A new dimension hidden in the shadow of a wall

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Abstract

We propose a new way to hide the fifth dimension, and to modify gravity in the far infra-red. A gravitating tensional membrane in five dimensions folds the transverse space into a truncated cone, stoppered by the membrane. For near-critical tension, the conical opening is tiny, and the space becomes a very narrow conical sliver. A very long section, of length comparable to the membrane radius divided by the remaining conical angle, of this sliver is well approximated by a narrow cylinder ending on the membrane. Inside this cylindrical throat we can reduce the theory on the circle. At distances between the circle radius and the length of the cylinder, the theory looks 4D, with a Brans–Dicke-like gravity, and a preferred direction, while at larger distances the cone opens up and the theory turns 5D. The gravitational light scalar in the throat can get an effective local mass term from the interplay of matter interactions and quantum effective potentials on the cone, which may suppress its long range effects. We discuss some phenomenologically interesting consequences.

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In this Letter, we outline a novel mechanism to hide an extra dimension and to change gravity at very large distances. It draws on the fact that gravitating tensional codimension-2 objects fold two transverse dimensions into a conical space. We will focus on membranes in 5D, but other examples abound, such as point masses in 3D [1], local cosmic strings in 4D [2], or 3-branes in 6D [3]. In realistic cases when membranes are thick, their finite core resolves the tip of the cone, which truncates on the membrane. For near-critical tensions $\lambda \to 2\pi M_5^3$, the opening of the cone is tiny, and the space looks like a semi-infinite conical sliver. Tuning this may be easier than tuning the tension to zero. The cosmological constant problem may in fact *help*. In field theory, quantum corrections drive vacuum energy up to the UV cutoff [4]. A field theory in the membrane core, and on it, will generate large corrections to the tension. If its UV cutoff is close to 5D Planck scale, the tension may be close to critical. Alternatively, membranes could come with a full range of tensions, some infinitesimally close to the critical value. Here we will explore the consequences of near-critical tension.

The conical sliver is well approximated by a thin cylinder, of a radius r_0 set by the membrane thickness, out to distances from the membrane of the order of r_0 divided by the remaining conical opening. This scale is our crossover scale. If we live on this space, away from the membrane but inside the cylinder at distances between r_0 and the crossover scale we would not see the fifth dimension. The membrane is a domain wall, sitting at an end of the world, its tension 'propping up' the compact dimension. Inside the cylindrical throat ending on the membrane, the theory looks 4D, with towers of heavy KK modes and a light gravitational sector which contains the usual General Relativity, a Brans–Dicke-like scalar, and a KK vector. The heavy KK states are separated from the light modes by a mass gap set by the membrane radius, $m_g \sim 1/r_0$, and so are strongly Yukawa-suppressed inside the cylinder. The KK vectors do not couple to light matter directly. The scalar has a non-vanishing *vev* $\Phi \sim r_0$ and varies very slowly along the direction normal to the wall, memorizing that the background is really a 5D cone. Its *vev* sets 4D Planck mass, by the usual Gauss law $M_4^2 = M_5^3 \Phi \sim M_5^3 r_0$. In vacuum, its fluctuations would couple gravitationally to matter. However, inside matter distributions this field may be screened by a combination of the environmental effects [5,6] and quantum-mechanical effective potentials [7].

Farther out the cone opens up. In dimensionally reduced theory, this shows up as the scalar field increases with distance,

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making 4D gravity weaker and the KK mass gap smaller. We no longer can ignore the gravitons moving around the circle, and their contributions begin to change the force. Eventually these infra-red modifications change the theory back to a 5D theory on a cone. This could have interesting observational consequences.

We start out with a thin membrane in an empty 5D space-time, with a tension λ. Its gravitational equations are, in a membrane-fixed Gaussian-normal gauge [3,8],

$$M_5^3 G_5{}^A{}_B = -\lambda \delta^\alpha{}_\beta \delta^A{}_\alpha \delta^\beta{}_B \delta^{(2)}(\vec{y}). \tag{1}$$

The indices $A, B, \ldots$ run over 5D and $\alpha, \beta, \ldots$ run over the 3D membrane worldvolume, G_{AB} is the 5D Einstein tensor, δ-function is the tensor $\delta^{(2)}(\vec{y}) = \frac{\sqrt{g_3}}{\sqrt{g_5}} \Pi \delta(y_i)$, and (y_1, y_2) coordinatize the transverse space. A flat membrane, with metric $g_{\alpha\beta} = \eta_{\alpha\beta}$, is a solution of Eq. (1) when the transverse space is a cone [3], whose metric is

$$ds_5^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta + dr^2 + \left(1 - \frac{\lambda}{2\pi M_5^3}\right)^2 r^2 d\phi^2. \tag{2}$$

The deficit angle depends on the tension as $\Delta\phi = \frac{\lambda}{M_5^3}$. The solution (2) is not well defined at the critical value of the tension $\lambda_{\rm cr} = 2\pi M_5^3$, when it becomes degenerate. It is not clear what (2) describes for the super-critical tensions $\lambda > 2\pi M_5^3$, since there is no limit connecting such solutions to the vacuum. This puzzle also appears for cosmic strings in 4D. It is resolved by regulating the thin string with a finite core [9].

We do the same here, and replace the thin membrane by a tensional 3-brane wrapped on a circle, as in braneworld setups [10–12]. To wrap a tensional 3-brane up and make it look like a hollow membrane, we must cancel the pressure $\propto \lambda_4$ on the circle. For this we put an axion field Σ on the 3-brane, whose vacuum action is

$$S_{\rm vacuum} = -\int d^4x \sqrt{g_4}\left(\lambda_4 + \frac{1}{2}(\partial\Sigma)^2\right). \tag{3}$$

Since the vacuum stress energy tensor is $T^a{}_b = -\lambda_5 \delta^a{}_b + \partial^a\Sigma \partial_b\Sigma - \frac{1}{2}\delta^a{}_b g^{cd}\partial_c\Sigma\partial_d\Sigma$, with lower case latin indices running over the 3-brane worldvolume, we can take $\Sigma_0 = q\phi$ and pick the 'charge' q to obey $q^2 = 2r_0^2\lambda_4$, where r_0 is the radius of the cylindrical brane. This cancels the tensional pressure on the circle. In a more realistic model of a thick membrane, this tuning of q vs. r_0 should be replaced by a calculation of r_0 for a given field configuration that resolves the core. For a thin membrane we rewrite $\delta^{(2)}(\vec{y})$ in polar coordinates, using axial symmetry, as $\delta^{(2)}(\vec{y}) = \frac{1}{2\pi r}\delta(r)$. Shifting the argument to $r - r_0$ to model a thick hollow membrane, with the source $\delta^{(2)}_{\rm thick}(\vec{y}) = \frac{1}{2\pi r_0}\delta(r - r_0)$ we are led to identify $\lambda = 4\pi r_0 \lambda_4$. The effective membrane tension λ includes the contributions of the axion Σ. The field equations (1) thus change to

$$M_5^3 G_5{}^A{}_B = T^a{}_b \delta^A{}_a \delta^b{}_B \delta(r - r_0). \tag{4}$$

The stress energy tensor $T^a{}_b = -\frac{\lambda}{2\pi r_0}\delta(r - r_0)\,{\rm diag}(1, 1, 1, 0)$ is covariantly conserved, and supports a solution which looks like a truncated cone for small tensions, ending on the brane

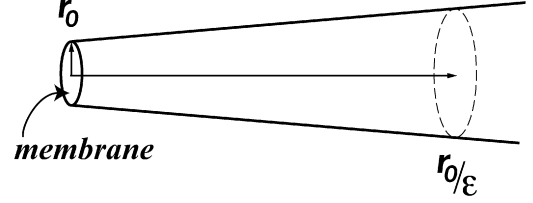Fig. 1. 2D conical transverse geometry of a thick membrane vacuum.

at $r = r_0$ [12]. If we introduce a parameter ε which measures the deficit angle according to $\varepsilon = 1 - \frac{\lambda}{2\pi M_5^3}$, such that $\Delta\phi = 2\pi(1 - \varepsilon)$, we can write the metric solution as

$$ds_5^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta + dr^2 + \big[(1 - (1 - \varepsilon)\Theta(r - r_0))r + (1 - \varepsilon)r_0\Theta(r - r_0)\big]^2 d\phi^2, \tag{5}$$

where $\Theta(x)$ is the Heaviside step function.

In the critical membrane limit $\lambda_c = 2\pi M_5^3$, so that $\varepsilon = 0$. In this limit, the exterior geometry of (5) deforms into a semi-infinite cylinder of constant radius, equal to the membrane thickness. This cylindrical throat looks like a 4D spacetime, at all distances $\ell > r_0$, compactified by the critical membrane tension. On the other hand, the supercritical solutions $\varepsilon < 0$ are singular at $r = \frac{1 + |\varepsilon|}{|\varepsilon|} r_0 > r_0$, outside of the membrane, and so they spontaneously compactify on a 2D teardrop, similar to [13]. So supercritical vacua (5) look like 3D spacetimes. Therefore static, flat, lonely branes in infinite space only occur for $\lambda \leqslant \lambda_c$.

Here we will be most interested in near-critical membranes, with $0 < \varepsilon \ll 1$. Their surroundings looks like a truncated conical sliver in Fig. 1. The exterior metric is

$$ds_5^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta + dr^2 + \big(r_0 + \varepsilon(r - r_0)\big)^2 d\phi^2. \tag{6}$$

It approximates a cylinder for distances $r_0 \lesssim \ell \lesssim r_0/\varepsilon$, because the radius of the sliver changes very little in this regime. To make the cylindrical throat in Fig. 1 very long, the tension must be very close to the critical tension $\lambda_{\rm cr} = 2\pi M_5^3$, to get $\varepsilon \ll 1$.

Since the vacuum (5) is axially symmetric, we can dimensionally reduce the 5D theory to 4D, and explore it using effective field theory methods. For simplicity, we take

$$S = \int d^5x \sqrt{g_5}\left(\frac{M_5^3}{2}R_5 - \mathcal{L}_{\rm matter}\right)$$
$$- \int_{r=r_0} d^4x \sqrt{g_4}\left(\lambda_4 + \frac{1}{2}(\partial\Sigma)^2\right)$$
$$+ \text{boundary terms}, \tag{7}$$

which describes full 5D gravity and matter, and a wrapped 3-brane of radius r_0, with tension and axion Σ. We could also add another 3-brane, orthogonal to the tensional brane in (7), to localize additional light 4D matter fields, and avoid matter KK partners. For the time being we will work with (7), but will elaborate this later on. In (7), the boundary terms covariantize membrane's gravitational couplings. Any axially symmetric deformations of (5), that describe axially symmetric fluctuations

of the radius of the sliver and its shear relative to the membrane, will play the role of light fields in the gravitational sector upon reduction to 4D. They are encoded in

$$ds_5{}^2 = g_{\mu\nu}(x^\mu)\,dx^\mu\,dx^\nu + \Phi^2(x^\mu)\big(d\phi - V_\mu(x^\mu)\,dx^\mu\big)^2. \quad (8)$$

Here we have *recombined* the longitudinal membrane coordinates x^α and the transverse coordinate r together, into a chart of a 4D spacetime: $x^\mu = \{x^\alpha, r\}$. Treating ϕ-dependence of all the fields perturbatively, and expanding them in Fourier series

$$\Psi_{\{\mathcal{N}\}}(x^\mu, r_0\phi) = \sum_{n=-\infty}^{\infty} \Psi_{\{\mathcal{N}\},n}(x^\mu) e^{in\phi}, \quad (9)$$

we can rewrite (7) as a 4D theory with KK towers of fields, with masses $M^2 = m^2 + n^2 m_g^2$, where m are 5D mass terms and m_g are mass gaps. The label $\{\mathcal{N}\}$ denotes different 4D representations of 5D fields. For membrane-borne fields, the mass gap is just $m_g = 1/r_0$. For the 5D matter fields, the mass gap is set by the radius of the circle to $m_g = \Phi_0^{-1}$. Inside the cylindrical throat, at distances $r_0 \lesssim \ell \lesssim r_0/\varepsilon$, the gap is $m_g \sim 1/r_0$ and these states will be strongly Yukawa-suppressed, $\propto e^{-M\ell} \ll 1$. So in this regime we can neglect all the heavy KK states. The light ones behave as our 4D degrees of freedom. As distance increases, the background value Φ_0 grows, and so the gap eventually disappears. At very large distances $\ell \gg r_0/\varepsilon$ we cannot ignore the KK towers any more. In that limit, the theory reveals the fifth dimension.

Thus inside the cylindrical throat (5) we can truncate (7) to only the light fields, and get

$$S_{\text{4D eff}} = \int d^4x \sqrt{g_4}\Big(\pi M_5^3 \Phi R_4 - \frac{1}{4}\Phi F_{\mu\nu}^2 - 2\pi\Phi\mathcal{L}_{\text{matter}}\Big)$$
$$- \int\limits_{r=r_0} d^3x \sqrt{g_3}\bigg(\frac{\lambda}{2}\Big(\frac{\Phi}{r_0} + \frac{r_0}{\Phi}\Big) + \pi\Phi(D_\alpha\sigma)^2\bigg)$$
$$+ \text{boundary terms}, \quad (10)$$

in the membrane-fixed gauge. Here $F_{\mu\nu}$ is the field strength of the Abelian KK vector field $A_\mu = (\pi M_5^3)^{1/2} V_\mu$, $\sigma = \Sigma - \Sigma_0$ is the lightest, axially symmetric, axion field fluctuation on the membrane, and $D_\alpha\sigma = \partial_\alpha\sigma + qA_\alpha/(\pi M_5^3)^{1/2}$ is its Stückelberg gauge-covariant derivative. In evaluating (10) we have used $\Sigma_0 = q\phi$, where $q^2 = 2r_0^2\lambda_4$, and the relationship between λ and λ_4 given in the text before Eq. (4). The matter fields in $\mathcal{L}_{\text{matter}}$ couple minimally to the metric $g_{\mu\nu}$ and multiplicatively to Φ, as is manifest in (10). The light fields, except σ, are KK gauge singlets. The heavy KK states are not, but in the regime we are exploring they play no role. From (10), σ is a Stückelberg field of A_μ, localized on the membrane. In a unitary gauge, given by $\hat{A}_\mu = A_\mu + (\pi M_5^3)^{1/2}\partial_\mu\sigma/q$, this term is just the membrane-localized mass term for $\hat{A}_\mu$. So light matter is decoupled from $\hat{A}_\mu$ in the leading order, and we can drop it from further consideration as mostly harmless.

This leaves the graviton and the light Brans–Dicke-like scalar Φ, whose action reduces to

$$S_{\text{4D eff}} = \int d^4x \sqrt{g_4}\big(\pi M_5^3 \Phi R_4 - 2\pi\Phi\mathcal{L}_{\text{matter}}\big)$$
$$- \frac{\lambda}{2}\int\limits_{r=r_0} d^3x \sqrt{g_3}\Big(\frac{\Phi}{r_0} + \frac{r_0}{\Phi}\Big)$$
$$+ \text{boundary terms}. \quad (11)$$

This is a scalar-tensor gravity non-minimally coupled to matter and to the membrane. At distances $\ell > r_0$ the membrane looks like a domain wall at the end of the universe. When the matter fields are in the vacuum, so $\mathcal{L}_{\text{matter}} = 0$, the field equations which come from the action (11) admit the flat space solution $g_{0\mu\nu} = \eta_{\mu\nu}$ when $\Phi|_{r=r_0} = r_0$, reducing to a single equation for the scalar field $\pi M_5^3 \partial^2 \Phi = -\frac{1}{2}\lambda\delta(r - r_0)$. Choosing $\Phi|_{r=0} = 0$ by using the Gauss law inside the membrane, we recover $\Phi_0 = (1 - (1 - \varepsilon)\Theta(r - r_0))r + (1 - \varepsilon)r_0\Theta(r - r_0)$, as expected. We focus only on the boundary conditions inherited from 5D because (11) is just a tool to study the IR dynamics of the original 5D theory.

To see how matter gravitates in the throat, we go to the Einstein frame, corresponding to the normal modes description of (11). We define the dimensionless scalar $\hat{\phi} = \Phi/r_0$ and 4D Planck mass $M_4^2 = 2\pi M_5^3 r_0$, and go to the new variables by $\hat{\phi} = \exp(\sqrt{\frac{2}{3}}\frac{\varphi}{M_4})$, and $g_{\mu\nu} = \exp(-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4})\bar{g}_{\mu\nu}$. Redefining the matter Lagrangian by $2\pi r_0 \mathcal{L}_{\text{matter}} \to \mathcal{L}_{\text{matter}}$, we get

$$S_{\text{4D eff}} = \int d^4x \sqrt{\bar{g}_4}\bigg(\frac{M_4^2}{2}\bar{R}_4 - \frac{1}{2}(\bar{\nabla}\varphi)^2$$
$$- e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4}}\mathcal{L}_{\text{matter}}\Big(e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4}}\bar{g}_{\mu\nu}\Big)\bigg)$$
$$- \frac{\lambda}{2}\int\limits_{r=r_0} d^3x \sqrt{\bar{g}_3}\,e^{-\sqrt{\frac{3}{2}}\frac{\varphi}{M_4}}\Big(e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4}} + e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_4}}\Big)$$
$$+ \text{boundary terms}. \quad (12)$$

To get the background solutions for the Einstein frame fields φ and $\bar{g}_{\mu\nu}$ we substitute in the redefinitions the expressions for $\hat{\phi}_0$ and $g_{0\mu\nu} = \eta_{\mu\nu}$. The short-distance singularities in these variables, present because $\exp(\sqrt{\frac{2}{3}}\frac{\varphi_0}{M_4}) \sim r/r_0$ and $d\bar{s}_0^2 \sim \frac{r}{r_0}(\eta_{\alpha\beta}dx^\alpha dx^\beta + dr^2)$, are harmless, because the scalar is really a shrinking polar radius of the fifth dimension, describing how the full 5D metric approaches Minkowski space in the membrane core.

As it stands, the theory (12) is phenomenologically problematic. To see why, consider the scalar field equation. By varying (12), and denoting the membrane term by $\lambda(\varphi)$, it is

$$\nabla^2\varphi = \frac{\partial\lambda(\varphi)}{\partial\varphi}\sqrt{\frac{\bar{g}_3}{\bar{g}_4}}\delta(r - r_0)$$
$$+ \frac{1}{\sqrt{6}M_4}e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4}}(\bar{T} + 2\mathcal{L}_{\text{matter}}), \quad (13)$$

where $\bar{T}$ is the trace of the matter stress energy tensor, defined by the variation of the matter action as $\delta S_{\text{matter}} = \frac{1}{2}\int d^4x \sqrt{\bar{g}_4}\exp(-\sqrt{\frac{2}{3}}\frac{\varphi}{M_4})\bar{T}^{\mu\nu}\delta\bar{g}_{\mu\nu}$. The Lagrangian term $\mathcal{L}_{\text{matter}}$ appears due to non-minimal couplings in the action (12),

as is known from [14], but can be handled easily. It behaves as pressure, and for non-relativistic sources, it can be neglected relative to $\bar{T}$. The membrane terms set field gradients in the vacuum, controlling the very long range asymptotics far from matter thanks to the codimension-1/codimension-2 membrane dynamics (after/before reduction, respectively), and the fact that the fields outside of local sources decrease with distance. On the other hand, they do not play a significant role in the local source dynamics far from the membrane. Neglecting them, we see that φ, as it stands in (12), is too light and gravitationally coupled.

However in physically realistic situations quantum corrections may generate an effective potential for φ. For example, in conical spaces quantum corrections may generate potentials, that would depend on the logs of fields, including $V_{\text{eff}} \sim \ln(\Phi)^{-1}$ in 5D [7]. After dimensional reduction, and with the overall conical radius being held up by the membrane, a relevant correction from such a potential may be $V_{4D\,\text{eff}} \sim -\mu^5/\ln(\hat{\Phi})$, where μ is a scale which depends on the conical radius r_0 and 5D Planck scale M_5. In the Einstein frame, this may yield an extra term $V_{4D\,\text{eff}}^E = -\mu^5/(\varphi + v_0)$, for some scale v_0, chosen so that this potential is small near the classical vacuum $\varphi = 0$.

Further, we can use the conservation of the stress-energy tensor, and apply it to non-relativistic sources. It is $\bar{\nabla}_\mu \times (\exp(-\sqrt{\frac{\phi}{M_4}})\bar{T}^{\mu\nu}) = 0$. For non-relativistic sources, with our conventions $\bar{T}^{00} \simeq \bar{\rho}$, while all other components of stress energy tensor, and the Lagrangian itself, vanish in the leading order. So the conservation equation yields that the conserved quantity independent of φ, which in the φ-equation plays the same role as the centrifugal barrier term in the central force problem, is $\rho = \exp(-\frac{\varphi}{\sqrt{6}M_4})\bar{\rho}$. Then, after adding the effective potential, dropping the membrane term and replacing $\bar{T}^{\mu\nu}$ by $\propto \rho$ terms, Eq. (13) near mass distributions becomes

$$\nabla^2 \varphi = -\frac{\rho}{\sqrt{6}M_4}e^{-\frac{\varphi}{\sqrt{6}M_4}} + \frac{\partial V_{4D\,\text{eff}}^E}{\partial \varphi}. \qquad (14)$$

Inside mass distributions, *vev* of φ shifts from its vacuum to a φ_*, where the right-hand side of (14) vanishes. Around this shifted background, small perturbations of φ become massive, with the effective mass given by $m_{\text{eff}}^2 = \frac{\partial^2 V_{4D\,\text{eff}}^E}{\partial \varphi_*^2} \sim \frac{\rho^{3/2}}{M_4^{3/2}\mu^{5/2}}$. This may screen most of the interior of the distribution ρ from enacting a large long-range scalar force, allowing only a force from a thin outer layer of thickness $1/m_{\text{eff}}$ [6]. Also, the total shift of φ from its vacuum value should be much smaller than M_4 in order to avoid conflicts with bounds on the variation of Newton's constant.

Having μ in this formula helps; it cannot be too large since in that case the screening mass for φ would be too small. In fact, to pass the terrestrial table-top bounds, for example, the scale μ must obey, roughly, $\mu < 0.1$ eV, implying that the potential $V_{4D\,\text{eff}}^E$ had better be very small. While calculating this potential explicitly is beyond the scope of the present work, there exist some ideas for how such small potentials could be obtained [7,

15–17], after a suitable subtraction of UV divergences. Other scenarios, where gravitational light scalars decouple due to environmental effects, were discussed in [5].

We get more bounds from requiring that the theory looks 4D at observationally accessible scales. If our matter comes from the reduction of a 5D action, then KK mass gap must be $\mathcal{O}(\text{TeV})$, or $r_0 \lesssim 10^{-18}$ m, to conform with collider bounds. If we also require that gravity is 4D out to the horizon scale (which may be too conservative), $r_0/\varepsilon \gtrsim H_0^{-1} \sim 10^{26}$ m. These bounds combine into $\varepsilon \lesssim 10^{-44}$, implying that the deficit angle must be extremely close to 2π. As we noted, this may occur if the UV cutoff of the theory on the membrane is extremely close to 5D Planck scale. If so, this value, once set, may not change so much by subsequent radiative corrections. In this case KK mass scale is in the LHC reach, while $M_5 \sim 10^{14}$ GeV is close to M_{GUT}. If we take an additional 3-brane in the bulk, with zero tension so it does not disturb the background, and let the light matter including the Standard Model live on it, we can raise r_0 up to the table-top gravity bound of 10^{-4} m. Then 5D Planck scale is $M_5 \sim 10^9$ GeV. In this case, matter couples differently to Φ, but similar environmental decoupling mechanisms may still neutralize the scalar force.

The background (5) has a preferred direction, given by the outward normal to the membrane. As we move away from the membrane, both the particle physics couplings, controlled by the slowly varying Φ_0, and the geometry will change. Thus Lorentz and translational symmetries are broken by the membrane's gravitational field. Similar Lorentz violations have been noted recently in [18]. In our example, this is how the background memorizes that it is a part of a conical space in 5D. The breaking is tied to the scale of gravity modification, and so it is small. However this opens up an interesting possibility, that both Lorentz symmetry is broken and gravity is modified at cosmological scales. One might use such backgrounds to model cosmologies with a preferred direction, as in [19]. Alternatively, one may be able to constrain such Lorentz breaking and gravity modification from cosmological data.

To sum up, we have outlined a novel way to hide a spatial dimension at short and intermediate scales, but let it reopen at cosmological scales. The theory at distances $r_0 \lesssim \ell \lesssim r_0/\varepsilon$ looks like a scalar-tensor gravity with a membrane at the end of the world. The scalar long range force may be suppressed by a combination of environmental effects and an effective potential from quantum corrections. In that case, the theory may yield interesting correlations between gravity modifications and Lorentz breaking at cosmological scales, while remaining consistent with current bounds. It would be of interest to explore this mechanism further.

Acknowledgements

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