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Metastable dark energy

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ABSTRACT

We build a model of metastable dark energy, in which the observed vacuum energy is the value of the scalar potential at the false vacuum. The scalar potential is given by a sum of even self-interactions up to order six. The deviation from the Minkowski vacuum is due to a term suppressed by the Planck scale. The decay time of the metastable vacuum can easily accommodate a mean life time compatible with the age of the universe. The metastable dark energy is also embedded into a model with $SU(2)_R$ symmetry. The dark energy doublet and the dark matter doublet naturally interact with each other. A three-body decay of the dark energy particle into (cold and warm) dark matter can be as long as large fraction of the age of the universe, if the mediator is massive enough, the lower bound being at intermediate energy level some orders below the grand unification scale. Such a decay shows a different form of interaction between dark matter and dark energy, and the model opens a new window to investigate the dark sector from the point-of-view of particle physics.

1. Introduction

At the present age, around ninety five percent of the universe corresponds to two kinds of energy whose nature is largely unknown. The first one, named dark energy, is believed to be responsible for the current accelerated expansion of the universe [1,2] and is dominant at present time ($\sim 68\%$) [3]. In addition to the baryonic matter (5%), the remaining 27% of the energy content of the universe is a form of matter that interacts, in principle, only gravitationally, known as dark matter. The simplest dark energy candidate is the cosmological constant, whose equation of state is in agreement with the Planck results [3].

This attempt, however, suffers from the so-called cosmological constant problem, a huge discrepancy of 120 orders of magnitude between the theoretical (though rather speculative) prediction and the observed data [4]. Such a huge disparity motivates physicists to look into more sophisticated models. This can be done either looking for a deeper understanding of where the cosmological constant comes from, if one wants to derive it from first principles, or considering other possibilities for accelerated expansion, such as modifications of general relativity (GR), additional matter fields and so on (see [5–7] and references therein). Moreover, the theoretical origin of this constant is still an open question, with several attempts but with no definitive answer yet.

There is a wide range of alternatives to the cosmological constant, which includes canonical and non-canonical scalar fields [8–19], vector fields [20–27], holographic dark energy [28–35], modifications of gravity and different kinds of cosmological fluids [5–7].

In addition, the two components of the dark sector may interact with each other [36,37] (see [38] for a recent review), since their densities are comparable and the interaction can eventually alleviate the coincidence problem [39,40]. Phenomenological models have been widely explored in the literature [37,41–45,7,31–34,46–50]. On the other hand, field theory models that aim a consistent description of the dark energy/dark matter interaction are still few [51–53,19].

Here we propose a model of metastable dark energy, in which the dark energy is a scalar field with a potential given by the sum of even self-interactions up to order six. The parameters of the model can be adjusted in such a way that the difference between the energy of the true vacuum and the energy of the false one is the observed vacuum energy (10^{-47} GeV^4). Other models of false vacuum decay were proposed in [54,55,52] with different potentials. A different mechanism of metastable dark energy (although with same name) is presented in [56]. Furthermore, a dark $SU(2)_R$ model is presented, where the dark energy doublet and the dark matter doublet naturally interact with each other. Such an inter-

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action opens a new window to investigate the dark sector from the point-of-view of particle physics. Models with $SU(2)_R$ symmetry are well-known in the literature as extensions of the standard model introducing the so-called left–right symmetric models [57–61]. Recently, dark matter has also been taken into account [62–69]. However, there is no similar effort to insert dark energy in a model of particle physics. We begin to attack this issue in this paper, with the dark $SU(2)_R$ model.

The remainder of this paper is structured as follows. In Sect. 2 we present a model of metastable dark energy. It is embedded into a dark $SU(2)_R$ model in Sect. 3 and we summarize our results in Sect. 4. We use natural units ($\hbar = c = 1$) throughout the text.

2. A model of metastable dark energy

The current stage of accelerated expansion of the universe will be described by a canonical scalar field φ at a local minimum φ_0 of its potential $V(\varphi)$, while the true minimum of $V(\varphi)$ is at $\varphi_\pm = \langle\varphi\rangle$. The energy of the true vacuum is below the zero energy of the false vacuum, so that this difference is interpreted as the observed value of the vacuum energy (10^{-47} GeV^4).

We assume that by some mechanism the scalar potential is positive definite (as e.g. in supersymmetric models) and the true vacuum lies at zero energy. As we will see below this value is adjusted by the mass of the scalar field and the coefficient of the quartic and sixth-order interaction. The rate at which the false vacuum decays into the true vacuum state will be calculated.

The process of barrier penetration in which the metastable false vacuum decays into the stable true vacuum is similar to the old inflationary scenario and it occurs through the formation of bubbles of true vacuum in a false vacuum background. After the barrier penetration the bubbles grow at the speed of light and eventually collide with other bubbles until all space is in the lowest energy state. The energy release in the process can produce new particles and a Yukawa interaction $g\varphi\bar{\psi}\psi$ can account for the production of a fermionic field which can be the pressureless fermionic dark matter. However, as we will see, the vacuum time decay is of the order of the age of the universe, so another dominant process for the production of cold dark matter should be invoked in order to recapture the standard cosmology.

If one considers a scalar field φ with the even self-interactions up to order six, one gets

$$V(\varphi) = \frac{m^2}{2}\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{\lambda^2}{32m^2}\varphi^6 \quad , \tag{1}$$

where m and λ are positive free parameters of the theory and the coefficient of the φ^6 interaction is chosen in such a way that the potential (1) is a perfect square. This choice will be useful to calculate the false vacuum decay rate.

The potential (1) has extrema at $\varphi_0 = 0$, $\varphi_\pm = \pm\frac{2m}{\sqrt{\lambda}}$ and $\varphi_1 = \frac{\varphi_\pm}{\sqrt{3}}$, but it is zero in all of the minima (φ_0 and $\varphi_\pm$). In order to have a cosmological constant, the potential should deviate slightly from the perfect square (1). Once the coupling present in GR is the Planck mass M_{pl} it is natural to expect that the deviation from the Minkowski vacuum is due to a term proportional to M_{pl}^{-2}. Thus we assume that the potential (1) has a small deviation given by $\frac{\varphi^6}{M_{pl}^2}$. Although the value of the scalar field at the minimum point $\varphi_\pm$ also changes, the change is very small and we can consider that the scalar field at the true vacuum is still $\pm\frac{2m}{\sqrt{\lambda}}$. The difference between the true vacuum and the false one is

$$V(\varphi_0) - V(\varphi_\pm) \approx \frac{64m^6}{\lambda^3 M_{pl}^2} \quad . \tag{2}$$

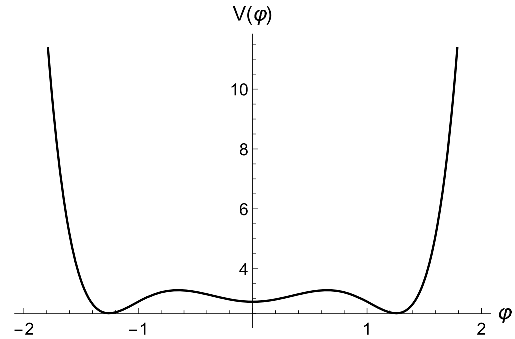

Fig. 1. Scalar potential (1) with arbitrary parameters and values. The difference between the true vacuum at $\varphi_\pm \approx \pm 1.2$ and the false vacuum at $\varphi_0 = 0$ is $\sim 10^{-47}$ GeV^4.

As usual in quantum field theory it is expected that the parameter λ is smaller than one, thus, if we assume $\lambda \sim 10^{-1}$, the Eq. (2) gives $\sim 10^{-47}$ GeV^4 for $m \sim \mathcal{O}$(MeV). Bigger values of λ imply smaller values of m. Therefore, the cosmological constant is determined by the mass parameter and the coupling of the quartic interaction.

The potential (1) with the term $\frac{\varphi^6}{M_{pl}^2}$ is shown in Fig. 1.

2.1. Decay rate

The computation of the decay rate is based on the semi-classical theory presented in [70]. The energy of the false vacuum state at which $\langle\varphi\rangle = 0$ is given by [71]

$$E_0 = -\lim_{T\to\infty}\frac{1}{T}\ln\left[\int \exp\left(-S_E[\varphi;T]\right)\prod_{\vec{x},t} d\varphi(\vec{x},t)\right] \quad , \tag{3}$$

where $S_E[\varphi;T]$ is the Euclidean action,

$$S_E = \int d^3x \int_{-\frac{T}{2}}^{+\frac{T}{2}} dt \left[\frac{1}{2}\left(\frac{\partial\varphi}{\partial t}\right)^2 + \frac{1}{2}(\nabla\varphi)^2 + V(\varphi)\right] \quad . \tag{4}$$

The imaginary part of E_0 gives the decay rate and all the fields $\varphi(\vec{x},t)$ integrated in Eq. (3) satisfy the boundary conditions

$$\varphi(\vec{x}, +T/2) = \varphi(\vec{x}, -T/2) = 0 \quad . \tag{5}$$

The action (4) is stationary under variation of the fields that satisfy the equations

$$\frac{\delta S_E}{\delta\varphi} = -\frac{\partial^2\varphi}{\partial t^2} - \nabla^2\varphi + V'(\varphi) = 0 \tag{6}$$

and are subject to the boundary conditions (5). In order to get the solution of Eq. (6) we make an ansatz that the field $\varphi(\vec{x},t)$ is invariant under rotations around $\vec{x}_0, t_0$ in four dimensions, which in turn is valid for large T [72]. The ansatz is

$$\varphi(\vec{x},t) = \varphi(\rho) \quad \text{with} \quad \rho \equiv \sqrt{(\vec{x}-\vec{x}_0)^2 + (t-t_0)^2} \quad . \tag{7}$$

In terms of the Eq. (7), the field equation (6) becomes

$$\frac{d^2\varphi}{d\rho^2} + \frac{3}{\rho}\frac{d\varphi}{d\rho} = V'(\varphi) \quad . \tag{8}$$

The above equation of motion is analogous to that of a particle at position φ moving in a time ρ, under the influence of a potential $-V(\varphi)$ and a viscous force $-\frac{3}{\rho}\frac{d\varphi}{d\rho}$. This particle travels from