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Darkessence

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Abstract

Darkessence, the dark source of anti-gravity and that of attractive gravity, serves as the largest testing ground of the interplay between quantum matter and classical gravity. We expect it to shed light on the conflict between quantum physics and gravity, the most important puzzle in fundamental physics in the 21st century. In this paper we attempt to reveal the guidelines hinted by darkessence for clarifying or even resolving the conflict. To this aim, we question (1) the compatibility of the renormalization-group (RG) running with the energy conservation, (2) the effectiveness of an effective action in quantum field theory for describing the gravitation of quantum matter, and (3) the way quantum vacuum energy gravitates. These doubts illustrate the conflict and suggest several guidelines on the resolution: the preservation of the energy conservation and the equivalence principle (or its variant) under RG running, and a natural relief of the vacuum energy catastrophe.

1. Introduction

Dark-essence is the most mysterious unknown in cosmology in the 21st century. It contains two parts: (1) the dark source of attractive gravity that helps to form and to hold the cosmic structures, and (2) the dark source of anti-gravity that drives the acceleration of the cosmic expansion. Darkessence is so influential that its effect on the evolution of the present universe reaches 95%, leaving merely 5% to the ordinary matter such as protons, neutrons, and others in the standard model of particle physics. What is the nature of darkessence? What is its origin? These are the most urgent questions for us to answer. The quest of the answer will certainly widen and deepen our understanding of the universe. Moreover, it may shed light on fundamental physics.

Fundamental physics concerns the constituents of the world, the laws of nature, and the framework for formulating the former two. The need of darkessence in cosmology invites unknown constituents and/or new physical laws, e.g., dark matter, dark energy and/or modified gravity. This need happened to come at the end of the 20th century when both particle physics and gravity, two major branches in fundamental physics, were getting old. So in time did modern cosmology bring them back to youth! As to the framework, long before modern cosmology, the conflict between gravity and quantum physics has been puzzling physicists since the last century. The reconciliation between them remains the most important puzzle in fundamental physics.

Phenomenologically, darkessence is all about gravity (anti-gravity and extra attractive gravity) that is described in a classical framework. Theoretically, one may expect darkessence be played by some matter field(s) that is described in a quantum framework. Accordingly, darkessence provides an important stage for the interplay between quantum matter and classical gravity. We therefore expect darkessence to give hints and guidelines on the solution to the fundamental conflict between quantum physics and gravity. Hopefully, the knowledge of darkessence can illuminate the way to the reconciliation and eventually lead us to a new revolution in physics in this century.

Concerning the interplay between quantum matter and classical gravity, we are pondering how to formulate the classical gravitation of quantum matter. This paper attempts to reveal hints of the answer from the following three doubts, which will be discussed one by

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one in the succeeding three sections.

1. Is the renormalization group (RG) running in quantum field theory compatible with the stress energy conservation required by the Einstein equations?
2. Is it legitimate to treat an effective potential obtained in quantum field theory as an ordinary source of gravitation or use an effective action to calculate the energy-momentum tensor in the Einstein equations?
3. Does the quantum vacuum energy gravitate as all other energy sources?

These three doubts are profoundly related. They appear when one applies to gravity the results of quantum field theory that excludes gravity in the quantum realm.

2. Energy Conservation and RG Running

To present the conflict between gravity and quantum physics, here we start with a potential conflict between the stress energy conservation in general relativity and the RG running in quantum field theory. The Einstein equations require the stress energy conservation as a constraint on gravitational sources, which involve physical parameters such as gravitational masses (in contrast to inertial masses). If gravitational masses can change with RG running, the stress energy conservation will be in trouble.

Ideally, in a full quantum treatment, the physical parameters and the stress energy do not change with RG running, and therefore the stress energy conservation is not troubled by RG running. Nevertheless, the true quantum treatment of gravity remains unknown or uncertain. In many cases the quantum treatments are incomplete or even simply exclude gravity; in all cases the quantum treatments involving gravity have not been tested experimentally. Therefore, the problem with the energy conservation under RG running may appear and should be examined carefully.

To better understand this problem, here we consider an analogy in electrostatics: The electro-effect of a static electric charge should be independent of the RG scale μ, although the renormalized charge can be μ-dependent. However, if one restricts the description of the electro-effect to the inverse-square Coulomb law (i.e. the tree-level result), the charge invoked therein will depend on the RG scale. Back to gravity, by putting the stress energy of quantum matter into the Einstein equations, one is restricting the way matter gravitates. In this case, the gravitational charge, which involves the gravitational constant G and the stress energy $T_{\mu\nu}$, may change with RG running, and the conservation of $GT_{\mu\nu}$ becomes doubtful.

This doubt motivates the consideration of the running of the gravitational constant G and the cosmological constant [1] and the consideration of possible corrections to the Friedmann equation [2]. These considerations are bottom-up, i.e, conjecturing the possible form of the quantum correction to gravity via the requirement of the energy conservation. However, after all we need to a top-down solution, a task yet to be accomplished.

This doubt indicates the lack of a consistent framework for formulating the classical gravitation of quantum matter. One can extend this doubt to the action level and question whether an effective action of quantum matter can truly describe its gravitational effects, an issue to be discussed in the following section.

3. Effectiveness of an Effective Action

In quantum field theory one may use effective actions to describe lower-energy physics. Even the standard model of particle physics might be regarded as an effective theory. In cosmology people are using effective actions of quantum field theory to describe gravitational phenomena, such as the late-time acceleration driven by quintessential dark energy and the early-time inflation driven by an inflaton field. For example, in axion inflation, the effective potential of the axion field is utilized to drive the inflation.

Here we question the effectiveness of an effective action when it is involved in gravitational physics: Is the stress energy (e.g. the expectation value of the energy-momentum tensor operator) derived from the effective action a valid source of gravitation? Is the energy-momentum tensor so derived truly the quantity we can put into the Einstein equations? Conservatively speaking, the effectiveness of an effective action holds in the calculation of correlations and scattering amplitudes of quantum fields in quantum field theory that excludes gravity in the quantum treatment. It is not clear whether an effective action can describe gravitational physics, e.g., whether an effective potential can be directly utilized in the Einstein equations.

A part of the problem is related to the contrast between inertial mass and gravitational mass. In quantum field theory one obtains the physical mass from a propagator. Conventionally, one utilizes such mass to write down the stress energy in the gravitational field equations. By doing so, one is assuming the mass involved in the propagators is the charge of gravitation. Is this a good assumption?

While a mass is obtained from propagators, a charge should be obtained from vertices and can be independent of a mass. One may find the mass-charge equivalence good in perturbative quantum gravity. However, the validity of the perturbative treatment of gravitational quantum fluctuations is neither verified experimentally nor convincing theoretically because of the non-renormalizability that makes it unclear whether the higher-loop corrections can be ignored. In general, even if one sets a relation between a mass and a charge in the bare action or in the action at some energy scale, after RG running this relation may be changed at other scales if the treatment of RG running does not include gravity appropriately.

We note that the mass involved in a propagator is analogous to an inertial mass, while that in a vertex a gravitational mass. Whether the former can be the charge of gravitation is similar to the question whether the equivalence principle holds. The maintenance of a relation between the mass in propagators and the charge of gravitation may be an important guideline on the construction of quantum gravity or an alternative way to reconcile quantum physics and gravity.

4. Cosmological Constant Problem

In quantum field theory a quantum vacuum provides the stress energy in the same form as a cosmological constant. Does quantum vacuum energy gravitate? Does it gravitate in the same way as ordinary energy sources? This fundamental question is yet to be answered through experiments. If quantum vacuum energy gravitates as other energies, we will face the notorious cosmological constant problem [3]: We have too much vacuum energy, a tiny part of which can have already destroyed (the structures of) our universe; even the quantum fluctuations at the well-tested low-energy scales (e.g. micron scales) can ruin our universe by contributing too much vacuum energy.

For example, one may calculate the vacuum expectation value of the energy-momentum tensor operator and find it divergent or its scale as large as the cut-off energies. However, why should we put this vacuum energy into the Einstein equations? Why not use the difference of two expectation values with respect to two quantum states: the state of the universe and the vacuum state?

This problem demonstrates how little we know about an appropriate way to calculate the gravitational effect of quantum vacuum energy. We expect the problem will be solved or even automatically disappear in the reconciliation between quantum physics and gravity. A widely studied direction to the reconciliation is quantum gravity. This is still under construction and complicated to use.

A simplified version of quantum gravity is quantum cosmology with mini-superspace. In this framework the whole universe is described by a wave function $\Psi(a, \phi)$ governed by the Wheeler-DeWitt equation [4], $\hat{H}\Psi(a, \phi) = 0$, where a is the scale factor in the Friedmann-Lemaitre-Robertson-Walker metric, ϕ represents matter fields, and $\hat{H}$ the quantum Hamiltonian operator containing both the matter and gravity parts. The Wheeler-DeWitt equation is a quantum version of the Hamiltonian constraint. It requires the universe be in a stationary state; accordingly the wave function describes the correlation between quantum variables, a and ϕ, but not their dynamics. That is, the system is *timeless*.

From the timeless Wheeler-DeWitt equation one can still retrieve dynamics [5, 6, 7]: When the phase of the wave function varies fast, while its amplitude changes slowly, with the gravitational quantum variable a, time can be introduced through the classical histories (of the scale factor a) designated by the Hamilton-Jacobi relation of the rapidly varying phase. Then, the classical gravitational field equation (i.e. the Friedmann equation) and the quantum Schrödinger equation of the matter wave function can be derived via the semi-classical approximation.

Nevertheless, how to construct quantum cosmology? How to write down the action and Hamiltonian for the Wheeler-DeWitt equation? Conventionally, one may use a classical action to construct a quantum theory, an approach widely taken in the construction of quantum field theory. This approach probably makes sense when the quantum theory is renormalizable. However, quantum gravity does not appear renormalizable. In this case, the action and Hamiltonian in a quantum theory can be very different from their classical counterparts. Even the quantum variables might be entirely different from the classical dynamical variables. Thus, it is unclear how to construct quantum gravity or quantum cosmology, and it can be misleading to calculate the classical gravitation of quantum vacuum energy by simply wrapping gravity in the quantum framework.

Regarding possible unexpected gravitational effect of a cosmological constant, Hartle, Hawking and Hertog recently raised a drastic example [8, 9]. They consider the Wheeler-DeWitt equation of the scale factor a and a scalar field ϕ with negative mass-square, in which the cosmological constant is negative. As a result, the Friedmann equation they derived contains a positive effective cosmological constant (as well as a positive effective mass-square for the scalar field). That is, the cosmic acceleration can be generated by an originally negative cosmological constant. This surprising example demonstrates that the gravitation of quantum vacuum energy can be very different from what one expects.

5. Summary

Cosmology has become an active experimental science since the end of the last century. It invokes fundamental physics to describe the universe. Thereby, precision cosmology provides a powerful testing ground and a natural laboratory of fundamental physics.

In fundamental physics, the conflict between quantum physics and gravity is the most important puzzle yet to solve. For the interplay between quantum matter and classical gravity, darkessence—the greatest unknown in modern cosmology—provides the largest and probably the most important stage. We expect the knowledge of cosmology and a better understanding of darkessence will shed light on this fundamental conflict, clarifying the problem and guiding us to the solution.

In the present paper we ponder this conflict with three doubts related to both darkessence and such interplay. All of these doubts concern the gravitation of quantum matter. They appear when one puts into the Einstein equations the stress energy calculated in quantum field theory that excludes gravity in the quantum realm.

1. The first doubt about the stress energy conservation under RG running indeed concerns the gravity part—whether general relativity and the Einstein equations provide a good description of the gravitation of quantum matter.
2. The second doubt about the effectiveness of an effective action obtained in quantum field theory concerns the matter part—whether the effective action of quantum matter can be used to calculate the stress energy in the Einstein equations.
3. The third doubt specifically concerns the gravitation of quantum vacuum energy, i.e., the cosmological constant problem. We particularly emphasize an important message it delivers: The conflict between quantum physics and gravity is important not only at high-energy scales but also at the well-tested low-energy scales (e.g. micron scales).

A basic source of these doubts is the fact that the current ways of calculating the gravitation of quantum matter are not yet verified by experiments. For some of the ways, the "theoretical" validity can be verified via a semi-classical approximation of quantum gravity or other quantum gravity approaches. Nevertheless, no matter how beautiful a quantum theory of gravity is theoretically, without experimental verification we can hardly assess its validity in the real world. Putting the experimental verification aside but standing on the theoretical side, to be honest, we do not know whether gravity should be quantized. The necessity of quantizing gravity is simply a conjecture.

In addition to concerns, these doubts suggest possible guidelines on a better description of the gravitation of quantum matter: the preservation of the energy conservation and the equivalence principle (or its variant) under RG running, and a natural relief of the vacuum energy catastrophe. These requirements may eventually guide us to the resolution.

We believe the resolution to the conflict between quantum physics and gravity is not far. Hopefully it will lead us to a new revolution in physics. Cannot miss the great opportunity of playing a part in the revolution!

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References

[1] I. L. Shapiro and J. Sola, "Scaling behavior of the cosmological constant: Interface between quantum field theory and cosmology," JHEP **0202** (2002) 006 [hep-th/0012227].
[2] S. Basilakos, D. Polarski and J. Sola, "Generalizing the running vacuum energy model and comparing with the entropic-force models," Phys. Rev. D **86** (2012) 043010 [arXiv:1204.4806 [gr-qc]].
[3] S. Weinberg, "The Cosmological Constant Problem," Rev. Mod. Phys. **61** (1989) 1.
[4] B. S. DeWitt, "Quantum Theory of Gravity. 1. The Canonical Theory," Phys. Rev. **160** (1967) 1113.
[5] T. Banks, "T C P, Quantum Gravity, the Cosmological Constant and All That...," Nucl. Phys. B **249** (1985) 332.
[6] R. Brout, "On the Concept of Time and the Origin of the Cosmological Temperature," Found. Phys. **17** (1987) 603.
[7] R. Brout, G. Horwitz and D. Weil, "On the Onset of Time and Temperature in Cosmology," Phys. Lett. B **192** (1987) 318.
[8] J. B. Hartle, S. W. Hawking and T. Hertog, "Accelerated Expansion from Negative Λ," arXiv:1205.3807 [hep-th].
[9] J. B. Hartle, S. W. Hawking and T. Hertog, "Inflation with Negative Λ," arXiv:1207.6653 [hep-th].