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Über-gravity and the cosmological constant problem

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ABSTRACT

Recently, the idea of taking ensemble average over gravity models has been introduced. Based on this idea, we study the ensemble average over (effectively) all the gravity models (constructed from Ricci scalar) dubbing the name über-gravity which is a *fixed point* in the model space. The über-gravity has interesting universal properties, independent from the choice of basis: (i) it mimics Einstein–Hilbert gravity for high-curvature regime, (ii) it predicts stronger gravitational force for an intermediate-curvature regime, (iii) surprisingly, for low-curvature regime, i.e. $R < R_0$ where R is Ricci scalar and R_0 is a given scale, the Lagrangian vanishes automatically and (iiii) there is a sharp transition between low- and intermediate-curvature regimes at $R = R_0$. We show that the über-gravity response is robust to all values of vacuum energy, ρ_{vac} when there is no other matter. So as a toy model, über-gravity, gives a way to think about the hierarchy problems e.g. the cosmological constant problem. Due to the transition at $R = R_0$ there is a chance for über-gravity to bypass Weinberg's no-go theorem. The cosmology of this model is also promising because of its non-trivial predictions for small curvature scales in comparison to ΛCDM model.

1. Introduction

A century ago Einstein introduced the cosmological constant (CC) to address static universe [1] which became his biggest blunder after Hubble's discovery of expanding universe. On the other hand, from the viewpoint of particle physics it is well-known that there is a non-vanishing vacuum energy, ρ_{vac}, which has no effect on most of particle physics' calculations. But in presence of gravity, it predicts an inflating universe which is not compatible with the observations before 1998. Accordingly it raised a question: why the vacuum energy has no effect on gravity? Which is known as old CC-problem. Data acquired by Supernovae observations in 1998 [2] and recent Plank data [3] implies a tiny value for CC, which shall be 120 orders of magnitude smaller than ρ_{vac}; this prediction sometimes will refer to as "the worst theoretical prediction in the history of physics" [4]. To solve this discrepancy a fine-tuning is required which is known as the new CC-problem (CCP) [5].

There are three different approaches to solve the CCP: (*i*) modifying the Einstein–Hilbert (EH) model in a way that gravity becomes insensitive to ρ_{vac} [6], (*ii*) revising field theory calculation of ρ_{vac} [7] and (*iii*) connecting the CCP (which is in IR regime) to UV-completion of gravity [8]. An idea in the context of modifying gravity is degravitation which proposes switching off the gravity for very large wavelengths and consequently filters ρ_{vac} [9]. It is worth mentioning that some believes old CCP shall be addressed before moving to new CCP. This idea is supported by 'tHooft conjecture: if the gravitational effects of ρ_{vac} can be canceled by a symmetry then a tiny fluctuation from this symmetric situation is natural. Supersymmetry is an idea in this direction assuming the presence of a boson particle for each fermion consequently paving the way for a mechanism to eliminate ρ_{vac} [10].

In this paper, we will study the CCP within the context of über-modeling introduced in [11]. We try to show that über-modeling of (effectively) all gravitational models eliminates gravity for low-curvature regimes which can be interpreted as degravitation. Our model coincides with the EH model in high-curvature regime although, there is an intermediate-curvature regime where gravity is stronger than the standard EH model. It will be shown that our model is not sensitive to value of vacuum energy, ρ_{vac}, thanks to a sharp (but continuous) transition from low- to intermediate-curvature regime. Interestingly, this means there is no need of fine-tuning and the CC is "natural"[1].

2. Über-gravity

In [11], we introduced an idea based on ensemble average of models within the context of gravity. According to this idea, we start with the space of all consistent models of gravity, $\mathbb{M}$, and then take an ensemble average over all models. This idea is inspired by

[1] This result has been shown for a certain circumstance where all the matter fields are turned off except the vacuum energy. At this step our model is same as the first steps in other models e.g. unimodular scenario and should be studied for more details in the future.

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statistical mechanics which employed in a very different context. In [12], Arkani-Hamed et al. employed a similar idea to address the hierarchy problem in particle physics. They mention that in principle an average should be taken on all possible models but for simplicity, they just considered the standard model with different Higgs masses. The main idea behind addressing the hierarchy problem in both [11] and [12] is a dynamical mechanism which can make our current model dominant. In [12] this mechanism is realized by introducing a new field, named reheaton, which "deposits a majority of the total energy density into the lightest sector" (which is our observed standard model of particle physics). In our über-modeling this mechanism is given by the assigned probability to each model which is introduced by hand at this step. On the other hand our idea can be seen as a realization of the Tegmark's mathematical universe idea [13], specially when he argues "all logically acceptable worlds exist". In [11] we assumed all the theoretically possible (gravity) models play a role in the final model (of gravity). To make über-modeling idea applicable, we assigned a Lagrangian to each model and define (ensemble) average of all the Lagrangians as following:

$$\mathcal{L} = \left(\sum_{i=1}^{N} \mathcal{L}_i e^{-\beta\mathcal{L}_i}\right) \Big/ \left(\sum_{i=1}^{N} e^{-\beta\mathcal{L}_i}\right), \tag{1}$$

where β is a free parameter and model space is represented by $\mathbb{M} = \{\mathcal{L}_i \mid i \in \{1, N\}\}$ while N is number of all possible models. We emphasize that the above formulation is inspired by ensemble average procedure in statistical mechanics. However our suggested probabilities are fundamentally different with what is in statistical mechanics. As it is obvious from (1) that we use the Lagrangian in the exponent while in statistical mechanics it is E_i which is energy of each state. The above Lagrangian can be beautifully re-written in a more compact form as

$$\mathcal{L} = -\frac{d}{d\beta}\ln\mathcal{Z}, \qquad \mathcal{Z} = \sum_{n=1}^{N} e^{-\beta\mathcal{L}_n} \tag{2}$$

which reminds us of the partition function and its relation to energy. In [11] we assumed $\mathbb{M} = \{R, G\}$ where R is the Ricci scalar and G is the Gauss–Bonnet term. In this paper we generalize the model space to (effectively) all the gravity models based on curvature scalar: all analytic $f(R)$. Schematically we can write corresponding partition function as

$$\mathcal{Z} = \sum_{f(R)} e^{-\beta f(R)}. \tag{3}$$

Here we deal with analytic functions of $f(R)$ and we can arbitrarily choose the basis. We are working with $\mathbb{M} = \{R^n \mid \forall n \in \mathbb{N}\}$. The ensemble averaged Lagrangian takes the following form

$$\mathcal{L} = \left(\sum_{n=1}^{\infty} \bar{R}^n e^{-\beta\bar{R}^n}\right) \Big/ \left(\sum_{n=1}^{\infty} e^{-\beta\bar{R}^n}\right), \tag{4}$$

where $\bar{R} = R/R_0$. This model, which belongs to $f(R)$ family, has two free parameters: R_0 and dimensionless β. In Fig. 1, the above Lagrangian is plotted for $\beta = 1$. The above Lagrangian belongs to the $f(R)$ family and effectively is ensemble average of all possible models of gravity based on the curvature tensor. There is a possibility to add a constant to each $f(R)$, i.e. working with $R^n - \lambda_n$ as our basis. We plotted its Lagrangian in Fig. 2 for $\lambda_n = \lambda$, which mimics GR plus a cosmological constant. This model with additional constant has been studied in [14] with very interesting observational consequences. But in this work we focus on (4) to study the theoretical properties of the model. Note that in a general case we could work with all possible linear combinations e.g. $\mathcal{L} = \alpha_1 R + \alpha_2 R^4$ with two constants α_1 and α_2. It is easy

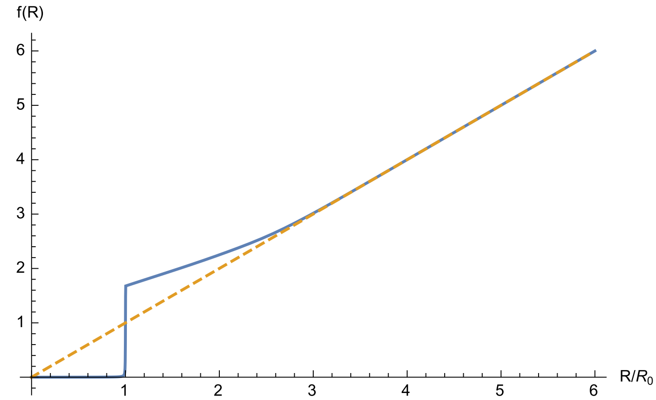

Fig. 1. Blue line is our Lagrangian (4) where we do sum up to $N = 1000$ (It is easy to see that for larger N's the plot is practically the same.) and yellow dashed line shows the EH action for comparison. The universal behavior of our model is obvious: (i) in high-curvature regime our model coincides with the EH model, (ii) in intermediate-curvature regime where gravity is stronger than the EH model, (iii) for $R < R_0$ gravity vanishes and (iiii) there is a sharp transition at $R = R_0$.

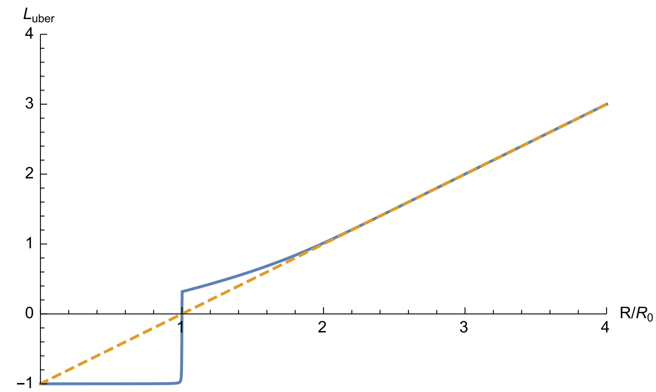

Fig. 2. We plotted the über-gravity Lagrangian with $R^n - \lambda_n$ as our basis. We assumed $\lambda_n = R_0^n$ and obviously our model mimics GR plus cosmological constant for high-curvature regime.

to observe that adding such terms do not change the interesting aspects of the model, so without loss of generality we focus on the above Lagrangian. Only difference will be in the form of the Lagrangian over the intermediate-curvature regime while for both high- and low-curvature regimes nothing is changed. Even in the intermediate-curvature regime the general prediction is a stronger gravity compared to the EH model. However, the form of our model in the intermediate-curvature regime is sensitive to the parameter β. As an example Fig. 3 shows the Lagrangian (4) for $\beta = 0.01$ which represents a very different behavior in intermediate-curvature regime.

In summary, the über-gravity model has the following universal properties (independent to the choice of basis i.e. $\mathbb{M}$):

- for high-curvature regime it reduces to the EH action,
- for intermediate-curvature regime it predicts a stronger gravity than the EH model,
- it is vanishing for low-curvature regime ($R < R_0$),
- there is a sharp transition at R_0.

It is worth mentioning that adding the über-gravity (4) to $\mathbb{M}$ and re-employing the über-modeling procedure cannot affect above universal features.[2] This is a very significant property since it

[2] We thank S. Baghram for pointing out this issue.