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The warped dark sector

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ABSTRACT

Five-dimensional braneworld constructions in anti-de Sitter space naturally lead to dark sector scenarios in which parts of the dark sector vanish at high 4d momentum or temperature. In the language of modified gravity, such feature implies a new mechanism for hiding light scalars, as well as the possibility of UV-completing chameleon-like effective theories. In the language of dark matter phenomenology, the high-energy behavior of the mediator sector changes dark matter observational complementarity. A multitude of signatures—including exotic ones—are present from laboratory to cosmological scales, including long-range forces with non-integer behavior, periodic signals at colliders, "soft bombs" events well-known from conformal theories, as well as a dark phase transition and a typically small amount of dark radiation.

1. Introduction

Decades of astronomical observations point to the existence of dark matter (DM) and dark energy (DE). It is a pressing question in fundamental physics to determine how these connect to the standard models of particle physics and cosmology. Both DM and DE may suggest the existence of low-mass particles with weak interactions to visible matter. The physics of such a *dark sector* is the target of a new frontier of particle experiments [1,2].

In this Letter we present a framework for a dark sector based on a truncated, warped extra dimension. Unlike the conventional Randall–Sundrum scenario, visible matter is localized on the ultraviolet (UV) brane. Dark particles are localized on the infrared (IR) brane and interact with the visible sector through a 5d bulk mediator particle (see Fig. 1). Recently it was shown that the IR brane becomes inaccessible to bulk fields with large absolute *four*-momentum due to 5d gravitational dressing [3]. As a result, high-energy experiments do not see the IR-localized particles and can only probe the mediator's near-continuum. A qualitatively similar behavior is known to occur at finite temperature, where a phase transition replaces the IR brane by an AdS-Schwarzchild black hole [4].

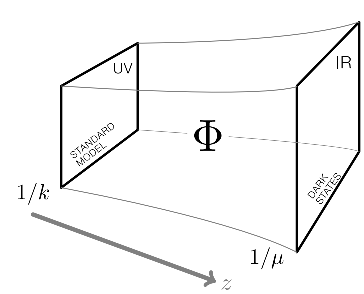

Fig. 1. The warped dark sector: The "visible" sector (*i.e.* the SM) lies on the UV brane of a slice of AdS_5, while bulk and IR-brane localized degrees of freedom form the dark sector.

Through the AdS/CFT correspondence, our setting describes a strongly interacting and nearly-conformal sector coupled to the SM, which develops bound states at low-energy, *i.e.* our setup is the AdS dual of a *composite dark sector* scenario.

Our dark sector scenario may be applied to constructing a theory of dark matter and a theory of modified gravity. The scenario offers diverse and abundant observable phenomena; some are new, others have been mentioned in the vast extra dimensional and CFT literature. Our proposal sheds new light on these phenomena by connecting them in a unified theoretical framework and by making use of the precise quantitative developments which are possible in 5d.

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Dark sector constructions with a flat extra dimension have recently been proposed in [5–7]. Unlike these models, our scenario builds on properties that are unique to AdS space. Our proposal also differs from earlier warped constructions made in [8–11]. In these models, Dark Matter is on the UV brane, no states are on the IR brane, and the bulk mediator is an abelian gauge field. The CFT portal model of [12] is also similar to constructions with DM on the UV brane. The bulk mediator phenomenology developed in the present work mostly differ from those studied in these references. Early work on 5d Kaluza-Klein dark matter and on secluded sectors include [13–20]. See also [21] for a recent application to axion model-building.

2. AdS space and IR opacity

The stabilization of curved, truncated background has been studied at length, see e.g. [22]. We consider a slice of AdS space in the Poincaré patch with conformal coordinates, in which the metric is

$$ds^2 = \gamma_{MN} dX^M dX^N = (kz)^{-2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2) \tag{1}$$

where $\eta_{\mu\nu}$ is Minkowski metric with $(+,-,-,-)$ signature. The fifth dimension is assumed to be compact with $z \in [z_0, z_1]$, where $z_0 \equiv 1/k$, $z_1 \equiv 1/\mu$ are respectively referred to as UV and IR branes. The AdS scale k is taken to be $O(M_{\rm Pl})$ and the IR scale μ is a free parameter that may be very different than the TeV scale. We define the *warp factor* $\varepsilon = \mu/k$.

We focus on a scalar field propagating in the 5d spacetime. The 5d action is

$$S = \int dX^M \left[\sqrt{\gamma}\left(\frac{1}{2}\nabla_M \Phi \nabla^M \Phi - \frac{1}{2} m_\Phi^2 \Phi^2 + \mathcal{L}_{\rm int}\right) + \sqrt{\bar\gamma}\mathcal{L}_{\mathcal{B}}\right] \tag{2}$$

where $\mathcal{L}_{\mathcal{B}}$ contains brane-localized Lagrangians and $\bar\gamma_{\mu\nu}$ is the induced metric on the branes, $\sqrt{\bar\gamma} = (kz)^{-4}$. We assume brane-localized mass terms,

$$\mathcal{L}_{\mathcal{B}} = -\frac{1}{2}\Phi^2 k\big(\delta_{z,z_0}(2-\alpha+b_{\rm UV}) - \delta_{z,z_1}(2-\alpha+b_{\rm IR})\big) \tag{3}$$

with $\delta_{u,v} \equiv \delta(u-v)$. The special case $b_i = 0$ for a given brane i is compatible with the BPS condition $V_{\rm bulk} = (\partial V_i/\partial\phi)^2 - V_i$, with V_i the potential on brane i. The Feynman propagator is

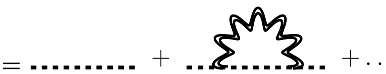
$$\langle \Phi(p,z)\Phi(-p,z')\rangle \equiv \Delta(p;z,z') = i\frac{\pi k^3 (zz')^2}{2} \times \frac{\left[\tilde Y_\alpha^{\rm UV} J_\alpha(pz_<) - \tilde J_\alpha^{\rm UV} Y_\alpha(pz_<)\right]\left[\tilde Y_\alpha^{\rm IR} J_\alpha(pz_>) - \tilde J_\alpha^{\rm IR} Y_\alpha(pz_>)\right]}{\tilde J_\alpha^{\rm UV}\tilde Y_\alpha^{\rm IR} - \tilde Y_\alpha^{\rm UV}\tilde J_\alpha^{\rm IR}} \tag{4}$$

where $z_< = \min(z,z')$, $z_> = \max(z,z')$ and $p = \sqrt{p^\mu p_\mu}$ is real for timelike four-momentum p^μ and imaginary for a spacelike one. The coefficients

$$\tilde J_\alpha^{\rm UV,IR} = pk^{-1} J_{\alpha-1}(pk^{-1}) - b_{\rm UV,IR} J_\alpha(pk^{-1}) \tag{5}$$

are set by the boundary conditions. Further details on propagators can be found in e.g. [23,24].

The propagator tends to be exponentially suppressed for $z_> \gg 1/|p|$ *i.e.* in the IR region of the bulk, an AdS property with no flat-space equivalent. This behavior has been long-known for spacelike momentum [25]. It has been recently shown that the suppression also occurs for timelike momentum, which is relevant for s-channel processes [3]. This is a result of the dressing from 5d interactions, including from 5d gravity,

$\Delta^{\rm dr}(p;z,z') =$ 

$$\approx \Delta(p(1+ic);z,z') \propto e^{-cpz_>} \quad \text{if} \quad pz_> \gg 1\,. \tag{6}$$

The c coefficient, estimated in [3], comes from the imaginary part of the self energy resulting from the decay of the bulk scalar into AdS gravitational excitations via the optical theorem. For a first order phenomenological picture, it is enough to take c as a $O(0.1-1)$ free parameter.

Interestingly, the exponential suppression plays the role of a censor for the IR region $p \gg 1/z_>$, which is the region where the 5d EFT breaks down [3,26]. From the viewpoint of the UV brane, an observer producing Φ with timelike momentum sees a series of Kaluza-Klein (KK) modes becoming broader and broader and tending to a smooth continuum for $p \gg \mu$ (see Fig. 3).

3. The warped dark sector

The fact that the IR region of the bulk becomes opaque for $p \gtrsim 1/z_>$ opens a tantalizing possibility of dark sector scenario. The SM may lie on the UV brane while additional dark particles, such as DM, may lie on the IR brane where the natural mass scale is $O(\mu)$. The branes communicate via a bulk field chosen to be a scalar Φ and described by the Green's function given in previous section. The action describing these interactions takes the form

$$S \supset \int dX^M \left(\frac{\lambda}{\sqrt{k}}\mathcal{O}_{\rm SM}\Phi\delta_{z,z_0} + \frac{\kappa}{\sqrt{k}}\mathcal{O}_{\rm D}\Phi\delta_{z,z_1}\right). \tag{7}$$

The IR-brane degrees of freedom and the bulk mediator together form the dark sector.

The key parameters in this framework are the dark sector scale μ, the bulk mass parameter α which determines the KK mode profiles and thus the coupling to the SM brane, and the $b_{\rm UV} \equiv b$ parameter which is taken to be either 0 (BPS case) or $O(1)$ (non-BPS case). The other parameters are given values suggested by dimensional analysis, including $b_{\rm IR} = O(1)$. For $b = O(1)$, the bulk field couples weakly to the UV brane. For $b = 0$, this coupling can be larger.

Let us first study the low-energy behavior, $p < \mu$. The bulk field is integrated out and the physics is described by a 4d EFT. When $b \neq 0$, the effective operators have the following magnitudes,

$$\mathcal{L}_{4d} \sim \lambda^2 \frac{1}{k^2}(\mathcal{O}_{\rm SM})^2 + \lambda\kappa\frac{\varepsilon^{|\alpha|}}{k\mu}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm D} + \kappa^2\frac{1}{\mu^2}(\mathcal{O}_{\rm D})^2\,. \tag{8}$$

For $b = 0$ and $\alpha < 1$, the effective operators behave instead as

$$\mathcal{L}_{4d} \sim \lambda^2 \frac{\varepsilon^{2-2\alpha}}{\mu^2}(\mathcal{O}_{\rm SM})^2 + \lambda\kappa\frac{\varepsilon^{1-\alpha}}{\mu^2}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm D} + \kappa^2\frac{1}{\mu^2}(\mathcal{O}_{\rm D})^2\,. \tag{9}$$

For $b = 0$ and $\alpha > 1$, an ultralight mode with mass $m_0 \sim \mu\varepsilon^{\alpha-1}$ is also present in the spectrum, however this is not the focus of this letter. While the dark sector always has strong self-interactions, the effective SM-dark sector coupling $\mathcal{L} \supset \Lambda^{-2}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm D}$ naturally ranges from strong ($\Lambda \sim \mu$) to extremely small as a result of the localization of Φ—which is controlled by α.

At high energy, $p \gg \mu$, the IR region becomes opaque [3]. The correlators between UV and IR branes are suppressed for both timelike and spacelike momentum,

$$\langle \mathcal{O}_{\rm SM}\mathcal{O}_{\rm D}\rangle \propto \left\{e^{-cp/\mu} \text{ if } p^2 > 0\,,\ \ e^{-p/\mu} \text{ if } p^2 < 0\right\}. \tag{10}$$

This behavior is totally different from a UV completion of the 4d EFT by 4d mediators, a standard scenario in the dark sector literature. Here the number of 4d mediators is infinite and their

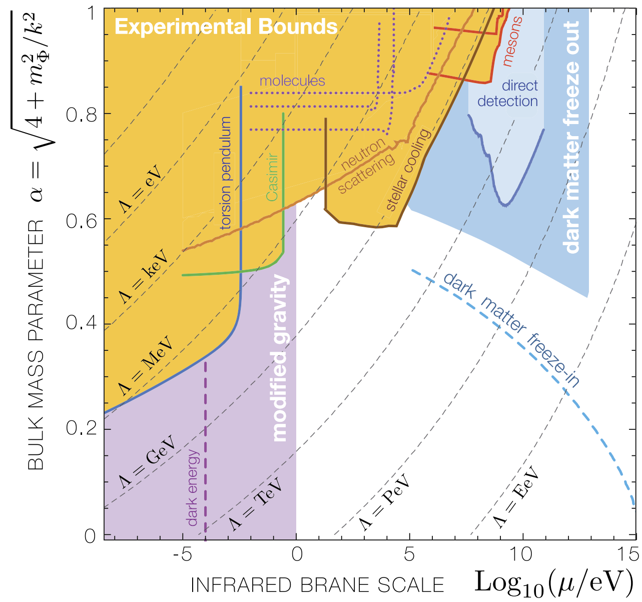


Fig. 2. Scales and scenarios in the BPS (*i.e.* $b = 0$) case. Particles on the IR brane have $O(\mu)$ mass and Λ is the SM-dark sector coupling, $\mathcal{L} \supset \frac{1}{\Lambda^2}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm dark}$. The orange region is excluded by measurements of processes involving the bulk mediator (see Sec. 6). Regions compatible with dark matter and modified gravity scenarios are also shown.

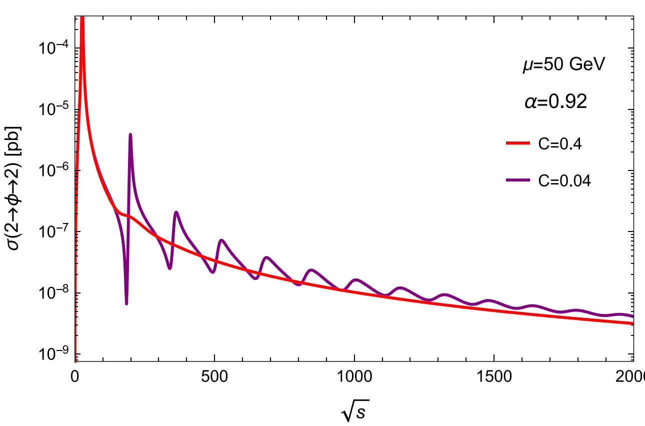


Fig. 3. Example of periodic signal in SM $\to \Phi \to$ SM. Both bumps and dips are present. Interference with the SM is not shown and could dominate the signal.

couplings are set by the theory such that destructive interference occurs, rendering the IR region inaccessible.

The SM-to-SM amplitudes are also important for phenomenology. At $p \gg \mu$ they behave as if there was no IR brane, for instance

$$\langle \mathcal{O}_{\rm SM}\mathcal{O}_{\rm SM}\rangle \propto i\left[bk + (b+2\alpha)k\left(\frac{p}{2k}\right)^{2\alpha}\frac{\Gamma(-\alpha)}{\Gamma(\alpha)}\right]^{-1} \qquad (11)$$

for $b \neq 0$, $\alpha > 0$. This result can be exactly reproduced with a CFT model where the SM operator couples to a massive source ϕ_0 mixing with a CFT operator $\mathcal{O}_{\rm CFT}$ of conformal dimension $\Delta = 2 + \alpha$ [24,27].

The *warped dark sector* can be envisioned as UV completion of low-scale 4d EFTs and is interesting as a DM or DE scenario. In this Letter we focus only on a hadronic coupling, with $\mathcal{O}_{\rm SM} \equiv \bar{N}N$ below the QCD scale. As a direct consequence of opacity, the low-energy SM–dark sector coupling $\mathcal{L}_{4d} \supset \Lambda^{-2}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm D}$ is only moderately restricted by experimental tests from the $p > \mu$ regime. The experimentally allowed values of Λ are shown in Fig. 2. For example, the red giant bound vanishes below $\mu \sim 100$ eV as a result of opacity, such that a model with for instance $\mu \sim 10$ eV, $\Lambda \sim 1$ MeV is *not* excluded experimentally. Improvements in molecular bounds or neutron scattering would be needed to probe such region.

4. Modified gravity

The question of how to hide a light scalar has generated significant activity over the last decade [28,29]. A few mechanisms are known, such as the chameleon [30] and Vainshtein mechanisms [31]. Our setup introduces a new, geometric way to hide a scalar φ: the IR brane where the scalar lives is ineluctably out of reach in the UV. There are multiple model-building possibilities.

An attractive scenario is to have $f(R)$ gravity on the IR brane. After a Weyl transform this results in a scalar φ coupled to the stress-energy tensor of Φ evaluated on the IR brane. At low-energy the Φ fields can be integrated out at loop-level, leaving a 4d EFT containing φ and the SM. This interesting case is not treated further here.

A more minimal possibility is that the bulk field shares a bilinear term with a brane scalar $\mathcal{O}_{\rm dark} \equiv \varphi$, i.e. $\mathcal{L} \supset \delta_{z,z_1}k^{-1/2}\omega\Phi\varphi$ with $\omega = O(\mu^2)$. This case can be treated exactly by noting that φ dresses the bulk field such that

$$\langle \Phi(p,z)\Phi(-p,z')\rangle = \Delta^{\rm dr}(p;z,z') - \qquad (12)$$
$$\Delta^{\rm dr}(p;z,z_1)\Delta^{\rm dr}(p;z_1,z')\frac{i\omega^2}{p^2 - m_\varphi^2 + i\omega^2\Delta^{\rm dr}(p;z_1,z_1)}\,.$$

For $p < \mu$ the Φ propagators are constant and Eq. (12) contains the light scalar pole with mass squared $\sim m_\varphi^2 - i\omega^2\Delta^{\rm dr}(m_\varphi;z_1,z_1)$ and a contact interaction—notice these features can be matched onto the 4d EFTs described in Eqs. (8)-(9). In contrast, at $p > \mu$ the $\Delta^{\rm dr}(p;z,z_1)$ propagators vanish exponentially, such that only the $\Delta^{\rm dr}(p;z,z')$ term remains. For instance, when considering the nonrelativistic spatial potential between $\mathcal{O}_{\rm SM}$ operators—given by $\langle\Phi(p,z_0)\Phi(-p,z_0)\rangle$, Eq. (12) interpolates between a $\sim 1/r$ potential at distances $r > 1/\mu$ and a short range, non-integer behavior at $r < 1/\mu$ (see details in Sec. 6).

Finally our framework may also be used to UV complete models with a screening mechanism, such as chameleon or symmetron models (see *e.g.* [30,32–34]), that are otherwise ad-hoc low-energy EFTs with no obvious UV completion.

5. Dark matter

The observed abundance of DM can be explained by the existence of a sufficiently stable dark particle. Historically favored models of weakly interacting massive particles motivated by theories of electroweak naturalness are in tension with searches. A compelling alternative is the secluded dark matter framework where DM interacts with visible matter through a low-mass mediator particle [2,35]. Such a possibility is naturally realized in our warped framework, Eq. (7), by identifying $\mathcal{O}_{\rm D} = \bar{\chi}\chi$ where the DM particle χ is assumed to be a Dirac fermion localized on the IR brane.

A natural scale for the DM mass is $m_\chi \sim 4\pi\mu$ while the lightest KK mode of the mediator, Φ, has $O(\mu)$ mass. The p-wave t-channel annihilation of dark matter into the first KK mode(s) controls DM thermal production in the early universe and its subsequent present-day abundance. In turn, the properties of the mediator control the experimental signatures. However, because of the properties of AdS space, these signatures differ significantly from those of standard 4d scalar mediators [36]. The resulting experimental fingerprint thus contrasts the benchmarks of experimental complementarity in dark matter searches.

There are essentially *no* missing energy events at colliders for $|p| \gg \mu$. The annihilation rate occurs in the intermediate energy regime $|p| \sim \mu$, while nucleon–DM scattering occurs in the 4d regime $|p| \ll \mu$ described by Eqs. (8)-(9). The model's SM$\to \Phi \to$SM signatures are exotic, see Sec. 6.

Bulk field localization permits natural values of the mediator–SM coupling to over many orders of magnitudes, such that both thermal freeze-out or freeze-in [37–40] mechanisms may explain the abundance of DM thermal relics. Both regions are shown in Fig. 2 in the BPS case. In the case of thermal freeze-out, the mass is bounded from above by annihilation unitarity [41] and from below by dark radiation constraints [42]. The coupling κ is set to satisfy the DM abundance, which fixes direct detection bounds shown in Fig. 2 [37]. The first KK mode coupling to the SM depends crucially on its 5d profile, and cannot be too suppressed to maintain pre-freezeout thermal equilibrium [43]. Freeze-in mostly depends on the mediator–SM coupling [39,44] and thus on the first KK mode profile. The freeze-in mechanism can also take place in the non-BPS case for $\mu \gtrsim 10^3$ TeV.

Finally, the radion mode—whose exact mass depends on brane stabilization—can induce long range DM self-interactions while having a negligible coupling to the SM brane. Hence the warped dark sector naturally admits a mechanism for self-interacting DM as a way to address small scale structure [45].

6. Signatures and constraints

Our warped dark sector scenario has effects at terrestrial and astrophysical scales that qualitatively differ from scenarios with 4d mediators.

Non-integer fifth force. For $p > \mu$, the t-channel SM$\leftrightarrow$SM exchange of the KK modes induces a non-relativistic long range potential between nucleons. Strikingly, this force has a non-integer power-law behavior, such as

$$V(r) \propto \frac{1}{r}\frac{1}{(kr)^{2-2\alpha}} \tag{13}$$

in the BPS case with $0 < \alpha < 1$. As a result, while fifth forces bound on the theory are stringent for $\alpha \sim 1$, they are quickly relaxed for $\alpha < 1$. Bounds on $V(r)$ obtained by recasting results from the Eöt-Wash experiment [46], Casimir measurements [47,48], molecular spectroscopy and neutron scattering data [49–53] are shown in Fig. 2.

Momentum losses. Particles on the UV brane can decay into states localized on the IR brane, such that UV observers see an effective loss of momentum. This usually puts strong bounds on light dark sector models. The situation in our warped dark sector is strikingly different because the energy loss into the dark brane is exponentially suppressed whenever $E_{\rm process} \gg \mu$. The rates for such processes take an exact form

$$\Gamma(\{SM\} \to \{SM'\} + (\Phi \to \{dark\})) = \tag{14}$$
$$\int \frac{dq^2}{\pi}\Gamma_{\{SM\}\to\{SM'\}+\Phi}(q)\,|\Delta^{\rm dr}(q;z_0,z_1)|^2\, q\,\Gamma_{\Phi\to\{dark\}}(q)$$

where the suppression occurs from $\Delta^{\rm dr}(q;z_0,z_1)$. We show examples of exclusions from red giants cooling via Compton-like scattering [54] and from K and B mesons invisible decays [55–59]. Collider bounds would require dedicated data analyses.

Soft bombs. Spherical soft events with higher multiplicity are expected from both CFT [60] and AdS sides [61]. Our model provides a concrete 5d realization of the phenomenon. The total rate has been analytically estimated in AdS in [3] and seems to be exponentially suppressed with p. Nevertheless soft bombs are an important signature which should certainly be searched for.

Periodic signals at colliders. The KK near-continuum can be produced at colliders when the c.o.m. energy exceeds μ. Production of a continuum is typically challenging to detect since its lineshape is similar to the one of the background. Importantly, if the first KK modes are narrow enough, a periodic lineshape with bumps and dips is present. Such signature has been pointed out only recently in the context of the linear dilaton model [62], our model reinforces the motivation for searching for such signature—temptingly by taking the Fourier transform of the signal. As an example we show a $q\bar{q} \to \Phi \to q\bar{q}$ cross section $\sigma \propto s|\Delta^{\rm dr}(\sqrt{s};z_0,z_0)|^2/k^4$ in Fig. 3. The presence of dips can be understood as a result of interferences between KK modes, and also happens in the interference with the background.

7. High-temperature cosmology

The warped dark sector at temperature $T \gtrsim \mu$ has two key features compared to 4d models.

Dark phase transition. First, it is well-known [4] that a first order Hawking-Page-like phase transition occurs at $T \sim \mu$. For $T > \mu$, the IR brane vanishes and the metric is AdS-Schwarchild, with a black hole in the IR region. This implies that the IR brane-localized states (e.g. DM) do not exist in the $T > \mu$ phase, leaving only bulk excitations. A key signature is that gravitational waves are generated by nucleation during the phase transition, and could be accessible by future gravitational waves experiments depending on the value of μ [63].

Dark radiation. The second key feature is that dark radiation from the bulk mediators remains potentially quite small, unlike the effect of a simple relativistic 4d mediator. This fact has been studied in detail for gravitons in the original braneworld models [64–66], and is tied to a subtle compensation between energy density and transverse pressure on the brane [66]. The case of a bulk scalar turns out to depend crucially on brane couplings and on α. A detailed study is left for a dedicated work. Here we simply state that for $\alpha < 1/2$ the dark radiation behavior is found to be similar to the graviton case, such that the effect of dark radiation is small enough to evade BBN bounds, thereby allowing the dark sector scale μ to be below the MeV scale.

8. Outlook

We have argued that the properties of AdS have novel implications in the context of the dark sector paradigm. In this letter we present a general framework with specific choices. We demonstrate that the basic phenomenology of these choices differ from previous models in Refs. [8–12] and identify new interrelations between experimental searches. A number of developments follow from the present study, with for instance further analyses of the opacity property, soft-bombs events, stellar cooling, dark radiation, or details of the dark phase transition. The warped dark sector scenario opens new possibilities for modified gravity model-building and phenomenology, as well as for the secluded dark matter scenario. It also strengthens the case for a number of observables and new experiments, motivating advances in Casimir and torsion pendulum experiments, neutron scattering and precision molecular spectroscopy, as well as new kinds of LHC searches for soft bombs and periodic signals. The warped dark sector is also relevant for future experiments dedicated to dark sector searches [1].

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2019.135012.

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