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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?