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Bouncing universe with a non-minimally coupled scalar field on a moving domain wall

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ABSTRACT

We study dynamics of a dark energy component non-minimally coupled to gravity on a moving domain wall. We use this setup to explain late-time accelerated expansion and crossing of the phantom divide line by the equation of state parameter of this non-minimally coupled dark energy component. By analyzing parameter space of the model, we show that this model accounts for accelerated expansion and crossing of the phantom divide line with a suitable fine-tuning of the non-minimal coupling. Then we study the issue of bouncing solutions in this framework.

1. Introduction

Recent evidences from supernova searches data [1,2], cosmic microwave background (CMB) results [3–5] and also Wilkinson Microwave Anisotropy Probe (WMAP) data [6,7], indicate an positively accelerating phase of the cosmological expansion today and this feature shows that the simple picture of universe consisting of pressureless fluid is not enough. In this regard, the universe may contain some sort of additional negative-pressure component dubbed dark energy. Analysis of the WMAP data [8–10] shows that there is no indication for any significant deviations from Gaussianity and adiabaticity of the CMB power spectrum and therefore suggests that the universe is spatially flat to within the limits of observational accuracy. Further, the combined analysis of the WMAP data with the supernova Legacy survey (SNLS) [8], constrains the equation of state w_{de}, corresponding to almost 74% contribution of dark energy in the currently accelerating universe, to be very close to that of the cosmological constant value. Moreover, observations appear to favor a dark energy equation of state, $w_{de} < -1$ [11]. Therefore, a viable cosmological model should admit a dynamical equation of state that might have crossed the value $w_{de} = -1$, in the recent epoch of cosmological evolution. In fact, to explain positively accelerated expansion of the universe, there are two alternative approaches: incorporating an additional cosmological component or modifying gravity at cosmological scale. Multi-component dark energy with at least one non-canonical phantom field is a possible candidate of first alternative. This viewpoint has been studied extensively in literature (see [12] and references therein). Another alternative to explain current accelerated expansion of the universe is extension of general relativity to more general theories on cosmological scales. In this view point, modified Einstein–Hilbert action resulting $f(R)$-gravity (see [13] and references therein) and braneworld gravity [14–16] are studied extensively. For instance, DGP (Dvali–Gabadadze–Porrati) braneworld scenario as an infra-red modification of general relativity explains accelerated expansion of the universe in its self-accelerating branch via leakage of gravity to extra dimension. In this model, equation of state parameter of dark energy never crosses $\omega(z) = -1$ line, and universe eventually turns out to be de Sitter phase. Nevertheless, in this setup if we use a single scalar field (ordinary or phantom) on the brane, we can show that equation of state parameter of dark energy component can cross phantom

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divide line [17]. Also quintessential behavior can be achieved in a geometrical way in higher order theories of gravity [18]. One important consequence in quintessence model is the fact that a single minimally coupled scalar field has not the capability to explain crossing of the phantom divide line, $\omega_\phi = -1$ [19,20] (see also [21]). However, a single but non-minimally coupled scalar field is adequate to cross the phantom divide line by its equation of state parameter [12]. On the other hand, in the context of scalar-vector-tensor theories, realizing accelerated expansion and crossing of the phantom divide line with one minimally coupled scalar field in the presence of a Lorentz invariance violating vector field has been reported [22].

In this Letter, we consider a non-minimally coupled scalar field as a dark energy component on a moving domain wall. In this extension, brane is considered as a moving domain wall in a background 5-dimensional anti-de Sitter–Schwarzschild ($AdSS_5$) black hole bulk. In other words, we consider a static bulk configuration with two 5-dimensional anti-de Sitter–Schwarzschild black hole spaces joined by a moving domain wall. Then we study dynamics of equation of state parameter of a non-minimally coupled scalar field on this moving domain wall. We show that adopting a phenomenologically appropriate ansatz with suitable fine-tuning of the parameters of the model, provide enough room to explain accelerated expansion and crossing of the phantom divide line by the dark energy equation of state parameter. We also investigate the existence of bouncing solutions in this setup. Based on recent observational data, parameters of this model are constrained in the favor of late-time accelerated expansion. The importance of this study lies in the fact that currently, models of phantom divide line crossing are so important that they can realize that which model is better than the others to describe the nature of dark energy. In this respect, possible crossing of the phantom divide line(PDL), $\omega = -1$, by equation of state parameter of non-minimally coupled scalar field and existence of bouncing solutions in this braneworld setup are discussed.

2. The setup

We consider a moving domain wall picture of braneworld [23–25], to discuss the issue of quintessence and late-time acceleration along with the phantom divide line crossing of the equation of state parameter of a non-minimally coupled scalar field on the brane. Following [23], we consider a static bulk configuration with two 5-dimensional anti-de Sitter–Schwarzschild ($AdSS_5$) black hole spaces joined by a moving domain wall. To embed this moving domain wall into 5-dimensional bulk, it is then necessary to specify normal and tangent vectors to this domain wall with careful determination of normal direction to the brane. We assume that domain wall is located at coordinate $r = a(\tau)$ where $a(\tau)$ is determined by Israel junction conditions [26]. In this model, observers on the moving domain wall interpret their motion through the static 5-dimensional bulk background as cosmological expansion or contraction. Now, consider the following line element [23]

$$dS_{5\pm}{}^2 = -\left(k - \frac{\eta_\pm}{r^2} + \frac{r^2}{\ell^2}\right)dt^2 + \frac{1}{k - \frac{\eta_\pm}{r^2} + \frac{r^2}{\ell^2}}dr^2 + r^2\gamma_{ij}\,dx^i\,dx^j, \tag{1}$$

where $\pm$ stands for left($-$) and right($+$) side of the moving domain wall, ℓ is curvature radius of AdS_5 manifold and γ_{ij} is the horizon metric of a constant curvature manifold with $k = -1, 0, 1$ for open, flat and closed horizon geometry respectively and $\eta_\pm \neq 0$ generates the electric part of the Weyl tensor on each side. This line element shows a topological anti-de Sitter black hole geometry in each side. Using Israel junction conditions [26] and Gauss–Codazzi equations, we find the following generalization of the Friedmann and acceleration equations [23]

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{\rho}{3} + \frac{\eta}{a^4} + \frac{\ell^2}{36}\rho^2, \tag{2}$$

$$\frac{\ddot{a}}{a} = -\frac{\rho}{6}(1 + 3w) - \frac{\eta}{a^4} - \frac{\ell^2}{36}\rho^2(2 + 3w), \tag{3}$$

where we have adapted a Z_2-symmetry with $\eta_+ = \eta_- \equiv \eta$ and ω is defined as $\omega = \frac{p}{\rho}$. We assume there is a scalar field non-minimally coupled to gravity on the moving domain wall. The action of this non-minimally coupled scalar field is defined as [27–29]

$$S_\varphi = \int d^4x\,\sqrt{-g}\left[\frac{1}{{k_4}^2}\alpha(\varphi)R[g] - \frac{1}{2}g^{\mu\nu}\nabla_\mu\varphi\nabla_\nu\varphi - V(\varphi)\right]. \tag{4}$$

Energy–momentum tensor of this non-minimally coupled scalar field is given by

$$\mathcal{T}_{\mu\nu} = \nabla_\mu\varphi\nabla_\nu\varphi - \frac{1}{2}g_{\mu\nu}(\nabla\varphi)^2 - g_{\mu\nu}V(\varphi) + g_{\mu\nu}\Box\alpha(\varphi) - \nabla_\mu\nabla_\nu\alpha(\varphi), \tag{5}$$

where $\Box$ shows 4-dimensional d'Alembertian. We assume a FRW type universe on the brane with line element defined as

$$ds^2 = -dt^2 + a^2(t)\,d\Sigma_k{}^2, \tag{6}$$

where $d\Sigma_k{}^2$ is the line element for a manifold of constant curvature $k = +1, 0, -1$. Then equation of motion for scalar field ϕ is

$$\nabla^\mu\nabla_\mu\varphi = V' - \alpha' R[g], \tag{7}$$

where a prime denotes the derivative of any quantity with respect to φ. This equation can be written as

$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} + \frac{dV}{d\varphi} = \alpha' R[g], \tag{8}$$

where a dot denotes the derivative with respect to cosmic time, t and Ricci scalar is given by

$$R = 6\left(\dot{H} + 2H^2 + \frac{k}{a^2}\right). \tag{9}$$