remain quiescent for geologic timeframes (yes, black-holes eat things but when our entire black-hole is the size of a proton, it will not eat anything with any great efficiency). However, before that happens, the disruption to the Earth will be considerable, with earthquakes, volcanic eruptions, we name it … not a good day, not a good millennium for anyone.
So, there really are no good choices here. Let's pick a black-hole that is too small, and we are vaporized by its heat before it goes up in a tremendous explosion. Let's pick one that's too big and it messes up the planet big time. And in neither case can we hold the darn thing anyway. As a conclusion, let's keep black-holes away from the Earth, please.

138 -

If the Higgs Field exists everywhere, why don't we find it everywhere?

We do find the Higgs Field everywhere. Let's stand on a scale to measure our weight.
Roughly 1% of the value that we see is due to our body interacting with the Higgs Field that is everywhere (technically, our body is interacting with the Higgs Field's non-zero vacuum expectation value after symmetry breaking).
What is much harder to find are excitations of the Higgs Field, i.e., *Higgs-boson particles*. These excitations themselves are very *massive* (weighing more than 100 H atoms; that's a huge Mass in the world of Elementary Particle Physics) and take a lot of Energy to create. And, precisely, because they are so massive, their existence is fleeting, they decay very rapidly into a shower of lighter particles.
Therefore, we need a gigantic instrument like the Large Hadron Collider to produce Higgs bosons in sufficient numbers such that they become detectable despite their fleeting existence.

139 -

Are all (elementary) particles continuously interacting with the Higgs Field to have Mass or just one time and than keep their Mass?

This question is a perfect example why it is very difficult to provide a 'popular' explanation of a complicated physical theory.
No, elementary particles that acquire their masses by interacting with the Higgs Field do not interact with it once, nor do they interact with it continuously. At least that's not how to describe what happens. The actual picture is more subtle, and *symmetry breaking* plays an essential role.
Let's take the electron. Without symmetry breaking, it would be massless, and it would be interacting with the pre-symmetry-breaking form of the Higgs Field (the so-called *Higgs doublet*). Obviously, this interaction would only do anything when excitations of the Higgs Field are, in fact, present; in the vacuum, the electron would be moving unimpeded, as a massless particle.
But the Higgs Field is a very special animal. For all other fields, the field is in its lowest energy state when it has zero excitations (no particles present). Not so with the Higgs. As a result, the Higgs Field has a so-called Vacuum expectation value (to make sense of this sentence, it is really important to keep in mind that we are talking about a field theory here; particles are abstractions, quantized excitations of these fields, *the real, fundamental physical object is the field itself*).
Symmetry breaking means settling down to the lowest energy state. What used to be excitations of the Higgs Field now define the *new Vacuum*. But in this new Vacuum, the electron behaves as if it was interacting with the Higgs Field even when no excitations of the Higgs Field are present! Essentially (and very crudely speaking), instead of interacting with Higgs particles, the electron now interacts with the Higgs Field Vacuum expectation value, which is a *constant value*; the strength of the interaction serves as the electron's Mass. In other words (and still very crudely speaking), because the electron can interact with the Higgs Field before symmetry breaking, it behaves as a massive particle after symmetry breaking even when the Higgs Field is in its so-called ground state (no Higgs particles present).
The mechanism by which massive vector bosons acquire their Masses is different, but also related to symmetry breaking; and neutrinos, not to mention the Higgs itself, have a priori masses not related to symmetry breaking.

Maybe this explanation is likely more confusing than helpful. Unfortunately, it is not possible to offer more clarity without going into the math. This is one of those cases in theoretical Physics when non-technical explanations can only go so far … it's only through the relevant math that terms like *symmetry breaking* or *vacuum expectation value* acquire their real meaning.

140 -

Could neutrinos be the 'de facto' gravitons?

No, and the reason why is beautifully explained in Feynman's '*Lectures on Gravitation*'.
Neutrinos are spin-$1/2$ particles. If Gravity were mediated by the exchange of single neutrinos, that exchange would change spin-$1/2$ particles into integral spin particles and vice versa. We certainly do not see that happen (e.g., electrons don't change into W-bosons under the influence of Gravity) so single-neutrino exchange is ruled out right there as a means of mediating Gravity.
Could pairs of neutrinos be responsible for Gravity, though? When we work out the potential that follows from two neutrino exchange, it will be proportional to the inverse 3^{rd} power of the distance between two bodies. This contradicts our observation that the gravitational potential is proportional to the inverse 1^{st} power of that distance. An inverse 1^{st} power relationship could be obtained using three bodies (e.g., the Earth and the Moon under the influence of the Sun) but even that fails to work out in the end because of an additional *logarithmic* term that is much too large and conflicts with observation.
So, the exchange of neutrinos just *does not work* as an explanation for Gravity. In fact, this reasoning is easily extended to any spin-$1/2$ particle. That leave integral spin particles, but a spin-1 particle, as it is well known, would produce a *repulsive* force between like Masses. Spin-0 is also out, because it would violate the Equivalence Principle in observable ways. So, we are stuck with a spin-2 particle as the simplest possible particle to serve as the quantum of the Gravitational Field, and indeed, a spin-2 graviton has all the right properties.

141 -

What is the end for black-hole and what will it turn into after? Or will it eventually expand to absorb the whole Universe?

In a Universe that is not expanding exponentially, a black-hole will continue to grow. That is because even a modestly sized black-hole has a *Hawking Radiation Temperature* of about $2 \cdot 10^{10}$ K and the bigger a black-hole gets, the colder it is ... and this is much colder than the cosmic background radiation, which means that the black-hole receives more heat from the background radiation than it emits through Hawking Radiation.
Did we mention *Hawking Radiation*? Yes, black-holes can emit thermal radiation through this process. But it is an incredibly tiny amount of radiation. For the aforementioned 3 solar-Mass black-hole, Hawking Radiation amounts to about 0.00 ... 001 W, where there are 28 zeros between the decimal point and the digit 1.
However... if the expansion of the Universe accelerates rapidly enough, it is possible for the temperature of the microwave background to fall below Hawking Radiation Temperatures, essentially 'catching up' with all black-holes. When that happens, black-holes that have no readily available source of matter to swallow will slowly begin to lose energy through Hawking Radiation. How slow? *Incredibly slow*. But in the unimaginably distant future (if measured in years, we are talking about timescales that can be represented by 100-digit numbers or bigger) it is indeed conceivable that these black-holes radiate away all their Mass-Energy.
Whether or not at the end of this process, something like a 'naked singularity' remains or if the black-hole evaporates completely remains, as far as we know, an open question.

142 -

Does Gravity have Mass?

This is a tough question! Here is the easy part: to the best of our knowledge, the Gravitational Field, just like the Electromagnetic Field, has no 'rest-Mass'. What this means that if we think of Gravity as a Quantum Theory, its mediating particle, the hypothetical *graviton*, is a *massless* particle *traveling at the speed of light*, just like photons in the Electromagnetic Theory.
However, when it comes to gravitating Mass, rest Mass is just part of the picture. For instance, when we look at our own bodies, only about 1% of our Mass is due to the rest Masses of quarks that constitute the protons and neutrons in your body that, in turn, constitute the atoms from which the molecules of your cells form. The remaining $99\ \%$ or so is mostly due to the *binding energies* between those quarks. Yet it is still very much part of our Mass.
So, in the same sense, the Gravitational Field has Energy content and that, in turn, can contribute to the Mass of a system. Which means that *Gravity itself gravitates*.
And we know this for certain because of one of the classical tests of Gravitation: the famous perihelion advance of Mercury. The 'nonlinearity of gravity', that is, Gravity acting on itself, reduces this perihelion advance by a factor of 3/4 compared to what we would measure if gravity was 'linear'. This correction is important and agrees with the observed value, that famous $43\ \mathrm{s}$ of arc per century, which Einstein successfully explained using his new Theory of Gravitation back in the 1910's.
So, why did we say then that this is a tough question? Because another important property of gravitation is that it can be made to 'vanish' when you fall freely. In other words, if we were in a windowless elevator chamber, we would have no way of knowing if the chamber is falling freely towards the ground in a Gravitational Field or floating freely in interstellar space without falling anywhere. But if the Gravitational Field has *Energy density*, we should be able to measure it and tell the difference! Except … that the Energy density of the Gravitational Field cannot be localized in this manner. We can talk about the Gravitational Field Energy of a system (like the Sun-Mercury system) but we cannot pinpoint precise locations in space and say exactly how much gravitational field energy is at those specific spots.

143 -

Does Gravity consist of *curvature* in Space? Space stretching around the Earth, the force/unit-Mass we know as Gravity, is like wavy water: two objects in Space are attracted by each other because Space is stretched around them. Once they are close enough, does Space force the objects to join together?

Einstein's Theory of Gravitation presents the Gravitational Field in the form of the *metric* of SpaceTime. That metric indeed *determines curvature*, i.e., the curvature of SpaceTIME.
Why do we emphasize the Time part? Because when it comes to Weak Gravity (like what we are used to, here, on the surface of the Earth) and nonrelativistic velocities, the dominant part in Einstein's theory is what happens to the rate of clocks, not what happens to meter sticks, i.e., *Time curvature*, *not Space curvature*.
So, Gravity *is not* the curvature in Space: Gravity, as we experience it, is the *slowdown of clocks near massive bodies*.

It is this that alters the dynamical behavior of Matter and alters the trajectories of particles to bend, or fall, towards the gravitating Mass.
Space curvature on the surface of the Earth contributes only a tiny amount, $1/10^9$ or so. This part only becomes relevant when it comes to particles moving *near the speed of light*. For instance, when it comes to how a gravitating body, such as the Sun, bends light, Space and Time curvature play *equal* roles; therefore, Einstein's Theory predicts *twice* the bending compared to what one would predict using Newtonian Physics. It was experimental confirmation of this result just over a century ago, in 1919, by Eddington's expedition to observe the apparent sky positions of stars near the Sun during a solar eclipse, that elevated Einstein to a definitive scientific genius status.

144 -

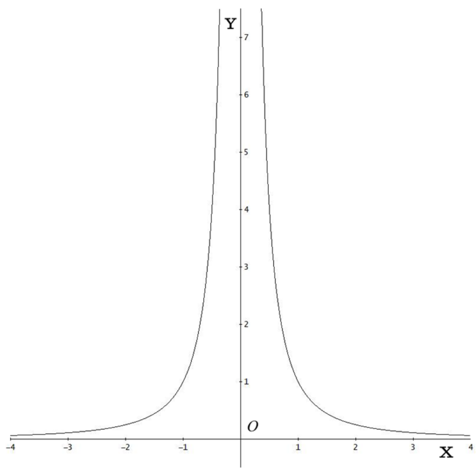
How is it possible that the Higgs Field is giving Mass to some particles by slowing them down?

Here is a sketch of how it works.
We start with a Higgs Field and a massless particle. The two interact. So, whenever the Higgs Field is not zero (i.e., whenever a Higgs particle is present (not yet the common Higgs boson)), that massless particle, say, a massless electron, interacts with it. But when the Higgs Field is zero, the electron is moving about freely, as a massless particle.
However, the Higgs Field has a curious property: unlike all other fields, the lowest energy state of the Higgs Field is not when the field is zero. So, the vacuum (characterized by a zero Higgs field value) *can decay into a new, lower energy state by making the Higgs Field non-zero*. This new, lower energy state is stable and it will be the new, 'true' Vacuum. But the Higgs Field is still non-zero (the technical term is its *Vacuum expectation value*, or *V. e. v.*, that is non-zero). Particles, such as the electron, still interact with it or, rather, they now interact with this new Vacuum with the non-zero Higgs V. e. v. . This interaction can never go away. The non-zero Higgs V. e. v. is now a property of the 'true' Vacuum. So, the electron is no longer free to go on its merry way as a massless particle. There is an extra term, this interaction energy between the electron and the Higgs V. e. v. . The form this interaction energy takes is indistinguishable from the form of energy associated with a non-zero rest Mass. So, now the electron no longer behaves like a massless particle. Its behavior, in the 'true' Vacuum, is that of a particle with a well-defined rest Mass; this rest Mass is determined by the strength of the interaction between the electron and the Higgs V. e. v. .
Something similar happens in very ordinary circumstances, e.g., when light travels in a refractive medium. Photons slow down in water or glass, for instance. Their behavior changes from that of a massless particle to that of a particle with rest Mass. The difference is that water, glass, etc., are materials from which photons can escape. The Higgs V. e. v. is present everywhere, so, the electron cannot escape it and behaves as a massless particle.
In addition to charged fermions, the massive bosons that mediate the weak interaction also acquire Mass due to the *Higgs mechanism*. The technical details are somewhat different, but the essence is the same: their rest Mass results from symmetry breaking and how they behave in the new, 'true' Vacuum in which the Higgs V. e. v. is $\neq 0$.

145 -

Why, when we read about the Big Bang, does it always say there was an 'infinitely' dense *singularity*? Was it in fact just close to being infinite or was it actually infinite?

Such a question represents a misunderstanding of what 'singularity' means.
Let us discuss the analogy with the simple mathematical singularity of the function $y = x^{-2}$ at the point $x = 0$:



What it really means is that *the function has no value at* $x = 0$. The nearer you get to this point, the larger y becomes (it is divergent) but $x = 0$ is not part of the function's domain. As a result, it is not meaningful to talk about the value of the function at $x = 0$. It *is not* small, *is not* large, it *is not* infinite: it, simply, *does not exist* there.

The meaning of *singularity* in Physics is identical. When it comes to the 'moment' of the Big Bang in standard Cosmology, the time value $t = 0$ *is not* part of the Universe. The density of the Universe *is not* big at $t = 0$ *nor it is* small *nor it is* infinite. The moment $t = 0$, simply *does not exist* (for that matter, no time $t \leq 0$ exists either).

At times approaching $t = 0^+$, the density of the Universe was *very large*. If we get really close to $t = 0$, the density was *large enough for quantum effects to play a role in Gravity*. At that point, our ability to describe things ends because we do not have a viable Quantum Theory of Gravity. So, perhaps, once the equations are suitably modified to account for Gravity, we will know better whether $t = 0$ is part of the Universe after all. But insofar as the standard Cosmology (without Quantum Gravity) tells us, it is not. The singularity – any singularity – is called such because it is not part of the Universe; rather, it is a point *missing from the Universe*, just as the point at $x = 0$ is missing from the curve with equation $y = x^{-2}$.

146 -

Why does the public believe that the Universe is infinite when most top physicists say nobody knows if the Universe is infinite or finite?

We cannot account for what the general public believes but we can tell precisely what the equations say.

The Standard Model of Cosmology, the so-called 'Concordance' or 'Lambda-CDM' Model, is a *homogeneous* and *isotropic* Cosmological Model with a non-zero Cosmological Constant and a parameter governing *spatial* curvature.

When this model is fitted to the data, what emerges is a Universe with near-zero *spatial* curvature. The property of spatial curvature in an expanding universe is that if it is near-zero today, it had to be even closer to zero in the past, extremely close to 0 as a matter of fact. The consensus is that it wasn't merely extremely close to zero; it *was*, and *is*, 0 *always*. In other words, we live in a *spatially flat* Universe.

A spatially flat Universe means *Euclidean* Space, that is *infinite*. Of course, we do not know for certain what the Universe looks like outside the boundaries of the finite section that we call the 'observable' Universe, which is the part of the Universe that we can study. We can only form our models on the basis of what we observe. And the simplest model that we can form, based on actual observational data, is this *Standard Cosmological Model*.

In other words, if the general public indeed believes that the Universe is infinite, they are not wrong, far from it: their belief matches the predictions of the prevailing mathematical model of our Universe. Of course, it is important to stress, when communicating this to the general public, that any discussion of an infinite Universe is necessarily speculative, since we extrapolate from observing only a finite segment of it, and there are no guarantees that what we observe remains typical of the rest of a much bigger (possibly infinite) Universe.

147 -

Atoms have been visualized and have a round shape, as predicted. Should we think smaller particles like neutrons, electrons, and various others will ever be visualized?

There are visualizations of atoms, but it would be a big mistake to conclude when we see one that this is what an atom looks like. An atom is a very complicated object and what it looks like depends a great deal on how we are obtaining our 'visualization'.

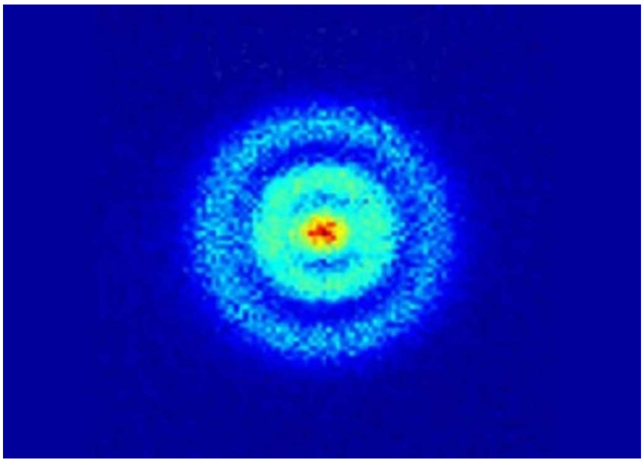
First, in visible light, an atom does not look like anything. The wavelength of visible light is several thousand times the radius of even the largest atom. Let's imagine a page of Braille script, used by the vision impaired. Now try to read that page by repeatedly bouncing a gigantic beach ball off it. Will we succeed? It's doubtful.

So, we need something smaller. Such smaller things do exist. The most obvious is smaller wavelength light! To get the necessary resolution, though, our 'light' has to be in the form of γ- rays. That's not very helpful, because γ rays are a little too energetic: they destroy the very atom that we are looking at. Not only will they strip off all electrons, but they may also even disrupt the nucleus! Going back to the Braille example, it's as if we replaced the beach ball with machine gun bullets. They may be small, but instead of bouncing back from the sheet of paper with Braille on it, they rip it to shreds.

We could use alternatives, e.g., electrons instead of γ- rays, but the result is the same: to get an image at that resolution, the energy of the electrons will be too high.

Still, there are indirect ways to obtain information about the 'shape' of atoms. Various techniques exist that allow low-energy probes to work; and yes, it is just as difficult as finding ways to read small-print Braille script by bouncing a

beach ball off it.
Here is one example, taken from: **Hydrogen Atoms under Magnification: Direct Observation of the Nodal Structure of Stark States** (2013):



Now, *Hydrogen atoms* are very simple creatures; other atoms are much more complex and would have more complicated shapes. No, *they are not always round*. And here is the thing: the deeper you probe, the more complicated they become.
Let's take that Hydrogen atom. At its center is a *proton*. Now at the resolution of this imaging technique, the proton is pretty much a point. But let's suppose we increase our resolution somehow. Eventually, we get to see that the proton has structure. Just as atoms consist of protons and *neutrons*, protons and neutrons consist of *quarks*. The 'interior' of a proton would look complicated, but not unlike the picture above, it would show various amplitudes corresponding to the likelihood of quarks occurring at various spots therein. In essence, we would be looking at the quantum mechanical wavefunction of the particles in question.
But now, let's move on to the 'smallest' particles, that is, those that are believed to be fundamental building blocks. Being *fundamental* means *no substructure*, no matter how high the energy is at which these particles are probed. That would mean that the particle is truly point-like, with no meaningful radius or volume.
However, even this case is not as clear-cut as we'd like. Because if we probe at high enough energies, the combined energy of whatever we use to probe the particle and the particle itself may be enough to create a shower of new particles. So, instead of a nice, clear-cut picture of a point, we get a *messy shower* of, well, all sorts of things. This, in fact, is what particle accelerators do: they smash fundamental particles together to create showers of new particles that can then be studied.
Finally, … what is a particle anyway? In the best theory that we have, *Quantum Field Theory*, a particle is neither an object nor a fundamental concept in this theory. The fundamental concept is the *field*; *particles are its excitations*. Worse yet, allow accelerating observers or allow Gravity, and two observers may not even agree on the particle content that they see. So, how do you visualize something that exists for one observer but does not exist for another?
If this answer is longer and less satisfying than we would have liked … well, welcome to Nature. It is not under any obligation to be easily comprehensible to us. And as this seemingly simple question (what's the shape of a particle?) illustrates, Nature sometimes does its darnedest to be obscure and difficult to understand.

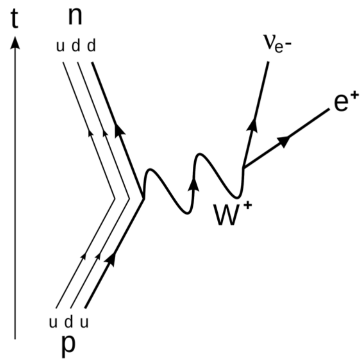
148 -

How could a proton turn into a (free) neutron?

A *proton* is made up of 2 up-quarks and 1 down-quark. A *neutron* is made up of 1 up-quark and 2 down-quarks. To turn a proton into a (free) neutron, we need to either

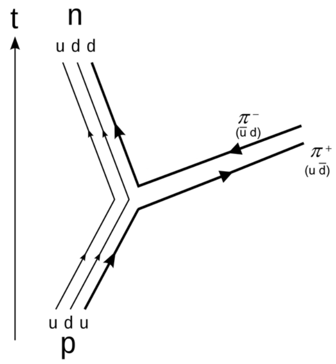
a. turn an up-quark into a down-quark, or
b. lose an up-quark and acquire a down-quark.

The first process can happen if an up-quark emits a *positron*, e^+, and an electron neutrino, ν_{e^-}, and becomes a down-quark in the process. This cannot happen directly, but it can happen through the *weak interaction* via W^+ boson exchange:



Alternatively, the proton may absorb an electron and an anti-electron neutrino.

The second process happens if the proton emits a *positively-charged pion*, π^+, which is a combination of 1 *up* quark and 1 *anti-down* quark. Emitting 1 *anti-down* quark is the same as capturing 1 *down* quark:



Alternatively, the proton may absorb 1 *negatively-charged pion*, π^-, which is made up of 1 *anti-up* and a *down* quark.

In all cases, however, we must also be mindful that the neutron is *heavier* than the proton; the *excess Mass must come from the outside*, e.g., in the form of the Kinetic Energy of the particles that the proton absorbs in the process.

The (free) neutron will spontaneously decay back into a proton, with a half-life of about $14' 39.6''$.

149 -

If a photon is found to have Mass, then how would c be redefined? It seems arbitrarily set now, on the assumption that a photon is massless.

The modern formulation of Relativity Theory is not based on the speed velocity of actual light. Rather, it is based on the idea (which, in turn, is based on *experimental* evidence) that, in our Universe, there exists an *invariant speed* that is the same for all observers. This invariant speed can be measured using particles that have (kinetic) energies *much, much larger than their rest Mass* (times c^2), *regardless* of whether their rest Mass is 0 or not.

So, if it turns out that photons have Mass, *nothing changes*: the invariant speed is still what it is and the ratio of the photons energy and its rest Mass will determine just how close its speed will be to this invariant speed.

The fact that we happen to call this invariant speed *the* (*vacuum*) *speed of light* is part an artifact of history, part a reflection of the fact that, to date, the photon has been found to have no Mass at all, and extremely stringent limits have been placed on its maximum possible rest Mass based on laboratory and astrophysical observations.

It is, of course, true that while Maxwell's Equations are invariant under transformations that leave the invariant speed, well, *invariant* (these would be the Lorentz-Poincare Group of transformations or, perhaps, the more general conformal group), the Maxwell-Proca Equations that govern massive photons *are not*. So, we would find that Electromagnetism is necessarily Lorentz violating, a tiny but, nonetheless, interesting effect. But that takes us beyond the question of the meaning of the invariant speed that we call the (Vacuum) speed of light.

150 -

How can the Sun's supply of hydrogen last for billions of years? Does the Sun produce hydrogen as well as convert it to helium?

Great question, and there are two major reasons the hydrogen in the Sun doesn't all burn up at once. We're entirely correct in saying that the Sun generates energy by converting hydrogen into helium, but that process mostly occurs through the sequence of the following three reactions:

$$\begin{cases} {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \to {}^2_1\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e} \\ {}^2_1\mathrm{H} + {}^1_1\mathrm{H} \to {}^3_2\mathrm{He} + \gamma \\ {}^3_2\mathrm{He} + {}^3_2\mathrm{He} \to {}^4_2\mathrm{He} + 2\mathrm{e}^+ + 2\nu_\mathrm{e} \end{cases}.$$

The first of these reactions is the 'rate-limiting step'. It takes billions of years for the average hydrogen nucleus (i.e., a proton) to fuse to another nucleus in the core of the Sun, even at extremely hot temperatures (10^7 K) and high densities ($10^{32}\ \mathrm{particles/m^3}$). This is because two protons have to 'collide' to fuse together, and their *Coulomb barriers prevent these collisions from happening*.

In fact, if we model the cross section of a proton and ask (in a classical/statistical mechanics sense) how hot the Sun would have to be for protons to collide at a rate that would produce the luminosity we see, we would find it's $10^9\ \mathrm{K}$, and we know from the structure and surface temperature of the Sun that this isn't true. Protons have to quantum-mechanically tunnel through their Coulomb barriers in order to produce the nuclear reaction rates that we infer.

But nuclear reactions produce heat and higher temperatures mean higher velocity particles, which would further increase the nuclear reaction rates. Why doesn't the Sun undergo a runaway reaction where hydrogen is burned faster and faster until there's nothing left?

The second reason that the Sun's hydrogen lasts for billions of years is that it's constantly pulsating in order to stay in thermal and hydrostatic equilibrium. If the Sun got too hot, it would expand, lowering the density in the core and slowing down nuclear reactions, thus making the core cooler. If it got too cold, it would contract, increasing the density in the core and speeding up nuclear reactions, thus making the core hotter. So, the nuclear reaction rate is 'calibrated' to the Mass of the Sun and the core temperature and density that is 'stable' for a star of that Mass.

151 -

Is Quantum Field Theory derived from Quantum Mechanics or vice-versa?

The history of the development of Quantum Field theory (QFT) was … we say, complicated but, in reflection, we can say that Quantum Field Theory is a straightforward *generalization of the Quantum Theory to fields*.

How does this generalization work? The principle is quite simple. We know how to do Quantum Mechanics of simple systems, including the so-called *harmonic oscillator*. Now take a field, such as the Electromagnetic Field. How would you 'quantize' it? Through the magic of the Fourier Transform, that's how. The Fourier Transform that decomposes a field into an infinite sum of – we guessed it – *harmonic oscillators*.

Each of these harmonic oscillators has *quantized excitations*, just as in Quantum Mechanics. But in QFT these excitations gain new meaning: *we associate them with particles*. Because interactions *create* or *annihilate* excitations, QFT scores a huge victory right here: it can account for the creation and annihilation of particles, something ordinary Quantum Mechanics cannot do.

Another big point in favor of QFT is that it is *fully relativistic*: in QFT, anything faster-than-light or backwards-in-time, i.e., anything that would violate causality, is strictly and unambiguously canceled out. Not even relativistic versions of Quantum Mechanics can do this; there is still a little bit of 'leakage', an exponentially vanishing but non-zero likelihood of causality violation. This *is not* the case with QFT.

Of course, all this comes at a price. The worst part is that a harmonic oscillator has non-zero energy in its ground state. But in QFT we have an infinite number of harmonic oscillators and summing their ground state yields an infinite amount of energy. That, of course, is nonsense. Much of Quantum Field Theory is about finding specific versions of the theory and specific techniques that allow us to get rid of these infinite terms: this is called *renormalization*.

But, in the end, QFT boils down to an application of the Quantum Theory to fields. The basic principles remain the same: promoting observables to non-commuting quantities that can be represented by operators, and then observing that the equations of the system are linear and homogeneous in terms of the state of the system, which implies that *any linear combination is also a valid solution* (i.e., a particle can indeed be in two places simultaneously), something that makes no sense in Classical Physics.

152 -

Why do photons not acquire Mass by the *Higgs Mechanism*. What determines if an elementary particle can interact with the Higgs Field?

The answer is that the theory is set up to work this way, because it is intended to describe *what we actually see in Nature*.
Specifically, *electroweak unification* is based on the symmetry group $SU(2)\times U(1)$, with massless *gauge bosons*. However, as a result of the *Higgs mechanism*, symmetry breaking occurs and the gauge bosons corresponding to most of the $SU(2)$ bit (plus a piece of the original $U(1)$) acquire Mass (these would be the Z^0- and $W^{\pm}$- bosons).
Meanwhile, the boson corresponding to an Abelian $U(1)$ symmetry that is a combination of the original $U(1)$ plus a little of the $SU(2)$, namely the photon, remains *massless*.
Of course, we could have written the theory differently. But then, *it would not describe what we actually see in experiments*.

153 -

If the Higgs Field gives Mass, and Mass curves SpaceTime and the curvature of SpaceTime is Gravity, why look for a graviton?

Interaction with the Higgs Field means Potential Energy. As an outcome of the so-called *Higgs Mechanism*, through symmetry breaking, this potential energy manifests itself as *rest Mass for charged fermions*. Symmetry breaking also endows some vector bosons with Mass, but not because they interact with the Higgs Field directly.
Moreover, this interaction energy with the Higgs Field is just one of many sources of Mass-Energy. In 'normal' Matter composed of ordinary atoms and molecules, roughly 99% of the energy-content, i.e., 99% of *inertial* Mass, has absolutely nothing to do with the Higgs Field: it is the interaction energy of the Strong Force that holds quarks together inside protons and neutrons.
In any case, whatever the origin of Mass-Energy is, Mass-Energy itself acts as the source of the Gravitational Field. It doesn't say anything about what the Gravitational Field is, i.e., how it mediates the gravitational interaction between bodies.
If the Gravitational Field is a *quantum field* like all other known fields, in the *weak field*, low energy, 'perturbative' limit, it would be describable using elementary field quanta, which we call *gravitons*.
These gravitons are a necessary consequence of just about any more or less reasonable-looking Quantum Theory of Gravitation, and *this has nothing to do with the origin of inertial Mass*. Whether inertial Mass is due 100% to the Higgs Field, no Higgs Field at all or, as is the actual case, due roughly to the tune of 1% to the Higgs Field and 99% to something else *makes no difference*.

154 -

If the reaction of a particle and an antiparticle creates pure energy, then what makes Dark Energy?

Two common misconceptions seem to have inspired this question. Particle-antiparticle reactions do not create 'pure energy'; Dark Energy is not really energy in the sense we seem to think it is.
Particle-antiparticle reactions do one thing: they produce *new particles*. So, for instance, let an electron and a positron collide. What do we get? A pair of photons. But let us make it even more interesting: *photons are their own antiparticles*. So, what do we get if we can make two photons collide? We guessed it: an electron and a positron. And while this reaction is rare, it does occasionally happen; such photon-photon scattering is the reason why ultra-high energy photons do not arrive from very deep space, from beyond the Milky Way: they get scattered on the photons of the microwave background radiation.
So, as we can see, no 'pure energy' here unless we consider random electromagnetic radiation (photons) 'pure energy'.
As to Dark Energy, it is simply a catchy name attached to a hypothetical medium that permeates the Universe. Cosmologists tend to view everything that fills the Cosmos as a 'perfect fluid', a *medium with no viscosity or internal friction*. This is legitimate, since we certainly don't see effects due to viscosity or internal friction on galactic or extragalactic scales. Now a perfect fluid is easily categorized by its so-called *equation-of-state*, the *ratio of its pressure to its density*. This ratio is a *pure number* (any units of measure get canceled out) that can range between -1 and $+1$ for 'reasonable' perfect fluids. A special case is when the ratio is zero (no pressure): essentially, most matter is like this, as, at non-relativistic temperatures, pressure becomes negligible. The ratio for photons (ultra-relativistic gas) is $1/3$. As for Dark Energy? It is another special case, the extreme case when this ratio is -1.

So, having established that Dark Energy is not really energy in the sense we might have thought it was, the question remains: what is it? We haven't the foggiest idea, that's what. Just because we think this stuff exists (because when we plug it into the equations of Cosmology, we get sensible results) doesn't mean we know what it is made of. Sure, there are candidates: things that have this weird equation-of-state include *Einstein's Cosmological Constant*, a *self-interaction potential* of a so-called *scalar field* or even the *Vacuum zero-point energy of quantum fields*. But, as we have not observed Dark Energy directly, we are only guessing; and perhaps (assuming it even exists) it is something else altogether.
Now we know that this isn't, strictly speaking, an answer to the question, but perhaps it nonetheless is useful as it explains how the question itself a result of common misunderstandings was.

155 -

What is the simplest way to understand *Schrödinger's wave equation*? What is a *wave function* and *wave equation* and what does it tell us?

By way of an answer, let's explore the simplest modern 'derivation' of Schrödinger's wave equation.
Reminding what the Hamiltonian is, it's really just the (total mechanical) Energy of the system of (non-relativistic) Mass m, but for conventional reasons, it's denoted by $\mathcal{H}$. So, the Energy of a system is the sum of its *kinetic* and *potential* energy. For a particle of Mass m, with *generalized* position $\boldsymbol{q}$ (again, for conventional reasons the letter q is used) and *generalized* Momentum $\boldsymbol{p}$, this leads to the scalar equation

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + V(\boldsymbol{q}) \tag{1}$$

or

$$\mathcal{H} - \frac{\boldsymbol{p}^2}{2m} - V(\boldsymbol{q}) = 0\,. \tag{1.1}$$

Now let's multiply both sides of Eq. (1.1) by the complex-valued quantity

$$\psi := e^{i(\boldsymbol{p}\cdot\boldsymbol{q} - \mathcal{H}t)/\hbar} \tag{2}$$

(t is the time and $\hbar$ is just a constant). Why are we choosing this quantity ψ will become apparent shortly but, for now, the only thing we need to know is that ψ is a *unit complex number*, so, *it is never zero*. Therefore, the meaning of the equation *does not change*: its solutions remain exactly the *same solutions as before*:

$$\left(\mathcal{H} - \frac{\boldsymbol{p}^2}{2m} - V(\boldsymbol{q})\right) e^{i(\boldsymbol{p}\cdot\boldsymbol{q} - \mathcal{H}t)/\hbar} = 0\,. \tag{3}$$

Now, let's *assume* that the following *four* scalar identities hold in the *classical* picture:

$$\begin{cases} \boldsymbol{p}\psi := -i\hbar\dfrac{\partial\psi}{\partial\boldsymbol{q}} \equiv -i\hbar\boldsymbol{\nabla}\psi \\ \mathcal{H}\psi := i\hbar\dfrac{\partial\psi}{\partial t} \end{cases}. \tag{4}$$

This means that we can rewrite the (*classical*) Eq. (3) as $\left(i\hbar\dfrac{\partial\psi}{\partial t} + \dfrac{\boldsymbol{p}^2}{2m} - V(\boldsymbol{q})\right) e^{i(\boldsymbol{p}\cdot\boldsymbol{q} - \mathcal{H}t)/\hbar} = 0$, i.e.,

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 - V(\boldsymbol{q})\right)\psi\,. \tag{5}$$

But this looks just like Schrödinger's equation! Well, it does look like it ... but it *is not yet* it. We shouldn't forget that $\psi = e^{i(\boldsymbol{p}\cdot\boldsymbol{q} - \mathcal{H}t)/\hbar}$, so this is just Classical Physics in disguise.
However, if we look at this equation differently and try to solve it for ψ, we notice that the equation is *homogeneous* in ψ. Which means that for any two solutions ψ_1 and ψ_2, their linear combination, $\alpha\psi_1 + \beta\psi_2$, is *also* a solution, with α and β being arbitrary complex constant coefficients.

But with rare exceptions, $\alpha\psi_1 + \beta\psi_2$ cannot be written in the form $e^{i(p\cdot q - \mathcal{H}t)/\hbar}$. Therefore, these 'mixed' solutions do not describe Classical Physics: Quantum Physics begins when we acknowledge that, nonetheless, these mixed solutions *describe valid Physics*, *the actual state of a physical system*.
We call ψ the *wave function* for historical reasons but we'd better call it the *state function* because that's what it really is: it describes the *state of the system* more generally than through the classical (generalized) variables $\boldsymbol{q}$ and $\boldsymbol{p}$.

156 -

If an increase in Energy is an increase in Mass, but an increase in Mass creates more Gravitational Potential Energy, which means *more* Mass, why doesn't this result in infinite ratio Mass/Energy (m/E)? Is it just a convergent sum?

Well, for starters, Gravitational Potential Energy is negative! That is, when we bring two bodies close together, we extract Energy from the system; if we want to pull the bodies apart, we need to invest Energy into the system.
But, beyond that, the Gravitation Field Theory is a *non-linear* theory, meaning that the Gravitational Field itself is also a source of Gravitation but, because Gravity is very weak, the infinite sum of ever smaller terms that forms consists of terms that die down very rapidly, and the sum remains *finite*.
However, it is a noticeable effect. If Gravity were linear, the anomalous perihelion advance of Mercury would be 4/3 of the value that is calculated using General Relativity. So, precise measurement of that perihelion advance amounts to *experimental confirmation* that *Gravity is indeed a non-linear field theory*.

157 -

Why do SpaceTime curvature representations show the fabric bent down to the South pole of the massive object as if a less massive one could fall all the way down? Shouldn't the lowest point of the grid go through the massive object's center?

This is one of the most misleading graphic illustrations that appears in many popularizations of Gravitation and Cosmology. It is most unfortunate that this graphic exists because … well, it has very little to do with actual reality.
Let's recall that General Relativity is a theory of Space and Time. Why do we emphasize Time? Because when we look at Newtonian Gravitation, it is almost entirely about Time, and it has very little to do with Space. That is to say, when we look at the actual equations of General Relativity, Newtonian Gravity emerges not because Space is bent but because *clocks tick at different rates at various points in a Gravitational Field*.
An object's trajectory between two events is ultimately determined by a simple condition: if undisturbed, the object will follow the trajectory along which it measures the most Time. In the absence of Gravitation, this is a straight line. Say, we meet in a room today, and we meet in the same room tomorrow at the same time. If we both stay put, our respective ultraprecise atomic clocks will both measure exactly 86,400 s. But if you hop into an airplane and do a quick trip somewhere before you return, you will find that your atomic clock that you carried with we will have measured slightly less time, say, 86399.995 s. This tiny difference in Time governs the motion of objects and keeps them in inertial trajectories. In the presence of a Gravitational Field, clocks tick at different rates: that means that the *trajectories are no longer straight lines*. This is the reason why we end up with objects falling (accelerating towards a gravitating body; their worldlines are no longer straight lines in a spacetime diagram) or objects in orbit.
Now clocks ticking at different rates is a tad hard to illustrate graphically. At the same time, it is easy to draw a rubber sheet that is bent by a heavy object. And it is impressive indeed! Never mind that it has nothing to do with reality; never mind that here on the surface of the Earth, spatial curvature amounts to an absolutely tiny, one-part-in-a-billion correction to the Newtonian law of Gravitation.
So let's forget those visually impressive grids that we see in popular documentaries. We should always keep in mind that Newtonian Gravitation is all about how clocks tick at different rates in a Gravitational Field and has *nothing to do with spatial curvature*.

158 -

What happens to the Gravity of the Mass when that Mass is converted into Energy? Can Gravity be converted into energy?

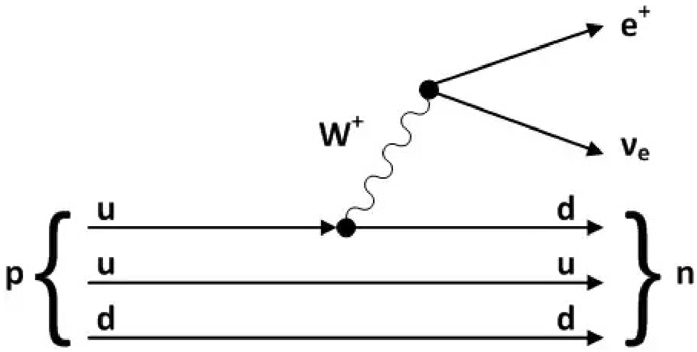
Mass is not converted into energy. Mass is Energy.
The well known equation $E = mc^2$ *is not* called the 'convert Mass into Energy equation'. It is called *Mass-Energy equivalence*. Einstein's 1905 paper, in which this equation was introduced, was not talking about converting into anything. The title of the paper is a question: "Does the inertia of an object depend on its Energy-content?" A question that Einstein answers in the affirmative: the inertial Mass of a body is determined by the Energy contained by that

body. *Mass is Energy*.
So, now that we have established that Mass is not converted into Energy … it is, of course, possible to convert forms of energy into each other through chemical, nuclear, etc., reactions. When we burn a chemical fuel in the presence of an oxidizer, a tiny amount of chemical potential energy is converted into kinetic energy (random motion of particles, i.e., *heat*). If we allow a nuclear reaction to take place, some nuclear binding energy, which can be orders of magnitude greater than Chemical Potential Energy, is converted into random motion. Other processes, such as Matter-anti-Matter annihilation, might convert all rest-Mass into Kinetic Energy.
But if we did this in a sealed, closed container, the overall *Gravitational Mass* of that container would not change. Of course, if we allow the generated heat to escape, then you do lose Energy and the container becomes lighter as a result. That Energy will still be a source of Gravitation but, having escaped the container, it is to be now somewhere else.
Lastly, to answer the bit about Gravity, the Gravitational Field itself has Energy and thus it can itself be a source of Gravitation. This is what we mean when we describe Gravitation as a *non-linear* theory. This non-linearity adds a very small but measurable correction to the equations of Gravitation; the precisely measured value of Mercury's orbit *precession* is not otherwise related to Mass-Energy equivalence and inertial or gravitational Mass.

159 -

What is the inner mechanism of *hadron decay*, say, of a proton?

First, when a proton decays *inside* an atom (β^+-decay), it ejects a W^+ vector boson that decays into an anti-electron, β^+, and an electron neutrino, ν_{e^-} :



This decay happens only *inside* atoms, as the rest Mass of the proton is less than that of the neutron, so the decay requires an input of energy.
What we see in this diagram is how the constituent quarks inside the proton participate in this reaction. Specifically, one of the up quarks in the proton emits a W^+ vector boson and transforms into a down quark in the process; the vector boson itself decays in short order into a positively charged anti-electron (positron), and the electron-neutrino.
The dots in this diagram, its vertices, represent interactions. As far as we know (that is, according to the Standard Model of Particle Physics) these interactions are *fundamental*. That is, there is nothing inside. The fact that the up and down quark fields and the W^+ boson field interact this way is written as a fundamental assumption into the theory's Lagrangian. Because this is a quantum theory, all such interactions happen in the form of the *creation* or *annihilation* of *unit excitations* of the respective fields: in this case, a unit excitation of the *up* quark field is destroyed while unit excitations of the W^+ and down quark fields are created.
Of course, it is entirely possible that the Standard Model is not the final word in Particle Physics, and that an even deeper theory will provide some insight as to what is 'inside' those dots. However, at present, any such theories are, at best, speculative.

160 -

If the electron is constantly interacting with the Higgs Field, and that field has an energy (thus Mass), how can it ever move in straight lines and have any predictable dynamics?

Well, it gets really complicated, so without the math, all can be offered is a very superficial overview.
The electron is not constantly interacting with the Higgs Field. The Higgs Field is in its ground state, there are no Higgs particles with which to interact. The electron moves about freely.
However, … this is after *electroweak symmetry breaking*, in the *new Vacuum*, in which the Higgs field has a so-called

nonzero *Vacuum expectation value* (V. e. v.). It is this V. e. v. with which the electron interacts. In other words, *it interacts with the Vacuum*.
Which, for all practical intents and purposes, is the same as the electron having Mass: its trajectory will be the trajectory of a massive, free particle in the Vacuum.

161 -

Is the Wave Function real like an ocean wave or is it just a probability wave?

Quantum Physics describes physical systems in terms of their *states*. The state of a physical system in Classical Physics is well-defined. For instance, a point particle in Classical Physics has a well-defined *position* and well-defined *Linear Momentum*. In Quantum Physics, a system is usually found in a so-called 'linear combination' of states: e.g., instead of having a well-defined, unique position, an electron may be a little bit here, a little bit there, and a little bit somewhere else, all at the same time. We know, this makes no sense (literally, it is not something that we can envision or intuit) but our observations consistently inform us that this is how Nature works. It is important to remind us that *Nature has no obligation to appeal to our intuition*. At least, we have the next best thing, namely Mathematics, with which we can model physical systems even if we find it difficult to intuit or visualize what those models say.
Anyhow, given that the quantum state of the system is essentially a weighted sum of potentially an infinite number of possible well-defined states, the next question is how best to describe such a system using the language of Mathematics. This description comes in the form of the wavefunction, which basically assigns a value, or weight, to every possible state that the system can be in.
Why is it called a *wavefunction*? Because the equation we discovered that characterizes this function is, in fact, a well-known wave equation (the *Schrödinger equation*), an equation that describes a wave pattern.
This is neither an ocean wave nor a probability wave, though it can in fact be used to infer the probability of the outcome of an experiment when we make the quantum system interact with a classical device (a camera, a laboratory instrument, a cat, an experimenter – it doesn't matter – so long as it is an entity that behaves, by and large, according to the rules of Classical Physics). *It is a mathematical abstraction that characterizes the state of a quantum system.*

162 -

In black-hole theory, have mathematicians finally lost all connection with Physics?

The awareness of any 'black-hole theory' is still missing.
We are, of course, aware of

a. the existence of black-hole type solutions in the General Theory of Relativity, and

b. the prediction that a self-gravitating spherical cloud of dust would collapse indefinitely, forming a black-hole.

However, we are also aware of the observational evidence of objects such as core collapse supernovae that leave behind no visible remnant; invisible compact companions to visible stars in certain stellar systems; invisible compact objects with the Gravitational Field of millions of solar Masses or more, with other stars following extremely fast, tight orbits around them; the successful attempt to image the accretion disk of M87*, obtaining a result consistent with the predictions of a black-hole's *photon sphere*; and last but not least, successful gravitational wave observations that are consistent with the theoretical prediction of black-holes merging.
All this sounds very much like 'Physics'.

163 -

Do gravitons emit Higgs bosons, do Higgs bosons emit gravitons, or something else?

Gravitation couples to Matter 'universally and minimally'. This means that it couples to the Higgs Field (which is a Matter field) the same way it couples to everything else: through the formation of inner products and integration volume elements. In short, anything that has Mass-Energy is a source of Gravitation; and anything subject to the Law of Inertia will follow geodesics determined by Gravitation in the absence of other forces. Quantizing Gravity and expressing it in the form of gravitons in the low energy limit does not change this.
So, the Higgs bosons couple to gravitons the same way photons, electrons, neutrinos, etc., do.
It is a common misconception that because the Higgs Field and symmetry breaking are responsible for the Masses of many elementary particles, they have something to do with Gravitation. In any case, when it comes to the Masses of ordinary things, only about 1% comes due to the Higgs; the rest is due primarily to the Mass-Energy content of the strong force that holds quarks together inside protons and neutrons and as such, completely unrelated to the Higgs.

164 -

If we quantize SpaceTime in the General Theory of Relativity, what nonsensical predictions arise as a consequence?

Quantizing SpaceTime is not the issue, because SpaceTime is not the field that we need to worry about. Quantizing the Gravitational Field, i.e., the metric of SpaceTime, now that's where the problems begin.
The process starts with recognizing that in the absence of gravitating bodies, the metric of SpaceTime is the flat Minkowski-metric of Special Relativity, $\boldsymbol{g}_{\mu\nu} = \boldsymbol{\eta}_{\mu\nu}$. When a Gravitational Field is present, the metric can be written as a perturbation of this *flat metric*:

$$\boldsymbol{g}_{\mu\nu} = \boldsymbol{\eta}_{\mu\nu} + \kappa \boldsymbol{h}_{\mu\nu} ,$$

where the perturbing field to be quantized, $\boldsymbol{h}_{\mu\nu}$, is multiplied by the coupling constant $\kappa = G^{1/2}$ (where G is Newton's Constant of Gravitation).
So, herein lies the problem: we know that the expression describing the Gravitational Field and its interactions with Matter is 'non-polynomial'. In other words, if we were to write it down as a sum of terms ever higher in powers of $\boldsymbol{h}_{\mu\nu}$, that would be an infinite sum. That's OK; other fields produce infinite sums, too. The problem is the coupling constant κ that will also appear with ever *higher exponents*.
Why is that a problem? Because in this case, κ *has units attached*. It is not simply a so-called dimensionless number, but something measured using a combination of units of Length, Time and Mass. That means that *its numerical value can be arbitrary*, *depending on choice of units*. In particular, it can be bigger than 1. That means its ever-higher powers will be *divergent*, and there is no way that we know that could let us get rid of this divergent infinity.
So, that's the nonsense that we are talking about a Quantum Theory plagued with infinities that cannot be removed by a technique called *renormalization*, which worked so well for all the other fields in Nature.

165 -

Why are scientists not able to convert every material other than Uranium into Energy, according to the Einstein's celebrated formula $E = mc^2$?

First of all, let's grab a match, light it and watch it burn.
If we had a sufficiently accurate scale, we could measure the very tiny difference in Mass between the match (and the oxygen it would ultimately consume) vs. the resulting combustion products (smoke, ash, etc.). That tiny difference is the amount of energy removed from the system by way of heat. Yes, according to $E = mc^2$.
In fact, any chemical reaction does that. But chemical bonds are very weak in the big scheme of things. A pile of TNT exploding may look like a big kaboom to us, a human being but, compared to the kinds of energies that exist in this Universe, it is almost nothing.
So, let's go up a few notches. About 5 or 6 orders of magnitude (that is, a factor of a few hundred thousand to a few million) above Chemistry, comes *Nuclear Energy*, splitting heavy atoms or fusing light atoms. Uranium, in particular, is useful because, just like that match, it can undergo a *chain reaction*. In the case of the match, rapid oxidization is a *chemical chain reaction*: the heat produced when some molecules combine with Oxygen helps other molecules combine with Oxygen. In the case of Uranium, the energy released when a Uranium atom splits helps other Uranium atoms split.
Nuclear reactions are tremendously *more powerful* than chemical reactions but even so, even in nuclear fusion, *only a fraction of a percent of the total Mass of the fuel is converted into Thermal Energy*.
So, to be honest, we should continue to be baffled as to why $E = mc^2$ is associated with Nuclear Power in the popular imagination. we know that, in the wake of WW2, this formula was often touted as the 'secret', so much so that they even spelled it out for that iconic photo on the flight deck of a nuclear-powered aircraft carrier … but nuclear power is not unique in this regard. $E = mc^2$ is the *universal equivalence* of *Mass* and *Energy* (in fact, Einstein's very paper on this topic, from 1905, asserts that a body's inertial Mass is its *Energy content*), not a secret of converting one into the other. *Mass is Energy*; no conversion is needed. What these reactions (chemical, nuclear) do is converting one form of Energy (chemical or nuclear binding Energy) into another (Kinetic Energy of particles, ultimately *random motion*, i.e., Heat). And just as certain things (e.g., paper, wood) burn and other things (e.g., ceramics, glass) don't, certain elements can undergo fusion or fission and other elements cannot.
However, it should be emphasized, nobody is converting Uranium into Energy. What happens in the case of Uranium fission is that the Uranium atom splits into two lighter atoms, and some of the *binding Energy* holding the constituent protons and neutrons together is released as Kinetic Energy in the form of fast-moving particles that, in turn, bounce into other things and heat everything up.

166 -

The Higgs boson is said to have a huge Mass and it permeates the Universe. But it seems we do not feel the Mass of Higgs bosons. Why is that?

Don't let us misunderstand what a *particle* (really: a *field quantum*) is *massive* in Quantum Field Theory means. It simply means that it is

a. difficult to create such field quanta (lots of Energy required) and that

b. any force mediated by such quanta are extremely short-range.

As an example, there is the neutral Z^0 boson of the Weak Interaction. For all practical intents and purposes, it is like a photon with Mass. But the result of that Mass means that the Weak Interaction it mediates is extremely *short-range*, applicable only inside an atomic nucleus. In contrast, Electromagnetism is *long-range*: the Magnetic Field of a galaxy, for instance, can stretch to hundreds of thousands or even millions of light years, *influencing the motion of charged particles*.
When it comes to the Higgs, the field quanta are *massive* so, they are hard to create, but that does not prevent the field itself from interacting with other fields ... notably quarks and electrons. This interaction endows quarks and electrons with an *effective Mass*.
Surprisingly though, most of the Mass of everyday objects does not come from the Higgs. *The Mass of ordinary atoms is concentrated in the nucleus*, which is made of protons and neutrons. Only about 1% of the Mass-Energy of a proton or a neutron is due to the constituent quarks; the remaining 99% is due to the *Potential Energy of the Strong Interaction between them.*

167 -

If the Universe (Space) is infinite in size, then it has alway existed. If this is true, does that mean that the hot, dense state (Matter and Energy) popped up inside already existing endless Space and then Matter and Energy evolved into galaxies?

This question is based on a *false* inference. A spatially *infinite* Universe *need not have eternal existence*.
To illustrate why, think of a simple mathematical model: the half-plane. That is, take the plane (which is infinite), draw a line, and discard everything below, up to, and including, that line.
We are left with the half plane. In the direction parallel with the original line, this half-plane is *infinite* but, in the perpendicular direction, it has a definite beginning but *no end*.
So, if the Universe is like the half-plane (though obviously 4-dim, not 2-dim), it is *spatially* infinite, has a *definite* beginning in time, but no end in time.
Obviously, the topology of the Universe in the Standard Cosmological Model is a bit more complicated. In particular, whereas nothing stops you from mentally extending this half-plane below the dashed line, the Universe *cannot be extended in the past time direction beyond the initial moment*. This is what 'singularity' means in this context.
Nonetheless, the same principle applies: a Universe that has a finite beginning is not necessarily finite in *spatial* size.
Maybe, part of the problem is that many popular accounts of Cosmology try to impress by describing the singularity as a 'point' and telling us that 'in the beginning, everything was compressed to a point!'. That is simply not true or, rather, perhaps it is true, perhaps not; we presently have no way of knowing.
What we do know is that the observed properties of the Cosmos are consistent with a *spatially infinite* Universe with a finite age, and that, in fact, is the simplest self-consistent mathematical model of the Universe.
The Science is about extrapolating from the (observed) present as far into the past as we can, but not beyond, not about postulating some magical 'moment of creation' and speculating on that basis. In this regard, we can go back as far as roughly a picosecond after the presumed initial moment but, about that first picosecond, we know very little; we cannot even be certain if it was indeed a picosecond $(= 10^{-12}\text{ s})$ or perhaps an eternity.

168 -

How could the Universe be *infinite* in size if it has started from a definite point in the past with an expansion rate no matter how fast?

Let's take any decent textbook on Physical Cosmology, let's open it, let's search for the chapter that tells you that the Universe 'started from a definite point' or something to that effect.
Found it? Guess not. Because no physical Cosmology textbook ever makes that claim. It is an oversimplification that you see in popularizations of Cosmology, often made by folks more interested in impressing their audience with dazzling graphics and grandiose statements than explaining the actual theory.

Fact: We observe a Universe, using our instruments (telescopes, radio telescopes, other detectors including now gravitational waves and neutrinos) with specific properties. These include the nature and distribution of Matter on the large scale: the redshift of light from distant lumps of Matter, the existence of a microwave background and its specific spectrum, minor statistical fluctuations in the data with recognizable statistical patterns.

Fact: We have well-tested theories including General Relativity and Quantum Field Theory, specifically the Standard Model of Particle Physics. We can apply these theories in an attempt to model physical systems. Specifically, we can treat the Universe as a whole as a physical system and use what we learned elsewhere (be it the orbits of artificial satellites in the solar system or the behavior of elementary particles in large particle accelerators) to figure out how the Universe works, by finding a suitable mathematical model that describes its behavior.

We can do all this and arrive at the Standard Model of Cosmology, the so-called Lambda-CDM model (Lambda representing *hypothetical* Dark Energy, CDM standing for 'Cold Dark Matter'). We can explore what this model says about the past, present, and future of the Universe using parameters that best fit observational data.
With that preamble: the best model of the Universe that we have is a *spatially infinite* Universe that has a *finite* age. It is *homogeneous* (same everywhere) and *isotropic* (no preferred direction), and it has no 'spatial curvature' (meaning that if we formed a triangle, no matter how large, the sum of its angles would be exactly 180°).
Running the clock of the mathematical model backwards, general relativity by itself would tell us that this Universe is, about, $14 \cdot 10^9$ years old and its beginning is marked by a 'time-singularity'. *The singularity is not a point*: *it is a moment in time*, *the* '*initial moment*' *that is actually not part of the Universe* (not part of the SpaceTime manifold). Neither the Universe nor Time itself existed at that moment. An arbitrarily *small* time later, there is already a Universe that is homogeneous, isotropic, and *spatially infinite*, just a lot hotter and a lot denser than it is today.
But do we trust General Relativity to make this prediction of a singularity? We do not: we cannot. We don't know if General Relativity is valid in this regime of extreme energies and densities. *It most likely is not*. So, the earliest time that we can go back to with our predictions is about 10^{-12} s this *presumed* singularity, to a Universe that is still extremely hot, extremely dense but an environment that we can, in fact, briefly *replicate* in large particle colliders like the LHC. So, we have experimental data against which we can validate our theories.
There we have it: no Cosmology textbook tells you that the Universe started from a definite point. What they do tell you is how to use our existing Science, validated by data from *observation* and *experiment*, to extrapolate back to the past, and also what the limits of our knowledge are.

169 -

Can we derive the Hubble Constant from the values of the parameters of our planets (as from the Mass, radius, and acceleration at the surface)?

No. The Hubble *parameter* (not a *constant*!) is not derivable from the characteristics of tiny planets in a tiny solar system, one out of several hundred billion solar systems in our own Milky Way galaxy, one of many trillions of galaxies in the visible part of the Universe.
The Hubble parameter is measured when we look at the large-scale motion of distant galaxies relative to each other, or when we look even deeper, at the fundamental properties of the Cosmos, such as the statistical distribution of many millions of observed galaxies (each containing hundreds of billions of solar systems like ours!) or the *cosmic microwave background radiation*.
The approximate value of 70 km/s/Mpc tells us that on average, two galaxies that are one megaparsec (Mpc) or about 3 million light-years apart are moving away from each other at the rate of about 70 kilometers every second. Again, this is an average; individual galaxies can have speeds that deviate from this value.
We know that the Hubble parameter *is not* a constant. Let's imagine, for a moment, a Universe in which there are no forces acting on those galaxies that are flying away from each other, so their velocities remain *constant*. So let's take two of those galaxies, 1 Mpc apart, flying away from each other at 70 km every second, without speeding up or slowing down: 1 Mpc is an incredibly large distance, a 20-digit number in terms of kilometers. So it will take a very long time, about the same as the present estimated age of the Universe, $14 \cdot 10^9$ years, before the distance between those two galaxies doubles. But when that happens, they would still be moving away from each other at 70 km/s, even though they are now 2 Mpc apart. That implies a Hubble parameter that has been halved, from 70 to $35\,\mathrm{km/(Mpc \cdot s)}$.
In reality, there is Gravity acting on those galaxies, slowing them down (or speeding them up, in the presence of Dark Energy), so the relationship is not quite this simple, but let it suffice that the Hubble parameter is, nonetheless, *slowly decreasing* over time, *it is not constant*. Also, its value was larger (much larger in the distant past when the Universe was very young) than it is today.

170 -

We created *negative* Mass. What's next, wormholes?

(Ref.: Physicists create 'negative Mass' - Phys.org)

Sorry, no wormholes in sight. We really wish Science writers were a little more restrained. True, the original research article in question indeed mentions *negative Mass* but with an all-important qualifier: '*effective* negative Mass', i.e., perfectly ordinary (*positive* mass) Rb atoms behaving *as though* they had negative Mass under a very narrow set of circumstances. It is like those laboratory experiments in which they created black-holes and event horizon *analogs*. Those, too, were systems that behaved as though they were black-holes or event-horizons, under a *very narrow set of circumstances*. They were not, in fact, laboratory black-holes, just as this Bose-Einstein condensate didn't really have negative Mass. Such sensationalist coverage (that often comes not even from writers working for commercial popular science outlets but straight from the press releases of the respective institutions) is ultimately, counterproductive, damaging and undermines the credibility of Science overall.

So, here we are, with someone asking a very legitimate question, since negative Mass exotic Matter might indeed be the key to manipulate SpaceTime in ways not possible if *only positive Mass exists*, such as creating a stable, traversable wormhole.
Unfortunately, exotic Matter would also imply the *Vacuum becoming unstable*, as it could then decay into a lower energy state, creating exotic Matter in a runaway process. This really would be *very bad news* for our Universe, so, it is much preferable a *stable* Universe with no exotic Matter, even if it means no wormholes, antigravity or Alcubierre warp drives.

171 -

In relativistic length contraction, do the atoms get 'squished' or do they move closer to each other and make the object denser? In this second circumstance, what will happen to neutron and white dwarf stars because of neutron and electron degeneracy pressure?

Relativistic effects, such as length contraction, *are not physical effects*. Nothing is happening to the object in question.
Rather, these effects simply describe what observers who are moving relative to the object (or relative to whom the object moves – same thing) see.
So, nothing happens to neutron stars because of length contraction. We are simply describing the exact same neutron star from the perspective of a moving observer's reference frame.

172 -

Will there ever be an end to the Universe expanding? Where is that energy coming from to fuel the expansion? If there is an end of the Universe, what could the barrier be?

a. In the context of the Standard (Lambda-CDM) Cosmological Model in conjunction with the Standard Model of Particle Physics, will there be an end to the Universe expanding? Probably not: the presumed presence of Dark Energy means that the Hubble parameter *decreases to a constant non-zero* (*positive*) *value* as opposed to going down to zero or becoming negative, so the expansion *will continue forever*;

b. where is the energy coming from to fuel the expansion? It is a popular misunderstanding that the expansion is some kind of a force that needs to be powered. It is not. Things are flying apart because *they were born in a state of flying apart*, so to speak. Gravity influences the rate at which things are flying apart (slowing them down or, in the dominating presence of Dark Energy, speeding them up) but even in the absence of Gravity, the expansion would continue. 'Fuel' would be needed to decelerate things and bringing them to a stop; no 'fuel' is needed to just let things continue flying apart as they do;

c. if there is an end of the Universe, what would the barrier be? I would not exactly call it a 'barrier' but … Things that collapse into black-holes ultimately 'evaporate' in the form of *Hawking Radiation*, mostly electromagnetic radiation. Things that don't collapse into black-holes normally may, over insanely, insanely long timeframes, collapse anyway due to quantum tunneling, and also evaporate as a result. If this picture is true, ultimately all Matter gets converted into mostly electromagnetic radiation, with some gravitational radiation thrown in; and as the Universe continues to expand, even this radiation vanishes as it is redshifted into oblivion. This version of the 'heat death' of the Universe produces a somewhat paradoxical result of an empty, forever expanding Universe with a non-zero Cosmological Constant (Dark Energy) and in a state of *maximum entropy*. However, the fly in the ointment is that *the vacuum itself may not be absolutely stable*. If that is the case, an even more dramatic end may await the Universe as after an even more immensely long period of time, the present, *metastable vacuum may tunnel into an eternal instability*.

Let's just take all of the above with a *huge* grain of salt, by the way: it represents an extrapolation of our present-day knowledge of Physical Cosmology across countless orders of magnitude, so it really is highly speculative and almost certainly incorrect. The time-frames here are immense; never mind how many years, even if we express that number in exponential form, we would end up with a hideously large number in the exponent. But this is basically what awaits us according to the Standard Cosmological Model.

173 -

If black-holes can lose Mass, doesn't that logically imply that Mass 'comes out' of a black-hole (contrary to the fact that nothing can come out of a black-hole)?

To answer this question, first, it is important to distinguish between an astrophysical black-hole that forms from stellar collapse vs. a possible 'primordial' black-hole that may have been there all along.
Why? Because an astrophysical black-hole, though for all practical intents and purposes it is *indistinguishable* from a primordial black-hole by observation, is nonetheless very different. This happens because of extreme *gravitational time dilation* in the presence of a soon-to-be-forming black-hole's Gravity: things that approach the (soon-to-form) event horizon will appear to slow down completely to an outside observer. It's like slowing down a movie at an exponentially increasing rate: as the time between frames continues to increase, there would be frames in that movie that never end up on screen. The *event horizon* itself is like that; it is never seen; it remains stuck forever in the future.
It is for this reason that a black-hole was often called a 'frozen star' in older or foreign scientific literature. It is also for this reason that the very first paper that describes the formation of an astrophysical black-hole, a 1939 paper by Oppenheimer and Snyder, talks about 'continued gravitational contraction'.
So, for an astrophysical black-hole, there really is no contradiction: if Hawking Radiation causes it to lose Mass, that Mass being lost is still outside the horizon, which itself has not yet formed, so if the black-hole evaporates in a finite amount of time the horizon simply never forms.
Things would be different if there were black-holes that came 'fully formed' with the Universe. These 'primordial' black-holes that are sometimes *conjectured* to exist come with fully formed horizons. Even so, when it comes to Hawking Radiation, nothing comes out of the black-hole; rather, what 'goes into' the black-hole is *negative energy*. No, this is not just a clever play on words: what it amounts to is that even as causal influences still travel from the outside in, energy travels from the inside out.
But rather than trying to explain it further, let's point out that there are no known primordial black-holes; their existence is pure conjecture, usually in the context of more exotic theories. The only black-holes that are actually known to exist are astrophysical black-holes that are the result of collapse and possibly merger events, and the horizons of these black-holes remain forever in the future, as explained above.

174 -

Why is Quantum Field Theory necessary? More specifically, why are fields required as opposed to some other kind of mathematical formalism? What is the motivation?

One reason why we are interested in a field theory is because our best classical theory of 'stuff' is, in fact, a field theory: Maxwell's theory of Electromagnetism. So, it stands to reason that we seek a generalization of this theory to the quantum realm.
But there are also the failures of Quantum Particle theories. Specifically, a particle theory cannot account for the *creation* or *annihilation* of particles, which we observe in Nature. These phenomena are almost trivially accounted for in a theory of interacting fields, where the interaction is responsible for creating or annihilating excitations of those fields.
Moreover, even a relativistic quantum particle theory *fails the principle of causality*. For instance, Dirac's relativistic equation allows for two measurements to influence each other *faster* than light. In contrast, in a Relativistic Quantum Field Theory these influences, almost miraculously, cancel, leaving only influences that propagate no faster than the speed of light, so the theory remains strictly *causal*.
Finally, yet another motivation (specifically for the path integral formalism) comes from Feynman. Think of the two-slit experiment. The electron goes through both slits, right? What if we add a third slit, or a fourth? The electron goes through all of them, right? What if we include additional screens? The electron now goes through all combinations of slits and screens. What if we fill all space with screens, and then fill each screen with slits? The electron now takes every possible path between its initial and final location. But we just described free space: all slits, nothing else. So, to describe the electron in free space, we need a formalism that considers every possible path that the electron might take, and essentially sum (integrate) the probabilities of each of these paths to get a final result (that Feynman's path integrals are, actually, equivalent to more conventional formulations of Quantum Field Theory by Schwinger and Tomonaga, was demonstrated by Dyson).

175 -

If gravitons are massless, exactly what is being measured when gravitational waves are detected?

What are we measuring when massless photons hit your retina? Light, of course. The energy delivered by those massless photons to the receptors in our retina, causing a chemical reaction that in turn produces a signal to be processed by our brains.
Gravitational wave detectors do the same thing, except that they measure the energy delivered by *gravitational waves*, not electromagnetic waves. Or, if we prefer the Quantum Field Theory viewpoint, they measure the energy delivered by the field quanta of the Gravitational Field, *gravitons*, not by the field quanta of the Electromagnetic field.

176 -

Is the Mass of a black-hole located in/at the event horizon, all at the singularity, or uniformly spread from the event horizon to the center? They still gravitate, so there must still be Mass somewhere.

The Mass of the archetypal black-hole, the spherically symmetric, static Schwarzschild solution, is, perhaps surprisingly, not located anywhere.
"How come?" we ask. Why? The Schwarzschild solution is a *vacuum solution* of the equations of General Relativity. That is to say, the mathematical term that represents Mass density, the so-called *Stress-Energy-*(*Linear*)*Momentum Tensor*, is identically zero everywhere.
The solution, nonetheless, has a parameter that we call the *black-hole Mass*. It is a very useful concept to have, because of what is known as *Birkhoff's Theorem*, the general relativistic version of the shell theorem from Newtonian Physics: that outside the source of Gravitation, the Gravitational Field of spherically symmetric bodies of the same Mass are *identical*, regardless of the geometric size or layered composition of those bodies. In other words, outside a body like the Sun or the Earth, that body's Gravitational Field is the same (to a very good approximation) as the Gravitational Field of an equal Mass Schwarzschild black-hole would be at the same distance.
But none of these changes the fact that the Schwarzschild black-hole is a solution of the Gravitational Field Equations in empty space. Absolutely empty, nothing in it.
"So, where is all the Mass?" we ask. Well, … there is one way to think about it, not exactly one that should recommend but not grossly misleading. Real, astrophysical black-holes are never 'fully formed'. The collapse of Matter into a black-hole may only take a few seconds if you are an unlucky observer who is part of that collapse, but to an external observer, it takes forever, because of extreme gravitational *time dilation*. So, this outside observer never actually sees the black-hole's event horizon form; rather all the Matter that is in the process of collapsing ends up 'frozen' just before the horizon appears (this is why in the older literature, and in some foreign languages, black-holes were often called 'frozen stars').
So, the Schwarzschild solution would represent the end state of collapse after an infinite amount of time (which is just a fancy way of saying, 'never') when the collapse is complete and all the Matter that formed the black-hole vanishes, ceases to exist (that's what the 'singularity' really means), leaving behind the *vacuum Gravitational Field*.

177 -

Why do we state that the SpaceTime metric is real and Quantum Fields that inhabit SpaceTime are real, but SpaceTime itself is somehow not real? What is missing? Space and Time are both involved here, aren't they?

When it comes to Physics we should be a bit pragmatist since we talk about *things that can be measured*.
We do not measure SpaceTime, we *cannot* measure SpaceTime. We measure things, things that are made of Quantum Fields, things that affect other things by way of Quantum Fields. These Quantum Fields carry Energy and Linear Momentum, possibly Angular Momentum and other conserved quantities. These Quantum Fields carry signals and information; they can carry *influences* from one place to another place.
SpaceTime cannot do any of that. It has no energy. It has no Momentum. It contains no information. Even when we talk about the bending of SpaceTime (Gravitation) what we are really talking about is how distances and time intervals, determined by the metric, change between events that are characterized by things.
It is not something we should unduly emphasize, were it not for the fact that, in popular accounts, quite often 'SpaceTime' is represented pictorially (often very misleadingly, such as the 'trampoline' depiction of a Gravitational Field), implying that Space and Time have an existence independent of Matter … Perhaps they do, perhaps they don't, but in the Physics that we actually know, *they don't*.
Therefore, it is sensical to stress the point that even when it comes to Gravitation, it is not Space, it is not Time, it is the *metric* that acts as the *physical field*, coupling universally and minimally to all fields (and thus doubling as the one-and-only SpaceTime metric).

178 -

Why don't two substances with Mass repel each other despite both positive Mass? If substances with negative Mass exist, what makes positive and negative Mass substances separate? Is there possibility Dark Matter is a negative Mass substance?

It is not a universal fact that like charges repel; rather, it is a specific property of a 'vector field theory', such as Maxwell's Theory of Electromagnetism, or its Quantum Field theoretical version.
Gravitation *is not* a vector field theory; *it is a tensor theory*, which works differently and, as a result, positive Masses *attract* each other.
Does *negative Mass* (also referred to as *exotic Matter*) exist? Almost certainly not: unless we badly misunderstood something, *negative rest Mass* means *negative Energy*. The existence of *negative Energy Matter* would imply that the vacuum, with zero energy, could 'decay' into a lower energy state by producing *negative energy Matter particle-antiparticle pairs*. This would mean that the vacuum itself is *unstable*, which would put a rather abrupt end to the existence of the Universe as we know it. So, postulating *exotic Matter* almost necessarily has to come hand-in-hand with postulating some mechanism that prevents the vacuum from collapsing in this manner, and that makes any such theory contrived and implausible.
Having said that, people have speculated about the possibility that instead of Dark Matter, some form of exotic Matter exists outside of galaxies, and that it is such *exotic Matter* that is responsible for the *excess rotation* of galaxies. Until/unless Dark Matter is unambiguously discovered and its nature is fully understood, the possibility of exotic Matter, however unlikely, cannot be completely excluded.

179 -

Photons have *relativistic* Mass, m, so that $\boldsymbol{p}_{\text{rel}} := m\boldsymbol{v} \equiv \gamma m_0 \boldsymbol{v}$. Therefore, we can say they are Matter. What is their anti-Matter?

Photons have no *rest Mass* $(\equiv m_0)$. Having Mass is not a prerequisite for Matter. For instance, up until the late 1980's, neutrinos were believed to be massless, yet they are definitely Matter.
As a matter of fact, 'Matter' doesn't have a precise definition in the literature. E.g., to a cosmologist, the Electromagnetic Field (of which photons are quanta) is just one special form of Matter, but a condensed-Matter physicist may consider Electromagnetism an interaction between particles of Matter.
Photons are their own antiparticles: two photons can 'annihilate', producing an electron-positron pair, for instance. Such interactions are rare (the photons must be pretty energetic, so that in the CM (center-of-Mass) system, their total Kinetic Energy exceeds the combined rest Masses of the electron and the positron) but such two-photon Physics does happen, and in fact limits the Energy of the γ- ray photons that arrive from deep space, as they scatter on the photons of the Cosmic Microwave Background radiation.

180 -

If a black-hole 'eats' light, why does it grow in Mass if light is massless?

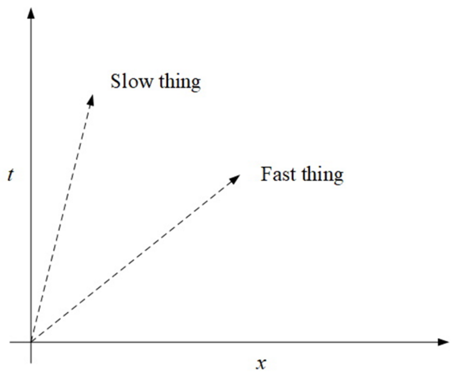
First of all, black-holes 'eat' everything, not just light: they are extremely inefficient eaters. If we replaced the Sun with a black-hole of the same Mass, the radius of that black-hole would be just a tad under 3 km, a small fraction of the 695000 km radius of the Sun. Therefore, things that would collide with the Sun's surface, e.g., comets that fall into the Sun, would safely fly by the black-hole most of the time. So, contrary to their popular reputation, black-holes are not gigantic vacuum cleaners (if anything, the opposite is true).

Second, light may have no rest Mass, but it certainly has Kinetic Energy, which is just one of many forms of Mass-Energy (let's remember what the famous equation $E = mc^2$ is all about: it is called the *Mass-Energy Equivalence* relationship for a reason). If we had a box lined on the inside with perfect mirrors and you allowed some light in there, as that light bounces about indefinitely between the mirrors, its Kinetic Energy would add to the Mass of the box. So, when a ray of light is 'eaten' by a black-hole, the Kinetic Energy of that ray of light is added to the total Mass-Energy of the black-hole.

181 -

Does the fact that all objects travel through SpaceTime at c serve as a basis for explaining acceleration in Space due to Gravity (i.e., a change in Time requires an acceleration in Space) as in the case of the falling apple?

This is another one of those things we occasionally encounter in popularizations of Science, trying to impress us more than they should.
Objects travel through space, at whatever velocity you measure in your frame of reference, dividing the distance in space that the object covers by the interval of time that it takes for the object to complete that journey.
Now it is true that the trajectory of objects in Relativity Theory is often characterized by a 4-dim vector quantity, $\boldsymbol{v}$, called the *4-velocity*. The magnitude of this vector quantity has no meaning; its direction, anyway, determines the 3-dim velocity of the object.
OK, this sounds more complicated than it should. So, let's illustrate with a simple diagram (nothing to do with Relativity) how the angle of an arrow tells you if a thing is fast or slow:



As we can see, a fast thing covers more territory in the x-direction (space) than a slow thing, while they both travel the same amount in the t-direction (time, vertical in this diagram). The more an arrow deviates from the vertical in this diagram, the faster the object is that the arrow represents. The length of the arrow has no meaning.
So, given that the magnitude of the 4-velocity doesn't matter, we can make things simple and create a 4-dim vector of unit length. But … length is calculated differently in SpaceTime. Instead of using the theorem of Pythagoras and adding squares, we have to subtract some of them. To make a long story short, we get a 4-velocity that looks like this:

$$\boldsymbol{u} = \left(\frac{c^2}{(c^2 - v^2)^{1/2}}, \frac{v_x^2}{(c^2 - v^2)^{1/2}}, \frac{v_y^2}{(c^2 - v^2)^{1/2}}, \frac{v_z^2}{(c^2 - v^2)^{1/2}} \right).$$

When we take the SpaceTime version of the Pythagorean length of this 4-dim vector, we get

$$\boldsymbol{u}^2 \equiv \boldsymbol{u} \cdot \boldsymbol{u} = \frac{c^2 - v_x^2 - v_y^2 - v_z^2}{c^2 - v^2} \equiv \frac{c^2 - v^2}{c^2 - v^2} = 1,$$

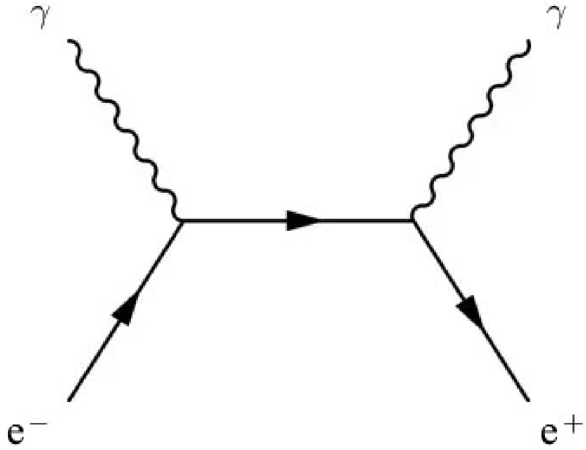
i.e., a 4-vector of *unit length*. Or, if we wish, we could have used $(c^2 - v^2)^{1/2}$ in the denominator and, in that case, the 'length' of the 4-vector $\boldsymbol{u}$ would equal to c.
It is this fact that is sometimes (grossly) misrepresented in popular texts, suggesting that objects 'travel through SpaceTime at c'. Never mind that traveling through SpaceTime (as opposed to Space) has no meaning conceptually, that the length of the 4-velocity is chosen rather arbitrarily, and last but not least, the one thing that actually travels at the vacuum speed of light, namely light, has a 4-velocity that is a so-called *null vector*, the 'length' of which is actually zero … Therefore, things do *not* travel through SpaceTime at c.

182 -

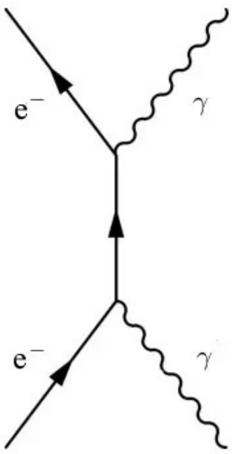
When Matter and anti-Matter collide creating *pure Energy*, what kind of Energy is it?

The decay products of annihilation depend on the particles involved and the nature of their interaction, but it is not 'pure Energy'. There is no such thing.
The easiest way to think about it is through *Feynman diagrams*. Let's take a diagram of a particle and an anti-particle annihilating (and producing some decay particles). Now consider the fact that an anti-particle is just a particle with negative energy going backwards in time. So, if we look at the diagram *sideways*, we don't see an anti-particle at all, just a particle that is deflected after emitting or absorbing some other particles.

Here below, we see a diagram of an *electron* and a *positron* annihilating and producing a pair of photons:



Rotate the diagram *sideways* (say, by $-90°$ vs. the reader) and what do we see instead? An electron *absorbing* and then *re-emitting* a photon, getting deflected as part of the process:



Comparing the two diagrams shall make something very clear: the decay products of the annihilation are the same particles with which the particle in question can interact in the first place.
So, for instance, electrons don't interact with gluons. Therefore, when electrons annihilate, they will not produce gluons (at least not directly).
On the other hand, electrons do interact through the *weak interaction*, e.g., by *emitting or absorbing* Z^0*- bosons*. So, electron-positron annihilation can produce, in principle, two Z^0- bosons or one Z^0- boson and a photon. This just happens a lot less often, because Z^0- bosons are very massive, and unless the electron and the positron collide with a huge amount of kinetic energy, there just isn't enough energy present to produce a Z^0- boson.
Of course, Z^0- bosons are not stable, they decay. So, what we observe are the Z^0- boson *decay products*. And this leads us to an important point: if a particle and an anti-particle collide with a very high Kinetic Energy, there is also enough Energy to produce very high Energy *unstable particles*, which then decay into other things and even more other things. Therefore, even an ordinary electron-positron collision can produce a shower of particles of every kind, so long as the collision energy is high enough. No, not 'pure Energy' at all.

183 -

How do gravitational waves take away orbital Energy from the black-hole merger pair if the fabric of SpaceTime is only imaginary and a concept and does not exist tangibly in the real world?

The 'fabric of SpaceTime' is a nice pictorial expression with no real meaning. It suggests, wrongly, that SpaceTime itself has a physical reality that can be conceived and perhaps measured independently of the physical fields therein.
The 'metric of SpaceTime' is a physical field that carries Energy and Momentum, much like the Electromagnetic Field. It does so in the form of *gravitational waves* (the fact that this gravitational field couples universally and minimally to all Matter fields is why it also determines the magnitude of measured SpaceTime distances between

events and, as such, can double as the metric of SpaceTime).
Close binary stars or merging black-holes lose orbital kinetic energy by inducing changes in the metric of SpaceTime, which then travel in the form of *gravitational waves*: periodic (plane wave) changes in the metric, propagating at the Vacuum speed of light.

184 -

What exactly is Mass in Quantum Mechanics? Is it interaction of particles with Higgs Field or what?

The Mass of a particle in a Relativistic Quantum Field Theory is its *intrinsic energy*. This can have, in principle, three sources: *rest Mass*, *interaction with the Vacuum* or, in case of a composite particle, *interaction between its constituent bits*.
For most particles in the Standard Model rest Mass is not an option, as it would break the *gauge symmetry* of the theory, which is essential for the theory to work.
Interaction with the vacuum is another matter. This arises for fermions through interaction with the Higgs field. Normally, this would be just a particle interaction, i.e., an electron may interact with a Higgs particle when they collide … that's clearly not Mass. However, there is symmetry breaking, which happens because for this Higgs field, the lowest energy state is not the state in which the field is *free of excitations*. This new lowest energy state becomes the new Vacuum after symmetry breaking, and in this new Vacuum, the Higgs field has a non-zero so-called *Vacuum expectation value* (V. e. v.). Fermions interacting with the Higgs field now interact with the V. e. v., which means that effectively they interact with the Vacuum … and that's just like *rest Mass*.
Finally, particles like protons and neutrons get most of their Mass from the (positive) *Strong Force Binding Energy* that holds constituent quarks together.

185 -

How does the Higgs field give an electron Mass? If Energy and Mass are the same, does it give the particle Energy?

Indeed, Mass and Energy are the same. What gives the electron Mass (that is, Energy in the form of rest Mass) is the Higgs Field, in combination with what is known as *electroweak symmetry breaking*.
Electrons interact with the Higgs Field. That is to say, *there exists a potential energy term that links the electron field and the Higgs Field*.
However, 'out of the box', the Higgs field itself is *unstable*. What this means is that the field with *no excitations* (*no particles present*) has more energy than the field with some excitations (particles) present. Which means that the Vacuum (no particles) can decay (get into a *lower* energy state) through the *creation* of particles. Very rapidly, this is precisely what happens, and a new, lower energy, 'true' Vacuum emerges; with respect to this Vacuum, the Higgs field is said to have a 'non-zero Vacuum expectation value (V. e. v.)'.
But the consequences for particles such as electrons is even more drastic. Before this symmetry breaking process they interacted with the Higgs field; now they interact with its non-zero V. e. v., that is to say, with the Vacuum itself. So, *an energy term exists now between the electron field and the Vacuum*. This, for all practical intents and purposes, makes the electron behave as though it had *rest Mass*.
So, yes, the Higgs Field, through *symmetry breaking*, endows electrons with an *effective rest Mass*.

186 -

Is it true that the observable universe is growing? How is it possible for the observable Universe to grow, if everything beyond the Hubble horizon is receding faster than the speed of light?

Indeed, it happens every day. But not necessarily in the way you think. Light from things beyond the observable Universe emitted at the present will never reach us in a Universe that, like ours appears to be, is undergoing accelerating expansion.
But light from things that were beyond the observable Universe at some point in the past might be reaching us today for the very first time.
However, this statement needs a strong qualifier, because, yes, light from distant things took a long time to get here, and that means that it was emitted when the Universe was very young. And the very young Universe was too dense, not transparent to light at all. When it did become transparent, it was still glowing from heat; that glow, *redshifted* into the microwave part of the electromagnetic spectrum, is what reaches us today in the form of the cosmic microwave background radiation, coming from all sky directions.
Now, let's take one of those directions and 'look' at it using your radio telescope. What do we actually see? Why, it's a cloud of glowing, incandescent gas?

Again, let's look in the same direction the next day. We still see a glow but it is no longer exactly the same patch of gas. The gas that you saw yesterday has since cooled a little more and became completely transparent. But behind it, there is more gas (at the time when this light was emitted, the Universe was filled with gas everywhere). So the next day, we see glowing, incandescent gas that is a little farther away, a patch that we could not see the previous day because a more nearby, not yet quite transparent patch was in the way.
And so, with each passing day, we see things that are a little more distant than the things we saw the previous day: things become observable to us that were not observable yesterday.
Granted, it is a little bit less exotic than seeing behind the cosmological event-horizon but we, nonetheless, find it quite fascinating: every day we measure the CMB, we see 'light' from things that reaches us for the very first time in the history of the Universe. And if we could follow that patch of light for billions of years to come, we would see it cool down slowly, form 'clumps' under its self-gravitation, which eventually coalesce into stars and galaxies of stars. All this would unfold in 'slow motion' because if the extreme relativistic Time dilation that is associated with such distant objects on a cosmological scale. And because the expansion of the Universe is accelerating, the time dilation increases; over time, those distant patches of gas turning into galaxies would be harder and harder to see, moments of time would stretch longer and longer as measured by our watch … eventually, they would fade from sight, and there would be a final moment that (again, according to our watch) stretches into infinity, and we will not be able to see what happens to that galaxy beyond that moment. It will have disappeared beyond *our cosmological event-horizon*, but that act of disappearance, though it represents a finite amount of time for inhabitants of that patch of gas, will take forever as measured by our watch.
That is the nature of the cosmic event horizon.

187 -

How does Quantum Field Theory (QFT) address wave particle duality?

QFT addresses what is popularly known as the wave-particle duality the same way ordinary Quantum Mechanics (the actual Science, not popularizations of it) does: through the *complementarity of fields* and *corresponding canonical momenta*. That is, whereas in ordinary Quantum Mechanics, we have

$$[\hat{q},\hat{p}] \equiv \hat{q}\hat{p} - \hat{p}\hat{q} = i\hbar$$

($\hat{q}$ is the canonical generalized *position* operator, $\hat{p}$ is the canonical generalized *Linear Momentum* operator), in QFT, we have

$$[\hat{\phi},\hat{\pi}] = i\hbar\delta^3(\boldsymbol{r}-\boldsymbol{r}'),$$

where $\hat{\phi}(\boldsymbol{r},t)$ is the operator-valued field-variable (a function of the coordinates $\boldsymbol{r}$ and time t) and $\hat{\pi}(\boldsymbol{r},t)$ is the corresponding canonical Linear Momentum.
If that sounds like it is unnecessarily technical, … it is not. Not unnecessary, that is, technical though it might be. If there is a shortcut to understanding Quantum Theory, especially QFT, we have yet to discover it. So far, all we have seen are popularizations that are far more likely to mislead than to help.
Still, … the essence of what we call the *wave-particle duality* is that a particle either has a well-defined Linear Momentum but it is spread out in space (like a wave) or it has a well-defined position (like a particle) but no well-defined Momentum. In the case of a field, the position is replaced by the field value, whereas the Momentum is formed through the same mathematical operation as in the particle case. In other words, … whereas popularizations tell us that a quantum 'thing' can be either a wave or a particle, in reality, it is neither wave nor particle … in fact, any attempt to try to shoehorn that quantum 'thing' into a box made for classical concepts is doomed to failure.

188 -

We get that the Higgs field isn't at its lowest energy state and that a *Higgs boson* could tunnel its way to a lower energy state but how does a particle tunnel to a lower state of energy?

The Higgs field in the present-day Universe is *already* at its lowest energy state. The original Higgs Field (a complex doublet) before symmetry breaking has this curious property that its lowest energy state is not when the field is free of excitations. Thus, the Vacuum (no excitations) can 'decay' and produce a lower energy state by creating *excitations* in this Higgs Field. This continues until the lowest energy state is reached. This new, stable, equilibrium state will be the new Vacuum.
With respect to this new Vacuum, the Higgs Field has a so-called *non-zero Vacuum expectation value* (V. e. v.). Other particles, e.g., electrons, which interact with the Higgs Field, thus interact with the Vacuum now, through this non-zero V. e. v. . When a particle interacts with the Vacuum in this manner, it plays precisely the same role as *rest Mass*

in the particle's equation of motion. So, for all practical intents and purposes, the electron *acquires Mass*.
As to the Higgs Field, something else happens to it. It originally has 4 degrees of freedom (two complex numbers). But 3 of those 4 degrees of freedom are 'eaten up' by the 3 vector bosons of the *Weak Interaction*, as they also acquire Mass because of the Higgs *symmetry breaking*.
The *one* remaining degree of freedom is the *one* degree of freedom the Higgs Field has in this new vacuum: a *scalar particle* that we call the *Higgs boson*. It doesn't tunnel into anything. It is a *massive*, *unstable* particle, which can be created in high-energy collisions, but which rapidly decays into lighter particles. That's all.

189 -

If Dark Matter exerts Gravity, how come it doesn't clump together like regular Matter?

Well, … Dark Matter does clump (in fact, in the Standard Cosmology Theory, this clumping plays an essential role in the early formation of galaxies), but not quite the same way as regular Matter. When regular Matter (say, a gas cloud) collapses, it *heats up*. There is *pressure*. *Sound waves* are produced. All these are mechanisms through which Kinetic Energy is dissipated, essentially turning into waste heat and radiation (heat or light).
Non-interacting Dark Matter does not have these mechanisms. Particles may still clump into over-dense structures, but they do not shed their kinetic energy. So, while they end up forming, e.g., galaxy-sized halos, they won't coalesce into stars and planets, because they just won't slow down. There is no mechanism to convert their kinetic energy into waste heat, with one exception: the occasional gravitational ejection of particles from a complex N-body system. But this is a much more inefficient process.

190 -

Is it true that if a finite amount of Matter were confined within a small enough radius, there would be a point of infinite curvature and density, a 'singularity'? How can a finite amount of Matter create infinite level of Gravity?

Not exactly. What is true is that if Matter is allowed to collapse under its *Self-gravity*, it will indeed form a black-hole.
So here is what a black-hole means: to an external observer, it means *never-ending collapse* (the first paper that discussed gravitational collapse, the one by Oppenheimer and Snyder in 1939, was in fact titled 'On Continued Gravitational Contraction'). The reason is that as the object approaches its own so-called *Schwarzschild radius*, the observed gravitational time dilation becomes divergent. So, anything that happens there is seen increasingly in slow motion by the outside observer. The 'film' slows down so much that it in fact comes gradually to a halt, never advancing beyond a specific moment; the outside observer never actually sees anything reach, or cross, the so-called *event horizon*.
To an infalling observer, ignoring Quantum Physics, that event horizon is not in any way special. The observer will pass through it without necessarily even noticing that it was a point of no return. However, once past the horizon, the horizon itself for this observer becomes a *moment in the past*, *not a place* that can ever be reached again (this is this 'SpaceTime' thing of General Relativity coming in with a vengeance!). This observer will find himself in a collapsing 'mini-Universe' with a *future singularity*: a moment in Time when everything comes together and even time itself ends.
If we do not ignore Quantum Physics, however, the situation changes. The black-hole radiates heat. Exceedingly tiny amounts of heat, to be sure, but non-zero amounts. This is the infamous *Hawking Radiation*. Sure, in the present-day Universe it will always receive more heat, more Matter than it radiates. But in the extreme distant future, things will change, and the black-hole will slowly lose Mass-Energy. Over an immensely long but finite amount of time it evaporates completely. Which means that there is no singularity, no infinities, no 'geodesic incompleteness': extreme Gravity, to be sure, but always *finite*.
So, that's the nuanced picture of what happens. No infinite Gravity. Some possible infinities, to be sure, but they may be tamed by Quantum Physics.

191 -

If, in the field of Quantum Physics, 'fields' are the fundamental constituents of everything, are there any boundary conditions between fields? And if not, if the Universe is a 'field-soup', then how do discrete states maintain themselves?

In any practical calculation in perturbative QFT, the boundary conditions are basically the initial and final observed states. On a more 'philosophical' level, for the Universe as a whole, one would define a suitable initial and final state as well, with the initial state possibly singular, and the final state perhaps a '*heat-death*' with no excitations, all fields in the ground state.

Discrete states have nothing to do with any of this. Discrete states do not arise because of boundary conditions. They arise because the fields in question are not classical fields: they are not number-valued fields but *obey a non-commutative algebra*. A direct consequence is that even for the free field, after it is Fourier-transformed into what is effectively an infinite sum of harmonic oscillators, excitations of those oscillators (just like in the case of the simple quantum harmonic oscillator) are now described by creation and annihilation operators, yielding those discrete, countable states that we associate with particles.
On a side note, this becomes especially relevant when we do QFT on the curved background of General Relativity, where there is no longer an unambiguous inertial reference frame with respect to which that Fourier-decomposition can take place. Thus, different observers may decompose the field differently, and observe different particle content. This can also happen in flat SpaceTime for accelerating observers; this is the mechanism behind *Unruh-Radiation*.

192 -

Why is 'Pilot Wave' theory less popular than the Copenhagen Interpretation when *both* theories fit the empirical data?

Assuming that the premise of the issue is actually true (was there a survey recently? Was the general public asked, or only physicists, or perhaps only specialists in the Quantum Theory?), perhaps one reason is that the de Broglie-Bohm theory has issues with Relativity and QFT; additional assumptions are needed to reconcile these concepts and, ultimately, no interpretation can evade the fact that the Quantum Theory is manifestly *non-local*. On the other hand, once non-locality is accepted, the extra baggage of de Broglie-Bohm may seem superfluous and unnecessary as it brings no new observable phenomena to the table. Rather, it is designed to satisfy some human need to make the theory more palatable intuitively but, at the same time, it also makes it more cumbersome.
In any case, worrying about interpretations is rarely productive. Generally, most people who actually work with QFT (e.g., building extensions to the Standard Model, trying to construct functioning theories of Quantum Gravity and to resolve open questions such as the origin of neutrino Masses or the *hierarchy problem*) do not pay much attention to the business of interpretations and if we insisted on discussing the topic with them, they would soon tell you that they have urgent business elsewhere. That's because they worry about the testable predictions of the theory at hand instead.

193 -

Are there 3 Higgs Fields which would then explain the 3 generations of elementary particles in the Standard Model?
(compare with Issue 60, P. 25)

No, there are no 3 Higgs Fields, nor would they explain the three generations of the Standard Model. The one-and-only *Higgs Field* in the basic *Higgs Model* (there are alternative, more complicated models, with multiple Higgs fields) is a so-called *complex scalar doublet*. This complex scalar doublet (basically, the field value is a pair of complex numbers assigned to each point in SpaceTime: this means 4 *real* degrees of freedom) interacts with the massless vector bosons of the gauge invariant electroweak theory. It also interacts with itself, in such a way that its infamous 'Mexican hat' potential plays a vital role: it defines an excitation of the *Higgs doublet field* that is lower in Energy than the excitation-free Vacuum.
As a result, the Vacuum promptly decays into this *lower* Energy state. As part of the decay, two important things happen:

first, 3 of the 4 degrees of freedom are 'eaten up' by 3 of the 4 electroweak vector bosons, which acquire huge Masses as a result. The remaining 4^{th} degree of freedom manifests itself as the Higgs particle that can be observed in a particle accelerator;

second, interactions between the Higgs doublet and charged fermions now become interactions between the fermions and the new Vacuum. For all practical intents and purposes this works like Mass, therefore, charged fermions acquire Masses as well.

This is the gist of the *Higgs mechanism* and its role in Electroweak Symmetry Breaking. Now one thing about the electroweak theory is that it is not sensitive to 'flavor' (the word used to describe the 3 generations of fermions). This is how the Electroweak Interaction makes it possible, for instance, *to convert electrons into muons*. Multiple generations of the Higgs Field would not change this *experimentally observed fact*, which is why we stated above that the Higgs would be *useless* for this purpose.
If this sounds like some fairy tale, a word of caution should be in order: it is merely my attempt to compress, in a few short paragraphs what pages of equations say with precisely testable consequences. The math of the Standard Model, or Quantum Field Theory in general, is not easy, but the darn thing works. It works almost unreasonably well, which is why we trust it, not because of pretty words.

194 -

It's hard to understand what scientists mean when they say that "the Universe came from nothing". We know they don't literally mean 'nothing' but, in simple terms, how the Universe came into being from this 'nothing'? What does it mean?

We have absolutely no idea what it means when someone claiming to be a scientist says that "the Universe came from nothing". That is because the Physics we are familiar with starts with the present: the data we observe. These include things like the distance-redshift relationship of celestial objects; the spectrum and statistical properties of the cosmic microwave background radiation; the large-scale statistical distribution of galaxies; primordial isotope ratios; the morphology and chemical composition of distant galaxies; and a host of other data. Using these data along with the best theories that we have, starting with General Relativity and the Standard Model of Particle Physics, we can extrapolate backward from the present and uncover what the Universe likely looked like in the distant past.

We can establish with a very high degree of certainty that early on, the Universe was very homogeneous, isotropic, hot and dense. The data tell us that it was likely 'spatially flat', that is to say, if we drew a triangle in this Universe, no matter how large, the sum of its angles would be $180°$, no more no less. The data also tell us that about 95% of the stuff in this Universe is of an unknown nature: we call these constituents 'Dark Matter' and 'Dark Energy' but giving them names hides the fact that we know next to nothing about them, indeed not even whether they really exist (which is the consensus view) or perhaps their presence is mimicked by Gravitation that, on the large scale, deviates from Einstein's model.

Either way, we can reliably extrapolate backwards all the way to the epoch when the properties of the entire Universe were akin to what we observe inside the reaction chamber of our most powerful particle accelerators. According to our model, the Universe at this point in Time may have been as young as $\sim 10^{-12}$ s.

But what happened in that pico-second? Was it indeed a pico-second or an eternity? That, we do not know. Everything about that is pure speculation; informed speculation maybe, but more likely science-fiction (or, sadly more often than not, fiction with little or no-science). All these flights of fancy: a 'bounce', cyclic Universes, inflation, eternal inflation, the 'multiverse', all of it firmly belong in this category, that is, until and unless they offer hard, testable predictions.

One of these flights of fancy is based upon the notion that the combined Mass-Energy of all Matter fields in this Universe might be exactly canceled out by the combined (negative) Gravitational Field Energy in the Universe, resulting in what some folks dubbed 'the ultimate free lunch'.

But this is no-science. Nobody can explain how we can *integrate the energy density* of Matter over the entire Universe. Nobody can tell us how we can provide a sensible definition for a local Gravitational Field Energy Density that could be integrated over a *well-defined finite integration volume*. And of course, nobody knows for sure if the Universe has the same properties beyond the boundaries of the observable Universe that it has within those boundaries. We can speculate … but that's all it is, *speculation*, *not Science*.

It's as though it isn't amazing enough already that in less than a century, we progressed from barely understanding the nature of 'spiral nebulae' (galaxies beyond the Milky Way) to having firm knowledge taking us back all the way to that first pico-second! Just in our lifetime, we made such astonishing progress … what's the point of trying to make it sound more impressive than it already is?

195 -

If the 'fabric' of SpaceTime is expanding does that mean everything (each thing) is getting bigger?

The 'fabric' of SpaceTime is not expanding and everything is most decidedly not getting bigger. This most common of misconceptions in Physical Cosmology is one has been written about many times, even quoting numerous textbooks by well-known authors that make this point clear.

When we look at distant galaxies, the distance between them is increasing. In other words, if we could affix a gigantic measuring tape to one and stretch it all the way to the other, the other galaxy would be rushing along the tape, and you'd need more and more tape each second. This is the very definition of motion: those two galaxies are moving away from each other.

In some cases, this motion was stopped because the *mutual* Gravity between the galaxies was enough to keep them together. Such gravitationally bound systems are no longer flying apart. That, too, should tell you that SpaceTime is not doing any stretching here; it's those things, namely those galaxies, that are doing the moving. And of course, smaller things (solar systems, stars, planets), or things small enough to be held together by forces other than Gravity (rocks, houses, people, bacteria, atoms) are not getting bigger either.

So where does the misunderstanding come from? When you look at two distant galaxies that are flying apart, away from each other, both may nonetheless be at rest with respect to the cosmic microwave background. This is the nature of expanding SpaceTime: 'at rest' here where the Milky Way is, is not the same as 'at rest' a great distance away from here.

What has been just described is formally encoded in a coordinate system that is often used to describe the expanding Cosmos: in *co-moving coordinates*, the two galaxies' positions remain unchanged even as the distance between them increases because the metric of SpaceTime changes.
But this is when we should remind ourselves that Physics does not depend on our choice of coordinates. We are not obliged to use co-moving coordinates. What Physics should describe is the result of a measurement. And when we measure the distance between those two distant galaxies, it increases over time, so they are moving away from each other. SpaceTime is not doing any stretching here; it is Matter that is doing the moving.

196 -

What is the evidence that neutrinos have Mass?

The main evidence for neutrino Masses is in the form of *neutrino oscillations*. Neutrinos come in three flavors: *electron neutrinos*, *muon neutrinos* and *tau neutrinos* (this corresponds to the 3 generations of charged fermions: the *electron*, the *muon*, the *tau* particle and 3 pairs of *quarks*).
Ever since the 1960's, we faced a mystery. The fusion process inside the Sun was thought to be well understood. But when neutrino observatories came online, they showed a deficit in solar neutrinos.
One possible explanation has been around since the 1950's: *the possibility that not only are neutrinos massive, but that their Mass eigenstates do not coincide with their flavor eigenstates*.
What does that mean? It is, in a sense, a *variation* on the Uncertainty Principle: when we measure some property of a particle, other properties become indeterminate. In the case of neutrinos, the hypothesis goes, if we measure the Mass-Energy of a neutrino, *its flavor becomes unpredictable*.
In the case of the missing solar neutrinos, this hypothesis would mean that some solar neutrinos, though they began their existence as electron neutrinos, ended up being detected (or not detected) as muon neutrinos here on the Earth. The deficit arises because the detectors in question were sensitive to electron neutrinos but not to muon neutrinos.
This was eventually confirmed when the missing neutrinos were in fact detected as muon neutrinos. This flavor-changing of neutrinos is called neutrino oscillation, and it has since been detected by many detectors, using both solar neutrinos and neutrinos from terrestrial sources.
The mathematical model of neutrino oscillations uses a matrix, the so-called *Pontecorvo-Maki-Nakagawa-Sakata* (*PMNS*) *matrix*, to quantify neutrino Masses and flavor mixing. A variety of experiments can 'fill in' the elements of this matrix, but with limitations. Strictly speaking, we don't know for sure *if all* 3 neutrino flavors are *massive*; we do have some limits on the magnitudes and differences of their Masses, so we know that at least 2 out of the 3 flavors must have Mass. Curiously, we don't even know which of the 3 is the heaviest. Trying to nail down neutrino Masses remains a very active area of research, with wide-ranging implications; for instance, neutrinos can contribute to Cosmology as a form of Dark Matter, if they are sufficiently massive to make noticeable contribution.

197 -

How can a black-hole emit radiation with such a strong Gravitational Force?

If the question refers to *Hawking Radiation* (as opposed to radiation that might come from the accretion disk, the swirling disk of material falling into the black-hole) the strong gravitational force is precisely why the black-hole emits radiation!
The technical term is *Gravitational Vacuum Polarization*. In a strong Gravitational Field, even a small change in distance can result in a significant change in Energy. This makes it possible, in particular, for *virtual* {particle, anti-particle} pairs to form in such a way that they actually gain enough energy from the Gravitational Field to become 'real' before they would disappear again. Particles that form in this manner in the vicinity of the black-hole have a chance to escape; when they do, they become part of the black-hole's Hawking Radiation.

198 -

Is it true that around 20,000 stars per second leave the observable Universe? Is this just a conjecture? Can we watch it live with a telescope or will I have to wait thousands of years for changes to become detectable?

No, it really doesn't work exactly that way.
Say, we are in possession of the Insanely Powerful Telescope™ and that we are also blessed (or cursed) with eternal life. Our telescope can view any object in the observable Universe with clarity. Because we are immortal and bored, we decide that we will spend the next half eternity watching a star leaving the observable Universe. We pick a star and we start watching it. What will we see?
Well, as that star *near* the edge of the *observable* Universe is receding from us with increasing speed (due to

accelerating expansion, a consequence of the dominance of Dark Energy on cosmic scales) it will be increasingly redshifted. Never mind, our Insanely Powerful Telescope™ can deal with extreme redshift and it can make sure that everything remains visible to us. But that red-shift is actually a consequence of time dilation. Everything that happens to that star will appear increasingly in slow motion to us.
We use our calculator (the calculation is fairly simple, certainly it does not require an Insanely Powerful Computer™) to predict the moment in time in that star's life when it will cross our cosmological event-horizon. Now you are watching that star through our Insanely Powerful Telescope™ as it reaches that moment in its life. Except that it never does. The red-shift and the associated time dilation will continue to increase beyond limit. As a result, the final moments in that star's life just before it would disappear stretch all the way to eternity.
Through a normal telescope, we would not see the star anymore. Its light would have faded into invisibility as a result of extreme red-shift. However, our Insanely Powerful Telescope™ can still pick up that light, no matter how faint, and we confirm that the star is still in our observable Universe. A trillion years later it will still be there. A quadrillion years later? Still there, 'frozen' on the edge of our observable Universe, never actually crossing our cosmological event-horizon. This is how event horizons work in SpaceTime.
Therefore, the number of stars that we can actually view leaving our observable Universe per second, per year, per millennium or per half-eternity, *is precisely* 0 .
Now, arguably, the light we see from that star was emitted a long time ago, and at present, the star is far beyond the boundaries of our observable Universe, but that is not something we observe, that is, something we conjecture.

199 -

What happens inside a black-hole? Is it true Time becomes Space inside a black-hole?

At the event horizon, it is true that the radial and temporal coordinates switch roles. But we should not read too much into this. Coordinates are mathematical artifacts, not to be confused with Physical Reality.
If we were to fall into a black-hole that is large enough not to tear you apart first through its strong tidal force (also known as 'spaghettification'; the larger the black-hole, the smaller its tidal forces in the region of its horizon) and we have no external reference, we would not notice a thing. If we lived inside a windowless space capsule, everything would continue to appear perfectly normal both before and after crossing the horizon.
The bad news is that after crossing the horizon, we'll find ourselves trapped inside a collapsing 'mini-Universe', with the inevitable singularity (a *moment in Time*, when the environment becomes infinitely hot and infinitely dense and Time itself ends along with everything else) in our immediate future. And even before that happens, 'spaghettification' will likely catch up with us as different parts of our spaceship, ultimately different parts of your body try to follow wildly different trajectories in the rapidly changing strong Gravitational Field.
But all this has nothing to do with the swapping of coordinates; it simply is a consequence of extreme Gravity.

200 -

Why is Schrödinger's cat 'alive *and* dead' instead of 'alive *or* dead'?

Schrödinger's cat is *not* alive *nor* alive *or* dead. This is a decades-old mischaracterization of a whimsical thought experiment.
Before our issue, let's bring up another thought experiment: an apparatus (e.g., a two-slit experiment) in which a particle, say an electron, can take two different paths to get to its destination (e.g., a screen). The interference pattern that we observe on the screen tells us that individual electrons did not follow definite paths; rather, they took both paths simultaneously, which an electron can do so long as it is not 'caught in the act', i.e., not observed. And just looking at the point of impact of an individual electron does not allow us to reconstruct a specific path either ... the electron was really in two (or more) places at once. The electron has no well-defined position until it interacts with its environment (that is to say, a macroscopic apparatus) that measures its position.
In the famous cat thought experiment, something like to the electron, a quantum system that can exist in a superposition of two states, is used to trigger a mechanism to kill a cat. The cat, the fable goes, exists in both states at once until the box is opened, at which point it collapses into a well-defined (alive or dead) state.
Nonsense. When we open the box and find a live cat, we have zero doubt in our minds that the cat was alive all along. Similarly, when we open the box and the cat is dead, we can solicit the help of a qualified veterinarian and ascertain the exact time the cat died (or better yet, just put a camera set to record into the box along with the cat).
Unlike the two-slit particle experiment, in which case no definite path can be reconstructed even after the particle impacts the screen and is measured, for the cat, its history can be reconstructed unambiguously. The wavefunction of the particle triggering the mechanism decohered when it interacted with a large, complex system with many degrees of freedom (namely, the cat); it did not have to wait for the box to be opened.
Quantum Mechanics can be counterintuitive and, sometimes, difficult to reconcile with our everyday (classical)

experience, but not this difficult. The 'cat is alive and dead' issue is just nonsense that stands in the way of understanding; it does not improve understanding. Of course, Schrödinger was no fool either; he offered this thought experiment as a means to ridicule certain ideas, now somewhat outdated in the light of Quantum Field Theory, about the interpretation of Quantum Mechanics.

201 -

Is Quantum Mechanics essential to understand before learning Quantum Field Theory?

Yes, very much so.

First of all, would we want to tackle Continuum Mechanics without understanding Point-particle Mechanics first? So even in the classical theory, a good understanding of Point-particle Mechanics is essential before we can move on to fields.

Second, the underlying logic is very similar, and more easily understood in the case of a Point particle Theory: the progression from a Lagrangian to a Hamiltonian, the motivation and the methods of Canonical Quantization, the operator formalism. So learning the Point-particle Theory is not a waste of time, quite the contrary: it provides some essential tools of understanding.

Third, it is important to understand the main motivations behind Quantum Field Theory, specifically, the failure of a Point-particle Theory to

a. describe particle interactions, and

b. be *fully relativistic* and *causal*.

In short, if we don't know how the *quantum harmonic oscillator* works, we don't really stand much of a chance understanding how a Quantum Field (which can be viewed as a *continuum of oscillators*) works.

202 -

In General Relativity, why does the explanation say 'SpaceTime' needs to bend when light goes by the Sun, and not just that light itself bends in space?

The flip side of the question is whether or not it is possible to describe forces other than Gravitation using Geometry.
The answer is that it is eminently possible; such a geometric description is, in fact, fundamental to Gauge Theory. However, … the Geometry associated with the Electromagnetic Field, for instance, *is not unique*. If we introduce a Geometry that, say, describes how electrons travel in an Electromagnetic Field, the same Geometry *will not* work for protons, or even for positrons. Meanwhile, for neutral particles, the Geometry remains Euclidean: they do not sense the Electromagnetic Field at all.
In contrast, Gravitation is universal (this statement, which is called the 'Weak Equivalence Principle', is one of the basic principles of Relativity Theory). This means that not only is there one Geometry that describes the motion of all objects in the presence of a Gravitational Field, regardless of their material composition, it is also the only available Geometry. In other words, because our instruments themselves are made of material objects subject to the same Geometry, if we use them to measure things, we will, in fact, measure, for instance, that the sum of the angles of a triangle is ever so slightly greater than 180° in the Gravitational Field of the Sun.
Which really leaves us with two choices: either accept this Geometry is the true Geometry of Nature or cling to our misguided intuition and insist that there is, in fact, another background Geometry that is Euclidean, and it is more 'real' even though we cannot measure it or ascertain its existence. But worse yet, … it can be shown that such a background Euclidean metric fails completely in the case of extreme Gravity, at the event horizon of a black-hole, in much the very same way, say, as a cylindrically projected 'flat Earth' map fails at the poles: the geometry becomes degenerate. This is the point where we need to remind ourselves that Nature is under no obligation to satisfy our intuition efforts.

203 -

What are the hidden errors in the Special Theory of Relativity that Einstein could not solve?

There aren't 'errors' (hidden or otherwise) in Special Relativity. Quantum Gravity is an *unsolved problem*: there is a problem with General Relativity (which is all about Gravity) – which is the problem of making it work with Quantum Theory (which doesn't even mention Gravity). This is something that Einstein was still trying to solve, literally on his deathbed … and we still cannot solve. The kind of problems we get into are things like:

- Quantum Theory requires that particles like the electron, the proton and the neutron have non-zero Mass and zero size. Without that, bad things happen to the Math.
- General Relativity says that anything that has Mass and zero size is a black-hole with a non-zero sized event horizon from which nothing can escape and, without that, bad things happen to the Math.

So, if every particle is a black-hole, from which nothing can escape, how can a particle decay and thereby emit something?
Another error Einstein thought he had made (then fixed, then had to un-fix) was the problem of the *Cosmological Constant* Λ (or lack thereof): his equations predicted that the Universe would either expand or contract. He thought this was wrong, so, he added an ugly, arbitrary constant in there to prevent that from happening; then we found out that the Universe actually DOES expand, so, he sheepishly admitted his mistake and removed the constant again … which handily allows the 'Big Bang' to work just nicely.

204 -

Are *gluon*, W^+, W^-, Z^0 and *graviton* particles similar to *photons*?

No, those other bosons *are not* quite like photons, but there are similarities.
As a matter of fact, in the Standard Model or Particle Physics, both the photon and the Z^0- boson begin their existence as massless vector bosons: they are, for all practical intents and purposes, identical in behavior. But then comes the Higgs-mediated symmetry breaking, as a result of which the Z^0- boson acquires Mass and the photon does not. Consequently, the interaction mediated by the (very heavy) Z^0- boson becomes extremely short range (hence, we perceive it as 'weak') whereas Electromagnetism remains a long-range force (dropping with the inverse square of distance but never fully diminishing).

The $W^\pm$- particles are different: They are *charge carriers*. When a particle interacts by emitting or absorbing either a photon or a Z^0- boson, the particle remains unchanged. When a particle interacts by emitting or absorbing a $W^\pm$- boson, it does change. An electron may change into an electron neutrino or vice versa. An up quark may change into a down quark. The $W^\pm$- particles are also very massive, which severely limits the range of the interactions they mediate.

Gluons are again quite different. First, like the $W^\pm$- particles, they are *charge carriers*, but the charge they carry is not the simple plus-or-minus charge of Electromagnetism: rather, they carry the 'color' charge of the SU(3) *strong interaction*. And while gluons are *massless*, the interaction they mediate is *short-range*. In their case, the reason is different: as we try to separate quarks held together by the strong interaction, the energy that is invested grows without limit, and at one point, it is sufficient to create new quark-antiquark pairs. It's kind of like snapping a tension spring: the original spring had two ends, of course, but when it snaps, we don't end up with two objects with one end each; both half-springs will have two ends again.

And *gravitons* are again different. They are *massless* like photons (so, the interaction that they mediate, Gravitation, is long-range) but they are not vector but *tensor* particles. Also (as far as we know), the gravitational 'charge' is always positive (there is no negative Mass). These facts have various consequences, such as the *absence of dipole gravitational radiation*, making gravitating systems very inefficient emitters. A good thing, too, because we would not want, e.g., planets in our solar system *lose their orbital kinetic energy by radiating gravitational waves* and fall into the Sun as a result. We should also hasten to add that gravitons are *hypothetical*; unlike the other bosons, gravitons have not been detected, nor do we have a fully formed, viable Quantum Theory of Gravitation. However, it is generally believed that it should be possible to quantize Gravity and, when we do so, in the weak field perturbative limit it will have well-defined quanta, which we call *gravitons*.
So, similar? Yes. But those similarities hide some rather fundamental differences.

205 -

According to General Relativity, Gravity is not a force. So, how come we still include it as a force like for the Grand Unified Theory?

In a paperback edition of a little book of less than 200 pages, with the pretentious title 'The Meaning of Relativity', the author, Einstein, says, for instance, the following (never mind the Math, though it is part of the text, what we're discussing here does not depend on specific mathematical details): "… the motion of a material particle, under the action only of inertia and Gravitation, is described by the equation

$$\frac{d^2\boldsymbol{x}_\mu}{ds^2} + \boldsymbol{\Gamma}^\mu_{\alpha\beta}\frac{dx_\alpha}{ds}\frac{dx_\beta}{ds} = \mathbf{0}\ldots \tag{90}$$

In fact, this equation reduces to that of a straight line if all the components, $\boldsymbol{\Gamma}^\mu_{\alpha\beta}$, of the Gravitational Field vanish". Does this sound like Gravity is not a force?
A little later, Einstein himself says: "The Gravitational Field transfers Energy and Momentum to the Matter" in that it exerts forces upon it and gives it Energy … . It seems reasonable to conclude that Einstein *unambiguously* considers Gravity a force. Mistake or sloppiness?

206 -

In what way could the *picosecond* $(= 10^{-12}\ \mathrm{s})$ right after the Big Bang have been an *eternity*? What do/don't we know of this part of SpaceTime?

Our knowledge has limits. We look at the present-day Universe. What do we see? Galaxies full of stars. Very, very far from here, we see galaxies in the early stages of formation, full of very young stars. Beyond that, we see the Cosmic Microwave Background. Beyond that, we see *nothing*: the very early Universe was *opaque*, i.e., not transparent to Electromagnetic Radiation, and we have not (at least not yet) been able to detect other 'messengers' from this epoch, such as neutrinos or gravitational waves.
We look at our experiments. The largest particle experiment to date, the Large Hadron Collider, produces conditions that correspond to temperatures of trillions of *kelvin degrees*. Therefore, we know how Matter behaves under such extremes, but not beyond.
We take our knowledge of Theoretical Physics. What do we know? We know the basic building blocks of Matter and their interactions: the Standard Model of Particle Physics. We understand the Relativistic Theory of Gravitation. The two theories are not fully reconciled. We can do Particle Physics in the presence of Gravitation, but when it comes to describing how particles act as the source of Gravitation, our theory is far less than adequate.
So, taken what we know for a fact (observational and experimental data) together with our working theories, we can try to extrapolate. At face value, General Relativity would tell us that the Universe had an initial moment (the *initial singularity*) that marks the beginning of Time itself. It has expanded ever since, reaching the present. It will continue to *expand*, it appears, at an accelerating rate, *forever*.
But can we trust General Relativity? Arguably we can, so long as the conditions correspond to conditions that we can observe. Going back to the past, the Universe of General Relativity was 1 picosecond past the beginning of Time, when its conditions became comparable to what we see in the Large Hadron Collider. Which means that we can make statements with reasonable confidence about the Universe when it was this young.
But going further back into the past, within that first picosecond, we can *no longer trust* the theory. It doesn't mean that the theory is bad. It simply means that we have not been able to verify it experimentally. Moreover, in this 'strong Gravity' regime, interactions between Matter and the Gravitational Field at the particle level become important, and this is where our inability to describe how particles can be a source of Gravitation hits us: we simply have no reliable knowledge of how things worked in this very early Universe.
General Relativity tells us that this earliest epoch was a mere picosecond. But, is that true? We have no way of knowing. Perhaps it stretched to an eternity. Perhaps there was no 'initial moment'. Perhaps there was a collapsing phase of the Universe followed by a 'bounce' that resulted in the observed expansion. Perhaps our expanding Universe is just a 'pocket' in a much larger, eternally inflating super-Universe (eternal inflation). Perhaps, … the possibilities are nearly endless. We have no firm knowledge.
Our knowledge is similarly limited when it comes to the far future. We can reasonably extrapolate what we know for up to (at least) several hundred times the present age of the Universe. We have good ideas of how galaxies will merge. How stars will age. How new star formation will come to a halt. How cosmic expansion continues.
But, beyond that, do protons decay? Will black-holes evaporate through Hawking-radiation, as the theory suggests? Can Matter 'tunnel' through a black-hole state and become radiation (waste heat)? Is the vacuum itself stable or will the Universe, as we know it, be destroyed when the 'false' Vacuum decays? We just don't know. Actually, we may never know firm answers to some of these questions.

207 -

If Planck's constant could be simply derived, would that effectively torpedo the paradigm that is Modern Physics?

Let's just 'derive' Planck's constant:

$$\hbar = 1\,.$$

The values that we are familiar with, $h \approx 6.626 \cdot 10^{-34}\,\mathrm{J \cdot s}$ or $\hbar \approx 1.055 \cdot 10^{-34}\,\mathrm{J \cdot s} \approxeq 6.582 \cdot 10^{-22}\,\mathrm{MeV \cdot s}$, are dependent on our culturally derived choices for the units of *Length*, *Time* and *Mass*. This is why physicists often use *natural units*, that are free of such cultural artifacts. Using a commonly used set of natural units, the three fundamental dimensioned constants, the gravitational constant, the speed of light and the *reduced* Planck's constant, are *all* 1: $G = c = \hbar = 1$.

Are there any constants of nature that would not go away when we use a clever choice of units? Indeed, there are. These are constants that are plain numbers, the values of which do not depend on our choice of units. One such constant is the *fine structure constant* that characterizes the strength of Electromagnetism: $\alpha = 1/137.036\ldots$. It is one of 18 such dimensionless constants in the Standard Model of Particle Physics, or one of up to 26 *dimensionless* constants in an extended version of the Standard Model that allows for neutrino Masses, neutrino Mass mixing and axions. And we indeed do not know how to derive the values of these constants; it would be a major breakthrough if we found a way.

Regarding the question about Modern Physics, if by Modern Physics we mean Quantum Physics, no, the value of Planck's constant, in *whatever* system of units of measurement we opt to use, does not define Quantum Physics. The simple fact that it is not 0 does. The key paradigm of Modern Physics is that it is characterized by non-commuting quantities: for instance, the quantities q representing *generalized position* and p representing *generalized momenta* obey the following non-commuting relationship: $qp - pq = i\hbar$. Clearly, if $\hbar = 0$, we would have $qp - pq = 0$, behaving like *ordinary* numbers. But *they don't*. Hence, we are compelled to use 'Modern' (i.e., Quantum) Physics to describe Nature, instead of Classical Physics.

208 -

What is the temperature that the Voyagers 1 or 2 is recording while passing through interstellar space?

To be pedantic about it, it is not very meaningful to speak of the 'temperature' in case of the Voyagers. That's why.

First, imagine stepping outside for a moment. Let us say that it is a pleasant 20 °C (68 °F). There is no wind, and the humidity is normal. But the Sun is right above our heads, shining brightly. Soon, we feel warm and take off our jackets.

A few hours later, it is night. The temperature is still 20 °C and it is a perfectly cloudless night. Still no wind, still normal humidity. We step outside and soon, we feel a bit chilly. Soon, we decide to put on a sweater because we feel cold.

How can this be? In both cases, the air temperature is 20 °C. How can we feel hot during the day and cold at night?

It's obvious: the Sun is shining during the day. At night, especially on a cloudless night, not only is there no Sun, but your body freely radiates heat towards the cold, dark sky.

In short, our body exchanges heat with its environment in multiple ways, so, there is both heat conduction and heat convection. But there is also radiative heat exchange. During the day, you absorb a lot of extra heat from the Sun, so you are not in thermal equilibrium with the surrounding air. Conversely, during the night, you radiate a lot of heat into the sky (basically, into deep space) so once again, you are not in equilibrium with the surrounding air.

Now let's go back to the case of a distant space probe like Voyager. It travels in an environment that is a near perfect vacuum. There are some particles, to be sure: stray atoms (mostly hydrogen), charged particles from the solar wind, charged particles from the interstellar medium. But they are extremely few in number. Any heat exchanged with these particles through conduction or convection is going to be absolutely negligible. So, it doesn't really matter if the solar wind has a temperature of 1 K or a 10^6 K (or if it even has a meaningful temperature; such a high-velocity flow of particles is not necessarily in a state that can be reasonably described by a temperature value); it will not noticeably affect the temperature of the probe.

The probe will also receive light (heat) from the distant Sun, some of which it absorbs. And it will radiate heat into deep space. The math is actually rather simple. If the probe is as far from the Sun as the Earth, it would receive about 1370 W of solar heating per square meter (this number is called the *solar constant*, in some of the literature.) But Voyager 1 is about 140 times as far away as the Earth, and the intensity of solar heating is proportional to the *inverse square* of distance. So, Voyager 1 receives only about $7 \cdot 10^{-2}\,\mathrm{W}$ of heat per square meter from the Sun. Now, let's imagine, just to keep things simple, that the spacecraft is spherical, and its cross-sectional area is 1 m^2. The total surface area of that spherical spacecraft would be 4 square meters. If it is in thermal equilibrium with its surroundings, it would be radiating that $7 \cdot 10^{-2}\,\mathrm{W}$ of heat into deep space. The so-called *Stefan-Boltzmann law* tells us how its temperature T and the radiated power P are related: $P = \sigma A T^4$, where A is the surface area and σ is the *Stefan-Boltzmann constant*. Solving for T, we get $T \approx 24\,\mathrm{K}$.

So, if Voyager 1 was a so-called *thermodynamic black-body*, it would measure a temperature of about 24 K at 140 AU from the Sun. But that does not mean that this is the temperature of the interplanetary/interstellar medium at this

location: heat conduction and heat convection are quite *irrelevant* in an environment that's a million times better vacuum than anything we can do in a terrestrial laboratory. This is just the equilibrium temperature of the spacecraft itself.
To be precise, it would be the equilibrium temperature of a *dead* spacecraft. But Voyager 1 is not quite dead yet. It has a power source on board: a RTG (Radioisotope Thermoelectric Generator) that produces kilowatts of *waste* heat, and even now, about a couple of hundred watts of electricity. Most of that electricity is used to power the spacecraft's subsystems and is eventually converted into heat. So, there is a lot of excess heat on board, never mind the teeny amounts of solar heating that the spacecraft receives; its internals are still at a decent temperature, well within operating specifications, and this will remain so until the spacecraft shuts down, its power supply exhausted. Even then, there will be residual heating from the nuclear fuel in the power supply. When that's gone, centuries from now, the spacecraft will slowly come to an equilibrium temperature that is determined by the amount of sunlight it receives as well as its own thermal properties: how well it absorbs sunlight and how readily it emits thermal (infrared) radiation. These characteristics are, in fact, part of the spacecraft's specifications and were used in engineering calculations when the spacecraft, and particularly its thermal management, were designed.

209 -

Why does General Relativity require tensors whilst Newtonian only requires vectors?

First, a clarification. In the same sense in which General Relativity is a *tensor theory*, Newtonian Gravity is a *scalar theory*. That is, the Gravitational Field is represented by a number (for a point source, it's the Newtonian Potential function $\phi_G = -GM/R$), not by a vector. The vector we're talking about is the *Gravitational Acceleration*: this would be the gradient of ϕ, to be precise, $\boldsymbol{a} = -\nabla\phi_G = -GM\boldsymbol{R}/R^3$ for a point-like source. The Gravitational Acceleration is also a *vector* in General Relativity; but the Gravitational Field, that is the source of that acceleration, is not a scalar but, rather, a *tensor* field.
However, Newtonian theory is not really a scalar field theory either. To see this, first of all notice the biggest flaw in Newton's theory (which, incidentally, Newton himself was totally aware of, and it bothered him enough to delay the publication of his theory for many years): Newton's theory is an *action-at-a-distance* theory, i.e., *the effects of Gravity are instantaneous across empty space*.
Sure, there is this ϕ, that we call a Gravitational Field. It looks like a scalar field but it really isn't a dynamical field in the Physics sense. Why? Because it has no Energy or Momentum. Indeed, that's one of the reasons why the effects of Gravity must be *instantaneous*: if they weren't, then the Energy and Momentum transferred from one object to another would, at least temporarily, *must be carried by the field itself*, which the Newtonian 'Gravitational Field' cannot do.
So, what happens when we try to turn Gravity into a proper field theory? This is actually beautifully explained in the book, 'Feynman's Lectures on Gravitation'. So, say, we try to turn ϕ into a proper field, which carries its own Energy and Momentum. How would this field couple to other forms of Matter? Not very well, it turns out. Take the simplest atom for instance, a hydrogen atom, which is just a proton. A proton is made up of constituent particles (quarks) and the binding Energy that holds them together. It turns out that a scalar theory violates the *weak Equivalence Principle*: the Masses of the quarks and the Mass-Energy of their binding Energy respond to scalar Gravity differently. This is not what we observe (the weak equivalence principle is the observation that Gravity doesn't care about what things are made of, only their Mass-Energy counts), so a scalar theory just does not work.
A *vector* theory of Gravity doesn't work either. An example for a theory in which the fundamental field is a vector field is Electromagnetism. But in a vector theory, like charges repel and opposite charges attract, whereas in Gravity, all masses are *positive*, yet they *attract each other*.
So that leaves a *tensor theory* as the *simplest* choice that might work …, and it indeed does. So following Feynman's logic, the simplest theory that

a. satisfies the *Weak Equivalence Principle* and

b. has like Masses attract each other, is a *tensor theory*.

Historically, this is not how Gravity Theory evolved, however. Einstein wasn't following modern Particle Physics; he was trying to generalize the (then not yet called Special) Theory of Relativity to treat *accelerating* frames of reference on an equal footing with *inertial* frames. This process led to the use of Riemannian Geometry and its fundamental object, the *metric tensor*, which turns out to be the *tensor of the Gravitational Field*. But again, we can see the same principles at work here: What led Einstein in this direction was the desire to incorporate Gravity into Relativity Theory, which in turn was motivated by the *weak equivalence principle*.

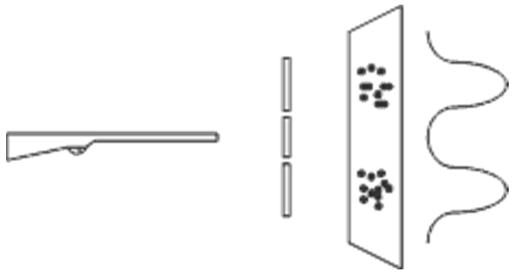
To make the story short, a tensor theory is the *simplest* field theory in which *like* Masses *attract* and in which the *Weak Equivalence Principle is satisfied*.

210 -

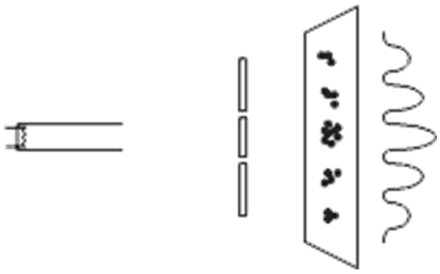
How can physicists be sure that a photon is in a *superposition* while they only find it in one place when it is measured?

The simplest experiment (either an *actual* experiment or a *thought* experiment) that demonstrates that elementary particles *do not* have a well-defined position is the famous *double-slit experiment*.

Imagine the following: you are firing a gun at a wall randomly. But between you and the wall, there is a steel plate in the path of your bullets, with two holes. You will see *two* spots on the wall, corresponding to the two holes that the bullets could fly through. The spots will be a little spread out and there may be occasional bullet holes elsewhere due to some bullets ricocheting, but most of the bullets will land close to each other, forming the two spots, somewhat like in this picture:



Now, let's repeat the same experiment except that instead of a gun firing bullets, use a cathode emitter firing electrons. (photons would work, too). Instead of getting images of two holes, the 'wall' (which should be replaced, e.g., by a fluorescent screen, recording the impact of electrons) now shows the multiple peaks of an interference pattern:



One might say this proves only that particles going through one hole may have interfered with particles going through the other hole. This is especially plausible if the particles in question are electrons, as they do interact, repelling each other due to their like charges.
However, … we can modify this experiment by reducing the cathode current so that our cathode emits, say, one electron per second. Or one electron per hour, slow enough so that there is not a chance for two electrons to interfere with each other.
Yet, even in this case, an interference pattern forms eventually. Which is only possible if a single particle interferes with itself as it goes through both holes, In other words, as the particle passes through the plate, it is in a *superposition of two position eigenstates*, one corresponding to each of the two holes.

211 -

What were the initial conditions of the Big Bang that led to distant objects leaving at *more* than the speed of light and currently accelerating?

Really a wrong question. Anyone who says that 'the Universe started with a Big Bang and the initial conditions were […]' is either ignorant or lying. Needless to say, we will find no textbooks saying such things either. Here is what the textbooks do say:

first, they describe the Cosmos as we see it (sometimes they call this Cosmography, a beautiful word that for some reason fell into disuse). They will tell us about things we discovered, such that there is a relationship between distance and redshift (the Hubble Law). Or that very high redshift, very distant galaxies appear immature and deficient in heavier elements; or how on the largest of scales, galaxies are distributed; or the specific properties of the observed cosmic microwave background. In short: tons of observational data, which is the foundation of Physics;

second, they describe the theory, beginning with the General Theory of Relativity and how it can be applied to the

Cosmos as a whole entity; the Physics of a homogeneous medium and its small perturbations; the Physics of an incandescent, cooling plasma; high energy Particle Physics. All this theory, by the way, is also based on observation, including, for instance, experiments performed in particle accelerators.

Theory and observation together tell us that we live in an *expanding* Cosmos, in which things are flying apart. Which means that things were closer together in the past. Not only that, but we know that things appear to be flying apart faster today than about $4 \sim 5 \cdot 10^9$ years ago, but up until then, things were slowing down. We also learned that $13.8 \cdot 10^9$ years ago the Cosmos was very *hot*, very *dense*, very *opaque*, full of high-Energy particles.

It is true that General Relativity tells us that such a Cosmos had to have a specific moment of beginning (the i*nitial singularity*), but we also know that we cannot trust General Relativity in this regime, as we have no observational data that would validate the theory under such extreme circumstances (and we have reasons to believe that the theory is inadequate to describe such conditions).

In short, we don't even know for sure that there was, in fact, a specific beginning, much less anything about the associated initial conditions! Which is precisely why we don't 'start with a Big Bang' and work forward; rather, we start with the present (which we can observe) and work backwards, extending our understanding as we collect more data and refine the theory. That is how Physical Cosmology works.

Incidentally, in the SpaceTime of General Relativity, it is eminently possible for two distant objects, neither of which exceeds the speed of light locally, to be moving apart from one another at many times the speed of light. As for the acceleration, what it takes is for there to be a substance, or equivalent, with a so-called *negative equation of state* (implying *negative pressure*). Such stuff will behave a little like bubbles in the sea that rise in the presence of Gravity: it will behave as though Gravity were *repulsive*. So, when this stuff dominates over Matter, this *repulsive* response to Gravity *dominates* over attraction, and instead of slowing it down, Gravity *accelerates* the expansion.

212 -

Are 'Conservation of Energy' and 'Conservation of Mass' laws valid when the system is the whole Universe? If not, does it mean that Energy and Mass are destructible after all?

It depends on how the law is stated.

Mass and Energy are equivalent: they literally mean the *same* thing. For instance, what we consider the Mass of a brick, about 99% of that is the *binding energy* holding *quarks* together, roughly 1% is the binding energy between those quarks and the *Higgs field's Vacuum expectation value*, and a tiny fraction of a percent is due to other contributions. Yet, we call it the *Mass* of the brick.

So, is Mass-Energy conserved? The answer is a very cautious yes, but first, we need to ask: who is doing the measuring? A moving train has lots of kinetic energy. However, to a passenger on board, the train is stationary. So, no kinetic energy. What about someone on a motorcycle, catching up with the train? As that person accelerates, the velocity difference between the bike and the train decreases, so the train's kinetic energy becomes less and less. Does this mean energy is not conserved? Well, not exactly: what it means is that the conserved quantity is something more complex, called Energy-Momentum.

Energy-Momentum is conserved *locally*. Let's take a small volume, and measure the Energy-Momentum within it, and the Energy-Momentum crossing its surface. If the enclosed Energy Momentum changes, this change will be reflected by the amount of Energy-Momentum that crosses the surface of that small volume. So, the only way for Energy-Momentum to increase or decrease is if it is added from the outside or if it is removed to the outside: Energy-Momentum is not created or destroyed.

So, herein comes the problem: the 'whole Universe' is a tricky concept. The Universe may be infinite. Even if it is finite, there may not be observers who can simultaneously observe the entire Universe and measure its Energy-Momentum. Therefore, there is no mathematically consistent way to define the Energy-Momentum content of the whole Universe.

But as far as we know, in small, *finite* volumes in this Universe, *Energy-Momentum is always strictly conserved*.

213 -

In an atom, if neutrons have no charge, how do they stay in the nucleus and 'stick' the protons together?

Electric charge has nothing to do with keeping an atomic nucleus together. On the contrary, electric charge is doing its darnedest to push a nucleus apart.

Fortunately, there is the *nuclear force*, sometimes called the *residual* strong force. It is called the *residual strong force* because it is not a fundamental force like the strong force that keeps quarks together inside a neutron or a proton or a meson. The residual strong force entails the exchange of force carriers like *pions* that are themselves composite particles (like the proton or the neutron). But never mind that, the important bit is that while the residual Strong Force has very short-range, it is also fairly strong, stronger than Electromagnetism, in fact. Which means that if we push some protons and neutrons together and they are close enough to each other, the residual strong force may be strong enough to make them stick together.

Or not. The residual Strong Force is not that much stronger than Electromagnetism. So, if a nucleus has too many protons, for instance, electromagnetic repulsion wins the day and the nucleus flies apart (this is why some isotopes are unstable, and other combinations don't even exist).

214 -

How certain are we that the Heisenberg Uncertainty Principle is true?

The Uncertainty Principle is true because another thing is true: on the level of individual particles, their properties *do not behave like numbers*. This is very weird, very difficult to digest, but this is the fundamental truth behind Quantum Physics. Specifically, these quantities *are not commutative*, so we have $qp - pq \neq 0$ (in this case, q and p can represent anything but, in common notation, q is the (generalized) position and p the (generalized) Momentum).

These *non-number* quantities have another special property: sometimes, they behave like numbers. When one of the quantities of a system happens to behave like a number, the system is said to be in an *eigenstate* (half-German, half-English word) with respect to that quantity.

However, here is the thing: imagine a system that is *simultaneously* in an eigenstate vs. both q and p. If that were to happen, we would have $qp - pq = 0$, according to the rules of ordinary arithmetic. This violates our fundamental discovery about the quantum world, namely that $qp - pq \neq 0$.

This contradiction is resolved when we realize that when the system is in an eigenstate with respect to p, it cannot be in an eigenstate with respect to q at the same time. In short, if p is a number, q is not, and vice versa.

What this means is that measuring p (that is, interacting with the quantum system using a measurement apparatus in a specific manner) puts q in a state in which it has no well-determined number value. Or alternatively, we can try to measure p and q simultaneously, but cannot do so accurately; the error, or *uncertainty* in the measurement must be large enough such that $qp - pq$ deviates from 0 by the requisite amount.

As to why Nature behaves in this manner, why fundamental quantities do not behave like numbers … that's not a question Physics can answer.

215 -

In Quantum Theory, is the observer a universal observer or unique to each individual observing each instance?

The choice of the word, 'observer', in descriptions of the Quantum Theory is most unfortunate. It leads to misguided philosophical discussions about *Quantum Reality* and *consciousness* and opens the door to … *quantum mysticism*.

Reality is far simpler. There is Quantum Physics and then there are systems (say, a human, a cat, a hammer, a video camera) that are large, which consist of a very large number of *uncorrelated* particles. The quantum behavior of these systems is completely averaged out: they are almost in an eigenstate (*classical* state) almost all the time, and emphasis on 'almost': we could wait until the Universe is a *zillion* times older than it is at present, you could measure things with exquisite precision, and still would not observe any deviation from Classical Physics.

This behavior remains true even when these classical objects are used as instruments to probe Quantum Reality. When the quantum system interacts with such a *classical* (or *almost* classical) instrument, it is confined to an eigenstate with respect to the property that is measured by this interaction.

This is all. This is what 'observation' is. It is not about individuals. There is no consciousness involved. It is simply an interaction between the quantum system and a classical (or almost classical) system.

216 -

What does it mean in Quantum Field Theory when one says a particle, like a photon, is a *local excitation* of a field?

Let's take the electron. In Quantum Field Theory, all the electrons that there are in the Universe are described by a single field: this is the *electron field*. However, because this is a Quantum Theory, this field cannot just have any values. Its excitations come in the form of unit packages (the so-called *creation* and *annihilation* operators). Each application of the *creation* operator *increases the number of excitations by one*; each application of the *annihilation* operator *decreases it by one*, unless it is already zero (the ground state): *each excitation amounts to exactly one*

electron.
Now, these excitations have positions and (linear) momenta. And the important thing is that they are essentially *Fourier-transforms of each other*. So, if an excitation has a well-defined Momentum (i.e., a Dirac delta-function in *Momentum space*), its 'position' would be a uniform wave that is present everywhere, hence, no well-defined position. In contrast, if an excitation has a well-defined position, its Momentum will be spread out and will not have a definite value. This is where the Quantum Field Theory takes on the Uncertainty Principle.
When we measure the position of an electron, it basically amounts to interacting with the electron field in such a manner that the excitation in question is confined to a well-defined position, at the cost of having less well-defined Momentum. In this case, the excitation can be said to be *spatially localized*, and we perceive it as a particle.

217 -

If neutrinos can pass straight through the Earth and not be captured by its Gravity could they go through a black-hole and out the other side?

Neutrinos participate in two interactions: Gravitation and the Weak Force.
The Weak Force is really *not* weak at all (it is comparable in strength to the Electromagnetic Force) but it is very *short-range*. For this reason, it *appears* weak: it is very rare that two weakly interacting particles get close enough to one another to, well, interact.
However, neutrinos are subject to Gravity just the same as all other particles.
Also, when it comes to black-holes, they behave exactly like every other particle. They will follow trajectories determined by the Gravitational Field of the black-hole. If this trajectory intersects the black-hole's event horizon, they are gone. There is no way out of the black-hole unless we have a time-machine, and not even neutrinos have time-machines. To 'reach the other side' once we are inside the event horizon, we have to travel back to the past, because once inside, the event horizon is not something that surrounds us; rather, it is a *moment in Time*, in our past.

218 -

Is the World effectively *indeterministic* because of Quantum Physics?

Saying that the World is indeterministic, presumably, misses the point altogether. We should admit that the laws of Quantum Physics, especially Quantum Field Theory, are quite *deterministic*.
The indeterminism enters the picture when we mix quantum and classical systems. Or to be more precise, when we describe something (e.g., a measuring apparatus, a cat, an observer) as classical in an otherwise quantum environment.
In other words: take two quantum systems with the exact same set of initial conditions and we get the same outcome (but the outcome won't be an eigenstate). Take two systems that mix quantum and classical components, and even with the exact same set of initial conditions, we get different outcomes (different eigenstates).
Of course, we know full well that these 'classical' components are, in reality, quantum systems themselves, albeit ones with a very large number of degrees of freedom; and their states are not true eigenstates, just indistinguishable from such, due to the law of averages over those many degrees of freedom. Thus, the indeterminism enters the picture because our description of these presumed classical components is itself incomplete.
Of course, if there are truly classical phenomena (e.g., some argue that Gravity may be classical, i.e., there is no Quantum Theory of Gravity), then, the interaction between the classical and the quantum would make the World genuinely indeterministic. But the present-day mainstream view, despite the lack of a satisfying Quantum Theory of Gravity, is that the World is thoroughly *quantum* in nature, Gravity included. As said, the laws of Quantum Physics are quite deterministic, and the indeterminism of 'wavefunction collapse' is an artifact of mixing the Quantum Theory with an imperfect, classical description of some components.

219 -

How does the Higgs Boson complete the Standard Model of Mass in Physics?

The Higgs Field plays several roles in the Standard Model of Particle Physics (there is no 'Standard Model of Mass'). The Higgs Field, in its pure form, can be represented by 4 numbers (two complex numbers). That is to say, it has 4 so-called *degrees of freedom*.
The Higgs Field also has a so-called *self-interaction energy* that behaves very weirdly. When the Field is free of excitations (particles are absent) its self-interaction energy *is not the lowest*. To achieve the lowest self-interaction, the field must have excitations *present*. So, given a Vacuum with a Higgs Field free of excitations, very rapidly this vacuum evolves into a new, lower-energy version in which the Higgs Field has a *non-zero so-called vacuum expectation value* (V. e. v.). This will be the new, stable Vacuum. Why is this important? Because the Higgs Field

interacts with most other fields in the Standard Model in very specific ways.
Let's start with the mediating particles of the Electro-Weak interaction (combination of Electromagnetic interaction and the Weak interaction). In its pure form, the Electro-Weak interaction has 4 types of massless mediating particles: two are electrically charged, the other two are neutral, basically just like photons. But when the Higgs Field does its thing with its non-zero v. e. v. with respect to this new vacuum, 3 of the 4 mediating particles *become massive*.
Now this would normally be bad news: a massless particle always travels at the speed of light; as a wave, it can 'wiggle' in directions perpendicular to its direction of motion, but not longitudinally (along the direction of its motion). But once a particle becomes massive, it is moving *slower* than the vacuum speed of light and it *can* have *longitudinal* wiggles, too. This extra degree of freedom would normally destroy the theory. But here comes the Higgs to the rescue: for each of the 3 electroweak mediating particles that become massive, the Higgs 'lends' 1 degree of freedom, 'eating' the unwanted longitudinal degree of freedom and keeping the Theory mathematically self-consistent. As a consequence, the Higgs Field is now left with only a single remaining degree of freedom. This degree of freedom is the one that we can observe as a particle: the *Higgs Boson*.
The Higgs Field also interacts with charged fermions (electrons, quarks). This story is much simpler. As the Universe settles in a Vacuum in which the Higgs Field has a non-zero V. e. v., these fermions now interact with the Vacuum itself through this V. e. v.. This, for all practical intents and purposes, makes them behave as though they were *massive*. Presto, electrons and quarks just became massive!
So, to sum up, the Higgs Field lends the weak interaction's mediating particles their mass; it 'eats up' the unwanted degrees of freedom of the model, keeping it self-consistent; and it allows charged fermions to behave as though they were massive, by way of interacting with the Higgs Field's non-zero V. e. v. .
All that being said, it is important to offer a reminder that not all Mass is due to the Higgs Field or Higgs Mechanism. Neutrinos, as far as we know, get their Masses in a way which not related to the Higgs Boson at all. Furthermore, roughly 99% (!) of the Mass of everyday objects is not related to the Higgs Boson in this manner: it is due to the mass-energy of the Strong Interaction holding quarks together inside protons and neutrons.

220 -

Do particles move 1 Planck Length-unit within 1 Planck time-unit? If so, doesn't that mean it moved at light speed for a moment?

The Planck Length is the 'natural' unit of Length, defined as $l_P := (G\hbar/c^3)^{1/2}$. The Planck Time, similarly, is the 'natural' unit of time, defined by $t_P := (G\hbar/c^5)^{1/2}$ (look back at Issue 91, P. 40). Now, let's divide l_P by t_P and we get $l_P/t_P = c$, the speed of light, by definition. Of course, c the 'natural' unit of speed. And that's all it is: *massless* particles move at this speed. *Massive* particles, instead, are slower. End of story.
There is certainly no stop-and-go motion of particles. In fact, in Quantum Field Theory, what we call *particles* are just *quantized excitations* of the underlying quantum field. These propagate at a *finite* speed (equal to or less than the speed of light) but they are certainly propagating continuously. The word 'quantum' does not mean stop-and-go motion; it simply means that at any given frequency, the excitations of the field are added or removed one set unit at a time.
Now we can try and read all sorts of things into the Planck scale, that below the Planck Length, or over the Planck Time, Quantum Field Theory breaks down. Perhaps, ... but then, we still don't know why Quantum Field Theory doesn't break down either below, or above, the Planck Mass, $m_P := E_P/c^2 \equiv (c\hbar/G)^{1/2} \approx 2.177 \cdot 10^{-8}$ kg .
One thing we do know with reasonable certainty though is that, at the Planck Energy,

$$E_P := (c^5\hbar/G)^{1/2} \approx 1.956 \cdot 10^9 \text{ J} \equiv 1.221 \cdot 10^{28} \text{ eV} ,$$

Gravity can no longer be ignored in Particle Physics, so, on this energy scale, Quantum Gravity becomes dominant. This energy scale exceeds the energies of the LHC by more than 14 orders of magnitude!

221 -

If light is Electromagnetic Radiation, then, how comes that we never hear about positively or negatively *charged* light-photons?

Because Electromagnetic Radiation, the electromagnetic field in fact, has no electric charge. Electric charges play a different role. They act as *sources* of the Electromagnetic Field.
A static source, such as a stationary electron, will produce an electrostatic field. A source that undergoes accelerating motion produces a change in the electromagnetic field that then propagates away from the source.
Far from any sources, these changes still propagate, as plane wave solutions of the 'vacuum' Electromagnetic Field. No electric charges are present, just the (charge-less) Electromagnetic Field itself. These propagating changes are what

we see as Electromagnetic Radiation.
Now imagine what it would be like if the Electromagnetic Field did carry a charge. Then an accelerating electron would not only produce a change in the Electromagnetic Field, but it could also gain or lose its charge. Now that would be bad news! This could mean, for instance, that atoms could change into different atoms (protons losing charge and becoming neutrons or vice-versa) simply as a result of accelerating motion. The periodic table itself would not be stable; we would not have Chemistry as we know it.
So, it is a good thing that even though the Electromagnetic Field is sourced by charges, *the Field itself carries no charge*.
But just to confuse the heck out of us (Nature has the habit of doing this to us) this is not quite the full story just yet. In the Standard Model of Particle Physics, photons (which are the quanta of the Electromagnetic Field) are just one of four different types of particles that together make up the Electroweak Interaction. There is another *neutral* particle, the Z^0- boson; but then there are also two 'charged photons', the W^+- and W^-- particles. And when these particles *mediate* an interaction, they do indeed add or remove charge, converting electrons into neutrinos (or vice versa) or protons into neutrons (or vice versa). In fact, the weak interaction plays a role in one form of radioactivity (β- decay).
Thankfully, unlike the photon, these additional bosons are *very massive*. *Mass means Energy*, and that much excess Energy means that these particles decay, *break down very rapidly*. So, they cannot carry an interaction over great distances. This is why the Weak Interaction appears, well, weak, *because of its very short range*. And this is why things like β- decay happen relatively rarely instead of messing up our basic Chemistry.

222 -

Does the very act of observing cause a wave function to collapse (double-slit experiment), or is it due to an interaction between a particle and what constitutes a measurement?

Forget all century-old, misleading terminology that does create unnecessary confusion; forget 'observing', forget 'measurement'. When a Quantum System interacts with a Classical System, that interaction may confine the Quantum System to an eigenstate. This is what happens when an electron hits a fluorescent screen: that interaction confines the electron to a specific location (i.e., it's in a *location eigenstate*). Along the way, including passing through the barrier with the slits, the electron is not confined to an eigenstate. That is all.
No 'measurement', no 'observer', no 'collapse'. Just a well-defined, clear, complete description of the electron and the *classical* apparatus, something that can be represented in the form of a so-called Lagrangian, from which the system's equations of motion can be derived and solved. These will show that, while *en route*, the electron has no classically defined position, but it will evolve to a classically defined position when it interacts with the fluorescent screen.

223 -

Are QED and QCD major shifts in Quantum Mechanics – or just refinements?

QED and QCD are both applications of Quantum Field Theory.
Quantum Field Theory was a major step forward in the development of the 'new' Quantum Theory, which began in the 1920s with *Schrödinger's wave equation* and *Heisenberg's Matrix Mechanics*. These were followed by *Dirac's relativistic wave equation*, which did account for the *relativistic electron* but still had two major shortcomings: it could *violate causality*, and it did not account for particle *creation* and *annihilation*.
Quantum Field Theory addresses these shortcomings: it is *relativistic*, and *free of violations of causality*, as any faster-than-light signaling is identically canceled out in the theory. More importantly, as the theory treats 'particles' as *excitations of fields*, interactions between fields *do account* for the *creation* and *annihilation* of particles.
QED is the first major application of Quantum Field Theory, a *relativistic theory* of electrons and photons. QED is also an example of a *gauge theory*, a theory in which an internal symmetry plays a pivotal role. The next step was the development of *non-Abelian gauge theories* (that is, theories with an *internal symmetry* that is associated with a *non-commutative group*) leading to the development of the Electroweak Theory and QCD.
The basic principles, however, remain the same that are behind Schrödinger's wave mechanics: a formulation that starts with *promoting canonical variables to operators or operator-valued fields*.

224 -

Did Einstein himself ever find an analytic solution to his own *Field Equations*?

No, the early solutions to Einstein's Field Equations were all found by people other than Einstein.
The earliest, of course, is the *Schwarzschild solution*: a considerable surprise to Einstein, who thought that his field

equations are too complex to ever have analytic solutions, it also paved the way by showing that simple, idealized scenarios – with a high degree of symmetry – might lead to solvable cases.
Another early analytic solution is the *Reissner-Nordström solution* for the electrically charged spherically symmetric source of Gravity. Then there were *Weyl's axi-symmetric* solutions, *plane wave solutions*, the *Lemaître–Tolman-Bondi* metric of an expanding or collapsing dust sphere, and of course the *Friedmann-Lemaître-Robertson-Walker metric* of Cosmology. That's pretty much it prior to World War 2 … and none of these were found by Einstein.
More exact analytic solutions began to emerge after the war (e.g., Gödel, Taub-NUT, Kerr) but many of these developments occurred after Einstein passed away in 1955.

225 -

What is a *charge*, as the charge of the electron, the proton, etc?

(See the more extended Answer 699)

The *charge* of an elementary particle is the *strength* with which that particle (or rather, the *field*, of which that particle is an *excitation quantum*) *couples to the Electromagnetic Field*.
By way of an example, the theory of Quantum Electromagnetism consists of three parts: the *kinetic energy* of the Electromagnetic Field (free photons), the *kinetic energy* of the Electron Field (free electrons) and the *Potential Energy* of their coupling. Or, as Feynman once described it:

- a photon goes from place to place,
- an electron goes from place to place,
- An electron emits or absorbs a photon.

This last item, the emission or absorption of photons, i.e., the coupling between the two fields, is determined by the electron charge. If the electron charge was bigger, electrons would emit or absorb photons more vehemently. If it was zero, there would be no emission or absorption of photons at all; the fields would exist completely independently of each other.

226 -

If particle content is relative to an *accelerating* reference frame, does this demote the particle concept from fundamental status?

Indeed, in QFT (Quantum Field Theory), the particle concept has no fundamental status (kind of ironic, considering that QFT is our best theory for Particle Physics).
Here is the crude picture. The starting point is a *field*: a *continuous* set of values, with a value assigned to every point in Space at every moment in Time. The Electrostatic Potential is a good example (or the Gravitational Potential, doesn't matter). If this field is indeed a continuous set of values, it can be decomposed, by way of a Fourier-transform, into a (potentially infinite) sum of basic sine wave patterns (*harmonic oscillators*). Once this decomposition is done, we know how to apply the rules of Quantum Physics: harmonic oscillators can be *quantized*, and each harmonic oscillator will have a lowest energy (ground) state and excitations, stepwise (quantized) higher energy states. *It is these stepwise excitations that we recognize as particles*.
But here is the rub. When we do a Fourier-transform, it is necessarily with respect to some *chosen system of coordinates*. Which system? There is no a priori prescription that tells us that we must use this or that set of coordinates.
Now it turns out that so long as we confine ourselves to coordinate systems used by inertial (non-accelerating) observers, it doesn't matter. There will be no non-trivial differences between the Fourier-decompositions.
However, once we allow accelerating coordinate systems, the picture *changes*. The same field that has a Fourier-decomposition with all harmonic oscillators in the ground state in inertial frames may have a Fourier-decomposition with some harmonic oscillators in the excited state when the decomposition is done with respect to *accelerating* coordinates. This basically tells us that an accelerating observer may see particles where an inertial observer sees nothing (this effect even has a name: *Unruh Radiation*).
In the presence of Gravity, things get even worse. In an arbitrary Gravitational Field, there is *no global inertial reference frame*. So we do not have a 'preferred' frame for the Fourier-decomposition. The frame we pick is a choice we make, not something imposed upon us by Nature. So, the observed particle content *depends upon that choice*.
This is important to remember when we stare at wonderful Feynman diagrams depicting interacting particles. The diagrams are useful. The particle concept is helpful. But it also helps to keep in mind that they are just bookkeeping devices for terms in an integral, and if we were to express that integral using a *different* Fourier-decomposition, we would end up with *different* diagrams, a *different* set of particles, even as we describe the *same* Physics.

227 -

If virtual particles in QFT are merely mathematical constructs used to describe field interactions, why does the Standard Model contain *real* gauge bosons, which are referred to as *force carriers*? Which bosons mediate forces, real or virtual?

When an interaction occurs, it is mediated by *virtual* particles.
Let's take, for instance, two electrons colliding and scattering off one another. This event is mediated by the Electromagnetic Field, of course. When we break it down at the quantum level, the Electromagnetic Field is decomposed (by a Fourier-transform) into a potentially infinite sum of pure sine waves. Each of these sine waves has a coefficient that, in the quantum theory, basically has integral values: 0, 1, 2, 3, etc. When an electron interacts with the Electromagnetic Field, it can either increase or decrease the coefficient of one of these sine waves by one unit. This is the mathematics behind 'emitting or absorbing a photon'.
Photons mediating an interaction are virtual in the sense that they are never detected directly. One electron creates one, the other absorbs it. The photon is how the two electrons exchange Energy and Momentum. As it is not detected, the photon is not even required to be on the 'Mass shell': that is to say, it can behave very differently from a 'real' photon, in particular, it can behave as though it were massive (real photons are massless): the more a photon deviates from a 'real' photon, the less probable its existence. This, among other things, is one of the factors that constrains the strength of the interaction between two electrons.
The situation is very different when an electron interacts with the Electromagnetic Field, producing an excitation that is not immediately absorbed by another electron (or some other charged particle) nearby. Such photons serve as the quanta of *free radiation* (that is, radiation far from sources). They are 'real': they behave strictly as massless particles, traveling great distances. These are the photons that we can directly detect even when they come from very faraway sources.
When it comes to, e.g., the massive gauge bosons of Electroweak Theory, their behavior is very similar but with one crucial difference: a 'real' gauge boson is *very heavy*. This has several consequences. First, when two particles interact via the *exchange* of these $W^{\pm}$ or Z^{0} bosons, unless the virtual boson's energy is comparable to the Mass of the corresponding 'real' boson, its existence is *very unlikely*. So right there, it tells us that lots of energy is needed for the interaction to occur at all, simply to create a gauge boson with the required Mass or something close to it. This can only happen if the interacting particles are pushed really close together to begin with. Second, when these gauge bosons are 'free', their tremendous *excess energy* means they *decay very rapidly* into other, *less energetic* particles. So, they don't get to travel great distances like photons.
The specific families of particles are part of the Standard Model; the general idea that has been sketched above, however, is not specific to that model, but a *general characteristic* of QFT. In the theory, 'real' particles can be free, travel great distances, and are on the 'Mass shell' with well-defined rest Masses; 'virtual' particles mediate interactions, are short-lived, and may be 'off the Mass shell' with no well-defined rest Mass, but the farther they are from their real particles, the less likely they exist and the less role they play in mediating the interaction.

228 -

How do 'excitations' of *quantum fields* gain stability and permanence? The word 'excitation' seems to imply that particles will only exist momentarily.

No, *excitations* are not intended to imply something ephemeral. Rather, we should think of an *excited* state as something above the *ground* state (which is the state free of excitations).
Excitations may gain stability and permanence because of *conservation laws*. An excitation of the Electron Field, for instance (i.e., an electron), carries a unit of *electric charge*. That unit of electric charge is *conserved*, so the excitation cannot just vanish. It can turn into something else, to be sure, but electrons already represent the lowest energy excitation that there is that still carries a charge. So, electrons are *stable*.
In contrast, $W^{\pm}$- particles, which also carry charge, are not stable. Conservation laws still apply, but there exists a lower energy configuration of excitations that carries the same conserved quantities. In other words, a $W^{\pm}$- particle can easily turn into an electron and an anti-electron neutrino, with plenty of Kinetic Energy left over that can dissipate.

229 -

Does Quantum Physics disprove *Causality*?

Quantum Physics *does not* disprove *Causality*. On the contrary, our best working Quantum Theory to date, Quantum Field Theory, quite properly respects Causality both on the macroscopic and on the microscopic level. *Acausal* (faster-than-light, backwards-in-time) influences are explicitly and precisely canceled out in the theory. This, in fact, is one of the major motivations behind Quantum Field Theory.

Some confusion arises because of misunderstandings surrounding the obvious *non-locality* of the Quantum Theory, in particular the non-locality of *quantum entanglement*. Therefore, it is important to reiterate that although entanglement may be counterintuitive, 'spooky' even, it does not imply the transmission of information, the transmission of Energy or Momentum or other influences. It is simply a *non-local manifestation of conservation laws*, but no acausal signaling is involved.

230 -

Does String Theory offer any additional insight into explaining the strangeness of Quantum Physics?

String Theory *is not* intended to, *nor* does it, explain what we call the 'strangeness' of Quantum Physics. Quantum Physics is strange indeed, but the explanation lies elsewhere. The key-equations of Quantum Physics (e.g., the Schrödinger equation) can be 'derived', in a manner of speaking, from Classical Physics. But the equations also admit solutions that *have no classical meaning*. Quantum Physics begins when we make the statement that *these solutions, too, describe Reality*. The reason why this is strange is because *this Quantum Reality really has no classical meaning*. Any attempt to shoehorn it into a classical explanation necessarily destroys its quantum essence. So, the naïve expectation that it is somehow possible to visualize Quantum Physics – or otherwise interpret it – using classical concepts is what leads to a sense of strangeness, contradictory-ness.
Take the famous two-slit experiment. Did the electron's path go through one slit or the other? The correct answer, of course, is neither … that is, almost as though it was a line from 'The Matrix' [a well-known 1999 American science fiction action-movie], the correct statement is that there is no path.
No, String Theory is needed here. The explanation is contained within the Quantum Theory itself, it is just difficult to internalize it as we are clinging to our classical perception of the World around us.

231 -

The force of Gravity inside a spherical shell is 0, but presumably, Space is still curved. Is this correct and if so, how?

Newtonian Gravitation *is not* due to Space being curved (please, ignore pretty *artist's renderings* of curved Space as an 'explanation' of Gravity). Newtonian Gravitation, at least at its everyday level of strength, is due to *Time dilation*, at least up to about the 9^{th} digit or so, after the decimal point. It is the rate at which clocks tick that determines the changing Gravitational Field. Inside a massive spherical shell, clocks still tick more slowly than far away from that shell, in empty space. But inside a spherical shell, all (non-moving) clocks tick at the same rate. There is no difference depending on position.
The Gravitational force that we experience would depend on this difference. Since inside the spherical shell, no such differences exist, there is no net gravitational force.

232 -

Are fundamental particles basically *packets of Energy* in Quantum Field Theory?

Not packets of Energy, but close. In our best theory of Matter, Quantum Field Theory, all Matter appears in the form of *fundamental fields* and their *excitations*. Let's take Quantum Electrodynamics, for instance. It is a theory of *two* fields: the *Electromagnetic Field* and the *Field of Electrons*. Every time something happens, it amounts to either *creating* or *destroying* one excitation of the Electromagnetic field (a photon); or to *creating* or *destroying* a *pair* of excitations in the Electron Field (an *electron* and its anti-particle, a *positron*).
Now, we might wonder why there is this difference; why it is possible to create a *single* photon, but electrons and positrons have to come *in pairs*. It is because these excitations are not just packets of Energy. They are packets of Energy, Momentum, Angular Momentum (Spin) and possibly, other conserved quantities such as Electric Charge.
A photon has *Energy*, *Momentum* and *Spin*; it can be created so long as these quantities are conserved in the interaction that creates the photon. In an observer frame of reference, this means that whatever Energy, Momentum or Angular Momentum is transferred to the photon, the same amount of Energy, Momentum and Angular Momentum must be lost by the particle or particles that create it (this actually leads to some restrictions as to what interactions are possible and what are not, but let's not go there).
An electron, however, also carries Electric Charge. So, creating an excitation in the Electron Field, i.e., an electron, means that a unit of Charge must come from somewhere. This is resolved if simultaneously, a positron is also created, which has one *opposite* unit of charge. The two charges cancel each other out, the overall *change in charges* remains 0, so, the creation of the electron-positron pair can go ahead so long as other conservation laws are satisfied.
To sum up, fundamental particles are, in Quantum Field Theory, packets, or quanta (*quantized excitations* of the *underlying fields*) but they are a lot more than simply packets of Energy.

233 -

Is that we cannot disappear and reappear like *quantum particles* just because we are 'being observed'?

No. In fact, quantum particles do not disappear and reappear either. Rather, most of the time quantum particles simply do not have a well-defined position. Their position, described mathematically not by a set of numbers but by a so-called *operator*, is really a combination (*superposition*) of many, perhaps infinitely-many possible positions. This behavior can sometimes be carried over to something macroscopic, e.g., a quantity of superfluid, when that macroscopic object's quantum particles are *all in the same state*, i.e., *correlated*.
But we are not like that. Our bodies consist of a very large number of particles that are uncorrelated. As a result, any 'quantum-ness' in their behavior is just averaged away, and we are left with a macroscopic object that is almost all the time in an almost perfectly *classical* state. The actual probability that our bodies behave in any manner other than classical is so vanishingly small that it would never happen in a trillion lifetimes of a trillion upon a trillion Universes and then some.
Now, it is true that when a quantum particle interacts with something classical (that could be us, a cat, an instrument or, for that matter, a brick), some of its properties may be confined by that interaction to an 'eigenstate', i.e., become well-defined in the classical sense. This is what 'being observed' really means (no consciousness is implied). But our bodies behave the way they do not because they are being observed but because they consist of a *very large* number of uncorrelated *quantum* particles.

234 -

When measuring the spin of an *entangled particle* and finding that its counterpart instantly takes up the opposite spin, how do we know that they didn't possess their spin directions before they were actually measured?

This is the question behind the famous *Bell's inequality* (see: *Bell's Theorem*). The question is usually framed this way: is it possible that particles constituting an entangled pair carry all information needed to determine the outcome of a measurement along with them, in the form of 'local hidden variables', which are revealed by the measurement but have been present all along?
For example, suppose we travel abroad and upon arrival, we notice that we only packed half of each pair of socks that we own. Immediately we will know that our socks drawer at home contains the same number of unmatched pairs of socks. Nothing mysterious about this, and we don't need Quantum Mechanics to explain how we 'instantaneously' acquired information about your sock's drawer thousands of miles away.
The thing with things like *spin* or *polarization* is different, in a very *non-trivial* way. Suppose we release, in opposite directions, a pair of *entangled polarized photons*. Let's say they are polarized vertically. That means that if we put a vertically oriented polarization filter in either photon's path, *both* photons will pass through. And they will both fail to pass through when the filters are *both* oriented horizontally.
But what if the filters are oriented at $45°$? Each photon has a $50\ \%$ - $50\ \%$ chance of passing or not passing through.
However, when we perform this experiment, we will find that the photons will remain correlated; they will either both pass through or neither will, no matter how far from each other the two filters are. Perhaps, it is still possible that the photons carried more than just information about their initial polarization. So, let's suppose the two photons agreed in advance on how they will behave. But the experimenter, now, sets the two polarization filters, one at the end of each photon's path, at different angles, say, one at $45°$, the other at $135°$. Then, he calculates the probability of one of the photons passing through and the other failing, using one very simple assumption: that the photon on one end has no way of knowing the setting of the polarization filter on the other end, and vice-versa. This assumption alone is sufficient to calculate a maximum value for a correlation function between the two observations. And this value is violated in actual experiments, including experiments in which the polarization filters were set only after the photons were already well on their way. Which means that the outcome cannot be explained using merely information that the photons possessed all along. They, also, needed information that was somehow instantaneously communicated from the other end, in order to exhibit their correlated behavior. This is the essence of *Bell's Inequality*.
And this is how we know that photons (the same argument applies for electrons) could not exhibit the behavior that they actually exhibit, using only information that they possessed before the measurement took place.

235 -

Quantum Mechanics says that the Moon is in a *superposition* [state] when we are not observing. Would an unobserved brain in a superposition constitute a quantum computer?

Quantum Mechanics says no such thing. The Moon is a macroscopic object: to be more precise, it is characterized by a very, very large number of uncorrelated quantum degrees of freedom. As such, the probability of it being in a state other than an eigenstate is, well, technically non-zero, but it is, for all practical intents and purposes, zero.
Moreover, it will not be any more zero just because someone looks at it. As a matter of fact, a human has a lot fewer quantum degrees of freedom than the Moon, so a human is more likely to be in a superposition [state] than the Moon. But even in the case of the human, that probability is vanishingly small.
And of course neither the Moon nor the human exist in isolation. Rather, they both continuously interact with their environment through Electromagnetism and Gravity. So, both the Moon and the human interact with the Earth and the Sun, for starters, but also with other planets and smaller or more distant objects.
For a human brain to behave like a quantum system, two requirements would be that

a. some process 'prepares' the brain and places it in a state of superposition, and

b. the brain remains isolated from its environment to prevent decoherence. Neither of these requirements are satisfied. But even if they were satisfied, they would simply make the brain akin to a container of superfluid helium (i.e., a macroscopic system that is in a coherent state), not a quantum computer.

236 -

Are *electrons quanta* of the *Electron Field* in the same sense that *photons* are quanta of the *EM Field* ?

Yes, exactly, that's precisely what electrons are. In Quantum Field Theory, *fields* reign supreme. The fields can be written up as a sum of *elementary oscillators* after a Fourier Transform. Each of these oscillators is *quantized*. As a result, each of these elementary oscillators ends up with *discrete excitation levels*, *created* or *destroyed* one at a time when the field interacts with another field. These excitation levels are what we perceive as *particles*.
This is true for the Electromagnetic Field and its quanta, the *photons*; the Electron Field and its quanta, the *electrons*; and all the other fields in the Standard Model (muons, taus, neutrinos, quarks, gluons, electroweak vector bosons and the Higgs bosons).

237 -

Is there something analogous to *wavefunction collapse* in Quantum Field Theory?

Yes, of course. Quantum Field Theory is still the same old Quantum Theory, just applied differently.
One way of looking at it is that the field is decomposed (by way of a *Fourier Transform*) into elementary *harmonic oscillators*. We then assume an initial and a final state for these oscillators and ask a simple question: how can a system transition from a given initial state to a given final state? We then, in effect, assess the relative probabilities of the various ways in which that transition can occur.
In other words, all the machinery known from ordinary Quantum Mechanics, including the wavefunction and its presumed collapse, together with all the implied philosophical baggage (the measurement problem, the physical reality of wavefunction collapse, the various interpretations) is still present, it's just that these questions play little or no role when the theory is applied the usual way to predict the outcome of actual experiments, e.g., in a particle accelerator.

238 -

Should we believe in a *multiple Universe* (also known as *Multiverse*) and in *wormholes*?

First, Physics, or the Natural Sciences in general, *are not about belief*. They are about mathematical descriptions of Nature, used to produce firm, quantitative, testable predictions that can be validated through *observation*. That's the only thing that matters. A theory that reliably predicts what happens is a good theory, even if it is non-intuitive, even if it is difficult to comprehend. Such a theory's predictions ultimately turn into engineering, allowing us to build wonderful things from spaceships to smartphones, from miracle medications to architectural marvels. In contrast, a theory with failing predictions is a bad theory, no matter how intuitive it is, no matter how much its proponents believe in it.
The concept of the *Multiverse* goes against this principle. It is something that is *a priori* untestable: we have no means to leave our Universe, enter another Universe (which may not even have a concept of Time as we know it) and perform an experiment. To be sure, there are theories in which multiple Universes interact in some ways, thus the

existence of other Universe may have a recognizable imprint on ours, making the concept *testable*. But this is generally not what the Multiverse concept is about, and even these supposedly testable consequences are very far-fetched and speculative.

As to *wormholes*, so far, every attempt to create a mathematical model of a stable wormhole showed that the wormhole would not be useful: it would collapse. But even if we could have a *stable* wormhole that could be used, in principle, to transmit Matter or Information, how would we go about creating it? Not the mathematical model but the actual, *physical* wormhole? There is no known mechanism, not even on the most speculative fringes of Physics, that would allow us to create a usable wormhole or, for that matter, 'tame' one that we might find in Nature.

In short, these ideas can be considered mostly fodder for science fiction or, at best, limits of what theory can do on its speculative fringes, unburdened by the requirement of *testable* predictions. They have very, very little to do with what Physics strives to be about: a means to provide an understanding in the form of a thorough, ever more complete, ever more reliable, predictive *mathematical model* of the actual World in which we live.

239 -

What is the simplest conceptual derivation of Einstein's Gravitational Field Equations?

Einstein's derivation of the Field Equations of Gravitation was *heuristic*. After publishing what was then known as the Theory of Relativity (today known as the *Special* Theory), Einstein spent a few years on other things, but soon enough, he returned to the topic of Relativity. The thing that bothered him was that Special Relativity treated accelerating observers as second-class citizens. The Laws of Physics were the same for all inertial (nonaccelerating) observers, but not for accelerating observers. He sought to build the 'general theory' (now known as *General* Relativity) that generalizes the concepts of Relativity to *arbitrary* coordinate systems, including those of accelerating observers.

The next realization (which Einstein later referred to as the happiest thought in his life) was the Equivalence Principle. In this context, the Principle basically means that an observer in a windowless enclosure (say, the cab of an elevator) cannot tell the difference between sitting on the Earth's surface (in terrestrial Gravity) or being accelerated by a rocket in outer space; or conversely, cannot tell if he is free-falling in an elevator shaft or floating weightlessly in space. This implied that any generalization of Relativity Theory to accelerating reference frames must necessarily be a Theory of Gravitation as well.

Meanwhile, there have been attempts to create field theories of Gravity. Everyone (including Newton himself) knew that Newtonian Gravity had a serious problem: the effects of Gravitation on distant objects were *instantaneous*. This instantaneous *action-at-a-distance* had to be replaced by a theory in which the effects of Gravitation are mediated by something. By the late 19th century, it was clear that, like Electromagnetism, Gravitation has to be mediated by a field of some sort.

Einstein's realization of the Equivalence Principle, combined with what he learned about the Riemannian Geometry of SpaceTime from his friend Marcel Grossmann, led Einstein to the understanding that the Gravitational Field must be represented, somehow, by the so-called *metric of SpaceTime*. What is the source of Gravitation? Why it is Matter or, more specifically, the *energy density of Matter*. However, it turns out, energy density alone is not a useful quantity for this purpose because *Energy is not an observer-independent quantity*. Instead, he ended up with the *Stress-Energy-Momentum Tensor* of Matter, a more comprehensive quantity that incorporate *Energy*, *Momentum*, as well as *Pressure* and *Stresses* (see matrix representation back on P. 21). If the Stress-Energy-Momentum Tensor is on one side of the equation, what is on the other side? Here, Einstein was guided by an important tidbit of information: the Stress-Energy-Momentum Tensor is a *conserved* quantity, meaning that it obeys a specific *conservation law*. So, if this quantity is on one side of the equation, whatever comes on the other side has to obey a *similar* conservation law. The rest was kind of a given: find a quantity that can be constructed from the metric of SpaceTime, that has a similar form and obeys a similar conservation law. This was a struggle for Einstein but eventually he stumbled upon the correct expression.

Meanwhile, Einstein's colleague Hilbert was also working on the problem. Hilbert's goal was more modest yet more ambitious at the same time than Einstein's. Instead of leaving the nature of Matter unspecified, Hilbert focused on the Electromagnetic Field. This allowed him to represent matter by a so-called *Lagrangian*, so to him, the question was this: What is the correct Lagrangian for the Gravitational Field? Eventually, Hilbert was able to derive the correct equation from the *Lagrangian Action Principle*. To this date, it is the subject of much heated discussion as to which of these two scientists wrote down the right equation first. Notably though, although there was some tension between the two for a while, Hilbert never referred to the theory any other way other than calling it Einstein's.

One ironic footnote is that both men would have been greatly helped had they been aware of the work of Hilbert's student, Emmy Noether, who was working on what later became known *Noether's Theorem*: the *connection between the symmetries\/invariances of a Lagrangian vs. corresponding Conservation Laws*. Hilbert, specifically, would have known that any Lagrangian that does not change under a translation of SpaceTime coordinates *would automatically conserve Energy and Momentum*, so he could have been able to tell if a Lagrangian represents correct Physics or not, just by looking at it.

240 -

Are massive photons possible?

Indeed, massive photons are possible in theory, and in a sense, they do exist in Nature. The classical Maxwell Theory of Electromagnetism can be constructed using three ingredients: a metric SpaceTime, a 4-dim vector field, and a definition of a *massless current*. With these ingredients, the theory follows as a set of mathematical identities.
But it is indeed possible to replace the *massless current* with a *massive current*. The resulting classical theory is due to the Romanian physicist Alexandru Proca and is referred to as *Maxwell-Proca Theory*.
The main difference between the two theories is that the *interaction strength* varies with the *inverse distance squared* in the case of Maxwell's theory; in the case of Proca's theory, there is a range, determined by the Mass term, beyond which the strength of the integration vanishes *exponentially*. This is what people are talking about when they describe Maxwell's theory as having *infinite range* whereas a theory like Proca's as having *finite range*.
All this can be readily applied in the Quantum Theory as well, and not just as idle theorizing. The massive, electrically neutral Z^0- boson of the weak interaction is, for all practical intents and purposes, a heavy cousin of the photon.
The Z^0- boson is not just massive; it is *very* massive (about 90 times heavier than a H atom) and as such, very short-lived (all that energy packed into a small package wants to get out). This is another way of looking at the range of the interaction that the Z^0- boson mediates; it cannot get very far before decaying into other, lighter particles (its Mass mostly converted into those decay particles' kinetic energies), so if it is to mediate an interaction between two other particles, those other particles *must be very close to each other*. This is, in fact, why we perceive the weak interaction as, well, weak; it really isn't any weaker than Electromagnetism, but these interactions happen very rarely, because it is not common for particles to be close enough to interact by exchanging Z^0- bosons (or the only slightly lighter, electrically charged $W^{\pm}$- bosons).

241 -

How can a singularity exist? Time dilation increases with Mass and – although invariant in its own frame – would never have time to form before loss of Mass caused the black-hole to explode in a relative moment, trillions of years into our future?

An astrophysical black-hole, that is, a black-hole that forms as a result of stellar collapse, would indeed take forever to form as seen in the reference frame of any outside observer. To outside observers, infalling Matter disappears from sight due to exponential Time dilation near the (yet to form) event horizon but it never actually appears to cross the horizon; in fact, the formation of the horizon itself *remains forever in the future*.
In classical General Relativity, this question is resolved by looking at the black-hole from the point of view of an infalling observer. That observer would reach the event horizon in a finite amount of time. Once past the horizon, the horizon itself would be represented as a past moment in Time (not a place that one can return to) for that observer. The observer would find himself in a collapsing 'bubble Universe' with a Big Crunch, the final singularity, awaiting him in the (very near) future when tidal forces, Gravitation, energy density and pressure all become divergent and the 'bubble Universe' ceases to exist.
Hawking Radiation does indeed change this picture as arguably, the horizon never gets a chance to form: to any outside observer, that would take an infinite amount of Time, whereas the black-hole evaporates in a finite amount of Time. What this actually means remains the subject of a lot of current research and controversy.
Then, there is the possibility, taken quite seriously at least by some authors, that our Universe has 'primordial' black-holes: that is, black-holes that 'came with the Universe' as opposed to forming through some astrophysical process. Such primordial black-holes are assumed to be fully formed, complete with horizons hiding singularities.

242 -

Is *wave-function collapse* something that *really* happens or just something that *appears* to happen?

In the considered opinion of many, it is a piece of fiction, a badly misleading piece of fiction.
Wavefunction collapse happens because we begin the description of our system by pretending that the quantum systems evolve in the absence of the measuring instrument. Then, we perform an act of … divine intervention: we suddenly, unceremoniously, replace the Universe, retroactively, with one in which the measuring instrument is

present, feigning surprise when this means that the wavefunction undergoes a non-unitary change.
In reality, the measuring instrument is *always* present. Its presence constrains the wavefunction all along. This implies *non-locality* but we know that non-locality is part of Quantum Physics and, in any case, it does not lead to *classical violations of locality*. So, it doesn't make much sense to believe that wavefunction collapse is a physical process.

243 -

Why is *locality* considered so important in Quantum Mechanics when Gravity and the Electromagnetic Force already behave *non-locally* in Classical Physics? We handle that by using fields, so why can't the fields of QFT do the same thing?

Neither Gravity *nor* the Electromagnetic Force behave non-locally in Classical Physics. Quite the contrary, their local nature is fundamental. The history of this goes back several centuries. Back in the 17th century, one reason why Newton was reluctant to publish his Theory of Gravitation is best explained by the great physicist himself in a letter he wrote to the scholar and theologian (later, master of Trinity College) Richard Bentley:

"*That Gravity should be innate inherent and essential to Matter so that one body may act upon another at a distance through a vacuum without the mediation of anything else by and through which their action or force may be conveyed from one to another is to me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws, but whether this agent be material or immaterial is a question I have left to the consideration of my readers.*"

This issue was resolved satisfactorily by Einstein's Theory of Gravitation, in which, bodies do not act on one another through the vacuum, instantaneously with no mediating medium: rather, there exists an 'immaterial' (to use Newton's phrase) medium, the Gravitational Field, that *mediates the interaction*, carrying influences from one body to another at a *finite* speed.
The Electromagnetic Interaction is mediated by a similar, immaterial agent, Maxwell's Electromagnetic Field.
The important thing about these fields is that their behavior is fundamentally *local*. At any given point in Time, the behavior of the field at a given location in Space is determined completely by the *values of the field and its sources* in the immediate vicinity of that location at that time. If the field changes, this change is propagated through the field at a finite speed without any 'action-at-a-distance'.
Quantum Physics is different. While the theory remains local in the sense that no Energy, no Momentum, no information can travel faster than the vacuum speed of light between different locations, it is manifestly non-local in the sense that distant measurements are correlated, and *this correlation cannot be explained by localized influences*.
One analogy that is sometimes used that highlights the difference concerns a pair of socks. Suppose we travel to a distant land and upon arrival, we notice that you only packed half our favorite pair of socks in our suitcase. As soon as we realize this, we know that if our significant other were to open our socks drawer back at home, it would contain the missing half of the pair. The two measurements (our observation of half a pair of socks in our suitcase, our significant other's observation of the missing half in the drawer) are correlated, but there is no surprise there: the information was there all along, even though it was *hidden* until the suitcase, or the drawer, were opened.
Now, suppose that these socks are magical, that their color is indeterminate until someone observes them. So, it is only upon opening the suitcase that the half pair of socks acquires its color, say, yellow. Meanwhile, our significant other opens the drawer at home and guess what: that missing half is also yellow. It is not even clear which one of us looked at the sock first. And we know (through other experiments) that the sock's color truly is undetermined until it is observed. So, there is no way for the sock to have known in advance that we would be measuring its color (as opposed to, say, its size or its pattern) and what color we would observe. This information could not have been *hidden* as it did not even exist yet. Nonetheless, the two halves of the pair *remain correlated*, across any distance, across any gap of time, with no influence traveling between the two, indeed with no unambiguous way to even determine which measurement happened first (let's remember, in Relativity Theory, simultaneity is not always a well-defined concept).
That's how 'magical' quantum non-locality is.

244 -

How does hydroelectricity work by using Gravity if Gravity, according to the Theory of Relativity, is not a force?

Einstein wrote the following words in his little book 'The meaning of Relativity': "The Gravitational Field transfers Energy and Momentum to the 'Matter' in that it exerts forces upon it and gives it Energy …".
Now that it is established that the Gravitational Field exerts a force, we can move on to how that force is explained. In the General Theory of Relativity, it is explained, similar to the centrifugal force, as a *pseudo-force*: a force that is experienced by *non-inertial* observers. An observer on the surface of the Earth is a *non-inertial* observer, because of

the ground pushes him upward preventing him from falling freely, from orbiting the Earth's CM along a worldline that is described as a geodesic line in 4-dim SpaceTime.
It is the same ground that also pushes water upward in the reservoir of a hydroelectric dam, preventing that water from falling downward. Except where it doesn't: when said water can, as a matter of fact, fall downward while it moves through the blades of the generator's turbine.
Nitpicky nuances concerning pseudo-forces notwithstanding, the basic fact remains: the Gravitational Potential (whether it is the Newtonian Potential that appears in Poisson's equation for Gravitation or the full-blown Tensor Potential of Einstein's Gravity) is different at the top of the reservoir vs. the bottom of the dam. Therefore, any quantity of water that travels from the reservoir to the bottom of the dam will see a change into Kinetic Energy. That Kinetic Energy is then transferred to the turbine blades, spinning the turbine and driving the station's generators.

245 -

What is a very basic definition of Quantum Mechanics?

Quantum Mechanics represents the realization that, when it comes to atoms and elementary particles, Nature does not work as we would naïvely expect. This realization grew out of the observation of many curious properties of atoms, not the least of which is that, when an atom absorbs or emits energy, it always happens in well-defined units, or 'quanta', which are specific to each type of atom.
Ultimately, we understood that these phenomena happen because of the way physical systems with few 'degrees of freedom' work. Each 'degree of freedom' characterizes the way in which something can move, rotate, vibrate, etc. For instance, a free elementary particle has 3 degrees of freedom: it can move in the 3 spatial directions. However, since it has no internal parts or shape, it cannot vibrate or rotate, so, no additional degrees of freedom are present.
Contrary to our naïve expectations, systems with *few degrees of freedom* do not have well-defined positions and velocities in the classical sense. Rather, their state is usually defined as a multitude of possible positions and a multitude of possible velocities, mixed together in a superposition.
Something classical (such as a measuring instrument), in turn, would be made of a *huge* number of atoms, thus represented by a *very large* number of individual degrees of freedom. All that superposition weirdness gets averaged away for such classical things and we end up with our usual perception of the world, in which baseballs, cannonballs, people, cats, etc., all have well-defined trajectories and velocities. Elementary particles (with few degrees of freedom) only have such well-defined positions or velocities (but *never* both!) when they interact with a classical system, which temporarily confines the particle to an eigenstate: an ugly but useful compound noun combining the German word 'eigen' (meaning 'own' or 'inherent' or 'intrinsic') with an English word.

246 -

Do all individual photons have a quantized wavelength and why is the spectrum of light considered a *continuum*, then?

Let's investigate what photons actually are in Quantum Electrodynamics. Our starting point is the Electromagnetic Field of Maxwell's Theory.

As the *first* step, we write down this field as a sum of contributions at *every possible* frequency. Since the range of possible frequencies is *continuous*, the sum becomes an *integral*. Converting the Electromagnetic Field into this sum of 'harmonic oscillators', elementary sine waves if we like, is basically done using a *Fourier transform*.

Next, we take each one of these elementary harmonic oscillators and do what we do with harmonic oscillators in Quantum Mechanics: we *quantize* them. We find that the energy levels of each of these harmonic oscillators is increased or decreased one step at a time (the mathematical operators that have this effect are called the *creation* and *annihilation* operators) and that the *ground state energy* of the harmonic oscillator is 1/2 unit of Energy.

Now that we have a way to count the 'number of excitations' of each of these oscillators, it is time to give these excitations a name: we call them *photons*.
This is what photons are: they do not have a quantized wavelength. Each photon has a specific wavelength, chosen from a *continuum of possible wavelengths*. But at any given, specific wavelength, the field is quantized into a *countable* number of photons.

247 -

If the *double-slit* experiment proves that all possibilities exist in any moment and that it's our consciousness that creates reality, can we consciously make all the photons only pass through one slit?

No, but *yes* (though not in the way we mean). *No*, the double-slit experiment does not 'prove that all possibilities

exist'. It simply demonstrates that a particle such as an electron *does not have a well-defined position when it is not being measured*.
No, consciousness has nothing to do with it. The act of measurement is an interaction between the particle and a classical system (a human, a cat, a measuring instrument).

But *yes*, we can certainly make all particles pass through one slit if we cover the other one! In other words, we use our brain and our tools to change the experiment to our liking. Who needs magic when we have knowledge and hands to work with? We already have our brain and our tools to alter Nature to our liking, why are we waiting for quantum mysticism to do the job for us?

248 -

What is the biggest object discovered that obeys Quantum Theory?

A common misconception is that Quantum Physics is about size, i.e., small things are *quantum* things while large things are *classical* things. This is not really the case. What makes a thing 'quantum' is not so much its geometric size but its *number of degrees of freedom*.
When a thing has a *small* number of degrees of freedom it will behave as a *quantum* thing. Small things like elementary particles have a small number of degrees of freedom but sometimes, even large things (e.g., a macroscopic quantity of superfluid He, or a laser beam of coherent photons) fall into this category.
When a thing has a *large* number of degrees of freedom, it will behave classically, as its quantum-ness will be *averaged out over its many degrees of freedom*.
As to physical size, if we want something tangible that we can grab (or at least, hold in a container), we'd think a laboratory container of superfluid helium might do the trick. We don't know what the largest quantity of superfluid was He ever created, but it is certainly macroscopic.
On a much larger scale, the interior of a neutron star is believed to be in a *superfluid state*, but nobody observed the interior of a neutron star, so it's just conjecture at present, which probably doesn't count.
If we allow something more ephemeral, how about a current in a superconducting wire, a bunch of electrons forming a *condensate of Cooper pairs* along the length of a wire that may be many kilometers long?
And then there are those cases of entangled particle states created for tests of *Bell's inequality* or for experiments in *quantum communication*, which remain entangled even across geographic distance scales of 100 km or more.
Or how about a *laser beam* with coherent photons sticking together thanks to the *Bose Statistic*. Laser beams have been bounced off the Moon and have been used to communicate with spacecraft orbiting the Moon.
Lastly, as others pointed out, Classical Physics is just a *limiting* case of Quantum Physics when a large number of degrees of freedom are involved, i.e., a permissible approximation. So, it is true that everything, namely the entire Universe follows, as far as we know, Quantum Theory (we must include the phase, 'as far as we know', as we don't presently have a viable Quantum Theory of Gravity).

249 -

How is it possible for atoms to be at two different places at the same time, according to Quantum Mechanics?

It is not. The moment we imagine that atom as a miniature cannonball that is in two places at once, we lost the game: we are failing to understand Quantum Mechanics.
Quantum Mechanics does not say that the atom is in two places at once. What Quantum Mechanics says is that the atom has *no classically defined position* at all between measurements. Its position, rather than being represented by a set of numbers (as in Classical Mechanics, where the position would be a set of coordinates), is represented instead by the so-called *position operator*. Unlike the numbers, the position operator does not tell us where the atom is. The atom is neither here nor there, nor anywhere else. The position operator tells us *how likely* it is that we find the atom at a particular place, if we look. *It does not tell us where the atom is.*
But when we actually look and find the atom somewhere, the atom is in exactly one place: the place where you found it. It is never in two places at once. However, most of the time (that is, always when we are not looking) it is in no place at all, *in a classical sense*, as it has no well-defined position.
Just to be clear, when we somewhat whimsically say, "when we are not looking", we don't really mean that a human or a cat has to look at the atom for it to have a position. No, the atom simply has to interact with a macroscopic object or instrument, one that consists of a *very large* number of particles such that any quantum behavior is averaged out and it behaves *classically*.

250 -

Is it possible to influence the path a photon has been travelling for billions of years in the past by observing it in the present?

It's more than simply an influence: we destroy those photons. In other words, when a photon is detected by our retinas, it is absorbed. Its kinetic energy is transferred to an electron, and ultimately, becomes a form of chemical energy, which is then going to be part of a signal in your brain. Eventually, the excess energy is dissipated by your head as heat (lots of infrared photons that have nothing to do with the original visible light photon). Similar processes can be used to describe a photon that is detected by an electronic camera or conventional film.
But this is the fate of every photon. A photon connects two events: its *emission* and its *absorption*. That's what a photon does: it is the *unit excitation* of the Electromagnetic Field, the field mediates the Electromagnetic Interaction between *charged* particles. Whether those charged particles are, say, protons inside an atom, their mutual repulsion mediated by (virtual) photons, or they are separated by billions of light-years, say, an electron inside the exploding cloud of a supernova vs. another electron, billions of light years from there, inside the CCD sensor of an optical telescope, is irrelevant.
But as to the path of those photons, they don't have any. A quantum particle's path in the classical sense exists only when it is *observed*; that is to say, when the particle interacts with something *classical*, such as a measuring instrument. The *classical* position of the photon is determined by *observation*. The likelihood that a particular photon is observed then and there is determined by its *position operator*. The presence of a telescope represents a boundary condition on the evolution of that position operator in both all of Space and all of Time, but this is not something that is directly observable. So, there is *no observable influence traveling from the present to the past*, even if knowing the existence and location of the instrument is essential for a full quantum mechanical description of the system (in the absence of that knowledge, we end up with incomplete, changing descriptions, say, a world in which the photon travels freely vs. a world in which an instrument magically appears and captures the photon, these two connected by that piece of non-unitary fiction called *wavefunction collapse*).

251 -

Was the Higgs Field the cause of the Big Bang, did all Matter just instantly appear with the Field?

We should not misunderstand Big Bang Cosmology. Physics is not about what caused the Big Bang nor does it say that "it all started with a Big Bang". The phrase was actually born as a disparaging term, used by the astronomer Sir Fred Hoyle (who was an opponent of the Big Bang paradigm at the time) in a 1949 BBC radio show.
What Physical Cosmology is about is making observations in the present and then, using our knowledge of Physics, extrapolating backwards to the past to figure out what the universe must have been like billions of years ago. And invariably, we find that our present-day observations, including light from very distant things that traveled billions of years to get here, tell us that the early Universe was hot and dense.
If we take General Relativity's predictions literally, there is an initial moment in Time when the Universe began. This initial singularity *has no cause*, there is *no prior Time*. The law of causality does not apply to this initial event but only to subsequent events (this is not empty philosophizing, by the way, these are the strict mathematical properties of the SpaceTime of General Relativity).
But extending the laws of General Relativity to this initial moment is folly. In the very early Universe, quantum effects dominate even Gravity. We have no viable theory of Quantum Gravity at present. So, we really do not know what the extreme early Universe was doing. We most certainly do not know if there were any prior causes and, if so, what these causes were.
Not the Higgs Field. What we do know about the Higgs Field plays a role much, much later. The Universe was already at the respectable age of about a a trillionth of a second counting from the presumed initial singularity when, as a result of the nature of the Higgs Field and the way it interacts with certain other particles, electroweak symmetry breaking took place, the *vacuum* reached its current, lowest energy state and certain particles, including charged fermions such as the electron, became massive.

252 -

Are quarks or electrons made of even smaller particles?

It is possible to go one level deeper mathematically, while preserving all the desirable symmetry properties of the quark picture. In the so-called *Preon Model*, all the known fermions: leptons like the electron and its neutrino, and quarks, are composite particles made up from different permutations of two *preons*, one *neutral*, the other carrying $1/3$ *unit of electronic charge*, $e/3$.

However, it must be emphasized that this is a purely speculative model with no experimental support whatsoever.
Also, it should be emphasized that although we refer to them as particles, these are really just unit excitations, 'quanta' of quantum fields. So, the fundamental object is not, e.g., the electron particle but the one and only Electron Field, which can have many excitations. Indeed, when we do the theory on a background SpaceTime curved by Gravity, we find that two observers don't even necessarily agree on what particles they see; where one observer sees particles, another observer may see nothing whatsoever. That's why our best theory to date, the theory behind the Standard Model, is called *Quantum Field Theory* ...

253 -

In Quantum Physics, are there particles that can be in multiple places at the same time?

Here is what the equations of Quantum Physics, verified by numerous experiments in the past 100-odd years, tell us.
In Classical Physics, a particle always has a well-defined position. In Quantum Physics, a particle's state is defined by what is called a *superposition of positions*. That is to say, it is a *weighted* mixture of all possible positions.
When we measure the position of a particle, we get one result. However, the equations don't tell us which result it will be. They only give us *probabilities*. The coefficients, or *weights*, in that superposition tell us how probable various positions are.
A measurement will always find a particle at a specific location. We will never catch the particle in two places at once. However, between measurements, a particle can be in two (or more) places at once. The famous experiment here is the so-called *2-slit experiment*, which allows an electron to go through a barrier that has two holes. Detecting electrons on the other side tells us the story: each electron goes through both slits, and then these two 'potentialities' (for lack of a better word) proceed to interfere with each other, determining ultimately where the electron will be detected.
So, *yes*, in Quantum Physics particles are in multiple places at once, but don't let us think of them as miniature cannonballs sprouting clones. Rather, between measurements, a particle has no well-defined position, only this superposition business that ultimately determines the probability of finding the particle at various locations. When we measure the particle, we only ever measure the one particle and, at the moment of measurement, it will have a well-defined location.

254 -

Can *gravitational waves* escape a black-hole?

No, nothing can escape from inside the event horizon of a *black-hole*, not even *gravitational waves*. Which, apart from the fact that they are gravitational, really aren't that different from light waves insofar as their propagation is concerned. Far from sources, these waves travel at the speed of light and follow the same trajectories as unimpeded light rays.
Gravitational waves can be produced, e.g., by two bodies in close orbit around each other. So it is conceivable, for instance, for a very large supermassive black-hole to 'eat' an inspiraling pair of neutron stars, for instance, without tidally destroying those neutron stars or pulling them apart first. The pair would then continue to produce gravitational waves even after crossing the event horizon. But these gravitational waves would stay *within* the event horizon.
This, really, is the fundamental SpaceTime geometry of the 'interior' of a black-hole: the event horizon represents the past, and all future directions point 'inward'. No material object, no ray of light, no gravitational wave can return to the event horizon as it would mean *going backward in Time*.
Having said that, black-holes are quite capable of producing gravitational waves: for instance, pairs of inspiraling black-holes happen to be the most frequently detected sources of gravitational waves to date. But these waves are not coming from 'inside' either of the black-holes; rather, they are produced by the two-body system itself, as the black-holes lose Kinetic Energy and approach each other, eventually merging.

255 -

Where do *virtual particles* go when they phase out of our Universe?

Virtual particles do not come; they, also, do not go. They are called *virtual* because they *are not real*. They literally do not exist. What virtual particles actually are: they are convenient tools for computation and visualization. That is to say, mental crutches.
Here is the thing. The theory in which virtual particles pop up is Quantum Field Theory. It describes *interacting fields*. It describes, specifically, how a set of fields can evolve from an initial state to a final state. And the math gets nasty, with multiple integrals. But there is one way to treat those integrals sensibly: they are expressed as successive sums of ever smaller terms. So, a good result is obtained after summing only a small number of terms, as the rest of them

become *very small very rapidly*, and thus do not change the result by much.
When we look at the terms of these summations, they resemble something. They resemble expressions that describe individual particles (which are themselves excitations of those quantum fields). Well, not exactly: they describe particles with the *wrong Mass*, in fact, with every conceivable value of Mass between 0 and ∞ (the technical jargon term is 'off-shell', short for '*off the Mass shell*'). But formally, they look like particles.
So, let's say that we calculate how the Electron Field and the Photon Field interact when a photon scatters off an electron. The initial state includes one excitation of the electron field and one excitation of the Electromagnetic Field. The final state, ditto, but with different values for kinetic energy and momenta.
And now, we do the integral. *First* term: the electron and the photon *exchange* some Energy and Momentum. Check. *Second* term: the photon dissociates into an electron-positron pair that recombine into a photon, which then exchanges Energy and Momentum with the electron. Or the electron emits a photon which it reabsorbs, either before or after it exchanges Energy and Momentum with the other photon. And so on.
These terms can be nicely represented by way of *Feynman diagrams*, further reinforcing the intuition that we are, in fact, seeing 'particles' that have a fleeting existence as they facilitate the various ways in which this interaction can take place. But we are not seeing particles. *We are seeing interacting fields*. We are seeing a nasty piece of mathematics that is 'tamed' with that series expansion, which contains terms that look like terms representing particles. But this is not Reality. These particles are not 'real' (hence the name '*virtual*'). They are useful pieces of fiction, that's all.

256 -

In Quantum Mechanics, when the spin of one *entangled* particle changes, how fast does its twin change its spin? Does it happen faster than the speed of light?

Entanglement does not mean that, when we do something to one particle, its entangled pair mimics it. This is a huge misunderstanding that leads to all sorts of false conclusions. Entanglement simply means that when you measure the entangled properties of the affected particles, they are statistically correlated.
So, say, we have an entangled pair of electrons. One of them would be a spin-up electron, the other would be a spin-down electron, but we don't know which one is which. We produce a stream of such pairs of electrons, the two members of each pair going in *opposite* directions. Some distance away, we measure their spin. At each location, we get a random sequence of spin measurements, say, {*up*, *up*, *up*, *down*, *up*, *down*, *down*, *up*, …}. We, also, get a random sequence of spins at the other location, {*down*, *down*, *down*, *up*, *down*, *up*, *up*, *down*, …}. Each sequence appears completely random. It's only when we bring the two sets of observations together (using very conventional means, bringing over the data electronically or perhaps even on a sheet of paper) that we observe that the two sequences are strongly correlated.

257 -

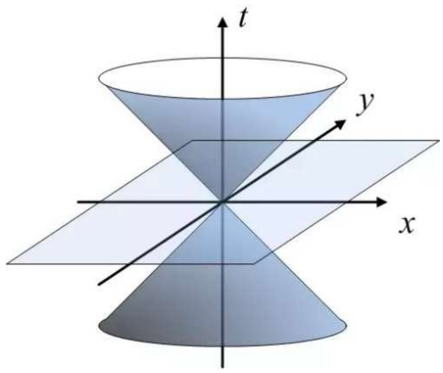
If electrons aren't particles but instead 'collapsible wave functions', then what are physicists accelerating in their accelerators?

Electrons are particles. In ordinary Quantum (Particle) Mechanics, particle states are characterized by *wavefunctions*. The wavefunction can be used to predict the probability of a measurement concerning the particle. Interaction with the measurement apparatus constrains the particle. The act of measurement changes our knowledge of the particle state, thus we 'collapse' the wavefunction to reflect the newly acquired knowledge that the particle has interacted with the apparatus producing a certain outcome.
In Quantum Field Theory, particles are the *quantized excitations* of the underlying fields. *Fields are physical reality*, i.e., particles are observer-dependent (e.g., an accelerating observer may see field excitations, i.e., particles, where an inertial observer sees nothing). But all the above still applies insofar as the field is concerned: its state is described by a wavefunction, *the field is constrained by its interaction with the measurement apparatus*, and we reflect our knowledge acquired through measurement by 'collapsing' the wavefunction, *replacing it with a wavefunction that represents the measured state of the field*.
Particle accelerators accelerate particles. That is to say, the accelerator transfers energy to the field, creating excitations (particles) and/or imparting large quantities of Kinetic Energy and Momentum to these excitations. The 'particles collide', i.e., the underlying fields interact through these excitations, Energy and Momentum are exchanged, some excitations are annihilated, and new excitations are created. This is modeled mathematically and, also, symbolically (by way of Feynman diagrams), testing the validity of the theory, confirming its quantitative predictions (e.g., the existence of a field like the Higgs Field by way of interacting with its quantized excitations, the Higgs bosons) and also looking for new phenomena that are not predicted by existing theory.

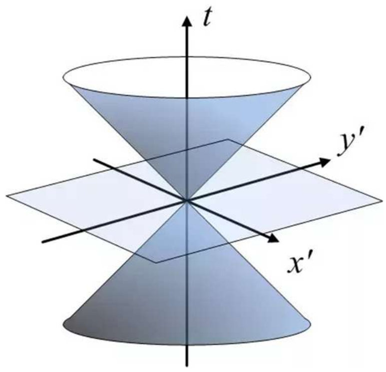
258 -

If Time, t, is another dimension, why can't we go back and forth?

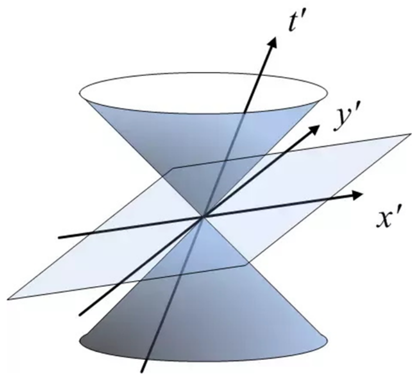
First, let us draw SpaceTime with one space dimension suppressed. In this drawing, we (the observers) sit at the origin, and the two cones represent your *past* and *future* light cone (i.e., light rays that are reaching our eyes 'just now', vs. light rays that we emit with a light source 'just now').



Now let us rotate our drawing in Space. The t- axis remains in place, as we're rotating in the $X \times Y$- plane:



As we can see, the rotation is unconstrained. If we did a π rad rotation, we would have ended up with both the x- and the y- axis *reversed*.
But what happens when we rotate in such a way that it involves the t- axis? Here is an example:



As we can see, the rotation (a hyperbolic rotation, which corresponds to a *change of velocity*) works in such a way that the light cones remain exactly where they were: they are *invariant* (this is the geometric representation of the fact that light cones and, more generally, the laws of Electromagnetism, are invariant under Lorentz transformations).
And most importantly, what is inside the upper (or lower) light cone *stays inside* the upper (or lower) light cone. What is outside stays outside. And as a corollary, no matter how we perform this hyperbolic rotation or how many different ways we do it, we can never change the direction of the Time axis. It will never turn upside down because for that to happen, it would have to get outside the upper light cone and then inside the lower light cone somehow, and that is just not possible.

The t- axis, of course, represents the *world line* of the observer *at rest* (the Space coordinates of that observer would remain unchanged, only Time would pass). So, the fact that we cannot turn the time axis around *is equivalent to saying that an observer can never move backwards in Time*. This is how the Relativistic Geometry of SpaceTime works.

259 -

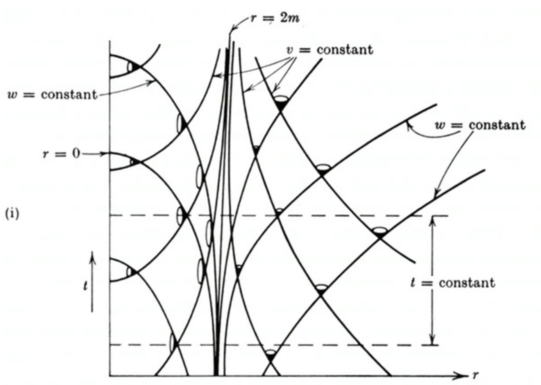
What are the reasons that Quantum Mechanics is formulated in an *infinite-dimension* Hilbert Space rather than a *finite-dimension* one?

It can be felt that behind this question there is possible confusion regarding the meaning of Hilbert Space in Quantum Physics, so, let's begin with an important clarification: Quantum Physics is formulated in the $3+1$- dim space in which we live. The Hilbert Space that this question is about *is not* directly related to the number of SpaceTime dimensions.
Rather, the Hilbert Space is about all the possible states of a quantum system. When we actually measure a property of a particle, we get a specific value. This will be one of the basis vectors of this Hilbert Space. But, in between measurements, the particle's state is a combination of all possible measurement values. This is formally similar to how we describe an arbitrary vector in a vector space as a weighted sum of basis vectors.
So, how many basis vectors are there in this Hilbert Space? There is one for each possible outcome for the measurement. If the measurement yields only a small handful of possible outcomes (e.g., we are measuring the spin of the electron, which is either $+1/2$ or $-1/2$, with no other values possible), there are *only two* basis vectors. The abstract space that represents all the possible spin states of the electron will be two-dimensional.
But another measurement may have an infinite number of possible outcomes. Say, we measure the position or the Momentum of a free electron. It can be anything. In between measurements, the electron is in a combination of all (infinite) possible position states or all (infinite) possible Momentum states. The number of basis vectors (possible outcomes of the measurement) is infinite, hence the Hilbert space that describes the state of the electron is infinite-dimensional in this case.
Again, in all these examples, the electron 'lives' in $(3+1)$- dim SpaceTime. That does not change. It's the state of the electron, with respect to some measurement, that is represented by the mathematical abstraction of a Hilbert Space. The number of dimensions of that Hilbert Space corresponds to the number of theoretically possible outcomes of that measurement.

260 -

Some people (e.g., Victor T. Toth) often say 'a black-hole singularity is not a *location* but a *future moment in Time*'. What does this mean?

Let's give, by way of a more detailed explanation, a diagram from the famous monograph by Hawking and Ellis, '*The Large Scale Structure of SpaceTime*' (Cambridge, 1973):



The above is a representation of the simplest black-hole, the *Schwarzschild black-hole*. The Schwarzschild black-hole is *spherically* symmetric, so it is characterized fully using the radial space coordinate r and the time coordinate t or, at least, the coordinates that pass for radial space and time coordinate for an observer *far from* the black-hole (like us). The meaning of these coordinates is not as straightforward closer to the black-hole as we will see in a moment (please, let's ignore v and w; they are part of another coordinate system discussed in the book, which we do not need here).

The thick lines in this diagram correspond to rays of light in these coordinates. Between pairs of such rays of light, the authors drew teeny light cones, which represent the observer's immediate future at that position.
The $r = 0$ position, that is, the vertical axis on the left side of this diagram, is the *singularity*. Another vertical line, marked $r = 2m$, represents the *event horizon*. We might wonder what is happening at the event horizon in this diagram.
The coordinates that are used here, Schwarzschild coordinates, are those of a *distant* observer. From the perspective of a distant observer, nothing is ever seen to cross the event horizon. This is precisely what we see here: rays of light approaching the horizon are subject to ever increasing *Time dilation*, so, indeed, from the outside observer's perspective, they never reach the $r = 2m$ vertical line nor can they originate from it.

But it is possible to use the same t and r coordinates to describe the *interior* region. It should be emphasized that there is no continuity here: the t and r coordinates are completely *inadequate* when it comes to describing the horizon itself, because at the horizon, the metric of SpaceTime becomes undefined using these coordinates (other coordinate systems exist that do not go bonkers there, but again, let's not go there).
However, notice a very critical qualitative difference between the 'inside' and the 'outside': the orientation of the little light cones. Outside, they are oriented upward: the *future* is boundless in the $+t$ direction. But inside? They are oriented leftward, towards the singularity. The future is now in the $r \to 0$ direction and Time ends at $r = 0$. And the t coordinate? *It no longer behaves like a Time coordinate: it behaves as a Space coordinate*.
So inside the horizon, there is no avoiding the singularity: it is part of everyone's future. It is a future moment in time no more avoidable than 3 PM tomorrow afternoon.
Digging a little deeper into the maths of the Schwarzschild solution, all of this is evident from the definition of the Schwarzschild *line-element*, which is obviously undefined when $r = 2m$ but, more importantly, the coefficients of dt^2 and dr^2 change sign when $r < 2m$. This is what is graphically represented in the diagram above. The end result of this is that when we use these coordinates to describe the interior, t and r flip roles, r becomes the *time-like* coordinate, and the future time-like direction is the $r \to 0$ direction; at $r = 0$, the SpaceTime becomes *singular* (e.g., the curvature scalar becomes *divergent*) and *Time itself ends*.

PS

In all of the above, as customary, it was assumed units such that the *speed of light* and the *Gravitational constant* are both in 'natural units', i.e., $c = G = 1$, for sake of simplicity. Conventional units can always be restored into the equations when necessary, e.g., when calculating something that is compared against measurement.

261 -

Is Relativity not compatible with Quantum Physics? (Look back at Issue 13, P. 6)

As a matter of fact, Relativity Theory is quite compatible with Quantum Physics. Ordinary Quantum Physics, rooted in Schrödinger's equation, is not relativistic, of course. Dirac's equation, instead, is a realization of Relativistic Quantum Mechanics, but even it has a few issues with *causality* and *cannot account for particle creation and annihilation*.
However, Quantum Field Theory is demonstrably a *causal* theory, and it is, by design, fully compatible with Relativity. Not just that, but it even works on the curved SpaceTime background of Gravity, in General Relativity.
So, why do we keep hearing that the two theories are not compatible after all? Well, … it has to do with attempts to *quantize* Gravity. We want to quantize Gravity because of Einstein's field equation (here, in MKSA units; in 'natural' units, set $c \equiv 1$):

$$\boldsymbol{R}_{\mu\nu} - \frac{R}{2}\boldsymbol{g}_{\mu\nu} - \Lambda \boldsymbol{g}_{\mu\nu} = \frac{8\pi G}{c^4}\boldsymbol{T}_{\mu\nu},$$

The left-hand side of this equation represents the geometry of SpaceTime. It's basically a bunch of numbers. The right-hand side is Matter. Specifically, $\boldsymbol{T}_{\mu\nu}$ is the tensor that represents the Stress-Energy-(Linear)Momentum of Matter. If Matter is quantized (as it is, in the Standard Model of Particle Physics) then $\boldsymbol{T}_{\mu\nu}$ is not a collection of numbers but a collection of *operators*, which is usually represented by a little caret on $\boldsymbol{T}$:

$$\boldsymbol{R}_{\mu\nu} - \frac{R}{2}\boldsymbol{g}_{\mu\nu} - \Lambda \boldsymbol{g}_{\mu\nu} = \frac{8\pi G}{c^4}\hat{\boldsymbol{T}}_{\mu\nu},$$

And this equation can never be correct, because it basically says something like, 'some apples = some oranges'.

There is, actually, a trivial resolution to this problem: we can modify Einstein's field equation so that its right-hand side contains the *expectation value* of the $\hat{\boldsymbol{T}}_{\mu\nu}$ tensor. The expectation value consists of numbers, so now we have apples on both sides of the equation, which means it has solutions coming from

$$\boldsymbol{R}_{\mu\nu} - \frac{R}{2}\boldsymbol{g}_{\mu\nu} - \Lambda\boldsymbol{g}_{\mu\nu} = \frac{8\pi G}{c^4}\langle\hat{\boldsymbol{T}}_{\mu\nu}\rangle.$$

This approach is called *semi-classical Gravity*. But this is deeply unsatisfactory to most physicists, because it means, *first* of all, that Gravity is not like the other fields at all, i.e., *it is not a quantum field theory*; and, *second*, the expectation value had to be put into the equation 'by hand', its use *is not derived from an underlying fundamental principle*.

So, why can't we just quantize Gravity? The problem there is technical. All (almost) quantum field theories are plagued with unwanted *infinities*, but for theories that are 'well-behaved', these infinities can be removed through a mathematical process called *renormalization*, leaving behind a theory that actually makes sense. But Gravity *is not renormalizable* this way. So, the standard, straightforward approach to turn Gravity into a Quantum Field Theory the same way as, say, Electromagnetism was turned into a Quantum Field Theory, does not apply. Something new is needed, and this is where our Science ends (and speculations begin). There are many theoretical proposals, but none completely satisfactory, and basically none can be tested by observation … that's because in all regimes accessible to us either in the laboratory or in astrophysical observations, semi-classical Gravity works perfectly well and the possibility, however unpalatable, that Gravity is not a quantum theory cannot be excluded, after all. In fact, there are plenty of theoretical proposals pushing in this direction, too.

262 -

As for *cosmic expansion*, where does the constant increasing amount of Space come from?

There is no 'increasing amount of Space'. *Space is not a physical quantity* (and certainly not a conserved quantity). It is not something that we measure; it does not have little markers that tell us how much Space there is or there isn't.

We measure distances between things, we do not measure Space.

When we talk about *cosmic expansion*, we mean that the average distance between things increases over time. It does not require any mysterious non-existent substance called 'Space' to be inserted between them. The distance between things is a relationship between those things, not the quantity of some ethereal medium between those things.

It simply means that the relationship between things changes in such a way that, for instance, over time, it takes longer and longer for those things (e.g., two distant galaxies) to exchange a signal between them.

263 -

What is a *false Vacuum* and could it really bring about the end of the Universe?

First of all, let's recall that in Quantum Field Theory, the fundamental objects of Nature are not *particles* but *fields*. *Particles are unit excitations of these fields*. For instance, there is the one-and-only Electromagnetic Field. Its unit excitations are what we recognize as *photons*. When an interaction adds energy to the field, it *creates an excitation*. When the field transfers energy to another field, it *loses an excitation*. Normally, the lowest energy state of a field is when it has no excitations at all. In other words, it is the *Vacuum with no particles in it*. However, some fields are weird. Their lowest energy state comes not when they are free of excitations but when a certain number of excitations are present. The infamous Higgs Field is like this, or, we should say, was like this in the very early history of the Universe.

But this has consequences. This means that the vacuum (no excitations) is 'false' in the sense that it can decay (enter a lower energy state) by creating new excitations (new particles). So, the 'false' Vacuum rapidly decays into the 'true' Vacuum, which has some excitations for the given field, but as a result of which, the system *as a whole* is now in its lowest energy state.

The Higgs Field did this in the very early Universe and as a result, the Laws of Physics changed: with respect to this new, 'true' vacuum, previously massless particles such as electrons and quarks became massive, for instance.

Then, the question becomes: what if our present-day vacuum is not really the true Vacuum either? Sometimes, the decay from false vacuum to true vacuum *does not happen instantaneously*, as something (such as a potential barrier, that is to say, a transitional state that is a higher energy state than the 'false' Vacuum) may be in the way.

Indeed, if this were to happen, the Universe as we know it would likely end. That is to say, the Laws of Physics would fundamentally change. Chemistry, atoms, the periodic table, protons, neutrons … these might all vanish. Sure, Matter and Energy won't go anywhere, and in this new version of the Universe, may end up forming different structures under different rules but the stuff we are familiar with *would be completely and irreversibly gone*.

Having said that, … there is absolutely no reason to believe that we live in such an unstable Universe, or that the Vacuum of our Universe is not the 'true' Vacuum. Sometimes physicists publish speculative papers on this topic, which are then promptly picked up by science journalists, sometimes resulting in breathless coverage that may even make it to the pages of tabloids. That does not mean a thing: insofar as the actual data goes, there is zero observational evidence, zero reason to believe that we live in an unstable, 'false' Vacuum.

264 -

How come Einstein said that Energy equals Mass but also said that light has energy though it doesn't have Mass?

Energy is an *observer-dependent* quantity, rest Mass *is not*. This is, in fact, reflected in the title of Einstein's original 1905 paper, which discusses the question whether or not the *inertia* (i.e., *inertial Mass*) of an object is determined by its energy-content. The phrase *energy-content* should be emphasized, to distinguish it from another form of energy: *kinetic energy*. Say, there is a brick coming at us at 100 miles an hour. It has a lot of energy, right? In fact, if it hits any part of our body, serious injury, even death, may likely result. Except … except that both the brick and we happen to be sitting in a vehicle zipping down at 100 miles an hour. Relative to us, the brick is sitting at rest on the seat next to us. It isn't going anywhere. As far as we are concerned, it has no kinetic energy.

Obviously, the brick's intrinsic property, its *rest Mass*, cannot depend on who is looking. And it doesn't. But things get even trickier. That brick consists of a lot of atoms. Those atoms wiggle about a lot unless the brick is cooled to absolute zero (which it isn't). So those atoms each have a lot of kinetic energy. It has just been stated that kinetic energy is not part of the rest Mass of an object. And that's true for those individual atoms. But the thermal energy of the brick is part of the brick's energy-content. So the brick's total Mass will include not only the rest Masses of its constituent atoms but also *their thermal kinetic energy*: the energy that is measured in the brick's center-of-Mass frame. This kinetic energy cannot be removed by choosing some other frame of reference: in any reference frame other than the center-of-Mass frame, the brick's total Kinetic Energy will be more, not less than this minimum value. So, *this minimum amount is an intrinsic property of the brick, part of its rest Mass, even though it is not part of the rest Mass of any of the brick's constituent atoms*.

Finally, this takes us to photons. Indeed, a free photon has no rest Mass. We cannot catch up with a photon, of course, but in principle, we can get arbitrarily close. And the closer we are to catching up with the photon, the less kinetic energy it has as seen from our reference frame. If we could catch up with it completely, that kinetic energy would go to zero. The photon has no rest Mass, so we are left with nothing.

But now, let's think of something else: a box lined on the inside with perfect mirrors. Let a few photons into this box and seal the box. Those photons will be bouncing back-and-forth between the mirrors. They would, in fact, behave like a very hot (so-called *ultra-relativistic*) gas. Their kinetic energy is not intrinsic to the photons themselves, of course, but they are now part of the box's energy-content. So, the total Mass of the box will now be the rest Mass of the box plus the Kinetic Energy of the photons trapped therein, as measured in the system's center-of-Mass reference frame. This, incidentally, is why we prefer not to use the concept of relativistic mass anymore. The problem is that relativistic Mass is not an intrinsic property of an object: it depends on the observer. It is, in fact, *the sum of the intrinsic rest Mass of the object* (*which is determined by the object's Energy-content*) *and its Kinetic Energy measured in the reference frame of an observer who moves relative to the object*. As such, it is a concept that is more likely to mislead than to enlighten, but, perhaps, in light of the above explanation, it makes some sense (and also, perhaps, why this concept has fallen into disuse).

265 -

Galaxies seem to recede *faster than the speed of light*. How can we show the way math proves it? Are there any reference(s) on how it shows that simply?

The answer to this question is part of any introductory course into Physical Cosmology, so, a very superficial sketch will be given here.

For instance, we can just look at the *Friedmann-Lemaître-Robertson-Walker* (FLRW) metric,

$$ds^2 = c^2 dt^2 - (a(t))^2 d\Sigma^2$$

(i.e., the most generic metric that is spatially *homogeneous* and *isotropic*). The radial velocity of a distant object, at distance r from the observer, in these coordinates will be given by

$$v = \frac{dr}{dt} + r\frac{da}{dt} .$$

Clearly, if $da/dt \neq 0$, that is, if the Universe is not static, then even for distant objects that are at rest with respect to

the FLRW coordinate system, $dr/dt = 0$, their coordinate velocity relative to the observer can be *arbitrarily large*, *not limited by the vacuum speed of light*.
The fact that in these (so-called co-moving) coordinates objects that are locally at rest with respect to the isotropic reference frame nonetheless move at high-speed relative to each other is what often leads to the common conception that 'space expands'. Space may expand or contract ds^2, we wouldn't know, because *Space is not measurable*. We measure *distances between objects* or even more precisely, *time intervals between events* that involve objects. And, of course, a good distance measurement doesn't depend on arbitrary coordinate choices. This becomes a bit of a problem in a curved spacetime, such as the expanding SpaceTime of Cosmology, as the concept of distance itself is no longer unambiguous. So, rather than trying to assign a number (which will inevitably depend on the choice of coordinate system) to the speed of a distant object, we might just ask: can that object causally influence us by sending a signal (one that travels at the vacuum speed of light or less)? Can we influence that object? And again, the answer is no: it doesn't matter what speed our signal travels at in FLRW coordinates, there will be objects far enough away for which rda/dt will be larger than the speed of that signal so the signal will never catch up.

266 -

In *Hawking Radiation*, when the particles leave the black-hole, where do they go exactly, or is the business more complicated than that?

The particles of Hawking Radiation do not 'leave the black-hole' as they do not come from the black-hole proper.
Hawking Radiation arises because of the *Gravitational Vacuum Polarization* in the vicinity of the black-hole, due to the Gravitational Field and how rapidly it changes with distance from the black-hole.
The characteristic wavelength of Hawking Radiation is, in fact, several times the *Schwarzschild radius* of the black-hole so it really isn't some point particle being produced at the black-hole; it is the region of space surrounding the black-hole from which this radiation originates.
As to where it goes: *everywhere*. This is radiation that any distant observer sees (at least in principle; in practice, Hawking Radiation is *undetectable* for astrophysical black-holes) in any direction away from the black-hole.
This radiation consists overwhelmingly of *photons*. The reason for this is simple. As it has been mentioned, Hawking Radiation is very weak. There really isn't enough energy to produce *massive* particle-antiparticle pairs (e.g., electron-positron), so we are left with *massless photons*. Perhaps neutrinos (which are very light) could be produced too, but because neutrinos interact very rarely, such pair production would occur with a *vanishingly small probability*. Other particles are just too massive, except for gluons, but those *cannot exist as free particles* in the low energy limit due to the nature of the *strong interaction*. So, we're left with photons (it is for these same reasons that hot objects radiate heat mostly in the form of photons, too).
Therefore, the black-hole behaves like a compact thermodynamic black-body, radiating waste heat (corresponding to its *extreme low* temperature) in all spatial directions.

267 -

How does the Special Theory of Relativity figure into the Quantum Field Theory?

Quantum Field Theory is fully relativistic. The Theory is usually formulated using the concepts and notations of Special Relativity, with the underlying SpaceTime being the Minkowski-SpaceTime of *flat space*. QFT textbooks often go into detail demonstrating how, even though the Hamiltonian formalism (which superficially breaks Lorentz-invariance) is used in the Theory, its results remain *independent of the choice of coordinates*.
It is also possible, however, to rewrite the Theory using the language of *general covariance*, in the context of General Relativity. There, interesting issues arise, not the least of which is that there is no longer a preferred Fourier-decomposition of the fields of the Theory, corresponding to globally inertial reference frames. The consequence of this is that *accelerating observers will no longer agree on the particle content they see* (this is the fundamental background behind such semi-classical effects as *Hawking* and *Unruh Radiations*).
It can also be shown that one of the nicest features of QFT, its fully causal behavior (no 'leakage', not even an exponentially dampened 'leakage' of probabilities that would be faster than light or backwards in time) is completely preserved even when the theory is formulated on a curved SpaceTime background.
The one thing where the theory fails Relativity consists in its *inability to provide a renormalizable Quantum Field Theory of the Gravitational Field itself*, i.e., treating curved SpaceTime not merely as a background but as a *dynamical quantum field*.

268 -

If two photons are entangled, If the wavelength of one photon changes is the wavelength of the other affected?

First, when we speak of entangled particles, what we really mean is that we created a set of particles that, at least temporarily, are not entangled with everything else. Because that is the normal state of things: everything is entangled with everything else almost all the time. In these laboratory experiments, we manage to isolate, e.g., a pair of photons from everything else in the world, so that we can study entanglement under such artificially created, "clean" circumstances without the unpredictable, random environment.

Second, the wavelength of a photon is not an intrinsic property: it is observer-dependent. An observer that is running after the photon will see a longer wavelength. An observer that is running in the opposite direction will see a shorter wavelength.

With that in mind, if the photon's wavelength changes because an observer changes reference frames (e.g., a previously stationary observer begins to move) than obviously, the other photon's wavelength would change the same way. They do not even need to be entangled; what changed, after all, is not the photons but the observer's reference frame.

If the photon's wavelength changes because it interacts with its environment (e.g., it enters a refractive medium) then it really is no longer entangled only with its counterpart. There is now a complex interaction between this photon and the environment that caused its wavelength to change. As such, the 'pure' entanglement (involving only the two photons, with the environment excluded) is broken, so we would no longer describe the pair as entangled.

269 -

If Gravity is not a force but the curvature of SpaceTime, does Matter fall towards the center of Earth because the underlying SpaceTime curvature is descending like a well?

Let's challenge the notion that Gravity is not a force. If we don't believe this, let's grab a brick, hold it (not too high) over our big toes and let's release it. It would be difficult, afterwards, to say that we didn't experience a force …

Now, it is true that, in a popular interpretation of General Relativity, Gravity qualifies as a *pseudo-force*: it is a force the same way the *centrifugal* force is a force, namely in that it arises because the observer measuring this force *is not in an inertial reference frame*. That does not make a force any less real: let's just ask any astronaut-in-training how fictitious the force felt when they were in that centrifuge.

Now, the Gravitational Field, on account of coupling to Matter universally (same way to all forms of Matter) and minimally (in a certain mathematical sense) can, in fact, be viewed as the metric of SpaceTime, indeed the only metric that can be measured using physical instruments, since (because Gravity is universal) our instruments themselves are subject to the same metric. So, the question is still relevant: why does the resulting 'bending of SpaceTime' cause Matter to fall towards the center of the Earth? The answer is: *because clocks ticks more slowly there*.

The bending of SpaceTime is not like those rubber sheet visualizations that we see in popular accounts. Newtonian Gravity is (almost) all about clocks (here on the surface of the Earth, any additional correction comes it at a rate of 1 part in 10^9, or so).

As to why trajectories bend in the direction where clocks tick more slowly: a *fundamental principle* in Physics, the *Principle of Least Action*, tells us that any object will follow, between two events, a trajectory alongside which the object experiences the highest amount of elapsed time. Emphasis on events: say, if the Moon is at a certain position today at noon and at a certain other position tomorrow at noon (i.e., two events characterized by location and time), the Principle of Least Action tells us what the Moon's trajectory was between these events. And it could not have been arbitrary: if the Moon, say, decided to elope at near the speed of light and then return just in order to be found at the right place and the right time the next time, clocks on the Moon would have experienced very little elapsed time because of relativistic time dilation. So, it turns out that the trajectory between these two events that guarantees the maximum amount of time for those clocks is (almost) precisely the Moon's Newtonian orbit about the Earth.

The same applies to rocks thrown, cannonballs fired, etc. . And, of course, the same would apply to us humans, were it not for the ground that stands in our way most of the time: the pseudo-force of Gravitation is counteracted by the force exerted on us by the floor, keeping us at rest in our non-inertial reference frame here on the surface of the Earth.

270 -

Could the explosion of a hyper-massive black-hole be the cause of the Big Bang? The Big Bang started out as small as an atom, and isn't the singularity the same size as that?

NO!!!

First, the Big Bang *was not* an explosion. Please, do not imagine the Big Bang as something small exploding into pre-existing empty space. That really is not how things work in Cosmology. Rather, the standard assumption (that fits the observational data) is that the Cosmos is approximately uniformly filled with Matter and has always been that way. The early Cosmos was dense, sure, but it was not a pocket of Matter in an empty Universe. The entire, infinite Universe was dense everywhere. There is no 'outside'. Now, of course, it is eminently possible that far beyond the realm that we can observe, the Universe is very different and not uniform at all but that is something we don't know. What we do know is that a uniform model is the simplest, and the available data fit into such a model.

Second, the Big Bang was not 'as small as an atom'. As described above, the infinite (!) Universe was simply *very dense everywhere*. Now it is true that the parts of the Universe that we can actually observe were, in the Standard Model, confined to a very small volume, perhaps, even smaller than an atom (although we know next to nothing about the state of the Universe that early on; theories like early Cosmology inflation remain highly speculative). But the parts that we can observe is not the whole Universe. Again, as far as we know, there is infinitely more of the Universe out there, beyond what we can observe.

Third, a technical point: a black-hole may harbor a singularity, but it is a *future singularity*. The singularity that characterizes the beginning of our Universe (that is, if we assume that General Relativity remains valid in that extreme regime) is a *past singularity*. The two are manifestly different. So, *no*, a black-hole just doesn't fit the picture. Its time-reversed cousin, a *white-hole*, might, and there have been speculations that we are, in fact, experiencing a SpaceTime that is akin to just such an object. The thing is, we don't know, perhaps we cannot know; the metric of SpaceTime inside such a white-hole would be identical to the expanding (so-called 'FLRW') metric that we use to describe our Cosmos, so this remains a distinct but unproven (and, perhaps, unprovable) possibility.

271 -

Black-holes have Mass but not Matter. Why and how does it work?

Let us distinguish two completely different things:

a. *Astrophysical black-holes*,

b. *theoretical vacuum solutions* of Einstein's General Theory of Relativity.

Regarding a, the simplest solution of General Relativity, the Schwarzschild solution from 1916, is a Vacuum solution that is *static* (not changing with time) and *spherically symmetric*.

When it comes to b, the following points can be shown using Mathematics:

- b.1 the so-called Oppenheimer-Snyder solution from 1939, demonstrates how a spherical cloud of pressureless Matter ('dust') collapses in such a way that ultimately, the limiting case (in the far future) is the Schwarzschild solution;
- b.2 even if the original cloud deviates from spherical symmetry, the result is still the Schwarzschild solution if there is no net rotation (or the Kerr solution, which is an axisymmetric, static vacuum solution, if the cloud has net rotation).

Finally, there is another important theorem in General Relativity, *Birkhoff's Theorem*, which tells us, among other things, that outside a *spherically symmetric Mass* (or far enough from a Mass so that its deviations from spherical symmetry don't matter), SpaceTime is the same as in the Schwarzschild solution.

Putting these pieces of knowledge together, we can deduce that when a cloud of Matter collapses under its *self-gravity*, it can be treated more or less as dust (since Gravity proved stronger than pressure, so as the collapse progresses and Gravity becomes even stronger, pressure becomes irrelevant); and that although the 'end stage' will never be observed by outside observers, as a result of collapse and extreme gravitational time dilation and redshift, the collapsing Matter rapidly vanishes from sight, leaving behind an apparent 'hole' that, for all practical intents and purposes, is indistinguishable from a Schwarzschild (or Kerr) black-hole.
So, real black-holes have Mass and Matter. The *idealized* end stage is a *vacuum solution*, however, this is arguably Mathematics, *not* Physics, as it describes 'Physics' in the *infinite future* as seen by outside observers.

272 -

Is energy an independent object or a property of objects?

Energy is a property of a physical system. For physical systems that are described by mathematical laws that remain *unchanged under time-translation* (i.e., for systems that are governed by the same mathematics today, tomorrow and after tomorrow), this property is a constant of the motion: the quantity remains constant over time.
The actual value of the quantity is *observer-dependent*. There is a related concept, *Momentum*, which is a vector

quantity (has a magnitude and a direction). For systems that are invariant under *space-translations* (i.e., governed by the same mathematics here, the house next door, or on the Moon), this quantity, too, is a constant of the motion. Its value, too, *depends on the observer*.
Energy and Momentum can be combined in 4 dimensions into a 4-dim vector quantity. This quantity is a constant of the motion if the system that it characterizes is governed by mathematical laws that are invariant under translations in both Space and Time. For these systems, the 'norm' (basically, the magnitude) of this quantity is actually the rest-Mass of that system, which is a fundamental property of any system; as we know thanks to Einstein since 1905, it is the *intrinsic* energy-content of that system (the word *intrinsic* has been used to distinguish it from the energy of the system that is observer-dependent; i.e., a system may have a lot of kinetic energy for an observer who is moving fast relative to the system, but zero kinetic energy for an observer who is at rest relative to the system. But the two observers would agree on the intrinsic energy-content, i.e., the rest-Mass, of the system they observe).

273 -

How does Heisenberg's Uncertainty Principle ($\hbar \lesssim |\Delta x||\Delta p|$) change in extremely warped time\space (e.g., near a black-hole)?

Let's keep in mind that the elementary version of the Uncertainty Principle, expressed as an inequality, is a consequence of something far more fundamental: that in the Quantum World, physical quantities are described by non-commuting variables, not numbers. To wit, $pq - qp = -i\hbar \neq 0$, so, the *order* in which things are multiplied *matters*.
What does this mean in practice? It means that when either p (the generalized Momentum) or q (the generalized Position) has a definite numerical value (i.e., if it is *measured*) the other cannot have a numerical value, otherwise $pq = qp$ and canonical commutation relation above would not be satisfied.
What if we do not determine either p or q precisely, only approximately? Well, then there is room for the other quantity to be determined inaccurately. The limit to which both quantities can be confined to be approximately numbers is what is captured in the Heisenberg's equality above.
The canonical commutation relation *always remains valid*, even when the quantum system exists on the curved background of a Gravitational Field. So, the Uncertainty Principle also remains valid, though care must be taken to ensure that *generalized positions* and (*linear* and *angular*) *momenta* are expressed in a manner that is not dependent on the choice of observer's coordinates.

274 -

Does light ever become Mass?

Yes, light can become Mass. Here is the simplest example: let's take an object and measure its Mass. Now, let's shine a powerful light onto that object, allowing it to absorb some of that light. Therefore, the object warms up a little (its constituent particles wiggle a little faster, having a little more kinetic energy). Now, let's measure the object's Mass again: we'll find that it's ever so slightly more, as the Mass associated with that thermal Energy is now added to its Mass.
This measurement may not be realizable in practice (the Mass difference is really, very tiny) but other, more complex measurements can be, so we know that light does become Mass.
As an extreme astrophysical example, there are super-giant stars, in which a considerable fraction of their total Mass is in the form of a 'photon gas', which is some sort of *trapped radiation* (that is, light or electromagnetic radiation at different wavelengths).

275 -

Are *wormholes* a fact, or just a belief? Is there any theory that indicates that wormholes are possible to exist and can be opened artificially? Can wormholes occur naturally or the only way for them to exist is to be created artificially?

A fact in Physics would be something that we *observe*. We have not observed wormholes. A theory (i.e., a body of established knowledge) can predict things that have not, or have not yet, been observed. Wormholes are a prediction of General Relativity. Or to be more precise, wormholes represent a class of *possible* solutions of Einstein's Field Equations of Gravitation.
However, 'possible', in this case, must be seen with a caveat. The solutions are possible in the sense that they are mathematically valid solutions of the equations. But are they possible physically? That is, *are they consistent with the nature of things that are not part of General Relativity Theory, such as the known nature of Matter*?

The answer is, probably not. Wormholes, especially stable (traversable) wormholes may only exist in the presence of Matter with *negative Mass*. While such Matter is allowed by the rules of General Relativity, in Quantum Field Theory, negative (also known as 'exotic') Matter means an unstable Vacuum, and that would be very bad news for our Universe. Wormholes may also *violate Causality* (e.g., by allowing Time travel), running into *contradiction about our understanding of the causal nature of this Universe*.

These are all reasons to believe that wormholes do not exist but let's, then, make a point about the word 'believe'. In this context, it does not mean something like unconditional acceptance of an article of faith in the absence of hard evidence. Rather, it is an (admittedly sloppy) expression stating an informed opinion, a likelihood, if we wish, something that is not proven with mathematical rigor or not observed but what is likely to be the case based on the expert's prior experience with theory and observation. That doesn't mean that the expert cannot be wrong; quite the contrary, we call it a 'belief' precisely because it is subject to change in the light of new evidence.

Finally, even if we find, despite all the above, that wormholes exist in this Universe, it doesn't imply that they can be created. That may not at all be possible or it may require steps, such as manipulating Matter or the scale of entire stars or larger, that will likely remain forever impractical.

276 -

Does Quantum Mechanics say that everything that is not being perceived *is in a wave* rather than a particle?

No. Perception has nothing to do with it. Quantum Physics tells us that a physical system can exist not just in a state familiar from Classical Physics but also in a mixture, a *superposition*, of such states, which makes no sense whatsoever in Classical Physics.

Quantum Physics also tells us that this deviation from Classical Physics is most pronounced for *simple systems* (systems with 'few degrees of freedom') and rapidly disappears for complex systems (systems with 'many degrees of freedom').

So, when a simple system (say, an electron, a photon) interacts with, and thus becomes part of, a complex system (e.g., a human, a laboratory instrument), its behavior becomes indistinguishable from the classical one: it will appear to have a well-defined position, for instance, if it is through its position that it interacts with the complex system.

But when the same simple system is left alone, without interacting with its complex environment, it can exhibit behavior related to the notion that it is in a superposition of many possible states.

277 -

Why does *Noether's Theorem* prescribe *conservation of quantities* over Time but not over Space?

Noether's theorem does both, and more:

- for a system that is invariant under Time translation (that is, if the laws of Physics are the same yesterday, today and tomorrow), Noether's Theorem results in the conserved quantity, the constant of the motion that we call *Energy*;
- for a system that is invariant under *translations* in Space (that is, if the laws of Physics are not dependent on where we observe them), Noether's Theorem results in the conserved vector quantity that we call (*Linear*) *Momentum*;
- for a system that is invariant under *rotations* in Space (that is, if the laws of Physics do not change just because we look north or east or west or south or up or down), Noether's Theorem results in another conserved quantity that we call *Angular Momentum*, which measures the rate of a system's rotation;
- for a system that is invariant under SpaceTime 'boosts' (or *velocity changes*, i.e., if the laws of Physics are the same at the railway station and on board the moving train), Noether's Theorem results in another conserved quantity that turns out to be the system's CM (*center-of-Mass*);
- more generally, for every invariance, or symmetry, of the system that is *global* ('global' meaning that the same transformation is applied to all parts of the system), Noether's Theorem yields a corresponding *conserved quantity*. And for every *invariance* or *symmetry* of the system that is *local* (its parameters changing from point to point), the invariance translates into a corresponding *force law*. These relationships are fundamental not just in Classical Mechanics but even more importantly, in Quantum Field Theory.

278 -

Does the Vacuum have Mass?

In Classical Physics, the Vacuum is the absence of Mass-Energy, so no, it does not have Mass. The very definition of the Classical Vacuum is that its 'Stress-Energy-Momentum Tensor', the quantity that measures, among other things, its Mass-Energy content, is identically 0 .

But when it comes to Quantum Physics, Quantum Field Theory in particular, things get … interesting.
Quantum fields have *ground states*. These lowest Energy ground states are associated with *non-zero Energy*. Naïve calculation, in fact, tells us that this non-zero Energy-density is *infinite*. That is not very useful, of course, since infinities do not lead to useful predictions; rather, they mess things up big time. So, the standard assumption is that we can only trust Quantum Field Theory up to a reasonable limit (the *Planck scale*), but not beyond; so, we only add the ground state Energy up to this limit.
The result is that such a residual zero-point Energy of quantum fields has all the right properties to serve as 'Dark Energy', resolving one of the conundrums of Cosmological Physics, except … that, depending on how we adjust our assumptions, the resulting number is off by anywhere between 50-some to 120-some orders of magnitude.
This rather embarrassing issue, known as the *Cosmological Constant problem*, remains unresolved at present. So, the truthful answer to our question is that *we don't know* if the Vacuum has Mass. The Classical Vacuum doesn't. The Quantum Field Theory Vacuum? All bets are off. Do we misunderstand zero-point Energy? Does it violate the Equivalence Principle? Does it even exist? Is it something else? There are many ideas in the literature, but no meaningful answers.

279 -

When physicists say that a particle is really an *excitation in a field*, does this refer to the particle before or after the *wave-function collapse*? Or both?

Wave-function collapse has nothing to do with it. Wave-function collapse describes the act of observation: it refers to the fact that when a specific property of a quantum system is observed, it has a numerical value, but at all other times, it is 'operator valued', i.e., a formal representation of a quantity that does not obey conventional math rules.
However, while conventional *Quantum Particle Mechanics* can describe how a particle moves about and the *probability densities* that characterize the outcome of various measurements, it cannot do one of the most basic of things that we observe in Nature: it cannot tell us how, e.g., a photon is created or absorbed. It can only tell us what the photon does in between the two events.
Quantum Field Theory offers a completely different take. Let's forget particles and think fields, like Maxwell's Electromagnetic Field. A field can always be decomposed into an infinite sum of elementary sine waves (this is the essence of a Fourier-transformation). We know how to apply the rules of Quantum Mechanics to these sine waves: they are so-called *harmonic oscillators*. And a *quantum harmonic oscillator* has very interesting behavior: its energy levels are quantized. Its energy increases and decreases one quantized unit at a time.
So, now that we decomposed the field into quantum harmonic oscillators and recognized that the energy levels of these oscillators are indeed quantized, comes the next step: we associate these energy levels with what we perceive as *particles*. So let's introduce another field, the '*Electron Field*'. It interacts with the Electromagnetic Field. Both fields are *quantized*. As a result of these interactions, excitations of the Electromagnetic Field may turn into excitations of the Electron Field or vice-versa. As it turns out, this picture correctly describes *quantitatively* (!) phenomena such as the emission or absorption of a photon, or the creation or annihilation of electron-positron pairs.
This all happens between observations. So, no wave-function collapse is involved. The fields that we are talking about *are not* the wave-function. They are *operator-valued quantum fields*, those (mathematical) operators acting upon the wavefunction. Ultimately, the way they act upon the wave-function can be used to determine the likelihood of detecting a particle at a certain place with specific properties. That part works the same way as in ordinary Quantum Mechanics. It's how we get to that point, using a theory that can describe particle interactions (and which, incidentally, is also fully relativistic and causal) that is different.

280 -

Is there any evidence that *Semi-classical Gravity* isn't the full story?

There really isn't. The celebrated BICEP2 result a few years ago, which showed polarization in the CMB due to primordial gravitons, might have been such evidence. Unfortunately, the result (which, incidentally, would also have confirmed inflation) turned out to be bogus, the data contaminated by foreground noise originating from our own galaxy, which rendered it useless.
Others mentioned black-hole evaporation as indirect evidence, since evaporating black-holes might violate the linearity of Quantum Mechanics. But this is likely to be true only if we presume the existence of event horizons, i.e., primordial astrophysical black-holes, which are the result of gravitational collapse, only form a horizon in the outside observer's *infinite Future*; if these black-holes evaporate in finite Time, that means that no horizon forms and, consequently (presumably), even this indirect evidence disappears.
In short, apart from it being unsatisfying, inelegant, whatever we want to call it, Semiclassical Gravity covers, to the best of our knowledge, all regimes available through our *observation* or *experiment*, now or in the foreseeable Future.

281 -

Energy is stored in the *vibration* of particles. Atoms can be turned into Energy $(E = mc^2)$. Where would the Energy go if all atoms would be turned into Energy and there are no particles left?

No, most Energy *is not the vibration of particles*. That is just a specific form of Kinetic Energy. $(E = mc^2)$ is not about 'atoms can be turned into energy'. The actual statement (the title of Einstein's 1905 paper) is that the *inertial mass* of a body is that body's *energy-content*; contrary to a popular notion, it is not about turning anything into Energy.
To clarify further: there are two types of Energy: the energy of *motion* (*Kinetic Energy*, including the aforementioned energy of *vibrational motion*) and *Potential Energy*. Both forms of Energy are, fundamentally, associated with particles. Kinetic Energy, ultimately, boils down to particles *moving*; Potential Energy boils down to particles *interacting*.
As particles interact, they can turn into different particles. Potential Energy may get converted into Kinetic Energy and vice-versa. Thermodynamically closed systems evolve from lower probability to higher probability configurations, in accordance with the 2nd Law of Thermodynamics (Entropy). But we do not end up with everything 'turning into Energy'. Energy is not some magic substance that things can turn into: *it is a property of particles*.

282 -

Is the *Multiverse Theory* taken seriously by physicists or is it just some wishful thinking from comics fans?

Multiverse can mean many things (*). However, from the question details, it appears that the question refers to the assumption that our observable Universe is just one of a multitude of universes, and its properties happen to be what they are because otherwise, humans wouldn't exist to observe it …, i.e., the *Anthropic Principle*.
Unfortunately, it is taken very seriously by many (though certainly not all) cosmologists; it may be said unfortunately, because it means giving up too early.
To offer an analogy: we know that there are many planets out there. We also know that the Earth is special: the solar system in which it lives, the system's location in the Milky Way, the orbit of the Earth, its chemical composition, its large satellite are all exceptions rather than rules. But there is no need to attribute this to any fine tuning: we know that our planet is special because it's the only planet that can support our existence. So, it is not by random chance that humanity didn't develop on Mars, Jupiter, or one of the super-hot exo-planets.
But here is the thing: we understand, at least approximately, how planets form. We understand that planets like ours, though unlikely, probably form from time to time, and of course we live on one, otherwise we wouldn't be alive.
But when it comes to Cosmology … we don't understand how universes form. We have no observational data about other universes. We don't really know how (un)likely our Universe happens to be. We have no observation to suggest that other universes even exist. Unless we can conclusively show that there is no viable theory involving just a single Universe (namely, ours), jumping to the Multiverse is premature. And what if our universe's parameters are special? Do we know for sure that it's not just random chance? Do we know for sure that if the parameters were different, no intelligent species would form to ask these questions? Until we know the answers to these questions, it's way too early to abandon such research, spread our arms, and utter the magic words, 'Multiverse'.
But that's just an opinion.

(*) Other things to which 'multiverse' may refer include Everett's 'many worlds' interpretation of Quantum Physics; the multiple 'bubble universes' of eternal inflation; or the 'landscape' of a near infinite number of string theories, just to name a few examples.

283 -

If we threw an indestructible camera into a black-hole and watched what's on it, what would we see?

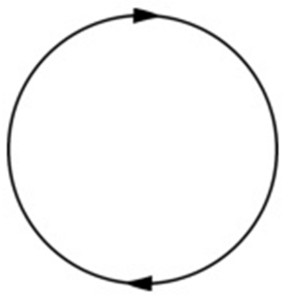
We would see nothing. The problem with black-hole event horizons is not that we get destroyed (we will, but that's beside the point). The problem is that once inside, nothing can ever get out, and that applies to 'indestructible' equipment, too.
Let's recall that Relativity Theory is about Space and Time. Let's try to forget the intuitive notion of *absolute Time*, some divine clock that ticks, measuring Time in a manner that is independent of us, observers (or our cameras or other equipment). No such absolute Time exists. Time is whatever a device, a clock, a biological entity measures along its worldline.
So, we drop that camera into the black-hole and watch that camera approach that black-hole. From our perspective, it will never reach the event horizon. That is to say, the moment that corresponds to that camera's worldline intersecting the event horizon is *in future infinity* insofar as we are concerned. The camera would fade from our sight because of

exponential redshift, any signal from it vanishing; but, in principle, the camera is still there, its time frozen as measured by us, its internal clock never reaching that final millisecond that would mark its arrival at the horizon.
Meanwhile, on the camera everything seems normal! It will measure a finite amount of Time as it reaches the horizon in due course and continues to fall. However, here comes the second problem: from the infalling camera's perspective, that horizon *is not a place*, it is not a spatial boundary. It is, rather, to be specific, a *past* moment in Time.
So to get out of the black-hole, the camera would have to be better than indestructible: it would have to be a Time machine. Otherwise, its doom is inevitable: just as the horizon is a past moment in Time, the singularity (at least so long as it's a Schwarzschild black-hole) is an unavoidable *future* moment in Time. Even an indestructible camera cannot avoid this fate: when Time itself ends inside the black-hole, the camera will cease to exist, too.
As to what the camera would record: if it is a quiescent Schwarzschild black-hole, it would record absolutely nothing. The Schwarzschild solution is a vacuum solution of Einstein's Field equations. What that means is that there is no Matter, no Electromagnetic Field, no Light. There is *nothing to see*, so the camera would see nothing.

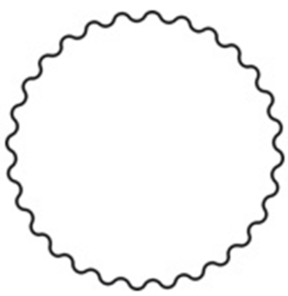
284 -

The Vacuum creates *virtual particles* in *pairs*, a particle, and its anti-particle, which rapidly 'destroy' themselves. A photon is its own anti-particle. Does that mean the Vacuum can create virtual photon pairs? Would they 'destroy' themselves?

Indeed, the Quantum Field Theory description of the Vacuum includes photon loops. Let's think in terms of Feynman diagrams. A Feynman diagram depicts an initial state (incoming particles represented by incoming arrows), something that happens (e.g., an interaction) and a final state (outgoing particles represented by outgoing arrows).
The diagram must respect Conservation Laws (that is to say, at every vertex of the diagram, Energy, Linear Momentum, Angular Momentum and various charges must all add to zero). It can be used to calculate the 'cross section' if reaching the given final state from the given initial state. Knowing the 'Feynman rules' of a theory, one can simply read from this diagram the mathematical expressions (vertex rules and propagators) that go into an integral that is used to make this calculation.
When the initial and final states both represent the Vacuum, it means there are no incoming or outgoing arrows, only loops. The simplest such diagram is just a circle. The circle may have an arrow representing a particle that has a distinct anti-particle, or it may be arrow-less for a particle like the photon that is its own anti-particle. Either way, we pick one point on the circle and call it 'now'; we pick one direction and call it the *particle*, the opposite direction being the *anti-particle*; and pick another point on the circle and call it 'then'.
Here's the one-loop Feynman diagram depicting an electron-positron pair:



Let's imagine Time going from left to right: the top of this loop, then, represents the electron, the bottom is the anti-electron (positron). As we move from left to right, they get created, happily go on their merry way for a little while, and then are annihilated; we get back the Vacuum.
Now here is the same diagram for photons:



As we see, no arrows. The photon being its own anti-particle, no arrow is needed but the logic is still the same: as we move from left to right, a pair of photons is created, they go on their merry way, and then they are annihilated.
Let's remember, though, what has been said above: Conservation Laws are always obeyed. If we read these diagrams, it means that one of the two particles has *negative energy*, since the sum of their energies must be zero. This alone tells us that these are *virtual particles*. These diagrams *do not represent physical reality*. There are no miniature cannonballs created and destroyed in the Vacuum. These diagrams are bookkeeping devices, which help us keep track of terms in an integral that depicts the fields of Quantum Electrodynamics in the vacuum (ground) state. *Virtual particles do not really exist; fields do*.
Finally, two more thoughts reflecting upon what we read elsewhere:
first, even though photons are their own anti-particles, they still need to be created in pairs, because *they have Angular Momentum*. *A single photon never has* 0 *Angular Momentum*, so the only way to satisfy the conservation law for Angular Momentum is by *photons coming in pairs* with *opposite angular momenta*;
second, this diagram of the photon does not depict photon *self-interaction*. That would be a photon emitting or absorbing another photon, i.e., a vertex with three photon lines (which doesn't exist because photons *do not self-interact* in the linear theory of Quantum Electrodynamics). There are no vertices in this diagram, simply a photon *chasing its own tail in SpaceTime*.

285 -

Why did Einstein assume that the maximum possible speed is the speed of light in a Vacuum?

Two reasons: *one* is theoretical. A constant speed of light is predicted by Maxwell's Equations of Electrodynamics so long as the electromagnetic properties of the Vacuum are treated as constants of Nature. If different observers, moving at different speeds, measured different values for the speed of light, that would mean that the properties of the Vacuum (its electric permittivity and magnetic permeability) would not be the same for these observers. This made little sense.
The *other* is experimental: Einstein probably knew about the result of the 1887 Michelson-Morley experiment that showed that the measured speed of light is not affected by the Earth's motion in space.
In terms of modern language, we know that the Vacuum Maxwell Equations are *conformally invariant*: they do not change under an arbitrary *angle-preserving* transformation in 4-dim SpaceTime. If we also allow charges, this symmetry is reduced to an invariance under a subset, namely the Lorentz-Poincaré group of 4-dim *hyperbolic rotations* and *translations*. Special Relativity, fundamentally, is the Physics that ensues once we assume Lorentz-Poincaré invariance, which, for all practical intents and purposes, is *equivalent* to assuming that the speed of light is *constant*.

286 -

How can we observe two black-holes merge together making a single object? Why there is no infinite gravitational redshift? And why time duration of the approaching/merging process is not extended to infinity for us, for external observers?

There is indeed extreme redshift when it comes to processes happening in the immediate vicinity of a black-hole's event horizon, but that is not what we observe when we see black-hole mergers.
What we do see is extremely rapid and violent changes in the gravitational field in the neighborhood of the black-hole, but not inches from the horizon.
The gravitational wave events being detected have frequencies measured in tens or hundreds of Hz. The corresponding wavelength is measured in thousands or tens of thousands of kilometers. This is at least one or two orders of magnitude bigger than the Schwarzschild radii of the participating black holes (maybe ~ 100 km for a 30 solar Mass black hole). So, neither Time dilation nor redshift prevents us from observing the propagating changes in the Gravitational Field, though a precision model of the merger event certainly must take into account this and other general relativistic effects.

287 -

Are there other 'imaginary' numbers such as or beyond $(-1)^{1/2}$ or perhaps of another more abstract class? Could any other 'imaginary' numbers be useful to apply or describe more tenuous interactions such as for advances in Quantum Field Theory (QFT)?

There are different ways to answer this question depending on how these mathematical constructs are used.
First and foremost: complex numbers came about because they were needed to represent the solutions of some algebraic equations. Now we might wonder, why bother? If an equation has no (real) solutions, it has no solutions.

What's wrong with that? This would be a perfectly normal attitude, were it not for the fact (which puzzled mathematicians like Cardano and his contemporaries so much, it brought them by their own admission to the verge of insanity) that in order to solve a perfectly ordinary cubic with three real roots, you need to solve first a quadratic equation that has no real roots whatsoever.

So then, we have complex numbers and with their help, we can solve *cubic* and *quartic* equations. Can we solve all algebraic equations using only complex numbers? The answer is that yes, we can: the field of complex numbers is *algebraically closed*, that is to say, every algebraic equation with complex coefficients will have complex roots. (In contrast, the real numbers are not algebraically closed: e.g., the roots of the equation $x^2 = -1$ are not real even though all its coefficients are real).

Therefore, from a purely algebraic perspective, complex numbers represent the final answer: we found the field that is the natural playground for algebraic equations.

Still … complex numbers have other remarkable properties beyond algebraic equations. For instance, they form a *division algebra*. A division algebra is made of things that, when multiplied together, obey this simple property: if $ab = 0$, then at least one of a or b must be 0.

That this is far from self-evident, can be demonstrated through two examples. *First*, the *dot product* of vectors: if vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ are orthogonal, $\boldsymbol{a} \cdot \boldsymbol{b} = 0$, even if neither $\boldsymbol{a}$ nor $\boldsymbol{b}$ is zero. *Second*, the *matrix multiplication*: there are infinitely many non-zero matrices that, when multiplied together, yield the $\mathbf{0}$-matrix as their product. So, a division algebra is far from trivial: it is something quite special, as a matter of fact.

As it turns out, there are altogether *four* division algebras. That is to say, every other division algebra is either a trivial subset of these four or something that can be mapped, one-on-one, onto one of these four. We already saw two of them: the real numbers and the complex numbers. They share many of their nice properties, e.g., *commutativity* and *associativity* of multiplication. The *real* numbers do have one property though that complex numbers *lack*: they form an *ordered set*. That is to say, it makes sense to state things like $a < b$ if $\{a, b\} \subset \mathbb{R}$, but *not* when they are complex.

Going beyond $\mathbb{C}$, we discover another set that forms a division algebra: *quaternions*. Quaternions have *three* 'imaginary' units: i, j and $k := ij$. Besides the expected *square* relationships $i^2 = j^2 = k^2 = -1$, they obey the *cyclic* relationships $ij = -ji = k$, $jk = -kj = i$ and $ki = -ik = j$. A quaternion can be represented by using 4 *real* numbers, $(a, b, c, d) \equiv a + bi + cj + dk$. As the defining relationships already imply, quaternions lack a property that both real and complex numbers have: *quaternionic multiplication is non-commutative*, in general, i.e., $ab \neq ba$ if a and b are quaternions.

Quaternions are surprisingly useful! For instance, unit quaternions can be used to represent *rotations* in 3-dim space, and they do so in a fashion that helps avoid instabilities inherent in other, more conventional representations, e.g., near the poles of an imaginary sphere (for this reason, quaternions are often used in diverse applications, including Celestial Mechanics or Computer Graphics). Quaternions can also be thought of as a part of the representation of *relativistic fermions* in the *Dirac Equation*.

Beyond quaternions, there is one more division algebra: the *octonions*. They are constructed using *seven* imaginary units. In addition to being *non-commutative*, octonion multiplication is also *non-associative*: $(ab)c \neq a(b, c)$, in general, if a, b and c are *octonions*. Octonions are less often used in Physics (in part because of this non-associative property, which makes them somewhat cumbersome) but there have been attempts to put them to use as a building block in putative fundamental theories of Particle Physics.

So, these are the four *division algebras*, the only four algebras in which $ab = 0$ is true *if and only if* at least one of a or b is 0.

But there are still other ways to generalize the concepts of complex numbers. If we forget about the division business, we can introduce as many 'real' and 'imaginary' units as we want! For instance, nothing stops us from creating an algebra that has, say, two units such that $i^2 = j^2 = 1$, and two for which $k^2 = l^2 = -1$, or whatever. These generalized algebras are collectively called *Clifford algebras*. Beyond abstract mathematics, they play a role in Geometry and also in Physics: abstract algebras can be used not only to describe, say, Lorentz transformations in Special Relativity or the properties of the Dirac Equation but, also, the more abstract mathematical properties of *gauge theories* that play a fundamental role in the Standard Model of Particle Physics.

288 -

How close are physicists to solving the mystery of Dark Matter and Dark Energy?

We won't know until we know, seriously.
There have been numerous experiments trying to detect Dark Matter directly. To date, all these experiments produced either negative results (only upper limits on the rate at which Dark Matter may interact with normal Matter but no actual detection) or detections that were not confirmed by other experiments and didn't reach the statistical certainty needed to claim a discovery (in other words, the data may just be random noise).
On the other hand, modified Gravity theories, which attempt to do away with Dark Matter, have also failed to deliver a result that would be widely accepted. In the opinion of some people, the field is hindered by the famous 'MOND' (*MO*dified *N*ewtonian *Dynamics*) that is an ad hoc formula designed to replicate the anomalous rotation curves of galaxies but accomplishes little else, violates even basic Conservation Laws, still requires some form of Dark Matter on the cosmological scale, and nowadays, it is increasingly presented with equally ad hoc modifications such as the famous 'external field effect'. Unfortunately, those who do not work in the field find it hard to distinguish MOND from properly constructed, relativistic field theories of Gravitation, and often use MOND as a straw man to criticize modified Gravity theories in general, not realizing that many of the shortcomings they address are specific to MOND. But even if we put MOND aside, no modified Gravity Theory can claim full success on all fronts; even the more successful theories struggle when confronted with the totality of observational data on all scales (ranging from the lab, through precision solar system tests, all the way to astronomical and cosmological observations).

All the above is about Dark Matter; Dark Energy is an even tougher case. The fundamental problem is that there are several 'easy' candidates for Dark Energy, but no known way to distinguish them experimentally. If there is a Cosmological Constant, for instance, then it's just that, a constant of Nature. Or could it really be the zero-point energy of *quantum fields*, but with a much lower energy cutoff than the Planck scale value, which is itself suggested by the somewhat ad hoc assumption that Quantum Field Theory is 'just an effective theory', so the summation must stop at the scale where the theory is believed to lose its validity? Or is there perhaps a yet to be discovered so-called *scalar field*, which yields a self-interaction potential with the right Dark Energy like behavior? We do not know.

So, really, we don't know how close we are, because we don't even have the faintest perception of what we don't know. We still have much to learn.

289 -

Why does Relativity not affect the speed of light?

It all begins with Maxwell's Equations. Maxwell's Equations beautifully unify all previously known electric and magnetic phenomena. But more than that, they also predict that there will be propagating waves in the Electromagnetic Field. The speed of propagation can be computed from the measurable electric and magnetic properties of the vacuum (its *permittivity* and *permeability*) and came to be very close to the already known *speed of light*. So an immediate conclusion drawn from Maxwell's Theory was that light itself is probably electromagnetic radiation; thus Maxwell's Theory unified not only *Electricity* and *Magnetism*, but also *Optics*.
The existence of electromagnetic radiation, at wavelengths unrelated to visible light, was verified by the Hertz's experiments, thus solidly confirming the key predictions of Maxwell's Theory.
There was only one problem. The theory not only predicted the existence of *electromagnetic waves* but also their speed. Why is that a problem? Naively, we would expect the speed of anything to depend on the observer. A fast moving train is motionless relative to an observer who is traveling on board that train. But this would mean that either Maxwell's theory only works for a set of privileged observers (who are *at rest* with respect to some absolute, perhaps celestial, reference frame) or that the properties of the Vacuum (from which the speed of electromagnetic radiation is computed) would be different for moving observers.
Either way, it should be possible to measure changes in the propagation speed of light with clever experiments. This takes us to the celebrated experiment of Michelson and Morley, who conclusively demonstrated that there is no effect on the observed speed of light by the Earth's own motion, at a considerable speed, around the Sun.
What these observations measured were captured correctly by the *transformation rules* proposed by Lorentz. But what do those transformation rules mean?

This is where the Theory of Relativity enters the picture. If the speed of light is the same regardless of the observer's motion, perhaps it is because what an observer measures depends on his state of motion: different observers measure different distances and different time intervals between events.
This is not as strange as it sounds. Again, we refer to the moving train example. Suppose we are on that train and clap twice without changing location. To us, the two events took place at exactly the same location. But for someone standing at the station platform, there may be a considerable distance between the two events. So, spatial distances between events were always *relative* (this is called Galilean Relativity). However, before Relativity Theory, time was

assumed to be absolute: if two events were separated by 1 second of time for one observer, all other observers would measure 1 second regardless of their motion. It is this idea that was abandoned by Relativity Theory, making time relative as well. This was the price to pay to ensure that Maxwell's equations remain valid in all inertial (non-accelerating, non-rotating) observers' reference frames.

In the modern formulation, we know that Vacuum (no charges present) Electrodynamics is '*invariant*' under a group of SpaceTime transformations called the *conformal group*; and that even if we introduce charges, the theory remains invariant under a more restrictive group called the *Lorentz-Poincaré group*. Special Relativity amounts to just asserting that the reference frames of inertial observers are related to one another by the *Lorentz-Poincaré group*, as *opposed* to the non-relativistic *Galilean group* of Newtonian Physics.
This has many consequences, perhaps the most important of which is that we live as a result in a *Causal Universe*, in which the past determines the present. A Universe with different rules can be *a-causal*, with Future and Past mixed up and mutually influencing one another.

290 -

Do neutrinos interact with the Higgs Field to acquire Mass? We see contradictory online articles arguing they do/don't interact with the Higgs Field, so if they don't, then what's our best guess for their Mass acquisition?

In the original Standard Model, neutrinos are *massless*. This also explains their 'handedness': all neutrinos observed have *left-handed helicity*. This makes sense for a massless particle that travels at the Vacuum speed of light; for massive particles, however, at least in principle, if we could run faster than the particle, looking back at it we'd see the particle with *opposite* helicity. The fact that we never saw right-handed neutrinos seemed like a strong indication that neutrinos have no rest Mass.

But Nature likes to mess with our minds, we guess, because then came the mystery of *missing solar neutrinos*. This was eventually explained by the concept of neutrino oscillations: that not only do neutrinos have Mass, but their 'Mass-eigenstates' do not coincide with their 'Flavor eigenstates'. What this means is that we can either measure the Mass-Energy of a neutrino or its Flavor (electron, muon, tau-type neutrino) but *not both at the same time*; and by measuring the Mass-Energy of the neutrino, its flavor becomes indeterminate. This explains why electron neutrinos, received from the Sun, often end up being detected as muon neutrinos (or not detected at all if the detector is only sensitive to electron neutrinos).
Bottom line is: neutrinos not only have Mass, their Mass comes in the form of the Mass-mixing 'matrix' (the so-called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix).
This Mass mixing matrix *is not* part of the Standard Model. Furthermore, adding it to the Standard Model 'by hand' *breaks renormalizability of the model*. We tend to ignore this because neutrino Masses are so small anyway, whatever happens to renormalizability, it happens at energy levels that are orders of magnitude above what we can study.

Long story short, we really do not know where neutrino Masses come from or indeed, what their values are. From Mass mixing, we can estimate the differences between Masses, but we cannot even say for sure whether or not the lightest neutrino Mass state might be massless after all! In any case, this Mass mixing cannot come from interaction with the Higgs Field; the mechanism behind neutrino Masses must be something different.
And then, there is the issue of handedness. Massive or not, we still have not seen right-handed neutrinos or left-handed anti-neutrinos. Perhaps because these states are 'sterile' and do not participate even in the weak interaction? Perhaps because these states have different, very large Masses which makes them incredibly difficult to produce and detect?

So that's what we know (to the best of our present knowledge, hopefully reasonably up to date). Beyond that, there's just a lot of speculation.

291 -

How different the Universe would look if Gravity was not limited to the speed of light?

Gravitational Fields *do not travel*. They simply *are*. Changes in Gravitational Fields do travel. Far from a source, they travel much like changes in the Electromagnetic Field travel, at the invariant velocity also known as the *vacuum speed of light*. But this has nothing to do with the range of Gravity. In fact, Gravity is one of the two forces (the other being Electromagnetism) the range of which is not finite. Yes, the Gravitational Potential diminishes as the inverse of distance (and the Gravitational Acceleration, as the inverse square) but it never quite disappears. However, this has little to do with the speed of gravitational waves. In fact, if Gravity propagated at any speed other than the *invariant* one, chances are its range would be less, not more. But if it propagated faster than the invariant speed (i.e., if Gravity were a *tachyonic* field), it would lead to a Universe in which *causality* is not strict, in which effects may precede causes. Moreover, it would very possibly lead to a Universe that is fundamentally unstable and would decay, through

some form of symmetry breaking, into a new version in which Gravity propagates at or below the invariant velocity. This is pretty much what happened in the very early Universe, except that the culprit wasn't Gravity but the Higgs Field.
In other words, if we want a Universe that is still mathematically self-consistent, it really isn't that easy to circumvent the rules without disastrous consequences.

292 -

Is it possible for a Galaxy to have a star in the center instead of a black-hole?

A galaxy doesn't have a black-hole in its center. In fact, most galaxies do not even have what we could call a well-defined *center*. Galaxies are not like solar systems, dominated by a single object. Galaxies are immensely large collections of stars.
Yes, many (most? all?) of them harbor large black-holes in their central region. We do not understand the origin of these supermassive black-holes or the exact role they played in the galaxy's evolution.
But one thing we do know: in a mature galaxy, even a very large supermassive black-hole is puny compared to the galaxy as a whole. This is profoundly true in our own Milky Way; its supermassive black-hole, Sagittarius A*, at a mere 4 million solar Masses, is extremely tiny compared to the billion solar Masses or more (depending on how we define it) of stellar matter and gas that lurk just in the inner 'bulge'; not to mention the rest of the Milky Way, its spiral arms, and its presumed Dark Matter halo that together weigh in at nearly a trillion solar Masses if not more.
So, if we take out Sagittarius A*, what happens? A few stellar orbits change, that's all. Otherwise, Sagittarius A* plays no role in the dynamics of our Milky Way. And while it is in the central region of the Milky Way bulge, it by no means defines any 'center'.
It is tempting to think in terms of hierarchical systems; planets have planetary systems; stars have solar systems; and supermassive black-holes have galaxies, but that's not how it works. Galaxies do not orbit a single central object. They are held together by the mutual Gravity of the very large number of stars they consist of.

293 -

If gravitons are real, how do they traverse the event horizons of black-holes?

The same way photons traverse the event horizons of charged black-holes: simply, they don't.
Elementary particles in a Quantum Field Theory are unit excitations of the underlying field. Especially 'virtual' particles, the ones that mediate interactions (as opposed to the 'real' particles that represent radiation a large distance away from its source) are just mathematical conveniences, terms in a mathematical expression, a series expansion of an integral.
The Gravitational Field of a black-hole is like the Gravitational Field of any other massive object. It interacts with other massive objects. We represent these interactions in perturbative Quantum Gravity using an integral that splits into terms that we call, among other things, gravitons, but no miniature cannonballs called 'gravitons' traverse anything.

294 -

Are physicists certain SpaceTime exists and is thus bended by Mass, or is its existence just a theory to help explain phenomena?

In any direction we look, Space exists, in a sense that we can identify 3 (and only 3) principal directions towards other things. As we do this, our clocks tick. So, Time exists, marking an irreversible sequence of events.
Do we all measure the same Space? Do we all measure the same Time?
Let's do some precision Physics. Measure the Space and measure the Time between things that happen, i.e., events. Soon we find that we do not always measure the same distance and the same time between events. Something that happens to we at the same place (e.g., row number three in the second car) on a moving train happens at different places (say, half a kilometer apart) as we observe them, standing next to the track. Perhaps more surprisingly, we find that the interval of time we measure between two events is also not the same. So, does anything remain the same? Sure: the measured speed (measured distance, divided by measured time) of a ray of light, traveling in a vacuum, between the moment it is emitted and the moment it is absorbed somewhere else.
The rest is pure math. We establish the rules that allow us to calculate what we would measure based on what we measure or vice-versa. We find that these rules are in fact consistent with the mathematical idea of combining Space and Time into a pseudo-Euclidean metric manifold, which has certain nice mathematical properties. We find that this mathematical entity correctly and accurately captures what we measure.

But what really exists are *things* and the *events* that happen that we measure and their relative relationships expressed (among other things) in terms of *distances* and *intervals of Time*. 'SpaceTime', on the other hand, while it is a very useful concept, a framework for us to work with, is not a thing that we actually observe or measure on its own right.

295 -

As we know, increasing velocity does not increase the Mass of an object, *Relativistic Mass* should not be used. However, if we put this accelerating object in a system (box), does its Mass increases according to General Relativity?

Let's illustrate the question using the most extreme of examples: light. Photons, as we know, are weightless. That is to say, if we could catch up with a photon and measure its Mass, it would be zero. Actually, we cannot catch up with a photon, but in principle at least, we can get close. And the closer we are to matching that photon's velocity, the less energetic it will appear to us; by extension, we can calculate the 'asymptotic limit' that as we approach the photon's speed, its Momentum and kinetic energy would both vanish in our observer reference frame. So, now that we established that the photon is weightless, what happens if we put photons in a box? Imagine a box lined with perfect mirrors. Let in some light and seal the box. So, the box now contains photons that are bouncing back-and-forth.
First, by bouncing, they exert a force on the walls. This 'photon gas' has pressure!

Now, let us try to move the box by pushing it. As we accelerate the box, a strange thing happens. The wall closer to us will bounce into photons a little harder because it is accelerating towards the photons impinging it. Photons hitting the far wall would bounce into that wall a little less hard in turn, pushing it away from us less efficiently. So, what used to be uniform pressure now translates into a little bit of an extra force resisting our push, and a deficit of force on the far side that might help our push. The end result is that it's harder to push the box. It is as though the inertia of the box just increased!
That is indeed what happens: the *inertial Mass* of the box increases by the amount of Energy that these *added* photons represent. But is this 'relativistic Mass'? Not really. The point is, we're not talking about how the inertial Mass of the box changes because of its speed relative to us. We're talking about how the inertial Mass of the box changes *because of the stuff that was put in it*. This Mass increase is there even in the box's own rest-frame-of-reference, i.e., *the frame in which the box is not moving*. Because of the photons bouncing back-and-forth inside, it is harder to accelerate the box than it was before the photons were let in.

This, then, is the distinction: even when we account for its relativistic content, the inertial Mass of the box is measured in its own rest frame of reference, independent of any observer. The 'relativistic Mass' concept, in turn, would depend on the relative velocity of box and observer.

296 -

What was the radius of the surface of 'last scattering'? What is the maximum radius of the cosmic spheres visible in our past light cone? And what would we see if the surface of last scattering was somehow transparent to photons?

The 'surface of last scattering' refers to the spherical surface from which we are receiving the cosmic microwave background (CMB) radiation now. Whatever its radius is today, it will be larger tomorrow, as we will be receiving CMB radiation from more distant parts of the Universe.
A good analogy is this: let's imagine we are in a very large crowd of people where, at a certain moment in time, everyone screams (say, something happens like a lightning strike that frightens everyone *at the same time*). Immediately afterwards, we'll be hearing the screams of people near us. One second later, we'll be hearing the screams of people at ~ 343 m from us, and so on. The 'surface of last screaming' would be expanding (at the speed of sound, in this case).
In the case of the CMB, the surface of last scattering expands at the speed of light, but this must be accompanied with the caveat that this is a relativistic Universe, and what appears to be $299\,792\,458$ m/s to a local observer may appear less, or more, to a distant observer who is situated in a different Gravitational Field or moves. In fact, the very concept of 'distance' (hence, 'radius') becomes ambiguous, with multiple different possible definition.
But there is, in this case, an intuitively useful measure: 'light travel distance'. By this measure, the surface of last scattering is a sphere of $13.8 \cdot 10^9$ light-years surrounding us and growing in size by 1 light-day every day. The surface of last scattering that is seen by an observer in a distant galaxy will not be the same as the surface of last scattering that we see. Again, let's think of the 'surface of last scream' in the example above and think how someone else, some distance away in the crowd, experiences it compared to us.

297 -

Is there a medium less dense than a Vacuum, in which light can travel faster than c ?

The relevant quantity is not density, but yes, light can travel faster than it does in a Vacuum with a big caveat: what determines the speed of light is the *index of refraction*. For instance, the index of refraction for water is around 1.333; as a result, light in water only travels at 3/4 of the Vacuum speed of light.
So the natural question arises: are there media with an index of refraction less than 1, which would imply a speed of propagation greater than that in a Vacuum? Indeed, there are: a charged *electron plasma* is a good example. And where would we find a charged electron plasma? In the solar wind, among other things.
So then, if light (or electromagnetic waves in general, such as radio waves) travels faster than the Vacuum speed of light here in the solar system, what does it mean? Unfortunately, not much unless we are into things like precision spacecraft navigation, where we need to know about minute propagation delays of the radio signals used for navigation. The reason? This is the so-called *phase velocity* of light. It's basically the speed of pure sine waves, delivering no change whatsoever from source to destination. The phase velocity can be higher than the Vacuum speed of light but *it does not carry information, it does not carry Energy or Momentum*. That would be associated with the so-called *group velocity* and the group velocity is always less than the Vacuum speed of light, regardless of the index of refraction.
Well, almost always. There are anomalous circumstances when the group velocity, too, can exceed the Vacuum speed of light, but even in these specific scenarios, *no actual transmission of Energy, Momentum, or information takes places faster than the Vacuum speed of light*.
In short, Nature is rather strict when it comes to this business of *relativistic causality*.

298 -

What is the General Theory of Relativity? Can this be explained in simple words without that complicated math?

The Theory of Relativity is ultimately about the equivalence of observers. Namely that the laws of Physics should be the same for all observers, regardless of these observers' motion.
When we put this principle to use given the Physics that was already known to us in the 19th century, we immediately run into a problem. Maxwell's Theory of Electromagnetism tells us that electromagnetic waves (light, radio waves, etc.) travel at a fixed speed. But if the waves travel at a certain speed for us, and we chase those waves, shouldn't they travel at a different speed for someone else?
To illustrate why this is a concern, think about a passenger on a train and the book he reads. For us standing next to the tracks as the train rolls by, the book moves by us at a high speed. But from the passenger's perspective, the book in his hands is not moving at all. In fact, if the train ride is smooth and he's not looking out the window, he may not even know that the train is moving. Or is it the Earth that's moving backwards underneath the train? What's the difference? How could you even tell?
This much was known to Galileo already, but light does not behave like this passenger's book. If the Laws of Electromagnetism are the same on the train and on the ground, we should both measure the same speed when measuring a given ray of light, regardless of our own motion. Galilean Relativity cannot explain this.
Einstein's insight was to change the rules. Galilean Relativity 'makes sense' but Nature doesn't care what does or doesn't make sense to us humans. So, let's go where the data leads and simply postulate that however these 'reference frames' (of the train, of the ground) relate to each other, they leave a certain speed (which happens to be the Vacuum speed of light) invariant. As it turns out, this can be done. The resulting transformations are weird, not intuitive, but mathematically self-consistent and agree with Reality.
This takes care of reference frames in uniform motion. That is, reference frames that move at constant speed relative to each other. But this is not general enough. Einstein was interested in describing arbitrary frames of reference, including those of accelerating observers.
This is where another important realization comes in, and this one concern Gravitation. *Gravitation is universal*. This means that unless something (like air resistance) is in the way, all objects fall at the same rate. This, too, was known to Galileo already. But if all objects fall at the same rate and we're one of those objects, what would we see? we would see objects nearby either float near me or move relative to me at a constant speed. In other words, if we're high up in the sky, falling with a bunch of objects around us and we do not see the ground, we would have no way to tell if we're in fact falling, or floating freely in empty space (again, let's ignore the air).
This is important! This means that Gravitation can be 'turned off' (mathematically speaking) by *changing the Geometry*. This means that a theory that deals with the *Geometry of accelerated motion* must – necessarily – *account for Gravitation* as well. This was, reportedly, Einstein's 'happiest thought in life'.
This means that if we extend the Theory of Relativity so that its effects can change from one location to the next and from one moment in time to the next, to deal with accelerating motion, we necessarily also describe Gravity. So, the generalization of Relativity Theory is automatically an extended Theory of Gravitation as well.

This was the path towards what Einstein himself called the 'General Theory'. Once the mathematical formalism was finalized and the theory was published, the previous, 'special' case that dealt only with uniform motion became known as the 'Special Theory of Relativity'.

299 -

If the Universe is already infinite and also constantly increasing in its infiniteness due to expansion, wouldn't that indicate that Energy is not constant in the Universe and, therefore, the law of conservation of Energy does not hold?

First, let's address the premise of the question. While it is true that the simplest Cosmological Model (spatially flat, homogeneous, isotropic Universe with trivial topology) implies an infinite Universe and this model fits the data reasonably well, it does not mean that we know that the Universe is infinite.
We can only explore parts of the Universe that were about 4 to $5 \cdot 10^9$ light-yr from here when the light that we see was emitted (just to make things confusing, that light actually took nearly $13.8 \cdot 10^9$ light-yr to get here, and the parts in question are estimated to be about $46 \cdot 10^9$ light-yr from here today). Light (or any other kind of information) from beyond that just didn't have enough time to get here yet, so beyond that distance, anything is possible. To date, we have no way of knowing and no way of falsifying.
Still, our expectation is that the Universe behaves rationally even beyond the boundaries of the observable region, so, yes, in that case, it is not unreasonable to expect that we live in a spatially infinite Universe.

Expansion does not 'increase its infiniteness'. Infinity is a funny thing. We might think that there are twice as many integers as there are even numbers, but that is not true. It is possible to assign, to every integer, *twice* its value, and it is a one-on-one mapping between integers and even numbers: 1:2, 2:4, 3:6, 4:8, and so on. Thus, the cardinality of integers and even numbers is the same. This should serve as an important reminder that *infinity itself is not a number* and *does not behave like a number*. So, when it comes to an infinite Universe in which things are flying apart, yes, that means that things become more dilute over time, but it does not mean more 'infiniteness'. It just means a more dilute Universe that is otherwise just as infinite today as it was yesterday. [cf/c Issue #563, P. 246]

When it comes to the conservation of Energy, we realize that we are probing a touchy subject here. For sake of clarity, let's first consider a neat equation: $\nabla_{\mu\nu} \cdot \boldsymbol{T}^{\mu\nu} = 0$. This very concise expression carries a lot of punch. As any relativist will tell us, its meaning is that 'the Energy-Momentum Tensor is divergence-free'. What it tells us, basically, is that the Energy of Matter is always conserved, no exceptions, always.
But (there is a 'but', after all), … this formula is manifestly *local*. What it basically tells us is that at any point in Space where there is Matter, if the amount of Energy there changes, that change will be equal to the amount of Energy exchanged between that point and its *immediate* neighborhood. And if we wanted to pretend that we know everything, we'd just finish our answer right here: Energy is always conserved. Except … Let's think about a simple system of two stars, orbiting each other. For the sake of simplicity, we can assume that the two stars are point Masses; yes, there are mathematical ways to deal with that, and they will still obey that neat conservation equation. Everything is working fine until we consider *gravitational radiation*. The combined Gravitational Field of those two stars, orbiting each other, changes all the time. These changes propagate to distant places and carry the ability to do work: to move things at least a little, such as squeezing our own Earth ever so slightly this way or that way, detectable (barely) by the gigantic detectors of LIGO. In other words, these waves carry energy. But $\nabla_{\mu\nu} \cdot \boldsymbol{T}^{\mu\nu} = 0$ says nothing about Energy being carried away to distant places by way of propagating changes in the Gravitational Field (i.e., *gravitational waves*). As a matter of fact, this equation says nothing about the Energy contained in the Gravitational Field at all; and before we jump and attempt to fix the equation, we must pause for a moment and realize that this is the way it should be. Why? Because the fundamental idea behind General Relativity is that Gravity is really just Geometry and, therefore, a suitable geometric transformation, a clever choice of coordinates can always eliminate the Gravitational Field locally (this is basically the idea that if we are floating in a closed elevator cab, we cannot tell, without an external reference, if you are free-falling in the Earth's Gravitational Field or floating in empty space).
This is quite embarrassing, really: we not only do not know what the Energy of the Gravitational Field is, we can actually prove (sort of) that it doesn't have any (locally, at least)! Yet … we have seen since the 1970s that very close pairs of stars orbiting each other lose noticeable amounts of Kinetic Energy over the years, consistent with the idea that they *emit gravitational radiation*. In recent years, we have been able to observe gravitational radiation directly. So, *gravitational radiation does exist* (despite doubts expressed over the past century by some very knowledgeable people). And we have come up with various ways to measure its energy content after all, in the form of various 'pseudo-tensors'. The problem with that, though, is that as the name implies, these 'pseudo-' quantities do not behave as physical quantities should: their value is not independent from the (completely artificial, *subjective*) choice of coordinate system that we use to represent things. This topic is far from settled, even in 2021.
So back to the question, then, about Energy conservation. *Energy is always conserved locally*: $\nabla_{\mu\nu} \cdot \boldsymbol{T}^{\mu\nu} = 0$, always.

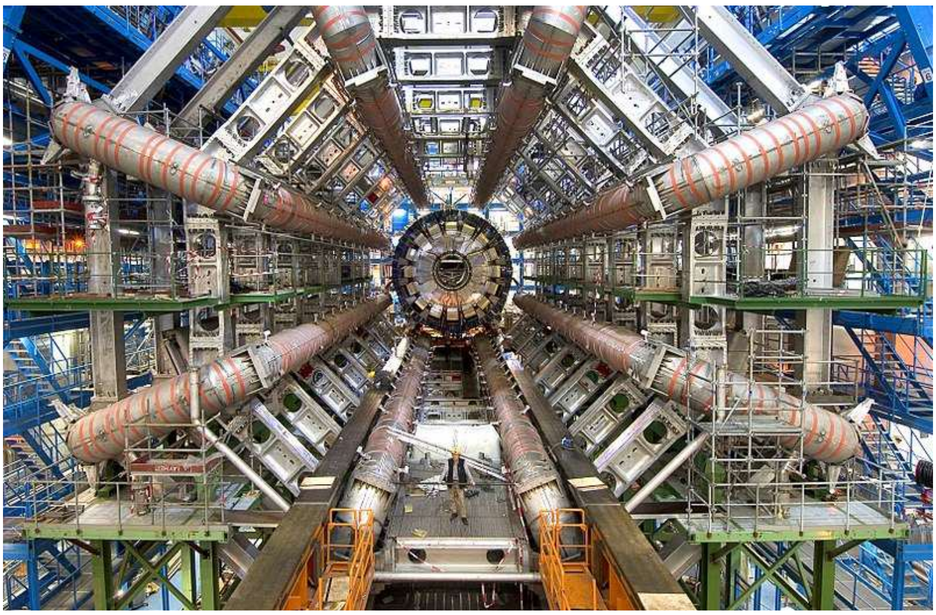
But this statement conveniently ignores the Energy of the Gravitational Field itself. With some effort, we might be able to say something about the Energy in a larger but finite volume, Gravitational Field included, using pseudo-tensors or other contraptions. But the total Energy of a possibly infinite Cosmos? As far as we know, there is no meaningful way to define its Energy content, much less deduce any statement about some hypothetical global conservation of Energy.

300 -

How many fields are there in Quantum Field Theory (QTF) and how are they organized spatially?

QTF is a generic framework. The number of fields is unspecified; the framework is used by postulating the Matter-content separately. In the Standard Model of Particle Physics, the field content is usually described by its symmetries: $SU(3)_c \times SU(2) \times U(1)$. These symbols correspond to the *Strong* (*Color*) Interaction, the *Weak Interaction* and *Electromagnetism*. The fields mediating the Strong Interaction (gluons) are massless; the $SU(3)_c$ group in this case has 8 independent particle degrees-of-freedom. The weak $SU(2)$ group has 3 particle degrees-of-freedom, whereas $U(1)$ (Electromagnetism) has 1 .

Apart from these fields that mediate the known forces, we also have *fermions*, organized into *left-handed doublets* (e.g., electron + elecrton neutrino, $e^- + \nu_{e^-}$) and *right-handed singlets* (except for the neutrino). The total number of the resulting particle degrees-of-freedom is 7. However, these fermions come in 3 nearly identical generations (electron, muon, tau) that differ only in Mass.
Lastly, there is the *Higgs Field* that originally appears in the theory as a complex-valued scalar doublet; but out of its 4 real degrees of freedom, 3 are 'eaten' as the longitudinal degrees of freedom of the massive vector bosons of the Weak Interaction, leaving only one scalar degree of freedom that we recognize as the *Higgs Boson*.
If this explanation sounds a little complicated, it's because it is! The Standard Model is a massively complicated piece of business that is also manifestly unfinished: Its massless neutrinos obviously don't match reality (as evidenced by neutrino oscillations and the measured components of the neutrino Mass mixing matrix), while the resulting concerns about renormalizability, the large Mass differences especially between fermion generations, the absence of additional fermion generations, the large number (up to 26) of dimensionless parameters that characterize the model but which are not predicted by any theory all remain unexplained, and then of course there is the business of incorporating Gravity and extending (or replacing) the theory to make it work up to and beyond the *Planck scale*.
In other words, it's work-in-progress, and many physicists believe that QFT itself is not the way to go to find the needed answers. But these are specific statements about a specific model. The QFT framework is agonistic as to what particle model we use. Therefore, many QFT textbooks begin by introducing fields that do not exist in Nature (e.g., a simple *massless scalar field*) because they are pedagogically useful introductions to the methods of QFT, allowing a student to learn the tools before applying them to more complex scenarios.



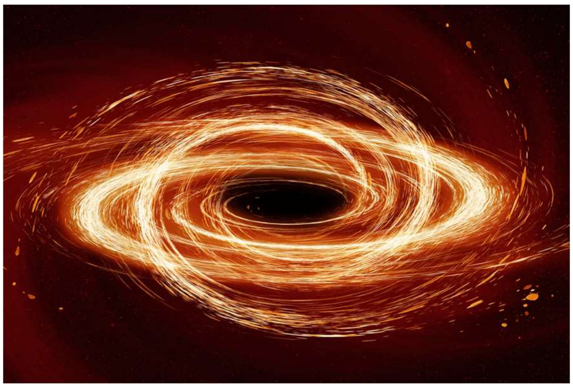
The ATLAS inner experimental structure (CERN)

301 -

Near the *event horizon* of a SMBH (Super-Massive Black-Hole), no '*spaghettification*' (see figure below) will take place because of *weak* gravitational accelerations. But the curvature of SpaceTime lines is *extreme*: an event horizon will 'form'. So, does this region belong to the *weak field limit* or not?

If we are interested in Classical (as in, non-quantum) Gravity, we might be working in what is known as the *post-Newtonian framework*: the Gravitational Field expressed as Newtonian Gravity plus progressively smaller corrections, essentially a power series. This framework breaks down near the event horizon of any black-hole. It relies on the assumption that velocities are small $(v/c \ll 1)$ and deviations from the metric due to Gravity are *small* $(G\mu/(c^2r^3) \ll 1)$. Both these conditions fail in the vicinity of a black-hole's event horizon: things in orbit would be *orbiting at near the speed of light*, infalling things would be accelerated to near the speed of light, and, well, the Gravitational Field is quite strong, *strong enough to twist SpaceTime into an event horizon*.

On the other hand, if we are particle physicists interested in Quantum Gravity, we'll find that the Gravitational Field of a black-hole, stellar or super-massive, is *far too weak for Quantum Gravity effects to matter*. Even in the immediate vicinity of the black-hole, the interaction is just not strong enough for individual gravitons to be seen, for quantum effects to matter. For that, we'd have to go far beyond the regime of the event horizon, approaching the singularity itself, to encounter conditions resembling the Planck era of the early Universe, with the Gravitational Interaction approaching the strength of Electromagnetism and producing discernible quantum effects. In other words, even at the event horizon, the Classical Theory is perfectly adequate to describe conditions: Quantum Gravity will not yield any observable effects. The *Weak Field limit* applies.



Space '*Spaghettification*' of SpaceTime curvature lines in moving into a black-hole

302 -

Why do some physicists insist virtual particles are just math while others say they're real, citing the *Casimir effect*?

Because words in any language do not have unambiguous, precise definitions and their meaning often depends upon context.

'*Real*' particles are real in the sense that *they can be detected*. A Geiger counter registers the arrival of a charged particle with an audible click. A fluorescent screen lights up briefly when an electron hits it. A sensitive photodetector produces an electrical signal when it detects a single photon. There, these particles are obviously 'real'.

'*Virtual*' particles, by definition, *do not do any of these things*. They are '*off the Mass-shell*', meaning that they can have *arbitrary Energies and Momenta*, as they appear under an integral sign when we calculate the *multitude of ways* in which a physical process can take place.
But let's hold on a moment … did we just say *physical*? We are still talking about tangible, observable things, like the Casimir effect, where we observe a small force between two conducting plates in a Vacuum. It should be noticed that *we are not actually observing virtual particles*. We observe what happens when the Electromagnetic Field, confined between charged plates and thus subject to different boundary conditions, behaves differently from the *free* Electromagnetic Field. We observe what this means in terms of the zero-point Energy of these fields which is a manifestly quantum thing. When we calculate it in detail, we may resort to mathematical expressions that involve, we guessed it, virtual particles: which is a nice, pictorial expression assigned to a mathematical expression that is the integral of the free particle propagator in *Momentum Space*.
So, the Physics that we describe using virtual particles is real. The (real) particle content is *real*, too, in the sense that these particles are *directly detectable* using appropriate instruments, but even here we must pause for a moment: if we allow accelerating observers or Gravitational Fields, two observers may no longer even agree on the particle content

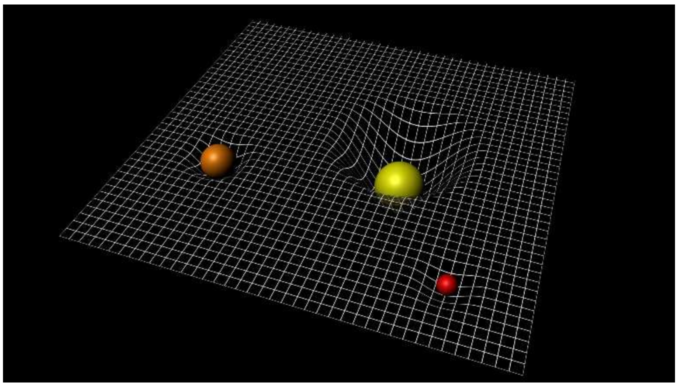
they see! E.g., an accelerating observer may see *Unruh Radiation* where an inertial observer sees nothing. So, are these particles 'real' or not? They are: the inertial observer may not see Unruh Radiation on his own, but he can certainly observe his accelerating counterpart interacting with the Electromagnetic Field.

However, ultimately, it's like arguing about the number of angels on the head of a pin. What makes a 'real' particle real is simply that it can, at least in principle, be observed. If a particle cannot be observed even in principle, it's 'virtual'. The part of what 'in principle' means and how it depends on the Energy scale involved with the observation is left as a topic for another day …

303 -

What's an intuitive description of *curved SpaceTime*?

The popular image of Gravity with a heavy ball pushing down the rubber sheet of a trampoline. Rubbish. It is worse than *misleading* in a variety of ways, so it is definitely *not something that should be used* (see here below).



The problem is that the Gravitational Force we experience in our everyday lives, i.e., Newtonian Gravity, has to do with the *rates of clocks*. It is not the bending of space; it is the *changing rate at which clocks tick at different locations*. And the reason why this is of importance is because objects follow trajectories between events that *maximize* the amount of time the objects would measure. This is dictated by the Lagrangian concept, the *Principle of Least Action*. So rather than offering an intuitive description, which we do not have, let's offer a little bit of intuition why this geometrization of Gravity is possible in the first place: it has to do with the *Weak Equivalence Principle*.

The Weak Equivalence Principle states that all objects respond to Gravitation the same way, regardless of their material composition. What this means, in practice, is that if we are freely falling in a Gravitational Field, other freely falling things that are near us will either be stationary or move at a constant velocity as measured by us (this is why we feel 'weightless' in a space vehicle: the vehicle and we fall at the same rate, so relative to us, the vehicle is not accelerating at all). But this means that if we didn't know any better, if we were stuck in a windowless elevator cab that is freely falling, we might as well think that we are floating far from any gravitating body in empty space! (of course once the elevator cab reaches the bottom of the shaft, our perception would change rather rapidly ... and dramatically).

To be more technical, this means that for a freely falling observer in a Gravitational Field, there is always a frame of reference that appears '*locally inertial*', that is, indistinguishable from the reference frame of empty space. In other words, Gravity can be 'transformed away' by a *geometric transformation*.

This, then, is the intuition behind the geometrization of Gravity: if it can be transformed away altogether, that means it can also be represented by a geometric transformation.

One should also hasten to add that, as evident from some of his private correspondence, Einstein himself thought of this geometric view of Gravitation as not much more than a 'mental aid'; he still viewed Gravitation very much as a physical force, an interaction between bodies mediated by a physical field, not some artifact of Geometry.

304 -

Physicists state that the Universe is about x light-years large and y light-years old. We know these numbers are approximate. How can they be certain by just observing light, of size and age? How do they know for how long the light has been traveling?

Physicists *don't* state that the Universe is x light-years large and they most certainly *don't* state that it is y light-years old since light-years measure *Distance*, not *Time* (the distance that light travels per year, approximately 10^{12} km).

When we read estimates of the size of the observable Universe (the entire Universe, in the Standard Cosmological

Model, is actually *infinite*) they are indeed approximate, and simply reflect a calculated result of how far objects that had a chance to influence us in the past would be from us today. When we read estimates of the age of the Universe (measured in years), these are based on the observed rate of expansion of the Universe, extrapolated backwards to determine the time (under the rules of General Relativity) that elapsed since the so-called initial singularity.
All of this is based on observing light from distant things, though not only light: we observe electromagnetic waves across the spectrum (from radio to gamma rays) and, in recent decades, we also began to utilize *neutrino observations* and *gravitational wave observations* in the emerging discipline of 'multi-messenger astronomy'.
But it's correct, we of course do not know a priori how long light has been traveling. *That is deduced*.
To explain how, let's consider a simple analogy. Suppose we see an airplane in the sky. We recognize from the distinctive hump that it is a Boeing 747. We know how big a 747 is by looking up its specifications on Wikipedia. Buy observing how big it appears in the sky, we can ascertain its distance. We also hear the drone of its engines. Knowing how fast sound travels in air, we know how long it took for that sound to arrive.
The next day, we hear a 747 but we don't see it. The sky is cloudy or perhaps it's late at night, but now that we're familiar with the distinctive drone of its engines, perhaps aided by acoustical instruments or appropriate software, we ascertain that it is indeed a 747; and from previous measurements, we can deduce from the loudness of the sound just how far that airplane is. Using more than one microphone and clever software, we can even pick up its approximate direction.
Astronomers do similar things in the sky. They start with known things, say, a star that has all the same characteristics as our Sun. Simply observing how bright it appears compared to our Sun, we can ascertain its distance. And knowing (from experiment) how fast light travels in a Vacuum, we can ascertain how long it took for that light to arrive. Once we know how far a Sun-like star is, perhaps it has a companion in a binary system. Or, perhaps, it's part of a dense cluster of stars. Now, we have different types of stars the distance of which is known. Some of these stars are bright enough to be visible in other galaxies. This way, we can build what astronomers or cosmologists call a 'distance ladder', reliably ascertaining the distance of ever more distant things in the Universe.
This is how we stumble upon the relationship between distance and redshift. That is another property of light: its wavelength. Specific chemical elements emit or absorb light at characteristic wavelengths. We see these wavelengths shifted in light from distant objects. This shift is actually predicted by the mathematics of an expanding Universe. Observations of the shift help us nail down the parameters that characterize this model. One of them is the *Hubble-parameter*, which characterized the expansion rate itself. The other is the so-called *deceleration parameter* that characterizes the rate of acceleration (that's confusing: the deceleration parameter was defined in the literature before it was recognized that its value is negative, as the rate of expansion is *accelerating*, not decelerating).

So, this is how we know. As in all the sciences, we build upon previously established knowledge, layer upon layer, one layer at a time.

305 -

Why does a distant galaxy moving away faster than light not violate Special Relativity? An electron can't do that, but that receding galaxy would be full of electrons doing just that.

Distant electrons and distant galaxies are both *allowed* to move faster than the speed of light *relative to us in curved SpaceTime*. They will be hidden from us by an *effective* event horizon (the *cosmological* horizon) and they will not be moving faster than the Vacuum speed of light *at their location*.
In short, one should *never* try to apply *flat* SpaceTime *nor* special relativistic reasoning to the *curved* SpaceTime of General Relativity, i.e., to the current, recognized, General Theory of Gravitation.

306 -

An individual photon red-shifts as it travels through expanding space and therefore, as its wavelength increases, its Energy content decreases. As Energy cannot be destroyed, what balances this example photon's Energy loss?

Individual photons *do not* redshift. The redshift (difference in frequency or Energy between emission and absorption) is observed because we, the observers, are moving relative to the object that emitted the photon, even though both we and the emitter may be in our *locally* '*co-moving*' *reference frames*, in which, we both observe the Cosmic Microwave Background as isotropic *at our* respective locations.
If we had access to a fast spaceship and started traveling in the direction of the object emitting the photon, carefully calibrating our speed such that our distance from the emitter remains constant over time, we would notice that there is *no red-shift at all*.
As a more general reminder, let's keep in mind that motion (i.e., Linear Momentum), red-shift, Energy are quantities that depend on the *reference frame of the observer*, in Relativity Theory. They *are not* intrinsic properties of a photon or any other particle or object. Two observers may very well measure different values for these quantities. It does not

mean that we created or destroyed Energy or Momentum. It simply means that *the two observers are not using the same reference frame*.

307 -

Can the Heisenberg Uncertainty Principle cause objects to have an area of probable existence outside their light cone?

An excellent issue, which is indeed one of the rationales in favor of Quantum Field Theory (QFT). Ordinary Quantum Mechanics does not know about Relativity Theory, so, it certainly can *violate relativistic causality* and all that, no surprise there.
But what about Relativistic Quantum Mechanics? The theory of course had considerable success; it was, among other things, the first theory that predicted the existence of anti-Matter. As the name suggests, it is a relativistic theory, so we might expect it to obey causality. But it does not. Precisely because of the Uncertainty Principle, acausal behavior can 'leak' in from outside the light cone.
But QFT is different. In the case of QFT, things outside the light cone are canceled out exactly. There is no residual probability. No exponentially diminishing but non-zero chance of the future influencing the past or an influence to propagate faster than c. And the best part? This perfect cancellation of acausality is retained even when we do QFT on the curved SpaceTime background of General Relativity.
This, along with its ability to account for particle creation and annihilation, are the two main reasons why QFT remains the preferred theory of Matter, even though many suspect that it, too, will ultimately be superseded by something better, as it fails to account for Gravitation and may break down completely at or near the Planck Energy scale.

308 -

If a photon has no *rest-Mass*, how can it eject electrons by hitting them?

To move something, we do not require rest-mass. What we require is Energy and Momentum.
A photon has no rest-mass, but it does have Energy and Momentum. When it is absorbed by an electron, its Energy, Linear Momentum (and also its Angular Momentum) are transferred to the electron. If the photon had rest-mass, the Energy equivalent of that rest-mass would also form part of this transfer. Since the photon's rest-mass is zero, that term is zeroed out in the resulting equation. But that's okay because the photon still has *Kinetic Energy*.

309 -

Do virtual particles occur everywhere constantly and, if so, do they exert Gravity?

This question relates to one of the most profound unanswered questions in Cosmology. Yes, virtual particles occur everywhere, even in supposedly empty space. One way of looking at it (as others mentioned) is that the Uncertainty Principle would be violated if the Energy density of the Vacuum were precisely 0. Instead, the Energy of the Vacuum depends on the amount of time we spend looking at it; *the shorter the time*, *the bigger the Energy density*. For brief moments in Time, virtual electrons and positrons can come into existence, only to wink out of existence almost instantly. For even shorter moments in Time, much more massive particles can be created from nothing so long as they annihilate rapidly enough.
Now, the second part of the question is where things really get interesting. So, the Vacuum has some 'baseline' value of Energy associated with it. Who cares, one might say ... we are normally only interested in differences in Energy, which is what it takes to do useful work. Except when it comes to Gravity, which acts on the *actual Energy content*, not on differences. If the Vacuum has an Energy density associated with it, *it gravitates*, because (as far as we know) the Weak Equivalence Principle means every form of Energy gravitates the same way.
So, what is the Vacuum's Energy density due to all these virtual particles? A naïve calculation yields a divergent result: it's infinite. That's no good ... *infinite Energy density means infinite Gravity*, so, the Universe would collapse into nothing instantaneously.
A somewhat less naïve calculation introduces a cutoff at the Planck Energy scale and yields a finite number. But ... that number is still huge, *many orders of magnitude larger than anything sensible*. So, for a long time, cosmologists assumed that either Vacuum fluctuations do not gravitate, or maybe they don't even exist.
But then came the *Type* Ia *supernova* results, interpreted as an *accelerating* Universe. This acceleration comes about because of a presumed value for the so-called Cosmological Constant. The most evident interpretation of this constant is that it really is the Energy associated with Vacuum fluctuations. This would tie things together rather neatly, were it not for one little obstacle: the value of the Cosmological Constant inferred from supernova observations is some 120 orders of magnitude (!) smaller than the Energy density of Vacuum fluctuations calculated from theory. This is the so-called Cosmological Constant Problem, one of the worst unsolved problems in Theoretical Physics.

310 -

Do most things in Physics and where they are derived from come down to the Boltzmann Constant, the Gravitational Constant, Planck's Constant, and c ? [see answers to Issues 91, P. 40-41, and 207, P. 95]

Actually, quite the contrary: these being dimensioned constants, they can be easily eliminated from fundamental physics equations altogether by selecting units of measure that are 'natural' as opposed to units that are derived from human cultural traditions and the physical properties of our home planet.
Take the speed of light. Why is it $c = 299792458$ m/s? Because we express length using a unit originally derived from the polar circumference of our home planet, and we express time using a unit derived from the rotational period of the same planet. Nothing prevents us from using units in which $c = 1$.

Take the Gravitational Constant, $G = 6.67408 \cdot 10^{-11}\ \mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. Again, it has the value that it has because it is based, in addition to our culturally-inspired units of Length and Time, another culturally inspired unit, the *kilogram*, originally defined in terms of the gram that happens to be the Mass of a cubic centimeter of water under circumstances characteristic of our planet's surface. Again, nothing prevents us from using units in which $G = 1$.

Planck's Constant is a bit trickier, as it does nail down the magnitudes of the actual units (as opposed to their ratios) but it, too, can be set to 1 by an appropriate choice of units.
Finally, Boltzmann's Constant again depends on the definition of a unit, that of Temperature, that in turn is based on the properties of water on the surface of our planet. For this one, too, we can set the constant to 1 by choosing a different unit of Temperature.
In other words, when it comes to Fundamental Physics, none of the aforementioned constants matter: on the contrary, it is customary to assume that equations are expressed using units of measure such that these constants are set to 1 and can be omitted from the equations altogether.

311 -

How are we so sure that space is expanding and not the objects moving away from us?

First of all, what's the difference? How could we even tell the difference? We do not measure Space. Space does not have markers attached to it. What we measure is the *distance between objects*. When the distance between two objects increases for whatever reason, we say that those two objects are moving away from each other.
Objects in this Universe are moving away from each other. This much, we can actually derive from Newton's Laws, so no Relativity Theory is needed. The expansion is 'written into' the equations of Classical Mechanics, so to speak, together with its concept of *absolute Space* and *Time*.
But, what about *redshift*? Photons get stretched as they arrive from distant objects! Doesn't that mean that Space was expanding, stretching those photons? No. *Photons do not have an inherent wavelength*. Any stretching that is observed is the result of observers not being in the same inertial reference frame. The observer at a star that emits those photons is moving *relative to us*. So, there is some good old Doppler redshift, no more mysterious than the deepening of the sound of the siren of an ambulance car after it passes us.
There is more to this redshift business! For objects that are very, very far away, we also need to consider *gravitational redshift*. Light that comes from these objects was emitted at an epoch when the Universe was much denser than today, so, there was much more average Gravity. This light, coming from the past to the present, is 'climbing out' of a gravitational well, losing Energy. Hence, it appears redshifted incidentally, all this could be made to go away if observed that light on the surface of a very massive gravitating object that is moving in the direction of the source of light. If the gravitating object's velocity matches that of the source and its Gravitational Field compensates for the difference in Gravity between now and then, the photons we observe would arrive with no redshift at all.
On the other hand, what about things moving away from us faster than light? Surely that proves that it is Space that's expanding? Not exactly. It simply shows that the SpaceTime of this Universe is not 'flat'. And yes, the metric of SpaceTime changes with Time and, yes, it means that there are regions of SpaceTime that are causally not related to ours, and vice-versa. Even this does not make Space a measurable quantity, though. It simply means that, to the extent that a distance can even be meaningfully defined between such distant objects, this distance is increasing at a rate larger than c, the *Vacuum speed of light* (even though neither object moves faster than light).
One source of confusion comes from the fact that it is convenient to represent expanding SpaceTime using co-moving coordinates. As the name suggests, co-moving coordinates represent a coordinate system in which the coordinates of things that move with the bulk (or equivalently, things that are at rest with respect the Cosmic Microwave Background as seen from their location) do not change. So, how can it be that two objects do not change position in a coordinate system yet the distance between them increases?
But this is the point to remember that coordinates are mathematical abstractions, not physical reality. We do not measure coordinates. We measure distances between things. And when the distance between two things increases for whatever reason, those two things are moving away from each other.

312 -

Is it possible that any part of the known Universe might have a *negative Time*?

Einstein's General Relativity is *Time-symmetric*: Time could run backward or forward. In other words, it would be possible (theoretically) that any part of the known Universe could have backward Time.
The arrow of Time is determined by Thermodynamics. As far as we know, our Universe is characterized by a lower Entropy state *in the past*. Therefore, Entropy is *increasing in the future-pointing direction*.
If this were any different in a distant part of the Universe, that would be radically new Physics. As to the boundary between regions with a lower Entropy past and regions without (and perhaps with a lower Entropy future) … we cannot even begin to speculate what that would look like (weird, surely). But we can consider it *extremely unlikely*, bordering the impossible, never even mind our Universe, simply that such a Universe can exist as a *mathematically self-consistent* entity.

313 -

Why does the redshift of light from distant galaxies lead scientists to conclude that Space is expanding, instead of them simply concluding that distant galaxies are travelling away from us faster than nearer galaxies?

The business of expansion is simple and complicated at the same time. It is simple in the sense that its basic equations can be derived from Newtonian Physics. We don't even need General Relativity. Right there, that should tell us that Space isn't doing a thing here: *in Newtonian Physics*, *Space is absolute*, so whatever happens, it happens because it is stuff (that is, the *Matter-content* of the Universe) that is flying apart.
In the *relativistic* context, *the same remains true*. When two galaxies are a greater distance apart today than they were yesterday, it means that they are flying away from each other, period. What makes things messy and a source of much misunderstanding is that at the same time, both galaxies may be at rest with respect to the Cosmic Microwave Background radiation, as viewed from their respective locations!
But things can get worse. The Universe in the Standard Cosmological Model is *infinite in spatial extent*, which means that we can, in principle, find galaxies arbitrarily far away from us. These galaxies can be receding from us at a rate far, far in excess of the Vacuum speed of light (i.e., c). This seems like a contradiction until you consider that those distant galaxies, too, are at rest (more or less) with respect to the Cosmic Microwave Background at their location. They are certainly not moving faster than the Vacuum speed of light.
These things can easily lead one to conclude that, well, ultimately all galaxies are at rest (more or less) and it is Space that is expanding. However, this is a naïve conclusion that fails to account for two simple facts, one theoretical, one observational.
The theoretical fact is that even if these galaxies are indeed at rest in the 'co-moving reference frame', the choice of reference frame in General Relativity is *arbitrary* and carries no Physics content. Physics does not depend on what coordinate system we, human researchers, choose to represent it.
More importantly, let's just think a moment what velocity means: a change in position over time. So, let's forget about Space, about reference frames, and ask a very simple question. If we have a clock and a means to measure distance (using meter sticks or perhaps using a combination of light rays and clocks) so that we could measure the distance between two galaxies and how it changes over time, what will we see?
We will, of course, see that the distance increases over time. In other words, however we interpret it, those two galaxies are moving away from each other.
This remains true even if we add all the complications due to a changing Gravitational Field, consequently changing *time dilation*, and perhaps even changing *lengths* due to varying spatial curvature in our expanding Universe.
Last but not least, note that whereas we can measure distances between galaxies and time intervals between events involving objects (e.g., light rays being emitted or detected) Space and Time on their own *are not measurable*. They do not have independent physical existence. Empty space does not have markers that we can use to measure its expansion. Time on its own does not 'tick', absent a material clock. *What we measure is what things do*, *not Space and Time*. Which is why serious physicists seem to have little doubt that distant galaxies are, in fact, moving away from each other.

314 -

Is SpaceTime the quantum field associated to the *graviton*? Can SpaceTime even be considered a quantum field whatsoever? If so, does this not violate the idea that quantum fields exist in Space and Time?

No, not SpaceTime. Rather, a specific element of the '*SpaceTime metric manifold*', notably the metric itself. Otherwise known as the *Gravitational Field*. Nowadays, it is fashionable to describe Einstein's work on Gravitation as a *geometrization of Gravity*. It is important to remember, though, that Einstein himself was not particularly fond of this geometrization, that he considered it little more than a useful *mental aid*, and he never stopped thinking of Gravity as a

proper force, an interaction between material bodies, also as a field that, just like the Electromagnetic Field, carries Energy and Momentum at a finite speed, e.g., in the form of *gravitational radiation*.
As we now have experimental evidence (with numerous LIGO observations) that this is indeed the case, we should stress that the geometric interpretation notwithstanding Gravity is, first and foremost, a physical field mediating a force. This physical field is mathematically represented by the SpaceTime metric. We do not know how to turn the classical theory of this physical field, Einstein's Theory, into a proper Quantum Field Theory. However, we do know (more or less) what this theory would look like in the weak field, 'perturbative' limit. In this limit, the Gravitational Field, i.e., the metric, would be 'quantized' in the form of elementary oscillators that, in turn, are characterized by the usual *annihilation* and *creation* operators, creating and destroying *units of Energy*, *field quanta*. We call these field quanta *gravitons*. So, *gravitons would be the elementary excitations of the Gravitational Field*, also known as the metrical field of SpaceTime. This field exists in SpaceTime, just like all other quantum fields. It is not SpaceTime: it is a property of the SpaceTime manifold, the property that determines physically measured distances and intervals of time.
Of course, in the *absence* of a complete Quantum Theory of Gravity, it is eminently possible that perhaps Gravity is subject to different rules and may not be a quantum theory at all. Who knows? These remain open questions for now.

315 -

Why is Einstein's Theory of Relativity considered as a *theory* and not a *law*, and why is it unable to explain some astronomical aspects?

This question is about informal or semi-formal usage of terminology, also confusing every day, colloquial usage of certain terms with the way it is used (albeit not always consistently) in the Sciences.

Let's start with a relevant dictionary definition from The American Heritage Dictionary:

a. Systematically organized knowledge applicable in a relatively wide variety of circumstances, especially a system of assumptions, accepted principles, and rules of procedure devised to analyze, predict, or otherwise explain the nature or behavior of a specified set of phenomena.

b. Such knowledge or such a system.

Of course, this is not the meaning that we had in mind when we were wondering why Relativity is a *theory* and not a *law*. *Theories do not become laws in Physics*. Basic principles, or axioms upon which theories are based, are sometimes called *laws*. At other times, empirical relationships that were first discovered with no theoretical context are often first called laws, even when they are later explained in the context of a broader, more fundamental theory.
Let's take, for instance, Newton's 1st Law, the law of inertial motion (*An object either remains at rest or continues to move at a constant velocity, unless it is acted upon by an external force*). Newton did not derive this law. Rather, it was based on observation data, i.e., it was an empirical relationship that Newton simply postulated to be true.
Later, with the birth of Lagrangian Physics, we learned how this law can be derived from a more fundamental principle, the *Principle of Least Action*. We also learned that Newton's version is just a special case as, more generally, *objects travel along geodesics, not straight lines*. That alone should tell us that the Theory of General Relativity is far more fundamental, far more far reaching than the empirical Laws of Newton.
As to the limitations of General Relativity in astronomical contexts, we don't know for sure if there are any! In fact, the general consensus is that General Relativity works even on the largest of scales; to the extent that any conflict exists between theory and observation, it is because of our failure so far to detect Dark Matter and Dark Energy and establish their true nature. It is, of course, possible that Dark Matter and Dark Energy do not exist and General Relativity will need to be modified to fit the data, but this seems to be a minority view. In any case, none of this has anything to do with terminology, and our often-inconsistent usage of sloppy words like *theory* vs. *law*.

316 -

Did Einstein discover that the speed of light must be the universal speed limit as a consequence of the preservation of causality?

Not exactly. The constancy of the speed of light is a consequence of Maxwell's Electromagnetic Theory, combined with the observation that the theory remains valid in inertial reference frames that move relative to each other.
In the late 19th century, mainstream Physics attempted to explain this (and electromagnetic phenomena in general) by postulating the existence of a medium, the *luminiferous ether*, which was supposed to be the medium that waves in Maxwell's theory. This approach became increasingly untenable, in part, in light of the null result of experiments such as the celebrated Michelson-Morley experiment that showed no observable effects of the Earth's motion through this medium.
Einstein's radical departure with 19th century Physics was the abandonment of the concept of absolute time. Essentially it means the recognition that we cannot simultaneously assume that all inertial observers measure the same Time with their respective clocks and all inertial observers measure the same speed when observing a ray of light.

The resulting group of transformations were already well known: this is the *Lorentz-group*. This group has some special properties: In addition to leaving the Vacuum speed of light invariant, it also never mixes slower-than-light and faster-than-light speeds. We now recognize that this is indeed an essential property when it comes to the preservation of causality but that was not one of Einstein's motivations when developing the Special Theory of Relativity.

317 -

If an observer fell through the event horizon of the largest black-hole in the known universe, how long would it take for the observer to fall from that event horizon to the central singularity (from the observer's viewpoint)?

As measured by the observer's own clock (i.e., proper time along the observer's worldline), the time to reach the singularity for the largest supermassive black-holes would be measured in a few hours.
A reasonably straightforward calculation yields $t = \pi G\mu/c^3$ for a Schwarzschild black-hole, which, for a 10^9 solar mass black-hole, gives about 4.3 hours. Anyway, the observer would be long dead before the end of those 4.3 hours. For a 10^9 solar mass black-hole, tidal forces at the horizon are still pretty tiny, but they would increase rapidly as the observer approaches the singularity, causing the famous 'spaghettification'.
Also, let this serve as a reminder that although expressions like 'approaching the singularity' are in common use, for an observer who has crossed the event horizon, the singularity is not a location in place but a *future moment in Time* (and the horizon, similarly, is a *past* moment in Time). So, 'approaching the singularity' must be interpreted like 'approaching 5 PM in the afternoon' and not like 'approaching the town center'.

318 -

If the singularity of a black-hole is not a point in Space but, rather a *future* moment in Time, will an infalling observer ever reach it, and if so, what would happen to him?

Indeed, an infalling observer will reach the singularity of a Schwarzschild black-hole in a finite amount of *proper Time* (which may be mere milliseconds for a stellar-sized black-hole).
What would happen to them, we don't know. As the observer approaches the singularity, gravitational forces increase. Even assuming a microscopic observer who is not ripped apart by *tidal forces* at first, as it approaches the singularity, tidal forces grow beyond limit. Eventually, the strength of Gravitation becomes comparable to the other fundamental forces, even at the level of elementary particles. Correctly modeling this would require a Quantum Theory of Gravitation, which we do not have.
So, we really don't know what happens in this final instant of time. But it is very clear that no actual observer (not even a nano-robot) would survive long enough to experience this regime as, by then, tidal forces would rip apart even subatomic particles.

319 -

If the singularity of a black-hole is a moment in Time, what does it mean that even light can't escape when photons don't experience Time? From their reference frame, aren't they unaffected or do they not have a reference frame at all?

Photons do not experience anything, as they have *no observer reference frame* nor do they have *internal states*. Rays of light, however, still travel from the past towards the future.
Inside the event horizon of a Schwarzschild black-hole, the event horizon is a moment in the *past*. The singularity is a moment in the *future*. Since rays of light do not travel from the future to the past, they cannot return to the event horizon and escape the black-hole. It is no more possible than sending a ray of light from today to yesterday, e.g., to inform our yesterday self of today's winning lottery numbers. This has nothing to do with what photons do or do not experience.

320 -

If Time is influenced by Gravity, does that mean that in the 'void space' between two galaxies time will flow really fast, thus making humans and materials age much faster than if they were inside the Galaxy?

No, not 'really fast'. It is true that Newtonian Gravity and Gravitational Time dilation in General Relativity are more or less the same thing. But the actual measure if this Time dilation is tiny, except for the immediate neighborhood of very heavy, very compact objects. For instance, here, in our solar system, clocks run roughly one part in a million slower than clocks in intergalactic space. Even on the surface of the Sun, clocks run only a few parts in a million slower than clocks in those voids. Gravity, really, is *very weak*.

321 -

To which of the following can the concepts of Newtonian Mechanics be applied to? Objects with speed much larger than the speed of light, equal to the speed of light, twice the speed of light, or much smaller than the speed of light?

We can apply the concepts of Newtonian Mechanics to whatever we wish, so, the real question is, supposedly, at what point will Newtonian Mechanics yield nonsensical answers?
For systems with velocities much less than the speed of light: the error will be of $O(v^2/c^2)$, and it's up to us to decide how large that error can be to remain tolerable.
For systems at or above the speed of light, Newtonian Mechanics offers nonsensical results, which do not agree with reality, since in reality (which obeys Relativistic Mechanics), things do not move at, or above, the Vacuum speed of light. The one exception would be massless particles such as *photons*. Their straight-line motion would be correctly described by Newtonian Mechanics but *not their interactions*; in particular, Newtonian Mechanics underestimate by a factor of 2 the extent to which a Gravitational Field affects the trajectory of a massless particle.

323 -

What is the difference between the labels, 'Gravitational Field' and 'Gravitational Force'?

The answer applies to all fields, not just the Gravitational Field. A field determines the Energy of the interaction that the field mediates between objects.
The force is proportional to the rate at which the field changes. That is to say, what determines the force is how much Energy an object gains or loses as it travels a given distance in that field.
In the case of Newtonian Gravitation (which also serves as a very good approximation of General Relativity, except when the fields are *immensely strong* or things move at speeds comparable to c) the Gravitational Field of an object is *inversely proportional to the distance* from that object. The Gravitational Force, however, is *inversely proportional to the square of the distance* from that object.
The same is also true for the Electrostatic Field of charged bodies. Of course, the main difference is that Gravity acts the same way on everything (this is the Weak Equivalence Principle) whereas the Electrostatic Field exerts a force *only* on charged objects.

324 -

Since Gravity *does not* slow the speed of light in a Vacuum but only changes the frequency towards *red*, how do black-holes prevent light from coming out?

As they say, it's a lot more complicated than that.

First, redshift alone is sufficient for light to 'disappear', if the redshift grows beyond limit. As an object approaches the black-hole, its light is increasingly redshifted; as the object gets close to the event horizon, the redshift indeed grows to infinity. That means that the Energy of any photon coming from the object, in the reference frame of an observer outside, will go to zero. So, while the photons are technically still there, it becomes harder and harder to detect them as visible light becomes IR, IR becomes microwaves, microwaves become long-wave radio and so on.

Second, when it comes to that redshift, have we thought about the underlying reason? It's *Gravitational Time dilation*. That is to say, clocks near the black-hole tick much more slowly than clocks far from it. Now, it is true that if we were near the black-hole ourself, light would appear to travel as always at the invariant speed. But a distant observer would be seeing both us and our beam of light in slow motion. So, to that distant observer, light at our location would appear to move much more slowly.

Therefore, all this should tell us that even as an object approaches the black-hole, there are reasons why it would appear to vanish from sight. But that divergent Time dilation has another consequence. When the object reaches the event horizon in its own reference frame is going to be future infinity in your own external observer reference frame. That means that for any signal from the object to reach us after the object crossed the event horizon, that signal would have to travel back in Time from the infinite future. This is the nature of the event horizon: to outside observers, *it is forever in the future*; for observers who crossed the horizon, it is a past moment in time that would require a time machine to return to.

325 -

Some people say one *non-local* model has particles influenced by future interactions with observations. Is that different from *hidden variables*?

Let us first try to explain the concept of *hidden variables*. Suppose we go on a trip carrying a suitcase with our clothes therein. Upon arrival, you find that we only packed half our favorite pair of brown socks. We conclude that the other half is at home in your sock's drawer. By observing the sock in your suitcase and applying a conservation law (socks come in pairs), we instantly gained knowledge about the content of our sock's drawer. But there's nothing mysterious about this. Information about our socks might have been hidden from you before you opened the suitcase, yet it was present all along: the sock in our suitcase 'knew' its color before you looked at it, and similarly, the sock that was left back at home 'knew' its color also.

John Bell's famous theorem about non-locality in Quantum Physics tells us that when quantum systems exhibit a similar correlation, it *cannot be explained* using such hidden variables. Experiments can be constructed in such a way that when we look at the correlation between observations of your suitcase and observations of your drawer back at home, these systems could not possibly have evolved independently towards the observed state: that they must have been in correlation all along. The technical terminology is that *Quantum Physics is not a theory of local hidden variables*. This is what was alluded to in several answers here, and this has serious implications, among them, the fact that the two observations: we opening the suitcase and a family member opening our socks drawer back at home might happen simultaneously. Or, at the very least, they might happen so close in time to one another that no conventional signal can reach from one to the other at the speed of light or less. This means that we cannot unambiguously determine which observation comes first, and which comes second: to some observers, the opening of the suitcase, to other observers, the opening of the sock's drawer happened first. Yet, when we take either, it determines or, at least influences, the outcome of the other. So, which is cause and which is effect?

The 'conventional' interpretation of Quantum Mechanics is that observation, which confines a quantum system to a classically observed eigenstate, amounts to 'wavefunction collapse': a non-unitary evolution of the wavefunction into, well, a different wavefunction. But if the temporal ordering is observer-dependent, then which of the two observations caused this collapse? Whichever did it, at least as seen by some observers, the wavefunction collapse must be retroactive, backwards in Time, to ensure that the other observation remains in strict correlation with the first.

This is why, in some people's considered opinion, the concept of 'wavefunction collapse' solves nothing; it simply kicks the problem down the road but actually makes it worse. We'd much rather just embrace that Quantum Physics is non-local from the onset, especially as (in particular, this can be proved in the context of Quantum Field Theory) its non-locality does not undermine *causality* either on the microscopic or the macroscopic (classical) level.

But if we discard the concept of non-unitary collapse, it means that the wavefunction of a system that will encounter a classical instrument *in the future* must 'sense' that instrument ahead of Time in order to evolve towards what is an eigenstate with respect to that future measurement.

Ultimately, we see it as Lagrange's revenge: the concept of Lagrangian Physics, where the initial and final (!) states of a system are used together as boundary conditions to determine the equations of the system's evolution, finds its natural home in the context of Quantum Physics. Ironically of course, in the canonical formulation we develop Quantum Physics instead using the Hamiltonian formalism, which relies on initial positions and velocities instead. This, in turn, leads to the Uncertainty Principle, as Position and Momentum variables *do not commute and thus the system cannot simultaneously be in an eigenstate with respect to both*. We interpret this as our inability to measure\describe a system's Positions and Momenta with arbitrary accuracy, hence, necessarily *resulting in a probabilistic description*.

326 -

Some people say the 'rubber sheet' analogy for SpaceTime is deeply flawed. Why? It's not perfect, of course, but it seems to get the point across.

[see answer to Issue 303, P. 139]

The rubber sheet analogy is deeply flawed for two reasons: *first*, it would not work without Gravity! I mean, it's one thing to place something heavy in the middle of that rubber sheet, but that thing is only heavy because the Earth underneath the rubber sheet pulls it down. I was asked countless times the question, what "pulls" things in the rubber sheet representation of gravitation? And of course that's not the way things work.

This leads us to a second point which is even more important: the rubber sheet analogy wrongly suggests that Gravity is about curving Space. It most emphatically is not: spatial curvature is a 'post-Newtonian' effect that produces only a tiny, tiny correction to Newtonian Gravity and becomes significant only when relativistic speeds or extreme gravitational fields are involved.

What Gravity does primarily is that it makes clocks *run slower*. That is the term in Einstein's General Theory of Relativity that corresponds to Newtonian Gravity. Trajectories are deflected not because objects follow curved paths in Space, but because objects follow paths of *maximum proper Time* between events in SpaceTime.

This is not quite as easy to understand and certainly hard to visualize but this is the real Physics. The rubber sheet? It is worse than misleading because it conveys the illusion of understanding while, at the same time, completely misleads the unsuspecting reader.

327 -

How does a photon or an elementary particle 'know' it is being observed during experiments vs. when it is not observed?

A photon or some other elementary particle doesn't 'know' anything. It certainly doesn't know if it is being observed. *An elementary particle is a unit excitation of a fundamental field. E.g., the photon is a unit excitation of the Electromagnetic Field. Its basic properties include, e.g., its Energy-Momentum and Angular Momentum, which are strictly conserved quantities*.

Interactions between fields create or destroy such unit excitations. So, for instance, a photon may be created when the field of electrons interacts with the electromagnetic field. We visualize this as an electron emitting or absorbing a photon, but it is helpful to remember that we are describing the interactions of quantum fields, not miniature cannonballs emitted or absorbed by other miniature cannonballs.

In fact, during most of these interactions between elementary particles, when they are 'unobserved', they are in states that correspond to a multitude of possible Positions, Momenta, Energies, etc.. Conservation Laws are strictly obeyed, but we do not know which specific particle carries what amount of Energy or Linear Momentum or Angular Momentum; it could be a photon, could be an electron-positron pair emitted by and then reabsorbed by the photon, could be any other legitimate combination of such particles.

Sometimes, the interaction cannot be characterized at the level of individual particles, e.g., as in the example where the photon interacts with a specific electron. It is possible that the photon interacts with the 'bulk' of a macroscopic object, made up of an exceptionally large number of electrons and protons (both of which, on account of having electric charges, interact with the Electromagnetic Field).

The macroscopic object, with its exceptionally large number of electrons and protons, may behave in such a manner that its quantum behavior is 'averaged out'. So, for all practical intents and purposes, it is a 'classical' object. When a photon interacts with such a classical object, the interaction confines the photon to a classically meaningful state. E.g., the interaction may be such that it confers upon the photon a specific position.

This is not something the photon 'knows'. Rather, the interaction with the object 'measuring' its position ensures that the photon is confined to a state in which it actually has a classically defined position. To put it another way, the presence of the instrument creates boundary conditions on the Electromagnetic Field such that when the instrument actually detects an individual photon, that photon will have certain classically measurable properties (as to what those properties are, that depends on the nature of the object or instrument and its interaction with the Electromagnetic Field).

328 -

How did Einstein predict the shifts in the orbits of Mercury?

A short foreword, by Matt Crawford (Ph. D. in Theoretical Physics from Un. of Chicago, computer analyst, retired), is in order here:

> Einstein *did not* predict the precession of Mercury's orbit, the precession was already known, but he did explain it. Now, an explanation of an existing fact doesn't carry much weight unless it also predicts some things that have not yet been seen or measured and Einstein's explanation of Mercury's orbit also implied some other things, which had not yet been looked for. Foremost among these predictions, was the *angle* by which light form a star would be bent when it passed near the Sun. According to Newton's theory of Gravity, it would be bent a certain amount, and Einstein predicted *double* the bend. No one had yet measured this, so off they went during the next solar eclipse.
> But that was a quibble about explain vs. predict. To get back to the how … Einstein *took as a principle* that, if measurements are conducted purely locally (in a *small* volume, for a *finite* time), then *the effect of Gravity cannot be distinguished from acceleration*. Add to that the principle that the Laws of Physics should be *the same for everyone*, *even if they are accelerating*. And out comes a new theory of Gravity: those principles together yielded a new Theory of Gravity that agreed pretty well with Newton's when gravitational forces are *small* but differed when forces are *large*. Calculating with the new theory gave a much better account of Mercury's orbit and predicted the bending.
> Now we have other tests as well, including the *timing of clocks* on satellites and the observation of *black-holes* and *gravitational waves*.

The *short* answer to the question is: the *perihelion advance* of Mercury is predicted by solving the equations of motion for a test particle (the planet) in the Gravitational field of a point-source (the Sun) in the first order post-Newtonian approximation of General Relativity. The *long* answer is not terribly complicated, but we need to know what we are doing. We start with the *spherically symmetric*, *static metric* in the following very general form:

$$ds^2 = (1+u)dr^2 + (1+u)r^2 d\theta^2 + (1+u)r^2(\sin\theta)^2 d\varphi^2 - (1-v)dt^2,$$

where $u \equiv u(r)$ and $v \equiv v(r)$, functions of r alone. Both u and v are assumed to be $\ll 1$. We work using *natural* units, i.e., such that $G = c = 1$. Consequently, we can write the *inverse* metric *approximately* as

$$g^{\mu\nu} \simeq diag\left(1-u \quad (1-u)/r^2 \quad (1-u)/(r^2(\sin\theta)^2) \quad -(1+v)\right).$$

At the same approximation level, the non-zero Christoffel-symbols that correspond to this metric are given by:

$$\Gamma^r_{rr} = \frac{1}{2}(1-u)\partial_r u, \qquad \Gamma^\theta_{r\theta} = \Gamma^\varphi_{r\varphi} = \frac{1}{2}(1-u)\partial_r u + \frac{1}{r}, \qquad \Gamma^t_{rt} = -\frac{1}{2}(1+v)\partial_r v,$$
$$\Gamma^r_{\theta\theta} = -r^2\Gamma^\theta_{r\theta}, \qquad \Gamma^\varphi_{\theta\varphi} = \cot\theta, \qquad \Gamma^r_{\varphi\varphi} = -r^2(\sin\theta)^2\Gamma^\varphi_{r\varphi},$$
$$\Gamma^\theta_{\varphi\varphi} = -\cos\theta\sin\theta, \qquad \Gamma^r_{tt} = \frac{1}{2}(u-1)\partial_r v.$$

Where it occurs, $\partial_r \equiv \partial/\partial r$, obviously. The standard derivation proceeds with the *geodesic equation*

$$\ddot{x}^\mu + \Gamma^\mu_{\alpha\beta}\dot{x}^\alpha\dot{x}^\beta = 0,$$

where the *overdots represent* (*careful*!) *differentiations vs. s*. Some specific algebra for θ yields the equation

$$\ddot{\theta} + \left(\frac{\partial_r u}{1+u} + \frac{2}{r}\right)\dot{r}\dot{\theta} - \dot{\varphi}^2\cos\theta\sin\theta = 0.$$

This equation is trivially solved by $\theta = \pi/2$. The solution amounts to selecting coordinates such that the orbital plane coincides with this angle. This greatly simplifies the geodesic equations for t and φ:

- $(1-v^2)\ddot{t} - (1+v)\partial_r v\dot{r}\dot{t} = 0,$
- $(1-u^2)\ddot{\varphi} + (1-u)(\partial_r u + 2(u+1)/r)\dot{r}\dot{\varphi} = 0.$

We note that both equations can be brought to readily integrable forms:

- the equation for t can be written as

$$(1+v)\frac{d}{ds}((1-v)\dot{t}) = 0$$

or, after integrating the argument of the derivative vs. s here above,

$$\dot{t} = \frac{C}{1-v}.$$

If we require this *at infinity*, we have Minkowski Space with $(dt/ds)^2 = -1$, and the integration constant becomes fixed at $C^2 = -1$;

- the equation for φ can be written as

$$\frac{1-u}{r^2}\frac{d}{ds}((1+u)r^2\dot{\varphi}) = 0$$

or, after integration,

$$\dot{\varphi} = i\frac{J}{(1+u)r^2},$$

where we recognize the integration constant J as the *Angular Momentum per unit Mass*; the extra factor $i \equiv (-1)^{1/2}$ arises because of the *metric signature*.
Instead of solving the last remaining geodesic equation directly, we use the identity $g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu = 1$. Again, by setting $\theta = \pi/2$, it gives the equation

$$(1+u)\dot{\varphi}^2\left(\frac{dr}{d\varphi}\right)^2 + (1+u)\dot{\varphi}^2 r^2 - (1-v)\dot{t}^2 - 1 = 0.$$

After some rearrangement, and using the results for φ and t, we get:

$$\left(\frac{dr}{d\varphi}\right)^2 + r^2 - \frac{(1+u)v}{(1-v)J^2}r^4 = 0.$$

Substituting $r := 1/z$ and then multiplying through by z^4, yields

$$\left(\frac{dz}{d\varphi}\right)^2 + z^2 - \frac{(1+u)v}{(1-v)J^2} = 0\,.$$

Differentiating with respect to φ and dividing by $2dz/d\varphi$, we obtain

$$\frac{d^2z}{d\varphi^2} + z - \frac{(1+u)\partial_z v + (1-v)v\partial_z u}{2(1-v)^2J^2} = 0\,.$$

Now, we can assign values to u and v. In the standard PPN (*Parameterized post-Newtonian*) metric, we have $u = 2\gamma mz$ and $v = 2mz - 2\beta m^2 z^2$, where β and γ are two of the PPN parameters: γ represents the amount of *spatial curvature* due to Gravity whereas β represents the *non-linearity* of superposition. For General Relativity, $\beta = \gamma = 1$. After rearranging and dropping terms, quadratic or higher order in z (that is, we are assuming a *weak Gravitational Field*), we get

$$\frac{d^2z}{d\varphi^2} + z - 2(2+2\gamma-\beta)(m/J)^2 z = m/J^2\,.$$

This differential equation is readily solvable, with the solution given by

$$z = z_0\, sin((1-2(2+2\gamma-\beta)(m/J)^2)^{1/2}\varphi - \varphi_0) + \frac{m}{J^2 - 2(2+2\gamma-\beta)m^2}\,,$$

with z_0 and φ_0 as integration constants.

This solution is *periodic*; z *will return to its original value every time* φ *advances by* $\dfrac{2\pi}{(1-2(2+2\gamma-\beta)(m/J)^2)^{1/2}} \approx$
$\approx 2\pi(1+2(2+2\gamma-\beta)(m/J)^2)$.
After setting $\beta = \gamma = 1$ and restoring units, we find that the *perihelion advance* for Mercury is given by

$$6\pi\left(\frac{GM_\odot}{crv}\right)^2,$$

which, given $r \approx 5.8\cdot 10^7$ km and $v \approx 47$ km/s, yields about $5\cdot 10^{-7}$ rad/rev (about 0.241 yr), or $4''$/century.

A final comment on the meaning of the factor $2+2\gamma-\beta$: imagine a *linear* theory of Gravitation, in which there is no non-linear superposition, $\beta = 0$. In such a theory, the value of this factor is 4, as opposed to the general-relativistic value of 3. In other words, a linear theory of Gravitation would *overestimate* the magnitude of Mercury's perihelion shift by a factor of $4/3$. This is beautifully elaborated in Richard Feynman's *Lectures on Gravitation*, in which he presents a discussion by imaginary scientists from the planet Venus, who know about field theories but only just encountered Gravitation and try to formulate a theory that correctly captures gravitational phenomena.

329 -

Can we peek behind the cosmic horizon (observable Universe) through Gravity lensing?

What we call the observable Universe exists not because of a limitation of our instruments. It is not a technological barrier. It simply represents the slice of the Universe (which, as far as we know, is *infinite*, or if it isn't, it is very, very, very large) that is near enough such that signals from it could reach us in the time that elapsed since the beginning of Time.
No signal travels faster than c, the Vacuum speed of light. No *lensing* effect, no instrumentation can change this fundamental fact. So, no matter what clever trick we can think of, the Laws of Causality (as far as we know) are *absolute*; breaking them would amount to things like traveling in Time to kill our ancestors, that sort of thing, essentially the end of a logical, *causal* Universe.
The practical limit of how far we can see is substantially less than the observable Universe. Distant things are very highly redshifted, so the signal from them is weaker and even ultraviolet light is shifted into the infrared or radio domain. And then there is the Cosmic Microwave Background (CMB), which is light (redshifted to the radio domain) produced by the Universe when it was just becoming *transparent to light*.

The good news is, though, that this visible (in the practical sense), Universe expands every day. The region of the Universe from which we observe the CMB today becomes completely transparent by tomorrow; when we look in the same direction, we will still see the CMB, but it now comes from a slightly more distant part of the Universe. And if we could somehow track that patch of gas that produced the CMB today over the course of billions of years, we would see how it evolves, forms clumps of Matter under its self-Gravity and eventually forms galaxies and stars.

330 -

Has Hawking Radiation been verified?

There is *no direct experimental confirmation* yet (2023) and it's unlikely that there ever will be as the radiated power of an astrophysical black-hole is so minuscule. However, the prediction itself is based on very robust (and actually, fairly basic) Science within the context of Quantum Field Theory. Moreover, the principles behind this prediction have been validated by laboratory experiments, black-hole 'analogs' (often picked up and hyped beyond recognition by the popular science press as 'black-holes in a lab', but that's another story), so, we know that the Science really is solid.
That said, Nature has a nasty habit of offering surprises when we least expect them, so it is good to remain skeptical with any claim, no matter how robust, that lacks direct experimental confirmation.

331 -

If fields propagate through massless carrier particles like photons, why aren't they slowed down by a medium the way light is?

First, fields do not propagate through massless carrier particles like photons. The elementary excitation quanta for some fields are massless, for other fields they are *massive*. For instance, the electron field propagates by way of electrons, which have a rest mass of 511 keV, using the units customary in Particle Physics.
Second, when these excitation quanta propagate through a medium with which they interact, they are slowed down, just like light. Not because the quanta are absorbed and re-emitted (this is a commonly heard misunderstanding) but rather, because the field *as a whole* is no longer a free field in a Vacuum, so its behavior is governed by a different set of equations. However, this does mean that the propagation velocity changes, just as it does for light. So, for instance, a beam of electrons can be refracted by a crystal, just like a beam of light.
In short, light is not unique, nor are these phenomena restricted to fields with massless propagators.

332 -

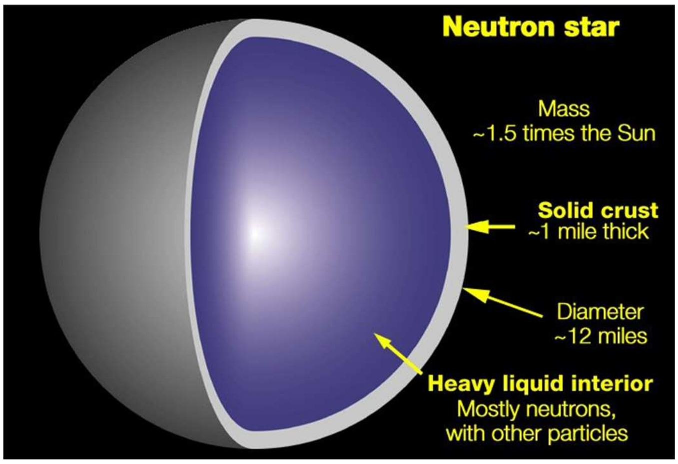
Since Planck Time is the smallest meaningful unit of time, can the Proper Time at the event horizon of a black-hole be equal to Planck Time?

Why should we think that the Planck Time is the 'smallest meaningful unit of time'? Do we know about the Planck Mass? It's about $22 \cdot 10^{-6}$ g , a small speck of dust, but something we can probably see, at least with a magnifying glass. So, it is obviously not the smallest meaningful amount of mass, as there are things much smaller. It's also obviously not the largest meaningful amount of mass. If the Planck Mass is not a limit in this sense, what makes us think that the Planck Time is? Just because it's small doesn't mean it is smallest.
It is true that the Planck Scale is the scale at which we expect our best theory of Physics, Quantum Field Theory (QTF), to fail. Our suspicion is that the theory cannot be meaningfully extended to, or beyond, the Planck Scale, which means that it is probably just an 'effective' theory, a low-Energy limiting case of a more comprehensive theory that is yet to be discovered. A theory that would be more comprehensive precisely because it can deal with Energy scales, lengths, time intervals and whatnot beyond the limitations of QFT. Or, perhaps, we'll find that there are ways to extend QFT beyond the Planck Scale without having to invent a whole new theory. There have been theoretical attempts to do just that.
Either way, this should tell us that there is a difference between there not being shorter intervals of time vs. a specific theory not being able to cope with such intervals.
Proper Time is the amount of time along a worldline. A null worldline is characterized by zero Proper Time, not Planck Time. The event horizon is a null surface. A null surface is characterized by, as we can guess, worldlines on it that all have zero Proper Time. It marks the boundary between two qualitatively different regions of SpaceTime, kind of like (vaguely) the transition between positive and negative. The Planck Time has nothing to do with it.

333 -

Neutron stars have the *strongest magnetic fields* in the Universe. But if neutron stars are composed of neutrons, shouldn't they have no net charge, and hence no magnetic field?

Apart from the fact that, as others pointed out, neutrons have a magnetic Moment (on account of being composed of *charged* quarks) consider also that a neutron star is not 'pure' *neutronium*. Rather, it is in a dynamic equilibrium of neutrons and (some) protons and electrons. In fact, there are reasons to believe that the interiors of neutron stars are both *superfluids* and *superconductors*. So, there are plenty of opportunities for there to be *currents* and, correspondingly, *magnetic fields*. And since we are talking about an object that may be at *relativistic temperatures*, spinning at *relativistic speeds* and (obviously, given its density) have *relativistic surface Gravity*, very strong magnetic fields are almost a self-evident consequence.



334 -

Is c^2 literal in Einstein's equation? Why the speed of light squared?

When we see c in theoretical Physics equations, we shouldn't think of it as a speed, rather, as a *conversion factor*. For cultural and historical reasons, we use incompatible units to measure Space and Time, even though now we know that they are directions in the same mathematical entity (the SpaceTime manifold).
The current unit of Time was originally derived from the rotation rate of our home planet; similarly, our standard unit of Length was originally determined using the size of the planet (or worse yet, in some parts of the world, using the typical sizes of certain parts of the human body). So, we ended up with definitions like, to spell it out in full, 'the speed of light is, approximately, three hundred million times one ten millionth the distance from the north pole of the third planet of this solar system to its equator, divided by one twenty-fourth of one sixtieth of one sixtieth of the duration of time it takes for the planet to make a full rotation around its axis and then some, so that the same spot of it surface faces the central star of this solar system'. Quite a mouthful, isn't it. Or worse yet, 'the speed of light is, approximately. 186 thousand times a length that is determined as eight times some other length that in turn is forty times yet another length, which is five-and-a-half times the length that is three times the length of a typical human foot, divided by…'.
And THIS quantity appears, raised to some power, in fundamental Physics equations? What does the planet Earth or the length of a human foot have to do with fundamental Physics? The answer is, *absolutely nothing*. The fact that we use such incompatible units for Space and Time is no more relevant to fundamental Physics than the fact that pilots use incompatible units to measure horizontal distance (in nautical miles) and vertical distance (height, in feet). *When we use incompatible units, conversion factors are needed.*
This is why theoretical physicists often sidestep this problem entirely and just state that the equations are written in '*natural units*'. Whatever these natural units are, they are characterized by the fact that, in these units, conversion factors such as c are 1 and, therefore, can be omitted from equations. For instance, if we measured Time in seconds and distance in light-seconds, we would have $c = 1$ light second per second, so, it can be omitted.
This is the reason why we might see, in Theoretical Physics texts, equations such as $E = m$ or $G_{\mu\nu} = 8\pi T_{\mu\nu}$ instead of $E = mc^2$ and $G_{\mu\nu} = (8\pi/c^4)T_{\mu\nu}$. *These latter forms are used only when it is necessary to compute something using culturally conventional units such as meters (or feet) and seconds.*
Again: c is a conversion factor that relates our 'unnatural' units of Space and Time, part of our cultural heritage. So, is the gravitational constant G. Only Planck's constant h (or $\hbar$) takes us a little beyond conversion factor territory, as it does define a fundamental unit of distance (the *Planck Length*) that in turn can be used to define other fundamental units

(*Planck Time*, *Planck Energy*, etc.).
There are physical theories that allow fundamental constants to have values that, well, *aren't constant*. But simply changing the value accomplishes nothing, as it simply implies using *different clocks* or *meter sticks* at *different times* or *places*. An actual variable-constant theory has to do more: it has to explain how the *changing constant* is accompanied by a *physical effect*, i.e., how the changing constant becomes a physical field with its own dynamics. Forgetting this is a rookie mistake that is often made by aspiring physicists.

335 -

How does the conceptual difference of Time keep Quantum Field Theory (QFT) and General Relativity (GR) from being compatible?

There is no conceptual difference of Time that keeps QFT and GR incompatible. Quite the contrary, Quantum Field Theory (QFT) is not only fully relativistic from the onset, it can also be formulated just fine on the curved background of General Relativity. There are, of course, technical challenges and conceptual difficulties (the lack of a globally defined inertial reference frame implies that *no unique decomposition* into particles exist; observers who see the same field may not agree on the particle content that they see) but the theory works just fine.
The incompatibility arises when we try to turn the metric of SpaceTime from an inert background into a dynamical field, sourced by Matter. The QFT approach would dictate that this field become just another *quantum field*. However, that does not work: such a quantized theory of Gravitation becomes *divergent* (*non-renormalizable*).
There is no obvious way to resolve this dilemma, at least none that we consider satisfactory. One possible resolution is called *semi-classical Gravity*, which basically states that it is not necessary to quantize the Gravitational Field, after all. This is inelegant, unsatisfying, yet it yields the right results in all observational regimes accessible to us. And therein lies the problem: *we get no observational hints from Nature as to what might work as a better theory*.
In any case, all this has to do with turning Gravitation into a dynamical quantum field; it does not affect the (relatively speaking) much simpler exercise of simply doing QFT on the curved background of General Relativity.

336 -

What is the relation between *Dark Energy* and *virtual particle production*? Can the expansion of the Universe be attributed to an increase in the number of virtual particles?

First, let's restate what Dark Energy is. There is not much we know about Dark Energy except its *equation of state*. Its equation of state is such that its pressure is *negative* and equal in magnitude to its Energy density: $p = -\rho_E\ (< 0)$. Let's take this as the *defining equation of Dark Energy*.

Now, we might ask: who comes up with stuff like this? Well ... Einstein came up with the so-called *Cosmological Constant* Λ back before it was realized that the Universe is expanding, as he hoped to find a solution of his field equations that would predict a static Universe. With Λ, he partially succeeded; the result was a Universe that was *static but not stable*. Meanwhile, Hubble et al. discovered that the Universe is in fact expanding, leading to Einstein's famous comment about his biggest blunder.
The thing about Λ is that if we put it into the field equations and pretend that it is not a constant of Nature but a term that represents a form of Mass-Energy (we are free to interpret things any which way we wish so long as the equations are not altered), well, if Λ is 'stuff', it is stuff with the equation of state $p = -\rho_E$, i.e., it has the Dark Energy equation of state.
Negative pressure gives Dark Energy two curious properties. *First*, ... normally, when we compress a gas, we do work and, when the gas expands, it does work. With *negative* pressure it is the other way around: we do work by making this stuff expand and it does work when it contracts. Gravity, in other words, makes Dark Energy expand, not contract like other stuff. So, Dark Energy behaves as though Gravity were *repulsive*. Which means that its self-Gravity actually pushes the Universe apart ... and *if Dark Energy dominates*, *it causes the expansion to accelerate*.
Now why would Dark Energy dominate? Here comes its *other* property: *as the Universe expands*, *most stuff gets diluted*. Let's think about describing the expansion using a length scale. As lengths increase, corresponding volumes go up by the 3^{rd} power of the length scale. So, ordinary Matter is diluted as the inverse of the 3^{rd} power of the length scale. Radiation fares even worse ... not only will there be fewer photons in a given volume, but the photons' wavelengths also increase, so, the *Energy density* of radiation changes as the *inverse* 4^{th} power of the length scale.
However, as for Dark Energy ... the Energy density stays *constant*; that is, *as the Universe expands*, *it just gets filled with more Dark Energy*. At any given time, the amount of Dark Energy in a unit volume is *constant*. So, as all other stuff is diluted in an expanding Universe *except for Dark Energy*. Ultimately, Dark Energy remains the only kid on the block ... and it dominates the expansion from then on.
But what is Dark Energy? Well, here is where Vacuum polarization\virtual particles come in. Quantum Physics tells us

that the *Vacuum is not empty*: *it is full of virtual particles and its Energy density is non-zero*. More than that ... the pressure of this Vacuum Energy, i.e., its Energy density, is *negative*. In other words, *Vacuum Energy is a perfect candidate for Dark Energy*!
Except that when we calculate the Energy density of the Vacuum, depending on how we do it, we end up with a number that's either *infinite* or some 120 orders of magnitude *larger* than the observed Dark Energy Density. This is known as the *Cosmological Constant problem* and remains one of the great unsolved problems in Physics.
But whether Dark Energy is really Vacuum Energy or something else, its curious property that its Energy density remains constant does play a role in the expansion. It is not the reason for the expansion; however, it is the reason for why the expansion accelerates, as we think we know it does from supernova data.

337 -

In a parallel Universe, all fundamental Physics constants are the same except the speed of light, which is measured to be only 1000 m/s. What would be properties of such a Universe? How things evolve after the Big Bang?

No, it really doesn't work that way. Honest. There is a reason why the modern meter is defined the way it is: the distance that light travels in exactly $1/299792458$ s . In other words, these units: the *meter* and the *second* are defined both with reference to the Vacuum *speed of light*. We could just as easily have defined the meter as the distance that light travels in exactly 1 second. However, such a 'meter' would be very inconvenient, as it is so much longer than lengths in our everyday experience. It shows the futility of treating a dimensioned constant (the value of which depends on our *choice of units*) as fundamental. Dimensioned constants can have *any value* we want, so long as we use the appropriate units of measurement.

The truly fundamental constants of Nature are not dimensioned constants. They are dimensionless ratios.

The best known, oldest among them is the so-called *fine-structure constant* α : its value is approximately $1/137.036$. This constant determines the strength of the electromagnetic interaction. If its value were different then yes, the ratio of the speed of light to other speeds would also change, even if we continue to measure the speed of light as 299782458 m/s by virtue of how the meter is defined. But a different fine-structure constant would also have rather dramatic consequences. Change it a little and there are noticeable *changes in the chemical properties of Matter*. Some chemical bonds that used to be stable become *unstable*. Some chemical bonds that were not previously possible become possible. But also on the nuclear level, *some previously stable isotopes may become radioactive and vice versa*. Change the constant by a large amount and Chemistry, as we know it, no longer exists; the periodic table, as we know it, is gone. Nuclear reactions inside stars would be very different, ranging from no reactions at all (hence, no stars) to all stars being unstable, exploding in spectacular bangs shortly after coming into existence.
The fine-structure constant is just one of many constants that we know. The Standard Model of Particle Physics has at least 18 such constants in total, some (like the fine-structure constant) more important than others to the stability of Matter that we are familiar with, the stability of Chemistry. Additional constants come into play when we losen things a little bit, e.g., allow neutrinos to have masses. Lastly, there may be fundamental dimensionless constants (at least one) associated with a Quantum Theory of Gravity, which we are yet to discover (assuming it exists).

Anyway, it should be emphasized, these are all *dimensionless* constants. Dimensioned constants are not fundamental really and their numerical value depends on our human, cultural choices.

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If all motion is relative, then, how can any speed or light speed be an absolute *constant*? Let's say two objects are traveling towards each other and both are traveling at $0.75c$, wouldn't their relative speed exceed the speed of light?

Not all motion is relative. The fundamental premise of Special Relativity is that there exists an *invariant speed* (the Vacuum speed of light, c) that is *the same for all observers*.
Two objects traveling towards each other in a 3rd (!) observer's reference frame at $0.75c$ would indeed approach each other in the *third* observer's reference frame at $1.5\,c$ but, in *either* of the object's reference frames, the other object would only be traveling at $0.96c$, in accordance with the velocity addition formula of Special Relativity (more generally, in accordance with the *Lorentz transformations*, which are precisely those SpaceTime transformations that *leave invariant* the *invariant speed* c).
In short, nothing ever travels, *relative to something else*, faster than the Vacuum speed of light, even though it is possible for two things to approach each other or fly apart faster than the c as measured in a 3rd observer's reference frame.

339 -

Did the Big Bang occur after inflation?

We shouldn't think of the Big Bang as something that 'occurred'. The concept of the 'Big Bang' is often described using the word 'paradigm'. That is to say, it's the general idea that we live in an expanding Universe that, a very long time ago, was *extremely hot* and *extremely dense*.
If we forget about Particle Physics and the Quantum Theory and just use General Relativity to describe the Universe, then, there is an initial moment in Time, which marks the beginning of Time itself. This moment, the 'initial singularity', is not actually part of the Universe (the same way the point at $x = 0$ is not actually part of the domain of $y = 1/x^2$ or similar functions that have singularities). So, in the context of General Relativity, it makes sense to talk about 'the Big Bang' (as synonym for the *initial singularity*) and everything that actually happened in this Universe did, by definition, happen after the Big Bang, i.e., *after the beginning of Time*.
But we do *not* live in a Classical, General Relativistic Universe. *We live in a Quantum Universe*, in which, Matter at least (we're not sure about Gravity) is described using *quantum fields*. We can reliably reconstruct the past history of the Universe all the way to about 10^{-12} s after this presumed Big Bang singularity, but no further. We do not have the data. We only have *speculative theories*.
One such speculative theory is *cosmic inflation*. The idea that in the extreme early Universe, well within that first picosecond, for a very brief amount of time the Universe expanded at an exponential rate. This is supposed to solve a number of issues with the basic properties of the Universe, including the so-called *flatness problem* or its obvious *homogeneity*. On the other hand, as none other than one of the founding fathers of inflationary theory, Paul Steinhardt, pointed out, the concept of cosmic inflation raises more questions than it solves; Roger Penrose also appears to think so.
As to when inflation occurred with respect to the Big Bang, now that becomes a matter of definition, in part dependent on the broader context. For instance, in 'eternal inflation' there is no true beginning of the Universe: it exists forever. However, 'our' pocket in this mega-Universe can mark its beginnings when inflation came to a halt in this region (much larger than the observable Universe but still finite) so arguably, it would make sense to say that it was after inflation ended that the 'Big Bang' paradigm took over in a more conventional form.
In any case, we must realize at this point that this is not Science so much as it is simply an argument about the dictionary definition of a catchy expression.

340 -

A common understanding is that accelerating to the speeds required for inter-stellar space travel would vastly increase the mass of the astronauts. Would their physiology cope with this, or would they be effectively crushed by their own weight?

This understanding is incorrect. It is the unfortunate consequence of a once popular concept, *relativistic mass*, which leads to such misunderstandings. The first thing to keep in mind is that Relativity Theory is not about what happens to us (or to an astronaut). It is how others see us, from their own frame of reference which may be moving relative to ours. In our own frame of reference, we never move. So, no relativistic effects. Even if we are in an interstellar spaceship, why would we notice anything different just because the rest of the Universe is moving backwards at high speed?
Now, from the perspective of an observer not traveling with us, we may be moving ahead at high speed. Our total Energy includes our *rest mass* as well as the (relativistic) *Kinetic Energy* associated with our motion. If that observer wanted to accelerate us, he would have to consider the total Mass-Energy of our system: our rest-mass and our Kinetic Energy combined, *as our inertial Mass*. Any force they apply would be opposed by this combined Mass-Energy as seen from his\her perspective. This is the origin of the *relativistic mass* concept: it basically *measures the inertia of a moving object from another observer's reference frame*.
However, it unfortunately combines two fundamentally incompatible things: the *rest-Mass* of the object, which is an inherent property, independent of any observer, and the *Kinetic Energy* of the object, *which depends on the speed of the observer*. For this reason, the concept of relativistic mass is not often used nowadays, as it leads to needless confusion.
In any case, the astronaut in his or her own reference frame will see no change in mass. If their mass increases during the journey, it's because they eat too much and exercise too little; Relativity Theory has very little to do with it!

341 -

If the Higgs Boson gives all particles their masses, why are there still attempts to find a graviton particle mediating the Force of Gravity? How are the Higgs and Graviton thought to be different?

Because Gravity is not about mass. *Gravity is about Energy-content*. Rest-mass due to interactions with the Higgs Field is just one of the many forms of Energy-content.
In non-relativistic Physics, i.e., in the everyday world around us, the Energy-content of Matter is dominated by its rest

mass. But even that rest mass has very little to do with the Higgs boson. Roughly 99% (!) of the mass of atoms comes not from interactions with the Higgs field, but from the strong force binding Energy that holds quarks together inside protons and neutrons. Only roughly 1% comes from interaction with, well, not the Higgs boson proper, but with the so-called *Vacuum expectation value* of the Higgs Field, a value that is non-zero even when there are no actual Higgs bosons around.
So, Energy-content takes many forms. Gravitation is sourced by, and acts on, the *Energy-content*. This would still be the case even when the Energy-content attributed to interactions with the Higgs Field didn't exist.
We have, so far, not been able to find a satisfactory Quantum Theory of Gravitation. However, if such a theory exists, we know that in the *Weak-Field limit*, it can be described using the concept of gravitons.
However, it does not mean that we are actually searching for gravitons. There are no known or foreseeable experimental techniques that could detect gravitons because Gravitation is so very weak. Freeman Dyson once estimated that if the entire Earth was turned into a perfect graviton detector, it would detect roughly one graviton every 10^9 years. So, that's not going to happen.
At the same time, that does not mean that we are not seeking a Quantum Theory of Gravitation or a suitable alternative, which resolves the apparent puzzling contradiction between some aspects of the Standard Model of Particle Physics (a Quantum Field Theory) and Classical Gravitation.

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Can 'wavefunction collapse' be used to send information?

The answer is: NO.
Let's start by explaining briefly what *wavefunction collapse* is. We have a quantum system. It has a property that is characterized by a mathematical *operator*, which we can use to deduce a *probability density*, associated with various possible outcomes of a measurement that we are yet to perform. We allow the quantum system to evolve towards the moment when it interacts with the *measuring apparatus*: a classical instrument that offers a classically well-defined reading of the property in question.
At this point, with a magic wand, we perform the following magic (at least in the conventional, canonical, Copenhagen interpretation of Quantum Mechanics): we, retroactively (!), throw away our previous description of the system and replace it with a description in which the measuring apparatus was present all along, confining the quantum system to a *classical* state (a so-called *eigenstate*). This change from one description of the system to another, different description of the system is not prescribed by any of the equations of Quantum Mechanics. Rather, it is the result of magical thinking. It is granted legitimacy by giving it fanciful names, such as 'wavefunction collapse' or the even more impressive 'non-unitary evolution of the wavefunction'.
If the wavefunction actually changed in this manner as a result of the measurement, it could, of course, be used to send information. By the act of measurement, we change something that can be observed, in principle, not just anywhere in the Universe but *at any time* in the Universe (hence our point above about the change being *retroactive*). So, we could send information *faster than light*, we could send information back into the past, whatever suits our fancy.
But if we come back from the realms of science-fiction to the planes of Reality and look at what the equations actually say, a rather different picture emerges. The so-called *Lagrangian representation* of the quantum system is predicated on knowing its *initial* and its *final* state; the equations then tell us *how* the system evolves between these two states. This approach predates Quantum Physics by many decades: *Lagrangian Physics*, in its modern form, emerged in the 19th century. The reason why we can use the Lagrangian approach to predict the future (as opposed to simply describing how a system reaches a predetermined future state) is because it can be readily transformed into a so-called *Hamiltonian representation*, which, in turn, tells us the future state of the system based on more detailed knowledge of its present state. This (classical) knowledge of the present state is not accessible in Quantum Mechanics. So, the *Hamiltonian representation necessarily only offers probabilities, not certainties*. But that is not the case with the Lagrangian representation. Knowledge of the initial and final state of the system still allows us to determine how the system evolved between the two.
What this tells us (if we really believe in the math) is that *Quantum Mechanics is non-local*: that the actual (unitary, no wavefunction collapse) evolution of the system *is determined, in part, by its future interaction with the measuring apparatus*. This sounds like knowledge of the future. However, precisely because the initial state of the system is not accessible, this knowledge of the future by the quantum system does not mean any knowledge in the present that would be exploitable classically, and *causality is fully preserved*. Which leads to the answer presented up front: NO, *wavefunction collapse is not a physical process that can be used to communicate information*. While using correlated quantum particles and wavefunction collapse as a means to send information has turned into a much beloved science-fiction trope, in actuality, *Nature is very strict when it comes to maintaining Causality*. And that is a *good thing*, too, otherwise we'd find ourselves in a surreal, callously unpredictable Universe in which the *Present might influence the Past and Effects might precede Causes*.

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Since there is no such thing as a perfect Vacuum, does light ever actually travel at the speed c?

Indeed, it doesn't. Actual rays of light traveling through interstellar/intergalactic space still encounter charged particles, an extremely, extremely thin plasma, and technically, that slows light down ever so slightly.
The electron number density in interstellar plasma is extremely low. Even in the densest regions, it's no more than, maybe, 10^6 electrons (and 10^6 positively charged ions) per cm^3. But elsewhere, the number density can be as low as 1 electron in every $10000\ \mathrm{cm}^3$. The index of refraction that corresponds to these tiny numbers is itself insanely low. Let's take, as an average, $1\ \mathrm{electron}/\mathrm{cm}^3$. Assuming we used our calculators correctly, the index of refraction for visible\near infrared light will be *less* than 1 by a number that contains 33 zeroes after the decimal point, followed by the digit 5. This means that light traveling to us from the farthest corners of the visible Universe will be delayed by less than about $2\cdot 10^{-15}$ s or, in terms of distance, by about $(1/2)\mu \equiv 5\cdot 10^{-7}$ m (i.e., half 1 millionth of a meter).

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Does Milky Way Galaxy have the same unexpected rotation curve as most other galaxies? If so, and assuming that Earth is located in outer parts of Galaxy, should we expect to have Dark Matter in our vicinity?

Yes, the Milky Way follows the same pattern as other spiral galaxies, rotating faster than what would be consistent with the *gravitational pull* of visible Matter therein.
And yes, this means that we would expect the Milky Way's Dark Matter halo to extend to parts that include the location of our own solar system.
Indeed, this is why there have been a number of experiments, and will doubtless be many more, attempting to detect this Dark Matter constituent directly (as opposed to inferring its existence from rotation curves). One example is the increasingly ambitious XENON series of experiments currently under way in Italy.
To date (2021), intriguing partial results notwithstanding, there has been no unambiguous detection of Dark Matter by any credible experiment.

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What makes *Higgs boson* give different masses to the different fundamental particles? What makes the different particles interact stronger (or more) with the Higgs Field (and\or boson)?

We don't know! This is one of the great unresolved questions in the Standard Model of Particle Physics.
We know that charged fermions (charged leptons, like the electron, and quarks) acquire their masses through *Yukawa-type interactions with the Higgs Field*. The actual observed mass of these fermions arises as a result of the *Yukawa coupling constant* that couples the fermions to the Higgs Field. Each fermion has its own coupling constant. The values of these coupling constants span several orders of magnitude. Nobody really knows why. There is no true underlying pattern.

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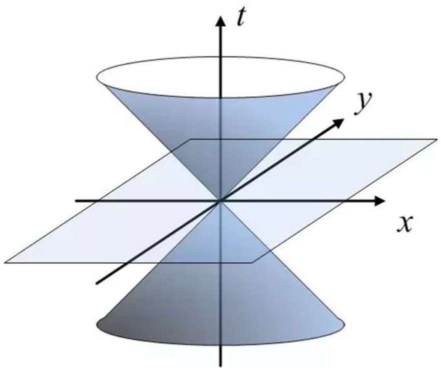
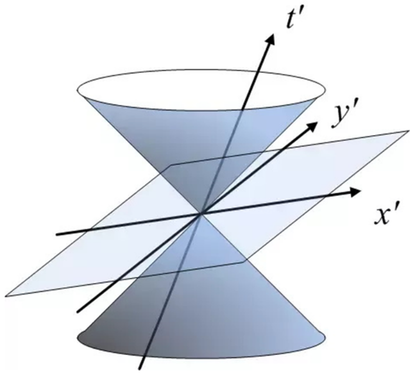
What is the speed of light *relative to us* if we're already travelling at c?

[a bit simplified version of the answer to Issue 258, P. 116-117]

The simple answer is: *we don't*, no way (at least, not within the context of Relativity Theory). It is a basic postulate of Special Relativity that there exists an *invariant speed*, namely the *Vacuum speed of light*. By *invariant*, we mean that this speed is the same *for all observers*.
An observer traveling at the speed of light, $c \equiv 2.99792458\cdot 10^8\ \mathrm{m/s}$, would, of course, be traveling along a ray of light that is moving in the same direction. So, for this observer, the speed of light could not be invariant. Since this contradicts our postulate, we conclude that there are no observers traveling with speed c.
A more detailed investigation reveals that this simple postulate endows SpaceTime with a topological structure that is characterized by light cones. *The light cones correspond to the speed of light*. Slower-than-light motion is confined to within 'light-cones' and we find that there is no velocity-related transformation that can exchange the 'inside' of a light cone with the 'outside' of a light cone; and that, furthermore, a velocity-related transformation leaves the light cones themselves unaffected.
Let's draw an example below. This is the light cone of an observer sitting at the coordinate origin, with the z-coordinate suppressed:



The observer, by sitting still, is 'moving' up the t (Time)-axis. That is, time progresses but the spatial coordinates of the observer are unchanged: he\she is *at rest*.
But now, here is the same observer's reference frame as seen by *another* observer moving *relative to the first*:



Notice how everything ends up tilted (this is a visualization of the Lorentz transformation) but the Time axis remains 'inside' the light cone. And the light cone itself remains the same as before.
So, this is the thing. The Time axis can never touch the light cone; if it did, the $X \times Y$ - plane would do so as well, and the whole shebang becomes degenerate. In other words, there is no observer reference frame that moves at the speed of light. Assuming such a reference frame exists is inconsistent with the geometry and topology of the SpaceTime of Special Relativity.
Now we might wonder why we do this nonsensical thing instead of plain old common-sense Galilean transformations. The thing is, we aren't making it up: *this is how Nature works* (and it took us a long time to figure it out).
Electromagnetism, Maxwell's Equations, predict an *invariant speed of light*. This is inconsistent with the Galilean Transformations of common intuition, where the speed of a ray of light depends on how fast we are running toward it or away from it. Yet, experiment after experiment (starting with the famous 1887 Michelson-Morley experiment) confirmed Maxwell's Equations and the invariance of the speed of light.

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Do *electrons* move faster than light when they change Energy levels within an atom?

No. Electrons do not have classically defined positions within an atom, so, it is not meaningful to think of a change in Energy levels as a change in position.
This may sound like an evasive answer, but it really isn't. The fundamental difference between Classical and Quantum Physics is that basic quantities such as position *do not* exist in a classically well-defined sense unless they are being measured (i.e., the quantum system in question is being brought into an interaction with a *classically* behaving object, such as a *laboratory instrument*). That act of measurement confines the particle into a state (an eigenstate) in which its property being measured acquires a *classically meaningful* value. But between measurements, no such value exists. So when an electron in an atom absorbs a photon, its Energy (which, in the atom, can only have discrete, well-defined levels) changes, but *there is no meaningful classical definition for its position*.
The electron really isn't a miniature planet zipping around the atom like in a miniature solar system. That is a cute picture, but it is very misleading. We wish we had a better visualization but one of the fundamental things about Quantum Physics is that it very explicitly *defies* classical intuition; so there really is no better visualization.

348 -

What is the interpretation of square speed of light in the Special Relativity, $E = mc^2$?

It's about *units of measure*.
Let's imagine a world in which people learned about the invariant nature of the Vacuum speed of light before anything else. So, by the time it came to standardizing their units of measure, they'd be measuring Time and Space in compatible units. The speed of light would just be the number 1 (1 standard unit of distance over 1 standard unit of time). Any other velocity would just be a dimensionless number, a ratio: e.g., the Earth is traveling around the Sun at $0.0001c$; an airplane is moving at $0.000001c$, and so on.

Now, recall the title of the paper in which Einstein introduced this infamous formula: "Does the inertia of a body depend upon its Energy-content?" The answer, of course, is yes, and in this imaginary world, it would simply be written as $m = E$: the Inertia (*inertial Mass*) of a body is its *Energy-content*.

But we don't live in that imaginary world. We live in a world in which Babylonian priests, thousands of years ago, had a preference for numbers divisible by $2, 12$ and 60 and, hence, we ended up measuring time using a unit that was originally conceived as $1/86400 \equiv 1/(2 \cdot 12 \cdot 60 \cdot 60)$ times the length of the solar day of the 3rd planet in an insignificant solar system in the Milky Way; and unrelated to it, some French scientists, more than 200 years ago, decided that subdividing the distance between the north pole and equator of the aforementioned planet into 10 million parts makes for a good unit of length.
In these units (or rather, their modern, refined versions), the speed of light is not 1 ; it is 299792458 m/s; and also in these units, inertial Mass and Energy (which is proportional to mass times velocity squared) are no longer measured using compatible units. So, to be able to compare them, they must first be made compatible with an appropriate unit conversion.
In Einstein's paper, this appeared as $m = E/c^2$. Since then, the expression is customarily presented as $E = mc^2$, which expresses the same thing. *The c^2 is there because of the need to convert between units of inertial Mass and units of Energy*; *a conversion that is made necessary by the historical/cultural accident of not using compatible units for spatial distances and time intervals*.
Incidentally, theoretical physicists often do use such units. So, in a text dealing with, say, General Relativity, the expression is often just $E = m$, as the author assumes units in which $c = 1$. This makes the equations shorter, simpler, easier to write and, also, to comprehend; and it is always possible to 'restore units' in the end, if need be.

349 -

Is $E = mc^2$ an exact equation or is it just $E = m$ times a very large number? Has anyone measured the exact Energy we get by destroying Mass or is it just an engineered guess that could actually be $E = m(9 \cdot 10^{16})$?

The important thing to remember is that physical quantities such as E, m and c are not just numbers: they are numbers with units attached, i.e., *measurable quantities*.
For instance, what if we measured distance using light-seconds and time using seconds? There is no law of Nature that says that we must measure distance using a unit that was once defined as one ten millionth of the distance on the surface of a random, unremarkable planet from its equator to its north pole, or worse yet, a unit of distance that is $1760 \cdot 3$ times the average length of the hind paws of a bipedal mammal on the same planet?
So, what is the value of c in light seconds per second? Why, it is 1 exactly, is it not? And 1 is not a large number.
When a number has units attached, the *magnitude of that number depends on the choice of units*. Physicists often assume that the units are 'natural' units, which means that Space and Time are measured using compatible units (such as *light-seconds* and *seconds*) and $c = 1$.

Therefore, the equation in question is just $E = m$. The c^2 part is there only because of a *human convention* (*), and the need *to convert from units of mass into units of Energy under that convention*.
The meaning of this equation is that *Mass and Energy are equivalent*: more precisely, *the inertial Mass of a body equals its Energy-content*. This statement is proven as a mathematical truth under the assumptions of the Theory of Relativity. So, no, it is not about 'destroying mass' and 'getting Energy' that way. *Mass is Energy*. Sure, we can convert some of the Energy-content of a body into motion, i.e., *Kinetic Energy*. When we burn something, this is what happens. But the mass is still there, *we have not destroyed anything*. If we burn something in a closed, sealed, insulated container, the total Energy-content of the container does not change, hence its *inertial* mass remains the same, even if, internally, some of that Mass-Energy was converted from, say, the form of chemical bonds into the form of *random motion* (Kinetic Energy), i.e., *heat*.

To make it short, $E = mc^2$ *does not describe a process of physical conversion*: this relationship is simply a *statement of equivalence*.
Can this relationship fail? Yes, of course. Our theory could be wrong. But that would have far-reaching consequences from Particle Physics to Astronomy, consequences that we do not see.

(*) A similar human convention is used in aviation, where horizontal distance is measured using nautical miles, but vertical distance in feet. Thus, we end up with strange units such as a descent rate measured in $\mathrm{ft/nm}$. Why do we do such crazy habits? For convenience. Airplanes routinely travel fast in the horizontal direction but change altitude more slowly. So, it makes sense to measure these two things using different units, even though they are both distances. It's for similar reasons of convenience that we don't measure distance in light-seconds (too long) or time using units comparable to what light requires to travel, e.g., $1\ \mathrm{m}$ (that would be a time unit that is far too short for practical use). Thus, we end up with superfluous conversion factors, such as c.

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Could Newton and Einstein combine Quantum Physics and Relativity if they were alive today?

Presumably, neither Newton nor Einstein would be qualified to accomplish that task.
Newton would have a very long way to go before he could even begin to comprehend the problem. He would have to catch up with two centuries' worth of developments in Theoretical Physics. For starters, he'd have to get used to his rival's Leibniz's notation when it comes to infinitesimal quantities and accept that the dotted notation of his 'fluxions' survived only when denoting derivatives with respect to time. Newton was not very tolerant of rivals!
Beyond that, he'd have to learn the very concepts of Lagrangian and Hamiltonian Physics. He'd have to become familiar with vector and tensor calculus and the concepts of *Riemannian Geometry*. He'd have to understand modern (that is, 19th century) developments in *axiomatic Thermodynamics* and *Statistical Physics* and then, of course, the entire body of electric and magnetic phenomena, culminating in Maxwell's theory of *Electromagnetism*, which also unified these phenomena with *Optics*. He would then have to learn the conceptual foundations behind a field theory. As background and by way of motivation, he'd also want to become familiar with the basics of *Atomic Physics*, the *Periodic Table* and *Physical Chemistry*, which means letting go of some concepts in alchemy that he, apparently, was fond of. Learning about *Spectroscopy*, *Modern Astronomy* including *Astrophotography* and what the world learned about distances to stars and the nature of 'spiral nebulae' in the early 20th century might also have been helpful to him.
Only with these foundations would he be able to understand the two conceptual contradictions present in late 19th century Physics: the invariance of the *Vacuum speed of light* and the '*ultraviolet catastrophe*'. Understanding these would enable him to appreciate the need for both Relativity Theory and Quantum Physics, but he would still be facing a steep hill to climb: learning how *General Relativity* combines *geometric concepts* with the *Field Theory of Gravitation*, how the Quantum Theory can be made relativistic, how a *Relativistic Quantum Particle Theory* can account for things like anti-particles or the *Spin* of the electron.
With all this done, Newton would finally have caught up with where Einstein was when he embarked on his last, decades long, but ultimately unsuccessful quest in his life, the quest for a Classical Unified Field Theory. That quest, as we now understand very well, was doomed from the start: *a Classical Field Theory is not the way to go*.
So, both Newton and Einstein would have another daunting task ahead of them: understanding *Quantum Field Theory*. Now, if we thought General Relativity is hard, let's think again: as any graduate student in Theoretical Physics will tell us, it's a cakewalk compared to Quantum Field Theory. But Newton and Einstein were both smart cookies, so, presumably, after making the effort, they would succeed:

- they would learn how a field can be *Fourier-decomposed* into an *infinite sum of elementary oscillators*, which can be quantized the usual way;
- they would learn how this, while yielding some seemingly sensible predictions, also offers the non-sensical conclusion that the *ground-state Energy* of a field is *infinite*;
- they would then learn how certain classes of quantum field theories are 'renormalizable': how these *unwanted infinities* can be removed systematically, in a process that, despite misgivings by giants of 20th century Physics such as Dirac, Landau, Fermi and Feynman, actually yields sensical and mathematically consistent answers;
- they would learn how such a renormalizable Quantum Field Theory can account for pretty much most of the *Matter-content* of our Universe in the form of the *Standard Model of Particle Physics*;
- they would also learn that Quantum Field Theory can be formulated on the curved SpaceTime Geometry of Einstein. They would marvel at the seemingly insane conclusion that in such a curved geometry, *different observers would Fourier-decompose the field differently*, which means they *observe different particle-content*;
- they would understand that this means that *fields reign supreme*: particles are, at least to some extent, in the eye of

the beholder.

And only then, after all this learning, would they be caught up with what present-day theoreticians know about the successes and limitations of our current understanding of Nature:

- how the Standard Model, though it works very well, has some serious shortcomings;
- how its ground state Energy could very easily play the role of 'Dark Energy' in Cosmology, were it not for the fact that it's either infinite or, even after it is tamed by way of some questionable assumptions, is still dozens of orders of magnitude too large compared to observational values;
- how neutrinos cannot be massive in the theory, and how neutrino masses *put the renormalizability of the theory into question*; and, last but not least,
- how a spin-2 theory of gravitons with a *dimensioned* coupling coefficient *is not renormalizable in principle*, and
- how cancellations, which seem to work almost miraculously at the 1-loop level, nonetheless *fail* to rescue the theory.

At this point, and only at this point, they would finally have the knowledge and competence to participate in, and perhaps materially contribute to present-day research on Quantum Gravity and its alternatives. And then we would find out that *though* they are both very smart people, Newton and Einstein *were not* exceptional: plenty of physicists alive today are in the same league, they just are not as lucky, are not 'the right people at the right time', because foundational revolutions *do not* happen in Physics every day, no matter how many smart physicists are around.

351 -

Does Gravity attract particles for their Mass or for their Charge? And why do scientists say that the Gravity of black-holes attract light in the time that photons don't have neither Mass nor Charge?

To every force, there is a corresponding charge. For the Electrostatic force, that charge is the well-known electric charge. Particles can have other kinds of charges: e.g., quarks have this famous 'color charge' (nothing to do with actual colors; it just happens to have three possible values, which inspired the analogy with human vision and its three primary colors). So, what is the corresponding charge for Gravitation? It is the *Energy-content* of a system.
For ordinary (nonrelativistic) Matter that we encounter in our everyday experience, that Energy-content is dominated by the object's rest-Mass. So, we end up with a simplified version of Gravitation, in the form of Newton's Theory, in which mass serves as the source of Gravitation. This simplified version is still highly accurate when the Gravitational Field is relatively weak (e.g., on the Earth) and when Matter is not moving at speeds close to the Vacuum speed of light.
Photons, on the other hand, move at the Vacuum speed of light, so, Newton's Theory does not work here. We need to look at photons in the broader context of General Relativity. Whether we treat them as ultra-relativistic particles (taking the limit of mass going to zero and speed approaching the Vacuum speed of light) or as traveling plane waves in Maxwell's Electromagnetic Field far from electric charges, we arrive at the same conclusion: not only are they affected by Gravity, but the effect is twice what would be predicted using a naïve application of Newton's Theory, assuming photons have a vanishingly tiny mass.
Going back to Newton's Theory for a moment, it is easy to see why the theory cannot really offer a definitive answer. If we think of light as waves in Maxwell's Electromagnetic Field, those waves would be unaffected by Newtonian Gravity. If we think of light as particles, then we have a conundrum. In every similar theory, the amount by which a particle is deflected by a force depends on the particle's 'Charge-to-Mass ratio'. A light particle with a big electric Charge, for instance, is deflected a lot more by an Electrostatic Field than a heavy particle with a small electric charge. For Gravitation, mass is charge, so the (gravitational) charge-to-mass ratio is always 1 for every object. This is why Gravity is universal. So, what happens when the mass vanishes, as in the case of photons? The Charge-to-Mass ratio would be $0/0$. Is it 0 ? Is it 1 ? It can be anything.

Newtonian Gravity cannot provide a meaningful answer when it comes to a particle with *no rest Mass*, and it provides the wrong answer for Electromagnetic Waves. General Relativity offers a definitive answer, and better yet, the answer is consistent whether we think of photons as ultra-relativistic particles or as electromagnetic fields deflected by gravitation. Even better, this prediction has been confirmed spectacularly on multiple occasions, starting with Eddington's historical observations during the 1919 solar eclipse.

352 -

How fast was the Universe expanding in the first *yoctosecond* $(\equiv 10^{-24}\text{ s})$ after the 'Big Bang'?

Let's give a very serious answer based on our best current knowledge of cosmic expansion, using the most appropriate technical terminology: "Who the hell knows it?"

We can extrapolate back, based on the Physics we know and the Universe that we observe at present, roughly to the first 10^{-12} s or so (that would be 10^{-18} s, i.e., a trillion yoctoseconds). We have a reasonably clear understanding of the conditions prevalent in the Universe at that time, like the conditions present in the Large Hadron Collider when it is running at its highest Energy. We could even derive a value of the Hubble parameter at this time, though it would be a rather meaningless number: speaking of km/s per megaparsec at a time when all the Matter in the visible Universe was still confined to a microscopic volume, expanding at nearly the Vacuum speed of light even on the distance scale of elementary particles, is not a very meaningful thing to do.
But yoctoseconds? *Just no*. Sure we can speculate. Inflationary Cosmology tells us that after the first yoctoseond we are already well into the epoch of reheating if not past it already, when the decaying inflation potential provides the *Energy content* that produces the known particle spectrum of the Standard Model. And if that sounds like gobbledygook, well, it almost is: the words are not completely random, in fact entire textbooks have been written on the subject, but the Physics is extremely speculative and *not supported* by one shred of observable evidence.
As a matter of fact, we don't even really know if that first picosecond was indeed a picosecond or an eternity. And while cosmic inflation remains a popular concept, it has been abandoned by many, including one of its creators (Steinhardt).
It is remarkable that we live in an era in which we have a reasonably firm understanding of the Universe when it was a mere picosecond old, and a reasonably firm understanding of the Universe when it will be hundreds of times older than its present age. But our knowledge still has significant limits. And a yoctosecond is still a dozen orders of magnitude beyond the furthermost limits of our knowledge of the Universe's past.

353 -

What happens when we get very far away from the light source? Does the inverse-square Law still hold? If it does not hold there, why could this be? Could we do something law governs a wider range of distances?

The inverse-square Law can mean different things in different contexts. When it comes to Electromagnetism, the inverse-square Law governs the strength of the Coulomb force; it also governs the intensity of radiation from a compact source. The Coulomb force law basically tells you that the Electrostatic Force between two point-charges varies with the inverse-square of the distance between them. This is directly related to the fact that the electromagnetic interaction is mediated by a massless field, or alternatively, that the *quantum* of the Electromagnetic Field, the photon, *has no rest mass*.
Could it be any different? Yes, of course. The resulting theory is called *Maxwell-Proca Theory*, after the Romanian physicist Alexandru Proca, who first wrote down this theory in its modern form. The essence of the result is that a theory mediated by a *field with mass* will have a range that is *inversely proportional* to that mass. Within this range, the theory obeys the inverse square law (more or less). But as this range is approached, the strength of the interaction *drops rapidly*, *exponentially*, in fact.
Such forces are sometimes referred to as *Yukawa Forces*, named after the Japanese physicist Hideki Yukawa, who first proposed such a force as mediating the interaction between subatomic particles. In the modern Standard Model of Particle Physics, the weak interaction is a fundamental force that is a Yukawa type force: mediated by very massive particles (the $W^{\pm}$ and Z^{0}) this force has very short-range (hence, its perceived weakness; it really isn't any weaker than Electromagnetism, it just vanishes very rapidly, over subatomic distance scales).
Now, as to radiation, the inverse-square Law holds mainly because, when we think about it, if we have a source of radiation, the surface area of a sphere that surrounds it will grow as the square of its radius; consequently, the same amount of radiation is now spread over this larger area, so, its intensity diminishes as the inverse square of the radius.
This relationship holds over any distance, but when we consider the particle-nature of radiation, when it becomes very weak, what actually happens is not that, e.g., photons become less energetic; rather, there will be fewer of them. Eventually there will be so few photons, they will only be detected one at a time, here and there, somewhat at random. At such distances, what the inverse-square Law governs is the probability of detecting a photon over a unit area.

354 -

If Entropy increases in an isolated system by the 2nd Law of Thermodynamics, and the Universe is considered infinite, how can Entropy increase in an unbounded Universe?

The 2nd Law of Thermodynamics refers either to *infinitesimally small volumes* or to systems that are *closed* and *finite*. This has interesting consequences for certain bouncing cosmologies, in which the Universe is finite and goes through cycles of expansion and collapse. In such a Universe, Entropy would increase in each cycle, so they will not be 'carbon copies' of each other. This is a key objection against many cyclic Universe models.
But the question is how Entropy can increase in an *infinite* Universe. For starters, the 2nd Law simply says that Entropy cannot decrease in closed (infinitesimal or finite) systems; it can increase just fine. Furthermore, it does not even make sense to talk of the *total* Entropy of an infinite Universe, just as it does not make sense to talk of its *total* Energy. But if

the Universe is approximately homogeneous (which it is believed to be), then, it makes sense to speak of its average *Energy Density*; similarly, it may be possible to speak of its average *Entropy Density*; and that can increase just fine, because of *irreversible* processes.

355 -

Is the deflection angle of starlight by gravitating objects always exactly *twice* the amount predicted by Newtonian theory of Gravity, i.e., the ratio would not change whether the object is the Sun, a white dwarf, or a neutron star?

No, not exactly. The deflection angle calculated by Einstein comes from two sources in the SpaceTime metric of General Relativity. One part is *temporal* curvature, which is the source of Newtonian Gravity. The other part, which becomes relevant only when the speeds involved are relativistic (such as a photon), comes from *spatial* curvature. This is the reason why the deflection angle is *twice* the Newtonian value.
However, these calculations are carried out only to the *first* order. Higher-order terms are ignored. In the case of the Sun, ignoring these terms is legitimate, since the contribute on the order of a few parts per million. The relative magnitude of these terms is governed by the expression $GM/(c^2R)$, where G is Newton's constant, M is the Mass of the *lensing* object [see Wikipedia], c is the Vacuum speed of light and R is the *impact parameter* (at the distance of closest approach) of the light ray. For the Sun, this quantity is around $2 \cdot 10^{-6}$. For a neutron star, however, it can be as large as 0.1 or larger, so the deflection can no longer be computed using the simple formula that works for the Sun.
In the extreme case of a black-hole, the deflection angle can be anything: a photon that passes inside the so-called photon sphere radius (1.5 times the Schwarzschild radius) can temporarily orbit the black-hole, so, if it escapes again, its 'deflection' could amount to several times the full 360°!

356 -

How can a graviton have Mass? If the quantum loop Gravity Field has Mass, then it would be distorted by its own Mass.
[See answer to Issue 328, P. 148]

Gravitons are supposed to be *massless*. A massive graviton would have quite a different consequence: it would render the range of the gravitational force finite.
A massless graviton corresponds to a Gravitational Force that drops with the inverse-square of distance. In contrast, when a massive mediating particle is involved, beyond a certain range the corresponding force vanishes very rapidly (exponentially), which is why we say that such a force has a finite range.
An actual example is the weak force: its mediating particles are very massive; hence the range of the weak force is subatomic. It is actually not any weaker than Electromagnetism, but, unlike Electromagnetism, it acts only over such a short-range, which means that actual interactions are rare (this is why it is hard to detect a neutrino, for instance).
As to being distorted by its own … well, not Mass, Mass-Energy! The source of Gravitation is not rest-Mass. It is Mass-Energy (and Momentum and Pressure and Stresses, represented by the infamous Stress-Energy-Momentum Tensor). And while the Gravitational Field has no rest-Mass (equivalently, the graviton has no rest-Mass) it certainly has Energy. And that means that it can indeed *interact with itself*.
This *self-interaction* of the Gravitational Field is what makes the theory *nonlinear*. This non-linearity is very tiny, but detectable. It is in fact detectable in the oldest measurement confirming General Relativity: the perihelion precession of Mercury. Without the *self-interaction*, Mercury's *perihelion precession* would be $4/3$ times its actual value.
The derivation is not very hard but technical (still, any student of General Relativity should be, make it *must be*, able to derive the result). The actual result contains the coefficient $(2+2\gamma-\beta)$, where the parameter γ represents the *non-Newtonian* contribution of *spatial* curvature; the parameter β, in turn, represents the *non-linearity* contribution. In General Relativity, both these parameters are 1; hence, the overall factor is 3; without β, that factor would be 4. So there, accurate 19th century measurements of Mercury's orbit are sufficient to show not only that General Relativity works, but also that it is, indeed, a *non-linear* theory.

357 -

What is the most obvious example of Quantum Field Theory and General Relativity giving different answers?
[see Issue 6, P. 13]

They don't give different answers. The incompatibility between the two theories means something else altogether.
Here is what we can actually do: we can do Quantum Field Theory on the curved background of General Relativity. The math can get tedious, but the application is clear, and it can even be shown that the theory remains self-consistent,

without, e.g., predicting a-causal behavior (such as faster-than-light or backward-in-time signals).
The problem lies elsewhere. Matter is the source of Gravitation. Specifically, the Energy-content of Matter is the source of Gravitation. Symbolically, without getting lost in details, it is in the form of an equation $G \propto T$, where G represents Gravitation (it would be the Einstein-Tensor of the Gravitational Field if we wanted to spell it out in all its gory details) and T represents the *Energy-content of Matter* (the proportionality symbol $\propto$ indicates that these two quantities relate to each other by a *constant* factor).
Why is this a problem? Because when we change our theory of Matter from a classical to a quantum theory, we end up with an equation in the form $G \propto \hat{T}$. It should be noticed that the little hat on top of the T on the right-hand side indicates that the Energy-content of Matter is no longer represented by numbers but rather, by a *quantum mechanical operator*. The left-hand side is still a number. This clearly will not work.
There is, however, an easy way to fix this problem: $G \propto \langle \hat{T} \rangle$. What did we just do? We replaced the operator-valued quantity on the right-hand side with its number-valued *expectation* value (let's think of it as an average of sorts). This is called *semi-Classical Gravity*, and it works in every regime that we can access through astronomical observations or laboratory experiments. However, it is generally not seen as a fundamental theory, rather, as an approximation. An approximation of what? That's what *we do not know*.

358 -

Do elementary particles get 'spaghettified' too, and what does it mean for them?

In a sense, yes, but now is the time to offer another reminder that elementary particles, in the best theory that we have, Quantum Field Theory, are simply excitations of the underlying quantum fields (e.g., photons are unit excitations of the one-and-only Electromagnetic Field in the quantized version of Maxwell's Theory, Quantum Electrodynamics).
Also, in curved SpaceTime, the concept of a particle becomes observer-dependent: an *accelerating* observer may see *particles* (the *Unruh Radiation*, after William Unruh, Un. of British Columbia (‡)), while an *inertial* observer sees *nothing*. With that in mind, the question must be slightly rephrased: what does *spaghettification* mean when it comes to *quantum fields*? It means *Gravitational Vacuum Polarization*; in other words, the very mechanism that is at the heart of *Hawking Radiation*. So, yes, the same tidal forces that *spaghettify* extended objects also affect quantum fields: the result of that is *black-body thermal radiation*, as first described by Stephen Hawking in his landmark 1974 paper.

359 -

Is Vacuum Energy created out of the 'Absolute Nothing'?

Absolutely no! *First*, quantum fluctuations do not do anything. It is a lovely, pictorial expression that is used to describe a property of quantum fields, namely that their zero-point Energy (the absence of any excitations, i.e., the absence of 'particles') is non-zero. One way to represent this mathematically is through an expression that basically tells us how we can get from Nothing (the Vacuum) to Nothing (the Vacuum): in addition to the trivial way (Vacuum all along), we can also get terms that we visualize as the *creation* of *particle-antiparticle pairs*, the *emission* and *re-absorption* of a particle, etc.. Now, here is the point to remember: *these things don't actually happen*. These are terms in the series expansion of an integral. *They are not actual physical processes*; they are called 'virtual' because *they don't really exist*!
Second, this 'Vacuum Energy' doesn't get created. It doesn't get destroyed. It simply is. It is a property of the quantum fields that make up our Universe. It's not Energy in the sense of the 'ability to do work': it is simply a measure of a *residual* Energy term when all excitations of a field are removed. Normally, we would not even worry about such things (in most of Physics, only differences in Energy matter) but, because Energy is the source of Gravitation, its value and properties do matter when it comes to General Relativity.
Finally, *Energy is never created out of nothing*. To the best of our knowledge, the fundamental fields that constitute the Universe all obey equations that are 'Time translation invariant', meaning that there will be a *constant of the motion* we call Energy. This Energy is strictly (*not probabilistically*!) *conserved* in every quantum interaction, at every vertex of a Feynman diagram, everywhere, together with (Linear) Momentum and Angular Momentum (constants of the motion associated with equations that do not change under translation and rotation in Space), no exceptions.

(‡) The *Unruh effect* (also known as the *Fulling-Davies-Unruh effect*) is the *hypothetical* prediction that an *accelerating* observer will observe a *thermal bath*, like black-body radiation, whereas an *inertial* observer would observe *none*. In other words, the background appears to be warm from an accelerating reference frame; in layman's terms, an accelerating thermometer in *empty* space, removing any other contribution to its temperature, will record a *non-zero temperature*, *just from its acceleration*. Heuristically, for a uniformly accelerating observer, the ground state of an inertial observer is seen as a mixed state in thermodynamic equilibrium with a non-zero temperature bath.
The Unruh effect was first described by S. Fulling in 1973, P. Davies in 1975 and W. G. Unruh in 1976. It is currently not clear whether the Unruh effect has actually been observed, since the claimed observations are disputed. There is also some doubt about whether the Unruh effect implies the existence of Unruh Radiation. [Source: WIKIPEDIA]

360 -

When we run, does our Mass increase?

Let's clarify something when it comes to Relativity Theory: no matter what we do, our mass does not change unless we

a. accumulate Mass by absorbing Matter (Mass-Energy) from the outside, or

b. lose mass by expelling Matter (Mass-Energy) or radiating Energy to the outside.

Motion does not change Mass. In fact, motion does not change anything, for one simple reason: relative to ourselves, we never move. When we walk, our frame of reference travels with us. In that frame, it's the rest of the Universe that is moving backwards. This is the reason why it is called the Theory of Relativity. So, what the theory tells us is not how our properties change: they don't. What the theory tells us is how some of our properties might be measured by someone else, someone who is not moving with us. Therefore, to the extent anything changes, that's what changes: other people's perceptions of our properties. There is no intrinsic change. We are not becoming shorter; our biological or mechanical clock is not ticking slower. We may appear shorter; our clock may appear to slow down as seen by someone else.

As to Mass, … that is even messier. There is this silly concept called 'relativistic Mass' that used to be popular in the literature decades ago but has since fallen into disuse because it causes more confusion than it's worth. It basically amounts to lumping together our *rest mass* (which is our intrinsic property) and our *Kinetic Energy* (which depends on who is looking). This is not a smart thing to do, with one exception: the kinetic Energy of the particles that make up our body, as measured in the frame of reference in which our body is at rest, is part of our overall Mass. But our 'bulk' Kinetic Energy? Again, it depends on the observer. Say, we're on a fast train. What exactly is our speed? Maybe, say, $50\ \mathrm{m/s}$? That fast train is on the surface of the Earth, spinning a lot faster perhaps in the opposite direction, as fast as $460\ \mathrm{m/s}$ near the equator. So, is our speed $410\ \mathrm{m/s}$? But it's on the Earth that is moving at something like $3 \cdot 10^4\ \mathrm{m/s}$ around the Sun. Then, … which is our 'real' speed?
There is no such thing. It depends *on the observer*. Our mass, on the other hand, is an *intrinsic property*, and it amounts to the total 'internal' Energy-content of our body, as measured in the frame of reference *in which our body is at rest*. This quantity does not change just because someone else is moving fast relative to us and measures us from his moving frame of reference.

361 -

What is Higgs Boson? Will it destroy the Universe?

Short technical answer:
The Higgs Boson is the excitation quantum of the one remaining degree of freedom of the Higgs Field after *Electro-weak Symmetry Breaking*.

First, all elementary particles in quantum field theory are just excitations of the underlying quantum fields. The basic logic in a very concise summary goes like this: just as an arbitrary sound can be expressed as a sum of pure sounds (sine waves), any continuous field can be expressed as a sum of 'harmonic oscillators'. In the Quantum Theory, harmonic oscillators have a curious property: their Energy of oscillation can only increase or decrease one unit (quantum) at a time, it cannot take intermediate values. In the Quantum Field Theory, creation of a particle means increasing the Energy level of one of the many elementary oscillators in the corresponding quantum field by one unit; annihilation of a particle means the opposite. So, the particle itself is one Energy quantum, one unit of excitation of that field.

Second, the Standard Model of Particle Physics is a quantum field theory involving many fields (e.g., leptons, quarks, vector bosons). For a quantum field theory to make mathematical sense, it has to be 'renormalizable' (meaning that it must not predict infinities that cannot be removed in a mathematically self-consistent manner). The Standard Model is such a theory, but only in the presence of another field, the so-called *Higgs Field*.

Third, the Higgs Field is normally described by four numbers (two complex numbers actually; it's a 'complex doublet') at every point in Space and Time. It has four 'degrees of freedom'. But the Higgs Field interacts with other fields. In a mathematical process called *symmetry breaking*, three of its four degrees of freedom go on and play another role: they give mass to the three vector bosons of the Weak Interaction. This process in an indirect way also gives masses to charged leptons, like the electron, and quarks.

The remaining degree of freedom of the Higgs Field corresponds to a *very heavy* elementary particle: the Higgs Boson. This particle can be created in high Energy particle accelerators, but its existence is fleeting: it decays very rapidly. So, on its own, it will not destroy the Universe.
However, as it turns out, the Higgs Field ... might. Probably not, certainly not anytime soon, but if some calculations are to be believed, the same renormalization business that makes the theory works in the first place also predicts that the Higgs Field, in its current low Energy state, is *unstable*. If these calculations are correct then sometime in the very distant future, perhaps trillions of years from now or more, the Vacuum may undergo a phase transition to a new, lower Energy

state, completely changing the basic laws of Physics governing particle interactions in this Universe. So, that would amount to a destruction of the Universe as we know it.
All this is very speculative and quite likely not true.

362 -

How can one electron be everywhere? If it is only at a certain position at a certain point in time then how can the electron get excited by photons?

Before answering this question, we need to ask: what is an electron?
The Standard Model of Particle Physics is quite a misnomer. The grandfather of all physics misnomers, arguably. Because it really is the Standard Model of Quantum Field Physics. Its fundamental objects are all fields. Take the part of the Standard Model that is known as Quantum Electrodynamics (QED): This theory has two fundamental objects, the Electromagnetic Field and the Electron Field. That's it.
Both these fields are functions of SpaceTime coordinates (one is a vector-valued function the other is a spinor-valued function). Apart from very special spots that may or may not exist, the fields are not null anywhere. I.e., these fields are present everywhere.
Because these fields are quantum fields, their interactions are subject to certain rules. Most notably, when they interact, they exchange Energy and Momentum in set units. Not only that, but we can even define mathematical operators that allow us to count these units. So, these units of excitation have a distinct existence. These unit excitations are our 'particles'.
What these units of excitations do not necessarily have is a specific location. They are not miniature cannonballs. Imagine a bowl of water, with small ripples on its surface. We shake the bowl a little. More ripples appear. Can we point at a specific location and say, this is where we made the bowl ripple more? Of course not.
So, except for very exceptional circumstances, the excitations of the Electromagnetic Field or the Electron Field are not spatially localized. They are indeed everywhere. Now depending on how a particular interaction is arranged, an excitation may (briefly) have a well-defined position (let's imagine sticking our finger into the bowl of water; the ripples we create are initially localized, but the 'natural' state of these excitations is that they are spread out in space.

363 -

How can we explain the Schrödinger's Cat thought experiment?

Schrödinger's Cat is itself an analogy, or perhaps better described as a 'thought experiment'.
The basic idea is that Quantum Mechanics tells us that a particle experiment that has two equally likely outcomes is, in fact, in a superposition (a mix) of the two possible outcomes until it is actually observed.
Schrödinger's thought experiment was supposed to demonstrate the absurdity of this notion, by placing a cat in a sealed box with the quantum experiment connected to a mechanism that would kill, or not kill, the cat depending on the experiment's outcome. The naive reasoning is that until the box is opened and its contents observed, the cat, just like the particle that may or may not cause it to die, would be in a superposition of states: it would be alive and dead at the same time.
This leads to all sorts of implications and questions, including questions about what an experiment really is, but fundamentally, it relates to a gap, still present, in our understanding of Quantum Physics: precise understanding of what a measurement is, and the so-called collapse-of-the-wave-function business.
Many well-known physicists 'went off the deep end', so to speak, trying to make sense of this. Therefore, we will spare ourselves from our own half-baked thoughts, except for raising one important point that is often missed when discussing the aforementioned feline.
We like to contrast the cat with another experiment (this one can actually be carried out in the laboratory): the infamous *two-slit experiment*, where we end up producing a nice interference picture with electrons going through one hole or another. Even when the electrons are fired one at a time, over time, the density of where the electrons arrive on the detector screen will show a nice, wavy pattern, which leads to the inevitable conclusion that each electron goes through both slits, interfering with itself as though it was a wave, before it makes a point-like impact on the detector screen.
The important thing is this: when we observe the impact location of an electron in that two-slit experiment, it does not allow us to reconstruct the path of the electron, because the electron had no path in the classical sense.
In contrast, when we open the box containing Schrödinger's cat, if the cat is found alive, we know without a doubt that it was alive all along; and if it is dead, its time of death can be determined by an experienced veterinarian. In short, its history can be reconstructed. Unlike the electron in the two-slit experiment, the cat does have a classical state all along, we're just not aware of it until after we open the box.
That's food for thought for those who think that just like the electron going through both slits, the cat was in a superposition of states until the box is opened.

364 -

If virtual 'particles' are mere mathematical abstractions, as some advocates, how do we explain Hawking Radiation?

Hawking radiation is in the form of *real* particles, not virtual particles.
How we 'explain' them is laid out clearly in Hawking's own 1974 paper in Nature (*Black-hole explosions*?, NATURE, VOL. **248**, MARCH 1, 1974). In it, he analyzes the absorption and emission of wave-packets by the black-hole and concludes that a small difference exists between the two, resulting in an emission spectrum that corresponds to that of a thermodynamic black-body at a given temperature. Although Gravitation in his calculation is represented classically, the emission and absorption are represented using a proper quantum theoretical description of the fields in question, such as the Electromagnetic Field; the emission, then, can be readily expressed in the form of outgoing quanta, 'real' (not 'virtual') photons.

365 -

Why do physicists believe that miniature primordial black-holes may exist, when Hawking showed that black-holes this small would have already evaporated?

No. The largest primordial black-hole that would have evaporated by now weighs about $1.73 \cdot 10^{8}$ metric tons. That's a lot of metric tons, but in the big scheme of things, it's nothing. In terms of the Sun's mass, it amounts to about $8.7 \cdot 10^{-20}$ solar masses.
The smallest black hole that can form through gravitational collapse would weigh roughly 3 times as much as the Sun. So, anything in-between $8.7 \cdot 10^{-20}$ solar masses and 3 solar masses would be a 'miniature' primordial black-hole: a black-hole smaller than what can form through gravitational collapse, but large enough to have survived since the beginning of the Universe.
That said, even though the primordial black-hole issue may not be found particularly interesting, we should not assume that physicists cannot use their calculators.

366 -

In Physics, we have Dark Energy and Dark Matter. Why is there no Dark Force?

Who ever said there isn't? There are, in fact, hundreds of papers out there mentioning a 'Dark Force' of some sort or other. Nonetheless, this question reveals a misconception about the way Science works. It's not like we realized, there's Dark Stuff there, so, let's attach the word 'Dark' to whatever we can think of!
Admittedly, in some ways it's actually worse than that. We have suspected since the 1930s that there may be more Matter in the Universe than what we see. Eventually, it became clear that this unseen Matter cannot be made of normal particles, i.e., it is not just a dark cloud of gas or dust. But we don't know what it is. Unfortunately, 'stuff we don't know that must be out there' doesn't sound very 'scientific', so, instead, we call it 'Dark Matter'. The only thing we know about this 'Dark Matter' is that it has *zero* pressure.

Then, something else happened. We realized in the 1990s that the evolution of the Universe is governed by a non-zero value of the so-called Cosmological Constant. Increasingly, the idea that it's not just a constant of Nature but another constituent of the Universe gained a foothold. If that is what it is, it has huge *negative* pressure, so it's obviously not 'Dark Matter'. But then, what is it? No one knows but again we gave it a name: 'Dark Energy'.
It should be emphasized that the only thing we actually know about 'Dark Matter' is that it has *no pressure*. The only thing we actually know about 'Dark Energy' is that it has huge *negative* pressure. Everything else is speculation. In particular, 'Dark Matter' is not any more Matter-like than 'Dark Energy'; and 'Dark Energy' is not any more Energy-like than 'Dark Matter'. We shouldn't read anything into these words. We might as well call these hypothetical constituents of the Universe 'Dark Apples' and 'Dark Oranges'. Let's come to think about it, that would actually be better as it would likely lead to fewer misunderstandings concerning their nature.
Now it is true that in the Standard Cosmological Model, there are only these two 'dark' things, because the model doesn't need more in order to work. There are other models, however, that introduce different ideas, including possible 'Dark Forces' through which Dark Matter may interact with itself (so it's not completely pressureless) or some other interaction involving 'Dark Anythings' might take place.

As of now, however, we have zero direct experimental confirmation that any of these Dark Anythings actually exist. People do go on to explore theoretical and modified theories of Gravitation, which do not need '*Dark Whatever*' at all.

367 -

If Einstein's Theory of General Relativity says that astronauts are in a different time frame than those on Earth, how can we video chat with people on space stations? Is it because the space station has no velocity?

The space station is orbiting the Earth at a speed of approximately $7.8\ \mathrm{km/s}$. That is quite a respectable velocity, but insofar as Relativity Theory is concerned, it is next to nothing.
The time dilation associated with this velocity is about $0.34\ \mathrm{parts}/10^9$. That is, over the course of a full year, the astronauts' watches will fall behind by roughly one hundredth of a second compared to terrestrial watches. That is certainly not a difference that we would notice, nor does it interfere with our ability to communicate with the ISS.
However, although this difference is very small, it is certainly measurable using sufficiently accurate clocks and instruments. Indeed, Gravitational Time Dilation, which is an order of magnitude smaller in this case, is also measurable. And while it does not interfere with our ability to communicate, these tiny corrections are important when it comes to using precisely timed signals for navigation, namely satellite positioning systems, such as GPS.
For Relativistic Time Dilation to become sufficiently significant to be noticeable without instruments, much higher velocities would be needed. A musician with a good ear may be able to hear a difference in pitch amounting to about a quarter tone (*). This amounts roughly to a 3% change in frequency. For Relativistic Time Dilation to produce this much of an effect, a spacecraft would have to move at nearly the quarter of the Vacuum speed of light. That would be nearly 10000 times faster than the ISS. This is kind of misleading, as the relativistic Doppler effect would be more significant than time dilation by itself, as at a mere 3% of the speed of light, the difference would become noticeable to that trained musician. But even that is still more than a thousand times the speed at which the ISS orbits the Earth.

(*) Several comments on this point need a clarification: the reference was to *absolute*, or perfect pitch, in this answer. It is true that when we hear two pure sounds in rapid succession, we can distinguish a difference in frequency as small as 0.3%. But if we present two pianos, one of which is mistuned by less than a quarter tone, we may be able to tell that one of them is mistuned, but not which one. On the other hand, if the difference is a quarter tone or more (3% or more in frequency) a trained musician with perfect pitch can indeed tell which of the two pianos is tuned correctly, not just that one is mistuned.

368 -

What if Space expanded so fast that virtual particle pairs were pulled away from each too quickly for them to annihilate each other?

Not a silly question, but let's clarify a few things, common misunderstandings concerning cosmic expansion.
Space doesn't expand and the expansion itself is not pulling anything apart. Let's forget poetic expressions like 'SpaceTime fabric'. The equations that describe cosmic expansion contain only two things: Matter and Gravity. Expansion means that Matter becomes *diluted*, i.e., its density decreases. As a result, the Gravitational Field changes of course and, in General Relativity, the Gravitational Field doubles as the metric of SpaceTime, determining the measured features of Geometry.
Normally, Gravity slows down the expansion because it tries to pull things back together. In fact, in some cases it succeeded: this is how self-gravitating structures like galaxies, solar systems, stars and planets formed. These structures stopped expanding a long time ago, and nothing is pulling them apart.
It was said 'normally' in the previous paragraph, because under the right circumstances, Gravity can act as though it was repulsive. This is when the Matter-content of the Universe is dominated by the so-called 'Dark Energy' component, also known as the Cosmological Constant. Dark Energy behaves effectively as though its Mass density were *negative*, so its response to Gravitation is *repulsive*. Therefore, *it accelerates the rate of expansion*.
But even this does not pull apart things which are held together by other forces.
However, … it is possible that our Universe contains what is known as '*Phantom Energy*' in the literature. A Universe with Phantom Energy is *unstable* because the density of Phantom Energy is increasing when the Universe expands, but, just like Dark Energy, Phantom Energy accelerates expansion. However, in this case, it becomes a runaway process, known as the '*Big Rip*'.
Yes, a 'Big Rip' can pull apart even self-gravitating structures, even small structures like planets, mountains, houses, people, even subatomic particles; and ultimately the runaway (repulsive) Gravitation of Phantom Energy can become large enough to cause significant *Vacuum polarization*, in a process not unlike that which is responsible for Hawking Radiation near black-holes. An observer might see this process as the creation of particle-antiparticle pairs (of course the observer would have to survive in this extreme, runaway Universe first, which is an unlikely possibility).

369 -

Why does it take 40000 years for a photon to go from the core of the Sun to the surface, but only 8 minutes from the sun to Earth?

It doesn't. Essentially no photon that is produced in the deep interior of the Sun ever reaches the surface. That happens to be a good thing, too. The deep interior of the Sun has a temperature of over $1.5 \cdot 10^7$ K, which means that most photons produced there are *hard* (and deadly) γ- rays, not visible light.

The deep interior, however, is also dense and quite *opaque*, so, any photon, even a highly energetic gamma ray photon, gets quickly reabsorbed by the medium.

Even though this region is opaque, it is not completely opaque: it is sufficiently transparent for high Energy photons to travel a little before they're absorbed. As such, radiation is the main mechanism of heat transfer from the deep solar interior to the outer layers of the Sun, but no individual photon will travel several hundred thousand kilometers from the solar core all the way to the convection zone.

Nonetheless, we can calculate how long it takes for the Energy produced by fusion to reach the surface, or conversely, at any given time, how much Energy is contained in the form of photons in transit, i.e., a 'photon gas'. These calculations are approximate but tell us that about a million years' worth of photons are in transit at any given moment in Time. Hence the popular suggestion that 'it takes a photon a million years to reach the solar surface'.

In the outer layers of the Sun, the role of radiation diminishes, and convection takes over. Like a boiling liquid, the outer layers of the Sun are churning all the time, transporting heat from the interior to the surface. The hot gas reaching the surface can freely radiate its own heat into space, cooling and eventually sinking back into the interior. What about the sunlight that we see? It is thermal radiation from the hot gas on the surface of the Sun. It's not coming from the interior. That sunlight travels in space unimpeded at $3 \cdot 10^8$ m/s , taking approximately 500 s to cover the Sun-Earth distance of about $1.5 \cdot 10^8$ km.

370 -

What is the *inverse Lorentz transformation*?

The *inverse* of a Lorentz transformation is *another Lorentz transformation*.

It is possible to demonstrate this explicitly but understanding the principle doesn't even require formulas.

From a physicist's viewpoint, Lorentz transformations relate inertial reference frames that move relative to each other. So, if a Lorentz-transformation tells us how to translate Space and Time coordinates from one reference frame to another, its inverse would tell us how to translate Space and Time coordinates from the second reference frame to the first; and that, too, must be a Lorentz-transformation, of course.

From a more mathematically inclined perspective, it is not very hard to show that Lorentz-transformations form what is known as a *group*. Basic group properties include the existence of an *identity* (this would be the trivial Lorentz transformation that does nothing, i.e., the Lorentz transformation of zero velocity and no spatial rotation), a group operation (in this case, combining two Lorentz-transformations together) and the existence of an *inverse* for every element in the group. So, for every Lorentz-transformation in the group, there exists another Lorentz transformation that, when combined with the first, yields the trivial *identity transformation*.

Looking at Lorentz transformations from a Group Theory perspective may sound like mathematical overkill, but it is actually quite helpful. It can help us understand that spatial rotations form a group. We next learn that the *group of rotations* can be extended to include velocity boosts, resulting in the *Lorentz group*. We also learn that velocity boosts alone do not form a group: what is a pure velocity-transformation from the perspective of one reference frame is a velocity transformation and a spatial rotation as seen from another frame.

The group can be further extended to include translations (displacements) in both Space and Time, yielding the *Lorentz-Poincaré group*, which is the most general group of transformations in Special Relativity. However, it is possible to extend the group further, to the so-called *conformal* (*angle preserving*) *group*. Maxwell's Theory of Electrodynamics in the Vacuum (no charges) actually 'lives' in this group, but once we allow charges, we are restricted to the Lorentz-Poincaré group (conformal transformations would change charges and currents and that is not something we see happen in Nature).

One important thing to remember is that there is a lot more to Lorentz-transformations than the naïve high-school formula involving the parameter $\gamma := (1 - v^2/c^2)^{-1/2}$. That formula is useful, important, but it barely scratches the surface of this rich subject.

371 -

Are there other dimensions/Universes as described in String Theory on The Big Bang Theory?

It really isn't right to say that there are dimensions in (Supersymmetric) String Theory. Rather, the correct statement is that Supersymmetric String Theory only works in 10 SpaceTime dimensions. This is unfortunate, because our World is rather blatantly obviously $(3+1)$-dim, so to make sense of String Theory, people have come up with various schemes to 'compactify' the unwanted dimensions (the basic idea is: the 2-dim surface of a garden hose looks like a 1-dim line from far away).

There are no 'Universes' in String Theory. Rather, there is no unique String Theory; there are many, incredibly many possible theories. Sometimes, this 'Multiverse' of possible String Theory Universes is conflated with other theoretical frameworks in which multiple Universes show up in some form or another, e.g., the 'many worlds' interpretation of Quantum Physics, even though the two have nothing to do with each other.

Others observed that The Big Bang Theory is a television sitcom. The concept of an expanding Cosmos with a hot, dense early state, colloquially referred to as a Big Bang Cosmology, is not a theory. The theory is Physical Cosmology, specifically, applications of the theories of General Relativity, Thermodynamics, and the Standard Model of Particle Physics. These are very conventional theories in the sense that they involve only the 4 well-known SpaceTime dimensions and certainly no alternate Universes.

372 -

Does the ground do work on us to keep us from falling in General Relativity? A video describes the Earth's surface pulling us away from our SpaceTime geodesic by 'adding Energy to us', but there's no force through distance by the Earth …

To answer this question, we must remember first that Energy is not an intrinsic quantity. The Kinetic and Potential Energies of an object depend on the observer reference frame. This is true even in Newtonian Physics, i.e., Galilean Relativity. By way of a rather trivial example, when we sit on a moving train, the Kinetic Energy of our fellow passenger, sitting next to you, is zero in your reference frame; but both we and our fellow passenger have plenty of Kinetic Energy in the reference frame of an observer standing on the station platform, watching our train speeding by.

So then, let's think about us standing still on the floor, the floor preventing us from falling. Does the floor do work on us? *Certainly not in our own reference frame*, our position doesn't change, our velocity doesn't change, so, neither our Kinetic Energy nor our Gravitational Potential Energy changed.

But now imagine another observer, someone else who is freely falling (say, our floor was a platform on top of a very tall skyscraper, and now our Energy is expressed in the reference frame of a skydiver zipping by, parachute not yet open). From the reference frame of this freely falling inertial (!) observer, our velocity is increasing very rapidly, so clearly something accelerates us, doing work on us! And that something, of course, is the floor pushing us up, preventing us from following an inertial trajectory.

373 -

How much time will it take for a *stable* black-hole created on Earth to engulf the whole planet?

The smallest black-hole that is cold enough to actually gain weight here on the Earth as opposed to losing mass by radiation would have to be roughly 1% the mass of the entire Moon, which is roughly 0.01% of the entire Earth.

If we have what is essentially a point-mass (its radius is still $< 1\,\mu\text{m}$) weighing this much here on the Earth, being engulfed will be the least of our problems. Long before that, simply the presence of something this compact and this heavy would completely mess up everything: it would break up the Earth's crust as it wobbles around, it would release energies compared to which a global thermonuclear war every millisecond is just a faint summer breeze as matter falling into it releases copious quantities of *heat and radiation* due to internal friction.

Needless to say, we do not have the ability to create things weighing as much as $1\,\%$ of the Moon.

The smallest black-hole that can exist (only momentarily, before it disappears in the form of Hawking Radiation, essentially instantaneously) is about $21\,\mu\text{g}$. This is still *very many* orders of magnitude beyond the highest energies that we can achieve in particle accelerator experiments.

374 -

What known things can escape a black-hole? Clearly nothing with mass, but Gravity and Magnetism can, presumably because they are fields, not particles. Charge, say? And can those fields draw out Mass/Energy?

Gravity and Magnetism do not 'escape' a black-hole. The *static* Gravitational Field and Magnetic Moment are simply *properties* of the black-hole. The black-hole may also have an Electric Charge, but no charge 'escapes' the black-hole either; there can be no current flowing from the black-hole, its charge is *static*, too.
And being static, these things do not 'draw out' anything from the black-hole either. They simply represent *properties* of the black-hole through which the black-hole can interact with other objects (its Gravitational Field can attract things, its electric charge can attract or repel charged things, its magnetic field can alter the path of charged particles) without changing the black-hole itself, other than by adding *mass*, adding *charge*, or adding\removing *Angular Momentum* through the infall of Matter that may have Charge and Angular Momentum in addition to its Mass.

375 -

If, as according to some people (e.g., Victor T. Toth), SpaceTime is not expanding, and it is merely things *flying apart*, then why are photons which have no mass bent by Gravitational Fields?

Photon trajectories are bent by Gravitational Fields because the Electromagnetic Field (of which photons are the quanta) interacts with the Gravitational Field.
All fields interact with the Gravitational Field. Sometimes, this interaction is described using the words 'universal and minimal'. *Universal* means, of course, that the interaction makes no distinction: massive or massless, bosons or fermions, whatever, doesn't matter. The only thing that matters when it comes to Gravity is the *Stress-Energy-Momentum* of the field (which is certainly not 0 for the photon even though its rest-Mass is). And *minimal* means a prescribed mathematical relationship that, in a specific sense, is the simplest possible.
Because of these two properties, it is possible to reinterpret the Gravitational Field as the metric of SpaceTime. We should hasten to add that other fields can be described using the language of Geometry as well; however, as their interactions are not universal, the nature of that *geometry* changes depending on what particles are used to measure it. This is not the case for Gravity, because of universality, all particles measure the *same effective geometry*.
And this is why we sometimes say that 'Gravity bends SpaceTime'. In other words, it changes the one-and-only SpaceTime metric that all particles sense.
This is also the case when it comes to cosmic expansion. Things fly apart (literally: the distance between two distant galaxies increases over time. Thus, they fly apart, in the most pragmatic, most literal sense of the word). But as things fly apart, the Gravitational Field, also known as the SpaceTime metric, changes as well.
But to speak of 'SpaceTime expanding' implies that SpaceTime itself has measurable properties, little markers attached to it by which we can measure changing distances. That is not the case. We can only measure distances between things. And things fly apart: *the distance between them increases*. This is an unassailable fact, no matter what interpretation we attach to it using the best theories that we have.

376 -

Can a black-hole itself (not its accretion disk) have a Magnetic Field?

Indeed, the answer is: yes. It is known that the end state of *gravitational collapse* is completely characterized by three parameters: Mass, Electric Charge and Angular Momentum. A black-hole that has both an Electric Charge and Angular Momentum is called a *Kerr-Newman* black-hole. The Kerr-Newman black-hole indeed has a non-zero *magnetic dipole Moment* m. So, yes, a black-hole itself can have a *magnetic field* $\boldsymbol{B}$.

377 -

If Matter can't be created nor destroyed, why do Matter and anti-Matter annihilate each other into pure Energy?

Matter CAN be created and destroyed! We do this all the time. There is no 'conservation of Matter Law' in Physics. There are Conservation Laws, but these are a bit more specific: conservation of Energy-Momentum, conservation of Angular Momentum and conservation of Charge are but a few examples.
Particle interactions (including, but not limited to, interactions between particles and corresponding anti-particles) convert particles into other kinds of particles. As a result, particles that we traditionally associate with 'Matter' (which is an ill-defined word to begin with) get created and destroyed all the time. In fact, that is one of the main points of Quantum Field Theory: through its *creation* and *annihilation* operators, the theory can account for the *creation* and *destruction* of particles!

What these interactions never violate, not even probabilistically, are the Conservation Laws. These Conservation Laws are *absolute* and always *exactly obeyed by physical interactions*, even in the Quantum Theory. So, what cannot be created nor destroyed are things like Energy-Momentum or Angular Momentum. That quantities like these are absolutely conserved follows from a beautiful theorem (1915) named after the person who found it, Emmy Noether (1882-1935), which tells us that *if a physical system obeys certain symmetries*, *Conservation Laws follow*. As an example of the kind of symmetry that the theorem talks about, if a physical (isolated) system's basic laws remain *unchanged* over Time (Time-translation invariance), that implies the existence of a *Constant of the Motion*, and this constant is the Energy of the system.

378 -

How did the Universe go from being a measurable size to one which is infinite?

It did not. In the Standard, *spatially flat* Cosmological Model (the so-called *Lambda-CDM* or *Concordance Model*), the Universe is *spatially infinite* and *has always been spatially infinite*.
Unfortunately, popular accounts put the emphasis on the 'Big Bang' and present it as a moment in Time when the Universe was 'confined to a point' (or some similar expression).
But this is not what the equations tell us. The equations tell us that the actual moment of the Big Bang is a so-called *singularity*, which, by its very nature, is not actually part of the Physical Universe. Rather, measurable moments in time are those moments that are after the Big Bang. They can be arbitrarily close to the Big Bang: one millisecond, one microsecond, one femtosecond, or whatever; but that time interval *cannot be zero*.
Therefore, no matter how early a moment in the history of the Universe we study, and no matter how big a volume we study at that moment, there is always more stuff outside that volume.
Another source of confusion is that even though the Universe of the Standard Model is infinite, we only see those parts from which light could already reach us during the finite past lifespan of the Universe. And yes, this visible Universe is finite, and it can be confined to an arbitrarily small volume in the distant past, very close to the Big Bang. But that does not mean that there is no more Universe outside this visible Universe.
Of course, it is possible that the Standard Model is wrong. But barring some truly exotic mathematics, we can pretty much be certain that if the Universe is infinite today, it was always infinite in the past; conversely, if it was finite sometime in the past, it is finite today. These statements are true even if we contemplate the possibility that our knowledge of the extreme early Universe is very speculative, since we do not have a *decent* Quantum Theory of Gravity that could convincingly describe the Universe in that state of *extreme* density, pressure, and *extreme* gravitational fields.

379 -

If Gravity 'travels' at the speed of light, what propels it and what is its Energy source?

Gravity does not 'travel'; just like the Electrostatic Field of a charged particles does not 'travel' either. What may travel are *changes* in the Gravitational Field. Just like *changes* in the Electromagnetic Field can travel.
The Energy source of traveling changes in the Electromagnetic Field are accelerating charges. When you wiggle a charged particle back-and-forth, you transfer some Energy to the Electromagnetic Field, and this will propagate in the form of an *electromagnetic wave*. If the wiggling is fast enough, say, at least $4 \cdot 10^{14}$ wiggles/s or so, the resulting propagating wave, if it hits your eye, will be detected as light.
Similarly, the Energy source of traveling changes in the Gravitational Field are accelerating 'gravitational charges', i.e., accelerating masses. But Gravity is much weaker than the Electrostatic Force, so, it takes heavy masses and\or fast wiggling to produce a noticeable wave. This is what happens, for instance, when black-holes merge; near the end, they orbit each other extremely rapidly (two objects, each weighing many times the Sun, orbiting each other dozens, even hundreds of times a second!) and that is enough to produce a *gravitational wave* that can be detected by instruments.
But the static Gravitational Field of a quiescent Mass does not 'travel'. It simply 'is'.

380 -

All Mass is Energy, but not all Energy is Mass. Is this statement true?

This question requires a somewhat pedantic answer. The *Mass-Energy Equivalence* relationship expresses exactly that: The equivalence of Mass and Energy, i.e., that the two are just two different words for the same thing. Well, *almost*. So long as we are talking about the Energy of a system as measured in its own rest frame, it is true: the Energy-content of that system and the mass of that system really are the same thing.
However, … the quantity that we know as Energy depends on the observer. E.g., the Kinetic Energy of my fellow passenger sitting next to me on a train is zero in my reference frame, but quite a lot in the reference frame of a spectator

standing at the station. This Kinetic Energy term that depends on the observer is sometimes included in the concept of 'relativistic Mass', which has fallen into disuse in part because it can be very misleading at times. But it is certainly not part of the intrinsic rest mass of my fellow passenger; his rest mass will not change just because someone is watching him from the station platform!

So, a reasonably precise statement, then, is that, *in the rest frame of a system*, all the Energy-content of that system contribute to its Total Mass. When we are not in the rest frame of that system, the Energy we measure is greater due to the additional Kinetic Energy than the rest-Mass of that system.

381 -

Do electrons attract each other *at very short distances* like the strong force for protons?

No, electrons do not attract each other but no, it's not the strong force per se (at least not directly) that keeps protons together either. The *strong force* relates to the 'color' charge of quarks. It's called 'color' not because it has anything to do with color but, because unlike the *electromagnetic charge*, which comes only in one variety, there are three distinct 'color' charges, and that the interaction is such that the three charges must either cancel out with corresponding anti-charges or sum to 'white' for a particle to be neutral. So, it made sense to give the names red, green and blue to the three charges, in analogy with human vision.

Quarks have color charge, so they cannot exist as free particles; free particles are always color neutral. The proton consists of three quarks of different color; its total color charge therefore is 'white', so neutral.

Yet, … when two protons are close enough to each other, they can exchange short-lived particles called pions, which are made of two quarks each: a quark and an anti-quark. These pions can produce a force between protons (and neutrons) that can be both *attractive* and *repulsive*. The details are complicated, but under the right circumstances, the result is that protons and neutrons stick together and form stable atoms; in fact, the binding Energy is sufficient to make those neutrons themselves stable, even though free neutrons decay with a mean half-life of 14 minutes or so.

Electrons have no 'color' charge and they are not composite particles. They may interact at very high energies by way of the *weak interaction*, but that *will not produce an attractive force between two electrons*.

382 -

Why are we so sure that Dark Energy is an 'outward pushing' force, with the Vacuum Energy as its source, instead of an 'inward pulling' force, coming from an external source which surrounds the entire Universe, as a kind of inside out black-hole?

First, as others observed, there is no 'outside'. The Universe is the totality of everything, and in the so-called Concordance Model, its properties are the same everywhere. In other words, no matter how far we are from our Earth, we'd still see around you a Universe much like what we see, with the same average density of stars, same composition of isotopes, etc. I.e., the Universe is assumed to be *homogeneous*.

Second, it's not that we think about a pushing or pulling force. We ask a much simpler question: what is the composition of a Universe that is homogeneous to produce the observed expansion?

Moreover, when we discuss its composition, we are really interested in only one quantity: the dimensionless ratio of Pressure vs. Energy density, $w = p/\rho_E$. This simple number, with a value between -1 (yes, *negative Pressure*) and $+1$ (values outside this range produce weird effects and instabilities, violating our basic expectations of a causal and stable Universe) tells us all we need insofar as the expansion is concerned.

Long story short, if we do this, we find that a Universe that consists of $30\,\%$ stuff with $w = 0$ and $70\,\%$ stuff with $w = -1$, at present, fits the bill. For Matter on the *large scale*, $w = 0$ (e.g., there is no 'pressure' between stars), but the known quantities of ordinary matter only amount to about $4\,\%$; the remaining $26\,\%$, whatever it is, is not seen, we have no idea what it is, so, we call it 'dark'.

As to the $70\,\%$, we again have no idea what it is, so we give it a name, 'Dark Energy'. Something with large negative Pressure responds to Gravity as though it were *repulsive*, and when $70\,\%$ of the Universe is made of that stuff, we get the observed expansion.

Now, we are not prejudiced as to what this 'Dark Energy' is. If you can come up with a credible mechanism that mimics the right behavior, by all means! But it cannot come from the 'outside' as a homogeneous Universe has no 'outside'. We can, of course, postulate a different Universe, one that does have an 'outside', but if we do it for real, we might find that we are up against formidable obstacles: it would be extremely difficult to reconcile such a model with the observable properties of the Universe (in particular, that we see no signs whatsoever of an 'outside').

383 -

In the Schwarzschild metric, why is $1-2GM$ in the coefficient and not just $2GM$ as this is the actual coordinate? What does the 1 signify and why does it need to be there?

The expression $2GM$ (or $2GM/c^2$ if we restore the Vacuum speed of light) is not a 'coordinate'. It is the so-called *Schwarzschild radius*, r_S, a measure of the size of the black-hole. But it is not this expression that appears in the metric. What appears in the metric is the expression $1-r_S/r$, where r is the distance from the black-hole. When r is very large, this expression becomes just 1 and we get back the *empty space Minkowski metric* of Special Relativity. As r gets smaller, we deviate more and more from Minkowski SpaceTime, until we reach $r = r_S$, when this term becomes 0, the metric becomes *degenerate*, and this coordinate system *loses* its validity.
So, if we want to think of it this way, $r_S/r = 2GM/(c^2 r)$ measures the amount by which the metric *deviates* from the *flat*, *empty SpaceTime* metric.

384 -

The laws of Physics say that two objects cannot occupy the same space at the same time. So, why can Dark and Normal Matter occupy the same space at the same time and not interact?

Everyday objects do not readily go through each other because of *residual electromagnetic forces* that prevent one object from penetrating another.
However, even as we read this, there are literally trillions of neutrinos (a form of Matter), originating from the Sun, zipping through our body (and through the entire Earth) undetected. Why? Because they are *electrically neutral*, they only interact by way of the *weak interaction* at very short range. So, to neutrinos, we might as well not exist; our chances of winning the lottery every time through the rest of our life is much greater than the chances of any individual neutrino hitting one of the atoms in our body.
Dark Matter and Dark Energy are presumed to be like neutrinos, except even more so. Therefore, these particles can zip through us, the Earth, the Sun, even a neutron star unimpeded. They do interact, but only through Gravity; and perhaps through other (yet to be detected) means that are even weaker, much weaker than the weak interaction.

385 -

As Space expands, do we too?

Space *does not* expand. The Cosmos expands *on the large scale*, which is to say that *things in it fly away from each other*, so the *average density decreases*. But it's important to emphasize that we are talking about things flying apart, not space 'dragging' them along or whatever. Why? Because when things *fly apart* but are *attracted* to each other, the flying apart *may come to an end*.
This is precisely what happens in our Universe. *Things fly apart*. But there are places where things are packed a little more densely than in other places. More density means more Gravity, perhaps enough Gravity to turn these things around, especially if they can shed some of the excess Kinetic Energy (which they can).
The result? Self-gravitating systems that stopped flying apart a long time ago. Clusters of galaxies, galaxies, solar systems, planets … and yes, on the planets, even people, though they are held together mostly not by Gravity but by *secondary electromagnetic forces*, which act between atoms and molecules. But we all are made of stuff that stopped flying apart an exceptionally long time ago and coalesced instead into our solar system, our home planet, and its messy, mostly greenish coating that we recognize as the biosphere, with us being a part of it.

386 -

Why would Hawking's Radiation escape? What makes it different?

Hawking Radiation 'escapes' because it doesn't come from inside a black-hole. It is produced by gravitational Vacuum Polarization *in the vicinity* of the black-hole. And, by 'vicinity', it does not mean $\propto 10^{-6}$ m only. The characteristic wavelength of Hawking Radiation is about 20 times the Schwarzschild Radius of a black-hole (up to $\sim 2\cdot10^8$ km), *depending on mass*. So, 'escape' is not really an issue here.

387 -

How does Quantum Electromagnetism unify General Relativity and Quantum Mechanics?

Quantum Electromagnetism *does not* unify General Relativity and Quantum Mechanics. Quantum Electromagnetism applies the laws of Quantum Mechanics to Maxwell's Theory of the Electromagnetic Field. The result is basically our *Theory of photons and electrons*, which obeys the rules of Special Relativity. This is a given: without Special Relativity, Maxwell's Electrodynamics does not work.
The theory also works on the *curved SpaceTime of General Relativity*. This is far from trivial, but it can be shown that its predictions remain consistent, without introducing, e.g., signaling that would be faster than light or travel backwards in time. However, it does not explain why SpaceTime is curved, or how the *Stress-Energy Tensor* (which, in the Quantum Theory, is *operator-valued*) can be the source of the Classical Gravitational Field; or alternatively, how the Gravitational Field itself can be quantized. So, QED *does not* unify General Relativity and Quantum Mechanics.

388 -

How can the Sun have gravitational pull on all the other planets if it is not even solid?

Solid? Is there anybody thinking the Earth is solid? Please, let's think again. The diameter of the Earth is about 13000 km, give or take. The 'solid' crust that we stand on? At most a few tens of kilometers thick. The rest is … in a molten, *liquid state* (better: *liquid phase*) (*).
Let's imagine a large beach ball. Fill it with water. That's actually a surprisingly accurate analogy of what the Earth is like. Except that its skin is not even unbroken. It consists of pieces that slide over and under each other, and break from time to time. Which is why all that molten stuff from underneath gets to the surface all the time (in volcanoes) and which is why the 'solid' skin is often not solid at all (think earthquakes).
Meanwhile, take the interior of the Sun. Technically, it is in a *gaseous state* (*phase*). But this 'gas' is actually many times thicker than concrete; its density far exceeds that of lead or uranium.
Fortunately, none of this has anything to do with Gravity. Density, pressure, viscosity, and similar factors are irrelevant (well, almost; in Relativity Theory, they do contribute tiny corrections).
The only thing that really matters when it comes to Gravity is Mass. The Gravitational Field of the Sun is what it is because the mass of the Sun is roughly 300000 times the mass of the Earth. The Sun's Gravitational Field would not change if we suddenly managed to freeze the Sun solid. It makes no difference.

(*) We know about the solid (at least insofar as its ability to conduct shear waves is concerned) inner core and the stiff/rigid mantle that nonetheless behaves as a highly viscous fluid over long timescales. This is not the place to start a Geology lecture. The bottom line is that the Earth is a near perfect sphere because over geologic timescales, it behaves as a mostly fluid sphere under its self-Gravity.

389 -

In his celebrated first Special Relativity paper, Einstein refers to 'symmetry'. Is this where he saw the Mass-Energy connection?

No, the symmetry that plays a critical role in the development of Special Relativity is not directly related to the concept of mass-energy equivalence. It refers to the fact that in pre-Relativity Physics, modeling a moving charge in a stationary observer's frame of reference vs. modeling a stationary charge in a moving observer's frame of reference do not lead to the same result. This asymmetry between the two descriptions of what is fundamentally the same experiment is not supported by Nature; observation tells us that the only thing that matters is the relative velocity of observer and charge, it does not matter which one is 'stationary'. There is no absolute reference frame with respect to which 'stationary' could even be defined. Einstein illustrates this by mentioning that when it comes to the interaction of a conductor and a magnet, only their relative velocity matters.
The concept of Mass-Energy equivalence, the subject of Einstein's fourth *annus mirabilis* paper, arises from another reasoning: the change of the inertia of a body that emits Energy in the form of radiation. From this Einstein deduces that the Inertia (i.e., the inertial Mass) of a body is, in fact, its Energy-content.

390 -

Is any solar system generating *gravitational waves*?

Indeed, they do, so long as there are planets. But let's go step by step. The gravitational field of any system can be described, outside that system, using the language of what are called spherical harmonics. The first of these harmonics is the *monopole*: the Gravitational Field of a *point mass*. It is known (the so-called *Birkhoff's Theorem*, a general relativistic version of *Newton's shell Theorem*) that *outside* any spherically symmetric mass, the Gravitational Field is

the same as that of a point source of the same mass. So, it doesn't matter if the Earth has a diameter of 12,000 km or 10 cm; the Moon would follow the same orbit either way (this is why black-holes aren't any scarier than stars with the same mass; they both have the same gravity). Therefore, the *shell\Birkhoff's Theorem* also tells us that a pulsating object that remains spherically symmetric will not have a changing Gravitational Field; hence, no gravitational waves.
The second of these harmonics would be the so-called *dipole Moment*. Dipole Gravitational Fields would be produced if we separated positive and negative Masses. But there are no negative Masses. So, no dipole fields (the electric equivalent of dipole radiation very much exists because there are positive and negative Masses; antennas are, in fact, dipoles, effectively emitting electromagnetic radiation, i.e., radio waves).
That leaves the next, the so-called *quadrupole* term. This quadrupole term is produced by any system that is not spherically or axially symmetric, e.g., a planet orbiting a star. This is the bulk of Gravitational Radiation that is produced by a solar system.
How much? Not a heck of a lot. The Earth, following its orbit around the Sun, loses Kinetic (motional) Energy at a rate of a couple of hundred watts. At this rate, since the dawn of the solar system, the Earth will have lost only one hundredth of a trillion of its orbital Kinetic Energy in this form. Which is unmeasurably small.
But in principle, yes, even the Earth produces this small amount of gravitational radiation. And when the objects are heavier and are closer to each other, the rate increases drastically. At the other extreme, inspiraling black-holes just before merging emit gravitational radiation at a rate, at an insane rate that, if it were visible light, would outshine the entire visible Universe.

391 -

Is Quantum Mechanics incomplete or was Einstein wrong about his Special Relativity Theory?

Quantum Mechanics is indeed *incomplete*. But do not let us despair ... this problem has been fixed roughly three quarters of a century ago with the development of Quantum Field Theory (QFT). One of the main motivations of Quantum Field Theory was to create a quantum theory that is fully compatible with Special Relativity.
Our current Standard Model of Particle Physics is, in fact, a QFT and, as such, it is fully (special) relativistic. Also, it is possible to do QFT on a SpaceTime background that is *curved* by classical (i.e., non-quantum) Gravity.
Where things become less perfect is when we try to turn Gravity itself into a quantum theory. So far, Gravity resisted all such attempts. The reason why we feel compelled to do this is that in Einstein's field equations for Gravity, one side of the equation describes SpaceTime, the other, Matter; if one is represented by quantum operators, the other must be represented that way as well, otherwise the equation is *never* satisfied.
However, there is a well-known approximation called *Semi-classical Gravity*, in which quantum Matter is replaced in the equation by its so-called *expectation value*. And this approximation works almost everywhere, with two exceptions: Deep inside black-holes near singularities, and in the extreme early Universe.
So, Einstein was not wrong about Special Relativity, nor was he wrong when, in another pioneering work, he first offered a serious argument for quantizing the Electromagnetic Field, for instance. But the quest to create a truly unified 'theory of everything' remains unfinished. We're close perhaps, but no *cigar* just yet.

392 -

What is the effect of Gravity on the speed of light?

Well, it really doesn't but then again it does. A fundamental tenet of Relativity Theory is that the speed of light is *invariant*. It is the same, and always the same, for all observers. No exceptions, no ifs, or bits. This is the one invariant quantity around which the entire mathematics of Relativity Theory revolves. Also, if the speed of light was not constant, we could three Maxwell's equations, along with everything we know about Electricity and Magnetism out the window. But we know that Electricity and Magnetism work the way they're supposed to, not only because we used technology based on it every day, but also because all of chemistry is based on *electromagnetic interactions*; in short, our bodies depend on it.
But … imagine now for a moment that we are performing an experiment involving the speed of light in a lab. We measure the speed of light. It is what it is supposed to be, 299792458 m/s exactly.

But we have a buddy in the latest SpaceX starship, floating somewhere in deep space. He has a very powerful telescope, powerful enough to see us and our experiment in our lab. He verifies our experiment and, because we are inside the 'gravity well' of the Earth, everything our buddy sees us doing will appear to be ever so slightly in slow motion. This is a direct result of gravitational redshift. We measure 1 second, but to our buddy, something like 1.000000001 seconds will have passed. Consequently, while our buddy measures 1 second according to his watch, our ray of light will have traveled only 299792457.7 m, or about 30 cm less.

Not a big difference to be sure, but still, it is there, and it is measurable. So, is the speed of light constant or what?

Now comes the all-important qualifier: The speed of light in your immediate vicinity will always be the same, one and only constant value. But when you measure the speed of light at a distant location from afar, we may measure a different value. How different? That depends on the differences in Gravity. The deeper in the 'Gravity well' the light ray is, the slower it appears.
The resulting delay, known as the *Shapiro delay*, was first described in 1964 by Irwin Shapiro, who proposed it as a fourth 'classical test' of General Relativity (the first three being the *perihelion advance of Mercury*, the *gravitational deflection of light* and *gravitational redshift*, all three proposed by Einstein himself when the theory was introduced).
The Shapiro delay is very important when measuring the timing of radio signals from distant spacecraft, especially if those signals pass near an object with substantial Gravity, notably the Sun. Without taking this delay into account, we would get interplanetary orbits wrong. So, not only are the predictions of General Relativity confirmed, but the Shapiro delay is also part of the set of tools used in spacecraft precision orbit determination for interplanetary missions.

393 -

Is it possible for nothingness or Energyless particles to decay into a *positive-negative* mass pair?

No, 'nothing' cannot produce particle-antiparticle pairs. It is often obscured by too much talk about probabilities, virtual particles and similar things that in Quantum Field Theory, conservation laws are always exactly and absolutely respected. In particular, no Energy is ever created from nothing, not even probabilistically nor temporally. But, what about that 'foam' of virtual particles that is supposed to characterize the Vacuum, we might ask? Well, this is exactly what it is alluding to: let's not read more into the mathematics than what is really there. Just because we perform an integral from $-\infty$ to $+\infty$ in *Momentum Space* and then series-expand the integral into ever more complex terms does not mean that there are actual 'particles' out there with *negative* Energy or *excess* Energy, pictorial Feynman diagrams notwithstanding).
If there were negative Energy particles in this Universe, interacting with positive Energy particles, then it could indeed be possible for 'nothing' to decay into a *negative* Energy particle-anti-particle pair, with the excess Energy radiated away in the form of a photon, for instance. This would be really bad news: it would mean that the empty Vacuum of Space is *unstable* and can decay into a shower of particles, essentially ending the existence of everything that we know.
Fortunately, there appear to be no negative Energy particles. Thus, the Vacuum appears to be *absolutely stable* (or maybe not quite absolutely but, at least, close enough for us to feel safe) and we don't get particles coming out of nothing.

394 -

Does the Milky Way Galaxy have a *barycenter* (i.e., a *center-of-Gravity*)?

Well, now there's a surprisingly ill-defined concept, the *center-of-Gravity* for a system like the Milky Way! But let's start with the solar system. Its center-of-Gravity is supposed to be well-defined. We are, after all, routinely doing calculations (planetary ephemerides, spacecraft trajectories, etc.) in the 'SSB' (*Solar System Barycentric*) reference frame, and we do this with incredible precision, being able to model, e.g., the Doppler frequency shift of a spacecraft's radio signal because of its motion with few mHz accuracy. In other words, what do we mean when we say that the solar system's center-of-Gravity is ill-defined?
Well, let's suppose that tomorrow we discover a new planet, a really small one, one third the size of the Earth in a very, very distant orbit that takes it 1000 times as far from the Sun as the Earth is. We did not know about this planet previously. Now, we do, so, we now make it part of our new definition of the SSB. Well, that planet, with a mass that's one third that of the Earth, one millionth that of the Sun, will shift the SSB by as much as 150000 km.
In any case, what good is the SSB? Perhaps, we were taught in school that planets orbit not the Sun but the SSB. That is not true. Every planet in the solar system orbits the two-body *center of mass* [CM] defined by that planet and the Sun, with the other planets only introducing small perturbations to these orbits. So, the focal point of the Earth's elliptical orbit is the Earth-Sun barycenter [$\approx$ CM]; for Jupiter, it's the Jupiter-Sun barycenter; etc. In other words, the SSB is a useful convention, not much more. It would have some practical use if we

a. knew all the mass in the solar system (no undiscovered bodies) and

b. tried to calculate, e.g., the orbit of a spacecraft far outside the solar system, at a distance where the entire solar system can be modeled as a point-source of Gravitation with only small perturbations, but reality does not work that way.

There are bodies in the solar system that are still bound to the Sun yet have orbits that take them to many thousands of astronomical units from the Sun, there is also dust, gas, etc., which all carry some mass, and last but not least, the solar system *is not* in empty space, so, when we are far enough from it, the Gravity of other solar systems begin to play a significant role …
Now, the same thing applies to the Milky Way, even more so. *First*, we don't even know for sure the total amount of

visible, normal Matter in the Milky Way and its exact distribution. *Second*, there is the presume Dark Matter halo surrounding the Milky Way, the existence of which we deduce only from the rotational velocity of the Milky Way; its shape and extent are basically just guessed at. *Third*, there are a bunch of satellite galaxies that are part of the 'extended' Milky Way (and gravitationally bound to it, just like the planets are bound to the Sun) and we don't even know them all. With that in mind, the center-of-Gravity is somewhere in the central bulge of the Milky Way, we presume, but it's not like we know for sure.
And no, it's not the Sagittarius A* (Sgr A*) black-hole even if Wikipedia suggests otherwise. Its mass, about $4 \cdot 10^6$ Suns, is much too tiny compared to the whole of the Milky Way. It does not even dominate the central bulge, not even close. The Milky Way is just huge … with the Dark Matter halo, close to 10^6 times more massive than Sgr A*. Having said that, Sgr A* is close enough for all practical intents and purposes, so, might as well call it the Galactic Center; just let's be aware of all the caveats above.

395 -

Is our Universe a Riemannian manifold according to General Relativity?

Not quite. A Riemannian manifold is a mathematical abstraction, a point set with a quadratic distance function. The geometry of our universe is successfully modeled within Einstein's general theory of relativity as a four-dimensional pseudo-Riemannian manifold, one in which the distance function is not positive definite.
But this says nothing about the Matter-content of the Universe, nor do we know with any certainty how that Matter-content and the Geometry relate to one another at very high energies or very small scales, so it is by no means a given that a pseudo-Riemannian manifold (again, a mathematical abstraction) is a valid model of Space and Time at all scales; and it does not model Matter at all.

396 -

If the expansion of the Universe is accelerating, does it mean the amount of Dark Energy is increasing? If Dark Energy is constant, shouldn't the speed of the expansion of the Universe be constant, too, instead of increasing?

Indeed, if we want to think about it this way, the 'amount of Dark Energy' is increasing, although it is a surprisingly ill-defined concept. However, and this is important, Energy conservation is still maintained. Let's see how. First, let's start with ordinary Matter, say, a cloud of gas collapsing under its *self-Gravity*. That means that Gravitational Potential Energy is converted into some other form of Energy. In fact, we know what it is: it's Kinetic Energy as the atoms in that cloud accelerate towards each other. Eventually, they collide. The Kinetic Energy gets randomized through a multitude of collisions, the gas heats up, and that heat is ultimately radiated back into space. That's how Energy Conservation in this case is accounted for.
Now, Dark Energy has the curious property that it responds to Gravity as though it had *negative effective mass*, so *repulsively*. Therefore, a Universe dominated by Dark Energy expands at an *accelerated* rate. But the process still involves converting Gravitational Potential Energy into some other form of Energy. Except that (as far as we know) Dark Energy does not consist of particles that accelerate, so it's not Kinetic Energy. What will Gravitational Potential Energy convert into, then? And the answer is: more Dark Energy! That is how the Dark Energy density remains constant even as the Universe expands, without violating Energy Conservation Laws.
If it sounds like an unstable arrangement, we are not wrong. *Dark Energy accelerates cosmic expansion*. Dark Energy is a fancy phrase: what it covers is a so-called *perfect fluid* (an idealized substance with no internal friction or viscosity) with negative pressure. If we gave it even more negative pressure, we'd end up with stuff that's called '*phantom Energy*'. And when a Universe containing phantom Energy expands, the *phantom Energy density* actually increases! That has devastating consequences: ultimately, the *gravitational repulsion* due to phantom Energy becomes so high, it even rips atoms apart. So, a phantom Energy Universe would be very *unstable*.
In contrast, thankfully, in a Universe with only Dark Energy, bound structures (galaxies, solar systems, stars, planets, people, atoms) are never ripped apart, because the Dark Energy density doesn't increase; it remains constant, which itself is an interesting and counterintuitive notion, but not quite as bad as phantom Energy would be.

397 -

Could our 4-dim Space be thought of as a curved surface embedded in a flat 5-dim hyperplane? Would the Math predict Physics as we currently understand it?

Yes, of course we can think of a 4-dim manifold as being embedded in a higher-dimensional manifold. But the thing is … we don't have to. The reason is that there is a distinction between *intrinsic* and *extrinsic* curvature, and in Gravitational Physics, we only care about the former, not the latter.

To illustrate the difference, let's think why we can roll a sheet of paper into a cylinder shape but not into a spherical shape. In both cases, we introduce curvature. But we can form the cylinder without stretching or compressing that sheet of paper. Distances between points on that sheet remain the same. In contrast, we can only turn something flexible, like a rubber sheet, into a spherical surface. We need to stretch that rubber sheet. Distances change as a result.
Our best gravitational theory to date, Einstein's General Relativity, associates the Gravitational Field with the intrinsic curvature of SpaceTime. This curvature exists independent of any higher dimensional space into which our 4-dim manifold might or might not be embedded; it is measured by how distances change in SpaceTime (i.e., the *metric* of SpaceTime).
In short, whether our SpaceTime is embedded in a higher dimensional Space and how it appears there (i.e., its *extrinsic curvature*) seems to have no bearing on observations in Physics. As such, from a theoretical perspective, it looks like an unnecessary, superfluous assumption.

398 -

How can we derive Einstein's Field Equations by ourselves?

[also, see back at Issue 13]

The original derivation wasn't really a derivation; it was more like an educated guess, the right one, following several failed attempts.
Einstein knew that Gravitation is sourced by Matter. He knew that Gravitation cannot be a *scalar* theory (it fails the Equivalence Principle) and cannot be a *vector* theory (like charges, such as positive masses, would repel each other) so it had to be the next thing up on the ladder of complexity, a *tensor theory*.
Einstein knew that Gravitation is related to the *metric of SpaceTime* (again, thanks to the Weak Equivalence Principle) and he knew that the Energy-Momentum content of Matter is well represented by the *Stress-Energy-Momentum Tensor*. Finally, because he knew that the theory in the end would have to reproduce Newton's law of *Gravitation in the Weak Field Limit*, he knew that it would contain 2nd derivatives of the metric, and he knew the proportionality factor, $8\pi G$ (with $c \equiv 1$). He also knew that $R_{\mu\nu} = 8\pi G T_{\mu\nu}$ couldn't work because $T_{\mu\nu}$ (i.e., Energy-Momentum) is conserved, hence, it has *zero divergence*, $\nabla \cdot T_{\mu\nu} = 0$, but the same is *not true* for the *Ricci Tensor* $R_{\mu\nu}$. So, finally, he realized that if, instead of $R_{\mu\nu}$, he put $R_{\mu\nu} - (1/2) R g_{\mu\nu}$ on the left-hand-side, he'd have a winner. Thus, the theory was born.
Meanwhile, Hilbert pursued a goal that was more modest yet more ambitious at the same time: to derive a version of the Theory of Gravitation, not for arbitrary kinds of Matter, only for the Electromagnetic Field, but *from first principles*, from a *Lagrangian Action Principle* specifically. He succeeded, obtaining an equation formally similar to Einstein's, which precipitated more than a century of debate about priority (even though Hilbert himself never questioned Einstein's legacy).

A common modern rather simple derivation starts with the general relativistic *action integral*,

$$S = \frac{1}{2\kappa}\int R(-g)^{1/2} + L_M)\, dx^4 ,$$

where $\kappa = 8\pi G$ and the '*Matter*' *action* L_M is *unspecified*, except that its variation with respect to the metric tensor $g_{\mu\nu}$ *must yield the Matter Stress-Energy-Momentum Tensor in the form* $-(1/2) T_{\mu\nu}$. Variation of the Ricci scalar (warning for the uninitiated: the symmetries of the metric tensor must be accounted for either 'by hand' or, in a more rigorous derivation, through a Lagrange multiplier) yields the *Einstein Tensor*,

$$\frac{1}{2\kappa}(R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}) ,$$

which, combined with the Matter part, gives $(c \equiv 1)$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} .$$

The action used in this derivation is called the *Einstein-Hilbert Action*. It can also be extended by introducing a Cosmological Constant, $R \mapsto R + 2\Lambda$.
This derivation, in one form or another, can be found in just about any serious textbook on General Relativity.

399 -

Why do light and other electromagnetic waves have such a high speed? What gives them the ‘push’ to go at this speed?

No, they do not have high speed. In the units preferred by theoretical physicists, the speed of electromagnetic waves in the Vacuum is 1 . That is, one ‘natural’ unit of Space over one ‘natural’ unit of Time.
And it’s not that this speed is high, rather, that this speed is the same for all observers, regardless of their motion. The real question, then, is not why this speed is high but rather why, in comparison, the speeds at which things that we experience in our everyday world move relative to each other are so low. And the answer is that we live in a low Energy environment, near the Vacuum of Space, where most particles have Kinetic Energies far less than their rest Mass-Energy.
If something as complex as the Chemistry and molecular Biology of life could exist in the extreme high temperature interior of a star, for instance, for creatures that exist there, the Vacuum speed of light may be part of their everyday experience. To them, most particles would have kinetic energies far in excess of their rest-mass, and things would be happening very fast.
However, it is conceivable that there is a reason why we live on the edge of Space (so much so that a human can survive, even remain conscious for a few seconds in the Vacuum of deep Space) and not in the interior of a star. A low Energy environment almost seems like a necessity for complexity to emerge. So that, perhaps, is the answer. We live in a low Energy environment so the speeds at which things move relative to each other in this environment is far, far less than the Vacuum speed of light; the Energy of most objects is dominated by their rest Mass-Energy, dwarfing their Kinetic Energies.

400 -

What defines Mass at the quantum level? Is Mass at quantum level just movement or the Energy of elementary particles?

Rest Mass, in the case of a Quantum Field Theory, is just Potential Energy. This Potential Energy can come in many forms. For the charged fermions of the Standard Model, it is the interaction Energy between those fermions (such as the electron) and what is known as the *Vacuum expectation value* (V. e. v.) of the Higgs field. This V. e. v. is non-zero because of the celebrated symmetry breaking 'Higgs mechanism'. For neutrinos, for instance, their rest mass comes (as far as we know) from a form of self-interaction.
For composite particles such as protons and neutrons, the bulk of their rest masses are due to the binding energies that hold together their constituent quarks.
In all these cases, what we recognize as rest Mass is precisely what Einstein recognized as the inertial Mass of an object in his famous 1905 $E = mc^2$ paper: the Energy-content of the object in question.

401 -

What evidence do we use to determine the *curvature* of the Universe?

We have no evidence that the Universe has non-zero *spatial curvature*. In fact, to the extent that we have any evidence, it suggests that the Universe has *zero* spatial curvature.
The evidence is indirect. *First*, we accept, because of observational evidence that support its validity, the General Theory of Relativity. With that at hand, we proceed to model the Universe by assuming that on average, it is, more or less, the same everywhere and looks the same in all directions, i.e., that on average, it is *homogeneous* and *isotropic*. This yields a form of Einstein’s Field Equations (the Friedmann equations) that contain, among other things, a term characterizing curvature.
Next, we note that the way the equations work, *spatial curvature would increase over Time*. We compare this against observational evidence. Spatial curvature would show up in various forms when we look at very distant objects. We see no such effect, and, from this, we conclude that if spatial curvature exists, its value *cannot* be large.
But, as we know, spatial curvature increases over Time. So, if it is small today, it would have had to be astonishingly small in the early Universe. Such a ‘fine-tuned’ value is considered very unlikely. So, we conclude that much more likely, perhaps for reasons that we will one day discover, the Universe had no spatial curvature to begin with, which is why we see no spatial curvature today.

402 -

They say there are *black-holes* and *white-holes*, so, where do white-holes get the Matter from and push it out?

No, ‘they’ say no such thing. What ‘they’ actually say is that the Schwarzschild solution of General Relativity describes both black-holes and their *Time-reversed* counterparts, white-holes. In other words, both are valid solutions of the equations of General Relativity.

Now, for black-holes, we also know of a process that can form them: *Oppenheimer-Snyder collapse*, or variations thereof, as Matter collapses under its self-Gravity, with the *Schwarzschild* or *Kerr* (rotating) black-hole as the final, asymptotic state at *future* infinity.
We know of no such process for white-holes. In fact, because they are *time-reversed* black-holes, white holes would require to be formed 'backwards in Time', with Matter *from the future*, so to speak. They also break causality in another way: *nothing can fall into a white-hole because in the future, nothing is in there*.
Fortunately, we do not have to worry about these things as anything more than … nice mathematical games, because no white-hole has ever been observed in Nature, nor is one expected to be observed by relativists.

403 -

Do photons (picturing γ- rays with extremely high Mass-equivalence) bend SpaceTime? We see an E-M component in the Stress-Energy Tensor.

Kinetic Energy is *observer-dependent*. The same photon that appears to us as a very high-Energy γ- ray photon may appear as a mundane photon of light, or even as a low-Energy quantum of longwave radio, to an observer moving at high relativistic speed in the same direction as the photon.
For massive particles, we would normally just take the reference frame in which the particle is at rest, calculate its Gravitational Field there, and then express its components (if required) in some other moving reference frame.
However, for E-M radiation such a reference frame does not exist. It would correspond to a reference frame in which the *Poynting vector* is zero, i.e., the (Linear) Momentum and hence, the Energy of radiation is 0 .
It is nonetheless possible to speak meaningfully of the Gravity of Radiation, for instance when that radiation is trapped. As a thought experiment, let's consider a box lined on the inside with perfect mirrors. The Poynting vector won't be zero anywhere, yet when we integrate the Momentum over the whole box, we will find that there is no net Momentum; the trapped radiation doesn't go anywhere, it's just bouncing back-and-forth inside the box. And yes, in that case the Stress-Energy of this trapped radiation will contribute to the overall Gravitational Field of the box.
In terms of real Astrophysics or Cosmology, radiation contributed this way to the overall Gravitational Field of the Universe in the very early Universe (the *radiation-dominated* era) and, we understand, in certain very large stars, a non-trivial fraction of the total mass of the star may exist at any given time in the form of a 'photon gas', in dynamic equilibrium with the other constituents inside the star.

404 -

If interacting particles become entangled, why isn't everything entangled with everything else from the Big Bang?

That is precisely the point. Most of the time, everything is entangled with everything else. When we talk about, say, creating an entangled pair of particles, the point is not to get them entangled with each other; the point is to reduce or eliminate their entanglement with everything else to the extent possible, for as long as possible. In other words, we should make sure that the pair are isolated from the environment. That's the *hard* part, not entangling them with each other; that's a given.

405 -

Assuming we were immortal (!) and that we could walk through space, *how long* would it take to walk to the Sun?

The average distance to the Sun is about $1.4967 \cdot 10^8$ km. Since we want to know 'how long', then, we might assume we would walk about 4.83 km/h, which is what most people walk. That means it takes the average person about 20 minutes to walk 1.609 km $(= 1$ mile$)$. So, to walk to the Sun, would be $1.4967 \cdot 10^8$ km times 20 min$/1.609$ km, which equals $1.860 \cdot 10^9$ min $= 1$ billion 860 million minutes), which equals $31 \cdot 10^6$ h $= 31$ million hours, which (lastly) equals 1291667 days. Dividing this by 365, gives about 3539 years, provided we walked 24 h/day, 7 day/week. Since we would probably only walk 12 h/day, we could round that figure out to be about 7000 yr. Of course, we can't walk such a distance, no matter how 'immortal' we are, but that's how long it would take to walk $1.4967 \cdot 10^8$ km.

406 -

At $(100-10^{-15})\ \%$ of the Vacuum speed of light, can we thrust our rocket to generate or $1\ \mathrm{g}$ of Gravity?

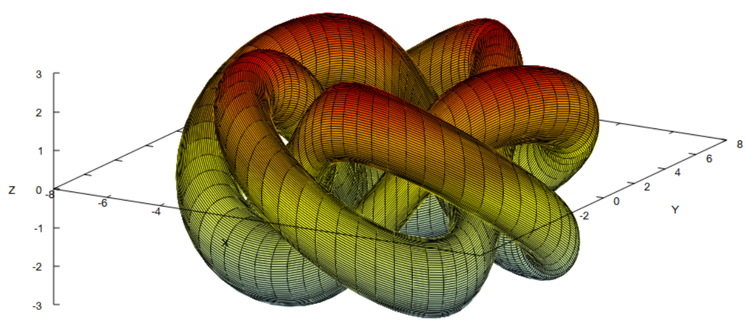
To answer this question, let's first remind ourselves that in our own frame of reference, we are always *at rest*.
So, who cares that the rest of the Universe is moving backwards at nearly the Vacuum speed of light (we did mean $(100-10^{-15})\ \%$ of c)? Say, we are in this situation. We take some random object from our spaceship and put it outside. It would float right next to our spaceship. Now, we turn on our engines and accelerate at $1\ \mathrm{g/s}$. We will find that the object we left behind is moving backwards, relative to us, at 10 m/s.
What would an observer see who is somewhere else in the Universe, moving backwards at $(1-10^{-17})\,c$ *relative to us*? To that observer, the object we left behind would be moving forward at $(1-10^{-17})\,c$. We? Let's just use the relativistic velocity-addition formula (†) to add 10 m/s to the object's velocity. The result is that we would be moving roughly at $6.7\cdot 10^{-25}c$ or $0.2\ \mathrm{fm/s}$ (that is, $0.0000000000000002\ \mathrm{m/s}$) faster in this distant observer's reference frame. Still *slower* than the Vacuum speed of light.

(†) See, e.g.: https://en.wikipedia.org/wiki/Velocity-addition_formula

407 -

How many *dimensions* are there in reality? Why aren't there more or less?

We see 3 spatial dimensions and we experience Time. People can conjecture additional dimensions all they want, but the fact remains that (for now, anyway), these 4 are precisely the dimensions we observe.
As to why, that's an interesting question! Without Time, well, there would be no change, no way to experience a progression from *past* to *future*. So, we need a Time dimension for a *causal* Universe in which 'things happen'.
Could we have more than 1 Time dimension? Perhaps, but it is very difficult to conceive of a Universe with 2 or more Time dimensions that, nonetheless, remains *causal* (with the *present* uniquely determining the *future*). So, 2 (or more) Time dimensions, that's probably out.
Could there be fewer than 3 Space dimensions? Sure, but 'Flatland' is very restrictive. For instance, we couldn't have an internal digestive track in Flatland: something with 2 openings would split our bodies into 2 disconnected parts necessarily. To allow such complexity, 3 dimensions appear to be the *least* requirement.
Could there be more than 3 spatial dimensions? Now that might actually be too much of a good thing. In 4 spatial dimensions, for instance, tying a knot is no longer possible: the knot can always be unmade by sliding parts of it through the 4th dimension. That shows that, somewhat paradoxically, more dimensions can lead to reduced complexity (e.g., no tangled mass of wires behind our desktop computer in 4-dim land).



A 3-dim Space knot

So, it seems that a $(3+1)$-dim Universe is almost an inevitability: anything, more or less, would lead to a Universe that is *incompatible* with the very idea of us being here and asking questions about its nature.
Now, of course, that does not exclude the possibility that additional dimensions are present but suppressed, e.g., by compactification, which of course is how Superstring Theory tries to hide its embarrassing riches of excess dimensions.

408 -

Special Relativity could explain acceleration and Gravity, right? Gravity is still a force in Special Relativity while Gravity is not a force in General Relativity, right?

Special Relativity *does not* explain Gravity. Special Relativity can accommodate easily a *scalar theory* of Gravitation that, in the *non-relativistic limit*, reduces to Poisson's equation for Gravity, but such a theory *does not respect the Equivalence Principle*. Specifically, in such a theory, Potential Energy will appear with the *wrong* sign as a source of Gravitation. Since a *vector theory* would mean a repulsive force between 'like charges' (*positive* masses) and a theory involving the exchange of fermions *would not* obey the Inverse-square Law, the next simplest theory that might actually work is a *tensor theory* of Gravitation.
A *tensor theory* has all the right properties. It produces an *attractive* force between like masses. Potential Energy has the *right* sign. Finally, it can accommodate the *Principle of Weak Equivalence* but, to do so, it must couple to Matter in just the right way, meaning the same way as the metric would in 4-dim pseudo-Riemannian SpaceTime. Moreover, it has to be a *non-linear theory*, meaning that the Energy-content of the Gravitational Field itself has to be a source of Gravitation. Apart from theory, we also have observational evidence for this: such non-linearity is what explains the precise value of Mercury's perihelion precession.
At this point, we arrived at exactly the formalism of General Relativity: a theory in which an interaction is carried by a *tensor* field that, on account of coupling minimally and universally to everything else, including itself, *doubles* as the metric of SpaceTime.
Some people then go on and cleverly tell us that this means Gravity is not a force! Well, do tell them to drop a brick (from not too high, we don't want any broken toes here) on their feet and then explain us how it was that they felt no force. Now, of course, we can go on and explain that it really is a *pseudo-force* (like a centrifugal force), because a system that is at rest in a Gravitational Field is a non-inertial system, whereas in a freefalling, inertial system the pseudo-force is not present, etc., etc. … At this point, we might rightfully conclude that no matter what fancy words we use to interpret it, the fact remains, when we hang a weight off a dynamometer, it registers a force, so there. Besides, Einstein himself warned us against reading too much into the geometric interpretation, and he was spot on: if we ever manage to turn Gravity into a proper Quantum Field Theory of some kind, it will almost certainly be the theory of a *physical field mediating a force*.

409 -

Why do some theoretical astrophysicists believe that the Universe is both *eternal* and its size is *infinite*?

It's not belief. It's parsimony of assumptions, otherwise known as *Ockham's razor*. The simplest mathematical model of the Cosmos, in the form of the *Friedmann Equations* (which are *Einstein's Field Equations* applied specifically to the case of a Cosmos that is approximately *homogeneous* and *isotropic* (i.e., same everywhere, with no preferred direction), when fitted against *observational data*, yields a Cosmos that has a *finite* age, *eternal future* existence, and is *spatially infinite*. This is not a matter of belief. This is a factual statement about a mathematical model's properties and its relationship to observational data.
Does this mean that the Cosmos is, in fact, eternal and infinite? We don't know. Simple models are good until they no longer fit the data and additional assumptions are needed, making the model more complicated. By way of a silly example, a simple model says that the Earth is spherical. This is a good model, but not a perfect one. A more detailed model describes quantitatively how the shape and mass distribution of the Earth both deviate from perfect spherical symmetry. Sometimes, these corrections are just that, *corrections*; sometimes, new information changes our view of the world altogether, such as when humanity first learned, in times of antiquity, that the Earth is round and that it may, in fact, be orbiting the Sun; or much later, that the Sun is not the center of the Universe but one of countless billions of suns in the Milky Way, which itself is just one of countless galaxies.
Is such a paradigm shift possible in Physical Cosmology? We bet. But for now, the simplest mathematical model that fits the data well describes an *infinite*, *eternal* Universe, and there are no observations that fundamentally conflict with this model.

410 -

Is there any probability that Earth will be destroyed by a black-hole?

Certainly yes, but what are the odds? All this black-hole stuff is vastly overrated.
Let's give an example. Let's take a black-hole that is approximately 10 times as massive as the Sun. Suppose this black-hole travels by the solar system so that, at the closest approach, it is 10 times as far from the Sun as the Earth. What consequences do we expect?
The devil is in the details of course, and such a black-hole would certainly be able to perturb orbits significantly. In a

worst-case scenario, it might alter the orbit of the Earth so much that the Earth could no longer support life. It might also perturb the asteroid belt or the Kuiper belt in ways that would result in excessive asteroid impacts in the coming millennia. But there is also a chance that the perturbations would remain minor, and the Earth would escape mostly unscathed; there would be slight changes in its orbit so the length of the year and seasons would change, but the Earth would remain safely habitable.

Now, let's replace that 10 solar mass black-hole with the star Canopus, which has the same mass. Canopus also has 10000 times the *luminosity* of the Sun. At 10 times the distance, that means it would appear 100 times brighter than the Sun. In other words, Canopus passing by at that distance would burn everything on the surface of the Earth to a crisp.

As another example, look at the Sun itself. How close do you think we could fly to the Sun in a good, well-shielded spaceship before we would burn anyway? Maybe a few million kilometers, that would be a consistent guess. And of course certainly not less than about $700000\,\mathrm{km}$, which is the radius of the Sun. Otherwise we end up inside the Sun, which is probably not healthy.

Now take a black-hole, three times as massive as the Sun. What would happen if we flew by it at $700000\,\mathrm{km}$? The answer is, absolutely nothing. We wouldn't even know it's there unless it has a visible accretion disk or something. To be actually destroyed by the black-hole, you would have to fly incredibly close to it, at least close enough for its tides to rip us apart. Talk about threading a needle! Otherwise, we'd just end up in a hyperbolic orbit and emerge unscathed.

The point, of course, is that the gravity of a black-hole is no different from the gravity of any other object of the same mass. It only gets scary because a black-hole is very small, very compact, so we can get much closer to it than we can get to an extended object, without hitting the object. But unlike those extended objects, namely stars, *black-holes only have Gravity*. Stars can destroy us in so many ways! Burning us, irradiating us, swallowing us … *black-holes can neither burn nor irradiate* us (their accretion disks perhaps can but that's another story) and to be swallowed by them, we have to get much, much, much closer to them than to a star. So, among cosmic events that might destroy the Earth, an encounter with a black-hole must rank very low on the list.

411 -

Besides his Theory of Relativity, what are Albert Einstein's other major findings that most people have never heard about?

During his '*annus mirabilis*' (1905), Einstein published four papers, only two of which were related to Relativity Theory: *one* is his paper on Special Relativity, the *other*, based on the first, demonstrating Mass-Energy equivalence, the famous $E = mc^2$ business. The *third* paper was on Brownian motion: one of the early convincing demonstrations that Matter must consist of molecules, at a time when the atomic\molecular nature of Matter was by no means a settled issue. The *fourth* paper was about the *photoelectric effect*: the first serious study demonstrating the necessity *to quantize the Electromagnetic Field itself*. This paper was so revolutionary, that many (including some of Einstein's friends) still thought it was misguided and mistaken a decade later. Yet, it was this paper that earned Einstein's sole Nobel Prize. It also earned him a mention as one of the founding fathers of the Quantum Theory.

In 1915, of course, Einstein published his definitive paper on General Relativity. As he was studying *Tensor Calculus* and *Riemannian Geometry*, with the help of his friend Marcel Grossmann who served as his tutor, Einstein introduced a notational convention that has been used since by many physicists and mathematicians dealing with complex tensorial expressions, the so-called *Einstein Summation Convention*.

Not quite done with the Quantum Theory, in 1924 Einstein helped Satyendra Nath Bose publish his work on the Quantum Statistics of photons after it was rejected by a journal; he personally translated Bose's work into German. Building on Bose's work, Einstein extended it to atoms. The result is the *Bose-Einstein Statistic*, one of the two important statistical descriptions for quantum particles (for integral spins; the analogous description for particles with half-odd spin is the Fermi-statistic). The Bose-Einstein statistic represents the quantum mechanical foundations for phenomena such as *Superfluidity* or *Laser Light*.

His later efforts were not as spectacularly successful but still in many ways groundbreaking. In search of a stable cosmological solution in General Relativity. he introduced the concept of a Cosmological Constant. Though he later called it his greatest blunder (if instead, he chose to believe his own theory, he could have predicted the cosmic expansion that was later discovered by Lemaître and Hubble) it nonetheless proved prescient: Since 1998, we know that either a Cosmological Constant or something closely resembling one, playing the role of '*Dark Energy*', is responsible for the *accelerating expansion of the Cosmos*.

Later in life, Einstein was pursuing the dream of a Unified Field Theory: An attempt to unify the classical (that is, non-quantum) theories of Gravity and Electromagnetism *in a common framework*. Unfortunately for him, by the time the world of Physics moved on: new interactions that work on the sub-atomic level were discovered, the concept of a Quantum Field was invented, and the resulting Quantum Field Theory led to an entirely different form of unification of all forces other than Gravity. Still, some of Einstein's work lives on, e.g., when folks study things like generalizations of the *metric theory* of General Relativity.

413 -

Once *gravitational waves* are released, will they travel forever, becoming weaker and weaker, but never completely disappearing? If the strength of the waves starts to decrease, shouldn't the strength decrease to 0, and then the waves cease to exist?

The intensity of gravitational waves far from the source behaves the same way as the intensity of electromagnetic radiation far from the source: *it decreases with the square of distance*.
So, yes, gravitational waves do become weaker, but if they were powerful enough to begin with, *they remain detectable even over cosmological distances*, just as we detect light over cosmological distances from very distant galaxies.
So, no, 'weak' does not necessarily mean 'vanishing'.

414 -

Would the two orbiting black-holes emit *gravitational waves* even if they are moving at a constant speed in orbits? Can we consider the changing orbital direction of black-holes as acceleration that can be a cause of gravitational waves?

Yes, any two bodies (including black-holes) in orbit around each other emit gravitational waves, and yes, it is on account of their acceleration in reference to a distant inertial reference frame.
As a result, their orbital speed is not constant. The orbits are decaying over time. For most systems, this orbital decay is imperceptible. For very close binary stars, it can be observed; this is how Gravitational Radiation was first observed indirectly, through binary pulsars back in the 1970s. And of course, if the pair of objects is two black-holes, near the end of their merger the process becomes extremely powerful, potentially converting several solar masses worth of Gravitational Potential Energy into gravitational waves in the final split second.
As a general rule, any gravitating system that is

a. changing over time, and

b. has *no axial symmetry* produces gravitational waves. Systems with axial symmetry would produce gravitational *dipole* radiation, but such radiation does not exist; it has to do with the fact that *there are no negative masses*.

415 -

Is Avogadro's number applicable for systems such as black-holes?

Avogadro's number *is not* a fundamental constant of Nature. Rather, it is a constant of convenience, relating the human-defined unit of mass to the number of atoms or molecules. In other words, it is designed to define the *mole*: one mole of anything happens to contain $N_A \equiv 6.02214076 \cdot 10^{23}$ atoms or molecules of that thing. And the idea is that 1 mol of ^{12}C (the most abundant isotope of carbon, with atomic weight 12) will weigh (almost) exactly 12 g. As to why grams and not pounds, ounces or some other human-defined unit measuring mass, the reason is *entirely cultural*. An extraterrestrial civilization may develop a concept similar to the mole, but it is extremely improbable that their version of Avogadro's number will be anywhere close to ours.
And, of course, it only makes sense to use Avogadro's number for stuff that is made of atoms or molecules. '1 mol of photons' or '1 mol of black-holes' doesn't really mean anything. But if an unfortunate human traveled to a black-hole and entered its event horizon, for however little time he still had left to live, he could still be using moles and Avogadro's number to quantify experiments involving atoms and molecules.

416 -

Have there been any experiments that have shown cracks in Einstein's Theory of General Relativity?

Experiments, not so much. Observations … maybe, but with huge caveats. We are, of course, referring to the fact that we have known since the 1930s that galaxies spin faster than they should be able to under their own self-Gravity, yet do not fly apart. How can this be? Well, the conventional explanation is that this must be since there's more Matter in galaxies than what we see, i.e., there is additional non-luminous, 'Dark Matter' that is responsible for the excess Gravitation.
Originally, this 'Dark Matter' was simply presumed to be things like cold gas, dust, dead stars, whatever suits our fancy. Unfortunately, now that we have a much better, much more thorough understanding of the evolution of the early Universe and how it correlates with Particle Physics, we know that ordinary, 'baryonic' Matter cannot fit the bill: there just isn't enough of it, and even if there was, it would alter other observable properties of the Universe, such as the statistical behavior of the Cosmic Microwave Background or the large-scale distribution of Matter.

So, if Dark Matter exists, it cannot be made of ordinary baryons (protons and neutrons). It has to be something else, stuff that we have not yet discovered, '*non-baryonic Dark Matter*'.
But what if that's not the case? What if the problem really lies with our understanding of Gravity? What if General Relativity does not correctly describe the dynamics of galaxies?
Though the majority view among cosmologists is that this is unlikely, there are credible efforts to introduce so-called *Modified Theories of Gravitation*, which change some aspects of Einstein's theory to fit galaxy rotation curves.
To be clear, this is not an easy thing to do. General Relativity does work very well, with exquisite precision, in the solar system, as demonstrated through numerous experiments involving precision navigation of interplanetary spacecraft. Elsewhere, gravitational wave observations (both indirect, dating back to binary pulsar measurements from the 1970s and direct, thanks to the more recent discoveries of LIGO) also confirm many of the predictions of Einstein's theory beyond the Newtonian level.
So, a MOdified Gravity (MOG) Theory must be able to account for all these observations; must be able to provide a credible Cosmological Model that works at least as well as General Relativity; and must, in addition, be able to explain the rotation of galaxies without introducing dark matter. This is a tall order.
Nonetheless, the persistent failure to detect Dark Matter directly (and the falsification of many promising theories of Dark Matter by this lack of detection) is motivation to continue research in this direction as well.

417 -

What are the conditions that cause SpaceTime to appear to be Euclidean? Since empty Space has non-zero Energy, one would expect it to be *curved*.

We stumbled upon the problem of 'empty Space', here, in the presence of *quantum fields*, presumably. And the issue is absolutely sensical. The Vacuum of Quantum Field Theory has non-zero Energy Density. In fact, this Energy Density would be *infinite* in a naïve calculation. A more sophisticated (?) version considers that the theory is an *effective theory*, and that its validity may end at the *Planck Scale* [see Issue 91, P. 40]. So, instead of summing to infinity, we just sum to that scale.
But we still have a problem, the so-called *Cosmological Constant problem*, namely that 'Empty Space' not only has non-zero Energy-content, but its Energy-content is also *quite high*, *dozens of orders of magnitude higher than the presumed value of the Cosmological Constant*. And while this constant background Energy Density does not pose issues for Quantum Field Theory (where only differences in Energy matter), it does mess up Gravitation, which depends on the *actual* Energy-content.
So, yes, 'Empty Space' would not only be curved but *very curved*. A Universe like this, dominated by a Cosmological Constant, is known as a *De Sitter Universe* (†). Or rather, it should be said '*Empty SpaceTime*'. Because in a De Sitter Universe, space is Euclidean, *SpaceTime is not*. A De Sitter Universe is a Universe undergoing *accelerating expansion*.

(†) See, e.g.: https://en.wikipedia.org/wiki/De_Sitter_universe
https://en.wikipedia.org/wiki/De_Sitter_space

418 -

What is the central core of a black-hole called?

Black-holes have no centers in the conventional sense. But this is very difficult to conceptualize unless we make an effort to understand that black-holes are creatures of SpaceTime, not of Space.
The simplest of black-holes is the so-called *Schwarzschild black-hole*. It is a mathematical solution of Einstein's General Theory of Relativity in a very special case, assuming

a. Vacuum,
b. a static solution (i.e., that does not change over Time), and
c. spherical symmetry.

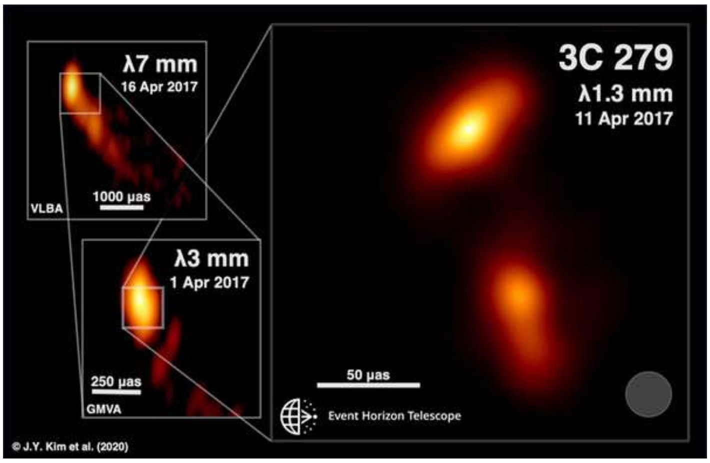
The solution actually *breaks down at the event horizon*, the 'no return' point, a *spherical* surface. It being a spherical surface, it is natural to assume that its inside is like the inside of a sphere, a finite enclosed region of Space with a center. But that is not the case, though it took decades, almost half a century after the initial publication by Schwarzschild in 1916, to understand this fully.
If we are unlucky enough to fall through the event horizon of a black-hole (and the black-hole is large enough, gigantic as a matter of fact, so that we survive that experience and live long enough to experience the inside a little before being torn apart by rapidly changing Gravity), we would not be experiencing a spherical volume. Rather, we would be experiencing what it's like to live in a collapsing Universe (the opposite of our expanding Universe). The collapse has no center. Everything is approaching everything else everywhere, and the Universe becomes *denser*. The event horizon

that we passed through? No, *it's not a spatial boundary* to which we can return. *It is a past moment in Time* that we could only cross *backwards* if we had a backwards-in-Time Time-machine.
Without a Time-machine, the inevitable happens: no matter where we are in this mini-Universe, its collapse will eventually crush us along with everything else, as Time itself comes to an end. That final moment in Time is called the *singularity*, and yes, it is often mistaken for the 'center' of the black-hole. But it really isn't. *It is a future moment of Time in the Time-line* of every observer unlucky enough to have passed through the event horizon.

419 -

Are there plans to upgrade the Event Horizon Telescope and study any other targets, maybe even something besides a black-hole?

The Event Horizon Telescope (EHT) is not a physical instrument that can be upgraded. It is an international collaboration, using facilities around the world in what is called very long baseline interferometry, in an attempt to image specific targets. These targets must share a few important characteristics.
First, they must emit radio waves, because that's what we detect. They obviously have to be bright enough for the radio signal to be observable by the participating telescopes;
second, the source must be large enough to be resolvable. The resolution of the EHT is limited by diffraction. At 450 GHz (the highest frequency used by the EHT presumably) with a 10000 km baseline, the diffraction limit is about 16 micro-arcseconds (10^{-6} arcseconds $\equiv 1~\mu$as). Anything that appears much *smaller* than this is just *not resolvable* by the EHT. For comparison, the size of the M87* black-hole photon sphere 'shadow' is about $42~\mu$as, whereas Sgr A* in our own Milky Way would be $53~\mu$as. These two of the largest black holes that the EHT can 'see', and even these are near the limit of the EHT's resolution;
third, the source has to be *static*, not changing too rapidly, in order for the EHT to be able to collect data over long periods of time to achieve the necessary signal quality to reconstruct an image. This, understandably, is the main reason why Sgr A* has not been imaged yet: it just changes too fast!
They have, however, imaged another object: the *blazar* 3C 279. So, the collaboration continues, and yes, it is 'upgraded' over time, e.g., by including more telescopes and performing observations at even shorter wavelengths.



420 -

If an object weighs about 229792458 pounds, will it fall at the speed of light?

What is there so special about 135983571.532 kg? Or 4796679328 ounces? Or 149896.229 US tons? The fact that something happens to have a mass that, expressed in an archaic unit of measure that is no longer in use by most countries, happens to coincide with the numerical value of the Vacuum speed of light, expressed using SI units of measure, means nothing. This is actually an important point to remember. 'Dimensioned' quantities, that is to say, quantities that have *units of measure* attached to them, can have any numerical value that we want, simply by *cleverly choosing* our units.
For instance, … we think that the speed of light is 229792458? Let's think again. How about 1802613915? Or how about … 1? These are all valid numerical values for the Vacuum speed of light. It is, of course, 229792458 m/s, as per the standard definition of the meter in the SI of units. It is also 1802613915 kilofurlongs/fortnight. But in units

often preferred by theoretical physicists – the so-called '*natural*' units –, the speed of light is simply $c \equiv 1$; e.g., 1 (light-second)/second.
Now it so happens that the unit used to measure mass is entirely independent of the units used to measure distance or time. In other words, the fact that a mass happens to have the same numerical value when some unit of mass is chosen as the numerical value of the Vacuum speed of light using certain units of Length and Time has no significance whatsoever. These choices of units are *entirely human*, *cultural constructs* that *have no fundamental physical significance*.
In any case, when it comes to falling in Gravity, a very important observation of Galileo, which represents the foundation of our modern understanding of Gravitation, is that all objects fall at the same rate regardless of their weight or material composition. Whether something weighs 1 g or 10^{12} g, $229\,792\,458$ pounds or $229\,792\,458$ firkins, has no bearing on the rate at which it falls. In the atmosphere of the Earth, air resistance might slow down things a bit (or a lot, if they happen to be light and possess a large surface area), but once we take air out of consideration, any differences vanish: a feather and a large block of lead, released together, will hit the ground *at the same time exactly*.
Finally, all gravitating material objects, even the heaviest, most compact ones such as neutron stars (which have surface Gravity so strong, if we were stood there, we would be instantaneously flattened to a subatomic film on the surface, accompanied by a flash releasing multiple H-bombs' worth of Energy), have a surface escape velocity that is less than the Vacuum speed of light. So, no matter how high up something is, even if you are throwing that thing at the surface, it will hit the surface at a speed less than $229\,792\,458$ m/s (or $670\,616\,629.384$ mph). The only Gravitational Field that can accelerate something to the Vacuum speed of light is the Gravitational Field of a black-hole *at its event horizon*, but that's another, very different can of worms, discussed at length and repeatedly in these answers.

421 -

If an object weighs about $229\,792\,458$ pounds, will it fall at the speed of light? If a photon is not re-emitted (reflected) *immediately* but transformed into thermal Energy after being absorbed by a bounded electron, does that mean the electron stays in a higher Energy level for longer time before giving out thermal radiation?

A photon is not transformed into thermal Energy when it is absorbed by a bound electron. Rather, its Energy and Momentum are transferred to the electron, which now occupies an orbital with higher Energy and Momentum than before. There is nothing 'thermal' about this at point; *this is not random kinetic motion in a multiparticle system*.
And yes, the electron can stay at that higher Energy level for a while. It depends on the specifics of the atom as to how long it takes on average before the electron drops back to a lower Energy state, emitting a photon.
But no, *that photon is not* '*thermal radiation*'. Thermal radiation arises from *random collisions of the random motion of a large ensemble of particles*, and it has the characteristic black-body spectrum. In contrast, electronic transitions like this result in the emission of photons of very specific wavelengths, which is in fact how atoms can be identified, through their emission spectra.

422 -

Is relativistic length contraction real or apparent? To test length contraction, we setup two beams that trigger atomic clocks when an object passes by. Does the length of an object passing by really change according to the times measured?

Everything 'relativistic' *is apparent by definition*: it is about how lengths in Space and intervals in Time appear to different observers. Meter sticks do not shrink, nor clocks do not run slower. But meter sticks *appear shorter*, and *clocks appear slower to moving observers*.
This is what Relativity Theory is about: it tells us how geometric observables appear relative to different families of observers *based on their motion*. But more importantly, *motion itself is relative*. You speak of an object passing by. But from that object's perspective it is we who are passing by, moving in the opposite direction. The two viewpoints are equivalent. There's no difference.
This was first recognized (as far as we know) centuries before Einstein, by Galileo actually. It was Galileo who noted that if we were in a windowless cabin on a sailboat moving smoothly on calm seas, we would never know that the boat is moving at all. Every physical experiment we perform in our cabin would have the same result, the boat's motion notwithstanding. Adding Relativity Theory to the mixture, it also means that our clocks will run unadulterated, our meter sticks would still be exactly 1,000 millimeters long, and, of course, all experimental results would come out the same, regardless of what a distant observer who is not moving along with we see, perhaps looking at us through the cabin walls with X-ray vision. Indeed, from our perspective, it is that distant observer who is moving backwards and it is that distant observer whose clock runs slow and whose meter stick gets shorter.

423 -

If a black-hole were large enough, could a person spend her\his whole life (80 + years) inside one quite happily, without being torn apart by tidal forces?

Yes, it is true that, in principle, crossing the *horizon* is survivable if the black-hole is large enough, as tidal forces for a very large super-massive black hole are modest at the horizon. However, we still do not have much time left. A good approximate formula to calculate the time t to go from horizon to singularity in a black-hole of mass M is

$$t = \pi GM/c^3 \simeq M/M_\odot \cdot 1.54 \cdot 10^{-5}\,\mathrm{s}\,,$$

where $M_\odot$ is the Sun's mass. Even for a 10^9-solar-mass super-massive black hole, this gives only about 4.3 hours. Long before we reach the singularity, tidal forces do become strong enough to rip us apart. Any attempt to accelerate shortens the Time to the singularity (to understand why, let's consider that once *inside* the horizon, the singularity *should no longer be regarded as a place*; rather, *it is a future moment in Time*. If we attempt to accelerate, relativistic Time-dilation kicks in and *shortens the Time we have left until that unavoidable future moment*).

424 -

Mass distorts SpaceTime, and it is said that so do magnets and charges. But if magnets\charges just add to the distortion of SpaceTime, why are non-magnetic objects or uncharged particles not affected?

Let's take a step back here. Why exactly do we say that Mass (ok, Stress-Energy-Momentum, of which rest Mass is just one component) 'distorts SpaceTime'? The answer to this question is because *Gravity is universal*. What do we mean by that? It is indeed true that we can describe both Gravitation and Electromagnetic Interactions using the language of Geometry. To use more technical language, both forces can be expressed in the form of covariant derivatives, which in turn implies a geometric structure. But there is a difference. As it was mentioned, Gravity is universal. That is to say, the *covariant derivative*, i.e., the *geometric distortion*, does not depend on the particle that is used to measure it. There is only one Geometry in town, and every particle 'senses' that same Geometry. So, we are free to interpret Gravitation as a *distortion of SpaceTime* if it suits our fancy (but many people forget that Einstein himself cautioned us against reading too much into this interpretation).
In contrast, the covariant derivative and associated Geometry in the case of Electromagnetism do depend on the properties of the particle used to measure it. There is no universal Geometry. Charged and uncharged particles sense different Geometries; particles with different charge-to-mass ratios sense different Geometries. So, it does not make sense to use a geometric interpretation of Electromagnetism, as we would need a different interpretation for every different type of fundamental particle (and we won't even mention composite particles that may be electrically neutral but still have a *magnetic Moment*, so, they end up producing yet another different type of response to the Electromagnetic Field).

425 -

Given the scale of the *observable Universe*, how come that the speed of light is so slow?

The 'scale of the observable Universe' is *proportional to the speed of light multiplied by the age of the Universe*. In other words, it is what it is precisely because the speed of light is what it is. If the speed of light had any other value, if it was bigger or smaller, the scale of the observable Universe would be proportionately bigger or smaller as well, because, well, the observable Universe is defined as the parts of the Universe from which light had a chance to reach us since the beginning of the Universe.

426 -

How does Einstein's stating that $E = mc^2$ compare to Newton's stating that $F = ma$ and $F = GMm/d^2$?

They all express *different* things, *not directly related*. The expression $F = ma$ is essentially *the Law of Inertia*. If we divide by m, we get $a = F/m$, which is to say, the acceleration of an object is directly proportional to the force acting on it and inversely proportional to its Inertial Mass. In other words, Inertial Mass determines how an object resists a force. What that force is, that's not specified. It can be anything … including the force of Gravitation, determined by $F = GMm/d^2$. It is instructive, though, to combine the two, that is to say, replace F with ma: $ma = GMm/d^2$. Note how the value of m cancels out as both sides can be divided by it: $a = GM/d^2$. That tells us that the acceleration

if the Gravitational Field of mass M will be a, and it doesn't matter what the mass m of the object is that is used to measure this acceleration. *This is the universality of Gravitation*.
Newton was not satisfied with his law of Gravitation. In fact, for years he refrained from publishing it. His main reason: he could not see how a body, e.g., the Sun, could act on a distant body, e.g., the Earth, without anything that mediates this action. That is to say, the 'action-at-a-distance' nature of this law bothered him. Eventually, this was resolved by our modern Field Theory of Gravitation, General Relativity. The first step on that path was of course Special Relativity, and its consequence concerning the Inertial Mass of objects: namely that this Inertial Mass is determined by the object's Energy-content, $m = E/c^2$. Or, as it is better known (multiply by c^2 to obtain this form) $E = mc^2$.

427 -

If a black-hole's event horizon is 10 km in diameter, and another black-hole 10 cm in diameter, then why do we get *spaghettified* outside of the event horizon of the smaller black-hole, But inside of the bigger one?

Actually, we get 'spaghettified' by both a 10 km and a 10 cm black-hole long before we get near their respective event horizons. *Spaghettification is a tidal effect*. It relates to the fact that different (strong) gravitational forces pull on different parts of our bodies, so, those parts try to follow wildly different trajectories.
Let's think about this: a black-hole with a 'diameter' of 10 cm is *more than 5 times as massive as the entire Earth*. So, we would get 5 times Earth Gravity … if we were 6370 km (the Earth's radius) from that black-hole. Gravitation is inversely proportional to the square of distance. Therefore, if we were as close as, say, 6.37 km from that 10 cm black-hole, its Gravitational Field would be 10^6 times stronger than the Earth's.
That by itself is not a problem since we don't actually feel Gravity if we are in free fall. We feel weightless. But herein lies the problem: not all parts of your body can be in freefall at the same time and still stick together. At 6.37 km from that 5 Earth mass black-hole, if our head is, say, 1 m closer to it than our legs, the difference in acceleration itself amounts to 1500 times the surface Gravity of the Earth. Now, let's imagine what would happen if someone hung us upside down and then tie, say, a 5 metric ton weight to our neck. That would rip our head off, would it not? That's precisely what would happen to your body 6.37 km (!) from that 10 cm diameter black-hole.
The larger a black-hole, the gentler is the 'slope' of its Gravitational Field near its horizon. But a 10 km diameter black-hole is still not large enough. The mass of that black-hole is about 1.7 times the mass of the Sun. But we can get a lot closer to it than the solar radius of about 695000 km. At a 100 km from that black-hole, the Gravitational acceleration is already some $2.3 \cdot 10^9$ times the Earth's surface Gravity; and, once again, the difference in Gravitational acceleration between our head and our legs would amount to an even larger number, about 45000 times Earth's surface Gravity. So, we would be spaghettified, ripped to shreds by tidal forces instantly.
In fact, it takes a black-hole of over 30000 solar masses, with a radius close to 100 km, before tidal forces become gentle enough near the horizon so that we can reach the horizon intact, only to be spaghettified afterwards. The reason is that even though such a black-hole obviously as more Gravity than a smaller black-hole, its event horizon radius is also greater, and *tidal* forces (*the rate at which the Gravitational Field changes*) become gentler on smaller scales, such as the scales of a human body.

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Is the reason that we cannot see light any further than about $1.4 \cdot 10^{10}$ light-years because light did not have time to travel from further distances or because further distances are basically *opaque* due to the high Energy early Universe?

Yes, on both counts. It is true that the oldest light that we can see is light from a distance (light travel distance; there are other distance measures in an expanding Universe, and it can get quite confusing) of $1.4 \cdot 10^{10}$ light-years, since light originating any further out could not reach us just yet. But it is also true that, for the first 380000 years or so, the Universe was *opaque* to light, so any light that we actually do see is light that was produced when the Universe became *transparent* (the light in question is light emitted by *incandescent hot gas*; it has been red-shifted in frequency by a factor of about 1100, and today we can detect it in the form of radio-waves in the microwave band. This is the CMB (*Cosmic Microwave Background*) *Radiation*.

429 -

What is so peculiar about the black-hole M87*, and why?

There is nothing peculiar about M87* other than the fact that from our vantage point, it is the second biggest (in terms of observed size, i.e., angular diameter) black-hole that we can observe.
The biggest of course is our Milky Way's own super-massive black-hole, Sagittarius A*, because of it's relatively nearby, in our own galaxy, less than 30000 light-years from us. But it is 'only' a roughly $4 \cdot 10^6$ solar mass black-hole, so tiny by the standards of *super-massive* black-holes.
M87* is a lot farther away, more than $5 \cdot 10^7$ light-years from here. But it is gigantic: its estimated mass is about $6 \cdot 10^9$ solar masses. For this reason, its angular size in the sky is almost as large as the angular size of Sgr A*.
Moreover, because it is so big, its *accretion disk* is changing *more slowly*. We know how hard it is to photograph fast-moving targets. That gets even harder when our 'camera' is a worldwide network of radio telescopes and they must collect data for days, weeks or longer periods to achieve the desired sensitivity and angular resolution. Sgr A* just changes too much, it's like trying to photograph kittens or overactive children. M87* in turn stays put. This is why the Event Horizon Telescope (EHT) collaboration was able to obtain a reconstructed image of M87*, but not yet able to accomplish the same feat for Sgr A*. And that's what makes M87* special for us, humans, as we try to explore and understand the Universe around us.

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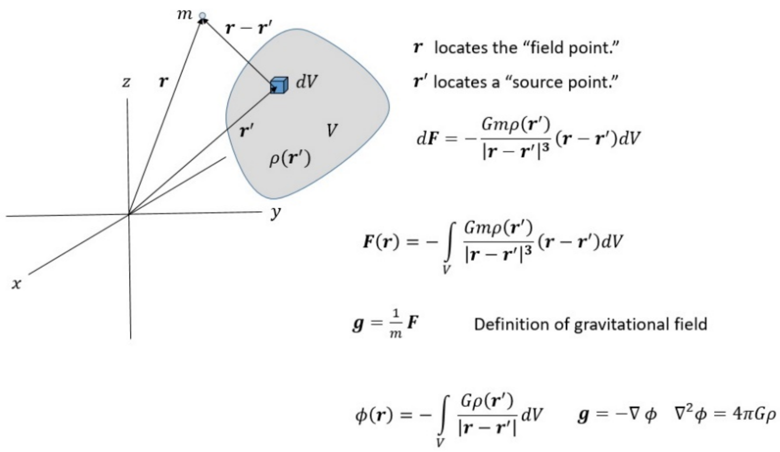
It may be worth hosting here a *worked* synopsis of some issues in this PDF document. The author is R. D. Gray – former Professor of Physics (1996-2008), Un. of North Texas – about the *Newtonian approximation in General Relativity*.

Newtonian Gravitation involves, not only Newton's inverse square formula for calculating the force one point-mass exerts on another, but also Newton's three Laws of Motion. To deal with this question, I will state how Newton's 1st Law of Motion is generalized to curved SpaceTime and how Newton's 2nd Law of Motion, when a Gravitational Force acts on a particle, is approximated by a *curvature* of SpaceTime. Then, I will show how Einstein's Field Equations include an approximation to Newton's Theory written in general mathematical terms.

Newton's 1st Law states that, relative to an *inertial frame*, a particle will remain at rest or continue moving in a *straight* line, if it is initially doing so, if the *net* force *on* the particle is zero. In the curved SpaceTime of General Relativity, Newton's 1st Law must be replaced with a statement that a particle will move along the *straightest path possible* in SpaceTime, i.e., along a *geodesic*, if the *net* force *on* it is 0. This assumption, called the *Geodesic Law of Motion*, is incorporated into General Relativity, just as Newton's 1st Law of Motion is assumed in all Newtonian Mechanics, including Newtonian Gravitation.
The framework of General Relativity contains Special Relativity in the case where SpaceTime is *flat*, i.e., where SpaceTime allows straight lines, and we already know that when *small relative* velocities are considered, Special Relativity approximates Newtonian Mechanics. Therefore, we should expect that Newtonian Gravitation approximates General Relativity if velocities are *small*. But there is an additional requirement we should expect as well. We should expect that the curvature of SpaceTime is *slight* if we are to get an approximation to Newtonian Gravity. Both assumptions, *low speeds* and *slight curvature*, will be made.
The picture below summarizes the general mathematical theory of Newtonian Gravitation.



The gray shaded region represents a distribution of mass, characterized by a *Mass density* function $\rho: \boldsymbol{r} \mapsto \rho(\boldsymbol{r})$, to act as a source of Gravitational Force on a mass m. The *gravitational acceleration* of a point-mass m is

$$\boldsymbol{g} = -\boldsymbol{\nabla}\phi \equiv -\frac{\partial \phi}{\partial x}\hat{\boldsymbol{x}} - \frac{\partial \phi}{\partial y}\hat{\boldsymbol{y}} - \frac{\partial \phi}{\partial z}\hat{\boldsymbol{z}} \,. \tag{1}$$

It will be seen that the Geodesic Law of Motion of General Relativity, under the previously mentioned assumptions, leads to Eq. (1). However, first the usual notation above must be modified so that it matches the notation used in General Relativity. The following will be used in a coordinate system in General Relativity if the coordinates approximate a *local inertial system* at some SpaceTime point: $(x^0; x^1; x^2; x^3) \coloneqq (ct; x; y; z)$.

As usual, Greek indices, such as μ , will be used to take values $\mu = 1, 2, 3$, Latin indices, such as i will take values $i = 1, 2, 3$, and summation on *repeated* indices, one *up* and one *down*, is implied.

Free particles with rest mass will follow geodesics which will be parameterized with their *proper time* τ , measured from some reference event, according to the Geodesic Equation

$$\frac{d^2x^\mu}{d\tau^2} + \frac{dx^\nu}{d\tau}\frac{dx^\sigma}{d\tau}\Gamma^\mu_{\nu\sigma} = 0\,. \tag{2}$$

The quantities $\Gamma^\mu_{\nu\sigma}$ are called *Christoffel symbols* of the 2nd kind (see, e.g., [41], P. 289; [47], P. 195) and are calculated from the *metric tensor* components $g_{\alpha\beta}$,

$$\Gamma^\mu_{\nu\sigma} \coloneqq \frac{1}{2}g^{\alpha\mu}\left(\frac{\partial g_{\nu\alpha}}{\partial x^\sigma} + \frac{\partial g_{\alpha\sigma}}{\partial x^\nu} + \frac{\partial g_{\nu\sigma}}{\partial x^\alpha}\right). \tag{3}$$

Equation (2) will be used to arrive at the Newtonian acceleration in Eq. (1) as an approximation under the previously mentioned assumptions and the case of a *static* SpaceTime. By low speed, it is meant that we will drop terms as small as $\beta^2 \coloneqq (v/c)^2$. We also assume that in the coordinate system used, the Christoffel symbols are of the same order of magnitude. The latter assumption is necessary if the spatial coordinates are to approximate non-rotating Cartesian coordinates. Some details will be left out but can be found in the text by by R. Dale Gray, *Manifolds, Groups, Bundles, and Spacetime*, ISBN 978-1-329-408256. Under the assumptions of a *static SpaceTime* and *small curvature*, coordinates can be chosen at *any* SpaceTime point such that $g_{00} \approx 1,\ g_{ij} \approx -\delta_{ij}$ on a neighborhood of the point, and $g_{\mu\nu}$ is independent of $x^0 \equiv ct$.

With the assumption of *low velocities* (i.e., $v/c \ll 1$) , we have that

$$\frac{d\tau}{dt} = \frac{1}{c}\frac{ds}{dt} \approx \left(1 - \frac{v^2}{c^2}\right)^{1/2} \approx 1\,.$$

Therefore, Eq. (2) gives

$$\frac{d^2x^i}{dt^2} \approx -\frac{dx^\mu}{dt}\frac{dx^\nu}{dt}\Gamma^i_{\mu\nu} \approx -c^2\Gamma^i_{00} - 2c\frac{dx^j}{dt}\Gamma^i_{j0} - \frac{dx^j}{dt}\frac{dx^k}{dt}\Gamma^i_{jk}\,. \tag{4}$$

The Christoffel symbols Γ^i_{j0} are *identically zero* in the coordinate system employed here. Also, since $|dx^j/dt| \le v$, the last term on the right side is of the order of β^2 , so Eq. (4) reduces to

$$\frac{d^2x^i}{dt^2} \approx -c^2\Gamma^i_{00} = \frac{c^2}{2}\frac{\partial g_{00}}{\partial x^i}\,. \tag{5}$$

Equation (5) agrees with the Newtonian expression in Eq. (1) if $g_{00} = 1 + 2\phi/c^2$. The Gravitational Potential is arbitrary up to an additive constant and the 1 is added so that we have $g_{00} = 1$. As a comparison, $2\phi/c^2 \approx 1.4\cdot 10^{-9}$ at the Earth's surface.

For a *spherically symmetric* mass distribution, M , the Newtonian Gravitational Potential,

$$\phi = -\frac{GMm}{r}\,,$$

can be used in Eq. (5) in the region exterior to M , to get

$$\mathbf{g} = -\frac{GM}{r^2}\hat{\mathbf{r}}\,,$$

where G is the Universal Gravitation Constant, r is the distance from the CM of M and $\hat{\mathbf{r}}$ is a radially *outward-pointing* unit vector. This is the Newtonian acceleration of Gravity at a distance r from the mass M .

Next, consider Einstein's 1915 version of the Field Equations of General Relativity,

$$R_{\mu\nu} - \frac{R}{2}g_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}\,,$$

where $R_{\mu\nu}$ is the *Ricci Tensor*, $R \equiv R^\mu_\nu$ is the *scalar curvature* and $T_{\mu\nu}$ is the *Energy-Momentum Tensor*. The Field Equations can be written in the equivalent form

$$R^\mu_\nu - \frac{1}{2}\delta^\mu_\nu R = -\frac{8\pi G}{c^4}T^\mu_\nu$$

by raising the first index and using the *saturation* relation

$$g^{\mu\alpha} g_{\mu\nu} = \delta^{\mu}_{\nu} .$$

Contracting on the indices μ and ν gives

$$R = \frac{8\pi G}{c^4} T ,$$

where $T \equiv T^{\mu}_{\mu}$ and $\delta^{\mu}_{\mu} = 4$ are used. Substitution in the original form of the field equations and algebraic rearrangement give

$$R_{\mu\nu} = -\frac{8\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right).$$

To get Poisson's Equation as an approximation, the 'dust cloud'-approximation for the mass distribution is assumed:

$$T^{\mu\nu} = \rho_0 \frac{dx^{\mu}}{d\tau}\frac{dx^{\nu}}{d\tau} ,$$

where ρ_0 is the *proper* Mass density. The *dust cloud approximation* means the particles of the mass distribution have *no mutual interactions* and exert *no pressure*. We see that, under the assumed approximations,

$$T_{00} \equiv T^{00} \approx c^2 \rho_0 .$$

Considering the time-time component of the Field Equations, one can show that, for a dust cloud, we get

$$R_{00} \approx -\frac{4\pi G}{c^2} \rho_0 .$$

Also, in the above referenced textbook, it is shown that, for a *static* SpaceTime,

$$R_{00} \approx -\nabla^2\left(\frac{1}{2} g_{00}\right) + g^{00} \boldsymbol{\nabla}\left(\frac{1}{2} g_{00}\right) \cdot \boldsymbol{\nabla}\left(\frac{1}{2} g_{00}\right),$$

where ∇^2 and $\boldsymbol{\nabla}$ are the Laplacian and gradient operators in the space-like hyper-surfaces $x^0 = \text{constant}$. With the approximations we are making, this gives

$$-c^2 R_{00} \approx \nabla^2 \phi = 4\pi G \rho_0 ,$$

which is Poisson's Equation for the Gravitational Potential.

431 -

An eerie tale: what can mankind do to defend Earth against a black-hole? Say, if a black-hole has a trajectory towards Earth, what would be our weapon against it?

Let's say that tomorrow astronomers announce that, after having observed the perturbed orbits of certain Kuiper belt objects, and perhaps a fortuitous gravitational microlensing event or two, they have confidently determined that a stellar size black-hole, a small one really, is on its way towards the inner solar system, and its trajectory will likely intercept the Earth. At this point, let's say, the black-hole is still a considerable distance away, say, 300 astronomical units (300 times the Sun-Earth distance), but its velocity is significant, say, about 140 km/s (not at all unreasonable for an object originating from outside the solar system) relative to the Sun. Which means that we have about 10 years before the black-hole arrives. So, what can we do?

First of all … this is a stellar-size black-hole, i.e., 'small', but small is in the eye of the beholder. The smallest black-hole that can form by a known physical process weighs about three times as much as the Sun, or roughly a 10^6 (!) times as much as the Earth.

Right there, that should tell us that the question is like an ant asking another ant what they can do if a battle tank is about to roll over their home-mound.

In this scenario, our black-hole, quite invisible of course, approaches the inner solar system. At first, the signs are seen only by astronomers. The black-hole itself won't be seen, but its effect on planetary orbits will become increasingly noticeable. Let's say the black-hole approaches in the plane of the ecliptic, in the direction of Saturn. In 2028, this will eventually take the black-hole on a trajectory between Uranus and Neptune. But we're not there yet; at first, the perturbations are subtle.

The world goes bonkers in the meantime. As news of the imminent approach of the black-hole spread, there will be widespread panic. There will be plenty of cranks and crackpots proposing all sorts of magic schemes to save humanity. There will be political upheavals. Perhaps, even wars. There will be outlandish, mad schemes to build spacecraft (for which we don't have the technology) to escape. There will be resignation, acceptance of an unavoidable fate.

There may be more sensible plans to try to save at least some of the cultural heritage of humanity. Perhaps save a few human beings, maybe a future Adam and Eve. But these plans, too, are doomed; we will not learn in a few short years

how to create a self-sustaining presence in space, and no artifact created by humanity will survive for geological time scales.
And the black-hole approaches relentlessly. When it is less than 50 AU from the Sun, with a year and a half left until arrival, its gravitational influence on Neptune is already comparable to that of the Sun, which means that Neptune's orbit is changing quite substantially. Uranus is next, its orbit will be disrupted, too. Depending on the actual trajectory, both planets may permanently detach from the solar system, becoming rogue planets in interstellar space.
OK, to make it truly spectacular, let's say our black-hole actually brushes by Saturn. The result will be dramatic: as the black-hole approaches, Saturn will be tidally disrupted, ripped apart. It will be quite a light show, visible to the naked eye. At this point, there will be less than five months left until the end.
As the remnants of Saturn wink out of existence, there will be no more light shows. The black-hole itself will remain quite invisible as it approaches the Earth. It will first announce its imminent arrival by altering tides. These effects will become noticeable when the black-hole is less than a month away. Tides will be disrupted and will increase in magnitude each day. As a further omen, we lose the Moon; even if it survives the encounter with the black-hole, it ceases being a satellite of the Earth, and more likely, becomes a rogue body itself.
Finally, we get to the last day. Tides are now gigantic. Coastal cities will have been washed away. There will be seismic and volcanic activity worldwide, on unprecedented scales. Millions will have died already, with no refuge for the survivors. Our infrastructure will break down; there will be no more electricity, no more running water as transmission towers topple, water lines rupture, dams collapse.
Finally, in the last 90 minutes the Earth gets within its so-called *Roche limit*. Tidal forces now exceed the Earth's own gravity, and the planet is literally ripped apart. No human will survive this on the surface (indeed by this time, there is no surface, only a planet-sized drop of molten rock that is being stretched by tides) but humans in spacecraft may witness the final moment as the material that was once the Earth is ripped apart completely and forms a rapidly rotating disk of material around the (still invisible) black-hole, spiraling in.
And the black-hole continues on its path of destruction. The trajectory we picked, in 2028, actually takes it quite close to the Sun. Which means that the Sun is likely to suffer a similar fate; once it is inside its Roche limit with respect to the black-hole, it, too, is ripped apart. Some of it may be sucked in by the black-hole, the rest may form a gas cloud that, perhaps one day, may yet coalesce into another star.
The black-hole, slightly heavier, now continues its path, exiting the solar system. Planets that it did not approach may remain largely untouched, in orbit around the remnants of the Sun. For all we know, hundreds of millions of years from now, a diminished but newly stabilized Sun may yet bring life to Venus. Or maybe not, and the solar system remains barren forever.
As to human civilization, it will be all gone. Earth is gone. Everything we ever built, ever created, is gone. One possible exception: refugees in primitive spacecraft who escaped the immediate destruction. They will float in space for weeks, maybe months, but ultimately, their supplies will be exhausted, their life support systems will shut down, and these spacecrafts become tombs, possibly remaining in orbit around the remnants of the Sun.
What can we do face such wholesale destruction? Absolutely nothing. In fact, that colony of ants has a better chance surviving being run over by a battle tank. Again, a reminder:

> the mass of the *smallest* astrophysical black-hole exceeds the mass of the *entire* Earth by a factor of 10^6.

432 -

What are the top theories competing with the Big Bang Theory?

There are no competing theories with the Big Bang Theory, because there is no such thing as the Big Bang Theory (other than the television show, that is).
The discipline is called Physical Cosmology. Its theoretical foundations include General Relativity and the Standard Model of Particle Physics, and additional assumptions about the conditions in the very early Universe and about additional, yet-to-be-discovered fields that may have played a role, especially in the very early universe (e.g., during inflation).
As to the Big Bang itself: the idea that the *early Universe was hot and dense* is no longer really subject to debate. The reason is that it is no longer a far-fetched conjecture supported only by the luminosity-redshift relationship (Hubble relationship) of distant objects. We now have direct observational evidence of very early galaxies, the composition of which is very different from galaxies of the present day: they contain virtually no heavy elements, for instance. We also have very detailed maps of the Cosmic Microwave Background, which provide very specific constraints on the evolution of the Universe. In particular, the so-called concordance or Λ-CDM model of Cosmology actually predicted the shape of the curve that characterizes temperature fluctuations in the Cosmic Microwave Background; these predictions were confirmed.
Now it is a good question if the early, dense phase of the Universe really marked the beginning of it all (*initial singularity*) or if there was a prior state, e.g., a Universe that contracted before it 'bounced' back and started expanding again. Such bounce models are frequently proposed, though they are not without issues and shortcomings. There is also

the concept of eternal inflation, in which our 'pocket' of the universe (a 'pocket' that is much larger than the observable Universe, but still just a 'pocket' in the big scheme of things) is just one region of something much larger, a Universe in which rapid expansion (inflation) takes place all the time, forming pockets like ours, in a never-ending process.

And there are many other possibilities. The existence of Dark Matter, a core concept in the concordance model (CDM stands for Cold Dark Matter), is questioned by those who attempt to attribute the same effects that Dark Matter is supposed to explain to modifications of Einstein's Gravity instead. The acceleration of the Universe, deduced from the luminosity-distance relationship of TYPE IA supernovae, is questioned by those who attribute these observations to large-scale inhomogeneities in our universe (so-called 'void Cosmology' models), and so on.

Physical Cosmology is still a young science, and there are many unknowns (which makes it more exciting). New theoretical proposals appear almost daily on ARXIV.ORG. Not even the most ardent advocates of the concordance model suggest that it is the last word on the topic. There are many alternatives. But there are a few things we know already, and the idea that the early Universe was hot and dense is one of them.

This wasn't always so. Before the observational discovery of the Cosmic Microwave Background, there was another widely favored model: steady-state Cosmology, in which the expansion of the Universe is balanced by the continuous, spontaneous creation of Matter, so that on the largest of scales, the Universe is eternal and unchanging. One of the best-known advocates of steady state Cosmology was Sir Fred Hoyle, who, incidentally, was also the person who coined the term, 'Big Bang', when he ridiculed Big Bang Cosmology on a BBC radio show. The Hubble redshift also had an explanation in the form of 'tired light', the idea that over cosmic distances, photons *lose Energy*, e.g., by interacting with the intergalactic medium. These alternatives have since been discredited by data; as has been mentioned, very little doubt exists that the early Universe was in a hot and dense state, which is what the Big Bang is all about.

433 -

How can we claim that Vacuum speed of light is *constant* if there is no Absolute Time (as a smooth flowing continuum in which everything in the Universe proceeds at an equal rate)?

No Absolute Time is required to establish the independence of the speed of light from the motion of the observer's reference frame.

The current definition of the meter obscures this, since it is defined in terms of the second, *assuming* that the speed of light is *constant*. But let's take the previous definition, in terms of the *wavelength* of a certain emission of $^{86}\mathrm{Kr}$.

Combination of this with the definition of the *second*, which is made in terms of the *frequency* of a certain emission of $^{133}\mathrm{Cs}$ (transition between the two hyperfine levels of the *fundamental unperturbed* ground state of $^{133}\mathrm{Cs}$). We can now measure the length of the path that a ray of light covers between two events using a $^{86}\mathrm{Kr}$ atom one carries, and the time it takes using a $^{133}\mathrm{Cs}$ atom someone else carries.

Different observers, each carrying their own respective atoms, can make this measurement. Depending on their motion, they will measure different numbers, because of *Length contraction* and *Time dilation*.

However, when they take the ratio of their respective measurements, they will find that within the limits of measurement error, it always comes to 299792458 meters (defined using $^{86}\mathrm{Kr}$ atoms) / second (defined using $^{133}\mathrm{Cs}$ atoms).

This is done without any reference to Absolute Time. Just observing two events (the moment of emission and moment of absorption of a ray or pulse of light, at two respective locations).

434 -

Is the 'M87* photo', a photo of a black-hole, or of the accretion disk of a black-hole, or a photo of a galaxy with a giant black-hole at its center? Why is it called 'photo of a black-hole', if black-holes don't reflect light, and can't be seen?

[Refer back to Issue 92, P. 42]

First, it is not a photograph. It is a *reconstructed image*, based on radio-astronomy observations, a campaign involving several radio-telescopes around the world. They did not 'snap a picture'. They made a very large number of observations of the inner region of M87*, from which this image, using a variety of mathematical algorithms, was reconstructed.

What the image depicts are *radio emissions* from *material falling into the black-hole*. The region in question is very small, spanning only a few hundred AU, hence, comparable in size to our solar system. It is a very compact, small, central region in a huge galaxy.

The material forms an accretion disk. However, 'light' from this accretion disk is blocked by the black-hole itself, or to be more precise, by the black-hole's so-called *photon sphere*, the region within which the black-hole bends light so much, photons can in fact (briefly) even get into orbit around it. The black-hole itself is not visible, only this 'shadow'.

One reason why this image is of particular importance is that the size and appearance of this shadow *can be predicted* using the equations of General Relativity. The fact that this very difficult observation yields a result in *reasonable agreement* with those predictions is a huge thing, yet another significant confirmation of Einstein's General Relativity.

435 -

Why is the spatial recessional velocity limited to c for an event horizon of a ‘frozen star’ but not limited at c for the cosmic background radiation? Both are due to spatial expansion, one elongation and the other (spatially additive) expansion. In curved SpaceTime, the definition of the velocity of distant things is ambiguous. There is no universal, preferred definition.

Let’s take the event horizon. On the one hand, we know that any object falling through the event horizon of a black hole reaches the speed of light at the event horizon. On the other hand, we also know that for any observer *outside* that event horizon, the infalling object will never even reach the horizon, as it is seen increasingly in *slow motion*, ‘freezing’ in Space (and becoming *invisible* because any light from it is *infinitely red-shifted*) just before reaching the horizon.
So, which is it? Is it moving at the Vacuum speed of light? Or is it frozen? Actually, it is both and neither; the problem is, we are trying to describe it in the reference frame of an observer who *cannot* observe the moment of the object reaching the horizon.
Something similar happens with cosmic expansion. Very distant things near our cosmological event horizon are moving away from us at a very high speed, far exceeding the Vacuum speed of light according to one measure (the scale factor). Yet, at the same time, when we look at those things, we see them *slowed down* by a tremendous time dilation factor, so their *actual* speed is just a fraction of the speed of light. Again, at the (unobservable) cosmic event horizon, these things reach their respective extremes: things would be moving away from us at an ever-higher rate yet appear to freeze relative to us *because of Time dilation*.
This is not just idle theorizing, by the way. In the 1960s, Irwin Shapiro added a 4th test to the 3 classical tests of General Relativity proposed by Albert Einstein: the *Shapiro Time-delay*, due in part to the fact that from an Earth observer’s perspective, light (or radio waves) propagating near the Sun will appear to move slower than the Vacuum speed of light despite being in the Vacuum. An observer located near the Sun, where the rays are passing, would see *no* such slowdown, because that observer’s own clocks *would slow down* proportionately.
The bottom line is what has been said at the beginning: in General Relativity, in curved SpaceTime, no unambiguous definition exists for the speed of distant things, and depending on the reference frame used, that speed can end up being anything between 0 and $+\infty$.

436 -

If we humans were able to discover a *white-hole*, how strong would it be, and how fast would it push us away?

A white hole doesn’t push. *White-holes are time-reversed black hole solutions* in General Relativity. Time-reversed doesn’t mean repulsive Gravity. Let’s think of a thing in orbit around a black-hole. Let’s make a movie of it and play it in reverse. The thing would still be orbiting the black-hole.
What Time-reversed does mean is that instead of a future horizon hiding a *future singularity*, anchored in past initial conditions, a white-hole has a past horizon hiding a past singularity, anchored in future initial conditions. In other words, *it breaks causality*. We cannot fall into a white-hole because in the future, we are somewhere other than inside the white-hole. This is one of several reasons why we believe that white-holes are *unlikely to exist in this causal Universe* of ours.

437 -

Do we know which direction we are moving away from the Big Bang?

Indeed, we do. That direction is called the *Future*.
No, this is not playing with words. Contrary to a prevalent misconception, the Big Bang was neither an explosion nor a location in Space. It was a *past epoch in Time*, when the entire Universe, everywhere, was *very hot* and *very dense*. This epoch marks the beginning (as far as we know) of our Universe, and the only direction we can move from the Big Bang is towards the Future.
And just to repeat, it is not playing with words here, honest, this is a fairly accurate description of what the mathematics of SpaceTime tells us about the Big Bang and the subsequent evolution of the Universe.

438 -

Does Dark Matter actually have to be Matter? Isn’t it possible it’s some kind of massless particles, since, in General Relativity, Mass isn’t required for Gravitation?

It is ‘Matter’ because we call it ‘Matter’. It does not by itself imply any specific property. In the sense cosmologists use the word, ‘Matter’ *does not necessarily involve rest Mass*.
But Dark Matter does have one specific property in the Standard Cosmological Model: its *equation of state*. Specifically,

the statement that its pressure is *negligible* compared to its Mass-Energy density.
So, *no*, it cannot be massless particles, because massless particles form an ultra-relativistic medium in which pressure equals $1/3$ one the Energy Density. The whole point of Dark Matter (if it exists, in the first place) is that it is 'cold' (not moving fast), massive, but non-interacting (no pressure).
So, whether we call it 'Matter' is up to us. But its fundamental property (the so-called '*dust*' *equation of state*) is critical to the success of the Standard Theory.
There are of course other cosmological models that assume Dark Matter with different properties or try to do away with Dark Matter altogether. But for now, for all its shortcomings, the 'concordance' model of Cosmology is more successful.

439 -

When light from an object falls on the eye, we see. If a black-hole absorbs light, then why do we see it?

Presumably, the question is referring to the famous image of M87* shown in Issue 92, P. 42. Yes, this picture depicts a black-hole, sort of. But only sort of. More than an artist's impression, but not quite a photograph, this is a reconstructed image, using a mathematical model and a large series of radio telescope observations of the M87* super-massive black hole and its accretion disk.
In any case, the orange (not in reality; the orange color is chosen for purely artistic reasons) 'donut' is not the black hole. It corresponds to *radio emissions* from infalling material, the so-called *accretion disk*.
The hole in the center? Now that's the black-hole (more or less). To be technically precise, that hole in the center is the shadow cast onto the accretion disk by the black-hole's so-called *photon sphere*. This is the region, pretty much, where the black-hole intercepts light (or, in this case, radio waves) so that they do not proceed in our direction. Hence, we see darkness.
So, … not a photo, a synthesized image; not visible light but *radio waves*; and what we actually see is Matter surrounding the black-hole with the black-hole casting its shadow.
It is still absolutely remarkable that here, in the first quarter of the 21st century, we have the ability to reconstruct the appearance of something as dramatic as a super-massive black hole in the central region of a distant galaxy.
But it is important to understand what the picture actually represents.

440 -

If not even light can escape the event horizon of a black-hole, how can a black-hole radiate as *Hawking Radiation* says? Won't the radiation be pulled in, nonetheless?

Hawking radiation is not coming from inside the black-hole. Not even from its event horizon. Hawking radiation is the result of *gravitational Vacuum polarization* in the vicinity of the event horizon. And 'vicinity' should be taken in a rather relaxed sense: the characteristic wavelength of Hawking radiation is about 20 times the *Schwarzschild radius* of a black-hole.
Another important thing to understand about black-holes is that although their Gravitational Field is *strong*, they are geometrically *tiny*, very compact compared to their mass. That means that it is very easy to miss them: an infalling object is far more likely to pass by the black-hole and escape on the other side in a hyperbolic trajectory than to intercept its event horizon. This also applies to radiation; if we place a light source near a black-hole, most of the light from that source would not end up hitting the event horizon.

441 -

What would the *temperature* of the Universe be if all stars (including white dwarfs, neutron stars, brown dwarfs and black-holes) all burned out and stopped forming?

The *characteristic temperature* of the Universe is only negligibly affected by starlight. The value, $2.7\ \mathrm{K}$, is the temperature of the *Cosmic Microwave Background* (CMB) radiation. The CMB is very cold, granted, but it is radiation from every part of the sky. Starlight, in contrast, even in a relatively dense part of the Universe where we live, comes only from specific point sources. Now, if we found yourself floating in a spacesuit in intergalactic space in one of the large voids between clusters of galaxies, chances are we would see absolutely nothing with our named eye; the Universe would appear completely black, as even the nearest galaxy would be too far away for your eye to detect without instruments.
So, whereas in our solar neighborhood, the Energy density of starlight is comparable to that of the CMB, in much of the Universe, starlight is only a small fraction of the CMB. Therefore, even if all stars vanished, it would make little difference: an object in deep intergalactic space, in thermal equilibrium, would be at $2.7\ \mathrm{K}$ either way.

442 -

Would CBM (cosmic background microwaves) have escaped (passed us) because they travel at the speed of light? So, how can we now detect these *micro-waves*?

Here is the basic premise of the standard Cosmology: the Universe is the same everywhere. It has no boundary, no center, no edge. It is spatially infinite and, on average, contains the same kind of Matter, same density of Matter, has the same age, etc. . And it was the same everywhere, nearly $1.4 \cdot 10^{10}$ yr ago, when it first became cold enough everywhere for the fully ionized, mostly H-gas that it contained to recombine into neutral atoms. *The ionized plasma is not transparent to radiation. The neutral gas is*. The hot, ionized plasma was emitting radiation; it was incandescent. But that radiation was quickly captured by neighboring bits of plasma. The Universe was not transparent. But as it was cooling, it was becoming *more and more transparent*, so, *radiation could propagate over longer and longer distances before it was reabsorbed*. Until one day, it was not reabsorbed at all; it was now free to travel, even for billions of years.
So, fast forward to today, with us looking at a patch of sky with a radio telescope. We are looking through stuff that has become transparent a long time ago. The further we look, of course, the further back in time we see, since it takes time for light (or radio waves) to arrive, and it is *proportional to distance*.
Therefore, if we imagine our line of sight going backwards in time, eventually it will hit a bit of plasma that was not quite transparent yet; it was blocking light coming from even further behind it. But this bit of plasma was itself incandescent. So, we see light coming from this bit of plasma, having traveled for $\sim 14 \cdot 10^{9}$ years.

Now let's look at the same sky direction after a day. The bit of plasma that we saw the previous day is now fully transparent; it is neither blocking nor emitting light. Instead, we now see another bit of plasma behind it. We are looking a little further back in time, of course, as this new bit of plasma is a little further away; so, we see this new bit of plasma at the moment in Time when it was becoming transparent, emitting the last bits of its own incandescent radiation.
And this continues, going on and on. No matter how long we wait, in an infinite Universe there will always be a bit of plasma at a sufficiently great distance from us, which we see at the moment when it was becoming transparent, emitting the last bits of its own radiation.
Therefore, we see the CMB on a *continuous* (*microwave*) *basis*. Behind every bit of hot gas that we see today, there is more gas waiting to be seen tomorrow.

443 -

If we could create a miniature black-hole, could we control it? Would we be able to use it as an Energy source, or would it destroy us?

Let's suppose that a process exists by which we can create a 1 kg black-hole. Here is the problem with that 1 kg black-hole: it would evaporate due to *Hawking Radiation* within less than a *hundred attoseconds* $(= 100 \cdot 10^{-18}\ \mathrm{s})$. That 1 kg of Mass-Energy would be radiated away in a flash of extreme high-Energy γ- radiation. Most of this would be absorbed by nearby Matter (air, ground, etc.) which would heat up to *tremendous temperatures* as a result and *expand explosively*. In other words, we have an explosion on our hands, the equivalent of a 20 megaton H-bomb. Bang!
A smaller black-hole would have less Energy, but would evaporate even faster. So, a smaller but *quicker* bang. Not very useful, actually.
What about a black-hole that lasts a little longer? Well, a black-hole of about 230 metric tons lasts 1 full second. But in that 1 s, it releases the Energy of 230000 20- megaton H-bombs. Now that's one almighty BANG!

Let's approach this the other way around. Let's create a black-hole that emits only a modest amount of radiation, say, one MW. That's still a lot of radiation, but it's something we can handle. It is still in the form of hard γ- rays, so careful handling is required, but it's something we know how to do. But here is the problem: this black-hole weighs $1.9 \cdot 10^{13}$ kg or 19 billion metric tons. This is the mass of a pure iron asteroid that is more than 16.5 km in diameter. The mass of, never mind a single mountain, more like a respectable mountain range.
So, we have an object not much larger than a proton, weighing as much as a small astrophysical body with a Gravity that, at a distance of 10 m, already exceeds the Gravity of the Earth, and which is insanely hot, about $6.5 \cdot 10^{9}$ K, emitting thermal radiation in the form of hard γ- rays, at a rate of 1 MW. Fantastic!

And the worst part? As all these objects weigh much less than the minimum required for spontaneous gravitational collapse (about 3 solar masses), chances are that we invested more, a great deal more Energy into creating these black-holes than what we get out of it in *uncontrolled thermal emission*.
In short, if it were possible to create a microscopic black-hole, it would be one of the most singularly (pun intended) useless thing ever created.
Thankfully, no such known process exists.

444 -

Gravity is infinite in a black-hole singularity. If Gravity strips atoms in a black-hole, how is it classed as the weakest fundamental force?

Without even elaborating on how not to misinterpret this singularity business, let's just stress one simple point. In a region of such extremes, where Gravity becomes *extremely strong*, the other forces *also* become extremely strong, even stronger than Gravity. So long before Gravity gets a chance to 'strip atoms', Electromagnetism will do the trick, because the Electromagnetic Interaction is *much stronger* than the Gravitational Interaction. In other words, though strong near a singularity, Gravity remains *weaker* than any of the other forces, so, it is still the weakest.
Elephants may be giant animals but even in a herd of elephants, we'll find one who is smaller than all the others. Same thing here: Gravity is the smallest of the elephants.

445 -

How cold is the empty cosmic Space?

[same answer as for Issue 441, P. 199]

Empty Space has no temperature. However, if we were to leave an object somewhere in deep space, far from any stars, planets or other bodies, it will, eventually, come into thermal equilibrium with the *Cosmic Microwave Background* (CMB), which is *thermal radiation* with a temperature of 2.7 K.
Stars continuously produce heat, which they radiate into empty space. They also receive a little radiation from the CMB. However, the power of thermal radiation is proportional to the 4^{th} (!) power of temperature. So, a star like our Sun, with a surface temperature of nearly 6000 K, will emit trillions more times the heat that it receives from the CMB.
As for planets, they receive a lot of heat from the Sun. They also emit heat into deep Space. And given that a planet like the Earth has an average surface temperature of nearly 300 K, it, too emits millions of times more heat than it receives from the CMB. No problem: it receives plenty of heat from the Sun. Ultimately, a planet like the Earth receives the same amount of heat, on the average, from the Sun that it emits into deep Space, so its temperature remains approximately constant. In fact, if Space were not this cold, we would all be in deep trouble. The Earth could not shed the tremendous amount of heat it receives from the Sun. Eventually, its oceans *would boil*. So, we really need the cold of deep Space as a sink for our waste heat. As does the Sun … if it could not radiate its heat into deep Space, it would blow up soon as its temperature would continue to increase due to the ongoing nuclear fusion in its interior.

446 -

What is Matter? Is Matter just a form of Energy with Mass?

[look back at Issue 4, P. 2, for a more extended answer]

'Matter' does not have a universally accepted definition. To most cosmologists, everything that's not SpaceTime is Matter. In Einstein's Field Equations, all 'Matter' are lumped together into a single tensor-valued quantity, the Stress-Energy-Momentum Tensor of 'Matter'.
To the particle physicist, 'Matter' may mean *fermionic* fields, whereas *bosons* mediate 'forces'.
But to most of us ordinary folks, 'Matter' would be what cosmologists call '*baryonic Matter*', stuff made of protons and neutrons, with electrons to balance *charges*.
None of these would be 'just a form of Energy with mass'. For starters, (rest) Mass is just one form of Energy, not to mention that one observer's rest Mass (e.g., the rest-mass of a proton) is another observer's Energy ($99\ \%$ of the proton's mass is the Binding Energy holding its constituent quarks together). But also, Matter has properties beyond Energy, such as *Angular Momentum* and *Charge*.

447 -

Can the twin-paradox really be resolved using just Special Relativity? Because if it is possible, it would seem to refute Special Relativity, which claims that it is not possible to tell if you are at rest or moving at constant speed?

Yes, the twin-'paradox' is quite resolvable in Special Relativity. While Special Relativity indeed treats accelerating observers as second-class citizens, we do not need tools beyond the Lorentz Transformation of Special Relativity to calculate *proper Time* along the *worldlines* of the two twins.
And truth to tell, we don't even need to worry about acceleration. We can make acceleration instantaneous. What we need to realize is that the twin-paradox with the twins meeting at least twice (first to synchronize, second to compare their clocks), necessarily involves at least 3 frames of reference, because at least one of the twins needs *to change direction* to return to the other.

448 -

How does Gravity assist increase spacecraft velocity, given the velocity leaving should equal the velocity entering?

A Gravity assist does not change the magnitude of a spacecraft's velocity, but it *changes its direction*. All with respect to the reference frame that is attached to the planet or other body that provides the assist.
What is a change in direction in one reference frame, however, can also produce a change in magnitude in another reference frame.
As a naïve (but not unrealistic) example, imagine a spacecraft approaching the Earth from the direction in which the Earth travels around the Sun, with an initial Earth-relative velocity of 10 km/s. Since the Earth itself travels around the Sun at 30 km/s and this object moves in the opposite direction, its Sun-relative velocity is 20 km/s.
Now suppose that after the approach, the spacecraft is now traveling in a direction perpendicular to the Earth's orbit, going outward, still at 10 km/s relative to the Earth. But now its Sun-relative velocity is the vector sum of the Earth's 30 km/s orbital velocity plus this 10 km/s velocity of the spacecraft in a perpendicular direction: using the equation of Pythagoras, it is easy to calculate that its Sun-relative velocity is, now, 31.6 km/s.
So even though the spacecraft's velocity is 10 km/s, both before and after the encounter in the Earth-relative frame of reference, in the Sun-relative frame, it gained 11.6 km/s.

449 -

Are massless particles affected by the Higgs Field? If they don't, why would they be affected by Gravity?

This question reflects a popular misunderstanding about the Higgs Field: namely that it has anything to do with Gravity. *It does not*. What the Higgs Field does in the Standard Model is providing a mechanism for *charged fermions* and *electroweak vector bosons* to acquire non-zero rest-masses. Concisely put, massless particles that interact with the Higgs Field acquire rest masses as a result of electroweak symmetry breaking; those that do not, don't.
By way of example, the photon and the Z^0- boson are very similar. But whereas the Z^0- boson interacts with the Higgs, the photon does not. Consequently, the Z^0- boson becomes very massive, and 'neutral weak currents' interaction mediated by Z^0- bosons, becomes very *short-range*; the Electromagnetic Interaction mediated by the photon remains *long-range* as the photon remains massless.
As another example, electrons become massive after symmetry breaking as a result of their interaction with the Higgs Field. Neutrinos don't interact with the Higgs Field, so if they are nonetheless massive (as indeed, we believe, they are) the source of that mass must be sought elsewhere.
None of this has anything to do with Gravity. *The source of Gravity is not mass, but Stress-Energy-Momentum*, of which rest Mass is but one component. Massless particles like the photon still have Energy and Momentum so they can be both a source of Gravitation and respond to Gravitation.
As yet another example, roughly $99\ \%$ of the mass of the particles of which we are made (protons and neutrons) comes not from any interaction with the Higgs, but from the Strong Force Binding Energy holding quarks together inside baryons.

450 -

Does the observable Universe have a *center-of-Gravity*?

Yes. And the center-of-Gravity of our observable Universe is us! Within rounding errors, that is, accounting for minor inhomogeneities.
The thing is, by definition, we are always at the center of our observable Universe. And the center-of-Gravity of all the Mass that we can see is us (more or less).
Of course, for a being in a distant galaxy, their observable Universe is not the same as ours and for them, its center-of-Gravity will, of course, be them.
Of course, it is not a very meaningful concept, to speak of the center-of-Gravity of the observable Universe. It's kind of like asking where the zenith is … always above our heads! But for someone else at a different location on the Earth, their zenith is quite different from our zenith.

452 -

Is there an explanation for Hubble's constant crisis?

First, it should not be called a 'crisis'. The word we see in the professional literature is 'tension', which is a lot less loaded. This tension exists because different estimates based on different data sets yield markedly different values for the Hubble parameter (quick reminder: *it's not a constant*. Its value *changes* – albeit very slowly – *over time*).
Why is this so? We don't know. Could it be that we're misinterpreting the data? Perhaps. Is it possible that the Universe is less homogeneous than we thought? Possibly. Or is this an indication that something is fundamentally wrong with our standard 'concordance' model of Cosmology? Maybe.
The point is, we do not yet know. We can offer informed speculation but, ultimately, it will be more data collected that will help decide one way or another.
To answer the question, then, 'explanations' are a dime a dozen. The literature is full of them. Are we able to decide which one is correct? Now that's the hard part, and that's where more data are needed.

453 -

What is wrong with the representation of a black-hole like a black ball? Some say this leads to singularity/infinity. Wouldn't it be better just to say we know little about Physics at the *density* close to infinity and be done with it?

What is wrong with representing a black-hole as a black ball? Well, … (almost) everything! *A black-hole is a creature of SpaceTime, not simply Space*. To understand a black-hole, it is essential to understand its *SpaceTime behavior*.
Naïve illustrations often depict a black-hole as a black ball. But a black ball exists *in the present*. In contrast, the event horizon of a black-hole *is not* something you can observe in the present (not unless we pass through it and get trapped inside the black-hole). To an outside observer, *the event horizon remains forever in the future*.
Near the event horizon, *Time dilation* becomes *divergent*. Again, to the outside observer, any process near the event horizon appears to slow to a halt. In fact, this is why the horizon remains forever *in the future*: if we could track an infalling particle, it would take forever, by our reckoning, for it to reach the event horizon.
Now let's suppose we enter the event horizon of a black-hole to experience it from the inside. The moment we cross the horizon, it becomes a moment *in the past*, not a surface, spherical or otherwise, but a *moment in Time*. And our future now *inevitably means the singularity*. But like the horizon, *the singularity is also not a location in Space*. It is a future moment in Time. In fact, once we are past the horizon, we find ourselves in a collapsing 'pocket Universe' that is becoming *denser and denser everywhere*. Over time (a very short amount of time, we might add, even if the black-hole is a supermassive black-hole), the collapse reaches its conclusion: *the end of Time*, i.e., the *singularity*.
Our Physics works well up to, maybe, 10^{-12} s (~ 1 picosecond) before this *singular moment*, because the conditions in this collapsing mini-Universe, at that point, are still reproducible in particle accelerator experiments. That final picosecond, however, remains an *educated guess*. We can make reasonable (albeit *speculative*) predictions up until the point where we are just one Planck Time interval ($t_P \approx 5.4 \cdot 10^{-44}$ s) *away from the singularity*, which is when the lack of a credible theory in Quantum Gravity makes us unable to offer sensible predictions. Or, perhaps, none of it happens because the black-hole *evaporates* in its entirety in *finite* time by way of Hawking Radiation, before the horizon can even form! In any case, perhaps this illustrates the point. The Physics of black-holes is rich, and thanks to experiments like LIGO or the EHT, we can now actually observe some aspects of it in the Cosmos. None of this rich Physics would be represented by a naïve 'black-ball' model.

454 -

When they figure for the Gravity of any 'solar system', galaxy or cluster, are they accounting for the Gravity of all the photons within that volume?

Most of the time, we don't have to. The contribution of photons is small. But there are cases when we do have to, and in that case, we indeed do.
First, to dispel a misconception: photons have no rest Mass, but their Energy does contribute to the total Mass of the object in which they are contained. By way of a *thought experiment*, if we had a box lined on the inside with perfect mirrors, we weighed that box, then let some light in (so that it now bounces inside, back-and-forth, forever) and weighed the box again, it would be slightly heavier in the second case.
So, what 'boxes' are there in Nature where the weight of photons matter?
Let's start with the Sun. The Sun radiates roughly $3.85 \cdot 10^{26}$ W of power. This corresponds approximately to $4.3 \cdot 10^{6}$ metric tons of radiation expressed using units of Mass. All this Energy is created *deep inside* the Sun in nuclear fusion processes, and slowly percolates to the top; it is estimated that it takes *a few million years for the heat to reach the solar surface*. So, let's be generous and use, say, $5 \cdot 10^{6}$ yr as a very crude measure and assume that all that Energy in transit

is in the form of photons (as opposed to, say, the Kinetic Energy of H or He atoms). Multiplied together, we get a Mass of about $6.7 \cdot 10^{23}$ kg , which is more than $1/10$ the mass of the Earth. A lot! But compared to the Sun's mass of $2 \cdot 10^{30}$ kg , it is still *negligible*.

In any case, when we do gravitational calculations in the solar system, we do not try to estimate the mass of the Sun from first principles; we actually measure the Mass using planetary observations and observations of spacecraft orbits. So, we don't have to know what that Mass is made of; we just get the final result *from observation*.

There are other stars, especially giant stars, where the contribution of this 'photon gas' is proportionately larger but even in these cases, it remains a small fraction of the total Mass of the star.

There was, however, a time in the history of the Universe when this was not the case. During the so-called *radiation-dominated era* in the history of the early Universe, radiation contributed more to the Mass density of the Universe than either normal Matter or Dark Matter or Dark Energy. This situation changed quickly, however, as in an expanding Universe, the wavelength of radiation increases in the so-called *co-moving frame of reference*; the result is that radiation not only gets diluted but also loses eEnergy as measured by such co-moving observers. So, the Mass-Energy density of radiation goes as the *inverse* 4th power of the scale of the Universe, as opposed to the *inverse* 3rd power that's the case for ordinary or Dark Matter. Therefore, the radiation dominated era ended quickly and Matter took over; in the present-day Universe, radiation represents only a *very tiny contribution* to the overall Mass density of the Universe.

455 -

If we calculate the light speed divided by *Hubble constant*, we get about $13.9 \cdot 10^9$ light-years, which is close to a light beam traveling for the age of Universe. Is it a coincidence?

The answer is, we don't know! It may be a coincidence, but … yes, it is true that, expressed in inverse years, the value 70 km/(s·Mpc) comes to almost precisely one divided by $14 \cdot 10^9$ years, which is the approximate age of the Universe.

If the rate of expansion were constant, this is what we would expect to see. But that would assume that Gravitation plays no role in the rate of expansion.

On the other hand, in the standard so-called *Concordance Model of Cosmology*, decelerating expansion for the first $9 \cdot 10^9$ yr or so was followed by accelerating expansion in the most recent 4 to $5 \cdot 10^9$ yr. As a result, at present, we live in an era when the *inverse Hubble parameter* is approximately equal to the age of the Universe. This wasn't like this in the past and will not be like these billions of years from now, so, in this model, it is indeed a coincidence that this is the case today.

But we are not the first to marvel if this is more than just a random coincidence. A sensical assumption is that the last word on this subject has not been written yet and we may yet find a more compelling reason why this coincidence exists and what significance it has, if any.

456 -

Accepted theory shows black-holes emit *Hawking Radiation as Electromagnetic Radiation or particles*. This happens by *tunnelling* and\or quantum mechanical *uncertainty*. Should they also lose Energy by *Gravitational Radiation*? How much? And is it significant?

Tunneling and uncertainty have *nothing* to do with it: Hawking Radiation is a result of Gravitational Vacuum Polarization. Nonetheless, the question is very valid and a good one. Never even mind black-holes. What about an ordinary *thermodynamic* blackbody? Why does it not emit radiation other than Electromagnetic Radiation? The answer is, it does: *just a lot less*.

Take the Sun (which acts as a near-perfect blackbody when it comes the Thermodynamics). It radiates, as far as we know, about 79 MW in the form of *thermal Gravitational Radiation*. Sounds like a lot … until we compare it against the nearly $4 \cdot 10^{20}$ MW that is its *total output* in the Electromagnetic Spectrum! That's a nearly 19 orders of magnitude difference!

And yes, a body that's hot enough could also emit *other forms* of radiation, e.g., neutrino-antineutrino or electron-positron pairs. But *colder* bodies (and in this respect, even the Sun counts as *cold*) would only emit minuscule amounts of such radiation, with Electromagnetic Radiation dominating their output, simply because Electromagnetic Radiation is the easiest to emit.

This is also true when it comes to black-holes, although their Gravitational Radiation output is much more significant, relatively speaking: a crude estimate is that as much as roughly $10\,\%$ of the total output of a black-hole in terms of Hawking Radiation would be in the form of thermal Gravitational Radiation.

457 -

As the Universe expands, Matter becomes more dispersed. As the overall density of Matter is decreasing, doesn't the *rate* of Time passing change? Can this account for the perceived acceleration of the expansion?

Indeed, there is a changing in *gravitational Time-dilation* due to the changing Matter density, and this actually figures in the equations when we consider the redshift of distant Matter. But it is all accounted for in the cosmological equations. The accelerated expansion that we observe (or think we observe) is on top of, and in addition to, all these effects.

458 -

One black-hole cannot lose Mass, Hawking Radiation excluded but, in the merger of two black-holes, Mass is released as *gravitational waves*. How does this happen?

No, individual black-hole *loses mass in a merger*. But the system does convert Energy from one form into another form even as Energy conservation is respected. In the initial configuration, we have two black-holes with the given masses, so far away from each other that the Gravitational Potential Energy between them is negligible and may be taken to be zero. As they approach each other, the Gravitational Potential Energy, which is a *negative* quantity, becomes larger and larger in magnitude (i.e., an ever bigger negative number). This, in turn, is offset by a gain in Kinetic Energy as the two black-holes move faster and faster. But, as they are not moving in a straight line, their trajectories bent into inward *spirals* by their mutual gravitational attraction, a lot of that Kinetic Energy is converted into *gravitational waves* and radiated away to infinity. This has the effect of slowing down the black-holes and is in fact the reason why they are spiraling towards each other instead of happily orbiting one another for all eternity.
When the black-holes finally coalesce, their horizons merging, settling down to a new configuration, the resulting black-hole is a *merger* of four things: the two black-holes with their respective rest masses, the combined Kinetic Energy of the system and the combined Gravitational Potential Energy of the system. These quantities together determine the *total* Mass-Energy of the resulting merged black-hole.
In short, nothing is taken from inside any black-hole. It is the dynamics of the *entire* system that must be considered.

459 -

Do rays of light travel infinitely? Do they dissipate over Time and Space or do they travel infinitely?

Yes, in principle, … but with some caveats.
First, real sources of light always have a finite size. Looking at the source from far enough away, its size shrinks to a point. So, that makes it obvious that any light from that source comes in the form of a spherical wave, which may be practically indistinguishable from a plane wave at a large enough distance but it still spreads out a little over large distances.
Second, suppose we nonetheless succeed with creating a perfectly collimated beam of light that never spreads out, ever. In empty, flat Space, that beam would indeed travel to infinity. But real space is not completely empty. There are the occasional (mostly H and He) atoms. There are even larger molecules here and there and specks of dust. Give it enough distance and that beam or ray of light will encounter one of them and will get absorbed or scattered.
Third, even if we removed all such particles from Space, there is still the *Cosmic Microwave Background radiation*. Now it is true that in Maxwell's Theory, light does not interact with light. But things get more nuanced in Quantum Electrodynamics, where photons can interact with other photons through the *creation of electron-positron pairs*. Such two-photons interactions are *ultra-rare*, especially at low energies, but they *can happen*. Again, if we give it enough distance, this means that the ray of light *may get scattered in the photons of the Cosmic Microwave Background radiation*.
Finally, we live in an expanding Universe. What this means is that light that is emitted at a given frequency with respect to the 'isotropic rest-frame' at a certain location (the frame of reference in which the Cosmic Microwave Background appears *the same* in all directions) will arrive at a lower frequency at another location, as measured in the local isotropic rest frame there. Again, give it a large enough distance and the photon will be redshifted into oblivion.
What this means, among other things, is that if, over time, in an expanding Universe, everything is converted into photons (*thermal radiation*), those photons are redshifted into oblivion leaving behind, as the ultimate asymptotic end state in the *infinite future*, *empty SpaceTime*.

460 -

If the acceleration is $(v - v_0)/t$, then, what is the formula for v? Distance/time, right? If the distance to *core* for Gravity is 0, isn't it $0/t = 0$? Wouldn't the acceleration be 0, in this case?

No, not exactly. Velocity is the change of distance over an interval of time. Specifically, it is the infinitesimal change of distance over an infinitesimal amount of time: $v := ds/dt$. If we are not moving, our change of distance is 0. Hence, our velocity is 0. But if we move, the change of distance is $\neq 0$.

Similarly, acceleration is the infinitesimal change of velocity over an infinitesimal interval of time: $a := dv/dt$.

As to what 'core of Gravity' means, God knows, but in any case, once we have a formula for acceleration, we can connect it with Newton's 2nd Law, $F := ma$; and indeed, if there is no force, there is no acceleration, the change in velocity is 0, but the velocity itself can still be $\neq 0$ (but unchanging). This is the characteristic of *inertial motion*.

The need to deal with such infinitesimal quantities (by making them first just small, and then shrinking them and obtaining a rigorous limit of their ratios) is what led Newton to develop Calculus. It is one of the first examples of the needs of Physics driving a significant development of Mathematics. Also, arguably, Calculus, the mathematics of *infinitesimal quantities*, is fundamental to much of what we know today as modern Science and Engineering.

461 -

Is there ever *consensus* in Science? Isn't that consensus in Science anti-scientific?

If the validity of Science was decided on the basis of 'consensus', that would indeed be unscientific. *Science is not a democracy*. The validity of a result is not decided by voting. *Nature doesn't care what the majority of experts think*.
On the other hand, … consensus reflects the results of Science, in particular, when said results are supported by *overwhelming evidence*.
By way of example, it is the scientific consensus that the Earth is round and that it orbits the Sun (well, technically, the Sun-Earth two-body system's center-of-mass, with slight perturbations from other planets). But scientists believe this to be true not because of the consensus but because they see the data and understand the sound reasoning that makes sense of that data.
To the non-scientist, consensus is a useful guide. A non-scientist (or even a scientist in a field who is outside his areas of expertise) does not have the background or the means to collect and evaluate the data and contrast it against theory. That often requires a level of specialization that requires years, maybe half a lifetime's worth of hard work. What do we do when we lack expertise in a topic? We listen to the actual experts. Sometimes, even the experts do not know. But when the data are sound and the understanding is robust, the vast majority of experts will tell us the same thing: the Earth is round and it orbits the Sun. This, then, is consensus.
As a non-expert who does not know how to derive Kepler's laws from the Einstein-Hilbert Lagrangian of General Relativity and apply it to the Earth-Sun system, who does not know how to collect and analyze astrometric data to evaluate the Earth's orbit, we may have no means to independently verify this claim. But knowing that the overwhelming majority of actual experts agree on this interpretation gives us assurance: even if what they say is not the final word on the topic, they're far more likely to be right than wrong, so our winning bet, if we will, is to go with the consensus opinion.
But once again, *consensus does not decide Science*; that would indeed by un-scientific. In fact, any scientist worthy of the name would soundly reject the suggestion that something should be accepted uncritically because of 'consensus'. That's a well-known logical fallacy called *appeal to authority*. Scientists are in fact trained to do the exact opposite: *be skeptical, question assumptions, verify deductions, scrutinize the data*.
No, consensus reflects the result of the scientific process.

462 -

Have astronomers ever seen a planet's Gravity turn a passing asteroid into a new satellite?

No, the Gravity of a single object cannot do that. When an asteroid approaches a planet, it does so in a hyperbolic orbit. That means that its Kinetic Energy exceeds its Gravitational Potential Energy with respect to the planet. After passing by the planet, it will change direction, but eventually it will depart the planet's vicinity with the same speed with which it arrived. This is Energy and (linear) Momentum Conservations at work.
It takes at least two bodies (e.g., the Earth and the Moon acting together) to capture an asteroid in orbit. In this case, the excess Kinetic Energy and Momentum of the satellite is transferred to the Earth-Moon system, reducing the asteroid's speed so that its orbit is changed from hyperbolic to elliptic, and thus it ends up being captured.
The reverse can also occur: a body already in orbit around the Earth or the Moon may interact with the two bodies and

gain Kinetic Energy and Momentum to escape the system. The same mechanism is also used in 'gravity assist' maneuvers when a spacecraft flies by, e.g., Venus or the Earth in such a way that it gains Energy and Momentum at the expense of the planet's orbital Kinetic Energy and Momentum.
But a single body, especially an approximately spherical body like a planet, just cannot capture an asteroid on its own. At least not with Gravity alone. It is possible for an asteroid to graze the Earth's atmosphere, lose some Kinetic Energy as a result but without breaking up or burning up and, thus, get captured … though chances are that such an orbit will repeatedly cause the asteroid to enter the upper atmosphere, lose more Energy and linear Momentum in the process and eventually either burn up or fall to the Earth.

463 -

Is the super-massive black-hole at the center of the Milky Way Galaxy actually a tiny runt compared to other super massive black-holes in the larger Universe?

Tiny is in the eye of the beholder, but indeed, there are much bigger black-holes out there. Take the synthesized image of the M87* black-hole that was the top science news last year, thanks to the Event Horizon Telescope (EHT) collaboration's incredible effort.
The EHT collaboration had two potential imaging targets: our own Milky Way's super-massive black-hole, Sagittarius A*, roughly 25000 light-years from here, and M87* roughly $5 \cdot 10^7$ light-years from here. M87* is about 2000 times farther away from us than Sgr A*. Yet it was M87* that they were able to image. The reason? M87* is roughly 1000 times *more massive* than Sgr A*. As a result, its 'shadow' is 1000 times *bigger*. So, it appears almost as large, seen from the Earth, as the 'shadow' of Sgr A*, despite being 2000 times farther away.
And it was easier to take a picture of M87* for the same reason: *large means slow*. Any changes in the appearance of M87* due to Matter swirling around it take scale on the timescales of weeks or months. In contrast, the appearance of Sgr A* changes over timescales measured in mere *hours*. Which means that it is just not possible to collect data for a long enough time (analogous to long exposure times used by photographers trying to take pictures of things in low light) before the thing just changed too much to be meaningfully captured.
So, while it is questionable to call a $4 \cdot 10^6$ solar-mass object a 'runt', it is certainly a small SMBH compared to some of the really big ones out there.

464 -

If light speed is only constant in a perfect Vacuum, then why is that constancy even a valid postulate in Relativity?

The postulate *is not* that 'Electromagnetic Radiation travels at a constant speed'. The postulate is: '*There exists a speed that, when measured, is the same for all inertial observers regardless of their motion*'.
Even though this postulate emerged to address the need to reconcile Maxwell's Electromagnetism with Classical Mechanics, today we know that the fact that Electromagnetic Radiation in the Vacuum travels at this speed is accidental, *not essential* to the theory. Although we call it the '(Vacuum) speed of light' for historical reasons, what it really is, it's the 'invariant speed' of Relativity Theory. It so happens that plane waves in a *massless field* like Maxwell's Electromagnetic Field, in the absence of sources, travel at this invariant speed. But actual Electrodynamics could be governed by a different theory, such as the Maxwell-Proca Theory of *massive* Electromagnetism, where Electromagnetic Radiation always travels *slower* than the invariant speed.
Today, we accept Maxwell's Theory as the right theory for Classical Electrodynamics (and as the classical foundation of Quantum Electrodynamics) because its predictions *agree with experiment*. Whether it is laboratory tests or astronomical observations, they all confirm that, within the limits of observation, the photon is *massless*. If we ever find out that the photon has, after all, a very tiny mass, we would know that Electromagnetic Radiation travels ever so slightly slower than the 'speed of light' and that its speed would be dependent on its Energy (Frequency). But, to date, no such experimental result has been obtained. As far as we can tell from the data, the photon is truly *massless*.

465 -

If galaxies have different shapes, densities, and speeds of rotation, how can we explain that each one has the right amount of Dark Matter to keep itself in balance without collapsing or taking a part?

Let's pose a different but analogous question: if, after a rainstorm, puddles come in different shapes and depths, how can we explain that each one has the right amount of water to keep itself in balance without spilling or overflowing?
Because, of course, it's not like a pre-existing quantity of water with pre-existing shape magically finds itself the right hole in the ground. Rather, water will fill the available depression in the ground.

The same thing is true when it comes to galaxies: it's not like a galaxy with a pre-existing shape, density or rotation finds somewhere just the right amount of Dark Matter to keep itself together. Rather, it is the already present amounts of normal and Dark Matter (assuming Dark Matter exists and it's not some modified Gravity Theory that's responsible for galaxy rotation curves) that will determine the shape, density, and rate of rotation of any given galaxy.
So, they will come in all shapes and sizes, just like puddles come in all shapes and sizes. And just like puddles are kept in hydrostatic equilibrium with the available quantity of water and the shape of the depression as boundary conditions, similarly galaxies remain in a dynamic equilibrium of sorts with the amount and distribution of normal and Dark Matter plus any perturbations or influences from the neighborhood acting as boundary conditions.

466 -

If the Universe's expansion rate is $68\ \mathrm{km/(s \cdot Mpc)}$, is it only a coincidence that the distance at which objects would be moving away from us at the speed of light is roughly the size of the Universe?

Indeed, a very valid question. To put it slightly differently: $68\ \mathrm{km/(s \cdot Mpc)}$ is the inverse of about $4.538 \cdot 10^{17}\ \mathrm{s}$, which is about $1.44 \cdot 10^{10}\ \mathrm{yr}$, pretty darn close to $1.38 \cdot 10^{10}\ \mathrm{yr}$. And since there is some *uncertainty* in the *Hubble parameter*, what if it is, say, $71\ \mathrm{km/(s \cdot Mpc)}$ instead? Then we'd get $1.38 \cdot 10^{10}\ \mathrm{yr}$, which is our best current estimate of the present age of the Universe.
In short, how come the *inverse* of the Hubble parameter is almost precisely the present age of the Universe? This would be no coincidence if the rate of the Universe's expansion was *constant*. This is precisely the result that we would expect in that case. But the rate of expansion of our Universe is not constant. It was decreasing for the first 8 to $9 \cdot 10^{9}\ \mathrm{yr}$, and has been increasing (accelerated expansion) in the past 4 to $5 \cdot 10^{9}\ \mathrm{yr}$. As it turns out, the two effects almost exactly cancel out, so in the present era, the age of the Universe is indeed the inverse of the Hubble parameter. This wasn't the case a couple of billion years ago and will not be the case anymore a couple of billion years hence.
Therefore, in the Standard Cosmological Model, this is simply a *coincidence* that the present is somewhat special.
Still, some skepticism may be legitimate, and serious cosmologists sometimes indeed ask the question: is it just a coincidence? Is it just random chance that the observed start of accelerating expansion happens to coincide with the birth of our solar system (an insignificant solar system out of countless trillions, but the one that we happen to live in and from which we make our observations), and that it is precisely in the present epoch when humans appeared and learned how to observe and understand the Cosmos that acceleration caught up with the earlier deceleration, such that the age and the Hubble parameter have this simple relationship?
Sometimes, coincidences just happen. At other times, they're a hint that we're missing something deep and important. Right now, everything we know suggests that this is truly just a coincidence, but given all that we don't yet know, we feel reluctant to shut that door completely yet.

467 -

Would it be possible (in principle) to encase a black-hole with a superstructure and harvest the Energy released from Hawking Radiation?

Sure. The question is, how much Energy? Let's take a typical astrophysical black-hole, 3 solar masses, say. Its Hawking Radiation produces … $10^{-29}\ \mathrm{W}$. We'd need an awful lot of these black-holes to run, say, one modest flashlight.

But let's hold on a moment, we heard that the smaller a black-hole gets, the more it radiates? True. A $2 \cdot 10^{7}$ metric ton black-hole (size of a small asteroid) would be radiating $10^{12}\ \mathrm{W}$ (1 Terawatt). Now that sounds a lot better!

Except that … for an astrophysical black-hole to decay to this point, it would take something like $6 \cdot 10^{68}\ \mathrm{yr}$, i.e., 6 followed by 68 zeroes. And that would be in empty Space. Our Space *is not* empty: even deep inside intergalactic voids, where no other Matter is present, there is still the *Cosmic Microwave Background radiation* (CMB), which, at $2.7\ \mathrm{K}$, is a lot hotter than our astrophysical black-hole at $2 \cdot 10^{-8}\ \mathrm{K}$. So, our black-hole would actually be *growing* by gaining Energy from the CMB and will continue to do so for a long time before the Universe cools down sufficiently for the black-hole to start radiating *more heat than it receives*.
Anyhow, once we are down to $2 \cdot 10^{7}$ metric tons sometime in the *unimaginably distant future* (e.g., by this epoch, our Universe would have *no visible stars*, as all usable nuclear fuel would have been exhausted a long time before), we do have a terawatt-source of … incredibly energetic γ-ray photons that will destroy any material structure nearby by smashing atoms to smithereens, as our black-hole is now subatomic in size, but has an effective temperature measured in trillions of K degrees. So, it would take some real fine engineering to make use of these photons in any practical

sense. Sure, we can do it (the LHC deals with more energetic particles) but, at this point, whether it is our civilization or advanced aliens, there are plenty of ways more practical than this to generate useful forms of Energy.

468 -

If the event horizon of a black-hole is *forever in the future of a distant observer*, do all stellar black-holes still seem to have their original star's remnant Matter in an accretion disk? Can an outside observer ever see a black-hole with no disk?

An accretion disk is a specific feature that emerges as material falls into a very compact, massive object, forming a dense cloud around that object first. Collisions and friction in that dense cloud help dissipate Kinetic Energy, which is how the material can fall towards the object in the first place (as *opposed* to just escaping to infinity in hyperbolic orbits). But Angular Momentum cannot be dissipated away, so as the cloud settles, *flattening in its plane of rotation*. This process is not unique or specific to black-holes.

So, let's forget accretion disks for a moment, just think of the simplest case: a spherically symmetric, frictionless (so no dissipation) *cloud of dust* collapsing under its own self-Gravity. This case was first investigated by Oppenheimer and Snyder in a landmark 1939 paper. The title of the paper already offers a complete answer to our question: 'On Continued Gravitational Collapse'.

So, yes, to a distant observer, the collapse goes on *forever*. Time dilation increases exponentially. Sometimes a silly analogy is used: let's imagine projecting a movie with 1000 frames, but at an ever slower rate. The time between frames increases beyond limit, so that the very last 1000th frame never actually gets shown. That 1000th frame would be the frame showing the formation of the actual event horizon.

So, whether the infalling material rotates, forms a disk, or stays spherically symmetric, is not really relevant. What is relevant is that the outside observer *never* gets to see the fully formed black-hole.

Having said that, the material we do see will still disappear in a very *finite amount of time* unless it is replenished. Why? Because of the same extreme Time Dilation. Any light emitted by that material is stretched in wavelength beyond limit. So, not only does it turn into hard-to-detect longwave radio waves, but it also becomes extremely weak, to the point of becoming invisible for all practical intents and purposes. Therefore, in terms of appearance, what we do see is indistinguishable from a fully formed black-hole: material disappears from sight in an extremely compact region of Space, in the presence of extreme gravitational effects.

469 -

How far have Hubble Space Telescope traveled? How much of the Universe have it been to? How big is the Universe?

The Hubble Space Telescope hasn't traveled anywhere. It is exactly where it has been put more than 30 yr ago by the Space Shuttle Discovery, in orbit (*) around the Earth, approximately 540 km above the Earth's surface.

The significance of the telescope is that it can make observations of the deep sky without having to peer through the Earth's thick, often hazy, and turbulent, atmosphere. An atmosphere that also blocks a lot of light in ultraviolet and infrared wavelengths not visible to the human eye but important to Astronomy.

Also, because the telescope does not have to worry about the daylit sky, it can make observations focused on a specific target, collecting light for many hours, not limited by the available number of hours while that target is over the horizon at night (of course there are still targets that would be hidden from it by the Earth part of the time).

Because of this, the telescope has been able to 'see' deeper into the sky than most other telescopes, able to see objects such as GN-z11: a galaxy so far away, its light was shifted in wavelength by a factor of 11 before it reached the sensors of Hubble. This light traveled roughly $13.4 \cdot 10^9$ yr, originating when the Universe was a mere $4 \cdot 10^8$ yr old. The galaxy that is the source of this light would be roughly at $3.2 \cdot 10^{10}$ light-years from us, today.

But Hubble can see this not because it goes anywhere, but because it has incredible optical capabilities unhindered by the Earth's atmosphere.

(*) OK, if it's in orbit, technically that means it travels; but it just keeps going around and around the Earth, with a revolution period of about 95', without actually going anywhere else.

470 -

Is most of what we know about black-holes speculation?

Not anymore! Originally, black-holes were …, well, more than speculation, at the very least informed speculation, but it's fairer to say that they were bona fide predictions of General Relativity (and before that, black-hole like things were predicted, as far back as the 18th century, based on the known properties of Gravitation and the finite speed of light).

Now granted, it took more than half a century to *fully understand the meaning* of Karl Schwarzschild's beautiful solution to *Einstein's Field Equations*, and a little more to understand what happens when the black-hole *spins* or has an *electric charge* (and to find out eventually that mass, spin and charge *fully characterize* an astrophysical black-hole; otherwise, black-holes have no distinguishing characteristics, no 'hair').
But, over the past half century, black-holes gradually but firmly moved from the domain of speculative Mathematical Physics to observational Astronomy. *First*, there were indirect detections: binary systems in which a star was behaving as though it was orbiting a companion, but the companion was not seen. Granted, it could a compact, cold object not a black-hole, but everything we knew about Physics dictated that such things are strong candidates for black-holes.
Then, came the detection of *super-massive* black-holes, like Sagittarius A* in our own Milky Way. Though the black-hole itself is not seen, the close orbits of some stars reveal its mass (about $4 \cdot 10^6$ times the mass of the Sun) and simply the fact that something that massive and that compact (and unseen) exists is a strong indication that it cannot be anything other than a black-hole.
But, in the past decade or so, we went further. The Event Horizon Telescope project was able to 'image' a black-hole. Well, not exactly; being black, a black-hole cannot be seen. But the shadow it casts when there is a light source behind it, that shadow can be observed. And this is precisely what the EHT has done, except that the 'light' in their case was in the form of radio waves, but they were indeed *obscured* by the black-hole exactly as *predicted* by General Relativity.
And *last* but not least, *gravitational wave* observations of black-hole mergers match precisely the predictions of General Relativity. Therefore, we can now speak of *gravitational wave Astronomy*, and these detections genuinely amount to observations of black-holes doing what they are supposed to do in accordance with Einstein's Field Equation.

The center of our Galaxy (Sagittarius A* in Milky Way)

471 -

The reciprocal of the Hubble (parameter (constant?) equals the age of the Universe. How can this be a coincidence?
[see also Issue 466, P. 208]

It is a bit of a coincidence, and indeed, it has puzzled cosmologists. Yes, the dimensions of the Hubble parameter are those of *inverse time*. And yes, $71\,\text{km}/(\text{s}\cdot\text{Mpc})$ translates into the inverse of $1.4 \cdot 10^{10}$ yr , which is almost precisely the current *estimated* age of the Universe.
Now, if the rate of expansion were constant (i.e., if Gravitation were *absent*) this would indeed be the predicted age of the Universe. Conversely, if we lived in a Universe that contained $100\,\%$ cold, pressureless Matter ('normal' Matter at non-relativistic temperatures, or Dark Matter), the estimated age of the Universe would be two $2/3$ of this value, or about $9.3 \cdot 10^9$ yr : way too young, considering that we know of objects that must be at least $1.3 \cdot 10^{10}$ yr old.
But the Universe we actually appear to live in contains about $73\,\%$ Dark Energy. Dark Energy became the dominant constituent in this Universe about 4 to $5 \cdot 10^9$ yr ago, and since then, its *repulsive* response to Gravitation has been *accelerating* the expansion. When we calculate the age of the Universe on this basis, we get the well-known figure of $13.8 \cdot 10^9$ yr , which is almost exactly the *inverse* of the Hubble parameter.

This happens only once in the history of the Universe. The age of the Universe was *less* than the inverse Hubble parameter billions of years ago, and it will be *more* than the inverse Hubble parameter billions of years hence. So, yes, it appears to be a coincidence that the epoch in which we live is precisely the epoch when the age of the Universe is approximately equal to the inverse Hubble parameter.
It is entirely legitimate to wonder if perhaps this is not a mere coincidence. What if we got this expansion business all wrong? What if the standard, Lambda-CDM model (also known as 'concordance' model) is not correct?
Sometimes, coincidences are just that, coincidences. At other times, not infrequently, a coincidence in Nature is a hint at something deeper. The jury is still out on this one. Certainly, something worth thinking about.

472 -

If light can orbit a black-hole at 1.5 Schwarzschild (event horizon of black-hole (as far as we know)), but every path between 1.5 and 1 *Schwarzschild radius* leads into the black-hole anyway, shouldn't 1.5 Schwarzschild radius be the event horizon of the black-hole?

As this question is phrased, it represents a *misunderstanding* of the nature of a black-hole's *photon sphere*. It is true that the photon sphere radius is the radius of circular orbits, but we should not misunderstand what it means. Photons still won't be orbiting the black-hole very long, because all such orbits are unstable. Instead, here's what the photon sphere means: a photon passing by the black-hole outside the photon sphere will be deflected, but the angle of deflection will always be less than $360°$. That is, a photon that never reaches the photon sphere will never fully go around the black-hole.
A photon that does reach, or get inside, the photon sphere, may be deflected by more than $360°$. This means that the photon may go completely around the black-hole. In fact, it may do it multiple times, before either escaping back to infinity or intersecting the horizon and getting trapped by it.
So, not every (photon) path inside the photon sphere does not lead into the event horizon. Some paths do; some paths don't.

473 -

Does people understand, or even realize, that there's a difference between Newton's ideas about Gravity vs. Einstein's ideas in General Relativity?

Is there even a significant difference? Newton's Gravitational Law was pure and simple: an *instantaneous* influence by one *massive* body over another across a great distance.
But Newton himself was rather unsatisfied with this (in fact, it was the reason why he even delayed publishing his ideas about Gravitation), as he wrote, in a letter to Richard Bentley: "That Gravity should be *innate*, *inherent* and *essential* to matter so that one body may act upon another at a *distance through a Vacuum without the mediation of anything else* by and through which their action or force may be conveyed from one to another is to me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it. *Gravity must be caused by an agent acting constantly* according to certain laws, but whether this agent be material or immaterial is a question I have left to the consideration of my readers."
Of course, back in Newton's time, the concept of a Field Theory did not yet exist, so he could not conceive of the notion of the Gravitational Field as that 'agent' that he sought. This came about a century later, in the form of *Poisson's Law of Gravitation*. But, even in Poisson's Equation, the influence was still *instantaneous*, and the Gravitational Field was what, in modern language, would be called a *scalar field*.
Then came Relativity Theory in the early 20th century, immediately prompting several physicists to investigate how Poisson's Law could be made *relativistic*. By this time, it was quite clear that the Gravitational Field must be a little like the Electromagnetic Field: it would be sourced by Mass and influences in it would travel at a *finite* speed. But what form should it take? Einstein's great insight (his 'happiest thought') was the realization that if *Gravity is universal*, it cannot be disentangled from the *geometry of acceleration*: so, the generalization of Relativity Theory that he was after (which would treat inertial and accelerating observers on the same footing) must necessarily be also a theory of Gravity. This resulted in the theory we know today as General Relativity, i.e., Einstein's Theory of Gravitation.
Now the cognoscenti would readily tell us that this means that 'Gravity is not a force', that it's all Geometry. They may even show you pretty diagrams with the Gravitational Field represented by a rubber sheet, depressed by a central weight. But this is grossly misleading. For starters, in the *SpaceTime Theory of Einstein*, Gravitation is associated primarily not with the curvature of Space but with the *rate at which clocks tick*, so that visualization is flat out wrong. Even more importantly, Einstein himself warned *against* reading too much into the *geometric interpretation* of his Theory.
And indeed, it is possible to develop General Relativity with no direct reference to Geometry at all, as it is beautifully demonstrated, e.g., in the book Feynman's *Lectures on Gravitation*. Feynman imagines some extraterrestrial scientists who know modern (Classical and Quantum) Field Theory but never heard of Gravitation until now. So, they try to

formulate a theory. One thing they do know is that Mass and Energy are the *same thing*. This alone leads them to reject Poisson's *scalar* theory: it produces the wrong result for binding Energy in an atom, violating the universality of Gravitation. A so-called *vector* theory (like Electromagnetism) is rejected because masses would *repel* each other just as like electric charges do. A *spinor* theory is rejected as well because it would not produce the observed inverse-square force of Gravitation. Therefore, the simplest theory that actually works is a so-called *tensor* (or *spin-2*) theory that '*couples universally to Matter*'. Moreover, observation would tell these alien scientists that Gravitation must act upon its own Energy-content as well (i.e., it is a so-called 'non-linear' theory) because otherwise, it yields the wrong results, e.g., for the *perihelion advance* of planets like Mercury.

So, there we have it. Einstein's Theory of Gravitation has more to do with Newton's than we might realize. It is still an *interaction between systems*, it's just that it acts on more than Mass alone: it acts on Mass-Energy, Pressure and Stresses (but in everyday scenarios, Mass *overwhelmingly dominates* the other constituents). It is mediated by a field just as Newton had hoped it would. The fact that it is not a scalar theory might have confused Poisson, but there are sound reasons for it, and again, the deviations from the scalar theory in everyday situations is *imperceptibly minor*. Lastly, the fact that it acts upon itself, i.e., that the Energy-content of the Gravitational Field can itself be a source of Gravitation, is a technical subtlety but one that might even make sense to Newton himself.

As Newton has said (though arguably, it was not as noble a statement as we might think, as some surmise that it was a jab at his rival Robert Hooke, who was short in stature), *we stand on the shoulders of giants*. Newton himself was one of those giants, on whose shoulders many stood, including Einstein. Einstein's work refined the ideas that Newton presented and filled some of the gaps that Newton was concerned about. It was a huge leap forward in 20th century Physics. But ultimately, it was not so much a deviation from Newton's conceptual foundations as a continuation of Newton's work.

474 -

Why do physicists call the Universe *flat*, and Space *non-sparkling*? We see galaxies in Space at $360°$. And in the General Theory of Relativity, Space is called *curved*. Is there a contradiction here?

'Flat' has a very specific meaning in the context of Relativity Theory. On a flat sheet, the sum of the angles of a triangle is $180°$ exactly. But if we draw a triangle on a non-flat surface, such as a sphere, the sum may be more (or less) than $180°$. The SpaceTime of General Relativity *is not flat*. However, Space itself appears to be. All our measurements suggest that the sum of the angles of a triangle, no matter how large, will always be $180°$ in Space.

Of course, we cannot draw million light-year triangles in Space, but we can infer their behavior by studying stuff that is in Space, including Matter and rays of light.

So, 'flat' doesn't mean two dimensional, like in a cartoon. Yes, there are galaxies in all sky directions and SpaceTime is *curved*. But let's pick any three galaxies anywhere in Space, draw lines between them, and the angles of the resulting triangle will sum to exactly $180°$. That's why Space (not SpaceTime, not 'the Universe', but Space) is called *flat*.

475 -

What does 'propagate' mean in QFT (Quantum Field Theory)? In QFT, a propagator describes a *free* particle.

Given a particle at an initial position, it gives us the probability amplitude of finding that particle at any given time later at various positions; or conversely, given a particle with an initial Momentum (QFT is typically done in 'Momentum Space') it gives you the probability amplitude of finding the particle with any given Momentum some time later.

When we see a Feynman diagram, every *internal line* in that diagram represents a *propagator*. The total probability amplitude for a given interaction is calculated by multiplying together the corresponding propagators and so-called '*vertex rules*' (which characterize the *vertices* in the *diagram*) and placing them under the appropriate *integral* sign. As a matter of fact, Feynman diagrams are just this: bookkeeping devices that make it easy to keep track of the terms that are needed for this computation.

When a QFT (e.g., Quantum Electrodynamics, Electroweak theory, etc.) is developed, one key step, after the theory is formulated according to its Lagrangian or Hamiltonian form, is the derivation of the corresponding vertex rules and propagators that describe *interactions* and *free particles*, respectively, and make such calculations (which can be compared against experimental data) possible.

476 -

We hear that quarks have no size. Why do we think this? Also, we recently watched *Kurtzgast scale of the Universe* (e.g., check on Wikipedia) and they had size there. What is it?

Fundamental particles have no size. We can probe them at higher and higher energies, which means smaller and smaller scales, and they reveal *no substructure*. So, they truly behave in High Energy Physics experiments as point-like: any deviation from point-like behavior would be an indication of substructure, an indication that the particle is not elementary, after all, but made of more fundamental building blocks.
That said, it is possible to define a *classical radius* for fundamental particles. This 'classical radius' has no real physical meaning and is actually misleading. Nonetheless, it is sometimes used, e.g., in science popularizations, especially when size comparisons are made between elementary particles and other structured physical systems.

477 -

If Einstein proved that Gravity is simply the 'warping' of Space, then is there really any such thing as Gravity (or gravitons)? If not, then there are only *three* forces in Nature, right?

Einstein proved *no* such thing.
First, proof is something mathematicians do. Physicists use Mathematics to construct theories, which are then *either validated or refuted by experiment*.
Einstein did exactly that, when he used the Mathematics of Riemannian Geometry to construct a theory that accounts for *accelerating observers* and, incidentally, also for the effects of Gravitation. His 'happiest thought' leading to this theory was the realization that because *Gravity is universal*, the observable effects of Gravitation can disappear for an accelerating observer in his close neighborhood (if we are falling freely and objects near us are also falling freely, they'd appear to float or move in a straight line at constant speed in our *falling* reference frame).
However, Einstein himself cautioned against reading too much into this geometric interpretation. His writing, including his letters, reveal that he always thought of *Gravity as a force*. Moreover, as we now know in light of our modern theories, other forces can also be presented using the language of Geometry (so-called *covariant derivatives*): what makes Gravity special is that the Geometry is *independent* of the material properties of the test particle that we use to measure the field (in contrast, the observed Geometry of the Electromagnetic Field depends on the *Charge-to-Mass ratio* of the particle used to probe the field).
Lastly, even if we act against Einstein's advice and take the geometric interpretation seriously (which appears quite fashionable these days), Newtonian Gravitation has nothing to do with the warping of Space; it is due to the *warping of Time*, so to speak, the *rate at which clocks tick*. This is why popular pictorial representations of General Relativity (the bent rubber sheet with the heavy 'gravitating' object at the center) are so grossly misleading.

478 -

If a black-hole and a white-hole ever collided, what would happen?

Nothing. Such a solution *does not exist* in the context of General Relativity. A white hole is a *Time-reversed black-hole*. Just as a black-hole is characterized by a *future* event horizon and beyond that, a *singularity*, its Time reversed version is characterized by a *Past event horizon and a singularity preceding that*.
In other words, a white-hole doesn't really exist anymore. To any observer in the Present, the event horizon is in the infinite Past. The black-hole event horizon, in turn, is in the infinite Future.
A collision between the two is not possible for the same reason *falling into a white-hole is not possible*: It would require *traveling backwards in Time*. In other words, a white-hole's existence is predicated on a future that guarantees that nothing, ever, can fall into it.
Does anybody say that it doesn't make sense? That it violates causality? That it's like going backwards in Time? Lastly, a white-hole is a Time-reversed black-hole. Of course, *it violates causality*. That's what Time-reversed really means: the Future influencing the Past.

479 -

If photons cannot interact with themselves, why is there an interference pattern in the double slit experiment?

If light consisted of miniature cannonballs, we would see *no interference pattern*. But that's not how things work. Photons are indeed the quanta of the Electromagnetic Field, but *they're not miniature cannonballs*. They are *units of Energy that may or may not be localized* (confined to a small, compact *volume*).
When an electromagnetic wave (*not a photon*!) goes through the pair of slits, the wave pattern changes. This wave

pattern determines the probability that we will be detecting photons at various places. The waves (*not the photons*!) interfere with each other constructively and destructively, increasing and decreasing the probability of photons arriving at various locations on the fluorescent screen.
Let's remember, we can perform the double slit experiment with such a weak source that there's only ever at most one photon, one unit of Energy *en route* at any given time. Say, $1\ \text{photon}/\text{s}$, along a path that takes less than $1\ \mu\text{s}$ to cover. So, even if photons did interact with each other, they'd have no opportunity to do so. And each impact is recorded. After some time, the interference pattern will still emerge: there will be many more individual photon impacts on the screen at locations characterized by *constructive interference*, and fewer impacts elsewhere.
The double-slit experiment is a very powerful reminder *not to use classical concepts when thinking about the quantum world*. We may call elementary quanta 'particles' but they're anything but that: their behavior is very distinct from what our intuition tells us as to how particles should behave.

480 -

Are believers allowed to be scientists and, if so, how do they resolve when Science contradicts the Word of God?

Many believer-scientists were listed in other answers [just remember, e.g., Nicola Cabibbo (1935-2010)]. It should be also mentioned the current Pope, Francis, who, although not a scientist (there were some erroneous reports about him having a Master's degree in Chemistry), has nonetheless obtained a diploma in his youth as a chemical technician, so he is certainly no stranger to Science.
But as to the second part of the question, the best answer may come from a Christian scholar, one of the early saints of Christianity, St. Augustine of Hippo, who wrote the following in a treatise about the literal interpretations of Genesis written roughly 1600 (!) years ago:

"*Usually, even a non-Christian knows something about* [*Science*] *and this knowledge he holds to as being certain from reason and experience. Now, it is a disgraceful and dangerous thing for an infidel to hear a Christian, presumably giving the meaning of Holy Scripture, talking non-sense on these topics* […]. *The shame is not so much that an ignorant individual is derided, but that people outside the household of the faith think our sacred writers held such opinions, and* […] *the writers of our Scripture are criticized and rejected as unlearned men*."

What can we say? Heed the words of this saint instead of listening to zealots preaching biblical literalism. Value the cultural foundations of Christianity that made it possible for thinkers like Augustine to emerge, eventually leading to the Enlightenment, industrialization, and our modern age (and yes, many missteps along the way, too, all too often invoking the name of God by way of justification).
What Augustine tells us, presumably, is that *Science does not contradict the word of God*; it only contradicts stupid (or worse yet, evil) people who try to use misleading interpretations of the word of God to promote themselves, to keep us in the dark, to prevent us from learning about Nature, from thinking critically and, ultimately, from questioning their authority over what we are allowed to think or do in life. But non-believer themselves, ought to be asked a simple question: isn't this precisely what the fruit from the *Tree of Knowledge* was supposed to be about? That we follow not a predetermined course set by God like some algorithmic automaton, certainly not orders given to us by other men who claim divine authority, but *our own conscience*, having learned to tell good from evil?

481 -

Why is the Big Bang a theory if it is not testable?

The 'Big Bang' *is not* a theory, but it is, in fact, quite testable. The discipline is known as *Physical Cosmology*. The underlying theories include General Relativity, the Standard Model of Particle Physics that is an application of Quantum Field Theory, Thermodynamics and Statistical Physics.
The idea is simple enough: we observe the Cosmos as it is, and then we apply our knowledge of Physics to extrapolate back to the past to figure out what the Cosmos must have looked like back whenever. The analysis results in testable predictions (i.e., if the Cosmos looked a certain way in the past, it has certain observable consequences in the present) which can be verified or refuted through astronomical observations.
Observed facts that include the redshift of distant objects, and the fact that very distant galaxies are immature, not yet fully developed, and have a severe deficit of heavy elements are interpreted as evidence of an *expanding Cosmos with a finite past age*. This is precisely what General Relativity would predict (or, alternatively a collapsing Cosmos with a *finite future*). This is the Big Bang scenario, or *paradigm*, whatever. It is a name that was used disparagingly by the astronomer Sir Fred Hoyle in a 1949 BBC radio show; Hoyle was a proponent of an alternative concept, the so-called *Steady-State Cosmology*, which involved a Cosmos that expands *at a uniform rate* but in which Matter is spontaneously replenished by some processes, to the fundamental properties of the Universe, which is eternal.
The Big Bang scenario, however, had a trump card. It made a very important testable prediction: if the Universe was

hot and dense in the past, that means leftover relic thermal radiation that can be detected as radio waves. This is precisely the prediction that was confirmed by Penzias and Wilson in the mid-1960s (earning them a Nobel prize) and it pretty much settled the debate in favor of the Big Bang concept.

Since then, much more detailed predictions of the standard Cosmology have been subject to rigorous testing. These include detailed features of the *Cosmic Microwave Background*, predictions about the formation of large-scale structures (galaxies, galaxy clusters), the ratios of *primordial isotopes* and more. So far, though there are minor glitches (which may mean nothing or may lead to refinements of the Standard Cosmological Model) by and large every prediction of the model came true, sometimes with uncanny accuracy.

Unfortunately, popular accounts often describe the standard Cosmology with words not unlike the Barenaked Ladies song: "It all started with a Big Bang." Even professional cosmologists sometimes do this, oversimplifying things when talking to the general public. But that's not what Physical Cosmology is about. In fact, it is completely backwards. We do not postulate a Big Bang as the beginning of everything and work forward from there. We use observations of the present, and our knowledge of basic Physics to work backwards to figure out what the early Universe must have been like. Which is why, in the professional literature, you almost never see the phrase, 'Big Bang theory'. The hot-and-dense early Universe is a *consequence*, not a postulate, not a theory.

482 -

If *acceleration* due to Gravity is directly proportional to Mass, then, why does a heavier object not fall faster than a lighter one?

Acceleration due to Gravity *is not* proportional to the mass m of the particle being accelerated. *It is proportional to the mass* M *of the body that is the source of Gravitation.*

Here is the way it works: the force due to Gravity is proportional to mass: $F = GMm/r^2$. But the *ability to resist a force*, Inertia, is also proportional to mass: $F = ma$. Combine the two equations to get $\cancel{m}a = GM\cancel{m}/r^2$. The mass m of the test particle appears on both sides of this equation, so, it cancels out and we are left with $a = GM/r^2$. Acceleration is due to the mass M of the source, but independent of the mass m of the body being accelerated. So, lighter and heavier objects, objects with bigger or smaller values of m, *fall at the same rate*.

And, yes, in case we're wondering if its symmetrical: if we were to calculate the influence of m on M, we would draw the same conclusion with the roles of M and m reversed.

483 -

Can a particle have *vector* Mass?

No, it can't. Rest mass is a *scalar* quantity, the invariant *norm* of a particle's 4-Momentum: $m = (g_{\mu\nu}p^\mu p^\nu)^{1/2}$, or (in Minkowski-Space), $m = c^{-2}(E^3 - (pc)^2)^{1/2}$. The concept is defined as a *scalar*, *not as a vector*.

The closest thing to 'vector mass' would be the 4-Momentum. The components of this 4-vector of course depend on the reference frame in which it is observed.

484 -

What is meant by 'Hubble friction' and 'slow roll inflation'? And does 'Hubble tension' have anything to do with that?

The problem with *inflationary* theory is how to come up with a field theory that briefly causes the Universe to expand across many orders of magnitude in littler more than an instant, but which then comes to a halt, resulting in the slowly expanding Universe in which we live today. The simplest inflationary model is 'slow roll', meaning that the Universe 'slowly rolls' down a potential hill (that is, its state changes slowly) while it is expanding rapidly, resulting in near constant rate of rapid expansion before the phase transition.

'Hubble friction' is a technical term that has nothing to do with friction, other than the fact that the equations controlling inflation are formally like the equations of a particle moving in a potential field and subject to friction.

None of this stuff has anything to do with 'Hubble tension', which is a non-technical term describing the apparent *disagreement* between different measurements (those based on *global cosmological parameters* vs. those based on *astronomical observations* of our more immediate neighborhood) of the Hubble parameter.

485 -

How is the Universe expanding faster now than it was in the beginning?

No, not at the beginning. The rate of expansion in the extreme early Universe was very high. In fact, ignoring possible quantum effects, no matter how high a rate of expansion we postulate, we can always find a moment in the early history of the Universe when the expansion rate was higher than that. The expansion rate decreased for the first 8 to $9 \cdot 10^9$ yr in the Universe's history, as Gravity slowed down expanding Matter.
However, in addition to Matter, the Universe also seems to contain something dubbed 'Dark Energy'. We know next to nothing about this stuff, other than the fact that its *pressure* is huge and *negative*. Because of its negative pressure, it *responds to self-Gravity* in a manner opposite to that of normal Matter: instead of making it contract and clump, *self-Gravity causes Dark Energy to expand*. Moreover, the work done by Gravity on Dark Energy produces more Dark Energy; its density, therefore, remains *constant* even as the density of everything else decreases in the expanding Universe. As a result, there is a point in Time in an expanding Universe when the density of Dark Energy becomes the dominant constituent. From this point onward, Gravity, instead of slowing down the expansion, begins to speed it up.
So, it is true that the Universe expands faster today than it did in the last 6 to $8 \cdot 10^9$ yr, give or take. The reason for that is the presence of Dark Energy, its negative equation of state (negative pressure), and its behavior under Gravity.

486 -

Many people have thought for years that, for the Universe to be infinite, it must be *expanding*. If it is not expanding, it is, by definition, *finite*. What is a sensical theory\opinion on this?

As a counterexample to the premise of this question, it could be mentioned Minkowski SpaceTime. It is *devoid of Matter*, *static*, and *infinite both in Time and Space*. So, there really is *no a priori* mathematical reason for there to be such a strong link between *expansion* and *extent*.
Many other counterexamples can be constructed (as another obvious counterexample, an infinitely old, spatially infinite Universe that contains Matter, and which is contracting to a singularity at a *finite* time in the future, i.e., a Time-reversed version of the Universe in which we seem to live).
Having said that, it is true that in the standard Cosmology, a Universe with a density greater than the critical density, i.e., a Universe in which the expansion comes to a halt and is followed by collapse, would indeed be *spatially finite* with *positive spatial curvature*.

487 -

How did the physicist come up with the standard model Lagrangian? What can it be used for?

With few exceptions, any modern field theory (classical or quantum) is presented in the form of a *Lagrangian functional*. The advantages of the Lagrangian method are numerous. For instance, symmetries of the Lagrangian (e.g., *invariance under translations*, *rotations*, *displacements in Time*) directly lead to *conservation laws* (this is the essence of the famous *Emmy Noether's Theorem*). Other (so-called *local*) symmetries in the theory lead to the forces that are present in the theory. The so-called *equations of motion*, which define how fields evolve over Time or how particles move, can be derived from the Lagrangian in an almost algorithmic fashion, through the so-called Euler-Lagrange equations.
Most importantly, a mathematical transformation of the Lagrangian, the so-called *Legendre transformation*, yields another, equivalent form, the so-called *Hamiltonian*. The Hamiltonian is fundamental to *canonical quantization*, which is how a quantum version of a theory is formulated. Canonical quantization leads directly to the so-called *propagators* and vertex rules of the theory, which fill those pretty *Feynman diagrams* with precise meaning, yielding *testable predictions*.
The Standard Model of Particle Physics is presented in the form of a monstrous Lagrangian. The form of this Lagrangian is dictated by the observed particle content of the Universe. The task is to find a Lagrangian that correctly reflects what we know about all the known particles and their interactions.
Not all Lagrangians lead to sensible theories. Many theories are '*non-renormalizable*', which means that the quantum version of the theory yields *non-sensical infinities* (this is the issue that plagues the attempts to quantize Gravitation). This would also be the case with the Standard Model if we just naïvely plugged in the known particles and their known rest-masses into a Lagrangian. So, decades of research went into a simple question: can we construct a Lagrangian that leads to a *renormalizable theory*, but which also accurately reflects the Universe as we see it? The answer came in the form of the fabled *Higgs Mechanism* and its *spontaneous symmetry breaking*, which allows us to construct a Standard Model Lagrangian with *massless* particles, but which incorporates the mechanism that eventually endows these particles with *masses without breaking renormalizability*.
The amazing thing about the Standard Model is that *it works*. For it to work, it needed particles that were not known to

exist previously, including the Z^0- *boson* and the *Higgs-boson*. Both particles were found, *just as predicted by the theory*, in particle accelerator experiments. This is a huge validation that the Standard Model, even if it is not the final word on the subject, is definitely on the right track.
Lastly, it ought to be mentioned, by way of clarification, that it has been pretty much used 'particle' and 'field' in this answer interchangeably. The reason for this is simple: in a quantum field theory, *a 'particle' is just an excitation of a field*. So, when something emits light, for instance, creating photons, what actually happens is that Energy is transferred to the (one-and-only) Electromagnetic Field, creating *quantized excitations* (photons) of this field. This is how we end up with the *confusing* concept of a *quantum field theory becoming the Standard Model of Particle Physics*.

488 -

Could Dark Matter originate from normal stars in *unknown nuclear processes* before being released?

No, it could not. We know this with *near certainty*. How do we know it? Quite apart from the need for Dark Matter (deduced from the rate of cosmic expansion, details of the Cosmic Microwave Background, the large-scale distribution of Matter in the Universe and other observables) we can also establish just how much 'normal' Matter can possibly exists. Whether a 'nuclear process' is known or unknown, in a sense it's just like Chemistry. Unknown Chemistry may create new molecules, but they're still made up from the same old atoms of the Periodic Table. Similarly, an 'unknown nuclear process' may create new composite particles, but they're still made from the same building blocks of the Standard Model of Particle Physics. In other words, they'd be made primarily of *baryons* (protons and neutrons), which are the only *stable*, *massive* building blocks that exist.
And we have an upper limit on the amount of Baryonic Matter that can be present in the Universe. The amount of Dark Matter needed to balance the books is roughly 6 to 7 times this limit.
There is also another reason. If Dark Matter were produced in quantity through an 'unknown nuclear process', that means it would be interacting with other, known forms of Matter through the same processes. But that means it's not 'Dark'! Because that's what being 'Dark' really means: *it is 'Dark' because it does not interact with other, known forms of Matter, so, it does not offer a detectable signal*.
Dark Matter, *if exists*, necessarily needs to be *something other than Baryonic Matter*, something that is not produced from, or interacts with, Baryonic Matter, or at best interacts with Baryonic Matter very, very weakly.

489 -

Is it possible to reduce or modify Einstein's Field Equations so they exactly mirror Newtonian Gravity behavior?

Indeed, it is possible to recover Newtonian Gravity in the *non-relativistic limit*. It is demonstrated in most introductory textbooks on General Relativity. The (presumably) simplest derivation available just starts with the *geodesic equation*:

$$\frac{d^2 x^\alpha}{d\tau^2} + \Gamma^\alpha_{\mu\nu}\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau} = 0\,,$$

where x^α $(\equiv \boldsymbol{x} \equiv (x^0\ \ x^1\ \ x^2\ \ x^3))$ is the 4-vector describing a test particle and τ is *proper Time*. When the motion is *slow*, we can *neglect* $dx^i/d\tau$ $(i = 1, 2, 3)$ compared to $dt/d\tau$ $(t \equiv x^0)$. Thus,

$$\frac{d^2 x^\alpha}{d\tau^2} + \Gamma^\alpha_{00}\left(\frac{dt}{d\tau}\right)^2 = 0\,.$$

In a *stationary* Gravitational Field, all time-derivatives vanish, thus, $\Gamma^\mu_{00} = -(1/2)g^{\mu\nu}(\partial g_{00}/\partial x^\nu)$.
Writing the metric in the form $g_{\mu\nu} := \eta_{\mu\nu} + h_{\mu\nu}$, we have, approximately, $\Gamma^\mu_{00} \approx -(1/2)\eta^{\mu\nu}(\partial h_{00}/\partial x^\nu)$.
The Time term in this approximate expression amounts to $dt/d\tau$ being *constant in Time*, which is as it should be, given the *static metric*. Let $h_{\mu\nu} = diag(2\phi\ \ 2\phi\ \ 2\phi\ \ 2\phi)$. Then, the rest of the geodesic equation reads

$$\frac{d^2 \boldsymbol{x}}{dt^2} = -\nabla\phi\,,$$

a 3-vector which is just the Newtonian Gravitational Acceleration Law in a Potential Field given by ϕ.

490 -

In comparing Newton's with Einstein's conceptualization of Gravity, don't we ignore how Lorentz's showing that Mass is a function of (*relative* vs. *Time-invariant*) speed led to Einstein's conversion of $E = mv^2$ into $E = mc^2$?

Lorentz showed no such thing about Mass. Einstein did not convert the (incorrect, physically meaningless) equation $E = mv^2$ (the correct non-relativistic Kinetic Energy is given by $E \mapsto K \equiv (1/2)mv^2$, but it's not relevant here) into the Mass-Energy equivalence formula $E = mc^2$. The source of that formula *is not* Kinetic Energy but a *thought experiment* concerning *radiation* and the resulting *change in the Inertia of the emitting body*. To the extent that it is related to Kinetic Energy, it is through the *dispersion relation* $(mc^2)^2 = E^2 - (pc)^2$, which it represents a special case of when $p = 0$. In the non-relativistic limit, the *approximation*

$$E = ((mc^2)^2 + (pc)^2)^{1/2} \equiv mc^2\left(1 + \frac{p^2}{m^2c^2}\right)^{1/2} \approx mc^2 + \frac{1}{2}\frac{p^2}{m} + o(p^2/m)$$

holds. So, using the (also *non-relativistic*!) expression $p := mv$ and *dropping the Mass-Energy term*, we are left with the Newtonian Kinetic Energy.

491 -

What imparts Mass to the Higgs particle?

Unlike the *charged fermions* and *massive vector bosons* in the Standard Model, which acquire their masses as a result of *Electroweak Symmetry Breaking*, the Higgs is 'born' with a *non-zero rest-mass*, so to speak. In other words, in the mathematical expression that describes the charged fermions and vector bosons, there is no *mass-term*. However, they interact (in different ways) with the Higgs Field. Symmetry breaking results in the Vacuum in which all particles live today, and in this Vacuum, the so-called *expectation value* of the Higgs Field is non-zero. Particles that interact with the Higgs Field, to begin with, now seemingly interact with the Vacuum itself: mathematically, that interaction behaves just like a mass-term.
So, it is really a 'can have your cake, and eat it, too' mechanism: particles are born without masses which makes the theory's infinities *tamable* (*renormalizable theory*) but then get masses anyway thanks to the Higgs Mechanism.
However, key to that Higgs Mechanism is a so-called Self-interaction Potential, the well-known '*Mexican hat*' (referring to the shape of the curve that characterizes this Self-interaction Potential Energy [see images in Issue 60, P. 26]). After Symmetry breaking, this same Self-interaction Potential remains but in a different form: of its two parameters, one goes on and becomes a term that contributes to the final values of charged fermion and vector boson masses, whereas the other remains and serves as the Higgs Mass.

492 -

Could the CMB (Cosmic Microwave Background) Radiation and the Dark Energy Radiation actually be the same thing?

Absolutely not. For starters, there is no 'Dark Energy Radiation'. Rather, we are stuck with a rather bad misnomer that leads to all the wrong conclusions among non-physicists, unfortunately. 'Dark' doesn't really mean dark like a black suit. It really means *invisible*, as in not interacting with light at all. A black suit *absorbs* light. Dark Matter and Dark Energy are, instead, completely *transparent*: *they neither absorb nor emit* (nor otherwise interact with) light.
In contrast, the CMB is actually *light*. It's just that as a combination of cosmological Doppler and gravitational redshifts. This radiation, which begins its existence as the glow of *hot*, *incandescent gas*, gets reduced in frequency by a factor of about 1100, so, *light turns into radio waves in the microwave part of the spectrum*.
Light has *pressure* (imagine a box lined on the inside with perfect mirrors. Let some light in. As that light bounces back and forth between the mirrors, it pushes the walls outside: it's *pressure*). It also has Energy. The ratio of its Pressure to its Energy density is $1/3$. This characterizes *radiation* in the language of cosmologists.
In contrast, Dark Matter is stuff with no Pressure and Dark Energy is stuff with *huge negative* Pressure, with a ratio of -1 between Pressure and Energy density (for normal Matter *at non-relativistic temperatures*, this ratio is almost 0; when expressed using the appropriate units, the Pressure of ordinary forms of Matter is much, much less compared to its Energy density).
So, there we have it. Dark Energy is very much not light, rather, it is completely *transparent* to, and *not interacting* with, light; and it has a very different equation of state than light, including the redshifted 'light' of the CMB.

493 -

Why is Hubble's constant *equal in all directions*? Are we relatively central to where the Big Bang occurred?

No, our position is not 'central'. *There is no central position in a homogeneous Universe*; the expansion looks the same everywhere. However, our velocity is 'central'. In other words, we are moving together with the bulk of Matter. So, relative to us, there is no preferred direction: all we see is that everything is getting farther and farther away from us over time.
Actually, this is just (a little) lie. Our solar system is not completely at rest with respect to the bulk of Matter in our cosmic neighborhood. The Sun moves around the Milky Way, the Milky Way has its own peculiar motion in the Local Group of galaxies … bottom line, we are, in fact, moving at a speed of a few hundred km/s relative to the bulk of Matter. So, if we were to just measure a 'raw' value of the Hubble parameter using relatively nearby galaxies or clusters of galaxies, it would indeed be direction dependent. But we don't do that. We compensate for this by removing this 'velocity-dependent dipole anisotropy' from the observations. We know how fast we are moving relative to the bulk of Matter, e.g., because it also skews our observations of the Cosmic Microwave Background.
In any case, it is important to keep in mind that when everything moves away from everything else, every location is 'central': from our vantage point, no matter we are, so long as we 'move with the flow', everything else will appear to be receding from us.

494 -

Why doesn't Dark Energy in cosmic voids become weaker by being diluted as the voids become larger?

The very nature of Dark Energy is that it doesn't get diluted. The math itself is simple: Dark Energy is characterized by *negative pressure*. Its pressure is exactly the *negative of its Energy Density*: $p = -\rho_E$, or as it is conventionally written, its *equation of state* is

$$w = p/\rho_E = -1\,.$$

For any stuff in an *expanding* Universe, its *Density* will change according to the proportionality term

$$\rho_E \propto a^{-3(1+w)}\,,$$

where a is the so-called *scale factor of the Universe*. For Matter with *negligible* pressure, the so-called 'dust', $w \approx 0$ and the density goes as the *inverse cube of scale*, i.e., as the *inverse of volume*, just as we would expect. But when $w = -1$, Energy Density remains unchanged even as a changes because the exponent approaches zero.
That's the math. But what is the intuition here?
When Gravity acts on stuff, it does work: Gravitational Potential Energy is converted into some other form of Energy, such as heat or pressure. That's what happens with normal stuff anyway: e.g., a star contracts under its self-Gravity, and as a result, *its interior heats up*.
But when the stuff has *negative* pressure, the opposite happens. Gravity does work not by making the stuff contract but by making it *expand*. But Gravity still does work: Gravitational Potential Energy is still converted into something else. What is this 'something else'? We guessed it: *more Dark Energy*. So, it makes up the *deficit*. And that's why the Density of Dark Energy does not decrease in the expanding Universe.

495 -

Is 'Particle Number' a *conserved* quantity?

No, 'Particle Number' *is not* a conserved quantity. It changes all the time, everywhere, even in mundane everyday contexts. For instance, when we turn on a flashlight, we create trillions of photons. These photons exist until and unless they are *absorbed* by some material, which *annihilates* them.
In fact, much of modern Quantum Field Theory is centered around what are called *creation* and *annihilation* operators, mathematical operators that model how particles are *created* or *destroyed*.
Certain quantities are conserved. For instance, electrons and positrons are created in pairs, conserving what is the so called '*lepton number*' ($+1$ for the electron, -1 for its anti-particle, the positron) and also *electric charge*, but not *Particle Number*.
As to whether these conserved quantities are conserved *globally* (the entirety of a possibly *infinite* Universe), we do not know. What we do know is that the quantities are conserved *locally*, i.e., in small, *finite* volumes.

496 -

Is there any way to block the pull of Gravity or cause a condition that can keep Gravity from touching Mass?

Unfortunately (as far as we know) the answer is *no*. The reason is that Gravity is *universal*. What this means is that Gravity couples to all forms of Matter and Energy in exactly the same way. This is quite unlike Electromagnetism, where there are charged and uncharged bodies, bodies that are magnetic and those that aren't, conductors and insulators, and so on, all of which respond differently to Electric or Magnetic Fields $\ldots$. For Gravity, the only thing that matters is Mass-Energy. All other material properties are *irrelevant*. A kilogram of anything responds to Gravity like a kilogram of anything else.
Since all material particles are affected by Gravity the same way, it is also possible to perform a geometric transformation that, in effect, makes the effects of Gravity go away. The price of this mathematical 'trick' is that SpaceTime itself will be *distorted* as a result of that geometric transformation, and straight lines are replaced by curved *geodesics*. This is the essence of Einstein's General Theory of Relativity. If we accept that theory as a valid description of Nature, Gravity is not a 'force' that can be blocked or shielded; there is no 'pull'. What there is, instead, is *distorted Geometry*, and that is not something that we can block or shield against.
While it has not yet been confirmed experimentally (as far as we know), we have every reason to believe that anti-Matter *gravitates*, and responds to Gravity, the same way as normal Matter. The reason is that the Mass-Energy of anti-Matter particles remains *positive* and, in Einstein's Theory, which has worked spectacularly well so far, the source of Gravity is Mass-Energy.

497 -

Why is Gravity so difficult to include in the Standard Model?

The simplest reason is that, unlike all the other interactions in the Standard Model, *Gravity is non-renormalizable*. Here is what that means. Let's take some theory that describes an interaction. The strength of that interaction is characterized by its *coupling constant*, let's call it α . If α is a plain (dimensionless) number (no units attached), the strength of the interaction may be expressed in some form of a power series $1+\alpha+\alpha^2+\ldots$, with successive terms becoming smaller and smaller if $\alpha \in (0,1)$. Such dimensionless coupling constants characterize Electromagnetism as well as the Weak and Strong Nuclear interactions.
But the coupling constant of Gravity is not dimensionless. Let's remember the Newtonian Potential Energy, $U = Gm_1m_2/r$ between two masses m_1 and m_2. A particle physicist would tell us that the r in the denominator has the same dimensions (in units particle physicists use) as Energy, and Mass of course is Energy, so, this formula, basically, says something like Energy equals G times (Energy)^3. Which can only happen if G (Newton's constant of Gravity, which measures the *strength of gravitational coupling*) has the dimensions of [Energy]$^{-2}$ or [Mass]$^{-2}$, again, Mass and Energy being equivalent).
So, now when we examine an interaction involving gravity in the manner particle physicists do, the power series expansion might look like $1+GE^2+(GE^2)^2+\ldots$, where E is the *interaction Energy* and its square must be included in order to make each successive term dimensionless. But this means that when the interaction Energy is large enough such that $GE^2>1$, this expression 'blows up' rather quickly, as successive higher powers of GE^2 become bigger and bigger, producing an infinite (divergent) sum.
This is a (very simplified) form of explanation why particle physicists call Gravity notoriously *unrenormalizable*, and why all the standard approaches (which were used to 'tame' all the other interactions and all the Matter fields that constitute the Universe) fail when Gravity is concerned.

498 -

Why didn't Kepler realize that his equation, $F = GMm/d^2$, is not always correct? Did he ever test it for Earth and the Moon?

Maybe, for starters, $F = GMm/d^2$ *is not* an equation offered or contemplated by Kepler (note that the force formula contains the product of both masses involved in the interaction). No, the *inverse-square Law of Gravitation* is called *Newton's Law of Gravitation* (with a minor controversy and some priority claims on behalf of Hooke and others). This formulation came decades after Kepler's death.
Perhaps, the other reason is that $F = GMm/r_{mM}^2$, or better yet, in vector form, $\boldsymbol{F} = -GMm\boldsymbol{r}_{mM}/\|\boldsymbol{r}_{mM}\|^3$, is actually always *correct*, except for very tiny *general-relativistic corrections* ($\boldsymbol{r}_{mM} := \boldsymbol{r}_m - \boldsymbol{r}_M$ points from M to m; M is the

gravitating (source-)body of density $\rho(\boldsymbol{r})$, as measured at *any field-point*). This form, or more conveniently, the field potential $\phi = -GM/r_{mM}$, where $r_{mM} \coloneqq \|\boldsymbol{r}_{mM}\| \equiv \|\boldsymbol{r}_m - \boldsymbol{r}_M\|$, is the so-called *Green's Function solution* to the most general formulation of *non-relativistic* Gravitation, i.e., *Poisson's equation* for Gravity:

$$\nabla^2\phi = 4\pi G\rho(\boldsymbol{r}).$$

In other words, any extended body can be treated as a (*potentially infinite*) continue collection of *point-sources*, each contributing to the Gravitational Field according to Newton's Law of Gravitation.
The first, and for many decades, only indication that Newton's Law of Gravitation is not the full story, came in the form of the anomalous *perihelion advance* of Mercury, discovered centuries after Newton and Kepler, in the mid-1800s. Relativistic corrections in the Earth-Moon system are only detectable using modern observational technologies.

499

If, after the Big Bang, everything was projected randomly, how is it possible to have some heaps of the same type of atoms? Isn't the probability too tiny for that?

We are a long way away from the Big Bang. If we had access to Doctor Who's Time-machine, the TARDIS, and we could travel back in Time to the very early Universe, we would notice that

a. there really are only *very few types of atoms present*: H, D, He, a little Li, and trace amounts of a few more; and

b. they are very *evenly distributed*.

But that was a long, long, long time ago. Since then, Matter in this Universe became *lumpy* under its self-Gravity. The lumps turned into clusters of galaxies, galaxies, and stars therein. The stars, as nuclear factories, ended up producing a *great many more elements*; even more heavy elements were produced in supernova explosions and neutron star mergers. These cataclysmic events spewed out a lot of the freshly produced elements, which then became part of other, freshly forming lumps of 2nd, 3rd generation solar systems in which there was already an abundance of nuclides like carbon $({}_6C^{12})$, nitrogen $({}_7N^{14})$, oxygen $({}_8O^{16})$, calcium $({}_{20}Ca^{40})$ or iron $({}_{26}Fe^{56})$, just to name a few. Further processes in the formation of planets often caused specific elements or chemical compounds to *precipitate* preferentially in certain ways, resulting in deposits where a particular element or compound was dominant. This is what we see today.
But as we already noticed, there is a long, convoluted path from the Big Bang until this present situation. And the process was by no means random; rather, it was governed by (mostly) well-understood Laws of Physics and Physical Chemistry. So, considering our actual knowledge, the probability of this outcome *was not tiny at all*; it was, as a matter of fact, pretty much $100\,\%$ because this is the outcome that follows from well-established Laws of Nature.

500 -

Does a *single* wavelength of a radio-wave carry more or less Energy than a *single* wavelength of γ- radiation?

A *single* wavelength (sine wave) radio-transmission with $1\,\text{W}$ of Power carries exactly the *same* Energy as a *single* wavelength γ- ray source (not that such exist, but that's beside the point) with $1\,\text{W}$ of Power: $1\,\text{J}/1\,\text{s}$.
The difference in wavelength, however, means vastly different photon energies. Hence, $1\,\text{J}$ of γ- rays consists of far *fewer* (and far *more energetic*) photons than that $1\,\text{J}$ of radio-waves.

How much fewer and how much more energetic? Let's take something simple: a $3\,\text{GHz}\,(\equiv 3\cdot 10^9\,\text{Hz})$ radio-wave (similar in wavelength to that used in Wi-Fi, for instance) vs. a $300\,\text{EHz}\,(\equiv 3\cdot 10^{20}\,\text{Hz})$ γ- ray. The corresponding wavelengths are $10\,\text{cm}$ and $1\,\text{pm}\,(\equiv 10^{-12}\,\text{m})$, respectively.

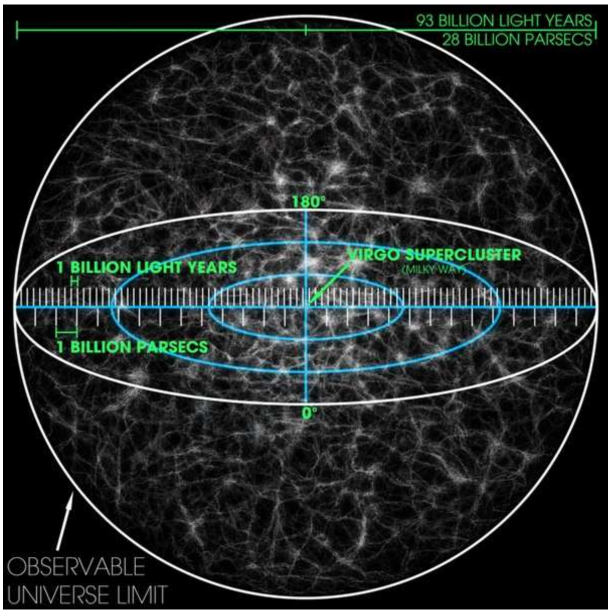
Individual photons in these γ- rays would be 10^{11} times *more energetic* than the individual photons in that radio-transmission. But there would also be 10^{11} times *fewer photons* in that γ- ray, which is why the total Power remains $1\,\text{J/s}$ in both cases.

For comparison, visible light frequencies begin not too far above $300\,\text{THz}\,(\equiv 3\cdot 10^{14}\,\text{Hz})$. The corresponding wavelengths are not too far under $1\,\mu\text{m}\,(\equiv 10^{-6}\,\text{m})$. That means that each visible light photon is about 10^5 times *more energetic* than the photons of that radio-transmission, but 10^6 times *less energetic* than the photons in the γ- ray.
This, incidentally, is why γ- rays are more dangerous than their mere power might lead us to believe. $1\,\text{W}$ is not a lot, after all, just a powerful flashlight. But whereas radio waves can only produce *heating*, and even visible light can only

cause chemical changes in a certain class of molecules (including molecules in the retina of our eyes), γ- ray photons carry so much Kinetic Energy, they can *smash* molecules altogether. This can lead to all sorts of trouble when the molecules in question are DNA molecules that contain the genetic code of the cells of our bodies. If we are lucky, disrupting these molecules 'only' kills the cell; if we are unlucky, it will introduce mutations that can cause cancer or worse. And there are plenty of photons in a 1 W beam of γ- rays to cause a lot of damage.

Finally, it should be mentioned that whether a photon is a radio- or a γ- ray photon, it is in the eye of the beholder! If we run towards a radio-source *fast enough*, even 'benign' radio-waves may be *blueshifted* into the γ- ray part of the spectrum. Conversely, even γ- rays can be *redshifted* into visible light or radio waves if we run away from them *fast enough*.

This is part of the reason why we see the Cosmic Microwave Background Radiation as radio-waves. Though these photons didn't start their existence as γ- rays, they did begin as *visible* light. But because of *cosmic redshift*, they now show up in our instruments as *microwave-radiation*.



501 -

Is a black-hole technically 2-dimensional?

What is commonly called a black-hole is a mathematical solution of Einstein's Field Equations for Gravity in (3+1)-dim SpaceTime.

The simplest black-hole solution is the *Schwarzschild solution*, which describes the Gravitational Field in the *spherically symmetric, static, Vacuum case*. This solution is characterized with a *single parameter*, which corresponds to the *Mass* of an object that produces the same Gravitational Field.

The next simplest black-hole solution is the *Kerr solution*, which describes the Gravitational Field in the *cylindrically symmetric, static, Vacuum case*. This describes a black-hole with *Mass* and *Angular Momentum*, i.e., a rotating black-hole.

The next simplest black-hole solution is the *Reissner-Nordström solution*, which describes the *spherically symmetric, static case in the presence of an Electromagnetic Field*. This is a *non-rotating black-hole with Charge*.

The next simplest solution generalizes the previous three: the Kerr-Newman solution is a *cylindrically symmetric, static solution in the presence of an Electromagnetic Field*; take the Electromagnetic Field away, and we get the Kerr black-hole; take the Angular Momentum away and we get the Reissner-Nordström solution; take both away and we get the Schwarzschild solution.

Next, there is a theorem: the 'no-hair Theorem', which is a mathematical theorem (or conjecture, as the proofs of the theorem *do not* cover every mathematically conceivable scenario) that states that a black-hole in the *Einstein-Maxwell* case (*Gravity* and *Electromagnetism* only, no other forms of Matter) is completely characterized by the 3 parameters of the Reissner-Nordström solution: *Mass*, *Angular Momentum* and *Electric Charge*.

All these are mathematical solutions of the Equations of Gravity (and Electromagnetism) in (3+1)-dim SpaceTime. There is nothing 'technically 2-dim' about any of this.

502 -

What does it mean that 'Quantum Gravity has no symmetry'?

Presumably, this question refers to the recently published paper by Harlow and Ooguri that shows that Quantum Gravity cannot have *global* symmetries, if the so-called AdS-CFT correspondence conjecture is true.
The AdS-CFT correspondence is a *conjecture* (a mathematical statement that is widely believed to be true but remains to be rigorously proven) that relates a certain type of solution (the so-called *anti-de Sitter Space*) to Einstein's Field Equations for gravitation in N dimensions and a specific type of Quantum Field Theory (*Conformal Field Theory*) in $N-1$ dimensions. As such, it is a realization of the celebrated *Holographic Principle*. This got a lot of folks working on String Theory very excited, as they see this as a possible vehicle to relate Quantum Field Theory to the real world. Others are more skeptical, pointing out (among other things) that we do not live in anti-de Sitter Space: our SpaceTime is stubbornly 4-dim and our actual, working Quantum Field Theories are not conformal … but this is a digression.
Anyhow, the statement about Gravity and symmetries is that if Gravity obeys the Ads-CFT Correspondence Principle, then, it cannot have so-called *global symmetries*, symmetries that are *intricately related to Conservation Laws*. An example for a global symmetry is a theory that is invariant under Time-translation (i.e., a theory that does not change, works the same today as it did yesterday, and as it will work tomorrow). Time-translation symmetry is the underlying symmetry behind Energy Conservation, so, the paper by Harlow and Ooguri seems to imply, among other things, that Gravitation may *violate* the Law of Energy Conservation.

503 -

Apparently, *Matter cannot be created nor destroyed*. What happens when things go in a black-hole?

'Matter', itself an ill-defined concept, is routinely created or destroyed, e.g., in particle accelerators. 'Matter' *is not a conserved quantity*.
Energy is a *conserved* quantity (with caveats) in *closed systems*. And just as one form of Energy (e.g., Kinetic Energy) can turn into another form of Energy (particles that we typically call 'Matter') in a particle accelerator, so, can one form of Energy (in the form of infalling Matter) turn into another form of Energy (the black-hole's Mass) when it falls into a black-hole.
Conservation Laws are not violated by black-holes; but *there is no law of* '*Matter conservation*'.

504 -

What does 'Energy' mean in the context of Dark Energy? Is Dark Energy the same as the charge of a battery or the Energy in the grid? Is Dark Energy the same as the force we create when we hit an object and make the object to move?

Dark Energy is a *perfect fluid*. Here is the thing. To cosmologists, dealing only with the large-scale structure of the Universe, every form of Matter can be characterized by only two numbers: *Density* and *Pressure*. The Pressure is assumed to be *isotropic* (not dependent on direction) and there is *no Viscosity*, there are *no Stresses*, *no Shear*. A substance that is characterized only by Density and Pressure is a *perfect fluid*.
Since Mass and Energy are *equivalent*, we can use *Energy density*, instead of *Mass density* to characterize the density of this fluid. And *Pressure is pressure*. This leads to a simple characterization. $[\text{Energy density}] := [\text{Energy/Volume}]$; $[\text{Pressure}] := [\text{Force/Area}]$. When we work it out, in *any system of units*, *these two are the same*. So, their ratio is a *pure number*. When cosmologists talk about an 'equation of state', they mean this number.
This pure number is 0 for 'dust': stuff with *negligible* Pressure. To a cosmologist, everything that is not an ultra-relativistic gas or something else exotic is 'dust'. We all are dust, planets are dust, stars are dust. Internally, a star may have large Pressure, but scattered stars in a galaxy. They behave like particles of dust, not interacting with each other at all. And let's remember, cosmologists are only interested in these large scales, not the interiors of stars.

505 -

If the *Inflaton Field* and *Gravitational Field* did not interact, how did the *cosmological inflation* happen?

[see, e.g., WIKIPEDIA for the terms 'Inflaton Field' and 'Inflaton', the associated field mediator particle.]

Who says that the Inflaton does not interact with Gravity? Of course, it does. Gravity (except in more exotic theories) interacts with all forms of Matter *universally* and *minimally*. The Inflaton Field is just a *scalar* field. Its Lagrangian is computed using the same *invariant volume element*, $(-g)^{1/2}$, as other fields. So, in the field equations, the coupling the $g_{\mu\nu}$ is the same. Like all other fields, *the Inflaton both responds to*, *and acts as a source of*, Gravitation.

And it is indeed through Gravitation, which becomes *repulsive* when the *Inflaton Field's Lagrangian* is dominated by its Self-interaction Potential, that the field becomes responsible for the rapid, accelerated expansion – *inflation* – of the early Universe.

So that number we mentioned? It can have 'sensible' values between -1 and $+1$. We already mentioned *dust* for which the equation of state is 0. Its value is $1/3$ for an 'ultra-relativistic gas', which consists of particles that have much more Kinetic Energy than their rest Mass-Energy (i.e., particles that zip about at nearly, or at, the speed of light c). But even more extreme equations of state values are possible all the way up to $+1$. Beyond $+1$, they would *violate causality*, as it would describe a substance in which *sound* (*pressure waves*) travels faster than the Vacuum speed of light c.

And yes, Pressure can be *negative* all the way down to -1, as a matter of fact. And there are candidates for such negative Pressure. Einstein's Cosmological Constant behaves in the equations, for all practical intents and purposes, as a perfect fluid with -1 as its equation of state. But there are also types of quantum fields whose Self-interaction Energy has this equation of state.

And yes, when the equation of state is -1, we call it '*Dark Energy*'. We could just as well call it 'green jelly' or 'transparent smoke', words mean nothing in themselves. What is meaningful and 'actionable' in terms of the equations of Cosmology is the *value* – the co-domain – its equation of state may take.

But it is also a sign of our ignorance. We assign a name to something and that creates the impression that we know what it is. We don't. The candidates notwithstanding, we know nothing about Dark Energy other than its equation of state.

The reason why we need it is because it is by assuming that roughly 70% of the Universe is presently made up of this Dark Energy that we get equations that *match reality*: fluctuations in the Cosmic Microwave Background, the large-scale distribution of Matter in the Universe, the luminosity-redshift relationship of distant supernovae.

But just because we need it doesn't mean we found it nor that we know what this 'Dark Energy' is really made of.

506 -

An infinite plane *classically* has a finite and uniform Gravitational Field. Does this change in General Relativity?

It does change in General Relativity, but in a non-trivial way. In pre-Relativity Physics, Space is flat and infinite, and Time is absolute (and also infinite). The distribution of (rigid) Matter can be freely postulated, so nothing prevents us from postulating, in a thought experiment, an infinite plane of uniform Density and then calculate its Gravitational Field.

This approach does not work in General Relativity. The metric of SpaceTime is the Gravitational Field, and the Gravitational Field is defined by Matter. So, we cannot postulate the presence of Matter in some shape or form without ignoring the consequences when it comes to the *metric* of SpaceTime.

Here is what happens: as we increase the *linear size* of that planar distribution of Matter while keeping its density *constant*, its Mass will increase as the *square* of its linear size. That means that its Schwarzschild Radius will also increase as the *square*, eventually catching up and *surpassing its linear size*. At that point, the entire (still finite) surface is now inside its own Schwarzschild Radius, i.e., instead of a (still finite) plane, *we now have a black-hole*.

So, it turns out that it is simply *not possible to postulate an infinite plane of uniform density in General Relativity*. Such a distribution of Matter is not consistent with Einstein's Field Equations.

507 -

Einstein said $E = mc^2$, that is, that Mass increases with Speed, but Antoine-Laurent de Lavoisier said Mass remains *constant*. Which is true?

No, *Mass does not increase with Speed*. If there are speeds involved, the correct *dispersion* relation changes to $E^2 = (mc^2)^2 + (pc)^2$, where p is the Linear Momentum. Throughout, m, the Mass, remains constant. $E = mc^2$ is valid only when there is *no motion*, hence, the Linear Momentum value is $p = 0$, which means that we are in the rest-frame of the physical system in question.

Having said that, Lavoisier was wrong, but not very wrong. *Mass is not a conserved quantity*; Energy is. But compared to the rest Mass-Energy of the atoms and molecules involved, the Binding Energy of Chemical Reactions is so tiny that the change in Mass is not measurable even by modern methods. For instance, the Binding Energy between the two ^{1}H atoms in a H-molecule is $< 4/10^9$ parts compared to the combined Mass of the two atoms. So, for practical purposes, *Mass does remain constant in Chemical Reactions*. Not so in Nuclear Reactions: for instance, the Mass of one ^{2}He atom is roughly 0.6% *less* than the Mass of two D (≡ ^{2}H) atoms, even though they consist of exactly the same set of elementary particles. This 0.6% difference is readily measurable, and its size explains why Nuclear Fusion releases so much more Energy/atom than Chemical Reactions.

508 -

How can the Universe expand if the Space is incompressible and then inextensible?

Well … because *Space is neither compressible nor incompressible*; *nor is it extensible or inextensible*. *Space is not a physical entity*: it cannot be measured. There are no little markers attached to Space with which we can align our meter stick to measure how Space expands or gets compressed. Space has *no independent physical reality*.

The equations that govern the expansion of the Cosmos, the so-called Friedmann Equations, are a specific representation of Einstein's Field Equations of Gravitation. These equations describe the Gravitational Field (not Space!) and its source, the Stress-Energy-Momentum of Matter.

Now, it is true that, because the Gravitational Field couples to all forms of Matter in a specific way (the technical term that is sometimes used is that it '*couples universally and minimally*' *to Matter*), it can be readily reinterpreted as the *metric of SpaceTime*. The metric of SpaceTime does indeed determine how we observe Geometry. What we actually observe is not SpaceTime but the relationship between systems *in that* SpaceTime. Galaxies, stars, planets, atoms, elementary particles: whatever it is, that's what we *observe*, that's what we *measure*, not 'Space'.

The confusion arises, in part, because when we use one particularly convenient coordinate system to measure the relationship between things, the Gravitational Field in this coordinate system is represented by a 'scale-factor', which increases over time. This (wrongly!) suggests that, over time, meter sticks become longer. No, *they do not*: *coordinate systems are not physical reality*! And it is just as easy to switch to a different coordinate system in which there is no changing scale factor. It is mathematically (slightly) less convenient, that is all.

Then, what is the physical reality of the SpaceTime expansion? It is that the average distance between things that are not bound to each other (by Gravity, chemical forces, or other kind of forces) increases over time. Matter in the Universe is becoming more and more *dilute*: stuff flies apart.

That's the nature of the expansion and that's what the Friedmann's Equations describe, with the Gravitational Field (represented by the 'scale-factor' in this convenient coordinate system) on one side of the equation, and the Density and Pressure of Matter (tangible, *observable* stuff) on the other.

509 -

What is the General Theory of Relativity?

In 1905, Einstein created a theory that became known, at the time, as the Theory of Relativity. However, this theory treated inertial (i.e., *non-accelerating*, *non-rotating*) observers as special cases; both accelerating and rotating observers were … second-class citizens.

When, a few years later, Einstein's attention returned to the Theory of Relativity, he decided to seek a generalization of the theory that would treat all observers on an equal footing. He called this theory that he was pursuing the *general* theory.

As we know, he was eventually successful, after realizing that such a *general theory* must necessarily include Gravity. In late 1915, the General Theory of Relativity was born in the form of what has since become known as Einstein's Field Equations for Gravitation.

So, what about the old theory? Well, because it represented a special case (inertial observers), it was from that point onward known as the *Special Theory of Relativity*.

510 -

How does Einstein's Theory of Gravity explain why an object falls to the ground?

Objects fall to the ground *because of the curvature of SpaceTime due to the presence of the Earth*. Why does curvature mean falling? Here is a simple thought experiment: we and a friend start driving straight north from the equator. We both drive in absolutely straight lines. If the Earth was flat, the distance between our two vehicles would never change: our paths would be parallel. But the Earth is not flat. As a result, as we get closer and closer to the North Pole, our

vehicles begin approaching each other. What began as parallel trajectories are now trajectories that will eventually intersect. Does this mean that one of us deviated from the straight line? No, it means that on the surface of the Earth, which is not flat, there are no straight lines, only geodesic lines, and geodesics that start off originally as parallel eventually meet anyway. The same happens with the geometry of SpaceTime.
Oh, but we say we are NOT moving when we start falling towards the Earth? But we do. Even if we are not changing your position in Space, we are still moving forward in Time. So, we are always moving in SpaceTime, and unless a force (a *real* force, not Gravity) acts on your body, we will be moving along a SpaceTime geodesic. And just like on the surface of the Earth, geodesics in curved SpaceTime are *curved*. To keep us on a 'straight' path, a force is required, just like one of the cars in the driving example would have to steer itself actively away from the 'straight line' to maintain a constant distance from the other car.

511 -

If a black-hole is a specific point that's infinitely dense, then why do they have a diameter? In other words, if they have such a large Mass, why do they have any Volume? Shouldn't they just be a single point in Space we can't even see?

First, a black-hole does not have a 'specific point that's infinitely dense'. If we are referring to the Schwarzschild black-hole's singularity, that is not a point in Space: that is a point in any infalling observer's *future*, i.e., a moment in Time.
Second, we have to be careful when it comes to the concept of diameter. Technically, no such thing exists for a black-hole. The 'surface', which is the event horizon of the black-hole, is a so-called null surface: a ray of light could, in principle, follow this surface without ever either escaping or falling into the black-hole. But there is no stationary reference frame in which this surface can be characterized. So, speaking of its radius, circumference, or diameter is a *perilous* thing to do. Sure, we can talk about the Schwarzschild Radius of a black-hole, that is, a radial coordinate. But this coordinate has no direct physical meaning. As a matter of fact, Schwarzschild coordinates fail (the system has a *coordinate singularity*) at the horizon; to describe that region, we need to use a Time-dependent coordinate system, e.g., the coordinate system of an infalling observer.
As to the Volume of the black-hole, that is even more ill-defined, for the same set of reasons.
Now, the clincher: both the Schwarzschild and Kerr black-hole solutions are Vacuum solutions of General Relativity. In other words, the Matter density is 0 everywhere in Space and Time according to these solutions. So, they really aren't about describing Mass; they are about describing the Gravitational Field that surrounds that Mass in empty SpaceTime. Therefore, the event horizon is not about where Matter is; it is about where the Gravitational Field itself becomes so strong that *escape from the Gravitational attraction of the object is impossible*. And as a result of the *relativistic* version of Newton's *shell-Theorem* (which says that *outside of a spherically symmetric object, its Gravitational Field is exactly the same as the Gravitational Field of a point-mass of the same magnitude*), *Birkhoff's Theorem*, we know that for instance, the Schwarzschild solution is a valid description of the Gravitational Field of any spherically symmetric object outside of that object; thus, if the object is compact enough, it collapses into a black-hole and its Gravitational Field will include an event horizon.

512 -

Why isn't 'Dark Matter' called 'Dark Force'? Why is there an assumption that a form of Matter is what is causing the force?

Because, in the Standard Cosmological Model, *it is not a force*. It is a form of Matter that, on the largest of scales, behaves as a *pressureless ideal gas*, characterized by its *Mass density*.
There are other, alternative cosmological models that indeed postulate some modified Gravity theory, usually in the form of an extra force. This force is typically called in the literature a '5th force', not a 'Dark Force'.
The expression 'Dark Matter' dates back many decades, long before the current cosmological model was developed. All the way back to the 1930s, in fact, when it was first recognized that some galaxies rotate too fast considering the amount of visible Matter that they contain, so it was conjectured that in addition to the Matter we see, there is also additional Matter that is non-luminous, *dark*, which we do not (or do not easily) observe, but which still *contributions to the overall Gravitational attraction*.

513 -

How can the age of the Universe be estimated? And if it is true that it is $13.8 \cdot 10^9$ years, then the observable Universe can only be within a sphere of that radius. So, how can the known Universe be $9.3 \cdot 10^{10}$ light-years if it is not seen?

The age of the Universe is estimated using many different data sets. We can observe the rate of cosmic expansion (the *Hubble parameter*). Putting it together with what we know about the *density* and *distribution* of Matter in the Universe, we can plug these numbers into the equations of General Relativity and the age pops out.
We can observe stars. We see many stars today at different stages of their evolution and by studying them, we understand how they work and how long it took them to reach the point where they are today. We can, therefore, estimate the ages of the oldest stars.
Closely related, we can look at the ratios of various *isotopes* in the Universe. Light atoms (mostly $^1\mathrm{H}$ and $^2\mathrm{He}$) are *primordial*. Heavier atoms were made in stars or in stellar cataclysms like *supernova explosions* or *neutron star mergers*. Some of these heavier atoms are not stable and decay by *nuclear fission*. Again, looking at how isotope ratios change in the near vs. far parts of the Universe, we can estimate the time elapsed.
We can also look at the Cosmic Microwave Background Radiation and its minute fluctuations. Again, plugging the numbers into the equations, we get estimates about the time it took for that radiation to appear as it does today.
All these help us build a (more-or-less) consistent picture (but with some notable tension) leading to the $13.8 \cdot 10^9$- year figure.
Now, it is true that the present-day 'comoving distance' to the most distant lumps of Matter that we see is estimated to be about $4.6 \cdot 10^{10}$ light-years. But 'comoving distance' is a piece of mathematical fiction, not something we can measure with a cosmic yardstick. The distance to those same lumps of matter at the time when the light we see was emitted was only a few billion light-years. In fact, we must wonder why it then took so long for that light to arrive: the reason is general relativistic Time-dilation, because of which, as measured in our frame of reference, those rays of light were initially moving much slower than the Vacuum speed of light. This sounds odd but it is a real effect: on a much smaller scale, it happens right here in the solar system, where light rays or radio waves slow down when they pass near the Sun, traveling through the Sun's Gravitational Field, exhibiting the so-called *Shapiro-delay*.
And while the comoving distance to those lumps of Matter is today $4.6 \cdot 10^{10}$ light-years from here, light from those lumps of Matter emitted now (as measured in the comoving reference frame) will never reach us at all. Rather, if we could follow those lumps of Matter with a telescope over extraordinarily long Time-scales, we'd find that as a result of accelerating expansion, there will be increasing Time-dilation; and that as a result, things will appear to tick slower and slower in that lump of Matter, so that its apparent age will never advance beyond a certain value.
We can interpret this, of course, as those lumps of Matter reaching and exceeding the Vacuum speed of light *relative to us*. Some will even 'explain' this as 'space expanding'. But neither correctly captures the reality of SpaceTime. What actually happens is that those lumps of Matter are *pushed away* from us by Gravity that is *dominated* by Dark Energy and is, thus, on these large scales, repulsive; and that these lumps of Matter would reach our 'cosmological horizon' after a finite amount of Time as measured by a clock embedded in the lump, but which would be *future infinity* for us (something very similar happens to Matter falling into a black-hole: it reaches the horizon in a finite amount of time as measured on board but, to outside observers, *it takes an infinite amount of time for that to happen*).
OK, the one thing to take home from this overly lengthy explanation is that comoving coordinates, in which the $4.6 \cdot 10^{10}$ light-years are calculated, *do not represent physical reality*. They're simply a mathematically convenient coordinate system, that's all.

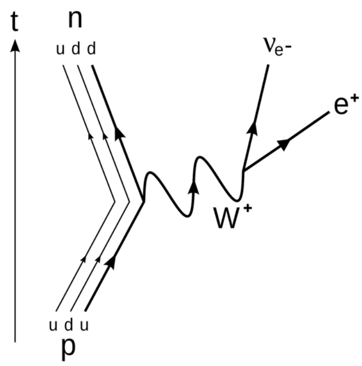
514 -

When a proton emits a positron, e^+, where does it come from? 2 up-quarks and 1 down-quark become 2 down-quarks plus 1 up-quark plus 1 neutrino, ν, plus 1 positron. Are quarks fissionable?

[compare with Issue 148, P. 70]

Quarks are not 'fissionable' but, like all elementary particles, they interact with other elementary particles. Specifically, up-quarks and down-quarks can turn into one another by *emitting* or *absorbing* 1 W- boson. Similarly, electrons and neutrinos can turn into each other by emitting or absorbing 1 W- boson. This also means that 1 up- and 1 anti-down (or 1 anti-up and 1 down)-quark can turn into 1 W- boson. Also, 1 electron and 1 *anti-electron neutrino*, or 1 positron and 1 *electron neutrino*, ν_{e^-}, can turn into 1 W- boson; and 1 W- boson can turn into either.

So, we have it: 1 up-quark borrows a little excess-Energy, which is enough to create a *virtual* {down, anti-down} pair. The {up, anti-down} quark pair form a W^+- boson, leaving 1 down-quark behind. The W^+- boson, in turn, decays into a *positron* and 1 *electron-neutrino*:



This reaction can only happen if there is *excess Energy* available because protons (udu) represent a *lower* Energy-state than the resulting neutron (udd).
The opposite reaction – a (free) neutron turning into a proton by β-decay – can, and does, happen *spontaneously* (in about $14'$).

515 -

Why are quarks found in pairs?

Pairs, triplets, tetra-quarks, … The point is that quarks are only found in combinations that neutralize their net '*color*'-*charge*. To understand this there are two things to understand about the Strong Interaction that holds quarks together.
First, that it is more complicated than Electromagnetism. In Electromagnetism, there is *only one* kind of charge. Kind of like a monochrome image. In contrast, the Strong Interaction has *3 kinds* of charges. This is where the analogy with *color* comes from since the human eye sees three primary colors.
An electrically neutral system consists of an equal number of positive and negative charges. A system that is neutral with respect to the *color charge* either consists of an equal number of charges and anti-charges of the same color, or it consists of the same number of 'red', 'green' and 'blue' color charges. So, a {red, anti-red} pair of quarks is *color-neutral*; but so is a triplet consisting of 1 red, 1 green and 1 blue quark (or a triplet consisting of the corresponding anti-particles). So, that tells us why neutral combinations of quarks come in pairs, triplets, or combinations thereof (e.g., two pairs bound together would make a *tetra-quark*, a pair, and a triplet a *penta-quark* – these are short-lived, unstable, but color-neutral combinations of quarks that *have been observed* in accelerator experiments).
But why is that we can see electrically charged particles existing on their own, whereas quarks always come in neutral combinations? The reason is the *second point*: that the force required to separate bound quarks *increases linearly with distance*. Consequently, the amount of Energy required to separate them increases *without limit*. Eventually, the Energy invested into their separation exceeds the rest Mass-Energy of a brand-new pair of quarks. The binding between the quarks we are trying to separate 'snaps' but a brand-new pair of quarks is created, one assigned to each of the quarks that we were trying to pull apart. So, instead of having two isolated quarks, we end up with two new pairs!
As a crude analogy, it's like asking why a string always has two ends. Trying to separate them by force eventually causes the string to snap, and two *new ends* are created.
To sum up: 'color neutral' quark combinations involve either *pairs* or *triplets* and trying to separate a quark always results in the creation of new quarks, so a lone quark is *never* obtained.

516 -

Why do many scientists keep saying that Gravity is caused by the *warping of curvature* of SpaceTime when it has never been observed?

Let's go back in time a little over the last 100 years, to the years following Einstein's first publication on what back then became known as the Theory of Relativity in 1905.
The Theory of Relativity revolutionized the way we think of Space and Time (not SpaceTime, not yet; that concept came from Minkowski in 1909). It also introduced the concept of an invariant speed: the Vacuum speed of light, which would have the *same measured value for all inertial observers*.
But there was a *serious shortcoming* from Einstein's perspective. The theory treated accelerating observers as second-class citizens. How could this be resolved? Einstein's newfound ambition was to find a generalized version of his Theory of Relativity that can treat inertial and accelerating observers as equals.

Then came a thought. Let's imagine observers who are falling in a *homogeneous* Gravitational Field. Relative to each other, these observers are either *at rest* or *in uniform motion*. And if they have no *external* reference (they do not, for instance, see the ground approaching or feel the wind) they would have no way of knowing that they are falling at an *accelerating rate*, not just floating in empty space: the difference between the two is a simple *geometric transformation*. In other words, a theory that deals with geometric transformations between *accelerating systems* is necessarily also a Theory of Gravitation. It must be. Einstein later described this line of thinking as the 'happiest thought' in his life.
Ultimately as we know, Einstein was successful and by late 1915, published his *Generaltheorie*, the generalization of the Theory of Relativity, which we now know simply as General Relativity (the 1905 theory, which is a *special* case covering (mostly) inertial motion, thereafter, became known as Special Relativity). The theory is as much a Theory of Gravitation, as it is a Theory of Acceleration, finally creating a framework in which the Laws of Physics are the same for all (not just inertial) observers, regardless of their motion. A technically correct description of Einstein's Theory of Gravitation is that it can be interpreted either as the theory of a Classical Field Theory or as a Geometric Theory. The math is the same, either way.
But there is yet another, *more modern way* of looking at it, more or less along the same lines as Feynman did, in his posthumously published Lectures on Gravitation. Gravity is not unique: other forces, such as Electromagnetism, can also be expressed in a geometric representation (through the so-called *covariant derivative*). There is, however, a crucial difference. For Electromagnetism, the Geometry depends on the *charge-to-mass ratio* of the particle we investigate. Protons experience a Geometry quite different from that experienced by electrons, and electrically neutral particles just experience the background, *unaffected Geometry*. In contrast, *Gravity is universal*: every particle experiences the same Geometry defined by Gravity. Moreover, since no particles exist that do not participate in the Gravitational Interaction, there is no observable 'background', 'Gravity-free' Geometry: the *warped Geometry* defined by the Gravitational Field is the only Geometry that can be observed.
Long story short: Gravity is not caused by Geometry. Gravity can be interpreted as a *force*, or as *Geometry*, just like other forces can. But Gravity is special: it defines the only Geometry we experience, which will be also experienced by every particle, every object, every physical system.

517 -

If a black-hole 'eats' everything that goes into it, how long will it take for the entire Universe to be devoured by a giant black-hole, and why is the Universe expanding when it's supposed to be consumed by millions of black-holes?

Let's offer a silly analogy. Let's imagine the following: we dig a giant cavity underground, a cave big enough to contain all the tennis balls in the world. Then, we connect that cavity to the surface, say, in the middle of a tennis court, with a tiny hole, a hole just wide enough to swallow a tennis ball. Now, we make a *misleading* but *technically correct* statement: "The hole is big enough to swallow all the tennis balls in the world."
But let's hold on a moment: the actual hole in the ground that the tennis ball must find and enter is *tiny*, just 7 cm across.
In fact, people could continue playing tennis in that very tennis court for years, only occasionally losing a ball. And even if every ball swallowed by the hole erodes away its walls a little, making the hole slightly wider, anyway, it will still take a very long time for it to swallow more balls, and, of course, most tennis balls in the world will never even come close to *this* tennis court. So, *they will never be swallowed*.
This is how a black-holes works: sure, it has the capacity to swallow things and grow. Its inner region is *technically limitless* but *quite small geometrically*. For something to be swallowed by a black-hole, it first must find that black-hole. Never mind doing so at random, it would be difficult even for precision-navigated spacecraft to actually hit a target so tiny and get swallowed by it.
So, the Universe is no more supposed to be consumed by black-holes than tennis balls are supposed to be swallowed by a tiny hole in the ground, no matter how big the cavity is underneath.

518 -

Why are there still *opponents* of the Theory of Relativity?

We experience there are two groups (†) of people. The first group consists of folks who understand Relativity Theory. These folks know how to derive Einstein's Field Equations from the Einstein-Hilbert Lagrangian, know how to linearize the resulting equations, understand the post-Newtonian formalism, can devise testable predictions, know how to calculate the bending of light by the Sun, the perihelion advance of Mercury and other planets, the Shapiro delay of radio signals, know how to apply the field equations to an isotropic, homogeneous Cosmos and derive its Friedmann Equations, know the conceptual issues concerning singularities and horizons … in short, they know what they are talking about, they know what the theory says, they know what its predictions are and how they can be tested.

The second group of people include those who talk about Relativity Theory as a 'dogma', complain about apparent paradoxes, deride the Physics 'establishment', question Einstein's legacy, and propose outlandish alternatives (often in

the form of meticulously produced, richly illustrated manuscripts or self-published books). Surprisingly, this group not only includes *bona-fide* scientists but occasionally, *even physicists* from other fields.
However, the overlap between these groups is precisely *nil*. Is there anybody who actually made a (honest) effort to understand Relativity Theory and then became an opponent of it? Surely, there are people who explore sensible modifications or extensions of the Theory: doubly Special Relativity, scalar-tensor theories, $f(R)$ theories of Gravity, conformal Gravity, higher-order Gravity, bimetric theories … these are all proposals made by *gravitational* physicists who understand Relativity Theory *very well*. But proposing a *sensible* modification or extension of the Theory is not the same as being in opposition to it. Again, it's (very) hard to meet a person who opposes Relativity Theory but argues from a position of deep knowledge, not profound ignorance.

(†) These two groups are not the only two, of course. There are people who do not belong in either of these categories, i.e., people who do not have a professional level of understanding of the Theory but *do not* buy into anti-science conspiracy theories either.

519 -

Could the accelerating Universe's expansion rip black-holes apart at some point in the future?

No, the accelerating Universe does not rip any-self-gravitating structures apart. Clusters of galaxies, galaxies, solar systems, stars, planets … and yes, black-holes, too, remain intact. The *average density* of Matter in the Universe continues to decrease so the Cosmological Constant dominates *on average*, but that is not the case in a self-gravitating system, the density of which does not change on account of the expansion.
This is the case under the standard cosmological scenario involving Dark Energy. If we permit the violation of one of the so-called Energy conditions and let Dark Energy turn into 'Phantom Energy' with even *greater negative pressure* than Dark Energy, the situation changes. In essence, the Phantom Energy scenario amounts to a Cosmological 'Constant' that increases over time. As such, it eventually overwhelms even compact self-gravitating systems, such as galaxies, solar systems, stars, planets … and, ultimately, even elementary particles. It actually means that, over time, the maximum Schwarzschild radius that such a Universe 'tolerates' decreases as well. Therefore, this would indeed rip black-holes apart or, perhaps more accurately, prevent them from collapsing in the first place. As we know, the gravitational collapse into a black-hole *takes forever* in the reference frame of any *outside observer*. So, what happens is that, over time, the expansion catches up with infalling Matter. That Matter might have been almost infinitesimally close to, but not quite at, the yet-to-form event horizon of the black-hole, but it doesn't matter: *accelerating expansion in the presence of Phantom Energy would win that race*.
This 'Big Rip' scenario is not part of the Standard Cosmological Model, and there are plenty of fundamental reasons to believe that Phantom Energy doesn't, indeed *cannot*, exist in our Universe. Again, in the Standard Cosmology with 'normal' accelerating expansion, nothing is ripped apart. Things that accelerate away from each other are things that were never gravitationally bound to one another in the first place, such as distant clusters of galaxies.

520 -

If $E = mc^2$ and the Higgs boson gives objects their Mass, is Energy made up of the Higgs boson?

Yes, $E = mc^2$. In other words, the rest Mass of an object is determined by the object's intrinsic Energy-content. There are other forms of Energy (Kinetic Energy, Potential Energy) that depend on the object's *motion* or its *interaction* with other things, and do not contribute to its Mass. So, for instance, the Mass of a system of two objects may differ from the sum of the individual masses: e.g., a H atom is just a tad lighter than a proton and an electron, because the atom's Energy-content, also includes the negative Potential Energy holding the electron and the proton together, but this Potential Energy *is not* part of either the electron's or the proton's Mass.
No, the Higgs boson *does not give* objects their Mass. The Higgs Mechanism is responsible for the Masses of elementary particles, including electrons and the quarks that constitute protons and neutrons. However, roughly 99% of the Mass of a proton or a neutron is due not to the quark rest Masses but the (in this case, positive) Strong Force Potential Energy holding them together. *This has nothing to do with the Higgs boson*, at least not directly (indirectly, yes, as quarks need to be massive in order to be in such a bound state, so, massless quarks couldn't form protons or neutrons in the first place).
Therefore, *Energy is not made up of Higgs boson*. As a matter of fact, very little of the Energy we experience around us has anything to do with the Higgs boson. Take a brick. Roughly 99% of its Mass is not due to the Higgs boson. The Gravitational Potential Energy that holds it on the surface of the Earth or causes it to fall is not due the Higgs boson. And while it is moving, its Kinetic Energy is not due to the Higgs boson either.

521 -

Is the Electromagnetic field 'everywhere' in the same way the Force of Gravity is everywhere and affects all Mass?

It is important to distinguish three things:

1. the *field*,
2. the *excitations* of the field,
3. the *interactions* (forces) mediated by the field.

Regarding item 1, indeed, both the Electromagnetic and the Gravitational Fields are present everywhere, even in the complete absence of Matter or excitations, in their so-called 'ground state';

regarding item 2, when the Electromagnetic Field receives Energy from some source, it is called an excitation. And if the field is a quantum field, these excitations are created or destroyed one unit at a time. We like to think in terms of particles, but in the world of Field Theory, particles are just elementary excitations of the field. When we say that an electron emits a photon, what actually happens is that the Electron Field (yes, that is a *field*, too) interacts with the Electromagnetic Field, transferring Energy and Momentum to it, creating a *unit of excitation* in the Electromagnetic Field. The Gravitational Field works similarly. Of course, we don't know for sure if it is a quantum field (nobody succeeded quantizing Gravity just yet) but even if it isn't, it's still a field that can carry excitations, even to faraway places, in the form of gravitational waves, just as the Electromagnetic Field carries light.

Finally, regarding item 3, things that interact with a field can interact with each other through the field. For instance, electrons can repel each other by exchanging excitations through the Electromagnetic Field. Similarly, masses attract each other through the Gravitational Field. While it is true that the influence of an Electric Charge or a Mass, though it diminishes with distance, is present everywhere, this is not the same as the field being present everywhere. The (unexcited) Electromagnetic Field is present *everywhere* even when there are no charges and no electromotive forces. The (unexcited) Gravitational Field is present *everywhere* even when there are no Masses and no Gravitational Forces.

522 -

If a black-hole created from Matter, and a black-hole created from anti-Matter collide, is the result of a bigger black-hole or would something else happen?

We may have heard of the '*no-hair*' *Theorem* (‡). What it basically tells us is that a black-hole is fully characterized by 3 properties: its *Mass*, M, its *Intrinsic Angular Momentum*, S, and its *Electric Charge*, Q. Other than that, a black-hole *has no other properties*, hence, it is '*bald*'. It does not matter where that Mass comes from, if from Matter or anti-Matter, it makes no difference: a collapsing star, Dark Matter, neutrinos, … no difference whatsoever.
So, there is no such thing as a Matter black-hole or an anti-Matter black-hole. A black-hole is a black-hole. And when two black-holes merge, the merger event is defined entirely by the black-holes respective Masses, Intrinsic Angular Momenta, Electric Charges, and *relative* orbits.

(‡) The '*no-hair*' *Theorem* states that all black-hole solutions of the Einstein–Maxwell Equations of Gravitation and Electromagnetism in General Relativity can be completely characterized by only 3 externally observable parameters: Mass, Intrinsic Angular Momentum (Spin) and (only very rarely) Electric Charge. All other information – for which, the 'lack of hair' is a metaphor – about the Matter that formed a black-hole or is falling into it 'disappears' behind the black-hole event-horizon and is, therefore, permanently *inaccessible to external observers*. Physicist John A. Wheeler expressed this idea with the phrase "Black-holes have no hair", which was the origin of the name. In a later interview, Wheeler said that Jacob Bekenstein (1947-2015, a Mexican-born Israeli-American theoretical physicist) coined this phrase. [Source: WIKIPEDIA]

523 -

From a scientific standpoint, what is the meaning of life, given that our Universe will eventually return to the singularity and all the information (everything we have created and can ever create) will be destroyed?

Science won't tell us about the meaning of life. For that, we need to ask priests or philosophers. However, Science will tell us that, to the best of our knowledge, the Universe *will not return* to the primeval singularity. Rather, the expansion of the Cosmos is, in fact, accelerating and will *continue to do so forever* (forever is a long time, but that's what our equations tell us; equations with other, testable predictions that have in fact been validated through observation). There will be less and less fuel left to power stars, ultimately we'll be seeing a Universe that's cold, dark, and diluted by expansion almost into nothingness, but that will take an almost unimaginably long time, and even that does not mean the end of everything as the future time direction is *unbounded*.
A return to the singularity is really not possible even on thermodynamical grounds. It would mean a return to the initial, low Entropy state of the Universe, which would necessarily mean a *reversal of the thermodynamic arrow of Time*.

524 -

Einstein's Theory of Relativity is based on the idea that *there is no absolute motion*. But the Theory of Special Relativity is built upon the idea that the motion of light is *absolute*. Do we have some trouble with interpretation here?

A (reasonably) correct statement of the premise of Special Relativity would be in the form of the following two postulates:

- Physics is the same *in all inertial* reference frames;
- the *Vacuum speed of light*, c, is the same *in all inertial* reference frames.

A consequence of the 1st postulate is that *no reference frame* is *special*; e.g., there is no 'absolute rest' reference frame. Now indeed, the 1st postulate would be at odds with the 2nd, if there was a reference frame associated with a ray of light, as such a reference frame would surely have special properties! But here is the thing: no such reference frame exists.

The easiest way to see why is by considering the following: the speed of a reference frame is always 0 in that reference frame. But the 2nd postulate says that c is the same in all inertial reference frames. So, if there were a reference frame moving at the Vacuum speed of light, its own speed, *measured in that reference frame*, would be simultaneously both 0 and $c\ (\neq 0)$, which is a clear contradiction.

This contradiction is resolved when we realize that no such reference frame exists (in fact, if we try to construct such a reference frame by *accelerating* a reference frame until it reaches the c, we find that at that point, the reference frame becomes *degenerate*: its Time-direction and one of its spatial directions collapse into a so-called 'null' direction.
This has nothing to do with any 'interpretation'. We just need to be consistent about the math. Above, a sketch of the math has been offered, but it can also be carried out rigorously, as indeed it has been done, in many ways, in the past century or so.

525 -

How do we know the Universe is infinite?

As for the simplest Standard Cosmological model, the *Friedmann-Lemaître-Robertson-Walker* (FLRW) *model*, the Cosmos is

a. *homogeneous* (same, on average, everywhere) and
b. *isotropic* (does not have a preferred direction, such as a *global* axis of rotation).

This model yields the so-called *Friedmann-Equations*, an application of Einstein's Field Equations that describes the *large-scale* properties of the Universe. The Friedmann-Equations yield 3 possible overall classes of solutions, characterized by *spatial curvature*, Ω_K. The curvature can be *positive*, *negative*, or *zero* (*flat*).

A Universe with $\Omega_K > 0$ has an *initial* and a *final singularity* and a *finite lifespan*. The simplest topology of this Universe is closed (one could, if one could fly *faster* than light, fly off in some direction in a straight line and eventually arrive back at her\his point of origin) and has a *finite volume*. The prerequisite for a closed Universe is for there to be *enough Matter for Gravity to halt the expansion*.

A Universe with $\Omega_K \leq 0$ curvature is, in turn, characterized by either an initial or a final singularity (*but not both*). Its simplest topology is an *open* one: Euclidean Space (for $\Omega_K = 0$ curvature) or Hyperbolic Geometry (for $\Omega_K < 0$ curvature, characterized by triangles in which the sum of angles adds up to *less* than 180°).

Our Universe appears to be with $\Omega_K = 0$ curvature. Its curvature could, of course, be small yet $\neq 0$. The problem with this assumption is that the magnitude of curvature *grows over time*; if it is $\neq 0$ but small now, it had to be $\neq 0$ yet astonishingly small in the early Universe, a problem referred to as 'fine tuning'. So, an 'almost flat' Universe is usually rejected, unless there is some additional Physics (e.g., inflation in the early Cosmos) that explains away the 'fine tuning'.
That said, we are of course well aware that we extrapolate from what we know (the very finite, visible slice of the Universe) to what we don't know (the whole Universe, which may or may not be infinite, but it is almost certainly many orders of magnitude bigger than the parts we see). So, take all this with a big grain of salt, as informed speculation, not observationally confirmed Science. What we can confirm is that in the Universe that we can see, *there are no signs of large-scale spatial curvature*, and that it is consistent with that simplest of Cosmological Models, the FLRW model, which predicts a *spatially infinite* Universe governed by *Euclidean Geometry*.

526 -

How can a *singular point* in a black-hole hold so much Energy without exploding?

There is no 'singular point' in a black-hole. This is a gross oversimplification and misunderstanding of black-hole Physics. When Matter collapses into a black-hole, as seen *from the outside*, it *never gets past*, never even reaches in fact the event-horizon. That is because the event-horizon itself remains, in the reference frame of any observer *outside* the black-hole, *forever in the future* (that's extreme Relativity for us).
For an infalling observer, the event horizon is reached in a *finite* amount of Time of course, after which the observer is doomed: his Universe, his timeline *will end shortly* (milliseconds for a stellar-sized black-hole, maybe hours or days in a super-massive black-hole). But the reason for this is, in part, the nature of the singularity! It is not a 'singular point', at least, *not a point in Space*. Rather, it is a *singular moment in Time*, which is precisely what makes it unavoidable: we cannot avoid tomorrow afternoon 3 p. m. either by going around it. And to continue with this silly but not completely stupid analogy, tomorrow afternoon 3 p. m. will hold all the Energy in the Universe at that moment in Time, but it certainly won't explode as a result.
Having said that, a black-hole's singularity is not like a wintry weekday afternoon, because things do go haywire there: the Energy density of Matter approaching the singularity *grows beyond limit*. However, this is offset (in fact, the growth is fueled, in a way) by the negative Gravitational Potential Energy present. No new Energy is created, so there is nothing that would do any exploding, even if the singularity were a point in Space, *which it is not*, as it was stressed above.

527 -

Is Special Relativity's negation of an *absolute* and *universal* reference frame the reason that we don't have a 'sensible renormalizable Quantum Field Theory (QFT)'?

We *do have* a sensible, renormalizable QFT in the form of the Standard Model of Particle Physics. The issue of *renormalization* comes up, e.g., as a direct consequence of how fields are quantized, in the first place. We take a field and decompose it into *harmonic oscillators* by way of a *Fourier-transform*. Each of these harmonic oscillators is then treated as a *quantum harmonic oscillator*. The Energy of a quantum harmonic oscillator comes in quantized units. More importantly, the lowest Energy state of a quantum harmonic oscillator is not zero but $(1/2)\hbar\omega$ where ω is the oscillator's *angular frequency*. When we sum this up for all possible values of ω, we get an *infinite* result.
When a theory is renormalizable, it basically amounts to a mathematically sensible process to discard the unwanted infinity but still properly account for the finite differences, which are responsible for physically *observable* processes. For instance, we may sum Energies not to infinity but to some finite cut-off value and use it to compute physically observable values. Then show that in the limit of the cutoff going back to infinity, the physical prediction doesn't change. Not all QFT's have this 'nice' behavior, but Relativity Theory has nothing to do with it.

528 -

If Gravitation is not related to Electromagnetism, why is *graviton* still limited by the speed of light limit?

Two things do not have to be related for to be subject to the same fundamental Laws of Nature. Apples are not oranges, yet both fall at the same rate from a tree.
Maybe, that part of the problem is that, for historical reasons, we call the *invariant speed of Relativity Theory* the '(Vacuum) speed of light'. The reason, of course, is that the theory was inspired predominantly by the observation that the speed of light remains constant regardless of the reference frame of the observer measuring it.
However, the theory itself is not about light or the propagation speed of electromagnetic radiation. The theory (talking about Special Relativity, in particular) *is about the mathematical relationship of inertial reference frames*. A key postulate of the theory is the existence of an *invariant speed that is the same for all* (*inertial*) *observers*.
Now, it so happens that if we write down a field theory (Gravitation, Electromagnetism, 'toy' theories like an arbitrary scalar field theory) in the context of Special Relativity, there really are two possibilities: either the theory is 'massless' (that is to say, the field has *no self-interaction Energy*) or it is 'massive'. If the theory is massless in the absence of sources (*Charges* in the case of Electromagnetism, *Masses* in the case of Gravitation), its equations are solved by *plane waves* that propagate at the *invariant speed* of Special Relativity.
Since both Maxwell's Electromagnetism and Einstein's Theory of Gravitation are *massless field theories*, this result applies to both. Free field solutions (waves) in these theories propagate at the invariant speed, namely the '(Vacuum) speed of light' (consequently, the free-field quanta in corresponding quantized versions of these theories would also propagate at the invariant speed c).
Now we might wonder what an alternative might look like. In the case of Electromagnetism, the alternative to Maxwell is Proca (or Maxwell-Proca) Theory (named after the Romanian physicist Alexandru Proca who first proposed it in the mid-20th century). In a quantized version of Proca's Theory, photons would be *massive* and travel *slower* than c. The

corresponding interaction of *Proca charges* would be like the behavior of Electromagnetic Interactions at *short range*, but beyond that short range, the interaction strength would drop very rapidly (exponentially). This behavior is, in fact, characteristic of the heavy Z^0- bosons of the Weak Interaction, which, for all practical intents and purposes, behave like (very) *heavy photons*. Similarly, it is possible to conceive of theories of Gravitation with 'heavy' gravitons.
But insofar as we can tell based on observation, neither Maxwell's Electromagnetic Field nor Einstein's Gravitational Field are *massive* fields. So, influences in both these fields, far from sources, *propagate at the invariant speed of Relativity Theory*.

529 -

How do Gravity waves escape black-holes that produce them?

Black-holes *do not* produce gravitational waves (sorry, a bit of pedantry: Gravity waves are what we see on the surface of the sea, distinct from *Gravitational Waves* which are propagating changes in the Gravitational Field). In fact, no spherically symmetric object (e.g., a pulsating star, a collapsing dust sphere) produces gravitational waves.
An inspiraling pair of objects (neutron stars, black-holes in particular) *does produce gravitational waves, but it doesn't come from inside those black-holes*. Rather, it is *their orbital Kinetic Energy that is converted into gravitational waves*, because of their non-straight-line motion. As a result, they lose Energy, fall towards each other, and eventually merge. The gravitational waves output is maximal around that moment and has a rapid 'ringdown' as the freshly merged object, spinning rapidly, settles down to a form that no longer emits gravitational waves at all.
Incidentally, even the Earth produces gravitational waves because of its motion around the Sun. But this gravitational wave output is so minuscule, a few hundred watts in total, that it is absolutely dwarfed by the total orbital Kinetic Energy of the Earth and wouldn't be observable even over the entire lifetime of our planet.

530 -

What is the origin of the *metric tensor* $g_{\mu\nu}$ that appeared in Einstein's General Relativity?

Feynman, in his Lectures on Gravitation, explains how a bunch of imaginary scientists from the planet Venus, who know Quantum Field Theory but until now never heard of Gravity, would go about constructing a Field Theory of Gravitation.
The math gets nasty, but the logic really isn't that complicated. A field theory is of course a theory in which some value is attached to every point in Space and Time. Maxwell's Theory is a field theory; the value at every point in Space and Time is a *vector*, with a magnitude and a direction. Newtonian Gravity can also be viewed as a field theory, with a single number (a *scalar*) attached to every point in Space and Time, measuring the strength of the Gravitational Field.
But Newtonian Gravity is not good enough. When we look at it in detail, we find that it necessarily violates the *Weak Equivalence Principle*: different forms of Mass-Energy respond to a Scalar Gravitational Field Theory in different ways. *This contradicts observational evidence*.
So, what could a sensible Gravitational Field Theory look like? Could it be a vector theory, like Maxwell's? Not really; in Maxwell's Theory, like charges repel, whereas in Gravitation, we know that two identical masses attract each other. Could it be a theory based on the exchange of half-spin particles like neutrinos? Again, the answer is no: such a theory would not even yield the inverse-square Law of Gravitation. So, by necessity, we end up with a so-called *Spin-2 Theory*, in which the value of the field to every point in Space and Time is a *tensor*, represented by a 4×4- matrix in a given coordinate system.
Because the theory is universal, this tensor 'couples' to all Matter Field equally. Therefore, the tensor can be viewed as a *geometric* object, determining the geometric relationship of Matter-particles. And in fact, because all Matter couples to this tensor the same way, every measurement we make will reflect this *altered* geometry, in which the Tensor Field of Gravitation determines Time intervals and distances, i.e., it acts as the *metric tensor* characterizing distances in SpaceTime. That's the gist of it.
Another hint comes from Einstein himself, what he reportedly characterized as his 'happiest thought': namely that because Gravitation is universal, things falling in a Gravitational Field will all *accelerate at the same rate*, so, when we are falling freely and look at objects near us that also are falling freely, we cannot tell if we are in fact falling in a Gravitational Field or floating freely in Empty Space. This geometric equivalence suggests that Gravitation itself can be represented by a *geometric transformation*, and that transformation is embodied in the *metric tensor*.

531 -

Are the equations of General Relativity used in NASA programs and missions?

Yes, very much so. When it comes to orbit determination, the equations that are used are based on what is known as the 'parameterized post-Newtonian', or PPN, formalism. These include the Newtonian Gravitational Equations for extended bodies, combined with corrections due to General Relativity, including corrections that account for general-relativistic terms due to the presence of velocities and accelerations.
When it comes to radio signals and precision radio-navigation, it is extremely important to account for the *Shapiro-delay*. First proposed by Irwin Shapiro in 1964 as a 4th classical test of General Relativity (the first 3, proposed by Einstein himself, were the *orbital precession of Mercury*, the *gravitational bending of light rays* and the *gravitational redshift of light*), it is a Time-delay due to the fact that rays of light not only travel on bent paths near a gravitating body but also that, as seen by a *distant* observer, they appear to be moving a little *slower* due to gravitational Time-dilation. Without the Shapiro Time-delay, *we would get the orbits of distant interplanetary probes all wrong, especially if their radio signals pass near the Sun*.
Closer to the Earth, the GPS constellation is navigated using the equations of General Relativity to achieve the desired precision. Also, experiments like GRACE and GRACE-FO, which use minute changes in the trajectories of an orbiting pair of satellites, are sensitive to very small deviations in the Earth's Gravitational Field, capable of building extremely detailed maps of the geo-potential; these details would not be possible without accounting for general-relativistic effects.
Finally, General Relativity is also used when it comes to astronomical observations, covering a range of phenomena including strong and weak *gravitational lensing*, the physics of extreme stars (e.g., neutron stars) and Cosmology.

532 -

Why is General Relativity (GR) not enough to correct Global Positioning System (GPS) time, considering that Special Relativity (SR) is a simplification of GR?

We should not be confused by the fact that there are two distinct effects determining the rate at which the clocks of GPS satellites appear to tick compared to terrestrial clocks. One of these effects is due to the *velocity of the satellite relative to the Earth*. To a good approximation, this effect can be calculated using SR alone (but not completely accurately, since the satellite *is not* moving in a straight line). The other effect of course is due to Gravity, notably the difference in the Gravitational Potential here on the surface of the Earth vs. at the satellite's altitude. This effect falls firmly within the scope of General Relativity.
But the actual calculation does not go like the question or this simplistic explanation implies. Sure, sometimes it may be convenient to do things this way. But oftentimes, the computation is done in one step: a general-relativistic coordinate transformation between the coordinate system of the satellite vs. the coordinate system of the Earth tracking station. These coordinate transformations consider *position*, *velocity*, and *local values of the metric*, i.e., the Gravitational Field. There are practical formulas that turn the tensor equations of General Relativity into equations that can be directly programmed into a computer as part of the tracking, navigation, and orbit determination of the satellites.
By way of an actual example for the interested people, here is the simplified version (some smaller terms, that would only confuse things, have been dropped) of an actual formula that is used in spacecraft navigation to convert a time interval Δt from the *solar-system barycentric* (CM) reference frame to a *geocentric* (GC) reference frame:

$$\Delta t_{\rm GC} = \left(1+\frac{v^2}{2c^2}\right)\left(\left(1-\frac{U}{c^2}\right)\Delta t_{\rm BC} - \frac{1}{c^2}\left(1+\frac{U}{c^2}\right)\boldsymbol{v}_{\rm E}\cdot\boldsymbol{r}_{\rm E}\right),$$

where $\boldsymbol{v}_{\rm E}$ and $\boldsymbol{r}_{\rm E}$ are the CM-*velocity* and *position* of the Earth (E), and $U \equiv Gm_{\rm E}/r_{\rm E}$ is the Newtonian Gravitational Potential at the Earth's location due to other solar system bodies.
This formula is *approximate*. It omits terms of order $(v/c)^3$ or $(U/c^2)^{3/2}$ and smaller, but these terms are usually much too small to make a difference (for the Earth orbiting the Sun, these terms amount to about 1 part per 10^{12}). But there are, of course, more accurate versions with additional, smaller corrections included.
This is just one example of the many practical formulas that use GR and a one-step calculation to account for the effects of both Gravity and *relative* motion.

533 -

According to the Equivalence Principle, an *accelerated observer* rightfully thinks that he is in a Gravitational Field. What is the source of that Gravitational Field according to the accelerated observer?

According to the Equivalence Principle, an accelerating observer *does not think* that he is in a Gravitational Field. The

accelerating observer thinks (and sees) that he is being *pushed by a force*.
What the accelerating observer cannot tell without an external reference is whether

a. he is being pushed by a force in *free space*, with his *speed increasing* relative to the distant stars, or

b. if he is being pushed against a Gravitational Field, *remaining at rest* relative to the distant stars.

Inside a windowless chamber, no gravitational experiment can be used to distinguish between the two scenarios. This is one way to state what is usually known as the Einstein Equivalence Principle (though more commonly, it is stated by comparing freely falling laboratories).

534 -

Since Gravity propagates at the speed of light and the path of light describes the curvature of Gravimetric Space, why aren't photons identifiable as gravitons?

By way of an answer, let's rephrase this question by way of a silly analogy: "Since transport trucks travel at the speed limit, and since the path of passenger vehicles describes the curvature of the road followed by transport trucks, why aren't passenger vehicles identifiable as transport trucks?" The answer is obvious: passenger vehicles don't do what transport trucks do, even if they follow the same trajectory, possibly on a highway that was primarily built for transport trucks. That is to say, the speed and trajectory alone do not define the type of vehicle.
Same goes for Gravity vs. Electromagnetism. Sure, Gravitational Radiation travels at the same speed as Electromagnetic Radiation in a Vacuum. Sure, both Gravitational Radiation and Electromagnetic Waves follow the same trajectories in curved SpaceTime. But otherwise, they have *very different properties*. The 3 fundamental differences (which have nothing to do with their speed or path of propagation):

1. the Electromagnetic Field couples to Electric Charges, the Gravitational Field couples to Mass;
2. the coupling of Electromagnetism to Matter is *many orders of magnitude stronger* than the coupling between Gravity and Matter; and
3. the *Polarization* properties of Electromagnetism and Gravitation are also very different, with Gravity having more, and more varied, states of polarization than Electromagnetism.

535 -

The Universe is expanding. Is it the space between Matter that is expanding, since galaxies are not moving further away but it's SpaceTime that's stretching?

Not for the first time, let's allow to be the contrarian here and challenge our esteemed colleagues who are telling that Space is expanding, by making three rather important (to me) points:

- what is this 'Space' that is expanding?
- How do we measure it? Where are its little markers to which we can attach our measuring tape?
- And exactly how is this 'Space' represented in the *Friedmann Equations*?

Speaking of which, if it were Space expanding, how come we can derive (see, e.g., books by Weinberg or Mukhanov) the aforementioned Friedmann Equations purely in the context of Newtonian Physics, with its concept of Absolute Space and Time?
Finally, when Gravity brings expansion to a halt, how does it do that? Is it somehow acting on 'Space', as opposed to acting on Matter (see also Peacock's Cosmological Physics)?
No, *Space is not expanding*. It's not even something we could measure if it did. The Friedmann Equations contain two entities: Matter (represented by its *density* and *pressure*) and the Gravitational Field (represented by one component of the very special, homogeneous and isotropic *FLRW* (*Friedmann-Lemaître-Robertson-Walker*) *metric*).
Galaxies are moving further apart. If we could stretch a measuring tape from the Milky Way to a distant galaxy, the distant galaxy would be zipping alongside that measuring tape at quite a clip (probably several hundred kilometers per second, at the very least). And when, in a region where Matter is denser-than-average, Gravity prevails, it stops those galaxies from moving away from one another.

536 -

Is the Higgs Field present in a black-hole? If not, then, there's no Mass, what is the source of the enormous gravitational pull of a black-hole? In the absence of Mass how can SpaceTime be distorted?

First, in Quantum Field Theory, *all fields are present everywhere*. The distinguishing characteristic of the Higgs Field after Electroweak Symmetry Breaking is that its 'Vacuum expectation value' (V. e. v.) is *non-zero*, hence particles that interact with the Higgs Field effectively interact with the Vacuum, even when the Higgs Field is free of 'excitations' (no actual Higgs particles are present).
However, when it comes to rest-Mass, the Higgs Field is only a *very small* part of the story. For ordinary Matter, almost all the rest-Mass comes from constituent protons and neutrons. But only about 1% of the masses of these protons and neutrons is due to their constituent quarks. The remaining 99% is due to the *Strong Force Binding Energy*, which has nothing to do with the Higgs Field.
Lastly, it is also important to recall that Gravity is not about rest-Mass. It is about all forms of Energy, including rest-Mass. And whereas rest-Mass is not conserved, Energy is. So, even if a physical process were to cause the Higgs V. e. v. to vanish, it would just mean that the Energy in the form of rest-Mass is converted into some other form of Energy; however, insofar as Gravitation is concerned, *the same amount of Energy remains*.

537 -

Gravity slows down Time. Acceleration and Gravity are indistinguishable in a *closed* system. Yet, they say that traveling at near light-speed slows Time dramatically. How is speed part of the equation when it appears it's all due to Gravity?

We may always hear that traveling at near light speed slows Time (indeed, it is something that unfortunately we hear frequently everywhere), but that does not make it true. In fact, 'traveling at near light speed' is a meaningless expression by itself. Why? Because *speed is always relative*. Therefore, we need to specify what we are traveling at near light-speed relative to.
As to time slowing down, if we are traveling at near light-speed relative to some observer, that observer will see our clock tick more slowly than his. But for us, nothing changes. In fact, as seen by us, our own clock is ticking just fine and it is that observer's clock that is running slow.
So, yes, if we are accelerating, the rate at which our clock ticks will differ from the rate of a clock belonging to an observer who is not accelerating with us. But this does not mean that we can distinguish Acceleration from Gravity. Without an *external* reference we cannot tell if

a. we are in an accelerating spaceship and the observer floats outside our spaceship without acceleration, or

b. we are standing on the floor in a homogeneous Gravitational Field, and the observer falls freely, passing by us.

538 -

Where do quarks get their charge?

Let's give an answer by recalling how Richard Feynman summed up the rules of Quantum Electrodynamics:

1. a photon goes from place to place;
2. an electron goes from place to place;
3. an electron emits or absorbs a photon.

That's it. Those are the basic rules of Nature that we discovered. We don't know why *these are* the rules. And unless we find a more fundamental rule from which these rules are deduced, we will never know the answer to that why question (and even then, we'd just replace one why with another).

Replace *electron* with *quark* and the same rules apply, insofar as the Electromagnetic Interaction is concerned (quarks also interact through the Weak and Strong Nuclear Interaction). The charge (of the electron or the quark) is, by the way, described by rule #3: it tells us that the Electromagnetic Field (photons) interacts with, is 'sourced by', the field of *electrically charged* particles (electrons or quarks). We could write these three points in a more precise language as

$$\begin{cases} -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ \bar{\psi}(i\gamma^{\mu}\partial_{\mu}-m)\psi \\ -\bar{\psi}\gamma^{\mu}eA_{\mu}\psi \end{cases} .$$

These symbols each have precise meaning. They directly correspond to the three points above. Summed together and put under an integral sign (the so-called *action integral*), they form the entirety of Quantum Electrodynamics. If one knows how to use these symbols (see, e.g., [17], …, [25]), exquisitely precise, quantifiable predictions can be made for the outcome of experiments. Similar rules (though a tad more complicated) apply to quarks.

But *we may never know* why Nature uses these rules and not some other rules that we can conceive. That is probably a question best left to priests or philosophers.

539 -

Why do electrons emit photons?

Electrons carry Electric Charge. Electric Charge is the source of the Electromagnetic Field. So, electrons interact with the Electromagnetic Field. In standard Quantum Field Theory, this interaction between the Electron Field and the Electromagnetic Field comes in set chunks, set units at any given *Frequency/Energy*. Therefore, whenever an electron interacts with the Electromagnetic Field, this interaction is in the form of emitting or absorbing such a unit, or quantum, of Electromagnetic Field Energy. That *quantum* is known as the *photon*.
In contrast, electron neutrinos do not interact with (emit or absorb) photons at all, even though apart from their lack of Electric Charge and smaller Mass, they are just like electrons. On the other hand, W- bosons, which are, very crudely speaking, just like electrons with their electron-ness removed (that is, an electron can emit an electron neutrino and turn into a W- boson), do interact with (emit and absorb) photons.
So, it really is the Electric Charge. If there was no Electric Charge, the Electromagnetic Field would exist just by itself, without interacting with anything else. No photons would be emitted or absorbed.

540 -

If the Cygnus X-1 black-hole is 15 solar masses, then how can it be feeding on a star that is 20 solar masses? Wouldn't the star have more gravity than the black-hole in this instance?

Let's remember that Gravitation is proportional to the inverse square of the distance to the center of the object (at least so long as we are outside that object).
Now, Sun's radius is about 696000 kilometers. That means we cannot get any closer to the Sun than 696000 km without colliding with it.
In contrast, a black-hole with the same Mass of the Sun has a radius that's < 3 km. So, we can get more than 200000 times closer to that black-hole than to the Sun. At that distance, the gravitational pull of the black-hole will exceed that of the Sun at the Sun's surface by a factor $> 10^{10}$.

So, now let's imagine this compact, tiny, but massive black-hole orbiting the Sun near the Sun's surface. The Sun's gravitational pull there, more than 696000 km from its center, is still quite gentle. In contrast, any Matter that is near the black-hole will be pulled towards that black-hole by a force that exceeds the Sun's by a factor of millions or billions (depending on how close that Matter is).
The Sun would be ripped to shreds in short order, its interior disrupted, eventually forming a dense, hot accretion disk around the black-hole and ultimately falling into it, producing a two solar-mass black-hole (less a small amount that might escape instead to infinity as a result of the complex dynamics of the two objects).
This would even be the case if the black-hole was only 1/10 or 1/100 as massive as the Sun, it'd just take longer.

541 -

Somebody said that when an electron passes through the barrier with the two slits it does not enter an eigenstate. Yet when it hits the fluorescent wall, it does. What accounts for the difference? Isn't the barrier a classical object?

The business of eigenstates is a bit trickier than the question implies. A particle may be in a position eigenstate. A particle may be in a Momentum eigenstate. A particle may be in some other eigenstate as defined by the way the apparatus is arranged.
So, just because a classical apparatus is present does not automatically imply that a particle is in a position eigenstate. The eigenstate that the particle may be in is determined by how its interaction with the apparatus is arranged. In this particular case, the apparatus forces the particle to a state that is a superposition of two paths but does not confine the particle to a single path. So, the particle will not be in a position eigenstate. The fluorescent screen, on the other hand, does confine the particle to a single, well-defined classical position, i.e., a position eigenstate.

542 -

How do we know CMB (Cosmic Microwave Background) is the remnant of the Big Bang and not supernovas or other microwave signals?

For starters, the CMB is a prediction of the Standard Cosmological Model, which was later verified by observation. The statistics of minute temperature fluctuations of the CMB in different sky directions can also be modeled. There is exquisite agreement between these model predictions and actual observations, including observations by the WMAP and Planck satellites.
Simply put, no alternative explanation exists that would produce such a smooth microwave background, never even mind its statistical properties and their precise match against the Standard Cosmological prediction.

543 -

If we had better neutrino beams and detectors, could we better transmit large amounts of data over long distances in space?

Neutrinos offer virtually no advantage for communication in space, even if we could transmit and detect them with the same efficiency as we can do with radio or light.
Neutrinos do, however, offer advantages here on the Earth, albeit only in very limited scenarios.
Years ago, for instance, we read about a proposal to use neutrino transmissions to rapidly communicate stock market information between distant exchanges, e.g., NYC vs. Hong Kong. Being able to transmit information at nearly the speed of light through the Earth's bulk in a straight line, as opposed to being confined to surface infrastructure such as undersea cables to transmit the same information can mean the difference of several milliseconds and apparently, that makes a difference in high-speed trading.
(Un-)fortunately (?), detecting neutrinos is incredibly hard, detecting them with the efficiency needed for practical data transmission is even harder, so, that probably put an end to this concept for the time being (the money, instead, went into burning enough fuel to satisfy the Energy requirements of several small countries, just to generate some pointless random numbers …).

544 -

The Higgs Field allows particles to have Mass and in return, it causes the curvature of SpaceTime. So, while trying to merge Gravity with Quantum Physics, can Higgs Field actually be 'Gravity'?

Interaction with the Higgs Field endows some particles with Rest Mass, but Rest Mass is not the reason for Gravitation (also known as the *curvature of SpaceTime*).
Gravitation is sourced by the combination of Rest Mass, Kinetic Energy, (Linear) Momentum, Pressure and Stresses. Massless particles are just as capable of being the source of a Gravitational Field.
So, the Higgs Field is not Gravity. In terms of fundamental theory, interaction with the Higgs Field, and specifically, interaction with its non-zero so-called Vacuum expectation value, is like any other particle interaction; it is a form of Potential Energy and, as such, one of the many sources of Gravitation, not the mechanism of Gravitation.

545 -

The unification of all forces is relevant to us even though forces ceased to be unified less than 10^{-9} sec after the Big Bang. Why is it relevant? Why massless particles do not experience Time and how the act of observing affects outcomes?

The unification of forces and fields is not about the first nanosecond. It is about finding a fundamental theoretical framework that is internally consistent and complete. The search is a result of our conviction that reality is mathematically consistent and logical, not some combination of disjoint and incompatible elements.
Whether unification is achieved in the sense alluded to by the issue (i.e., the notion that at high enough Energies, all fundamental forces are one) is debatable, and it is certainly not necessary to achieve our main goal of having a unified, self-consistent framework.
The problem is that we lack data. The Standard Model of Particle Physics is unsatisfactory in that it has as many as 26 dimensionless parameters the values of which must be measured and cannot be predicted. We aren't even certain that the Standard Model is fully consistent. Furthermore, it does not include Gravitation. Gravitation can be tacked on top by way of what is known as Semi-classical Gravity, but it is a deeply unsatisfying mix of Classical and Quantum. Yes, for all its shortcomings, the combination of the Standard Model and Semi-classical Gravity covers everything that we can explore through experiment or astronomical observation. There are no further hints from Nature as to what direction to take. This is frustrating enough for some physicists to propose that experiment should be abandoned altogether in

favor of pure reasoning.
As to particles not experiencing Time: none of them do. It is true that massless particles follow so-called null worldlines, worldlines along which the elapsed, 'proper' Time is always 0. But even massive particles lack any internal clock that would allow them to change, age, thus experience Time. In any case, this has no bearing on the business of unification.

546 -

What is the size limit of a black-hole, and could our Universe be inside of one?

Size is not the issue, really. Geometry is. The SpaceTime Geometry of a black-hole is characterized by a future singularity. The interior of a black-hole is like a collapsing Universe. Any Matter therein becomes denser over time, and light from distant Matter is blueshifted. An observer inside a black-hole could predict a finite future lifespan for the observable Universe.
In contrast, we see an expanding Universe, characterized by (it seems) a past singularity. Light from distant objects is redshifted. As observers, we note that the Universe has a finite age, but its future seems open and possibly infinite. So, this is the exact opposite of a black-hole.
In fact, it could be, in principle, that we live inside a Time-reversed black-hole, i.e., a so-called white-hole. It should be emphasized that there is no evidence of this, it is simply that the interior of a white-hole is well modeled by the same equations that we use in Cosmology to model the actual, observable Universe. So, it is conceivable. But a black-hole is not. Its interior has properties that would conflict with our observations.

547 -

What exists between the black-hole’s event horizon and its singularity?

Empty space. The celebrated solutions: the *Kerr solution* of a rotating black-hole, the *Schwarzschild solution* as the non-rotating special case, these are both Vacuum solutions. There is no Matter anywhere, just SpaceTime and Gravity.
Now, if we throw Quantum Theory into the mix, that Space won’t exactly be empty anymore, as there is *Hawking Radiation*, and we can expect the effects due to Gravitational Polarization of the Vacuum to only get bigger inside the horizon. But insofar as standard General Relativity is concerned, it’s all *empty space*. It is the asymptotic final state of a collapsing sphere of Matter, once all the Mass is concentrated in the infinitesimal vicinity of the singularity itself, and no Matter is left anywhere else.

548 -

How can galaxies move faster than the speed of light?

So, we heard that

a. in Relativity Theory, nothing moves faster than light, yet

b. in our expanding Universe, very distant galaxies may be receding from us faster than the speed of light.

Well … both true. First, it is true that nothing can move faster than the Vacuum speed of light at that location. Why is this important? Because once we are talking about a Universe in which Matter is present, so SpaceTime is no longer ‘flat’ but has curvature, the speed of light becomes a bit tricky.
For instance, if we were to float near the Sun, and measured the speed of a laser beam passing by us, we’d find that, as usual, it travels at 300000 km/s.
But if we were here on the Earth and watched through a telescope how fast that beam of light passes by an observer near the Sun, we’d measure a lower speed. This is a very real, observable effect, part of what is known as the *Shapiro delay*.
Something similar happens when we consider very distant parts of the Universe. We see (or rather, don’t see, as these things are beyond our observational horizon) galaxies that do not move faster than the speed of light in that neighborhood; in fact, compared to the Cosmic Microwave Background at their location, they are not moving any faster than our own Milky Way or other nearby galaxies, no faster than a few hundred km/s typically.
But when we measure how fast the distance between us and these galaxies is increasing … it is increasing *faster than the speed of light*.
This would not be possible if SpaceTime were ‘flat’. But it isn’t. Which means, among other things, that clocks tick at different rates in various parts of the Cosmos and at various times. So, what is measured by a local observer using a local clock as slower than light, is measured by a distant observer using his distant clock as much faster.
If this does not sound like an easy-to-digest explanation … it isn’t. It’s really another one of these cases where one can only go so far without the math. But the gist of it is that in curved SpaceTime, it is possible for two distant objects, neither of which moves faster than light does at its location, to move faster than the speed of light relative to each other.

549 -

Do black-holes induce Time dilation time because of their Gravity or because of the speed we would have to travel to stay out of its event horizon?

The Time dilation that characterizes a black-hole is *gravitational*. With the exception of the so-called *ergosphere* of a rotating black-hole (a rather shallow region), we do not need to travel at any speed to stay out of the event horizon (inside is another matter, but we're not discussing that here). We may need an immensely powerful rocket to hover (and we may not survive the acceleration) but we could be at rest.
Still, our clock would run a lot slower than the clock of a distant observer. One way to think about it is to think of what happens to a light ray that we aim upwards. As that light ray 'climbs' out of the gravitational pull of the black-hole, it loses Energy. But light rays do not slow down. Their Energy is determined not by their speed but by their frequency: the number of cycles per second of the actual electromagnetic wave that we perceive as light.
So, let's suppose we send a light ray upwards, and it has $7.5 \cdot 10^{14}$ cycles/s (blue light). When it arrives at a distant observer, he counts $5 \cdot 10^{14}$ cycles/s (red light).
But suppose we modulated our light ray so that every $7.5 \cdot 10^{14}$- th pulse is stronger. In other words, we marked every second. At the receiving end, they will still see every $7.5 \cdot 10^{14}$- th pulse stronger, but they are now separated by 1.5 s as measured by their clock. So, for every second we measure, the observer some distance away measures 1.5 s. All this because of the difference in the Gravitational Potential at our location vs. at that observer's location. No motion is involved.

550 -

At a certain angle, would light be able to travel through a black-hole and then orbit the singularity for a bit, before using the extra acceleration due to orbit to fire out of the black-hole?

Here is something important to remember about black-holes. They are not simply structures in Space, with absolute Time ruling everywhere. They are structures in SpaceTime.
Let's recall what that means. When we think of a black-hole's event horizon as a spherical shell … OK, it can be described like that from the outside. Except that this spherical shell has not yet formed. When we are outside, no matter how close to the black-hole, the event horizon is still something that hasn't come into existence yet, and it will remain forever in the future … unless we cross it.
When we cross the event horizon, we experience it not as a spherical shell but as a *moment in Time*. Indeed, from this point onward, what we may have thought of as the radial coordinate plays the role of Time. The arrow of Time points from the event horizon (which is now a *past* Time-moment) towards the singularity (which is a *future* Time-moment).
The singularity at this point is no more avoidable than 2 PM next Friday. We cannot evade a moment in Time by some clever trajectory. And to get us of the black-hole? We'd need to cross the event horizon backwards, but that means we must go back in Time because the event horizon is a *past* Time-moment.
So, cleverly chosen angles won't help us. The only we or a photon can get out of a black-hole is by using a *Time machine*. Without it, we are doomed to end up in the singularity (at least for a spherically symmetric Schwarzschild black-hole) because we are in what is, for all practical intents and purposes, a collapsing mini-Universe. Around us, all Matter and light that ever fell, will ever fall into the black-hole is there, taking part in this inevitable collapse: things become denser, Gravity become stronger, until eventually time itself comes to an end.

551 -

What is the relationship between the Higgs Field and Higgs Boson? How does discovery of Higgs Boson prove the Higgs Field?

The Higgs field is a surprisingly complicated beast. Mathematically it is represented by a pair of complex numbers (a so-called *complex scalar doublet*). A complex number has two components of course; so, a pair of complex numbers has four. Particle physicists will count these as *degrees of freedom*.
The Higgs Field interacts with many other fields, including the so-called *gauge bosons* of the Weak Interaction. These bosons start their life as *massless* bosons, just like photons of light. But photons do not interact with the Higgs Field; the gauge bosons do. As a result of this interaction, they behave as though they had Mass (we can think of the Potential Energy they gain as a result of the interaction as their rest Mass-Energy). As these gauge bosons become (very) massive, they are much harder to produce than photons and *decay very quickly*. Consequently, the Weak Interaction range is (greatly) reduced. Interactions that would otherwise be as obvious and as long-range as the Electromagnetic Interaction thus become barely detectable, extremely 'weak'.
But there are only 3 gauge bosons. These 'eat' 3 of the 4 degrees of freedom in the Higgs complex doublet but 1 degree

of freedom remains. The prediction, a fundamental prediction of the Standard Model of Particle Physics was that if the Higgs Mechanism is a correct, valid description of Nature, this 4th degree of freedom will manifest itself, will be seen, as a scalar boson particle. Its mass could not be predicted from theory, but it was known to be somewhere between a little over 100 GeV (giga-electronVolt; 1 GeV is roughly the mass of a proton) and several hundred GeV.
Finding this Higgs boson therefore became top priority for Particle Physics. Its detection would confirm the Standard Model; failure to detect would indicate that something is very wrong with the model. So, when the *Higgs Boson* was finally detected in 2012, this was a major vindication of the theory.

552 -

If a planet could successfully orbit a black-hole without being harmed, what would the sky look like from its surface?

This question is another example of how badly black-holes are misunderstood. Suppose we replaced the Sun with a black-hole of the same Mass. It would have two consequences:

First, the Earth would continue to orbit exactly as before. The thing about Gravity is that it doesn't matter what does the pulling: two things of the same Mass will produce the same amount of Gravity. So, the Earth's orbit doesn't change so long as the Mass of the central object doesn't change.

Second, the sky would be dark, apart from the stars. Where the Sun would be, we'd see nothing. The black-hole's event horizon is only a few kilometers across, and any weird optical effects due to its strong Gravity are confined to a region not much larger ... far too small to see, never mind the naked eye, even with a large telescope. So, it's as though there was nothing where the Sun used to be. We'd see the stars just fine, in that and every other direction. We would not see the Moon of course, since there is no sunlight for it to reflect ... and we would not see any planets, for the same reason. And of course, in short order, Earth's weather would start to go berserk, the oceans would freeze over, and within a few months at the most, life on the surface of our planet would come to an end as *nitrogen* snow falls from the cold sky. But that is simply due to the lack of sunshine, not due to anything the black-hole does.

553 -

What is the maximum density of Matter, such as in the case of a black-hole? Since a blackhole with higher Mass also has a higher volume, do we know how dense all Matter within the black-hole is?

While it is tempting to calculate a density for a black-hole using its mass and dividing it by the volume of a sphere with the same radius as the black-hole, this is *misleading*.
For starters, the 'standard' black-hole solutions (Schwarzschild, Kerr) contain no Matter at all: *they are Vacuum solutions* of the equations of General Relativity (the Mass parameter is attributed as a *non-local property* of this object, or, if we wish, as a property of the singularity itself; there's no actual Matter involved.)
Also, the volume of the black-hole is technically undefined. Static coordinates do not exist inside the horizon, and it is not possible by any meaningful maths to integrate the interior to obtain a sensible measure of volume.
Having said that … if we go with the naïve calculation (Mass divided by Volume of the sphere) and assume that a black-hole cannot get much smaller than the Planck Mass before it evaporates completely by way of Hawking Radiation, the highest possible value for this 'effective' density would be roughly the Planck Density, which, in SI units, is more than $5 \cdot 10^{96}$ times *larger* than the density of water.

554 -

If electrons have no size, how can two electrons collide?

The answer is … *electrons do not collide*, at least, not in the classical sense. Electrons do not interact with electrons directly (or, in the language of Quantum Field Theory, the electron field is 'linear', free of self-interactions).
However, electrons do interact with the Electromagnetic Field, i.e., they emit and absorb photons and, on account of their Electric Charge, act as sources of the Electromagnetic Field, changing its properties. When two electrons get close to each other, each electron begins *to respond to the changes in the Electromagnetic Field due to the other electron*. Or, if we wish to use that language, they exchange *virtual photons* at a growing rate. The closer they are, the more intense this exchange gets, manifesting itself as a repulsive force between the electrons. As a result, the two electrons 'bounce off' each other (even though they never actually touch in the Classical sense), an event that we describe as a *collision*.

555 -

To address how Gravity can increase the speed of light in a Vacuum, should c in $E = mc^2$ be called 'the c in the Lorentz Transformations, which is the ultimate speed limit of the Universe $\approx 3 \cdot 10^8$ m/s ' instead of 'the speed of light in a Vacuum'?

Gravity does not increase the speed of light, Vacuum or no Vacuum. As a matter of fact, as seen by a *distant observer*, light actually *slows down* slightly in the presence of a *strong* Gravitational Field (this is called the *Shapiro delay*, and it is a measurable effect when it comes, e.g., to radio signals from distant spacecraft passing near the Sun).
Nor is the Vacuum speed of light necessarily the 'ultimate speed limit' in an absolute sense. Sure, it is the ultimate speed (unattainable) for any observer reference frame but there are things, e.g., the red dot from a rapidly swung laser, a shadow, even the start of the gap between the blades of a pair of scissors, which can move faster than the Vacuum speed of light. What the Vacuum speed of light really is, it's an *invariant speed*. That is its key identifying property: this speed is *the same for all observers*. *All other speeds depend on the observer*. A fast-moving train is *stationary* relative to a passenger on board but the speed of a ray of light, very counterintuitively, is the same for both the train passenger and a person standing on the platform.
We call this invariant speed the Vacuum *speed of light* mainly for historical reasons. What led to the discovery of Special Relativity was the recognition that if Maxwell's Electrodynamics holds *in all* observer reference frames, the associated speed of electromagnetic waves, i.e., the Vacuum speed of light, *must be the same for all observers*.
Since then, we know that alternative theories exist (the so-called Maxwell-Proca Theory and its variants) in which light actually travels slower than the invariant speed. But every observation to date suggests that the *correct* theory of Electromagnetism is the Maxwell theory, so we are not making any mistake calling the invariant speed the *Vacuum speed of light*. Still, it is true that the concept of an invariant speed is much more generic than the concept of the propagation speed of waves in specific field theory.

556 -

When scientists say that Space is expanding, do they mean that just the edge of Space is expanding out, or is all Space expanding? Is there any real way to measure Space expanding? Is there an accepted rate which it expands at?

Scientists who understand the fundamental equations of Cosmology *do not say* that Space is expanding. To quote from one of the best Cosmology texts, Peacock's '*Cosmological Physics*' (Cambridge Un. Press, 1999):

"Many semi-popular accounts of Cosmology contain statements to the effect that 'Space itself is swelling up' in causing the galaxies to separate. This seems to imply that all objects are being stretched by some mysterious force. Are we to infer that humans who survived for a Hubble Time would find themselves to be roughly 4 meters tall? Certainly not. Apart from anything else, this would be a profoundly anti-relativistic notion, since Relativity teaches us that properties of objects in *local inertial frames* are independent of the *global* properties of SpaceTime. If we understand that objects separate now only because they have done so in the past, there need be no confusion. A pair of massless objects set up at rest with respect to each other in a uniform model will show no tendency to separate (in fact, the Gravitational Force of the mass lying between them will cause an inward relative acceleration). In the common elementary demonstration of the expansion by means of inflating a balloon, galaxies should be represented by glued-on coins, not ink drawings (which will spuriously expand with the Universe)."
There we have it, straight from the horse's mouth, so to speak. *Space is not doing any expanding*. It is the things in this Universe that fly apart, and they do so because they've been doing so in the past; if something (e.g., their mutual Gravity) stops them from flying apart, they will not be flying apart. There is no force involved.
There is indeed *no way* to even measure '*Space expanding*'. Space does not have little markers attached to it. We can only measure things flying apart from each other, i.e., the distance between them increasing.
Finally, there is no edge (as far as we know), no matter how far we go, there is more Space, still more galaxies, still flying apart. This includes (as far as we know) regions of Space where the galaxies fly away from us faster than the Vacuum speed of light, but these regions are not accessible to us, cannot be observed, so Relativity Theory (which predicts this!) remains intact. Again: Space does not expand, it's things that fly apart.

557 -

If Time doesn't exist at the speed of light, does it mean that a photon experiences no lifetime of its own and being absorbed at the same time of being emitted, regardless of the distance between emission and absorption?

Photons do not 'experience' anything. They are not 'observers', not only because they are elementary particles with no internal state, but also because no observer reference frame exists at the Vacuum speed of light.
The point raised in the question is one reason why: any such reference frame would be degenerate, with 0 *proper Time*

and with Space collapsed along the direction of the photon's Momentum.
Another way to think about it is by noting that

a. by definition, a particle in its own reference frame is always at rest,

b. a key postulate of Special Relativity is that the Vacuum speed of light is the same for all observers. Therefore, for an observer moving at the Vacuum speed of light, his own speed would simultaneously be

c. zero (the observer is at rest in his own frame of reference), and

d. the Vacuum speed of light (if some observers see this observer move at the Vacuum speed of light, the observer himself should see the same thing, since the Vacuum speed of light is the same for all observers). These two statements contradict one another; hence no observer can exist that moves at the Vacuum speed of light.

558 -

Gravity warps SpaceTime, we envision 'no-gravity' as a plane, with indentations where there is Mass, but would negative Mass or anti-Gravity be shown as 'hills' on the plane of SpaceTime?

While Gravity indeed warps SpaceTime, the visualizations that we often see, with Gravity causing indentations in Space, are just plain wrong. Sure, Gravity does warp Space, and it does have a tiny effect, a small correction to Newtonian Gravity. But most of Newtonian Gravity arises from how Gravity warps Time. When we work out the equations, we fall downwards in the Gravitational Field of the Earth because clocks tick more slowly further down. And indeed, if there were such a thing as anti-Gravity, it would manifest itself as clocks speeding up.

559 -

Why is there a cosmic speed limit? Why does nothing in the Cosmos travel faster than light speed?

For starters, it's not so much a speed limit but a fixed speed. Observations tell us that the Vacuum speed of light is the same for all observers, regardless of their own motion. This is very counterintuitive: Whether we run away from, or towards, a light source, the speed of light that we measure will be the same. This observation is elevated to a principle, and the existence of an 'invariant speed' becomes the foundation of Relativity Theory.
Now, this has many consequences. They can be explored using the appropriate rigorous math, but the business of a 'speed limit' can be explained even without getting lost in the mathematical details.
As mentioned before, the Vacuum speed of light is the same for all observers. So, something that moves at the Vacuum speed of light *will appear to move at the Vacuum speed of light to everybody*. At the same time, an observer is always at rest in his own reference frame. Our speed relative to ourselves is 0. Now let's suppose we are actually moving at the Vacuum speed of light. That speed is the same *for all observers*, including us. So, we would simultaneously measure ourselves as moving at the Vacuum speed of light and as being at rest. This is clearly a contradiction, which is resolved by concluding that no observer reference frames exist that move at the Vacuum speed of light.
What about moving faster than the Vacuum speed of light? The math tells us that a speed that is faster than the Vacuum speed of light for one observer is faster than the Vacuum speed of light for all observers. Again, this leads to the same contradiction: if we move faster than the Vacuum speed of light, we will simultaneously appear to ourselves to be moving faster than the Vacuum speed of light and being at rest (which is obviously slower than the Vacuum speed of light).
These naïve descriptions are not without some plot holes, but the actual mathematics is airtight. The inevitable conclusion is that only slower-than-light reference frames exist. But that does not mean that nothing travels faster than the Vacuum speed of light! By way of a simple thought experiment, let's imagine a very powerful laser pointer aimed at a very distant wall. If we were to wiggle the laser pointer fast enough, the red dot on that wall may move faster, way faster even, than the Vacuum speed of light. Similarly, shadows can move faster than the Vacuum speed of light. Even the start of the gap in a gigantic pair of scissors can move faster than the Vacuum speed of light. The so-called *phase velocity* of light itself in certain mediums, such as a charged plasma, can be faster, way faster even.
What is common in all these things is that they are not associated with observer reference frames. They also cannot be used to carry signals. The red dot of the laser pointer may move very fast on a distant surface, but someone at that surface cannot influence the red dot to send a message to someone else at a different location at that surface. And again, all this is due to the existence of an invariant speed.
On the plus side, what appears like a restriction is quite beneficial: it is this invariant speed that grants our Universe its *causal structure*, allowing the future to follow logically and predictably from the present, with all effects having identifiable causes, and ultimately, allowing us to exist and make sense of the world around us.

560 -

Why does Gravity accelerate?

For the same reason other interactions cause acceleration. When we say that two things interact, that means that Energy is required to either separate them or pushing them together; and Energy is released when we do the opposite.
What do we mean, 'Energy is released'? Contrary to popular misconceptions, Energy is not some mysterious substance that can be 'released'. Energy exists either as Potential Energy or as Kinetic Energy. Potential Energy is what has been just described, the Energy associated with the relative position of things that interact with each other. Kinetic Energy, in turn, is the *Energy of motion*.
So, when we say, Energy is released, it means conversion of Potential Energy into Kinetic Energy.
Overall, Energy is conserved. But as Potential Energy is depleted, Kinetic Energy increases. Or conversely, as Kinetic Energy is depleted, it can result in an increase in Potential Energy. Either way, the presence of an interaction can cause motion to change. In other words, acceleration.
This is not unique to Gravity. Every interaction works this way. If Gravity is special, it's only because it is *universal*: things respond to Gravity the same way regardless of their material constitution (this is not true for Electrostatic Fields, for instance. A charged particle behaves differently from a neutral particle in such a field: one interacts with the field and through the field, the source of the field, the other does not).
Finally, we may wonder why there's a tendency for Energy to convert from Potential to Kinetic more than the other way around. The reason has to do with statistics. Once we have Kinetic Energy, things move. As things move, they may collide, redistribute that Kinetic Energy. What starts off as nice, orderly motion may become randomized. Random motion of particles is otherwise known as *heat*. This heat is then dissipated in the form of *Thermal Radiation* (another form of Kinetic Energy, the Kinetic Energy of the infrared or visible light photons of *heat* from a hot object). It then becomes quite impossible to collect all that Energy and put the genie back into the bottle, so to speak (it is the unscrambling an egg problem). This is quantified by the concept of Entropy, which as we know always increases in an isolated system: eggs break and get scrambled, but never get unscrambled on their own and return into the unbroken shells.

561 -

Could we tell if a star or Galaxy was made of Antimatter?

Almost certainly, yes. Here is the thing: the Cosmos is very, very, very empty but not completely empty. Among other things, it contains H atoms. Not a lot of H. Less than 1 H atom per m^3. But there are lots and lots of cubic meters.
So, place an Antimatter galaxy in this Matter-dominated Universe and what happens? Where it meets the intergalactic medium, there will be the occasional annihilation as a H atom meets with its anti-Matter counterpart from the anti-Matter galaxy. Again, not a lot of such encounters per m^3, but there are lots and lots (and lots and lots) of m^3 in volumes so large, they are best measured in $(\text{Mlight-yr})^3$, not m^3. The resulting characteristic γ- radiation would be seen by our instruments. And it is not so.
Therefore, even in the largest so-called voids in intergalactic space, we could determine if a galaxy is made of Antimatter by the way it interacts with its environment. To date, no such galaxy has been seen.

562 -

If Gravity moves at the speed of light, does that mean Gravity is electromagnetic light? Such as photons moving outward from the source?

No, it means that both electromagnetic waves and gravitational waves (which is what is meant, presumably; they are often confused, but gravity waves are the waves on the surface of the sea) obey the same rules of Relativity Theory. Rules that, among other things, tell us that in a so-called massless field (such as the Electromagnetic Field or Einstein's Gravitational Field, i.e., the SpaceTime metric) so-called Vacuum solutions are plane waves propagating at the invariant speed of Relativity Theory. This invariant speed (invariant meaning it is the same for all observers, regardless of those observers' own motion) is usually called, for historical reasons, the (Vacuum) speed of light.

563 -

If the Universe is growing, what lies beyond to edge of growth if not more Space?

The Universe is not 'growing' (not in the Standard Cosmological Model, anyway). It is not 'getting bigger'. It is an infinite Universe, with no boundary, no edge, and no meaningful concept of 'size'. It is getting *less dense* over time as

everything (on average) is *flying away from everything else* everywhere.
This sounds a bit counterintuitive, but that is the nature of infinity. Let's take a line, infinitely long and imagine it is marked with numbers in both the positive and the negative direction: $\ldots, -3, -2, -1, 0, 1, 2, 3, \ldots$. Now, let's make a copy of this line and connect every number on the first with *double* that number on the second: 0 to 0, 1 to 2, 2 to 4, and so on, also in the negative direction, -1 to -2, -2 to -4, etc., we can find a double for every number, no matter how big right? So, no number will be left over. Yet for every number on the first line, we picked an even number on the second line, which are spaced *twice as far apart*.
That's pretty much how a spatially infinite Universe works. It is the same infinite Universe even as the spacing between the things it contains continues to increase (on average; it is not increasing inside bound structures, such as clusters of galaxies, specific galaxies, solar systems, stars, planets, people, molecules, atoms).

564 -

How is the value of Gravity 9.81?

Let's go back to first principles to give a thorough answer to this question. The first principle, in this case, is Einstein's theory of Gravitation, General Relativity, which states that the presence of Matter determines the Gravitational Field. In turn, the Gravitational Field determines Matter's motion and dynamics. Einstein formulated his Theory in 1915; in 1916, K. Schwarzschild offered *the simplest* (and celebrated) *analytical solution* to Einstein's Field Equation, known as the *Schwarzschild solution*. This solution also describes black-holes, as well as the Gravitational Field of any *spherical* object *external* to that object.
The Earth is spherical to a good approximation. Its Gravitational (vector) Field $\mathcal{G}$, compared to a black-hole or a neutron star, is extremely *weak*. In this case, the Schwarzschild solution can be approximated satisfactorily by the Newtonian Gravitational Potential function,

$$\phi_{\mathrm{G}} = -\frac{GM}{r} \ .$$

Here, G is Newton's Constant of Gravitation, M is the mass of the (*spherical*) *gravitating* (*source*-)object and r is the distance from the center of this object (*larger* than the radius of the object, so that we are *outside* of the object).
The Gravitational Acceleration that determines the motion of a (*test* or *field*) particle in this Gravitational Field is given by the radial derivative of the Gravitational Potential function,

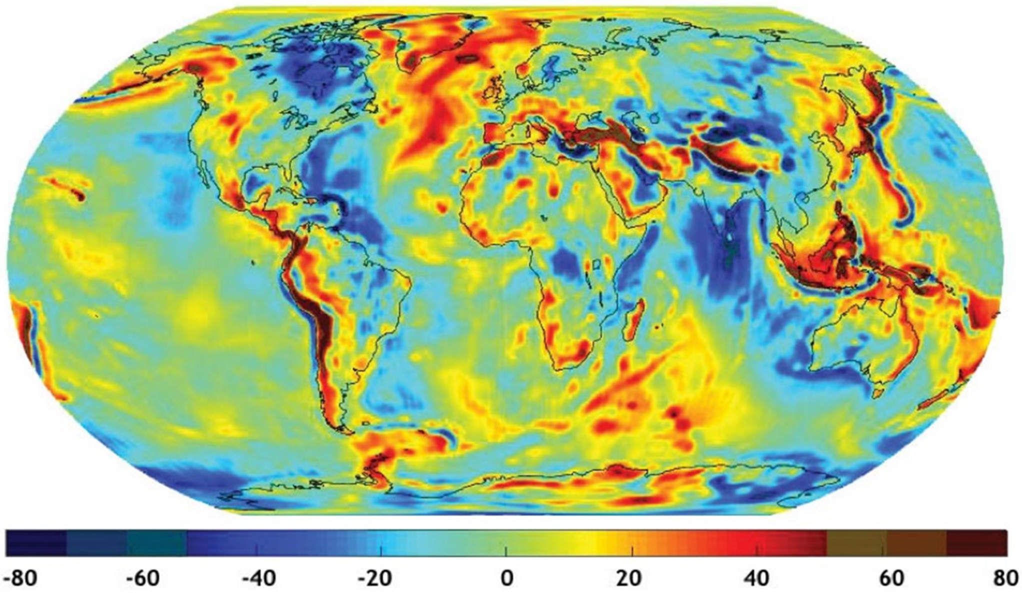
$$g = -\frac{d\phi_{\mathrm{G}}}{dr} = -\frac{GM}{r^2} \ ,$$

where the *negative* sign is used to indicate that acceleration points *towards the* (*source*-)*object*.
This is all we need to know: the value $G = 6.67408 \cdot 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$, the Earth's mass $M \approx 5.97243 \cdot 10^{24}\,\mathrm{kg}$ and the *mean* Earth's radius, $R \approx 6.37280 \cdot 10^6\,\mathrm{m}$. So, when someone stands on the Earth's surface, we get:

$$g = -\frac{GM}{R^2} \approx 9.81481\,\mathrm{m/s}^2 \, .$$

However, in this calculation the small contribution of the Earth's rotation has been *ignored* and the resulting *centripetal* force that *cancels out* some of the *gravitational* force. This tunes of as much as $0.03\,\mathrm{m/s}^2$ at the equator, diminishing toward the poles.
For this reason, the value of $9.81\,\mathrm{m/s}^2$ is just a *mean value*; the actual value can vary significantly from place to place, depending on the distance from the equator, altitude, but also local gravitational anomalies due to varying densities of the underlying rocks, oceans, etc.

In fact, here is a map of the Earth's Gravitational Acceleration, as observed by the GRACE spacecraft:



The units are $0.00001\ m/s^2$, and the color coding measures small *local deviations* from the idealized Gravitational Field of a rotating *spherical* and *homogeneous* Earth.
This spacecraft could not only map the Gravitational Field with great precision (let's note how changes in the Gravitational Potential closely follow geographic features such as the outlines of continents, major mountain ranges, etc.), but also seasonal changes in it, due for instance to changing groundwater levels or snow and ice cover.
Finally, let's note that the number, 9.81 is a *dimensioned* quantity: it is measured in m/s^2. Both units are *cultural* artifacts, not constants of Nature. In different units, the numerical value is different. For instance, in US customary units, we have $32.2\ ft/s^2$; or whatever else. Such cultural artifacts depend on the units being used to measure Length and Time. However, the *physical meaning* is the *same* for all cases.

565 -

Why doesn't the Universe have 4 *spatial* dimensions?
[cf/c answer to Issue 407, P. 184]

While usually, Physics cannot answer 'why' questions (these are best left to priests or philosophers), we may find a surprisingly straightforward answer. If there were 4 spatial dimensions, we could not tie a knot, really.
There are no knots in 2-dim, of course. A segment of that string or rope could not go above or below another segment, as there is no 'above' nor 'below' in 2-dim.
So, we need at least 3 dimensions to tie a knot. But what about 4? Well … here is one way to represent 4 dimensions conveniently, at least for some problems: give that rope or string some *color* and *postulate* that two string segments can glide through each other *if they are not of the same color*. Now when we tie a knot, all we must do is 'move' part of the string in the 'color' direction, so that it becomes a little redder, a little bluer, or whatever, and now it just glides through the other segment that would hold it in place. Presto, the knot is gone, and we didn't even need a sword.
So really, 2 spatial dimensions are just too few for meaningful structures (e.g., having an internal digestive system with two separate orifices would cut our bodies into two *disconnected* parts) but 4 dimensions *are too many*. Just 3 spatial dimensions offer the *right combination of freedom and constraints*.

Same goes for Time, by the way. We need 1 Time dimension for there to be, well, Time, and it must be 1 Time dimension (i.e., a dimension that makes the metric pseudo-Euclidean) for the Universe *to be causal*. But if we add another Time dimension, causality goes out the window: the future becomes *unpredictable*, no longer determined by the 'present', as the 'present' with respect to 1 Time dimension is not the 'present' with respect to the other.

Then again, it is possible to have additional dimensions so long as their observable effects are strongly suppressed. Superstring Theory, for instance, which requires (at least) 10 dimensions in total, deals with the additional dimensions by 'compactifying' them. The basic idea is illustrated intuitively with the surface of a garden hose: it is a 2-dim surface, of course, but when we look at it from a distance, we only see a line (the length of the hose). The other dimension, which is ‘curled up’, can only be seen *if we are close*. If this curling up business happens far below the subatomic scale, the extra dimensions become unobservable, and we are left with the $4\ (= 3 + 1)$ familiar macroscopic dimensions.

566 -

What happens if part of a *long object* goes into the event horizon? What does an external observer see?

From an external observer’s perspective, this never happens. The long object will approach the event horizon. The external observer will see simultaneously divergent length contraction and divergent time dilation. The object will appear shorter and shorter as it approaches the horizon, its near end never quite reaching the horizon; meanwhile, it will slow down. Eventually because any light from it is redshifted into invisibility, it vanishes from sight without ever reaching the horizon.
From an infalling observer’s perspective, the situation is even more interesting. For the infalling observer, a) the horizon is nothing special, and b) it is not a place but a moment in Time. The infalling observer would have no way of measuring it, but the moment when he crosses the horizon is also the moment when everything else crosses the horizon, including both ends of the infalling long object. In other words, this is when the ‘mini-Universe’ that contains everything that ever has fallen and ever will fall into the black-hole, is created. *And this is not a pleasant Universe*. The observer will also note that this is a *collapsing Universe* in which everything is approaching everything else. Trying to evade the collapse is not possible as it is a future moment in Time. In fact, the more the observer accelerates, the less it takes in terms of his own *proper Time* until *complete collapse*. Complete collapse is represented by a ‘final singularity’ when the *density* and *pressure* in this mini-Universe becomes *infinite* and Time itself comes to an end. It happens at the same time for everything, including this hapless observer and for both ends of the long object.

567 -

It’s said that our Universe is at the exact balance between expansion and contraction (critical density), but considering that Dark Energy does not attenuate, will it eventually overwhelm other forces and break the balance?

This question seems to reveal a slight misunderstanding of the nature of the critical density and a spatially flat Universe. The critical density means just that: a Universe with no spatial curvature. In other words, if we could draw a triangle in this Universe, no matter how large, its three angles would always add up to $180°$.
Now, it is indeed true that in a Universe with no Cosmological Constant, containing only Matter with a 'reasonable' equation of state (and specifically excluding one of the limiting cases, Dark Energy), this also means that the expansion of the Universe will continue forever, but the rate of expansion will asymptotically tend towards zero. So, yes, there is a balance of sorts.
But once we introduce a *positive* Cosmological Constant (or Dark Energy, which means the same thing insofar as the equations are concerned), this changes: instead of tending towards 0, the rate of expansion, i.e., the *Hubble parameter* H_0 will tend towards a limiting value, which is determined by the magnitude of the Cosmological Constant.

A truly constant Hubble ‘constant’ actually (confusingly) means *accelerating expansion*. Say, the constant in the far future is $50\ \mathrm{km/(s \cdot Mpc)}$. That means that two galaxies one megaparsec (Mpc) apart will recede from each other at $50\,\mathrm{km/s}$. But then, billions of years later, when the two galaxies are already at 2 Mpc apart, they’ll recede from each other at $100\,\mathrm{km/s}$ 100. This means they *accelerate*. The force that causes this acceleration is (again confusingly) Gravity.
When Dark Energy dominates the Gravitational Field, the field becomes repulsive (the reason for that is that, in the Newtonian limit, the source of Gravitation is not the Mass density ρ but, rather, $\rho + 3p$, where p is the *pressure*; for most ordinary Matter, $|p| \ll \rho$ in the appropriate units and can be safely ignored, but for Dark Energy, $p = -\rho$, so, $\rho + 3p = -2\rho < 0$).
Therefore, there is really no balance to be broken, but it is indeed true that without Dark Energy, expansion tends towards 0; with Dark Energy, it tends towards a *positive* value when expressed in terms of the Hubble parameter.

To pile confusion on top of confusion, it should also be noted that the Cosmological Constant was initially introduced by Einstein in an attempt to preserve a balance of *another kind*: to create a Universe that can stay in equilibrium, neither expanding nor contracting over Time. The attempt failed: even if such a configuration is obtained, it is not stable and begins to either expand or contract after the slightest perturbation. And this attempt prevented Einstein from actually trusting his equations and predicting cosmic expansion; supposedly he characterized it as his biggest blunder.

568 -

If objects in the Cosmos are flying apart rather than space expanding, why does recession velocity increase with distance from the position of the observer?

The recession velocity does 'not' increase with distance for any specific object. A galaxy that is today, say, 2 Mpc from here and is moving away at $140\ \mathrm{km/s}$ will, some $1.4\cdot 10^{10}$ yr from today, be at 4 Mpc but still moving away from us at roughly $140\ \mathrm{km/s}$ (it is slightly faster, actually, because of the *repulsive* Gravity of Dark Energy and the *resulting accelerating expansion*, but let's leave that aside from now).
So, yes, this means that in a Universe without Gravity, the Hubble parameter H_0 is not a constant but decreases over Time. This decrease is a negative exponential relationship. For $H_0 = 70\ \mathrm{km/(s\cdot Mpc)}$ the value is halved roughly every $1.4\cdot 10^{10}$ yr . Galaxies that are farther away from us move faster, but that is the very reason why they are farther away in the first place: they traveled a greater distance over the same amount of time.

569 -

Could the *Pauli blocking* (that predicts the quantum effect of a cloud of gas *cold and dense enough* makes it invisible) explain Dark Matter?

Maybe, what inspired this question makes sense, but the answer is *no*. Indeed, recent news is that fermion condensates in the laboratory have been used successfully to demonstrate *Pauli blocking*: *in a dense, low Energy state in which all Energy states available to the fermions present are filled*, the medium cannot absorb Energy from light because that would mean that a fermion could jump to a state already occupied by another fermion (Pauli Principle). Consequently, this medium *does not* interact with light and becomes *transparent*.
But all this comes with caveats. Shine something stronger, say, UV-, γ- rays, or whatever, and we are going to dislodge some fermions, *destroying the state*. And there is the business of *pressure*! Dark Matter in cosmological models is characterized not simply by the fact that it does not interact with light at any wavelength (including very high Energy γ- rays). It also does not interact with itself and has 0 pressure. This is certainly not how the condensates used to demonstrate Pauli blocking are described.
Finally, the condensate state may be exotic, but the stuff it is made of is not: it's still perfectly ordinary atoms. We have upper limits from cosmological observations on the ratio of ordinary (baryonic) Matter in the Universe. This is how we know that whatever Dark Matter is, *it cannot be baryonic Matter*. There just aren't enough baryons, not even close.

570 -

What makes the *Planck units* the *smallest* units of Time and Space?
[see Issue 91, P. 40-41]

Planck units *are not* the smallest units of Time or Space. This is one common misunderstanding that frequently appears in popular accounts about Quantum Physics. The standard theory that forms the backbone of our understanding of the nature of Matter, Quantum Field Theory (QFT), *does not quantize Space or Time*. They are *continua*: neither Space nor Time have 'smallest units'. The stuff that is actually quantized are the *fields* that are the fundamental constituents of Matter. They are broken up into an *infinite sum of harmonic oscillators*, every one of which gains or loses Energy in the form of *quantized excitations* (elementary units), *which we perceive as particles* under the right circumstances.
So, what is it with Planck units, then? Well, they are so-called '*natural*' units, which offer certain advantages in calculations. But let's notice how most Planck units depend on, among other things, the *Gravitational Constant*, despite the fact that we do not have a generally accepted Quantum Theory of Gravity, and *Gravitation is not part of our Standard Model of Particle Physics*. That alone should tell us that these Planck units *may not have any physical significance*.
So, why do people think that perhaps Planck units do have some physical significance after all? Because the general consensus is that QFT itself is an *approximation*, an '*effective*' theory, *which loses its predictive power near the Planck Energy*, in part because it cannot account for Gravity, which becomes just as strong as the other forces at these energies. Therefore, when it comes to the Planck Length or Planck Time, they *represent the scale at which our existing theory of Matter presumably becomes useless*. It does not mean that they are units of Space and Time. *They simply represent the limit where our knowledge ends*.

571 -

As the Universe expands presumably Space-Time expands, but is the expansion of Space-Time more like stretching or is new Space-Time being created or does the expansion occur by some other process?

Physical Cosmology is about Physics. Physics is about stuff we measure. We measure *cosmic expansion* because there are things in the Cosmos and these things are flying apart. The distance between these things is increasing. It should be emphasized the word 'thing', referring of course to galaxies or clusters of galaxies, i.e., the largest gravitationally bound structures that follow different trajectories and, well, fly apart from each other. This is reflected by the famous *Friedmann Equations of Cosmology*, which relate the *average density* of Matter (i.e., *things*) in Space to the Gravitational Field; the latter expressed in terms of the *Hubble parameter*, which can be derived from the metric of SpaceTime, i.e., Gravity). Here is what we do not measure: We don't measure SpaceTime; SpaceTime is not a tangible thing. It does not have little markers in it to which we can attach meter sticks or affix clocks nor does SpaceTime appear in the Friedmann Equations. Yet, it is often presented as though SpaceTime was expanding. That is because a very convenient form of the SpaceTime metric is written in what is known in the literature as 'co-moving coordinates': in this coordinate system, the coordinate positions of things remain the same over Time, the distance between them increasing because the metric changes.
But, and it cannot be emphasized this powerfully enough, Physics does not depend on the theorist's mathematical choice of a coordinate system! Co-moving coordinates are convenient, but they do not represent Physical Reality. Physical Reality is the distance we measure between two clusters of galaxies. The practical measurement is fraught with difficulties, but in terms of principle, if we had billions of years at our disposal, we could set up transmitters in both clusters and simply use synchronized light pulses and timing to precisely measure their distance, much the same way as we do ranging measurements with spacecraft in our solar system. The result is that the distance is increasing. This measurement is not dependent on the choice of coordinate system: these physical objects are flying away from each other. And it doesn't require SpaceTime to expand, stretch or do anything else. Cosmic expansion, Einstein's Field Equations in particular, is about things we measure. SpaceTime is not one of those things.
As to those things that are flying apart, they would continue to fly apart at a constant rate, were it not for the fact that there is, in fact, a force acting on them: Gravity. Their mutual gravitational attraction is slowing down the expansion. Or at least, it used to slow down the expansion until about $5 \cdot 10^9$ yr or so ago. But in addition to Matter, our Universe is also believed to contain Dark Energy. Dark Energy has tremendous *negative pressure*, and that means that it behaves as though Gravity were *repulsive*. Moreover, the density of Dark Energy remains constant even as it expands (no, it does not violate any conservation laws; rather, Gravitational Potential Energy is converted into Dark Energy). So, over time, Dark Energy begins to dominate over other things, and when that happens, Gravity no longer slows cosmic expansion; on the contrary, it is now accelerated.
But at no point is 'SpaceTime' involved in all of this. We are talking about Matter fields (even if it is something as outlandish and exotic as Dark Energy, it is still a form of 'Matter' in the most general sense of the world) and Gravitation interacting with each other.
In the past, quotations were made from books by noted scientists and cosmologists, such as Weinberg, Peacock, Mukhanov and others, but in the end, we need not appeal to authority, as that is not scientific. Ultimately, it's about what the equations say, not how notable a physicist is. And the equations do not talk about SpaceTime doing anything nor do the equations suggest or imply in any way that SpaceTime is quantifiable, that it can be created, destroyed, stretched, or measured. The equations talk about the SpaceTime metric (i.e., the Gravitational Field) and Matter.
The final witness is not (... insert the name of some famous physicist here ...) but equations like

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

(see, e.g., WIKIPEDIA: *Friedmann equations*). That says it all.

572 -

Why do some physicists say that QM is not deterministic when it clearly is? Schrödinger Equations are a set of partial differential equations, by definition, deterministic. Surely, the measurement is probabilistic, but the theory is not. Why?

It is absolutely correct: the Schrödinger Equation is a deterministic equation that describes the evolution of the wavefunction. The problem is not how the wavefunction evolves but what it means. In the standard Copenhagen interpretation, the wavefunction is a *probability amplitude*. It can be used to compute the probability that when a measurement is being made, the system will be found in a specific eigenstate. We cannot predict the outcome of that measurement. We can only predict these probabilities, based on the exact, deterministic evolution of the probability amplitude, i.e., the wavefunction. But we might say, perhaps we got this all wrong. This 'measurement' business involves a *classical instrument*, and we all know that, in reality, no truly classical instruments exist. Everything is made

of quantum particles, so perhaps it will be some monster of a Schrödinger equation, but we ought to be able to, at least in principle, describe the world as a whole using a deterministic Schrödinger equation.
Well … true. But in order for the equation to work, the way it's supposed to, we need initial conditions. Initial conditions in the form of Positions and Momenta. This is not a problem in Classical Physics; we can happily define initial Positions and Momenta however we want. But in the Schrödinger equation, in Quantum Physics in general, Positions and Momenta are not numbers. They are non-commuting quantities: $pq - qp = -i\hbar$. If one of them is in an eigenstate, *the other cannot be*. We cannot simultaneously define both Positions and Momenta with arbitrary accuracy (of course, this is the Uncertainty Principle at work).
Still, the mathematical equations are deterministic, but now a full description of the system requires additional information, such as the future (final) state. In short, we can regain the deterministic nature of the theory, but we must pay a price in the form of giving up the notion of *locality*: the evolution of the system is no longer uniquely defined by initial conditions, final conditions (i.e., the 'future') also influence the system at the present.

573 -

What is the main cause and the inevitable mechanism of *slowing down* photons in glass?

To understand what happens to photons in glass, it is first important to understand what photons really are. Because if we think of photons as miniature cannonballs, we will inevitably arrive at the wrong conclusion: photons absorbed, re-emitted, or bounced around by atoms in glass. That actually can happen (it is called *scattering*) but this is now how light that passes through glass without being scattered by it interacts with the medium.
So, what are photons, then? Why, they are the quanta of the Electromagnetic Field. Here's a brief recap of Quantum Field Theory. Let's take a field and express it as an infinite sum of sinusoidal oscillations (that is, let's do a *Fourier transform*). Let's treat each of these 'modes' as a *harmonic oscillator* and use the rules of Quantum Mechanics to quantize it. We find that each of these oscillators will have discrete levels of Energy. The field can interact with the environment by gaining or losing Energy one step at a time. What we perceive as particles are these discrete chunks of Energy.
What even this brief explanation should make clear is that the fundamental concept in Quantum Field Theory *is the field, not its quanta* (the particles).
Now let's take specifically the Electromagnetic Field. In the absence of other fields, its Vacuum solutions are plane waves propagating at the Vacuum speed of light. This remains true even when we quantize the field, it's just that now those plane waves have *quantized units of Energy* (i.e., photons).
Now let's solve the field equations in the presence of a medium that interacts with the field. The presence of that medium changes the equations. The solutions are now plane waves traveling at a speed other than the Vacuum speed of light, and a speed that is dependent on the frequency of that wave. When we quantize the field with these new boundary conditions, we get quanta that *behave like massive particles*, moving *slower* than the speed of light.
So, it's not that something happens to photons in glass: *it's that something happens to the Electromagnetic Field in glass*, so that its quanta, the photons, behave differently.

574 -

How do quantum particles communicate when separated by great distance?

They are not particles and they do not communicate. That's how.
The fundamental objects of modern Quantum Physics *are not* particles (miniature cannonballs) but *fields* that are present everywhere. Take Quantum Electrodynamics, for instance. There are only two things in this theory: the one-and-only Electromagnetic Field and the one-and-only Electron Field. That's it. Nothing else.
Now because these are *quantum fields*, they don't just willy-nilly start wobbling about. Their excitations come in *set units* (*quanta*). So, when the Electron Field interacts with the Electromagnetic Field, it may create a *unit excitation*, which we call a *photon*. Or when the Electromagnetic Field interacts with the Electron Field, it may create two opposite unit excitations (an *electron* and an *anti-electron*, i.e., a positron).
Again, these things are *excitations of fields*. The reason why we call them particles is because, well, first they can be counted. We can count how many excitations an electron field has, one at a time. That's what *being quantized* means.
Second, when we interact with these excitations, they tend to be *localized*. We detect a photon, we know where we detected that photon, even though prior to the detection, the excitation was everywhere … but what the excitation really determined is the *probability density* of detecting that photon at various locations.
So that, then, is the answer: *quantum particles do not communicate*; *quantum fields have correlated properties*. But when we detect the excitations of these fields, sometimes a great distance apart, it is as though some magic communication took place, *as we observe that correlation*.
If we find this explanation less than satisfactory (as we indeed should), unfortunately all we can say is that we need to

learn the math. To understand how interacting quantum fields can behave this way yet not violate *causality* nor communicate over great distances, we really need to learn the math of Quantum Field Theory. Without the math, clumsy explanations will have to do, like the current attempt above.

575 -

We know that this vast Cosmos was created billions of years ago. How did the cosmologist find this duration?

The basic idea is rather simple: when we look at a cloud of things that are flying apart and measure the speed at which they are flying apart, we can deduce how long ago they began flying apart.
Of course, the Cosmos is a tad more complicated than that. The rate at which things are flying apart is controlled by Gravitation, described using Einstein's Field Equations for General Relativity. The source of that Gravitation includes Matter, the presumed Dark Matter (the existence of which is yet to be confirmed independently) and the even more mysterious Dark Energy, which has a *repulsive* contribution to Gravitation.
But we also have more observable quantities. *First*, the business of things flying apart: estimates of the rate depend on accurate measurements of their distance and velocity. Of course, we cannot take a piece of measuring tape to a distant galaxy, so the distance has to be estimated using its physical characteristics (e.g., observing certain types of stars with known physical characteristics in that galaxy and measuring their apparent *brightness*). As to the velocity, we are basically measuring the *Doppler frequency shift of light*; but this is complicated by the fact that the frequency of light is also changed by Gravitational Fields.
Then, there are other observables including the *Cosmic Microwave Background* radiation, the *statistical distribution* of millions of galaxies throughout the Cosmos, or the *ratios of isotopes of light elements* like H and He.
Our cosmological theory has to be consistent with all these data. And it is, although there are issues and open questions. Still, when we fit the model to the data, we find that it is consistent with a $13.8 \cdot 10^9$ year-old Universe. That is to say, the time when the Universe was very *hot*, very *dense*, with conditions comparable to the reaction chambers in our largest particle accelerators was $13.8 \cdot 10^9$ years ago.
What happened before that, we don't really know. General Relativity tells us that this early Universe at that time was only a pico-second or so old, starting with an initial 'singularity' a moment in Time when the distance between anything and everything was 0, the Density was ∞, and Time only *just began*. But we have no reason to trust General Relativity in this case, or indeed any of our theories, *because they are not validated by experiment in this extreme regime*, far beyond anything we can either see in the Universe today or replicate in the laboratory.
Therefore, we don't really know for sure that the Universe is $13.8 \cdot 10^9$ year-old; we only know with reasonable certainty that $13.8 \cdot 10^9$ years ago it was extremely hot and extremely dense everywhere, a so-called *quark-gluon plasma* with atoms yet to form.
Well, that's the short version of the story. The long version? Well, that's what's in the textbooks on Physical Cosmology.

576 -

What is 'symmetry breaking' and how can Higgs Field break 'symmetry'?

First, let's illustrate what 'symmetry' means in this context through a simple example.
We buy a new car. The manual tells us that the car consumes 8 L of gasoline on a highway over 100 km. It does not matter when we are doing the driving. We can do it now or an hour from now. Or tomorrow. It is still 8 L/100 km. This an example of Time translation symmetry. The figure is invariant under *Time translation*.
It also doesn't matter which stretch of the highway you use. Say, we are driving from A to B. Fuel consumption will be 8 L/100 km near A, and 8 L/100 km near B. This is a symmetry under a *Space translation*.
Now let us break the symmetry. For instance, instead of driving today, we postpone my driving until a very hot, sunny day in July, when we would be using the air conditioning in the car throughout the journey. As a result, fuel consumption increases to 8.5 L/ 100 km. So, in this case, weather *broke Time translation symmetry*.
Or, how about a cross-country drive. For a long time, we drive in open, flat, 'big sky' country. But eventually, as we approach a mountain range, the road starts to climb, relentlessly climb, kilometer after kilometer. And we can easily find that our fuel consumption rises significantly, say, from 8 L/100 km to as high as 10 L/100 km or more. So, the varying terrain *broke the symmetry under Space translations*.
Not every symmetry is this easy to visualize. Many modern theories of Physics have abstract, 'internal' symmetries. For instance, Electromagnetism can be described, in part, using a complex number, but in such a manner that only the *magnitude* of the complex number matters, not its phase (if you are not familiar with complex numbers, just think of an arrow in a plane. The arrow has a direction and a magnitude. But Electromagnetism depends only on the magnitude of the arrow, not its direction). This is called $U(1)$ *gauge symmetry*.
A similar, but even more abstract symmetry is called $SU(2)$, and it is the symmetry of the Weak Force. Or would be, if

the Weak Force was mediated by particles with no *rest mass*, just as Electromagnetism is mediated by the photon, which has *no rest mass*.
But in comes the Higgs Field. Most fields have a simple property: they are in their lowest Energy state when they are 'free of excitations', i.e., when no particles are present. This is not the case with the Higgs Field. Its 'no excitation' state is a higher Energy state compared to when some excitations are present. So, the 'Vacuum' (no excitations) 'decays' and goes into this *lower* Energy state by producing excitations of the Higgs Field.
What happens with these excitations? We do not see them around, because they are, to use imprecise but figurative language, 'eaten up' by other fields, notably charged fermions and more importantly, the mediating particles of the Weak Force. As a result, excitations (particles) of these fields gain Energy even when they are at rest. We know of course that Energy is Mass, so this process endows the respective particles with Mass.
The moment the mediating particles of the Weak Force are endowed with Mass, they *no longer* obey the $SU(2)$ gauge symmetry mentioned above. So, the Higgs Field, together with its strange Potential (which is responsible for the decay of the Vacuum) and its non-zero so-called Vacuum expectation value, is responsible for the Weak Force vector bosons' mass and the fact that they no longer obey the abstract $SU(2)$ symmetry.

577 -

In Quantum Field Theory, do the *excitations* vary from observer to observer?

An excellent question and the answer is ... *yes*! In the general case, two observers indeed do not necessarily see the same excitations in a quantum field theory. The excitations of a quantum field theory arise when we Fourier-transform the field into a sum, or integral, of harmonic oscillators, each of which is then quantized.
In Minkowski SpaceTime, there is an unambiguous preferred frame (the inertial frame; as to which inertial frame, it's irrelevant so long as the Quantum Field Theory itself is Lorentz-Poincaré invariant) for this Fourier transformation, and the result is the same for all inertial observers. However, even in Minkowski SpaceTime, we get a different result for accelerating observers. This is how, for instance, an accelerating observer gets to see *Unruh Radiation* (a thermal bath, basically) where an inertial observer sees nothing.
And once Gravity is present and the SpaceTime is not Minkowski SpaceTime anymore, we lose that nice, unambiguous inertial reference frame. Excitations, the observed particle content, will in fact vary from observer to observer. To be clear, all observers agree on the fields they see, but for different observers, the field decomposes into elementary harmonic oscillators and their excitations (particles) in different ways.

A very good (technical) reference on this topic is Wald's 'Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics' (Chicago Lectures on Physics, 1994).

578 -

Do Einstein's Field Equations really change the fact that, in the final analysis, massive objects attract each other as Newton said?

Let's first quote from Newton himself, from a letter to Bentley from 1692:

> "Tis unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon & affect other matter without mutual contact; as it must if gravitation in the sense of Epicurus be essential & inherent in it. And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate inherent & essential to matter so that one body may act upon another at a distance through a vacuum without the mediation of anything else by & through which their action or force may be conveyed from one to another is to me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws, but whether this agent be material or immaterial is a question I have left to the consideration of my readers."

Newton himself knew that his 'gravity project' was unfinished: he described a force acting instantaneously over a distance, without a mediating agent, which he himself considered 'unconceivable'. Einstein supplied that mediating agent in the form of the Gravitational Field. In the process, two things happened:

1. Einstein's Gravitational Theory introduced *small corrections* (which only become large/significant in *extreme gravitational fields* or at *velocities near the speed of light*) to Newton's Gravity; this provided an explanation for Mercury's anomalous *perihelion shift*, and offered a markedly different prediction for the deflection of light by the Sun compared to Newton's corpuscular theory;

2. The universality of Gravity offered an interpretation of it as a form of geometry, because a geometric transformation can always be used to 'remove' the effects of Gravity in the vicinity of a freefalling object (as other freefalling objects nearby will appear at rest or moving at constant velocity).

So certainly, Einstein's work did not change the *qualitative* features of Newton's Theory, nor its applicability to weak fields and objects moving at non-relativistic velocities. Rather, Einstein offered a refinement of a theory, while at the

same time solving its most puzzling aspect that Newton already found disturbing.
Ultimately, if we drop higher-order corrections, Einstein's Field Equations reduce to *Poisson's Equation for Gravity*, which is simply the modern (as in, 18th century 'modern') representation of Newtonian Gravitation. In a terrestrial context, Poisson's Equation is good to the tune of 1 part in 10^9, give or take, which is more than good enough for most applications (but not all; one, often cited exception, is GPS satellite navigation).

579 -

What is the core difference between the theory of General Relativity and the Quantum Theory? Do they interpret certain phenomena differently? How?

General Relativity, like all classical theories, deals with numbers and objects (vectors, tensors, etc.) constructed from numbers. A key property of numbers is *commutativity under multiplication*: $pq = qp$ for any (generalized) *Position* q and (generalized) *Momentum* p.
Quantum Physics, in turn, deals with quantities that *do not obey* this commutation rule. Whether represented by operators acting on the wavefunction, by matrices, or by other mathematical entities, a key property of the quantities used in Quantum Physics is that they do not commute under multiplication: $pq - qp := -i\hbar$.
The process of 'promoting' quantities to such non-commuting entities is nowadays done using fairly rigorous mathematics; this is what is referred to as *quantization*.
Now we wonder why this is needed. What's wrong with a theory that involves perfectly sensible, ordinary numbers? Such theories are great but, unfortunately, *that's not how Nature works*. As experiment after experiment shows, *Nature works according to the rules of Quantum Physics*.
One particular quantum system that we can investigate is the *simple oscillator* (the *harmonic oscillator*). It is a good approximation for many physically relevant cases. When we quantize the harmonic oscillator, we find that it has *discrete* Energy levels (hence the name, '*quantum*'!) and has a *minimum Energy that's not zero*.
Quantizing Classical Mechanics gives Quantum Mechanics. We can also quantize a Classical Field Theory, such as Electromagnetism. The trick is to break the field down into a sum of harmonic oscillators, which we can do by way of a *Fourier-transform*. These oscillators can then be *quantized*. A potential obstacle is that there are *infinitely many* of them, each with a non-zero ground-state Energy. The sum of these would be *infinite*. Fortunately, we are only interested in differences in Energy between different states, and those remain *finite*. This is how we can go from Maxwell's Classical Theory to Quantum Electrodynamics.
The problem is that this nice, clean prescription *fails for Gravity* because those infinite sums refuse to go away, refuse to leave us with only manageable, finite differences. Therefore, we were not able to develop a satisfactory theory of Quantum Gravity so far.

580 -

Is Mass quantized?

The answer is *no*. So, first: Mass is a *type* of Energy but not all Energy is Mass. This is a common logical jump and is simply not correct. (*)
Energy (nor Frequency) *is not quantized* in general and, therefore, *Mass is not quantized*. Only a few things in Quantum Mechanics end up being quantized, these happen to be some of the most interesting phenomena in Quantum Mechanics, but they are not the norm. For instance, certain transitions in bound states (e.g., atoms) give rise to photons of specific Energies, but a photon can have *any* Frequency/Energy, in general.
So, there are numerous subtleties that are confusing. First, $E = mc^2$ is for the *rest-Mass* of the particle (i.e., the Energy for a particle when it's sitting still). The more general formula is $E = (c^2(m^2c^2 + p^2))^{1/2}$ where p is the (Linear) Momentum of the particle.
Photons do not have any Mass yet have Energy. A photon's Energy is proportional to its (Linear) Momentum. So, when physicists say that photons are quantized, what that means is that if we have an Energy, E, and want to divide that up into photons, we can divide it into

- 1 photon with a frequency $\omega = E/\hbar$,
- 2 photons with frequencies ω_1 and $\omega_2 = E/\hbar - \omega_1$,
- n *monochromatic* photons with frequencies $\omega = E/(n\hbar)$, etc.,

where the more standard *angular* frequencies $\omega = 2\pi\nu$ is used. Let's notice that *when we have 2 or more photons, their frequencies aren't quantized*. (**)

Now there is a related concept of a *Compton frequency* for a *massive* particle, which is defined to be

$$\omega = mc^2/\hbar$$

This is the frequency when *relativistic effects become important* for a particle. However, the Compton frequency is a *derived* quantity and *does not mean* that Mass is quantized.

(*) The formula we give actually is meaningful, but it is usually stated as $\nu = mc^2/h$. This is known as the *Compton frequency* of a (*massive*) *particle*. At time scales *smaller* than the Compton frequency, *relativistic quantum* effects become important.

(**) As a side note, this phenomenon is observed in the H atom for the 2s → 1s transition. The dominant decay mode is into 2 photons which do not have quantized frequencies (there is a subdominant 1-photon transition that has a quantized frequency that occurs very rarely).

581 -

Electromagnetic waves are often represented as *linear* waves going in one direction while *gravitational waves* are represented as *concentric* waves going in all directions. Is this really the case or they are the same?

Both *electromagnetic* waves and *gravitational* waves can be represented different ways, depending on whether we are looking at waves produced by a nearby source, or looking at waves approaching us from a great distance.
When it comes to *sources*, the representation uses *spherical* waves. This is true both for Electromagnetism and Gravity.
When it comes to waves coming 'from infinity' (that is to say, produced by a source so far away, it might as well be infinitely far) the waves can be described very accurately using the *Vacuum*, *plane-wave* solution of the theory.
The one difference is that whereas *electromagnetic* radiation is *dipole* radiation (basically, the 'wave' is just *perpendicular* to the direction of propagation), *gravitational* radiation is *quadrupole radiation* (the wave is *two* waves, *perpendicular to each other and the direction of propagation*, causing a *metric distortion* of SpaceTime that *alters shapes but conserves volumes*). However, this is not usually depicted in popular accounts.

582 -

For a distant observer, does a black-hole event horizon form before it *evaporates*?

To the best of our knowledge, nobody knows for sure (a definitive answer would require a working Quantum Theory of Gravity) but our (hopefully reasonably educated) guess is that no, the horizon *will not form*. Let's remember the title of the first landmark paper that describes gravitational collapse, by Oppenheimer and Snyder: On *Continued* Gravitational Contraction (emphasis on 'Continued').
For the outside observer, the collapsing object very quickly becomes *indistinguishable* from a fully formed black-hole, due to exponentially increasing Gravitational Time Dilation. But 'indistinguishable' is not 'same'. The actual horizon formation remains in the outside observer's *infinite* future, whereas Hawking Radiation, due to Gravitational Vacuum Polarization, is present now, and will lead to *evaporation* in *finite* time.

583 -

In Special Relativity, the object's Mass becomes *infinite* when moving at the speed of light. So, light should have infinite Mass, but it doesn't. How can this be explained?

In Special Relativity, an object's rest-Mass remains exactly what it is, an intrinsic property of the object, certainly not dependent on the fact that some random observer is moving relative to the object very fast in some direction.
Oh, but you heard about 'Relativistic Mass'? Relativistic Mass is a piece of mathematical fiction. These days, it appears less and less in courses or textbooks on Relativity Theory, precisely because it is so misleading. It can be a useful calculational tool to compute things like the Energy or Momentum of a massive (!) object in a *moving* observer's reference frame. It is utterly useless as a tool to deal with things that have zero rest mass to begin with, such as photons.
To explain in more detail, consider the famous *dispersion relation*:

$$E^2 = c^2(m^2c^2 + p^2)\,,$$

where m is the *invariant rest-Mass* of the object, p is its Momentum, c of course is the *Vacuum speed of light* and E is the *total* Energy, in some observer reference frame. If the observer is co-moving with the object, for that observer the object is at rest with zero Momentum: $p = 0$. The dispersion relation therefore gets reduced to the well-known equation

$$E = mc^2\,.$$

On the other hand, for objects with no rest Mass, we get

$$E = cp\,,$$

which tells us that for objects like photons, their *total* Energy is proportional to their Momentum.
We can generalize this relation to *objects with non-zero rest-Mass*, for which the following is true:

$$E\frac{v}{c} = cp\,,$$

where v is the speed of the object. Substituting this back *into the dispersion relation*, we obtain

$$E = \frac{mc^2}{(1 - v^2/c^2)^{1/2}}$$

and

$$p = \frac{mv}{(1 - v^2/c^2)^{1/2}}\ .$$

Introducing the 'Relativistic Mass',

$$m_{\text{rel}} = \frac{m}{(1 - v^2/c^2)^{1/2}}\ ,$$

allows us to write things like

$$\begin{cases} E = m_{\text{rel}}c^2 \\ p = m_{\text{rel}}v \end{cases}.$$

Note that this only works to begin with when $m > 0$ and $v < c$, so, *photons are out*. And in any case what's the point? The sole benefit we get is that by using m_{rel} we recovered a formula for the Momentum that is formally identical to its non-relativistic counterpart. But why is that a 'good thing'? It really isn't. It obscures, not enlightens. So, let's forget about Relativistic Mass. It is not a helpful concept.

584 -

What if Dark Matter and Dark Energy don't exist and it's something else pulling the galaxies apart? What could it be?

(Guest contribution by Richard Muller, Professor of Physics, UC Berkeley)

(When physicists don't understand something, they do what everyone else does: give it a name. That helps them talk about it, but don't confuse that with understanding (!)).

A few years ago, physicists discovered that the expansion of the Universe is *accelerating*. It turns out that the equations of General Relativity could accommodate that easily; just put back in the 'Cosmological Constant' that Einstein had originally put in, and then *mistakenly* taken out.
So, the first conclusion of the discoverers was that the Cosmological Constant was not zero. But if you take that constant, and simply move it over to the other side of the Einstein Equation (with a minus sign, of course) then it looks like an Energy term. So, physicists called it 'Dark Energy'.
Is it Energy? Actually, we have no idea what it is but it behaves exactly like Energy does, and is part of the conservation of Energy. So, we might as well call it Energy. Does it exist? As much as any Energy exists. What if it doesn't exist? To say that we must argue that the experiments are wrong, but they have been verified independently, they have become more precise, and there is independent evidence now (from microwaves) *that it is there*.

Dark Matter is similarly established. We see motions of stars, clusters, and galaxies that deviates from the motion that would exist if all Mass was related to light-emitting Matter like *stars* and *molecular clouds*. There are two possibilities:

a. Einstein's Equations for Gravity are *wrong*, and

b. there is some *dark* (*unseen*) *Matter* that has a *Gravity Field*.

Given the variety of the deviations (seen within the plane of our Galaxy, seen in galactic clusters; seen in the expansion of the Universe) nobody has been able to come up with a variation on General Relativity that could account for it. So, we take the other interpretation: it is 'Dark Matter'. We don't know what it is. If we speculate that 'Dark Matter doesn't exist' then we are left with an *anomalous* behavior of Gravity that is even more mysterious.

585 -

If 70 years ago, somebody had said: “When you fire two protons at each other at non-crazy speeds, electric repulsion pushes them away from each other before they get too close”, how does she\he would expect Gravity to create fusion from a cloud of gas in space?

Well, for starters … take a glass of water. Every one of its molecules contains two protons (H atoms) and they are held quite closely together by a simple chemical bond; not close enough to fuse, but still. Same thing in a H_2 molecule: just two H atoms, stuck together quite close.

The secret, of course, is that every one of those protons comes with an electron attached, so the bulk electric charge is canceled out. This way, it is quite possible to create blocks of H that stay together for *extended* periods of time even in *empty space*: just frozen bricks of H far from any heat source.

So, let’s now start putting lots and lots of frozen bricks of H together. We can, because these bricks are electrically neutral (again, those pesky electrons are present).

When we reach a certain point, we will notice that Gravity and the resulting *pressure* deep inside our growing mass of H becomes large enough such that, in the deep interior, we surpass the *triple point* and, eventually, the *critical point* of H, so that there is no real distinction anymore between solid, liquid, and gaseous phases; it’s just an *increasingly degenerate medium*. And we can still keep adding bricks of frozen H to the pile. We could, in principle, start with just H gas instead of frozen blocks of H (it may seem easier to imagine blocks of frozen H).

So, the point is, when our pile of H reaches a mass that is up to a few percent of the mass of the Sun, the pressure deep inside becomes large enough to occasionally *squeeze protons* together to the point where they *begin to fuse into heavier atoms*, releasing Energy. The process will be very inefficient at this point, of course, but it begins, and a star is born.

But OK, if the electrons were not present, none of this would happen. The electric repulsion between protons far exceeds their gravitational attraction. A ‘pure proton’ star would be fundamentally *unstable*; it would never form in the first place, but if we somehow managed to make one, it would instantaneously explode in one of the biggest explosions this Universe has ever known.

This is not the way things work, however. Rather, a star is electrically neutral (more or less) as it contains the requisite number of electrons to balance out the charges of the protons.

586 -

Relativity, Special and General, are described in terms of Space-Time. Yet all the non-math descriptions of expanding Universe are given in terms of expanding distances between objects. Is there an explanation of the expansion that included Time?

Actually, Relativity Theory is described in terms of the Gravitational Field and Matter. The Gravitational Field is represented by a mathematical quantity (a tensor). It has a very *special property*: sometimes it is described as a *field that couples to Matter universally and minimally*.

What it means is that first, the Gravitational Field makes no distinction between different types of Matter. The strength of the coupling is determined by the Energy-content of Matter, and material composition is irrelevant. *Second*, the coupling is of such a nature that it can be reduced to the mathematical language of *pure Geometry*.

The result of all of this is that the *same tensor field* that characterizes Gravity is also the tensor field that determines the lengths of measured Time intervals and distances. In other words, the *observed geometry of the Universe*.

But it is important to remember that all these lengths and Time intervals are measured between events, determined by the presence and properties of Matter. An electron emits a photon and another electron absorbs it: the relation between these two events is determined, *in part*, by the tensor field of Gravitation.

When it comes to the expanding Universe, it boils down to the following observation: we note that, on average, Matter in this Universe seems to be *uniformly* distributed. So, we ask what the equations of Gravitation say about a Universe with uniformly distributed Matter. We find that such a Universe can exist, but the *density* of Matter in such a Universe is either increasing or decreasing over Time. In our Universe, we observe a persistent redshift in the spectra of distant objects, which is consistent with the *density decreasing* over Time; which is to say, the average distance between particles (the ‘particles’ in this case would be the *largest self-gravitating structures*, clusters of galaxies) is increasing over Time. Or to be more accurate, if we imagine a family of observers, each of whom is *at rest* with respect to their local neighborhood, the distance between these observers will be increasing over Time. But of course, we could imagine different families of observers. If we were to use a family of observers who remain at a fixed distance from each other, we would indeed find that their clocks would be ticking at different rates. There would be one observer who is at rest with respect to his local neighborhood of Matter; according to this observer’s clock, the universe is $13.8 \cdot 10^9$ yr old, whereas other observers in this family, all moving with respect to their local neighborhood, would be measuring a *shorter* timespan as the age of the Universe.

The reason why we do not normally use such systems of observers is that the math gets rather messy, and there is no benefit from this description. Having said that, the ‘conventional’ picture of co-moving observers, though convenient, has been the source of many misunderstandings, not the least of which is the misguided notion that 'space is expanding'; no, space is doing no such thing (space isn't doing anything on account of it having no substance, no measurable properties on its own), what we see is the artifact of selecting one particular family of observers (the so-called *co-moving frame*).

587 -

Why must the wavelength of *Hawking Radiation* be much bigger than the Schwarzschild Radius $R_S := 2GM/c^2$?

'Must' is the wrong word to use here. Hawking Radiation is *thermal radiation*, so all frequencies are present. However, the *peak frequency* is determined by *temperature*. The temperature of Hawking Radiation for a Schwarzschild black-hole of mass M can be calculated as (‡)

$$T = \frac{\hbar c^3}{8\pi G M k_B} ,$$

where the notation is the usual: $\hbar$ is the reduced Planck constant, c is the Vacuum speed of light, k_B is Boltzmann's constant and G is the Gravitational Newtonian constant.
The spectrum of this radiation is the standard Planckian blackbody spectrum. Its peak wavelength (technically, its maximum with respect to the *logarithm* of the wavelength) can be computed as

$$ln(\lambda_{\text{peak}}) = \frac{16\pi^2 G M}{c^2(W(-4e^{-4}) + 4)} ,$$

where $z \mapsto W(z)$ is Lambert's W - function and $W(-4e^{-4}) + 4 \approx 3.92$.
Dividing this value by the Schwarzschild Radius, we get

$$\frac{ln(\lambda_{\text{peak}})}{R_S} = \frac{hc}{k_B T(W(-4e^{-4}) + 4)} \approx 20.13 \text{ m}^{-1} .$$

We realize that these are just math formulae that convey little by way of intuition. Perhaps it is helpful to contemplate that first, Hawking Radiation is a result of Gravitational Vacuum Polarization, i.e., it is not something that the event horizon does (indeed, the popular explanation, unfortunately from Hawking himself in his book '*A Brief History of Time*', about particle pairs, one of which is absorbed by the event horizon, conflicts with his own math), but something the *Gravitational Field itself produces*. Then, let's consider that the effect would be strongest where *tidal forces* are the strongest, but that is confined to a *small* volume in the vicinity of the black-hole; farther away, the effect is weaker, but the available volume of space is *larger*. So, it seems to stand to reason that there is a 'sweet spot' between the two, where *tidal effects* are still quite strong, but there's also enough volume to produce the most radiation. That maximum is centered on roughly 20 times the Schwarzschild radius.

(‡) $z \mapsto W(z)$ is a complex multi-valued transcendental function, studied by Lambert (Johann Heinrich, 1728-1777) and Euler. Its principal (real) branch, $x \mapsto W_0(x)$, resulting from *Lagrange inversion theorem*, is defined in $(-e^{-1}, +\infty)$ and has a convergence radius $r = e^{-1}$. $graph(W_0)$ passes through the origin. From *Lagrange inversion theorem* also, $W_0(x)$ can be Maclaurin-expanded as

$$W_0(x) = \sum_{n=1}^{+\infty} \frac{(-1)^{n-1} n^{n-1}}{\Gamma(n+1)} x^n = x - x^2 + \frac{3}{2}x^3 - \frac{8}{3}x^4 + \frac{125}{24}x^5 - \frac{54}{5}x^6 + \frac{16807}{720}x^7 - \frac{16384}{315}x^8 + \dots .$$

The importance of Lambert Function in Quantum Physics (atomic, molecular, optics, etc.), General Relativity and Quantum Gravity has been recognized only recently, say, down from the '90s to date, and is in full expansion. See, e.g., WIKIPEDIA for properties and further details.
[Note added by CM.]

588 -

Is the Higgs Field homogeneous in the Universe? If not, does that mean particles have different masses in different locations?

The masses of elementary particles do not depend on the value of the Higgs Field in the Universe. It is more subtle than that. What (certain) particles interact with to gain an effective Mass is the so-called *Vacuum expectation value* (V. e. v.) of the Higgs Field. This is a fundamental parameter of the field and one of the parameters that determines these Masses. But other parameters also play a role: for fermions, it would be the corresponding so-called *Yukawa coupling constants*,

for the vector bosons it would be the parameters of the electroweak sector, such as the fine structure constant or the Weinberg angle. In the Standard Model of Particle Physics all these parameters are fundamental constants.
Now, it is a good question, what if they aren't? What if their values depend on when and where they are measured? In other words, could these constants be promoted to *physical fields*, the values of which *would vary from location to location*?
Such fields would undoubtedly be 'proper' quantum fields themselves, carrying Energy and Momentum, subject to quantization, capable of being detected. So, the real question is, could such fields be meaningfully added to the Standard Model without breaking the model?
The answer, as far as we know, is: *perhaps*, *but not easily*. And presently (2022), there is no observational evidence to suggest that such fields exist. But it is indeed true that if we were ever to detect that things we think are fundamental, such as (for instance) the electron Mass, change from place to place or from time to time, that would be a very strong indication that such an extension of the Standard Model should be considered.

589 -

Newton said that Gravity is a force that pulls objects. Einstein said that Gravity is a curvature in SpaceTime that pushes objects. How to clarify this point?

First, before reading any further, let's go and grab something heavy, say, a brick. Let's feel it in our hands. Let's feel as it is trying to pull our hands down. If we do not feel a force, we need not read any further. Once we have established that Gravity is a force instead, let's take a look at how it works.
Newton's Law of Gravitation is an example of *action-at-a-distance*: two bodies influencing each other over a distance *without anything mediating that influence*. This troubled Newton so deeply, he delayed publishing his work on Gravity for many years; and even after it was published, he had deep misgivings, as evidenced, e.g., by these words from a letter to Bentley in 1692 or so: "It is inconceivable that inanimate Matter should, without the Mediation of something else, which is not material, operate upon, and affect other Matter without mutual contact [...]. *Gravity must be caused by an Agent acting constantly according to certain laws*".
In the late 1800s, thanks to the work of Maxwell, the concept of a *field* was born in Physics. Electricity and Magnetism (and, incidentally, light) were explained by the concept of the Electromagnetic Field and its fluctuations. Soon, it became evident that Gravitation must also be *mediated by a field*. But what form shall that field take?
Gravity has an important property: unlike other interactions, it is *universal*. *All material particles respond to Gravitation the same way, regardless of their material composition or other properties*. This is what made Einstein realize that Gravity is necessarily a *geometric theory*: that is to say, the effects of Gravity are *indistinguishable from the effects of acceleration*, so, if the latter can be described using Geometry, so can the former.
But let's now jump ahead a bit and ask … could we not describe other forces, e.g., Electromagnetism, using Geometry? And the answer is that we can … but with an unpleasant twist. The Geometry 'experienced' by particles with different *charge-to-mass ratios* will differ. There will also be a 'reference' Geometry, the one sensed by neutral particles that do not respond in any way to the Electromagnetic Field.
In contrast, because Gravity is universal, *all particles experience the same Geometry*. Not only that, but there are no gravitationally neutral particles, so there is no reference Geometry that we can explore or measure. Really, *the only Geometry in town is that determined by Gravity*.

So, whereas for Electromagnetism, the geometric interpretation is either a curiosity or a useful mathematical tool depending on our preference, for Gravity, it has *unique* significance. This is what allows us to proclaim that *Gravity and SpaceTime curvature are really the same thing*, because no matter what we use to measure SpaceTime: rulers, beams of light, etc., we will experience the same *distorted Geometry* when Gravity is present.
In the end, a force arises when a particle tries to follow a SpaceTime geodesic that deviates from a straight line, mostly due to the presence of 'Time curvature', that is, since clocks tick at different rates at different points in a Gravitational Field. This force may be a *fictitious* force, like the infamous *centrifugal* force, or it may be a *real* force, like the *centripetal* force, when there is something (say, a floor) in a body's way preventing the body from following a geodesic. Either way, it is a very real force that we can feel, measure with a force gauge, or even experience as pain if we are clumsy enough to drop the brick on our feet.
To make things short: *Gravity is a force*. It is *mediated by a field that has a geometric interpretation*. This Geometry *applies uniformly to all particles* as the only Geometry that can be measured \ experienced, *because Gravity is universal*.

590 -

Is it possible that the Universe that we see is just part of bigger Universe, but we can't see it because the other part of the Universe is moving at a speed $> c$?

Well, yes, this is pretty much what the Standard Theory says. As far as we can tell, the Spatial Geometry of our Universe is Euclidean, which means, among other things, that it is infinite in extent. We can, of course, only see light that has had enough time to reach us since the beginning of the Universe, i.e., light from bits that are less than 13.8×10^9 light-years (light travel time) from here. These also happen to be the bits with a Doppler velocity less than the speed of light relative to us (because SpaceTime is curved, there are many different, equally valid ways to define distance and velocity, hence my use of these specific terms).

But the Universe does not end there. In fact, the Standard Cosmology tells us that it is infinite and the same (on average) as here. Now obviously we don't know for sure that it is the same everywhere, but we do know that, unless the Universe behaves in a spectacularly weird way, it will be roughly the same as it is here in a volume that's millions of times bigger than the visible volume.
So, yes, the so-called visible Universe is just a part of a bigger Universe, and while the rest we cannot see, we can infer that unless Nature is truly weird, it is roughly like the parts we can see, at least over a distance scale that is many times the size of the visible part.

590 -

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The LHC particle accelerator can accelerate many particles to over $0.99\,c$ (each) and crash them into each other. How aren't these collisions releasing an infinite amount of Energy being that $0.99\,c + 0.99\,c = 1.98\,c$?

Protons are accelerated at the LHC to more than $0.9999\,c$. So, it is true that, in the laboratory frame, the two proton beams *approach each other* at $1.9999\,c$, do not let us be misled by this fact. In the reference frame of either proton, the other proton is approaching at $0.9999997\,c$. That's a respectable speed, but it is *below* the speed of light. It always will be; this is how the addition of velocities works in Relativity Theory.
In any case, we should not put the cart before the horse. It's not like at the LHC we accelerate particles to a set velocity and then marvel at their Energy. No, we accelerate particles to a set Energy: this is the Energy that is *transferred* from the apparatus to the particles in the form of Kinetic Energy. So, the Energy is a *constant*, given by the experimental setup. The particle velocities are the result of this transfer of Energy. Therefore, when we say that the beam Energy at the LHC is $6.5\,\text{TeV}$ (tera-electronVolts), we know that every proton in the beam is accelerated to an Energy that is roughly 6930 times its rest-Mass Energy, *not infinite*. How we then calculate the proton velocities in various reference frames is up to us, but the fact remains that *no individual particle moves faster than* c *in any* (*inertial*) *reference frame*.

592 -

Why do we say that time speeds or slows from space-time perspective when time itself is an artificial concept to measure duration/how long like a meter is for how far? We can't literally age faster in space or travel at higher speed, can we?

Time is not an artificial concept. The unit used to measure Time, the second (or any other unit that was used to measure time in human history) is, but do not confuse the two. Today, the second is defined as the duration of 9192631770 hyperfine transitions of a Cs^{133} atom. So, let's imagine that we are floating in our spaceship somewhere in space and we

are using an atomic clock to measure these hyperfine transitions. We count 9192631770 transitions.
Meanwhile we are watching someone on the Earth. For the sake of simplicity, let's say we are motionless relative to the Earth, and the person doing this experiment is at the North Pole, so that lab is not moving either because of the Earth's rotation. Let's say that lab at that North Pole is equipped with a huge digital display that we can see with your telescope, and it is counting how many such hyperfine transitions are, occur there.
Let's guess what: while we are counting 9192631770 transitions on board our spaceship, the lab at the North Pole will count 9192631763 or 9192631764 transitions only.
So, yes, independent of any cultural artifacts, Time literally flows more slowly in the Gravitational Field of Earth than in space far from the Earth. The fact that we happen to call 9192631770 and not 9192631764 transitions the second is up to us. The fact that a different number of transitions is measured at the North Pole compared to deep space is not up to us; it is the way it is, even if humans never invented any means to measure Time.
And yes, it means that someone in a Gravitational field literally ages more slowly. In Gravitational Fields that humans can survive, the change is imperceptibly small, but it is there, and it is measurable with the right instrumentation.

593 -

What is the intuition behind the Einstein's Field Equations?

The best intuitive description that we know seems to come from Wheeler (2000): "*SpaceTime tells Matter how to move; Matter tells SpaceTime how to curve*."
This is precisely what is expressed by Einstein's Field Equations, with derivatives of the SpaceTime metric on one side (in the form of the so-called Einstein Tensor) and the Stress-Energy-Momentum Tensor of Matter on the other side. And in the Weak-field, non-relativistic limit, the equations are reduced to a simple equation describing Newtonian Gravity, the *Poisson Equation* for Gravitation.

Note: The one thing we feel compelled to add to this is that 'SpaceTime' in the Wheeler quote should really be '*SpaceTime metric*'. Though this may appear like unnecessary pedantry, it really isn't. There is that *misleading* conceptualization (reinforced by colorful expressions like 'SpaceTime fabric' or catchy visualizations like the bowling-ball-on-trampoline analogy) that 'SpaceTime' has independent physical existence, that it is some substance that can be measured, be created, destroyed, or bent. Actually, the only physical field that appears in the equations is the Gravitational Field, also known as the *metric*, which, incidentally, also tells us how we can measure distances between things in SpaceTime; but *the metric itself is not SpaceTime*, it is something that is added to the 4 dimensions of SpaceTime, turning that point set into a *metric manifold*.
In our defense (how dare we pedantically nitpick on something said by a legendary physicist), we should also mention that in an earlier version of this quote, Wheeler used 'Space' instead of 'SpaceTime', which is *wrong*; in fact, the Weak Gravitational Fields that we experience in our everyday lives are due almost entirely to *how measurements of Time intervals change*, *not Space distances*.

594 -

Is the Big Bang theory still accepted as how the Universe was created?

Let us make something clear: the actual Science, that is, the stuff we read in textbooks and research papers, is not about 'how the Universe was created': *it has never been*. Rather, it is about the observation that the Universe appears to expand; the derivation that General Relativity predicts either an *expanding* or a *contracting* (but never a static) Universe; and the reconciliation of these and other facts into a body of knowledge that takes what we know factually about the Universe at the present, using our theories that have been validated by experiment, to explore what the Universe was like in the past.
General Relativity, by itself, predicts an initial moment (*initial singularity*) under a wide range of circumstances. This led some scientists, back in the first half of the 20th century, to oppose the concept on philosophical grounds, as they saw it as a backhanded way to sneak a religiously inspired creation story into the actual Science. The irony of it all is that one of the fathers of the expanding Universe concept, Georges Lemaître, who was not only a top-notch physicist but a Jesuit-trained priest, was actually pursuing one of those alternatives at the time that involved no moment of creation, but an eternal Universe (there we go: the priest was able to remain more objective than some of his atheist\ agnostic opponents. Whether we are religious or atheist, let that be a lesson).
It was in part this initial singularity business that prompted the astronomer Sir Fred Hoyle, who was pursuing an alternative theory (steady state Cosmology) at the time, to mockingly characterize the expanding universe paradigm with the expression, 'Big Bang'. The name stuck.
Today, the expansion of the Universe is not in question among serious scientists. The evidence is overwhelming. In addition to the *redshift* that first led Lemaître and Hubble to postulate that the Universe is expanding, we have amassed a lot of evidence that is difficult, if not impossible, to explain by any sensible alternative. These include the existence of the Cosmic Microwave Background, its blackbody spectrum, minute statistical deviations from that spectrum, the large-scale distribution of Matter, the luminosity-redshift relationship of distant 'standard candles' such as the supernovae (which also offer evidence that the expansion is accelerating), the *ratio of primordial isotopes*, the *morphological and chemical differences between very distant galaxies* (which we see in their early stages of development) *vs. mature,*

nearby galaxies … the list goes on.
But, again, it does not mean that 'it all started with a Big Bang'. It simply means that we have confidence in our observations and validated theories that the Universe is expanding at present, and that we can reliably trace its past evolution all the way back to the first pico-second after the presumed Big Bang.
But not that first pico-second (if indeed it was a pico-second). About that pico-second, all we have is *conjecture*. And the *closer* we are to the presumed Big Bang moment, the *less* we can believe what the Science says, as we are in uncharted territory. In fact, there is strong reason not to believe what the Science says, because we do not have reliable Science that tells us how Gravity behaves in this *strong regime*, *where quantum effects of Gravitation cannot be ignored*.
So no, Physical Cosmology *does not* tell us how the Universe was created. It never did. It does tell us, however, how the Universe *evolved*, from fairly early on in its existence to the present, and how it *will likely evolve* in the future.

595 -

If we turn on a flashlight in interstellar space, would the light propel the flashlight backwards? If so, what's the maximum speed it might achieve?

Indeed, our flashlight experiences a small *recoil force* every time it is on, but it is a very, very, very tiny force. The relationship between the Energy and Momentum (or Power and Force) of light involves the speed of light as the conversion factor. Say, our flashlight emits 1 Watt in the form of a beam of light. The corresponding force will be approximately $3.3\cdot10^{-9}$ N. Say, our flashlight weighs, with batteries, 100 g and it can operate for 1 h before the battery is depleted. That $3.3\cdot10^{-9}$ N will accelerate a 100 g $(0.1\,\mathrm{kg})$ object at the rate of $33\cdot19^{-9}\,\mathrm{m/s^2}$. After $3600\,\mathrm{s}$ (1 h), this means that the flashlight will have achieved the velocity of $0.12\cdot10^{-3}\,\mathrm{m/s}$ mm/s. That will be its final speed as its battery dies.
Still, it is not a completely negligible force. Light pressure (or the pressure due to *thermal* radiation, which is just infrared light) can affect the trajectories of spacecraft (indeed, it was the big secret behind the slightly anomalous trajectories of Pioneer 10 and 11). Light from other sources, such as the Sun or a stationary laser beam, can also be used to accelerate lightweight spacecraft, but for this scheme to be practical, the spacecraft need to use very large solar sails, get close to the Sun, or if powered by a laser, the laser must be immensely powerful. But these are technical challenges that can be manageable in some cases, which is why people consider solar sailing to reach the outer regions of the solar system faster than any other spacecraft to date or contemplate using ground- or space-based laser facilities to accelerate tiny spacecraft to relativistic speeds, allowing them to reach other solar systems in a matter of decades, as opposed to millennia or more.

596 -

Why do we need Dark Matter and Dark Energy in our existing models if we haven't detected all the Matter in the Universe yet?

Indeed, when Dark Matter was first proposed by Swiss astronomer Fritz Zwicky in the 1930s, it was assumed to be perfectly ordinary Matter that we have not detected yet, on account of it being, well, *dark*! But our understanding has evolved since, and this possibility is now excluded. Our models of Physical Cosmology place an upper limit on the amount of '*baryonic Matter*' (that is to say, *Matter made of ordinary protons and neutrons*). If more such Matter were present, precision observables like *minute fluctuations in the temperature* of the Cosmic Microwave Background or details statistical properties of the distribution of Matter in the Universe would be *very different* from what we observe. It is for this reason that we need to assume either that our models are completely wrong and 'new Physics' is needed, or that there is some Matter not made of baryons, which does not interact with light at all, does not interact with baryons, and doesn't interact with itself either (has 0 or, at least, negligible, *Pressure*). That's the Dark Matter part.

Dark Energy is different. It has an '*equation of state*' that is not like Matter at all. Certain forms of Potential Energy have this equation of state (amounting to *negative effective Pressure*), and the so-called Cosmological Constant can also mimic the behavior of Dark Energy. But ordinary Matter *cannot*. And again, we need Dark Energy, with this weird equation of state, to make sense of cosmological observables, including data on distant supernovae. Without Dark Energy, once again, 'new Physics' would be required.
Meanwhile, it is indeed true that we have not detected all the ordinary Matter yet. About half of the baryonic Matter that is supposed to be present in the Universe remains unaccounted for. But, as we have seen, this is not the same as Dark Matter. This is just *hard-to-detect ordinary Matter*, hard to detect because it is dim (let's avoid using the word 'dark' here) and difficult to see, but ultimately, this stuff is still made of the same ordinary atoms (mostly H) that we know.
To give some numbers, in terms of the so-called critical density of the Universe, about $4\,\%$ would be ordinary Matter (half of which remains unaccounted for), roughly $25\,\%$ would be Dark Matter, and the remaining $70\,\%$, give or take,

would be Dark Energy. And these three constituents have different properties:

a. baryonic Matter has (some) Pressure, interacts with itself and with light;

b. Dark Matter has no Pressure and doesn't interact with anything; and

c. Dark Energy has huge *negative* Pressure.

597 -

Is light really *massless* or is it massless because it cannot be measured? Can the Higgs particle give Mass to photons?

Our best theory to date (Quantum Field Theory in the form of the Standard Model of Particle Physics predicts the photon to be *massless*). The *Higgs mechanism* cannot give mass to the photon, not without serious modification. The Electroweak part of the theory involves the combination of two symmetry groups, $SU(2)$ and $U(1)$. Without going into details, the Higgs mechanism breaks the *non-Abelian symmetry* of $SU(2)$, this giving mass to the Weak Interaction's $W^{\pm}$- and Z^0- bosons, but it leaves the Abelian Symmetry Group $U(1)$ unbroken, and the photon *remains massless*.
Now, of course, theory is one thing, experiment is another. There have been numerous attempts to establish limits on the photon mass. If the photon had a rest-Mass, its speed of propagation would depend on its Energy. γ- rays would travel *faster* than, say, radio-waves. Furthermore, if the photon had a rest-Mass, the amount by which *gravitational lenses* deflect photons would also depend on the photon Energy. Neither of these effects have ever been seen, and the corresponding precision observations put extremely stringent upper limits on the photon Mass.
Now, if it turned out that the photon had a small mass after all, the theory would need to be revised. The Classical Theory is (relatively) easy: Maxwell's Theory would be replaced by *Maxwell-Proca Theory*. The Quantum Theory is trickier, since whereas the quantum version of Maxwell's Theory is readily renormalizable (this is Quantum Electrodynamics), Maxwell-Proca is not. One way around it is *symmetry breaking*, so perhaps there should be a way to extend the Higgs mechanism to involve also the $U(1)$ sector. Or, perhaps, some other solution can do away altogether with the need for renormalization. But, for now, in the absence of compelling theoretical reasons to keep the photon massless and *no experimental nor observational evidence* to the contrary, we're reasonably happy with the Standard Model and its massless $U(1)$ sector.

598 -

Is space inside a black-hole homogeneous and isotropic? Some competent people have said that. But it seems like a person in free-fall in a black-hole could do experiments to determine the direction to the center.

It depends on the black-hole but, yes, in a non-rotating (Schwarzschild) black-hole, the vacuum interior is *homogeneous* and *isotropic*.
In the case of a collapsing, *spherically symmetric* cloud of dust (*Oppenheimer-Snyder collapse*), after crossing the horizon, an infalling observer would find himself in a rapidly collapsing cloud of Matter that has the same *density* everywhere and *no preferred direction*. So, no, the observer could not determine the direction of the center by any experiment. The actual 'center' the *singularity*, is a *future moment in Time* in this observer's reference frame, *not a location in Space*. As to the *horizon*, it is a *past moment in Time*, again, with *no preferred direction in Space*.

599 -

If Gravity is quantized, does that mean, as the Cosmos expands, pixels of SpaceTime become larger?

No, for two fundamental reasons.
The *first* reason: *quantized* does not mean pixelated, be it about Gravity or else. Of course, the word 'quantum' implies kind of quantized Energy levels, and that is indeed how all this Quantum Theory business came about but as it often happens in Physics, reality is more nuanced than that.
To recap very briefly, one of the motivations for the Quantum Theory was the discrete (quantized) Energy levels of atoms; and the Quantum Theory indeed tells us that certain systems, such as the *quantum harmonic oscillator*, have such discrete levels. But even in the Quantum Theory, a free electron for instance has a *continuous trajectory*. And its Kinetic Energy can have *any* value. There's nothing pixelated about its behavior.
In our modern understanding, we know that what the Quantum Theory is about is that systems can exist not just in classically meaningful states (e.g., having a well-defined position) but in so-called *superpositions* of such states (yes, in a sense, the electron can be in two, or more, places at once). The actual quantized behavior arises in specific cases (such

as the harmonic oscillator) as a mathematical consequence, but there are many other situations in which there's no such quantized behavior.

The *second* reason: the expansion of the Cosmos is not about SpaceTime doing anything. *Spacetime is not something we measure*. There are no little markers attached to 'Space' by which we can measure its expansion. No, cosmic expansion is about *things* (*material* things, namely clusters of galaxies) *flying apart*. The confusion arises because, as a result, the Gravitational Field *changes*, of course; the Gravitational Field conveniently *serves as the metric of the SpaceTime manifold*; and in one particularly convenient form of a coordinate system (so-called *co-moving coordinates*) the coordinates of these galaxies remain the same, the change of distance between them is attributed to a component of the metric.

But coordinate systems are *mathematical fiction*. *Physical Reality is about distances between things*. When the distance between two things increases, those two things are flying apart. This is precisely what clusters of galaxies do.

Also, it should be mentioned for relevance that the governing equations (the so-called *Friedmann Equations*) that describe cosmic expansion can, in fact, be deduced entirely within the context of Newtonian Physics, with its *absolute* Space and Time. That, too, should underlie the point that what the equations describe is how Matter moves (expands) and how the Gravitational Field changes as a result and not what 'SpaceTime' does (unless we consider the Gravitational Field itself as part of the definition of SpaceTime).

600 -

What exactly is the *Higgs Field* and the *Higgs Boson*?

Let's take a step back and first clarify what a field is in Particle Physics. Don't let us feel embarrassed or ridiculous: the history of Science has its twists and turns, one of them being that our best Particle Theory to date is, as a matter of fact, a field theory, Quantum Field Theory (QFT) to be precise.

A *field* is something that has a value *at every point in Space at every moment in Time*. A good practical example would be the Magnetic Field: it is a *vector-valued field*, meaning that its value has *a magnitude and a direction*, like a little arrow, one attached to *every point in Space* and possibly *changing over Time*.

A *scalar field*, in particular, is a field that is *number-valued*: a magnitude (but no direction) is attached at *every point in Space and Time*.

A *physical field* can be in its so-called *ground state* or it can be 'excited', when it carries excess Energy and Momentum. A quantum field's excitations come in set units, the *quanta*. Actually, they can be counted, and interactions between fields increase or decrease the number of excitations in a field *by one unit at a time*. These excitations are what we *perceive as particles*. Which is how a field theory ends up as a theory in Particle Physics.

The Standard Model of Particle Physics is a Quantum Field Theory of many fields. These include the Electromagnetic Field (a field of 4-dim vectors, representing the 4-dim vector potential of Electromagnetism); the *Electron Field* (a *Spinor Field*; spinors are kind of like vectors, with pairs of spinors representing elementary quantities of rotation); and similar fields including *quarks*, *vector bosons*, *gluons*.

The Higgs field is part of the Standard Model. It is a curious field: its values are *pairs of complex numbers*. That is, a pair of complex numbers is attached to every point in Space and Time, representing the magnitude of the Higgs Field.

As we recall, a complex number has a real and an imaginary part. So, the Higgs doublet, as it is called, really has '4 real degrees of freedom'. It also has another, very curious property. The lowest Energy state of the Higgs Field is not when the field has no excitations. In short, empty space (no excitations) can 'decay' into a lower Energy state by creating new excitations in the Higgs Field. Stability is achieved when the Higgs Field reaches its so-called *Vacuum expectation value*; and this *stable* state will be the *new Vacuum*.

But here comes the rub: other fields interact with excitations of the Higgs Field. So, with respect to this new Vacuum, for all practical intents and purposes it will appear to us as though these other fields *were interacting with the Vacuum itself*. In practical terms, it means that fields that had no rest-Mass to begin with start to behave *as though they were massive*. These include the electrons, quarks and the vector bosons of the Weak Interaction. The vector bosons do something else: for lack of a better term (without resorting to mathematics) the three vector bosons 'eat' 3 out of the 4 'real degrees of freedom' of the Higgs Field, *leaving only one*.

So here we are. A new, stable Vacuum, with some particles now having Mass, and a residual Higgs Field with only 1 degree of freedom. If this Higgs Field gains Energy from interactions with other fields, its excitation will appear as a so-called *scalar particle*. That scalar particle is the *Higgs Boson*.

Apparently, this is not a simple explanation nor a simple topic, and it is quite difficult to describe in relatively few words and without using math. Still, hopefully, it suffices as a not altogether meaningless answer.

Note

If Matter and anti-Matter are both gravitationally *repulsive*, then, virtual particle-antiparticle pairs – which last for extremely short time intervals in the Quantum Vacuum – can be viewed as *gravitational dipoles*. Hence, if Quantum Vacuum contains very many virtual gravitational dipoles, it is equivalent to a region containing a collective relativistic (virtual) system corresponding to a *dipole quantum fluid*.

(D. S. Hajdukovic, CERN)

601 -

If the *Stress-Energy-Momentum tensor of Matter* causes SpaceTime's *local* curvature, then does the tensor for Dark Energy cause SpaceTime's *non-local isotropic expansion* (vs. the counterargument about Matter speeding outbound non-isotropically)?

The Stress-Energy-Momentum Tensor of 'Matter' includes *all forms* of Matter: *baryonic Matter* (stuff we are made of), the *Electromagnetic Field*, *Dark Matter* and even *Dark Energy*.

The Stress-Energy-Momentum Tensor determines the *Tensor Potential* of the Gravitational Field. This tensor couples to *all forms* of Matter (all the above) universally. The coupling is also 'minimal' in the sense that the Gravitational Field tensor determines *geometric* properties like integration volume elements, but there are no extra coupling terms.

For this reason, the Gravitational Field Tensor can be reinterpreted as the one-and-only *universal metric* of SpaceTime, which determines all measured geometric quantities (Space distances as well as Time intervals).

Going back to the question of Dark Energy, when pressure is not negligible, the equations of Gravitation, even at the Newtonian level, are modified: instead of the Mass-Energy Density ρ, the source of Gravitation becomes the quantity $\rho + 3p$. For Dark Energy, $p = -\rho < 0$, as is $\rho + 3p \equiv -2p$. Consequently, when Dark Energy dominates over other forms of Matter, its *repulsive Gravity* 'wins', leading to accelerating expansion.

602 -

How do we derive Maxwell's Equations?

The modern starting point is to *postulate* the existence of a 4-dim vector field with a *massless current*. If the vector field is *at least* 3 times differentiable and if the SpaceTime in which it exists is endowed with a metric, Maxwell's Equations follow as mathematical identities.

To get down into the nitty-gritty of things: let the (4-) *vector field* be denoted A_μ. The *Maxwell Tensor* is defined as $F_{\mu\nu} := \nabla_\mu A_\nu - \nabla_\nu A_\mu$. Using the language of *exterior* forms, this can be written as

$$F = dA.$$

Here comes the first demonstration of the power of exterior forms: *the exterior derivative is nilpotent*, meaning

$d^2 = 0$. Therefore,

$$dF = d^2 A = 0.$$

Spelled out in component form, this is two of Maxwell's famed Laws: Faraday's Law and Gauss's Law for Magnetism.

Exterior forms have *duals*. These are formed using the *Levi-Civita symbol* and the *metric* (hence the need for a metric). They are usually denoted by a *star*. Using the dual and the exterior derivative, we can define a *massless current*:

$$J := d\star F.$$

This definition amounts to Gauss's Law and Ampère's Law, i.e., the other pair of Maxwell's Equations.

The current is conserved. This follows from the fact that the dual *its own inverse,* and the exterior derivative is *nilpotent*:

$$\star d \star J = \star d \star \star d \star F = \star d^2 \star F = 0.$$

This is the equation of *Charge and Current Conservation*. All these results can be spelled out in component form and, ultimately, in the usual 3-dim form. The icing on the cake is that they remain valid even in the curved SpaceTime of General Relativity.

This approach is immensely powerful: to be able to derive pretty much everything we know about Electromagnetism in just a few short lines of equations tells us just how powerful these conceptual tools of mathematics really are.

Of course, just because we can derive these equations does not mean that they correctly describe Nature. Is a 3 times differentiable vector field with a conserved current a valid description of electromagnetic phenomena? *This can only be determined by experiment*; and if experiment said otherwise, we would have to modify the theory. For instance, we might have to make the field massive by defining the current differently:

$$J := d\star F + \mu^2 A.$$

This yields the so-called *Proca Theory*, named after the Romanian physicist Alexandru Proca (1897-1955).

Lastly, it should be mentioned that there is another way to derive Maxwell's Equations, from the Lagrangian

$$\mathcal{L}_{\text{EM}} := -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - A_\mu J^\mu .$$

This seems superfluous because the field equations can be derived, as it was showed above, from the existence of A_μ alone. However, the Lagrangian formalism has the advantage that it is easy to introduce other fields and forces. It also directly leads to a Hamiltonian formalism that, in turn, can be used to derive the quantum version of Electromagnetism.

Some additional details are given on V. T. Toth's website: A COVARIANT FORM OF MAXWELL'S EQUATIONS.

603 -

At the end of *cosmic inflation*, when atoms are pulled apart, is the Planck Length going to be stretched too?

First, cosmic inflation ended some 13.8 billion years ago. It took place in the first tiniest fraction of the existence of the Universe (that is, assuming that the Inflationary Cosmological Model is correct, in the first place).

It is true that according to the Standard Cosmological Model, we live in a Cosmos that is undergoing accelerating expansion, but that is *distinct from inflation*. Furthermore, it is not going to pull anything apart. It simply means that with Dark Energy/Cosmological Constant dominating, the *Hubble parameter* characterizing the rate of expansion never decreases to 0 but, instead, reaches a *constant* value in the *very distant* future. This means that things that are flying away from each other actually accelerate away from each other as the distance between them grows. But never mind atoms, any bound structure, including planets, stars, solar systems, galaxies, even clusters of galaxies will remain bound; nothing is pulling them apart.

There is a hypothetical scenario called the 'Big Rip', that involves something other than Dark Energy: so-called Phantom Energy, a constituent with a *forbidden equation of state* that, if present, would indeed rip atoms apart in the very distant future. However, there is no indication that such Phantom Energy exists in this Universe, and as said above, its equation of state really is *forbidden by other laws of Physics* because such a constituent is fundamentally *unstable*. In short, the Big Rip is a scenario that, likely, has nothing to do with reality.

However, even if the Big Rip was part of our future, it'd have nothing to do with the Planck Length, a measure of length constructed from fundamental constant that, as far as we know, has no physical significance. The only physical meaning associated with the Planck Scale is that our best quantum theory that there is, Quantum Field Theory (QFT), is expected to *fail* at this scale. That means that QFT is just an 'effective' theory, a low-Energy approximation of something more fundamental that remains to be discovered.

604 -

Can SpaceTime be infinitely divided, or does it consist of indivisible *quanta*?

One of the misunderstandings of the Quantum Theory is, well, that it is about quanta.

We know it's called the Quantum Theory for a reason. And indeed, what gave birth to its existence is that quantizing Electromagnetic Radiation into discrete packets of Energy solved the 'ultraviolet catastrophe'. This represented the first step towards the development of the modern Quantum Theory, taken by Planck at the turn of the last century.

Considering that, it is perhaps surprising how many things are not 'quantized' in the sense of being packaged into discrete chunks, quanta. Just take Quantum Electrodynamics. A photon can have *any* Energy: the spectrum is *continuous*. A free electron can be anywhere: its position is not confined to a grid or otherwise quantized, and so on.

Let's briefly retrace the path to a Quantum Field Theory. We start with Classical Physics. A little bit of mathematics can be used to convert an equation, called the Hamiltonian, into something that looks identical to Schrödinger's equation. Looking at this equation, we recognize solutions that make no sense in Classical Physics (the classical interpretation would be that the electron is in two places at once) but which, as we find out through experiment and observation, nonetheless accurately describe reality. Thus, ordinary Quantum Mechanics is born.

Next, we apply what we learn to the simplest nontrivial mechanical system, the *harmonic oscillator*. This is where we first encounter quantized behavior: we find that the oscillator is confined to specific Energy levels, characterized by units that are related to the oscillator's frequency. This is a profound result as it already explains why, e.g., electrons around atoms are confined to specific orbitals, and the discreteness of the absorption and emission spectra of atoms.

But we take another step: we take a field and break it down into a *sum* of harmonic oscillators. This we can do by way of a *Fourier-transform*. Now each of these harmonic oscillators has discrete Energy levels, related to its frequency. The field can gain or lose Energy when a specific oscillator's excitation count increases or decreases. These changes can be observed: when the field is the Electromagnetic Field, we recognize these observations as the *emission* or *absorption* of a 'photon'.

What does this have to do with SpaceTime? Dividing it into indivisible quanta? Very little. For starters, SpaceTime *doesn't have a dynamic on its own*. It has *no Mass*, *no Energy*, *no measurable properties*. We observe things in SpaceTime and their geometric relationships, *not SpaceTime itself* (we do observe the metric of SpaceTime, i.e., the Gravitational Field, but that's something else).

Having said that, it is certainly possible to contemplate a theory that does replace continuous coordinates with, say, a *discrete grid*. Many such speculative theories exist, but they have no experimental support, and it should be emphasized, this direction is by no means suggested or warranted by Quantum Field Theory, which is our one theory that actually works, accurately predicting our observations of Nature.

605 -

In Physics, what do we meant by a *metric*?

A *metric* is a definition of distance between elements in a set. Basically, it is a number that we assign to pairs of elements in a set. The set could be, for instance, the set of points in Space.

The metric usually satisfies a few basic properties. The distance of an element from itself is always zero. The distance between A and B is the same as the distance between B and A.

A *proper metric* is also always *positive* for *distinct* elements, and satisfies the 'triangle inequality': the distance between A and C is less than, or equal to, the sum of the distances between A and B, and B and C.

However, these two properties are not satisfied by the most famous metric of all, the metric of SpaceTime. The metric of SpaceTime can yield 0 (e.g., between points along the path of a ray of light) or even *negative* values. Because it is not a proper metric, it is sometimes called a *pseudo-metric*.

Pseudo- or not, the metric determines the *measurable geometry*. It determines basic things such as how the inner products of vectors are formed, or how integrals of functions are calculated. It is with the help of the metric that we can express fundamental physical laws in a manner that is not dependent on the choice of coordinate system (which is chosen by the physicist for mathematical convenience and should play no role in how things unfold in Nature).

In short, a metric is a powerful mathematical tool that is fundamental to General Relativity, but also finds broader use in other branches of Physics including *Field Theory* or *Fluid Dynamics*, for instance.

606 -

Does a photon, be it a wave or particle, stop moving for even a micro-femtosecond the instant it hits a mirror prior to bouncing back?

What we call a 'photon' is an accurate description of the *elementary quantum of the Electromagnetic Field* far from any charges, in the Vacuum, or (with some modifications) in a transparent medium.

It is not an accurate description of the behavior of the Electromagnetic Field in the immediate vicinity of electric charges, which constitute a non-transparent surface such as the surface of a mirror.

The photon is not some miniature ping-pong ball that bounces off a wall. Rather, it is a *unit of Energy* at a given Energy level in the free Electromagnetic Field. This lump of Energy may be localized when light is emitted or absorbed and may be confined (more or less) to a well-defined trajectory because of the wave properties of the Electromagnetic Field. But what happens in the vicinity of the mirror is that the properties of the Electromagnetic Field change. As such, the trajectories of waves propagating in the Electromagnetic Field change as well. Even at the microscopic level, the interaction is not between a miniature object and some solid wall, but between the *free* Electromagnetic Field and the combined Electrostatic Fields of all the protons and electrons that *constitute the mirror material*. As a result, the free field description of the field is no longer valid and the trajectories of light rays change.

607 -

How come the speed of light changes during refraction if it's a *universal constant*?

The speed of light is not constant according to Relativity. What Relativity Theory says is that there is an invariant speed, the measured value of which is the same for all observers; and that furthermore, massless particles or plane waves propagating in *massless fields* far from sources travel at this *invariant* speed.

In other words, the Vacuum speed of light, far from any sources (including the electric and magnetic dipoles that characterize a refractive medium) happens to be this *invariant speed*.

For this reason, and of course because of the history of the discovery, *we call the invariant speed the vacuum speed of light*; or more usually, because we are sloppy, simply the speed of light.

But let's repeat: at no point does Relativity Theory presume to tell us that light always travels at this speed, even in a refractive medium.

By the way, a commonly heard but grossly incorrect explanation is that light 'travels between atoms' at the Vacuum speed of light but bounces back and forth and thus it doesn't follow a straight line to its destination, hence it appears slower. *This is nonsense*. For starters, it doesn't even make any sense, considering that, e.g., the wavelength of visible light is much, much greater than the distance between molecules in a typical transparent substance like air, water, or glass. When light does bounce into things such as atoms, molecules or particles of dust, the phenomenon is called *scattering*, but it has nothing to do with the lower speed of light in a refractive medium.

Light travels slowly in such a medium because the 'boundary conditions' for the Electromagnetic Field in that medium *are not* determined by the Vacuum but rather, by the charges (dipoles) that characterize the medium. So, we no longer get the *Vacuum plane-wave solution* (lest we forget, even in the Quantum Theory, the solution for the *free* Electromagnetic Field is still a plane-wave solution; it's just that this plane wave solution is then 'quantized', written as a sum of elementary oscillators, which are the quanta that we *perceive* as photons).

608 -

What formulas are used in the study of gravitational waves? What is the (general-relativistic) gravitational wavelength? How to calculate the propagation speed of gravitational waves?

The following is a very superficial sketch of the key formulae.

Gravitational waves far from sources are governed by the vacuum field equations of General Relativity: $R_{\mu\nu} = 0$. Here, $R_{\mu\nu}$ is the so-called *Ricci Tensor*, formed from the *Riemann Curvature Tensor*, which in turn is formed from the SpaceTime metric, also known as the *tensor-valued Gravitational Field*.

To study gravitational waves, it is often useful to express the SpaceTime metric as a perturbation hμν of the 'flat' SpaceTime metric $\eta_{\mu\nu}$ in the absence of Gravity: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$. Gravitational waves are then described by whatever equation is imposed upon this perturbation. It is also useful to introduce the symbol $\bar{h}_{\mu\nu} = h_{\mu\nu} - (1/2)h\eta_{\mu\nu}$.

In the Vacuum, the Einstein Field Equations will reduce to a wave equation in the form $\Box^2\bar{h}_{\mu\nu} = 0$, where $\Box^2$ is the standard d'*Alembertian operator* $\Box^2 \equiv \partial_\mu\partial^\mu$. And this is all we need to know; the result is that, in a suitably chosen, convenient coordinate system (in the so-called *transverse trace* (TT)-*free representation*), we find that

$$\bar{h}^{TT}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+(t-z/c) & h_\times(t-z/c) & 0 \\ 0 & h_\times(t-z/c) & -h_+(t-z/c) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

What this matrix describes is a *transverse* gravitational wave that moves at the Vacuum speed of light c in the z-direction. The nature of the wave is such that it is like a moving tidal wave, 'squeezing' Matter in the x-direction while stretching it in the y-direction or vice versa, all the while *preserving volume*.

As for formulas, one very useful (from a practical perspective) formula is the so-called *strain*, which describes the magnitude of this passing *tidal wave*. If the gravitational wave is due to two masses m_1 and m_2 inspiraling and coalescing, currently separated by a distance Δs, at a distance r from our location, the strain will be given by

$$h_0 = \frac{2G^2 m_1 m_2}{c^4 (\Delta s) r} .$$

By way of example, two black-holes located 100 Mpc (megaparsec) from here, each 10 times more massive than the Sun, are currently at 100 km from each other in the final phase of their merger, the strain calculated using this formula is roughly $h_0 \sim 1.4 \cdot 10^{-21}$. Experiments like LIGO must detect relative changes in the path length of two perpendicular laser beams amounting to not much more than 1 part$/(10^{20})$. And that's what LIGO does.

609 -

According to some experts, a homogeneous plane is impossible in GR (General Relativity) because it hides under its gravitational radius. But then a material point is impossible in GR too because it always is under its gravitational radius. Doesn't it a contradiction?

There is no contradiction. Point particles also *do not exist* in GR. However, *point-particles are useful abstractions*, approximations in case when the distances between particles are much larger than the particles themselves, and the particles' own Gravitational Field can be safely ignored. E.g., if we study the orbit of a spacecraft around the Earth, we can treat the spacecraft as a point particle and ignore its own Gravitational Field. The resulting equations are much simpler, and the loss of accuracy is less than negligible.

Moreover, we can treat sources of Gravitation as point particles far from the source, because of *Birkhoff's Theorem*, which basically tells us that, *far from the source*, the field is *Schwarzschild's solution*. So, we only need to know the total Mass of the particle and *ignore* its geometry. In other words, it's not so much treating it as a point as simply ignoring what it is, noting that we are so far away from it, it might as well be a point.

An infinite plane has infinite Mass and infinite Schwarzschild Radius. It's not a useful approximation of anything. It's also not terribly useful in pre-Relativity Physics, but in pre-Relativity Physics, we can still calculate a corresponding Gravitational Field, but it is not possible in GR, because *the infinite plane would require a finite Universe*, which is a contradiction.

610 -

When it comes to 4-Momentum, can the Time-like part be thought of as a special type of spatial dimension where everything within that dimension is moving at the speed of light?

No. The Time-like part of the 4-Momentum is Energy. The spatial part corresponds to 3-dim Momentum. There really is no mystery here.

In fact, when we think about the one equation everybody knows, $E = mc^2$, it really is about the 4-Momentum. Write the 4-Momentum as $\boldsymbol{p} = (E/c, p_x, p_y, p_z)$. Take its norm using the pseudo-Euclidean summation rule of SpaceTime: $\|\boldsymbol{p}\| = (E/c)^2 - \mathbf{p}^2$. The norm of a 4-vector is independent of the coordinate system in which it is expressed, so we can choose the coordinate system in which the 3-Momentum vector, $\mathbf{p} = 0$ (as conventional, boldface is used to denote 3-dim vectors: $\mathbf{p} := (p_x, p_y, p_z)$). In this case, $\|\boldsymbol{p}\|^2 = (E/c)^2$ or $\|\boldsymbol{p}\| c = E$. The value of $\|\boldsymbol{p}\|$ has the dimensions of $[\text{mass}] \cdot [\text{speed}]$, so let's *define* a Mass as $m = \|\boldsymbol{p}\|/c$; then, $\|\boldsymbol{p}\| = mc$ and $E = mc^2$.

The more general form of this expression is the so-called *dispersion relation*, $E^2 = (mc^2)^2 + (pc)^2$. This is just the norm in disguise: $(\|\boldsymbol{p}\| c)^2 = (mc^2)^2 = E^2 - \mathbf{p}^2 c^2$.

611 -

What is Quantum Field Theory? Why is it hard to unify it with General Relativity?

Let's start with ordinary Quantum Physics. The process is straightforward in retrospect, though inherently mathematical. Don't let us look for intuition here; the whole point of Quantum Physics is to forget visualizations, forget what intuition tells us, and listen to the equations instead.

So, we start with Classical Physics. We do a bit of algebra and presto: we have a Schrödinger-like equation. It has many solutions. What is more, combinations (so-called *linear combinations*) of its solutions *are themselves* solutions. These combinations mean nothing in Classical Physics: they'd be describing, e.g., an electron that is in two (or two thousand or two million) places at once. But we *accept* this as a valid description of reality because, like it or not, that's how Nature seems to work.

Next, we apply what we learned to one of the simplest mechanical systems: the *harmonic oscillator* (let's think of a simple pendulum with a *small deflection*). We find two striking consequences. *First*, the Energy levels of that oscillator are now confined to *discrete values*. The Kinetic Energy of the oscillator will increase or decrease in distinct steps. *Second*, the lowest energy level of the oscillator is non-zero: there's always a tiny residual, a '*zero-point Energy*'.

All this is confirmed by experiments using elementary particles by the way. But none of this accounts for how particles are *created* or *destroyed*. Not to mention that Classical Physics *doesn't just have particles*; it also has fields, like the Electromagnetic Field.

But there's something we can do with any field: *Fourier-transform* it into a sum of harmonic oscillators! This will be an *infinite* sum, to be sure, but so what? We can still apply what we learned about the harmonic oscillator.

We do that and we have a quantum version of our field theory. We realize that increasing or decreasing the Energies of any one of the elementary oscillators is, in fact, a valid mathematical description of creating or destroying particles. Particles are just '*excitations*' *of the field*, its elementary oscillators, to be precise.

There's a catch, though. All those zero-point energies add up. Now we have infinitely many oscillators, so infinite zero-point Energy. Fortunately, there are ways to deal with this since what we're interested in is not the overall Energy of the field but how this Energy changes. So, if we can somehow remove the infinities … As it turns out, we can. *First*, we make them finite. *Then*, we do the calculations. Once we have the calculations done, we realize that the finite 'cutoff' disappears from the result, so we can safely take the limit to infinity and still keep a sensible result. Theories that let us do this (or something equivalent) are said to be *renormalizable*.

Now comes Gravity. First, Einstein's Theory tells us that Gravity is described by the concept of *curved SpaceTime*. Can we do Quantum Field Theory on curved SpaceTime? Not easy! And there are interesting consequences, not to least of which is that the Fourier-transform's outcome now depends on *which observer's reference frame we use*; in short, two observers looking at the same field may not see the same particle content. But it works.

But let us now look at the source of Gravity: Mass-Energy. Here, we run into not one but two fundamental issues.

First, let's remember those zero-point energies. We said we only care about differences. Mostly true, but not in the case of Gravity. Gravity cares about the actual value of the total Energy. If it is infinite, then so is Gravity.

Second, when we look at the equations of Gravitation, on the one hand we have Gravity: on the other hand, we have Matter. Matter is described by quantum fields. Einstein's Gravity is described by numbers. Apples and oranges … they cannot appear on two sides of the same equation, except for the trivial case, zero apples being equal to zero oranges. So, can we quantize Gravity perhaps? It makes sense except that it turns out that Einstein's Theory of Gravitation is *non-renormalizable*.

So that's the gist of it. A pragmatic resolution is so-called 'semiclassical Gravity' that replaces Matter fields with their so-called 'expectation value': then, Einstein's Field Equations make sense, everything is kosher, but it looks deeply unsatisfactory, ugly even. Hence, we continue looking for something better. Unfortunately, Gravity is so *weak*, its quantum effects (if any) may forever remain unobservable, so we are left speculating.

612 -

If particles interacting with the Higgs Field can give them Mass, and Mass causes Gravity, why do we still need to look for Graviton, isn't Gravity present because of the Higgs Field that give particle a Mass?

That's not precisely the way it works. The source of Gravitation is Mass-Energy. Gravitation doesn't care if the Mass-Energy is in the form of rest-Mass, Potential Energy, or even internal Kinetic Energy (e.g., the Kinetic Energy of vibrating atoms in a hot object). Energy is Energy.

Some fields interact with the Higgs Field. That interaction manifests itself as Potential Energy, so yes, it is a source (but by no means the sole source) of Gravitation. After Electroweak Symmetry Breaking, this Potential Energy will be in the form of an interaction between the respective fields and the Vacuum (the Higgs Vacuum expectation value, or V. e. v.). This, for all practical intents and purposes, will make the corresponding particles behave in the equations *as though they have rest-Mass*. So, basically, we observe a massless electron interacting with the Higgs V. e. v. as though it was a massive electron in *empty space*.

In any case, all this is about the sources of Gravitation. Then there is the Gravitational field itself! The two are not the same. By way of analogy, in Electromagnetic Theory, the sources of the Electromagnetic Field (electric charges) are not the same as the Electromagnetic Field itself (the Maxwell Field, with *photons* as its quanta in the corresponding quantum theory.)

When we look at the Gravitational field, the obvious question is, how it might be reconciled with the Quantum Theory. There are technical obstacles here, which even lead some folks to believe that perhaps the Gravitational Field is not a quantum field at all. If it is a quantum field, in the low-Energy limit its behavior can be described using *hypothetical* quanta, the *Graviton*. And if we can somehow, even indirectly, confirm the existence of the Graviton, that would be a strong indication that the Gravitational Field is, in fact, a quantum field.

613 -

If there are no particles, only quantum fields, what is the LHC colliding together?

Particles *are not* the fundamental entities in Quantum Field Theory but that doesn't mean they don't exist. The theory describes fields. In the so-called perturbative limit (basically, when the fields and their interactions are reasonably weak), these fields can be described using sums of 'pure' fields, sinewaves basically, which are known in Physics as *harmonic oscillators*.

When we quantize the harmonic oscillator, we find that its Energy levels are restricted to discrete values, incrementing, or decrementing, one unit at a time. It is these discrete chunks of Energy that play the role of particles in a quantum field theory.

What the LHC collides are exactly these 'particles'. But never mind the LHC. When we look at an old style CRT TV screen, we see electrons (quanta of the Electronic Field) hit the fluorescent screen, transferring some of their Kinetic Energy to the Electromagnetic Field, creating excitation quanta that we know as *photons*, some of which then ultimately transfer their Kinetic Energy to certain molecules in your retina, causing tiny chemical changes and currents that deliver the visual signal to the rest of your brain.

Thinking of all these events in terms of particles is convenient. But a particle physicist should never lose sight of the fact that those wonderful *Feynman diagrams* are really bookkeeping devices as we perturbatively expand an integral while evaluating an interaction cross-section.

614 -

We read that virtual particles do not exist. So, how is Heisenberg's Uncertainty Principle *really* satisfied in *empty space*?

Well, for starters, when we think in terms of particles, the Uncertainty Principle applies to particle Positions and Momenta (essentially, velocities). When there are no particles, there are no Positions, no Momenta, no Uncertainty Principle either.

Of course, when we think in terms of particles, there are no virtual particles either, because virtual particles are entirely a product of Quantum Field Theory.

Now, a field theory can get rather complicated. But when the fields and their interactions are *relatively weak*, we can describe those interactions 'perturbatively'. What this means, in practice, is that mathematically we represent the fields as sums of elementary 'pure' oscillations (so-called *harmonic oscillators*). When these oscillators are put through the quantum theory, we find that they have *discrete* Energy levels, expressed in terms of their *frequency*, starting with 1/2 unit and *incrementing in integral units*. These discrete Energy levels, or packets, are the quanta of the field, i.e., what we know and sometimes *perceive* as particles. But we use these quanta to describe all field interactions, including those that do not involve free, 'real' particles. So, this (basically a mathematical tool) is what virtual particles really are (in effect, they become a bookkeeping device for the mathematical expressions that describe the interacting fields).

The Uncertainty Principle is still present, but not because of virtual particles. It is present because in the Quantum Theory, *Positions and Momenta do not work as numbers*. They are so-called *non-commuting quantities*, i.e., they are represented by mathematical entities that, when multiplied together, will form *different results depending on the order in which the multiplication is carried out*. This has profound consequences, most notably among them that when one of these quantities has a well-defined numerical value, the other cannot have such a value (otherwise the two numbers would commute under multiplication.) This is basically the origin of the Uncertainty Principle.

This principle also applies to the variables that describe the field itself, even when the field is in its ground state (i.e., the lowest Energy 'Vacuum' state). This remains true even though we do not use the pictorial representation, this mental/computational aid, the concept of *virtual particles*.

615 -

Is it possible that Dark Energy will run out and the Universe will contract again in the very distant future?

Despite its name, 'Dark Energy' isn't powering anything, nor is it something that can 'runout'.

A little bit of background.

In Physical Cosmology, 'stuff' that fills the Universe is represented by a very simple model: so-called *isotropic perfect fluids*. In other words, any stuff is fully characterized by its *density* and *pressure*. The relationship between the two is the so-called 'equation of state'. The simplest of this stuff is called *Dust*: Matter with no or negligible pressure. Now, negligible is the key word here: we are talking about any pressure that is significantly *less* than relativistic. E.g., pressure at the deepest depth of the ocean? Negligible. Pressure in the deep interior of the Sun? Well, … still mostly negligible as the electrons there are relativistic, but the protons, not yet. In any case, things like the Earth and the Sun are compact objects, speckles of dust in the big scheme of things, and they only interact with one another, not to mention other stars and planets, through gravitation, so there really is no pressure between them. So, … essentially all visible Matter is just Dust. Then there's also that fabled Dark Matter: it, too, is Dust.

In the distant past of the Universe, there was a time when 'radiation' dominated: that is to say, stuff with such high pressure that its pressure played a significant role in its gravitational behavior. A 'relativistic gas'. But as the Universe expands, relativistic gas cools and *becomes non-relativistic* … so again, the result is Dust. That would be the end of the story were it not for the fact that, as far as we can tell, the rate at which the Universe expands is accelerating. In the equations, this can be 'explained' by the so-called *Cosmological Constant*, but what is that constant? One possibility is that it really isn't a constant at all, but some form of Matter. If so, what is its pressure, its equation of state? Well, the curious result is that it would have huge negative pressure. As a result, *its contribution to Gravitation is repulsive*. So, when it dominates, it accelerates the rate at which things fly away from each other, i.e., *accelerates the expansion*.

Moreover, the Energy that is released by this expansion perfectly balances the books, so that this 'constant' indeed remains constant: the density of this negative pressure stuff remains the same even as the density of everything else decreases.

What is this *negative pressure* stuff? We don't know. So, clever monkeys that we are, we pretend we know more than we do by giving it a name: 'Dark Energy'.

Now, Dark Energy density is *constant*. But what if it weren't? Even if Dark Energy vanished, the expansion would continue. It simply would cease to accelerate. Rather, Gravity would continue to slow it down. But to reverse it, we would need a lot more Gravity, i.e., a lot *larger* density of ordinary Matter – *Dust* – than what we *observe*. As things stand, there doesn't appear to be enough Gravity to bring the expansion to a halt, much less reverse it, even if Dark Energy suddenly went missing.

616 -

Why did Einstein warn that the geometrical interpretation of Gravity is just a model? Can the EM force be interpreted as the bending of the EM Field?

The Electromagnetic Field can be interpreted using Geometry in much the same way the Gravitational Gield can: through the somewhat abstract concept of a *connection*. Essentially, a *connection* describes what happens to a vector when we parallel transport it in a Space.

To give an example, let's take the spherical Earth, and imagine a vector, an arrow, attached at the equator at 0° longitude, pointing north. Now let's imagine sliding this vector first east 90°; then north 90° degrees all the way to the North Pole; and finally, back the equator along the prime meridian, i.e., 0° longitude. We will notice that the arrow *now points not north but west*. This happens because the surface of the Earth has *intrinsic curvature* (we cannot flatten it without stretching it).

The concept of a *connection* makes this business of parallel transport precise. It is also a useful mathematical tool in Physics, as it can be used to describe many physical interactions, including both Gravitation and Electromagnetism.

There is a key difference. Gravitation, as far as we know, is *universal*. So, the geometric description of Gravitation applies to all objects. In other words, there is only one Geometry when it comes to Gravity, and all objects 'sense' this one-and-only Geometry.

In contrast, the *connection* that describes Electromagnetism depends on the properties of the particle used to measure the Electromagnetic Field, specifically, the particle's so-called *charge-to-mass ratio*. Different types of particles will 'sense' *different connections*. Instead of a Universal Geometry, there are *many geometries*. There are even particles that do not interact with the Electromagnetic Field at all, so they sense no change in Geometry whatsoever in the presence of an Electromagnetic Field.

Does this mean that the geometric interpretation of Gravity is more fundamental than the geometric interpretation of Electromagnetism? Perhaps, but we wouldn't bet the farm on it. Neither did Einstein, as it is apparent from many of his writings. And when we read, e.g., Feynman's beautiful (dated, but still beautiful) Lectures on Gravitation, he shows very convincingly that

a. we don't need the geometric interpretation to come up with Einstein's Field Theory for Gravitation, and

b. the geometric interpretation might even stand in the way if our goal is to find a sensible Quantum Theory of Gravitation (assuming one exists).

617 -

Can *virtual* particles have the mass provided by the Higgs Field with a different value than *real* particles?

No.

First, let's keep in mind that virtual particles are called *virtual* because they *do not exist*. *They are not physical reality*. They are pieces of mathematical fiction. Useful, practical fiction, but still fiction. Specifically, they are bookkeeping tools that allow us to keep track of interacting fields in a Quantum Field Theory, so long as the interaction is sufficiently weak such that so-called *perturbative methods* can be used.

Second, even though they do not physically exist, the mathematical form that describes these bookkeeping tools very specifically depends on their very specific masses. These are called *propagators*. By way of example, this is one way to write down the *propagator* that describes a *virtual electron*:

$$\frac{\gamma^\mu p_\mu + m_e}{p^2 + m_e^2 + i\varepsilon}\ .$$

The value of this expression is obviously dependent on the *electron mass* m_e, and if it were any different than the observed value, that would result in different outcomes in a variety of Particle Physics experiments.

618 -

If we travel faster than light, would we become invisible because the light couldn't reach us?

Others were quick to point out that it is difficult to answer a Physics question when one asks to suspend the rules of Physics.

That said, it is important to stress that what Relativity Theory says it is simply that the (Vacuum) speed of light is *the same for all observers*. One consequence of this is that we cannot accelerate from slower-than-light to faster-than-light and vice versa. Another consequence is that there are no faster-than-light reference frames, i.e., no faster-than-light observers. But the theory does not a-priori rule out faster-than-light worldlines.

And in General Relativity, all these rules become 'local', applicable only in our *immediate vicinity*. Things that are far away from us may, in fact, move faster than the speed of light relative to us (indeed, in our expanding Universe, everything beyond our so-called *cosmological horizon* is moving away from us faster-than-light).

And, at least in principle, it just might be possible to 'warp' SpaceTime locally so that although we never exceed the Vacuum speed of light in our immediate vicinity, our 'warp bubble' moves much faster than the speed of light relative to distant observers.

We should hasten to add that although this is valid theory (it is referred to as Alcubierre's drive in the literature, named after Mexican physicist Miguel Alcubierre, who first proposed this speculative solution to the equations of General Relativity) it may not be realizable in practice, for a whole host of reasons. Nonetheless … assuming we have some way to exceed the speed of light, such as Alcubierre's drive, no, we would not become invisible, just as a faster-than-sound airplane doesn't become inaudible. Sure, nobody will see us coming before we arrive because light from our previous position would not have had a chance to reach them yet; but those you leave behind would be able to see us because we would still

a. emit light,

b. reflect light that you run into, and

c. obscure light.

Of course, if we are using something like a warp drive, things can become weird indeed, as the warping of SpaceTime necessarily involves other effects, which would change the wavelength of emitted\reflected light or perhaps block that light altogether. But that is another story.

619 -

Is the axial Higgs boson a fundamental particle that has a different fundamental field than the conventional Higgs boson? Do we already have some approximation of its Mass?

No, *it is not a fundamental particle*. In fact, it is not really a particle at all.

The misunderstanding stems from the fact that the methods of Quantum Field Theory can be used in many diverse fields, including Condensed Matter Physics. The same mathematical apparatus that, say, describes the Electromagnetic Field and can be used to describe, for instance, sound propagating in a dense medium. Does this mean that the 'phonon' is an elementary particle? Of course not. To imply otherwise, to intentionally confuse a condensed Matter mode described using the mathematical methods of Particle Physics with a fundamental particle? That's not simply silly, it even raises possible ethical questions. Peter Woit, in his aptly titled blog, *Not Even Wrong*, properly debunks this nonsense using stronger words than here above.

Let's get a little technical: whenever fields are involved and the Quantum Theory is involved, we can take the formal, mathematical steps of expressing that field as a sum of pure waves (that is, perform a *Fourier-transform*) and then treat these pure waves as *quantum harmonic oscillators*. The discrete Energy levels of these oscillators will act as the 'particles' of this system, providing a useful, practical mathematical apparatus to model the system. As has been mentioned above, we can do this with sound, ending up with the concept of phonons.

620 -

What is Mass? Why does it produce gravitons to affect Space and Time? Does it mean that Space and Time are parts of Mass? Or, rather, Mass is a part of Space and Time?

Mass characterizes the ability of a body to resist a force. It is the quantity that determines how rapidly a body accelerates when subjected to a force: the more massive it is, the more force is required to achieve a given acceleration $F = ma$.

Since 1905, we know that the Mass of an object is its internal Energy-content $E = mc^2$. That Energy-content is usually in the form of either Kinetic Energy (the Energy of motion) or Potential Energy (the ability to do work). Kinetic Energy in this case, in particular, refers to the internal Kinetic Energy of the body; e.g., the thermal motion of its constituent molecules measured in the reference frame on which the body as a whole is at rest.

Mass does not 'produce gravitons'. Rather, all physical systems interact with the Gravitational Field, and it is their Energy-Momentum that characterizes that interaction. For ordinary objects at non-relativistic speeds, this is dominated by their Energy-content, i.e., their Rest Mass.

The Gravitational Field may or may not be a quantum field (it probably is, but we do not – yet? – have a working theory of Quantum Gravity). If it is a quantum field then, and only then, when the field is *weak*, it can be described 'perturbatively', that is, in terms of small deviations from the field's ground state. In the quantum form of the theory, these small deviations come in discrete steps, or quanta; it is these quanta of the Gravitational Field that are called *gravitons*. What produces or absorbs gravitons is the interaction between the Gravitational Field and any other field (including the Gravitational Field itself) with which it interacts.

As to the relationship between Gravitation and SpaceTime, Gravitation is not the only theory that can be expressed using the mathematical language of Geometry. But Gravitation is unique: *it is universal*, which means that the SAME Geometry applies to everything (in contrast, if we use Geometry to describe the Electromagnetic Field, the Geometry depends on the Charge-to-Mass ratio of the particle used to measure the field). Because this Geometry is universal, it is tempting to think of it as THE Geometry of SpaceTime. It is prudent to remember, though, that Einstein himself cautioned us against reading too much into this geometric interpretation, and that taking it too literally might stand in the way of either creating a successful Quantum Theory of Gravitation or come up with possible modified theories of Gravitation.

621 -

If a spin-2 particle behaves like the carrier of Gravity how do spin 3, 4, 5 and 6 particles behave?

It is the other way around: It's not that a spin-2 particle behaves like a carrier of Gravity but rather, the gravitational field itself is a spin-2 field (and its quantum, the *graviton*, is therefore a spin-2 particle).

Could there be extensions of Gravitation using higher-spin fields? Undoubtedly. But the discussion rapidly gets both very technical and very speculative. The Wikipedia article on the topic offers an illustrative example:

———————————

Higher-spin theory - **Wikipedia** (https://en.wikipedia.org/wiki/Higher-spin_theory)

———————————

Then again, this topic has not been studied at depth, and even Wikipedia informs us that the landscape of these theories is not well explored, for instance, *action principles* (which would be essential to defining a specific higher-spin theory) are not known.

622 -

How can modern theoretical physicists abandon one model of calculation (the Particle) for another (Field Theory) without noticing it is the difference in their own calculations that is described, not Reality *per se*?

Abandon we don't. Rather, we refine. A pure particle model in Quantum Physics, characterized by Schrödinger's Equation, has two significant shortcomings:

first, Schrödinger's Equation describes how the Particle gets from place to place, but not how it is created or destroyed (which we see all the time in experiments, e.g., photons are created by a light source, and absorbed, which is to say, destroyed, by our retina);

second, Schrödinger's Equation, even in relativistic form, is 'leaky': it yields a rapidly vanishing but non-zero probability of things happening faster-than-light, which is equivalent, in different observer reference frames, to a direct *violation of causality*, with effects preceding causes.

Quantum Field Theory solves both these problems. By *treating particles as excitations of quantum fields*, it accounts for their *creation* and *annihilation* in interactions. And Relativistic Quantum Field Theory *preserves causality* exactly, even in the presence of Gravity and its curved SpaceTime metric.

Reality of course doesn't care what models we use. We pick models based on how well they describe Reality. And it so happens that the Quantum Field Theory Model describes Reality better than a Particle Model.

More generally, Physics (even more broadly, the Natural Sciences) *does not create Reality*. It describes Reality using the language of Mathematics. And yes, we abandon models in favor of better models all the time, if the new model provides a more accurate, more robust match with Reality. This is precisely the case here with Quantum Field Theory.

623 -

What are gravitational waves made of?

Gravitational waves are propagating changes in the Gravitational Field, far from any sources of Gravitation. They are the *gravitational analog of electromagnetic waves*: Those, in turn, are propagating changes in the Electromagnetic Field, far from any sources of Electromagnetism (think a ray of light in otherwise empty space, far from the light source, also far from anything that might absorb it).

Just as electromagnetic waves are produced by accelerating electric charges, gravitational waves are produced by accelerating sources of Gravitation, i.e., anything with Mass-Energy that undergoes accelerating motion.

There is a *caveat*, however. The nature of gravitational waves is such that *there is no so-called dipole gravitational radiation* (this is directly related to the fact that Gravity has no 'negative charges': Mass-Energy is always *positive*). There are also *no monopole gravitational waves*. So, a body that is rotating or pulsating will not emit gravitational waves; the motion necessarily must be more complex.

Things that do emit *gravitational radiation* include the famous 2-body system: a planet orbiting a star, for instance. But because gravitation is very weak, the emitted radiation is minuscule. The Earth, for instance, emits no more than a couple of hundred watts by way of gravitational radiation as it orbits the Sun. It takes *extremely massive* systems with *extremely rapid orbits*, such as inspiraling neutron stars or black-holes orbiting each other at nearly the Vacuum speed of light shortly before merging, for gravitational radiation to become significant.

As to the nature of the radiation, the propagating change is like a propagating *tidal* wave. A body that experienced as gravitational wave passing through will be stretched in one direction and compressed in a perpendicular direction, even as its volume remains unchanged.

It is this effect that is measured by two perpendicular laser beams in the LIGO gravitational wave detectors. The effect is very tiny, hence the need for extremely stable, miles long tunnels in which laser beams are reflected back and forth many times, for there to be a measurable difference between the lengths traveled, and thus observable interference between the two beams.

624 -

We know Mass and Energy are interchangeable according to Einstein's Theory of Special Relativity, $E = mc^2$. Does energy need to have Mass to be Energy? If not, what is a form of massless Energy and how does it create Energy without having Mass?

What $E = mc^2$ really means is told by the title of Einstein's 1905 paper: "Does the inertia of a body depend upon its Energy-content?" Einstein, of course, answers this question in the affirmative.

So, what does it mean? It means that there is no such thing as 'Mass' as a stand-alone concept. We measure Mass as the ability of a body *to resist an accelerating force*. In other words, Newton's 2nd Law, $F = ma$: the acceleration a will be determined by the Force divided by the body's Mass, $a = F/m$. Einstein's paper amounts to the statement that the m in this equation *is not* some independent quantity but the *Internal* Energy-content of the body being accelerated. The Kinetic Energy of a body is not part of its Energy-content: *it depends on the observer*. The *Internal* Potential Energy of a body (e.g., a charged particle) in an *external* field (e.g., an outside electrostatic field) *is not* part of its Energy-content either: it represents a relationship with another body. So, neither of these forms of Energy figure in the body's inertial Mass. But they may be part of the Mass of a system as a whole! Imagine a star with a planet orbiting it. The inertial Mass of the star is its Energy-content. The inertial Mass of the planet is its Energy-content. But the inertial Mass of this solar system? Why, it is the Energy-content of the entire solar system: that includes the inertial Mass of the star, the inertial Mass of the planet, plus the Kinetic Energy of the planet orbiting the star minus the (negative) Gravitational Potential Energy that holds the planet captive in its orbit.

So, perhaps, the best way to think about it is that inertial Mass is something that we associate with a specific body or system, but it really is just a shorthand for the *total* Energy-content of that body or system. The fundamental concept is Energy. What constitutes inertial Mass depends on what we look at as a body or system.

As an everyday yet somewhat extreme example: ley's think of the Mass of our own bodies. Roughly 99% (!) of that Mass is not due to the inertial Mass of the particles that constitute our bodies, but the binding Energy holding them together, notably the binding Energy of quarks that make up the protons and neutrons inside the nuclei of our bodies' atoms (that binding Energy is a dynamic combination of – in this case, positive – Potential Energy due to the strong nuclear force and the Kinetic Energy of the quarks themselves). The remaining 1% is mostly quark and (to a lesser extent) electron *rest Masses*, but these, too, are due to a form of Potential Energy: the coupling between charged fermions and the Higgs field or rather, its *Vacuum expectation value*.

So really, even our own bodies' inertial mass, when fully accounted for, is just a sum of all its *Internal* Energy-content. Again, emphasis on *Internal*.

625 -

How well defined is the event horizon of a black-hole? Is it a distinct and clear line where we cross even 1 molecule into, it will pull in the rest of the attached molecules? Or fuzzier?

The event horizon is indeed distinct and clear… but not a line. This is really where you need to keep in mind that general Relativity is a theory involving both Space and Time. That means that for an infalling observer, the event horizon is a distinct and clear *moment in Time*.

Observers who are not crossing the event horizon never see it, never experience it; to them, the event horizon remains forever in the future (yes, this is an extreme case of Relativity). But for observers who cross the event horizon, it's a *well-defined moment*, *not a location*. One moment we're still outside the event horizon and in fact, as far as we are concerned, the horizon does not yet exist; the next moment, we are inside the horizon, the horizon is now in our past, and everything that ever crossed, would ever cross, the horizon is already 'inside', forming a collapsing mini-Universe in which the singularity is now the 'end of everything', an unavoidable *future moment in Time*.

This is Classical General Relativity, by the way. When people involve Quantum Physics, especially semiclassical approaches to Gravity, the horizon may indeed become 'fuzzy'. But these are very speculative theories that remain contentious and far from being generally accepted, with no *observational* support.

626 -

What is that Dark Matter that keeps expanding our Galaxy?

Our galaxy *does not expand*, and Dark Matter *does not keep expanding it*.

Dark Matter plays a role in the dynamics of our galaxy (that is, the Milky Way), but it's not expanding it; rather, *it's keeping it together*. Our galaxy, like most other galaxies, rotates too fast compared to the amount of visible Matter that it contains. This violates Newtonian Mechanics. There are two possible solutions to this problem: *either we don't understand Gravity correctly on galactic scales or there's more than just visible Matter in the galaxy*. This second explanation is the Standard Cosmological Paradigm: our galaxy, in addition to the visible stars, also contains several times that much Matter in the form of 'dark' (as in, *not visible* – should really be called 'transparent') Matter.

As to the expansion: perhaps it is helpful to first offer a reminder of scales since these terms are surprisingly often confused. We live on the Earth. The Sun is about 100 times bigger than the Earth. The distance between the Sun and the Earth is again about 100 times the diameter of the Sun. The solar system is many hundreds of times larger than the orbit of the Earth. The next solar system, our nearest neighbor, is hundreds of times farther away (see what we've done here? We already went up the scale 100-fold 4 times in a row; that's a factor of about 100,000,000! And that's just to our nearest stellar neighbor, and the actual number is more like 3,000,000,000. We live in a mind-bogglingly big Universe).

So, now that we know how far the nearest star is to our Sun; our galaxy, the Milky Way, contains several hundred billion stars. Its diameter is *tens of thousands of times* the distance to the nearest star, and the Milky Way is just one of many trillions (!) of galaxies in the parts of the Universe that we can see (more distant parts are so far away, light has not yet had a chance to get from there to here in what is still a young Universe).

It is these galaxies that recede from each other in the form of cosmic expansion. But not because something 'keeps expanding' them. What keeps expanding them is simple *inertia*: once in motion, it always stays in motion. Except that mutual Gravity, which tries to pull things together, would be slowing the expansion.

We say 'would be' because that's where the last piece of the puzzle enters the picture, Dark Energy (not to be confused with Dark Matter; and don't take the words 'Matter' and 'Energy' too literally, since we really don't know what either of these two constituents really are). Dark Energy differs from Dark Matter in that it has large *negative pressure* (Dark Matter has no pressure) and as a result, its gravitational contribution is *repulsive*. Dark Energy, therefore, accelerates the expansion: it does not cause the expansion. It's only *helping to speed it up*.

As to what Dark Matter or Dark Energy really are, nobody has the faintest clue! There are numerous proposals around. Dark Matter? A new particle. Some hypothetical particle (sterile neutrinos, axions, whatever) that is kind of predicted as a possibility by the Standard Model but not yet seen. Primordial black-holes. Whatever. As for Dark Energy, perhaps it's 'only' a *cosmological constant*. Maybe Vacuum Energy (except that it's dozens of orders of magnitude too weak for that). The *self-interaction Potential* of a scalar field. Who knows? The point is, we have no observational evidence, so we are left guessing. And perhaps neither of them exists, and instead, it's the Theory of Gravitation that needs to change. We won't know for sure until we find corroborating evidence. Until then, all we can do is speculate.

627 -

Why doesn't Dark Matter clump? Why is Dark Matter not able to form aggregates of itself, despite being equipped with Gravity.

Let's begin with another question: what is it that allows ordinary matter to form aggregates of itself? If we thought that the answer is Gravity, please let's think again.

Two particles approach each other from a great distance, falling toward each other. As they get close, they accelerate. When you work it out, they both follow hyperbolic orbits around their mutual center-of-mass. After closest approach they depart back to infinity. No structure is formed. This is just Kepler's Laws in action: the Kinetic Energy of the particles doesn't vanish, so they depart with the same Kinetic Energy with which they entered the system. This is true for two particles but also for two thousand or two million or more. *Unless they interact*! That is, unless they interact by means other than Gravity!

Then they can bounce off each other. They might even absorb some of that Kinetic Energy and turn it into some form of Internal Energy (if the 'particle' is, say, a golf ball, it can absorb some Kinetic Energy and heat up in the process – Energy is still conserved, of course). Particles that interact in different ways can 'stick', become bound. The excess Energy may be *radiated away as heat*. One way or another, some dissipative process makes it possible for the system to shed that Energy and for its particle to aggregate.

The hypothesized Dark Matter does not have interactions like that. *Dark Matter particles do not interact with ordinary Matter* but they also do not interact with each other (again, by means other than Gravity). So, there are no dissipative processes to shed excess Kinetic Energy. When a cloud of Dark Matter particles collapses, the particles *accelerate* and eventually, they again fly apart. Nothing slows them down; nothing keeps them bound to one another.

As a matter of fact, Dark Matter in the modern Cosmological Theory plays a crucial role precisely because it behaves this way, which distinguishes it from ordinary (*baryonic*) Matter. Now, as to whether Dark Matter actually exists, or perhaps the observed behavior is due to some other Physics, notably a modified Theory of Gravitation … The jury is still out on this question, especially considering that to this date, no experiment designed to detect Dark Matter directly proved successful.

628 -

What else curves SpaceTime, besides Mass? Can a Charge or Magnet curve SpaceTime? Does the same apply for the strong and Weak Force? Does it apply to any acceleration?

No, it's not Mass that curves SpaceTime. Everything curves SpaceTime. The manner and degree to which everything curves SpaceTime is determined by that everything's so-called *Stress-Energy-Momentum Tensor*: a mathematical quantity that includes *Energy*, *Momentum*, *Pressure,* and *internal Stresses*.

For most ordinary objects, only the Energy part matters; the contributions of other bits (e.g., Momentum, Pressure) are insignificant. Moreover, for most ordinary objects, Energy is dominated by *rest* Mass (which is a form of Energy). So, it is true that under everyday circumstances, Gravity is largely determined by Mass alone, with other things contributing only *tiny corrections*.

But let's re-emphasize everything curves SpaceTime, because everything (other than empty Space) has a non-zero Stress-Energy-Momentum Tensor, even when it has no *rest*-Mass.

As to interpreting the Electromagnetic Force or other forces as curvature … yes and no. Yes, it is possible to describe other forces using the same geometric language. But there exists a crucial difference. *Gravity is universal*: it applies to all things equally, regardless of their composition. *Electromagnetism is not universal*; it affects, e.g., positive and negative charges differently. For this reason, there is no unique Geometry for Electromagnetism (or similarly, for the Strong or Weak Force). For Gravity, a *unique Geometry* exists because the interaction is *universal*.

629 -

Why do scientists believe that singularities shouldn't exist? Why is it called a flaw\incompleteness of General Relativity? Does it contradict with Quantum Mechanics?

A singularity is not a physical thing. *It is a mathematical concept*. Let's take something simple, say, a function like $y = 1/x$. This function is singular when $x \to 0$. The mathematical expression itself becomes meaningless at $x \equiv 0$.

So, if this mathematical expression is used to describe a physical system, at $x \equiv 0$ the description becomes meaningless. The mathematical language literally says: 'At $x \equiv 0$, the result is nonsense'.

Now, in our experience, when the mathematical language goes like this, it is usually a consequence of an *inadequate representation of the physical world*, perhaps a result of a simplification or approximation. That is entirely legitimate. For instance, when we wish to calculate the orbit of a planet around the Sun, it is entirely legitimate to treat the Sun as a point-like source of Gravitation (unless the planet gets close to it) and just use the Newtonian formula Gm/r for the Gravitational Potential. We know that this formula is singular at $r = 0$, but we don't care, because we apply it only when r is not only non-zero, but orders of magnitude larger than the radius of the Sun. And if we wanted to represent the Sun's Gravitational Field accurately even near, or inside, the Sun, we can always take a step back and use *Poisson's equation for Gravitation*, $\nabla^2\phi_{\mathcal{g}} = 4\pi Gr$.

People get excited when we discuss singularities in General Relativity, but ultimately, they're no different. The story is

the same: the mathematical expressions become meaningless for certain values of the independent variables. The conclusion to draw here is that we need a better model, which leads to a mathematical description that does not 'lose its mind', so to speak.
And knowing that Classical (i.e., Non-quantum) Gravity is likely not the final word in the study of Gravitation, it is not an unreasonable thing to expect that a future, better theory will evade singularities just as Poisson's equation, treating a gravitating source as an extended body, evades the singularity of the naïve point-source approximation.

630 -

In our region, SpaceTime is curved (we are attracted to the planet) but Space is Euclidean and flat; so too, presumably, is Time (since we have conservation of Energy laws). So, where does the curvature of SpaceTime enter the picture?

As a matter of fact, up to *extremely tiny* corrections, what we perceive as Newtonian Gravity is the *Time dilation part of SpaceTime curvature*. This is one of the reasons why we should eschew using images of rubber sheets or trampolines as visualizations of SpaceTime curvature. They are grossly misleading.

No, the reality is: Newtonian Gravity is really the 'Time curvature' part of the metric tensor. And it is measurable: clocks on the surface of the Earth tick ever so slightly slower than clocks in deep space.

Conservations Laws remain intact. It's just that at this level of accuracy, we must write them down using the mathematical language of General Relativity, Riemannian Geometry, using *covariant derivatives* to be precise.

631 -

If SpaceTime is not a real thing, then how is the value of a massive object's Gravitational Field 'informed' and influence the motion of distant objects? What is it between them that mediates this force?

Here we stumble upon the question that puzzled none other than Newton himself! And the answer is: why, it's the Gravitational Field! Which, in a sense, is very similar to the Electromagnetic Field. The basic principle is the same. There are sources (charges in the case of Electromagnetism, Mass-Energy in the case of Gravitation), which determine the field that, in turn, determines how those sources move in the presence of that field.
Influences in that field propagate according to rules that we describe using the mathematical language of *field equations*. Far from sources, changes in the fields propagate as plane waves at the invariant speed of Relativity Theory: *electromagnetic waves* (including light) in the case of Electromagnetism, *gravitational waves* in the case of Gravity.

But, what about SpaceTime?

In the modern formulation, we can describe both Electromagnetism and Gravitation using a mathematical language that is closely related to Geometry, the language of *covariant derivatives*. Without going into deeply technical details, the basic idea is that the effect of the field can be represented using *geometric concepts*. But there's a key difference. In the case of Electromagnetism, the effect of the field depends on the *material properties* of the object that is used to probe the field. An electrically neutral particle detects no field. A particle that has a large charge and a small mass is deflected a great deal more than a particle with a *small charge and large mass*. And so on.
In contrast, the Gravitational Field is *universal*: all particles are affected the same way. In other words, the 'geometry' of Electromagnetism depends on what is used to measure it; the 'geometry' of Gravitation is independent of the properties of the probe. In the case of Electromagnetism, it is possible to establish a 'geometry' unaffected by the field using *neutral* particles as probes; in the case of Gravity, *no such neutral particles exist*, so, the only 'geometry' is the one we measure.
Thus, it is easy to conclude, then, that *Gravity is Geometry*. Yet, none other than Einstein himself cautioned against reading too much into this geometric interpretation. It can also stand as an obstacle in the way towards understanding possible *quantum* theories of Gravitation, which, necessarily, *must treat the Gravitational Field as a physical field*, not just 'geometry'. Not to mention that the very fact that *gravitational waves* have tangible, measurable physical existence as they carry Energy and Momentum (e.g., from a distant merger of black-holes or neutron stars to the detectors of the LIGO experiment) should tell us that we are dealing with a field as *physical* as the Electromagnetic Field.
Lastly, concerning the point about SpaceTime itself, it is wrong to say that it is not real. Distances between objects are real; intervals of time between events are real. But SpaceTime has no independent existence. *Space has no little markers by which it can be measured in the absence of material fields*. What we measure are distances and Time intervals between things or events that involve things.

632 -

Is it possible that Dark Energy will run out and the Universe will contract again in the very distant future?

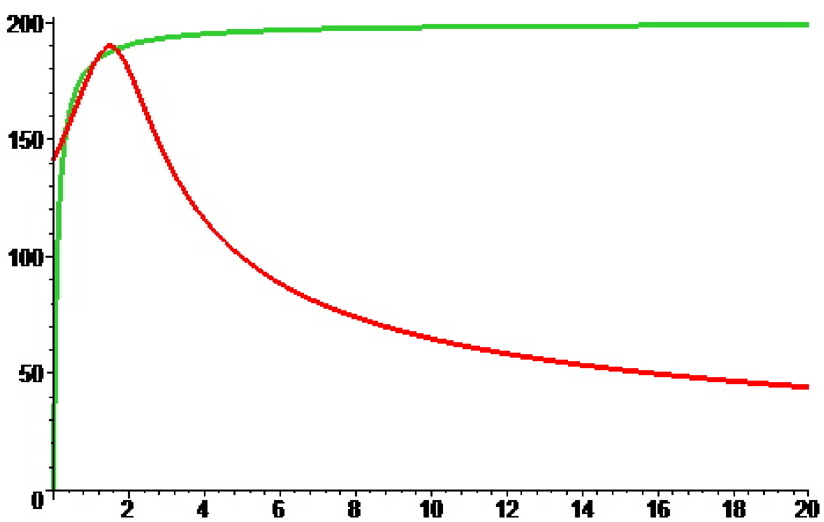
Despite its name, 'Dark Energy' isn't powering anything, nor is it something that can 'run out'.
A little bit of background. In Physical Cosmology, 'stuff' that fills the Universe is represented by a very simple model: so-called *isotropic perfect fluid*. In other words, any stuff is fully characterized by its *Density* and *Pressure*. The relationship between the two is the so-called *equation of state*. The simplest of this stuff is called *Dust*, i.e., Matter with no or negligible Pressure. Now, *negligible* is the key word here: we are talking about *any pressure* that is significantly *less than relativistic*. Pressure at the deepest depth of the ocean? Negligible. Pressure in the deep interior of the Sun? Well … still mostly negligible as the electrons there are relativistic, but the protons, not yet. In any case, things like the Earth and the Sun are compact objects, speckles of dust in the big scheme of things, and they only interact with one another, not to mention other stars and planets, through Gravitation, so, there really is *no pressure between them*. Therefore, essentially *all visible matter is just dust*. Moreover, there's also that fabled Dark Matter: it, too, is dust.
In the distant past of the Universe, there was a time when 'radiation' dominated: that is to say, *stuff with such high pressure that its pressure played a significant role in its gravitational behavior*, a 'relativistic gas'. But as the Universe expands, relativistic gas cools and becomes nonrelativistic … so, again, the result is dust. That would be the end of the story were it not for the fact that, as far as we can tell, the rate at which the Universe expands is *accelerating*. In the equations, this can be 'explained' by the so-called *Cosmological Constant*, but what is that constant? One possibility is that it really isn't a constant at all, but some form of Matter. If so, what is its Pressure, its Equation of State? Well, the curious result is that it would have huge *negative Pressure*, such that contribution to Gravitation is *repulsive*. So, when it dominates, it accelerates the rate at which things *fly away from each other*, i.e., accelerates the expansion. Moreover, the Energy that is released by this expansion *perfectly balances the books*, so that this 'constant' indeed remains *constant*: the Density of this negative Pressure stuff *remains the same even as the density of everything else decreases*.
What is this negative Pressure stuff? We don't know. So, clever monkeys that we are, we pretend we know more than we do by giving it a name: 'Dark Energy'.
Now, as we have seen above, Dark Energy Density is *constant*. But what if it weren't? *Even if Dark Energy vanished, the expansion would continue*. It simply would *cease to accelerate*. Rather, Gravity would continue to slow it down. But to reverse it, we would need a lot more Gravity, i.e., *a lot larger Density of ordinary Matter*, *dust*, than what we observe.

As things stand, there doesn't appear to be enough Gravity to bring the expansion to a halt, much less reverse it, even if Dark Energy suddenly went missing.

633 -

How do galactic rotation curves suggest the presence of Dark Matter?

Here is the simplest schematic representation of the problem by way of a diagram:



This is not any specific galaxy, just a generic representation of a typical *spiral* galaxy. The horizontal axis would be the

distance from the galactic center, measured in kpc (kiloparsecs, with one parsec equal approximately 3 light-years); the vertical axis would be the *orbital speed* of stars around the galactic center, measured in km/s.
Now, in the case of a spiral galaxy, the bulk of the *visible* Mass is in the galaxy's central, compact bulge. Therefore, it is not completely unreasonable to use Keplerian Dynamics to estimate the orbital speeds of stars *far from the bulge*. This is depicted by the red curve: it falls off roughly as the *square root of the radial distance*.
But this is not what we see. Rather, we observe *galactic rotation curves* that are more like the green curve in this example: the orbital speeds of stars remain roughly constant or fall of very slowly with increasing radii.
How can this be? Well, there are two possible explanations. Either we do not understand Gravity, or there is Matter in the galaxy beyond that which we see, altering its Gravitational Field and, consequently, the orbital speeds of stars.
While *modified Gravity* theories exist, it is very difficult to build a modified Gravity theory that is *consistent* with all the observations we have (ranging from the solar system to the Cosmos as a whole) and not run afoul of the data. The Dark Matter hypothesis, in the meantime, though not without issues of its own, can nonetheless deal with *galaxy rotation curves* and other challenges from Cosmology.
So, this is how: it is the difference between the red curve in this schematic plot (representing orbital speeds using visible Matter alone and Kepler's Laws) and the green curve (representing the actual, *observed* orbital speeds) that suggests the presence of *unseen Matter*.

634 -

If the rate of the expansion of the Universe is increasing, does it mean the amount of Dark Energy is increasing, too? If yes, from where is the extra amount of Dark Energy coming from?

[e.g., compare with **Answer 601**]

There is a very simple formula, easily derivable by any student in a Cosmology course, that relates the density ρ to the cosmic *scale parameter* a, as a function of the so-called *equation of state*, w:

$$\rho = a^{-3(1+w)}.$$

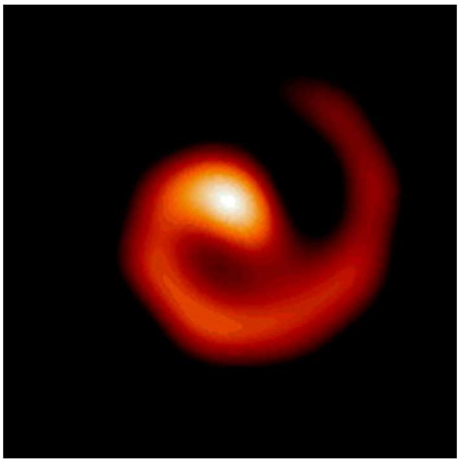
For Dark Energy, $w = -1$. Therefore, the exponent on the right-hand side becomes zero and consequently, Dark Energy's Density, ρ, is constant, *does not change with scale as the Universe expands or contracts*.
But this is dry math, so let's try to fill the equations with meaning. First, the definition of the *equation of state* parameter $w = p/\rho$ i.e., it is the *ratio of pressure vs. density*. For Dark Energy this ratio is *large* and *negative*: *Dark Energy has negative pressure*.
Now, let's think about Gravity for a moment. Suppose Gravity does work on a cloud of gas with normal, positive pressure. The result: the cloud of gas contracts, and the work done by Gravity converts into greater pressure therein. This is a form of Potential Energy: if we could somehow 'turn off' Gravity, the cloud of gas would expand explosively *because of its pressure*.
But what if pressure were *negative*? Then Gravity would be doing work by making the medium expand, not contract (in a very practical sense, this is similar – although by no means the same – to how Gravity causes a bubble in the sea to rise, not fall). But what happens to the work done by Gravity when the medium expands? Well, if that medium is Dark Energy, the work done on it by Gravity *produces more Dark Energy*. So, even as it expands, its density remains constant. So, *the 'extra Energy' is just the work done by Gravity*. The books are always balanced. Energy conservation prevails.
It's important not to forget that Gravitational Potential Energy is *negative*. Therefore, *the* (*positive) Energy-content of Dark Energy is balanced by the negative Energy-content of its Gravitational Field.*

635 -

What is a *naked singularity*?

To understand what a *naked singularity* is, first it is a good idea to look at the simplest black-hole, the *Schwarzschild solution* in General Relativity. The Schwarzschild solution is characterized by two things: the *event horizon* and the *singularity*. The event horizon is a spherical surface that is intersected by 'timelike' (slower than light) and 'null' (speed of light) world lines *only from the outside-in*, *never from the inside-out*. In other words, *it acts as a one-way membrane, allowing objects and light in from the outside, but preventing anything from escaping from the inside*.
Along world lines inside the horizon, in turn, the effects of Gravity (e.g., *tidal forces*) continue to increase beyond limit. The point, or rather, moment in Time when these effects become *divergent* (i.e., infinite) is the singularity. It is a big word, but there are singularities even in Classical Physics; for instance, any point-particle (a frequently used idealization in Classical Physics) is a point with infinite *Mass density* or, if it is for instance a charged particle, infinite *Charge-density*. The thing about the Schwarzschild singularity is that in this case, it is the geometry of SpaceTime itself that becomes singular, 'breaks down' at that point (a *moment in Time*). Moreover, whereas a point-particle is a *mathematical*

idealization that can be dispensed with, e.g., in Continuum Physics, the singularities out of General Relativity are unavoidable predictions of the theory.
But here is the thing … *we don't see this singularity*. To us on the outside, the singularity is *hidden* behind the one-way membrane of the event horizon. Not even an infalling observer can see the singularity; to them, once they cross the horizon, the singularity becomes a *future moment in Time*, which they can only reach by 'falling into it'.
There are, however, more complicated solutions for black-holes, among them the *Kerr solution* for a *rotating* black-hole, the *Reissner-Nordström solution* for a black-hole with electric charge, or the combination of these two in the so-called *Kerr-Newman solution*. These solutions are characterized by multiple event horizons and more complicated singular regions (e.g., a '*ring*' singularity) that may even be avoidable. But even these singularities are hidden behind their respective event horizons.



WR-104 binary star rotation (Sagittarius constellation)

But there are more extreme cases. For instance, if a Kerr black-hole rotates *fast enough*, it has no event horizons at all. But it still has a singularity. This singularity is no longer 'hidden' from the outside. In principle, it could be studied, that is, information about it can be obtained by an outside observer. Such a singularity is called 'naked'.
But it appears that *there is no physical process that can produce such a naked singularity*. This is formalized in the form of a *conjecture*, the so-called *cosmic censorship* hypothesis, which asserts that there are no naked singularities (other than the Big Bang itself, which is certainly 'visible' in the sense that the consequences of its existence are all around us) in the Universe.

636 -

Are there people who don't see the need for the Higgs boson\mechanism\field?

First, the existence of the Higgs boson, H^0, is not a conjecture. It was experimentally confirmed at LHC, CERN, between 2011 and 2013, and since then, its properties have been extensively studied.
Now as for the need … The existence of the Higgs Field was conjectured as how the Standard Model would be made renormalizable. With the help of the Higgs Field, it was possible to create a theory that starts with massless fermions and massless vector bosons. In such a theory, unwanted infinities can be removed using a self-consistent mathematical procedure (*renormalization*). This required the existence of not only a *neutral vector boson* (the Z^0 - boson) in addition to the *charged vector bosons* $(W^{\pm})$ of Electroweak Theory, but also the existence of a 'leftover' *scalar boson* (the *Higgs boson*) after the remaining degrees of freedom of the Higgs Field were 'used up' to make the theory complete.
This, then, was the prediction that was confirmed by the 2012 *discovery* of the Higgs boson.
If only *neutrinos* were massless and we didn't have to worry about Gravitation, the theory could be considered pretty much complete. But *neutrinos are not massless*. How to incorporate their masses into the theory without breaking its 'nice' properties? Especially considering that we never observed *right-handed* neutrinos? This could be easily explained if neutrinos were *massless*, but with *massive* neutrinos that is no longer the case.
There are several proposals to resolve these open issues and yes, it is true that at least some of them do away with the 'need' for a *Higgs mechanism* in the first place.
None of that changes the fact that the existence of the Higgs boson is experimentally confirmed. So, *symmetry breaking* or not, the Higgs boson is here to stay, and the fact that its existence and properties were predicted by theory is a strong point in favor of said theory, despite its known limitations.

637 -

What's the logic behind the Higgs boson giving Mass to objects?

The logic is called *spontaneous symmetry breaking*. Not easy to explain without the math, but the gist of it is this: our best theory of everything is a *theory of interacting fields*. The Electromagnetic Field, the Electron Field, Quark Fields, etc. These fields are *quantum fields*, which means that when they interact, they gain or lose Energy in set units: we call these units 'excitation quanta'. And when these units are well localized, they appear to us as *particles*. Thus, for instance, we see excitations of the Electromagnetic Field as *photons*.
These fields are initially *massless*. That is to say, the excitation quanta do not have any intrinsic rest Mass; to the extent that they carry Mass-Energy, it is entirely due to their Kinetic Energy.
Moreover, these fields share a common property: their lowest Energy state is when the excitations are absent. Hence, no particles.
Now, there is another field added to this mix: the *Higgs Field*. It has a unique property: it is not in its *lowest Energy state* when there are no excitation quanta. The absence of any Higgs excitation quanta, also known as *Higgs particles*, represents a 'false' Vacuum: a Vacuum that is actually a higher Energy state than the state in which some Higgs particles are present. So, this Vacuum is *unstable* and quickly decays, by creating Higgs excitation quanta, into a new, 'true' Vacuum that is really the lowest Energy state.
Now comes the trick: we take this new, stable Vacuum and redefine everything with respect to it. That is, we redefine the Electromagnetic Field, the $W^{\pm}$ and Z^{0} boson Fields, the Quark Fields, the Neutrino Fields such that this new, stable Vacuum is treated as the, well, Vacuum. And we find that we now have new terms in the equations: with respect to this new Vacuum, all these fields (except for *photons* and the *gluons* of the Strong Interaction) now behave as though they did have Mass! And that, then, is our 'effective' particle content in the Universe that we observe: massive electrons, massive quarks, massive $W^{\pm}$ and Z^{0} bosons.
That said, we should hasten to add another important point. When we grab an everyday object and weigh it … about $99\ \%$ of its Mass *is not due* to the Higgs mechanism. Only $1\ \%$ is due to the quark and electron Masses obtained through symmetry breaking; the remaining $99\ \%$ is, in fact, the *strong force binding Energy* (let's remember, Mass and Energy are equivalent) that holds the quarks together inside protons and neutrons.

638 -

Since light does not lose Energy in a Vacuum, why is the light from the most distant galaxies observed by the JWST (*J*ames *W*ebb *S*pace *T*elescope) so long? Shouldn't the frequency be the same as when it was issued?

The frequency of light is not an inherent property. *It depends on the observer*. Say, we emit blue light, with a frequency of $7.5 \cdot 10^{14}$ Hz. But someone is running away from us at a high speed in our *relativistic* spaceship. So, instead of observing that light as blue, we observe it as red, at $5 \cdot 10^{14}$ Hz due to the velocity-related *Doppler shift*. Or, say, we emit a red light in space at $5 \cdot 10^{14}$ Hz. But we are standing on the surface of a neutron star and, as a result, because of *gravitational time dilation*, our clock ticks slower than someone's. So, where someone counts $5 \cdot 10^{14}$ cycles/s, we count more, $7.5 \cdot 10^{14}$ cycles/s between ticks of my clock. We see the light as blue, at $7.5 \cdot 10^{14}$ Hz.
This is exactly what happens when it comes to distant galaxies. *First*, they are moving away from us at relativistic speeds. This produces a significant shift in frequency downward, not because of what happens to light, but because of our relative motion compared to that galaxy. *Second*, the light was emitted by that galaxy when the Universe was much denser and the average gravitational field stronger. That means that clocks back then were ticking more slowly in comparison to clocks now. So, our clocks being faster, they count fewer cycles between ticks, i.e., we measure a still lower frequency. It is the combination of these two things: the velocity-related Doppler effect and the gravitational redshift due to the changing overall Gravitational Field of the Universe that causes us, as observers, to see that same light at a lower frequency than the frequency at which it was emitted. In fact, we could easily correct this, at least in principle. Just grab a suitable neutron star, launch it in space towards the distant galaxy so that it moves at the same speed as that galaxy, and place a telescope on that neutron star. This way, both the velocity-related Doppler and the gravitational redshift are compensated, and this telescope would see light from that distant galaxy at just the same frequency at which it was emitted.
Long story short: Frequency is not an inherent property. *The observed frequency depends on the relationship between emitter and observer*: their relative motion and the differences in Gravitational Potential at the two locations.

639 -

Should we believe that Mass cannot be converted into Energy?

Mass cannot be converted into Energy for the same reason (more or less) water cannot be converted into a liquid: *it already is Energy*.
Einstein's fundamental 1905 paper makes it very clear: the Inertia (i.e., what we call Mass) of an object is its *Energy content*. All forms of Energy, combined. This may include *rest Mass*, but for most elementary particles, there is no true rest Mass (e.g., the rest Mass of the electron is really a result of how it interacts with the Higgs Field's Vacuum expectation value, not an inherent rest Mass). In any case, Energy can be converted from one form into another (e.g., Potential Energy may be converted into Kinetic Energy) but *Mass plays no special role in this respect*.
To stress this point, let's suppose we have a box lined with perfect mirrors, and inside that box, an electron and a positron. We weigh the box on a perfect scale and find that its Mass is the Mass of the box plus the Masses of the electron and the positron. But now we let the electron and the positron inside the box collide and let their combined 'Mass convert into Energy', namely the Kinetic Energy of the two photons that are produced in their annihilation. So, we converted Mass into Energy, right? Not quite. Those two photons, still inside the box, now keep bouncing back and forth between those perfect mirrors, forming an Electromagnetic Field that carries the *same amount* of Energy that was the combined Mass-Energy of the electron and the positron. If we weigh the box on our perfect scale, the box's Mass remains unchanged: it is still the Mass of the box proper, plus the Mass of an electron and the Mass of a positron. That is because the total Energy content of the box *has not changed*, despite the dramatic conversion of the electron-positron pair therein into a pair of photons.

640 -

What is the meaning of 'Lagrangian' in Particle Physics?

Not just in Particle Physics. One of the most general principles in many branches of Physics is the so-called *Principle of Least Action*. A generalization of the Fermat Principle in Optics, the Principle of Least Action basically states that we can formulate the theory by way of a mathematical expression called the *Action*, and that the equations of motion of the theory will be those equations that *minimize* this Action (Fermat's Principle tells us that light follows the path of *least time* between two points. Same principle, just a more restricted application).
Now in practice, 'Action' usually appears in the form of an integral, and under the integral sign, there is the expression that will need to be minimized as the system *evolves from an initial to a final state*. This expression under the integral sign is called the *Lagrange Functional* ('functional' because it acts on a set of functions, describes the system's generalized positions and velocities, and produces a number) or, in short, *Lagrangian*.
This approach works both in Classical Mechanics (for point particles as well as extended objects) and in Classical Field Theory (continuous media). For instance, the Electromagnetic Field can be specified by way of a Lagrangian; the Gravitational Field, too.

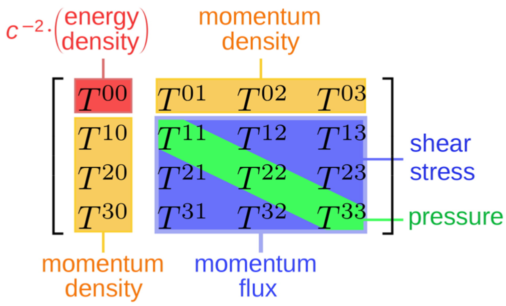
In the case of Quantum Physics, the situation is a little different since particles have *no well-defined trajectories*. However, it turns out that the Lagrange Functional is closely related to the *phase* of the wavefunction that describes a quantum particle, and that ultimately, what the wavefunction does is again very similar to what light does as it obeys Fermat's Principle. Finally, *modern Particle Physics is not Particle Physics at all, but the Physics of Quantum Fields*. These fields, too, are specified in the form of Lagrange Functionals that are then 'quantized' according to a set of procedures that, in essence, *decompose the field into a sum of pure* (*distinct*) *frequencies*, each of which will have an operator-valued coefficient that will have discrete states corresponding to the notion of a particle. But the starting point is still the Lagrangian that defines the theory.

When a physicist looks at a Lagrangian, she\he can usually tell, just by looking at it, what kinds of entities the Lagrangian describes and what kinds of interactions these entities have. Whether it is the Lagrangian that describes, say, a classical charged particle and an Electromagnetic Field, the Lagrangian of a metric Theory of Gravity, or the Lagrangian of interacting scalar, spinor, and vector fields in a Quantum Field Theory, the Lagrangian reveals a lot, at least qualitatively, to the experienced physicist simply through its appearance (e.g., the nature of the interaction terms, their coefficients, etc.).

641 -

Is the Stress-Energy Tensor the source of all gravitational effects?
[compare with Issue 48, P. 20]

This nice graphic from Wikipedia shows what physical properties are represented by the Stress-Energy Tensor $T^{\mu\nu}$:



Why in the form of a tensor? Because, in Relativity Theory, coordinate systems are *arbitrary*, and the goal is to describe Physics using only quantities that *preserve their properties under arbitrary coordinate transformations*.
Energy *is not* such a quantity. We say a car's Energy is $(1/2)mv^2$; we say it is 0 because we travel in the car and the car is motionless relative to us. Same thing for Momentum. Or we say that air pressure is isotropic; but we sit in a rapidly accelerating rocket and feel a lot more air pressure up front than from the sides, and some Shear stress as well.
In other words, the components of the Stress-Energy Tensor depend on the reference frame of the observer. But if we treat the Stress-Energy Tensor as a fundamental object (regardless of how it is represented in various coordinate systems), *its properties remain the same for all observers*, including how it relates to other quantities, such as the curvature of SpaceTime (also represented by a tensor).
The source of Gravity is not the Stress-Energy Tensor but, rather, Energy, Momentum, Pressure and Shear Stress. Under everyday circumstances, *Energy density dominates*, and we get back Newton's Law for Gravity. But if speeds are high enough, if Pressure is high enough, if Stresses are high enough, the other components play major roles as well.
The reason why we write these quantities in the form of a tensor is because for the same physical configuration, different observers *measure* different values for Energy, Momentum, Pressure and Shear Stress. By writing these in the form of a tensor and treating the tensor as the *fundamental* mathematical object, we achieve a description of Nature that is the same for all observers, regardless of their motion.

642 -

If Gravity works at $360°$, why do we always see pictures of *accretion* '*discs*'? Shouldn't the object attract gases and Matter from all directions? Shouldn't Matter be also sucked by the poles of the object? Isn't SpaceTime curved in all directions?

It's very simple, actually. If we take a perfectly spherical cloud of gas or particles and let it collapse, it remains perfectly spherical throughout. But now, let's take a random cloud of gas or particles. Chances are that it has a small, but non-zero, net Angular Momentum, and Angular Momentum is *conserved*, so the more the cloud collapses, the faster it spins (the classic example is about the spinning ice skater who pulls-in her arms and, as a result, she spins faster).

Now, particles are of course moving in all directions, but they also collide randomly, dissipating their Kinetic Energy (into heat). So, any motion that is perpendicular to the of rotation plane will eventually die out. However, the rotation remains because of the conservation of Angular Momentum. So, the cloud can collapse in the direction perpendicular to the plane of rotation, but *cannot* collapse in the plane of rotation itself, not without shedding that Angular Momentum somehow. As a result, the cloud flattens, and we end up, never mind accretion disks, even ordinary solar systems in which most stuff is orbiting the central star in (more or less) the *same* plane (this would be the plane of the ecliptic in our own solar system).
To reiterate: the symmetry is broken not because Gravity fails to act the same way in all directions but because a random cloud of gas or particles usually has a small but non-zero net Angular Momentum, and that Angular Momentum defines a *rotation plane*.

The image above shows the first clear detection of the equatorial disc fed by ejected dust jets from a proto-star. Presumably, the dust cloud will 'accrete' into planets and other cosmic systems. (Source: Chin-Fei Lee et al., *Science Advances* (2017)).

643 -

Why cannot black-holes be just neutron stars with huge Gravity which doesn't let the light out? Why must there be *singularity* inside them?

The answer to this question is hidden in the question itself. If the Gravity of a star is powerful enough not to let light out, that means that the escape speed of that star is greater than the Vacuum speed of light. But if the escape speed is larger than the Vacuum speed of light, it means that there is no 'rest'. The star is in *continuous gravitational collapse*. This has been worked out in a landmark paper by Oppenheimer and Snyder all the way back in 1939 ('*On Continued Gravitational Contraction*').
The bottom line is that *there is no force* that can counteract Gravity that is this strong, not even the so-called 'neutron degeneracy pressure' which is responsible for the stability of neutron stars. Continuous collapse is then *unavoidable*, resulting in the black-hole singularity.

644 -

What does the Schrödinger's Equation mean for laymen?

Schrödinger's Equation means almost nothing for laymen because, unfortunately, *Quantum Physics is not intuitive*. But if there are two lessons that can be taken home from Schrödinger's Equation without equations, they'd be these:

1. Nature is under no obligation to be easy to understand or intuitive. The limitations that stand in the way of comprehension *are ours, not Nature's*;
2. Schrödinger's Equation admits solutions that make perfectly good sense intuitively; but also admits solutions that are impossible mixtures of these perfectly sensible solutions. Yes, it literally means that the electron is in two places at once, but if we try to then intuit the electron as a miniature cannonball that splits into two copies of itself that go their separate ways, we are doing ourselves a disservice, because that's not how it works.

Beyond this, unfortunately, we just need to learn the math. Until words like *eigenvalue* or expressions like *linear combination of eigenstates* make sense to us, we will not be able to understand Quantum Physics. Anyone who says otherwise is (perhaps unintentionally, but nevertheless) misleading us. The very basics of Quantum Physics is that solutions of equations that make absolutely no sense in terms of *classical intuition* nonetheless correctly describe Reality. The moment we appeal to intuition, we're no longer doing Quantum Physics.

645 -

Is the concept of particle-antiparticle pairs appearing and annihilating continuously and invisibly throughout the empty space mere speculation, a hypothesis, a theory, or a proven theory? If it's not a proven theory, what are the reasons behind it?

It is a pretty picture but let's be careful not to take it too literally. The reality behind that picture is the following: when we look at the evolution of a quantum system from its initial to its final state, we look at *every possible way* for the system to get from here to there.
Now let's take the Vacuum: its initial state and its final state will both be the ground state. But there are many ways to get from the ground state to the ground state. The straightforward way, of course, is when the system stays in the ground state throughout. But it is also permissible for the system to form, e.g., a particle-antiparticle state and then return to the ground state. More complicated scenarios are also acceptable.

However, we should note, at this point, the importance of two issues:

first, these intermediate states *are not observable*;

second, talking about them as particle-antiparticle pairs is really just using convenient labels for bookkeeping purposes; what we are actually describing are quantum fields, not actual particles as miniature cannonballs.

To what extent is this proven? Well, we do know that the nature of the Vacuum plays a role, e.g., in the way atoms work: the *Lamb shift* is a good example. Furthermore, the standard explanation of the famed *Casimir effect* is that in the gap between conducting plates, *certain energies are excluded*, and thus the ground state Energy density of the Vacuum will be *less than elsewhere*. This manifests itself as a *slight negative pressure* between the plates, trying to pull the plates together.

646 -

Why is Gravity still considered a fundamental force when we know it is a consequence of General Relativity? Is the *graviton* still a possibility?

It's a 'consequence' of General Relativity? No. General Relativity is a (*plausible*) theory of Gravitation. Specifically, it is a *classical field theory* of the fundamental force that we know as Gravitation.
Whether or not gravitons exist is a *separate* question. It is generally assumed that the Classical Theory of Gravitation, General Relativity, can be 'quantized', reformulated as a *quantum theory*. So far, we have not been able to do so, for mainly technical reasons. But assuming that it can (and ultimately, will) be done, we know that, in the *perturbative limit*, we can then express the field using *field quanta* that we call *gravitons* (this conclusion is *independent* of the specific form a Quantum Theory of Gravity might take).
Now, it is of course possible that Gravity is not a quantum theory. Some people pursue serious research in this direction. In this case, *there would be no gravitons either*.
But whether gravitons exist, General Relativity stands as the *classical* theory of the *fundamental* force we know as Gravitation, just as Maxwell's Theory of Electromagnetism remains the *classical* theory of another *fundamental* force.

647 -

How big was the Universe 1 minute after the Big Bang?

In the standard Cosmology (flat Lambda-CDM (Cold Dark Matter) Cosmological model with no *spatial* curvature) the Universe is – and has always been – *infinite in spatial extent*.
Contrary to popular notion, the Big Bang was neither big nor a bang (explosion). Rather, the early Universe was *hot and dense everywhere*: *the earlier we go*, *the hotter and denser it was*. And things that are far apart today were close to each other back then. But it was still an *infinite* Universe.

648 -

What is there left to discover or explain about Gravity?

Here are a few examples, some mysteries about Gravity:

- the question of *Quantum Gravity*: is Gravity a *quantized field*? Or, unlike most other fundamental phenomena in Nature, is Gravity 'emergent' and, fundamentally, *Classical*?
- Gravity on cosmic scales: are the anomalous rotation curves of galaxies, the dynamics of galaxy clusters, and cosmic evolution overall due to yet-to-be-discovered Dark Matter and Dark Energy, or is it perhaps our Gravity Theory that is incomplete?
- The *Cosmological Constant* problem: the zero-point Energy of Vacuum fluctuations shall *gravitate*. Indeed, it has the same equation of state as Dark Energy. Could it be Dark Energy? But then, Quantum Field Theory tells us that its Energy density is either *infinite* or *many dozens of orders of magnitude too big compared to the observed value*;
- the Energy of the Gravitational Field: the Gravitational Field, obviously, carries Energy (e.g., there is the Gravitational Potential Energy that is released when two massive objects approach each other, or the Energy carried by gravitational waves). Yet, General Relativity tells us that in the immediate vicinity of an observer, SpaceTime is *indistinguishable* from *empty SpaceTime*, i.e., its *local* Energy density must be 0 . How can these two issues be convincingly reconciled?
- Event horizon firewalls: in a *quantum-mechanical Universe*, can an observer ever reach the *event horizon*? Or

would the observer be destroyed by a 'firewall'? Does the event horizon even exist, given the finite lifetime of an evaporating black-hole?

As these examples show, there is still plenty to do.

649 -

What do we mean when we say that light has Momentum? It can't be the same as *regular* Momentum because, as far as we know, light is *massless* (in other words, *relativistic Mass* doesn't count).

[cf/c Issue 610]

It is true that in the non-relativistic approximation, the Momentum of a point-particle is its Mass multiplied by its velocity (*vector*), so it would be 0 for a zero-Mass particle. But this is only an *approximation*. This approximation works very well at *low speeds*, but not when it comes to *speeds approaching the speed of light*.
The *relativistic Momentum* of a *massive* particle is given by

$$p = \frac{mv}{(1-v^2/c^2)^{1/2}} \ (\equiv \gamma m v) .$$

This is not 0 for a particle with $m = 0 \wedge v = c$; rather, it takes on the *indeterminate* form $0/0$.
The *relativistic Energy*, in turn, is given by

$$E = \frac{mc^2}{(1-v^2/c^2)^{1/2}} \ (\equiv \gamma m c^2) .$$

This, too, becomes indeterminate when $m \to 0 \wedge v \to c$. But now, let's take their *ratio*:

$$\frac{p}{E} = \frac{v}{c^2} \ .$$

The beauty of this formula is that it stands *independent of the Mass* of the particle in question. It is never indeterminate: $p = vE/c^2$ holds for any particle, *regardless of its Mass or Speed*. So, for photons, when $v = c$, we just obtain $p = E/c$, the well-known relationship between the photon's Energy and the magnitude of its Momentum.

650 -

Does a photon have a Gravitational Field? This is hard to accept because a photon cannot produce any *shadow effect* into *ether* nor is a Matter wave which absorbs and re-emits *ether waves*.

Yes, photons have Gravitational fields: this has nothing to do with shadows, but yes, photons can produce 'shadows' under the right circumstances. Let's take one step at a time.
We know that the gravitational field of the Sun deflects light; this was first confirmed observationally in 1919. This means that the photon's Momentum (a *vector* quantity) changes. Change in Momentum implies a *force*. And we have known since Newton that forces are always balanced: If the Sun exerts a force on a photon, the Sun also experiences a force. So, yes, the photon has a Gravitational Field.
In fact, in the early Universe, during the 'radiation-dominated era' it was the Gravitational Field of photons that was the primary factor determining the *rate of expansion* (this era ended when the Universe was a few 10^4 years old, long before it became *transparent to light*, when the *Cosmic Microwave Background* (CMB) radiation was emitted.)
This has nothing to do with shadows. Things can be completely transparent, without casting any shadow, yet have a Gravitational Field.
But photons *are not* completely transparent, even if they come very close. Electromagnetism is a *linear theory*, meaning photons do not interact with photons directly. But photons can, in principle, produce *particle-antiparticle pairs* (e.g., an e^-e^+ pair) and those, in turn, *can influence* other photons. This does not happen easily because the Mass-Energy of an e^-e^+ pair is something like 10^6 times more than the Energy of a typical photon of *visible* light. But when *very high-Energy* photons are involved, this can, and does, happen. Specifically, certain astrophysical events produce *extreme high-Energy* photons, which never reach us. The reason? They collide with the photons of the Cosmic Microwave Background. To such extreme high-Energy photons, the Microwave Background photons can 'cast a shadow': the Microwave Background is *opaque* to them, so, these *high-Energy* photons are scattered on the CMB.

651 -

Since the Universe is finite, do scientists speculate what lies beyond the edge?

There is no (*experimental*) evidence that the Universe is finite. The simplest model (a so-called *Friedmann-Lemaitre-Robertson-Walker Universe*) that fits the data shows a 'flat', *infinite* Universe.
But even if the Universe is 'closed', *which implies finite*, *it does not have an edge*. Topologically, it's the same idea as a circle that is finite but without endpoints. Or the surface of a sphere that is finite but without boundary. The Universe is not 1-dim (like the circle) or 2-dim (like the surface of a sphere) but 3-dim. Its presumed finiteness is in the same spirit, so to speak.
So, no edge: there is no credible mathematical model of the Universe that predicts an edge of any kind.

652 -

How does the mass of an electron come from its interaction with the *Higgs Field* and how much comes from Einstein's equation $E = mc^2$?

The equation $E = mc^2$ is not about where mass is coming from. It is the Mass-Energy Equivalence relationship, which tells us that *rest-Mass* and *internal Energy-content* are really the *same* thing.
In the case of the electron, that internal Energy-content is entirely due to its interaction with the Vacuum, specifically with the Higgs Field's non-zero *Vacuum expectation value* (V. e. v.). This V. e. v. comes about because of the famous Higgs Mechanism, the notion that the *lowest Energy state* of the Higgs Field is an *excited state*. That means that other particles, such as the electron, *can interact* with the Higgs Field in its *lowest* Energy state, i.e., with the *Vacuum state*.
The result of this so-called *Yukawa-type interaction* is an interaction Energy of about $511\,\text{keV}$ which, of course, also happens to be the electron's mass by virtue of $E = mc^2$.

653 -

Supersymmetry claims that every known particle has a *supersymmetry partner*. The massless photon must have a massless *photino*. But such a photino is not seen. Why doesn't this disprove Supersymmetry?

In a simple theory with 'unbroken' Supersymmetry, all known particles including the photon would indeed not only have corresponding *superpartners*, but these superpartners would have the *same* Mass. So, the massless photon would have a counterpart, the equally massless photino, a fermion. This is, in fact, what fundamentally Supersymmetry is all about: a quantum field theory that is *invariant* (i.e., its equations remain the same) under a transformation that swaps particles and their superpartners.
Obviously, this is not what we see. We never detected a photino, an electrino or any quarkinos or gluinos for that Matter. The usual answer to this conundrum in supersymmetric theories is that the symmetry is 'broken': because of which the superpartners exist, but with masses that differ – perhaps *differ wildly* – from the masses of their counterparts.
Thus, a Supersymmetric Theory may posit that a photino exists, but its Mass is so high, it's beyond anything we'd have been able to detect to this date in Particle Physics experiments.

654 -

What would happen if a photon were to travel forever, considering it experiences Time *instantly*?

A photon has no point of view: *we cannot attach a reference frame to a photon*, at least, not within the context of Relativity Theory, a *basic principle* of which is that the Vacuum speed of light is *invariant vs. any* (*inertial*) *reference frame*, the same for all observers. At the same time, such an observer is always *at rest* with respect to himself. In other words, the observer's velocity in the observer's own reference frame is always 0 .
Now, let's imagine that the photon is an observer. Given the *invariance* of the Vacuum speed of light, it would have to observe itself as traveling at the speed of light; on the other hand, relative to itself, it is at rest. So, it is simultaneously traveling at the speed of light and standing still, which is clearly *impossible*.
If we do not want to throw away Relativity Theory, only one choice remains: *we need to throw away the assumption that we can attach a reference frame to a photon*.
This makes sense, because when we look at reference frames that move very close to the speed of light relative to us, they appear increasingly *degenerate*. If we were to take the limit of that at the speed of light, we would end up with a reference frame in which the Time coordinate and the coordinate along the direction of motion *collapse to a point*. Which is not very useful; this is not a reference frame anymore. In short: *a photon has no point of view*.

655 -

Why does Dirac Equation predict the existence of anti-particles while Schrödinger Equation does not?

Primarily because of *Lorentz Symmetry*.
The Dirac Equation is a relativistic version of the Schrödinger Equation. Dirac was looking for a linear equation, specifically guided by the Schrödinger Equation, but that was relativistically invariant. He couldn't find one that didn't involve *taking the square root of an operator*. However, he devised a brilliant factorizing scheme that allowed the linearization he was looking for. However, it required *non-commutative algebra*, from which he realized that the factors needed to be *matrices*. Dirac determined that 4×4 matrices were needed due to the 4-dim SpaceTime symmetry. Thus, the Schrödinger-like equation became a family of 4 equations. These 4 equations were found to represent the 2-spin states and their antiparticles. More specifically, the antiparticles were identified as the *negative Energy solutions*, which result because of the *relativistic invariant* involving the *square* of the Energy.
The above is just a brief sketch of how the Dirac Equation was developed. In essence, it was modelled after the Schrödinger Equation, but the necessity for *relativistic invariance* led to a more complicated equation that revealed both the spin property and antiparticle solutions in one fell swoop.
In hindsight, it was the only way to construct a relativistic invariant version of the Schrödinger Equation. Therefore, we can say that the only real distinction between the Schrödinger Equation and the Dirac Equation is the inclusion of Lorentz symmetry in the latter.
Thus, the symmetry of SpaceTime revealed some remarkable consequences when coupled with Quantum Theory. We find the fact that so much was revealed about our observable Universe through the merging of two distinct theories quite profound. The power of using *symmetry principles* in theoretical Physics was proclaimed loud and clear with the development of the Dirac Equation.

[656] -

What is the difference between 1st and 2nd Quantization?

(A historical interlude by Sanjay Sood on 2nd Quantization, Renormalization and Quantum Electrodynamics)

The 1st Quantization was the creation of Quantum Particle Mechanics, between 1925 and 1928, by Heisenberg, Schrödinger, Dirac, Pauli, Jordan and Born. This theory quantized the Matter particles such as an electron. The allowed values of Momentum and Energy for an electron are severely constrained by Quantum Mechanics as required by Heisenberg's Uncertainty Principle.
Quantum Mechanics quantized the Matter while considering the *interaction between Matter and Electromagnetic fields*. The Electromagnetic Field itself remained *classical*.
Three of the founders of Quantum Particle Mechanics recognized this asymmetry between the way Quantum Mechanics treated Matter and the Electromagnetic Field. They understood that a true quantum description must include a *quantized Electromagnetic Field*.
They decided to reformulate Quantum Mechanics not in terms of particles but *in terms of fields*. Both Matter and Electromagnetism would be described in terms of *quantum fields* and each individual particle, say an electron, would be understood as a *quantized excitation of this field*. This program is known as the *2nd Quantization* or the *Quantum Field Theory*.
The *first* theory of this program was published in 1929 by Heisenberg, Jordan, and Pauli. It included a Relativistic Quantum Field of an electron which was obtained by transforming Dirac's Relativistic Equation from one electron to a *continuous field*. The degrees of freedom are *infinite* in both cases.
The *second* constituent was the Relativistic Quantum Electromagnetic field obtained by Dirac by quantizing Maxwell's Classical Electromagnetic Field.
Third and final component was the *interaction between the two quantum fields*. In a Quantum Field Theory, electron and photon are nothing more than the *quantized excitations of their respective quantum fields*.
It is this third component that led to trouble. The theory turned out to be very sick. It was plagued with *infinities* that made it impossible to obtain any *finite value* for a physical quantity such as the Magnetic Dipole Moment of the electron. Although this was an interesting first attempt of its kind, the failure of the theory to yield a finite value remained a deep mystery to the leading theoretical physicists of the day. It was not a very serious problem because it didn't have any negative impact on the ability of Quantum Mechanics to provide answers to all the problems it was applied to at the time such as the spectra of molecules or the binding Energy of the nucleons.
Right after WW2, during spring 1947, a remarkable measurement was made by Willis Lamb in Isidor Rabi's Lab at Columbia University. Using the microwave generator developed to generate the radar waves during the world war, Lamb was able to measure the *Energy gap* between the $2s$ and $2p$ states of a neutral H atom.
To the great surprise of everyone this gap turned out to be $\neq 0$ – it corresponded to the microwave frequency of 1030 MHz. The Energy of $2s$ state is *higher* than that of the $2p$ state by this amount. This was indeed a very big surprise since Dirac's Equation predicted this gap to be exactly 0. In other words, these two states should be *degenerate*.

This discovery then led to a great deal of renewed interest in the old Quantum Field Theory of Heisenberg, Jordan, and Pauli. It was recognized immediately by the leading theorists of the day that one must remove the infinities from this theory to obtain a finite value of the Energy gap measured by Lamb.
This new program was called *Renormalization of Quantum Field Theory*. It was quickly completed independently and successfully by Tomonaga, Schwinger and Feynman between 1947 and 1949. The new theory was called *Quantum Electrodynamics*. The new renormalized theory was used to calculate values that exactly matched Lamb's measured value of the Energy gap of the H atom.
Renormalization program put Quantum Field Theory on a solid foundation and turned it into a tool that could be used to successfully calculate other values of physical quantities such as Magnetic Dipole Moment of an electron or the scattering cross-section of 2 electrons. One may call *Renormalization* the completion of 2nd Quantization.

657 -

Is Time fundamentally different from other dimensions?

There is a technical reason, which means a little bit of math, but it is not that hard to understand if you remember the Theorem of Pythagoras from high school.
What's the square of the distance from the origin in 2-dim, for Cartesian coordinates x and y ? It is $x^2 + y^2$, of course.
What about 3-dim? It is the same idea: the square of the distance is $x^2 + y^2 + z^2$.
But what's the distance between two events in SpaceTime (and *distance*, here, has a precise mathematical meaning, because it is an *invariant norm*, or *length of a vector that does not change under a change of coordinates*)? It is $t^2 - x^2 - y^2 - z^2$.
Le's see all those minus signs in front of the 3 spatial coordinates but not in front of t^2 : that's what makes Time special. In the SpaceTime of Relativity Theory, its 'signature' is *opposite* to that of Space. As a result, SpaceTime has rules of Geometry that are different from the Geometry of ordinary Euclidean Space. One consequence is the existence of an *invariant speed …*: the *Vacuum speed of light*.
If Time and Space weren't distinct in this way, we would not have Relativity Theory, but we also *would not have a Universe in which the Law of Causality applies*. This simple rule of Geometry also ensures that if a cause precedes an effect for one observer, it precedes the other for all observers; nobody sees the cart before the horse, so to speak.

658 -

Does Time only exist in the human mind?
(A philosophical interlude by Richard Muller, Prof of Physics, UC, Berkeley, author of '*Now -The Physics of Time*')

Time exists in Physics, but *the flow of Time does not*. Physicists do not understand the flow of Time. In any given coordinate system, we can be at rest in Space, but in that same coordinate system, *we cannot be at rest in Time*. Time has this qualitatively different feature: it progresses.
This movement is currently ignored in Physics. The relativistic transformations show that rotations in SpaceTime wind up converting spatial coordinates into Time, and Time into Space. But the SpaceTime diagram does not include any sense that Time flows, that it is different. It has no special Time-location for 'now' – a moment of Time that is central to our sense of Reality because it divides that Reality into two realms: that which we cannot influence, and that which we can.
Here is a quote from my upcoming book '*Now - The Physics of Time*': "Brian Greene in his book '*The Fabric of the Cosmos*' suggests that Relativity "declares ours an egalitarian Universe in which every moment is as real as every other". He says that we have a "persistent illusion of past, present, and future" – a perspective reminiscent of Augustine. He concludes that because Relativity doesn't discuss the flow of Time, such flow must be an illusion, not part of Reality. To me, this logic is backward. Instead of insisting that theory explain what we observe, this approach implies that *observations must be twisted to match the theory*.
Einstein despaired of his inability to explain the flow of Time. But Einstein, despite his despair, moved forward and showed that *the rate of the flow of Time depends on both velocity and Gravity*. That suggests strongly that the flow of Time does not originate in the human mind but has a *true external Physical Reality*.
Another quote from '*Now - The Physics of Time*': "Space and Time together provide the stage on which we live and die; it is the stage upon which Classical Physics makes predictions. But until the early 1900s, the stage itself wasn't examined. We were supposed to notice the story, the characters, the plot twists, but not the platform. Then, along came Einstein. His great genius was in recognizing that the stage was within the realm of Physics, that Time and Space had surprising properties that could be analyzed and used to make predictions. Even if he despaired of understanding now, his work is central to our understanding. Einstein gave Physics the gift of Time."
Einstein opened this very deep question to physicists. We need to think about the origin of Time's flow.

659 -

Is the virtual particle hypothesis the reason why there's *Hawking Radiation*? Another hypothesis was that the black-hole itself is radiating from its *gravitational well* and *the curve shrinks*.

Not exactly. The prediction of Hawking Radiation arises from writing down the equations of Quantum Field Theory on the curved background of a Gravitational Field. The result is an asymmetry of sorts, which manifests itself for distant observers in the form of Hawking Radiation, slowly draining Energy from the Gravitational Field.
The popular description of Hawking radiation as virtual particle-antiparticle pairs created in the Vacuum, then separated, with the negative Energy member of the pair getting absorbed by the black-hole and the positive Energy one escaping the black-hole's vicinity, though it comes from Hawking himself (from his popular book '*A Brief History of Time*'), is nonetheless not consistent with his own scientific papers on the topic.
A couple of years ago, Ethan Siegel wrote an interesting piece, published on the Forbes Web-Site, about this. Though a less fiery language can be chosen, it is sensical that what he wrote is correct: it is inappropriate and misleading to think of Hawking Radiation in these terms.

660 -

What is the name of the material that makes up *neutron stars*?

The interior of neutron stars is usually described as a 'neutronium fluid', although its composition changes with depth, ranging from *degenerate Matter* (completely ionized nuclei, electrons) in the crust to a superfluid of neutrons, protons, and electrons further down, with the neutron-to-proton ratio increasing with depth. The deep interior may contain something else altogether, a quark-gluon plasma.
These would not be considered elements. Rather, this is what we get when Pressure and Temperature are both so high, the usual forces binding protons and neutrons together inside atomic nuclei break down, and we end up with a structureless 'soup' of constituent particles.
Contrary to what science-fiction stories told us, we cannot bring a piece of a neutron star-back to the Earth. In the absence of the compression due to the neutron star's *self-Gravity*, it would instantaneously explode like a nuclear bomb (and that is not an understatement; in fact, its *Energy density* would be much larger than that of a thermonuclear bomb, so even a very small piece would make a very big boom). And it's not because of Temperature: the explosion would happen even if the fragment is from an extremely old neutron star (that would have to be one much older than the Universe) so that it is completely cooled to room temperature, as its Pressure would still be unimaginably huge.

661 -

If the Sun is losing $5.5 \cdot 10^9$ kg/s, causing the Earth to move *slowly away from the Sun*, what is the change in the Earth's orbit compared to the retreat of the habitable zone due to stellar aging? How long will they stay in synchronization?

The Sun is indeed losing billions of kg/s, but this is an extremely small quantity compared to the whole Sun. It is roughly $3 \cdot 10^{-19}$ %. In a whole year, that amounts to, roughly 10^{-11} %. So, after 10^9 years, assuming that the present mass loss rate is approximately constant, the Sun will have lost no more than 0.01% of its Mass.
Assuming no other changes, that means that the Earth's orbital radius would increase by a proportionate amount, or about 13000 km. That is just about the diameter of the Earth.
In short, while the definition of the habitable zone depends on whom we ask (and consequently, the estimated time left for the Earth while water can stay liquid on its surface varies from anywhere between ½ billion to several billion years, depending on whose estimate we're looking at and what their assumptions are) the mass loss of the Sun and its effect on the Earth's orbit is completely negligible in comparison.

662 -

What happens if a spin-up *electron* combines with a spin-up *positron*? The resulting photon can't have any spin. Where would the extra spin go?

Electrons (and positrons) are $1/2$-spin particles. Given an electron and a positron, their combined spin therefore is either -1, 0 or $+1$, *depending on the individual spins*.
Photons are *vector particles* with spins (okay, helicity, but just not to be overly pedantic here) of -1 or $+1$ (if they had mass, a 0-spin state would also exist, but since photons are massless, that state is out).
Electron-positron annihilation must produce at least *two photons*. Why? Because of *conservation laws*. No matter how

they collide, we can always view the collision in the reference frame in which their combined center-of-mass is at rest, so the *total Momentum* is 0 *before* the collision. That means it is 0 *after* the collision. So, if they annihilated into a single photon, it would be a photon with non-zero Energy (the combined rest Mass-Energy of the two particles plus their Kinetic Energies) but 0 Momentum, *which is not possible*.
Two photons will have a combined spin of $-2, 0$ or $+2$, depending on their individual spins. Only the 0-spin combination *can be produced by electron-positron annihilation*, and that assumes that the electron and the positron had *opposite* spins. Three photons, on the other hand, can have a combined spin of $-3, -1, +1$ or $+3$. Of these, the -1 and $+1$ spin combinations can be produced by electron-positron annihilation if they had identical spins.
So then, to sum up: When the electron and the positron have *opposite spins*, the result is 2 *photons with opposing spins*; if the electron and the positron are *in the same spin state*, the result is 3 photons with a combined spin of -1 or $+1$.

663 -

How is a *neutrino* in free space different from a *photon* in free space?

First, let's see how similar they are. Both neutrinos and photons travel fast, photons at the speed of light, neutrinos, almost so. They both travel in approximately straight lines, their direction of propagation affected only by Gravity and the occasional interaction with Matter. But they are nonetheless quite different.
For starters, *neutrinos have Mass*. This means that they travel slightly slower than massless photons in the Vacuum. However, the neutrino mass is so tiny, we have never been able to measure this difference in speed in any observation. When neutrinos were observed from distant supernova explosions, they arrived at the same time as photons, the difference limited to the measurement error and uncertainties in our knowledge of how these explosions unfold in detail.
Another difference is that photons are the *quanta of a vector field*; neutrinos are the *quanta of a spinor field*. This difference means less in practice than one might think, but there is a curious twist that is explained below.
The nature of massless vector-particles like photons is such that they come in two Polarization-states, which are *perpendicular* to each other. A polarization filter, like some sunglasses, filters out photons in one Polarization-state and forces the rest to be in the other state. This helps filter out some sunlight, polarized by the atmosphere. Two polarization filters in sequence can be oriented at 90°, so that they let no light through whatsoever. This principle is used in liquid crystal displays.
In contrast, neutrinos have two *Spin-states*, similar, but not quite the same as Polarization. The curious twist is that neutrinos only ever appear in one of those 2-spin states. The other spin-state is absent, and *we don't know why*. Anti-neutrinos, in contrast, only appear in the other Spin-state.
Photons are their own anti-particle. This really doesn't mean much, because even if two photons were to annihilate each other, they'd produce … we guessed it, two photons. Neutrinos? Anti-neutrinos mentioned before, but we really don't know if they are distinct particles, or if neutrinos, like photons, are their own anti-particle (there are some on-going experiments aimed at finding out more about this).
But perhaps, the biggest practical difference is that we can see photons, but we don't see neutrinos. Photons interact directly with any charged particle, including positively charged atomic nuclei and the negatively charged electrons around them. Specifically, they can induce chemical changes (changes in how electrons bind atoms together), which is how our vision works. Neutrinos? They really don't interact with anything *except for some extremely massive particles* (the Z^0 and $W^\pm$ bosons). This means that for a neutrino to interact with an atom via these particles, it must have very high Energy … otherwise, the interaction is very improbable. So, neutrinos normally fly through Matter as though it wasn't even there. They fly through the Earth, they even fly through the Sun, *mostly unimpeded*. Therefore, whereas detecting photons requires nothing more than a Mark I eyeball, detecting neutrinos requires extremely large, complex detectors … and even those detectors *fail to detect most of neutrinos* that fly through them, as if they were in free space.

664 -

Why do physicists (e.g., in Quantum Mechanics) always speak of Momentum rather than Velocity?

The simplest way this can be phrased is: 'Velocity' is *Kinematics* while Momentum is *Dynamics*. What this means is that Velocity describes the *geometry of motion* but says nothing about the *dynamical relationships* between bodies that influence that motion. For instance, Kepler's Laws of planetary motion are *kinematic in nature*: they describe the geometry of planetary orbits with no regard to the dynamics of the Gravitational Force that shapes these orbits. Momentum, on the other hand, is a *dynamical* quantity; its time-derivative, which is Force, directly relates to another important quantity, Potential Energy, and its spatial derivative (gradient), determining the equations of motion.
But if this explanation feels less than satisfactory, it's because there is a much deeper relationship. It has to do with Lagrangian vs. Hamiltonian Physics:
First, it is not true that physicists always speak of Momenta instead of Velocities. The Lagrangian description of a

physical system involves positions and their time-derivatives, i.e., Velocities, not Momenta. The Lagrangian description leads to equations of motion that are 2nd-order partial differential equations, with boundary conditions that are determined by the *initial* and the *final* state of the system. This is a bit unsatisfactory, philosophically speaking, because what's the point trying to determine the equations of motion if we need to know the final state of the system in advance?

This is where the Hamiltonian formalism enters the picture. It represents a change of variables through what is called a Legendre Transformation. It involves what are called Canonical Momenta (a much more general concept than the high-school definition of Momentum as the product of Mass and Velocity, although, in simple cases, the two definitions coincide). The result is a set of 1st-order differential equations, twice as many as before, but equations for which unique solutions exist based on just the initial state of the system. These equations can be used to predict the future behavior of the system *with no advance knowledge* of its end state.
Lastly, in the Hamiltonian formalism, (generalized) Positions and Momenta are treated as independent variables, and the state of the system can be described as a point in an abstract space called phase space (for a point particle, this phase space is 6-dim: 3 position coordinates and 3 components of the Momentum vector). This formalism can be directly used in the transition from Classical to Quantum Physics, when the Positions and Momenta are replaced with quantum mechanical operators. This transition is not possible in the Lagrangian formalism, as Velocities are not independent quantities but time-derivatives of Positions.

665 -

Is the Cosmic Microwave Background (CMB) the light emitted from the explosion of the Big Bang?

In a sense, yes! Except that the Big Bang was not an explosion in the conventional sense, nor did it emit any light directly. Rather, what Physical Cosmology tells us is that the early Universe was *very hot and very dense* (everywhere; it had no 'inside' nor 'outside', hence no explosion either).
The Universe became less dense over time, and it was also cooling. Elementary particles recombined into protons and (some) neutrons; protons are of course the nuclei of H atoms, while some protons and neutrons recombined into He and trace amounts of heavier elements. Still cooling, still becoming less dense everywhere.
But it was still ionized gas, and ionized gas is not transparent. So, while this gas was hot and incandescent, any light it emitted was readily absorbed by it the next moment.
Until the time came, some 385000 years later, when the gas became cold enough for atomic nuclei and electrons to recombine into electrically neutral atoms, now forming a transparent gas. Any light this gas was still emitting was now traveling freely, in a suddenly *transparent* Universe (of course the transition was somewhat gradual, not instantaneous, but it was relatively quick compared to the other timescales involved).
What we see today is this incandescent glow, except that its wavelength has been changed by a combination of Doppler and Gravitational Redshift (in accordance with the equations of General Relativity), so that today, it's roughly 1100 times longer than at the time of emission; instead of visible light corresponding to a temperature $T \approx 3000\text{ K}$, give or take, it is now Microwave Radiation, the CMB, corresponding to a temperature of only about 2.7 K.

And in case we are wondering, if we 'looked' (with a radio telescope, of course) in any random direction of the sky, observing the CMB, and we looked in the same sky direction the next day, the gas that we saw glowing the first day would have become transparent by the next day. What we see the next day is light coming from a patch of gas slightly farther away (so, it took a day longer to arrive), emitted when it was that patch turning transparent, traveling through the already transparent patch that we saw the preceding day.
And it goes on like that, forever, except that each day, the wavelength is ever so slightly longer, as we see a patch of sky ever so slightly farther away, moving away from us at an ever so slightly higher speed, and traveling through an ever so slightly greater change in the cosmic Gravitational Field.
But yes, the CMB is indeed the afterglow of the Big Bang.

666 -

The larger the black-hole, the weaker the Gravitational Force at its event horizon. So, why can't the light escape from it? E.g., the black-hole inside Phoenix A with 10^{11} Sun's mass only has $(152\text{ m/s}^2)/\text{g}$ force at its event horizon.

What is weaker at the event horizon is the Newtonian Acceleration term, $c^4/(4GM)$. However, we cannot rely on Newtonian Physics at or near the event horizon. Relativistic effects dominate.
The actual acceleration at the event horizon is divergent. In other words, to hover at the event horizon, we'd need an infinitely powerful rocket exerting an infinite force upon our body. So, it makes sense to suppose that means that the Gravitational Acceleration is always *infinite* there, *regardless of the size* of the black-hole.
Perhaps even more confusingly, this is not what a distant observer sees. A distant observer sees things slow down at an exponential rate as they approach, but never quite reach, the horizon. Therefore, as measured by a distant observer,

acceleration at the event horizon would be 0 . But that, too, is a meaningless number because when we're falling through the event horizon, what distant observers see is the least of our concerns. Again, what matters is how powerful a rocket we need to maintain position. The closer we get to the horizon, the more powerful the rocket must be: at the horizon, its power has to be infinite.

667 -

Does Matter reach the speed of light in a black-hole?

Actually, things get really weird in the vicinity of the event horizon of a black-hole.
As all of us probably know, the escape velocity at the event horizon is the Vacuum speed of light. This would suggest that an object, falling from infinity, would reach the speed of light when reaching the event horizon. And in a sense, this is true … this is, after all, why it's an event horizon!
But suppose we are watching this event from afar with a telescope. Would we see an object reach the speed of light and vanish in a blink of an eye? Not exactly. Rather, *extreme* gravitational time-dilation kicks in and we see everything in slow motion. Such slow motion, in fact, that the object falling towards the horizon would appear to come to a complete halt. Not that we get to see this … because light from this object would also be exponentially redshifted, so, it would disappear. But if somehow, we could continue tracking the object, we would find that as measured by us, the object never reaches the event horizon. It just hovers there, frozen in Time.
Therefore, what would we experience if we fell along with that object? In that case, we would cross the event horizon in a finite amount of time as measured by us, the falling traveler. The event horizon would in no way be particularly special. However, once we cross the event horizon, the horizon will no longer be a spherical shell around us, rather, it would become a *moment in past Time*. Conversely, the singularity at the center would no longer be a location in Space, but an unavoidable *future moment in Time*.
But we would never actually reach, nor exceed, the local speed of light. As we approach the singularity, our Kinetic Energy becomes divergent, but even in that case, our actual speed will always be less than the Vacuum speed of light, as measured by any observer who can see us (that is, observers who, like us, crossed the event horizon). Observers outside the event horizon do not count; let's remember, they never get to see us reach the event horizon in the first place.

668 -

What are fields?

(An interlude by R. Muller, Un. of California, Berkeley)

Faraday invented the idea of a 'line-of-force'. This is a line that illustrates how a particle, or any object, can exert a remote force on another object.
Are lines-of-force real? Or are they just an abstraction? Let's hold that question for a moment.
Later, physicists, particularly Maxwell, replaced the concept of line-of-force with one of 'field'. A field works in the following way: an object creates a 'field' around it. Then this field exerts a force on other objects. So, it is not a mapping of forces (like Faraday's concept) but a *separate entity*.
The field could be considered an abstraction except for the fact that Maxwell realized that fields could be separated from the original objects. Shake (accelerate) an electric charge, and some of the field will break away and travel through space. When he calculated the speed of such traveling fields, for Electromagnetism, he found that they moved at the speed of light. This led to one of the most daring and outstanding predictions of all time: that *light is a moving Electromagnetic Field*.
We think fields are real simply because treating them in this way enables us to make predictions that are proven experimentally. Radio waves are also Electromagnetic Field that have broken free of their generator (typically an antenna, which contains a collection of accelerating charges).
The concept of a field also works for Gravity, and for every other force known to Physics. Fields exhibit properties that we used to associate with particles (e.g., the Electromagnetic Field sometimes acts as if it is a particle we call the 'photon'). Now, all particles are believed to have a field aspect, and all fields have a particle aspect. We no longer think there are pure field or pure particles; there is *only one kind of quantum object* that has both kinds of properties (we should call such things 'wavicles'). That assumption is at the heart of Quantum 'Field' Theory.

669 -

Why does a strong Gravity slow down Time?

Here is how it can be explained: we know that light, travels at a *constant* velocity. The Energy of a ray of light *depends on its frequency*, *not its velocity*. But light, too, is affected by Gravity. Which means that if a ray of light is emitted from

deep inside the 'Gravity well' of a massive object, it has to lose some Energy as it 'climbs out' of that Gravity well.
So, let's suppose we stand on the surface of a planet and emit a ray of greenish light, which is to say, an oscillation of 600 THz ($\equiv 6 \cdot 10^{14}$ Hz). We're floating somewhere in deep space and see our light, but it has lost some Energy: it is now a deep red light, oscillating at about 400 THz.
But nothing *en route* can 'eat' oscillations. *They do not get created or destroyed.* So, if we make the Electromagnetic Field 'wiggle' $6 \cdot 10^{14}$ times/sec, and we only see a 'wiggle' $4 \cdot 10^{14}$ times/sec, the only other possible explanation is that *our second is not of the same duration as someone else's second*. Instead, we find the $6 \cdot 10^{14}$ wiggles, which we generated in 1 s according to someone else's watch, take 1.5 s to arrive *according to our watch*. Similarly, if we were to turn on and off our source of light every second (that is, emit $6 \cdot 10^{14}$ wiggles, then let's pause for the same amount of time, then repeat), we'll see a light pulse that lasts 1.5 s, followed by a pause of 1.5 s.
This also works the other way around: if we were to shine a reddish light at 400 THz in our direction, we will see it as green light at 600 THz. The shift in frequency corresponds, in this case, to the gain in Energy as the light ray 'falls' into the Gravity well. So, basically, if we assume that

a. the speed of light is constant, and

b. light nonetheless gains\loses Energy in a Gravity well,

we must conclude that the only way this is possible is if our watches do not tick at the same rate. The deeper a clock (be it mechanical or biological) is inside a Gravity well, the slower it ticks.

670 -

What is *Dark Matter*? What is its relation to General Relativity, String Theory, and the Holographic Principle?

Dark Matter is a *hypothetical* solution to two related problems:
First, many galaxies rotate much too fast. When we look at the visible mass in these galaxies and compared it to their rate of rotation, we find that these galaxies (including our own Milky Way) should fly apart, as their self-Gravity is *insufficient to hold them together*. Yet they are held together. A logical possibility is that it implies that there is more Mass in these galaxies that can be seen. This hypothetical 'Dark Matter' was first introduced by the Swiss American astronomer Fritz Zwicky in the 1930s.
Second, when we look at the large-scale evolution of the Cosmos, the nature and minute fluctuations of the Microwave Background, the density perturbations that led to the development of large structures like clusters of galaxies, something is off. Not only is there not enough visible Matter to account for what we see, it is Matter of the wrong type. Visible Matter has Pressure. It can lose Energy by emitting light. All these would lead to very different cosmic structures compared to what we see today. But if we assume that there was a lot more pressureless, non-interacting (not even with light), 'Dark' Matter in addition, then all is well: *cosmic evolution works as expected*.

In both cases, 'Dark Matter' is defined through its Gravity alone. We know nothing of its possible other properties, other than that it must be 'dark' really (or maybe 'transparent' is a better description as this stuff is supposed to be *invisible*, *not even absorbing light*) and *pressureless*.
The rest is conjecture. If we had a penny for every theory of Dark Matter out there, we'd be ... well, maybe not wealthy, but we'd certainly have more discretionary funds to spend on silly hobbies like Physics books. Everyone with their pet theories has a proposal for Dark Matter. This includes String Theory. It is, after all, supposed to be a theory of everything and everything includes Dark Matter.

As for the Holographic Principle, ... it is a concept so nebulous, that it is legitimate to doubt it'll ever have experimental verification. In any case, it's not related to Dark Matter in any *direct* way.
The relationship between Dark Matter and the Holographic Principle is a topic of ongoing research and debate in Theoretical Physics. The Holographic Principle is a principle in Physics that suggests that the Universe can be described as a hologram, with the information about the Universe *encoded on the boundary of the Universe*.
Dark Matter is a hypothetical form of Matter that is thought to make up the majority of the Matter in the Universe. Despite its name, Dark Matter does not interact with light and is therefore difficult to detect directly. However, its presence can be inferred from its gravitational effects on visible Matter.
The relationship between dark matter and the holographic principle is not well understood, but some researchers have suggested that Dark Matter may be related to the holographic information *encoded on the boundary of the Universe*. This idea is based on the observation that the amount of Dark Matter observed in the Universe is like the amount of information that can be encoded on the boundary of the Universe according to the Holographic Principle.
However, this idea is highly speculative and has not been proven. More research is needed to understand the relationship between Dark Matter and the Holographic Principle, if any.

671 -

Why does a negative Energy squared create *negative Mass*? Shouldn't it just be positive Mass since a negative Time itself is positive and not negative?

Presumably, it's understandable what is behind this question. The equation everyone knows is, of course, $E = mc^2$, but, as this question itself implies, this is a rather oversimplified version of something … more complicated. Others point out, correctly, that this equation is just a special case, applicable in the coordinate system in which the particle has 0 velocity, hence 0 Momentum, $p = 0$, of the *dispersion relation*,

$$E^2 = (mc^2)^2 + (pc)^2 .$$

This equation really ought to be written slightly differently:

$$(mc^2)^2 = E^2 - (pc)^2 ,$$

which is the square of the norm (according to the geometric rules of relativistic SpaceTime) of the 4-dim vector that consists of the Energy E as its *time-like* component and the 3 spatial components of the vector quantity $\boldsymbol{p}$. As such, this norm is *invariant*, *not dependent on the choice of coordinate systems*. The quantity m is intrinsic to the test particle in question. Taking the square root of the preceding equation, we get

$$mc^2 = \pm(E^2 - (pc)^2)^{1/2} ,$$

and the sign of that, of course, is *indeterminate*. We may choose it to be positive, but we might as well choose it to be negative. Just the same, we can replace E with $-E$ and nothing changes in this equation. This, actually, is what happens when we reverse the axis of Time. And that's not unexpected: the equations of Relativistic Mechanics are indeed supposed to remain valid under such a transformation, and that's exactly what we see here.
So, from these equations alone we cannot deduce that either Energy or Mass must be positive, nor can we deduce that the two must go together. For that, we need to look a little further.
We generally *assume* that negative Energy particles *do not exist* for one simple reason: *their existence would render our entire Universe unstable* (gravitational extension of the *electrodynamical Feynman-Stükelberg interpretation*). If it were possible to produce negative Energy particles, their existence would amount to an Energy state that is lower than the Energy state of the Vacuum. This means that pure Vacuum could 'decay' by endlessly producing such negative Energy particles. This would represent a *catastrophic change* that would wipe out the Cosmos as we know it (according to the Standard Model of Particle Physics, something very similar did, in fact, occur in the very early Universe, during the *electro-weak epoch*, when the Vacuum decayed due to the presence of a negative Energy state in the form of the Higgs Field Potential. But that process was not bottomless, and the result is the Vacuum as we know it, characterized among other things by the *non-zero* '*Vacuum expectation value*' of the *Higgs Field*, which is a key part of the mechanism that endows *quarks* and (pairs of) *charged leptons* with *Mass*).
As to negative Mass, we assume it does not exist because it would break the Weak Equivalence Principle. A particle with negative inertial Mass would be repelled by the same Gravitational Field that attracts particles with positive Mass. That means that objects with different ratios of constituent particles with positive and negative Mass would fall at different rates in a Gravitational Field. There is no evidence of anything like that ever happening, either here on the Earth in the laboratory, or in astronomical observations.
So, we assume that a particle's Energy is *positive* because negative-Energy particles yield an *unstable Cosmos*; and we assume that *rest-Mass is positive because negative rest-Mass would violate the Weak Equivalence Principle*. There are also other, more subtle reasons but these two are quite fundamental and sufficiently powerful arguments. We can reject the existence of either until, or unless, there is evidence that such objects do exist.

672 -

When two particles collide, Momentum is conserved, does the *center-of-mass* of this two-body system have a constant velocity which is same as velocity before collision? If Kinetic Energy is also conserved, how will velocities relate to each other?

Kinetic Energy is seldom conserved, except in elastic collisions (e.g., two low-Energy electrons gently bouncing off each other). Most of the time, when particles collide, *they interact*. As a result of the interaction, particles are annihilated, and new particles are created. What goes in may not be the same as what comes out.
What is conserved, in addition to Momentum, is *total Energy*, which is the *sum* of rest-Mass\Energy and Kinetic Energy. This is indeed conserved not only in terms of the overall before-and-after Energy of the system but also at each individual interaction, at each vertex of the corresponding Feynman diagram. Indeed, the Conservation of Energy and Momentum at vertices is an important part of how Feynman diagrams are evaluated to obtain quantifiable results.

673 -

If the Vacuum of a *quantum field* is full of *virtual particles*, what prevents them from being observed directly?

The Vacuum of a quantum field *is not full of virtual miniature cannonballs* that somebody may be able to observe. Particles are not miniature cannonballs. Let's take it one step at a time.
First, a digression. Let's start with elementary Quantum Physics describing the motion of a particle, but, after a little bit of algebra we arrive at the Schrödinger's equation, that needs to be interpreted. The striking feature of this interpretation is that it allows a particle to be in a state where it no longer has, e.g., a definitive position but it is in a multitude of positions at once. The expression that describes this is then interpreted as a *probability density*, because it really tells us *not where the particle is*, *but how likely we find it at various places if we were to measure its location*. This is strikingly different from Classical Physics (and contradicts our 'common sense') but *we find that this is how Nature works*!
Next, let's take a case from Classical Physics, one of the simplest mechanical systems, the so-called harmonic oscillator, a pendulum. As it swings, a force proportional to its deflection will try to pull it back. We know how to describe it in Classical Physics, and we find that it will undergo nice, periodic motion. We can also apply the Quantum Theory. Strikingly, we find that such a system in the Quantum Theory *cannot have arbitrary Energy levels*: its energy will change in set units. It is 'quantized'. Moreover, *its lowest Energy state is not a zero-Energy state*. Even in its lowest Energy state, it will have some residual Energy left.

Now we are ready to move on to a *field*. Say, the Electromagnetic Field. The important thing is that being a field, it has a value (even if it is 0) at every point in Space and Time. How can we tackle a field? One way to do so mathematically is to 'Fourier transform' it, which is to say, we express the field as a sum of nice, periodic sine waves, i.e., *harmonic oscillators*. And we already know what harmonic oscillators look like both in Classical and in Quantum Physics! So, we can apply what we know and have a Quantum Field Theory.
That theory is not without issues. Most importantly, that residual Energy of the harmonic oscillator in its ground state creates a serious problem, because the field is a sum of infinitely many such oscillators. Therefore, the *ground* state Energy is infinite. Fortunately, we are only interested in the rate at which this Energy changes, so in many cases, the background, though infinite, can be ignored (the theory can be 'renormalized'), and we have a working theory.
Quantum Field Theory works well. In the Quantum Field Theory, '*particles*' are the *excitations* of these constituent harmonic oscillators. Every time a harmonic oscillator gains one unit of Energy, we think of it as a particle having just been *created*. If one unit of Energy is lost, the particle is *destroyed*. We are justified in doing this because sometimes these 'particles' indeed appear localized and behave like we might expect miniature cannonballs to behave. But most of the time, they don't. We should never forget that these 'particles' *really are the Energy levels of the field decomposed into an infinite sum*, not tiny round little balls.
And let's remember what it was said about probabilities. In the Quantum Field Theory, things are usually worked out using a known initial state and a known final state, by computing all possible ways to get from one to the other. So, take the Vacuum. How can we get from an initial Vacuum state to a final Vacuum state? The easiest way is to do nothing. Once a Vacuum, always a Vacuum. But we might also consider other possibilities: *Vacuum to non-Vacuum to Vacuum again*, with the non-Vacuum state being a *temporary* balance between positive and negative Energy states. All these possible paths through a maze of possible states must be considered when we look at how the system evolves in Time.
This is sometimes visualized as a *sea* of teaming *virtual particles* which are 'popping in-and-out of existence'. Let's avoid such expressions because we learned how misleading they can be. They imply that miniature cannonballs can pop into existence out of thin air and then vanish. And indeed, if that were the case, there would be nothing to prevent us from observing them!
But that's not what happens. Nothing is popping in and out of existence. There is no stormy microscopic sea in the Vacuum. It's just the ground state of the quantum fields present. The 'virtual particles' are just a *practical way to account for terms in a mathematical expression*, an integral (Feynman's), as it is converted into a sum of ever diminishing terms and converted into a useful approximation.
What we observe is the Vacuum because that's the subject of our observation. The equations describe how a Vacuum state evolves into a Vacuum state. The pictorial description of terms in a mathematical integral that we call 'virtual particles'? Ignore them. *They are not reality* but only useful pieces of mathematical fiction.

674 -

Are photons the Energy of an Electromagnetic (EM) Wave?

No. Photons are the *quanta* of the EM Wave. Let's start with Quantum Mechanics. The equations of classical motion are replaced by Schrödinger's equation. Schrödinger's equation tells us many things but let's focus on one specific case: the so-called *harmonic oscillator*. A good example for a harmonic oscillator is a pendulum with a small swing. When we describe a pendulum using Schrödinger's equation, we find that its Energy levels come in discrete steps, related to the oscillator's frequency. The lowest possible Energy level is $1/2$-unit; and then, the oscillator's Energy can only increase in *integral* steps, to $3/2$, $5/2$, $7/2$, etc., units. In-between values of Energy *do not exist*.

Now, for something as macroscopic as, say, the pendulum of a grandfather clock, this discreteness is undetectable. But at the level of elementary particles, it is detectable, and this behavior is responsible, among other things, for electrons in atoms having only *well-defined*, *discrete* levels of Energy.

Why is it convenient to start with this? Because the next step is to tackle a field theory, like Maxwell's Theory of Electromagnetism. There are many ways to tackle a field theory mathematically. One of them is to perform a so-called *Fourier Transform*. Without getting bogged down in the details, a Fourier Transform is like *splitting the field* into a *sum of elementary sine waves*, each with its own *distinct frequency*. The mathematics of this is not trivial but not terribly hard either; such Fourier Transforms are used all over the place, in engineering, in digital signal processors, in image recognition, and so on. And we can Fourier-transform the Electromagnetic Field of Maxwell's Theory.

And when we Fourier-transform a field, we in effect split that field into a (possibly infinite) weighted sum of harmonic oscillators!

But we already know what happens to a harmonic oscillator in the quantum world: it has discrete Energy levels.

So, when we attempt to apply the Quantum Theory to Maxwell's Electrodynamics, Fourier-transforming the field first, we get an infinite number of harmonic oscillators (one for every possible frequency) and each of these will have discrete Energy levels. At any specific frequency, we can only increase, or decrease, the Energy of the field *one unit at a time*.

Now, these units have more than just Energy: they also carry (Linear) Momentum and Angular Momentum, i.e., the characteristics of the field. But none of that changes the fact that the field is now discretized, i.e., *quantized*.

It is these units of field, these field quanta, that we recognize as photons. They carry Energy, (Linear) Momentum, and Angular Momentum. And whenever the Electromagnetic Field interacts with sources (i.e., anything that can influence the Electromagnetic Field, anything with an electric charge), it results in an increase or decrease of the number of field quanta at one or several different frequencies. In other words, an *exchange of photons*.

675 -

What makes the Strong Force Theory (QCD) so difficult to study, make predictions, and test?

The nature of the Strong Force is manifestly different from the nature of all the other forces. The intuitive reason is that the Strong Force gets stronger with *increasing* distance.

To make sense of it, think of two examples.

First, Gravitation. A planet orbiting a star. The farther the planet is, the weaker the star's Gravity. If the planet is very, very far away, the effect due to the star's Gravity becomes negligible. In short, the force weakens with distance (in fact, the Gravitational Potential goes like the *inverse* of distance).

But now, let's imagine that the planet is connected to its star not by Gravity but by a tension spring. The more the spring is stretched, the greater the force. So, the farther the planet is, the stronger the force becomes that is pulling it back.

What happens if we keep stretching? A real tension spring made of actual materials would, of course, break. But here we are talking about an idealized model, so, let's suppose it doesn't break, at least not easily. The more we stretch it, the more Energy we inject into the spring itself. There is no upper limit.

So, let's suppose we inject tremendous amounts of Energy, really pulling the planet and the star apart. Eventually, we invest enough Energy to be equivalent to the rest-Mass\Energy of the planet and the star itself! And then, the spring breaks, and all that Energy that was stored in the spring is now converted … into a new planet and a new star. So, instead of one spring, we have two, but both now have a planet on one end and a star on the other. We never get to see a spring [in its stationary final state] with a loose end.

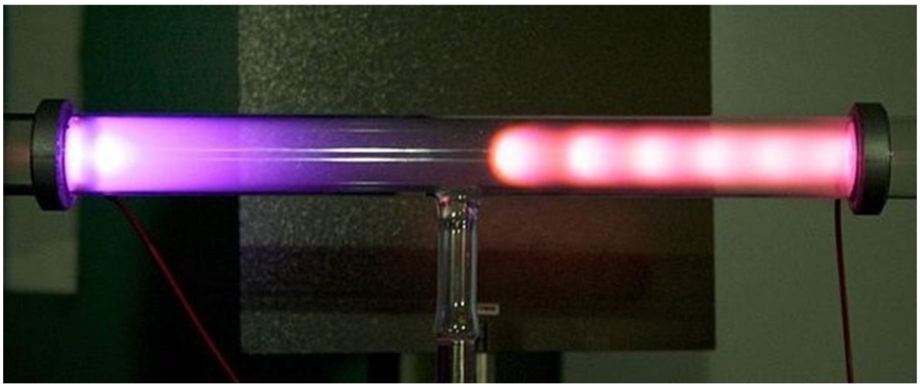
That, roughly, is how the Strong Force works and makes it difficult to study. Now, let's replace planets with quarks and springs with gluons. Do we want to see how quarks behave when they are mostly unaffected by the strong force? We need to see them in the low-Energy limit when the spring is relaxed. But that only happens inside hadrons, where the quarks are tightly packed, close to one another. Do we want to see gluons on their own? Not going to happen for the same reason we didn't see a loose spring in the case of the simple analogy offered above.

There is another possible way of studying quarks and gluons: let's pack them densely (so the interaction Energy remains low) but heat them up, so that their Kinetic Energy significantly exceeds their interaction Energy. In the resulting quark-gluon plasma, quarks and gluons begin to behave (more or less) like *free particles*. This state of Matter is thought to have dominated the Universe in the first microsecond or so after the Big Bang; then, as temperature dropped, the quarks became confined inside newly formed hadrons. Such a *quark-gluon plasma* can also be produced and studied in large particle colliders. But the Energies involved are quite significant. This is also one of the reasons why the Masses of light quarks is so hard to measure: these Energies far exceed the rest-Mass\Energies of the light quarks, so they will behave as effectively *massless*, *ultra-relativistic particles*.

676 -

What was the Universe like before it was transparent to light?

Shortly before recombination, the Universe might have looked a little bit like the gas in this tube:



In other words, it was a *low-pressure*, *ionized plasma* glowing at several thousand degrees kelvin. But unlike the gas in this tube, the Universe was very homogeneous: the glow was smooth everywhere.
The earlier we go, the *hotter* and *denser* this plasma was. Early enough, in the first few seconds of the existence of the Universe, it was in fact hot enough to produce *heavier isotopes*, e.g., *deuterium*, *helium*, or *lithium* atoms. There really is no intuition for this; that plasma was so hot, most of its glow would have been in the form of γ- radiation.

Also, this early in the life of the Universe, the dominant constituent (i.e., the constituent with the most Energy density) wasn't Matter at all, but *radiation*. In fact, radiation remained the dominant constituent until the Universe was about 50000 years old, cooled to roughly 4000 K.

677 -

Why does sunlight contain a fairly-even spread spectrum (white light) instead of a just few single frequencies equal to the quantized Energy differences between the ionic H isotopes and the resulting ionic He?

Because the source of sunlight is not due to changes of Energy levels in ionized H and He atoms. The source of sunlight is the same as the source of light from an incandescent filament or a glowing heating element on a hot kitchen stove: thermal radiation.
The surface of the Sun is hot, nearly 6000 K , so, it is *glowing with heat*. That's really it. Its spectrum is what you expect from an imperfect thermodynamic blackbody at this temperature. Imperfect because, yes, there is the solar atmosphere, there are atoms and ions that may emit or absorb light at specific frequencies, but by and large, these are just background noise over a strong signal, a *Planckian spectrum* corresponding to $T = 5778$ K , emitting roughly $\sigma T^4 \simeq 63.2$ MW of heat per m^2 of solar surface in accordance with the Stefan-Boltzmann Law, attenuated by distance as it travels from one solar radius to 1 AU (the Sun-Earth distance) to become the well-known value of $\approx 1361\ \mathrm{W/m^2}$, otherwise known as the *solar constant*.
As to why a blackbody emits electromagnetic radiation, it does so if it is made up of particles that have electric charge. Even neutral atoms are made up of electrically charged nuclei and electrons. As they wiggle and bounce around, they accelerate, and accelerating charge emit electromagnetic radiation. Curiously, because these particles have Mass, they also emit *thermal gravitational radiation*, but it is so many orders of magnitude less than the electromagnetic component, it is unlikely to ever become detectable (about 79 MW for the *entire* Sun).

678 -

Is Newtonian Gravity already *non-linear*? E.g., if we increase the Mass of an object that will also increase the Binding Energy and reduce the field produced by the increase.

That is not the way it works. Newtonian Gravity is proportional to Mass. A more massive object has a proportionately stronger Gravitational Field. The Gravitational Field of two objects is the sum of their individual Gravitational Fields. This is exactly how a linear theory works.
General Relativity is *non-linear*. The source of Gravitation in General Relativity is the complex quantity represented by the *Stress-Energy-Momentum* Tensor: it includes contributions from rest-Mass, from *internal* (Binding and Kinetic) Energies, from internal motions. The dominant contribution is from rest-Mass, which is why Newtonian Gravity remains a *very good approximation*.
To be specific, in General Relativity the Gravitational Field of two objects *is not* the sum of their individual Gravitational Fields. The Gravitational Binding Energy between the objects also contributes to the Total Gravitational Field. So, the theory is non-linear. Observational proof of this was, incidentally, obtained decades before the theory itself was discovered: Mercury's *perihelion advance* is sensitive to this non-linear behavior (that is, without the non-linearity, the Gravitational Field acting upon itself, the anomalous advance would be 4/3 times the actual value).

679 -

An atom has a positive charged nucleus orbited by a negatively charged electron 'cloud'. Why does this cloud not crash into the proton?

We have seen many answers but ultimately, it boils down to Energy. We heard that free neutrons are unstable and decay after about 15 minutes. They decay into a proton, an electron, and an anti-electron neutrino. The reason? Because the proton is lighter than the neutron. So, there is excess Energy 'stored' in the rest Mass of the neutron, which 'wants' to get out.
How much excess Energy? The neutron Mass, in the units preferred by particle physicists, is 939.565 MeV. The proton? 938.272 MeV. The difference is 1.293 MeV.
But here's the problem: the electron's rest-Mass is only 0.511 MeV. So, when we try to combine a proton and an electron, there just isn't enough Mass-Energy to create a neutron.
What it basically amounts to is that even though there is an attractive electrostatic force between a proton and an electron, there is also substantial repulsion due to nuclear forces. This repulsion 'wins' and the two cannot recombine, not unless the electron is given quite a substantial 'kick', enough Kinetic Energy to make up for the difference.
We're leaving out a lot of details, but this is the essence of it. The electron is stuck in the lowest 'orbital' (not really an orbit, just a 'state') because getting any closer to the proton would require extra Energy.
As to why electrons in an atom are different orbitals instead of all occupying this lowest Energy state, that is indeed due to the Exclusion Principle: *two electrons cannot be in the same state*. So, the lowest Energy orbital can only accept two electrons (distinguished by their Spin states), whereas higher orbitals are also distinguished by Angular Momentum and Magnetic Moment.

680 -

If black-holes emit light called Hawking Radiation, why do we call them 'black'?

First, the term 'black-hole' came into use well over a decade before it was realized that a collapsing black-hole emits *thermal radiation*, as per Hawking's 1974 paper.
Second, have we any idea how tiny the amount of radiation is that an astrophysical black-hole emits? A typical 'small' black-hole, weighing only about 3 times as much as our Sun, would emit 'light' in the form of extreme long wavelength (nearly 180 km) radio waves at a Power of 10^{-29} W. In other words, completely and utterly undetectable … so, for all practical intents and purposes, that black-hole is more black than anything else anywhere in the Universe. Except for larger black-holes, which emit even less Hawking Radiation at even longer wavelengths, so, they are *even blacker* than this!
Finally, 'black' in Physics parlance may not always mean what we think it means. That is because of what is known as *Kirchoff's Law* of Radiation, which basically guarantees that at any given wavelength, an object absorbs radiation just as efficiently as it emits radiation when heated. Now a thermodynamic 'blackbody' is called *black* because it absorbs radiation at all wavelengths with 100 % efficiency. But this also means that when this blackbody is heated, it will emit radiation just as efficiently, and will in fact be quite bright. The Sun is such an example: it radiates heat as an almost perfect blackbody, but as it its surface temperature is nearly 5800 K, its 'blackness' manifests itself as *dazzling white*.
But black-holes don't get that dazzling white unless they are very small. How small? A black-hole with the same temperature as the Sun would be about 1/3500 as massive as the Moon. Quite large by human standards but very, very

tiny by astrophysical standards! Apart from the fact that there is no known mechanism that would produce such a tiny black-hole, it should also be mentioned that although it would be hot it would also be microscopic: its *Schwarzschild radius* is barely over $3 \cdot 10^{-10}$ m (about 100 water molecules) and the power it emits would be less than $8 \cdot 10^{-7}$ W.

681 -

In Quantum Mechanics, Mass is the interaction of Energy with the Higgs Field. Does it mean that interaction means 'what happens between the particle and the field in order for the Mass to come'?

The premise of this question is incorrect, on multiple counts.
First, in Quantum Mechanics, Mass is just Mass. It is a parameter in Schrödinger's equation, corresponding to the Kinetic Energy of the particle. Nothing about any Higgs Field.
In Quantum Field Theory, Mass is still just Mass. It is a parameter in the so-called *Lagrangian*, a mathematical expression that describes the field; specifically, it is the parameter that characterizes the Kinetic Energy of the field.
Fields can interact. In other words, besides to their Kinetic Energies, there is also the Potential Energy that results from interactions: Potential Energy that can convert into Kinetic Energy as a result of that interaction (this is simply attraction or repulsion, depending on the nature of the interaction. Things made up of fields accelerating toward, or away from, each other as Potential Energy is converted into Kinetic Energy).
In the Standard Model of Particle Physics, our Universe and everything within it is described using a set of *quantum fields* (the *excitations* of these fields, i.e., the packets of Energy they can carry, are what we perceive under the right circumstances as *individual particles*.)
These quantum fields interact with each other. One of these quantum fields is the Higgs Field. The Higgs Field has a unique property: its lowest Energy state is not the state in which it has no excitations. It is a state with some excitations present. What this means is that 'empty' space (no excitations) *can decay into a lower Energy state in which excitations of the Higgs Field are present*. This new, lower Energy state will be the 'true' Vacuum, that is, the lowest Energy state possible.
But in this state, the quantity known as the *Vacuum excitation value* (V. e. v.) of the Higgs Field is *non-zero*. What this basically means is that anything that interacts with the Higgs Field now effectively interacts with this new Vacuum. And that interaction means Energy. Let's recall that Energy and Mass are equivalent. That interaction Energy will show up as Mass.
But this is not the only way in which fields and particles that are initially massless can acquire Mass. Far from it. As a matter of fact, our own Mass mostly comes not from the Higgs Field at all. Our body is made up of atoms, which in turn are made up of electrons and atomic nuclei. The nuclei contain protons and neutrons, which carry the bulk of the Mass of the atom (the electrons are some 2000 times lighter). Protons and neutrons consist of quarks, which get their masses from the Higgs Field. But they account for only about 1% of the Mass of the proton or the neutron. The remaining roughly 99% comes not from interactions with the Higgs Field, but from interactions between the quarks themselves: the Strong Force that holds the quarks together contributes a significant amount of positive Binding Energy that (once again, through the equivalence of Mass and Energy) will contribute to the total inertial Mass of those protons and neutrons.
Many popular accounts tell us that the Higgs field is how particles acquire Mass. While technically true for most particles (except for neutrinos and the Higgs boson itself) it only tells 1% of the story. The remaining 99% has very little to do with the Higgs Field, at least not directly.

682 -

How can Dark Matter clump out of a uniform soup if the only reaction it can participate in is Gravity? How does it lose Energy relative to the background of other Dark Matter?

The actual theory is called the *Newtonian Theory of small perturbations*, and it's basically a medium that begins as homogeneous with only very small density perturbations. What happens is that regions that are ever so slightly *overdense* have a little more Gravity than *underdense* regions. In an expanding Universe this means that overdense regions will expand more slowly, and in fact their expansion may even come to a halt if the density is high enough.
The Theory of small perturbations basically treats this *statistically*, and we end up with a spectrum of perturbations at various *length scales* that is rather smooth. The predictions of these equations can also be confirmed easily using N-body simulations with a large number of particles.
In contrast with collisionless Dark Matter, 'baryonic' Matter (i.e., 'normal' stuff) has Pressure. It also interacts with Radiation. These effects change how density perturbations in *baryonic Matter* evolve. The resulting spectrum will not be smooth; it will oscillate (so-called 'baryonic oscillations'), i.e., structures will form predominantly at *specific* length scales.
The presence and magnitude of these baryonic oscillations can, in fact, help distinguish between the Standard

Cosmological Theory (with Dark Matter) vs. modified theories of Gravity that do away with Dark Matter, as in these theories, baryonic oscillations will be *more significant*. Large-scale computerized surveys of the distribution of galaxies in the Cosmos are slowly taking us there but, very likely, we do not yet have large enough data sets to reliably assess the magnitude of baryonic oscillations and use it to confirm or refute theories.

683 -

What is the significance of boson Spin? The Higgs Boson has spin 0; photons, gluons, $W^{\pm}$ and Z^{0} bosons, have Spin 1; the hypothetical graviton is said to have Spin 2. What significance do these numbers have?

To make sense of Spin, it is important first to know about fields. First, Classical Fields.
A *scalar field* is a physical field that has a value at every point in Space and Time. That's it … just a number value. As a simple example, we may see a weather map that shows barometric pressure in various places. And we can easily imagine that barometric pressure can be measured everywhere, on every point of the map. And at altitude, too, so we can attach a number to every point in three dimensions. And we can of course measure how barometric pressure changes in time … so, now, we have a field of numbers spanning 3 Spatial dimensions and the Time dimension as well. That's a scalar field.

Next, there is a *vector field*. A vector field is also a number attached to every point in Space and Time, but it also has a *direction*. An example for a SpaceTime vector field is the classical Electromagnetic Field (Maxwell's Theory). A more intuitive example would be another weather map, one that shows wind: at each point, there is a little arrow, indicating not just the speed of the wind but also its direction.

To make things a little more complicated, let's recall curvature and think about the surface of a geographic globe. Let's imagine an arrow placed at the equator, pointing north. We can slide that arrow about without changing its direction. But if we slide that arrow first to the east, then all the way to the North Pole, then back to its original position on the equator, it will no longer point north. This is what characterizes a *curved surface*. But there are other paths that the arrow can take (e.g., move it east and then move it back west) that do not change the direction of the arrow. So, to know what happens to the arrow, we need to know the direction in which we slide it away from its original position, and the direction from which it returns to the original position. These two directions are really two vectors; or in an even more complicated case, a more generic object, a *tensor*. Tensors can also characterize things like internal shear and viscosity in non-trivial materials. Anyhow, if we assign a tensor like this to every point in SpaceTime, we have a tensor field. Einstein's Gravity Theory is characterized by such a field (the metric of SpaceTime, which determines SpaceTime curvature much like we can describe it with a geographic globe as an example, but in 4-dim).
So, *scalars*, *vectors*, *tensors*. Now let's move on to the Quantum Theory. When we quantize a field theory, we end up with 'unit excitations' of that field, which we can, under the right circumstances, *interpret* as 'particles'. A particle may or may not have Angular Momentum. Its Intrinsic Angular Momentum is called *Spin*. But like classical Angular Momentum, Spin defines a direction; the *axis of rotation*, if we wish.
A scalar field is just a number. A number has no direction. Therefore, the corresponding quanta *cannot have Angular Momentum*. These would be spin-0 particles. So, a scalar field, quantized, yields Spin-0 particles.
A vector field is a number and a direction. When we quantize it, we get quanta that each may carry one unit of rotation. This can be ± 1; or 0 if there is no net rotation. These quanta are Spin-1 particles.
Now things get weird and abstract. Rotations in 3-dim can be described using an algebra. But it is an algebra in which the elementary entities are not *numbers* but *rotations*. And rotations in 3-dim space have a very special property: they can be decomposed into something more elementary, which really are '*square roots*' of rotations. Every spatial rotation can be represented by not one, but two possible such objects, so, the totality of these objects is said to be a 'double cover' of spatial rotations. And let's guess what: in the Quantum Theory, it is possible to construct a field of these 'square roots' of rotations and then quantize it. This field, too, has a magnitude and a direction at every point, but it does not behave like a vector; it behaves like the 'square root' of a vector (this has a precise, but rather technical meaning). And the associated amount of rotation for the quanta $\pm 1/2$. These would be Spin-$1/2$ particles (*fermions*). They fundamentally differ from particles of integral spin (*bosons*) in that two fermions can never be in the same state; they cancel each other out (*Fermi statistics*). In contrast, two bosons in the same state reinforce each other (*Bose-Einstein statistics*).

Finally, we probably guessed already that the quanta associated with a *tensor* field each carry up to 2 units of Angular Momentum. So, it can be 0, plus or minus 1, or plus or minus 2. These are Spin-2 particles.

So, the short version is this: scalar field $\longrightarrow$ Spin-0 particle (no spin); vector field $\longrightarrow$ Spin-1 particle (one unit of Angular Momentum per-particle; 3 possible spin-states); 'spinor' field ('square root' of vectors) $\longrightarrow$ half a unit of Angular Momentum (fermion; 2 possible Spin-states); and tensor field: Spin-2 particle (up to 2 units of Angular Momentum; 5 possible Spin-states).

Therefore, when someone tells us that the Higgs is a Spin-0 particle, we immediately know that it really is the excitation of a *scalar* field. Or when they tell us that the $W^{\pm}$ or Z^{0} are Spin-1 particles, we know that they are the excitations of SpaceTime vector fields. And so on, same for Spin-1/2 and Spin-2. Other spins are also possible, leading to even more complicated geometric objects attached to each point in SpaceTime representing the field, but we know of no *elementary* particles with Spin other than 0, 1/2, 1 or 2.

684 -

Why haven't we been able to find the *Theory of Everything* (ToE) yet?

Let's answer this question with a rather serious question in its own: "How do we know that we haven't"?
Let's suppose we propose a *ToE* that is simply Quantum Field Theory on a curved background (which we know how to do), the background determined by semi-classical Gravity (which we know how to do), and the high Energy behavior suppressed, e.g., by a mechanism that relies on higher derivatives (such mechanisms exist).
Nobody thinks that such an approach is elegant, and it is intellectually unsatisfying, but it can be made mathematically self-consistent, and what is more important, *it is not contradicted by observation*. Everything we observe, from subatomic experiments to cosmological data sets, is *consistent* with this boring, mundane picture.
So, what if this is it? What if the answer is something this mundane: no superstrings, no extra dimensions, no Quantum Gravity even, no fancy pants multiverse, no inflation, no dilation fields or axions, no sparticles, just stuff we already know, building blocks we already have, assembled the right way?
The trouble is, absent observational evidence, we wouldn't know. *There's no way to tell the right theory from the wrong one without data*.
Let's go the other extreme. We sometimes muse those astronomers in the extreme far future, say, in a future alien race that exists a trillion years from now, will observe neither the CMB nor galaxies outside the giant elliptical galaxy in which they live. They might very well conclude that their one-and-only galaxy is a lone island in an infinite and eternal Cosmos. How would they know otherwise, in the absence of observational evidence such as distant galaxies with red-shifted light, or a microwave background? And what if similarly, there is evidence that was observable in the past but is no longer accessible to us, yet it would play a key role in understanding the Universe?
The point, of course, is that the answer lies not in theory but in *data*. Without data, our speculative ideas are worth no more than the speculative thoughts of prehistoric religions about the nature of creation. We are just not-so-clever monkeys who sometimes delude ourselves and think that we are smart enough to figure it out on our own. We are not, and don't let anybody convince us otherwise. What we need is more information to help us weed out the wrong ideas and improve our understanding. And we must face the very real possibility that key information about the nature of the Cosmos may forever remain hidden from us, perhaps simply because we arrived too late to the party.

685 -

Is the Heisenberg Uncertainty Principle applicable to large objects like humans?

The Uncertainty Principle is about the 'number of degrees of freedom'. In essence, that means the number of independent variables that are needed to describe an object fully and completely. Obviously, an elementary particle only has a few degrees of freedom. So, its behavior is described by Quantum Physics, including the Uncertainty Principle.
Most big things, such as humans, consist of very many uncorrelated particles, each bringing in its own number of degrees of freedom. The result is a macroscopic system that has a huge number of degrees of freedom; any quantum behavior is averaged out, so to speak, and we are left with Classical Physics.
But there are large systems that do not behave this way. Consider a pitcher of superfluid He. Many atoms, sure, but they are not uncorrelated. They are all in the same quantum state. So, they are all governed by the same, small number of degrees of freedom. The result is behavior that defies our expectations based on the classical world. Therefore, there are large objects (though not humans) that exhibit manifestly a quantum behavior.

686 -

Do black-holes actually have 'infinite density' or is it just that the relevant equations approach infinity and we don't know what they actually mean at that point?

The equations that describe some of the simplest black-hole solutions, including the *Schwarzschild black-hole* are equations of General Relativity in the Vacuum. There is no Matter, here, the density is 0 everywhere. The Schwarzschild solution is the simplest, spherically symmetric, static Vacuum solution of Einstein's Field Equations.
So, why do we blabber about the Mass of the black-hole, then? Well, these Vacuum solutions are singular. What that means is that there are points where the curvature of spacetime (which is really what we are solving for) goes infinite.

These points are not actually part of the solution, just like the point at x=0 is not part of the function $y = 1/x$.

Still, these 'missing' points can be parameterized, and in the case of that Schwarzschild solution, that parameter plays the role of Mass. Nonetheless, at no point in SpaceTime where the solution is defined is the Matter density anything other than exactly 0.

So, what is this singularity, then? Well, our strong suspicion is that it is unphysical. As we get close to the singularity, the Gravitational Field becomes immensely strong. At strengths like that, quantum effects of Gravity can no longer be ignored. But we do not have a viable Quantum Theory of Gravity. Hence, we don't know what this all means. Almost certainly *no infinities* are involved and quite possibly, *the singularity is not really a singularity either*, but we just don't know.

In any case, when we look at an actual, astrophysical black-hole, the situation is quite different. Looking at it from the outside, all this black-hole stuff: the singularity, the event horizon, all these things remain *forever in the future*.

Therefore, never mind the singularity; no matter how long we wait, a trillion years, a bazillion years, there will be no event horizon yet and no Matter will have fallen through it. This is why Wheeler maybe called black holes 'frozen stars', an expression that, we understand, was also used in the Russian literature. So, there is *no infinite density anywhere*, just *infinitely slowed down* (from our perspective) Matter, that is yet to form the black-hole. Combine this with what we know about Hawking Radiation (and we're really venturing onto speculative territory here, but still) and the black hole-may never form.

As a conclusion, we may never need to worry about singularities and event horizons as physical objects. But we don't really know yet. There is a lot more Physics there still waiting to be discovered.

687 -

Does spinning Mass weigh more, less, or the same as just hanging?

Since 1905, we know that the Inertia (i.e., the Mass) of an object is proportional to its Energy-content: that is to say, the Total Energy of the object represented *in its own inertial rest-frame*.

When we spin up an object, we invest Kinetic Energy. The inertial rest-frame of the object does not change (its center-of-mass does not move). So, its Energy-content increases. Which means that its Inertia will increase, too, by the amount of Energy that was added when the object was spun up. The difference is minuscule unless the object is spinning at relativistic speeds, but in principle, it is there.

We should also note that this Mass increase, which is within the realm of Special Relativity, is separate from the even smaller general relativistic gravitational effect, frame dragging, that is associated with spinning Masses, subtly altering their Gravitational Fields.

688 -

If the range of Gravity is infinite and all Mass interacts with all Mass gravitationally, wouldn't that require a graviton for every single interaction to the point where each particle would have to produce $> 10^{80}$ gravitons?

Of course, it would! Which is why it is a perfectly good moment to remind ourselves that gravitons, virtual particles in general, are convenient, intuitive labels that we attach to what is abstract and difficult to understand intuitively: terms in a nasty series expansion of a complicated integral in a perturbative description of Quantum Field Theory.

So, if we quantize the Gravitational Field, write down the resulting interaction in the form of an integral, series expand that integral according to its Feynman rules, which we conveniently represent using neat little diagrams with internal lines that we label 'virtual particles', … sure, once we account for every particle in the visible Universe, the first-order expansion alone will produce something like $> 10^{80}$ such lines for every particle.

But it does not mean that every particle continuously emits and absorbs an incredible number of miniature cannonballs we call *gravitons*. It simply means that every particle interacts, nicely and calmly, with the Gravitational Field, but because *we assume that the Gravitational Field is a quantum field* and represent it quantitatively in the form of an (incomplete) *perturbative quantum theory*, we can indeed write down that interaction as a near-infinite sum of elementary excitations that we call *gravitons*.

689 -

Is there an experiment that shows that Gravitational Fields don't influence each other like in Electrostatic Fields?

No such experiment exists because Gravitational Fields, unlike Electromagnetic Fields, do influence each other. This is called the *non-linearity* of Gravity. In fact, one of the earliest pieces of evidence in favor of General Relativity show this: the *anomalous perihelion advance* of Mercury. In the absence of self-interaction, this perihelion advance would have $4/3$ times larger than it actually is. This is ruled out by observational data going back to the 19th century. This ‘classical test’ not only validates General Relativity but explicitly shows that there is *self-interaction*.

690 -

If Einstein proved his Theory of Relativity, why then does Science not universally accept this over Newton’s model of Gravity?

Let’s show the equation of motion of a satellite around a cosmic body under Newtonian Gravity:

$$\ddot{\boldsymbol{r}} = -\frac{GM\boldsymbol{r}}{|\boldsymbol{r}|^3} \ .$$

Here,

G is Newton’s constant of Gravity,
M is the cosmic body’s Mass,
$\boldsymbol{r}$ is the satellite’s position vector relative to the planet’s CM, and the overdot means Time-differentiation.

Now let’s show the same equation of motion with the lowest-order correction under General Relativity:

$$\ddot{\boldsymbol{r}} = -\frac{GM\boldsymbol{r}}{|\boldsymbol{r}|^3}\left(1+3\frac{v^2}{c^2}\right) \ .$$

The $3v^2/c^2$ term (v is the satellite’s speed) amounts to a correction of about 2 parts in $1/10^9$ for satellites in low Earth orbit. Compared to this, the magnitude of the lowest-order correction due to the oblateness of the Earth is about 1 part in $1/1000$, which is 10^6 times larger than relativistic corrections. So, there really is no point to even worry about Relativity Theory before we learn how to expand the Newtonian Potential in terms of *spherical harmonics* and then use, e.g., satellites to measure the spherical harmonic coefficients of the Earth. Once that’s done, we can start worrying about the tiny relativistic corrections.
Therefore, it’s not that Science does not universally accept General Relativity. It’s that in most everyday scenarios, the corrections due to Relativity are so tiny that it is entirely sufficient to use the much simpler Newtonian Theory (simpler in part because the mathematics involved is much more elementary) for practical calculations.
We should remember that Einstein didn’t invalidate Newton ... his theory refined Newton’s Theory and did so in a way that Newton himself (who was much troubled by *the action-at-a-distance* nature of his theory) would have appreciated.
Incidentally, we cannot prove a physical theory. *Even if it is mathematically self-consistent, there’s no guarantee that its predictions will agree with the real world*. The predictions of Einstein’s Theory have been confirmed, sometimes with spectacular precision, but that’s not the same as proof.

691 -

The Universe is expanding faster than light. What would happen if we went faster than the Universe and went ‘outside’ the Universe? What’s out there?

The Universe *is not* expanding faster than light. The expansion is not measured by a speed. It is measured by the Hubble parameter, which has the units of speed/distance. It is approximately $70\ \mathrm{km/(s \cdot Mpc)}$. That means that two galaxies that are one megaparsec (1 Mpc is about $3.26 \cdot 10^6$ light-years) apart are receding from each other at a rate of roughly $70\ \mathrm{km/s}$ on average. So, two galaxies that are $1000\ \mathrm{Mpc}$ apart recede from each other at $70000\ \mathrm{km/s}$. And two galaxies that are, say, $10000\ \mathrm{Mpc}$ apart recede from each other at $700000\ \mathrm{km/s}$, i.e., *more than twice* the speed of light.
Now, if we could move faster than the speed of light, that means that, over time, we could catch up with distant galaxies that are beyond our cosmological event horizon and are moving away from us faster than light.
Cool. So, what. We are still in an infinite Universe with no boundary and no ‘outside’. Say, we moved 1000 times the speed of light. That means that eventually, we might catch up with galaxies that are nearly $4.3 \cdot 10^{12}$ from here, moving away from us at almost a thousand times the speed of light. And (at least in the context of the Standard Theory) we’d still find ourselves in a Universe that looks, by and large, *the same as it does here*: expanding, scattered with galaxies, each containing billions of stars.

692 -

Why is the *Planck Length* the smallest measurable length? Why can't it be smaller?
(Review Answer 91, P. 40)

First, the smallest measurable length given our present-day means is many orders of magnitude greater than the Planck Length. However, the question is not about what's measurable in practice but what's measurable in principle.
Let's think about it for a moment. Are the *Planck scale* units really about limits? The Planck Mass is about $21.7\ \mu g$. Is this the smallest measurable Mass? Certainly not since we can easily measure Masses less than $21.7\ \mu g$ with modest equipment. Is this the largest measurable Mass, then? Well, our bathroom scales disagree. Therefore, if the Planck Mass is not a limit either way, what makes us think that the Planck Length is such a limit?
Obviously, no one is going to produce a measuring stick shorter than about $1.6 \cdot 10^{-35}$ m but that's not how we would measure such a short distance anyway.

Let's imagine a bit of interferometry with some futuristic equipment using 1 TeV $(= 10^{12}$ eV$)$ γ rays. Say, two such γ rays differ in wavelength by ½ a Planck Length. If we're not mistaken, after a mere 10 cm or so, the two γ rays would be at opposite phase, canceling each other out. A carefully arranged apparatus, then, could measure a difference in wavelength that is just 1/2 a Planck Length, even in a tabletop scale (of course it's hard to find a source of coherent 1 TeV γ- photons, but we did say *futuristic*).
So then, if it is this 'easy' to measure lengths shorter than the Planck scale, what's the big deal one might wonder?
First, the Planck scale *is not an inherent limit* of anything. It is simply the set of 'natural' units that characterize Nature (in a rather weird way, it's basically Newton's Constant of Gravitation. The other constants in the calculation – the speed of light and the *reduced Planck Constant* – are both dimensionless and set to 1 *in natural units*. Newton's Constant, however, has the dimensions of inverse-Energy squared). The limit business arises from the fact that we have reason to believe that our best theory to date, Quantum Field Theory (in the form of the Standard Model of Particle Physics) is only an 'effective' theory that *fails at the Planck Energy scale*. So, the Planck scale *is not* a physical limit or a limit on what can be observed; rather, it's a limitation of the theory that we use to describe the quantum world.
Long story short, the Planck Length is probably not the smallest measurable length, but if it is, we don't (yet) know why that it so.

693 -

How was it not known that Energy and Mass are interchangeable before Einstein? It's quite literally in the formula for Joules. Using dimensional analysis, we see that the formula for Joules (kg m²/s²) is quite literally $E = mc^2$.

OK, so Energy has the units of Mass times Velocity squared. But why would it follow from this that the rest mass of an object is due to its Energy-content? And why would the proportionality factor be c^2? Why not $E = 0.75mc^2$? Or $E = 124.77\,mc^2$? Or, maybe, something that does not involve c at all ... wait a minute, isn't the non-relativistic Kinetic Energy actually $E = (1/2)mv^2$?
So, the fact that the units of Energy are Mass times Velocity squared *does not* in any way imply the key statement in Einstein's 1905 paper: namely, that the Inertia of a body is determined by its Energy-content. Nor does it imply that $E = mc^2$ is just a *special* case of some much more general relation, the so-called *dispersion relation*, which can be written either as $E^2 = (mc^2)^2 + (pc)^2$ (with p being the object's *Linear Momentum*) or, from equation inversion, as $m^2 = (E/c^2)^2 - (p/c)^2$, which really is the *invariant* (i.e., *observer-independent*) norm of the relativistic 4-vector $(E/c^2,\ p_x/c,\ p_y/c,\ p_z/c)$, the object's 4-dim *Energy-Momentum vector*.
All this stuff was new. The fact that the units are consistent with prior definitions of Mass and Energy is, of course, a given, otherwise the equations would have been worthless.

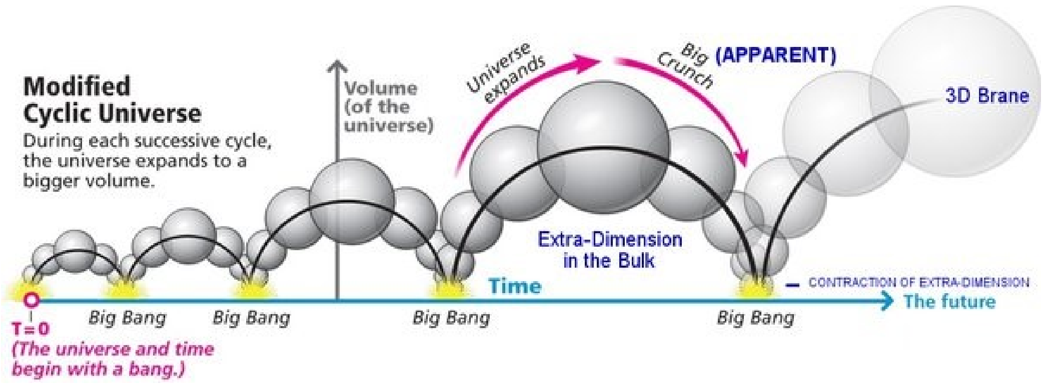
694 -

What makes the idea of a *cyclic Universe* implausible?
(Guest views by Jonathan Devor, Harvard Un.)

"*For every complex problem there is an answer that is clear, simple, and wrong*" (H. L. Mencken)

The *cyclic Universe* is exactly one of those clear and simple ideas.
It beautifully explains how an infinite Universe can have a 'big bang', yet still have an infinite Time-line without any

'special' moment of beginning. But it's also *wrong*. We know this because careful observations clearly show that the expansion of the Universe is accelerating, and this contradicts all the conventional cyclic Universe models!
This discovery was famously made independently by two competing groups of cosmologists, nearly at the same time. The leaders of both groups ultimately won the Nobel Prize [2011; Perlmutter, S. - Schmidt, B. P. - Riess, A. G.]. It is very unlikely that they both messed up the observations. We just must accept that sometimes *Nature behaves in a complex and un-intuitive manner*.



695 -

Has String Theory ruined Theoretical Physics?
(Guest views by Frank Witte, Un. College London (UCL))

Let me take the bold premise of this question and affirm it. Not because I believe it is true but because I do think the question comes from an angle which is very legitimate. String Theory has perhaps not ruined Theoretical Physics because it is hard to define exactly what a 'ruined state of Theoretical Physics' would exactly look like. It has received far more public attention that can ever be justified based on the phenomenological and empirical success of the theory as such. Not only does 'popularized String Theory' peddle narratives about 'stringy content' of Nature which are borderline deceitful (e.g., the 'strings' are mere mathematical structures in the theory, there is no proof they are physical objects of any reasonably defined sort). That certainly has inflicted a reputational cost on our Discipline, the full magnitude of which is yet to be uncovered.

String Theory sticks out like a methodological sore thumb when compared to General Relativity, the Electro-Weak Theory, Quantum Electrodynamics or even Quantum Chromodynamics. Up until the 1980's, Theoretical Physics lived relatively closely associated to Experimental Physics. String Theory has utterly abandoned that path. In it slipstream it has drawn in a generation of theoretical physicists many of whom – we can bet – fully understand the gravity of this methodological failure. They might be excellent string-theorists, but it'a a good question whether they are good 'physicists' if we interpret Physics as a discipline that studies the *measurable world*.
What has driven String Theory, and the occupation of so many theoretical physicists with it, are the driving forces from the sociology and economics of scientific communities. String Theory is a in my view a classic example of a 'speculative bubble'. Exaggerated expectations of the 'returns on investment' in the theory have been rife, herd-behavior has been frequent. Of course, these are things that physicists would love to believe they are immune from given their 'rational' occupation. But we live in an age of speculative bubbles and this one fits in just nicely. Why has this bubble not burst yet? On one hand, institutions are slow to change, especially when peer-review extends into funding and appointments and as a result a sufficiently large community can rig the system to ensure its survival. On the other hand, String Theory was lucky not to run into a 'experimentally ruled-out' scenario. There is a plethora of Grand Unified Theories which were less lucky. String Theory, on the other hand, has a wealth of free parameters that are hidden deep within the theory while, on the outside, it presents itself as a theory with only very few parameters. However, the String Theory *bear-market* will come when experiments at CERN, or elsewhere, will throw up something that has no natural place within String Theory. One can patch- and plaster-up a creaky car only so often.

The downside of this all? A colossal destruction of potential by devoting it to an ill-defined project that has, now 30+ years later, very little empirically relevant results to show for it. This has not 'destroyed' Theoretical Physics, but it would be interesting to calculate the 'cost' of the destruction and diversion of human capital and potential. The most exciting Fundamental Physics of the past three decades was found in *experimental Condensed Matter Physics*, observational Cosmology and Astrophysics, high-Energy Particle Physics well within the realm of the Standard Model and Gravitational Wave Physics well within the realm of General Relativity. If occasionally String Theory produces something of use to these fields, string theorists better not ask what the total cost associated with their contribution will have been.

I don't think String Theory has destroyed Theoretical Physics. However, I do think that it has been sucking up resources that could have been allocated elsewhere with more results. Almost 4 decades after String Theory set out to find that unified description of all forces, it is only making progress by positing ad-hoc Universes of mathematical structures *for which there is no empirical evidence*. Even the least controversial of those, Super-symmetry, has yet to show its face and every time they crank up the Energy at LHC another MeV its glaring absence becomes ever more painful. Should one day LHC spit out something entirely unexpected then let's be ready to sell all our shares in String Theory.

696 -

Are *radio-waves* also considered *photons*?

Neither radio-waves nor light nor X- rays or γ- rays are 'considered' photons. They are *electromagnetic waves*.

Anyway, in the Quantum Theory, more specifically, in Quantum Electrodynamics, when the Electromagnetic Field is quantized, in the *weak-field limit*, its excitations come in set units of Energy, or *quanta*. We give these quantized units of excitation the name 'photon'. All electromagnetic waves behave this way, at any frequency, from the longest radio-waves to the shortest-wavelength γ- rays.

However, this quantization is more obvious at *shorter* wavelengths at which quanta are *much more energetic*. Photons at radio frequencies are not readily detectable. At optical frequencies, however, the fact that light is quantized is already responsible for what we call *shot-noise*, the unavoidable noise that appears in photographs taken at low light with short exposure times and small apertures. The sensors may be enough to take a picture even in those conditions, but this picture will be *grainy* because of shot-noise: the fact that light arrives not as a continuous stream of Energy but in these discrete units. The same is true also of radio-waves, but the units are so tiny, the detected wave appears to be continuous with no apparent quantization.

697 -

How do *dimensions* work in Physics? Why are there 4 dimensions instead of 3 or 6 or 10?

There are no firm answers to this issue, but we can find at least a reasonable argument.
First, we have 1 Time dimension because, without a Time dimension, we'd have no progression of Time, *no change*, of course. One Time dimension makes a *causal Universe* (in which causes always *precede* effects) possible. More than one Time dimension would mess this up.
As to Space, there's not much we can do in one spatial dimension. Even 2 ('Flatland') is very restrictive: For instance, an internal digestive system with two openings would split a 2-dim creature in half. There are also limits to the complexity of a system that can exist in 2-dim. A classic exercise involves drawing three houses and three utility outlets (say, water, sewage, electricity): Can we connect each of the three utility outlets to each of the three houses without any of the lines crossing?
Now let's go to 3-dim. There is wonderful complexity here, but also some useful restrictions. For instance, in 3-dim, we can tie a knot on a string. Let's try it in 4-dim and it won't work: the loops can always slip past each other across that 4th dimension.
So, that kind of tells us that 3 spatial dimensions is 'just right': neither too restrictive nor too free, which leads to rich, complex structures.
Is this a rock-solid argument in favor of 3 spatial dimensions? Of course not. And there are indeed theories that propose more, albeit the extra dimensions are either curled up, 'compactified' to be small enough to remain unnoticeable (let's think how the 2-dim surface of a garden hose, when we look at it from afar, is reduced effectively to a 1-dim line) or play some very special role (e.g., a dimension that corresponds to Mass, not Space or Time). String Theory, in particular, has 6 extra, 'curled up' dimensions (the theory needs them, otherwise it doesn't work, but since we cannot see these extra dimensions, it was necessary to 'hide' them in some way).
But it makes good sense that the Universe is $\{3+1\}$- dim. Any other choice leads to a Universe in which complex systems either don't exist or *aren't stable*. Of course, this argument is based on a sample of 1, which is always questionable, but still.

698 -

As the Universe expands from a dot, doesn't it have to go through a regime where the local Mass has a concentration that will form black-holes?

First, the entire Universe (as far as we know, from the Standard Cosmological Model) was *never* a dot; it was always

infinite in extent, just *much denser* in the past.
But it is true that what we call the visible Universe (the parts from which light had enough time to reach us during the lifetime of the Universe) was confined to a very tiny volume very early on.
Why didn't it form a black-hole? Very simply because *it was not static*. It had tremendous outward Momentum, and Momentum also figures in the Einstein Field Equations. The result is a solution that is very different from the static, or collapsing, solutions that lead to black-holes.
It has been argued that it is, in fact, mathematically conceivable that what we experience as the Universe is the interior of a 'white-hole', a *time-reversed* version of the black-hole solution. But a black-hole it is not, because it is *expanding, not collapsing*, and expanding at a rate that makes collapse into a black-hole *impossible*.

699 -

How do the *four fundamental forces* exert force across *empty space*?

They don't, really, but the problem begins with how we come up with names that often create the wrong impression in our minds. In the Standard Model, we speak of '4 fundamental forces' along with the 'particle content'. But when we look at the actual mathematical expressions that describe the Standard Model, this is not exactly what we see. We can certainly interpret things this way but … What is essentially in the Standard Model is a bunch of *interacting fields*. Just that, nothing more.
Let's take the simplest part of the Standard Model, a theory that stands on its own right, Quantum Electrodynamics (QED). In QED, there are two fields: the Electromagnetic Field and the Electron Field. *These two fields interact*. They are both *quantum fields*: that means that with an appropriate Fourier-transform, we can turn these fields into a sum of elementary oscillations, and we can treat each of these oscillations as a *quantum harmonic oscillator*, with *discrete* levels of Energy. These levels are the *field quanta*. For the Electromagnetic Field, we call the quanta 'photons'; for the Electron Field, we call them 'electrons'.
The fields are present everywhere. When they interact, they exchange Energy and Momentum. When they don't interact, changes in the field propagate in the form of *waves*, described by an appropriate wave equation.
There is a crucial difference between the two fields, however: the quanta of the Electron Field also carry *Charge* in addition to Energy and Momentum (Linear and\or Angular). And these quanta have rest-Mass, which is to say, there exist configurations of the Electron Field that remain unchanged over time, with non-zero Energy (we perceive such a configuration, e.g., as a stationary electron). In contrast, the Electromagnetic Field has no charge, no rest-Mass, and no such 'static' configurations.
But apart from these differences, let's stress again, *both are fields*. *Both are present everywhere*. So, why do we think of the Electromagnetic Field as a 'force' and of the electron as a 'particle'?
Because the electron has Charge and rest-Mass, there is a 'smallest' field quantum: the electron at rest, with no Kinetic Energy. And electrons cannot be created on their own; *Charge is conserved*, so, if an electron comes into existence ('borrowing' Energy from the Electromagnetic Field) there must also be an anti-electron (positron) produced for Charge Conservation. *No such restrictions exist on photons*: they can have as little Energy as we want, and they can be produced *one at a time*.
So, this leads to Feynman's lovely description of QED in three points:

- electrons go from place to place,
- photons go from place to place,
- electrons may emit or absorb photons.

This is why we think of electrons as '*Matter*' and of photons as '*Force Carriers*': two electrons can interact by way of *exchanging photons*. But it is always wise to remember that these field quanta *are not fundamental*. In fact, an *accelerating* observer may see photons or electron-positron pairs in what seems like empty space to an *inertial* observer. *Particles are not fundamental*; *fields are*. And these fields are *present everywhere*; what are not necessarily present are the field excitations that we think of as *particles*. In the end, when the Electron Field has excess Energy (so, an 'electron' is present), and it passes on some of that Energy to the Electromagnetic Field, that influence can travel to another place where the Energy may be transferred back to the Electron Field (so, another 'electron' is influenced by a force).
That is how a fundamental force works.
The situation is the same for the Weak and Strong Force, and quite possible the same for Gravitation as well, although we do not have a generally accepted, working Quantum Theory of Gravitation. Then again, the story is pretty much the same when we consider the Classical Theory, it's just that no quanta are involved; the fields are still present everywhere, still interact with one another, and influences still travel as moving changes in a field's properties, in particular its Energy and Momentum (either Linear and\or Angular).

700 -

Do '*virtual particles*' in a Vacuum gravitate?

That's an interesting question! But before it can be properly answered, let's stress an important point.
'*Virtual particles*' are called such because *they are not real*. *They do not exist*. *They are pieces of mathematical fiction*. They are a convenient way to describe interacting quantum fields in the so-called *perturbative limit*, where nasty integrals can be series expanded into terms that can then be graphically represented by those nice *Feynman diagrams*, with the internal lines of the diagrams corresponding to our concept of virtual particles. Anyway, again, *only a mathematical fiction*.
However, this mathematical fiction can indeed be used to describe fields, including fields in their lowest Energy state, that is, the Vacuum. And one thing that follows from that quantum mechanical description is that not even the lowest Energy state is a *zero-Energy state*. In fact, as there are infinitely many possible frequencies for a field, each of which with a corresponding lowest Energy state, the sum of these lowest Energy states is *infinite Energy*!
That, of course, won't do, we can't have infinite Energy. So, let's take a leap of faith and assume that Quantum Field Theory is only an 'effective' theory, which breaks down at very high Energies. Thus, perhaps, instead of summing all the way to *infinity*, we only sum to this high (e.g., the Planck) Energy scale. The numbers now remain *finite*.
But when we add up those numbers, the result is still many, many dozens of orders of magnitude larger than our actual observation, the so-called *Cosmological Constant*, which could be a manifestation of the lowest state Energy of these fields in the Vacuum.
This embarrassing discrepancy is known as the '*Cosmological Constant problem*'. It has no conclusive resolution.
Perhaps, these ground states don't contribute to Gravity at all; perhaps, something else screens or weakens their Gravity; or, perhaps, we misunderstood the whole kaboodle. No one knows for sure.
Now, virtual particles (i.e., the fields that are represented by this mathematical convenience) do gravitate for sure in other situations. Let's consider our own bodies: most of our masses is in the form of protons and neutrons. And roughly $99\ \%$ of those proton and neutron masses is from the *interaction Energy* between their constituent *quarks*. Interactions that are mediated, we guessed it, by virtual particles (*gluons*, in this case) in a sensible mathematical approximation.
But whether the Vacuum or the virtual particles we use to represent the Vacuum contribute to Gravitation *remains unknown for now*.

701 -

What if the Universe is rotating? How could we tell?

If the Universe is rotating, it means it has a net (non-zero) Angular Momentum. Angular Momentum is a vector quantity: it has a direction. If the Universe has a net Angular Momentum, this means that *there is a preferred direction*.
The existence of such a preferred direction would be revealed by observations that study the large-scale properties of the Universe. These include studies of the Cosmic Microwave Background and studies of the large-scale distribution of Matter.
While from time to time, there is research that purportedly shows that such a preferred direction indeed appears in the data, no conclusive findings exist. Meanwhile, we do know from the data that if there is a net Angular Momentum, it cannot be very large.
Regarding two objects orbiting each other in an otherwise empty Universe … even at the Newtonian level we could tell that something is amiss. If they are extended objects, they would experience tidal forces due to the Gravity of the other object. Even if they are point-like, if we were to put a test particle next to one of them, it would follow a different trajectory if its distance from the other object is different. Finally, if we take Relativity into account, there are small but profound differences that exist due to rotation; these are measurable in principle, and the rotation rate of even a single, rotating object can be unambiguously determined (although the measurements may require exquisite precision).

702 -

Does Gravity affect the speed of light?
(Answered in *Silk Road*)

The concept of Gravity *affecting the speed of light* is a fascinating topic that delves into the realms of both Classical Physics and the revolutionary ideas brought forth by Albert Einstein's Theory of Relativity. To truly understand the relationship between Gravity and the speed of light, we must venture into the depths of the Cosmos and the fundamental nature of Space and Time.
At first glance, the idea of Gravity affecting the speed of light may seem counterintuitive, given that light is composed of massless particles known as photons. In the realm of Classical Physics, Gravity is understood to be a force that acts upon objects with Mass, and therefore, one might assume that light, being massless, would be immune to Gravity's

effects. However, this perspective changes dramatically when we consider the implications of Einstein's Theory of General Relativity.

Einstein's groundbreaking work in the early 20th century provided a radically new understanding of Gravity. Rather than being a force that acts upon objects with Mass, General Relativity describes Gravity as the curvature of SpaceTime, caused by the presence of Mass and Energy. In this framework, objects move along paths determined by the geometry of SpaceTime, and even massless particles like photons are influenced by the curvature of SpaceTime, giving rise to the phenomenon known as *gravitational lensing*.

So, does Gravity affect the speed of light? In a sense, it does, but not in the way one might initially think. The speed of light in a Vacuum remains *constant*, 299792458 m/s (SI units) and this value is a *fundamental constant of Nature*.

However, the path that light takes through SpaceTime can be altered by the presence of *massive* objects, which curve SpaceTime and cause light to travel along a *curved* trajectory. This means that the *apparent* speed of light, as seen by an observer, may appear to change when light is passing through a region of curved SpaceTime, even though the *intrinsic* speed of light remains constant.

This phenomenon has been confirmed through numerous observations and experiments, including the famous 1919 solar eclipse experiment led by British astronomer Arthur Eddington. By measuring the apparent positions of stars near the edge of the eclipsed sun, Eddington and his team were able to demonstrate that the light from these stars was indeed being deflected by the sun's Gravity, providing crucial support for Einstein's theory of General Relativity.

The speed of light in a Vacuum remains constant, the influence of Gravity on the path of light through SpaceTime can give the impression that its speed is changing. This remarkable insight, stemming from Einstein's Theory of General Relativity, has profoundly altered our understanding of the Universe and the fundamental forces that govern its behavior.

703 -

Mathematically, what's the difference between the EM field in Classical E&M and the EM Field in QED? What mathematical properties does the QED version have that the classical version doesn't and vice versa?

Let's just take a glimpse of the two most crucial steps in the path towards building a Quantum Field Theory from a Classical Field Theory.

The *first* step is to *Fourier-transform* the field. If we have a *field* $\phi(t, \boldsymbol{x})$, we get a Fourier integral in a form like this:

$$\phi(t, \boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3} (a(\omega, \boldsymbol{k}) + a^\dagger(-\omega, -\boldsymbol{k}))e^{-i(\omega t - \boldsymbol{k}\cdot\boldsymbol{x})}.$$

This is still the Classical Theory, by the way, just Fourier-transformed into 'Momentum Space'.

The *next* step, however, is assuming that the *Fourier coefficients* a and $a^\dagger$ are *eigenvalues* of non-commuting operators that obey the *commutation* rule,

$$[\hat{a}(\omega, \boldsymbol{k}), \hat{a}^\dagger(\omega, \boldsymbol{k}')] = (2\pi)^3\delta^3(\boldsymbol{k} - \boldsymbol{k}').$$

This is where we make the transition from Classical to Quantum Physics. The result is a Field Theory that can be thought of as an *infinite sum of quantum harmonic oscillators*, one corresponding to every value of the *angular frequency* ω.

This is also where the technical difficulties first emerge (every one of those harmonic oscillators has a *non-zero ground state*, so summing all those ground states yields infinite Energy; doing away with such infinities using sensible, consistent mathematics is what *renormalization* is about).

704 -

If Time freezes at the edge of a black-hole, does that mean that we could live forever if we could overcome the Gravity?

Whenever we think about Time dilation in Relativity Theory, let's keep in mind that the theory is not about us. It is about what others see. As far as we are concerned, no matter where we are or how we move, Time will always appear to flow as it always does.

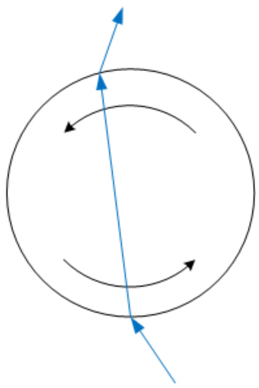
So, let's suppose we are in a super-fast spaceship. Every second of our life is a thousand years on Earth. Does this mean we live forever? No. We can still expect a normal human lifespan as measured by our own watch and calendar. Sure, billions of years would pass on the Earth in the meantime, but we will not experience billions of years. We will experience a few decades, like any human being would. Or suppose we are deep inside a very powerful Gravitational Field. Extreme Time dilation, right? But once again, it's about what others see. Others, *here on the Earth*, will see we get older slowly and our clock tick slowly. But as far as we are concerned … our clock will tick as it always does, and we will age exactly as fast as you would anywhere else. Therefore, the main point is: Relativity Theory is not about what happens to us but *about what others*, *who are observing us*, *actually see*.

705 -

We know that light slows down when travelling through, e.g., glass. If the glass is rotating while the light is inside, will light change direction? If so, will the rotation slow down as a result?

An intriguing question! We must admit that no attempt around is known to work out the math, we may have an answer that applies at least in the non-relativistic case (that is, when the speed at which the rotating object rotates is much less than the decrease in the speed of light in that medium compared to the Vacuum. Considering that in glass, light speed decreases by about $100000\ \mathrm{km/s}$, this condition is likely to be easily satisfied.

So, then, let's think about a light ray that would hit a rotating glass object with a circular cross section right in the center. If the object did not rotate, the light ray would pass through in a straight line, exiting the glass while traveling in the same direction and with the same *frequency* (Energy) as before; so, there would be no exchange of Linear Momentum or Angular Momentum between the ray and the glass.
But now let's spin up the glass and let us look at the problem from the perspective of a reference frame that rotates with the glass (again, ignoring Relativity). The light ray will now appear to enter the glass at a slight angle. So, instead of going through the center, it will be refracted and then refracted again when it exits the glass. Something like this:



Therefore, there will be a *change in direction*. This means an *exchange* of Momentum between the light ray and the glass, so, at the very least, the glass will be pushed in a direction that is approximately *perpendicular* to the light ray.
However, it is unlikely there will be an exchange of Angular Momentum. So, the rate of rotation *should not* change.
Is this correct? We don't know for sure. As said before, nobody is known to have worked out the math. Also, there is some concern that this effect is *very small*, perhaps comparable to the relativistic effects that has been ignored here on purpose, hence, this analysis may not hold. Still, it's a good starting point to consider the problem in the context of the reference frame that co-rotates with the glass object.

706 -

Is it possible that the *accelerating expansion* of the Universe is an illusion caused by Time dilation? Space is already expanding, so, from the perspective of a *Gravity well*, it should appear to expand faster in deep space, shouldn't it?

It is almost trivially easy to rewrite the basic equations of Cosmology so that instead of 'Space is expanding' we get Time Dilation. But rather than believing either, they should serve as a strong reminder that Physics *does not depend* on the choice of coordinate systems.
Sure, we can pick a coordinate system (the standard coordinate system used to derive the Friedmann Equations of Cosmology from Einstein's Field Equations) in which the expansion is characterized by a 'scale factor'. But if we think it means that meter sticks become longer-than-meter-sticks over Time because, say, Space is expanding, we are on the wrong track.
Again, we can switch coordinates and instead, write down the whole thing using changing clock rates. The thing is, in the end, *physical* clocks and *physical* meter sticks don't depend on what coordinate systems we use for mathematical convenience.
No, it's rather much simpler than that. *Things are flying apart*. Surprisingly, the correct equations can even be derived, sort of, from Newtonian Gravity, which of course has no expanding Space or Time dilation, since both Space and Time are fixed. So what? *Physics is about the relationships between things*, *not about mathematical abstractions*; those abstractions may be useful when we build models of Physical Reality, but *they are not Physical Reality*. Coordinates cannot be eaten or even measured; we measure distances between things, we measure Time intervals between events involving things, using other things, namely ticking clocks.
But when it comes to the redshift of very distant things, Gravity arises as a combination of two factors:

first, those things fly away from us at a high speed: so, we have *relativistic Doppler effect*;
second, light from those things originated at a time when the average Gravitational Potential throughout the Universe was much stronger; as these rays of light propagate from the past towards the present, they *climb out of a Gravity well*, and that produces additional redshift (indeed, due to relativistic Time Dilation).
But all of these are accounted for. To quote from Weinberg's wonderful 1972 tome, *Gravitation and Cosmology* (and also to put to rest the doubts of those who think that nonsense is being spouted here, going against their received wisdom that 'Space is expanding'): "[...] the frequency of light is also affected by the Gravitational Field of the Universe, and it is neither useful nor strictly correct to interpret the frequency shifts of light from very distant sources in terms of a special-relativistic Doppler effect alone."
The rate at which the expansion accelerates comes on top of all that. In other words, *relativistic Doppler effect* and *gravitational Time dilation* alone are insufficient to account for the redshifts we observe. If we assume, in addition, the presence of a Cosmological Constant (e.g., in the form of Dark Energy), then the numbers fit much better.

707 -

If we add up the Mass of all the quarks in the proton, it will only account for about 1% of its total Mass. Where is the rest of the Mass coming from?

Indeed, for protons and neutrons the constituent quarks only yield roughly 1% of their respective rest-Masses. The remaining Mass is due to the Strong-Force Binding Energy.
Now, we are used to Binding Energy being *negative*. For instance, when we think of the Binding Energy between a H nucleus and its lone electron, it is negative; we need to invest enough (positive) Energy to make up for this deficit and free the electron.
However, that is not how the Strong-Force works. It's more akin to a *tension spring*. A tension spring's lowest Energy state is when it is relaxed, its two ends are the closest they can be. As we pull the two ends apart, we invest Energy, so the tension spring holds *positive* Potential Energy when it is under tension. The Strong-Force binding works pretty much the same. There is always some Energy there (let's imagine two cannonballs connected by a tension spring but, say, rapidly spinning so the spring is always under tension (not exactly the best analogy to read into, but it illustrates the basic idea well). This Energy amounts to $\sim 99\%$ of the proton (or neutron) Mass.
Incidentally, this is also at the root of the mechanism that *prevents us from being able to free quarks from the nucleon confinement*. To do so, we must pull them even harder. But that means that we invest enough excess Energy *to create new quark-antiquark pairs*. It's kind of like (to continue with the imperfect tension spring analogy) when we pull a spring too hard: the spring snaps, but both fragments still have two ends. We will never end up with a tension spring that has only one end: that's *impossible*.
On the other hand, when the spring is relaxed, the weights at the ends can move about (at least, a little) with almost no resistance from the spring, as if they were free. This is that '*asymptotic freedom*' business that quarks are famous for.

708 -

Can black-holes be created in the lab?

No. Not even close. Not even remotely close.
Unfortunately, there's a lot of hype, sometimes even in the press releases issued by reputable institutions. They scream loudly, 'black-hole created in lab!' But those are not black-holes. Those are black-hole analogues, quantum mechanical experiments designed to *simulate* certain aspects of black-holes. They are as far removed from the real thing as … a small lightbulb simulating the Sun, more like, how about a drawing of a small lightbulb by a 4-year old, simulating the Sun?
The only physical mechanism that is known to us at present that can create a black-hole is *gravitational collapse*. And for gravitational collapse to overcome neutron degeneracy pressure, we need at least about 2 or 3 *solar masses*.
But let's believe the hype for a moment and suppose someone managed to compress one metric ton of material into a black-hole. That black-hole would last … less than $5 \cdot 10^{10}$ s . All that Mass-Energy, the equivalent of maybe 10^6 or so Hiroshima bombs, would be released instantaneously in a tremendous explosion. Have we heard of such tremendous explosions lately, wiping out a city perhaps? No, we didn't. So, nobody created that black-hole. No 1 kg black-hole either. Or a 1 g black-hole (releasing just slightly more Energy than the Hiroshima bomb, but in the form of γ- photons with Energies measured in the *tens of billions* of TeV).
So, not today, not tomorrow, not anytime in the foreseeable or not-so-foreseeable future, not unless someone invents some completely new science, or we learn how to manipulate entire stars much larger than the Sun and put them in our laboratories.

709 -

An electromagnetic wave emitted by a supernova billions of light-years away, upon reaching us, loses a good part of its Energy, but how is this possible if in a Vacuum it does not interact with anything?

There are really three things to consider here.
First, that light from that distant supernova spreads. So, even if it were true that it didn't interact with anything, by the time the wavefront reaches us, it will be in the form of a gigantic sphere billions of light-years in radius, so the Energy is proportionately diluted (radio engineers call this 'space-loss': the Energy, or Power, of the signal diminishes with the *square* of the distance it travels).
Second, we are running away from it! We should remember that Kinetic (motional) Energy *is not an intrinsic quantity*. That photon's Kinetic Energy relative to us is not the same as it is relative to us if we and none of us is at rest with one another. And in this case, none of us is both running away from that supernova (or the supernova, from us – same difference, either way the distance between the supernova and us is increasing over time) at nearly the speed of light.
Finally, … empty space? Not exactly. There is the Gravitational Field, which interacts with everything, including light. And billions of years ago, when the Universe was denser, on average the Gravitational Field was stronger. As that signal travels from the Past to the Present, it goes from stronger to weaker Gravity; as a result, it loses Energy, just as a cannonball loses Energy when we fire it upwards into the sky.
So, there we have it: *space-loss*, *velocity-related Doppler-shift* and *Gravitational redshift* (also known as *Gravitational Time Dilation*), together contributing to weakening the signal and shifting its frequency *downward*.

710 -

In what sense does General Relativity (GR) say that Gravity is a product of 'all things wanting to be where Time moves slowest'? K. S. Thorne describes this as the most fundamental aspect of GR, more fundamental than the bending of Space-Time.

It's not specific to GR. It is the far more general *Principle of Least Action* in the context of GR, which says that objects will follow trajectories between events that correspond to the amount of '*maximum Time*', *as measured by clocks attached to those objects*.
This sounds a little difficult to comprehend at first, but let's illustrate it with a trivial example. we are sitting at our desk, now, say, at 10:40 a.m. on July 11, 2023. That is event #1 (characterized by *Location* and *Time*). Say, a minute later, at 10:41 a.m., we are still sitting at our desk. That's event #2. Our clock measured exactly 1 minute of *elapsed time* between these two events.
Now suppose a guy has a very fast spaceship. He hops into his spaceship and zips away, at 90% of the speed of light, for 30 seconds as measured by our watch; he spends another 30 seconds on a return trip. For this, he used tremendous quantities of fuel, a gigantic engine, and who knows what magic technology that protected him from acceleration, but never mind … he is back. How much time elapsed by his watch? As a result of Relativistic Time Dilation, he will have measured just a little over 26 seconds instead of a full minute.
When we compare such trajectories in Space-Time, we find that in this specific case, the 'trajectory' that we followed between these two events at 10:40 a.m. and 10:41 a.m., sitting still at your desk, is the trajectory that corresponds to the longest amount of Time measured between these two events. Anyone who deviates from this trajectory needs to use some form of propulsion, accelerate, and when they return, their clocks will show less time elapsed than ours.
In "flat" Space-Time (in the absence of Gravity), these trajectories of longest elapsed time are the *inertial trajectories*: sitting still or moving in a *straight line* at *constant speed*, i.e., no acceleration, no forces acting on a body. In the 'curved' Space-Time of Gravitation, these trajectories are the so-called 'geodesic trajectories'. The orbit followed by a planet around its host star or a moon around its host planet are examples of such geodesic trajectories.
Again, the *Principle of Least Action* is not unique to GR. It is a fundamental principle in Classical Mechanics; it can also be used to derive field theories such as Maxwell's Electrodynamics; and it plays a fundamental role in the construction of quantum field theories as well. GR itself can be *derived* by the Principle of Least Action.

711 -

Why do physicists consider Gravity as one of the 4 fundamental forces, but according to the best theory of Gravity (GR), it is not a force at all? Is that why unification is not possible with QM?

Here is a quote from Einstein, written in a letter in 1926 to Reichenbach:
"Sie haben vollständig recht. Es ist verkehrt zu glauben, dass die 'Geometrisierung' etwas Wesentliches bedeutet. Es ist nur eine Art Eselsbrücke zur Auffindung numerischer Gesetze. Ob man mit einer Theorie 'geometrische' Vorstellungen verbindet, ist [unleserlich] Privatsache."
In English: "You are perfectly right. It is wrong to think that the '*geometrization*' has significant meaning. It is only a

kind of a clue helping us find numerical laws. Whether you connect a '*geometric*' view to a theory is entirely a private matter."

So, again, how is that 'Gravity is not a force at all'? We know that every popular science book or article on the subject tries to 'enlighten' us by saying that it is not a force, only Geometry and, sadly, even many physicists make this assertion. But let's talk about the physicists who don't.

For instance, physicists working on *modified* theories of Gravitation know very well that the *Weak Equivalence Principle* (which is what allows us to apply the '*geometric interpretation*' in the first place) is not some divine commandment, and that it is perfectly possible, reasonable even, to construct theories that do not obey this Principle. Whether or not those theories are falsified by observation is another matter but, excluding them a priori, because 'everybody knows Gravity is just Geometry' would be a profoundly nonsensical, unscientific attitude.

Then there are particle physicists who of course look at *Gravitation as a force mediated by a tensor field*, which they hope to quantize using some sensible approach. Particle physicists are also aware that the '*geometric interpretation*' is not unique to Gravity: that other *gauge theories*, including Electromagnetism, can be written down using the language of Geometry, by way of *covariant derivatives*. These covariant derivatives, however, depend on the '*Charge-to-Mass ratio*' of the object at hand. What makes Gravity unique (assuming the Weak Equivalence Principle holds) is that the charge-to-mass ratio *is the same for everything*, so it can be taken out of the equations altogether, simply by measuring 'Gravitational Charge' (gravitating Mass) in the same units as (inertial) Mass.

As a matter of fact, there are these delightful (albeit highly technical) lectures notes by Richard Feynman's '*Lectures on Gravitation*', in which he describes imaginary Venusian physicists who know Quantum Field Theory but, until now, never heard of Gravitation, so they are now trying to construct a sensible theory using the tools that they have. And indeed, not a renormalizable quantum theory, to be sure (we still have no such theory), but, at least, the foundations, including Einstein's Field Equations in the classical limit … and not a peep about Geometry!

So, don't let anyone tell us that Gravity 'is not a force at all'. If they try, just tell them to drop a brick on their big toe and then let them explain to us how they felt no force at all. It's unlikely they'll succeed …

As to the *unification*, the problem is *renormalizability* (Quantum Gravity predicting *infinities* that cannot be removed by the *usual* mathematical methods). But the real problem is not that we don't know what to do. There are plenty of ways to reconcile Gravity with the Quantum Theory: *String Theory*, *Loop Quantum Gravity*, *Emergent Gravity*, the *Semiclassical approximation*, *finite Quantum Field theories* … We could fill a thick tome containing only sensible, viable proposals. But which one to choose? For that, *we need data*, data we do not have. Gravity is so *weak*; its quantum effects may forever remain undetectable. The great F. J. Dyson (1923-2020) once calculated the odds of seeing a single atomic transition due to a captured graviton assuming we use the entire Earth as a perfect detector, exposed to the presumed Gravitational thermal radiation of the Sun, which amounts to just a tiny fraction of its output in the *electromagnetic spectrum* but still comes to a respectable ~ 79 MW. The result? One atomic transition every 10^9 years, give or take. That's the real problem. *The lack of data*, not the lack of ideas.

712 -

How can we derive a step-by-step relationship from a tensor to a black-hole condition?

[Ref.: [41], P. 179-182]

Let's start with the metric tensor $g_{\mu\nu}$. In the *spherically symmetric static-Vacuum* case, it is represented by the matrix

$$g_{\mu\nu} = diag\left(B, -A, -r^2, -(r\sin\theta)^2\right),$$

using Time and standard spherical coordinates. Or, in explicit *proper-Time* notation,

$$d\tau^2 = Bdt^2 - Adr^2 - r^2(d\Omega)^2,$$

with $(d\Omega)^2 = (d\theta)^2 + (\sin\theta)^2 d\varphi^2$ [careful! $d\tau^2 := d(d\tau)$ while $(d\Omega)^2 := (d\Omega)(d\Omega)$, etc.].

Because of *spherical symmetry* and *no Time dependence*, A and B must be functions of the *radial coordinate* r only. i.e., $A = A(r)$ and $B = B(r)$.

Using this metric, we can construct the *Einstein Tensor*, which must be *zero*. Its first diagonal component (by defining $A'(r) := dA(r)/dr$) is

$$G_t^t = A'(r)r + (A(r))^2 - A(r).$$

This must be *zero* for a Vacuum solution, which yields easily

$$A(r) = \frac{1}{1 - C/r} \equiv \frac{r}{r - C},$$

C being a constant of integration. Substituting into the second diagonal term of the Einstein Tensor, G^r_r, leads to the solution for $B(r)$ in the form of $B(r) = 1/A(r)$. Agreement with Newtonian Physics in the *Weak-field limit* fixes the integration constant at $C = 2GM$.

And there we have it: the *Schwarzschild solution*,

$$d\tau^2 = \left(1 - \frac{2GM}{r}\right) dt^2 - \left(\frac{1}{1 - 2GM/r}\right) dr^2 - r^2 (d\Omega)^2$$
$$\equiv \left(1 - \frac{2GM}{r}\right) dt^2 - \left(\frac{r}{r - 2GM}\right) dr^2 - r^2((d\theta)^2 + (sin\,\theta)^2 d\varphi^2).$$

This solution becomes *singular* at $r = 2GM$, indicating an *event horizon*, thus a possible *black-hole*.

[NASA's Wilkinson Microwave Anisotropy Probe (WMAP) project's nine-year 2012 data release estimated the age of the Universe to be about $(13.772 \pm 0.059) \cdot 10^9$ y (13.772 billion years, with an uncertainty of ± 59 million years).]

713 -

If Time goes backwards due to *negative Entropy*, we wouldn't realize it because our neurons utilize Entropy to store memories. So, could it be that reality is entirely random and timeless, and Entropy sometimes reverses, but we remain unaware of it?

Actually, we experience the 'arrow of Time' not because the laws of Nature are asymmetrical under Time reversal but because of the initial conditions: given a Universe that starts in a state of low Entropy with a final state that is unconstrained yields the 'arrow of Time' of *increasing* Entropy.

And yes, what any system (including members of the species *homo sapiens* sporting oversized brains) experiences as the 'arrow of Time' is really the direction determined by increasing Entropy. But Entropy cannot 'reverse', not unless everything we know is wrong about Thermodynamics and Statistical Physics. *An unconstrained system will always evolve towards more disorder, greater randomness*. Only if the system is constrained (e.g., by interactions with its environment) can that change.

And yes, of course that can create the illusion of Time flowing backwards. For instance, if we could create a machine that reassembles a broken egg, seeing the system in operation and unaware of the context, you might indeed conclude that it reversed Time. But zoom out and we see all the machinery that, say, uses electricity, solar energy, whatever, to accomplish this 'miracle' and we realize that the Entropy decrease was only local; that the Entropy of the entire system was still increasing, as it always, invariably, does.

714 -

If one can describe the expansion of Universe as of the motion of objects rather than expansion of Space, how does that deal with 'inflation' the whole of which point is to shift things that were casually in contact beyond it?

We deal with inflation the same way we deal with any Universe dominated by a perfect fluid with the $w = -1$ Dark Energy equation-of-state: *gravitational repulsion expands it at an exponential rate*.

And yes, things get pushed beyond causal contact all the time. Except that they don't. Suppose we are in an accelerating Universe. We look at a thing and keep watching it for a very long time. We will always see it, ever more *redshifted*, ever dimmer, but still there (assuming our instruments are sensitive enough). Our calculator may tell us that at the 'present' (putting it in quotes because in a relativistic Universe, 'present' is a rather fluid concept) that thing is already far, far, far beyond our cosmological event horizon but that's not the present we see: that light *comes from the past*, and the point is, we never actually get to see that thing cross the *cosmological horizon*.

Same thing happens with black-holes, by the way: we drop something and watch it, it becomes ever redder, ever dimmer, appearing to move ever slower (extreme gravitational Time Dilation) and we will never see it reach the horizon. In fact, we never actually see the horizon form: as an observable event, *it remains in our future forever*, unless we are unlucky enough to fall through it.

715 -

Did the Big Bang occur within the *observable Universe*?

No. The Big Bang is a past moment in Time that (at least, in the classical theory, without regard to Quantum Physics) is not even part of the Universe; it is like a mathematical limit in this sense, not part of the set (of SpaceTime events).

But let's consider the hot, dense Universe that happened immediately after the Big Bang (that is to say, an arbitrarily small-time interval after Big Bang moment). This hot and dense state characterizes the Universe *everywhere*, not limited to the parts that can presently be observed by us.
We can guess this question may be based, in part, on a misunderstanding that the Big Bang had a specific location. It didn't. It is a moment in Time, but its location is literally *everywhere*. It marks the beginning of the entire Universe and it happened at *every* location.

716 -

Is the statement about *how old the Universe is* wrong? The Theory of Relativity has shown that there is *no absolute Time*. If a clock is placed inside a black-hole, that clock *absolutely oppose* the statement that the Universe is about $13.8 \cdot 10^9$ y old?

Clocks in different places (on *different worldlines*) measure different things.
In an expanding Universe that approximately obeys the *Friedmann Equations*, clocks that are 'comoving' measure the longest amount of time between two events. So, if we imagine a family of clocks that were set up in the early Universe and have been ticking ever since, existing far from any peculiar concentrations of Matter (neutron stars, black-holes, whatever) and not moving relative to the Cosmic Microwave Background, today these clocks would all have counted approximately $13.8 \cdot 10^9$ years' worth of ticks.

But clocks placed in other worldlines would not have. In particular, a clock following a worldline that is crossing the event horizon of a black-hole would, at present (and indeed, *at any finite time in the future*, no matter how far into the future) would still be just outside the event horizon, its rate of ticking slowed down to *zero*, the clock essentially 'frozen' at the moment it'd cross the event horizon (if we fell with that clock, we'd see nothing special: we'd both cross the horizon and then, in due course, very soon thereafter get crushed as our inside-the-horizon mini-Universe collapses and Time itself comes to an end. But this is never seen from the outside).
The main point, of course, is that, in Relativity Theory, there is no Absolute Time. Time is what a clock measures, and what a clock measures is a *physical property* of the worldline the clock follows. So, the best question that we can ask is, what is the *maximum* amount of Time that clocks could have measured since the early Universe up to the present, and what worldlines did these clocks follow? And the answer is, as mentioned in the beginning, that it would be about $13.8 \cdot 10^9$ years, measured by *comoving clocks* not affected by any significant nearby concentrations of Matter.

717 -

How is the lambda CMB model referring to the whole Universe if it is fundamentally impossible for an observer to perceive more than a tiny fraction of it?

The Lambda-CDM 'concordance' model is a theoretical model based on the simplest of assumptions: *that the Universe is the same everywhere and our place in it is not special*. Of course, we do recognize that anything we assert about the Universe is based on what we see in what we call the '*visible Universe*'. Chances are that there are no dancing pink unicorns just outside the region that we can observe, but do we know for certain if the Universe is truly the same *everywhere*, even on Distance and Time scales far greater than the parts that we see? Of course, *we don't*.
But when it comes to theoretical models, we stick with the simplest until we have actual evidence to the contrary. This is not dogma or religion. Nobody is married to a homogeneous, spatially flat Universe. And as we gather more data, perhaps Nature will give us hints on how to make our models better.
In a sense, it's like those ancient Greek philosophers who realized that the Earth is round and even measured (crudely) its size. It was fundamentally impossible for them to perceive more than a tiny fraction of the Earth's surface. Yet, based on what they observed, they came up with a sensible yet simple model, namely that the Earth is a ball. In their case, the model proved correct (with only minor deviations from a perfect sphere). But it's not like they knew with any certainty that this will be the case. It just wouldn't have made sense to use any shape other than *the simplest that was consistent with their observations*.
This is exactly what we do when we establish a model like Lambda-CDM. It's the simplest model that is consistent with our observations. And that's all, really.

718 -

In General Relativity Theory, the Universe is moving at c in a 4th Time dimension. How can motion be measured in $\mathrm{m/s}$ in a Time dimension?

The Universe is not 'moving at c in a 4th Time-dimension'. Don't let seemingly erudite but ignorant science(-fiction?) writers tell us otherwise, all the while making we feel less smart than we are indeed.
Motion is, by definition, the *change in Space location*, measured as a function of Time. A change in Time as a function of Time is a non-sensical tautology.
This question is spot on! *Meters* are *measures* of Distance; *seconds* are *measures* of Time. We can of course measure Time and Space using compatible units, e.g., seconds vs. light-seconds but in these units, we simply have $c = 1$ (i.e., the speed of light is one light-second/second), and the 'motion through Time' nonsense basically says that in one unit of Time elapsed, one unit of Time will elapse. Very informative and enlightening indeed!

719 -

Does Hawking Radiation only apply to black-holes?

According to the explanation that comes from Hawking's (in part, we understand, ghost-written) popular science book, 'A Brief History of Time', the answer would be 'yes': particle-antiparticle pairs created near the horizon, the negative-Energy particle or antiparticle swallowed by the horizon, its positive-Energy counterpart escaping to infinity.
Never mind members of the public, generations of physicists (!) grew up on this stuff and unless they made an effort to study the *actual* Physics, *Quantum Field Theory* in the curved background of General Relativity in the semi-classical approximation, they have no idea that they might be spouting nonsense (for a long time, we all have been spouting the same nonsense (at least until we began to study Quantum Field Theory on curved backgrounds).
But when we do read the actual papers, including Hawking's own 1974 paper (BLACK HOLE EXPLOSIONS, *Nature* **248**, 30-31 (1974)), a very different picture emerges. As Ethan Siegel once put it in his essay 'Hawking lied to us' about Hawking's book. Hawking Radiation has nothing to do with event horizons, at least not directly. Rather, it has to do with the *asymmetry between Past and Future* when it comes to a Mass distribution, that is, in the process of *collapsing under its own self-Gravity*.
And when we think about it, this makes perfectly good sense. Hawking Radiation has a typical wavelength that is about 20 times (!) the size of the black-hole's *Schwarzschild radius*. That alone should tell us that the radiation does not originate 'at' the horizon, but rather, it is a result of the *Gravitational Polarization of SpaceTime* in the *vicinity* of the gravitating Mass. Not to mention that the horizon, insofar as we, the observers, outside the horizon are concerned, remains firmly in the Future. For Hawking Radiation to form because of the possible (but not certain yet!) formation of a horizon in the far (actually, infinite) Future would amount to a gross, macroscopic violation of Causality.
The existence of a horizon still plays a bit of a role (just to confuse us) not so much because of what it does but what it doesn't do: It does not act as a surface that would have its own thermal properties. The presence of such a surface in the case of another object would represent a different cutoff for the region in which Hawking Radiation would form, and *different boundary conditions*.
But, to answer the question, no, the equations make it clear that Hawking Radiation results from the Gravitational Vacuum Polarization in the vicinity of a gravitating Mass and, specifically, how that Gravitational Field changes over Time. Even if that Mass is not a collapsing Oppenheimer-Snyder 'dust sphere' (the first general-relativistic solution, from 1939, that showed how a self-gravitating Mass with no internal pressure would collapse), the fact that it radiates means that it loses Mass-Energy, which implies that its Gravitational Field changes over Time, so the process, in a sense, becomes self-feeding and the same conditions apply: the Past and the Future boundary conditions *differ*, and this implies the *asymmetry* that is the source of Hawking Radiation, as for Hawking's 1974 landmark paper.

720 -

If a photon starts to interact with the Higgs Field, what will happen?

Then the Standard Model of Particle Physics would be broken, along with everything else in this Universe. Nuclear Physics, Chemistry, the Periodic Table… everything we know about Physics would go out the window.
We do have an example of a 'massive photon': the Z^0 boson of the Electroweak Theory. It interacts with the Higgs Field (in a circumspect way, through *Electroweak Symmetry* breaking, but still). As a result, it acquires a Mass that is more than 90 times the Mass of an H- atom. The more massive a mediating particle is, the shorter the range of the force it mediates. Something that massive yields a force that has extremely short (subatomic) range. This is why we call the Weak Interaction 'Weak': it's not really weaker than Electromagnetism, it's just very hard to detect because its range is extremely limited.
Of course, in experimental Physics, we can never say never. Perhaps photons interact with the Higgs Field now, just

very, very, very weakly, so the *effective Mass* they acquire is very, very, very small, so small that it has no detectable impact. In that case, nothing *detectable* happens! But anything more than that and our problem is not really how far our eyes could see (free photons would still travel as far as they can, just slower than what we know as the Vacuum speed of light) it's whether or not we'd still have eyeballs, or a body, or a planet to stand on. Because everything we know about Chemistry, not to mention the Physics of ordinary objects, is based on Electromagnetic Interactions mediated by photons, and a massive photon would mess that up quite drastically.

P. S.:

To be clear, photons do interact with the Higgs indirectly; however, everything interacts with everything else indirectly, so that's kind of tautological (we took the question to refer to a hypothetical direct interaction between the Electromagnetic Field and the Higgs Field).

721 -

What is the relationship between Particle Physics and Quantum Mechanics?

[a guest interlude by Mark John Fernee, Un. of Queensland, Brisbane, AU]

Quantum Mechanics is the governing theory. It's a fundamental quality that a system can be described by a vector in an abstract space, called a *Hilbert Space*. The Hilbert Space is the space of all possible measurement outcomes, so it is distinct from 3-dim Space that describes the position of objects. For instance, the Hilbert Space can be, and often is, infinite dimensional. A vector in Hilbert Space has *complex-valued* coefficients and must be *normalized to unity length*. For an ∞ - dim Space it must be *square-integrable*.

Physical observables are described by *hermitian matrices* that act on the Hilbert Space vector such that measurement outcomes are *real-valued*.

The vector in Hilbert Space evolves according to *rotations* induced by various interactions described in the *hamiltonian operator* (or *Lagrangian density*). This is called *unitary evolution operator*, $\mathcal{U}(t) := e^{-i\,\mathcal{H}t/\hbar}\,|\,\psi(0)\rangle$, as the vector is just rotated *preserving the normalization*.

Following a measurement, the Hilbert Space vector is *projected* onto the measurement outcome. This evolution is considered non-unitary, as it is not a smooth rotation, but a *projection*.

So, that is the underlying theory of Quantum Physics.

For Quantum Mechanics, we consider particles as immutable with various properties, thus restricting the allowable evolution operators of the associated Hilbert Space.

However, for fundamental Particle Physics, the particles appear to be *transmutable*. Therefore, the theory required a mechanism to allow for this.

The first transmutable particle was the *photon*. The Quantum Theory of the Electromagnetic Field identified sets of *non-hermitian* operators, corresponding to the *creation* and *destruction* of photons as *Energy quanta* in the Electromagnetic Field.

This was the first *field theory*. The key to this theory was the mapping of the Electromagnetic Field to the quantum simple *harmonic oscillator* to identify quantum operators that satisfy the Heisenberg Uncertainty Principle. These field modes can be used to construct any field configuration using the Superposition Principle according to the Fourier field-decomposition. This opened the gates to current quantum field theories. Other fields were introduced that gave rise to particles as *excitations of the field* in a way analogous to the role of the photon in the Electromagnetic Field.

From here, it gets complicated as various symmetries need to be satisfied and *self-interaction* terms need to be dealt with. However, the theory is, essentially, the same, just with more widgets added to satisfy the properties observed in experiments. The Hilbert Space is still there; Unitary evolution is still there; hermitian operators are still there; the measurement procedure is still there.

With Particle Physics, we focus more on the scattering terms in the *hamiltonian* (or *lagrangian-density*) *operators*. These are generally expanded as a *perturbation series* with the high order terms truncated, allowing the calculation of scattering cross-sections that are applicable to Particle Physics tests.

722 -

The Einstein Field Equation predicts the metric tensor diverges at a point of *infinite density*. Why does *renormalization* not work in this case, and what are other mathematical attempts to reconcile this consequence of GR with Quantum Mechanics?

Renormalization has nothing to do with classical divergence in the case of idealizations like singular point sources. Newton's gravitational theory also predicts divergent behavior under suitable initial circumstances (e.g., a spherically symmetric cloud of pressureless Matter would collapse into an *infinitely dense point* after a *finite amount of Time*). Nor is the fact that General Relativity has singular solutions directly related to the failure to renormalize the theory.

Renormalization is about something else. Crudely speaking, what happens is that when we add all possible ways in which a Quantum Field Theory can predict the evolution of a system from an initial to a final state, the total Energy of the system is calculated as infinite, which is nonsense. However, what we are interested in, in these cases, is not the total Energy but the change in Energy because of whatever process is being described. Can this change in Energy be shown to be finite and can it be reliably calculated even in the presence of the aforementioned infinities? *If the answer is yes, the theory is renormalizable*.
Gravity, unfortunately, is not one of those theories. This has nothing to do with points of infinite density. The failure to renormalize affects every self-gravitating system described by Einstein's Field Equations, *including systems with no singular points*. Simply put, *there is no self-consistent Quantum Field Theory* (at least none that we know of) *that is consistent* with Einstein's Classical Theory of Gravitation.

723 -

What is the significance of *Noether's Theorem*?

[a guest interlude by Mark John Fernee, Un. of Queensland, Brisbane, AU]

Noether's Theorem tells us something rather interesting, that certain conserved quantities are only related to specific symmetries. In other words, it identifies generic properties of any physical system, independent of the *actual* Physics.
For example, the Conservation of Energy indicates that *Physics is Time-translation invariant*. In other words, the physical laws do not change in Time. Similarly, the Conservation of Momentum indicates that the physical laws are not dependent on their position in Space. That means, if we have such a set of laws with these properties, we must be able to identify the conserved quantities of Energy and Momentum. What we get from the spatial invariance is that Momentum must be a vector, while Energy is a scalar, as there is only a *single* Time dimension.
These statements say nothing specific about the character of the laws themselves.
The world we experience has a specific set of physical laws that describe how things interact. These specifics are represented by the *fundamental forces of Nature*. In the Standard Model of Particle Physics, the specifics are the zoo of particles that are associated with specific fields. In essence, this is the underlying Physics of our world.

Noether's Theorem then tells us that there must be these conserved quantities, which we call Energy and Momentum. However, we could have an entirely different physical theory of interacting gummy bears, for example. If this theory exhibits the aforementioned symmetries, we can identify Energy and Momenta as *quantities that must be conserved*. In other words, *Energy and Momentum exist as concepts outside any specific theory. They are purely concepts associated with the symmetry of the theory*.
This appears to be the most general definition of the terms: Energy and Momentum.
What this tells us is that Energy and Momentum are not something fixed by any specific equation but are things that must be identified in a physical system. For example, we have terms called generalized Momenta in Classical Mechanics as a means of identifying this property.
Therefore, we should distinguish between the specific Physics, which describes a mechanism for how things interact, and more general concepts such as Energy and Momentum. Noether's Theorem tells us that what we know about Energy and Momentum is derived from the Physics, whereas the *specific* Physics cannot be derived from knowing the Energy and Momentum. *The specific Physics needs to be developed from observing the world around us*.
This brings us to the concept that everything is just Energy. This concept offers us nothing, as explained below.
If we consider the Mass-Energy equivalence relationship, $E = mc^2$, we might be led to this conclusion. However, what this equation really tells us is that *Matter is not conserved*. It's telling us that Mass can be converted into Energy. In other words, it's telling us something about Mass. That's why it's useful.
However, the concept that everything is just Energy gets us nowhere in terms of understanding our world. It is essentially a *statement of existence*. The fact that the Universe exists is *empirical*. It is not explained by Energy. Similarly, the Laws of Physics are ultimately empirical, and not explained by Energy. Energy is essentially an accounting tool that helps us solve problems. The Physics is given in the nature and character of the *fundamental forces* that describe how things interact.
On the flip side: Energy and Momentum are quantities that will crop up in the analysis of virtually all physical systems that exhibit such symmetries.

724 -

Since the *Universe is flat on large scales*, how is Gravity assumed to cause the large-scale cosmic Acceleration? Wasn't Gravity supposed to be ignored in flat SpaceTime?

The Universe is *spatially* flat. Even on very large scales, if we were to form a triangle, its angles would add up to 180°, not anything more nor anything less.
Gravitation at the Newtonian level is entirely due to Time dilation, not Space curvature.

As to how Gravity causes *cosmic acceleration*, normally we assume that Gravity (at the Newtonian level) is proportional to the *Mass-density*, ρ_M. In Relativity Theory, however, this changes to $\rho_M + 3\mathrm{P}/c^2$, where P is the *pressure*. Because of that c in the denominator, the pressure part is usually a *negligibly small* quantity, so it can be safely ignored. But this is not the case for *Dark Energy*: it has *huge negative* pressure, $\mathrm{P} = -c^2\rho_{\mathrm{DE}}$.

As a result, the Gravitational contribution of Dark Energy is proportional to $-2\rho_{M,\mathrm{DE}}$, where $\rho_{M,\mathrm{DE}}$ is the Dark Energy Mass-density.

Two things about Dark Energy are that

a. it is *evenly distributed* over the Universe, and
b. its density *does not change* with cosmic expansion.

As a result, over time Dark Energy becomes *dominant* as other things become more dilute. We do not feel the effect of Dark Energy, e.g., here, in the solar system, because its density is so low (the ultra-rare interplanetary medium, which exists in part because of the solar wind, is several orders of magnitude more dense than Dark Energy). However, in the intergalactic voids where there really is very little Matter, Dark Energy dominates: hence, on the largest scales, regions on the scale of clusters of galaxies are pushed away from other regions as the Gravity between them is now *repulsive*. And again, all this has to do with the Time dilation component of the Gravitational Field, not Space curvature.

725 -

How does the Big Bang differ from a *white-hole*?

The Big Bang *may not* be different at all from a *white-hole*. It is true, as it is often pointed out, that a white-hole singularity is a *location in Space*, whereas the Big Bang is a *moment in Time*. However, this distinction is valid only for observers who are *outside* the white-hole's event horizon. To those *inside* the event horizon, the singularity is, in fact, a 'naked' singularity in Time, in the *Past*. And this observer would in fact experience a Universe that appears to be governed by the same *Friedmann Equations* that describe the *homogeneous, isotropic Big Bang Cosmology*.

There is still another difference. Whereas inside the white-hole event horizon, all world lines originate at the singularity, outside the event horizon there are world lines that have different origins or (depending on the nature of the surrounding Universe) may have existed forever. In contrast, in a Big Bang Universe, only those worldlines that originate at the singularity exist; *there is no* '*outside*'.
But observationally, at least at present, we don't seem to have the means to distinguish the two. So, it is conceivable that our Big Bang Universe is, in fact, the interior of a white-hole event horizon in a *larger* Universe.

726 -

Is SpaceTime the quantum field associated to the *graviton*? Can SpaceTime even be considered a quantum field whatsoever? If so, does this not violate the idea that quantum fields exist in Space and Time?

No, not SpaceTime. Rather, a specific element of the 'SpaceTime *metric* manifold', notably the metric itself. Otherwise known as the Gravitational Field.
Nowadays, it is fashionable to describe Einstein's work on Gravitation as a geometrization of Gravity. It is important to remember though that Einstein himself was not particularly fond of this geometrization, that he considered it little more than a useful mental aid, and he never stopped thinking of Gravity as a *proper* force, an interaction between material bodies, also as a field that, just like the Electromagnetic Field, carries Energy and Momentum at a *finite* speed, e.g., in the form of Gravitational Radiation.
As we now have experimental evidence (with numerous LIGO observations) that this is indeed the case, we should stress that the geometric interpretation, notwithstanding Gravity, is, first and foremost, a *physical field mediating a force*. This physical field is mathematically represented by the *SpaceTime metric*. We *don't know* how to turn the Classical Theory of this physical field, Einstein's theory, into a *proper quantum field theory*. However, we do know (more or less) what this theory would look like in the weak field, 'perturbative' limit. In this limit, the Gravitational Field, i.e., the metric, would be 'quantized' in the form of *elementary oscillators* that, in turn, are characterized by the usual *annihilation* and *creation* operators, creating and destroying units of Energy, *field quanta*, which we call *gravitons*.
So, gravitons would be the elementary excitations of the Gravitational Field, i.e., the metrical field of SpaceTime. This field exists in SpaceTime, just like all other quantum fields. It is not SpaceTime: it is a *property* of the SpaceTime manifold, the property that determines physically measured Distances and intervals of Time.
Of course, in the absence of a complete quantum theory of Gravity, it's very likely that Gravity is subject to different rules and may not be a quantum theory at all. Who knows? These remain open questions for now.

727 -

Inside a hollow sphere, no matter its Mass, there is no Gravitational Force. But is there still *Time dilation*? Does a cylinder (without the circular faces) or a circle have the same effect?

As for this issue, it is important to catch the difference between *Gravitational Potential* vs. *Gravitational Force*.
To use an analogy, let’s think of a hilly terrain. There are *high* and *low* places. These can include mountain peaks and high plateaus, deep valleys, or low-lying flat plains. If we drop a big ball, it will roll down but only if there is a slope. It doesn’t matter how high we are. If we are on a flat plateau, the ball will not go anywhere.
Conversely, when we are in a deep valley, climbing its walls takes an effort. But when we are on a low-lying plain, walking may take little or no effort at all, even though we may be closer to sea level than in the valley.
So, we should distinguish between *altitude* vs. *steepness-of-slope*. When it comes to Force, it’s the steepness that matters, not our sea level altitude.

This is also how the Gravitational Field works. There is the Field Potential, which is analogous to *altitude*. And then there is the *resulting* (or *net*) *Force*, which corresponds to the *rate* at which the Field changes from point to point, *analogous to the steepness-of-slope*.
Everywhere *inside* a *massive*, hollow sphere, there is still a Gravitational Field, and this Field is *uniform*. So, there is no resulting Gravitational Force. It’s like a flat plateau, whatever its altitude.
Outside the sphere, the Field gets weaker and weaker as our distance from the surface of sphere increases. This results in a Force *pulling* us towards the sphere. But, again, *inside*, everything is *uniform*.
Now Gravitational Time dilation is related to the *strength of the Feld*, *not its rate-of-change*. In other words, it is determined by the Gravitational Potential, not the Acceleration. There is a substantial Gravitational Potential inside the sphere, even though there is no Gravitational Acceleration. So, yes, there is also *Time dilation*.
Cylinders, instead, or other shapes are *not* like this. *Spherical Symmetry* is *required* for the Field to be *uniform inside*. Cylinders or circles *lack the 3-dim symmetry*, so the Field *will not be uniform*. Therefore, there will always be a resulting Force except perhaps at specific points, like the center of the cylindrical object, where the forces cancel out exactly.

728 -

Does a layman’s description of *Hawking Radiation* exist? Some people say the ‘popular’ description, in terms of virtual particles, is wrong. If one tries to find simple but simple consistent descriptions, these are either too simplistic or too complicated. How about one that’s ‘just right’?

[see answer to Issue 719]

When we read Hawking’s original 1974 paper (*Nature*, **248**, 30-31, 1974), there is a very important point he raises at the core of his explanation as to why there is an imbalance between *incoming* and *outgoing* radiation. As it should be emphasized, a key part of the relevant sentence reads: ‘The β_{ij} will not be 0 because the Time dependence of the metric during the collapse [...]’.

The black-hole *is not static*. It is *in the state of collapse*. As a result, the distant Past and the distant Future, *far outside* the black-hole, *are not identical*. When we solve the field equations of any quantum field theory under these conditions, describing it as a mix of incoming and outgoing *virtual* particles, the quantity represented by the β_{ij} term in Hawking’s paper will be *responsible* for an imbalance. That imbalance represents itself as *real radiation*: thermal radiation emanating from the *vicinity* of the black-hole.
Is this an explanation that is ‘just right’? It’s questionable, to be honest. The phenomenon is inherently *mathematical*. Trying to come up with naïve analogies or imperfect visualizations can be misleading. The ‘popular’ description (which comes from Hawking’s popular science book, A BRIEF HISTORY OF TIME) is itself an example, suggesting that the horizon ‘eats’ negative-Energy virtual particles. That is not so; actually, as seen by any outside observer, at the time Hawking Radiation is being emitted, *no horizon even exists yet*.

729 -

How does Albert Einstein’s General Theory of Relativity explain Gravity as a result of curved SpaceTime?

Albert Einstein's General Theory of Relativity revolutionized our understanding of Gravity by proposing that it arises from the curvature of SpaceTime caused by the presence of massive objects. This theory replaced Isaac Newton's Theory of Gravity, which described Gravity as a force between objects with Mass.
According to General Relativity, Space and Time are not separate entities, but are woven together into a 4-dim fabric called SpaceTime. The presence of Matter and Energy causes the fabric of SpaceTime to curve, similar to the way a heavy object placed on a trampoline would cause the trampoline to deform.
This curvature of SpaceTime is what we experience as Gravity. Objects moving in the vicinity of a massive object will

follow a curved path in SpaceTime, rather than a straight line. This means that even objects that are not directly interacting with the massive object, such as planets orbiting a star, will still be affected by its Gravitational Field and follow a curved path around it.
The curvature of SpaceTime is described mathematically by the Einstein Feld Equations, which relate the distribution of Matter and Energy to the curvature of SpaceTime. These equations predict a number of phenomena that have been observed and verified experimentally, such as the bending of starlight around massive objects, the gravitational redshift of light, and the precession of the orbit of Mercury.
In summary, General Relativity explains Gravity because of the curvature of SpaceTime caused by the presence of Matter and Energy. This theory has provided a deeper and more accurate understanding of the behavior of the Universe and has led to numerous advances in Astrophysics and Cosmology.

730 -

Are there any predictions of General Relativity which don't match experimental results?

Not really, but … to date, all precision tests of Gravity have confirmed the predictions of General Relativity with spectacular accuracy. These precision tests include navigating spacecraft in the solar system and measuring their radio signals (their frequencies and arrival times) using ultra-accurate atomic clocks. Not only have these tests confirmed Einstein's predictions, but they can also help us exclude many possible alternatives. For instance, the simplest alternative Theory of Gravity, the so-called *Jordan-Brans-Dicke Theory*, can be excluded this way unless its so-called coupling constant is given an unnaturally high value that leads to problems elsewhere.
There have also been a few puzzles that have been put to rest; one that I worked on was the famous Pioneer Anomaly. Many believed (many hoped!) that it was a result of some kind of deviation from Einstein's Relativity that caused this spacecraft to veer ever so slightly off course, but in the end, it turned out to be a much more mundane effect (waste heat, radiated in a preferred direction, pushed the spacecraft ever so slightly in the opposite direction).
There are, on the other hand, a few puzzles that are still in need of a fully convincing explanation, although the consensus seems to be that there is nothing much to see here, everybody should move on. One such puzzle is a small discrepancy between model predictions and actual measurements in lunar laser ranging (quite possibly, the explanation has more to do with the internal dynamics of the Earth than with Relativity Theory). Another puzzle is the so-called 'flyby anomaly', an unexplained change in Kinetic Energy experienced by several spacecraft (but puzzlingly, not experienced by others) as they flew by the Earth in tight hyperbolic orbits. Again, quite probably, this is merely an artifact due to how various coordinate systems are matched together in a fully General Relativistic approximation.
But then, there are cosmic puzzles, starting with the infamous rotation curves of galaxies. Galaxies spin much faster than they should. The standard explanation is that this is due to the presence of Dark Matter, which makes those galaxies much more massive. But what if there is no Dark Matter? At face value, the fast rotation of galaxies would then represent a gross violation of the predictions of, never mind General Relativity, simply Newtonian Gravity.
And then there are cosmological puzzles, starting with the need to postulate Dark Matter and Dark Energy (neither of which have ever been detected independently) as constituting as much as 96% of 'stuff' in the Universe. Could it be that instead of Dark Matter and Dark Energy, the real explanation is that the observations are due to a gross failure of General Relativity on these scales? We bet. And there are many modified Gravity Theory proposals offered by researchers as alternatives.
The problem with most such proposals is that Einstein's Theory is very tight; it is very difficult to modify without destroying it, without throwing the baby out with the bathwater. That is because the theory is based on very few assumptions (which is what makes it so beautiful). For instance, say, we choose to add a new field to the theory that couples to Matter non-trivially? Bang, you just destroyed the Weak Equivalence Principle. Or we tweak a little bit how Matter and SpaceTime interact with each other? Bang, you just made the wrong prediction for the bending of light by the Sun, or for gravitational effects on spacecraft radio signals. That is not to say that there are no theories that avoid these pitfalls, but it remains to be seen if a theory exists that avoids all such pitfalls and successfully predicts those large-scale deviations from Einstein's Relativity without having to postulate Dark Matter and\or Dark Energy.

731 -

Does a black-hole's death involve radiating its Mass away, or will it end in a violent explosion?

For much of its lifetime, a black-hole would radiate imperceptibly, at such a low rate that it is literally undetectable.
It would take an unimaginably long time (something like a 70-digit number, when expressed in years) for a stellar size black-hole to shrink down in Mass to the size of the Moon, at which point its temperature equals the present-day temperature of the Cosmic Microwave Background (this fact alone tells us that actual black-holes are not shrinking right now; as they are colder than the microwave background, they gain more Energy than they lose through Hawking Radiation).

And a black-hole with the Mass of the Moon radiates less then a picowatt. As said, undetectable. And it still has an unimaginably long lifetime left: something like a 45-digit number when expressed in terms of *years*.
By the time the black-hole shrinks down to a mere $2 \cdot 10^{13}$ metric tons, its temperature is $6.5 \cdot 10^{6}$ K. We might think that that's hot, which is true, but geometrically, this black-hole is so tiny, it is only emitting radiation at a rate of 1 W. And its remaining lifetime is still a 26-digit number!
Things do get interesting when the black-hole is down to $6 \cdot 10^{11}$ metric tons. At this point, it is radiating 1 W (mostly hard γ- rays, so we don't want to get too close) and its remaining lifetime is now a 21-digit number.
When it is down to just about $7.2 \cdot 10^{5}$ tons, the black-hole has 1000 years left. It is now radiating at $6.85 \cdot 10^{14}$ W. This is several hundred times the *total* electric power generation capability of our civilization. In short, a lot of power.
When it reaches its final year, the black-hole is down to about 72000 metric tons, and radiates $6.8 \cdot 10^{16}$ W of power (again, mostly as very hard γ- rays).
When its final day begins, the Mass of the black-hole is just over 10000 metric tons, and its radiative output is best expressed as 10^{-6} of 1% of the *total* output of the Sun. It reaches $1.8 \cdot 10^{-5}$ of the Sun's output at the beginning of its final second; and $18\ \%$ of the Sun's output in its final microsecond. During that final microsecond, as the rest of the black-hole evaporates, its averaged power output will be about $1/2$ of the Sun's.
So, what do we call this? Is it an explosion? The thing was already emitting power at a rate far exceeding all our Energy generation capability when it still had 1000 years to live. And although the process greatly accelerates near the end, it is still a gradual *increase in Power*, not a sudden kaboom.
But yes, to answer the other half of the question, the black-hole radiates all its Mass away, mostly in the form of Electromagnetic Radiation: long wave radio-waves at first, then heat, then light, and ultimately, as hard γ- rays.

732 -

Was Einstein right about disbelieving in black-holes?

The nature of black-holes was not clearly understood until some time after Einstein's death. The notion that *the process of collapse is eternal* first came to light in a famous paper by Oppenheimer and Snyder in 1939. A few years earlier, Lemaître showed that what we today recognize as the event horizon was merely a *coordinate singularity*. But the nature of the horizon was not well understood until 1958, when for the first time, Finkelstein showed what happens from the perspective if an infalling observer.
Einstein indeed attempted to come up with an argument against 'Schwarzschild singularities', but the singularity he was talking about was the *coordinate singularity at the horizon*, not what we recognize today as the singularity along the *future worldlines* of infalling particles that cross the horizon.
So, it's not really true that Einstein didn't believe in black-holes. Nobody believed in black-holes in 1955 when Einstein died, as the concept hasn't been invented yet. What Einstein didn't believe in was that *Matter density* and other properties of Matter can become *divergent* at the Schwarzschild radius. He was right of course, but not for the reasons that he presented in a 1939 paper when he argued the case. The real reason is that *a coordinate singularity is not a physical singularity*, and even though the event horizon acts as a one-way membrane of sorts, physical properties of Matter at the horizon remain finite.
But this knowledge was still several years in the future when Einstein passed away.

733 -

Since *Higgs bosons* can't escape a black-hole, how does Gravity get out of the black-hole?

For starters, Gravity doesn't have anything to do with the Higgs boson. The Higgs boson is what remains of the Higgs Field after Electroweak Symmetry-breaking, which is the process that (among other things) endows certain particles (charged leptons and quarks, and the vector bosons of the Weak Force) with rest-Mass. These particles would still exist, they would still respond to Gravitation, their Energy-content would still contribute to Gravitation even if they didn't have rest-Mass; the Universe would be vastly different, of course, but there'd still be Gravity.
Secondly, a static interaction should not be confused with the emission or absorption of Radiation. An electric charge may attract or repel another electric charge, but not because either is emitting light or Electromagnetic Radiation (don't confuse this with the mathematical tools known as *virtual particles*. They're not real things, hence the name, 'virtual').
Thirdly, in an actual, astrophysical black-hole (so-called *Oppenheimer-Snyder collapse*) the collapsing Matter is still (insofar as we, outside observers, are concerned) *outside* the yet-to-form event horizon. The formation of that horizon and infalling Matter crossing that horizon remain forever in our Future. So, the gravitating Matter is still all there, an infinitely thin and practically invisible shell (invisible because of *extreme* Gravitational Time-dilation and the associated

red-shift) but its Gravitational Field can still influence distant objects *without any Causality violation*. It's not 'escaping' anything; the source is still *outside* the event horizon.
But *lastly*, even if we somehow had a 'fully formed' black-hole, it would still have Gravity: the Gravitational Field is not a thing that 'escapes' from inside, rather, it is a *delocalized property* of the entire black-hole object. And once again, let's stress this, it has *nothing to do with Higgs bosons or the Higgs mechanism*.

734 -

How do we know that Time slows down due to Gravity? Do watch mechanisms start working differently?

We should not misunderstand the nature of Relativity Theory. Relativity Theory does not tell us that Time slows down. It does not tell us that rulers get shorter either. What it tells us is what different observers see.
So, say, we sit here on the Earth in its Gravitational Field. Our watches are working just fine. If they're good watches, they will measure one second in exactly one second. There is nothing wrong with their mechanisms.
But when I am watching you from deep space with a telescope and compare your watch to mine, what do I find? I find that your watch runs a wee bit slow. Less than 10^{-9}, but yes, slower than mine.
But it's not really your watch that is running slow. It is that I, as an observer at different location with respect to the Earth's Gravitational Field, see your watch tick at different rates.
As to why this is so, there is a meaningful thought experiment that should offer some insight. As we know, the speed of light in the Vacuum is constant. So, suppose we fire a laser beam up into the sky. A laser beam is just a light wave. Let's say your wave is a wave that wiggles exactly $6 \cdot 10^{14}$ times / second.

Now when that laser beam climbs up in the Earth's Gravitational Field, *it loses Energy*. But because it is a beam of light, its speed cannot change. What can change is its *frequency*. When we work out the numbers, we find that by the time it gets to my location in deep space, the beam loses roughly 0.4 wiggles every $1\ \mu$s .

But how can that be? There is no mechanism that can add or remove wiggles to or from a continuous stream of wiggles. How would that work anyway? Yet it is a fact that I measure fewer wiggles in deep space (incidentally; this fact is routinely verified every day with spacecraft and radio beams). So, if you sent $6 \cdot 10^{14}$ wiggles/sec and I only receive, say, $5.999999996 \cdot 10^{14}$ wiggles/sec, what gives? Well, … if my clock runs a little faster than yours, this is exactly what happens. The 1 sec I measure is slightly shorter than the 1 sec you measure, which means that I get fewer than the $6 \cdot 10^{14}$ wiggles that you sent.

So again, nothing is wrong with your clock, or mine. It is only when we compare the two, while situated at different locations with respect to the Earth's (or any other body's) Gravitational Field that we notice a difference. It is not due to any changes in the clocks' respective mechanisms but *to changes in the Gravitational Field*, which doubles as the metric of SpaceTime, which determines *Lengths* and *Time-intervals*.

735 -

How does Heisenberg's Uncertainty Principle relate to the Spontaneous Symmetry Breaking of the Higgs Field?

It doesn't, there is no direct relationship between the two. The Uncertainty Principle is a consequence of the nature of the quantities of the Quantum World. They are not number-valued; specifically, quantities such as generalized positions q and momenta p *do not commute under multiplication*: $pq - qp = -i\hbar$ (we'd get 0 if q and p were *ordinary numbers*).
The *spontaneous symmetry breaking* of the Higgs Field is a *classical effect*. It depends on the fact that the Higgs Field has a Potential Energy characterized by a *quartic* (complex) Potential, very crudely in the form $\mu|\phi|^2 + \lambda|\phi|^4$. This expression is not minimal when $\phi = 0$; rather, the constraint μ^2/λ determines the 'Vacuum expectation value' of the Higgs Field, which will be $\neq 0$. This specific $\neq 0$-value *breaks the perfect symmetry of the Vacuum with respect to a family of mathematical (gauge) transformations*. Hence the expression, 'Spontaneous Symmetry Breaking': as the system settles into its lowest Energy-state, the symmetry of the Vacuum gets broken *spontaneously*.

736 -

How does Modified Gravity work?

By and large, *modified theories of Gravitation* work by introducing small changes to the Newtonian acceleration law. These small changes can be in the form of ad hoc, semiempirical formulae, such as the formula of the famous 'MOdified Newtonian Dynamics' (MOND), which (kind of) works (in some cases) but lacks theoretical justification.
Or, the changes can come in the form of adjusting the theory's foundations: the nature of the Gravitational Field and how it couples to Matter.
In the Standard Theory, the Gravitational Field is a so-called massless tensor field that couples to Matter 'universally' and 'minimally'. The tensorial nature of the field ensures that 'like charges attract', that is to say, two positive Masses attract one another. (In contrast, in electromagnetism like charges repel). The fact that the field is massless results in an inverse-square law (massive fields, in contrast, have a finite range.) The universal nature of the coupling results in the weak equivalence principle: all material objects are affected by Gravity the same way, regardless of their material composition (in the Vacuum, absent air resistance, a pebble and a feather fall at the same rate). And the 'minimal' nature of the coupling is what makes it possible to interpret Gravitation as a change in the geometry of SpaceTime.
So then, this tells you how a modified theory of Gravitation might work. Any of these fundamental properties of the Gravitational Field can be changed. For instance, the tensorial Gravitational Field can be extended, e.g., with a vector or scalar component. Assigning a mass to either the tensor field or any of these new fields can introduce a contribution with a finite range. Changing the coupling to Matter can result in a Gravitational Field that affects objects differently based on their material composition. It might also yield a field that no longer has a simple geometric interpretation.
All these options are available to the theorist, but the constraints are stringent. We have precision tests of Gravitation here in the solar system, carried out using interplanetary spacecraft, that severely constrain deviations from Einstein's theory. Beyond the solar system, we need either a *modified* theory of Gravity or Dark Matter to account for some of the observations; but a modified theory of Gravity can easily run afoul of observations, especially cosmological observations such as the large-scale distribution of Matter or the features of the microwave background.
But this, generally, is the proper 'theoretical' route to modified Gravity: change the field (e.g., add Mass), change how the field behaves, add new fields, or change how the field(s) interact with Matter. Or any combination of the above. This is our modified Gravity playground.

737 -

How does the Theory of General Relativity explain why the speed of light is a *constant* in our Universe?

General Relativity is based, in part, on a postulate called '*general covariance*', i.e., a postulate that guarantees that *the Laws of Physics are the same for all observers regardless of their motion*.
These Laws of Physics include, among other things, Electromagnetism, specifically Maxwell's Theory, which has a mathematical property called *Lorentz-Poincaré invariance* that, in turn, implies a *constant* Vacuum speed of light (sometimes the constant speed of light is mentioned as a separate postulate, but so long as we accept Maxwell's Theory is valid, it follows already from *general covariance*).
So, it's not so much that General Relativity explains the constancy of the Vacuum speed of light *as it assumes it*.
It is possible to construct *alternatives* to General Relativity in which general covariance is violated in some shape or form (e.g., SpaceTime may have a preferred direction). It is also possible to construct theories of Electromagnetism that deviate from Maxwell's Theory. But (as far as we can tell, *based on observational data*) that is *not* how Nature works.
Ultimately, good Physics is really done this way: it's about finding a bunch of postulates, preferably as few as possible, *that result in a mathematically self-consistent description of* (*physical*) *Reality that agrees with observation*.

738 -

Was all the *hydrogen* in Universe created at once during the Big Bang or was it created over time as stars were forming?

As all of us may know, (ionized) H^+- atoms are just *protons*. So, we are really talking about the creation of protons in the early Universe, an epoch known as *baryogenesis*.
This process is not understood near as well as we'd like; specifically, we don't really know why protons prevailed over anti-protons and why the Universe mostly consists of stuff we call Matter as opposed to anti-Matter. But we have a pretty good idea when this process took place: baryogenesis ran its course by the time the Universe was approximately 10^{-12} s old.
So, it makes sense saying that, from that point onward, basically by the time the Universe became cold enough for protons to remain stable and not get smashed up all the time, all the H^+ atoms were present in the Universe.
A little bit later, some of these protons (and neutrons) combined to form heavier atoms, mostly He. This epoch is known

as *primordial nucleosynthesis*, and it ended when the Universe was about $10^3\,\mathrm{s} \approx 17'$ old.
Much much later (but still very early in the history of the Universe) these atomic nuclei recombined with electrons to form neutral atoms. This took place when the Universe was roughly 380000 years old, give or take. At this time, the Universe became *transparent to light*, and the afterglow of that incandescent gas is what we detect today (after a large *redshift*) as the Cosmic Microwave Background (CMB).
It was not until a few hundred million $(\propto 10^8)$ years later that the first stars began to form.

739 -

What is *Dark Energy*, and how does it expand the Universe against Gravity?
[see Issue # 601]

We don't know what *Dark Energy* is. There are potential *theoretical* candidates, but *none have any observational support*. What we do know is what Dark Energy does, assuming it exists in the first place (the alternative is that our understanding of Gravitation needs a *profound* revision).
The simplified equations of Cosmology assume that all Matter is in the form of '*isotropic perfect fluids*', which is to say, mediums that are completely characterized by their *density* and *pressure*. *There is no viscosity*, *no stress*, *no* '*stickiness*', and *no directionality* either.
Matter that we are familiar with: stars, planets, even interstellar dust and gas, are well-described by this approximation. Moreover, unless said Matter is *very hot* and *very dense*, its pressure, compared to its Energy-density, is *negligible*: so effectively, all forms of *visible* Matter are 'dust', which is to say, Matter with *zero*- (or *near-zero*) *pressure*. Dark Matter, too, is presumed to be *stuff* with *zero-pressure*.
In general, stuff can be characterized by a very simple equation of state, which is the *ratio of pressure to Energy-density*, P/ρ_E For 'dust', this ratio is zero: $\mathrm{P}/\rho_E := w = 0$. Electromagnetic Radiation (light) has pressure. Its pressure is $1/3$ its Energy-density $\rho_E = 1$, so, $w = 1/3$.
In the early Universe, Radiation dominated over Matter. But as the Universe expands, Radiation loses Energy more rapidly than 'dust', so, over time, it becomes less significant. Today, the contribution of Radiation is negligible.
Without getting into seriously exotic Physics, value of w in the equation of state cannot be greater than 1 or less than -1. Negative pressure? Yes. Let's think about it: pressure is positive when constituent particles *repel* each other and as a result, the medium fills all available space. If the particles *attract*, the opposite happens. So, *negative pressure is definitely possible*. Dark Energy is the limiting case of extreme negative pressure: $w = -1$. That's what we know about Dark Energy, and that's all indeed.
What does this mean? Well, the equations of Gravitation for *weak* Gravitational Field are quite simple. Normally, this would be Poisson's Equation for Gravitation, $\nabla^2\phi_{\mathcal{G}} = 4\pi G\rho_M$. Neglecting the details, it basically just says that the Gravitational Field Potential (function) $\phi_{\mathcal{G}}$ is due to the Matter-density, ρ_M, except that, if *pressure* is *significant*, we must modify this equation: $\nabla^2\phi_{\mathcal{G}} = 4\pi G(\rho_M + 3\mathrm{P})$, according to General Relativity (where $\rho_E \equiv \rho_M$).
So, what happens if $\mathrm{P} = -\rho_M$, as in the case of Dark Energy? The right-hand side becomes proportional to $-2\rho_M$, i.e., *negative*. So, the Gravitational contribution of Dark Energy is *repulsive*!
Lastly, recall that Radiation diminishes *more rapidly* than Matter in an expanding Universe. Dark Energy does the opposite: it does not diminish at all (the work done by Gravitation as the Universe expands produces more Dark Energy, keeping its density *constant*). Which means that over Time, Dark Energy becomes dominant over other forms of Matter as the Universe expands. Therefore, its repulsion, at least on the very large scales (between clusters of galaxies) *dominates over attraction*.
As a conclusion, it's not that the Universe expands against Gravity. The Universe would expand, even without Dark Energy, at a rate slower than it could be without attractive Gravity. But Dark Energy changes that picture: its repulsive Gravity actually *accelerates expansion*.

740 -

How can Binding Energy have Mass if it is not rest-Mass?

Energy doesn't 'have' Mass. Rather, the *resistance* of an object to Acceleration, also known as its *Inertia* or *Inertial Mass*, is determined by the object's *Energy-content*.
What the nature of that Energy-content is doesn't matter. For real objects, it is a combination of the rest-Masses of its constituent parts, the *Binding Energy* that holds them together, and any *Kinetic Energy* that is present due to internal motion (e.g., vibration due to *Heat*). Whatever it is, it all adds up.

This is the meaning of the *Mass-Energy Equivalence* relation. It is often misunderstood, in part, because the measure of Energy *depends on the observer*. A heavy object may have no Kinetic Energy when it is sitting next to us on a table; but what if we and the table are both on a fast-moving train and an observer Ω stands at the station? In the Ω- observer's reference frame, both we and the object have substantial Kinetic Energy, but none of that matters when it comes to an object's rest-Mass. *Its rest-Mass is its intrinsic Energy-content, i.e., the Energy therein measured in the reference frame in which the object itself is at rest*.
Witness the title of Einstein's famous 1905 paper, presented in the form of a question that the paper answers *in the affirmative*: "Does the Inertia of an object depend upon its Energy-content?".

741 -

If the Newtonian Gravitational Field is a limit of the Einsteinian one but knowing from General Relativity that the fields interact with each other, then do the Newtonian Fields also interact with each other? And how could it be expressed in math?

General Relativity describes two *interacting* Fields: *Gravitation* and *Matter*, everything lumped together, characterized by Stress and Energy. In the standard form of Einstein's Field Equations, Gravity is on the *left*-hand side, Matter on the *right*-hand side:

$$R_{\mu\nu} - (1/2) R g_{\mu\nu} = 8\pi G T_{\mu\nu} .$$

In the *Newtonian limit*, this equation simplifies to a form that is known as the *Poisson's Equation for Gravitation*:

$$\nabla^2 \phi_{\mathfrak{g}} = 4\pi G \rho_M ,$$

where $\phi_{\mathfrak{g}}$ is the Newtonian Potential (function) and ρ_M is the Mass-density of Matter, both of which we can think of as '*fields*'. So, the logic has not changed: *the Gravitational Field tells Matter how to move, and Matter in turn shapes the Gravitational Field*.

742 -

How is the law of Conservation of Energy accurately proven to be an accurate theory?

Energy Conservation *is not* a theory, nor do we prove theories in the Natural Sciences (theories may be supported or falsified by *observational evidence*, i.e., not proven).
Energy Conservation is a property of systems that are described by mathematical expressions that remain (in a precisely defined sense of the word) *invariant under Time-translation*. Crudely speaking, it means systems that are governed by the same Physical Laws tomorrow that govern them today.
This is a specific application of a much more general theorem in mathematical physics, *Emmy Noether's Theorem*, which relates Conservation Laws to *symmetries*, including the Time-translational *invariance*. Another example is Conservation of (Linear) Momentum, related to invariance under *Spatial translations*; or Conservation of Angular Momentum, related to invariance under *Spatial rotations*.
Noether's Theorem is proven rigorously as a mathematical theorem (note the word: theorems are proven, theories are not). Therefore, if a system can be described by a theory that is represented using a mathematical formalism that is *invariant* under Time translation, we know that in that system, *Energy Conservation applies*.
Our fundamental theories in Physics, including General Relativity and the Standard Model of Particle Physics, are invariant under these basic transformations (*Time translation* and *Spatial translation\rotation*). Therefore, they describe a physical Universe in which Energy, Linear Momentum and Angular Momentum are *conserved*. To date, observational evidence supports these theories, but we can certainly conceive of alternatives, theories in which one (or more) of these symmetries gets *broken* and therefore, the corresponding conservation law no longer applies.

743 -

The Universe expands with *Acceleration*. The Potential Energy of Gravitation increases (changes from *large negative* to *smaller negative*). The Kinetic Energy increases as well. Is there some other kind of Energy that *decreases*, to enforce Conservation?

Actually, it's kind of the other way around. If we want to think of accelerating expansion in Newtonian terms (yes, it is possible and *legitimate* to do so), we must keep in mind one correction to Newtonian Physics: the source of Gravitation is not the Mass-Energy density ρ_M but, rather, $\rho_M + 3\mathrm{P}$, where P is the *Pressure*.

For Dark Energy, the presumed source of accelerating expansion is $P = -\rho_M$, so, $\rho_M + 3P$ is *large*, and *negative*. Negative Mass-Energy density means *repulsion*. Repulsion implies *positive* Potential Energy that *decreases* as things fly farther apart. This is balanced by the *increase* in Kinetic Energy.
So, yes, locally at least, Energy-Momentum Conservation is maintained even in an *accelerating Cosmos*.

744 -

Can Dark Matter lose Kinetic Energy via Gravity waves, and thus be able to form orbits?

Indeed, all gravitationally interacting systems that are not *axially symmetric* produce Gravitational Radiation and thus lose Kinetic Energy over time but … *extremely* slowly. Gravity is *very weak*. Let's think about it: as the Earth orbits the Sun, it produces *gravitational waves*. The power of emission? Forgot the exact figure, but it's *a couple of hundred watts*. That's all. That would not noticeably alter the orbit of the Earth even over Time-scales that are orders of magnitude *greater than the present age of the Universe*.
So, no, the production of gravitational waves *would not significantly alter the evolution of Dark Matter in this Universe*.

745 -

If Gravity is the bending of Space and Time in the presence of a *large Mass*, why do we have *tides*?

Tides have nothing to do with 'Gravity-geometrization' of (Einstein's own choice of words!), which is an interpretation. Tides have to do with the fact that the effect of Gravitation changes with distance. So, an object that is closer to a source of Gravitation will respond differently from how an object farther away responds.
Different parts of the Earth are at different distances from the Moon. The effect of lunar Gravitation differs on them, so they try to follow different trajectories. They of course cannot because they are all parts of the same Earth, held together by its own Gravity, but the effect stretches the Earth a little. And it stretches the oceans a little more because the oceans are liquid, not rigid (albeit flexible) like the Earth's crust.
Whether or not we choose to interpret the tensorial Gravitational Field of General Relativity as the metric tensor of SpaceTime makes no difference.

746 -

Since *Cherenkov Radiation* is faster than light in the right conditions, does this mean that if it had eyes it would investigate the Past as it is catching up with light that was moving in the same direction? If yes, does it mean it's traveling in Time?

In a weird way, yes, but let stress up front that this has nothing to do with Relativity Theory. It is perfectly *ordinary* Physics and Geometry.
Forget light, Cherenkov Radiation, any of that fancy stuff. Suppose you are standing some distance away from a machine that is firing ping-pong balls at you, say, one ball a second. Just pretend these balls never fall to the ground and never slow down, they keep flying. And the ping-pong balls are numbered in sequence. We don't need to catch them, we just watch them fly by as you read their numbers: ball # 1, ball # 2, …., ball # 23195, ball # 23196, …, etc., ad infinitum.
But we are restless. We have been sitting still far too long, more than 6 hours already (23196 seconds is a long time!). So, we jump back onto our feet and start running in the same direction as the ping-pong balls, only faster. And see what happens? We catch up with ball # 23196. Next, we catch up with ball # 23195. Then # 23194, # 23193, etc. We are seeing the balls in reverse order! Not just that; rather than coming from behind us, the balls you are catching up with will be hitting us in the face if you're not careful enough to avoid them.
Something like this would happen if we could travel faster than about 225000 km / s in water, with a light source behind us. Ignoring complications due to Doppler and relativistic effects (which change only technical details, not the essence of what is being described here), if that light source was projecting a movie and we had a movie screen with us to catch that light, we'd be watching the movie play backwards. And just as in the case of the ping-pong balls, the movie screen will appear to be illuminated by light coming from in front of us, not behind us.
None of this involves Time travel or anything exotic: those ping-pong balls are telling the whole story.

747 -

Why did Einstein prefer Special Relativity over General Relativity?

We wonder whatever it was that might have given the impression that Einstein preferred Special Relativity. It is true that Special Relativity is simpler, since it does not need to deal with Gravity, and therefore it is easier to use in cases

when Gravity can be ignored or, at the very least, just approximated using a nonrelativistic Newtonian formalism. But … prefer? We can safely say that it's unlikely.
In the years following his publications on Special Relativity in 1905, Einstein became increasingly motivated to develop a theory that treats all observers, not just inertial observers, on an equal footing (contrary to some popular accounts, Special Relativity can deal with accelerations just fine, but accelerating reference frames in the theory are kinds of 'second class citizens'). He began to search for a *Generaltheorie*, a generalization of the Relativity Principle. The breakthrough came in the form of what Einstein later described as his 'happiest moment': the realization that a freely falling observer feels no Gravitational Field, i.e., the Weak Equivalence Principle, as a result of which, the Gravitational field, at least in the vicinity of the observer, can be 'transformed away' by introducing an *accelerating* reference frame. A direct consequence of this is that the sought-after *general theory* must necessarily also be a theory of Gravitation.
Einstein learned Riemannian Geometry from his mathematician friend Marcel Grossman. He was also communicating with the famous mathematician David Hilbert. Along the path towards a coherent theory, Einstein published several papers; some were actually plain wrong! Eventually, by late 1915 he figured it out and wrote down what today are known as *Einstein's Field Equations*, the fundamental equations of General Relativity (whereas Einstein essentially postulated these equations based on heuristic considerations – e.g., Gravity must be sourced by Matter, Conservation of Energy-Momentum must be respected – Hilbert derived the same equations for the special case of Gravity and Electromagnetism only, no other forms of Matter, from a Lagrangian Action Principle. The action functional of General Relativity is known today as the *Einstein-Hilbert Lagrangian*).
Up until this point Special Relativity was not even called 'Special Relativity': that designation came when it was realized that the 'old' Relativity Theory is indeed a *special case* of the General Theory that is valid in the absence of Gravitation. So, no, Einstein certainly did not prefer a special case over a much more powerful, general theory. But it is also true that in cases when it can be used, Special Relativity's toolset is substantially simpler. This is why Lorentz Transformations, at least in a simplified form, are sometimes even taught to high-school students, whereas Riemannian Geometry and the corresponding toolset of tensor calculus are definitely not high-school material.

748 -

We know that Gravitational field intensity is $E = -d\phi_g/dr$. But, if $\phi_g = -GM/r$, then how can E be GM/r^2? Shouldn't it be $E = -d(-GM/dr) = -GM/r^2$? So, why is E *positive* then?

Let us do the math properly. First, it is not the 'Gravitational Field intensity', but the *Gravitational Acceleration* that is associated with the *opposite* of the gradient of the Gravitational Potential. These are *vector* quantities:

$$\mathfrak{g} = -\nabla\phi_g = -(d\phi_g/dr)\hat{\boldsymbol{r}}\,.$$

For a point-source, $\phi_g = -GM/r \equiv -GM/|\boldsymbol{r}|$ indeed, assuming $\boldsymbol{r}$ is a radius vector with the origin at the point-source. Using its gradient expression, we get

$$\mathfrak{g} = -(d\phi_g/dr)(\boldsymbol{r}/|\boldsymbol{r}|) = (GM/r^2)(-\hat{\boldsymbol{r}})\,,$$

where $\hat{\boldsymbol{r}} \equiv \boldsymbol{r}/|\boldsymbol{r}|$ indicates a *unit* vector in the $\boldsymbol{r}$ direction.
What this tells us is that the magnitude of the Gravitational Acceleration is GM/r^2; its direction is $(-\hat{\boldsymbol{r}})$, i.e., that of an acceleration *towards the source*.

749 -

What is a black-hole? Is there any way to know for sure if our Universe is inside of one?

First and foremost, a black-hole is a *hypothetical* object of such Mass and Density, its *escape* velocity at its surface exceeds the Vacuum speed of light and therefore, it becomes *invisible*. Astronomers such as John Michell speculated about the existence of such objects all the way back in the late 18th century.
Moving on to the 20th century, a black-hole is a solution of Einstein's Field Equations for Gravitation, for very *dense*, very *compact* objects. Rather than having a defined surface, a black-hole in General Relativity is characterized by an *event horizon*. This horizon represents a point of no-return for infalling observers, as much a moment in Time as it is a location in Space: once the event horizon is reached, returning to it is not possible anymore, as the horizon is now a *past moment in Time* for that hapless observer. Inside the horizon, there is a SpaceTime in a state of *collapse*. Curiously, to those on the outside, the horizon itself *remains forever in the future*. The simplest black-hole solution was discovered by Karl Schwarzschild in 1916, though it took a good half-century to really understand what this solution represents.
How would such black-holes form? This question was first answered in 1939 by Oppenheimer and Snyder who described

a collapsing sphere of dust particles. They found that the collapse is *eternal* as viewed *from the outside*. The denser the cloud, the *greater the Time dilation*, so, for us on the outside, it appears like a movie clip that is shown increasingly in slow motion, slowed down to the extent that the very final frame never gets shown.
Therefore, a black-hole in this case is in a never-ending, continuous process of formation; indeed, the very title of the Oppenheimer – Snyder paper was, '*On Continued Gravitational Attraction*'.
Is our Universe inside a black-hole? A black-hole is characterized by collapse. If we are inside a black-hole, other objects would appear to be approaching us, their light blue-shifted. In contrast, we see distant objects, distant clusters of galaxies recede from us, their light red-shifted. So, no, we are not inside a black-hole. We might be inside a Time-reversed version of a black-hole (also a valid solution of Einstein's Field Equations), a '*white-hole*', although white-holes raise more questions than they answer; for starters, just as a black-hole is characterized by the state of Matter that forms it, a white-hole would be characterized by the state of Matter into which it decays, which violates the Principle of Causality. So, no, it's reasonable to think the safe bet is that we're not in a white-hole either.

750 -

Since Time slows down when an object approaches the speed of light, does that mean that galaxies will be torn apart at a slower rate during the Big Rip?

Forget 'Time slows down'. Forget 'object approaches the speed of light', since there is *no absolute* speed; speed is always *relative*. Instead, let's remember the following sentence: "Clocks that move close to the speed of light relative to us will appear to tick more slowly". Or, alternatively, "When we move close to the speed of light relative to a clock, that clock will appear to tick more slowly".
So then, what was the question again?

751 -

Why is there Gravitational *Time-dilation* but not *Length-contraction*? If Time dilates as an object drops in a Gravitational Field, shouldn't its SpaceTime be transformed with the same *Lorentz transformations*?

There is Length-contraction. The question is: 'How do we define and measure it?'
Gravitational Time-dilation in a *static* Gravitational Field is kind of easy to conceptualize. Populate the Field of a point gravitational source (i.e., the Schwarzschild metric) with clocks that stay in place. These clocks will of course be in *accelerating reference frames* (not freely falling), but never mind. The point is: we can measure the rate of these clocks by letting them emit a signal, say, every second. We will find that the clocks closer to the source of Gravitation will appear to run *slower*.
But if we populate the same Field with meter sticks … how do we compare them? What is the *synchronization procedure*? If we think about it, it becomes surprisingly tricky to compare lengths at different places in a *variable metric*. Even so, when we just look at the form of the Schwarzschild metric, it is very clear that in addition to Time-dilation, Spatial *line-elements* in the *radial direction* are also affected.
However, in practical terms, this Spatial effect is *minuscule*. What we perceive as Newtonian Gravitation *is due pretty much entirely to Time-dilation, not Spatial curvature*. Spatial curvature does play a role, however, for *fast* moving particles. In the extreme case, for particles moving *at or near* the speed of light, *Spatial curvature becomes as strong an effect as Time-dilation*. This is why, in Einstein's Theory, rays of light are deflected by a Gravitational Field *twice* as much as they would be in Newton's Corpuscular Theory of light. This was a key prediction of General Relativity, one of its 'classical tests'.

752 -

As far as often assessed, Quantum Physics and Relativity theory will never get along. Does that mean one of them is basically wrong?

Actually, Quantum Physics and Relativity Theory get along just fine in most respects, most of the time …
First of all, the *prevailing* quantum theory, Quantum Field Theory, is *fully relativistic* from the onset. Relativity is 'built into' the theory, so to speak. And it's the only quantum theory that is *fully causal* (effect never precedes cause, for *any* observer) and can account for particle *creation* and *annihilation*.
When we say 'fully relativistic', we mean Special Relativity. But Quantum Field Theory can 'live' on the curved background of General Relativity, too. Sure, things get interesting (in the general case, we must fully embrace the *field* concept and *give up* on the notion of particles altogether) but the theory works.
So, what doesn't work? Well, … Einstein tells us that matter is the source of Gravity, through the *Stress-Energy tensor*. But in a quantum theory, this Stress-Energy tensor consists not of numbers but of so-called *non-commuting operators*.

Does this mean that the Gravitational Field must also be described by a Quantum Theory? Well, maybe, … but nobody succeeded with that. *We do not have a viable Quantum Theory of Gravity*.
But do we really need one? There is a simple (almost too simple) modification that allows the two theories to coexist just fine: Instead of the quantum operators representing the Stress-Energy tensor, just use their so-called *expectation values*. Those are numbers that can be plugged into Einstein's Field Equations. This approach, called *semi-classical Gravity*, works very well; it accurately describes Nature everywhere except for the *immediate* moments after the Big Bang or the *immediate* vicinity of a *singularity*, deep inside a black hole's *event horizon*. In other words, *places* and *times* that we can never explore *experimentally*.
So, perhaps, *semiclassical Gravity* is the answer? But many people find it deeply dissatisfying, a kludge, if we wish. So, there are philosophical reasons to go *beyond* semi-classical Gravity. But perhaps philosophy misleads us. We won't know until we know which will be … who knows when.
But it is not true that Relativity and Quantum Physics do not get along. They get along just fine *most of the time*, *almost all the time*, as a matter of fact.

753 -

Why would a homogenous, infinite, and eternal Universe ever have needed a *Cosmological Constant* in the first place to stop it contracting? Did Einstein not properly understand the concept of *infinite* or *homogenous*? Did he not get Newton's 3rd Law?

Einstein got all the above just fine. He also understood his own *field equations*. When we plug into those field equations a Cosmos that is *infinite*, *homogeneous*, *isotropic,* and filled with Matter, the result is that this Cosmos is either *expanding* or *contracting* at a *variable rate*.
This result is seen directly when we write down Einstein's Field Equations in the *Friedmann-Lemaître-Robertson-Walker* (FLRW) *metric* and obtain what is known as the *2nd Friedmann Equation*. Spelled out in full,

$$\ddot{a}a = -\frac{4}{3}\pi G(\rho_M + 3\mathrm{P}),$$

where ρ_{M} is the Matter-density of this Universe, p is the *Pressure*, and a is a component of the metric, often called the *scale factor*. The *single-dot* represents 1st differentiation vs. Time; *double-dot* means 2nd derivative vs. Time. This equation implies that, when Matter is present, $\ddot{a}$ is $\neq 0$. So, not only does the scale factor change over Time, *its rate of change itself changes*.
Incidentally, this equation and its companion, the *1st Friedmann Equation*, can both be derived from Newtonian Physics alone. So, Relativity Theory is not even needed to arrive at the conclusion that a spatially homogeneous, isotropic Universe *cannot be in a steady state*. But in Relativity Theory, the consequences are more severe as they imply that the metric becomes *degenerate* at some point in the *Past* or the *Future*.
However, this problem can be 'fixed' by introducing a *Cosmological Constant* Λ, that changes the 2nd Friedmann Equation as follows:

$$\ddot{a}a = -\frac{4}{3}\pi G(\rho_M + 3\mathrm{P}) + \frac{\Lambda}{3}\ .$$

With a suitable value for Λ, the left-hand side of this equation can be set to 0. The problem with this fix is that it's *unstable*: even the tiniest *density fluctuation becomes a runaway effect*.
Trying to fix his equations in this manner instead of accepting the result as a prediction is what Einstein later called his *greatest blunder*, after it was discovered by Lemaître, Hubble and others that we indeed live in an *expanding Universe*.
The biggest irony is that Λ has since been reintroduced, to account for what appears to be a Universe in an *accelerating state of expansion*, as deduced from data on *distant supernovae*. So, the blunder perhaps wasn't a blunder after all.

754 -

How do we know that Dark Matter isn't just rouge planets, black-holes, galactic halos, and dust?

Indeed, when Dark Matter was first proposed by Fritz Zwicky (1898-1974) back in the 1930s, it was thought that it was indeed just ordinary Matter that was 'dark', as in not emitting enough light to be seen.
But that was before modern cosmological models and their quantitative predictions about certain observable properties of the Universe. And it all has to do with the fact that ordinary Matter has *Pressure*.
Which is to say, if we increase the concentration of ordinary Matter, it begins to resist it. Not only that, but it can also heat up. That means that it now produces *thermal radiation*, which can push away additional Matter, altering the rate at which structures (stars, galaxies, clusters of galaxies) form.
Long story short, by simply observing things like the statistical distribution of structures of Matter in the observable Universe, or minute temperature fluctuations of the cosmic microwave background radiation, we can infer how much ordinary Matter vs. pressureless, completely transparent 'Dark Matter' it takes to form the Universe the way it is. And we find that only about 4% of the so-called *critical density* can be ordinary Matter; about 26% would be Dark Matter that is not made up of ordinary protons, neutrons, and electrons, i.e., Matter as we know it (the remaining roughly 70% is 'Dark Energy', which is another thing altogether).
Incidentally, even this 4% is more than the ordinary Matter density that we can actually see in the form of stars, planets, dust, gas, etc. However, it is believed that, whatever is missing from that 4 % is just ordinary Matter that is too dim, too dark to be seen, just like Zwicky's Dark Matter. The problem is not this but the remaining 26%. That cannot possibly be ordinary 'baryonic' Matter, as it would completely change the large-scale statistical properties of the *observed* Universe.

755 -

What are black-holes? Could we use them as portals or worm-holes for travel throughout our solar system or even Universe? [Compare to Issue # 749]

Black-holes are, first and foremost, *mathematical constructs* representing the end stage of *gravitational collapse*: when a dense object, at least 3 times as heavy as our *entire* solar system, collapses under its own weight.
Right there, it's important to offer a word of caution: this end state may never happen. To outside observers, the process of collapse takes forever, stretched out to the infinite future by gravitational time dilation. Meanwhile, in a process that is extremely slow but not infinitely long, the black-hole-to-be-born *evaporates* by way of Hawking Radiation. Whether or not anything of interest remains afterwards is a Matter that is still sometimes debated.
As to using black-holes … for starters, the Gravitational Field, particularly the *rate of change* of the Gravitational Field, near a black-hole is *extreme*. We experience it as *tidal forces*: the tides are so immensely powerful, they'd tear apart, never mind planets, never mind spaceships, never even mind our bodies, how about tearing even our cells apart? Only the very largest of black-holes (the largest super-massive black-holes, which represent a mystery on their own right as we don't really know how they came into existence) have relatively tame tides in their vicinity.
'Throughout our solar system?' Our solar system is extremely *tiny*. It only takes light a few hours to reach the most distant planet, Neptune, but it takes light to reach more than 4 years to reach the nearest star … and more than 1500 years to reach the nearest known black-hole, This, in passing, is much more massive than our entire solar system.
To put this into perspective, the distance to the nearest known black-hole is roughly 500000 times greater than the distance to our most distant spacecraft to date, Voyager 1; and it took Voyager 1 nearly 50 years to get to where it is today. Humans talking about using a black-hole for anything is like ants in an ant colony looking up at the sky, watching a passenger plane fly by, and talking about how they'd be using that passenger plane for something. Except that a colony of ants has a better chance commandeering a 747 than us humans, at present, using a black-hole.
So, no, we're not going to use a black-hole for anything anytime soon. Even if it were possible in principle. But it would be advisable not taking speculative nonsense about worm-holes and whatnot too seriously. Yes, we can play with the math and come up with some fancy solutions of black-holes connected by worm-holes and even connecting distinct SpaceTimes. But speculative mathematics is not Physics, it's not Reality.
In Reality, the only thing we do know with any certainty is that there are objects that we observe that behave as black-holes; and that their behavior is consistent with the reasonably robust math of General Relativity, used to describe the *continuing process of Gravitational Collapse*.

756 -

Does the collapse in Quantum Mechanics happen *instantaneously*? If yes, what are the implications on Causality?

A tough question indeed! There is a school of thought, under the heading 'objective collapse', that views *wavefunction collapse as a physical process*. Of course, that becomes a thorny concept. Technically, when we look at the equations themselves, 'collapse' quite literally means taking the entire Universe, its Present, its Future, and its Past included, throwing it away, replacing it with a different Universe where the original wavefunction is replaced by a wavefunction representing the collapsed eigenstate. So, it's more than instantaneous: it is *retroactive*! Of course, people advocating 'objective collapse' know this very well, so, they have proposed various subtler mechanisms that avoid this extreme interpretation.

But in mainstream interpretations of Quantum Mechanics, wavefunction collapse *is not* viewed as a physical process. The interaction between a *quantum* system and a *classical* 'instrument' is necessarily an idealized model since no instrument is truly classical: a measuring apparatus, a video camera, a cat, even a human consists of a finite number of quantum particles after all.

So, maybe wavefunction collapse is just a piece of fiction that arises because we approximate that camera, cat, or human by an *idealized*, *classical* representation.

All this takes us to the core of Quantum Physics: namely that the theory is inherently non-local. Non-local, in this context, means that the physical system is governed, in part, by variables that cannot be nailed down to any specific point in Space and Time. These variables, e.g., some conserved quantities, are kind of ephemeral, representing the whole system, not any specific bits and parts of it at specific places and times.

This might indeed raise valid concerns about Causality! But this is where something almost miraculous occurs when we take Quantum Physics to the next level, *Relativistic Quantum Field Theory*. Even though the theory is fundamentally *non-local*, any faster-than-light, backward-in-time influences in the system are canceled out exactly, leaving us with a theory that is *manifestly non-local yet causal*. Take two correlated electrons a great distance apart. They cannot communicate. Individually, their behavior is *strictly random*. It's only *after we observe* them and bring the results together by *conventional* means or signals that we notice that they are correlated. No detectable influence passes between the electrons. One does not *cause* the other to behave in a certain way. The behavior of the two-electron system, however, is governed by those *non-local variables* that cannot be nailed down to either electron or any specific *location* or *time*.

757 -

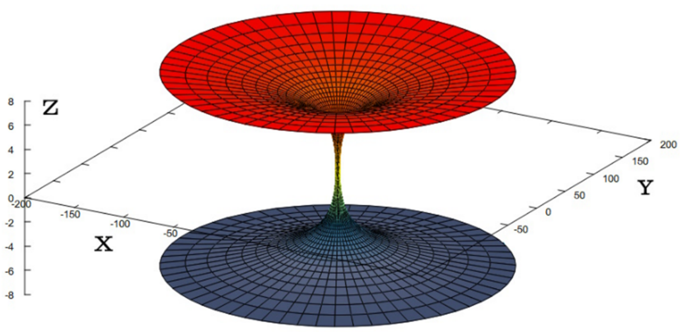
How does the Big Bang differ from a *white-hole*?

The Big Bang *may not* be different at all from a *white-hole*.

It is true, as it is often pointed out, that a white-hole singularity is a location in Space, whereas the Big Bang is a moment in Time. However, this distinction is valid only for observers who are outside the white-hole's event horizon. To those inside the event horizon, the singularity is, in fact, a 'naked' singularity in Time, in the Past. And this observer would in fact experience a Universe that appears to be governed by the same Friedmann Equations that describe the homogeneous, isotropic Big Bang Cosmology.

There is still another difference. Whereas inside the white-hole event-horizon, all world lines originate *at the singularity*, *outside* the event horizon there are world lines that have different origins or (depending on the nature of the surrounding Universe) may have existed *forever*. In contrast, in a Big Bang Universe, only those worldlines that originate at the singularity exist, i.e., *there is no* '*outside*'.

But observationally, at least at present, we don't seem to have the means to distinguish the two. So, it is conceivable that our Big Bang Universe is, in fact, the interior of a white-hole *event horizon* in a larger Universe.



Black\white-hole catenoid wormhole structure of SpaceTime

758 -

Why does Gravity travel at the speed of light? Is Gravity a wave like light? How is it similar?

Gravity does not travel at the speed of light just like Electromagnetism does not travel at the speed of light.
Changes in the Gravitational Field, far from sources, traveling in the Vacuum, do travel at the Vacuum speed of light as Gravitational waves. This is just like changes in the Electromagnetic Field, far from sources, traveling in the Vacuum, do travel at the Vacuum speed of light as Electromagnetic waves.
If changes in these fields traveled slower than the Vacuum speed of light, we'd be able to catch up with them in principle. So, we must ask ourselves what we'd see if we traveled alongside with them. Relative to us, these changes would now be at rest. Yet they'd still have to have Energy, i.e., Mass. In short, we'd see a static Gravitational Field (or Electrostatic Field) with Mass.
Therefore, the statement that changes in the Gravitational (or Electromagnetic) Field travel at the Vacuum speed of light is equivalent to stating that these fields are *massless*. As it turns out, this is quite important to the way these fields work. If they were massive, they would have a *finite* range: the range would be inversely proportional to Mass. Being massless, the range of these fields is *infinite*. Yes, Gravity gets *weaker* over distance, but even over cosmological distances, it is still there, affecting cosmic expansion, for instance.
In contrast, an example for a massive field is the Weak Nuclear Interaction: it really isn't weak (at the subatomic scale, it is just as powerful as Electromagnetism) but because this field is very massive, its range is extremely short.

759 -

Is SpaceTime the quantum field associated to the *graviton*? Can SpaceTime even be considered a quantum field whatsoever? If so, does this not violate the idea that quantum fields exist in Space and Time? [see Issue # 314]

No, not SpaceTime. Rather, a specific element of the 'SpaceTime metric manifold', notably the *metric* itself, otherwise known as the *Gravitational Field*.
Nowadays, it is fashionable to describe Einstein's work on Gravitation as a geometrization of Gravity. It is important to remember, though, that Einstein himself was not particularly fond of this geometrization, that he considered it little more than a useful mental aid, and he never stopped thinking of Gravity as a proper force, an interaction between material bodies, also as a field that, just like the Electromagnetic Field, carries Energy and Momentum at a *finite* speed, e.g., in the form of Gravitational Radiation.
As we now have experimental evidence (with numerous LIGO observations) that this is indeed the case, it should be stressed that the geometric interpretation notwithstanding Gravity is, first and foremost, *a physical field mediating a force*.
This physical field is mathematically represented by the *SpaceTime metric*. We do not know how to turn the Classical Theory of this *physical field*, Einstein's Theory, into a proper Quantum Field Theory. However, we do know (more or less) what this theory would look like in the *weak field*, perturbative' limit. In this limit, the Gravitational Field, i.e., the metric, would be 'quantized' in the form of *elementary oscillators* that, in turn, are characterized by the usual *annihilation* and *creation* operators, *creating*, and *destroying units of Energy*, *field quanta*. We call these field quanta *gravitons*.
So, gravitons would be the *elementary excitations* of the Gravitational Field, also known as the *metrical field of SpaceTime*. This field exists in SpaceTime, just like all other quantum fields. It is not SpaceTime: it is a property of the SpaceTime manifold, the property that determines physically measured *distances* and *intervals* of Time.
Of course, in the absence of a complete Quantum Theory of Gravity, it is eminently possible that perhaps Gravity is subject to different rules and may not be a quantum theory at all. Nobody knows yet.

760 -

If the Universe follows Causality, how can there be *free will*?

Let's ask ourselves what free will is through an example. Say, we come up on a set of traffic lights at an intersection. It is an old set of traffic lights, governed by a simple electromechanical timer. Does it have free will? Of course not. It's just a glorified conventional alarm-clock.
So, let's say that at the next intersection, we will find a newer set of traffic lights. It is controlled by more sophisticated electronics that considers the time of day and even sensors in the road, determining, e.g., whether to allow left turns during a cycle. Does this set of lights have free will? We would say: no, it doesn't.
But then, at the next intersection, we come across a still newer set of lights. It has sophisticated control electronics that is networked. It coordinates its behavior with other traffic lights in the neighborhood. It is connected to a network of sensors and cameras that are used to estimate traffic flow. It even recognizes emergency vehicles, adjusting its behavior. Moreover, let's say, it has a simple learning capability, so that it can adaptively adjust its cycle to minimize wait-times

and maximize vehicle-throughput, again in coordination with other traffic lights. Does this set of lights have free will? Again, we would say: no, it doesn't.
So, let's take one step further. The next set of lights is straight from the Future. It is governed by artificial *intelligence* (AI). AI annoyed and bored like Marvin the Paranoid Android from the Hitchhiker's Guide to the Galaxy, nonetheless, performs its job admirably. He may be using his spare brain capacity to study the limits of Quantum Theory or analyze 19th century French literature, but ultimately, he is a *deterministic machine*: every bit of his programming, every logic gate in its considerable brain follows a predetermined pattern, even if the overall complexity makes the machine's behavior practically *unpredictable*. Does this machine have free will, in anybody's opinion? Because if we say it doesn't, we must also ask: what exactly does it take for an entity to have free will? Is it the lack of deterministic behavior?
So then, going back to the first set of traffic lights, with its simple electromechanical timer: if we added to this setup a random number generator that causes the traffic lights to behave unpredictably, would we say that it suddenly acquired free will? Now, that would be silly, wouldn't it. But doesn't it demonstrate that it is not the lack of determinism, not the absence of Causality, that is the secret of free will?
In our minds, that AI machine that decided to spend its spare time reading Victor Hugo absolutely qualifies as an entity with free will. Sure, it is deterministic. Every one of its components behaves in a deterministic fashion. But the whole system is so complex, its behavior cannot be predicted: not unless we build an identical copy or simulation, and subject it to the exact same set of stimuli, so that it forms the same memories and responds in the same manner as the original.
But who says that if we had the means to build an identical copy or simulation of us and subjected it to the exact same stimuli that form our life experience, it would not develop the exact same identity that we call *our own*? Yet we presume we believe we have free will (we certainly believe that we have free will ourselves).
The bottom line: *we think it is wrong to present free will as an opposite of determinism*: *the opposite of determinism is randomness*. A sophisticated machine may, in turn, respond to stimuli in novel ways based on its *internal* state (*accumulated experience*), demonstrating every apparent aspect of what we call free will, even though ultimately, its behavior is *fully deterministic*.

761 -

Do *gravitational waves* pass directly through adjacent masses without interaction with each mass? For example, do the wave diffract?

Gravitational waves (please, allow for that bit of pedantry: 'gravitational waves', not 'gravity waves', the latter referring, e.g., to the surface waves of the ocean) do indeed pass through most items with *minimal interaction*. That is because Gravity is extremely *weak*, and thus any interaction between a gravitational wave and Matter is going to be minimal, unless the Matter is extremely *dense*.
But there is interaction. A passing gravitational wave causes Matter to stretch in one direction and compress in a perpendicular direction, all the while *preserving volume*. This introduces a tiny amount of *tidal stress*, i.e., the gravitational wave transfers a teeny amount of its Energy to Matter.
This is precisely why we can detect gravitational waves: the LIGO detectors measure this tiny deformation that occurs as gravitational waves from very distant sources pass through the Earth.

762 -

Lay articles on the Higgs Boson suggest that Particle Physics is understood very well. However, papers about even basic reactions, like at-rest proton-antiproton reaction\annihilation seem murky. Are the gaps in knowledge of Particle Physics trivial?

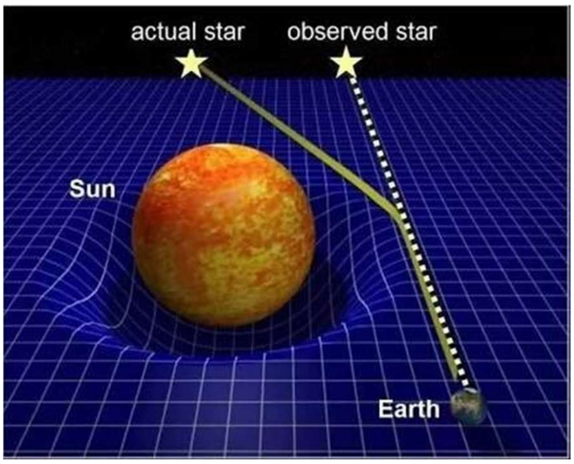
As a general comment, anybody should be advised against confusing *basic principles* vs. *complexity*.
By way of example, we understand the basic principles of Chemistry very well. Does this mean that we know everything about, say, complex organic reactions inside living tissue? Of course not. The building blocks may be simple, but the constructs in which they appear can become incredibly complicated. In principle it might be possible to deduce all the rules but, in practice, it may be an impossible task: consequently, many of the rules that we use to describe Organic Chemistry are empirical, not deduced from first principles, just based on observation.
Particle Physics is a little like that. The Standard Model of Particle Physics is indeed well understood. It is not a flawless model, so, pretty much everyone expects it will improve (and it doesn't just mean that it presently doesn't incorporate Gravity; there are other mysteries as well). At the same time, it is an incredibly powerful model that has successfully predicted the existence of several particles and is able to represent subatomic interactions with exquisite precision.
Yet, when it comes to modeling the structures that form from those subatomic particles, it's again a bit like Chemistry: in principle, everything follows from the fundamental theory, but in practice, modeling complex systems becomes incredibly difficult (certain properties of the Strong Interaction make this statement particularly true when it comes to things like protons and neutrons and their internal quark-structure).

So, no, the gaps are not trivial and might even hint at new Physics (which would be lovely, by the way). However, the basic principles of fundamental theory are indeed understood very well. The point is that *these two statements are not in contradiction*: We can have a well-understood fundamental theory yet huge gaps in our knowledge of the complex structures that these building blocks can produce.

763 -

(a contribution by Thomas Kolb, astrophysicist)

Einstein *falsely* claimed Gravity can bend and deform Space. However, this is not true, because Space is not a physical thing, but a mathematical artifact, meaning there is nothing to be bend\deformed, which is why warp drives are impossible, right?
Quite the contrary. Einstein himself suggested several experiments to validate or disprove his theory. One was to observe a star adjacent to the Sun's disc during a total solar eclipse. He suggested that the star would appear displaced as the photons from the star would be moving in a *slightly curved* trajectory as they pass beside the Sun. Since photons have no Mass, the Sun's Gravity could not directly affect the photons. So, if the photons in fact would bend, it could only be because of SpaceTime being warped near massive objects.



The experiment was first successfully performed by Eddington in 1919, and has since then been repeated countless of times, both with visible light and other forms of Electromagnetic Radiation. The photons indeed are affected, and to the very exact amount that was calculated beforehand. To be fair, Newton's Laws can actually be used to explain light bending to some extent, but not nearly as much as what is actually observed. There are no other valid explanations to this phenomenon.
Another effect of SpaceTime warping in the vicinity of large Masses is Time dilation. It is not only tested in lab experiments but has been proved countless of times with both aircraft and Spaceships. Time dilation is cause by both, speed as well as Gravity, and is today a part of every single GPS device, including our humble smartphones. If the SpaceTime warping effect caused by Earth's Mass would not be compensated for, the GPS system would not be able to provide a precise location, but would be many, many miles off. The precision of GPS (like other similar positioning systems based on satellite triangulation, such as GLONASS or BeiDou), itself is a living proof of SpaceTime warping.

764 -

What do astrophysicists believe is expanding when they assert in the consensus Cosmological Model that the Universe is expanding at an increasing rate?

The technical answer is that the *Matter Density* of the Universe is decreasing over Time. Locally, this manifests itself by things such as galaxies and clusters of galaxies *flying away from each other*, with the average distance between them increasing over Time.
Looking at greater distances (let's remember, it takes time for light to arrive from a great distance, so, we're really seeing things as they happened in the past), we notice that things were flying apart a little slower than they are today. As a matter of fact, the rate at which things fly apart has been *increasing* for the past 4 or 5 billion years.
We can work this information (observational data) on Einstein's Field Equations for Gravitation by assuming that, in addition to Matter with *negligible* Pressure, there is also an extra-term that has large *negative* effective Pressure. This 'Cosmological Constant', Λ, or '*Dark Energy*', can account for the observed rate-of-change, but the nature of this stuff remains elusive: we have not detected 'Dark Energy' by direct means, and we can only *speculate* about its nature.

And it is possible (not easy, but possible) to construct alternate theories of Gravitation that do away with the need for ‘Dark Energy’ and still account for these observations. Such theories, however, often come with their own baggage. Ultimately, what will help decide is not idle speculation (no matter how well-informed) but hard data from Future, more innovative astronomical observations (e.g., gravitational wave observations, especially *combined* with observations in the optical, radio, etc., bands of the Electromagnetic Spectrum, already helped a great deal at least by excluding some theories by falsifying their predictions).

765 -

The answered Issues 739 and 741 about SpaceTime Expansion – and if we are expanding along with it – makes sense if the expansion is constant, but how does it fit with the observed *expansion Acceleration*. Would it perhaps be due to more dimensions in play?

In the Standard Cosmological Model, accelerating expansion has a very simple cause: Gravity. But Gravity is supposed to be *attractive*, slowing things down rather than speeding them up, pushing them away from each other. This is what happens … insofar as *non-relativistic* Matter is concerned. Non-relativistic Matter is Matter for which $\mathsf{P} \ll c^2\rho$, i.e., Pressure is much, much less than *Energy Density*.
But for *relativistic* Matter, when the magnitude of Pressure is comparable to that of Energy Density, things change. In particular, the *Poisson*’*s Equation for Gravitation*, which appears in textbooks as $\nabla^2\phi_g = 4\pi G\rho_M$ and tells us how to compute the Gravitational Potential ϕ_g in the presence of Matter characterized by ρ_M, gets modified. It becomes

$$\nabla^2\phi_g = 4\pi G(\rho_M + 3c - 2\mathsf{P}).$$

For Dark Energy, $\mathsf{P} = -c^2\rho_M$, therefore, $\rho_M + 3c - 2\mathsf{P} \equiv -2\rho_M$. The sign changes. Gravitation becomes *repulsive*.
This is why, *on the scale of galaxy clusters and beyond*, *on scales where Dark Energy dominates over Matter*, *repulsion wins over attraction*, *accelerating the rate at which things fly away from each other*.

766 -

Special Relativity says that non inertial observers measure apparent velocities *greater* than the speed of light. Does this mean that any observer who accepts inertial forces must measure at least one *superluminal* speed?

It’s a tad more nuanced like that. Special Relativity is about inertial reference frames, and the idea that inertial reference frames are related to one another by *Lorentz-Poincaré transformations*. On the surface of it, this might preclude making any statements in Special Relativity about accelerating observers.
We can, of course, describe accelerating trajectories in the context of Special Relativity. So it is possible to assign an ‘instantaneous’ coordinate reference frame to an accelerating observer at any point alongside that observer’s trajectory. But these instantaneous reference frames do not form a consistent global coordinate system that covers the entirety of SpaceTime.
And indeed, at this point, despite the absence of Gravity, it is simply more convenient to invoke the mathematical machinery of General Relativity, namely, the Riemannian Geometry. We soon find that the reference frame of the accelerating observer actually has an *effective horizon* (a *Rindler horizon*) that vanishes at the moment they stop accelerating (the meaning of this horizon is simple: given an observer moving away from you at uniform acceleration, there is a final moment in Time when we can still shine a beam of light in direction so that it catches up with them at some point in the Future. Any beams of light emitted after this moment will *never* catch that observer unless they stop accelerating).
So, arguably, we could say that from this observer’s perspective, things behind this horizon are ‘faster than light’ or whatever. It shouldn’t be used the word ‘apparent’ though because the whole point of a horizon is that the observer doesn’t see what’s behind the horizon; so, it’s not ‘apparent’.
And these effective horizons vanish the moment the observer stops accelerating. Once they are back to inertial motion, their reference frame covers the entirety of SpaceTime and *nothing* (no material object or particle) in that SpaceTime has a superluminal speed.

767 -

How could we defend the statement: ‘Black-holes *do not* in fact evaporate’?

We can think of at least two ways right off the top of our heads:

1. Hawking Radiation is *purely hypothetical*. Whether or not it really exists, we don’t know. The arguments behind it are reasonable, but in the absence of a Quantum Theory of Gravity, we cannot be sure;
2. the typical temperature of an astrophysical black-hole is measured in nK (nano-kelvins) or below. Compare this to the ~ 2.726 K temperature of the Cosmic Microwave Background: it means that a black-hole receives *more thermal Energy from the Cosmos than it radiates*. Thus, at present, no black-hole can possibly be evaporating. This will continue unless the Cosmos expands rapidly enough that eventually, the Microwave Background temperature *falls below the black-hole temperature*.

768 -

Why does Gravity tend to infinity on the *Planck-length scale*?

Gravity does not tend to be infinite on the Planck-length scale. However, at the Planck scale, Gravity becomes strong enough to compete with the other forces. Therefore, its quantum nature cannot be ignored anymore, as we can safely ignore it when Gravity is relatively weak, treating it as a ‘classical’ background without worrying about its quantum properties.
The reason why this is a problem is that we do not have a sensible, viable Quantum Theory of Gravity. Therefore, we don’t really know at all what is happening at the Planck scale, where Gravity becomes a *significant* competitor to the other quantum fields. We certainly have no reason to believe that it would ‘tend to infinity’.

769 -

If *superluminal speed* were possible and we can climb out of blackhole beyond the horizon, could we theoretically travel ‘back’ in Time from $t = 0$, i.e., when we started falling in? If so, would there be a limit as to how far ‘back in Time’ we can go?

Let’s look at it from an outside observer’s O perspective, keeping in mind that from the outside, the event horizon is in the infinite Future: we travel to the black-hole, cross the horizon, turn on our magical *superluminal engine*, cross the horizon backwards and emerge, and then turn off our superluminal engine, resuming normal existence outside.
O, looking from the outside, sees the following: the original ‘we’, falling into the black-hole. Although we pretty much vanish from sight due to exponential redshift and Time Dilation, in principle, we could continue to observe us forever, nearly frozen, ever closer to, but never quite reaching, the horizon that has not yet formed.
Out of the blue, suddenly two of us pop into existence from nothing (this is the moment when we turned off our superluminal engine to resume normal life outside). One of us is a perfectly normal (but older) that just finished his journey. The other of us is a negative Energy, backwards-in-Time version of us operating a superluminal engine. From O’s perspective, this ‘we’ will also fall into the black-hole, also vanishing from sight, but still there, in principle observable, with our superluminal engine running, with our clocks all running backwards from O‘s perspective, but *ever slower*, *never reaching the horizon that has yet to form*.
So, from the moment when our forward-in-Time and backward-in-Time copies pop into existence, there will be 3 of us present: the original ‘we’ (yet to fall into the black-hole), the negative-Energy, backwards-in-Time ‘we’ that emerged from the black-hole (but from O’s perspective, actually falling into the black-hole with our clocks ticking backwards) and the final ‘we’, resuming normal life after we turned off our superluminal engine.
Of course, it all presumes the existence of superluminal travel, with all the nasty implications including *unstable* physical systems, *violations of Causality*, grandfather’s paradoxes, and all that.

770 -

What if there is ‘negative’ Gravity between galaxies that explains Universe expansion?

‘Negative’ or ‘repulsive’ Gravity *is not required* to make sense of the expansion. Ordinary Newtonian Gravity will suffice. When we conceive of a Universe that is uniformly filled with Matter, *it cannot be static*. Attractive Gravity would cause this Universe to collapse, its Density increasing over Time. If, instead, we conceive of a Universe that is expanding (i.e., things are flying away from each other), Gravity can slow them down, but if they have been flying away fast enough to begin with, *Gravity will never stop them*.
This basically explains most of cosmic expansion and as I said, although the equations are usually derived from General

Relativity, the basic equations are derivable (with some caveats) from pure Newtonian Physics.
Having said that, we know (based on the available astronomical evidence) that not only are things flying apart, but distant things *are also accelerating away from each other*. This can be explained if we introduce, into the system of equations, an additional term, which may represent *Einstein's Cosmological Constant* Λ or, alternatively, an unknown kind of medium that we dub *Dark Energy*.
But to stress this point, 'Dark Energy' is not required for there to be expansion, only for the expansion to accelerate over Time. There can be expansion even without the repulsive Gravity of 'Dark Energy'; attractive Gravity would be slowing it down, of course. It is the fact that we observe the opposite, that the expansion *appears to be speeding up*, that leads us *to assume the existence of Dark Energy*.

771 -

According to astronomers, the most distant stars and galaxies are accelerating away from us. Wouldn't that mean the speed of these objects relative to us exceed the speed of light given enough time?

Indeed, it does, in a manner of speaking, but this is where things get tricky.
First … how do you measure speed? Why, easy to tell us, it's Distance divided by Time. But … how do we measure distance over cosmological scales?
Well, as it turns out, there are several different *definitions of Distance*: say, *light-travel Distance*, *angular-diameter Distance*, *luminosity Distance*, *co-moving Distance*. That's just a few examples. Each of these definitions gives a different definition of speed. But most importantly, none of these definitions amount to we consider a *proper*' *Distance* measurement in our everyday experience, i.e., someone taking a measuring tape from object A to object B.
But let's put that aside. Let's look at a distant object accelerating away from us. Let's say that we live for a very long time, billions of years, and we have instruments that are sensitive enough to observe distant objects even when their light undergoes *extreme* Cosmological Redshift.
So, let's pick a distant galaxy and watch it. Over time, it will *appear smaller* (its angular diameter Distance increases). It will appear dimmer (its *luminosity-distance increases*). And it will appear … slower, because of Special Relativistic and Gravitational Time Dilation, which also results in the redshift of its light.
And that really comes to the point: no matter how long we keep observing that galaxy, it will not appear to exceed a certain distance. Its light increasingly redshifted, its motion increasingly Time dilated as viewed by us, it will eventually appear pretty much 'frozen' (and also quite invisible due to the aforementioned redshift) but we never, ever, see it achieve *superluminal* speeds. That moment remains forever in our Future.
Incidentally, this is very similar to what happens when something falls into a black-hole. We know that when an object falls into a black-hole, its velocity reaches the Vacuum speed of light at the horizon. Or does it? Because, if we were to watch such an object, we would never actually see it reach the horizon. That remains forever in our Future. Extreme Time Dilation will *slow down* the movie, so to speak, to the extent that that final moment never, ever comes.
And this is how General Relativity can have its cake, and eat it, too: distant things are indeed not constrained in their motion relative to one another so long as neither thing exceeds the Vacuum speed of light at its own Location. However, in most (all?) mathematically consistent SpaceTimes, an observer *never* gets to see distant things move truly faster than light (or backwards in Time, which really is the same thing); those things *remain forever hidden behind event horizons*, such as the observer's Cosmological event-horizon or a black-hole's Gravitational event-horizon.

772 -

If a wave function collapses by being observed and observers in different inertial systems have different 'nows', does that mean that the wave function collapses at different times, splits into different wave functions à-la 'many worlds'?

As others pointed out, wavefunction collapse is, first and foremost, a mathematical abstraction, not a physical process. If it were a physical process, it would be even weirder. Rather than subdividing SpaceTime with an arbitrarily chosen hypersurface called 'now' into a 'before observation' and an 'after observation' half, connected by the non-unitary transformation of the 'collapse', wavefunction collapse basically implies throwing away the entire Universe, replacing it with a different one (Past, Present, and Future included) containing the collapsed wavefunction instead of the original.
The mathematical fiction of wavefunction collapse was 'invented' to deal with the inconvenient fact that otherwise, we'd have to accept what the equations tell us, namely that Quantum Mechanics is non-local (as per Bell's Theorem) which means that there will be mutual correlations and constraints imposed upon events by other events, regardless of how far they are from one another in Space or Time. But when we think about wavefunction collapse, what can we say … talks about a solution that is worse than the problem itself!
That does not deter some folks from pursuing variations of 'objective collapse', trying to explain wavefunction collapse as a physical process (e.g., through interactions with the Gravitational Field) but it's still hard to find these schools of thought convincing.

At any rate, collapse or not, it's also important to note that 'observer' in this case does not mean a person with eyeballs or even a purposefully designed instrument. Whenever a quantum system interacts with something 'classical', it is constrained, confined to an 'eigenstate', which is exactly what we mean by *wavefunction collapse*. Of course, one might feel compelled to note that truly 'classical' systems don't really exist: just because a brick consists of a very large number of *uncorrelated quantum particles*, so many in fact that any observable quantum behavior is nearly completely *averaged out*, ultimately it is still a quantum system made up of a finite number of quantum degrees of freedom.
Yet, in the end, the observations that we make and the models we build are based on 'classical' observables, which means that we observe the *averaged behavior* of the particles in that brick, *not their individual quantum states*. Those states remain *inaccessible* to us, because of we, too, are part of this Universe. We do not have the option to 'step outside', stop the simulation, so to speak, and inspect all variables without interacting with them.

773 -

Is it possible we already are inside a black-hole? How would we know we aren't?

The interior of a *Schwarzschild black-hole* is a collapsing Universe characterized by a *future singularity*. The interior of a *spinning* (Kerr) black-hole is more complex, but the same basic idea prevails: It is still collapsing (though Kerr argues that rotation might *counteract* collapse, avoiding the final singularity). If we looked around, we'd see distant things *approaching* us, with the *associated blueshift*.
Instead, we see the exact opposite: things are *flying away* from us. As far as we can tell, this Universe is characterized by a past singularity (or, at the very least, a past epoch when it was very *hot* and very *dense*). In other words, the exact *opposite* of what we might expect inside a black-hole.
It is, perhaps, conceivable that we live in a *Time-reversed* black-hole, i.e., in a *white-hole*. Or that we live inside a black-hole so large, with an inhomogeneous interior, that there's room inside it for something the size of our visible Universe that is uniformly expanding, even though on even larger scales, the interior of the black-hole is still collapsing, our region is just a temporary glitch, deviation from the average.
But how likely is this? Well, never say never about things that we cannot ever verify observationally, but I'd say it's about as likely as the suggestion that our Universe is just a trinket hanging from a [Schrödinger] cat's collar. An idea one can never disprove, but one that still doesn't make a whole lot of sense.

774 -

What was the reason scientists had difficulty calculating the value of the speed of light, c? Why didn't they use the statement, 'The distance traveled by light in 1 second' as the definition?

Calculating the speed of light is not possible. Or, perhaps, we should say, it is trivially easy: in the so-called Natural Units of Measurement, it is 1. There, no calculation can be simpler than this.
But what does it mean, one may ask? Good question. Without going through the historical chain of events, let's first make an important statement: in the long run, all measurements boil down to two possibilities: *counting* and *comparing* things.
With that in mind, let's first look at the modern definition of the *second*. Behind this definition there is the observation that certain things, such as Cs^{133} atoms, 'tick' like a clock, and do so very reliably, i.e., that two Cs^{133} atoms always tick in sync, and no matter what we do to an Cs^{133} atom, if we don't destroy it, it will continue to tick at the same rate. So, Cs^{133} atoms are *reliable clocks*.
Now, let's pick a number. For historical reasons, let's pick 9192631770. This many Cs^{133} ticks we call the '*second*'. There, *we can count now*.
But we also want to *measure lengths and compare them against reference lengths*. To measure Length, we first invoke another observation: that the length traveled by a ray of light in the Vacuum over a given number of Cs^{133} ticks is always the same, *for all observers*. This allows us to define another standard. Again, for largely historical reasons, we define the *length* that light travels the '*meter*' in $(1/299792458)^{\mathrm{th}}$ of $1\,\mathrm{second}$). Therefore, the speed of light is defined as $1/299792458\ \mathrm{m/s}$ *exactly* in these *chosen* units. Any other length is expressed in terms of this one.
So, we don't measure the Length traveled by a ray of light; we *measure the ratio between this length and other lengths*. Which we can always interpret not as a measurement of c but of that other thing *in terms of the speed of light*.
Mass is defined similarly, by noting that there is a quantity, $\mathit{Action}\,(:=\mathit{Energy}\cdot\mathit{Time})$, given in an *elementary unit*, h, that is the *same for all observers*. h is *Planck's Constant*, so, the kilogram, *defined* in terms of this constant, is $1\,\mathrm{kg}:=(6.62607015)^{-1}\cdot 10^{34}\,\mathrm{m}^{-2}\,\mathrm{s}$. Again, the specific number comes mainly from *cultural\historical* reasons. But with this definition at hand, we can compare the resulting unit of *Mass* vs. other measurements and obtain *ratios*.

775 -

Could a black-hole be massive enough for something to be inside the *Schwarzschild Radius* of a black-hole while being out of range of gravitational waves of the singularity because of Universe expansion?

There are no 'gravitational waves of the singularity'. The Schwarzschild singularity is a *future moment* in Time for *infalling* observers. Once we cross the horizon, it is unavoidable, the same way we cannot avoid the moment of 2 PM next Tuesday. Whatever we do, wherever we go, that moment will be in our future and we will reach it in a *finite* amount of Time as measured by our own clock. The difference of course is that 2 PM next Tuesday won't kill us; the singularity (when the collapse of the interior of an event horizon comes to an end) *does*, instead.
Also do not misunderstand the business of *expansion*. All too often, it is popularized as 'Space' expanding. No. Stuff are flying apart. Unless they stopped flying apart. For instance, stuff in the Milky Way galaxy stopped flying apart billions of years ago and instead formed a *gravitationally bound structure*. Similarly, stuff in the solar system, in the Sun, in the Earth, in our own body stopped flying apart, and are held together by *gravitational*, *electromagnetic*, and *nuclear* forces.
Stuff that forms a black-hole similarly stopped flying apart, otherwise it'd not be forming a black-hole, in the first place. The interior of the event horizon is, in fact, a SpaceTime that has the opposite properties compared to our large scale Universe: instead of being in the process of expansion with a singularity in the Past, it is in the process of collapse with a singularity in the Future. And no, we cannot escape our fate although if the black-hole is *rotating* or it is *electrically charged*, things get a tad more complicated. But, even in those cases, tides will kill us long before we get a chance to find out if the final singularity is unavoidable or not.

776 -

What will happen if a black -hole and a white-hole collide? As we all know that black -hole pulls and white-hole push. One absorbs Energy then another release, in immense amount.

Keeping in mind that a white-hole is a *mathematical abstraction*, a Time-reversed version of the Schwarzschild (or Kerr) solution, characterized by an outward-pointing event horizon in the infinite Past …
Nothing can fall into a white-hole. This is one of the paradoxical characteristics of a Time-reversed solution: worldlines may be anchored at the event horizon in the infinite Past, but there's no event horizon in the Future of any worldline. An object approaching the white-hole would observe the entire future history of the white-hole, including its complete dissolution (in a Time-reversed version of a black-hole's accretion) before reaching the horizon. The horizon won't be there.
On the other hand, we'd expect a white-hole *as a whole* can, in fact, be swallowed by a black-hole (so long as we ignore things like *Hawking Evaporation*).
Of course, these are merely speculative, qualitative statements. The only 'proper' answer to this question would be an analytic or numerical model of this scenario, investigating in detail the precise predictions of Einstein's Field Equations using suitable set of initial conditions. That is (a lot) harder than it sounds.

777 -

Since we know that Energy (and therefore Mass) is made up of quanta, and that we can't measure anything under Planck's distance, why do we continue to use a continuous model (SpaceTime continuum) and not a discrete one?

No, we don't know that 'Energy is made up of quanta'. This is one of the most brutal misunderstandings of the Quantum Theory. Although, we'd admit, it is an understandable one, given the origins of the theory (as an explanation for the quantized Energy levels of atoms) and its very name.
No, what we do know is that *physical quantities behave as non-commuting operators of Mathematics*, not as numbers. That is the essence of the Quantum Theory.
This has consequences. For instance, when we apply the Quantum Theory to a *harmonic oscillator*, we find that the oscillator's Energy will indeed by quantized (made up of quanta). But in the meantime, the Kinetic Energy of a free electron, for instance, can be anything, even in the Quantum Theory. No discreteness there.
As for SpaceTime, it's the playground where Physics takes place. But SpaceTime itself has no independent existence. We cannot measure SpaceTime. It has no Energy or Momentum, no substance. It does not carry little markers by which to measure it. When we measure distances or time intervals, we measure those between things, or events that involve things. As such, quantizing SpaceTime doesn't make much sense either, not unless we fundamentally change the nature of SpaceTime in the theory first.

778 -

What did cosmologists think drove the expansion of the Universe before the discovery of *Dark Energy*?

Let's give a look at a simple equation:

$$H^2 = 8\pi G\rho_M/3\,.$$

In this equation, H is the *Hubble parameter* and ρ_M is the *Matter-density* of the Universe. The Hubble parameter can be $\lessgtr 0$ (its square, of course, is always > 0) but as long as is $\neq 0$, cannot be 0 either. This equation (the 1st of the so-called *Friedmann Equations*) alone guarantees that we live in either an *expanding* or a *collapsing* Universe. But now let's consider another equation:

$$\dot{H} = -4\pi G\rho_M\,.$$

This is the 2nd *Friedmann Equation* (in which, Pressure and Spatial Curvature have been omitted, for simplicity). In this equation, $\dot{H}$ is the rate of change of H over Time. And as we can see, it is < 0 if $\rho_M > 0$.

If the Universe is expanding, ρ_M decreases over Time, slowly approaching 0. When that happens, the Universe stops expanding, hence, $H = 0$.

The rate of change of H, $\dot{H}$, also becomes 0, so, the expansion stops forever.

But now, let's introduce *Dark Energy*, also known as the *Cosmological Constant* Λ, which changes the 1st Friedmann Equation to

$$H^2 = (8\pi G\rho_M + \Lambda)/3\,.$$

Therefore, when in the distant future, $\rho_M \to 0$, we have $H^2 \to \Lambda/3$, i.e., the Universe *will continue* to expand. And since the 2nd Friedmann Equation remains *unchanged*, then, $\dot{H} \to 0$. This means that the Hubble parameter becomes a *true constant*, guaranteeing a *constant rate of expansion for the rest of eternity*.

Constant, we ask? What about acceleration? Yes: a constant means that things at a given distance recede from us at the speed governed by H, but *things* twice as far recede at *twice* the rate. *Now, that is only possible if, over Time, something that is receding from us accelerates, so that by the time its distance from us doubles, its speed doubles as well.*

And that is what the Cosmological Constant, or Dark Energy, does: it is the secret to *accelerating expansion*. Without it, there would still be expansion, but its rate would be slowing down to 0, instead of some *constant* value $\neq 0$.

In case we're wondering, we didn't pull these equations randomly out of the hat. These are, in fact, the famous *Einstein Field Equations* in disguise, applied specifically to the case of a Cosmos that is *homogeneous* (same everywhere), *isotropic* (no preferred direction), *filled with pressureless Matter, and with no Spatial curvature. Nothing is* '*ad hoc*' *here*, *all this follows directly from the core principles of General Relativity*.

779 -

What is the value of the *repulsion force* between neutrons in a neutron-star in N/m² if we know that the distance between each neutron and another neutron in a nuclide is $\approx 10^{-15}$ m ?

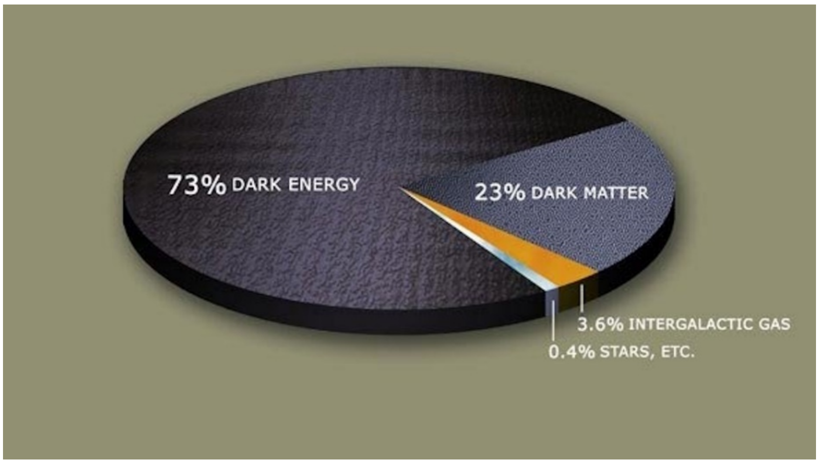
N/m² is Pa (Pascal), the standard SI units of Pressure (Force/(unit-area)).

The Pressure inside a neutron-star can be calculated easily, at least to the right order of magnitude, from its density without getting lost in the details of the physics of *degenerate neutron-Matter*, by assuming that the interior of the neutron-star is effectively a *relativistic gas*. For a relativistic gas, its pressure is $\mathsf{P} = (1/3)c^2\rho_M$, where ρ is its *Mass-density*. Given a typical neutron-star density of $10^{18}\ \mathrm{kg/m^3}$, the corresponding pressure is roughly $\mathsf{P} \approx 3\cdot 10^{34}$ Pa. In terms of more familiar units, this would be roughly $3\cdot 10^{29}$ times, 300 *octillion* – i.e., 10^{27} – times the average sea-level atmospheric pressure here on the Earth.

780 -

Since the distance between objects decreases the gravitational pull between them, is it possible that when this distance gets high enough it works in reverse, and this might explain why galaxies stay together, but repel each other?

An intriguing possibility but no. As far as we know, Gravity does not work this way. It does not become repulsive at large distances.
However, in the Standard Cosmological Model, in addition to normal Matter, we also have this uniformly distributed 'Dark Energy' thing. We don't know what it is. It could just be a constant of Nature (the Cosmological Constant). It could be the self-interaction Potential of a scalar field. It could just be the Vacuum Energy of quantum fields. We really don't know. But we do know that in all these cases, its Pressure is *negative* and *very large*: $\mathsf{P} = -c^2\rho_M$, where ρ_M is its Mass-density.
Why is this important? Because in Relativity Theory, the equations of Gravitation are indeed *modified*, though not exactly in the way this question suggests. Specifically, when we describe the Gravitational Potential $\phi_{\mathfrak{g}}$ using Poisson's equation, in the *non-relativistic* case we'd write $\nabla^2\phi_{\mathfrak{g}} = 4\pi G\rho_M$. But once General Relativity enters the picture, we must write $\nabla^2\phi_{\mathfrak{g}} = 4\pi G(\rho_M + 3c - 2\mathsf{P})$. In our case, $|\mathsf{P}| \le c^2\rho_M$, so we end up, for Dark Energy, with $-2\rho_M$ in the parenthesis on the right-hand side, getting a *repulsive* Dark Energy's contribution to Gravitation.
Usually this does not Matter because Dark Energy has the same, very small Energy-density everywhere, and usually, Matter dominates. But on very large scales, on the scale of galaxy clusters, the large, almost completely empty voids between individual galaxies are *dominated by Dark Energy*. So, the Gravitational Field of these large galaxy clusters, as felt by other, distant clusters, will be repulsive. And this causes the accelerating expansion of the Universe: things (clusters of galaxies) are pushed away from other things.



781 -

By what process can Mass be converted to Energy as per $E = mc^2$? Is it practical and can it cater to Energy needs replacing fossil fuels?

First, $E = mc^2$ *is not* about converting anything into anything, contrary to popular notions. It is simply a mathematical expression amounting to the statement that the *Inertia* (i.e., *Inertial Mass*) of a body is determined by its *Energy-content*. In fact, this statement (in the form of a question, answered affirmatively in the document) was the very title of Einstein's 1905 paper, in which this relationship was introduced.
Having said that, Energy (as far as we know) is *conserved*. So, if we extract Energy from a system by making the system do work, the system will have less Energy. This means it will have less Inertia: Its Mass *decreases*.
This applies always, in any reaction that removes (or for that Matter, adds) Energy to a system. We heat up a brick? It gets ever so slightly heavier. We burn a quantity of hydrogen and oxygen, using allowing the heat to escape? The resulting combustion product, namely water, will weigh ever so slightly less than the fuel and oxidizer, combined.
Granted, in most everyday reactions, the change in Mass is so utterly small, we have no means to detect it even with our most sensitive instruments. But that doesn't mean it's not there.
In nuclear reactions, however, the change in Mass can become quite noticeable. Hence the common misunderstanding, associating $E = mc^2$ with *nuclear power*. It is not unique to nuclear power, but since nuclear power can yield up to 10^6 times, or more, Energy per-atom compared to chemical reactions, the Mass change is also more easily noticeable.

On a more extreme scale, we have particle accelerators in which fast-moving particles have Kinetic Energies far, far in excess of their internal Energy-content, i.e., their *inertial Mass*. When we smash these particles together, the excess Energy helps produce new particles, including some very heavy ones like, say, a Z^0 - *boson*, a *Higgs boson* or a *top-quark*. Such heavy particles have fleeting lifetimes as all that Energy-content that gives them their huge inertial Mass just ‘wants to get out’ and it does: the heavy particles rapidly decay into lighter ones, with the difference in Energy turning into motion, the Kinetic Energies of the decay products.

In contrast, ordinary Matter is quite *stable*, because there is no lower-Energy state to which it can transition. Therefore, the Energy-content associated with its inertial Mass is ‘locked in’, so to speak. And that’s a *good thing*, too, since otherwise all of us would be made of unstable Matter, ready to go up in some tremendous explosion with the right trigger event. It’s much preferable to remain in a reasonably stable form for the foreseeable future.

As to replacing fossil fuels … that’s a complex topic with many (often conflicting) answers, but it should be mentioned one rather important point that is often overlooked. Let’s think of solar Energy, which drives most of the biosphere and is also the source of the stored Energy in most fossil fuels. So, … are we getting Energy from the Sun? Pumping Energy into a system without taking it out would cause that system to warm up without limit. Fortunately, that is not what’s happening here. The Earth emits just as much Energy into deep Space in the form of *waste-heat* as it receives from the Sun (it may be doing this slightly less efficiently today than in the pre-industrial era, resulting in a warming of its surface that we experience as climate change, but overall, the books remain balanced).

The key is that for every photon of sunlight, the Earth emits about 20 photons, mostly in the *thermal infrared domain*. This represents a tremendous *Entropy change*. We get low-entropy solar radiation and emit *high-Entropy waste-heat*. This difference in Entropy is what drives the biosphere and, by extension, us.

So, what we really need is not a limitless source of Energy. What we need is a *high quality*, *low-Entropy* source of Energy, balanced by a sink (such as the cold depths of Space) that can absorb *low-quality*, *high-Entropy* waste-heat. Finding a sustainable answer to this question is not easy, indeed, but it’s doubtful that Mass-Energy conversion would offer the right answer, even if it were possible.

782 -

What about Kerr’s recent paper that *rotating* black-holes may not have a singularity?

Roy P. Kerr (1934-) is one of the living legends of Relativity Theory. His *axi-symmetric* solution, published in the early 1960’s, was the first new solution in nearly half a century after K. Schwarzschild’s solution for a *spherically symmetric*, *static*, Vacuum SpaceTime (e.g., see [41], PP. 240-241).

Kerr now argues that the singularity theorems are nonsense, and that his axis-symmetric solution actually hides some non-singular configuration of Matter therein.

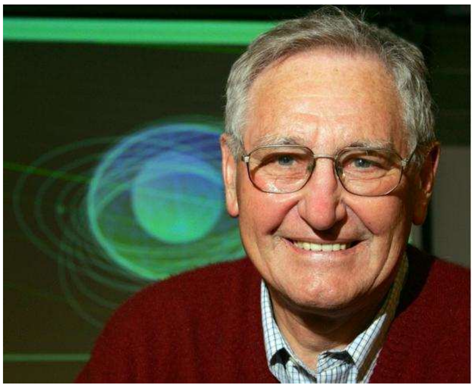
Kerr’s paper is well-written but a bit strange. It takes argument with ‘singularity believers’ using unfortunate language that almost sounds like pseudo-science. There are also some weird factual errors. For instance, the paper asserts that black-holes ‘as large as 10^{11} solar masses have been observed by the James Webb Telescope’ (not even close). Or it describes the famous Oppenheimer-Snyder paper of 1939 as “having used linear, 19th century ideas on how Matter behaves under *extreme pressures*” (actually, Oppenheimer and Snyder discuss the collapse of a ‘dust’ solution with *negligible pressure* using the tools of general Relativity with rigor). Kerr further criticizes the Oppenheimer-Snyder paper as attempting ‘to ‘prove’ that the ensuing metric is still singular’, even though that paper says nothing about the metric’s singularity, only that the collapsing star will eventually reach its gravitational radius (i.e., the Schwarzschild Radius). Nonetheless, later Kerr doubles down by writing that “Oppenheimer and Snyder proved that the metric collapses to a point”, whereas the closest the actual Oppenheimer-Snyder paper comes to this is describing collapsing stars as stars ‘which cannot end in a stable stationary state’.

Never mind, let’s ignore these issues as they may not be relevant to Kerr’s reasoning after all. His main argument is basically that Penrose and Hawking deduced the necessary presence of singularities from the existence of light rays of finite affine length; i.e., light rays that, in some sense, terminate (presumably at the singularity). Kerr says that no, the ring singularity inside a Kerr black-hole, for instance, may just be an *idealized substitute for a rotating neutron star*.

Now, Kerr has an interesting point here. Take the Schwarzschild metric. It is a Vacuum solution of General Relativity, but it also accurately describes the Gravitational Field outside any static, spherically symmetric distribution of Matter in the Vacuum, and we have *stable interior* Schwarzschild solutions that could describe a physical object, e.g., a star. So, a Schwarzschild solution *does not* imply an event horizon or a singularity: they can be *replaced* by an extended, *gravitating body* that has no singularities at all, so long as the radius of the body is greater than the Schwarzschild radius associated with its Mass. The Gravitational Field of the Earth is also well described by Schwarzschild *outside* the Earth.

Of course, real, actual astrophysical objects are *spinning*. And quite surprisingly, we do not have *stable* ‘interior’ solutions that match the *Kerr metric* on their outside boundary. The closest to such a solution is perhaps the one described in a 2017 paper, which introduces a stable interior solution which *postulates* an *anisotropic* (*direction-dependent*) *pressure* medium. This is not as crazy as it sounds (meta-materials exist with anisotropic pressure) but not quite as elegant as an isotropic perfect-fluid solution would be. Published isotropic solutions all appear to be *approximate*, not

exact solutions of the Einstein's Field Equations.
But this is not the point that Kerr argues. Rather, in his paper he speculates about the possibility that inside a Kerr black-hole, inside its interior *Cauchy horizon* (the Kerr solution is famous for its two horizons, an outer event horizon similar to Schwarzschild's, and an *inner* horizon that separates an interior region in which *Causality breaks down* and closed Time-like curves are possible) perhaps there is a spinning object after all, and that the famous *ring singularity* is merely a mathematical placeholder with no more physical meaning than the singular point at $r = 0$ in the case of *Newtonian Gravity* with the Potential $\phi_g = -GM/r$.
Is this possible? Probably not, and here is why. Between the two horizons of a Kerr black-hole, the 'radial' coordinate is now the Time-like coordinate, with the Future pointing 'inward', i.e., *towards the Cauchy horizon*. That means that particles of Matter do not have trajectories that would allow them to avoid the Cauchy horizon; no Matter what path they follow, they will reach that horizon in *finite* proper-Time.
Inside the Cauchy horizon, anything goes, since closed Time-like curves exist. So presumably, it might even be possible for particles of Matter to travel back-and-forth between the Past and the Future, never hitting the ring singularity, just wobbling back-and-forth between *yesterday* and *tomorrow*, like a short-circuited Time-machine. But that's not what Kerr is suggesting in his paper; he's not talking about *acausal* worldlines inside the Cauchy horizon, but some 'non-singular interior star with a finite boundary at, or inside, the inner horizon'. But such a stationary configuration of Matter *cannot exist inside the inner horizon*. Wobbling back-and-forth between *yesterday* and *tomorrow* in a closed Time-like loop *is not a stationary configuration*!
It is always a dangerous business to argue with someone who has the history and experience of a Roy Kerr, but in this case, it might be warranted. The language he uses (e.g., describing the business of singularities as 'dogma') is not helping either. Also, his description of the interior of the rotating black-hole sounds a bit off; to use his own words, '19th century' reasoning, much more so than the Oppenheimer-Snyder's paper that he criticizes.



Prof. Roy Patrick Kerr (1934-)

783 -

If we shone a torch a few inches outside the event horizon (EH) of a black-hole, would the photons still travel at c or be 'dragged back' to the EH and 'slowed down'?

Photons in our immediate vicinity, in the absence of a medium, will always appear to travel at the Vacuum speed of light.
However, when we are near an event horizon, we are in a region of SpaceTime where the Gravitational Field changes rather rapidly between neighboring points. As a result, beams of light would no longer appear to follow straight-line paths (just as they are bent, e.g., by the Sun, but this would be a much stronger effect) and moreover, the closer they are to the horizon relative to our position, the slower they will appear. This, too, has an observable analog here in the solar system: light rays or radio waves passing near the Sun, for instance, suffer a measurable delay caused in part by this effect (this delay is known as the *Shapiro-delay*).
Conversely, light rays that travel away from the black-hole, from our position near the horizon, will appear sped up. That is because when we are that near the horizon, deep down the black-hole's 'Gravity well', everything in the rest of the Universe will appear sped up from our perspective, because we are subject to Gravitational Time Dilation whereas the rest of the Universe is not.
Again, this does not mean that light goes faster than light, so to speak. It simply means that when we measure light at distant places in curved SpaceTime using our local Time reference for the measurement, we will get values that differ from c due to the *combined effects* of Gravitational Time Dilation and Length Contraction.

784 -

What is the difference between Time-like and Space-like singularities? Is the Oppenheimer-Snyder expression valid only for black-holes with a Time-like singularity?

A Time-like singularity is a location in Space (yes, a bit confusing, although there's reason behind the madness if we understand the meaning of 'Time-like' vs. 'Space-like' in Relativity Theory: crudely, *Time-like* is something that moves *forward in Time*, *Space-like* is something that spreads *across Space at a specific moment in Time*). A *Space-like singularity is an event in the Past or the Future*, i.e., *a moment in Time*.
The famous Oppenheimer-Snyder paper (not 'expression') has *nothing to do with either*. It describes a collapsing sphere of *dust* (*no-pressure medium*) with *uniform density*. Everything described in Oppenheimer-Snyder takes place, never mind any singularity, *before an event horizon forms*. The key message of that paper is that the collapse is *never ending*: to any stationary observer *outside* the would-be horizon, the collapse continues, appears to slow down because of Gravitational Time Dilation, and never quite concludes with horizon formation, no matter how long we wait.

785 -

Can two photons add together and become a single photon?

No, that would violate Conservation Laws. The photon's Spin can have two values: $+1$ and -1. Spin is *conserved*. Take two photons, let's add them together: their combined Spin would be $+2, 0, \text{or} -2$, values that a single photon cannot have.
A further problem: consider the reference frame in which the two photons are heading towards each other, i.e., the reference frame in which their combined (vector-valued) Linear Momenta sum to 0. However, their combined Energy is $\neq 0$. If they were to combine into a single photon, the result would be a photon with non-zero Energy but 0 Linear Momentum, whereas in reality, a photon satisfies $E = pc$, i.e., its Linear Momentum is proportional to its Kinetic Energy.
Knowledge of simple Conservation Laws (Energy, Linear Momentum, Spin\Angular Momentum) and knowledge of the properties of particles is often quite sufficient to determine what particle interactions can or cannot happen in Nature, without getting bogged down in complicated equations.

786 -

If Dark Matter and Dark Energy haven't been proven, why do scientists act as though both are 'real'? Is that bad science?
(A layman but terse answer by Krister Sundelin, Swedish software designer)

Dark Matter and Dark Energy are a bit like 'the footprints in the butter we keep in the fridge': we can't see Dark Matter and Dark Energy, but we do see their 'footprints'.
The 'footprints' of Dark Matter is *rotational velocities* in galaxies, *gravitational lensing*, the *abundances and decay times of chemical elements* in the Universe, and much more, all indicating that there are about 5 times as much Mass in the Universe, which we can't see, than ordinary Matter, which we can see.
The footprint of Dark Energy is that the expansion rate of the Universe started going up from about $5 \cdot 10^9$ years ago. We see that in the cosmic redshift of nearby galaxies vs. distant galaxies. All these are *real* effects and is well proven that they happen.
What we have not seen directly is *the cause* of these effects. We see the effects, but not the causes of them. We see the 'footprints in the butter, not the invisible elephant who left them'. So, we dubbed the causes 'Dark Matter' and 'Dark Energy' as placeholder names: 'Dark' because they do not interact with light (i.e., EM radiation), so, we cannot directly see them in any way using telescopes; 'Matter' because it has a gravitational influence like ordinary Matter; and 'Energy' because it usually takes Energy to speed things up.
And now we're trying to figure out what those causes are.

787 -

Is $E^2 = (pc)^2 + (mc^2)^2$ a clever math-trick, since it arbitrarily inserts $(pc)^2$ to prove photons are 'massless'?

No. It is not a 'math-trick' and it is not about photons in particular. It is all about the 4-dim Momentum: a 4-dim vector that consists of Energy and the 3-dim Momentum, a vector in the form $(E/c \quad p_x \quad p_y \quad p_z)$ in Cartesian coordinates.
The components of a 4-dim vector depend on the choice of coordinate system. The squared *norm*, or 'length' of the vector *does not*. In the coordinate systems of Relativity Theory this norm is formed by the expression

$$(E/c)^2 - p_x^2 - p_y^2 - p_z^2$$

or, simply,

$$(E/c)^2 - p^2 .$$

This *number* is a *coordinate-system independent property of the particle* that is characterized by E and p. Before we name this number, it makes sense to divide the expression by an additional factor of c^2. Why? Because $(E/c)^2$ and p^2 have the units of Mass times $(\text{Velocity})^2$; this additional division by c^2 (let's remember that c is just a *constant*, with the dimensions of Velocity) yields the expression

$$m^2 \equiv E^2/c^4 - p^2/c^2 .$$

This is very important. This number m, which appears squared in this expression, is an *invariant*, *coordinate system independent property of the particle* that is described using this expression. In the coordinate system in which the particle is at rest, $p = 0$, hence $m = E/c^2$. We know this expression already, as it is the expression of *Mass-Energy Equivalence*. Conversely, for *any* massless particle, we have $m = 0$ and this leads us to $E = pc$.
None of this 'proves' anything: we don't 'prove' that the photon is massless with $m = 0$. We measure it and find that we can set extremely stringent limits on the *maximum* possible Mass of the photon. Maxwell's Theory and its quantized version, Quantum Electrodynamics, assume a massless photon, with no proof involved. The Standard Model of Particle Physics kind of needs a massless photon, *otherwise the theory has trouble with renormalizability*, but that's no proof either. We don't prove things in Physics; proof is for theorems in Mathematics. In Physics, *we measure them*.
The most stringent limits for the photon Mass come from a variety of astronomical observations; depending on which set of observations we're looking at; we find that the upper observational limit for the photon Mass is something like two dozen orders of magnitude *less* than the Mass of the electron. Which kind of tells us that massless Electrodynamics, even if it turns out to be not strictly true (which would certainly be very interesting) is at the very least, *an extremely good approximation*.

788 -

It appears there may be no such thing as Potential Energy (PE) in General Relativity; better, *differences* in PE, rather than *absolute values*.

It looks like there's an inadvertent jump to the wrong conclusion here. There is definitely Potential Energy in General Relativity. We can write down two interacting fields or two interacting objects and there, we have it: *their Interaction Energy is Potential Energy*.
But the question may be referring to the Energy-content of the Gravitational Field itself!
Now, that Energy-content definitely exists. For instance, let's take a cloud of gas collapsing into a star. As things fall towards the center, they accelerate, until they collide into other things. Then, the motion becomes randomized, turns into Heat, which is then radiated away. Where is that radiated Energy coming from? We guess it, *it's the Gravitational Potential Energy that was the original source*.
The problem with the Energy of the Gravitational Field is that *it cannot be localized*. A central tenet of General Relativity is that for any observer, we can pick a coordinate system that, in their immediate vicinity, is indistinguishable from the coordinate system of empty Space (this is what the famous elevator cab thought experiment is about: if we are freely floating inside a windowless cabin, we cannot tell if we are falling in an elevator cab that has its cables cut, here on the surface of the Earth, or if we are floating in a space-capsule, somewhere in deep Space). But empty Space has no Potential Energy. And if a tensor is 0 at a point in some coordinate system, it is 0 *in all* coordinate systems. So, no tensor expression exists that can characterize the Energy-content of the Gravitational Field. It cannot be 'localized'.
This issue remains in many ways an open issue even today, more than a century since the initial development of General Relativity. It is an intriguing question. But it doesn't hurt to remember that what we are questioning is not the existence of Gravitational Potential Energy, but how it can (or cannot) be represented, whether it is a local or a non-local quantity, non-local meaning 'not associated with any specific point in Space but, rather, a property of a system as a whole'.

789 -

When will Cosmic Microwave Background (CMB) radiation become cosmic radio background radiation?

Indeed, but after a very, very long time. Of course, we assume that by 'radio', means wavelengths longer than microwaves, which is to say, UHF\VHF, shortwave, even medium or longwave radio.

The CMB is just *thermal radiation*. Currently, it corresponds to a temperature of about $2.726\ \mathrm{K}$, or at a *peak frequency* of about $160\ \mathrm{GHz}$. This is of course 'radio' but very firmly in the microwave domain, in fact significantly above most microwave frequencies currently in practical use.
For the CMB to shift down to the domain of FM or AM radio, the Universe would need to be (very roughly) about 10^6 times older than it is at present.
The catch, of course, is that when the Universe is 10^6 times older than today, there will likely be no burning stars left, no habitable zones, no planets, no creatures to make cosmological observations. Not to mention that its frequency drops, the intensity of the CMB also drops, so it becomes practically undetectable.
But yes, in principle the CMB frequency will over (a very long) time and indeed shift to the conventional radio part of the domain.

790 -

If a singularity is infinitely small, then it has no dimensions. How can it then interact with 4-dim SpaceTime when it shares no space properties?

A singularity is not infinitely small. It is not infinitely large either. Nor does it interact with anything. A singularity is not a thing. It is a mathematical abstraction. It is, literally, a point or set of points that is missing from SpaceTime. It is like the mathematical function $y = 1/x$. Its domain does not include $x = 0$. The function there is 'singular'. There is no 'point at $x = 0$' in the function's plot. It simply isn't part of the curve.
Certain solutions in Physics are singular. In some cases, it is obvious why. For instance, we may use the simplification of a 'point charge' when calculating something in Electromagnetic Theory. Given that the Electric Field of a charge is proportional to $1/r$, where r is the distance from the charge, at $r = 0$ the field is singular. Does this mean that there's an infinitely small thing with an infinitely powerful field confined to an infinitesimally small location? No, not really. In Classical Electrodynamics, there are no point charges. They are a useful mathematical tool, that's all. An actual object has an *extended size* and a charge density that is *nowhere infinite*.
General Relativity is weird because it predicts that when Matter undergoes Gravitational Collapse, *if it shrinks to its event horizon, it will inevitably become singular*. There is, however, a catch or two:
first, when viewed from the outside, the moment when a collapsing object shrinks to its event horizon remains forever in the future. We can never observe the horizon form, nor can we ever be sure that some unexpected, perhaps unknown physical process won't kick in and reverse the collapse at the very last split second (which may be trillions of years from now by our reckoning, viewing the event from the outside);
second, one has to wonder if, in light of Hawking Radiation that removes Mass-Energy from the system, the collapse ever completes. Not to mention that we're certain that our current understanding of Gravity is incomplete, and the missing bits may change our view of *strong gravitational fields* altogether. So, quite possibly, the singularity remains a *mathematical abstraction* just as in the case of Classical Electrodynamics: as such, *not a physical interacting system*.

791 -

Does a super-massive black-hole (or quasar) at a galaxy center gravitationally affect the surrounding Galaxy and Matter, causing it to fall into it? Or is the black-hole (or quasar) caused by the surrounding Galaxy and Matter falling into it?

We do not know precisely how supermassive black-holes form in galaxies, or what role, if any, they play in galaxy formation. This topic is a subject of active research.
However, we should be cautioned against overestimating the role a supermassive black-hole plays in the dynamics of a large galaxy, and particularly the very naïve (but often heard) view that just as planets orbit a star, stars orbit the galactic supermassive black-hole. That is quite simply not the case.
Take the Milky Way. Its supermassive black-hole Sagittarius A* (Sgr A*) is modest in size, 'only' about $4 \cdot 10^6$ solar masses. Compare it against the mass of the central region of the Milky Way: several *billion solar masses*. Except for its immediate vicinity, the gravitational influence of Sgr A* is dwarfed by the bulk of the Milky Way. Apart from a small handful of stars actually orbiting it, most other stars, even nearby ones, are only perturbed by its Gravity; farther out, the Gravity of Sgr A* is just a *minuscule correction* to the overall Gravitational Field; nor does Sgr A* represent the center-of-mass of the Milky Way.
There are, of course, galaxies with much larger supermassive black-holes, but even in those cases, the *Mass* of the entire galaxy usually exceeds the *Mass* of the supermassive black-hole by at least a couple of orders of magnitude.
One possible exception might by some of the really faint, ultra diffuse dwarf galaxies. If these harbor large black-holes, they might have masses comparable to the Mass of the entire dwarf galaxy. Then again, they may not have supermassive black-holes at all.

We should also be cautious against overestimating the rate at which a supermassive black-hole can accrete Matter. Its Gravitational Field may be strong, but the object is very compact. Anything infalling, therefore, is far more likely to *miss* the black-hole than to hit it; instead of being swallowed by it, such an object would just fly by the supermassive black-hole in a hyperbolic trajectory. black-holes in general, contrary to popular notions, are not ferocious eaters.
This of it this way. If something falls toward the Sun, any trajectory that takes it within 700000 km or so of the Sun's center will cause that object to intersect the Sun's surface and be swallowed by it.
Now, let's turn the Sun into a black-hole. Its radius is suddenly reduced from nearly 700000 km to less than 3 km. An object flying by that black-hole at 700000 km won't be eaten by the black-hole; it would miss the black-hole altogether. Much closer, the object flying by may be ripped apart by *tidal forces* (different parts of it trying to follow different trajectories) and the resulting interaction may cause some of the material to be captured by the black-hole, but even this is a slow process; the material, tidal debris really, rather than falling into the black-hole right away, will likely end up forming a ring, namely the accretion disk.

792 -

What is the significance of the *Higgs boson* in the Standard Model of Particle Physics?

The Higgs boson plays multiple (albeit closely related) roles in the Standard Model.
Let's look at the Weak Interaction. The first form of the Weak Interaction that was known to us involved the exchange of a boson (integral-spin particle) that carried Electric Charge. Emitting or absorbing such a boson allowed an electron to turn into an electron-neutrino (a fermion, ½-odd-spin particle, just like the electron, with all the 'electron-ness' associated with it, except for the electric charge itself) or vice versa. But the boson, which was named the W-boson, also had substantial mass, more than 80 times as massive as a hydrogen atom (this is why the Weak Interaction is 'weak'; it isn't weak, but with a massive mediating particle, its range is *extremely short*, so, it is very hard to detect. Hence its perceived 'weakness').
The problem with such a massive boson is that leads to a theory that is non-renormalizable. Which is to say it produces infinities that cannot be removed with a self-consistent mathematical procedure. However, this is resolved if we introduce another, *neutral* boson. This boson 'eats' the unwanted degrees of freedom of the $W^{\pm}$- bosons, so the theory can be renormalized. Except … that the Z^0-boson itself is predicted to be *massive* (so, it has *short* range). Therefore, it now introduces its own unwanted degree of freedom. What can we do about it? Well, if we only had a *scalar* particle at hand, it could 'eat' that degree of freedom, too …
This is indeed one of the things that the Higgs boson does. But how? How does its presence allow the Z^0-boson to 'eat' the $W^{\pm}$-bosons' unwanted degrees of freedom in the first place? It has to do with the fact that the Higgs boson has a funny 'self-interaction Potential'. For most fields, it's the lowest Energy state is the absence of excited states, but not so for the Higgs Field: its lowest Energy state is when some excitations are present. The field's 'V. e. v.' is $\neq 0$.
OK, we now put it all together. We end up with a picture in which the vector bosons (which become the $W^{\pm}$- and Z^0-bosons, as well as the photon) all start *massless*, and there is a Higgs Field, but it is a 'complex doublet', which is to say, characterized by 2 complex numbers, the equivalent of 4 'real degrees of freedom': 3 of these 4 numbers are used in the mechanism we know as *symmetry breaking*, which *endows* the $W^{\pm}$- and Z^0-bosons *with mass*. The remaining number is what emerges as the *observable* Higgs-boson particle. As a bonus, the symmetry breaking makes one other thing possible: we can postulate *charged fermions* (electrons, the up\down quarks, and the two heavier generations of the same) as initially massless but coupling to the Higgs Field. After symmetry breaking, they now couple of the Higgs non-zero V. e. v., which means an effective Mass. This is how the charged fermions gain Mass, again *keeping the theory renormalizable*.
All this sounds like a rather fragile construct until we consider that all the above *was verified by experiment*. The Z^0-boson and the Higgs boson were both theoretical predictions *until they were discovered* (in 1983 and 2012, respectively), their properties measured. The fact that these seemingly outlandish predictions of the Standard Model proved to be true was a huge triumph for the theory.
So, the Higgs contributes, through the *symmetry-breaking mechanism*, several features to the Standard Model: it endows the weak interaction's *vector* bosons and *charged* fermions with Mass, keeping the whole theory *renormalizable*.

793 -

Is Nuclear Force a *scalar* or a *vector* field?

If the issue is about the two fundamental short-range forces, *the Strong and the Weak Interaction*, they are both vector fields. The Weak Interaction is mediated by the $W^{\pm}$- and Z^0- massive *vector bosons*, whereas the Strong Interaction is mediated by *massless Gluons*.

What is commonly called the Nuclear Force, however, or sometimes the *residual Nuclear Force*, is a more complicated business as *it is not* a fundamental force. It involves the *exchange of mesons*, short-lived composite particles themselves made up of quarks, and this produces a binding between protons and neutrons inside a nucleus. These mesons include mesons with spin 0 and spin 1, so effectively, scalar and vector particles *are both present in the interaction*. It is, in fact, possible to describe the Nuclear Force as an *effective field theory* that contains both a *scalar* and a *vector* component, *both massive*.

794 -

Can graviton particles have their Momentum and Kinetic Energy?

Gravitons are the hypothetical quanta of the Gravitational Field, which would appear in the theory if

a. we had a Quantum Theory of Gravitation and
b. it made sense to work with what is called its perturbative expansion.

If this is the case, gravitons are expected to be *massless* and very similar in behavior to photons. As massless particles their Energy and Momentum would be governed by the same rule that governs photons: $E = pc = h\nu \; (\equiv \hbar\omega)$.

But we really don't know at present (2024) if gravitons *even exist*, and detecting them seems to be far, far, far beyond any *real* or *foreseeable* experimental capability.

795 -

Are irreversible processes *absolutely irreversible*, even in a Universe with infinite Time? For example, Entropy and *quantum decoherence*?

In the context of *axiomatic* Thermodynamics, indeed irreversible processes are *absolutely irreversible*.
However, axiomatic Thermodynamics is an *idealization*, valid only for systems with an *infinite* number of degrees of freedom. Real physical systems have a *finite* number of degrees of freedom and obey the laws of Statistical Physics.
And indeed, in the context of Statistical Physics, given long enough spans of Time, low probability events *can occur*.
So, yes, broken eggs can spontaneously reassemble themselves. But we might have to wait for far longer than the present age of the Universe multiplied by … who knows? but some number so insanely large, probably its number of digits is itself an insanely large number.
We should not confuse this with *quantum decoherence*. That is a completely different subject and, unfortunately, the words that we use to describe these phenomena often stand in the way of understanding. We speak of 'entangling' particles, which kind of implies that we created an invisible connection between two particles. Reality is that the connection (almost) always exist between anything and anything else; when we entangle a pair, it means we temporarily severe (or, at least, severely weaken) the *pair's connection with the rest of the Universe*, so that the pair are only entangled with each other, at least briefly … until the rest of the Universe makes its presence known again, and we speak of 'decoherence'.

796 -

Is there terminology for these ideas: a size that if it collapses will certainly be a black-hole, and a size that is too small to collapse?

What this question refers to is known as the *Tolman-Oppenheimer-Volkoff limit*: (very) roughly 2.5 solar masses.

If a neutron star reaches this Mass (the exact value of which is not precisely known), its so-called *neutron degeneracy*, pressure is no longer sufficient to withstand the pull of Gravity, and the star collapses to (probably) a black-hole.
That is not to say that more massive objects do not exist, but those objects (e.g., giant stars) are much larger in geometric size as well, and they are held in equilibrium by the *temperature and pressure of the thermonuclear reactions* that fuel the star. Once its fuel runs out, such a star may collapse into a neutron star or even a black-hole, depending on its Mass, Angular Momentum (rotation) and Composition.

797 -

You can switch off Gravity by falling, but can you switch off *tidal* Gravity?

It is true that we cannot distinguish freefall in a *homogeneous* Gravitational Field from freely floating in *empty space* if we are inside a closed environment like a windowless elevator cab.

But the emphasis is on *homogeneous*. Realistic Gravitational Fields change with distance from the source, which is the cause of the *tidal effect*. Sufficiently sensitive instruments, even inside a relatively small box, can measure this difference, i.e., the tidal force. Indeed, it cannot be 'switched off'.
And it's not even something that only exists in wild theory. Today's best atomic clocks can measure Gravitational Time dilation so accurately, they can tell an altitude difference of a few ten centimeters or less. So (assuming you can fit such clocks in there), even a shoebox may be large enough for such instrumentation to be able to measure *tidal Gravity* and thus distinguish between falling in the (inhomogeneous) Gravitational Field of the Earth vs. floating in deep space.

798 -

Does Gravity *have* to matter at the quantum scale? Can't we just account for Gravity as the collection of enough Matter, a sum of its parts? What should be meant is that Gravity means something to us because there's enough of it to shape our environment.

This is a valid question and indeed, there is an approach called *semiclassical Gravity* that does away with the need to quantize Gravity.
The basic idea is this. In Einstein's Field Equations for Gravitation, one side characterizes the Gravitational Field, the other side, Matter. If Matter is quantized, the expression representing Matter has values in the form of *quantum mechanical operators* (Dirac called them *q-numbers*). Meanwhile, Gravity being classical, it is represented by *ordinary*, *classical numbers* (*c-numbers*). Equating the two is like how many apples it takes to make an orange. The equation won't work.
But what if, as has been suggested, we do away with the need to make Gravity work as a Quantum Theory? To do so, we replace the expression for Matter with its so-called *expectation value*, *which is a c-number*. Everything is peachy now; the equation is solvable. And in fact, when it comes to observable scenarios, every conceivable present-day or future observation concerning Gravity is described very accurately by this semiclassical theory.
So, why not call it a day and go home? Two reasons. *First*, semiclassical Gravity is ugly. Is this how Nature operates? Hard to believe. But, *second*, it's also incompatible with at least some interpretations of Quantum Mechanics, especially those that view *wavefunction collapse* as an actual, physical process.
This also highlights the real problem with Quantum Gravity. It's not like we don't have ideas. We do. But how do we pick the winning idea? Normally, we'd do so *by way of observation*. But if observation is fully covered by semiclassical Gravity, how can it be used to distinguish between different versions of Quantum Gravity? Well, it cannot. So, Nature is not offering us clues as to which approach to take.

799 -

How is it that Mass which has fallen into a black-hole continues to be able to gravitate, even if, presumably, gravitons cannot escape the event horizon?

First of all, there is no 'Mass which has fallen into a black-hole'. Views from the outside, any Mass approaching the event horizon of a black-hole appears to slow down exponentially; the moment of that Mass reaching the horizon (indeed, the moment the horizon itself forms in the first place!) remains forever in the Future for any outside observer. The fully formed black-hole, horizon, and all, remains a mathematical abstraction, the 'asymptotic limit' of a physical process that, for outside observers, would literally take forever.
Second, black-holes and gravitons are different sides of the same coin: black-holes are predictions of our Classical Theory of Gravitation, Einstein's General Relativity. Gravitons are *hypothetical quanta* of a yet-to-be-discovered Quantum Field Theory of Gravitation in the so-called *perturbative limit*.
Of course, it is true that gravitons from the infinite Future (when the horizon forms) would not be able to observe the present. Or to put it differently, any influence from behind the event horizon necessarily involves Time travel backwards in Time from the infinite Future to the Present.
Third, even if so-called 'primordial' black-holes existed (i.e., black-holes that came *ready-made*, with fully formed horizons that always existed since the beginning of the Universe – a problematic proposal for a variety of technical reasons) their Mass would be their *intrinsic property*. Any exchange of gravitons would be with the entirety of this Gravitational-geometric object, not with any specific lump of Matter that may or may not be present behind its horizon, i.e., in the infinite Future insofar as we, outside observers, are concerned. But even for primordial black-holes, any Mass falling into the black-hole now would take forever (literally) to reach the horizon as seen from the outside.

800 -

Why does the particle that escapes from a black-hole gain Energy?

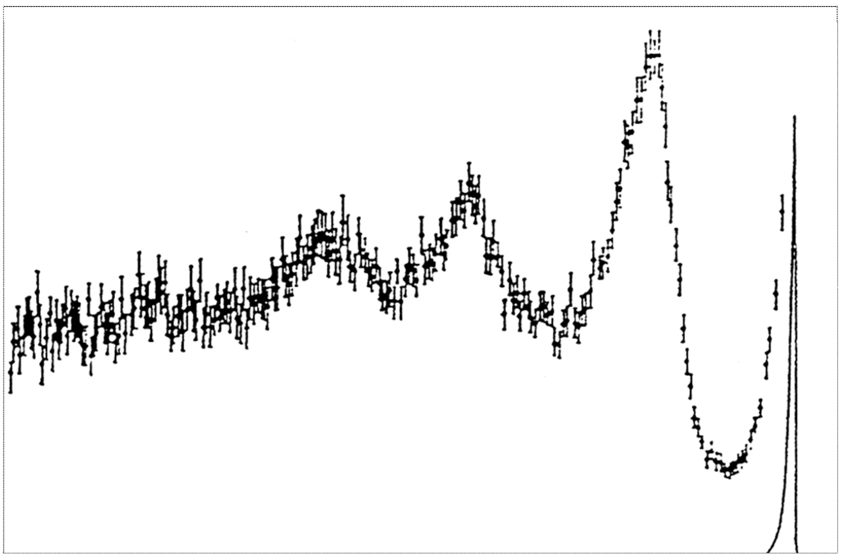
This question seems to be related to the popular Hawking's explanation of *Hawking Radiation*.
Hawking Radiation is *low intensity thermal radiation* that presumably comes from black-holes. The word 'presumably' is in order because the radiative power of astrophysical black-holes is so tiny that it will literally never be observed. Moreover, somewhat paradoxically, *the larger a black-hole gets*, *the less it radiates*.
Having said that … the 'gain Energy' bit in the question may have come from the unfortunately misguided explanation from Hawking's popular book, in which he explains Hawking radiation as particle-antiparticle pairs created at the event horizon, one with positive, one with negative Energy (virtual particles are not confined to positive energies – note that it could be either the particle or the antiparticle that has negative Energy, it doesn't matter) with the negative Energy particle 'eaten' by the black-hole, and the positive Energy particle escaping to infinity.
This explanation is kind of intuitive but it is blatantly at odds with Hawking's own 1974 paper that introduces the concept. Not to mention that the characteristic wavelength of Hawking Radiation is about 20 times the black-hole's event horizon radius, so the very idea that it is something tiny (a particle) produced very near the horizon makes no sense. No, Hawking's paper explains that the radiation is produced because there is an *asymmetry between Past and Future*, because the black-hole is in a state of *collapse*. It is not static. This imbalance manifests itself as radiation that 'steals' Mass-Energy from the infalling Matter. This is made possible by 'gravitational Vacuum polarization', i.e., by *the extreme Mass concentration of the collapsing cloud of Matter, with a rapidly-varying $\mathcal{G}$- Field in its vicinity*.

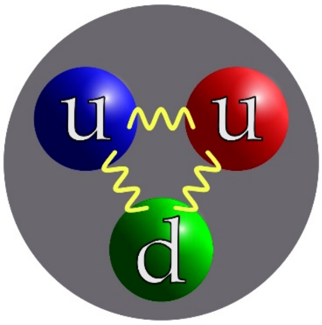
This of course is a lot less intuitive than the particle-antiparticle pair creation story. Probably not even comprehensible without the equations in Hawking's paper. But it is also a lot *closer to reality*.
In any case, Hawking Radiation takes place at the expense of the total Mass-Energy of infalling Matter.

801 -

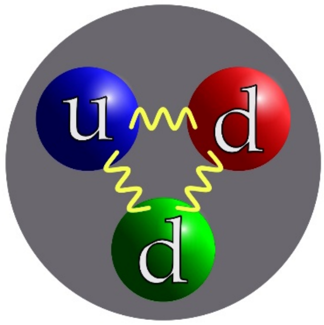
How were quarks discovered if they can't be detected apart from each other?

Quarks 'can' be detected apart from each other. What cannot be done is isolating a quark as a free quark as opposed to observing that quark in a bound state, e.g., inside a baryon.
The detection of quarks followed the same pattern that was established more than a century ago by Rutherford and his early experiments. Let's fire high-Energy particles at something and observe how they are scattered. Rutherford noted that some of the α-particle he fired at atoms were scattered 'hard', implying that they hit *something compact*. That's how it was discovered that atomic nuclei are rather small and compact things inside atoms.
Now, let's repeat the same experiment but with *much higher-Energy test-particles* and presto: we can see that, e.g., a proton is not a homogeneous sphere with uniformly distributed positive charge but rather, *something with a structure*, *with compact constituents*.
Here's a plot on the subject from: AITCHISON, I. J. R. - HEY, A. J. G., *Gauge Theories in Particle Physics - A practical introduction*, 3RD ED., (2003, IOP Publ. Ltd.) [27]. The actual details are rather complicated, but the basic idea is as follows: firing electrons at protons *produces peaks that wouldn't be there if the proton did not have a substructure*.





Protonic nucleon



Neutronic nucleon

802 -

Might detecting (hypothetical) graviton be impossible, even in principle?

In principle, it is certainly possible to detect a graviton.
In a lovely lecture, the famed physicist Freeman Dyson (1923-2020) calculated that if we were to use the entire Earth as a graviton detector (say, freezing the whole Earth to near $0\,\mathrm{K}$, and making sure it is not exposed to any radiation other than Gravitational Radiation while monitoring for electronic transitions induced by captured gravitons), we may detect gravitons from Thermal Gravitational Radiation originating from the Sun at a rate of a little under one graviton per billion years.
So, in about $5 \cdot 10^9\,\mathrm{y}$, which is roughly the time the Earth has before the swelling, aging Sun swallows it, we just might have 4 graviton detection events, give or take, enough to have a statistically significant 'discovery'.
Mind you, we may be interested in using the Earth for other purposes that are, well, ever so slightly incompatible with this experiment … but in principle, yes, this is what a direct detection of the graviton would look like.

803 -

If we never find the exact solution of rotating black-holes, would we still discover the ring singularity and wormholes using numerical simulation?

We do have an *exact* solution for *rotating black holes*. It is the famous *Kerr solution*. In the region *inside* its *outer* event horizon, the solution also predicts a second (Cauchy) horizon and a *ring singularity*, and indeed, its maximal extension can be interpreted as a means to travel to alternate Universes, i.e., using the black hole as a *wormhole*.
Since the solution is exact, no numerical simulations are needed. Whether or not the solution (which is an *axisymmetric Vacuum solution* of the equations of General Relativity) accurately describes a *collapsing*, *rotating* cloud of Matter is another question. To this date, no satisfactory analytical solution has been found, e.g., for a rotating 'perfect fluid' object (that is, an object made of stuff with no viscosity, no internal stresses, friction, etc.) that matches the Kerr solution on its exterior boundary (similar solutions do exist for the nonrotating, i.e., Schwarzschild, case). But a mathematical model of a spinning, gravitating physical object is quite distinct from the ring singularity and inner horizon that are characteristic of the Kerr Vacuum solution.

804 -

Does spinning a black-hole cause a *ring singularity*? If so, how?

If we could spin up a Schwarzschild black-hole (that is, change its Angular Momentum from 0 to $\neq 0$) it would indeed become a *Kerr black-hole* with a *singularity ring*.
But the above statement that was just made makes *less* sense than it might appear at first sight. Why? *Because it talks about mathematical abstractions as though they were physical objects.*
Take an actual astrophysical black hole, such as a collapsing star. Unless we are willing to end our lives prematurely, we'll be watching it from the outside. Watching it from the outside means that the black hole has not formed yet. Ever. That is because the formation of the actual event horizon remains forever in our Future.

To be sure, the object we see (or more precisely, *don't* see) is indistinguishable from a black hole. All Matter is very close to the future location of the horizon. Any radiation from it is exponentially redshifted into oblivion, so the thing appears 'black', emitting no (observable) light and absorbing all the light aimed at it. But technically, it is not a black hole quite yet.
If we spin it up, it's still not a black hole. All that means is that in the infinite Future and beyond, the horizon it forms will be different and the singularity it hides will be different.
But that hasn't happened yet and as far as we are concerned, it will never happen; we can wait trillions of years and the formation of the black hole is still not complete, because in our own reference frame, that event remains at future infinity.
So, the best statement that can be offered is that spinning a black hole will cause it to evolve towards a Kerr solution with its ring singularity *in the infinite Future*. We're not changing a point singularity into a ring singularity because no singularity exists at the present, indeed, no event horizon exists at the present either.

805 -

In the *Schwarzschild metric*, is r measured relative to a *local* observer or relative to a *distant* observer, or is r a Euclidean expression?

None of the above. The quantity r is simply a convenient coordinate. One of the fundamental properties of General Relativity is *general covariance*: the idea that *the Laws of Physics remain the same no matter what system of coordinates we use to express them*.
So, let's ask the following question: Given Einstein's Field Equations, is there a solution to them that is

a. *spherically symmetric*,
b. *a Vacuum solution* (no Matter present),
c. *static* (not a function of the Time coordinate), and
d. *very far away* from the solution-center, becomes *the metric of empty SpaceTime* (i.e., *asymptotically Minkowski*)?

The answer is the Schwarzschild solution. So, if we wish, we can think of this solution as a means of describing a spherically symmetric, *static* Gravitational Field in a coordinate system that is conveniently set up by a *faraway* observer.
But that does not mean that r is 'measured'! Before we think about things being measured, we need to think about *how that measurement should be carried out*. And when we think about measurement in General Relativity, ultimately, we find that all measurements boil down to measuring *proper-Times* (i.e., the number of ticks counted by a reliable clock) along a *world-line*. When we wish to measure the relationship between distinct world-lines, we may use light signals and then measure the time it takes along the transmitter's world-line to receive a response.

806 -

Is it possible that CMB Radiation was not emitted during or before the Big Bang event, according to Standard Cosmology?

First, the 'Big Bang event', i.e., the *initial singularity*, may or may not have been an event: it is a prediction of General Relativity, but we have no reason to believe that General Relativity is valid in what is assumed to be the first pico-second of the existence of the Universe. Our Science extrapolates back from the Present (which we *observe*) to the *distant Past*, but only as far as we can; after that first pico-second, conditions were like what we observe in large particle accelerators, so have some experimental data to back up our model, but before that? It's, at best, informed speculation, nothing more.
And 'Big Bang', in scientific literature, usually refers not to a specific event but, rather, to the *paradigm of an expanding Cosmos that was hot and dense in the distant Past*.
As to the CMB, it was certainly not emitted 'during the Big Bang event', unless we consider the entire existence of our Universe the 'Big Bang event'. It was emitted when the Universe was roughly 380000 years old. Up to that point, Matter in the Cosmos was in the form of *hot*, *ionized* gas, which is *not transparent to radiation*. At around 380000 years, the gas became cold enough for atomic nuclei to *recombine* with electrons, forming a neutral, *transparent* gas; any residual glow from the incandescence of this gas could now freely travel, originating at all points in this cooling Universe, *emitted in all directions*.
Here and now, almost 14 billion years later, we see this incandescent light from all sky directions, but it has been red-shifted by a factor of about 1100; thus, light that was emitted by gas at the approximate temperature of 3000 K now appears as *blackbody microwave radiation*, corresponding to a temperature of about 2.726 K.
Not just the existence but the detailed properties of the CMB match the predictions of the theory, notably among them its minute temperature *fluctuations* between different sky directions. This is an important confirmation that the 'Big Bang' paradigm is at the very least on the right track: even if some radically different theories were to predict the existence of a Microwave Blackbody Background, it's extremely unlikely that its predictions would match details, such as these temperature fluctuations.

807 -

Does the Dark Matter *displaced* by the Earth *displace back*, causing Gravity?

Dark Matter in the Standard Cosmological Model (assuming it exists, in the first place) *is not* displaced by the Earth.
The part about it being 'dark' refers to the fact that Dark Matter either does not interact at all with other forms of Matter (other than through Gravity) or, if it does interact with *ordinary* Matter, it does so very, very weakly.
In other words, Dark Matter and normal Matter are nearly perfectly *transparent to each other* in every possible sense of the word.
So, if there is Dark Matter in the solar system, it would go through us, through the Earth, through the Sun even as though these bodies weren't even there. We might have heard that neutrinos do that, too, flying through our bodies, our planet, even the Sun, unimpeded. True, but, at least, every so often a neutrino does get captured, which is how we get to detect them. Dark Matter doesn't even do that, which is why direct detection of Dark Matter is such an incredibly difficult task.
And no, Dark Matter does not cause Gravity. It contributes to Gravity with its added Mass, altering the way galaxies rotate and altering the *rate* at which the Universe expands.

808 -

What is the nature of Gravitational Waves? Are they a form of radiation or something else entirely?

Gravitational Waves and *Gravitational Radiation* mean the same thing: they are the *gravitational analog* of Electromagnetic Waves\Radiation.
An accelerating electric charge creates a 'ripple' in Maxwell's Electromagnetic Field. This ripple, far from the source, travels as a *free* electromagnetic wave, which we recognize as *radio* waves, *light*, X-*rays*, whatever, depending on its *wavelength*. Materials with the right electromagnetic properties can interact with this electromagnetic wave, detecting it, absorbing it, reflecting it, etc.
In a similar way, an *accelerating Mass* creates a 'ripple' in the Gravitational Field $\mathcal{G}$, and just like in the case of Electromagnetism, far from sources, the ripple travels as a *free* wave (in fact it travels at the *same* speed, the speed we know as the Vacuum speed of light).
Because the interaction between Gravitation and Matter is *very weak*, such waves are very difficult to detect (and would be even harder, much harder, to alter substantially).
Although there are many similarities, there are also differences between *gravitational* an *electromagnetic* waves, due to the *tensor* nature of the former. What this means in practice is that a passing gravitational wave can be thought of as a passing *tidal distortion*: a gravitational influence that *squeezes* Matter in some direction while, simultaneously, *stretching* Matter in a *perpendicular* direction, all the while *keeping volume constant*. So, if we were to think of a very powerful gravitational wave and a water-filled balloon standing in its path, the balloon would appear to be squeezed periodically, along two *perpendicular* directions, first one and then the other, repeatedly.
In fact, this is how we detect gravitational waves: using ultra-precise measurements of *relative travel times* of two perpendicular rays of light. When a gravitational wave passes through, that results in a tiny *phase difference* between these two laser beams. This is what is being detected when a distant astrophysical catastrophe, such as the merger of two black-holes, creates a powerful gravitational wave outburst.

809 -

Is there any special formula to calculate the *average speed* of an object orbiting a black-hole or is it just the same formula as the Sun and Earth?

Things get tricky in Relativity Theory since *velocity depends on the observer*. However, there exists a striking result: for observers *far away* from a black hole, the speed for a *circular* orbit will be the *same* as the Newtonian result,

$$v = \left(\frac{GM}{r}\right)^{1/2}.$$

We might find this result especially striking if we know the basics about Schwarzschild black-holes, notably the notion of a 'photon sphere': doesn't it tell us that at $r = 3GM/c^2$ the orbital speed is exactly c, the Vacuum speed of light? Well, it does, but there is also Time Dilation. A *distant* observer sees everything near the black hole in *slow* motion. What moves at the Vacuum speed of light at the radial coordinate $r = 3GM/c^2$ will appear to be moving at the speed

$$v = c\left(1 - \frac{2GM}{c^2 r}\right)^{1/2} = \frac{c}{3^{1/2}},$$

which is exactly what we get when using the speed formula for a *circular* orbit.
So, there we have it, one (but by no means the only one) of the surprising coincidences where General Relativity and Newtonian Physics yield the *exact same* result.

810 -

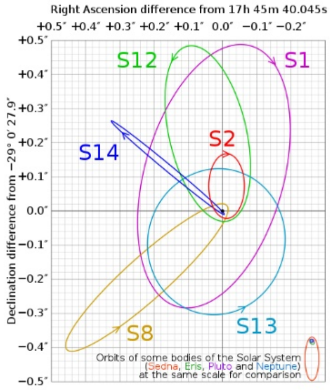
Combining *Special Relativity* and *Quantum Entanglement*, can it be said that measuring the state of a *quantum system* shared by 2 photons in some reference frames, can collapse the quantum state of a particle at a time *before* the other one was measured?

One of the critical misunderstandings concerning Entanglement is the notion that the act of measurement somehow ‘causes’ something to happen, especially something to happen *at a distance*. So, let’s clarify a few things.
First, Entanglement *is not* about A being entangled with B, our persistent misuse of the language notwithstanding. For starters, by default everything is entangled with *everything else*. When we casually discuss, say, an ‘entangled pair of photons’, what we really mean is that we somehow established an experiment in which those two photons are (at least, temporarily) *isolated* from the environment, so they are *only* entangled *with each other* for the duration of *that* experiment.
Second, putting aside theories that postulate ‘objective collapse’, the act of measurement doesn’t do anything: *it does not collapse any quantum state*. The collapse of the wavefunction is a *useful mathematical model*, *not a physical process*. When we look at what the actual equations (Schrödinger’s) say, if we introduce into the system the notion of a ‘classical’ instrument with which the measurement is being made, that instrument constrains the system, even if the actual measurement takes place in the Future. This is really what it means when we are told (e.g., by virtue of Bell’s Theorem) that the Quantum Theory is ‘non-local’.
Third, quantities related to Entanglement must not be viewed as properties of one photon or another. This really is the most critical aspect of non-locality. The *conserved* quantities in Entanglement experiments are *properties of the system*, *not of any individual particles*. So, we know, say, the *total* Angular Momentum of the system; we measure the Angular Momentum of *one part* of the system (e.g., a photon). That means that we know with certainty (because the quantity is absolutely *conserved*) the Angular Momentum *of the rest of the system*. When the rest of the system happens to be just a single photon, it means that all that remaining Angular Momentum ‘belongs’ to that *second* photon. But it’s not because anything happened to that second photon because of our measuring the first photon.
Lastly, Relativity Theory has nothing to do with this, at least not directly. These qualities of the Quantum Theory remain the *same* in both non-relativistic *and* relativistic formulations. Of course, when it comes to Relativity Theory, we are more focused about influences that appear to travel faster than c. But, hopefully, in a clearer (at least, a little bit) way, *no influences* whatsoever travel when parts of an entangled system are measured. The quantities involved *do not* travel; to begin with, they are non-local, characterizing the system, *not any individual* particle in that system.

811 -

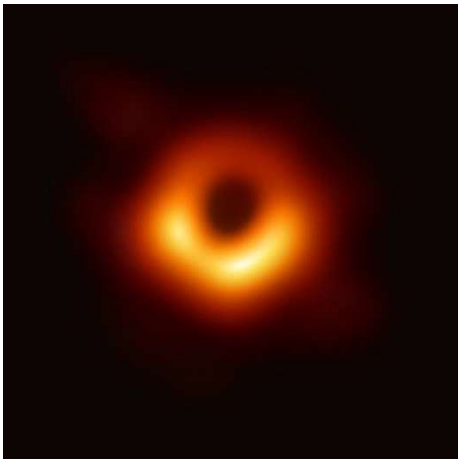
No one has ever observed black-holes directly but predicted them to be there. Is there any evidence of their existence ?

First, … do radio-waves exist? No one directly observed radio-waves since we lack the senses to detect them directly. But we have these devices called ‘radios’ that do the sensing for us and inform us of the presence of radio-waves when we listen to pleasant music or unpleasant news coming from a distant transmitter. We accept at face value the statement that it was radio waves that carried that content wirelessly from the distant station to our ‘radio’ device. So, maybe indirect observation might suffice, so long as it is not too indirect? We have been observing compact, massive objects indirectly by many decades. E.g., here’s a plot of some stellar orbits in the central region of the Milky Way:



These stars are orbiting something very *compact* and extremely *massive*, with a mass of over 4 million Suns. This image alone is, I’d say, as good evidence as those sounds coming from your 'radio' device, serving as evidence of the existence of radio waves. There have been many similar observations. Not all the presumed black holes weigh *millions of Suns*; some are not much bigger than the Sun, but we can detect them nonetheless when they are part of, e.g., a *binary* star-system. Then again, some supermassive black holes in other galaxies are more than 10^3 times bigger than our Milky Way’s puny Sagittarius A* object. So, there comes this iconic image:

No, contrary to popular descriptions, *this is not an actual photograph* of the M87* black hole, though it comes close. This is a *reconstructed image*, from observations by a worldwide network of radio telescopes. What it depicts is *radio emissions* from the black-hole's accretion disk, on which we can see, superimposed, the 'shadow' of the black-hole's *photon-sphere*, the innermost region just outside its event horizon, where Gravity is so strong, *it can cause light to go around in loops*.
As it was said, this is not a photograph, but this is as close as we can get to 'seeing' a black hole (by way of a crude analogy, consider 'seeing' an incoming airplane on an air traffic controller's radar screen).
So, considering these observations, we must conclude that say that, yes, there is overwhelming evidence that black holes (or, at the very least), compact, massive objects that turn out practically indistinguishable from black-holes, *exist*.



[See the same image in Issue 92, p.42]

812 -

How did Einstein come up with his equation, $E = mc^2$, which relates Mass and Energy in Special Relativity? Was it derived through a rigorous process or was it based on intuition?

Einstein's derivation of $E = mc^2$ is both simple and reasonably rigorous (certainly, by physicist's standards). So, let's review the essence of Einstein's derivation, as presented in his 4th 'annus mirabilis' paper (1905). The title says it all: "Does the Inertia of a body depend upon its Energy-content?" (in German: "Ist die Trägheit eines Körpers von seinem Energiegehalt abhängig?", *Annalen der Physik*, 18, **639**, 1905). Einstein investigates the Energy l (in the notation used in the 1923 English publication of the paper) of a system of plane electromagnetic waves, as measured by observer 1. An (inertial) observer 2, moving relative to (inertial) observer 1 with velocity $\boldsymbol{v}$ directed at an angle φ vs. the wave-vector $\boldsymbol{k}$, sees the Energy

$$l^* = l\,\frac{1-(v/c)\cos\varphi}{(1-v^2/c^2)^{1/2}} \;. \tag{1}$$

He then investigates a body that sends out 2 light signals with Energy $(1/2)\,L$ in *opposite directions* (such that its (*vector Linear*) Momentum doesn't change). If the body's Energy is E_0 before and E_1 after the emission, we have, due to Energy conservation,

$$E_0 = E_1 + \frac{1}{2}L + \frac{1}{2}L\,. \tag{2}$$

In the other (inertial) reference-frame, let the body's Energy be, before and after, H_0 and H_1. Then,

$$H_0 = H_1 + \frac{1}{2}L\,\frac{1-(v/c)\cos\varphi}{(1-v^2/c^2)^{1/2}} + \frac{1}{2}L\,\frac{1-(-v/c)\cos\varphi}{(1-v^2/c^2)^{1/2}} \;. \tag{3}$$

i.e., by simplifying,

$$H_0 = H_1 + \frac{L}{(1-v^2/c^2)^{1/2}} \;. \tag{4}$$

Now, subtracting Eq. (2) from Eq. (4) yields

$$(H_0 - E_0) + (H_1 - E_1) = L\left(\frac{1}{(1-v^2/c^2)^{1/2}} - 1\right) \;. \tag{5}$$

Einstein notes that H_0 and E_0 refer to the Energy of the *same body in the same state*, in two different inertial systems; same goes for H_1 and E_1. On the other hand, $H - E$ is the difference in K (Kinetic Energy), as seen in two systems that move relative to each other, up to some *additive* constant χ that is just a matter of how the Kinetic Energy is defined in the two systems:

$$H_0 - E_0 = K_0 + \chi\,, \tag{6.1}$$
$$H_1 - E_1 = K_1 + \chi\,. \tag{6.2}$$

So then,

$$\Delta K_{01} \equiv K_0 - K_1 = L\left(\frac{1}{(1 - v^2/c^2)^{1/2}} - 1\right). \tag{7}$$

When the speed is small, the square root in the denominator can be series-expanded, and terms containing higher powers of v can be dropped. The 1st order truncated expansion writes

$$\Delta K_{01} = L\left(\left(\cancel{1} + \frac{1}{2}\frac{v^2}{c^2} + \cancel{\frac{3}{8}\frac{v^4}{c^4}} + \cancel{\frac{5}{16}\frac{v^6}{c^6}} + \ldots\right) \cancel{-1}\right) \approx \frac{1}{2}\left(\frac{L}{c^2}\right)v^2\,. \tag{8}$$

Note that the body's speed doesn't change, yet its Kinetic Energy (which is $(1/2)mv^2$ at appropriate *low* speeds) changed by this amount after the emission. From this Einstein concludes that if a body gives off the Energy L *in the form of radiation*, its Mass *diminishes* by L/c^2. He also notes that the Energy withdrawn is in the form of radiation, makes no difference, which leads to the conclusion that *the Mass of a body is a measure of its Energy-content*, with c^2 being the *conversion factor* between the two (the actual formula, $E = mc^2$, doesn't appear in Einstein's paper but it is trivially implied by his result and is described in words).
This derivation, in addition to being rigorous enough, is also surprisingly intuitive once we understand the basics of Special Relativity. So, the two – intuition and Special Relativity – are not mutually exclusive.

813 -

Is Acceleration needed to produce *Twin Paradox*? One might say it isn't.
[Ref.: https://bit.ly/TwinParadoxNoReturn]

Acceleration, per se, *is not* required. Recognition that we need more than two inertial reference frames for the twins to meet a second time and synchronize their clocks *is*.
The Twin 'Paradox' arises because it is based on two contradictory assumptions:

a. the twins move inertially all the time, so, only two reference frames need to be considered, and
b. the twins can synchronize their clocks unambiguously.

The only way to synchronize two clocks without additional assumptions is to bring them together. To bring the clocks together, at least one of the twins must turn around. Yes, this means *Acceleration* (perhaps, infinite acceleration if we model the turnaround as instantaneous) but that's not the point; the point is, once the twin made the turn, *it implies a new inertial reference frame*.

814 -

According to the Big Bang theory, where did everything come from if there was nothing (i.e., no Space nor Time)?

First, though the expression is commonly used, there really is no 'Big Bang theory' outside of the former television sitcom. Cosmology textbooks usually talk about the 'Big Bang paradigm', referring to families of cosmological scenarios that describe an early Cosmos that was *hot* and *dense*.
The point is, Big Bang Cosmology is about Physics. It is not a creation myth. It is no substitute for the Book of Genesis or whatever other creation story one happens to favor. Because it is not about how everything came to be, even if Georges Lemaître, one of the earliest cosmologists to contemplate an expending Universe, mused about the *primeval atom*.
What physical Cosmology is about, first and foremost, are observations made here and now, at the present day. Observing the CMB (*C*osmic *M*icrowave *B*ackground). The large-scale distribution of Matter. Ratios of light element isotopes. Distant, early galaxies, their morphology and composition, and so on.
This is then combined with theory. No, not the 'Big Bang theory'. Rather, theories like General Relativity, Quantum Field Theory and the Standard Model of Particle Physics, Statistical Physics, or Thermodynamics. The idea is to find a coherent picture that models the present observations and tells us something about the Past.
With enough information at hand, we extrapolate into the Past. A key prediction was Thermal Radiation, by now redshifted by more than a factor of a thousand into the Microwave domain, remnant of an era when the Universe was hot and dense enough to glow everywhere. This radiation (the *Microwave* background) was found in the 1960s. More detailed predictions concern minute statistical variations of this Microwave background. Again, observations by the

WMAP (*W*ilkinson *M*icrowave *A*nisotropy *P*robe) and Planck satellites did confirm these predictions in the past two decades. Other predictions are not so easily confirmed. We still don't know exactly what happened between the era when the Microwave background radiation was produced and the emergence of the first stars. In fact, there's growing evidence that we are *missing* something important. In any case, we can go back further in time, thanks to experimental data we have available to us from particle accelerators. We can go back all the way to the epoch when the first atoms formed, indeed the epoch when baryons (neutrons and protons) formed. But no further.
That's the limit of our knowledge. What was the stuff baryons formed from? That quark-gluon plasma? We can speculate all we want where it came from, but we do not yet know. Going back even earlier would require robust knowledge of the extreme effects of Gravitation in the *quantum realm*. We have no such knowledge.
So, we absolutely, positively do not know where everything came from.
Now it is true that General Relativity actually tells us that there is an initial moment, a moment that, somewhat confusingly, is not part of SpaceTime (a 'singularity' is never part of the manifold just like the singular point at $x = 0$ is not part of the plot of the function $y = 1/x$) so there are no prior moments, there no 'from', the existence of the Universe in General Relativity is not an 'effect' attributable to any 'cause' … but, as just said, we cannot go back that far. General Relativity's predictions cannot be trusted in the realm where quantum effects of Gravitation are important. Simply put, we have no idea if there was even a beginning or, perhaps, if the Universe is eternal.
Maybe one day we'll know. But despite its popular name, despite Lemaître's *primeval atom*, the 'Big Bang theory' is not about a big bang at all (reminder: the name itself came from the astronomer Sir Fred Hoyle, himself not a fan of the Big Bang paradigm, when he ridiculed it in a 1949 BBC radio show). It is about how the Universe was hot and dense when it was younger, and how it expanded and cooled until it reached its present form that we observe today.

815 -

If Gravity can be alternatively described as a field in perfectly flat SpaceTime, how can it explain the existence of singularities (discontinuity of the SpaceTime)?

First, Gravity cannot be described as a field in 'perfectly flat SpaceTime'. At least not in the case of Standard Theory (i.e., General Relativity). What does 'perfectly flat' mean? Well, it means that all measurements of Distance and Time intervals yield the pseudo-Euclidean metric of Special Relativity.
This is not what measurements yield in the presence of Gravitation. So, if perfectly flat SpaceTime exists, we wouldn't know. Because Gravity is universal, all things, including all our instruments, 'sense' it. And because of the way Gravity interacts with Matter, that 'sensing' amounts to a *distorted geometry*.
This is what allows us to interpret the Gravitational Field as the geometry of SpaceTime.
If course if we take this interpretation a little too literally, we end up with solutions that have singular points or regions, which can be a problem. But, let's hold on, here. Now we are talking Mathematics, not Physics. And for what it's worth, we don't need fancy geometry to get singular solutions. Ordinary Electromagnetism is singular if we permit *point-particles*, where the Electric Potential becomes *divergent*. But do we observe divergent potentials? We do not. Nor do we observe Gravitational singularities.
Yes, we do observe black holes, to the extent it is possible to observe them. But that's not the same as observing any singularity! What we observe is Matter in the *process of collapse*. Granted, because of exponential redshift and Time Dilation, the result is indistinguishable from a fully formed black hole with an event horizon, but if we take those equations seriously, that event horizon remains forever in the Future. The singularity is there, so to speak, but not at the Present, but in the *infinite Future*.
So just as we have not observed electromagnetic singularities, we're not exactly observing Gravitational singularities either. Do they even exist? Maybe not. And are they really singularities of SpaceTime as opposed to singularities of a physical field?
These remain open questions because they are intricately related to how Gravity ties in with the Quantum Theory, which might one day tell us what happens when black holes try to form but perhaps evaporate even before the event horizon gets a chance to form in the first place. So, perhaps in the end, just as electromagnetic singularities do not appear exist, perhaps neither do Gravitational singularities.
For now, it's important to consider those singularities only as mathematical artifacts, very likely indicating limitations of the underlying theory, not observed physical phenomena.

816 -

If singularities do not exist (as proposed by Kerr), what broader implications, if any, would this yield to Theoretical Physics?

Well, for starters, as far as we know, singularities do not exist *in the present tense*.
When we look at solutions that predict singularities, like the Kerr-Newman family of solutions (which includes, as

special cases, the spherically symmetric Schwarzschild, rotating Kerr, and charged Reissner-Nordström solutions), the singularities they predict, insofar as we, observers outside the black-hole are concerns, forever remain in the Future. Not only that, even the nebulous event horizons of these black holes remain forever in our Future.
But … what about the surface of last influence, one may ask, having read the cautionary words on this topic in MTW [40], the telephone-book-sized volume that is considered the gold standard to this topic in Relativity textbooks. True: there is a moment in Time (confusingly called a 'surface' in the parlance of 4-dim SpaceTime Physics) after which no signal can reach an infalling observer before that observer hits the event horizon. However, it does not mean that we can ever witness that observer reaching the event horizon. Nor can we ever be sure that, long after we missed our chance to send them a warning signal, they won't come to their senses on their own, switch on their Very Powerful Rocket [tm], and turn around at the very last split second: that event, insofar as you are concerned, could be a million, a trillion, a septillion or more years from now.

So then, what about the actual infalling observer? Surely, they will see the event horizon when they reach it, in a finite amount of Time as measured by their own (mechanical, biological) clock? Sure. That is indeed what Classical General Relativity predicts, and not only that, after crossing the horizon they are doomed: even as they are ripped apart by divergent tidal forces, they will inevitably approach that future moment in Time (not a place!) that is the singularity. Or maybe not … because if the black-hole spins, even a little, or if it has charge, even a very small one, it no longer has that neat singularity that characterizes the Schwarzschild solution, and in fact, its actual singularity or singularities may never even be reachable by an infalling observer.
But before we even go there … this is all Classical Relativity, but the world *is not* classical. When we invoke the Quantum Theory, everything changes. The black hole, as we hypothesize, evaporates in *finite* time due to Hawking Radiation. No, this evaporation is not about the event horizon eating negative-Energy particles, however appealing that description was in Hawking's popular science book, *A Brief History of Time*. When you read Hawking's actual (now half a century old) paper, the situation is more nuanced: Hawking Radiation arises because the black-hole is in a state of *continuous collapse*, the Past and the Future are not symmetric, and when we take this *asymmetry* as a boundary condition in the semiclassical approximation, a Quantum Field Theory predicts an outflow, essentially radiation, that is like the blackbody radiation of classical Thermodynamics. This means that the Energy-content of all infalling Matter is ultimately radiated away in a *finite* amount of Time. So, does an event horizon even form?
But suppose it does. Event horizons and, in a more specific way, singularities that indicate *divergent* behavior are usually considered bad news for a theory: *what breaks down is not Nature, but our mathematical model used to describe it, which means we are in need of a better model*! This is nothing new.
As a matter of fact, let's consider Newtonian Gravity, with the Potential given by

$$\phi_{\mathrm{g}} = -\frac{GM}{r} \ ,$$

which is singular at the center, at $r = 0$, by the way. Does this mean that there are singularities in Newtonian Gravity? Not at all. Rather, it turns out that $\phi_{\mathrm{g}} = -GM/r$ is just a limiting case, a mathematical abstraction that describes a hypothetical point particle; if we go a tad more sophisticated and write down *Poisson's equation* for Gravitation,

$$\nabla^2\phi_{\mathrm{g}} = 4\pi G\rho_M \ ,$$

then we have solutions that correspond to physical distributions of Matter (characterized by ρ_M, the Mass Density) and which are *nowhere singular*. So, the simplistic point-mass formula turns into the Green's Function used in the construction of solutions.
By this example, it's self-evident how physical theories often evolve, becoming more sophisticated. Mathematical oddities like singularities are often indicators that *more sophistication is needed*. But the improvements are often technical, nothing dramatic, nothing spectacular, just refinements of the models that offer more nuanced descriptions of Reality.

817 -

Is the force of Gravity instantaneous, or does it take time?

A force is neither instantaneous nor does it take time. It is simply a *relationship between things*, which affects their respective motion.
A change in the force (or rather, the underlying Potential Field) does, however, relate to Time: changes in the position of a magnet changes, the magnetic field around that magnet, and changes the Gravitational Field around that Mass in the configuration of Mass-changes.
These changes in the Gravitational Field, far from the source of the change, propagate as waves, much like the electromagnetic waves that we know as radio waves, light, X-rays, etc. And just like electromagnetic waves, changes in

the Gravitational Field, i.e., Gravitational waves propagate at the *invariant speed* of Relativity Theory, the speed we know as the Vacuum speed of light c.

818 -

What's the difference between the 'Higgs Field' and the Gravitational Field? Don't both create Inertia?

Other than being completely distinct things that have nothing to do with each other … the Inertia of a body, as we have known since Einstein's famous 1905 paper, is proportional to the intrinsic Energy-content of that body. That Energy-content can come in many forms. It can be Potential (*Binding*) Energy that holds the constituent parts of that body together (or, for that Matter, keeps them apart). It can be Kinetic Energy (e.g., Internal Thermal motion of constituent particles). And yes, it can be rest-Mass.
But rest-Mass is a tricky concept. For most things, rest-Mass it not so much an *intrinsic quantity* as it is just a label we attach to more Internal Energy-content that we choose not to enumerate.
For instance, the rest-Mass of protons or neutrons comes mostly from the positive Internal Energy-content due to the strong-force binding Energy. This binding Energy can be in the form of, well, pure Potential Energy, the Kinetic Energy of the constituent *quarks*, and the rest-Masses of those quarks themselves.
The Higgs Field enters the picture because as it turns out, even those quark rest-Masses are due to a Potential: The quarks interact with the Higgs Field (to be precise, with the Higgs Field's *non-zero Vacuum expectation value*) and the resulting positive Potential Energy is what we measure as quark rest-Masses. Overall, this amounts to roughly 1% of the rest-Masses of protons and neutrons; the remaining 99% is the Strong-Force Binding-Energy in its various manifestations.
As to Gravity, Gravity determines the *geodesic trajectories* that free particle follow. Gravity neither creates nor cares about Inertia, because we want to think of it in terms of Inertia, the Gravitational force and the (inertial) resistance to motion are both proportional to Inertia, so, Inertia cancels out altogether from the Gravitational equations of motion. In any case, to the extent Inertia is present in this picture, the Higgs Field contribution to Inertia for ordinary Matter is only about the 1%; the rest comes from elsewhere.

819 -

How is an electron theoretically massless?

[See also Issue 792 for further details]

The electron is not theoretically massless, but we can bet we know what inspired this question.
In the Standard Model of Particle Physics, all fermions (both quarks and leptons) start in the theory as massless fields. They do not have an inherent rest-Mass (the particle physicist would tell us that their Lagrangians contain no Mass term). Charged fermions do, however, interact with another field, a *complex-valued scalar doublet* that is known as the *Higgs Field*.
The fact that fermions are massless is important: it makes it possible for the theory to be *renormalizable*. In other words, a naïve calculation using the theory results in nonsensical infinities, but these infinities can be removed through a systematic, mathematically rigorous process. This would not be possible if the fermions of the theory had Mass to begin with.
The Higgs Field has many interesting properties. Among them, it is responsible for what is known as *Electroweak Symmetry Breaking*. Most fields are in their *lowest* Energy state when they are free of excitations (particles). For instance, the Electromagnetic Field is in its lowest Energy state when there are *no photons present*. Not so the Higgs Field: Its lowest Energy state is *when some excitations are present*. This means that *the Vacuum can decay* (enter a lower Energy state) by producing *excitations* of the Higgs Field.
This new, lowest Energy state then becomes the *new Vacuum*. But as a result, *charged fermions* interact with this Vacuum (the particle physicist tells us that the Higgs field in this Vacuum has a *non-zero Vacuum expectation value*), and this interaction behaves exactly *as though* those charged fermions, including the electron, had Mass.
So, to sum up, the theory does not say that the electron is massless. What it does say is that the Mass of the electron *is not an inherent rest-Mass* but an *effective rest-Mass* that arises from the electron's interaction with the Higgs Field and, specifically, its *non-zero Vacuum expectation value*.

820 -

Why can't light come back from black-holes?

The simplest answer is, for the same reason we don't see light coming back from *tomorrow*.
The event horizon of a black-hole, in the reference frame of any *outside* observer, remains *forever* in the Future. That is

to say, unless we fall into a black-hole, we will never get to see an *event horizon* but only the process of *forming* an event horizon. That process never ends: the ‘movie’ of that process *slows down exponentially*, never quite reaching the final frame, no matter how long we wait.
OK, we might say, but what if we fall into the black-hole with a flashlight and then shine that flashlight at the event horizon, where will that light go?
Again, we cannot. If we fall into a black-hole, the event horizon we cross becomes a *past moment in Time*. We cannot shine a flashlight at the event horizon anymore than we can shine a flashlight at Christmas Day last year. It’s in the Past. Whatever our direction we aim our flashlight at, it will be towards the Future, so to speak, not the Past.
Long story short, unless we have access to a bona fide Time-machine, nothing, no entity, or signal, can escape the event horizon because it would require *traveling backwards in Time*.

821 -

Can Gravity be *repulsive* according to General Relativity? How could this concept be tested through experiments?

Yes, Gravity *can* be *repulsive*. This is the reason why, in the Standard Cosmological Model, the expansion of the Cosmos has been accelerating for the past 5 billion years, give or take.
The *classical* field equation for Gravitation, Poisson’s Equation, writes:

$$\nabla^2\phi_{\mathrm{g}} = 4\pi G\rho_M\,,$$

where ϕ_{g} is the Newton’s Gravitational Potential, and ρ_M is the Mass *density*. The inverse-square law of Gravitation follows from this expression, when ρ_M characterizes a perfectly *compact* source.
However, classical Poisson’s Equation must be modified if the medium has *relativistic Pressure*, which is to say, when Pressure P is comparable in *order-of-magnitude* to ρ_M. In this case, we need to write

$$\nabla^2\phi_{\mathrm{g}} = 4\pi G(\rho_M + 3\mathsf{P}/c^2)\,.$$

The weirdest part is that relativistic Pressure *can be negative*. In fact, *only* values of P obeying the condition

$$|\mathsf{P}| \le \rho_M c^2$$

yields self-consistent Physics. But when

$$|\mathsf{P}| > \rho_M c^2\,,$$

the Universe *either* becomes *unstable* ($\mathsf{P} < -\rho_M c^2$) *or violates Causality* ($\mathsf{P} > \rho_M c^2$) because, e.g., the so-called ‘*speed of sound*’, $v_{U,\,\mathrm{rel}}\ (\lesseqgtr c)$, becomes larger than c.

A few details by C M, also as a review of **Issue 346**, P. 158, and elsewhere:

An Ideal *Relativistic* (Gravitational) Gas should be fed by this own Internal Energy, U. Such a gas is *highly rarefied*, so, $|U|$ tends to the value of the *Total Kinetic Energy*, K, of the free-particle motion,

$$|E| \equiv |U| \approx K\,.$$

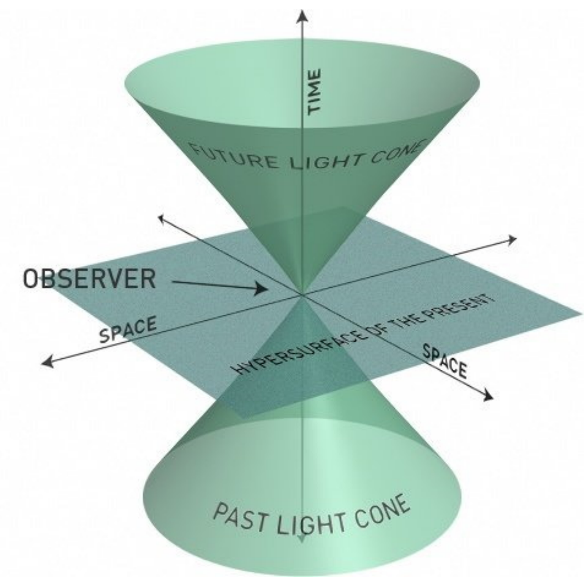
Then, the equivalence $|E| = Mc^2$ should correspond to a Mass-Energy conversion mechanism that, by taking place inside the two-nappe, ‘light cone’ $(v \lesseqgtr 0)$, allows for the *stability* of the Physical Universe and the plausibility of a Cosmic Thermodynamics. Therefore, any objection of a surreptitious introduction of ‘perpetual-like motion’ would vanish by the *Total* Energy Conservation Principle, raised to the *axiomatic extreme ultimate level*:

$$|U|\,(\approx K) = |\mathsf{P}|\,V = 2(1/2)\,M v_{U,\,\mathrm{rel}}^2 = \rho_M V v_{U,\,\mathrm{rel}}^2\,.$$

By getting rid of V between the 2nd and the 4th expression in the equality-chain just above, we get

$$|\mathsf{P}| = \rho_M v_{U,\,\mathrm{rel}}^2\,.$$

In this last result, $v_{U,\,\mathrm{rel}}\ (\lesseqgtr c)$ represents the analog of the classical (acoustic) *sound speed* in the *adiabatic* regime. $|\mathsf{P}|$, inside the (two-nappe) ‘light-cone’ must obey the *symmetric* constraint $|\mathsf{P}| \le \rho_M c^2$. When $|\mathsf{P}| = \rho_M c^2$, i.e., when P is evaluated just *at the surface* of the light-cone, it may happen that Dark Matter and its associated Dark Energy are generated.



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Thus, as for the Standard Cosmology 'Dark Energy' generation is concerned, we have

$$|P| \equiv \rho_M c^2 = \rho_M v_{U,\mathrm{rel}}^2 ,$$

which implies that, for Dark Energy, Poisson's Equation actually becomes

$$\nabla^2 \phi_{\mathcal{G}} = -8\pi G \rho_{M,\mathrm{DE}} .$$

The sign change vs. its classical counterpart may reflect the existence of solutions for possible *repulsive* Gravity.

822... -

By *Time curvature*, we mean regions where Time passes *more slowly*. But what is the *Space curvature*? After all, Space isn't made of nothing, it's empty, so how can something that has *nothing* curve?

Let's think about what we *can* measure. The issue makes sense, namely, that what we sometimes clumsily call ' Time curvature of Time' is indeed about the *rate of clocks*. When there is 'Time curvature', identical clocks at different locations will not tick synchronized. That is something that can be measured, e.g., an atomic clock at the top of a tall building will tick noticeably faster than the one at the ground floor.
So, what about curvature of Space? What can we measure? The easiest is to measure a triangle. Three 'straight' lines, forming a flat triangle, which, Euclid tells us, will define 3 angles that sum to 180°.
Or not. If they don't, it's because there is 'Space curvature'. Which is to say, instead of Euclidean Geometry, Space will have *non-Euclidean*, i.e., either *elliptic* or *hyperbolic Geometry*, thus violating Euclid's 5th 'parallel' postulate.

823 -

Why is our Universe considered flat with angles of a triangle adding to 180° degrees, when clearly SpaceTime is curved as Gravity, intrinsic curvature where the angles do not add to 180°?

We should not confuse *Spatial curvature* with *SpaceTime curvature*.
The geometry of SpaceTime involves both Space and Time, *Newtonian Gravity maps into the Time part*. Contrary to stylish but ultimately grossly misleading imagery that often accompanies popular science articles introducing Gravity and Relativity Theory, *Newtonian Gravity is not about bending Space: it is primarily about changing the rate at which clocks tick*.
This can be measured. E.g., an atomic clock at the top of a tall building ticks noticeably faster than the same clock at the ground floor (it is also accounted for in GPS navigation, for instance).
In contrast, Spatial curvature here, on the surface of the Earth, contributes no more than a few parts per-billion compared to the Newtonian part.

Now this is Spatial curvature in the presence of a *gravitating body*, such as the Earth.
When we talk about the Universe, we're not talking about *local gravitational fields*, but large, cosmic scales. We know that the Universe expands (plenty of evidence supporting this conclusion) and we know, therefore, that the average Gravitational Field changes over Time. That is the reason for *cosmological redshift*: when we look at very distant objects, much of the redshift we see is due not to the fact that they are receding from us (they do), but due to *gravitational Time dilation*, i.e., the rate at which clocks tick now vs. the rate at which they ticked back then.
But the question is, what about Space? Is there noticeable Spatial curvature on cosmic scales? *We see no evidence of that*. In fact, every indication is that the Universe, *on average*, is *spatially flat*.
Now the equations tell us that if the Universe is close to being spatially flat today, it had to be astonishingly close to being spatially flat in the distant past, because Spatial curvature increases over Time. Something astonishingly close to 0 just does not sit well in a fundamental theory. So, the prevailing assumption is that no, it's not astonishingly close to 0; it is 0 or, at least, we assume that it is 0 until and unless we see evidence to the contrary.

824 -

What is the *Higgs Field* explained simply?

The Higgs Field is one of the fields of the Standard Model of Particle Physics. What do particles have to do with fields? In in Quantum Field Theory, 'particles' are *quantized excitations* (units of Energy) *in a field*. Take the Electromagnetic Field, for instance. Light is *electromagnetic radiation*. It is a wave: countless experiments demonstrate its wave-like properties. Yet, when we let light interact with a sensor, we find that the Energy-content of the Electromagnetic Field is transferred to the sensor one unit of Energy (one 'photon') at a time (confusingly, *this is not* what people are talking about when they discuss *wave-particle duality*).

So, in this sense, the Higgs Field is – just like the Electromagnetic Field – the *electron-Field*, the fields associated with other charged leptons, quarks, neutrinos, vector bosons, gluons.
Fields interact. E.g., the *electron-field* can interact with the Electromagnetic Field: we experience this, e.g., when an excitation of the electron-field, i.e., a *charged* electron, accelerates and this creates *electromagnetic radiation*.
The Higgs field interacts with other fields, too. But the Higgs Field has one more curious property. Usually, a field is at its *lowest-Energy state* when it has no excitations. The Higgs Field is different: its lowest-Energy state is an *excited* state. It has a non-zero 'Vacuum expectation value'. What this implies, however, is that the Vacuum (containing the Higgs Field with no excitations) can decay into a *new* Vacuum state, in which the Higgs Field has some excitations, but the overall Energy-content is *lower*.
This has very crucial implications, because in this new configuration, we now have other particles interacting with what appears to be the Vacuum, which contains these *Higgs excitations*! The effect of this is that these other particles, which originally had no rest-Masses, now have Potential Energy by way of these interactions. And as we know, *Energy is Mass*. This is how several particles of the Standard Model become *massive*.
And the reason why this is important is that, by starting with originally massless particles, the Standard Model can be mathematically consistent ('*renormalized*'): the Higgs Field yields *massive particles*.
As an important side-note, it should be mentioned that the Higgs Field has nothing to do with Gravity (not directly; Gravity is sourced by Energy-content, but the Higgs coupling is not in any way special in this regard) and roughly 99% of the Mass of ordinary Matter has nothing to do with the *Higgs mechanism* (it is the Energy-content due to the Strong Interaction Binding Energy).

825 -

Does Quantum Mechanics contradict Determinism?

Quantum Mechanics says nothing about Determinism. In its canonical form, by way of Schrödinger's equation, it simply tells us how a particular mathematical entity, namely the *wavefunction*, representing the state of the system, *evolves*.
Interpretations of Quantum Mechanics, on the other hand, are a different story. The most popular 'Copenhagen' interpretation of Quantum Mechanics treats the wavefunction as a *probability amplitude*. The interpretation introduces the concept of a 'measurement' (an act that *is not* described by Quantum Mechanics itself) that replaces the state of the system with an 'eigenstate', *one of the many possible outcomes of that measurement*. The wavefunction can be used to compute the probabilities associated with the various outcomes.
If this 'collapse of the wavefunction' really happens (so-called 'objective collapse') that would make the Physics non-deterministic. *The present state of the system only determines the probabilities of the various possible outcomes of the measurement*.

But before we conclude that 'objective collapse' is the way to go, I'd advise caution. This whole 'collapse' business is introduced for reasons that are philosophical, not physical. What Physics (Math, actually) tells us is a different story.

The full present state of the system is not knowable from Classical observables. Quantities that characterize the present state cannot be localized in Space or Time. This implies that some of these ‘hidden’ properties of the system may, in fact, be constrained by future events. Seemingly paradoxically, this does not actually violate Causality: despite being fundamentally non-local, the Quantum Theory (at least in the form of Quantum Field Theory) cannot be used to send signals from the Future to the Past. Nonetheless, this non-local business is disturbing. It is resolved if we assume that no, the Future does not constrain the Present, rather, the actual Future happens because the act of measurement causes the system to collapse (again, objective collapse)! Unfortunately, that seems like a cure that is worse than the disease: this collapse has to happen simultaneously in the entire Universe (after all, we replace one non-local description of the state of the system with a different one) including not just all locations but all times!
OK, so what if we don’t go so far? Sure, ‘collapse’ is a useful concept to deal with practical scenarios, e.g., when the instrument is obviously a macroscopic object (say, a cat) and its state is never in doubt (no one has ever seen, or will ever see, a cat that is *both alive and dead*). But then we have an important point to ponder: sure, we use ‘collapse’ as a practical tool, but we know well that, in reality, things very seldom collapse, and the wavefunction simply evolves towards a near-eigenstate because it is constrained by a future measurement. In other words, we’d be taking the non-locality of Quantum Physics literally.
In this case, we have a theory that is deterministic but non-local. Yet, in the form of Quantum Field Theory, it would still be a theory that respects Causality, with no faster-than-light or backwards-in-time influences, ever.

I’m personally in favor of this viewpoint so my immediate reaction to the question is that yes, Quantum Physics *is deterministic*. I recognize though that there are many other popular interpretations, but in the end, all this interpretation business is firmly in the realm of Philosophy, *not Physics*. Instead, the equations are *the same*, the predictions are *the same*, the results of experiments are *the same* no matter what philosophical baggage we attach to them, mostly just to resolve the cognitive dissonance that the weirdness of the Quantum World can produce in our minds.

826 -

If Gravity is a *warping* of SpaceTime, why is it that we see no distortions in our *visual* field?

Well, the main reason is that Newtonian Gravity is primarily about distortions of Time, i.e., the rate at which clocks tick. The stronger the Gravitational Field, the slower the clocks tick in it compared to other clocks situated elsewhere. *Compared to this temporal distortion, spatial distortion is exceedingly tiny*.
As a matter of fact, the temporal distortion is tiny, too. Here on the surface of the Earth, terrestrial Gravity alters the rate of clocks by roughly one part in a billion compared to clocks in deep space. It would take several decades before the difference between two such clocks reach 1 second.
Yet the distortions are visible, just not with the naked eye. In 1919, an expedition lead by Arthur Eddington was measuring just that: the visual distortion due to the Sun’s Gravity during a total solar eclipse. As expected, some stars that appeared near the solar disk (its light blocked by the Moon) were displaced by a tiny amount. How much tiny? About 1.75 arc-sec. For comparison, that would be like looking at an object that is 1 mile away, and noticing that it is displaced by about 1.27 cm.
Curiously though, in the case of light both spatial and temporal distortions play an equal role. So, half of that 1.75 arc-sec was due to *temporal* distortion, but the other half was due to *spatial* distortion. As a result, this value is 2 times the value one would predict using Newtonian Gravity. This was therefore seen as a much-celebrated confirmation that Einstein’s Theory of Gravitation is the correct one.

827 -

Is Dark Energy a *scalar* field like the Higgs Field, for example?
[compare with Issues 60, p. 25, and 821, p. 363]

We don’t know what Dark Energy is. Its properties are not consistent with the *kinetic* term of a scalar field, like the Higgs’. Its properties may be consistent with a *strong self-interaction Potential function* in a hypothetical scalar field.
In other words, for a massless scalar field, its equation of state would be something like

$$w = \frac{\dot{\phi} - 2V(\phi)}{\dot{\phi} + 2V(\phi)} .$$

For Dark Energy to form, $w = -1$, which we get if $V(\phi)$ *dominates* in the preceding expression. Therefore, if the self-interaction term dominates, it behaves as a *perfect fluid* with *negative pressure*, which is the behavior of Dark Energy.
The Higgs Field does not work this way. The *scalar doublet* does not have this kind of behavior, and as for the Higgs boson after *symmetry breaking*, it would be a *massive* but *unstable* particle to begin with, so the *wrong* candidate.

828 --

Is *light* both a particle and a wave at the same time, or is it sometimes a particle, and sometimes a wave, or does it appear to be one or the other depending on how we look at it?

None of the above. What we call light is an excitation of the Electromagnetic Field far (at least, a few wavelengths away) from any source. These excitations are governed by a wave equation, so that are called *Electromagnetic Waves*.
But the Electromagnetic Field itself is a *quantum field*, which means that its behavior *is not like that of a classical medium*. Classical things have well-defined *positions* and *momenta* (both Linear and Angular). These positions and momenta are represented by *numbers*. Quantum things only have *states*; these states are interpreted as *probability amplitudes* that tell us how likely we are to measure certain values of positions or momenta if we were to measure the thing. *These states are governed by a wave equation*, the *Schrödinger Equation* (nothing to do with the wave equation we mentioned above).
Moreover, when the Quantum Field is a thing, its *excitations* come in *well-defined units*. When the field interacts with something else, the number of excitations is bumped up or down. These interactions are often perceived as *highly localized*, i.e., they will register in measurements as 'particles'.
So, *light is not a wave nor a particle*. Light is a propagating change in the Quantum Electromagnetic Field, a change governed by a wave equation of a field, the state of which is governed by another wave equation, the solutions of which are *quantized excitations* that *may* appear as particles.
And that is the simplest way that we can express this without omitting anything essential.

829 -

In 3 dimensions, Cartesian coordinate systems are *distinguishable* from their *mirror images*. What is the situation in $3+1$ dimensions and how many inequivalent images are there? [cf/c answer to Issue 713, P. 316]

SpaceTime, with its 3 *spatial* dimensions and 1 *temporal* dimension, has two '*mirror*' *symmetries*: *Parity* and *Time-reversal*. Parity is what we get when we look at things in a mirror. Time-reversal is what we get when we play the movie backwards, so to speak. These are important in Particle Physics. Most of our Laws of Physics remain *unchanged* under a Parity transformation: we cannot tell if we are watching an actual Physics experiment or its mirror image, as they both obey the same set of equations. But there are some exceptions, e.g., neutrinos and their mirror images *are not* equivalent.
Similarly, most of the laws of Physics are the same under *Time-reversal*: when we look at particle interactions, for instance, we cannot tell if the movie is being played normally or backwards, as the same equations apply in both cases. But again, there are subtle exceptions.
An important result is that when we simultaneously form a mirror image, play the movie backwards, and replace particles with anti-particles, the results are indistinguishable from Reality. *The Laws of Nature are invariant under a CPT* (*Charge-Parity-Time*) *transformation*.
But what about Thermodynamics, we might wonder? Entropy picks a direction of Time that cannot be reversed! True. But the underlying Laws of Nature are still CPT symmetric. What sets the direction of Entropy are *initial* or *boundary conditions*. If we set up a physical system in a *low Entropy* initial state and leave its final state unconstrained, it will evolve *from low to high Entropy*, even though the Laws governing any individual particle are symmetric under Time-reversal. As far as we know, the early state of our own Universe was such a *low* Entropy state, and the Future of our Universe is *unconstrained*. Hence, we have an 'arrow of Time' even though Physics is governed by fundamental Laws that are invariant under a CPT transformation.

NGC 2936, the PORPOISE GALAXY

'*The starry sky above me, the moral law within me*' (I. Kant, CRITIQUE OF PRACTICAL REASON)

830 -

Does the existence of *Hawking Radiation* suggest that nothing truly enters a black-hole?

It might. The jury is still out, given that Hawking Radiation represents an approximate solution to a rather tough family of problems. But first, the most relevant things.
First and foremost, black holes are *mathematical abstractions*, i.e., they are neat mathematical solutions to Einstein's Field Equations, but as we know thanks to Oppenheimer and Snyder's landmark 1939 paper and many other studies on the subject since, we know that the black hole is the 'asymptotic end-state' of Gravitational collapse. In other words, a black hole is what an *outside* observer would see after waiting an *infinite* amount of Time. At any *finite* Time, no matter how far into the Future, the observer would see 'continued contraction' (an expression used in the title of the paper by Oppenheimer and Snyder), subject to ever greater *Time dilation*, never ending, never reaching the end-state characterized by an event horizon.
An infalling observer, however, would supposedly reach the event horizon after a *finite* amount of measured (*proper*) Time. The horizon, for this observer, is a *moment in Time*: once it is reached, there is no going back, as a return to the horizon would necessitate Time travel to the Past. That's the Classical picture.

Now, enter Quantum Field Theory, in a so-called *Semi-classical approximation*. First of all, forget that neat but fundamentally incorrect depiction of particles and anti-particles created near the horizon, one with positive, one with negative Energy, with the latter swallowed by the black hole. Yes, this depiction comes straight from Hawking's book, even though it contradicts his own 1974 landmark paper that reveals the true nature of Hawking Radiation. It has to do with collapse. Namely that a black-hole is, as Oppenheimer-Snyder told us, in a state of continued contraction. This means that the Past and the Future *are not symmetric*. Let's express this statement in the language of Quantum Field Theory, in the presence of the strong Gravitational Field of the collapsing object and presto: we get *outgoing radiation*. The characteristic wavelength of that radiation is roughly 20 times the Schwarzschild Radius of the black hole that is yet to be formed.

The consequence of Hawking Radiation is that the Energy-content of the collapsing object evaporates in finite Time. A very, very long Time to be sure, but *finite*.
This statement seems to suggest that, in this case, no event horizon ever forms in the first place. We may be inclined to jump to that conclusion, but we need to be careful. The Semi-classical picture if fraught with traps for the unwary. We treat Gravity in this scenario as *entirely Classical*, ignoring any possible contributions from Quantum Gravity. And of course, part of the problem is that all this is the kind of Physics that may remain *forever untestable*. To create an experiment, we'd need to create black holes which requires several times more Mass than the Mass of our entire solar system. Then we'd have to wait an unimaginably long number of years, typically characterized by a 70- digit number, give or take, before the evaporation completes. Throughout most of this Time, Hawking Radiation is so incredibly weak, no conceivable instrument, present or future, can detect it (don't be misled by breathless pronouncements of laboratory 'black-holes' these are analogous experiments that, at best, replicate some superficial aspects of black-holes).

831 -

What effect does Gravity have on a photon moving directly away from a *massive* object?

We stumbled upon one of the three 'classical tests' of General Relativity Theory proposed by Einstein when the theory was new. The other two are the anomalous perihelion advance of Mercury and the bending of rays of light by a Gravitating body.
This one, however, is about *redshift*. Namely that rays of light, photons, arriving from a '*deep Gravitational well*', will appear to have lost energy. Key to understanding this is *Gravitational Time-dilation*: remembering that a 'perfect clock' appears to tick more slowly when in a Gravitational Field, compared to an *identical* clock that is far from any Gravitational source.
So then, let's imagine a ray of light, say, a very *blue/violet* ray of light with a wavelength of 400 nm leaving the surface of a compact, heavy object. Moreover, let's suppose that the object is so heavy that clocks there appear to tick at a rate that is $2/3$ the rate of a clock in deep space, far from sources of Gravitation. That 400 nm light ray corresponds to an Electromagnetic Field that oscillates $750\cdot10^{12}$ times-per-second (750 THz). That is, $750\cdot10^{12}$ oscillations while a clock near the light source counts 1 second.

Now, let's imagine someone in deep space detecting this light ray. That person uses *his own clock* to measure Time. and *his own clock* appears to tick *faster*. While the clock on the surface of the object counted 1 second, this clock in deep space will have counted 1 second $3/2$ times, which is to say, 1.5 seconds. Hence, it takes 1.5 seconds to receive those $750\cdot10^{12}$ oscillations, which means that in 1 second, this detector will have seen only $500\cdot10^{12}$ oscillations. In other words, it will have observed that light ray at 500 THz, not 750 THz. The corresponding wavelength, then, is not

400 nm but 600 nm . What started off as *very blue* light arrives at the detector as light that appears very much more like *orange*. And this, then, is the effect of Gravity on a photon. As it climbs out of the '*Gravity well*', the photon *loses* Energy, which is to say, its characteristic frequency *shifts down* while the corresponding wavelength *increases*.

832 -

Is a *single* electron considered an *actual* particle in Quantum Mechanics, or is it always just a *wave-packet* with definite properties at any given Time?

In Quantum Mechanics, a particle, like an electron, is always a particle, an *actual*, *immutable* particle.
The waves (which is to say, the *wavefunction*) determine the *physical properties*, including the *position* and *momentum* of this particle. In the Copenhagen interpretation, this wavefunction is interpreted as a *probability amplitude*, and it is used in conjunction with the concept of an idealized, *classical* measurement apparatus, to compute the probability of finding the electron somewhere, or moving with some momentum.

In Quantum Field Theory, there are no particles, *only fields*. The fields are *quantum* fields, which is to say, just like the position of that electron in Quantum Mechanics; the field *does not* have definite values at specific *places* and *times*; rather, a wavefunction determines (at least, in the Copenhagen interpretation) the probability of finding the field with specific values at specific places and times.
However, another property of these quantum fields is that when they *interact*, their values go up or down one unit at a time. It is these *unit excitations* that we observe, in *localized* interactions having a particle-like behavior.

So, to sum up/reiterate, in Quantum Field Theory, an electron is an *excitation* of the corresponding *fermionic field* (the *electron-field*). The *field wavefunction* (not to be confused with the field proper!) may be interpreted as a probability amplitude that tells us the *probabilities of finding the field in a definite state* using a *classical* instrument. *Interactions* between fields *create* and *destroy* excitations ('particle'-analogs).
In contrast, *quantum mechanical particles* are *eternal*, there are *no fields*, and the wavefunction can be interpreted as a probability amplitude that tells us the probability of finding the particle in some state somewhere using a *classical* instrument.

833 -

A photon has no rest-Mass, but something called relativistic Mass. What is relativistic Mass?

The concept of relativistic Mass thankfully fell into disuse in recent decades. It is based on what really is a gross misapplication of the fundamental formula,

$$E = mc^2 ,$$

the Mass-Energy equivalence. Energy is Mass, right? So, if a photon has Energy, it must contribute to its Mass, right?
Not so fast, anyway. Einstein's original 1905 paper on the subject used a very clear expression in its title: Energieinhalt, or *Energy-content*. Energy associated with motion, Kinetic Energy, is not 'Energy-content'. *It depends on the observer*.
A moving train has a lot of Kinetic Energy in the station's reference frame, but what happens in the train's own reference frame? There, it is *stationary*, and its Kinetic Energy is 0 . In fact, from the train's perspective it's the station that's moving backwards. Why on Earth would the train's Mass be affected by the fact that some distant stations are moving relative to it?
And of course, the answer is that it isn't. As a matter of fact, when we look at that formula again, we might realize that it is just a special case of what is known as the *dispersion relation*:

$$E^2 = (mc^2)^2 + (pc)^2 ,$$

where p is the object's Linear Momentum (quantity of motion). So, $E = mc^2$ is valid only when $p = 0$, i.e., *in the object's own reference frame in which the object is at rest*.
Photons have no such reference frame because *they are never at rest*. For photons, $m = 0$ and the dispersion relation becomes instead $E = pc$.
The photon's Energy is proportional to its Linear Momentum; its speed is always the Vacuum speed of light, c, *in all observer reference frames*.
Having said that, it is possible for photons to contribute to rest-Mass, albeit indirectly. For this, imagine a box lined on the inside with *perfect* mirrors. Let in some light. That light will continue to bounce back-and-forth forever. Now let's try to push the box. The near wall of the box will also accelerate some photons (that is to say, add to their Kinetic Energy) when they bounce off it while we're pushing. Meanwhile, the far well, accelerating away from the photons, will receive

a little less help from the photons while you push. The net result is that it is a bit harder to push the box with the photons inside. The box's inertia, its rest-Mass, increased a little. By how much? We guessed it: exactly by the amount of Kinetic Energy that those photons carry, as measured in the box's own CM reference frame.
But this is not really the rest-Mass of any individual photon. Rather, it is the Energy-content of the 'photon gas' that fills the interior of the mirror-lined box.

834 -

Near the Earth, in the Newtonian limit, Gravity is $00.9999\,\%$ due to warping of Time (the 'Gravitational Time-dilation') and only about $0.0001\,\%$ due to the warping of Space. How do we calculate these values?

The actual calculation gets a little bit involved, as it requires writing down the equations of motion (geodesic equations) of a particle in the Schwarzschild metric (characterizing the Gravitational Field of a spherically symmetric body outside of that body) and then using a suitable approximation, such as the *post-Newtonian approximation*, to find approximate solutions.
However, the result, especially for a particle initially at rest, is simple. Its initial radial acceleration in the Gravitational Field of a mass M is given by

$$a = -\frac{GM}{r^2}\left(1 - 2(\beta+\gamma)\frac{GM}{c^2 r}\right).$$

The first part of the expression on the right-hand side is just the Newtonian acceleration (inverse square law). It is, however, multiplied by the term in parenthesis, which contains contributions both due to the *non-linearity* of Gravity, characterized by β, and the *spatial curvature*, characterized by γ.
For General Relativity, $\beta = \gamma = 1$, but these so-called *Eddington parameters* can also accommodate alternative theories of Gravitation. When we calculate the magnitude of the correction, it comes to about 2.8 parts per 10^9, give or take, here on the Earth's surface.
Once the particle is in motion, the post-Newtonian equation of motion becomes more complicated, but this simple expression should give us an idea as to the magnitude and nature of the correction (see also

https://descanso.jpl.nasa.gov/monograph/series2/Descanso2_all.pdf

where these so-called *post-Newtonian equations* of motion are discussed in detail and put to practical use).

835 -

If light does not have Mass, then how can it be absorbed by a black hole?

There are several ways to answer this question. Here are three that we can think of right away:

First answer: Photons have no rest-Mass. However, Gravity acts on the total Mass-Energy of an object, of which rest Mass is just one part. Photons certainly have Kinetic Energy.

Second answer: Einstein's Gravity is a geometric theory. The presence of a Mass (including the Mass of a black hole) changes the geometry of SpaceTime, in particular, changes the geodesic structure of SpaceTime. Massive particles affected only by Gravity follow what are called 'Time-like' geodesics. Particles with no rest-Mass travel at the speed of light and follow what are called 'light-like' or 'null' geodesics. Both types of geodesics are altered by the presence of a gravitational source. So, both massive particles and photons will appear to be 'attracted' by Gravity, as their trajectories change.

Third answer: A fundamental property of Gravity is the Weak Equivalence Principle, namely that the motion of a test particle is determined by its Mass alone, and not its material composition. In the field theoretical view, this is translated into the notion that the Gravitational Field couples to everything else *universally* and *minimally*. 'Universally' means that there are no exceptions: 'minimally' means that Gravity does precisely two things: it tells us how to compute the inner products of vectors, and it tells us how to compute the volume of small regions of SpaceTime. As these rules apply to everything, they certainly apply to the Electromagnetic Field (which, in 4-dim, is characterized by a 4-dim vector field) and its Vacuum solutions (light).

These three explanations really describe the same set of fundamental properties of Gravity, they are just different ways to think about them.

836 -

Does the ‘Measurement Problem’ of QM remain in QFT?

The so-called ‘measurement problem’ is a problem related to how Quantum Mechanics is interpreted, not an actual issue with the theory (in other words, we don’t even need to know about the existence of this problem to work as capable, competent, productive physicist. The ‘problem’ is more of a philosophical issue than an issue with Physics).

My personal take (I call it ‘personal’ because it may not represent the thoughts of most physicists, though I am sure that at least a sizable minority share my view): it is an entirely artificial, apparent paradox. It arises because of how the measurement is envisioned. We envision a quantum system that just evolves in its own merry way, until suddenly, like some *deus-ex-machina*, the Universe changes as the classical measurement apparatus appears out of thin air, changing the boundary conditions of the system. Yet, we are surprised that suddenly, we have a discontinuous jump from a pre-measurement state that is a superposition of eigenstates to a post-measurement state that is an eigenstate with respect to the quantity being measured. This discontinuous jump is not described by the rules of Quantum Mechanics, and it is not a unitary evolution of the system, so we have a problem on multiple fronts: the ‘measurement problem’.

Let’s imagine instead making the classical measurement apparatus part of the system all along. Even if the quantum system that we are modeling is initially not interacting with the apparatus, the presence of the apparatus (e.g., represented by a Lagrange multiplier) is incorporated in the description in the form of a *boundary condition*. In this case, the wavefunction’s evolution will be unitary, even as it is confined to an eigenstate when it interacts with the apparatus. Of course it makes the theory manifestly *non-local*, since it implies that the wavefunction somehow ‘knows’ about a future interaction with the apparatus as it evolves. But that should hardly come as a surprise, given what we know about Bell’s inequality, for instance: sure, Quantum Mechanics is manifestly *non-local*. But in this description, there is no wavefunction collapse, no non-unitary evolution, no ‘measurement problem’. And there is still no classical non-locality: though the theory is manifestly non-local, it cannot be used to communicate *classical* information from the Future to the Past.

I think this is a little easier to conceptualize in QFT than in QM (QFT certainly helped in my case) but no, this does not mean that the 'measurement problem' does not exist in QFT. In other words, if we envision (incorrectly, in my opinion) the measurement by allowing the measurement apparatus to appear suddenly, out of thin air’, we have a problem in both QM and QFT.

837 -

Is Gravity both the force that Matter exerts upon SpaceTime, causing it to distort, and the force that directs Matter along the curvatures of distorted SpaceTime? Or are these two different forces?

Let’s not overthink it. Gravity is the force that pulls a brick out of our hands, accelerates it towards our feet, causing a rather painful impact. Gravity is the force that keeps the Moon orbiting the Earth, or the Earth orbiting the Sun. A spade is a spade is a spade, as the saying goes.
The explanation for the Gravitational force entails the recognition that *Gravity is universal*: it affects all forms of Matter (and by ‘Matter’, I really mean everything, the most general definition possible, including even things like light) equally. As such, not only can it be modeled using geometry (other forces can be modeled using geometry, too, with caveats), but in Gravity’s case, the geometry is the only geometry possible, as no material object (including clocks and meter sticks) can measure anything different. In short, instead of modeling Gravity as a force that pulls things away from moving in a straight line, we model *Gravity as geometry*, which distorts straight world lines into curved ones.
Without unduly complicating matters, the Gravitational force, then, is no different from the *centrifugal* ‘*force*’. It is often referred to as a pseudo-force (the real force being the string or whatever it is that holds the object in circular motion instead of letting it fly away) but explain that to an astronaut-in-training who sits with bulging eyes in a centrifuge while his body parts are weighed down by several g ’s of centrifugal force. Just like the centrifugal force, the Gravitational force exists (as a *pseudo-force*) because we are measuring it in an *accelerating reference frame*. In the case of the centrifuge, the acceleration is due to the apparatus that forces an object or an astronaut to undergo circular motion. In the case of Gravity, the acceleration is due to the *distortion of SpaceTime*, in combination with the presence of a floor or whatever else it is that prevents us from falling and following a geodesic trajectory.

838 -

What is m in $F = ma$, *rest*-Mass, *inertial* Mass, *variable* Mass, or *Gravitational* Mass?

Such an old question, yet without a decent answer! The mass in $F = ma$ refers to inertial Mass. *Inertia characterizes a body’s resistance to a force*. We can see how, when we divide this equation through the Mass m , $a = F/m$. Which is to say that given a force, a body's resulting *acceleration* is proportional to that force, but inversely proportional to the body's Mass. *The greater the Mass, the smaller the acceleration: a body with more Mass has more Inertia, more resistance to motion.*

The term 'rest-Mass' is synonymous with inertial Mass. Consider, in fact, the title of Einstein's famous $E = mc^2$ (1905). This paper establishes the equivalence of *Energy-content* and *inertial Mass*.

The term 'rest-Mass' means the same as inertial Mass. It came into usage along with another term, 'relativistic Mass', which combines the inertial Mass of a body (which is an intrinsic property) and its Kinetic Energy (which is observer-dependent). Fortunately, this concept is not much used anymore as it is grossly misleading and has been the source of much confusion. We can guess that 'variable Mass' in the question may have referred to this relativistic Mass.

Gravitational Mass measures how a body interacts with the Gravitational Field. According to the Weak Equivalence Principle, *Gravitational Mass and Inertial Mass are identical*. This is what allowed Einstein to generalize his original Relativity Theory (now called Special Relativity) and extend it to become a *Field Theory of Gravitation*. A theory that treats inertial and accelerating reference frames the same way (Einstein's original objective) naturally becomes a theory of Gravitation when the reference frame associated with falling in a Gravitational Field *does not depend on the material properties of the falling object*.

So, to sum up, the Mass m in $F = ma$ is Inertial Mass; it is the same as rest-Mass; thanks to the Weak Equivalence Principle, it's the same as Gravitational Mass; as to the concept of variable (relativistic) Mass, the best advice is to forget we ever heard about such a thing.

839 -

The two *Bell's Theorems* of John Bell

[a guest contribution by Howard M. Wiseman, Director, Centre for Quantum Dynamics, Griffith Un., Brisbane, AUS]

Many of the heated arguments about the meaning of *Bell's Theorem* arise because this phrase can refer to two different theorems that John Bell proved, the first in 1964 and the second in 1976. His 1964 theorem is the incompatibility of quantum phenomena with the dual assumptions of locality and determinism. His 1976 theorem is the incompatibility of quantum phenomena with the unitary property of local causality. This is contrary to Bell's own later assertions, that his 1964 theorem began with that single, and indivisible, assumption of *local causality* (even if not by that name). While there are other forms of Bell's theorems – which I present to explain the relation between Jarrett-completeness, 'fragile locality', and EPR-completeness – I maintain that Bell's two versions are the essential ones. Although the two Bell's theorems are logically equivalent, their assumptions are not, and the different versions of the theorem suggest quite different conclusions, which are embraced by different communities. For realists, the notion of local causality, ruled out by Bell's 1976 theorem, is motivated implicitly by Reichenbach's Principle of common cause and explicitly by the Principle of Relativistic Causality, and it is the latter which must be forgone. Operationalists pay no heed to Reichenbach's Principle, but wish to keep the *Principle of Relativistic Causality*, which, bolstered by an implicit 'Principle of *agent-causation*', implies their notion of *locality*. Thus, for operationalists, Bell's theorem is the 1964 one and implies that it is determinism that must be forgone. In my presentation, I will discuss why the two 'camps' are drawn to these different conclusions, and what can be done to increase mutual understanding.

840 -

Why does a particle have a *spin*?

It doesn't. Physicists borrow words from everyday language and use them as their jargon. Nothing is literally, physically spinning.

The word (and concept) of the 'particle' is a holdover from the early days of Quantum Physics when that was the way physicists thought and talked, but ever since QFT was developed, there's a new paradigm which dispenses with that misleading idea of particles, even though the word persists in the Quantum Physics narrative. QFT emphasizes the primacy of the *FIELD*, which oscillates due to the dynamics of the force interactions which generate fields, and when two oscillating fields interact (such as detection), the fields, which are contiguous, undergo an excitation of the field which is not contiguous; it is incremental, hence the concept of the quantum, a word which literally means 'minimum quantity'. All this time physicists have been talking about a moment in Time, the quantum, as if it is an object when in reality it is a measurement, the minimum quantity of Energy content that can be detected in a given field. A 'particle' is the localization in Time and Space *of the interaction of two oscillating fields*.

841 -

How can the Universe be *infinite* if it had a *finite* beginning size, and a *finite* growth speed?

A Universe that is *finite* at the beginning is going to remain *finite*. Its lifetime is finite, and it ends up collapsing.
Our Universe is believed to be *infinite* (or, at the very least, the best mathematical model that fits the *visible* Universe describes an *infinite Universe*). That means that *it was always infinite*, *even at its earliest moments*.
At this point, it is helpful to remember that the exact moment of the beginning, the 'initial singularity', the moment of the Big Bang, *is not part of the Universe's history*. And no matter how tiny a Time interval after this initial moment we are talking about, we find a Universe that is extremely (*but not infinitely*) dense, extremely (*but not infinitely*) hot, and *infinite in Space*.

842 -

The Mass of a proton *increases* in LHC near the speed of light. Since a proton is composed of 2 up and 1 down quarks, which of these Masses is increasing?

The Mass of a proton *does not* increase in the LHC.
So, what is it, then, that we keep hearing about the Masses increasing? It's people relying on a dated concept in Relativity Theory, lumping together the rest-Mass of the proton, which is an *intrinsic property*, and its *relativistic Kinetic Energy*, *which depends on the observer*.
Now, why would a proton care about the fact that (with respect to its own frame of reference, in which it is sitting still) we are moving at nearly the speed of light when we are observing it? Why should its Mass change just because some observers are moving very fast? And which observer's measure of Kinetic Energy should be considered part of the Mass increase?
Of course it doesn't. Its Mass *does not change*; *it is always the same* (and incidentally, only about 1% of its Mass is due to the quarks it contains; the remaining 99% is the *strong force* Binding Energy that holds the quarks together).
So, while it is true that Mass and Energy are really the same thing, it is still not a good idea to lump together Mass-Energy that is *intrinsic* to an object with Mass-Energy that depends on the *relative motion* of the object vs, the observer reference frame. This is why Kinetic Energy *should not* be considered part of an object's Mass.

843 -

When a particle is being observed, does its wave function collapse into a size-less point, or a very small Gaussian packet?
We don't observe particles. We observe *specific properties* of particles when we measure them.

In an idealized measurement, when we measure a particle's *position*, for instance, it means we ensure that the particle interacts with a *classical instrument* that confines the particle's position to a specific number (an eigenvalue). Consequently, its *momentum* is completely *unconfined*.
In a real measurement, our measuring instrument itself is made up of particles, so it's not a purely classical instrument. Therefore, it does not perfectly confine the particle position to a number. Interpreting the particle's state as a *probability amplitude*, it indeed means that, as per our measurement, we have something like a *Gaussian probability distribution characterizing the particle's position* (or whatever property it was that was being measured).

844 -

Hypothetically, if we were carrying a torch, entered the black-hole and switched it on, then what would we see?

Nothing special, actually. For the sake of this thought experiment, let's assume that the black hole is

a. a supermassive black hole (so that tidal forces don't kill you at its event horizon, and you can live longer than mere milliseconds after reaching the horizon),

b. fully formed (an actual, physical black-hole is always in the process of formation insofar as external observers are concerned; as an infalling observer, you'd be witnessing that formation, i.e., you'd be surrounded by all the matter and radiation ever consumed by that black-hole),

c. it's in an otherwise empty universe (so we don't have to worry about, e.g., you being killed by starlight blue-shifted into hard X-rays as you fall deeper in the black-hole's gravity well even before hitting the horizon) and d) there is no Hawking radiation or other semiclassical effects…

So really, just a purely geometric black-hole, Schwarzschild's Vacuum solution in other words, with a Mass parameter large enough to be survivable at least for a few seconds.

What would we see? *Absolutely nothing*. Before or after the horizon, we are still in *empty Space*. Our torch will reveal nothing. In fact, without detailed calculations, we would not even know when we crossed the horizon; to us, everything would continue to appear normal in our vicinity, just like before.
If we are freely falling, just wearing a spacesuit, we'd feel like floating in empty Space. *No change when crossing the horizon*. If we're inside a spaceship, everything would appear perfectly ordinary. If we were eating our dinner while falling through the horizon, we'd be taking your next bite, oblivious to the fact that we just crossed the horizon.
Our fate, of course, would be sealed. Once we cross the horizon, we are irreversibly cut off from the rest of the Universe. Anything that ever fell, anything that ever will fall into the black-hole is there with us, forming a collapsing '*mini-Universe*'. Though we may be moving relative to the bulk of Matter around us, an observation would reveal that we are, in fact, in a Universe not unlike the 'big' Universe out there, described by similar equations (the *Friedmann equations*), but unlike the 'big' Universe, which is expanding, ours is *collapsing*, *shrinking rapidly*, as a matter of fact. Even if it is one of the largest supermassive black-holes out there, we only have a few hours left, or less: long before the final moment, local differences in Gravitation, i.e., *tidal forces*, will rip us to shreds no matter what we do.
But what about the torch? It won't reveal anything special just because we're in a black-hole.

845 -

Why does the pressure inside of a black-hole become infinite?

The *interior solution* describing a *collapsing* astrophysical object turns out to be the same set of equations that would describe a *collapsing Cosmos*. A hapless observer who found himself falling into a black-hole, after crossing the *event horizon*, would find himself in such a collapsing *mini-Universe*. Depending upon its size (determined by the amount of Matter that fell, and will ever fall, into it), it may take anywhere from 1 millisecond to many hours, but the mini-Universe collapses. The observer would not live to see this, as ever-increasing *tidal forces* would rip his body apart before the end. But that end (at least for a spherically symmetric black-hole) inevitably happens: the famed 'singularity' is not some bad spot that we can bypass by clever maneuvering, but a *future moment in Time* at which (insofar as this mini-Universe is concerned) *Time itself comes to an end*. So, it's not so much that pressure, density, etc., become infinite at this moment but rather, this moment – literally – *is not part of existence*: Whatever is inside the mini-Universe ceases to exist at this point.
For outside observers, however, none of this ever happens. Even the event horizon itself *remains forever in their future*. Only by falling through it can the event horizon be experienced.

That is the 'classical' picture anyway. If we account for Quantum Physics, the answer is, we don't really know what happens. In the absence of a Quantum Gravity Theory, we can only take educated guesses, invoking what is known as the *Semi-classical Approximation*. One possibility (presumably, it's the most likely one) is that the collapse never even happens as the black-hole evaporates *before* its event horizon forms. In which case, there is no 'inside' at all.

846 -

Why is the Einstein Field Equation (EFE) a Lorentz invariant?

[a guest contribution by Mattias Sjö, PhD Student in Theoretical High-Energy Physics, Lund Un., Lund, SE)

Because it is very carefully constructed to be so. In fact, being Lorentz invariant is such a special property that a large reason why the Einstein Field Equation (EFE) has the form it does is due to Lorentz invariance.
For reference, the EFE in geometrical units $(c = G = 1)$ is

$$R_{\mu\nu} - \left(\frac{1}{2}R - \Lambda\right)g_{\mu\nu} = 8\pi T_{\mu\nu} .$$

Note how all terms have exactly two Lorentz indices $(\mu$ and $\nu)$, and that both are written as *subscripts*. This tells us something important: *all terms transform the same way under Lorentz transformations*. Therefore, *we can solve the equation in one frame of reference, transform to any other frame, and the solution will be equally valid*.

A bit more detail: in general, a physical quantity is only considered 'worthy' of carrying a Lorentz index if they have a very well-defined behavior under a Lorentz transformation. Such a quantity is called a $\begin{pmatrix} m \\ n \end{pmatrix}$-tensor, where m is the number of *superscript* indices and n is the number of *subscript* indices. Every transformation in SR or GR (translation, rotation, boost, whatever) can be defined with a *transformation matrix* $\mathbb{L}^{\mu}{}_{\nu}$. Then, for every *superscript* index on *any* tensor, one applies $\mathbb{L}^{\mu}{}_{\nu}$:

$$x'^{\nu} = \mathbb{L}^{\mu}{}_{\nu} x^{\mu}$$

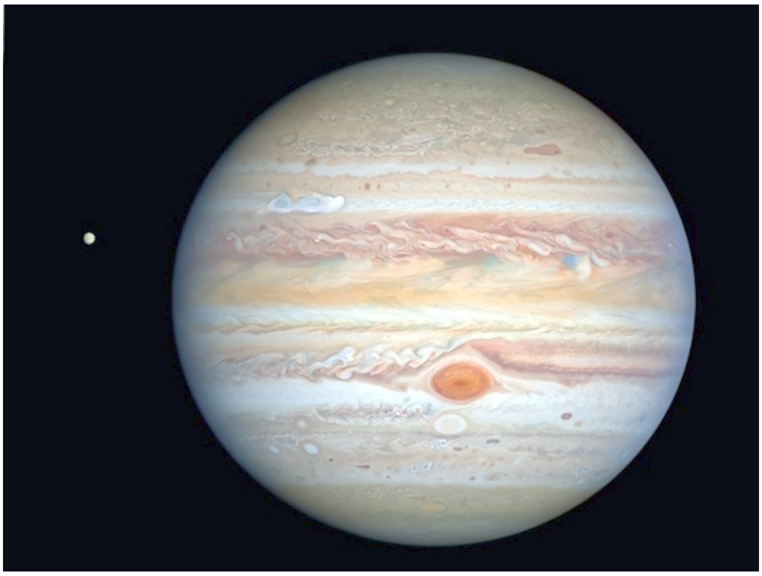
(using the Einstein summation convention) and, for every *subscript* index, one applies its *inverse*, $\mathbb{L}_{\nu}{}^{\mu}$:

$$y'_{\nu} = \mathbb{L}_{\nu}{}^{\mu} y_{\mu}$$

That's it. For similar reasons, *numbers that are formed by contracting away all pairs of Lorentz indices are the same in all reference frames*, *since all transformation properties have been cancelled*.
Whenever we see an object with Lorentz indices, we can be almost certain that it is a *tensor*; this is definitely the case with the terms in the EFE. There are only two objects that are commonly written with Lorentz indices that are not actually tensors: the *partial derivative* ∂_{μ} and the *Christoffel symbol* $\Gamma^{\mu}{}_{\nu\rho}$. However, the latter is designed to exactly cancel the *non-tensor character* of the first if arranged correctly. That's how $R_{\mu\nu}$ and R work in the EFE: they contain a lot of derivatives and Christoffel symbols but, in the end, they come out as *proper tensors*.
Thus, if you apply a Lorentz transformation to the EFE, all terms are multiplied by *the same* two transformation matrices, and the equation remains valid. But if you have an equation like $R_{\mu\nu} = T_{\mu\nu}$, it will be completely broken by any transformation, and something is most likely horribly *wrong*.
For the sake of sanity, GR mostly handles *Lorentz-invariant* equations.

847 -

How do we measure the mass of a planet, e.g., that of the gas-giant Jupiter?

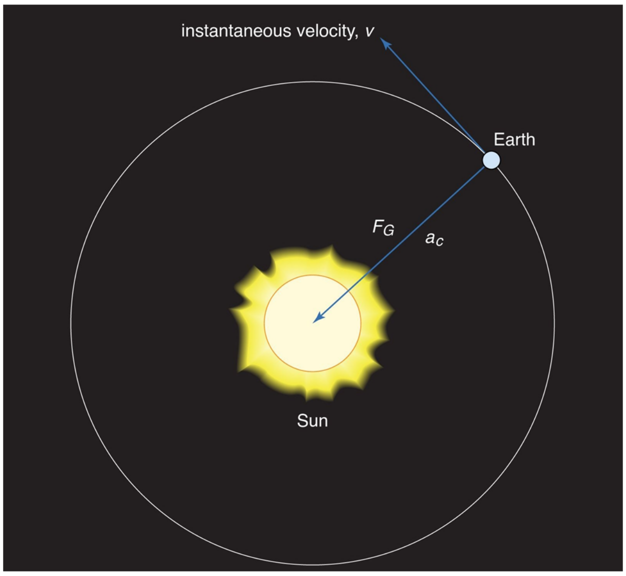


Jupiter and Europa (left)

Newton discovered that the same force that pulls an apple towards the ground is the same force that causes planets to orbit stars or in this case Moons to orbit planets. He derived the following formula for the *gravitational force* between two objects of mass m and M with G being the *gravitational Constant*:

$$F_G = G\frac{mM}{r^2} \quad . \tag{1}$$

This law describes the gravitational force acting between Europa and Jupiter. However, it leaves us with two *undetermined masses*.
Here comes a little trick. Jupiter's moon Europa is in an orbit around Jupiter, meaning it must have some Angular Momentum pushing Europa in a certain direction. Angular Momentum is *conserved*, meaning that both its magnitude and direction remain unchanged over time. The reason why Europa doesn't drift off into space is because of a force that acts towards the center of Jupiter. We call those forces *centripetal forces*. Centripetal forces act between all planets and moons which are on a certain orbit:



And what force is responsible for the centric attraction of Europa towards Jupiter which is also a centripetal force? Correct, Gravity!
We know that the centripetal force and gravitational force are equal. Hence, we can say that:

$$mr\omega^2 = G\frac{mM}{r^2} \ (\equiv F_G)\,. \tag{2}$$

Here the left side gives the formula for the centripetal force, where ω is the Europa's *angular speed*. Then, expressing ω in terms of the orbital period T and dividing by Europa's mass m, we get:

$$r\left(\frac{2\pi}{T}\right)^2 = G\frac{M}{r^2}\,. \tag{3}$$

Now, we only have to rearrange this equation to find an expression for Jupiter's mass:

$$M = \frac{4\pi^2 r^3}{GT^2}\,. \tag{4}$$

The only thing that is left to do is to measure the distance between Europa and Jupiter and measure the time T it takes Europa to complete a full orbit around Jupiter. Here are both *observed* and *accurately measured* quantities:

$$r = 6.71\cdot 10^8 \text{ m} \equiv 671000 \text{ km}\,, \tag{5.1}$$
$$T = 3\text{d } 13\text{h } 14\text{ s} \equiv 306840\text{ s}\,. \tag{5.2}$$

Putting those two values into our equation (4) and including the value of G, we get a mass value for Jupiter that is $M \approx 1.898\cdot 10^{27}$ kg. Now, if we compare the actual Jupiter's *estimated average mass*, $\langle M\rangle = 1.899\cdot 10^{27}$ kg (NASA Hubble module data), we see that Eq. (4) gives an extraordinarily excellent close value.

848 -

What is the fundamental equation for Dark Matter?

Here is the closest thing to answer this question:

$$w = 0\,.$$

This is not a joke. Any cosmologist recognizes this as the equation of state for *pressureless* Matter, i.e., *dust*.
In the prevailing cosmological model, Dark Matter is specifically Cold (i.e., *collisionless*) Dark Matter (CDM). That is, a field or substance with *negligible pressure*. The quantity $w := p/\rho_E$ denotes the *ratio* of *pressure* to *Energy-density*.
For Dark Matter, since pressure is 0, this ratio is also 0.
Of course this does not tell us what Dark Matter *is*, but only what Dark Matter *does*.

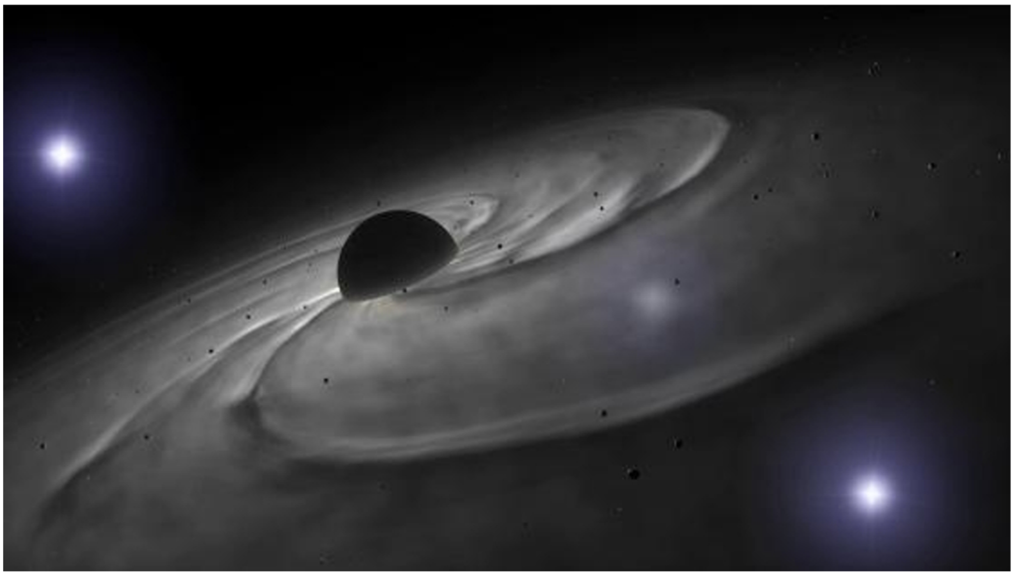
Here is another equation:

$$\Omega_{\mathrm{DM}} \approx 0.25$$

This equation, in turn, tells you that the Energy-density of Dark Matter amounts to roughly 25% of the so-called *critical density of the Universe*. This is contrasted with $\Omega_{\mathrm{B}} \approx 0.05$ (for ordinary, or 'Baryonic' Matter) and $\Omega_{\Lambda} \approx 0.7$ (for 'Dark Energy'), which are the other two main *presumed* constituents. It is no accidental that the *sum* of these three numbers is just 1, which means that we live in a Universe that is *on the boundary* of being *open* or *closed*, a Universe that is *open* but *spatially flat*.
Now the real equation for Dark Matter that people are looking for would be more in some form like

$$\mathcal{L}_{\mathrm{DM}} := \frac{1}{2}\left((\nabla\,\mathrm{something})^2 - V(\mathrm{something})\right),$$

or similar, … the so-called *Lagrangian density* of Dark Matter, that describes the Dark Matter *interactions* with other fields. There have been many proposals, the so-called Dark Matter *candidates*, presented in the form of proposed Lagrangians. None prevailed so far. Some were found to be in contradiction with known Physics (it is exceedingly difficult to introduce new fields without breaking, e.g., the Standard Model of Particle Physics); others predicted things that were *not* observed; and yet others fail to predict anything significant and thus remain unconfirmed proposals. There are also proposals that eschew Dark Matter altogether but ascribe what we see to modifications of the Theory of Gravity, instead; these, too, face the same issues as proposed forms of Dark Matter (contradicting known Physics or lacking experimental/observational confirmation).



Dark Matter waves about a black hole (source: NASA pictorial reconstruction)

849 -

Is explaining Dark Matter and Dark Energy as a fluid containing negative Gravity credible, or is it stretching theory beyond reason and common sense?

We shouldn't read more into the explanations than what theory actually says.
Cosmologists are simple-minded folks. They categorize all forms of matter using one simple number, which is defined by the so-called *equation-of-state*, $w := p/\rho_E$. That is to say, the *ratio of pressure to energy-density*. It so happens that *pressure*, p (i.e., force divided by area) and *energy-density*, ρ_E (i.e., energy divided by volume) are in fact measured by the same basic set of units, so their ratio is a pure number, not dependent on the choice of units of measurement.
This simple number describes many different categories of substances that can all be called '*perfect fluids*', substances with *no internal friction*, i.e., *no viscosity*.
The simplest case is $w = 0$, which means no pressure. Cosmologists call this dust. Just about everything out there is dust. Planets, stars, galaxies, clouds of actual dust, low temperature gas clouds … they are all characterized by $w = 0$, at least approximately.

Another important value is *radiation*: $w = 1/3$. If we imagine a box lined on the inside with perfect mirrors, and let some light in, it would be pushing on the sides of the box as it bounces around; so light has pressure. As it turns out, its pressure is exactly $1/3$ of its energy-density.

And this would be a good point to mention a simple relationship between the equation of state and the speed of sound in a medium: $c_s = c w^{1/2}$. That is to say, the speed of sound is the speed of light multiplied by the square root of the value of the equation of state. Therefore, it makes sense to talk about the speed of sound even in that radiation-filled box, as changes in pressure would propagate even in a radiation medium (another thing that behaves just like radiation is an ultra-relativistic gas: such a gas is so hot that its particles move at nearly the speed of light).

This simple equation for the speed of sound also tells us that w cannot be greater than 1 , otherwise the speed of sound would exceed the speed of light. A medium with $w = 1$ is called *stiff*: light and sound travel at the same speed in such medium.

Now, it so happens that it can be $w < 0$ also. Negative pressure we ask? Well, let's think about it. A container filled with gas particles has positive pressure if those particles repel each other, uniformly filling the container. Such a gas does mechanical work when it expands (e.g., in the cylinder of an engine). But what if the particles attracted each other instead? Then they would do the exact opposite and clump into dense little lumps. We would have to invest in work to separate the particles. This is how negative pressure works. And it so happens that the equations make sense all the way down to $w = -1$. But negative pressure stuff works in weird ways in the presence of Gravity: instead of causing the stuff to coalesce into ever denser clouds, self-Gravity causes negative pressure stuff to expand: it is as though Gravity was repulsive (a crude but valid analogy is that bubbles rise, not fall, in the sea because of Gravity). And the work done by Gravity ends up creating more negative-pressure stuff, so much so that at $w = -1$, the density of the negative-pressure stuff never decreases at all (and if it were $w < -1$, the density of the stuff would actually increase, rendering even the Vacuum *unstable*).

There we have it: stuff with $-1 < w < 1$ anywhere. The rest is a (relatively) simple exercise; what proportion of stuff with various values of w fit the observations that we have from the Physical Universe? The answer is that we need approximately 30% of the so-called *critical density*, i.e., with $w \approx 0$, and approximately 70%, i.e., with $w \approx -1$. Other combinations *do not* fit the observations well.

It so happens that the visible stuff we actually see, though characterized by $w \approx 0$, amounts to less than 5% of the critical density. Hence, we assume that *there is more stuff we don't see*, with $w \approx 0$, which we call *Dark Matter*, and with $w \approx -1$, which we call *Dark Energy*.

Then we start speculating as to what these things are made of. But that's another chapter. The important thing is that this is what we know: the observed characteristics of the Physical Universe fit our equations if we assume the presence of these constituents, whatever they might be, characterized by their equations-of-state. This statement is as credible as it gets; it is a direct application of Einstein's Field Equations, i.e., General Relativity, to the Cosmos, fitting the equations against observational data.

850 -

Why are the *negative* energy solutions to Dirac Equation interpreted as anti-Matter bit representations instead of virtual Matter's?

Because *virtual particles* are NOT bits of Matter. They are among the worst misunderstood things in popular accounts describing Particle Physics.

Virtual particles arise in Quantum Field Theory. An interaction in Quantum Field Theory can be described by a nasty integral. Most of the time, that integral *cannot* be evaluated directly, but it can be evaluated by turning it into a power series: a sum of smaller and smaller terms.

Formally, these terms actually describe ever more complicated pathways of interaction between the two fields, but we can conveniently think of them as *virtual* particles. So, instead of saying that, we say, accounted for how the field of electrons interacted with the EM Field directly, and then through a secondary interaction with the ELECTRON FIELD, etc., we now say that the '*electron emitted a photon, and the split into a virtual electron-positron pair that, finally, recombined into a photon again*'.

That 'virtual electron-positron pair' is not something that existed, other than as a mental aid, a bookkeeping device in the physicists' minds. It is called *virtual* because *it does not exist*.

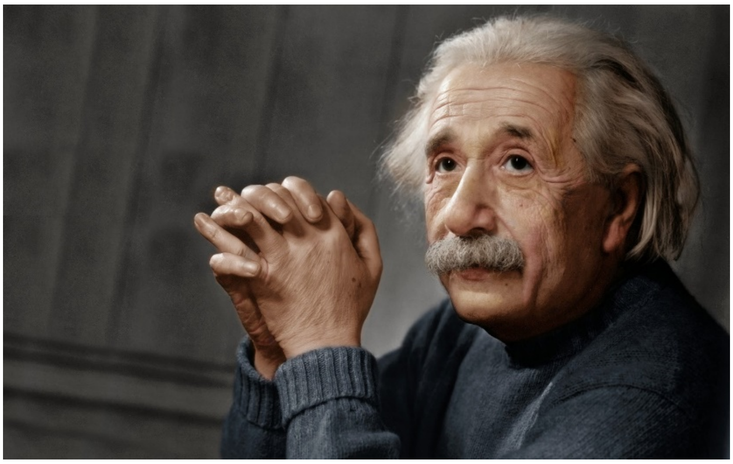
In contrast, the things described by Dirac's equation are *supposed* to exist. They are not fancy bookkeeping devices. The question is: what are they? What do these solutions mean?

Dirac originally thought that the oppositely charged solution might be the proton, but that didn't work very well, since the proton does not have the same *mass* as the electron. Then came the '*Dirac Sea*' business, the idea that the vacuum represents all negative energy states "filled in", unless a particle is missing, and it's this '*hole*' that Dirac's Equation describes. Sounds appealing, except that in the meantime, someone had the audacity to actually discover the positron, which fits nicely in Dirac's equation!

In the end, many of the paradoxical aspects of the Dirac Equation vanish when we move on to Quantum Field Theory. This is generally true: Particle Quantum Mechanics works, and it is useful, but it is obviously not a complete theory as it cannot account for particle *creation* and *annihilation* (which we do observe!) and *violates causality* (non-zero probabilities associated with *faster-than-light* and *backward-in-time* interactions). All this disappears with Quantum Field Theory, which also offers a more natural home, so to speak, for antiparticles.

Bottom line though, the negative energy solutions of the Dirac equation were associated with antiparticles because in the meantime, antiparticles (positrons) were actually discovered in experiment, and behaved just like Dirac's Equation described them.

Quasar galaxy J0529-4351 (~ $1.7 \cdot 10^{10}$ solar masses) and its inner black-hole, the largest ever observed
(data source: VLT (**V**ery **L**arge **T**elescope), Atacama Desert, Chile)



"The most incomprehensible thing about the world is that it is comprehensible."

Personal (pending) unanswered issues …

The term *Reality* may be referred to different things (historical, psychological, religious, environmental, …). If taken *per se*, 'Reality', lacking in a clear *qualifier*, let it be an *adjective*, an *adverb*, or whatever, sounds a rather fuzzy and ambiguous concept (to me), of rather poor use indeed. So, in these pages, we followed Viktor browsing into *Physical* Reality, dropping (as much as he could) any undue *ideological* bias.
As for myself, I can only borrow Samuel Johnson's words: "*I have found you an argument, but I don't feel obliged to find you an understanding*".
Now that our long wanderings have better come to a temporary (I bet) stop, what is left to our perception of *Physical Creation*? Did we really reach a deeper insight of (I venture to say) the *strictly material* side of 'God's Mind' or just getting astray, more confused and messed up instead?

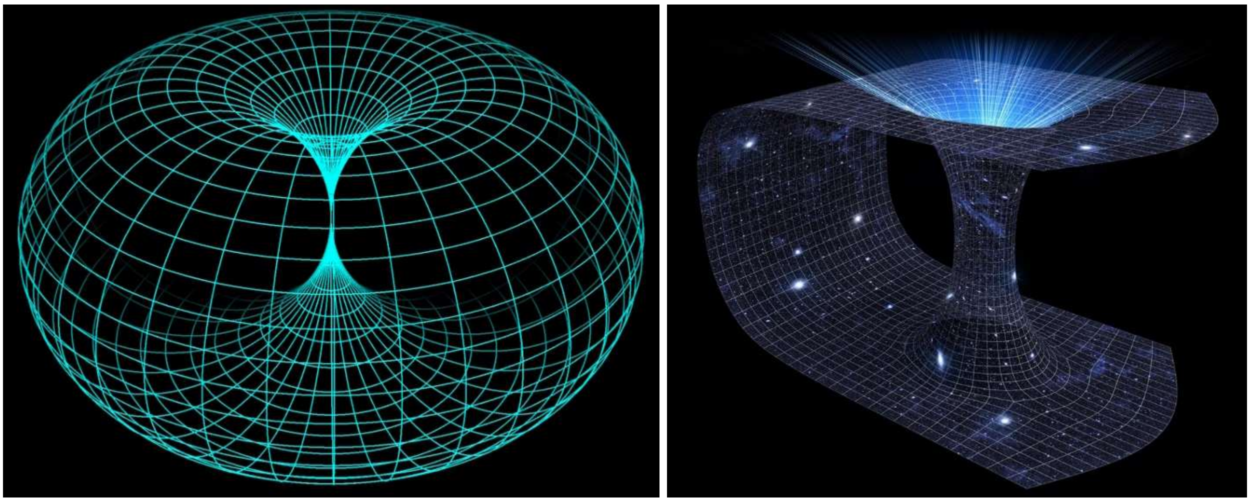
8 "*For My Thoughts are not your thoughts*,
neither are your ways My Ways",
saith the Lord.
9 *As the heavens are higher than the earth*,
so are My Ways higher than your ways
and My Thoughts than your thoughts".

Isaiah **55**

https://www.youtube.com/watch?v=aJxrX42WcjQ

dedicated to RGB, my beloved three 'little witches',
Lauretta, Ilaria, Azzurra

and to Forget-me-not (nameless, homeless,
just ripped from his games, school, FREEDOM)



The *toroidal* 3-dim Space surface of the *inflationary* Physical Universe

… with other unsound (?) views

Lemaître's evolutionary SpaceTime model sounds (to me) as the most acceptable frame for Gravitational Cosmology calculations. At the current stage of knowledge (2025), the model offers a plausible home to fit, e.g., the LIGO's and Hubble probe's observational data of the *visible* expanding *Physical* Universe.
So, the SpaceTime structure of the Cosmos can be *spatially* represented as a *toroidal surface* (images above), containing all the existing Matter. This surface is 'infinite' in the sense that it has no boundary facing any sort of 'elsewhere'; it swells as Time (of coordinate t, the 1st of the 4, say) increases through a continuous and inexorable process of *universal* 'spaghettification' and 'regeneration' of all its 'conserved' Matter-Energy content, as if it were to obey to some sort of global\generalized Principle, which restricts to a *local* representation we know as the *Noether's Theorem*.
As the swelling process goes on, a new *larger* toroidal 3-dim Space surface results. Time goes on *independent* of the Space coordinates, conserving the *same* amount of Matter-Energy inside. However, total Matter gets *diluted* within the inflating (toroidal) surface. So, cosmic systems generally appear *moving away* from one another. Time, per se, evolves uniformly *on the cosmological scale* and, in our (*locally restricted*) mathematical language, we're not prevented from guessing that $t \in (0, +\infty)$ (in passing, the *Feynman-Stückelberg interpretation* allows for *anti-Matter* existence): Time grows as an '*eternal*' physical quantity vs. any *local* frame, dragging behind all the existing – huge but *finite* – amount of Matter-Energy (readers had better go back over the answers to Issues such as **757**, p. 334, and **694**, p. 307, for comparison).

Is all this just nonsense? Or does it hide something obscurely true, behind? How do Dark Matter and Energy fit in this scenario? We *lack any answer whatsoever* to these issues, as Viktor Toth points out persistently.
Further cosmological data are needed to afford any consistent falsification process. However, as far as we know, the Physical World we *interact with*, *observe,* and *measure\estimate* repeatedly, either directly or from indirect induction, everywhere as well as anytime (till now, 2025), is basically *Quantum-Relativistic*. Other standard (classical) models, even highly successful in our daily practical usage, are, at best, only *convenient approximations*.

C M

■■■

a few (useful) basics

Yellow leading markers, like [1], refer to PDF file versions of texts *freely* available. Just link to the **Library** page for downloads: https://www.cm-physmath.net/libr_page.html .

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[60] **EMT** ™ **(Euler Math Toolbox)**: https://sourceforge.net/projects/eumat/files/Installer/ .

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Appendix

Gravitational Waves

Lecture Notes

Physics & Astronomy Dept., Utah State Un.

GEORGES ÉDOUARD LEMAÎTRE, S. J.,

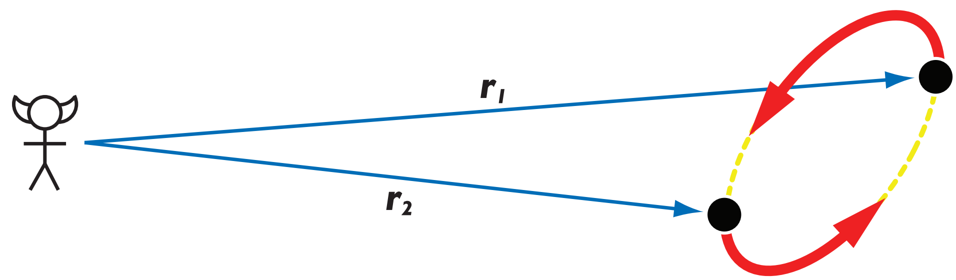
(CHARLEROI, JULY 17, 1894 – LOUVAIN, JUNE 20, 1966),
THE VISIONARY PROPONENT OF THE GENERAL-RELATIVISTIC PARADIGM OF THE BIG BANG

Gravitational Waves

Intuition

• In Newtonian gravity, you can have instantaneous action at a distance. If I suddenly replace the Sun with a $10,000 M_\odot$ black hole, the Earth's orbit should instantly repsond in accordance with Kepler's Third Law. But special relativity forbids this!

• The idea that gravitational information can *propagate* is a consequence of special relativity: nothing can travel faster than the ultimate speed limit, c.



• Imagine observing a distant binary star and trying to measure the gravitational field at your location. It is the sum of the field from the two individual components of the binary, located at distances r_1 and r_2 from you.

• As the binary evolves in its orbit, the masses change their position with respect to you, and so the gravitational field must change. It takes time for that information to propagate from the binary to you — $t_{propagate} = d/c$, where d is the luminosity distance to the binary.

• The propagating effect of that information is known as *gravitational radiation*, which you should think of in analogy with the perhaps more familiar *electromagnetic radiation*

• Far from a source (like the aforementioned binary) we see the gravitational radiation field oscillating and these propagating oscillating disturbances are called *gravitational waves.*

• Like electromagnetic waves

- ▷ Gravitational waves are characterized by a wavelength λ and a frequency f
- ▷ Gravitational waves travel at the speed of light, where $c = \lambda \cdot f$
- ▷ Gravitational waves come in two polarization states (called + [*plus*] and × [*cross*])

The Metric and the Wave Equation

• There is a long chain of reasoning that leads to the notion of gravitational waves. It begins with the linearization of the field equations, demonstration of gauge transformations in the linearized regime, and the writing of a wave equation for small deviations from the background spacetime. Suffice it to say that this is all eminently well understood and can be derived and proven with a few lectures of diligent work; we will largely avoid this here in favor of illustrating basic results that can be used in applications.

• The traditional approach to the study of gravitational waves makes the assumption that the waves are described by a small perturbation to flat space:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = (\eta_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu$$

where $\eta_{\mu\nu}$ is the Minkowski metric for flat spacetime, and $h_{\mu\nu}$ is the small perturbations (and often called the *wave metric*). The background metric, $\eta_{\mu\nu}$ is used to raise and lower indices.

• A more general treatment, known as the *Isaacson shortwave approximation*, exists for arbitrary background spacetimes such that

$$ds^2 = (g_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu$$

This approximation works in situations where the perturbative scale of the waves $h_{\mu\nu}$ is much smaller than the curvature scale of the background spacetime $g_{\mu\nu}$. A useful analogy to bear in mind is the surface of an orange — the large scale curvature of the orange (the background spacetime) is much larger than the small scale ripples of the texture on the orange (the small perturbations)

• If one makes the linear approximation above, then the Einstein Equations can be reduced to a vacuum wave equation for the metric perturbation $h^{\mu\nu}$:

$$\Box h^{\mu\nu} = \left(-\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h^{\mu\nu} = 0 \qquad \rightarrow \qquad \eta^{\alpha\beta} h^{\mu\nu}{}_{,\alpha\beta} = 0$$

• We recognize this is a wave equation, so let's assume that the solutions will be plane waves of the form

$$h^{\mu\nu} = A^{\mu\nu} \exp(i k_\alpha x^\alpha)$$

where $A^{\mu\nu}$ is a tensor with constant components and k_α is a one-form with constant components.

• Taking the first derivative of the solution yields (remember — the components $A^{\mu\nu}$ and k_α are assumed to be constant)

$$h^{\mu\nu}{}_{,\alpha} = k_\alpha h^{\mu\nu}$$

• Taking a second derivative gives us the wave equation back:

$$\eta^{\alpha\beta} h^{\mu\nu}{}_{,\alpha\beta} = \eta^{\alpha\beta} k_\alpha k_\beta h^{\mu\nu} = 0$$

• The only way for this to *generically* be true, is if k_α is null

$$\eta^{\alpha\beta} k_\alpha k_\beta = k_\alpha k^\alpha = 0$$

We call k^α the wave-vector, and it has components $k^\alpha = \{\omega, \vec{k}\}$. The null normalization condition then gives the *dispersion relation*:

$$k_\alpha k^\alpha = 0 \qquad \rightarrow \qquad \omega^2 = k^2$$

• The clean, simple form of the wave-equation noted above has an explicitly chosen gauge condition, called *de Donder gauge* or sometimes *Lorentz gauge* (or sometimes *harmonic gauge*, and sometimes *Hilbert gauge*):

$$h^{\mu\nu}{}_{,\nu} = 0$$

• Since $h^{\mu\nu}$ is symmetric, it in principle has 10 independent coordinates. The choice of this gauge is convenient; it arises in the derivation of the wave equation, and its implementation greatly simplifies the equation (giving the form noted above) by setting many terms to zero. This is very analogous (and should seem familiar to students of electromagnetic theory) to the choice of Coulomb gauge ($\vec{\nabla} \cdot \vec{A} = 0$) in the derivation of the electromagnetic wave equation.

• The choice to use de Donder gauge is part of the gauge freedom we have — the freedom to *choose coordinates*. There are plenty of coordinate systems we could choose to work in, and not have $h^{\mu\nu}{}_{,\nu} = 0$, but the equations would be much more complicated. There is no a priori reason why that should bother us, except it becomes exceedingly difficult to separate *coordinate effects* from *physical effects* (historically, this caused a tremendous amount of confusion for the first 30+ years after Einstein discovered the first wave solutions).

• One can show that choosing de Donder gauge does not use up all the gauge freedom, because small changes in coordinates

$$\bar{x}^\alpha = x^\alpha + \xi^\alpha$$

preserves the gauge if $\xi^{\alpha,\beta}{}_{,\beta} = 0$. This freedom indicates there is still residual gauge freedom, which we can use to simplify the solutions to the wave equation.

• The residual gauge freedom can be used to further constrain the character of $A^{\mu\nu}$. It is desirable to do this, because once all the gauge degrees of freedom are fixed, the remaining independent components of the wave-amplitude $A^{\mu\nu}$ will be physically important. We will skip the derivation, and state the conditions. Using de Donder on our wave solution, we find

$$A^{\mu\nu} k_\nu = 0$$

which tells us that $A^{\mu\nu}$ is *orthogonal* to k^α. We additionally can demand (the gory details are in Schutz, most introductory treatments on gravitational waves; a particularly extensive set of lectures can be found in Schutz & Ricci Lake Como lectures, arxiv:1005.4735):

$$A^\alpha_\alpha = 0$$

and

$$A_{\mu\nu}u^{\nu} = 0$$

where u^{α} is a fixed four-velocity of our choice. Together, these three conditions on $A_{\mu\nu}$ are called the *transverse-traceless gauge*.

• What does using all the gauge freedom physically mean? In general relativity, gauge freedom is the freedom to choose coordinates. Here, by restricting the gauge in the wave equation, we are removing the *waving of the coordinates*, which is not a physical effect since coordinates are not physical things (they are human constructs). In essence, if you have a set of particles in your spacetime, the coordinates stay attached to them (this, in and of itself, has no invariant meaning because *you made up the coordinates!*. What is left is the physical effect, the waving of the curvature of spacetime.

• In the transverse-traceless (TT) gauge, there are only 2 independent components of $A_{\mu\nu}$:

$$A^{TT}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A_{xx} & A_{xy} & 0 \\ 0 & A_{xy} & -A_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

• So what is the physical effect of this wave? If we want to build experiments to detect these waves, this question is paramount – we have to know what to look for!

• You might naively look at the geodesic equation and ask what effect the wave has on particle's trajectory, u^{α}, if that particle is initially at rest (for instance, in the corner of your laboratory). This is an exercise left to the reader, but you will find that given the form of $A_{\mu\nu}$ above, the acceleration of the particle is always zero. If the particle is at rest and never accelerates, it stays at rest!

• This should not surprise us; we said above that the choice of gauge was made to stop the waving of our coordinates! The particle stays at rest because it is attached to the coordinates!

• Experiments should be built around observations that can be used to create *invariant quantities* that all observers agree upon. So rather than a *single* test particle, imagine *two particles* and compute the *proper distance* between them. Imagine both particles begin at rest, one at $x_1^{\alpha} = \{0, 0, 0, 0\}$ and the other at $x_2^{\alpha} = \{0, \epsilon, 0, 0\}$:

$$\ell = \int \sqrt{ds^2} = \int |g_{\alpha\beta}dx^{\alpha}dx^{\beta}|^{1/2}$$

Because the particles are separate along the $x-$axis, we integrate along dx and this reduces to

$$\ell = \int_0^{\epsilon} |g_{xx}|^{1/2}dx \simeq |g_{xx}(x=0)|^{1/2}\epsilon \simeq \left[1 + \frac{1}{2}h^{TT}_{xx}(x=0)\right]\epsilon$$

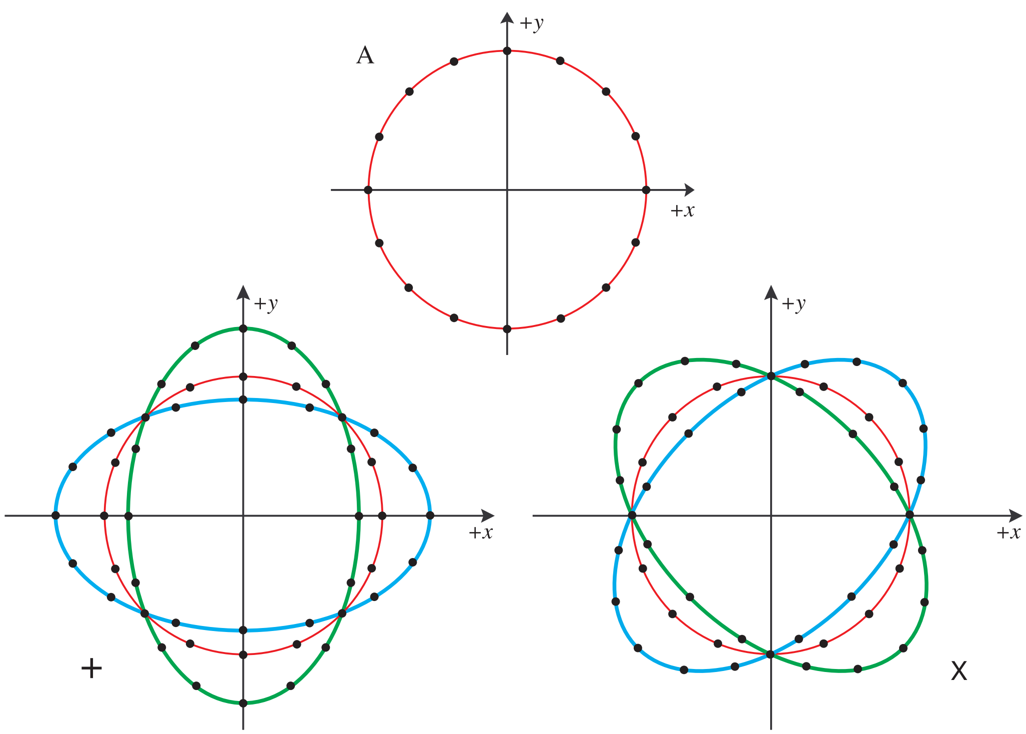
• Now our imposed solution for $h_{\mu\nu}^{TT}$ is a travelling planewave, so h_{xx}^{TT} is not (in general) going to be independent of time. *The proper distance between our test particles changes in time.*

• This is simply *geodesic deviation*, which is the relative trajectories of nearby geodesics in *curved spacetime*. The gravitational wave is curving the spacetime, which we can detect by the geodesic deviation it introduces (gravitational tidal forces).

• This same result can be derived directly from the geodesic deviation equation. It will require you to compute the components of $R^{\alpha}{}_{\beta\gamma\delta}$ in the TT gauge in the presence of $h_{\alpha\beta}^{TT}$.

• Looking at the geodesic deviation by setting first $A_{xx} = 0$ then setting $A_{xy} = 0$ will show that there are two distinct physical states for the wave — these are the gravitational wave *polarization states*. The effect of a wave in either state is to *compress* the geodesics in one direction while simultaneously *stretching* the geodesic separation in the orthogonal direction during the first half-cycle of a wave. During the second half-cycle, it switches the compression and stretching effects between the axes.

• A common way to picture this is to envision a ring of test particles in the $xy-$plane, as shown in A of the figure below. For a gravitational wave propagating up the $z-$axis, choose $A_{xx} \neq 0$ and $A_{xy} = 0$. This will yield the geodesic deviation pattern shown in B of the figure below. The ring initially distorts by stretching along the $y-$axis and compressing along the $x-$axis (the green oval), then a half cycle later compresses and stretches in the reverse directions (the teal oval). This is called the + *(plus) polarization state*. By contrast, $A_{xx} = 0$ and $A_{xy} \neq 0$ produces the distortions shown in C, and is called the × *(cross) polarization state*.



Making Waves: the Quadrupole Formula

• There is an entire industry associated with computing gravitational waveforms, particularly from astrophysical sources.

• Generically, there is a solution to the wave-equation that can be found by integrating over the source, just as there is in electromagnetism. In EM, the vector potential A^μ can be expressed as an integral over the source, the current J^μ. Similarly, in full GR the wave tensor $h_{\mu\nu}$ may be expressed as an integral over the stress-energy tensor $T_{\mu\nu}$:

$$h_{\mu\nu}(t,\vec{x}) = \frac{4G}{c^4}\int \frac{T_{\mu\nu}(\vec{x}', t - |\vec{x}-\vec{x}'|/c)}{|\vec{x}-\vec{x}'|} d^3x'$$

• Many sources do not need to be treated fully relativistically. If they are *slow-motion* and the gravitational contribution to the total energy is small, then this expression can be treated in the weak field limit, and reduces to the famous *quadrupole formula*:

$$h^{TT}_{jk} = \frac{2G}{c^4}\frac{1}{r}\ddot{\mathcal{I}}^{TT}_{jk}(t - r/c) \qquad \rightarrow \qquad \frac{2}{r}\ddot{\mathcal{I}}^{TT}_{jk}(t-r)$$

Here $\mathcal{I}_{jk}$ is the *reduced (trace-free) quadrupole moment tensor*, given by

$$\mathcal{I}^{jk} = I^{jk} - \frac{1}{3}\delta^{jk}\delta_{lm}I^{lm}$$

where

$$I^{jk} = \int d^3x\ \rho(t,\vec{x})x^j x^k$$

• The power radiated in gravitational waves (what astronomers call the *luminosity*) is given by

$$\frac{dE_{gw}}{dt} = \frac{G}{c^5}\frac{1}{5}\langle \dddot{\mathcal{I}}_{jk}\dddot{\mathcal{I}}^{jk}\rangle \qquad \rightarrow \qquad \frac{1}{5}\langle \dddot{\mathcal{I}}_{jk}\dddot{\mathcal{I}}^{jk}\rangle$$

Example: Compact Binary System

• In principle the Quadrupole Formula can be used for any system so long as you can compute the components of $\mathcal{I}_{jk}$; in astrophysical scenarios this may require knowledge about the internal mass dynamics of the system that you have no observational access too. Fortunately, astrophysicists are quite fond of models and guessing. `:-)`

• As an instructive example of the use of the quadrupole formula, consider a circular binary. This is the classic bread and butter source for gravitational wave astronomy. Treating the stars as point masses m_1 and m_2, and confining the orbit to the $xy-$plane, we may write:

$$x^i_1 = r(\theta)\frac{\mu}{m_1}\cdot\{\cos\theta, \sin\theta, 0\}$$
$$x^i_2 = r(\theta)\frac{\mu}{m_2}\cdot\{-\cos\theta, -\sin\theta, 0\}$$

where θ is called the *anomaly* (angular position of the star in its orbit, which changes with time), μ is the reduced mass, defined by

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

and $r(\theta)$ is the radius of the orbit as a function of position. Generically, it is defined in terms of the semi-major axis a and the eccentricity e by the *shape equation*:

$$r(\theta) = \frac{a(1-e^2)}{1 + e\cos\theta}$$

• For *circular orbits*, the stars are in constant circular motion. You should recall from your General Physics class that in this case the angle θ can be expressed in terms of the angular orbital frequency as

$$\theta = \omega t = 2\pi f_{orb} t = 2\pi \frac{t}{P_{orb}}$$

• We can get a value from ω from Kepler III:

$$GM_T = \omega^2 a^3 \qquad \to \qquad \omega = \sqrt{\frac{GM_T}{a^3}}$$

In the case of circular orbits, $e = 0$, and so $r(\theta) = a = const$[1]

• Since we are treating the masses as point masses, it is easy to write the mass density ρ in terms of delta-functions:

$$\rho = \delta(z)\left[m_1\delta(x-x_1)\delta(y-y_1) + m_2\delta(x-x_2)\delta(y-y_2)\right]$$

• With these pieces, we can evaluate the components of the quadrupole tensor:

$$\begin{aligned}
I^{xx} &= \int d^3x\left(\rho x^2\right) = m_1 x_1^2 + m_2 x_2^2 \\
&= \left(\frac{\mu^2 a^2}{m_1^2} m_1 + \frac{\mu^2 a^2}{m_2^2} m_2\right)\cos^2(\omega t) \\
&= \mu^2 a^2 \left(\frac{1}{m_1} + \frac{1}{m_2}\right)\cos^2(\omega t) \\
&= \mu a^2 \cos^2(\omega t) \\
&= \frac{1}{2}\mu a^2\left(1 + \cos(2\omega t)\right)
\end{aligned}$$

• Notice we have used a trig identity to get rid of the square of the cosine in favor of a term linear in the cosine. The penalty we pay is the frequency of the linear cosine is twice the original orbital frequency.

[1] An astute student will want to compare this with Schutz Eq. 9.94; if one assumes the stars are equal mass, so $M_T = 2m$, and that $a = \ell_o$, one recovers Schutz's result.

• This is a generic feature of circular gravitational wave binaries: *the gravitational wave frequency in a circular binary is twice the orbital frequency.* In practice what it means is that for each cycle made by the binary motion, the gravitational wave signal goes through *two* full cycles — there are two maxima and two minima per orbit. For this reason, gravitational waves are called *quadrupolar waves.*

• Writing out the other components of the quadrupole tensor:

$$I^{yy} = \mu a^2 \sin^2(\omega t) = \frac{1}{2}\mu a^2 \left(1 - \cos(2\omega t)\right)$$

and

$$I^{xy} = I^{yx} = \mu a^2 \cos(\omega t)\sin(\omega t) = \frac{1}{2}\mu a^2 \sin(2\omega t)$$

The trace subtraction is

$$\begin{aligned} \frac{1}{3}\delta^{ij}\delta_{lm}I^{lm} &= \frac{1}{3}\delta^{ij}\mu a^2 \left[\frac{1}{2}\left(1+\cos(2\omega t)\right) + \frac{1}{2}\left(1-\cos(2\omega t)\right)\right] \\ &= \frac{1}{3}\delta^{ij}\mu a^2 \end{aligned}$$

• These are all the pieces needed to write down the components of $\mathcal{I}^{ij}$

$$\mathcal{I}^{ij} = \frac{1}{2}\mu a^2 \begin{pmatrix} \cos(2\omega t) + 1/3 & \sin(2\omega t) & 0 \\ \sin(2\omega t) & -\cos(2\omega t) + 1/3 & 0 \\ 0 & 0 & -2/3 \end{pmatrix}$$

• Taking two time derivatives of $\mathcal{I}^{ij}$ yields

$$\ddot{\mathcal{I}}^{ij} = 2\mu a^2\omega^2 \begin{pmatrix} -\cos(2\omega t) & -\sin(2\omega t) & 0 \\ -\sin(2\omega t) & \cos(2\omega t) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

• Taking a third time derivative yields

$$\dddot{\mathcal{I}}^{ij} = 4\mu a^2\omega^3 \begin{pmatrix} \sin(2\omega t) & -\cos(2\omega t) & 0 \\ -\cos(2\omega t) & -\sin(2\omega t) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

• For circular orbits, these formulae are reasonably easy to work with, especially if you have computer algebra systems like `Maple` or `Mathematica` to help you out. They are somewhat more difficult to work with if the orbits are eccentric.

• For the case of eccentric orbits, the details have been worked out *in extenso* in two papers that have become the de facto starting points for many binary gravitational wave calculations:

- "Gravitational radiation from point masses in a Keplerian orbit," P. C. Peters and J. Mathews, *Phys. Rev.*, **131**, 435 [1963]
- "Gravitational radiation from the motion of two point masses," P. C. Peters, *Phys. Rev.*, **136**, 1224 [1964]
- "The Doppler response to gravitational waves from a binary star source," H. D. Wahlquist, *Gen. Rel. Grav.*, **19**, 1101 [1987]

• The most commonly used results from these papers are as follows. The *average power* (averaged over one period of the elliptical motion) is

$$\langle P\rangle = -\frac{32}{5}\frac{G^4}{c^5}\frac{m_1^2 m_2^2(m_1+m_2)}{a^5(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

• In addition to carrying energy away from a binary system, gravitational waves also carry angular momentum. The *angular momentum luminosity* is given by

$$\left\langle\frac{dL}{dt}\right\rangle = -\frac{32}{5}\frac{G^{7/2}}{c^5}\frac{m_1^2 m_2^2(m_1+m_2)^{1/2}}{a^{7/2}(1-e^2)^2}\left(1+\frac{7}{8}e^2\right)$$

• For Keplerian orbits, there are two constants of the motion, generally taken to be the pair $\{E, L\}$, or the pair $\{a, e\}$. The two sets of constants are related, so the luminosities can also be written in terms of the evolution of a and e, written here for completeness:

$$\left\langle\frac{da}{dt}\right\rangle = -\frac{64}{5}\frac{G^3}{c^5}\frac{m_1 m_2(m_1+m_2)}{a^3(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

$$\left\langle\frac{de}{dt}\right\rangle = -\frac{304}{15}\frac{G^3}{c^5}\frac{e\, m_1 m_2(m_1+m_2)}{a^4(1-e^2)^{5/2}}\left(1+\frac{121}{304}e^2\right)$$

• If you bleed energy and angular momentum out of an orbit, the masses slowly spiral together until they merge at the center of the orbit! This happens in a finite time called the *coalescence (merger) time*, τ_{merge}. For a circular binary with initial semi-major axis a_o, the expression for $\langle da/dt\rangle$ can be integrated to give

$$\tau_{circ}(a_o) = \frac{a_o^4}{4\beta}$$

where the constant β is defined as

$$\beta = \frac{64}{5}\frac{G^3}{c^5}m_1 m_2(m_1+m_2)$$

• For a general binary with initial parameters $\{a_o, e_o\}$ it is given by

$$\tau_{merge}(a_o, e_o) = \frac{12}{19}\frac{c_o^4}{\beta}\int_0^{e_o} de \frac{e^{29/19}\left[1+(121/304)e^2\right]^{1181/2299}}{(1-e^2)^{3/2}}$$

where the constant c_o is given by

$$c_o = \frac{a_o(1-e_o^2)}{e_o^{12/19}}\left[1+\frac{121}{304}e_o^2\right]^{-870/2299}$$

• It is often useful to consider limiting cases. For e_o small, we should get a lifetime similar to τ_{circ}. Expanding the lifetime for small e_o yields

$$\tau_{merge}(a_o, e_o) \simeq \frac{12}{19}\frac{c_o^4}{\beta}\int_0^{e_o} de\, e^{29/19} = \frac{c_o^4}{4\beta}e_o^{48/19}$$

This is approximately equal to $\tau_{circ}(a_o)$.

• For e_o near 1 (a marginally bound orbit that will evolve through emission of gravitational radiation — this is often called a *capture orbit*)

$$\tau_{merge}(a_o, e_o) \simeq \frac{768}{425}\tau_{circ}(a_o)(1-e_o^2)^{7/2}$$

Pocket Formulae for Gravitational Wave Binaries

• Because binaries are expected to be among the most prevalent of gravitational wave sources, it is useful to have a set of pocket formulae for quickly estimating their characteristics on the back of old cell phone bills; you can go back and do all the crazy stuff above if you need an accurate computation.

• For a gravitational wave binary with masses m_1 and m_2, in a circular orbit with gravitational wave frequency $f = 2f_{orb}$, then:

chirp mass $$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

scaling amplitude $$h_o = 4\frac{G}{c^2}\frac{\mathcal{M}_c}{D}\left(\frac{G}{c^3}\pi f \mathcal{M}_c\right)^{2/3}$$

chirp $$\dot{f} = \frac{96}{5}\frac{c^3}{G}\frac{f}{\mathcal{M}_c}\left(\frac{G}{c^3}\pi f \mathcal{M}_c\right)^{8/3}$$

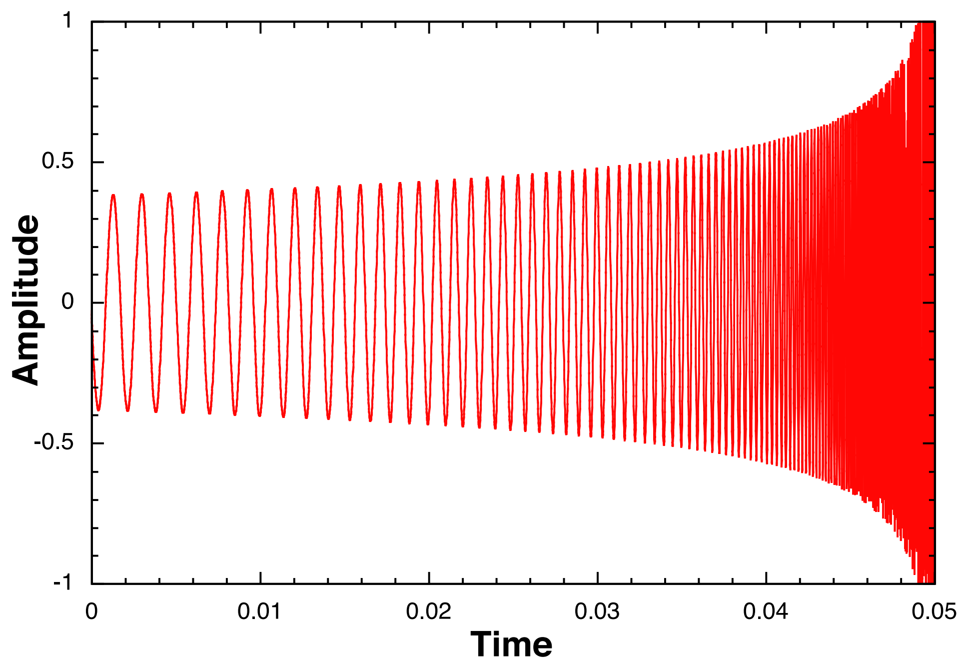
• The *chirp* indicates that as gravitational waves are emitted, they carry energy away from the binary. The gravitational binding energy decreases, and the orbital frequency increases. The gravitational wave *phase* $\phi(t)$ evolves in time as

$$\phi(t) = 2\pi\left(f\ t + \frac{1}{2}\dot{f}\ t^2\right) + \phi_o\ ,$$

where $\dot{f}$ is the chirp given above, and ϕ_o is the initial phase of the binary. A phenomenological form of the waveform then is given by

$$h(t) = h_o \cos\phi(t) = h_o \cos\left(2\pi f\ t + \pi\dot{f}\ t^2 + \phi_o\right)$$

• This expression has all the qualitative properties of a coalescing waveform, shown below.



• This is called a *chirp* or a *chirp waveform*, characterized by an increase in amplitude and frequency as time increases. This name is quite suitable because of the way it sounds if the amplitude is increased by a large factor and the waveform is dumped into an audio generator.

Luminosity Distance from Chirping Binaries

Suppose I can measure the chirp $\dot{f}$ and the gravitational wave amplitude h_o. The chirp can be inverted to give the chirp mass:

$$\mathcal{M}_c = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

If this chirp mass is used in the amplitude equation, one can solve for the *luminosity distance* D:

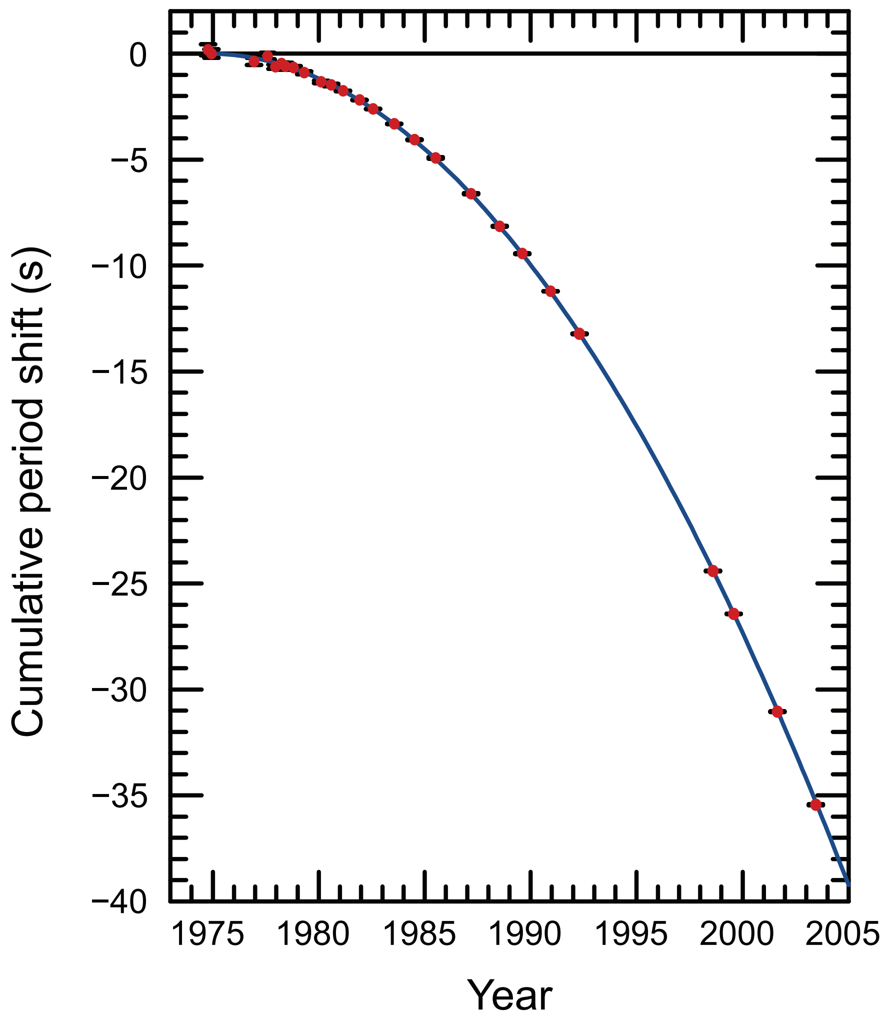
$$D = \frac{5}{96\pi^2}\frac{c}{h_o}\frac{\dot{f}}{f^3}$$

This is a method of measuring the luminosity distance using *only gravitational wave observables*! This is extremely useful as an independent distance indicator in astronomy.

Application: Binary Pulsar

• Early on we became confident in the existence of gravitational waves because we could observe their astrophysical influence. The first case of this was the pulsar, PSR $B1913+16$, my colloquially known as "The Binary Pulsar," or the "Hulse-Taylor Binary Pulsar," after the two radio astronomers who discovered it in 1974.

bullet The Binary Pulsar is famous because it is slowly spiraling together. As shown in the figure below, the rate at which the binary is losing energy from its orbit is *precisely* what is expected from general relativity! This is the strongest, *indirect* observational evidence for the existence of gravitational waves. Joe Taylor and Russell Hulse received the Nobel Prize for this discovery in 1993.



• Let's use our formulae for inspiralling binaries to examine the binary pulsar in detail. The physical parameters of this system are given in the table below.

Symbol	***Name***	***Value***
m_1	primary mass	$1.441 M_\odot$
m_2	secondary mass	$1.387 M_\odot$
P_{orb}	orbital period	7.751939106 hr
a	semi-major axis	1.9501×10^9 m
e	eccentricity	0.617131
D	distance	$21,000$ lyr

• If one computes the yearly change in semi-major axis, one finds

$$\left\langle \frac{da}{dt} \right\rangle = 3.5259 \; \frac{m}{yr}$$

which is *precisely* the measured value from radio astronomy observations!

• Because gravitational waves are slowly bleeding energy and angular momentum out of the system, the two neutron stars will one day come into contact, and *coalesce* into a single, compact remnant. The time for that to happen is

$$\tau_{merge} = 3.02 \times 10^8 \; yr$$

• This is well outside the lifetime of the average astronomer, and longer than the entire history of observational astronomy on the planet Earth! It is, however, much shorter than a Hubble time! This suggests the since (a) there are many binary systems in the galaxy, and (b) neutron stars are not an uncommon end state for massive stars to evolve to, then there should be *many* binary neutron stars coalescing in the Universe as a function of time.

• This is the first inkling we have that there could be many such sources in the sky, and that perhaps observing them in gravitational waves could be a useful observational exercise.

• If we are going to contemplate observing then, we should have some inkling of their strength. What is the scaling amplitude, h_o of the Hulse-Taylor binary pulsar?

$$h_o = 4.5 \times 10^{-23}$$

This number is extremely small, but we haven't talked about whether it is detectable or not. Let's examine this in the context of building a detector.

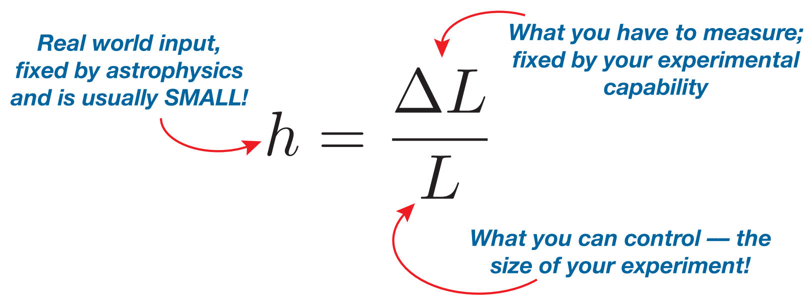
Detector Sensitivity

• When you decide to build a detector, you think about the physical effect you have to measure. We have seen that gravitational waves *change the proper distance between particles.*

We characterize this distance by the *strain* $h = \Delta L/L$. This fundamental definition guides our basic thinking about detector design. If ΔL is what we have to measure, over the distance L, then the kind of astrophysical strain from typical astrophysical objects is roughly

$$h = \frac{\Delta L}{L} \sim 10^{-21} \sim \frac{\text{Diameter of H atom}}{1 \text{ AU}}$$

• The way these quantities enter in the process of experiment design is shown schematically below:



• There are two ways to go about this. You could decide what astrophysical sources you are interested in, and determine what detector is needed, or you can decide what detector you can build (L is determined by size and pocketbook, whereas ΔL is fixed by the ingenuity of your experimentalists). But often the design problem is an optimization of *both* astrophysics and capability.

• In the modern era, gravitational wave detection technology is dominated by *laser interferometers*, which we will focus on here. In general, an interferometric observatory has its best response at the *transfer frequency* $f_\star$, where gravitational wavelengths are roughly the distance probed by the time of flight of the lasers:

$$f_\star = \frac{c}{2\pi L}$$

• If you build a detector, the principle goal is to determine what gravitational waves the instrument will be sensitive to. We characterize the noise in the instrument and the instrument's response to gravitational waves using a *sensitivity curve*.

• Sensitivity curves plot the strength a source must have, as a function of gravitational wave frequency, to be detectable. There are two standard curves used by the community:

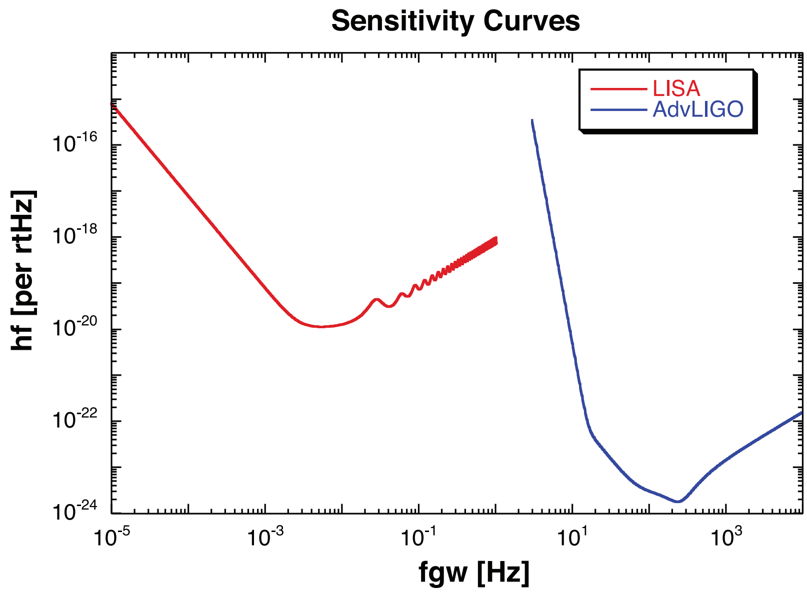
▷ **Strain Sensitivity.** This plots the gravitational wave strain amplitude h versus gravitational wave frequency f.

▷ **Strain Spectral Amplitude.** This plots the square root of the power spectral density, $h_f = \sqrt{S_h}$ versus gravitational wave frequency f. The power spectral density is the power per unit frequency and is often a more desirable quantity to work with because gravitational wave sources often evolve dramatically in frequency during observations.

• The strain sensitivity of a detector, h^D, builds up over time. If you know the observation time T_{obs} and the spectral amplitude curve (like those plotted above) you can convert between the two via

$$h_f^D = h^D \sqrt{T_{obs}}$$

• The sensitivity for LIGO and LISA are shown below. Your own LISA curves can be created using the online tool at `www.srl.caltech.edu/~shane/sensitivity/MakeCurve.html`.



• LISA has armlengths of $L = 5 \times 10^9$ m, which if you consider its transfer frequency $f_\star$ makes it more sensitive at lower frequencies. LIGO has armlengths of $L = 4$ km, but the arms are Fabry-Perot cavities, and the laser light bounces back and forth ~ 100 times; this puts its prime sensitivity at a much higher frequency.

Sources and Sensitivity Curves

• Sensitivity curves are used to determine whether or not a source is detectable. Rudimentarily, if the strength of the source places it above the sensitivity curve, it can be detected! How do I plot sources on these curves? First, it depends on what kind of curve you are looking at; second, it depends on what kind of source you are working with!

• If you are talking about observing sources that are evolving slowly (the are approximately monochromatic) then the spectral amplitude and strain are related by

$$h_f = h\sqrt{T_{obs}}$$

• If you are talking about a short-lived ("bursting") source with a characteristic width τ, then to a good approximation the bandwidth of the source in frequency space is $\Delta f \sim \tau^{-1}$

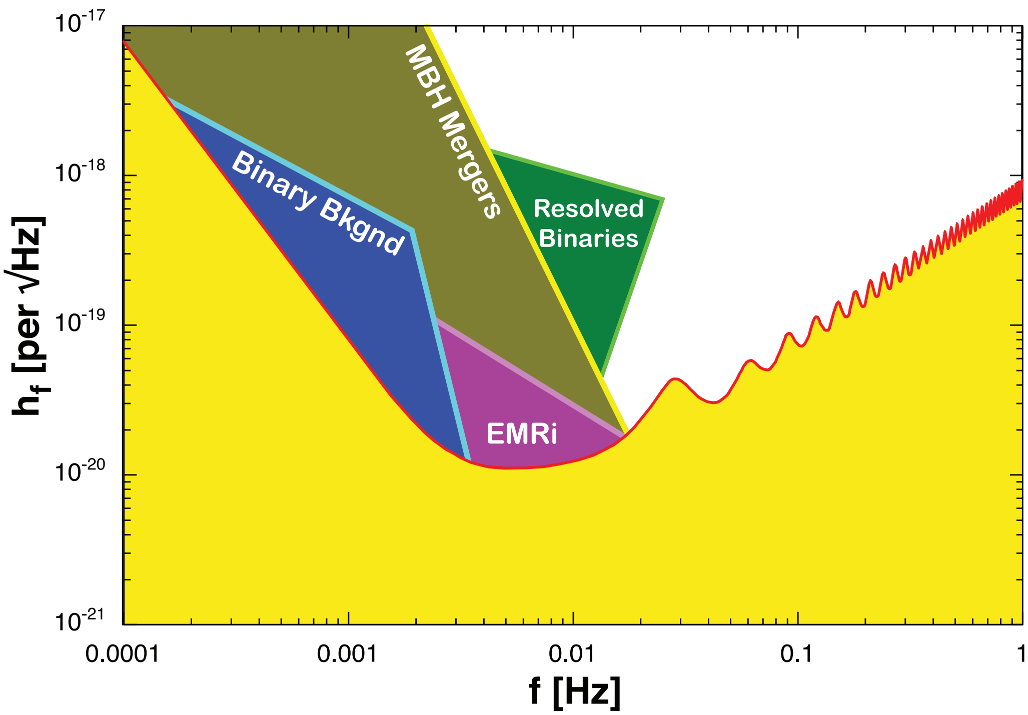
and the spectral amplitude and strain are related by

$$h_f = \frac{h}{\sqrt{\Delta f}} = h\sqrt{\tau}$$

• The fundamental metric for detection is the SNR ρ (signal to noise ratio) defined as

$$\rho \sim \frac{h_f^{src}}{h_f^D}$$

• To use this you need to know how to compute h_f^{src}. A good starting point is the pocket formulae from the last section.



Rosetta Stone: Orbital Mumbo Jumbo ▶ ....

- **a = semi-major axis.** The *major axis* is the long axis of the ellipse. The semi-major axis is 1/2 this length.
- **b = semi-minor axis.** The *minor axis* is the short axis of the ellipse. The semi-minor axis is 1/2 this length.
- **e = eccentricity.** The eccentricity characterizes the deviation of the ellipse from circular; when $e = 0$ the ellipse is a circle, and when $e = 1$ the ellipse is a parabola. The eccentricity is defined in terms of the semi-major and semi-minor axes as

$$e = \sqrt{1 - (b/a)^2}$$

- **f = focus.** The distance from the geometric center of the ellipse (where the semi-major and semi-minor axes cross) to either focus is

$$f = ae$$

- **ℓ = semi-latus rectum.** The distance from the focus to the ellipse, measured along a line parallel to the semi-minor axis, and has length

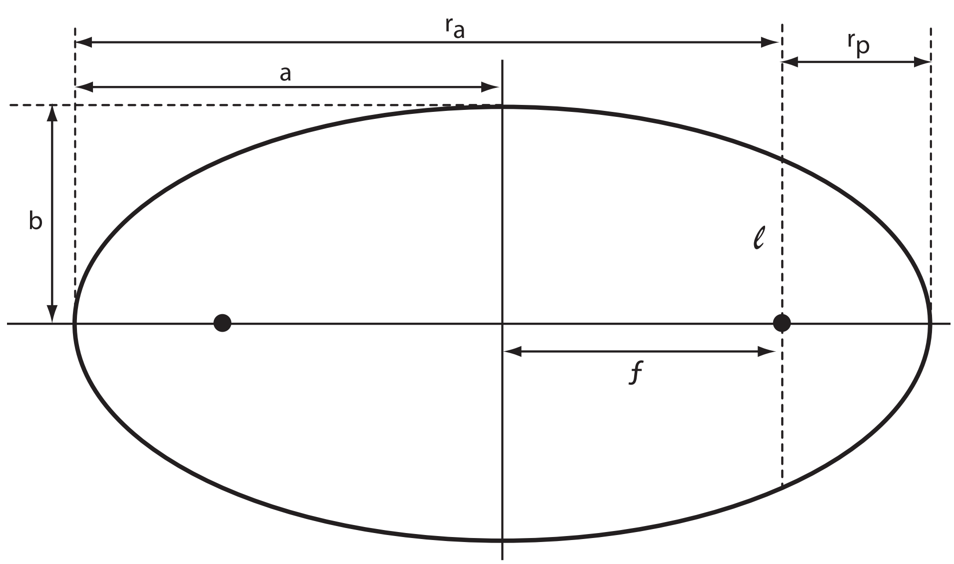
$$\ell = b^2/a$$

- **r_p = periapsis.** The periapsis is the distance from the focus to the nearest point of approach of the ellipse; this will be along the semi-major axis and is equal to

$$r_p = a(1 - e)$$

- **r_a = apoapsis.** The apoapsis is the distance from the focus to the farthest point of approach of the ellipse; this will be along the semi-major axis and is equal to

$$r_a = a(1 + e)$$



Basic Geometric Definitions ▶ ....

The game of orbits is always about locating the positions of the masses. For planar orbits (the usual situation we encounter in most astrophysical applications) one can think of the position of the mass m_i in terms of the Cartesian coordinates $\{x_i, y_i\}$, or in terms of some polar coordinates $\{r_i, \theta_i\}$. The value of the components of these location vectors generically depends on the coordinates used to describe them. The most common coordinates used are called *barycentric coordinates*, with the origin located at the focus between the two bodies.

▷ **The Shape Equation**. The shape equation gives the distance of the orbiting body (*"particle"*) from the focus of the orbit as a function of polar angle θ. It can be expressed in various ways depending on the parameters you find most convenient to describe the orbit.

$$r = \frac{a(1-e^2)}{1+e\cos\theta} \qquad \to \qquad r = \frac{r_p(1+e)}{1+e\cos\theta} \qquad \to \qquad r = \frac{r_a(1-e)}{1+e\cos\theta}$$

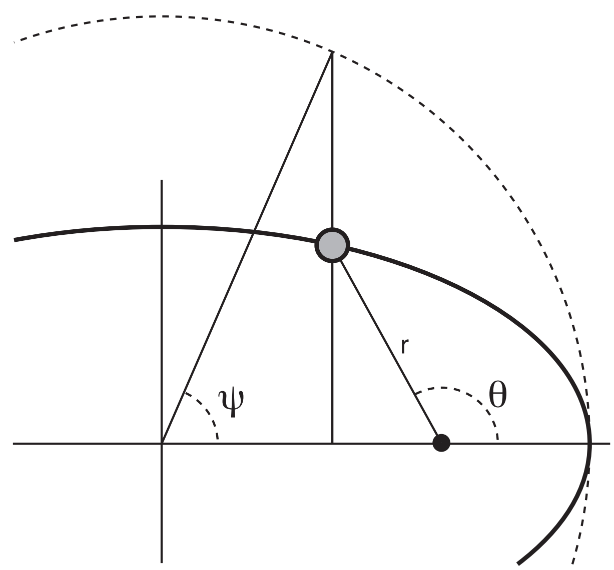
▷ **The Anomaly**. Astronomers refer to the angular position of the body as the *anomaly*. There are three different anomalies of interest.

- θ = **true anomaly.** This is the polar angle θ measured in barycentric coordinates.

- $\mathcal{M}$ = **mean anomaly.** This is the phase of the orbit expressed in terms of the time t since the particle last passed a reference point, generally taken to be $\theta = 0$

$$\mathcal{M} = \frac{2\pi}{P}t$$

Note that for *circular orbits*, $\theta = \mathcal{M}$.



- ψ = **eccentric anomaly.** This is a geometrically defined angle measured from the center of the ellipse to a point on a circumferential circle with radius equal to the semi-major axis of the ellipse. The point on the circle is geometrically located by drawing a perpendicular line from the semi-major axis of the ellipse through the location of the particle. The eccentric anomaly is important for locating the position of the particle as a function of time (using a construction known as *the Kepler Equation*, not to be confused with the three laws of orbital motion).