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Experimental Search for Quantum Gravity

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Experimental Search for Quantum Gravity

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Preface

If you have good eyes, the smallest objects you can make out are about a tenth of a millimeter, roughly the width of a human hair. Add technology, and the smallest structures we have measured so far are approximately 10^{-19} m, that is, the wavelength of the protons collided at the LHC. It has taken us about 400 years from the invention of the microscope to the construction of the LHC—400 years to cross 15 orders of magnitude.

Quantum effects of gravity are estimated to become relevant on distance scales of approximately 10^{-35} m, known as the Planck length. That is another 16 orders of magnitude to go. It makes you wonder whether it is possible at all or whether all the effort to find a quantum theory of gravity is just idle speculation.

I am optimistic. The history of science is full with people who thought things to be impossible that have meanwhile been done: measuring the light deflection on the sun, heavier-than-airflying machines, detecting gravitational waves. Hence, I don't think it is impossible to experimentally test quantum gravity. Maybe it will take some decades, or maybe it will take some centuries—but if only we keep pushing, one day we will measure quantum gravitational effects. Not by directly crossing these 15 orders of magnitude, I believe, but instead by indirect detections at lower energies.

From nothing comes nothing though. If we do not think about how quantum gravitational effects can look like and where they might show up, we will certainly never find them. But fueling my optimism is the steadily increasing interest in the phenomenology of quantum gravity, the research area dedicated to studying how to best find evidence for quantum gravitational effects.

Since there is not any one agreed-upon theory for quantum gravity, existing efforts to find observable phenomena focus on finding ways to test general features of the theory, properties that have been found in several different approaches to quantum gravity. Quantum fluctuations of space-time, for example, or the presence of a "minimal length" would impose a fundamental resolution limit. Such effects can be quantified in mathematical models, which can then be used to estimate the strength of the effects and thus to find out which experiments are most promising.

This volume collects some recent developments in the field of phenomenological quantum gravity that were subject of the recent conference on “Experimental Search for Quantum Gravity.” This meeting took place at the Frankfurt Institute of Advanced Studies (FIAS) in September 2016 as part of the first Giersch Symposion.

Frankfurt am Main, Germany Sabine Hossenfelder
June 2017

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Astroparticle Physics Connections to the Quantum Gravity Problem

Matthias Lorentz

Introduction

The Universe can be used as a formidable laboratory for high-energy physics. In contrast to particle physics at colliders where the experimental environment is well controlled, astroparticle physics deals with elementary particles in "natural" environments where diverse astrophysical processes are at play. While this can introduce an additional level of complexity in the physical interpretation of data, the particle energies achievable by cosmic accelerators are beyond the capabilities of man-made accelerators (see Fig. 1) and these high-energy particles propagate over cosmological distances, offering unique opportunities to address fundamental physics aspects.

The question of quantum gravity (QG) remains unanswered, as no consistent theory combining quantum field theory and general relativity have been found so far. Theories of QG have been developed based on mathematical consistency arguments but the lack of observational evidence due to the extremely small expected effects renders very difficult to properly test and guide such speculative theories. This situation is changing as more and more efforts are put into developing a phenomenology of QG, searching for viable experimental tests in various fields, and astroparticle physics offers many attractive possibilities. We briefly present here selected astroparticle aspects relevant in the experimental search for QG mainly focused on Planck-scale tests of Lorentz symmetry, in the perspective of current and future experimental facilities.

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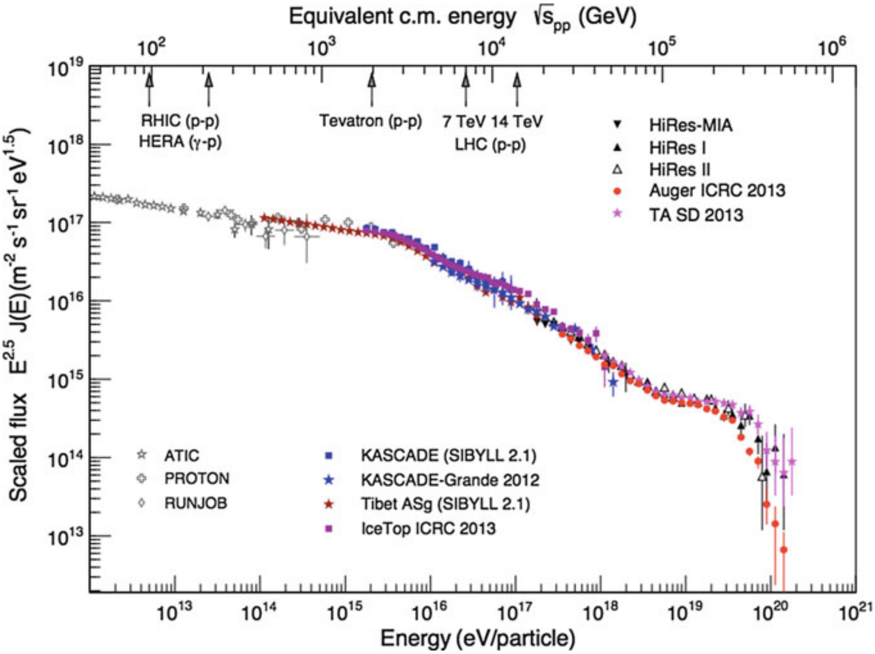

Fig. 1 Measurements of the all-particle cosmic ray spectrum (mainly protons). For comparison the center of mass energy reached at proton collider experiments is shown on the *upper horizontal axis*. Compilation of data by R. Engel, shown at RICAP16 conference

Lorentz Invariance Violation and Modified Dispersion Relations

A feature appearing in some approaches to QG is Lorentz invariance violation (LIV). Lorentz symmetry is a pillar of special relativity and has been established to be an exact symmetry of Nature up to the precision of current experiments. This symmetry is related to the scale-free nature of Minkowski spacetime, consequently the discretization of spacetime and the emergence of a fundamental length scale could mean that Lorentz symmetry is finally not an exact symmetry of Nature [11]. Such a fundamental scale is thought to be around the Planck scale (Planck length $l_{Pl} = \sqrt{\hbar G/c^3} \simeq 1.6 \times 10^{-35}$m, and Planck energy $E_{Pl} = \sqrt{\hbar c^5/G} \simeq 1.2 \times 10^{28}$eV). These quantities constructed using the fundamental physics constants for special relativity (c), quantum mechanics ($\hbar$) and gravitation (G), are the length and energy scales at which relativistic quantum effects of the gravitational interaction are expected to become significant.

Although Planck energy seems experimentally out of reach it has been recognized that LIV could leave distinctive signatures at lower energies, resulting in qualitatively new or distorted phenomena, and that Planck scale sensitivity to LIV could be achieved with already available astrophysical data [4] [3].

A generic and effective approach to introduce LIV effects consists of adding an extra term in the energy-momentum dispersion relation of particles, of the form [10]

$$E^2 = m^2c^4 + p^2c^2 \left[1 \pm \left(\frac{pc}{\xi E_{Pl}} \right)^n \right], \tag{1}$$

where E, m, p are respectively the energy, mass, and momentum of the particle, ξ is a dimensionless parameter comparing the LIV scale to Planck scale (parameter possibly depending on the type of particle), and n is the leading order of the perturbation, the simplest natural possibility being $n = 1$.

The consideration of such modified dispersion relations with no other modification to the theory may not necessarily be valid in a fully consistent framework but this toy-model approach to LIV permits the exploration of a rich phenomenology in astroparticle physics. Two aspects that have been actively explored are time delays in the arrival time of high energy photons that could be the sign of an energy-dependent speed of light, and propagation anomalies for the most energetic cosmic rays or photons that could be due to the modification of the energy threshold of particle interactions.

Time-of-Flight Studies

The realization of Eq. 1 in Nature would induce a energy-dependent velocity for photons. Consequently, photons with an energy difference ΔE emitted simultaneously and propagating over a distance l would acquire an arrival time difference Δt with respect to the standard Lorentz invariant scenario

$$\Delta t \simeq \frac{\Delta E}{\xi E_{Pl}} \frac{l}{c}, \tag{2}$$

where we see that this time-lag is most likely to be observable when E and l are large. The ideal experimental setup to test this effect would then consist of a beam of photons with an energy spectrum going up to very high energies placed at the furthest possible distance from the observer and suddenly turned on in order to compare the arrival time of photons in different energy bands. Such a situation is approximately realized in the observations γ rays coming from γ-ray bursts (GRB) at cosmological distances or during the flares of active galaxy nuclei (AGN). The progresses of γ-ray astronomy over the last decade have allowed significant progresses in that direction.

In the GeV band (high-energy γ-ray astronomy, $E_\gamma > 100$ MeV) the Fermi satellite has observed hundreds of GRBs since it began science operations in 2008. Bright and energetic GRBs with a known redshift (emission distance) can be used to put limits on the LIV scale. The best constraint to date comes from GRB 090510, with a limit up to $\xi \gtrsim 7$ [7] for the case in which higher energetic photons are slowed down (minus sign of the perturbation in Eq. 1) with $n = 1$ (configuration we will call subluminal linear LIV). The analysis of other GRBs have led to lower constraints, and in some cases results even suggest a linear energy-dependent correction to the velocity of photons like in the case of GRB 160509A with $\xi \simeq 0.03$ [15]. The apparent tension between those results and the ones obtained with other methods (see below) can be explained considering intrinsic energy-dependent variability in the γ-ray emission processes of some GRBs. In the TeV band (very high-energy γ-ray astronomy, $E_\gamma > 100$ GeV) the current generation of ground-based atmospheric Cherenkov telescopes (like HESS, MAGIC or VERITAS) has observed flares of AGN with rapid and intense flux variations. In particular the exceptional flare of PKS 2155-304 observed by HESS led to the limit $\xi \gtrsim 0.2$.

Time-of-flight studies with γ rays will benefit from the accumulation of data and population studies of both AGNs and GRBs will allow to disentangle intrinsic energy-dependent variability or other systematic effects from genuine LIV.

Photons and neutrinos could be affected by LIV differently. Testing such an idea now starts to be possible with the advent of sensitive high-energy neutrino experiments like IceCube, the south pole neutrino observatory. Although no astrophysical neutrino event have yet been associated with a γ-ray source, correlation studies of neutrinos with GRBs start to be feasible [2] and time-of-flight studies with neutrinos are an exciting and largely unexplored territory (not to mention the infamous 2011 OPERA anomaly, which turned out to be due to an instrumental effect).

Modification of Reaction Thresholds

Another consequence of Eq. 1 concerns the modification of the energy threshold of interactions between the most energetic particles propagating over extragalactic distances and low energy background photons.

Soon after the discovery of the cosmic microwave background (CMB) in 1964 it was realized that such a low-energy background radiation (Fig. 2) filling the Universe could act as a target material for high-energy particles, reducing their mean free path of propagation. For protons, the critical energy at which the the interaction with a CMB photon allow the resonant creation of pions through the reaction $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$ is $E_{GZK} \sim 5 \times 10^{19}$ eV. The observed cosmic ray spectrum is then expected to be rapidly suppressed around E_{GZK}, feature known as the GZK cut-off [9, 16]. In the case of Planck-scale LIV this threshold energy is affected (either enhanced or suppressed depending on the sign of the perturbation in Eq. 1) and the observations of anomalies could be attributed to LIV. While early results showed some signs of absence of the GZK cut-off, the recent results from the Pierre Auger Observatory unambiguously show a suppression of the cosmic ray flux at energies above 4×10^{19} eV [1] suggesting that the GZK prediction of spectral steepening have been verified, leading to stringent constraints on LIV for protons up to $\xi \gtrsim 10^4$

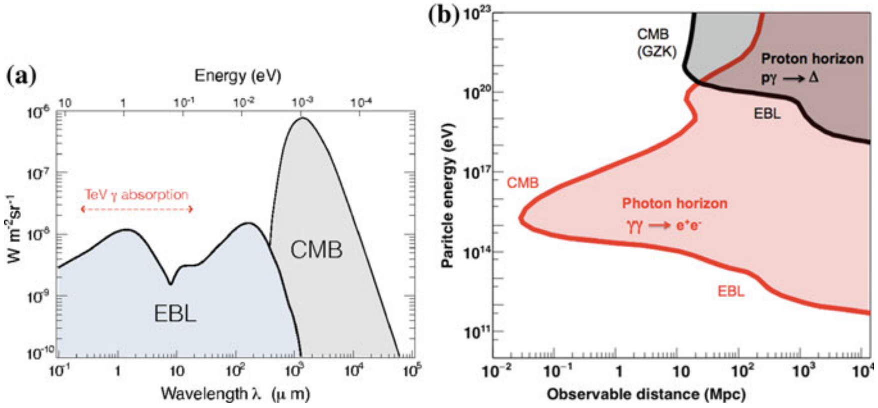

Fig. 2 *Left*: Energy distribution of low energy background photon fields in the Universe, see text (Courtesy of H. Dole). *Right*: Corresponding photon (*red*) and proton (*black*) energy-dependent horizon defined as their mean free path of propagation in Mpc (1 pc $\simeq$ 3.26 light-years)

[6] although this bound is dependent on the mass composition of the most energetic events which may not be exclusively protons but also heavier nuclei.

An interesting alternative possibility to study the GZK cut-off could be to look for the ultra-high energy neutrinos resulting from the decay of pions created in the GZK reaction. A reduction of the interaction rate due to LIV would induce a reduction of the associated neutrino flux [14]. Experiments like the ARIANNA radio array will have the sensitivity to detect these so-called cosmogenic neutrinos, possibly offering an additional way to put constraints on Planck-scale LIV.

For high-energy γ rays, background fields like the CMB also induce a reduction of the mean free path due to the electron-positron pair creation reaction $\gamma\gamma \rightarrow e^+e^-$ (see Fig. 3). The energy threshold for this reaction is reached when $E_{\gamma_{HE}} \simeq \frac{m_e^2}{E_{\gamma_{LE}}}$. For a low-energy photon at the typical CMB energy $E_{\gamma_{LE}}$, the required γ-ray energy $E_{\gamma_{HE}}$ exceeds several hundreds of TeV. This energy range is slightly beyond the capabilities of the currently operating γ-ray experiments and no such ultra-energetic γ rays have been detected so far. However, the CMB is not the only low-energy background photon field filling the extragalactic medium ; the integrated starlight of the Universe and its reprocessing by interstellar dust gives rise to what is called the extraglactic background light (EBL) made of photons in the optical and infrared energy bands. Attenuation due to pair creation on the EBL affects TeV γ-ray fluxes, which is precisely the maximum sensitivity range of atmospheric Cherenkov telescopes detecting the EBL attenuation effect in the energy spectra of AGNs with a high significance. An exceptional flare of the nearby AGN Mrk 501 in 2014 have allowed the measurement by HESS of a spectrum extending significantly up to 20 TeV in agreement with our current knowledge of the EBL [12], leading to the limit $\xi \gtrsim 2$ in the case of linear subluminal LIV perturbations affecting only photons.

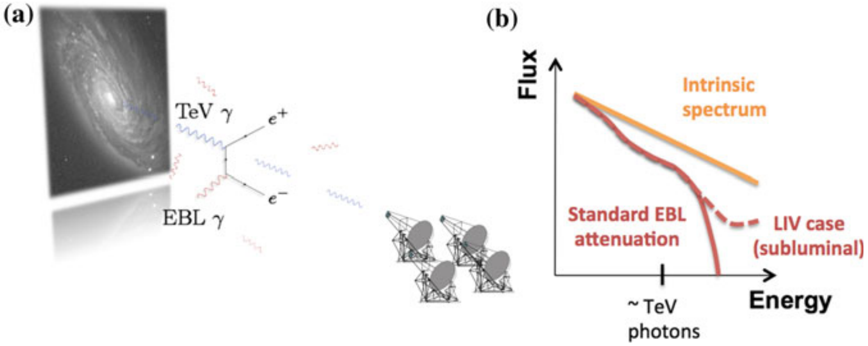

Fig. 3 *Left*: Illustration of the EBL pair production process for TeV photons propagating from an AGN. *Right*: Illustration of the principle allowing LIV constraints via the non-observation of deviation with respect to standard attenuation in the measured spectrum of a TeV γ-ray source

LIV studies with cosmic rays or γ-rays represents the major part of QG-related searches in astroparticle physics. In addition to the above-mentioned observational constraints, other possible LIV effects can be investigated like vacuum Cherenkov effect, photon decay, or cut-off in the synchrotron emission of the Crab nebula which actually provide the most stringent constraints on anomalous dispersion relation for electrons. The interested reader can find more complete informations in reviews like [11].

Other Astroparticle Windows to QG

Spacetime Interferometry

One aspect of the quantum nature of spacetime could be its “foaminess" at a scale close to the Planck lenght. While this notion of spacetime foam remains loosely defined, the basic idea is that Planck-scale spatial uncertainties may induce path-length fluctuations in the propagation of particles and the associated phase shifts (increasing with energy) could accumulate over large distances, affecting the image formation of distant sources. Models of spacetime foam are characterized by a parameter α related to the path-length fluctuation δl for a source at distance l by $\delta l = l^{1-\alpha} l_{Pl}^{\alpha}$.

Recent studies have explored the potential effects of spacetime foam, predicting a possible energy-dependent image blurring of distant astronomical objects or even the total disappearance of images because of accumulated wavefront distortions on small scales. In such a framework the mere observation of TeV γ-ray point sources at a cosmological distance can be used to put significant constraints on models of spacetime foam with a lower bound $\alpha \gtrsim 0.7$ [13].

Fast TeV Transient Signals as White Holes Bursts?

QG may allow a black hole to tunnel into a white hole, and this transition may induce a detectable burst. This possibility have been recently explored in the context of loop QG theories [5] and within this framework the lifetime of a black hole would be shorter than the one given by Hawking evaporation. For stellar-mass black holes the typical lifetime is still far too long to expect the observation of such bursts but low-mass primordial black holes formed in the early universe—if they exist—could be bursting today at a high rate. This could open a new window for quantum-gravity phenomenology as such a white hole burst is predicted to be associated with a short (millisecond) emission of photons in two different channels: a low-energy signal with radio wavelengths reflecting the size of the black hole reaching a critical density, and a high-energy signal reflecting the typical medium temperature at the time of the black hole formation, which for the very early Universe corresponding to the black hole masses considered is around the TeV scale.

Experimental investigation of this idea could benefit from already existing studies on the search for primordial black hole bursts at TeV energies like in [8]. Moreover, the possibility that the low-energy signal could be associated with the intense fast radio bursts (FRBs) of unknown nature is tempting, although many conventional astrophysical scenarios are being developed to explain their origin, and more data will be needed for reliable interpretations. The observation of a simultaneous TeV counterpart to a FRB could spark more interest for this idea. In this perspective, the triggering strategies for TeV follow-up observations of rapid transients like FRBs with current and future Cherenkov telescopes arrays may provide interesting insights, together with wide field of view TeV monitoring experiments like the currently operating High Altitude Water Cherenkov (HAWC) Gamma-ray Observatory.

Conclusion

The study of the most energetic cosmic particles like protons photons or neutrinos offers an experimental connection to the QG problem and has to some extent already allowed to limit the reasonable possibilities that might arise from fundamental Planck scale physics. The non-detection of anomalies that could have been interpreted as evidence for LIV in a simple framework automatically discard QG theories where effects due to Planck scale linear perturbations show up too easily. In the near-future, the increase in statistics due to the accumulation of data from current experiments and the increase in sensitivity with the advent of new generations of experiments (like the Cherenkov Telescope Array) will strengthen the already-existing constraints, enable more complex analyses, and data may also reveal unexpected surprises. Moreover the birth of gravitational wave astronomy and the opening possibilities of multimessenger astronomy using altogether photons neutrinos and gravitational waves will provide very interesting insights in the experimental search for QG.

On the theory side, the development of models associated with a clear phenomenology is essential to maintain a reasonable predictive power of theories. Ideally, QG theories should be able to predict smoking-gun signals for which it is conceivable to arrive at experimental signatures that can be disentangled from systematic effects, either of instrumental or astrophysical origin. A close collaboration between theorists and experimentalists in the field will certainly allow the exploration of new exciting possibilities. In this perspective astroparticle physics could be an active and rich area in the experimental search for QG for the decades to come.

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The Search for a Tiny Hint from Quantum Gravity in the Cosmic Relic Radiation

David Brizuela and Manuel Krämer

Abstract One of the most important open problems in current fundamental physics is to find a quantum theory of gravity, which means to incorporate the last missing fundamental force of Nature into the quantum picture. For over eighty years now, there has been an intense effort to develop candidate theories of quantum gravity, but none of them has been completely satisfactory. Among other more conceptual issues, the main problem lies in the difficulty to find tests for such a theory. In this essay, we will describe why this is so difficult and argue that the most promising possibility might be a tiny effect seen in the earliest light that we can observe from the beginning of the universe.

Whenever one wants to test a new theory in physics, there are in general two ways. The first one is to look for effects that are entirely new like all those strange effects that arose from quantum physics, whereas the second approach is to try to find small corrections to already known phenomena. In the past, the second approach has been very important in order to test and consequently confirm new theories, which are now considered to be a milestone in the development of physics. Take, for example, Einstein's general relativity. Already in 1859, the French astronomer Le Verrier, who had become famous for predicting the existence of Neptune a decade earlier, noticed that the orbit of the planet Mercury does not behave like the—at that time—established theory of gravity by Newton predicted. The closest point of Mercury's elliptical orbit to the sun—the so-called perihelion—shifts with each completed orbit. The effect was at that time too tiny to be observed for one Mercurial orbit, but it accumulated over a century to an observable effect, which puzzled the astronomers back then so much that they came up with speculations that e.g. there might be an additional planet orbiting the Sun closer to Mercury. Einstein, however, could explain this effect and also calculate the amount of the deviation very precisely using an approximation of his new theory of general relativity. Another example of a correction to an effect that established a new theory was a tiny difference in two energy levels of

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the hydrogen atom which, according to non-relativistic quantum mechanics, should have the same energy. This effect, observed by the American physicist Lamb, and thus called Lamb shift, could only be explained by using quantum electrodynamics, a theory that superseded ordinary quantum mechanics in the 1930s.

Therefore, we see that small corrections to certain physical processes played a crucial role in establishing new theories in the past and we want to take this path to find a test for a theory of quantum gravity. For this we need to find a suitable way to approximate our chosen candidate theory. In general, for any approximation in physics one needs a certain expansion parameter. In special relativity, this parameter is the speed of light, denoted by c. Thus relativistic effects, like the contraction of length or the dilation of time, become larger the closer the relative velocity between two observers is to the speed of light. In general relativity, one also uses the speed of light for the so-called post-Newtonian approximation; but in quantum mechanics, Planck's constant $\hbar$, which relates the frequency of light to a certain energy, is used. This constant can be understood as the product of an energy and a time, or of a length and a momentum. The larger these products are for characteristic quantities of a physical system, the less "quantum" this system is.

Another way to perform approximations in physics is to identify parts of a system that are less influenced by the rest of the system. For example, the movement of the Sun is almost not influenced by the smaller and much less massive planets. Similarly, the heavy nucleus of an atom is also hardly affected by the electrons around him. Thus one can construct an approximation scheme where one ignores the influence of the small electrons or planets onto the heavy nucleus or Sun. On our way to find an approximation to a theory of quantum gravity, we will make use of both the above-mentioned methods.

First, we need to find an expansion parameter. Since quantum gravity combines quantum mechanics and general relativity, it is natural to assume that the central physical constants of those theories are important; i.e. the gravitational constant G, together with the speed of light c, for general relativity and Planck's constant $\hbar$ for quantum mechanics. In fact, one can construct unique combinations of these three constants that give rise to a certain length, mass and time. The quantities constructed like this are called Planck quantities and they are generally thought of as the threshold from which effects from a theory of quantum gravity should become important. The Planck length is so tiny—20 orders of magnitude smaller than the diameter of a proton—that it is sometimes thought of as the tiniest possible length in the universe. The Planck mass is in principle not very special—it corresponds to about 0.02 milligrams—but multiply this mass with c^2, using Einstein's famous formula $E = mc^2$, and you get an energy that, if applied to a single particle, goes way beyond any physical process accessible to us. In order to probe such energies with a particle accelerator using current technology, we would need to build one having about the size of our galaxy.

This is certainly a crazy amount of energy. So, are there actually any fundamental physical processes in our universe which come close to this energy scale? One might think of black holes and, in fact, Hawking's prediction that black holes emit radiation is based on an approximation of quantum effects on a spacetime heavily curved by a black hole. However, the emitted Hawking radiation of stellar-sized or larger black holes is too small to be observable.

Another possibility is to look at the early stages of the primordial universe, where processes with energies close to the Planck energy were occurring. In fact, this approach turns out to be much more promising, because we actually can observe a certain kind of radiation that tells us indirectly what happened at the very beginning of the universe: the radiation of the cosmic microwave background.

The cosmic microwave background is made up of radiation that is received from all directions of the sky. As its name states, the frequency of this radiation lies in the microwave range and thus it is not visible for human eyes. One can associate a temperature of 2.7 Kelvin to it, which means that an idealized source with this temperature would emit the same kind of radiation. As we will describe later, the cosmic microwave background radiation is the "oldest" light we can see from the beginning of the universe.

Note that, since the speed of light is finite, observing an object at any given distance, implies seeing it as it was some time ago. The speed of light is very large, thus this effect is completely negligible in our usual life, when we look at objects a few meters away from us. Nonetheless, the effect is extremely important in cosmology when light takes much longer to travel from its source to us. In fact, cosmological distances are usually measured in light years, which corresponds to the distance traveled by light in one year. For instance, the closest star to the Sun is Proxima Centauri, which is around four light years away. This means that, when something happens there, we will not be able to see it until this time has elapsed.

Therefore, looking at a further distance means looking further in the past. A straightforward question is then, how far can we look back? The answer is: almost until the beginning of the universe or, more precisely, up to the point where the cosmic microwave background was formed. The reason that this is the furthest point we can look at, does not have anything to do with our current technology. It is due to the fact that before this point in time, light was unable to propagate freely. At the beginning, the universe was extremely hot and the state of matter was a plasma of fundamental particles; that is, electrons and protons were not yet combined to atoms or molecules because their energy was so large that they were moving too quickly to be bound into more complex systems. This plasma was opaque to light, which means that the photons—the light particles—could not cross it, since every photon was strongly interacting with the freely moving particles.The moment the temperature of the universe decreased up to the point that light could freely travel, corresponds to the emission of this relic radiation that we are able to detect nowadays—almost 14 billion years later—with our telescopes.

There are several theories that try to explain the very first instants of the existence of our universe, but currently the theory of cosmological inflation is the most widely accepted paradigm. This theory was proposed in the 1980s as a phenomenological way to solve some conceptual issues [1]. In particular, the fact that the cosmic microwave background radiation is highly isotropic; that is, it is almost exactly the same, regardless in which direction we observe it. This seems to be a priori in conflict with general relativity because, according to the usual implementation of this theory, which is used to describe the evolution of the universe and otherwise fits extremely well with most of the observations, all points that produced this radiation were not in causal contact at that time. In order to solve this puzzle, the idea of inflation is to assume a extremely rapid expanding phase at the beginning of the universe. This enables all those points to be in contact with each other before being inflated and torn apart. Intuitively, this process inflates everything in the universe from very small to extremely large scales and, in particular, it might convert typical quantum-gravitational effects—which are important at very small lengths that correspond to the high energies of the Planck regime discussed above—into larger-scale structures, which might be observable by our telescopes. Another way to argue why inflation might lead to measurable quantum-gravity effects is that it happens at an energy scale that is only five orders of magnitude smaller than the Planck scale, as opposed to 14 orders of magnitude, which is how much smaller the energy scale we can probe with the latest particle colliders is compared to the Planck energy.

So, what kind of features arising from inflation can we actually observe in the cosmic microwave background? The fact that inflation blows up microscopic scales to macroscopic ones means that also tiny quantum fluctuations of spacetime are inflated and actually give rise to the formation of structure in the universe. And we can see an imprint of these quantum fluctuations in the cosmic microwave background. We have written before that this radiation is highly isotropic; and this is true, but only to about 0.001%. There are tiny anisotropies in the cosmic microwave background, which we can measure very precisely and they encode a lot of information.

In fact, these blown-up quantum fluctuations of spacetime are somehow already some kind of quantum-gravitational effect, but the difference here is that these fluctuations are usually described as quantum fields living on a classical background spacetime and not on a fully quantized one. The latter part is the crucial difference a full theory of quantum gravity will account for.

Now that we have identified a suitable physical scenario where to look for effects of a theory of quantum gravity, we need to choose one of the candidate theories to test. We will work with a theory that restricts itself to quantizing gravity as described by general relativity, and that was already developed at the end of the 1960s in a series of works by Wheeler and DeWitt [2]. They came up with an equation that is currently known as the Wheeler–DeWitt equation, and which can be considered as the quantum version of the central equations of general relativity, the Einstein equations. If you are now wondering why physicists still look for a theory of quantum gravity and are not satisfied with the Wheeler–DeWitt equation, the reason is that it exhibits several conceptual and mathematical problems, many of which are still under discussion in the current scientific literature. In particular, one of the major conceptual problems is related to the understanding of the role of time. In general relativity, there is no preferred notion of time, in the sense that different observers feel a different flow of time and none of them can be regarded as the most natural one. In technical terms, the evolution in time corresponds to a mathematical transformation without any physical significance. Classically, one can use symmetries inherent to the problem under consideration in order to choose one specific flow of time over the others. This is done, for instance, when one wants to perform an approximation of the

Wheeler–DeWitt equation in order to get a simpler equation that describes quantum fields on a classical background. In this case, the background geometry behaves classically, as described by the Einstein equations, and does not feel the quantum effects of the fields living on it. Nonetheless, in the full Wheeler–DeWitt equation, where the background geometry is also quantized, the problem of time is exacerbated since the quantum Wheeler–DeWitt equation is literally timeless. Therefore, it is very difficult—and usually not possible to find a unique way—to extract a notion of a physical evolution as we know in other parts of physics and from our daily lives.

But, all in all, the Wheeler–DeWitt equation is a rather conservative approach to the quantization of gravity and, if one considers cosmological scenarios, many of the above-mentioned mathematical problems are not present anymore, which is why the theory is still very actively used nowadays in research on quantum cosmology. Even if it might not be the final answer to the problem of finding a theory of quantum gravity, it should anyway give us some hints about which route to follow. In fact, one of the currently most popular quantum gravity candidate theories, loop quantum gravity, is based on the same idea as the Wheeler–DeWitt approach; it just uses a different description of spacetime for the quantization, which leads to entirely new features like a discrete structure of spacetime at scales close to the Planck length. However, it should still give the Wheeler–DeWitt equation as a limit for length scales larger than the Planck scale.

We should thus now go ahead and set up a model of the universe during inflation that contains fluctuations of spacetime, quantize it and solve the Wheeler–DeWitt equation of this model. However, it turns out that this equation cannot be solved directly and therefore we need to turn to an approximation like the ones described at the beginning of this essay. In fact, we use a combination of the two methods described above. First of all, we expand the Wheeler–DeWitt equation in terms of the Planck mass and, secondly, we use the fact that the background—playing the role of the heavy nucleus—is only slightly influenced by the fluctuations—the light electrons—acting on it.

This framework to approximate the Wheeler–DeWitt equation was proposed in [3]. This approximation scheme led to a systematic method to convert the problem of solving the Wheeler–DeWitt equation into an infinite hierarchy of equations. The nice property of this hierarchy is that at every order one recovers more and more refined approximations to the full Wheeler–DeWitt equation and one can thus truncate this infinite hierarchy at any given order with the desired level of accuracy. In particular, at the first order, the classical Einstein equations are obtained and, at the next order, the limit of quantum fields on a curved classical spacetime—expressed as a Schrödinger equation similar to the famous equation of quantum mechanics. The following order then leads to a modified Schrödinger equation, which includes a correction term that encodes the most important quantum-gravitational effects.

In a series of papers [4], we have used more and more refined models of a primordial inflationary universe with quantum fluctuations of spacetime to solve this corrected Schrödinger equation and to calculate what kind of effect one would observe in the anisotropies of the cosmic microwave background radiation from this correction. One can describe these anisotropies as some kind of spectrum, which is a function of the scale, or rather size, of the anisotropies. This means that given a certain scale, the power spectrum essentially describes the energy—that is, the deviation of the temperature from the average value of 2.7 Kelvin—contained in the anisotropies of that typical size. The result that has been found is that the power should become slightly enhanced for large scales, i.e. large anisotropies should exhibit a slightly larger temperature deviation than smaller ones. Thus quantum gravity in this case has the most dominant effect on the largest observable scales in the universe, which sounds paradoxical at first, but the power of these large scales in the anisotropy spectrum is determined earlier—and therefore at higher energies, where quantum-gravity effects are also larger—than the power of smaller scales. However, as expected, the quantum-gravity correction is very small, suppressed by about 10 orders of magnitude, and in fact, unfortunately also too small to actually be detected in the anisotropies of the cosmic microwave background also with future, more refined observations. Nonetheless, given that the quantum-gravitational corrections we calculated also have an influence on other observations in the universe like the distribution of galaxies, not all hope is lost, as it cannot be excluded that there might be a way to observe such a tiny quantum-gravity effect elsewhere.

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Superfluid Helium: The Volovik Lessons

Tim Lappe

This essay contribution to the conference on "Experimental Search for Quantum Gravity" was expected to address the question of the general relevance of the phenomenology of quantum gravity in simple terms. In doing so, it is perhaps best to remark upon the slightly paradoxical nature of the idea of searching for quantum gravity *experimentally*. It is usually believed that the regime where quantum effects become relevant for gravity lies at so extraordinarily high energies that it is virtually inaccessible for any given experiment. How then can one speak of experiments in this regard? Well, it is in some sense the basic job description of a physicist to try to conceive of methods that make accessible natural phenomena that where hitherto out of reach, and to do so by devicing experiments. It is here that phenomenology comes into play by trying to work out models that can actually be tested by available data. This approach somewhat makes it the ugly duckling amongst its company within the quantum-gravity community. To understand why, it is necessary to view 20th century theoretical physics in the light of its dominating paradigm: that it be possible, by unifying the two great theories of our time, quantum mechanics and general relativity, to obtain a fundamental "theory of everything". In this way, following mostly theoretical intuition and mathematical guidelines, a final theory of quantum gravity was expected to pop out, preferably yielding new predictions that could have been verified experimentally. That it has not, plus that experimental techniques have much improved, are the two main reasons why phenomenology is back on the table. Possibly also, this younger development is indicative of a paradigm shift within physics, from theoretical dominance to a more empirical position. The excess of speculative theory, which has grown in recent decades to such an extent that part of its output is considered by some as unscientific, or outright science fiction, has its root in the history of physics during the last century. With Maxwell's

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unification of electric and magnetic phenomena and the subsequent prediction of the existence of electromagnetic waves as its earliest ideal, the speculative approach indeed has had a number of astonishing successes: Dirac's prediction of the positron and Pauli's deduction of the neutrino belong here. Most strongly, however, it was Einstein's publicity that established the speculative paradigm. The invention of general relativity as a theory of gravitation, made up from sheer 'principles', set the watermark for generations of theorists to come. Not much later, the stroke of genius by young Heisenberg to use non-commuting matrices in his formulation of quantum mechanics, led to a description of atomic processes that worked fascinatingly well. Both theories, however, always lacked the connection to physical elements of reality, or in other words, pictures conforming to human imagination. Consequently, the approach in theoretical physics shifted towards abstraction, the holy grail becoming the unification of the two great theories.

In accord with the leitmotif of the phenomenology of quantum gravity, this note will argue in favour of a second paradigm, call it heuristic, and for a paradigm shift towards it. We shall do so by following G. E. Volovik's approach [1] of contrasting the two paradigma by using condensed-matter analogies, the essence of which is that, by looking to systems that actually occur in nature, a purely theoretical program can be substantiated, and sometimes even perceived to be missing the point. There is a direct connection with the conference through J. Steinhauer's work on analogue black-hole horizons [2].

Given the decades-long attempts to solve the problem of quantum gravity theoretically, one might suspect that this problem, if not ill-posed, is simply too difficult. In such cases, science has usually progressed by unexpected input from experiments. Since the LHC has failed to produce input of this kind, the need for alternatives is urgent. Here, condensed-matter analogies enter the scene. Since black holes are believed to offer the best window to experimental clues on quantum gravity, but are unavailable for direct study, the prospect of creating at least an analogy in the lab must be taken quite seriously.

The main point of Volovik's treatment rests on the experimental fact that many quantum liquids, most prominently different forms of superfluid helium, can at low energies be described by *effective theories*, where the original particles of the fluid, say the helium atoms, no longer describe the elementary excitations of the system. Rather these are now given by so-called *quasiparticles*, sitting above a ground state that can be seen as a vacuum. So, at low energy, the complicated interacting many-body Hamiltonian for the bare atoms can be shown to be approximately equivalent to a different Hamiltonian consisting of a vacuum state and a dilute gas of free quasiparticles. This is the simplest model around, yet it nicely illustrates the conept of quasiparticles in condensed matter, the most prominent treatment of which was of course given by Bogolubov in the 60s. Very surprising, however, is that more realistic models of superfluid helium show behaviour that is reminiscent of general relativity: the bare atoms translate into an effective background for the quasiparticles that acts on them much like a gravitational field. This picture suggests immediately that the concept of curved spacetime from general relativity could be nothing more than an useful *effective* description of the low-energy corner that we are currently observing.

In reality, there would be an interacting system of so-called “trans-Planckian particles” constituting the quantum vacuum, just like the helium atoms in condensed-matter experiments constitute the superfluid quantum liquid. These trans-Planckian particles are somewhat analogous to the notion of “atoms of spacetime” that is being entertained by some theorists working on the quantization of gravity. Like quanta of fields arise in any quantum field theory, such atoms of spacetime are thought to arise in the “quantum geometry” of gravitation. That this is a problematic concept should be self-evident. Much less so for the idea of actually real trans-Planckian atoms living in ordinary space and time, with the four-dimensional curved spacetime of general relativity arising in the approximate treatment of the many-body problem. Naturally, the analogy between quantum liquids and the gravitating vacuum is not complete. But the task for the physicist becomes quite well-defined by virtue of it: find the properties of the trans-Planckian particles constituting the vacuum, such that most known phenomena, gravity included, can be reproduced from ordinary many-body theory. That is, presumably, what most theoretical physicists in the field are trying to do, although in many different guises. In any case, the importance of actual pictures appealing both to imagination *and* reality should not be underestimated, and that is why the program might be most fruitfully formulated in terms of condensed-matter analogies, with their direct link to performable experiments.

Its productiveness can be shown sort of “negatively” by looking to the quantization of gravity, in the sense that much effort spent on this problem might have been invested more productively elsewhere. That the task of deciding what to work on is actually important should be clear enough, yet let it be said that the geopolitical developments only underline the need for continued scientific and technological progress, which in decades from now will have to be nourished by the fundamental research going on today. The lesson of condensed matter for quantum gravity is illustrated by Volovik through an analogy with crystals. The atomic structure of crystals can be complicated, for which reason one might wish to perform an approximation called the “the acoustic or hydrodynamic” limit. Within this approximation, it is possible to describe deformations of the crystal on an effective level by means of the classic theory of elasticity, its main object being acoustic waves of the crystal. These have to be long-wavelength, however, for the approximation to be well applicable. More interestingly, one finds that most crystals are governed by the same set of equations, which clearly shows that knowledge of the exact atomic structure is lost in such a low-energy description. Now, one can take the next step and quantize the classical theory of elasticity to obtain the quanta of acoustic waves, which are called *phonons*. But, and this is the point being made, the quantum field theory won in this way is still approximate and only valid for low energies, and so one cannot learn much from it about the full quantum theory of crystals. Volovik then uses this analogy to conclude that the quantization of gravity, the latter being viewed as a low-energy “acoustic wave” of the bare-atom system, “will not add much to our understanding of the microscopic structure of the vacuum”. Quantum gravity would instead give only the respective quanta of its field, the analogy of phonons, which are called *gravitons*. According to Volovik, “the deeper quantization of gravity makes no sense in this philosophy”.

Another simple but interesting thing that can be learned from analogue condensed matter is a nice picture for gravity. It is well-known that by compairing the formulas for time-dilation from special relativity,

$$t^{'} = t\sqrt{1 - v^2/c^2}, \tag{1}$$

with that for gravitational time-dilation,

$$t^{'} = t\sqrt{1 - \frac{2GM}{rc^2}}, \tag{2}$$

it is possible to associate a "velocity" $v^2 = \frac{2GM}{r}$ with the gravitational field at distance r around a spherical body of mass M. The trick of the analogy with superfluids is to take this literally and to identify the velocity

$$\dot{r} = -\sqrt{2GM/r} = v_s(r) \tag{3}$$

with the superfluid flow velocity, $v_s(r)$. Moreover, the change in this velocity is what can be identified with the gravitational force, as can be seen easily from

$$\ddot{r} = -GM/r^2. \tag{4}$$

So, according to this picture, analogue gravity is caused by the increase in flow velocity of the liquid. A black hole can now be seen to correspond to an object around which the flow velocity of the quantum fluid exceeds the speed of propagation, c, of low-energy excitations such as phonons or photons, that is, $v_s(r_{BH}) \geq c$. Right at the horizon, a particle propagating outwards will get stuck, like a boat driving up a waterfall. Beyond the horizon, it will gradually be sucked into the black hole, whence of course its name. The last thing one has to relaize then is that due to the existence of the horizon, particles behind it will have negative energy, $E_{in} = -c|p|$, whereas particles outside it will have positive energy, $E_{out} = +c|p|$. Therefore, spontaneous pair creation becomes an energetically possible process, since $E_{in} + E_{out} = -c|p| + c|p| = 0$. Basically, this is the physics behind the famous *Hawking radiation*, which states that, although a black hole sucks up all the matter in its vicinity, it will still also *emit* a stream of particles. Hawking found that the spectrum of this emission will be just that of a black body at a temperature corresponding to the "surface gravity" of the black hole. It is precisely this radiation and the entanglement among its constituents on either side of the horizon that J. Steinhauer observed in the form of phonons at an analogue black-hole horizon created with a Bose-Einstein condensate of cold atoms [2].

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On the Paradigms of Quantum Gravity 2016

Fabian Müller

Introduction

One hundred years of quantum and gravity have not been enough to solve the riddle of the fundamental structure of our universe. Still there is an unquenchable strive to achieve the ultimate understanding of nature in the face of almost secure defeat. As the protagonists of this scientific field try to paint a picture of our physical reality in its utter completeness, I will now step back to attempt a reflection of their work process from an epistemological point of view.

Situation

In the first half of the 20th century two theories emerged, which described distinct natural phenomena on very different length scales. One is called *quantum mechanics* being concerned with the physics of light and particles on (sub)atomic levels, the other one is *general relativity*, which describes gravitational effects like the observable motion and attraction of astronomical bodies e.g. stars and planets. Both theories were considered very radical changes of paradigm at the time and though they have been tested successfully to astonishing accuracy by now, people are still unsatisfied enough to work on the next change of paradigm, which will (hopefully) be the unification of both: *quantum gravity*

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Quantum Theory

The advent of quantum mechanics was stimulated by the desire to know, what the physics of the microcosm of particles really is, since there were some phenomena, which could not be explained by the classical atomic models. To many physicists quantum mechanics is nothing but a vast apparatus of mathematics, which coincidentally describes the physics of particles. Their aversion arises in part by the theory's incompatibility with human intuition. This can be shown by the question: "What is light?" In the classical thinking light can *either* be a wave *or* a particle. Quantum mechanics, however, tells us that light is "quantum", i.e. it exhibits qualities of waves and particles equally, which is termed the *wave-particle-dualism*. This term alone signals how physicists cling to the traditional classification still today, instead of accepting that light is something new, which they cannot grasp with thinking in classical patterns.

While this is not an easy notion to digest, the world of physics has been shaken even more, as quantum theory revealed its probabilistic nature. To the horror of all scientists nature turned out to be not deterministic on the microscopic level. While one part of the scientific community accepts that chance, randomness and non-predictability is a fundamental concept of nature itself, the other part still hopes to resolve this undesired feature in a new quantum (gravity) theory, e.g. by introducing "hidden variables". That this desire could be solely rooted in the psychological constitution of the human mind seems to be consequently overlooked.

Independent of all these doubts quantum mechanics has been developed further over the course of the last one hundred years to what is known as *quantum field theory*. This powerful tool is able to describe three of the four fundamental forces of nature as fields of quantum states, namely electromagnetism, the weak and the strong interaction. However, any attempt to include the force of gravity into this picture has failed to this day.

Gravity

Newton's classical theory of gravitation has been challenged by Albert Einstein in 1915 as he postulated his theory of general relativity, which lead to the prediction of black holes and gravitational waves. The new idea was that space (and time) cannot be regarded as absolute quantities, rather they are subject to deformations or *curvature* caused by the existence of matter (or energy). Motion in a gravitational field can now be considered as geodesic motion in curved spacetime. Again the scientific community reacted with great reluctance to this new approach awarding Einstein the Nobel prize in 1921 for his quantum interpretation of the photoelectric effect, since there was no experimental proof of the correctness of general relativity. This should change in the following decades and today general relativity is tested successfully to similar accuracy as quantum mechanics.

Defining the Problem

Summarizing that we have two very successful theories on their own domain respectively we have to ask: Where is the problem?

To answer this question it could be helpful to differentiate between two different types of problems.

(i) The problem occurs, when we attempt to combine quantum mechanics and general relativity. While the first is a linear non-deterministic theory, the second is a non-linear deterministic one. From the conceptual point of view alone both theories differ fundamentally in their structure. One can now argue that this is nothing but an aesthetic flaw, which should play no role in the scientific edifice of ideas. However, the true physical problem becomes evident, if we try to drag gravitational effects to the microscopic quantum world of particles. On a mathematical level the so-called *quantization of gravity*, i.e. the description of spacetime by quantum states leads to physically inconsistent results (if a result is achieved at all). With this physicists are groping in the dark when describing gravity on short length scales.

(ii) Additionally scientists observe phenomena in experiment and theory, whose explanation goes well beyond the scope of their current theories. Examples for these are the existence and nature of dark energy and dark matter as well as the occurrence of singularities in black holes and the big bang. It is hoped that these problems might be resolved within a new theory of quantum gravity. However, one should point out that the phenomena mentioned need not necessarily have to do with either quantum or gravity theory. Like in the case of particles, waves and light it could turn out that we have to deal with something completely new.

Approaches to Quantum Gravity

The notion above is usually ignored and deemed quite “alternative”, so that people hope to solve problem (ii) automatically by solving problem (i). To achieve this two mainstream theories have been developed: *string theory* and *loop quantum gravity*. The first imagines particles as vibrating strings sweeping through world branes, which sounds not too unreasonable, since many phenomena in physics are described by oscillations. The second tries to quantize spacetime and apply techniques of quantum field theory. After more than two decades neither theory can provide a satisfying picture of the world without coming up with other undesired features like the requirement of more than four spacetime dimensions in the case of string theory. Admittedly it is a priori not ruled out that nature provides 27 spactime dimensions of which 23 are curled up so tinily that we cannot detect them, but it reveals the true bane of quantum gravity, which is that we lack experimental evidence of basically everything. No particle accelerator has enough energy to delve into the microscopic structure of strings and most probably none will ever have. By this illustration “scientists” can walk freely on the playground of quantum gravity and propose any theory they want, since it is not falsifiable anyway. Tuning all the parameters they have string theory alone provides 10^{500} different versions of its own. Since it cannot be hoped to reduce this to a reasonable number of candidates in the absence of very conclusive measurements, "alternative" approaches become attractive once more. But again the creativity of physicists, which is needed to solve the problem, is to the same extent its own downfall, since the possibilities are countless. Without any observational hints of quantum gravity the only directive that serves as a boundary condition is the necessity of the new theory to reduce to quantum mechanics and general relativity in the low energy limit.

Black Holes and Analog Gravity

Straight forward thinking leads the "experimental search for quantum gravity" to places, where energy densities take on values well beyond human imagination in the truest of all senses. Such places cannot be found on earth or even the solar system, but general relativity predicts the existence of infinetely dense points in spacetime that lie at the centers of black holes. Though black holes are astrophysically detectable by their gravitational attraction on their surroundings, their notion does not come along with some peculiar difficulties. First of all the spacetime singularities themselves are deemed unphysical and should not exist within a framework of quantum gravity. This is not a big deal for astrophysicists but a huge dilemma for theorists, since general relativity predicts the existence of black holes, while black holes predict the breakdown of general relativity. Unfortunately we are not half way done with black hole peculiarities, since they classically form what is called event horizons around them. These event horizons effectively prevent any insight "into" a black hole and in the words of the *cosmic censorship hypothesis* the black hole's singularity and with it all of quantum gravity is shielded away behind such an event horizon. So it could very well be that quantum gravity itself is simply not part of our universe.

One loop hole, however, might exist and it triggers debates for nearly four decades now, also being addressed at the ESQG conference many times. It is the assumption that black holes emit thermal Hawking radiation. With time they would shrink in size, loose mass and eventually explode revealing their interior. Again such a scenario brings along new undesired features like the information loss paradox and evaporation times are so large that the decay time of the most stable particle in the universe (the proton) is but a blink of an eye in the lifetime of a black hole, rendering the effect basically unobservable. Efforts in loop quantum gravity lead to shorter evaporation times, but still the astrophysical laboratory of black holes remains fairly intangible.

So what else can we do, if the natural systems of quantum gravity so successfully avoid experimental detection? Well, we can do analogies, literally, going from pho<u>t</u>ons to pho<u>n</u>ons. Much like black holes trap light particles (=photons), Jeff Steinhauer managed to trap "sound particles" (=phonons) in the laboratory by creating an artificial event horizon. This can be achieved by accelerating a quantum gas beyond its own speed of sound. Pairs of phonons that are spontaneously created within such a gas can never reach the fleeing edge and become trapped. If such a pair is created exactly on the event horizon, it can happen that one of the phonon partners becomes trapped, while the other one escapes into the subsonic region becoming visible as "sound radiation". This process is the accurate analogy to Hawking radiation at black hole event horizons, just that we now deal with sound instead of light. With Steinhauer claiming the measurement of entanglement between the phonon partners, many of the community are hesitant about the findings as it has always been in the history of physics. However, the more fundamental question is not about the validity of analog Hawking radiation, but about what exactly such an artificial black hole can tell us about a true astrophysical black hole. What conclusive power has a non-gravitational system about a gravitating one? Where does the analogy break down? Though Steinhauer's experiment might have the potential to become more than a footnote in the quest for quantum gravity, pessimists seem to have good arguments, when they say that this cannot solve the information loss paradox, since no information is lost in the first place and eventually one cannot possibly hope that artificial event horizons for sound are able to shed light on the gravitational physics on smallest lengths.

Giving up Symmetry?

The edifice of (theoretical) physics has been strengthened over the course of centuries and is built on very fundamental concepts that somehow came to savor the status of sanctity. These concepts are overarchingly known as *symmetries* and represent very powerful (mathematical) tools to describe nature and derive many of its properties. This is because symmetries preserve (phenomenological) appearances of a system under transformations, i.e. a system A looks the same as a system B after applying a transformation "x" to it. Eventually this procedure acts like a boundary condition for the system und reduces the degrees of freedom (=fewer parameters to adjust), thus *simplifying* it. Since the entire complexity of nature is well beyond the grasp of human understanding, physicists try to find and apply as many symmetries as possible, generating highly reduced and simplified systems.

Seemingly nature exhibits many of such symmetries, especially in the field of particle physics. One theorem states that our universe could be reproduced or "mirrored" exactly by inverting three particle properties simultaneously, which are C̲harge, P̲arity and T̲ime, representing *CPT-symmetry*. The idea is that a universe filled with antimatter (C-symmetry), inversion of spatial coordinates (P-symmetry) and reversal of time itself (T-symmetry) would yield exactly the same laws of particle physics as our original one. While to date all experiments are in accordance with CPT-symmetry, the picture changes, if one looks separately at CP-symmetry and T-symmetry, who do not need to be preserved each by itself, but only as the combination of CPT. In fact electroweak interaction *demands* the violation of CP-symmetry (and consequently T-symmetry) to explain the observed decay of certain particles, while it still preserves

CPT-symmetry as a whole. Contrarily CP-violation has not been observed for the case of strong interaction of quarks and gluons.

Another very fundamental concept of symmetry is the one of *Lorentz covariance*,[1] which states that physical laws are invariant under the transformation of coordinate systems. Obviously there is some connection between Lorentz symmetry and P- and T-symmetry, but furthermore it represents the corner stone of genera l relativity, which describes gravity as an effect of geometrically curved spacetime. Now Lorentz invariance demands that gravitation appears the same regardless of the choice of coordinates, which is also an appealing feature for any quantum theory. This apparent common thread of quantum gravity, its success and applicational power promoted Lorentz invariance to something that most physicists are not willing to give up. Also in experiment Lorentz invariance holds true at least as a *hidden* symmetry. Actually the theoretical description of the above mentioned phonons requires the spontaneous symmetry breaking of Lorentz invariance, i.e. the underlying equations still exhibit Lorentz symmetry, while their solutions and thus the phenomenology does not making the symmetry a *hidden* one.

It is the need to solve the riddle of quantum gravity that makes some physicists question the sacred paradigm of Lorentz invariance sparking an expanding field of search for Lorentz violating effects both in theory and experiment. E.g. Hořava-Lifshitz gravity as a modern alternative to general relativity explicitly breaks Lorentz invariance on the fundamental level and restores it in the large scale limit, rendering Lorentz symmetry an *emergent* or *effective* symmetry. So the question arises how fundamental a symmetry has to be. Actually symmetries seem to appear only on certain scales and under appropriate strategies of reductionism, which can be enlightened by numerous examples. The whole of Quantum Chormodynamics[2] (QCD) relies on the isospin symmetry, which implies that protons and neutrons have the same mass. However, we *know* from experiment that protons and neutrons have slightly different masses, but still the theory established on an incorrect assumption works out surprisingly well.

In the case of quantum gravity the concept of symmetric particles has been incorporated in some versions of superstring theory. The idea is that every fermion has a bosonic counterpart so that the standard model of particle physics is extended to one exhibiting a hidden supersymmetry, which is spontaneously broken at low energies, so that we again experience an asymmetric world of particles. So far no evidence of superstring theory has been found and the critical question to address is: Why are people so intent on finding and preserving symmetries, even when nature tells them straight in the face that there are none? The answer has already been given above with symmetries providing perfect tools of simplification, which is exactly what the human mind desires. Symmetries are easy to understand, they bring an order to the chaos, which nature unfurls before us, and order satisfies our natural psychological need for security. There is no scientific reason to believe in the fundamental symme-

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[1] The terms Lorentz *covariance*, Lorentz *invariance* and Lorentz *symmetry* are used synonymously in this text.

[2] QCD is the theory of the strong interaction of quarks and gluons.

try of quantum gravity other than our own human constitution, which *wants* nature to be symmetric, to make it understandable, ordered and secure.

The philosophical implication draws an analogy between our own universe and the ones artificially created in the industry of game design. Usually the virtual worlds are not created by imposing profound symmetry conditions, but game designers finetune parameters so that the emergent result exhibits an approximate symmetry and simply keeps the system functioning. Why should our universe be so different and perfectly ordered? Everything that nature has *really* told us so far, is that symmetry is being broken the deeper we look into it.

The Bottom Line

The chapter of quantum gravity in the book of nature remains fairly empty and everybody is welcome to take a blank page and fill it as one may see fit. Under such unbounded circumstances creativity lets scientists blend into artists of thought searching for the next change of paradigm, ignoring its complete inapplicability, just for curiosity's sake. Unwilling to accept the status quo of physics they make up the tiny community, who does sometimes not even believe in itself, which is highlighted by an anecdote of the ESQG conference, when Niayesh Afshordi said with a straight face: "I have evidence of quantum gravity."
Everybody laughed.

On the Measurement of the Speed of Light in a Cavity

Fabienne Schneiter

Introduction

How precisely do we know the value of the speed of light nowadays? Adopting the current definition of the SI units [1], we would simply say that the speed of light is constant and has the value $c = 299\,792\,458\ \frac{\text{m}}{\text{s}}$. In these units, the second is defined using transition properties of the caesium atom, and the meter is defined by the distance a light pulse travels in a certain amount of time with the speed of light set to the above value.

In this article however, which is based on [2], we work with units for distance and time that are defined independently of the speed of light. We want to measure the speed of light in a certain region of space and for a certain period of time. The measurement is done through the frequency and the wavelength of the light, thus implicitely using the definition of the units for distance and time. Although we need to assume that if the speed of light was not constant its variation would be negligible in the region of space and period of time we consider, we do not assume that the speed of light is constant everywhere and at every time. Performing the measurement at different places or at different times thus allows to verify if the speed of light actually takes the same value everywhere and at every time. If we measured the speed of light assuming that it is the constant parameter c as it appears in modern theories, we could infer it (possibly more precisely) by measuring other quantities—but this is not what we do in this calculation. Our approach can be considered as the measurement an observer does who does not want to rely on any theory and makes his setup in an according way. Looking at his procedure in the framework of quantum mechanics and general relativity, we analyse the errors he makes according to these theories. Assuming that quantum mechanics and general relativity are true, we thus set bounds on the precision of the measurement of an observer who does

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his measurement without using these theories, and thus implicitely set bounds on the testability of theories predicting deviations from pure general relativity or pure quantum mechanics, such as some approaches to quantum gravity.

For the measurement, we consider a cubic cavity with reflecting walls containing light. The wavelength of the light is given by the length of the cavity. We measure the frequency of the light at the wall of the cavity and determine its speed according to $c = \frac{\omega\lambda}{2\pi}$. How precisely can we measure this speed? When one wants to measure a quantum mechanical observable, as for example the momentum, the Heisenberg uncertainty relation states that the uncertainty of the observable scales as one over the uncertainty of the conjugate variable, which for the momentum is the position. When we now want to know the uncertainty in the measurement of the speed, we cannot simply use the Heisenberg uncertainty relation, since the speed is not a quantum mechanical observable. What we can do, however, is to estimate its uncertainty using quantum parameter estimation theory. Doing so, we find that it scales as one over the energy inside the cavity. However, when there is a lot of energy inside the cavity, we have to be careful with what we actually measure, since we are not dealing with a vacuum anymore. Determining the speed of light according to $c = \frac{\omega\lambda}{2\pi}$ and believing to be measuring the speed of light in vacuum, one makes a systematic error: Due to the energy inside the cavity, there is a gravitational field, which leads to a change of the frequency of the light, the gravitational redshift. This systematic error is proportional to the energy inside the cavity. Altogether, what we will call in the following the most accurate measurement of the speed of light in vacuum is a measurement for which the uncertainty of the quantum mechanical measurement and the systematic error are of the same order of magnitude. Since the former is inversely proportional and the latter proportional to the amount of energy inside the cavity, there exists a certain amount of energy as a function of the other parameters of the measurement which is optimal to perform the measurement. This optimal amount of energy can be obtained if one takes the light to be in a corresponding quantum state.

Quantum Parameter Estimation Theory and the Quantum Mechanical Uncertainty

Since quantum mechanically, we cannot measure a speed directly, we perform measurements of quantum mechanical observables (actually even more general measurements) and use these to estimate the value of the speed. Optimizing over all measurements leads to the minimal quantum mechanical uncertainty in the estimation procedure of the speed. This is done in quantum parameter estimation theory, which works as follows: Consider a quantum system that depends on a parameter, in our case the speed of light c. We describe the state of this system by the density matrix $\hat{\rho}(c)$. Performing M measurements on the system, we obtain the empirical data $\{x_1, x_2, ..., x_M\}$. Using this data, we find an estimate $c_{\mathrm{est}}(x_1, x_2, ..., x_M)$ of the real value c, depending on the results of the measurement. To know the precision of the measurement, we need to know how close the estimate c_{est} is to the actual value c. Making the reasonable assumption that for many measurements, the expectation value of the estimator c_{est} is equal to the parameter c, the precision of the measurement corresponds to the standard deviation of the estimator c_{est}. A lower bound which is optimized over all estimators and all measurements for this standard deviation is given by the Cramér-Rao Lower Bound (CRLB) [3]

$$\delta c_{\mathrm{est}} \geq \frac{1}{\sqrt{M F_Q(c)}} \;, \tag{1}$$

where $F_Q(c)$ is the Quantum Fisher Information (QFI). The QFI is a measure for the sensitivity of the quantum state on the parameter: If a small change of the parameter results in a big change of the state, the QFI is high, and if it induces only a small change of the state, the QFI is low (see Fig. 1). Intuitively this explains the statement of the CRLB, as when the state is very sensitive on the parameter (big $F_Q(c)$), the parameter is more easily measurable (small standard deviation of the estimator).

Let us now find the CRLB for our measurement of the speed of light. Our system is described by the Hamiltonian

$$\hat{H} = \sum_{m=0}^{\infty} \hbar \omega_m \hat{n}_m \;, \tag{2}$$

where ω_m is the frequency and $\hat{n}_\omega$ the number operator. We assume that the Hamiltonian is bounded, which is equivalent to claim that the total energy in the system is finite. It turns out that the CRLB depends only on the possible minimal amount of energy inside the cavity, which is zero, and the possible maximal amount of energy inside the cavity. Therefore we can choose that all photons have the same energy, i.e. the same frequency ω. We call the number of photons that gives the maximal amount of energy n_{max}. The QRLB for this system leads to the minimal standard deviation

$$\frac{\delta c_{\mathrm{CRLB}}}{c} \sim \frac{1}{t n_{\mathrm{max}} \omega \sqrt{M}} \quad \sim \quad \frac{1}{t c \sqrt{M} \frac{n_{\mathrm{max}}}{\lambda}} \;, \tag{3}$$

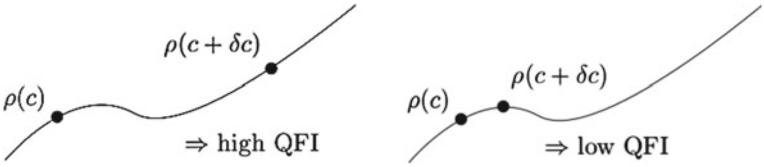

Fig. 1 The QFI is a measure for the sensitivity of the quantum state on the parameter. If the state is very sensitive on the parameter, it changes a lot when the parameter is changed by only a little, and the QFI is high (*left image*). When the state is barely sensitive on changes of the parameter, the QFI is low (*right image*)

where t is the duration of the measurement. The state for which this minimal standard deviation is achieved turns out to be the superposition of the states with minimal and maximal energy [4],

$$\left|\psi_{\text{opt}}\right\rangle = \frac{|0\rangle_\omega + |n_{\max}\rangle_\omega}{\sqrt{2}} \; . \tag{4}$$

The Gravitational Field of a Light Field Inside the Cavity and the Systematic Error Due to Gravitational Redshift

Once there is light inside the cavity, we are not in vacuum anymore. There is energy inside the cavity, and this energy leads to a gravitational field. We use the semiclassical approximation of general relativity [5], since we treat the light quantum mechanically and the gravitational field classically. To make the Einstein equations in this formalism meaningful, one takes the quantum mechanical expectation value of the energy-momentum tensor of the light, $\hat{T}_{\alpha\beta}$. Then the Einstein equations read

$$R_{\alpha\beta} - \frac{1}{2} R g_{\alpha\beta} = 8\pi G \left\langle \hat{T}_{\alpha\beta} \right\rangle \; , \tag{5}$$

where $g_{\alpha\beta}$ is the metric, $R_{\alpha\beta}$ the Ricci tensor, R the Ricci scalar and G Newtons constant. On the right-hand side of these equations stands the energy, and on the left-hand side terms describing the curvature of the spacetime and thus the gravitational field. Altogether, this equation tells us how energy induces a gravitational field. Since we deal with very small energies, we use the linearized theory of gravity [6]: We make the ansatz that the metric $g_{\alpha\beta}$ equals the Minkowski metric $\eta_{\alpha\beta}$ for the flat spacetime plus a small perturbation $h_{\alpha\beta}$,

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} \; , \tag{6}$$

where $|h_{\alpha\beta}| \ll 1$ ensures that the deviation from the flat spacetime is small. In other words, this equation is valid if the gravitational field is very weak. The Einstein equations lead to (in transverse-traceless gauge)

$$h_{\alpha\beta}(\vec{y}) = \frac{4G}{c^4} \int_0^L d^3y \, \frac{\left\langle \hat{T}_{\alpha\beta}(\vec{y}) \right\rangle}{|\vec{x} - \vec{y}|} \; . \tag{7}$$

Using this formalism, we calculate the frequency an observer measures at the wall of the cavity. Because of the gravitational redshift [6], i.e. the different frequencies an observer in the gravitational field and an observer in a space without a gravitational field measure, the observer at the wall of the cavity will measure a frequency which deviates from the frequency an observer in vacuum would measure. This deviation turns out to be

$$\delta\omega = \frac{h_{00}}{2}\omega \,. \tag{8}$$

Since the observer wants to measure the speed of light in vacuum, i.e. without any gravitational field, this deviation is a systematic error in his measurement. In terms of the measurement of the speed of light, it is found to be

$$\frac{\delta c_{\mathrm{err}}}{c} \quad \sim \quad \frac{\hbar G}{c^3 L}\,\frac{n_{\max}}{\lambda} \,. \tag{9}$$

Minimizing the Quantum Mechanical Uncertainty Plus the Systematic Error

We found that the minimal quantum mechanical uncertainty scales as

$$\frac{\delta c_{\mathrm{CRLB}}}{c} \sim \frac{1}{\sqrt{M t c \frac{n_{\max}}{\lambda}}} \,. \tag{10}$$

δc_{CRLB} can thus be lowered by

- increasing the number of measurements M
- increasing the measurement duration t
- increasing the energy (increasing the ratio $\frac{n_{\max}}{\lambda}$)

On the other hand, we found that the systematic error due to the gravitational redshift scales as

$$\frac{\delta c_{\mathrm{err}}}{c} \sim \frac{\hbar G}{c^3 L}\frac{n_{\max}}{\lambda} \,, \tag{11}$$

and we see that $\delta c_{\mathrm{err.}}$ can be lowered by

- increasing the size of the cavity L
- decreasing the energy (decreasing the ratio $\frac{n_{\max}}{\lambda}$)

By increasing the number of measurements or the measurement duration (and keeping the other parameters constant), we can make the quantum mechanical uncertainty of the measurement arbitrarily small, but without affecting the systematic error, which corresponds to a shift of the measured value. One can thus think of the measurement outcomes in this case as being close to a value which deviates from the actual value. On the other hand, increasing the size of the cavity (and keeping the other parameters constant), we can make the systematic error arbitrarily small, but not the quantum mechanical uncertainty. This case thus corresponds to measurement outcomes that are centered around the actual value of c, but possibly spread widely. Altogether, increasing at the same time the number of measurements or the measurement duration as well as the size of the cavity, one can make the quantum mechanical uncertainty of the measurement as well as the systematic error arbitrarily small.

Contrarily, since δc_{CRLB} is inversely proportional and δc_{err} is proportional to the energy inside the cavity, there must exist a certain amount of energy that minimizes the sum of both errors for given values of the length of the cavity, the number of measurements and the measurement duration (Fig. 2).

Equating the minimal uncertainty δc_{CRLB} and the systematic error δc_{err}, we find that the optimal amount of energy corresponds to the optimal ratio of number of photons per wavelength

$$\left(\frac{n_{\max}}{\lambda}\right)_{\mathrm{opt}} \sim c\sqrt{\frac{L}{\hbar G t\sqrt{M}}}\,. \tag{12}$$

Inserting this into Eqs. (10) or (11) leads to the minimal measurement uncertainty, and thus best precision

$$\frac{\delta c_{\min}}{c} \sim \frac{1}{c^2}\sqrt{\frac{\hbar G}{L t\sqrt{M}}}\,. \tag{13}$$

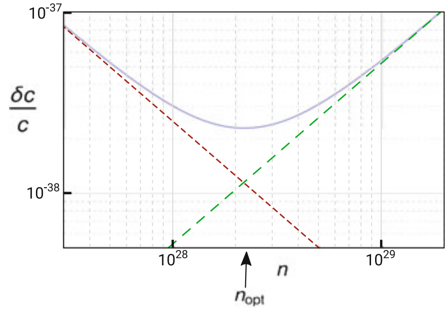

Fig. 2 The minimal uncertainty $\frac{\delta c_{\mathrm{CRLB}}}{c}$ (*short-dashed red line*, Eq. (3)) and the systematic error $\frac{\delta c_{\mathrm{err}}}{c}$ (*long-dashed green line*, Eq. (9)) as a function of the number of photons n: The sum of both of them is shown by the *plain grey line*, and one sees that the number of photons minimizing it lies at the intersection of the curves for the minimal uncertainty and the systematic error. For the plot we chose the wavelength $\lambda = 5 \cdot 10^{-7}$m, the measurement duration $t = \frac{L}{c}$, the length of the cavity $L = 1$m and the number of measurements $M = 10^6$

Conclusion

We consider an observer who has units for time and length that are defined independently of the speed of light. He determines the speed of light in these units by measuring the frequency of the light inside a cubic cavity and calculating the speed of light through $c = \frac{\omega\lambda}{2\pi}$. The minimal uncertainty in his measurement scales as $\frac{\delta c_{\text{min}}}{c} \sim \frac{1}{c^2}\sqrt{\frac{\hbar G}{Lt\sqrt{M}}}$. For a cavity of sidelength $L = 1$m, finesse $F = 10^4$, for a measurement duration of $t \sim \frac{LF}{c}$, and $M = 10^6$ repetitions of the measurement, the minimal uncertainty scales as $\frac{\delta c_{\text{min}}}{c} \sim 10^{-38}$. In an experiment, any additional noise or error taken into consideration will lead to a bigger uncertainty of the measurement, but not invalidate the lower bound we found.

Typically, the light used in an experiment will be in a coherent state, which is defined as $|\psi_{\text{coh}}\rangle_\omega = \exp\left(\alpha\hat{a}^\dagger_\omega - \alpha^*\hat{a}_\omega\right)|0\rangle_\omega$. Calculating the minimal uncertainty given by the the CRLB and the systematic error for a coherent state of a given average excitation number and comparing them, we find that the minimal uncertainty scales as $\frac{\delta c_{\text{min}}}{c} \sim \left(\frac{\hbar G\lambda}{Lc^5t^2M}\right)^{\frac{1}{3}}$. For the same parameters as we used in the numerical example for the optimal state and with $\lambda = 10^{-6}$m, one obtains $\frac{\delta c_{\text{min}}}{c} \sim 10^{-30}$.

Instead of assuming that we have units for time and length that are defined independently of the speed of light and use them to determine the speed of light, we can also proceed in the more modern way, consider the speed of light to have a fixed value and use it to define the unit for distances. Then we obtain in the same way a minimal uncertainty for a measurement of a distance, $\frac{\delta L_{\text{min}}}{L} \sim \frac{\delta c_{\text{min}}}{c}$.

The order of magnitude of δc_{min} or δL_{min} can be used to estimate whether a quantum effect will be measurable or not with this setup and certain values for the size of the cavity, the number of measurements and the measurement duration. For example, if a theory predicts values for quantum fluctuations of a length well below δL_{min}, it can, from a purely theoretical point of view, never be detected.

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Neutrino: The Elusive Particle Bringing us Closer to the World of Quantum Gravity

Giacomo D'Amico

The last September I had the privilege to be present at the fifth international conference to study the prospects of finding experimental evidence for quantum gravity, held at the Frankfurt Institute for Advanced Studies, which has brought together theoretical and experimental physicists from many different areas in this young and lively research field which is generally referred to as "quantum-gravity phenomenology".

The quantum-gravity phenomenology is, without a doubt, one of the most ambitious programs in physics today. For many years, what is generally called the "quantum-gravity problem" has been discussed assuming that no guidance could be obtained from experiments. This sort of prejudice is very well motivated by the smallness of the scale length (the Planck length $\sim 10^{-35}$ m) where the Standard Model of particle physics and General Relativity are both non-negligible and where one must take into account the quantization of the gravitational force by the, still unknown, theory of Quantum Gravity. Just to make clear how small the Planck length is, in order to reach the Planck regime we should build a particle accelerator 10^{15} (one followed by 15 zeros!) times more powerful than the Large Hadron Collider in Geneva, which is the world's largest and most powerful particle collider. And it will remain so for many years to come. Its power is of about 13 TeV, which means that with the Large Hadron Collider we are able today to probe scale length of the order of 10^{-20} m (compare it with the Planck length!).

The alert reader may ask at this point: "So then, how is it possible to even talk about a quantum-gravity phenomenology? And why should we care about it?". The latter question has an obvious answer: every theory, including a theory of Quantum Gravity, in order to be *physical* needs to be in accord with experiments; it doesn't matter how elegant, beautiful and mathematically consistent your theory is, in order

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to be *physical* it must be in agreement with nature, i.e. experiments. To quote Richard Feynman:"If it doesn't agree with experiment, it's wrong".

The first question, instead, is a very good question, whose answer is not so obvious. One way to answer this question is to think about molecules. They are very small and invisible to us, as the Planck length is very small and "invisible" relative to the physical regime we can achieve in our experiments. But the effects of molecules can be macroscopically significant in a length scale much bigger than the radius of a molecule ($\sim 10^{-4}$ μm). So bigger that in 1827 their macroscopical effects were observed for the first time by the botanic Robert Brown at scales of the radius of pollen grains (~ 10 μm), in what is now called the Brownian motion. This analogy with molecules is useful to give us the idea that "very small" doesn't mean necessary "invisible", and it may happen that microscopical effects can be amplified at macroscopical scales accessible to us.

In this sense many physicists working on quantum-gravity phenomenology are developing theories and toy models in which Planck scale effects may be observed in current (or soon) available experiments. This is a tough work because not only it is difficult to make falsifiable predictions from a theory of Quantum Gravity, but also because in order to spot in some experiments a Planck scale effect you need to exclude, at least with a good level of confidence, other possible explanations given by the "standard physics", i.e. the Standard Model of particle physics and the theory of General Relativity. Let me stress this point a bit more. We all know the "Occam's razor" and we use it properly in everyday life. This basic principle, which simply states that the simpler explanation for an occurrence is usually the better, also applies in science. For instance, Occam's razor arises naturally in the context of Bayesian inference, which is in science a useful method of model selection. At this point you can soon realize that, given a possible explanation in the context of one of the many plausible theories of Quantum Gravity and one in the context of the Standard Model or General Relativity, scientists will usually prefer the latter just because today the Standard Model and General Relativity are very well known and understood fundamental physical theories which give an accurate descriptions of the physical reality we have explored so far.

From this point of view of looking for strong deviations from the Standard Model or General Relativity, one of the most appealing field research in physics is "Neutrino Physics".

The neutrino is the most abundant particle in the universe. Every second 65 billion neutrinos pass through every square centimeter of our body and the Earth. Neutrinos do not carry electric charge, which means that they are not affected by the electromagnetic forces that act on charged particles such as electrons and protons. They are also extremely tiny because of which they travel mostly undisturbed through matter. This makes neutrino not only one of the most abundant particle in the universe, but also the most elusive.

Its appeal in quantum-gravity phenomenology is given by the fact that neutrinos have properties which are not still understood in the context of the Standard Model. Indeed neutrino is the only particle which provides the first solid hint towards physics beyond the Standard Model. The Standard Model includes three massless neutrinos: the electric neutrino, the muon neutrino and the tau neutrino, associated with the electron, muon, and tau, respectively. Physicists call this three species a “flavor”. However, the experimental observation of neutrinos changing from a flavor to another, a phenomenon known as neutrino oscillation, first theoretically predicted by Bruno Pontecorvo in 1957, has motivated people to suggest that neutrinos are actually massive. The mass of the neutrino is much smaller than that of the other known elementary particles, and this is the reason for which has been difficult to detect such effect. The experimental discovery of neutrino oscillation, and thus neutrino mass, by the Super-Kamiokande Observatory (in Japan) and the Sudbury Neutrino Observatory (in Canada) was recognized with the 2015 Nobel Prize for Physics.

As I stressed before, neutrinos are extremely hard to detect, and the harder (Fig. 1) a particle is to detect, the bigger and more sophisticated the detectors have to be. This is why neutrino observatories, such as the Super-Kamiokande Observatory or the most recent IceCube Neutrino Observatory, are huge structures, situated many meters below the ground surface in order to shield the detectors from other sources of radiation.

Current research looks for an extension of the Standard Model to include neutrino masses. Some physicists, such as professor Heinrich Päs, who gave during the Experimental Search for Quantum Gravity conference in Frankfurt an interesting presentation about neutrino physics, argue that the anomalous neutrino oscillations may be regarded as traces of the quantum nature of gravity. This makes indeed neutrino a perfect probe for quantum gravity.

Neutrino oscillation is not the only way in which neutrinos may provide us some hints towards a quantum theory of gravity. In recent years we have been witnesses to the birth of a new kind of astronomy: the “neutrino astronomy”. Since Galileo Galilei pointed for the first time in 1610 his telescope to the sky we have always been observing the universe in photons. This has been for centuries the only possible way of doing astronomy and this has led people to refer to “photon astronomy” simply as “astronomy”. But photon is not the only particle which can travel through space freely for millions of years bringing us informations about stars, galaxies and

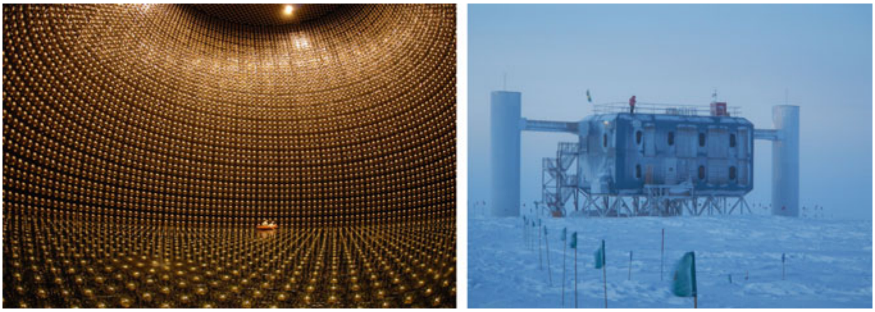

Fig. 1 Engineers examining instruments inside the half-filled Super-Kamiokande tank in a row boat (*Left*). The IceCube Laboratory at the South Pole in Antarctica (*Right*)

other mysterious and exotic things in the universe. We know that there is another particle that can do this job even better than photon: of course I am talking about neutrino. The problem is that we do not have eyes for neutrinos, we only have eyes for photons which make us see the universe around us, and since now, due to the elusive nature of neutrino, our technology was not capable of building "artificial ayes", i.e. detectors, that can "see" neutrinos coming directly from space. But fortunately things are changing and thanks to theoretical improvements in neutrino physics and experimental improvements in neutrino observatory, such as the IceCube Neutrino Observatory, we are now able to detect neutrinos from space.

The neutrino astronomy will give us the opportunity to see the universe in a totally different way, revealing us what cannot be directly observed using only photons. Take for instance the star nearest to us, the Sun. Only the surface of the Sun can be directly observed. Any light produced in the core of a star will interact with gas particles in the outer layers of the star, taking hundreds of thousands of years to make it to the surface, making it impossible to observe the core directly. Since neutrinos are also created in the cores of stars (as a result of stellar fusion), the core can be observed using neutrino astronomy.

But how can the newborn neutrino astronomy be relevant for the quantum-gravity phenomenology? Of course at this moment there is no clear answer to this questions. It is like guessing before Galileo Galilei gave birth to astronomy, how astronomy would have changed our knowledge of the universe and of the laws of physics. However there are already some physicists, such as professor Giovanni Amelino-Camelia, another speaker in the Experimental Search for Quantum Gravity conference in Frankfurt, who are proposing astrophysical neutrinos to test some Planck scale effects. Their proposal is to use astrophysical neutrinos to test Lorentz-invariance deformations, which is an effect predicted in some scenarios of Quantum Gravity.

Lorentz invariance is one of the two postulates on which is based Special Relativity, i.e. General Relativity on flat spacetime. This postulate states that the laws of physics are invariant (i.e. identical) in all inertial systems (non-accelerating frames of reference). In Special Relativity if you want to move from an inertial frame to another, in order to preserve the laws of physics, you must use the Lorentz transformation.

One consequence of deforming Lorentz invariance is an energy-dependent speed of light. If the energy-dependence is first oder in the particle's energy over the Planck energy ($\sim 10^{19}$ GeV), then it would become observable in the travel-time of highly energetic particles from distant gamma ray bursts. The most energetic the particle is the stronger the effect will be, till the point where we can discard that the feature we are observing could be the result of some (so far unknown) astrophysical properties of the sources. One of the major challenges in observing Lorentz-invariance deformations in photons is that the most energetic photons observed from gamma ray bursts are of energy in the range of 10 GeV. This implies that the expected size of the effects is between a few and ~ 100 seconds, which may well be the time scale of some mechanisms intrinsic of gamma ray bursts. The most energetic neutrinos of astrophysical origin so far observed, by the IceCube neutrino observatory, have instead energy in the range of 100 TeV (4 orders of magnitude in energy bigger than 10 GeV). This lead the size of the effect under investigation being of the order of a couple of days, so that one can safely neglect that such feature (if observed) may be of astrophysical origin. This studies for neutrinos, while inconclusive, preliminary favor Lorentz-invariance deformations, but more data are needed.

The phenomenology of quantum gravity is a young and ambitious program that brings together theoretical and experimental physicists from many areas. Here it has been presented shortly, and without entering into technical details, just one areas of physics, the neutrino physics, that may help physicists finally observe the first experimental evidence of quantum gravity, i.e. of Planck scale effects. To date we have no experimental signature for such quantum gravitational effects. This goal may be achieved in the next decades or maybe in the next centuries. We do not know it. But conferences like the one held in Frankfurt, with physicists bringing their ideas and creativity in the experimental search for quantum gravity, brought us closer to this goal. The payoff that could be expected appears to be well worth the effort, since such experimental signature for quantum gravitational effects will certainly revolutionize physics and our understanding of space and time.

Gravitational Waves: The "Sound" of the Universe

José Manuel Carmona

Abstract On September 14, 2015, for the first time in human history, mankind detected gravitational waves, a prediction of Einstein's general relativity, which in this case had been produced during the merging of two black holes in a very distant galaxy. This fact represents an awesome technological and scientific achievement, comparable perhaps to the moment when Galileo used a telescope for the first time to contemplate the cosmos. A second detection, produced on December 26, 2015, confirmed the beginning of an era in which the astronomy of gravitational waves will allow us to contemplate the Universe, or rather, to "hear" it, in a totally new way, and that surely will provide us with many and interesting surprises.

One thousand and three hundred million years ago, in a very, very distant galaxy, an astonishing event took place. A cataclysm of proportions difficult to imagine, whose record has been an extraordinary scientific and technological achievement. To illustrate what happened, let us think for a moment about something relatively familiar: the Sun.

Our star contains no less than 99.8% of the mass of the entire solar system, but it is also very large: about one million three hundred thousand "Earth planets" would fit inside. Well, let's take not one, but 29 suns, and compress all that amount of matter to occupy a region of about 150 km in diameter, something like the metropolitan area of Madrid or Barcelona. That enormous concentration of matter gives birth to a black hole. Now imagine such an object moving at half the speed of light. Let's take another mole even bigger, of 36 solar masses and similar size, and also at that speed. Finally, let's bump those two monsters, thus giving rise to one of the most extreme

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events in the Universe. This was the fact that, as we say, happened at a remote time and place.

In that event, the two black holes of 36 and 29 solar masses were merged into a new black hole of 62 solar masses (instead of 65, the sum of 36 and 29). That means 3 solar masses were annihilated, transformed into pure energy, according to Einstein's famous equation $E = Mc^2$. To give us an idea, in an atomic bomb, a few grams or kilos of uranium are converted into an enormous amount of energy. The one produced during the fraction of a second that lasted the black hole collision was the equivalent of 10 billion trillion trillion (a 1 with 34 zeros behind) of Hiroshima bombs. The emitted power (energy per unit of time) thus surpassed that of all the stars of the observable universe together!

Curiously, if we had been more or less near there, we would not have heard the noise of an explosion, since in the outer space there is no air that can carry the sound; we would not have seen a flash of light either, since black holes have the characteristic that nothing, not even light, can come out of them. What the tremendous energy of that collision caused was a deformation in the very structure of space and time, which extended around the newly formed black hole, spreading like a wave.

Right there, that distortion was undoubtedly brutal, creating a kind of hurricane that curved space, stretching and shrinking it in different directions, and speeding up and decelerating time exaggeratedly; something to which we would certainly not have survived. But all this happened in a galaxy far away, one thousand three hundred million light-years from us. This means that this space-time wave, this gravitational wave, travelled to us for one thousand three hundred million years, spreading into ever larger spheres from the source and therefore more weakened.

One fine day, on September 14, 2015, at 09.50 UTC (11.50 h in Spain at that time), the wave reached Earth. However, its ability to alter space-time was already small. Really small. The wave vibrated several times, and for just a few hundredths of a second, the 4 km arm of the LIGO detector in the USA, changing its length by ... a thousand times less than the size of a proton! Such an inconceivably tiny change is what LIGO scientists could measure, obtaining information on the astrophysical event described above.

Such a feat was announced by the LIGO collaboration on February 11, 2016, at a press conference followed live on the Internet by thousands of scientists and science aficionados, who listened holding their breaths and rubbing their eyes, hardly believing that the detection of gravitational waves, predicted by Albert Einstein exactly one hundred years ago, was finally a reality. The various articles with detailed analyzes made public that day by the collaboration, however, left no room for doubt. The impact on the media was immediate. Once again, they remarked, Einstein was right.

So it is curious that Einstein himself, having deduced mathematically the propagation of gravitational waves from his theory of general relativity in 1916, later believed that he had proven they had no real existence in an article entitled *"Do gravitational waves exist?"* which he, along with his collaborator Nathan Rosen, submitted to the journal *Physical Review* in 1936. However, the editor of the journal returned the article to its authors asking for corrections after having received a negative report from the specialist who had reviewed it. Peer review is a common practice today as a quality assurance of scientific publications, but the American magazine was beginning to put it into practice at the time, and Einstein had never been subjected to it. Annoyed with the editor, he withdrew the article without replying to the comments of the anonymous expert who had examined it. He eventually published the paper in a now much less prestigious journal, the *Journal Franklin Institute*, but with a title (*“On gravitational waves”*) and conclusions which were very different from those of the original work, since by then Einstein was convinced that, indeed, he had made a mistake and gravitational waves did really exist. It seems that this change of attitude was influenced by conversations with a renowned American relativistic physicist, Howard P. Robertson, who, as we now know, thanks to the archives of the Physical Review, was the anonymous reviewer who had evaluated that first article.

Einstein’s doubts were not unwarranted. General relativity is a complicated theory, in which the freedom of choice of coordinates (its main characteristic) can lead to identify as an apparent physical effect something that is really an artifact of a bad choice of coordinates. Since quite some time, however, the international community had already found firm but indirect evidence for the reality of gravitational waves.

In 1974 the first binary pulsar was discovered, an astrophysical object formed by two neutron stars that orbit around each other and that, according to general relativity, should lose energy by emitting gravitational waves. The modification of the orbit due to this emission was measured experimentally in the following years,[1] noting that the separation between the two stars decreases about two centimeters a day (they will end colliding in about 300 million years).[2] These results are in agreement with the predictions of general relativity, and constitute an indirect demonstration of the existence of gravitational waves.

LIGO (for Laser Interferometer Gravitational-wave Observatory) has been able, however, to obtain *direct* evidence of gravitational waves. In order to do so, it has measured the changes that occur in the distance between two mirrors that are suspended as pendulums, separated by a distance of 4 km that is maintained very precisely using all kinds of mechanisms to reduce seismic, thermal or electronic vibrations. These vibrations produce a background noise in the monitoring of the distance between the mirrors, which is performed by what is called an *interferometer*.

In this interferometer, two beams of laser light are sent respectively through two tunnels placed perpendicularly, inside of which a maximum vacuum has been made so that nothing disturbs their path. Both arms, 4 km long, have at their ends exquisitely carved mirrors between which the laser bounces several times. Finally, the two beams of light are gathered together and projected onto a screen. When both rays have traveled exactly the same distance, 4 km, the result of combining them produces dark on the screen (the two light beams interfere *destructively*). If there is a small

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[1] A pulsar emits radiation that can be detected from Earth and from which we can infer orbital properties, for example.

[2] The reduction of the distance due to emission of gravitational waves also occurs in the Earth-Sun system, but it is nothing to be worried about. The loss of power is of about 200 W (less than the consumption of a toaster), to be compared with the 10^{25} W emitted in the binary pulsar indicated above.

difference in the length traveled, such as the one that would be produced by the passage of a gravitational wave, both beams are no longer "synchronized" and light is collected on the screen. The amount of light can be very small, but it is a direct measure of that difference and, because the wavelength of the light used is of the order of the micrometer and the laser is very intense (which means that the number of photons collected on the screen is large even with a tiny desynchronization in the beams), the experiment has such incredible sensitivity.

Now, how to distinguish the variations produced by a gravitational wave from the background noise, which, as we have said, is constant and produced by other causes? This is the biggest trick: actually there are two LIGO detectors in northern and southern United States, separated about three thousand kilometers. A gravitational wave, which, according to general relativity, moves at the speed of light in the vacuum, takes about ten milliseconds to travel between both venues. This means that the signal produced by the wave, camouflaged over a random noise, will stand out when comparing the data of both LIGO sites, taken with a time difference of a few milliseconds.

The precise shape of the signal, an oscillation in the intensity of light collected as a result of the vibration produced in the LIGO arms, reveals the properties of the gravitational wave and the astrophysical event that gave rise to it. We have thus discovered, not only that general relativity is correct in a very high degree of precision and that gravitational waves exist and can be detected, but also that Nature produces binary systems of black holes with masses dozens of times that of the Sun, and that these black holes come to merge throughout the evolution of the Universe. Just as the sound waves produced by a musical instrument stimulate our ears, the gravitational waves of that fusion have excited the LIGO interferometer. We have not "seen" a black hole, but, following the analogy above, we could say that we have "heard" it.

The detection of September 2015 is just the beginning of a new branch of physics, the astronomy of gravitational waves, whose practical future applications can be difficult to predict,[3] but that it will soon revolutionize the way we see the Universe.[4] With it, figuratively speaking, we have acquired a new sense to explore the cosmos.

To date, we had essentially two ways of perceiving the Universe. The first one is through the sense of "sight": our telescopes, both optical, radio or X-ray, collect electromagnetic waves, photons that act as messengers of the sources that produce them and of everything that affects their propagation on their way to us.

The second is by means of instruments that use large extensions of polar or sea ice to detect the elusive neutrinos, particles that are produced in enormous quantities in many astrophysical processes, but that they barely interact, being thus as faint as,

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[3] In fact, a major oil company is already testing the usage in prospecting of a seismic detector which had been designed for use in gravitational wave detectors. Every basic research ends up producing practical applications, and even more so in cases like this field, which requires the most cutting-edge technology in disciplines as diverse as seismology, vacuum engineering, engineering of control systems or quantum optics, among other.

[4] In fact, the LIGO collaboration has recently confirmed a second detection occurred on December 25, 2016. The merging of black holes in the Universe is more frequent than we had previously imagined.

perhaps, a fragrance. This sense of “smell” allows one to study, for example, the interior of the Sun or the bursting of a supernova.

With the detection of gravitational waves, we have the ability to “hear” what we might call the “sound” of the Universe. LIGO and other detectors that will soon join it as a global network of gravitational wave observatories will be the “ears” that will bring us the echoes of black holes or neutron stars, but also of other more exotic objects. Today unknown objects that, although like black holes, do not emit light or neutrinos, they will be affected like them by the only truly universal interaction: gravity, which connects the very space with the mass and energy of the bodies that are inside it. Each of these objects will sound with a characteristic pattern in the received gravitational wave, and the careful analysis of this signal will allow us to understand its properties.

What new sounds will these ears hear? What new findings will reveal us, which we still cannot even imagine?

Essay on Planck Star Phenomenology

Alexander Maximilian Eller

In the last decades, a large scale search for theories of quantum gravity was made. There are several of them on the market but no realistic experiments which are able to reach energies where one would expect quantum gravity effects to be measurable. Within the framework of general relativity there are open questions like the existence of a true singularity inside a black hole.

In order to avoid the singularity at the center of a black hole, several modifications to the Schwarzschild metric were proposed. Most of these models agree on the fact that at scales of order of the Planck length, quantum effects need to prevent that matter falls into the singularity. How the quantum effects are introduced varies from model to model and in this essay we focus on the Planck star model originally introduced by Francesca Vidotto and Carlo Rovelli [1].

The inspiration for the Planck star comes from loop quantum cosmology where the Friedmann equations are modified by adding a density dependent term that makes a collapsing compact universe bounce into an expanding universe. There are two main points one needs to account for. On the one hand, quantum effects can act as a repulsive force preventing collapses to singularities. On the other hand, the quantum effects can already be important on length scales larger than the Planck scale. The latter point emerges because the Planck density is reached long before the universe is of Planckian size.

In this essay an overview of the Planck star model of Francesca Vidotto and Carlo Rovelli is given. After a first orientation that inspired the model, a discussion of its details is made. Then the main achievements of the model are pointed out. Finally a possible connection between Planck star explosions and short gamma-ray bursts is given.

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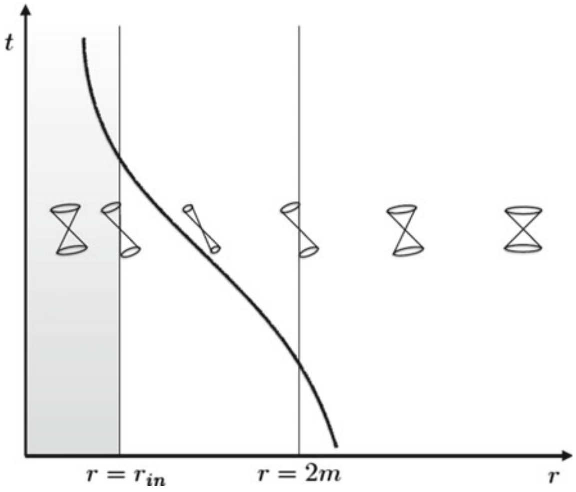

Fig. 1 Spacetime diagram of a non evaporating Planck star in Eddington-Finkelstein coordinates [1]

In the following we focus on the Planck star itself. If a neutron star collapses into an even denser object, the Law of Physics only allow for the formation of a black hole. By assuming that quantum effects are important at Planckian density, they should prevent the collapse into a singularity. Such models exist not only in loop quantum gravity but also in string theory and asymptoticaly safe gravity.

Figure 1 shows a spacetime diagram of a non-evaporating Planck star. One can see the tilting of the light cones in Eddington-Finkelstein coordinates. Quantum gravity is important in the shaded region. Also a second trapping horizon can be seen inside the Schwarzschild horizon.

In the case of the Planck star model, matter would be in a super dense core of the Planck star. Grude estimations of the size of this core give $\sim(m/m_p)^n \quad l_P$, where m_p is the Planck-mass and l_P the Planck length. Consequently, for a stellar-mass black hole, the radius of the Planck star would be 10^{-10} cm if one uses $n = 1/3$. This means that the Planck star would be well inside its "event" horizon, such that it would look like a black hole for an exterior observer.

Because of the quantum nature of matter, the core of the Planck star does not longer satisfy Einstein equations. In order to describe this region of spacetime, a full non-perturbative quantum gravity is needed, such as loop quantum gravity.

However, this is only one aspect of the full Planck star model. Inspired by loop cosmology, it is suspected that the core of the Planck star will not stay in this high-density state. The repulsive force due to quantum effects will not only prevent the gravitational collapse, but will also force the Planck star to "bounce".

A simple model that can describe the gravitational collapse into a highly dense object can be an infalling mass shell with negligible thickness. There are two distinct spacetime regions. The interior of the shell which should be flat and the exterior of the shell where effects of the mass m must change spacetime to a portion of the Schwarzschild metric.

Fig. 2 Penrose diagram of a bouncing star [4]

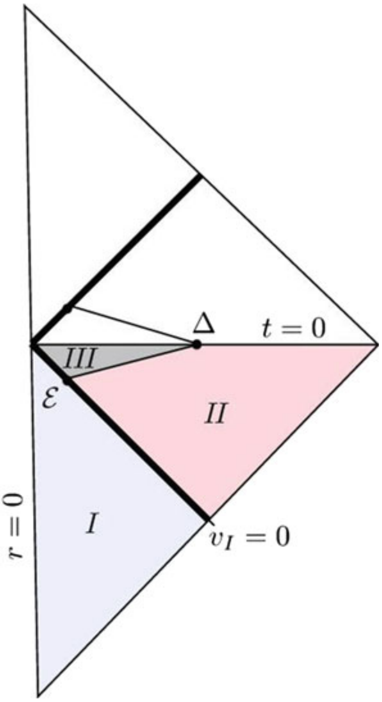

Figure 2 represents the spacetime of a bouncing star solution. The colored region 'I' belongs to the interior of the infalling shell and region 'II' represents the exterior. In this picture it is assumed that the bouncing process happens at the "$t = 0$"—hyperplane and the coordinate is chosen such that the center of mass is at the origin. The third region in this figure represents the spacetime region where quantum effects must appear. The radius of this region is approximately 7/6 r_S, where r_S is the radius of the event horizon of a Schwarzschild black hole. This region expands even outside of the possible horizon. The point denoted by Δ is the maximal spacelike extension of the classically violated region and ε denotes the time at which this violation happens for the first time.

One concludes that one should not trust classical GR solutions near the "event" horizon. The cumulative quantum effects can heavily effect the behavior of the metric, even if they are very small in this curved regions of spacetime [4].

We want to further expand this point for the Planck star model. The process previously described is like a quantum-mechanical tunneling process, from the collapsing black hole metric outside the quantum region, to an exploding white hole metric. The former "event" horizon would become a trapping horizon for the bouncing matter.

The most important point to note here is that the Planck star releases all of its matter in an explosion, so that there is no remnant of it after the evaporation. This has a huge impact on the thermodynamics of the Planck star and the associated Hawking radiation. However, this is beyond the scope of this essay [1–4].

Let us now have a look on what a Planck star looks like for different observers. An observer far away from the Planck star sees a long living black hole which suddenly explodes. He could detect the matter thrown out of the lookalike black hole. The Planck stars lifetime for this observer extremely differs from the proper time of the infalling matter due to the extreme gravitational time dilation for an exterior observer. Loop quantum gravity calculations for an effective metric for the quantum region yields a lifetime of the Planck star proportional to M^2, where M is the mass of the Planck star. The bouncing process is much faster than Hawking evaporation which is proportional to M^3. Consequently, if the hole process of gravitational collapse and bounce lasts milliseconds in proper time of matter, several billion years passes for an outside observer. This would mean that a Planck star act as a "time machine" to a far distanced future. If one uses the Hubble time, which has a value of 14.4 billion years, as the lifetime of a Planck star, one finds that it has a tiny mass. Primordial black holes are black holes, which were formed in the early universe by the high energy density of matter and not by the gravitation collapse of a star. Such tiny Planck stars could exist in the universe as primordial black holes. The existence of primordial black holes is controversial, although theories incorporated their existence because many creating processes for primordial black holes appear in different theories.

Short gamma-ray bursts are intense gamma radiation events observed in the cosmos. The origin of the extremely energetic explosions that create these bursts is not known so far. There are several theories of "standard" cosmology to explain the subclass of short gamma-ray bursts. The creators of the Planck star model think that nowadays light primordial black holes can explode and we would in principle be able to detect them. Moreover, they claim that the origin of the short gamma-ray bursts can be the explosion of a bouncing primordial black hole.

If exploding Planck stars are at the origin of short gamma-ray bursts, Vidotto, Rovelli and collaborators claim that there should be a unique red-shift signature in the signal. For a single event, one considers two signals which have different origins. First, the low energy signal is determined by the mass of the exploding Planck star. The second, the so-called high-energy signal component, is considered to be produced by high-energy photons which originally formed the Planck star in the early universe. These photons were created in a time where the universe was really hot compared to the present situation. Since Planck stars act as a time machines, one would expect these photons producing an energy spectrum similar to one, a black body at the temperature of the universe at the time of the Planck star formation. It is planned to perform precise calculations to determine the expected spectrum to compare with data of the detected short gamma-ray bursts [3].

This essay summarized the main ideas of the Planck star model and gave an overview of present research topics. In particular, the fact that quantum effects can have a major impact at scales many orders of magnitude larger than the Planck length, makes this model particularly interesting. Applying the quantum-mechanical tunneling process to the spacetime metric itself may change the understanding of its nature. The unknown origin of short gamma-ray bursts opens a large window for new ideas. Maybe Planck star explosions are responsible, but further research his needed in order to clarify this issue.

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Essay About Gravitational Measurements at Small Distances

Helena Schmidt

Overview

Although gravity has been well tested on several length scales, some *unified theories* predict that gravity might change somewhere below distances of 1 mm. This could happen, for example, through a set of small extra dimensions. Gravity propagates through all dimensions equally. This means the same amount of energy has different volumes to fill for different numbers of dimensions. Therefore, the strength of gravity changes with the number of dimensions. There are different methods of searching for deviations from gravitational force. The first experiment used to measure a direct gravitational effect between two bodies was the Cavendish experiment performed in 1797 and 1798 [1]. The experiment consisted of two large fixed spheres and two small spheres, attached to a torsion balance. The force between the small and the large spheres led to the torsion of the torsion balance. Knowing the torsion coefficient, it is possible to calculate the gravitational force. This experiment was used to determine the gravitational constant for the first time and also to measure the density of the earth.

Variations of this experiment are still the most precise measurement tools for determining gravitational force at distances larger than 1 mm and below 1 m. For larger distances, astronomical observations are used. During the moon landing missions between 1969 and 1972, several retroreflectors were placed on the moon's surface. Using these retroreflectors makes it possible to measure the distance between the moon and the earth [2]. This method is called lunar laser ranging and delivers the most accurate measurement of Newton's law of gravity at the moment (Fig. 1).

In smaller ranges below 1 mm distances, masses become smaller and forces like the electrostatic force grow stronger. It therefore becomes necessary to shield the electrostatic force by using a metallic membrane. This is only possible above a mini-

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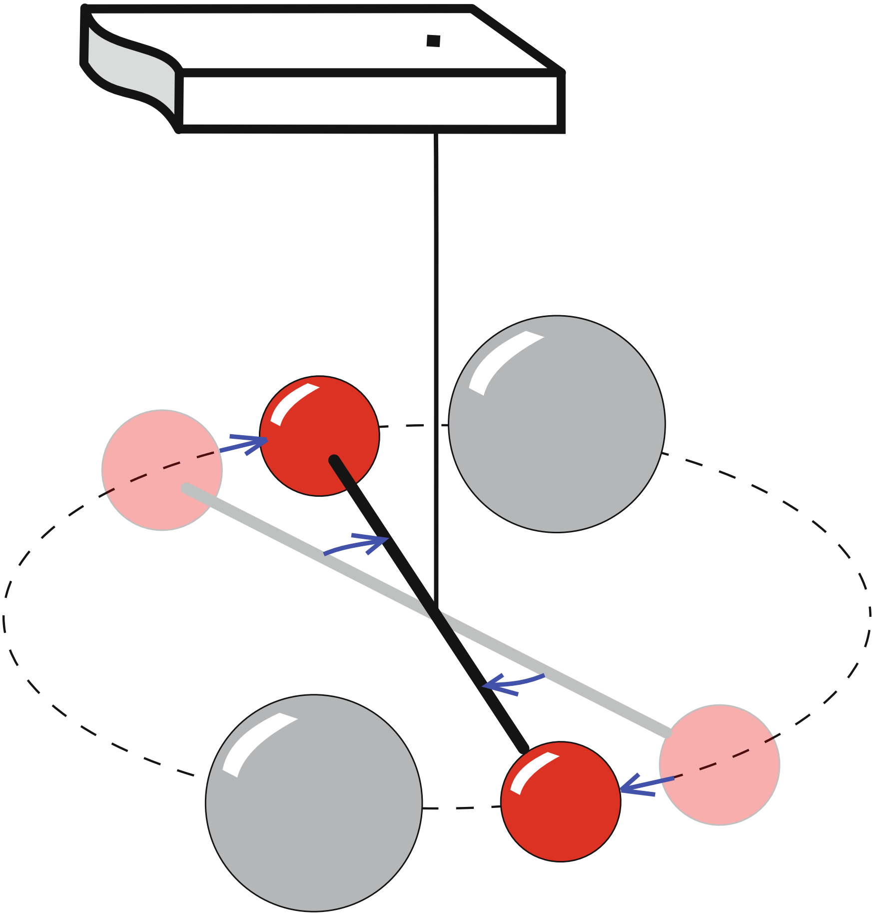

Fig. 1 Schematic torsion balance

mal distance of 10 μm. The thinner the shielding membrane gets at smaller distances, the less rigid it becomes. Bending the shielding membrane itself changes the electrostatic forces between the source mass and the test mass. Below the distance of 10 μm, it is necessary to measure the electrostatic force to compensate for it in the data analysis. Below 1 μm, additional forces come into play. One is the so-called Casimir effect, another is the patch effect. In 1948 [3], Dutch physicist Hendrik Casimir predicted the effect, which was named after him. In the quantum field theory, a harmonic oscillator has different quantized energy states. Most importantly, a harmonic oscillator without any excitation has finite energy at state zero. This is called the zero-point energy.

Standing electromagnetic waves can exist between two perfectly conducting parallel plates. The wavelengths allowed depend on the distance. For each allowed wavelength, there is a corresponding zero-point energy level. To receive the total amount of zero-point energy stored between the plates, the zero-point energies of all allowed wavelengths are summed up. This depends on the theory of whether there is a minimal allowed wavelength. Today, the Planck length ($\sim 1.6 * 10^{-35} m$) is use most often for this purpose. When the distance between the plates changes, the wavelengths allowed change as well. This means that the total amount of zero-point energy also changes. And energy that changes with distance leads to a force. This force is known as the Casimir effect.

In Einstein's general relativity, the cosmological constant is the vacuum energy density of space. The vacuum energy density of the quantum field theory is 10^{120} times larger than the vacuum energy density from general relativity [4]. This is called the cosmological constant problem and is one of the major issues between general relativity and the quantum field theory. It is thus one of the main reasons why a quantum gravity theory is necessary. The Casimir effect was first measured in 1958 by Marcus Sparnaay in Eindhoven. More precise measurements were conducted in 1997 by Steve Lamoreaux [5]. He changed the geometric setup from parallel plates to a sphere and a plate. A sphere has the advantage that its orientation is unimportant, while parallel plates need to be adjusted very precisely.

The other parasitic force, the patch effect [6], consists of different surface potentials on a metallic surface. The surface potentials are dependent on the various crystal structures within the solid. This force has to be measured and cannot be calculated from other parameters. It is the limiting influence of gravitational force measurements below 1 μm distances.

Most experiments within the range of 0.1 nm–10 μm use geometry similar to the sphere-and-plate geometry used for Casimir force measurements. The reason for this is that they are all Casimir force measurements in the first place. Furthermore, the calculation of possible deviations from gravity is performed with the residuals of the Casimir force model. The Casimir effect depends only on geometry and temperature. The temperature influence originates from the non-perfect conductors. Using force measurements at different distances, it is possible to fit models of the Casimir effect and the patch effect to the data. The residuals can be used to rule out gravitational effects to a specific uncertainty.

Below 0.1 nm distances, Casimir effect measurements are not possible. For these distances, the search for deviations from gravity can be conducted with helium atoms; the energy states of the electrons depend on the force between the core and the electrons. To look for any gravitational effect, the energy states of the helium atoms with electrons are compared to the energy states of the helium atoms with muons instead of electrons.

Example Experiment

Most force measurements use a spring-like setup, meaning that a spring or something that acts like a spring is used. When a force acts on the spring, the compression or stretching length of the spring is proportional to the force. This constant of proportionality is called the spring constant and is usually written as k. The length change is easy to measure. One way of measuring this is by using a laser interferometer. The smaller the spring constant, the larger the length change is. This also applies to the effect that the minimal distance between the two masses is limited. At a certain distance, the force becomes high enough to pull the spring all the way to the source mass. This distance increases with a smaller k.

In the 1990s, atomic force microscopes (AFMs) became more common. AFMs measure the force between a small tip, attached to a cantilever, and a surface of interest. With AFMs it became possible to scan over surfaces to obtain a microscopic image at an atomic scale. The cantilever is also a kind of spring with its own spring constant k. One problem with this measurement setup is that the cantilever tip jumps into contact with the surface. This is a problem, because there is a minimal possible distance for the force measurement and the tip may be damaged (Fig. 2). To overcome these problems, the frequency modulated AFM was developed by Giessibl [7]. With this method, not the length change but the measured frequency is used as the measure of the force. The resonance frequency of the AFM changes when a non-linear force is applied. With this method, it is possible to use a higher k with the same precision as before. A higher k means that measuring is also possible at smaller distances.

Testing gravity with an AFM requires some changes in the setup. Instead of a tip, a sphere, or half sphere is attached to the cantilever. Also, the AFM does not scan over the surface, but measures the force at different distances between the sphere and the plane surface. Both surfaces have a gold coating. Gold has a high density which leads to a higher gravitational effect. Also gold usually forms no oxides like

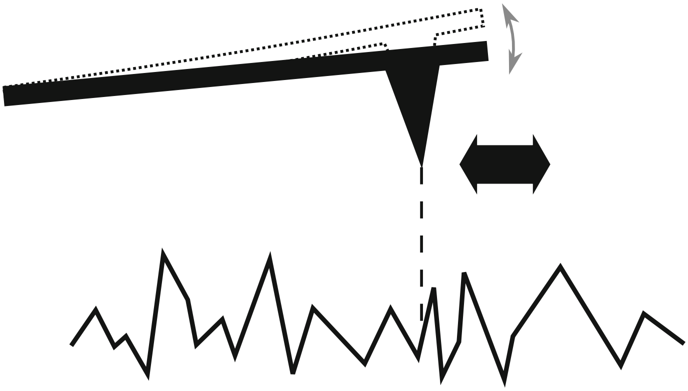

Fig. 2 Schematic AFM with cantilever

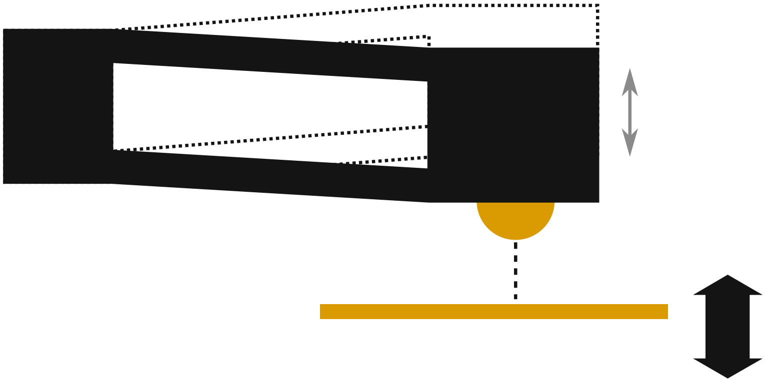

Fig. 3 Schematic parallelogram flexure

other high density metals. This has an advantage for measuring the Casimir effect, because oxides usually feature a lower conductivity than bare metals.

Melcher et al. (2014) [8] demonstrated that a parallelogram flexure (Fig. 3) can replace the cantilever. This means that force measurements with a resolution of 14 fN are possible. A parallelogram flexure has no parasitic rotation during vibration. To drive the vibration, it is possible to use radiation pressure. With this method, one can reach a vibration amplitude of 3.5 pm, which is 30 times smaller than the size of a hydrogen atom.

With this measurement method, the gravitational effect distance of 0.1 nm–100 nm comes into focus.

Promising Theoretical Approaches

In 1986, Fischbach [9] reanalysed experimental data from the Eötvös experiment of 1922. He proposed, based on the above analysis, that Newton's gravitational constant might depend on the material. This would mean that gold would fall differently from hydrogen, for example. This new type of gravitational interaction was called the *fifth force*. Up to now, there has been no evidence that the fifth force really exists, but it has also not been ruled out.

In 1998, the ADD model [10] (named after the authors' surnames) was proposed by Arkani-Hamed, Dimopoulos and Dvali. The ADD model is also called the model with LED which stands for Large Extra Dimensions. In this model, gravity can travel through more than our three spatial dimensions. While electromagnetism can only travel in three dimensions, in the ADD model, gravity also travels through, for example, two extra dimensions. This leads to a weaker gravitational force in our three dimensions and might explain why gravity is so much weaker than electromagnetic force.

In 1977, the Peccei–Quinn theory [11] tried to solve the problem that the neutron should have an electric dipole moment, according to quantum physical considerations, but none is observed. This theory proposed a new hypothetical particle called the axion. The axion is a dark matter candidate. Dark matter comprises 27% of all mass and energy in the universe, but has not been directly observed so far. Therefore the search for a dark matter candidate is mandatory. Dvali and Funcke [12] proposed the domestic axion hypothesis in 2016. This would also explain why the mass of a neutrino is not zero. Their model leads to predictions for gravity experiments at small distances.

Another component of the universe, dark energy, has also not been detected directly. There is a hypothesis about something called the chameleon particle, which is a dark energy candidate [13]. Chameleon particles have a mass that depends on the local energy density. This particular behaviour of the characteristics, depending on the local environment, gives the chameleon particle its name. Chameleon particles would cause the fifth force, and are therefore another reason for gravity experiments at small distances.

In 2016, Edholm et al. [14] proposed a model that tries to resolve the fact that gravity has singularities in Newton's and Einstein's theories. They also calculated how this model would change the behaviour of Newton's law of gravity and they found deviations below distances of 1 μm. In this model, the gravitational potential energy is saturated at very small distances, and a saturation of potential energy means that the force decreases at these distances.

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Return on Investment in Quantum-Gravity Research

Giovanni Amelino-Camelia

I characterize the objectives of fundamental physics in such a way that the only admissible "return" on investments in a research program is the experimental discovery of previously unknown physical phenomena. Accordingly scientists should assess, however subjectively, the "winning probability" of their research programs, here defined as the product between the probability that the idea is "good" and the probability that the idea, if indeed good, would lead to the experimental discovery of previously unknown physical phenomena. I observe that these criteria could affect in particularly significant way strategic choices in quantum-gravity research, where for most predictions of a new theory the probability that they be tested experimentally is very low. I also observe that estimates of the winning probability must be frequently updated in light of relevant theoretical and experimental developments, as I here illustrate in relation to tests of Planck-scale effects for macroscopic systems and tests of Planck-scale effects for the propagation of particles observed from cosmological sources.

The Winning Probability of a Research Program

Humankind invests resources (money, working hours) in physics with the objective of "getting to know Nature better": a research program is successful when the return on the investments takes the shape of the experimental discovery of previously unknown physical phenomena. Some ratio of the quantity and quality of these discoveries versus the amount invested must be the measure of success of a research program. While quantifying precisely is hard, evidently the research program on quantum mechanics of about a century ago is the most successful research program ever, while, for example, research programs on the magnetic monopole [1] are so far at a total loss.

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Assessing *a posteriori* this return on investment is of course mere academia. We need good decisions on investments, not some historical accounts of good and bad investments. Here is where estimates of the "winning probability" of a research program play a role. We need estimates of the probability that a research program will provide a good return on investment. In an appropriate sense the winning probability is the product of two probabilities, P_{th} and P_{exp}:

$$P_{win} = P_{th} \cdot P_{exp} \; ,$$

where P_{th} is the "probability that the idea is good" (the idea inspiring the research program is good), while P_{exp} is the probability that the idea, if indeed good, would lead to the experimental discovery of previously unknown physical phenomena. A proper definition of P_{th} is such that it should be given by the value one would obtain for P_{win} when making the hypothetical assumption that $P_{exp} = 1$, i.e. P_{th} is defined as the value of the winning probability obtained assuming hypothetically that $P_{exp} = 1$.

A key observation for this essay is that in most research areas $P_{win} \simeq P_{th}$ (i.e. $P_{exp} \simeq 1$), while one has evidently $P_{exp} \ll 1$ for all quantum-gravity research programs. In most research areas testing the predictions of a new theory is relatively simple ($P_{win} \simeq P_{th}$), and this explains why it is not customary in physics to also worry about P_{exp}. Working in most areas of physics one could be lead to assuming that the winning probability is P_{th}. Even quantum-gravity researchers are first trained in other areas of physics, exposing them to the risk that they too would take the professional attitude of assuming (however unknowingly) that the winning probability is P_{th}. However, with the information available at the present time we must expect that quantum-gravity effects are terribly small, resulting in estimates of P_{exp} which are $\ll 1$. The most commonly encountered quantum-gravity predictions are indeed very small effects [2], since their magnitude is proportional to $\left(\frac{E}{E_P}\right)^{\alpha}$, some power of the ratio between the typical energy E of the particles involved over the gigantic Planck scale ($E_P \sim 10^{28} eV$).

As recommended by the editors, this essay is addressed to "readers without a higher degree in physics". My main objective is to render tangible for such readers some challenges for strategic decisions in quantum-gravity research, due to its peculiarities.

Estimating the Winning Probability

Estimates of the winning probability are to a large extent subjective. Scientists can do no more than estimating subjectively the winning probability of research programs, in good faith, and to the best of their abilities. I can illustrate the nature of this effort by discussing briefly my subjective estimates of the winning probabilities of some research programs.

First however let me state explicitly a rather obvious fact: if the objective of a research program is exclusively the one of providing a more elegant (more "satisfactory") description of known physical phenomena, without leading to the experimental discovery of any previously unknown physical phenomena, it will for sure produce no return on the investment, and automatically $P_{win} = 0$.

I mentioned above research on the magnetic monopole, as illustrative example of a case where so far the return on investment is 0. I should mention however that at the present time my subjective assessment of the winning probability for magnetic-monopole research is of $P_{win} \sim 0.01$, which is evidently not good but also not so bad. My decisions on investments in magnetic-monopole research should take into account the costs, the amount of resources that appear to be needed, and compare that to the value of the possible "return", factoring in this small (but non-negligible) P_{win}. Overall I choose not to invest personally (my working hours) in magnetic-monopole research, but it is a rather close call, and I would not at all be surprised if other individuals (or funding agencies) choose to invest in magnetic-monopole research.

Moving on to topics of interest in quantum-gravity research, let me start by considering quantum-gravity research programmes focused on the hypothesis of compact spatial dimensions of size given by the Planck length (the inverse of the Planck scale, $\sim 10^{-35} m$). For this my subjective estimate of P_{th} is of $P_{th} \sim 0.1$, which is very high among the values of P_{th} that I attribute to physical predictions emerging from quantum-gravity research. However, my subjective estimate of P_{exp} for this case is of $P_{exp} \sim 10^{-80}$, reflecting the fact that, according to theoretical evidence gathered so far, these extra dimensions produce effects with very steep onset (they leave no trace at length scales below the compactification length scale). This 10^{-80} reflects my estimate of how difficult it would be to devise experiments capable of probing directly length scales comparable to the Planck length. So overall my subjective estimate of the winning probability for research programmes on the hypothesis of compact spatial dimensions of size given by the Planck length is of $P_{win} = P_{th} \cdot P_{exp} \sim 10^{-81}$, a typically minute value for quantum-gravity research. I shall not invest my working hours on the phenomenology of compact spatial dimensions of size given by the Planck length.

My interest in research on Planck-scale effects affecting relativistic symmetries reflects of course my subjective estimate of the winning probability for that research program. In this case it is useful to separate the discussion of the winning probability into two subcases, depending on the value of α in the factors of $\left(\frac{E}{E_P}\right)^{\alpha}$ that give the Planck-scale dependence of the effects. For $\alpha \leq 1$ my subjective estimate of the P_{th} is of $P_{th} \sim 0.01$, but the trends of sensitivity improvements over the last decade leads me to estimate $P_{exp} \simeq 1$. The case $\alpha > 1$ appears to be more generic in theory studies (more probably a good idea) but is more challenging experimentally, a situation which I subjectively characterize as a case of $P_{th} \sim 0.1$ and $P_{exp} \simeq 0.1$. So overall I estimate the winning probability for research on Planck-scale effects for relativistic symmetries at $P_{win} \sim 0.02$, which is by far the biggest winning probability I see among quantum-gravity research programs.

Of course my subjective estimates have no objective quantitative valence, but they illustrate how scientists could deal with the challenge of estimating, however tentatively and subjectively, both P_{th} and P_{exp}. Instead it often happens, particularly among young quantum-gravity researchers, that only P_{th} is taken into account in choosing a research program. Often discussions about priority between one and another quantum-gravity research program focus exclusively on which P_{th} could be higher, even though a high P_{th} when accompanied by a particularly low P_{exp} still gives a very low P_{win}.

Reassessing Winning Probabilities

Estimates of winning probabilities are not only subjective but also a reflection of the status of theoretical and experimental knowledge at the time when the estimate is performed. Good practice imposes that one should reassess frequently the overall situation and perform updated estimates of the winning probability.

In-Vacuo Dispersion

The possibility of quantum-gravity-induced in-vacuo dispersion, an energy dependence of the travel times of ultrarelativistic particles from a given source to a given detector, has been motivated in several studies (see e.g. Refs. [2–7] and references therein). This is in particular the most studied example of quantum-gravity effect affecting relativistic symmetries. Part of the interest in this possibility comes from the fact that it is a rare case of candidate quantum-gravity effect that could lead to observably large manifestations, even if its characteristic length scale is of the order of the Planck length.

The best opportunity so far studied for such experimental tests is provided by observations of GRBs [2–4], which set up for us a sort of race among photons of different energies and neutrinos of different energies, all emitted within a relatively small time window. A characterization of the present status of these studies is given in figure, relying on observations reported in Refs. [6, 8–13].

The neutrinos and photons in figure were selected using criteria [6, 8–13] which do not a priori favor the emergence of the correlation visible in figure. That correlation is the sort of feature one could expect from in-vacuo dispersion, as it follows immediately from the definitions of Δt and E^* (Fig. 1):

- For the photons in figure Δt is the time-of-observation difference between that high-energy GRB photon (interpreted tentatively as a photon emitted at or near the first peak of the GRB) and the first GBM peak [13] of the GRB, while for neutrinos Δt is the time-of-observation difference between that candidate GRB neutrino and the trigger of the relevant GRB.

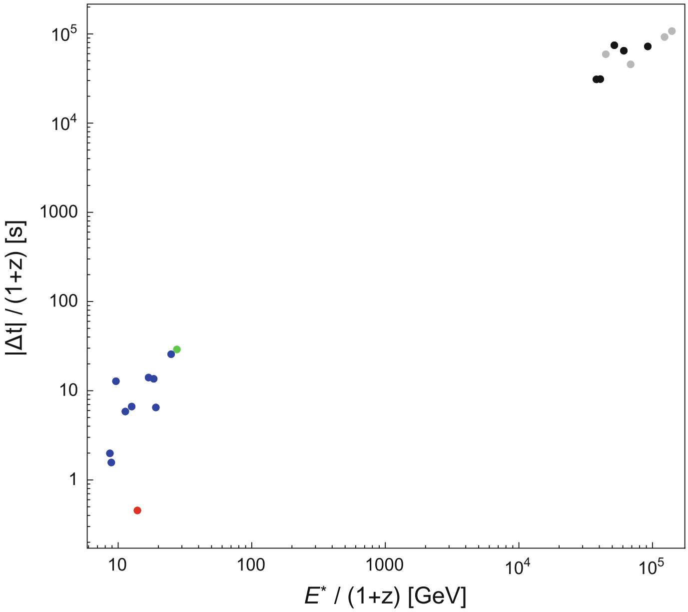

Fig. 1 The points here shown correspond to values of $E^*/(1+z)$ and $|\Delta t|/(1+z)$ for the GRB photons (*blue*, *red* and *green*, all observed after the first GBM peak) of highest energy at emission observed by the Fermi telescope and for IceCube-telescope neutrinos (*black* for those observed after the GRB trigger, gray for those observed before the GRB trigger) that fit the criteria for GRB-neutrino candidates proposed in Ref. [8]. z is redshift, while comments on $E*$ and Δt are here offered in the main text. The photon point in *red* is from 2009 (GRB090510) and its impact on the winning probability of these studies had to be reanalyzed when the photon point in *green* became available in 2016 (GRB160509a)

- The values of E^* are obtained from the energy of the particles (photons or neutrinos), rescaled by a suitable redshift-dependent factor [13], in such a way that for in-vacuo dispersion with $\alpha = 1$ one would expect an exactly linear dependence between Δt and E^* (up to uncertainties in the values of redshift, and the possible presence of spurious points corresponding to high-energy photons emitted not exactly at the first peak or neutrinos misidentified as GRB neutrinos).

The data point in figure taken from GRB090510 is not in agreement with the overall correlation shown in figure, and was one of the first such photons to be reported. When that photon was reported my subjective estimate of the winning probability for $\alpha \leq 1$ was lower than it is now. Some of the photons reported more recently (perhaps most notably one from GRB160509a [13]) strengthened the correlation now shown in figure, and inform my present assessment of the relevant winning probability.

Planck-Scale Effects for Macroscopic Systems

Quantum-gravity effects are usually postulated for “fundamental” microscopic particles, but of course it is important to then investigate what are the implications of those effects for macroscopic systems, composed of many microscopic particles. It is in principle possible that the effects are amplified for a macroscopic system, as a result of cumulative manifestations of the microscopic effects. First of all one must check that this amplification (if at all present) still keeps the proposal consistent with experimental facts, since of course we have very good experimental information on certain types of macroscopic system. Most interestingly the amplification could bring the effects to observable level, consistent with available experimental information but suitable for testing with forthcoming experiments.

The windows of opportunity for this sort of studies of macroscopic bodies should evidently be very rare: it is a delicate balance, which will rarely occur, for the effects to cumulate to observable level for foreseeable experiments, but still safe from falsification with already available experimental facts. Moreover, some arguments suggest that the types of effects for microscopic particles that most naturally arise in quantum-gravity research should automatically fade away as large numbers of microscopic particles combine to form a macroscopic system. Let me here briefly discuss the simplest of these arguments, where the microscopic effects take the form of noncommutativity of the spacetime coordinates of microscopic particles. It suffices for my purposes to use as illustrative example noncommutativity of the type

$$[x_n, y_n] = i\ell^2 + i\ell' y_n \,, \tag{1}$$

where the index n prepares me to consider many such particles, since n will label different particles composing a macroscopic system, while ℓ and ℓ' are length scales characteristic of the noncommutativity.

For the description of the coordinates of the center of mass of a macroscopic system composed of N constituent particles I take X, Y, with

$$X = \frac{1}{N}\sum_{n=1}^{N} x_n \;, \quad Y = \frac{1}{N}\sum_{n=1}^{N} y_n \tag{2}$$

Combining (1) and (2) one easily finds that

$$[X, Y] = i\left(\frac{\ell}{\sqrt{N}}\right)^2 + i\frac{\ell'}{\sqrt{N}} Y \,, \tag{3}$$

which evidently shows that the effects of coordinate noncommutativity for the center of mass of macroscopic systems are scaled down by a factor of $1/\sqrt{N}$.

This observation based on Eqs. (1), (2) and (3) is an example of theory result which, once established, must be taken into account when reassessing winning probabilities. My present subjective estimate of P_{win} for research programs on Planck-scale effects for macroscopic systems is of $P_{win} \sim 0.001$, taking into account theory arguments of the type in Eqs. (1), (2) and (3), but could have been much higher without such arguments.

Ace on the River

Some readers will be uncomfortable with the role played by subjective assessments and with the role played by chance in the methodology here advocated. I have argued that this is inevitably on the road to the only objective enrichment we can aspire to, which is the experimental discovery of previously-unknown physical phenomena. Knowledge is the collection of the physical phenomena we have witnessed (not their interpretation[1]).

Those dreaming a procedure for objective quantitative assessment of different ongoing research programs will be unimpressed, but might still appreciate that comparisons based on subjective assessments of both P_{th} and P_{exp} are better than comparisons based exclusively on subjective assessments of P_{th}.

Even more unsatisfied will be those feeling the urge to evaluate theories on the basis of their "internal qualities" (like being "absolutely true") rather than on their temporary usefulness for the experimental discovery of some previously-unknown physical phenomena (being "temporarily true"). I shall write elsewhere about the futility of the notion of "absolutely true theory" (i.e. "theory of everything"), but let me note here how the fact that this weak notion still has a hold on so much of our scientific efforts is probably to be attributed (and here I am at least in part influenced by Lakatos [14]) to the fact that the pivotal works by Galilei and Newton emerged against the background of centuries dominated by the all-pervading idea that religious knowledge was certain and indubitable. Science took shape inevitably at first as an alternative path to knowledge who should also produce certain and indubitable theories. However, neither the theories nor the religions can aspire to objectivity. We are lucky enough to have the objectivity of physical phenomena (not of their interpretation) to share.

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[1] One of my favorite examples of reinterpretation of experimental results is provided by comparing the description of experimental results on the gain or loss of weight by materials being burned that was fashionable at the time of the Phlogiston Theory and the description of those same experimental results that became fashionable after the discovery of oxygen. The discovery of oxygen in no way affects the robustness of previous experimental results on the gain or loss of weight by materials being burned. The discovery of oxygen in no way led to the discovery of unnoticed sources of systematic error in those experimental results. The same experimental results apply equally well to the interpretations informed by the discovery of oxygen. Experiments done nowdays on the gain or loss of weight by materials being burned still find results for those changes of weight that are fully consistent with the ones from 3 centuries ago. Surely now Phlogiston Theory feels like a pretty strange sort of interpretation. Chances are our current interpretation of gain or loss of weight by materials being burned will feel pretty funny at some point in the future. However, experimental facts gathered 300 years ago on gain or loss of weight by materials being burned are still equally valuable now and will still be equally valuable in the future.

Emphasis on winning probabilities might not be a frequent sort of emphasis for essays on knowledge, but it will be recognized as well-placed emphasis by anyone who analyzes successful scientific practices without prejudice. Talent is the ability to perform good assessments of winning probabilities, courage is the willingness to take a low winning probability when a big "return" is desired, honesty (with others and with self) is especially to be found in reassessing winning probabilities without bias (or at least attempting, in good faith, to keep bias under control) in light of novel evidence from theory work or experiments. However ultimately on the way to any good "return" some luck is needed. It's just that more often than not it takes a lot of hard preparation to be lucky. I like in this respect the book in Ref. [15]: at a certain point of the book there is a description of how an ace on the river played a peculiarly important role in the career of a poker champion; before that the book offers a detailed description of the hard work and talent that was required preparation for that lucky ace.

Acknowledgements I first presented my notion of winning probability for fundamental-physics research programs in September 2015 at a meeting hosted by the University of Wroclaw. I am indebted to Jerzy Kowalski-Klikman for reassuring me that such an unusual choice of topic could be a valuable contribution to that meeting. The choice of illustrative examples that I should focus on, among quantum-gravity-phenomenology research programs, took shape at a meeting hosted by the Frankfurt Institute for Advanced Studies in September 2016, also inspired by a discussion moderated by Sabine Hossenfelder, in which Sabine inspiringly urged participants to discuss their subjective priorities among quantum-gravity-phenomenology research programs.

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Semiclassical Gravity: A Testable Theory of Quantum Gravity

Sabina Scully

For nearly a century [1], how to understand Quantum Gravity has been one of the defining questions of modern physics—both in terms of trying to identify what those two terms actually mean in the context of each other, and in terms of creating a theory that supports that intersection. Thus far, these efforts have been challenged by a lack of experimental evidence—the two theories operate on such different scales, that having a single source simultaneously show measurable quantum and gravitational effects is dishearteningly difficult. While it is possible to insert an external gravitational potential into the Schrödinger equation and experimentally verify it (such as the COW neutron-interferometry experiment [2]), the challenge is to calculate and measure the gravitational potential of a quantised object. The fact that experimental evidence has proven so difficult to obtain has spawned a new way of doing physics, where theoretical physicists are forced to look for confirmation or repudiation entirely within the structure of their theories—the plausibility of the predictions, the internal coherence and the mathematical elegance. However, the experimental branch of the field is now starting to catch up—it may still be decades before we have conclusive tests of String Theory, or Loop Quantum Gravity, but there are simpler, less well known theories that are very nearly within the range of testability. This essay will introduce semiclassical theories of quantum gravity and will discuss the methods and benefits of testing some of those theories. Semiclassical gravity was one of the topics discussed at the recent 'Experimental Search for Quantum Gravity' workshop at the Frankfurt Institute for Advanced Studies in Germany (2016). This theory has had a resurgence in the last three or four years, largely because with new technology, it is possible to design experiments that will conclusively test certain theories of semiclassical gravity, providing much needed experimental evidence that can be used to place constraints on the field. The final part of this essay will focus on these

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new experiments, specifically those under development at the Australian National University (ANU).

At first glance, the problem of quantum gravity seems very similar to that of quantum electrodynamics, a problem that was solved in the 1940s, primarily by Julian Schwinger, Sin-Itiro Tomonaga, and Richard Feynman, who shared the 1965 Nobel Prize in physics for their efforts. Since Newtonian gravity is very similar to electrodynamics, one might hope that this solution would also hold for quantum gravity, however this is not the case. Gravitational fields differ from electrodynamic fields in that they have exclusively attractive charges, instead of positive and negative charges of electrodynamics. This detail means that when we look at gravity in terms of quantum field theory, it must be described with a spin-2 field, which turns out not to be renormalizable with the methods used for spin-1 fields (such as electrodynamics).

Most theories of quantum gravity focus on an interpretation that is dominated by quantum mechanics—they assume that quantum mechanics is correct, and then modify general relativity and the structure of space time to make it compatible with quantum mechanics; specifically, these theories often modify general relativity so that it is possible construct a renormalizable theory. Semiclassical theories of quantum gravity take the opposite approach—they leave general relativity comparatively unchanged, and modify certain assumptions of quantum mechanics to make the theories compatible. Semiclassical theories of gravity build from the semiclassical Einstein equation (1), credited to Rosenfeld [3] and Møller [4]

$$G_{ab} = \frac{8\pi G}{c^4} \left\langle \psi | \hat{T}_{ab} | \psi \right\rangle . \tag{1}$$

Where G_{ab} is the Einstein tensor, G is the gravitational constant, c is the speed of light, $|\psi\rangle$ is the quantum state of all matter evolving within the (classically defined) spacetime, and $\hat{T}_{ab}$ is the quantum stress-energy tensor operator. Those familiar with the classical Einstein equations will note that the only difference between the two equations is that the stress energy tensor has been replaced by its quantum equivalent, and then, since the physical meaning of a quantum operator is fundamentally different to that of a classical tensor, the expectation value of the stress-energy tensor was calculated, to give something that is approximately equivalent to the classical stress-energy tensor in the macroscopic limit, yet still takes into account quantum effects in the quantum limit.

The next step in the development of semiclassical gravity was to apply this idea of replacing a quantum operator with its expectation value to a density distribution to modify the Poisson equation for the gravitational potential (2), which is the Newtonian limit of (1),

$$\nabla^2 \Phi (\boldsymbol{r}) = 4\pi G \left\langle \rho (\boldsymbol{r}) \right\rangle . \tag{2}$$

Where Φ is the gravitational potential, $\boldsymbol{r}$ is the position vector, and $\rho(\boldsymbol{r})$ is the density distribution operator. The physical meaning of this is that instead of using the quantum, point-like density distribution, we use a density distribution equivalent to the probability density distribution of the particle's wavefunction—i.e. $\rho(\boldsymbol{r}) = m\,|\psi(\boldsymbol{r})|^2$, where m is the mass of the particle We can solve the Poisson equation, to give a semiclassical gravitational potential

$$\Phi(\boldsymbol{r}) = G\mathrm{m} \int \frac{\left|\psi\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right|^2}{|\boldsymbol{r}-\boldsymbol{r}'|} d\boldsymbol{r}', \tag{3}$$

However, the main concern with semiclassical theories also arises from this step—this gravitational potential implicitly depends on the wave-function, meaning that when we substitute the semiclassical gravitational potential into the Schrödinger wave equation, the equation becomes nonlinear, due to the presence of the $\left|\psi\left(\boldsymbol{r}-\boldsymbol{r}'\right)\right|^2$ term. This nonlinear Schrödinger equation is known as the single-body Schrödinger-Newton equation; it was developed by Diosi [5] and Penrose [6] and has the form

$$i\hbar\frac{\partial\psi(t,\boldsymbol{r})}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V - Gm^2 \int \frac{\left|\psi\left(t,\boldsymbol{r}-\boldsymbol{r}'\right)\right|^2}{|\boldsymbol{r}-\boldsymbol{r}'|} dr'\right] \psi(t,\boldsymbol{r}), \tag{4}$$

where V is used to account for any other potentials that may be present. It has been claimed that this nonlinearity automatically rules out semiclassical gravity or the Schrödinger-Newton equation as any sort of description of reality, but these arguments typically attack the basic assumptions used to make the theory—by crafting no-go theorems for non-linear quantum mechanics [7], and similar approaches—rather than the internal consistency of the theory. Since there are a number of vitally important theories in modern physics that rely on assumptions that seemed ridiculous when first introduced (wave-particle duality and quantum mechanics, for one), this seems like an insufficient reason to discount the theory. Other arguments cite the 'inelegance' of the theory as grounds to disregard it. This is an argument that comes up a lot in physics—anecdotally, at least, many physicists in my experience favour string theory because they believe it to be a very elegant model, and at the Experimental Search for Quantum Gravity workshop, a large part of one of the afternoon discussion sessions was dedicated to whether or not mathematical 'elegance' was an intrinsic requirement of a good model, and whether or not the bias towards elegant models was justified or excessive. As a physicist studying semiclassical gravity, I believe that there is too much of an emphasis on elegance in modern theoretical physics, but more importantly, I think that in this case whether or not semiclassical gravity is a 'good' model does not actually matter. The important thing about this model is that in the near future it will be conclusively proven or disproven and that result will provide one of the first concrete pieces of experimental evidence about quantum gravity theories.

Equation (4) implies that including a semiclassical gravitational potential will affect the rate of dispersion of the wave-function. This effect is somewhat analogous to how planets form—you start with a disperse distribution of mass, and then gravitational attraction draws it into a compact object. Similarly, in the Schrödinger-Newton equation, the wavefunction will gravitationally interact with itself, as an attractive force acting to reduce the width of the wavefunction [8]. This self-interaction effect is what experimental tests of the Schrödinger-Newton wavefunction are looking to measure, and analysis [8–11] suggests it is on the horizon of testability.

There have been several papers written about how to analyse the Schrödinger-Newton equation [9, 10], and so I will not include details here, but the broad strokes of the analysis begin with extending the Schrödinger-Newton wave equation to the many body case,

$$\begin{aligned} i\hbar\frac{\partial\Psi\left(t,\boldsymbol{r}_0,..,\boldsymbol{r}_n\right)}{\partial t} \\ =&\Bigg(-\sum_{i=0}^{n}\frac{\hbar^2}{2m_i}\nabla_i^2+\sum_{i=0}^{n}\sum_{j>i}^{n}V_{int}\left(t;\boldsymbol{r}_i,\boldsymbol{r}_j\right)+\sum_{i=0}^{n}V_{ext}\left(t;\boldsymbol{r}_i\right) \\ &-G\sum_{i=0}^{n}\sum_{j=0}^{n}m_im_j\int\prod_{k=0}^{n}\frac{d^3\boldsymbol{r}'_k|\Psi\left(t;\boldsymbol{r}'_0,\ldots,\boldsymbol{r}'_n\right)|^2}{|\boldsymbol{r}_i-\boldsymbol{r}'_j|}\Bigg)\Psi\left(t,\boldsymbol{r}_0,..,\boldsymbol{r}_n\right). \end{aligned} \tag{5}$$

Where V_{int} represents any internal interactions between the particles, V_{ext} represents external potentials, Ψ represents a many-body wave-function with $n+1$ particles, and m_i. represents the mass of the i^{th}. particle within that wavefunction. This equation may represent a physical object made up of a lattice of multiple nuclei—for example a crystalline or metallic structure. The self-interaction is strongest for more massive nuclei—such as osmium—because the strength of the gravitational self-interaction is proportional to m^2, which we can see in the many-body gravitational potential in (5)—the second double sum on the right-hand-side. The many-body Schrödinger-Newton equation is then recast in center-of-mass coordinates and expanded into a Taylor series around an origin fixed at the equilibrium centre-of-mass, $\boldsymbol{c}=0$. It is at this point where the two main papers [9, 10] diverge in their analysis—Giulini and Grossardt [10] measure dispersion of the wave function whereas Yang et al. [9] use oscillators to measure the self-interaction. In this essay, the focus will be on work in the paper by Yang et al., because at the ANU, there are currently a number of experiments idevelopment to test their work [11].

In the Yang paper [9], they evaluate a quantum harmonic oscillator, at a frequency ω_0, with a total mass M. and approximate the Schrodinger-Newton equation as a second order Taylor expansion of the gravitational Schrodinger-Newton potential in $c/\Delta x_{zp}$. (the centre-of-mass position over the width of the zero-point fluctuations of the nuclear wavefunctions of the particles). The Schrödinger-Newton equation they calculate using this method is

$$i\hbar\frac{\partial\psi\left(t;\boldsymbol{c}\right)}{\partial t}=\left(-\frac{\hbar^2}{2M}\nabla_{\boldsymbol{c}}^2+\frac{1}{2}M\omega_0^2\boldsymbol{c}^2+\frac{1}{2}M\omega_{SN}^2(\boldsymbol{c}-\langle\boldsymbol{c}\rangle)^2\right)\psi\left(t;\boldsymbol{c}\right), \tag{6}$$

where $\boldsymbol{c}$ is the centre-of-mass coordinate vector, and ω_{SN}. is an additional frequency term we will call the Schrödinger-Newton frequency. This equation is still obviously related to the Schrödinger equation of a quantum harmonic oscillator—in fact, if the value of $\boldsymbol{c}$ was set to zero, Eq. (6) would be exactly a quantum harmonic oscillator at a frequency $\omega = \left(\omega_0^2 + \omega_{SN}^2\right)^{1/2}$.

Equation (6) is the Schrödinger-Newton equation of a quantum harmonic oscillator simplified to a second-order Taylor expansion of the gravitational potential. Since the zero-order term of the expansion is a potential independent othe wave-function, it can be absorbed as a correction into the other parts of the Hamiltonian. The first-order term describes internal interactions between the particles, which will average to zeroherefore, the leading term of this expansion is the second order term, which describes an effect on the centre-of-mass motion by the gravitational self-interaction, and is approximately $1/2M\omega_{SN}^2\,(\boldsymbol{c} - \boldsymbol{c})^2$, and as such, includes the nonlinearity of that interaction, implicit in the term $\langle \boldsymbol{c} \rangle$ [9]. Because this equation is so similar to a quantum oscillator, it makes it relatively easy to analyseathematically, and also makes it easy to set up an experiment to probe this behaviour.

The Schrödinger-Newton frequency is essentially the coefficient of the second order term of the Taylor series of the gravitational potential. It is calculated in [9] and can be calculated using Fourier transforms and the method laid out in [12], and is proportional to the mass of the nuclei, m, the gravitational constant, G, and the width of the zero-point fluctuations of the nuclei, Δx_{zp}, which are confined in potential wells by the electrostatic lattice potential. The equation for the Schrödinger-Newton Frequency is (7)

$$\omega_{SN} = \sqrt{\frac{Gm}{12\sqrt{\pi}\,\Delta x_{zp}^3}}. \tag{7}$$

To experimentally test the Schrödinger-Newton equation as presented in (6), we will set up an optomechanical oscillator that can probe the frequencies of oscillation to a high degree of accuracy. The prediction is that in the frequency-power spectrum of the oscillator, we will measure a main frequency contribution at frequency ω_0, which is what we would see if there were no semiclassical effects, but that we will also see a secondary contribution at a frequency $\omega_{sc} = \left(\omega_0^2 + \omega_{\mathrm{SN}}^2\right)^{1/2}$, the 'semiclassical frequency'.

The parameters of this peak are detailed in [11], but essentially the relative size of the secondary peak increases proportional to decreasing: temperature, oscillator mass, and mechanical damping, and proportional to increasing power of the lasers in the optomechanical setup. The separation between the two peaks increases with increasing nuclear mass.

There are two experiments currently in development at the ANU which could conceivably test this theory. The first is the Torsion Bar Antenna, or 'TOBA', which is primarily designed to detect Newtonian gravitational fluctuations. The second is a levitating mirror, which might also be a highly accurate probe of g, the gravitational acceleration on Earth.

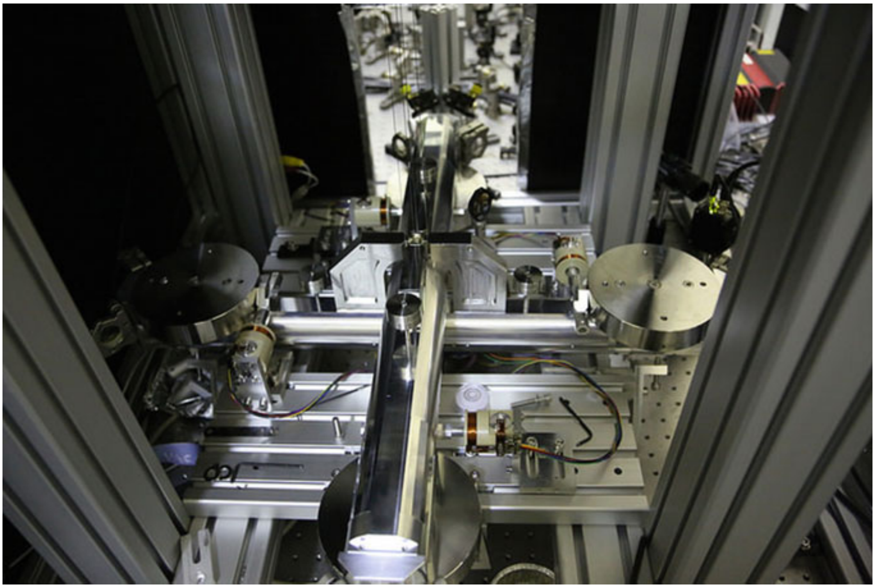
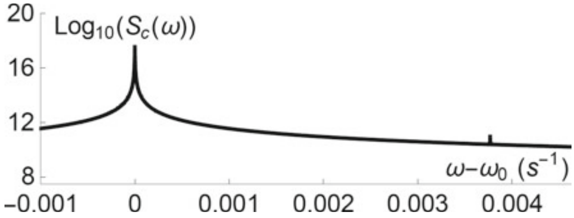


Fig. 1 The Torsion Bar Antenna 'TOBA' device, this experiment is being performed by David McManus and Bram Slagmolen. Although the device is still under construction, it is possible to see the two pendulums—the metal rods—with the disc-shaped masses at each end. Photo courtesy of David McManus

Fig. 2 The power spectral density of the output optical field phase quadrature predicted by the Schrödinger-Newton equation for the TOBA



The TOBA (Fig. 1) is a torsion pendulum, consisting of two perpendicular bars with a 10 kg mass at each end, which are independently suspended in a vacuum. The masses oscillate at a frequency of $0.2\,s^{-1}$ with a Schrödinger-Newton Frequency of $0.039\,s^{-1}$, and their positions are measured optically.

The TOBA device is too massive to have a large contribution at the semiclassical frequency, however, because the frequency of oscillations is so low, it is the best device for resolving the two frequency peaks, with $\omega_{sc} - \omega_o$ on the order of 4 millihertz. The predicted frequency-power spectrum is shown in Fig. 2, where $S_c(\omega)$ is the spectral power as a function of the frequency.

Fig. 3 The power spectral density of the output optical field phase quadrature predicted by the Schrödinger-Newton equation for the Levitating Mirror

The Levitating mirror is a small quartz mirror (0.3 mg), with a Schrödinger-Newton frequency of $0.013\,s^{-1}$. The mirror is suspended by the radiation pressure of a high-powered laser, and allowed to rock at a frequency of about $10\,s^{-1}$. The low mass of the mirror, combined with the low oscillator frequency should give rise to a very strong semiclassical frequency contribution—possibly even stronger than the primary frequency contribution, depending on the temperature and laser power chosen—but the separation between the peaks is very small—on the order of $10^{-5}s^{-1}$. The predicted frequency graph is shown in Fig. 3.

Between these two devices, it should be possible to conclusively test the Schrödinger-Newton theory and they should be completed in the foreseeable future.

The experimental search for quantum gravity still has a long way to go before it can catch up to the theoretical search for quantum gravity, but hopefully, these imminent tests of semiclassical gravity will be a step down the right path. If we do not observe the predicted double-peak signature, semiclassical gravity is ruled out as a theory of quantum gravity. If a semiclassical frequency signal is detected in these experiments, it would be a result of enormous significance, implying that gravity is fundamentally classical and meaning that models like string theory and loop quantum gravity would be ruled out, since they fundamentally assume quantized gravity. If we do not see this semiclassical signal, we can conclusively discount the Schrödinger-Newton equation as a theory of quantum gravity, and refocus our efforts to other areas, narrowing down the search. Either way, this theory of semiclassical gravity is at a critical juncture and is currently an important part of the broader field of quantum gravity, one that many people have overlooked.

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Quantum Gravity Deformations

Antonia Micol Frassino

Introduction

In this essay, we examine a set of uncertainty principles that are proposed in the literature to encode possible features of a theory of quantum gravity. Interestingly, the presence of such modified relations introduces a different structure of the space-time that can be encoded in non-commutative coordinates. This modification of space-time structure is a natural consequence of the appearance of a new fundamental length scale known as Planck length $\ell_P = \sqrt{G\hbar c^{-3}} \simeq 1.616 \times 10^{-33}$ cm, where

$$c = 2.99792458 \times 10^{-8} \quad \text{m sec}^{-1} \tag{1}$$

$$h/2\pi = \hbar = 1.0546 \times 10^{-34} \quad \text{kg m}^2 \text{ sec}^{-1} \tag{2}$$

$$G = 6.674 \times 10^{-11} \quad \text{m}^3 \text{ kg}^{-1} \text{ sec}^{-2}. \tag{3}$$

A Generalised Uncertainty Principle (GUP) was originally introduced in the framework of string theory using an analysis of Gedanken string collisions at Planckian energies [1] and as a result of a renormalization group analysis applied to the string [2]. Moreover, it can be shown that attempts to localize with extreme precision cause gravitational collapse so that space-time and the concept of black hole below the Planck scale have no operational meaning [3, 4]. Thus the impossibility of giving an operational meaning to space-time in the small is automatically incorporated into the mathematical structure of the model. It has been proposed in [3] that space-time should be described as a non–commutative manifold, i.e., the commutative algebra $C_0(M)$ of complex continuous functions on M vanishing at infinity should be replaced by a non–commutative algebra $\mathcal{E}$, and points of M by pure states on $\mathcal{E}$. As first step towards a quantum field theory on the quantum space-time, free fields have

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been constructed, and it has been shown that their commutator at spacelike distances decreases like a Gaussian [3]. However, there is also the hypothesis that gauge theories on the quantum space-time should be formulated under the unifying framework of the so-called "non–commutative geometry" [5].

Non-commutative physics has become an integral part of present-day high energy physics theories. Simply speaking, it reflects a structure of space-time which is modified in comparison to space-time structure underlying the ordinary commutative physics.

Uncertainly Relations

As already mentioned in the introduction, a way to introduce a fundamental length scale was given by Doplicher et al. in [3]. They proposed uncertainty relations for the different coordinates of space-time events, motivated by Heisenberg's principle and by Einstein's theory of classical gravity in this way:

> ≪*The energy transfer associated to the localization of an event by the Heisenberg uncertainty principle should be limited so that the generated gravitational field does not trap the event itself inside an horizon; otherwise the observation would be prevented.*≫

This principle implies space-time uncertainty relations which can be written as:

$$\Delta x^0 \left(\Delta x^1 + \Delta x^2 + \Delta x^3\right) \geq \ell_P^2 \tag{4}$$

$$\Delta x^1 \Delta x^2 + \Delta x^2 \Delta x^3 + \Delta x^1 \Delta x^3 \geq \ell_P^2. \tag{5}$$

The natural geometric background that implements commutation relations between coordinates that satisfy the requirements (4) and (5), is a non-commutative model of space-time. More precisely, the four space-time coordinates of an event are described by four operators which fulfill

$$\left[x^\mu, x^\nu\right] = i\theta^{\mu\nu} \tag{6}$$

with the constraints

$$\theta^{\mu\nu}\theta_{\mu\nu} = 0 \qquad \epsilon_{\mu\nu\lambda\rho}\theta^{\mu\nu}\theta^{\lambda\rho} = -8\ell_P^4, \tag{7}$$

where $\epsilon_{\mu\nu\lambda\rho}$ is the Levi-Civita symbol. In the original treatment of [3], the constant non-commutative parameters $\theta^{\mu\nu}$ are treated as "dynamical" variables, in the sense that their constant values are allowed to vary subject to the constraints (6). In this way, the quantum space-time is compatible with Lorentz invariance. However, in the following investigations $\theta^{\mu\nu}$ was thought as a fixed and arbitrary background tensor field, at the cost of breaking Lorentz symmetry and the explicit uncertainty relations (4), (5); the so-called "canonical non-commutativity." In literature, there is a model of space-time with non-commutative structure described by the algebra first introduced by Snyder in 1947 [6], that provide a non-commutative space-time structure of Minkowski space with undeformed Lorentz symmetry.

During the same period in which Doplicher, Fredenhagen, and Roberts (DFR) were developing their approach, there were investigations on possible mechanisms leading to such limitations also in the context of the quantum groups. In [7] Kempf asked himself whether non-commutative geometry, when introduced into quantum theory, regularises its short distance behaviour. The idea was, not to break symmetries by this regularising procedure, but to (*quantum group*-) generalise them instead.

Deformations of space-time symmetries have been extensively investigated in the last few years. In this approach, the notion of symmetries is generalised to quantum groups, i.e., to Hopf algebras. For example, in “Doubly Special Relativity” (DSR) approach [8], the Poincaré algebra of Special Relativity (SR) is elevated to the quantum (Hopf) κ-Poincaré algebra.

Quantum Groups

Quantum groups are (Hopf algebras) called “quantum” because they are obtained by a deformation of Poisson Lie algebras which shows an analogy with the Moyal quantization of Poisson manifolds leading from classical mechanics to non-relativistic quantum mechanics. One application for these mathematical objects is to consider the notion of a quantum group as a non-commutative generalisation of a symmetry group of the physical system, which means that a quantum group takes the place of a symmetry group of space-time.[1] The important point is that their mathematical structure is well known and even richer than that of a classical Lie algebra. For example, they have an extra structure Δ called the “co-product” which goes backwards in comparison to the product, from one copy of the algebra to two copies. So, quantum groups can be viewed as the deformations of some classical structures such as groups or Lie algebras, just like quantum spaces are non-commutative generalisations (deformations) of ordinary spaces. The most important in physics, and mathematically the simplest one, seems to be the canonical and the Lie-algebraic quantum deformations. It appears that quantum groups, which connect the features of both Lie groups and non-commutative geometry in an analytic way, should be a guide towards the realisation of the above ideas.

Doubly Special Relativity

The idea behind Doubly Special Relativity (DSR) is that there exist two observer-independent scales, one of velocity, identified with the speed of light, and the other of mass κ (or length $\lambda = \kappa^{-1}$), which is expected to be of the order of Planck mass

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[1] For example, the Poincaré group is replaced with the κ-Poincaré group.

and give rise to the “deformation”. Of course, it is assumed that in the limit $\kappa \to \infty$ DSR becomes the standard SR.

In the framework of DSR, it is often stated that the existence of a minimal length is not consistent with the ordinary Lorentz covariance because of Lorentz-Fitzgerald contraction. As a result, it is necessary to “deform” covariance in some appropriate sense (e.g., within the meaning of quantum groups). However, the DFR analysis provides a well-defined model where the Lorentz-Fitzgerald contraction is not conflicting with the presence of a minimal length, so the quest for DSR does not force us in principle to deform covariance. Therefore, DSR is an interesting intersection between non-commutativity a là DFR and quantum groups.

It has been shown in [9] that all these properties can be understood if one employs a simple geometrical language: The momentum space is not flat but rather a constant curvature manifold, a de Sitter space, and the DSR theory reflects a particular choice of coordinates of this space. Such a language implies that the sum of momenta does not respect the usual sum, but it has to encode the information coming from the “co-product”. However, the construction of the theory of Doubly Special Relativity is not completed yet; in fact, there is no single DSR candidate, which would satisfy all the requirements of internal and conceptual self-consistency; the multiparticle sector of DSR theory is still not understood, a problem caused by the non-trivial co-product [10].

In the past years, a new principle has been suggested where the geometrical language of a curved momentum space is taken as a principle at the cost of making the idea of ‘locality’ relative with respect of different observers [11]. The κ deformation parameter used in these theories is assumed to be associated with the Planck length (or mass) depending therefore on the Newton constant G, so it is possible to ask whether such a theories can be derived/considered as an effective theory for quantum gravity in some special regime [12].

In three space-time dimensions (3d), the link between quantum gravity and 3d DSR theory is well studied. Reminding that in 3d the Planck mass does not depend on the Planck constant:

$$\ell_P = \frac{G\hbar}{c^3} \qquad m_P = \frac{c^2}{G} \tag{8}$$

we can expect some (quantum) gravity effect due to the Planck mass even at the classical level, i.e. when $\hbar \to 0$. For example, in Ref. [13], it was noted that the algebra of (Dirac) observables of one particle coupled to gravity gives, at the classical level, the κ-deformed Poincarè algebra. In [14] a similar result is obtained in the framework of spin foam models for quantum gravity: the underlying symmetry of the Ponzano-Regge model was identified to be the κ-deformed Poincarè group [15] and particles were incorporated into the theory as representation of the deformed symmetry group.

Another approach is to include the cosmological constant Λ in the 3-dimensional quantum gravity theory. Classically, the symmetry group turns out to be the de Sitter or Anti-de Sitter group, $SO\,(3,1)_\Lambda$ or $SO\,(2,2)_\Lambda$, depending on the sign of Λ. When $\Lambda \to 0$, the group reduces to the usual Poincarè group. At the quantum level, it turns out that the relevant group is a quantum deformation $SO_q(3, 1)$ or $SO_q(2, 2)$ with the deformation parameter q being related to Λ. Typically, for positive cosmological constant $\Lambda > 0$ we have $q = e^{-\ell_P \Lambda}$. So that when $\Lambda \to 0$, q goes to 1 and the quantum group reduces to the classical group. Then, when looking at the limit $\ell_P \to 0$ of $SO_q(3, 1)$ or $SO_q(2, 2)$ we get the κ-deformed Poincarè group [16], which is then to be identified as the symmetry group of quantum gravity in the regime $\Lambda = 0$.

In four space-time dimensions, the situation is more complex because the Planck mass now depends on the Planck constant

$$\ell_P = \sqrt{\frac{G\hbar}{c^3}} \qquad m_P = \sqrt{\frac{c\hbar}{G}}. \tag{9}$$

One could consider a regime in which the Planck length is negligible and can be set at zero. This would be a semi-classical flat limit, where both $\hbar$ and G go to 0, while the quantum effects and the gravitational effects are still on the same order of magnitude $\hbar \sim G$ so that $\ell_P \to 0$ while m_P is fixed. In such a limit, we might expect to recover the DSR framework. Indeed DSR is investigated especially when purely quantum effects and purely gravitational effects can be neglected ($\hbar \to 0$ and $G \to 0$), and it is likely to be relevant in the large distance regime.

Generalized Uncertainty Principle

To look for testable scenarios, in the non relativistic sector, the presence of a minimal length can be encoded directly at the quantum level by a modification of the Heisenberg uncertainty principle: the relation that prevents an experiment to provide, at the same time, both the position and the momentum of a particle with infinite precision.

In one dimension,

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left[1 + \beta(\Delta p)^2\right] \qquad \beta \geq 0 \tag{10}$$

the Plank constant $\hbar$ sets the quantum scale, while the new parameter β encodes the maximal achievable resolution $\Delta x_0 = \hbar\sqrt{\beta}$ [17]. At the quantum level, the operators momentum and position change their commutation relation to

$$\left[\hat{x}, \hat{p}\right] = i\hbar\left(1 + \beta\hat{p}^2 + \ldots\right). \tag{11}$$

In general, a vast class of uncertainty principles could be proposed

$$\Delta x \Delta p \geq \frac{\hbar}{2} f(\Delta x, \Delta p, \ell_p) \tag{12}$$

where $f(\Delta x, \Delta p)$ is an arbitrary real, positive defined function such that

- It admits a quantum mechanics limit $f \to 1$ when the minimal length is negligible $\ell_p \to 0$;
- It does not violate quantum mechanics $f \geq 1$;
- The minimum of $\frac{f(\Delta x,\Delta p)}{\Delta p}$ exists and encode a minimal length.

Conclusions

In this essay, we have seen that there are different ways to think about the fundamental structure of the space-time. In particular, thought experiments [3, 4] suggest that there are limits to how well we can resolve the space-time structures. An extensive review of different models that have been developed in the past years to include a minimal length scale both in quantum mechanics and quantum field theory is presented in Ref. [18].

Classically, symmetries are described by Lie groups or Lie algebras, and the physical space is the representation space of the symmetry algebra. For example, the commutative Minkowski space-time is the representation space of the Poincaré algebra. Therefore, considering non-commutative space-time, the question arises if these deformed spaces can be introduced as representation spaces of some symmetry algebras. This seems impossible because Lorentz invariance is broken instead, but we have seen that it is possible to deform the concept of symmetry in such a way that it can be applied to deformed spaces as well. This is done in the framework of Hopf algebras. For example, in the "Doubly Special Relativity" (DSR) approach, the Poincarè algebra of SR is elevated to quantum (Hopf) κ-Poincarè.

In the last section, models based on generalised Heisenberg uncertainty relations (GUP) that provide a minimal length has been introduced. These studies include a correction to the position-momentum uncertainty relation that is related to this characteristic length. The development of a generalised quantum theoretical framework which implements the appearance of a nonzero minimal uncertainty in positions is described in detail in Ref. [17]. Contrary to ordinary quantum mechanics, in these theories, the eigenstates of the position operator are no longer physical states whose matrix elements $\langle x|\psi\rangle$ would have the usual direct physical interpretation about positions. One is forced to introduce the "quasi-position representation", which consists in projecting the states onto the set of maximally localised states. These maximally localised states $|\psi_x^{\mathrm{ML}}\rangle$ minimize the uncertainty and are centred around an average position $\langle\psi_x^{\mathrm{ML}}|x|\psi_x^{\mathrm{ML}}\rangle = x$. In the case of the ordinary commutation and uncertainty relations, the maximally localised states are the common position eigenstates $|x\rangle$, for which the uncertainty in position vanishes.

Although the models presented above do not have the ambition to be the complete theory of quantum gravity, they, however, aspire to provide important glimpses of the ultimate theory. In particular, they focus on the idea that some features of the theory could be experimentally tested and/or ruled out.

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General Relativity, Black Holes and Planck Stars

Matteo Trudu

After the formulation of Special Relativity in 1905, Albert Einstein began looking for an extension of the theory, since Special Relativity has two limits: it favors a particular class of reference frames, the inertial frames (reference frames without acceleration, for which the law of inertia holds) and it cannot describe gravitational effects. Einstein worked 10 years, from 1905 to 1916, in order to obtain a satisfying solution which was able to solve these problems and this led to the formulation of General Relativity.

There is a link between these two limits of special relativity: in fact it is very hard to describe the effects of gravity without considering accelerated reference frames. This connection is one of the foundations of the theory; physically it corresponds to the equivalence between inertial mass from the Second Law of dynamics:

$$\vec{F} = m\vec{a} \tag{1}$$

and the gravitational mass, from the Universal Law of Gravitation

$$\vec{F} = G\frac{mM}{r^2}\hat{r} \tag{2}$$

which causes, such as Galileo Galilei noted in XVII century, that all bodies fall with the same acceleration. Einstein's argument was that this equality between the two forms in Newtonian dynamincs, was lacking theoretical justification, while one of the main goals of General Relativity is to explain this equivalence between inertia and gravitation, unifying the two concepts.

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Another important element at the base of General Relativity is the study of the relationship between physics and geometry: from the traditional idea of a separate geometry from any physical content, used as a mere mathematical tool, we arrive at the concept of geometry closely linked to physics: the geometry becomes, in fact, a physical object.

The Universe is not only composed by matter but is both matter and geometry. From this statement follows that the geometry, or spacetime, must have its own dynamics described by a field; in the language of General Relativity, this translates to the metric tensor $g_{\mu\nu}(x)$ which interacts with both matter and energy.

These are the concepts of General Relativity. As in the case of Special Relativity, we can appreciate Einstein's genius[1]: with great simplicity, unification was managed since general theory of spacetime became the theory of gravitation itself.

As in any physical theory, General Relativity is described by a fundamental equation, the Einstein Field Equation, which is one principle of the theory itself. Formulated by Einstein himself, the theory is based on the ideas that we have discussed previously. The equation reads:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{3}$$

where

- $R_{\mu\nu}$ is the Ricci tensor: it is one of the possible contraction of a more general tensor, Riemann tensor $R^{\sigma}_{\rho\mu\nu}$; it contains the dynamical effects of the gravitational field.
- $g_{\mu\nu}$ is the metric tensor: it is the fundamental object of theory, as it has the role of the "potential" in General Relativity.
- R is the scalar curvature; simply put, it describes the trace of the Ricci tensor (in General Relativity it is the lagrangian density for the gravitational field).
- $T_{\mu\nu}$ is the stress−energy tensor which contains the momentum and energy density of the gravitational field; basically put, it is our source for gravity.

This equation, despite appearing very compact and elegant, is not so simple to understand let alone to solve. In a few words, with this equation you can deduct the geometric structure of spacetime ($g_{\mu\nu}$) once the distribution tensor of matter and energy is known($T_{\mu\nu}$): the term $R_{\mu\nu} - 1/2 g_{\mu\nu} R$ contains information about the curvature of the spacetime.

An object such like our sun curves spacetime around itself; this means that the Earth isn't so much attracted by a central force (as Newton stated), as it is forced to follow the curvature imposed by the presence of the sun: we can understand this through an analogy, for example by placing an apple on top of a stretched out bedsheet (so as to represent a plain); experience tells us that the bedsheet will curve because of it's presence: the apple warps our plain therefore any other small object, placed

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[1] It is important to say that Einstein was not the only one working on these ideas, other contributions from others were crucial for General Relativity.

near the region of the bedsheet deformed by the apple, would be inevitably attracted toward the it.

We can conclude that not only space is subject to curvature, but also spacetime. This led to Einstein's prediction that time flows slower as we approach a source of a gravitational field: suppose we examin the case of two twin brothers, one who lives on Earth while the other one on a space station; the one that lives on Earth ages slower with respect to his brother.

Perhaps the most fascinating objects of General Relativity, which have always intrigued human imagination, are black holes. So, what is a black hole exactly? Massive stars, in the last stage of their evolution, stop producing energy and then collapse because of their self-attractive gravity. The radius of a star with mass M that is collapsing progressively decreases until it reaches the value of the so called Schwarzshild Radius

$$R_S = \frac{2GM}{c^2} \tag{4}$$

and the star becomes a black hole. Gravity, due to enormously concentrated mass, forces any object to move toward the black hole until the object meets a surface called event horizon of the black hole. This surface is characterized precisely by the Schwarzshild Radius of the black hole. An object that passes through the event horizon cannot go back, not even light can escape. We know that the escape velocity v_f from a mass M is

$$v_f = \sqrt{\frac{GM}{R}} \tag{5}$$

so if we were to cross the event horizon, then $R < R_S$; this means that the escape velocity under these conditions would have to be greater than the speed of light: $v_f > c$; so on an experimental level, direct measurements are fairly difficult to obtain.

Today's Physicists try to study the possible effects of a black hole on its own surrounding environment. Recently the existence of gravitational waves was confirmed, another wonderful result of General Relativity. Basically, as electromagnetic waves are emitted by electrically charged sources, also matter itself can emit radiation, known now as gravitational radiation, in a very subtle way; In analogy to electromagnetic radiation, which is an electric or magnetic (or both) field that propagates in spacetime, gravitational radiation is a perturbation of the spacetime that propagates in itself; we can imagine this through a simple example: a pebble falling the surface of a body of water (spacetime) causes a series of the ripples (gravitational waves). In february 2015, the LIGO experiment confirmed the existence of gravitational waves, where the source consists of two black holes that merged.

Black holes, by a theoretical point of view, are very fascinating objects. They allow us to understand better gravity and they constitute a challenge to our ideas about the description of the fundamental laws of physics. One of the principles of the quantum mechanics is the assumption that in a system the information is conserved i.e. in our system all the information that we need to describe the initial state of the system, are contained in the system itself (in the language of quantum mechanics, physicists say that the time evolution of a system is described by a unitary transformation). During the formation of a black hole, the information contained in the collapsing matter is confined inside its event horizon. A black hole seen from the outside can be born by the union of stars or it can be formed by an aggregation with of much smaller objects, such as atoms or molecules. The two situations are completely indistinguishable: the information about the initial state of the black hole is not known for an observer outside the horizon.

By a classical point of view it is not a contradictory fact, the black hole lives forever and all the information contained in it are preserved but are also completely inaccessible. The situation is quite different if we consider quantum effects. As Stephen Hawking showed, a black hole can "evaporate" through the emission of thermal radiation from the event horizon. In proximity to the event horizon, quantum fluctuations can create a pair of particles and one of these is capable of escaping the black hole. It can then be revealed as radiation, while the other one is captured by the black hole. Thanks to this mechanism, a black hole loses mass which is released as radiation and and for this reason a black hole will evaporate. The final result of this process is the complete disappearance of the black hole but also consequently all the information contained in the black hole are destined to disappear, in complete contradiction with the principles of quantum mechanics which we discussed earlier.

One important thing to take into account is that Hawking Radiation is an effect of quantum mechanics in a classical gravitational field (described by General Relativity), therefore it is an approximation known as semi-classical: this approximation studies a physical problem partially in a classical way using gravitational interaction (a classical spacetime background) while on the hand, in a quantum mechanical manner since pair production due to the quantum fluctuations is obviously a quantum effect.

Hawking Radiation gives us a clear indication that general relativity is a model that cannot work at a fundamental level. We need a much more fundamental theory capable of overcoming the formal difficulties of General Relativity and be able to reconcile gravitation (the theory of spacetime) with quantum mechanics: a quantum theory of gravitation. Over the years, theoretical physicists proposed several theories (String Theory, Loop Quantum Gravity,Asymptotically Safe Gravity, Causal Sets, etc.) and each of these theories has some very interesting aspects but also all of them have unclear problems to solve.

An interesting answer to this information paradox is proposed by Loop Quantum Gravity. Black Holes could reach a new evolutional state of their life where a "quantum gravitational" pressure generated by quantum fluctuations of spacetime counterbalances the collapse of matter and causing it to become a new astrophysical object called "Planck Star"[2] When a massive star, as we said early, stops producing energy and becomes a black hole inside the horizon, matter keeps to collapse until it reaches the state of a Planck star. How big is this hypothetical astrophysical object? It would be so small that it would be odd to classify it as a star; in comparison, our sun would be as large as an atom if it were to become a planck star. Common sense

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[2] C. Rovelli, F. Vidotto "Planck Stars" https://arXiv.org/pdf/1401.6562v4.pdf.

dictates this is a quirky way to imagine this a atom sized star, since very compact objects such as neutron stars have a radius of roughly about a few kilometers, in this case we talk about 10^{-10} m. The example of the sun allows us to understand that the matter inside a planck star would have an extreme mass density. Furthermore the authors show that a planck star is not stable but after reaching a maximum compression, it subsequently will start an expansion mechanism which leads to the explosion of the black hole and all of the information it once held would be expelled. How long does this process last? It depends. As we have seen in the example of the two brothers, for an observer placed inside the event horizon of the black hole the process is of short duration, it is instantaneous; instead for an observer outside the horizon the process is extremely long because of time dilatation effects due to the presence of a very strong gravitational field. For this reason, we will never realize that this process is taking place and the black hole would seem to remain the same.

In the hypothesis of the existence of black holes old as the Universe (13 billion of years) and if they are exploding now we could measure some signals due to their explosion and it would for the first time be a quantum gravity effect.

A possible candidate for this type of signals could be a Fast Radio Burst. What we know about fast radio bursts is that they are intense radio signals isolated with a duration of milliseconds. The frequency of these signals is about 1.3 GHz (hence a wavelength of 20 cm). Fast Radio Burst are still a mystery in astronomy and their origin is unknown. These signals are, in theory, of extragalactic origin. They are extremely energetic signals since the total energy emitted in the radio length by a source is estimated to be of the order 10^{38} erg. The wavelength of the signal emitted during the explosion of the black hole was estimated by the authors and does not appear to be in perfect agreement with experimental data but the result could be improved using a more accurate model, for example, as the authors suggest, rotational effects of the black hole could be give greater wavelengths.

Spacetime Structure: Analogy in Condensed Matter and Quantum Information

Martin Seltmann

Abstract Analogies and equivalences provided by research in condensed matter and quantum information may give unexpected insights into the structure of quantum spacetime for fundamental physics. Several examples and implications for quantum gravity phenomology are discussed.

Intro

The current decade has witnessed two impressive vindications of modern physics. Discovery of the Higgs field and gravitational waves (plus a black hole merger as their cause) can each be regarded as the last missing piece in the empirical confirmation of the two corresponding Standard Models: the remarkable success of both Particle Physics or "microcosm" (Quantum Field Theory QFT) and Cosmology or "macrocosm" (General Relativity GR) was once again proven by spectacular experimental verification of their final key predictions—the Higgs mechanism in the electroweak sector and black holes/undulations in the fabric of spacetime, respectively.

Despite the incredible power of each model on its own, the desired fusion of microcosm and macrocosm (Quantum Gravity QG) via mathematical unification of QFT and GR poses new challenges: above all it seems to require a revision of our abstract notion of spacetime—for experts: a smooth 4D topological manifold as base space of fibre bundles whose sections are building blocks for tensor fields subject to canonical quantization. Einstein showed that instead of space and time being a passive backdrop/stage on which all physics unfolds, the combined spacetime is dynamical: matter tells spacetime how to curve and spacetime curvature in turn tells matter how to move. This interplay between spacetime and matter/energy content is captured in the GR field equations making heavy use of differential geometry.

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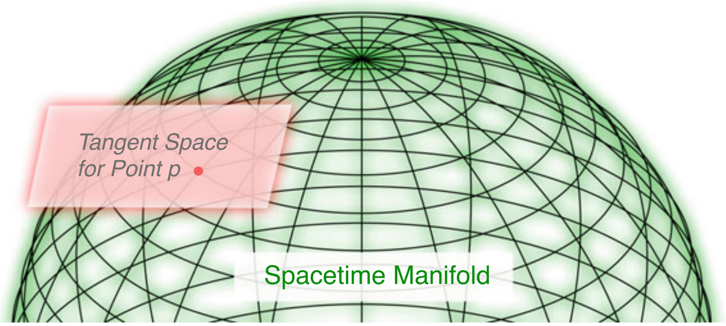
The procedure to construct a mathematical model of spacetime is instructive; starting with a totally unstructured set M like a "powder" without any shape and connectedness, M is endowed with more and more structure: first it is upgraded to a topological space (M, T) with topology T (a specific subset of the power set $P(M)$) enabling the notion of continuity, then (M, T) is promoted to a manifold (locally resembling flat space) allowing for (local, not global) charts just like mapping our round planet in an atlas, and finally differentiability/smoothness is introduced leading to diffeomorphisms (structure-preserving smooth maps) between smooth[1] manifolds. The core principle of GR demands background-independence of fundamental physics, meaning invariance under diffeomorphisms as smooth deformations of the spacetime manifold M.

A common misconception is that spacetime is modeled as a vector space. This would be too much structure—M in GR is only a topological manifold, but there is an associated vector space: the tangent space T_pM for every point p on M.



The quantum fields of QFT live on M and T_pM in the following sense: to each point p an element of T_pM is assigned, giving so-called sections of the tangent bundle that are the basic ingredients for all fields. QFT requires these fields to become operator-valued,[2] which has profound consequences: fields do not have fixed values at the points p, but are in a superposition of several values—just like electron positions get replaced by electron clouds (orbitals) in atoms/molecules. For the vast majority of fields—including scalar (Spin-0), spinor (Spin-1/2) and vector/gauge (Spin-1) fields—this intricate "smearing out" works, but there is one problematic field left: the metric tensor (Spin-2) field giving the concrete geometry of the manifold M

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[1] According to an intriguing result in Topology, four-dimensional spacetime is by far the most daunting case: there is an uncountable infinity of distinct ways to equip the open 4-manifold $\mathbb{R}^4$ with smooth structures, while in all other dimensions a unique single way exists! Somehow the dimensionality of our physical world is exactly big enough to allow wild mathematics, but small enough to tame the wildness—extra dimensions would give more wiggle room.

[2] Just like observables in basic quantum theory such as position x and momentum $p_x := -i\hbar\partial_x$ are not mere numbers but operators acting on the (Hilbert) quantum state space, fields like the electromagnetic potential A_μ turn into field operators acting on the (Fock) state space in QFT.

dictated by the solution to the Einstein equations. This metric field lives on M like all the other fields and should thus equally be in a superposition when quantized. But what does a superposition of geometries mean? Finding a (renormalizable) QFT for gravity has been a major headache; spacetime itself—as the very foundation of all theories—must be modified and the discussed picture of M might be doomed.

The seemingly unsurmountable difficulties in theory are mirrored by no less disheartening obstacles for the study of testable effects (phenomenology) in QG: the relevant energy scale (Planck: 10^{19} GeV) is considered way too high for direct experiments to be feasible and even related hints have not shown up so far in High Energy Physics HEP. Given this lack of direct testability and complete absence of (non-null) HEP results, questions about other (indirect) ways to test new ideas about QG and their connection to the frameworks of QFT and GR arise. Maybe some important concepts are accessible at lower energy densities and insights at those levels might give clues about fundamental physics by analogy.

Indeed for both aforementioned recent discoveries there are actually well-known analogies in Condensed Matter CM, an area of physics concerned with the interplay of many constituents and its consequences for the collective properties of the resulting total system.

Condensed Matter Analogies

That CM systems could tell something about HEP might not be so obvious at first sight: HEP symmetry groups (Poincaré/Lorentz invariance) are generally broken in CM microscopic models (Hamiltonians H), as most solid state systems like crystals only exhibit certain discrete symmetries reduced from the full spacetime versions—hence the somewhat derogatory term “squalid state” used by mean theoretical physicists to signal the spoiling of their beloved fundamental laws.

Symmetry breaking is a profound theme in science to explain how the deepest laws of nature can be more symmetric than the concrete world around us. According to this reasoning the fundamental equations possess maximal symmetry, but the solutions to these equations (describing the actual state) do not! Out of many degenerate solutions a specific ground state is chosen that breaks the original symmetry spontaneously, e.g. the rotational symmetry of spins reduced to an arbitrary direction by spin alignment below the ferromagnetic transition temperature.

Broken symmetry groups classify phases in Thermodynamics/Statistical Physics, the realm of “complexity” as the third pillar of modern physics in addition to “micro- & macrocosm” and equally important for a unified QG theory of QFT and GR. It seeks to bridge both worlds in explaining[3] how macroscopic properties such as tem-

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[3] The central postulate of Thermodynamics states that for constant energy all microstates (pure states: exact quantum states $|n\rangle$) are equally probable in the resulting macrostate (mixed state: probability distribution $p(n)$ over microstates) described by a so-called density matrix ρ, that allows the derivation of those for other macrostates, e.g. for constant temperature $\rho = \exp(-\beta H)/Z$ (thermal

perature emerge from the underlying microscopic physics. Phase transitions (reduction/expansion of symmetry groups to/from subgroups) are accompanied by jumps or bumps in thermodynamic quantities, ultimately leading to new phenomena.

The important point is that emergence of new rules and observables is quite common in both HEP and CM, yet in quite contrasting ways! While in HEP higher symmetry is normally achieved by higher energy, often the opposite is the case in CM: low energy gives birth to new symmetries absent in the microscopic Hamiltonian due to self-organization of the material. Novel patterns showing up at zoomed-out levels induce *emergent* symmetries previously not implemented—the system gains fresh types of symmetry responsible for new characteristics of the system at low temperatures. Even full Lorentz invariance can emerge, which is why CM systems cannot a priori be deemed unsuitable for spacetime analogies.

Emergent behavior is best understood from the perpective of Effective Field Theory: formalized via a powerful mathematical viewpoint called Renormalization Group, effective QFT describes nature in a certain energy range without encapsulating the full underlying "true" physics (called UV completion). Yet the IR approximation demonstrates all phenomena relevant at this energy/distance scale and it is astonishing that the same mathematical framework of QFT can be applied equally to the seemingly very different areas HEP and CM. The miracle of "the unreasonable effectiveness of mathematics in physics" alone is quite famous, but this is in fact a second puzzle: why should the math of QFT rule both the UV universe of elementary particles and (as effective QFT) the IR laboratory of squalid states? Nature could have chosen (or forced mankind to chose) a completely different formalism in each case. This nearly all-encompassing scope of QFT and the mathematical equivalence between formerly separate worlds never cease to amaze, but might be grasped more easily by introducing the quasiparticle concept:

Particles in QFT are excitation units (quanta) of an underlying quantum field. The interactions of fields in HEP collision experiments are computed via a so-called scattering matrix S using the pure vacuum (lowest energy) with its dispersion $p^2 = m^2$ as the "background" for the calculation. Observable particles are associated with poles of the S-matrix (including analytic continuation) with $E = mc^2$ in the rest frame, being stable for real and unstable[4] for complex E. In CM a nontrivial background (e.g. a crystal lattice) takes the place of the vacuum state and the elementary excitations described by the S-matrix are now called quasiparticles with a deformed

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(Footnote 3 continued)
equilibrium) with $\beta := 1/kT$ and partition function $Z := Tr\, \exp(-\beta H)$. All thermodynamic quantities can be extracted from this density matrix (or equivalently Z), most importantly the entropy $S := -kTr\rho \ln \rho$ quantifying the ignorance (missing information) about the exact microstate due to the probability distribution given by the thermal macrostate (providing only a coarse-grained picture). Emergent thermodynamic observables include temperature $T := 1/\partial_E S$ and pressure $P := T\partial_V S$

[4] For $E > Re(m)$ an unstable particle forms with $Im(m)$ determining its lifetime, for $E < Re(m)$ only a resonance as evidence of pole existence shows up in the scattering cross section.

dispersion law. An important instance of quasiparticles are quantized sound waves called phonons, being packets/quanta of the vibrational field similar to the way photons are quanta of the electromagnetic field. Both types are treated with the same mathematical scheme of QFT and this formal equivalence lies at the heart of correspondences between HEP and CM.

Cosmic Superconductor

The notion that CM analogies can inform about HEP is not really new: after the discovery of superconductivity in metals, exotic superconducting states were explained by the formation of bosonic Cooper pairs due to coupling of two fermionic electrons (mediated by virtual phonons) lowering the ground state energy. Like all bosons at low temperatures, these pairs can undergo a process called condensation. Such condensates (in general coined BEC because of Bose-Einstein vs. Fermi-Dirac statistics) are in a macroscopic quantum state where individuality of its constituents loses any meaning.

Of course the entry into the superconducting phase must break a symmetry: in this case it is the $U(1)$ gauge symmetry of electrodynamics—actually not a physical symmetry but rather a redundancy in our description. Dirac found the electron field to be complex because of its charge, giving an angle in the complex plane that is not determined a priori. Gauge freedom allows for different choices of the angle $\theta(p)$ at each spacetime point p without changing any physics if a compensating gauge field (the photon field A_μ) is introduced—in fact all force fields are an automatic consequence of the gauge principle, quite analogous to the GR equivalence principle that equates accelerated reference frames by demanding a compensating gravity field. The way matter fields change along or twist around the spacetime manifold is captured by so-called connections or covariant derivatives that naturally include force (gauge) fields. Both metric and gauge fields embody different types of curvature: that of outer space (metric) and inner space (gauge) in a nice geometrical picture.

The photon (the quantum of the $U(1)$ gauge field) is massless and therefore has no rest frame—in vacua it travels forever at the speed of light. But in superconducting materials (breaking local $U(1)$ symmetry by a fixed angle θ at all locations) a surprising new scenery is presented to an observer inside: external magnetic fields are expelled and the photon appears massive! A broken gauge symmetry causes an energetic cost for the formerly free choices of angle θ (gauge transformations) because they now disrupt the ordered (θ-correlation not present in the vacuum) superconducting state. Excitations of the photon field now cost intrinsic energy—the photon has acquired a mass.

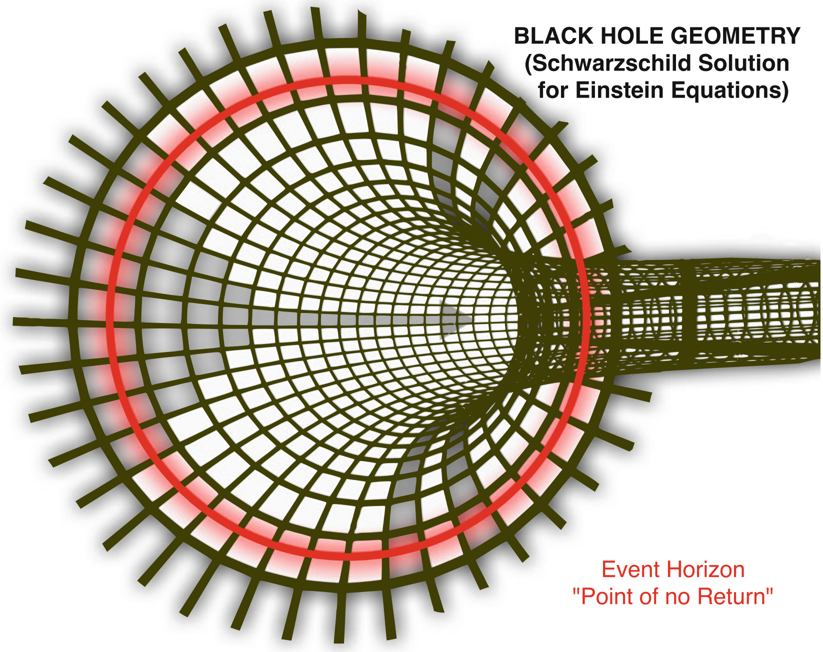
Contemplating this magical effect found by CM wizards, theoretical physicists speculated if similar magic could be found in HEP to account for the mass of other particles: two forces that had been described separately (Quantum Electrodynamics QED for electromagnetic and Quantum Flavor Dynamics QFD for weak interactions) were shown to unify in electroweak theory, provided that all force carriers are massless. Although this was not the case in reality, the prospect of unification (similar to the marriage of electricity and magnetism by Maxwell) was so attractive that solutions for mass generation without spoiling the beauty of the unified theory were pondered. Adopting the CM perpective, one might ask: could we live inside a giant superconductor that causes certain massless particles to appear massive? Taking this radical proposal serious demands an answer to the question: what would be the analog of the condensate?

Elaborate mathematical tinkering suggested the existence of an unobserved Higgs condensate in the universe. It would fill all spacetime (thus practically being a property of M) and cause the breaking of the electroweak symmetry just as the superconductor condensate destroys electromagnetic symmetry. The Higgs field could also reveal itself by its own excitation, the Higgs boson as the first elementary scalar particle.

Half a century passed before the experimental confirmation of this intellectual construct was finally announced. Both evidence and importance in HEP were so overwhelming that Nobel Prizes for the Higgs mechanism were awarded the following year. Yet the original idea was sparked by CM research and Higgs boson analogs were even seen in CM experiments before the "God particle" showed up in HEP. So it is not totally crazy to entertain the idea that CM can offer more tantalizing clues for relativistic physics and ultimately the structure of spacetime.

Sonic Black Holes

Gravitational waves and merging black holes (ripples and singularities of the spacetime manifold) as the second major breakthrough of this decade are ultimately the embodiment of spacetime curvature, which also has an analog in CM: the role of spacetime (background for material objects) can be played by a condensate of atoms (superfluid) providing a background for phonons as its quasiparticle-excitations. Just like flat spacetime may be stretched and curved, homogenous superfluids can be distorted by flow variations manipulated with a laser: fluid regions of supersonic flow constitute a horizon for phonons analogous to black hole horizons. Phonons (travelling at the speed of sound) cannot escape these sonic black holes in a way equivalent to photons being swallowed into cosmic black holes. This BEC analogon could provide a testbed for physical predictions about true black holes, in particular a phenomenon called Hawking radiation. Semiclassical calculations using the equations of QFT in curved classical spacetime show that in the presence of black holes the vacuum concept gets complicated: fields can always be decomposed into different modes very similar to the way a sound can be split into several harmonics in music, but this note decomposition depends on the choice of coordinates and can thus differ in various frames of reference—the coefficients do not agree and lead to frame-dependent field excitations. The extreme spacetime curvature of black holes implies accelerated frames giving rise to thermal radiation; the particle content has changed due to black hole formation—the empty vacuum has turned[5] into Hawking radiation!



Since BEC experiments can mimic spacetime curvature and horizons, there should also appear a thermal radiation of phonons. Recently the discovery of sonic Hawking radiation by its characteristic signature (density-density correlations in a BEC of ^{87}Rb atoms) has indeed been claimed, but would that also prove the existence of its spacetime version? To address this question it is crucial to distinguish what philosophers of science call different modes of inference or types of evidence: considering computer simulations as an example, one might ponder their heuristic value for theory confirmation beyond the reach of empirical tests. Simulations are not exactly of the same epistemic type as evidence drawn from direct experimental probing—but how to test a theory like QG with predictions that seem to exceed our technological abilities? These problematics have been the topic of many discussions in recent literature (and conferences) with wide-spreading ideas about non-empirical evidence

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[5] For experts: the asymptotic Bogoliubov coefficients depend on the acceleration (with respect to Killing time) just outside the horizon, resulting in a non-zero particle flux with blackbody spectrum at later times (*not* created in the immediate vicinity of the horizon as is often misrepresented in popular accounts). It has recently been argued that its origin could be traced to some form of "quantum atmosphere" hovering at a distance.

based on mathematical beauty/consistency or absent alternatives. Instead of purely non-empirical assessment, this essay focuses on a different approach: theory confirmation by analogies—using substitutes of the real system in question as means of performing empirical tests. Do analogue and conventional experiments provide evidence of the same epistemic type? Comparison of "true" and substitute systems in the most precise way is enabled by their mathematical models: if all central assumptions relevant for the hypothesis agree, evidence gained on one is potentially confirmatory for the other.

In the specific case of sonic horizons, all relevant math seems to be completely identical with its GR twin: an acoustic metric leads to the same equations describing a smooth horizon independent of the underlying microphysical details. The Hawking effect was allegedly shown to be sufficiently robust even for inhomogeneous BEC and modified dispersion relations (due to QG effects) for the spacetime vacuum (under certain assumptions like adiabatic mode evolution). Universality results thus seemingly make it safe to infer astrophysical black hole phenomena from CM dumb hole observations by replacing light with sound and thermal photonic flux with thermal phononic flux. Yet many physicists are not convinced and stay reluctant to accept this way of reasoning. Their legitimate objections are rooted in a war that began a long time ago.

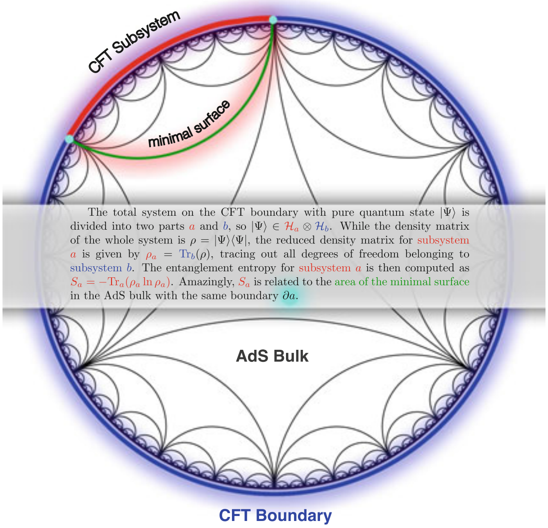
Holography

Thermal distributions after collapse of matter show that the formed black holes must have an entropy, but what are the necessary microstates? A uniqueness theorem in GR distinguishes all black hole solutions by only three external parameters (mass, charge, spin), so the vast microscopic information about the infalling matter is apparently hiding behind the event horizon—explaining the huge entropy (inaccessible information). But the semiclassical approach shows that black holes eventually evaporate completely via Hawking radiation—so what happens to this hidden information during/after the evaporation? This tricky question started a debate known as the Black Hole Information Paradox or “Black Hole Wars” in more martial parlance: Hawking himself originally claimed the information is lost, while other physicists maintained it should survive in some form. A central tenet of QFT called unitarity strictly prohibits any information loss: pure initial quantum states (the exact description of infalling objects) always evolve into pure final states, however scrambled they might get in the process. So it should always be possible to recover the starting point telling us exactly what made up the black hole, but Hawking radiation seems to lack this feature thanks to its entirely thermal character.

Evolution of pure states $|\psi\rangle$ to mixed states ρ clearly violates unitarity and this conundrum led to Black Hole Thermodynamics: the black hole entropy $S_{BH} =$

$c^3kA/4\hbar G$ was found[6] to be proportional to—instead of volume as in ordinary systems—the area A of the event horizon, a discovery that suggested all physics within a spacetime region (the bulk) is in some sense encoded on its boundary. Proclaimed as the Holographic Principle, this idea was corroborated at the turn of the millennium by a holography conjecture (highly likely to be true) with enormous impact: gauge/gravity duality. Also known as AdS/CFT-correspondence, it states that gravitational theories in certain types of spacetime (Anti-de-Sitter-space AdS) are equivalent to gauge theories without gravity (conformal field theories CFT) on the boundary.

Since in CFT unitarity holds, information loss must also be prevented in the dual AdS gravity theory; holography ended the Black Hole Wars by saving unitarity even for black hole evaporation—while still not specifying where the information goes. The main problem of AdS/CFT as a dictionary translating between two worlds is its inability to penetrate event horizons: the mathematical formalism does not let us look inside black holes and see what exactly happens to the stored information when they disappear. Holography actually obscures the link between information and spacetime location of the matter embodying it: while in QFT the entropy of regions can be ascribed to local degrees of freedom within the bulk and scales with volume, entropy in the holographic setting scales with area and resides on the boundary in a mysterious nonlocal way. To put it bluntly: where a bit (or qubit) of information "lives" in spacetime becomes a nontrivial issue under those circumstances. But the relation/interdependence of information and spacetime becomes an even greater mystery in the next chapter.



The total system on the CFT boundary with pure quantum state $|\Psi\rangle$ is divided into two parts a and b, so $|\Psi\rangle \in \mathcal{H}_a \otimes \mathcal{H}_b$. While the density matrix of the whole system is $\rho = |\Psi\rangle\langle\Psi|$, the reduced density matrix for subsystem a is given by $\rho_a = \mathrm{Tr}_b(\rho)$, tracing out all degrees of freedom belonging to subsystem b. The entanglement entropy for subsystem a is then computed as $S_a = -\mathrm{Tr}_a(\rho_a \ln \rho_a)$. Amazingly, S_a is related to the area of the minimal surface in the AdS bulk with the same boundary ∂a.

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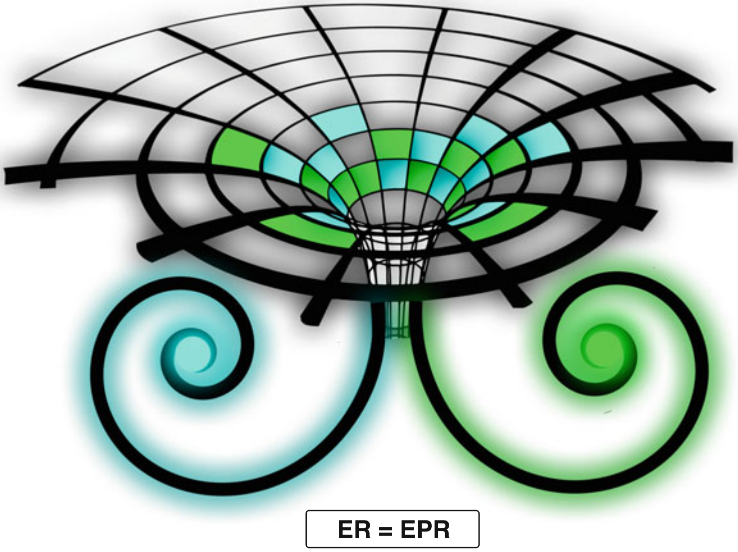
[6] The subscript BH can stand for either Black Holes or Bekenstein-Hawking who derived the formula touching on all areas of physics by using speed of light c from relativity, quantum of action $\hbar$, gravity constant G and thermodynamical constant k.

Quantum Information Approach



Conjecture
Degrees of Freedom inside/outside of Black Holes not independent:
"Quantum Wormholes" link Black Hole Interior and Hawking Radiation

The peace following the settlement of the Black Hole Wars did not last long; a few years ago the fighting recommenced when a blatant contradiction was found in the solution of the winners: the property of entanglement in quantum information casts new doubts about their victory. Entanglement results from non-separability of the entire quantum state into a product of subsystem states and yields nonclassical correlations that strictly adhere to monogamy: maximal entanglement only occurs between two (and not one more) subsystems. But the information war had been supposedly won by an explanation that secretly required the entanglement of late Hawking radiation with both early radiation and modes inside the black hole—one subsystem too many! This forbidden polygamy could be avoided in several ways: one possibility breaks the entanglement between inside and outside, rupturing the smooth vacuum in the vicinity of the horizon and thus creating a highly excited "firewall" state; another proposal is based on the radical view that interior and radiation in the exterior are not really separate systems but rather one and the same. The latter idea is summarized by the slogan ER=EPR: the black hole interior is connected geometrically to the outer radiation it is entangled with—shortcuts in spacetime called wormholes (ER bridges) link the inside modes to their entangled radiation counterparts (EPR pairs). The black hole spacetime would resemble a giant octupus with tentacles reaching far beyond its central body.

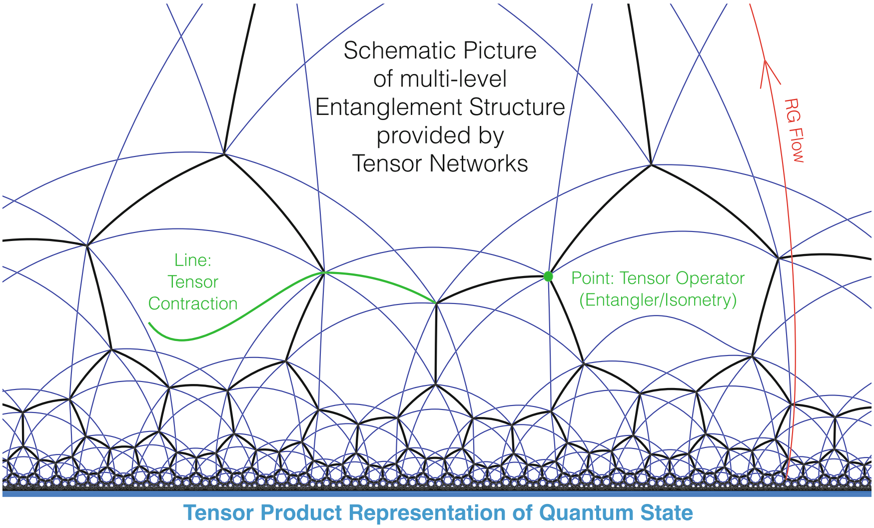
Firewalls, squid tentacles and other proposed deviations from the classical GR picture serve as a reminder that there is no absolute guarantee the smoothness of black hole horizons will survive in QG and the BEC analogon (depending on this innocent assumption) holds any truth regarding their phenomena like Hawking radiation. If the region around black holes fails to be a comparatively calm place, then sonic horizons could not provide any meaningful evidence for QG. The underlying supposition for the validity of reasoning by analogue experiments and subsequent inferences would simply be wrong—and sonic Hawking radition nothing more than a nice sample of sophisticated engineering. On the upside, even in that case CM analogies are still worthwile to pursue for scientific reasons: the *absence* of theoretically deduced phenomena like Hawking radiation in CM experiments would uncover errors committed already in our conventional (pre-QG) thinking; the semiclassical prediction would be ruled out.

The war has lasted for over 40 years now and is still not over: some (rather lone) soldiers insist that information is truly lost and QFT unitarity has to be abandoned, while an increasing number of opponents defend the modification of fundamental GR spacetime. In their view, the notion of a smooth manifold M could be as emergent as entropy arising from even more basic building blocks relevant in the field of Quantum Information: there Entanglement Entropy EE has been a useful measure to quantify the degree of entanglement between subsystems. In the context of AdS/CFT, the subsystems are disjoint regions on the CFT boundary and their EE was found to be given by the area of the corresponding minimal surface in the AdS bulk—in a sense generalizing the area law of black hole entropy. Moreover, decreasing EE of CFT subsystems is synonymous with pulling the respective bulk portions apart. Geometry and EE seem to be deeply connected, so entanglement promises to play a major role for the emergence of spacetime. Disentanglement (EE reduced to zero) results in a split of the AdS bulk—smooth geometries are hooked together by entanglement. In the holographic description, entanglement really is some abstract form of glue that holds spacetime together!

The revolutionary suggestion that the connectedness of spacetime is actually due to entanglement gained further support by the mentioned ER=EPR equivalence: spacetime connections between objects are the geometrical manifestation of their entanglement. In the case of two distant black holes, the entanglement between microstates on either side leads to a wormhole bridging the two (neither entanglement nor wormhole allow superluminal signaling). It is tempting to speculate that once entangled, even elementary quanta are connected by some sort of quantum wormhole. Though not comparable to common spatial connection, this thread would illustrate the geometrical essence of (dis-)entanglement: zipping together (or ripping apart) quantum spacetime.

The striking marriage of quantum information with spacetime suggests that maybe the manifold geometry does not have to be quantized after all, instead QFT and GR seem to be joined in a much deeper fashion than imagined. This has prompted researchers to analyse how exactly entanglement is shaping spacetime and even create "space from Hilbert space", trying to derive geometric notions such as distance from measures like EE in the abstract space of quantum states. Preliminary results look promising and the whole “emergent geometry” program has become increasingly popular. Parallels have also been drawn between the action A of spacetime regions and the quantum complexity C of holographic states ($C = A/\pi\hbar$). While in thermal equilibrium the entropy is maximized, the computational complexity continues to increase for a much longer time—corresponding to growth of the spacetime volume. On the whole, it seems obvious that concepts from quantum information and complexity theory will play a principal role in the construction of spacetime.

This is why the nascent discipline of quantum computing could be useful even for spacetime phenomenology: universal quantum simulators might one day serve as the substrate for testing spacetime models based on information theoretic notions. One concrete example are protocols in quantum error correction that provide a better understanding of how CFT holograms could encode all the details about the enclosed spacetime. Tensor networks well-known in CM have proven to be successful in this endeavour: in so-called MERA networks, the coarse-graining of quantum states (written as a product of tensors) gives rise to an intricate web that structurally resembles AdS geometry. Quantum simulation would shed light on the distribution of entanglement and assist in unlocking the secrets of quantum spacetime.



Quantum Topology

A final QG theory should have the required background-independence built in: the precise spacetime geometry would not be explicitly chosen, but rather follow from equations that themselves are invariant under diffeomorphisms. There is a special class of QFT that is indeed entirely insensitive to the shape of spacetime and therefore a promising starting point for QG research: Topological QFT (short TQFT) lack any way of “sensing” the spacetime metric—so a spacetime manifold can be continuously deformed into another without changing the fundamental laws. TQFT is blind to notions contained in the metric g (such as distance or angles) because it does not depend on g at all, which has profound consequences: all of the states of a topological system have zero[7] energy, so they are all (degenerate) ground states! Because of diffeomorphism invariance, local operators (such as environment perturbations) must be proportional to the identity—they cannot enact non-trivial transformations within the ground state space. TQFT allows to assign quantum amplitudes to geometrical objects like knots or other manifolds, relying heavily on very abstract math structures such as categories and cobordisms.

The peculiar properties of TQFT have generated tremendous interest in the CM community following the discovery of topological phases: while all previously known phases could be classified by the usual symmetry breaking paradigm, the newfound Quantum Hall effect provided the first example with no spontaneously broken symmetry. TQFT has opened up a new window on CM: not the specific geometry, but the topological order separates those “exotic” states of matter—revealing a much richer diversity of quantum materials than indicated by symmetry groups alone. Global properties of the topology can be computed as topological defects/invariants that identify distinct phases. These methods have become a new cornerstone of CM physics, culminating in the Nobel Prize 2016 and giving hope for exciting novel[8] applications.

Quantum matter as a trending research field could also provide yet another avenue for insights into the structure of spacetime: topological superconductors and other CM systems described by TQFT may exhibit emergent supersymmetry. An extension (in some sense the square root) of the Poincaré symmetry group of spacetime, supersymmetry SUSY interchanges bosonic and fermionic fields and is proposed in HEP due to potential benefits like unification of couplings. While many theorists see compelling reasons for SUSY to be realized in nature, it still awaits experimental verification. There has been no sign of supersymmetric particles at the Large Hadron Collider LHC and major parts of the parameter space originally considered at the conception of SUSY have been ruled out. But quantum phase transitions in lower dimensions at the boundary of topological superconductors were reported to display

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[7] The Hamiltonian H vanishes because the energy-momentum tensor $T^{\mu\nu} \propto \delta S/\delta g_{\mu\nu}$ is obtained by the variation of the action $S := \int dt \mathcal{L}$ (with topological Lagrangian density $\mathcal{L}$) with respect to g, so $H = T^{00} = 0$—leading to a significant degeneracy.

[8] One of those being topological quantum computing: since local perturbations do not transform between the multiple ground states, decoherence is much easier to avoid. The only unwanted effect of the environment could be exciting the system to such high energies (surpassing an energy gap $\triangle$) that it is no longer invariant under diffeomorphisms and TQFT does not apply anymore, but this possibility is suppressed exponentially with the energy gap ($e^{-\triangle/T}$, though the necessary excitation gap is not sufficient for the formation of a topological phase). The information is distributed among decentralized quasiparticles (Majorana zero modes are the leading candidates for those qubits) and computations are performed as operations in a non-local manner. Topological invariance does not imply trivial low-energy physics, as exemplified by the fractional statistics of anyons.

emergent SUSY at a critical point. This low-energy observation may provide clues for how and where SUSY appears. Interestingly, spontaneous SUSY breaking could actually be responsible for the topological state—hinting at a very deep relation between SUSY and TQFT. Understanding this mechanism in precise mathematical terms may pave the way for its implementation in QG theory and the CM analog of SUSY constitutes an alternative for experimentalists to test specific supersymmetric models and their consequences in tabletop systems. Once again one can hope to learn more about spacetime via this sort of phenomenology by analogy.

Outlook

While the "nightmare scenario" for particle physics with no new detections at the LHC seems more likely by the day and direct QG tests continue to be quite tricky, it was tried to make the case for a different kind of experiments conducted in the fields of CM and quantum computing/simulation. New materials expand the catalog of suitable analogue models, one of the most interesting cases being graphene: sheet curvature could elevate the Dirac equation to its curved version in order to probe a wide range of spacetimes and emergent massless spinor fields with modified propagation speeds could help to investigate ultra-relativistic phenomena. Moreover, theoretical QG research suggests that black holes are condensates (of gravitons) themselves and the fastest quantum computers possible—unifying all three aspects of this essay: spacetime, condensed matter and quantum information.

As viable options besides additional colliders and projects in astrophysics, analogies provide a huge opportunity for phenomenology. Instead of looking into the vast sky or gigantic accelerator tunnels, some lucky scientist might just as well stumble upon the next breakthrough for spacetime ontology in a tiny lab.

Experimental Search for Quantum Gravity Using Cosmology

Manon Bischoff and Vincent Vennin

There are four known fundamental forces in physics: the gravitational, the electromagnetic, the weak and the strong force. Three of the four forces have successfully been quantized and unified in a theory called the standard model. The standard model describes the fundamental particles known to us, like the electron, the photon and the quarks. All other known particles appearing are composed out of elementary particles. For example a proton consists of three quarks, one up and two down quarks. The standard model is described by quantum field theory. In this framework the elementary particles are described by quantum fields with a certain expectation value. The fields can fluctuate due to quantum effects. Furthermore, the fundamental forces are mediated by elementary particles (for example the photon in the case of electromagnetism).

The standard model has been tested by various experiments, which all confirmed the validity of its predictions. The only fundamental force that does not fit into this model is gravity. In 1915, with his work about general relativity, Albert Einstein linked gravity to the geometry of space and time. He showed that the gravitational force arises due to the curvature of spacetime. Particles of the standard model, with their associated energy and pressure, lead to a curvature of spacetime. One uses a mathematical quantity called metric that parametrizes spacetime. Also classical general relativity has been successfully tested experimentally (Fig. 1).

The standard model and classical general relativity seem to describe the world correctly. But the two theories are conflicting, since general relativity treats classical objects, as we know them from everyday life, and the standard model treats quantum objects. Quantum objects behave very differently than classical objects.

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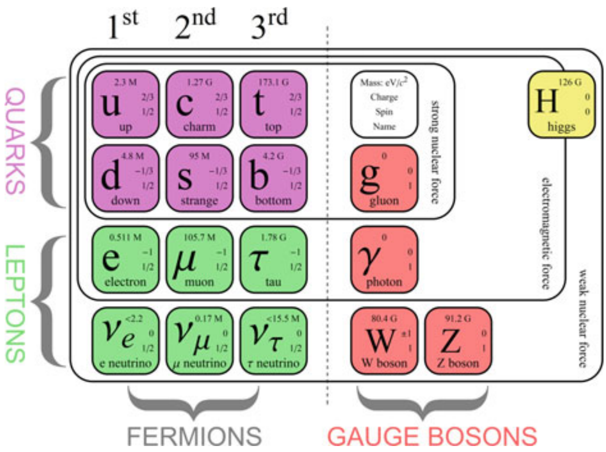

Fig. 1 The standard model of particle physics with its elementary particles. The fermions are the particles characterizing matter and the gauge bosons mediate the forces. Reference: http://www.physik.uzh.ch/groups/serra/StandardModel.html

For example, a macroscopic object like a ball can be located only at one place at a time. A microscopic object like an electron can be in a quantum superposition, where it is located at several distinct locations at the same time. But why bring those two different theories together?

First, the Einstein equation, which connects the energy and pressure of the particles of the standard model with the curvature (metric) of spacetime is inconsistent, since one part of the equation is quantum (the one describing the particles of the standard model), while the other part of the equation (describing the spacetime metric) is classical. Furthermore there are still open questions in physics, which could not be answered yet having two separate theories. For example: What is the gravitational field of a microscopic particle in a quantum superposition? How do quantum particles behave when gravity becomes relevant? How do quantum fields behave close to a black hole horizon? In the Big Bang model of cosmology, the universe reaches very high energy densities at early time, how do gravity and quantum fields behave in such a regime? If one takes the framework of quantum field theory seriously, one should expect gravity to be described by a quantum field theory as well.

Quantizing gravity results in quantizing the spacetime. This would mean that space and time are described by quantum fields, which can fluctuate. This is a hard theoretical task, but a naive quantization of gravity has been done. The problem is that the resulting theory is not meaningful. There are lots of theories trying to formulate a mathematically consistent theory of quantum gravity, for example string theory, loop quantum gravity, asymptotically safe gravity, etc. However the resulting theories are often challenging to describe in a mathematically consistent framework. Since it is also very difficult to calculate actual predictions within their framework, their falsifiability and testability is still questionable at this stage.

As has been pointed out before, a quantum field theory implies that the force is mediated by an elementary particle. One such mediating particle for gravity (if a quantum field theory of gravity would exist) is the graviton. A direct way to prove that gravity is quantized, would be to detect the graviton in the lab. In order to detect a graviton (like measuring the particles in the LHC), one would need a collider as big as the milky way. A direct experimental test of quantum gravity is out of our scope at the moment. So we have to search for indirect quantum gravitational effects.

Therefore we need to know where we expect quantum gravitational effects to take place. In our everyday life, we do not notice any quantum gravitational effects. At the LHC, the standard model is tested constantly, hoping to find new particles, which might lead to new physics. Up to now, nothing has been found contradicting the standard model. We expect quantum gravitational effects to play a role when a large amount of matter is confined to a small amount of space (since the gravitational force is coupling to mass, which is equivalent to energy). Such conditions are present in black holes. Black holes are still not fully understood. There is a mismatching when describing them classically and quantum mechanically. A reason for that might be the lack of having a theory of quantum gravity. Another case in which large amounts of matter were confined to a small amount of space was during the big bang and in the early universe.

The two presented scenarios including dense matter arise in astrophysics and cosmology, which therefore seem to be an ideal playground for detecting quantum gravitational effects. For example, one could assume that a theory of quantum gravity does not preserve the same symmetries (e.g. Lorentz invariance), as the one present in the formalism of classical general relativity formulated by Einstein. Assuming this, one can compute the impact this fact has on accessible observables, like the speed of light. Some of the scenarios where Lorentz invariance is violated by quantum gravity would imply that the speed of light is not constant. One can compare this theoretical result with different precision experiments on the speed of light and check if there are some fluctuations. So far, nothing has been found in this direction. A theory of quantum gravity seems to preserve the symmetries of general relativity.

Another method to investigate possible quantum gravitational effects is the study of the cosmic microwave background (CMB). The CMB is thermal radiation left over from the time when atoms were first formed in the universe out of protons and electrons (approximatively 378.000 years after the big bang). Following the classical theory of general relativity and assuming homogenous initial conditions, the expansion of the universe after the big bang was homogeneous and so the CMB should be isotropic. Nevertheless, there are small anisotropies in the CMB, of the order of $\approx 10^{-4}$ of amplitude (Fig. 2).

Those anisotropies can be described by cosmological models involving quantum fluctuations of the spacetime metric. Thereby, the spacetime metric is treated as that of a classical flat spacetime. So, one assumes a flat spacetime with small perturbations, which are generated from quantum fluctuations. Those perturbations from flat spacetime are treated as quantum fields. This is a semiclassical description, since the underlying spacetime metric is still classical in the sense of general relativity and only the perturbations are described quantum mechanically.

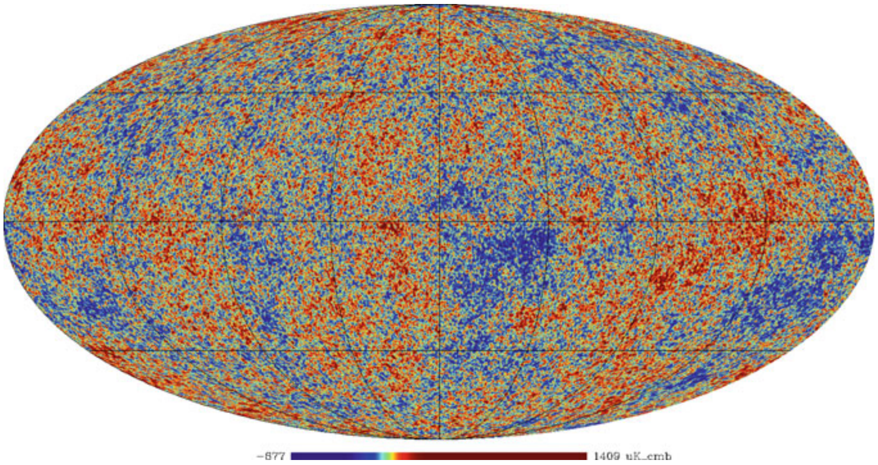

Fig. 2 The cosmic microwave background. The different colors stand for the fluctuations in the temperature. The CMB is not isotropic, as expected when quantizing linear perturbations around classizcal general relativity. Reference: http://dx.doi.org/10.1051/0004-6361/201527101

Those cosmological models can be compared to the experimental data of the CMB. Since the models combine general relativity and quantum mechanics, this leads to some insight about a possible quantum gravitational theory.

For about 80 years physicists have been looking for a theory of quantum gravity. There are lots of candidates with different assumptions, all suffering from different problems. In order to be able to determine which assumptions are correct and lead to a suitable theory, one should not only pay attention to mathematical rigorousness. A theory needs to be verifiable and falsifiable, and therefore one needs experiments to compare to. This is what makes quantum gravity phenomenology such an important field in physics.

The Cosmological Constant and Its Problems: A Review of Gravitational Aether

Michael Florian Wondrak

Abstract This essay focuses on the gravitational aether scenario which extends the well tested Einstein's theory of relativity to capture effects of the quantum regime in an effective thermodynamic manner. Quantization of gravity usually faces several issues including an unexpected high vacuum energy density caused by quantum fluctuations. The theory reviewed in this paper cures those so-called cosmological constant problems. As its name suggests, the gravitational aether introduces preferred reference frames, while staying compatible with the general theory of relativity. As a rare feature among quantum gravity inspired theories, it can predict measurable astronomical and cosmological effects. Observational data disfavor the gravitational aether scenario at 2.6–5σ. This experimental feedback gives rise to possible refinements of the theory.

Introduction

Probably everyone of us has experienced the benefits of satellite-based navigation systems, e.g. in route guidance systems for cars. The incredible accuracy to determine one's position is only enabled by consideration of the effects of general relativity. In everyday life this is an omnipresent evidence for the performance of Einstein's theory. Nevertheless, this theory is classical and could not yet be merged with quantum theory. This is important since quantum fluctuations may determine the expansion behavior of the universe. The gravitational aether is a phenomenological concept to effectively address this issue as an ubiquitous field interacting with ordinary matter. In this essay we want to examine the gravitational aether scenario as a testable theory inspired by quantum gravity.

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We begin with a short recap of the standard model of cosmology in Sect. "Einstein and the Cosmological Constant" before we focus on the cosmological constant and its problems in Sect. "Cosmological Constant Problems". Section "Gravitational Aether Scenario" introduces the gravitational aether concept and its repercussions on the cosmological constant problems. Section "Experimental Tests" is devoted to testable predictions of this theory, to comparison with observational data, and to possible improvements. We draw our conclusions in Sect. "Summary and Outlook".

Einstein and the Cosmological Constant

The revolutionary idea behind the general theory of relativity (GR) is to encode gravity in the geometry of the universe, more precisely, in its metric tensor $g_{\mu\nu}$ which serves as a local ruler telling us about deformations of space and time. The geometry is determined by the distribution of matter, or more generally, by the distribution of energy but specifies the evolution of matter in return. This interplay manifests itself in the so-called Einstein field equations which date back to 1915,

$$G_{\mu\nu} + \Lambda_{\mathrm{b}}\, g_{\mu\nu} = \frac{8\pi\, G_{\mathrm{N}}}{c^4}\, T_{\mu\nu}. \tag{1}$$

The Einstein tensor $G_{\mu\nu}$ is a function of $g_{\mu\nu}$ and represents the geometric part while the energy-momentum tensor $T_{\mu\nu}$ encodes information about the energy distribution. μ and ν denote the respective tensor components. Λ_{b} is the so-called bare cosmological constant, G_{N} denotes the gravitational constant, and c stands for the speed of light which we will set to unity, $c \equiv 1$, following the high-energy physics convention.

We can apply the Einstein field equations to describe the evolution of the universe as a whole. This is subject to cosmology. Already in 1924 Alexander Friedmann derived evolution equations of the universe's scale factor which allow a variety of different scenarios: forever expanding, static, or collapsing universes with open (negatively curved), flat or closed (positively curved) geometries. Einstein believed in a static spacetime and introduced the cosmological constant to compensate the attractive forces of matter. Investigating the relation between redshifts and distances of galaxies, Edwin Hubble concluded in 1929 that our universe is expanding. This contradiction to his original assumption caused Einstein to call his insertion the biggest blunder of his life, as is reported by George Gamow [1].

By now, new sources of cosmological information have been tapped, most prominently the cosmic microwave background radiation (CMB), baryon acoustic oscillations (BAO), and standard candles, i.e. cosmic objects or events like supernova Ia explosions (SNe) whose distance from us can be measured very precisely. In the future, gravitational wave (GW) observations could extend this spectrum. In 1998 SNe observations indicated that the expansion of the universe nowadays is even accelerated [2, 3].

According to the standard model of cosmology, the ΛCDM model, we suppose that the universe has formed in a hot big bang about 13.8 billion years ago. Shortly after its formation it underwent a phase of very fast expansion (inflation phase) which wiped out inhomogeneities leaving us with a nearly flat spacetime. The temperature of the universe decreased as it expanded. At first, radiation was the dominant constituent, followed by non-relativistic matter and finally by dark energy which is responsible for the accelerated expansion. The name ΛCDM is composed of Λ which stands for the cosmological constant as a specific type of dark energy and CDM denoting cold dark matter. Together with the ordinary so-called baryonic matter the latter builds up non-relativistic matter.

In order to proof that the cosmological constant Λ_b can lead to an accelerated expansion, we have a look at the second Friedmann equation,

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_\mathrm{N}}{3} \sum_j \left(\rho_j + 3p_j\right) + \frac{\Lambda_\mathrm{b}}{3}. \tag{2}$$

Here the acceleration $\ddot{a}$ of the universe's scale factor a is determined by the energy densities ρ_j and pressure contributions p_j of the different matter components j present. The implication of a positive Λ_b is to support an accelerated expansion, $\ddot{a} > 0$, and finally to cause an exponential growth. (For the experts: The matter components are modeled as perfect fluids which differ in their equations of state $w = p/\rho$: for radiation $w = 1/3$ and for non-relativistic matter $w = 0$.)

Cosmological Constant Problems

General relativity is a classical theory in the sense that it is not quantized and so the Einstein field equations perform primely for classical matter fields. But we know well that matter fields are of quantized nature which implies that there is a persisting non-vanishing energy density even in the vacuum state, i.e. if no particle is present. This vacuum energy density ρ_vac has the same value at every instance of spacetime and its energy-momentum tensor is of perfect-fluid type [4, 5]

$$T_{\mathrm{vac},\,\mu\nu} \equiv -\rho_\mathrm{vac}\, g_{\mu\nu}. \tag{3}$$

In the spirit of GR, $T_{\mathrm{vac},\,\mu\nu}$ is supposed to contribute to the total energy-momentum tensor $T_{\mu\nu}$ on the right-hand side of the Einstein field equations (1) and thus to have an impact on spacetime geometry. Since it has the same structure as the term for the cosmological constant Λ_b in the Einstein field equations, both lead to the same phenomena. They can be merged to yield the effective cosmological constant

$$\Lambda_\mathrm{eff} \equiv \Lambda_\mathrm{b} + 8\pi G_\mathrm{N}\, \rho_\mathrm{vac}. \tag{4}$$

In principle, for an accurate determination of ρ_{vac} one should take into account the fundamental nature of spacetime which is expected to be quantized—thus one would need a theory of quantum gravity. Since such a theory is not yet available, we can employ semiclassical gravity. We assume a classical curved spacetime within which we define quantum fields. Those in return influence the spacetime geometry according to the Einstein field equations. For details we refer the willing reader to [6, 7]. As theoretical result we obtain

$$\rho_{\text{vac}} = \sum_i (-1)^{2s_i}\, n_i\, \frac{m_i^4}{64\pi^2}\, \ln\left(\frac{m_i^2}{\mu^2}\right) \tag{5}$$

up to possible contributions from phase transitions in the early universe. Here the sum runs over all fundamental quantum fields in the standard model of particle physics. They contribute according to their mass m_i, spin s_i, and number n_i of degrees of freedom. μ is the renormalisation energy scale. Following [8], μ can be related to the photons from SNe observations which are used to experimentally determine the cosmological constant. With $\mu \approx 3 \times 10^{-25}$ GeV we find

$$\rho_{\text{vac}} \approx -2 \times 10^8\,\text{GeV}^4 \approx -5 \times 10^{28}\,\frac{\text{kg}}{\text{m}^3} \approx -2 \times 10^{11}\,\rho_{\text{nucl}} \tag{6}$$

The absolute value of the vacuum energy density is thus expected to be 11 orders of magnitude higher than the density ρ_{nucl} of atomic nuclei and, roughly, neutron stars. This is remarkable because the energy density of neutron stars is believed to be the largest stable one before a collapse to a black hole. This obvious strong conflict with measurements is referred to as the so-called *old cosmological constant problem* [9]. This is illustrated in Fig. 1. In the past, physicists assumed that ρ_{vac} would be exactly compensated by Λ_{b} due to an unknown symmetry which would lead to a vanishing effective cosmological constant Λ_{eff}.

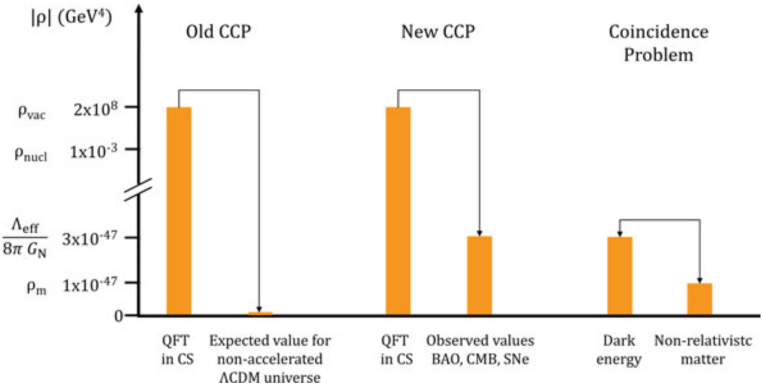

Fig. 1 Illustration of the cosmological constant problems (CCP)

As mentioned above, modern cosmological observations support the idea an accelerated universe and thus a non-vanishing effective gravitational constant Λ_{eff} [10]:

$$\frac{\Lambda_{\text{eff}}}{8\pi G_{\text{N}}} \approx 2.6 \times 10^{-47}\,\text{GeV}^4 \approx 26\,\text{meV}^4 \approx 6.0 \times 10^{-27}\,\frac{\text{kg}}{\text{m}^3} \tag{7}$$

whose energy scale is on the lower side of the standard model particles and similar to the estimated neutrino mass m_ν. Being 55 orders of magnitude smaller than ρ_{vac}, the only possibility to consistently relate the theoretical and the experimental value is to choose Λ_{b} with a high accuracy. This enormous fine-tuning—the first 55 decimal digits of Λ_{b} have to match exactly—constitutes the *new cosmological constant problem*.

The cosmological constant is even more puzzling: While other kinds of matter dilute during the universe's expansion, the vacuum energy density remains constant so that it finally becomes the dominant component. Today, Λ_{eff} is already the dominant contribution and accounts for about 70% of the total energy density. However, it is almost of the same order as non-relativistic matter which contributes to nearly 30% [10]. Although these fractions may vary over a wide range of magnitudes according to the ΛCDM model, the question why we observe a ratio close to unity is coined the *coincidence problem*. It could be a hint towards the idea of the so-called backreaction which hypothesizes that structure formation in the universe, i.e. matter accumulation into galaxies and galaxy clusters, could cause the cosmic acceleration.

In addition, the authors of [11] recently pointed out the possibility of a further problem stemming from fluctuations in the vacuum energy density. In contrast to the old cosmological constant problem, here the correlations of the energy-momentum tensor at different spacetime events lead to an additional non-vanishing energy contribution in the vacuum. This problem is dubbed the *cosmological non-constant problem*.

Gravitational Aether Scenario

There are several attempts to address the cosmological constant problems in literature, especially by modifying the Einstein field equations either on the matter side (e.g. by introducing a new scalar field in quintessence and k-essence models to explain the accelerated expansion) or on the geometric side (e.g. by changing the gravitational interaction in $f(R)$ gravity and scalar-tensor theories as well as other mechanisms [12, 13]). A detailed treatment is given e.g. in the book [14]. A particular elegant idea to phenomenologically solve the old cosmological constant problem has been suggested in [15]: the gravitational aether scenario (GA) which belongs to the matter-modifying theories.

The basic idea is to decouple the vacuum energy from the universe's geometry. For this purpose an additional term is inserted only on the matter side of the Einstein field equations which exactly cancels the vacuum contribution. Because of the special form of the vacuum energy-momentum tensor (3), the correcting term up to classical contributions can be isolated by using the trace of the ordinary energy momentum tensor $T_{\mu\nu}$, $T_\alpha{}^\alpha = 4\rho_{\text{vac}} + T_{\text{class}\,\alpha}{}^\alpha$. Therefore $\frac{1}{4}\,T_\alpha{}^\alpha\,g_{\mu\nu}$ is subtracted.

However, on the one hand we require that there is neither a source nor a drain for energy or momentum, they are supposed to be conserved. On the other hand we want the Einstein tensor to be compatible with the Bianchi identities, i.e. we want a torsion-free spacetime. These demands are expressed mathematically as the vanishing covariant divergences of $T_{\mu\nu}$ and $G_{\mu\nu}$. Both of them cannot be met at the same time until we introduce a second term on the right hand side of the Einstein field equations: $T'_{\mu\nu}$. We interpret it as the energy-momentum tensor of the so-called gravitational aether. The Einstein field equations of GA now read

$$G_{\mu\nu} = 8\pi\,G'\left(T_{\mu\nu} - \frac{1}{4}\,T_\alpha{}^\alpha\,g_{\mu\nu} + T'_{\mu\nu}\right). \tag{8}$$

This extension of GR is the most general one which complies with local covariance, linearity in the energy-momentum tensor, and elimination of vacuum energy influence. G' in (8) is treated as the fundamental gravitational constant in contrast to G_{N} in the ordinary Einstein field equations (1).

The equation which causes the need to introduce the gravitational aether determines at the same time how it couples to conventional matter,

$$\nabla_\nu\,T'^{\,\nu}_{\mu} = \frac{1}{4}\,\nabla_\mu\,T_\alpha{}^\alpha. \tag{9}$$

Thus the gravitational aether's energy and momentum are not conserved, but sourced by ordinary (non-relativistic) matter. However, this equation leaves open which kind of matter the gravitational aether consists of. Afshordi chose the gravitational aether to be a perfect fluid just like the usually considered types of cosmological matter. It possesses a pressure p' and an energy density p'/ω' where ω' is called the equation of state parameter.

This modified theory of gravity alters the history of the universe. Conclusions on the duration of the radiation-dominated era from big bang nucleosynthesis and light elements' abundances, cosmic microwave background signatures, and implications on the expansion behavior by redshift observations favor large values of ω'. From now on we assume $\omega' \to \infty$. This case describes an incompressible fluid of constant (vanishing) energy density, but non-zero pressure p'. This limit is named the cuscuton fluid because it is the thermodynamic analog of the cuscuton field [15–17] which stands for a family of k-essence scalar fields. The cuscuton field exhibits remarkable properties: First, even though in general it has a non-vanishing momentum field it is always possible to find a coordinate system in which the volume element of the phase space vanishes. This means that there is no local dynamics and the local entropy is zero. Thus the introduction of a cuscuton field into a theory does not alter the number of the system's degrees of freedom. This aesthetic feature makes it particularly appealing since it is common sense that a theory can solve any problem if it just has enough parameters. In this way theories should be designed to contain as few degrees of freedom as possible (cf. Ockham's razor). Second, as a consequence of the lacking local dynamics, causality is not violated in spite of the infinite speed of sound. Third, in the absence of own dynamics the cuscuton field follows the fields to which it couples. This tracking behavior is the reason for its name: Dodder, scientifically cuscuta, is a parasitic plant.

The parasitic property of the gravitational aether in the cuscuton limit simplifies the modified Einstein equations (8). They can be expressed in the original form (1) which only contains the ordinary matter if we replace the gravitational constant G_{N} by an effective gravitational constant G_{eff}. For the moment, we assume that there is only one type of matter with equation of state parameter w present and we disregard the bare gravitational constant Λ_{b}. G_{eff} solves the old cosmological constant problem since it already decouples the vacuum energy density. It is defined by

$$G_{\mathrm{eff}}(w) = \frac{3}{4}\ (1+w)\ G'. \tag{10}$$

As a consequence, the effective gravitational constant changes in time according to the dominant type of matter. During the radiation-dominated epoch we find $G_{\mathrm{R}} \equiv G_{\mathrm{eff}}(w = 1/3) = G'$, while the effective gravitational constant in the matter-dominated epoch reads $G_{\mathrm{N}} \equiv G_{\mathrm{eff}}(w = 0) = 3G'/4$ and is identified with the Newtonian gravitational constant G_{N} measured today.

Before we go on to discuss the gravitational aether scenario we ask ourselves why we call this type of matter aether. Aether originally denoted a fixed medium penetrating the whole universe which allowed light to propagate like acoustic waves spread e.g. in water. Therefore it predicted that observers in relative motion to this so-called luminiferous aether measured a different speed of light— in conflict with experiments like that of Michelson and Morley. The theory of special relativity states that there is no omnipresent fluid to carry light waves. Yet the aether concept returned: According to [18] it distinguishes a preferred reference frame, in which it is at rest. In other words, aether refers to a dynamical background field which violates local Lorentz covariance. General covariance is nevertheless not affected because the system's dynamics is independent of the coordinates and the aether is a dynamical field, so that the theory is in line with general relativity [19].

Although the gravitational aether concept was designed to solve the old cosmological constant problem, it is also capable of addressing the new cosmological constant problem [20]. Let's assume a scenario comprising a spherically symmetric black hole in which all conventional matter is confined, while gravitational aether distributes over the whole spacetime. Then this gravitational aether enhanced black hole (GABH) solution of the modified Einstein equations (8) is similar to the Schwarzschild black hole being the standard one in the ordinary theory.

In contrast however, the new black hole description shows a diverging behavior in the time component of the metric in the vicinity of the horizon and at infinite distance, corresponding to high and low energies, UV and IR, respectively. This deviation is caused by the pressure $p(r)$ of the gravitational aether, whose value scales with the integration constant p_0. For $p_0 = 0$, the solution reproduces the well known Schwarzschild case. Further investigation reveals that the event horizon lies at a larger radius than the Schwarzschild radius $r_S = 2G_N\, m$ where m denotes its mass. Furthermore, we encounter the curvature singularity not in the black hole's center, but at the event horizon. This geometry reminds of fuzzballs, a black hole concept inspired by string theory in which matter in form of strings extends to the event horizon and no curvature singularity occurs in its center [21, 22].

The gravitational aether black hole spacetime is capable of mimicking the current cosmological acceleration. For large distances the time component of the metric resembles a de Sitter universe, i.e. a flat spacetime which undergoes an exponential acceleration as in the Λ-dominated universe. Comparing the weak field limits, we obtain a relation between the dark energy density ρ_Λ and p_0, $p_0 = -\frac{2}{3}\, \rho_\Lambda$. Since the integration constant p_0 relates this far distance behavior directly with the behavior close to the event horizon, it can be used to adjust the black hole's properties. It is generally assumed that our current descriptions break down at last when quantities reach the Planck scale. For these regimes, quantum gravity is needed which e.g. could give rise to fuzzballs. Thus the authors of [20] conjecture that the highest possible temperature $T_{\max}$ in a local rest frame is of the order of the Planck temperature T_P, $T_{\max} = \theta_P\, T_P$, where θ_P is the so-called Trans-Planckian parameter. Comparing this maximum temperature with the Hawking temperature of black hole evaporation relates p_0 with the black hole's mass m. Finally, we find

$$m \simeq 85\, \theta_P^{-1/3}\, M_\odot \tag{11}$$

where $M_\odot$ denotes the solar mass. Thus if we lived in a gravitational aether universe with a black hole of the type discussed above, we would perceive an accelerated expansion away from the black hole. If in addition the black hole had a mass m of around 85 times the mass of the sun, this acceleration would match with cosmological observations and thus would solve the new cosmological constant problem. This description can be extended to include multiple black holes or rotating ones.

The distance between the Schwarzschild and the GABH event horizon is of the order of a Planck length $l_P \approx 1.6 \times 10^{-35}$ m. It was hypothesized in [23, 24] that a gravitational wave signal could be reflected several times by Planckian structures near the horizon leading to a series of echoes. This could offer the possibility for experimental tests of the quantum nature of black holes in the future.

So far we have dealt with the old and new cosmological constant problems. Matter aggregation is a key to black hole formation which in turn leads to an accelerated expansion of the universe. This backreaction mechanism would be a natural solution of the coincidence problem, too.

However, in spite of the elegance of the GABH solution open questions remain [20]. Among them are the following: There could be substantially smaller black holes, e.g. as a result of primordial fluctuations in the early universe. They would possess much higher Hawking temperatures leading to substantially increased pressures and cosmic accelerations being inconsistent with observations. Another issue is whether a real black hole formation can create the required gravitational aether distribution.

Experimental Tests

As we have seen in (10), the effective gravitational constant depends on the dominant type of matter via the equation of state parameter $w = p/\rho$ and thus differs between the radiation- and the matter-dominated era. Deviations from Einstein's general theory of relativity like this pressure dependence are cast in the so-called parametrized post Newtonian (PPN) formalism. Applying this formalism to the gravitational aether reveals that the only non-vanishing parameter is

$$\zeta_4 = \frac{G_\mathrm{R} - G_\mathrm{N}}{G_\mathrm{N}} = \frac{1}{3}. \tag{12}$$

Thus the gravitational aether theory makes predictions which can be tested by observations of e.g. systems with relativistic pressure or fast rotations [25, 26]. In this way, experimental constraints on ζ_4 can be obtained by investigating the structure of compact objects like neutron stars. However, the existing equations of state for neutron stars are yet not precise enough to allow constraining ζ_4 from observed data. Further objects to test ζ_4 could be hot accretion disks of black holes and compact remnants of supernova explosions. Focusing on the cosmological side, bounds on ζ_4 can be derived from chemical element abundances due to big bang nucleosynthesis (BBN), from the cosmic microwave background radiation (CMB), or from investigations of the intergalactic matter distribution via redshifted Ly-α absorption lines (Ly-α forest). Resulting values of ζ_4 are displayed in Fig. 2. It clearly shows that the gravitational aether scenario is disfavored against Einstein's general relativity by 2.6–5σ [26].

Facing this difference with experimental results, one may look for modifications of the theory. According to [26] the gravitational aether scenario could be improved in the following ways: Above, gravitational aether has been treated as a classical thermodynamic fluid. This effective description is only valid below a certain energy scale, i.e. it breaks down below a characteristic distance. In this picture, every particle is surrounded by a small aether halo of the order of the cut-off length $\lambda_\mathrm{c} \sim 0.1$ mm. This is comparable with the average baryon distance at the time of the CMB emission, which lies around 1.5 mm [26]. Another approach is to keep the thermodynamic aether description, but to change its equation of state. For example one can stay with a perfect fluid, but having a non-vanishing energy density. Furthermore, the theory could be extended to include the special role of neutrinos: Due to their small mass they behaved as radiation in the early universe and did not give rise to gravitational aether. Today, however they are non-relativistic and source gravitational aether.

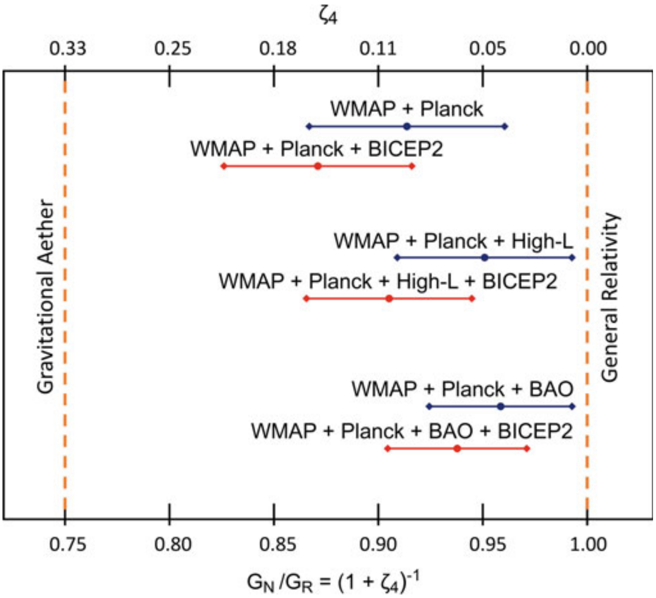

Fig. 2 Experimental constraints on the PPN parameter ζ_4 including 1σ error bars using baryonic acoustic oscillations (BAO), polarization of the CMB (BICEP2), high multipoles of the CMB power spectrum (High-L), CMB temperature anisotropies (Planck), and large angle polarization data of CMB (WMAP). Picture adapted from [26]

Summary and Outlook

We have seen that the cosmological constant is of interdisciplinary character since it is connected with the fundamental concepts of general relativity, quantum field theory, and cosmology. The gravitational aether scenario is an extension of Einstein's general theory of relativity in order to decouple the vacuum energy without introducing new degrees of freedom. It offers a possible way to solve the old, but also the new cosmological constant problem and the coincidence problem. As a special characteristic, this phenomenological theory predicts testable effects in different observable systems. In its present form it is excluded at 2.6–5σ by observations. Such feedback can be used to develop a refined concept.

The observed acceleration of the universe's expansion is one of the few possible candidates for an experimentally accessible manifestation of quantum gravity. The cosmological constant problems remain unresolved. This offers space for new self-consistent developments in the future. The gravitational aether scenario shows a particularly distinct ansatz in the variety of ideas.

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