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Four-dimensional gravity on supersymmetric dilatonic domain walls

R.C. Fonseca [b,c], F.A. Brito [a,*], L. Losano [a,c]

[a] Departamento de Física, Universidade Federal de Campina Grande, Caixa Postal 10071, 58109-970 Campina Grande, Paraíba, Brazil
[b] Departamento de Física, Universidade Estadual da Paraíba, 58.109-753 Campina Grande, PB, Brazil
[c] Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970 João Pessoa, Paraíba, Brazil

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ABSTRACT

We investigate the localization of four-dimensional metastable gravity in supersymmetric dilatonic domain walls through massive modes by considering several scenarios in the model. We compute corrections to the Newtonian potential for small and long distances compared with a crossover scale given in terms of the dilatonic coupling. 4D gravity behavior is developed on the brane for distance very much below the crossover scale, while for distance much larger, the 5D gravity is recovered. Whereas in the former regime gravity is always attractive, in the latter regime due to non-normalizable unstable massive graviton modes present on the spectrum, in some special cases, gravity appears to be repulsive and signals a gravitational confining phase which is able to produce an inflationary phase of the Universe.

1. Introduction

One of the main interesting results in higher dimensional physics in recent years, is the possibility of localization of gravity on braneworlds which was initiated in the seminal paper by Randall and Sundrum (RS) [1]. This attracted great attention because it was the first example where four-dimensional gravity could be localized even in the presence of extra dimensions with infinite size. Before this approach, the well-known Kaluza–Klein mechanism was the only largely considered alternative to achieve four-dimensional gravity from higher-dimensional theories by compactifying the extra dimensions into very small radii. On the other hand, braneworlds is an alternative to compactification, because a 3-brane embedded into higher dimensional space is able to localize four-dimensional gravity, even if the extra dimensions have infinite size. This mechanism works because the 3-brane is embedded in a curved higher dimensional space. More specifically, in the original set up [1], a 3-brane with tension sourced by a delta function is embedded in a warped five-dimensional bulk with negative cosmological constant, that is, an AdS_5 space. The relationship between the brane tension and the bulk cosmological constant plays the role of producing a zero mode solution to the linearized Einstein equations. This solution given in terms of the metric developing the suitable fall-off with respect to the extra dimension is responsible for localizing the four-dimensional gravity. The following massive modes of the full spectrum also enter in the computation of the Newtonian potential describing corrections to the four-dimensional gravity. They should be highly suppressed at large distance but should deviate the Newton's law from the four-dimensional behavior at very small distance, implying that the five-dimensional character of the full space shows up at very high energy.

Since the RS paper, many extensions to thick 3-brane have appeared in the literature [2] as domain wall solutions in five or higher dimensional theories with scalar fields coupled to gravity. Most of them are conceived in such a way that can be thought of as the bosonic sector of a supergravity theory or at least the bosonic sector of the sometimes referred to as fake supergravity [3]. One of the major problems in realizing the RS set up in five-dimensional supergravity is the difficulty to find normalizable zero modes. This issue was explored several times in the literature — see [4] for a review. The main point is that the warp factor found does not enjoy the required fall-off along the extra dimension. One can rephrase this problem in terms of the volume of the five-dimensional spacetime. In the RS scenario, in spite of the fact that the extra dimension is infinite, the compactification from five down to four dimensions is ensured because the volume of the AdS_5 space is finite – contrary to Minkowski space whose volume is infinite.

However, soon after the appearance of the RS scenario, it was presented alternative scenarios by Gregory, Rubakov and Sibiryakov (GRS) [5] and Dvali, Gabadadze and Porrati (DGP) [6] where the volume of the five-dimensional spacetime is not necessarily finite to localize gravity. This opened the possibility of localizing four-dimensional gravity in braneworlds embedded in asymptotically flat five-dimensional spaces. The price to pay is that instead

* Corresponding author.

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of zero modes the localization is due to massive graviton modes and the localization is metastable. In spite of its metastability, the localization of metastable gravity can survive long enough if one probes distances very much smaller than a crossover scale. In these alternative scenarios, the brane is still sourced by a delta function but the bulk in both cases is asymptotically five-dimensional Minkowski space. As it was previously stated [5,6,12,13], the crossover scale r_c can be related to the Hubble size as $r_c \sim H^{-1}$. We shall mostly consider the large crossover regime $r_c \to \infty$ which is consistent with the present Hubble size, though, we shall also briefly comment on $r_c \to 0$ that means the regime of the early Universe.

Furthermore, have also been considered in the literature thick brane realizations of metastable localization of gravity in the literature [7–15]. In most of these cases one has considered five-dimensional theories of scalar fields coupled to gravity in the realm of 'fake supergravity' where several issues were discussed. One should, though, also consider such realizations in supergravity domain wall solutions [16].

In the present study, we shall consider the supersymmetric dilatonic solution that can be found from a higher dimensional supergravity theory that after specific compactifications, such as toroidal compactification, turns to a simpler five-dimensional theory of a scalar field coupled to gravity [17–20] in the same fashion of those conceived in [2]. We shall investigate the possibility of localizing four-dimensional metastable gravity in supersymmetric dilatonic domain walls through massive gravitational modes by considering several scenarios, including those in which non-normalizable unstable massive graviton modes determine dominant repulsive gravity.

The Letter is organized as follows. In Section 2 we make a brief review on the mechanism of gravity localization on braneworlds. In Section 3 we present four scenarios by properly adjusting one of the free parameters of the theory. In all of these cases is recovered the four dimensional attractive gravity in the regime $r \ll r_c$. The first case gives the expected result since the localized gravity is attractive everywhere. However, due to non-normalizable unstable massive graviton modes present on the spectrum, the following three cases assume a new behavior at large distance, i.e., at $r \gg r_c$. In this regime they exhibit a repulsive gravity with exponentially increasing potential which signals a gravitational confining phase that is able to produce an inflationary phase of the Universe [24]. This effect has also been addressed in earlier similar studies on time-like extra-dimensions [25,26]. Finally in Section 4 we make our final comments.

2. Gravity on dilatonic domain walls

Let us briefly introduce the mechanism behind gravity localization in braneworlds. We consider a general dilatonic $(D-2)$-brane solution in a spacetime in D dimensions discussed in Refs. [17–20]. The spacetime is assumed to be the direct product $M_{D-1} \times K$ of the $(D-1)$-dimensional spacetime M_{D-1} and some noncompact internal space K. We shall focus our attention to obtain solutions describing braneworlds as the worldvolume of domain walls. The Einstein-frame action for the dilatonic domain wall is

$$S = \frac{1}{2\kappa_D^2}\int d^D x\sqrt{-g}\left(R - \frac{4}{D-2}(\partial\phi)^2 + \Lambda e^{-2a\phi}\right), \tag{1}$$

where κ_D is the D-dimensional gravitational constant, and the cosmological constant term is multiplied by the dilaton factor which depends on an arbitrary dilaton coupling parameter a in any D-dimensional spacetime. The dilatonic domain wall solution given in terms of a conformally flat form is

$$\bar{G}_{MN}\, dx^M\, dx^N = C(z)\left[-dt^2 + dx_1^2 + \cdots + dx_{D-2}^2 + dz^2\right], \tag{2}$$

$$\phi = \frac{(D-2)a}{2(\Delta+2)}\ln\left(1 + \frac{\Delta+2}{\Delta}Q\,|z|\right),$$
$$C(z) = \left(1 + \frac{\Delta+2}{\Delta}Q\,|z|\right)^{4/(D-2)(\Delta+2)}, \tag{3}$$

where

$$\Delta = \frac{(D-2)a^2}{2} - \frac{2(D-1)}{D-2}, \quad \text{and} \quad \Lambda = -\frac{2Q^2}{\Delta}. \tag{4}$$

For future discussions it is useful to define Λ in terms of the space curvature $1/L$. In the limit of sufficiently small curvature ($L \gg \ell_s$) being ℓ_s the string length, the supergravity approximation takes place. In order to study the spectrum of the graviton in the dilatonic domain wall background, we consider the metric describing the small fluctuation $h_{\mu\nu}(x^\rho, z)$ of the $(D-1)$-dimensional Minkowski spacetime embedded into the conformally flat D-dimensional spacetime

$$\bar{g}_{\bar{\mu}\bar{\nu}}\, dx^{\bar{\mu}}\, dx^{\bar{\nu}} = C(z)\left[(\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu\, dx^\nu + dz^2\right], \tag{5}$$

where $|h_{\mu\nu}| \ll 1$.

By using the linearized Einstein equations in the transverse traceless gauge, i.e., $\partial^\mu h_{\mu\nu} = 0$, and the metric fluctuation in the form $h_{\mu\nu}(x^\rho, z) = \bar{h}^{(m)}_{\mu\nu}(x^\rho)C^{-(D-2)/4}\psi_m(z)$, where $\eta^{\mu\nu}\partial_\mu\partial_\nu\bar{h}^{(m)}_{\mu\nu} = m^2\bar{h}^{(m)}_{\mu\nu}$, we obtain the Schrödinger-like equation

$$-\frac{d^2}{dz^2}\psi_m(z) + U(z)\psi_m(z) = m^2\psi_m(z), \tag{6}$$

with the potential

$$\begin{aligned} U(z) &= \frac{D-2}{16}\left[(D-6)\left(\frac{C'}{C}\right)^2 + 4\frac{C''}{C}\right] \\ &= -\frac{Q^2(\Delta+1)}{\Delta^2(1 + \frac{\Delta+2}{\Delta}Q\,|z|)^2} + \frac{2Q}{\Delta}\delta(z), \end{aligned} \tag{7}$$

where the prime denotes derivatives with respect to z. In this Letter, we shall discuss the properties of the KK modes for different values of Δ taking $Q > 0$. We explore the scenarios generated by the Schrödinger-like potentials that arises from four choices for the range of Δ, and we study the asymptotic behavior of the corrections for the Newtonian potential, which are derived from the wave functions that emerge from the corresponding Schrödinger-like equations. This means to investigate how easy four-dimensional massive gravity can be localized on the brane.

Notice that the structure of this potential allows to write the Schrödinger-like equation in a quadratic form [2]

$$H\psi(z) = m^2\psi(z), \quad H = \mathcal{Q}^\dagger\mathcal{Q}, \quad \mathcal{Q} = -\frac{d}{dz} + \frac{D-2}{2}A'(z), \tag{8}$$

where $A(z) = \frac{1}{2}\ln C(z)$. The zero mode obeying $H\psi_0 = 0$ is given by

$$\begin{aligned} \psi_0(z) &= N_0 \exp\left[\frac{D-2}{2}A(z)\right] \\ &= N_0 C(z)^{\frac{D-2}{4}} = N_0\left(1 + \frac{\Delta+2}{\Delta}Q\,|z|\right)^{1/(\Delta+2)}. \end{aligned} \tag{9}$$

It is easy to conclude from Eq. (9) that for $Q > 0$ there exists normalizable zero mode only in the range $\Delta \leqslant -2$, [19,20]. In the following, we consider four cases which do not fall into this range, and do not exhibit zero mode. This is because we aim to do