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

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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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S. Hossenfelder (ed.), *Experimental Search for Quantum Gravity*,
FIAS Interdisciplinary Science Series, https://doi.org/10.1007/978-3-319-64537-7_2

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.

Acknowledgements We thank Claus Kiefer for collaboration on the subject under discussion in this essay and for comments on the manuscript. D.B. acknowledges financial support from project FIS2014-57956- P of the Spanish Ministry of Economy and Competitiveness and from project IT956-16 of the Basque Government. The research of M.K. was financed by the Polish National Science Center Grant DEC-2012/06/A/ST2/00395.

References

1. Starobinsky, A.A.: Phys. Lett. B **91**, 99 (1980) (Guth, A.H.: Phys. Rev. D **23**, 347 (1981))
2. deWitt, B.S.: Phys. Rev. **160**, 1113 (1967) Wheeler, J.A.: Battelle rencontres, DeWitt, C.M., Wheeler, J.A. (eds.) pp. 242, Benjamin, New York (1968)
3. Kiefer, C., Singh, T.P.: Phys. Rev. D **44**, 1067 (1991)
4. Brizuela, D., Kiefer, C., Krämer, M.: Phys. Rev. D **94**, 123527 (2016). (Bini, D., Esposito, G., Kiefer, C., Krämer, M., Pessina, F.: Phys. Rev. D **87** (2013), Kiefer, C., Krämer, M.: Phys. Rev. Lett. **108**, 021301 (2012))

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http://www.springer.com/978-3-319-64536-0

Experimental Search for Quantum Gravity
Hossenfelder, S. (Ed.)
2018, VIII, 120 p. 24 illus., 19 illus. in color., Hardcover
ISBN: 978-3-319-64536-0