Light from Darkness

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For the coming centenary of general relativity, this article is devoted to great puzzles about gravity. In cosmology we are puzzled by unknown sources of gravitation, generally called dark energy and dark matter, which contribute 95% of the energy of the present universe. Even more vital in fundamental physics is the conflict between knowns: general relativity and quantum physics, i.e. between two revolutions in physics of the 20th century. This article elaborates how the greatest unknown in cosmology illuminates the most important problem in fundamental physics.

1. Introduction

The centenary of general relativity (GR) [1–3] is coming! Through out the past 99 years GR has been good at describing gravitation, except for (i) *darkessence* — dark energy and dark matter — and (ii) the conflict between GR and quantum physics (G-Q conflict). Darkessence [4] is to explain the mysterious gravitation revealed by observations in cosmology [5]: Dark energy is the unknown source of anti-gravity that drives the acceleration of the cosmic expansion at the present epoch, and dark matter the unknown source of attractive gravitation that helps to form and to hold the cosmic structures. We know the need of these two opposite types of gravitation, but we do not know what generates them. If presented in the form of energy, darkessence can contribute 95% of the energy of the present universe, while baryons and other standard model particles contribute only 5%. To capture their nature, we need more high-precision observations, without which building more and more models may produce papers but can hardly produce real progress on darkessence.

The even more vital problem about gravity is the conflict between GR and quantum physics, two revolutions in physics of the 20th century: Gravity in GR is classical, while the fields in the standard model of particle physics are quantum. The problem about these two essential knowns can be more serious than the greatest unknown in cosmology. Concerning darkessence, the problem is that we do not know what dark energy and dark matter are. Once we know their identity through observations, there could be no fundamental issue left. What we need at this stage is to make observations speak loud and clear about the nature of darkessence. As to the G-Q conflict, both GR and quantum physics have been well tested in a wide range of energy scales. They can hardly go wrong. Nevertheless, they do not share the same framework of formulation: GR is classical and difficult to quantize. This causes fundamental conflict because, generally speaking, gravity cannot remain classical when it couples to quantum fields — quantum nature can transfer from quantum fields to gravity through their coupling. This is a crisis in the foundation of physics. The framework incompatibility between gravity and other fields cannot be solved by discovering new fundamental fields and interactions, which may help darkessence though.

2. Light from Cosmological Constant Problem

The simplest candidate of dark energy is a positive cosmological constant, which can come from quantum vacuum energy. No matter whether dark energy is served by quantum vacuum energy, the observational constraint of the former gives an upper bound to the latter,

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i.e. $3 \times 10^{-11}\,\mathrm{eV}^4$ regarding the energy density. The typical value of vacuum energy in quantum field theory is determined by the cut-off scale; it is much larger than the upper bound no matter the cut-off scale is given by the Planck, the GUP or the electroweak scale — the Planck scale gives the notorious discrepancy of 123 orders of magnitude. This "ultraviolet catastrophe of dark energy" is called *cosmological constant problem* [6]. Like the ultraviolet catastrophe of blackbody radiation that motivated Max Planck to introduce *quantum* and opened the window to the quantum world of the 20th century, the contemporary ultraviolet catastrophe of dark energy is illuminating the most important problem in fundamental physics of the 21st century, the G-Q conflict.

I particularly emphasize that the cosmological constant problem is not only a high-energy catastrophe but also a low-energy crisis: Even the quantum fluctuations at eV (micron) scales can give too large vacuum energy and too large repulsive gravitation ruining our universe, i.e., destroying the cosmic structures we inhabit — we cannot survive. This dark energy crisis [7] is a real problem. It is not just a hierarchy problem which concerns naturalness or beauty of fundamental physics. It is not a hypothetical problem concerning unverified high-energy physics, but indeed a practical problem concerning well-known low-energy physics (e.g., around micron scales). It concerns the daily-life physics! Therefore, I suggest:

> *To solve the cosmological constant problem, we should look for a low-energy or an energy-independent solution.*

The cosmological constant problem is about the gravitation of quantum vacuum energy: Does quantum vacuum energy gravitate? Does it gravitate in the usual way, i.e., in the same way as the classical sources of gravitation? Generally speaking, the cosmological constant problem concerns the interplay between gravity and quantum vacuum. Furthermore, we can ask how the energy in quantum field theory is connected with the source of gravitation. Can the former be directly treated as the latter? This question is similar to that about the connection between inertial mass and gravitational mass. The role of the energy quantities, such as mass, in quantum field theory is more like inertial mass. Their connection with the source of gravitation is not clear [4]. The origin of these questions is indeed the lack of knowledge about the interplay between gravity and quantum physics. It is essential, but not done yet, to experimentally show how the energy in quantum field theory gravitates.

I propose reading the cosmological constant problem as a low-energy manifestation of the G-Q conflict and a signpost to the reconciliation. I expect the solution to the latter can also solve the former. That is, in the reconciliation between gravity and quantum physics, the cosmological constant problem should be solved or automatically disappear. Furthermore, since the cosmological constant problem is not only a high-energy but also a low-energy problem, I expect:

> *The reconciliation between gravity and quantum physics should give a low-energy or an energy-independent solution to the cosmological constant problem.*

I propose using this expectation as a *physical criterion* to evaluate possible solutions to the G-Q conflict such as string theory and loop quantum gravity, two mathematically successful theories of quantum gravity. In addition to the quantization of gravity, string theory contrives to unify fundamental fields and interactions, while loop quantum gravity demonstrates the possibility of constructing a quantum field theory without background. For gravity, these two theories mainly concern high-energy behavior, but give no distinct modification at low-energy scales; basically they come back to GR at low energies. It is not clear how they can give a low-energy or an energy-independent solution to the cosmological constant problem to pass the physical criterion, although they are profound mathematically. This shortcoming suggests a more thorough change of thinking. In particular, we may need novel vision for the interplay between gravity and quantum physics, either low-energy or energy-independent. Moreover, the reconciliation may require a thorough change in the framework of formulation.

Basically, the G-Q conflict is about the framework of formulation; to resolve it, the framework needs to be unified. Since the quantum framework is more fundamental than the classical, conventionally quantum nature is regarded as fundamental and the quantization of gravity has been widely considered. In quantum gravity it is believed that the interplay between gravity and quantum physics is important only at high energies. Accordingly, the quantum theories of gravity have focused on the high-energy regime, which, as I have commented on string theory and loop quantum gravity, does not catch the essence of the cosmological constant problem. Strictly speaking, the G-Q conflict does not necessarily suggest the quantization of gravity, although it does suggest a change of the gravity framework. It is possible that both classical gravity and quantum physics need to be reformulated in a new, common framework.

An intriguing example for gravity is *entropic gravity* [8], which hints at a novel possibility for reformulation: *the statistical formulation of gravity*. Entropic gravity puts GR at the level of thermodynamics and suggests a very different formulation of gravity: The Einstein equations are derived by extremizing a priori defined thermodynamic free energy such as entropy. In this scenario GR is a macroscopic theory of gravity analogous to thermodynamics, the geometrical quantities therein are macroscopic quantities, and the Einstein equations are no longer the evolution equations but the constraints of macroscopic quantities analogous to an equation of state in thermodynamics. Then, it makes no sense to quantize GR, as no one would quantize thermodynamics. To quantize gravity, it is the microscopic theory of gravity that should be quantized; however, such fundamental theory of gravity is yet to be constructed. As statistical mechanics underlies thermodynamics, to construct the underlying theory of entropic gravity we need a statistical framework for formulating the microscopic theory of "spacetime atoms," the building blocks of spacetime. Like the construction of statistical mechanics in the 19th century by Boltzmann [9] and other pioneers [10] who knew little about molecules and atoms, hopefully, without knowing the details of spacetime atoms we may still be able to construct the statistical formulation of gravity. In addition to gravity, can quantum physics also be recast in a statistical framework, thereby giving a way to reconcile gravity with quantum physics? This possibility, though sounds crazy and difficult to work, can be considered.

Contrary to the conventional wisdom that the solution to the G-Q conflict must invoke new physics at very high energies, the cosmological constant problem gives a low-energy manifestation of this conflict. I therefore conjecture:

> *The tools to solve the conflict between GR and quantum physics may be hidden in the well-known low-energy physics.*

I expect the cosmological constant problem will give hints and guidance for us to find these low-energy tools. In particular, note that the cosmological constant problem mainly concerns the constrained degrees of freedom of gravity.[1] For example, it concerns the cosmic expansion that is described by the scale factor in the Friedmann-Lemaître-Robertson-Walker metric, which belongs to the constrained degrees of freedom of gravity. Therefore, such degrees of freedom may be the right "lamppost" for us to find the key: An appropriate quantum treatment of the constrained degrees of freedom of gravity may be a key to the solution for both the cosmological constant problem and the G-Q conflict.

[1] GR contains four gauge, four constrained (under the Hamiltonian and momentum constraints), and two dynamical degrees of freedom (gravitational waves).

The path to the solution may have already existed in our current knowledge, though hidden in the darkness and covered with trivial details. It is waiting for us to find it with our wisdom and insight rather than fancy mathematics or random guesses.

3. Summary

In the 20th century GR and the standard model of particle physics — two major fields in fundamental physics — did an excellent job of describing fundamental fields and interactions, except for the conflict between GR and quantum physics. They were so successful that some physicists even thought fundamental physics was approaching to its end. To the contrary, cosmology brought great challenges at the end the 20th century: The standard model of particle physics can explain only 5% of the universe while the other 95% remains "dark" in our knowledge. With these challenges, darkessence very timely gave a new life to GR and particle physics when they were getting old.

Moreover, darkessence gives guidance on the exploration of fundamental physics. Dark matter ($\approx 25\%$) provides guidance on the search for new fundamental particles among a vast variety of hypothetical theories beyond the standard model. Dark energy ($\approx 70\%$), i.e. the acceleration of the cosmic expansion, stimulates the modification of GR at the cosmological scales, although modified gravity is not necessarily responsible for the cosmic acceleration. To test gravity and other fundamental physics, the universe provides an ultimate laboratory, e.g., cosmic evolution for gravity and ultrahigh-energy cosmic rays for high-energy physics. Even more profound is that the cosmological constant problem is giving insight into the conflict between GR and quantum physics. This is the main theme of the present article.

In this article I explore the light shed by the greatest unknown in cosmology on the most important problem in fundamental physics, i.e., how the cosmological constant problem illuminates the conflict between GR and quantum physics. The key points raised in this article are summarized as follows.

(1) The cosmological constant problem is not only a high-energy but also a low-energy problem. We should look for a low-energy or an energy-independent solution to it.

(2) The cosmological constant problem is a low-energy manifestation of the conflict between GR and quantum physics. Hopefully, it can guide us to the reconciliation.

(3) The reconciliation between gravity and quantum physics should give a low-energy or an energy-independent solution to the cosmological constant problem. This requirement provides a physical criterion for evaluating possible solutions to the conflict between GR and quantum physics.

(4) From the above points, I expect the tools to solve the conflict between GR and quantum physics can be found in the well-known low-energy physics. Very likely they are already in our hands rather than being far away!

History is repeating! In the 19th century people knew Newtonian mechanics and Newtonian gravity well, and successfully developed electromagnetism, thermodynamics, statistical mechanics, etc., which gave an illusion of the end of fundamental physics. This illusion was shattered by puzzles and unexplained experimental results during the transition from the 19th to the 20th century, such as the ultraviolet catastrophe of black-body radiation, the photoelectric effect, spectra of atoms, the constant speed of light, etc., which eventually led to the revolutions in physics of the 20th century: GR and quantum mechanics. Again, in the 20th century, the success of GR and the standard model of particle physics gave such illusion, which has been shattered by great unknowns in cosmology. Hopefully, the great puzzles in cosmology will eventually lead to a revolution in physics of this new century! This is our chance, being a part of the coming revolution!

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