U(1) Holography and a Continuum Dark Photon

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Motivation

Dark sectors often contain a small number of low mass states which mediate interactions

An alternative limit is when dark sector interactions are mediated by a continuum of states

This may occur if the mediator is part of a conformal sub-sector or, as in this work, if the mediator is a higher dimensional field in an appropriately warped spacetime

Unbroken and broken gauge fields in AdS and flat extra dimensions have been studied before

Our U(1) model differs from previous work in that it displays a nontrivial gauge spectrum with the possibility of a (un)gapped continuum or discrete modes

Not an unfamiliar effect, appears in soft wall models

Models where hidden sector states interact through a higher dimensional mediator have been of interest in recent years (Warped Dark Sector)

U(1) Gauge Boson in AdS$_{d+1}$ Background

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

Location of UV Brane

$$z = R = 1/k$$

AdS Curvature

We consider a U(1) gauge boson which propagates in an AdS background

The symmetry is spontaneously broken by the vev of a bulk scalar which develops as the result of a potential localized to the UV brane

We neglect the effect of the back reaction on the geometry

Bulk and Boundary Action

$$S_D = \int d^d x \int_R^\infty dz \left[\sqrt{g}\mathcal{L} + \sqrt{\bar{g}}\mathcal{L}_{\mathrm{UV}}\delta(z-R)\right]$$

$$\mathcal{L} = -\frac{1}{4g_{d+1}^2} g^{ML} g^{NP} F_{MN} F_{LP} + g^{MN} \left(D_M \Phi\right)^\dagger \left(D_N \Phi\right) - \mu^2 \Phi^\dagger \Phi$$

$$\mathcal{L}_{\mathrm{UV}} = -\frac{r_{\mathrm{UV}}}{4g_{d+1}^2} \eta^{\mu\rho} \eta^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma} + c_{\mathrm{UV}} R |D_\mu \Phi|^2 - V_{\mathrm{UV}}$$

$$D_M = \partial_M - i A_M$$

$$V_{\mathrm{UV}} = -m_{\mathrm{UV}}^2 R |\Phi|^2 + \lambda_{\mathrm{UV}} R^{d-2} |\Phi|^4$$

Must also include gauge fixing for the brane and bulk

Spontaneous Symmetry Breaking

UV brane localized potential induces a z-dependent vev for the bulk scalar

$$v(z) = \sqrt{\frac{d/2 - \alpha + m_{\mathrm{UV}}^2 R^2}{\lambda_{\mathrm{UV}} R^{d-1}}} \left(\frac{z}{R}\right)^{\frac{d}{2}-\alpha}$$

Bulk Mass Parameter for Scalar

$$\alpha = \sqrt{\frac{d^2}{4} + \mu^2 R^2}$$

Results in a z-dependent bulk mass for the first d components of the bulk gauge boson: $m_A^2 = g_{d+1}^2 v^2(z)$

Degrees of Freedom

Before SSB

d component gauge boson:	A_μ
z-component of the gauge field:	A_z
Goldstone boson:	π
Radial mode:	h

Coupled EOM (A_z, π)

After SSB

d component massive gauge boson:	A_μ
Physical scalar:	χ
Eaten Goldstone:	Θ
Radial mode:	h

Vector Propagator and Spectral Density

Phenomenology is largely determined by the UV brane-to-brane propagator

$$G_p(R,R) = \frac{g_{d+1}^2}{\mathcal{B}_G(p^2) + \Sigma(p^2)}$$

Boundary conditions

Gauge Boson Bulk Profile

$$\Sigma(p^2) = \partial_z \log f_{T,L}(p,z)\Big|_{z=R}$$

Transverse Spectral Density

$$\rho_T(p^2) = -2\mathrm{Im}\left[G_p(R,R)\right]$$

$$A^\mu_{T,L}(p,x) = \frac{f_{T,L}(p,z)}{f_{T,L}(p,R)} A^\mu_{T,L}(p)$$

Landscape of solutions depends on the bulk mass parameter

Landscape of Solutions

Holographic self-energy not solvable in general but can be found for various values of the scalar bulk mass parameter

$$\Sigma(p^2)\Big|_{z=R}$$

$\alpha \gg d/2$ Profile peaks at the UV brane and only affects boundary conditions

$$-\sqrt{-p^2}\frac{K_{\frac{d}{2}-2}(\sqrt{-p^2}R)}{K_{\frac{d}{2}-1}(\sqrt{-p^2}R)}$$

$\alpha = d/2$ Constant vev resulting in a gapless continuum

$$\frac{d-2(1+\nu)}{2R} - \sqrt{-p^2}\frac{K_{\nu-1}(\sqrt{-p^2}R)}{K_{\nu}(\sqrt{-p^2}R)}$$

$\alpha = d/2 - 1$ Gapped continuum characterized by gauge boson bulk mass

$$-\sqrt{-p^2}\frac{K_{\frac{d}{2}-2}(\sqrt{m_A^2 - p^2}R)}{K_{\frac{d}{2}-1}(\sqrt{m_A^2 - p^2}R)}$$

$\alpha < d/2 - 1$ vev dominates in the IR and induces discreet modes

$$-m_A - \frac{1}{2}Rp^2\left(\gamma_E + \log(m_A R) + H\left(-\frac{p^2 R}{4m_A}\right)\right)$$

$$\alpha = 0$$

Landscape of Solutions

$$|p|\, R \ll 1 \qquad \frac{d}{2} \neq \text{integer} \qquad \Sigma(p^2)\Big|_{z=R}$$

$\alpha \gg d/2$ — Profile peaks at the UV brane and only affects boundary conditions

$$-\frac{2}{R}\frac{\Gamma(2-\frac{d}{2})}{\Gamma(\frac{d}{2}-1)}\left(\frac{-p^2R^2}{4}\right)^{\frac{d}{2}-1}$$

$\alpha = d/2$ — Constant vev resulting in a gapless continuum

$$\frac{p^2R}{2(\nu-1)} + \frac{d-2(1+\nu)}{2R} - \frac{2}{R}\frac{\Gamma(1-\nu)}{\Gamma(\nu)}\left(\frac{-p^2R^2}{4}\right)^{\nu}$$

$\alpha = d/2 - 1$ — Gapped continuum characterized by gauge boson bulk mass

$$-\frac{2}{R}\frac{\Gamma(2-\frac{d}{2})}{\Gamma(\frac{d}{2}-1)}\left(\frac{(m_A^2-p^2)R^2}{4}\right)^{\frac{d}{2}-1}$$

$\alpha < d/2 - 1$ — vev dominates in the IR and induces discrete modes

$$-m_A - \frac{1}{2}Rp^2\left(\gamma_E + \log(m_AR) + H\left(-\frac{p^2R}{4m_A}\right)\right)$$

$$\alpha = 0$$

WKB Method For Near-AdS Background

For an AdS background, the four-momentum in vector propagator scales according to the vector bulk mass parameter:

$$\nu = \sqrt{\left(\frac{d}{2} - 1\right)^2 + \mu^2 R^2} = 2 - \Delta$$

For a near-AdS background we consider

$$\alpha = 2 + \epsilon \qquad\qquad \epsilon \ll 1$$

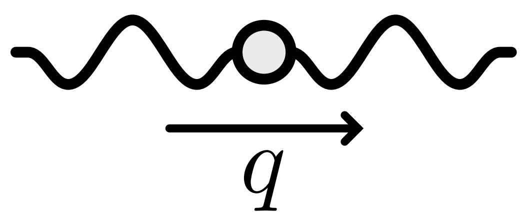
We employ a WKB like approximation to determine the four-momentum scaling the holographic self-energy

$$\Sigma(p^2) \simeq \frac{p^2 R}{2\nu^2} - \frac{\nu - d/2 + 1}{R} - \frac{2}{R}\frac{\Gamma(1-\nu)}{\Gamma(\nu)}\left(\frac{-p^2 R^2}{4}\right)^{\nu - \delta(p)}\left(\frac{pR}{\nu}\right)^{\delta(p)} \qquad \delta(p) = \epsilon\frac{m_A^2 R^2}{\nu}\log\left(\frac{\nu}{pR}\right)$$

Holographic Dark Photon

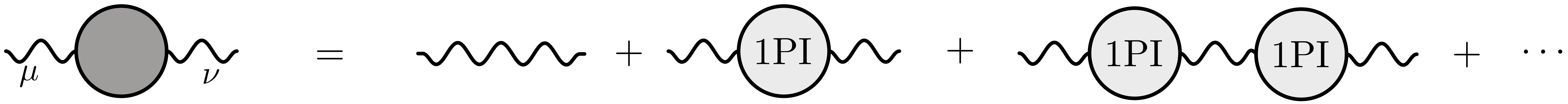
$$d = 4$$

$$S_{\mathrm{KM}} = \int d^4x \int_R^\infty dz \frac{\varepsilon}{2}\sqrt{\frac{r_{\mathrm{UV}}}{g_5^2}} F_{\mu\nu}\mathcal{F}^{\mu\nu}\delta(z-R)$$

A_μ 

$\mathcal{A}_\nu \; = i\varepsilon\sqrt{\frac{r_{\mathrm{UV}}}{g_5^2}}\left(q^2\eta_{\mu\nu} - q_\mu q_\nu\right)$

We compute the photon propagator exactly by resuming dark photon insertions



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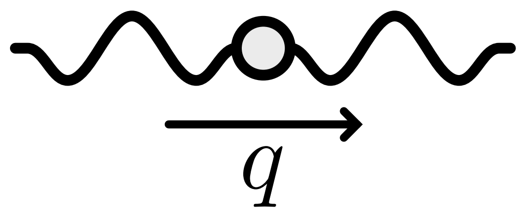
A_μ  $\mathcal{A}_\nu = i\varepsilon\sqrt{\frac{r_{\mathrm{UV}}}{g_5^2}}\left(q^2\eta_{\mu\nu} - q_\mu q_\nu\right)$

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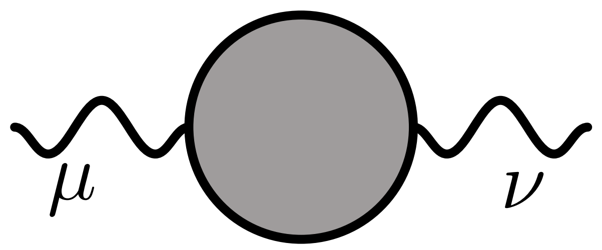


$$= \frac{-i}{q^2\left(1-\Pi(q^2)\right)}\left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) - \frac{i\xi}{q^2}\left(\frac{q_\mu q_\nu}{q^2}\right)$$

$$\Pi_A(q^2) = \varepsilon^2 r_{\mathrm{UV}} q^2 G_q\left(R, R\right)$$

Equivalent to diagonalizing the photon-dark photon system on the UV brane

Adapting 4D Bounds to a Continuum

In general, adapting current constraints on the kinetic mixing parameter would require full calculations of several observables; beyond the scope of this work

We present a simple way to adapt constraints for a dark photon with a definitive mass to one with a continuum spectrum.

Typically, an upper bound on the kinetic mixing parameter corresponds to a maximum number of scattering events

$$N_{\text{max}} = \sigma_{\text{max}} \mathcal{L}$$

$$\sigma_{\text{max}} \sim \varepsilon^2_{\text{max}}(m_A)\sigma_0(m_A^2)$$

Adapting 4D Bounds to a Continuum

In a 5D model with a continuum

$$\sigma_0(m_A^2) \to \int d\mu^2 \rho(\mu^2) \sigma_0(m_A^2)$$

$$\varepsilon \to \varepsilon_{5D} C$$

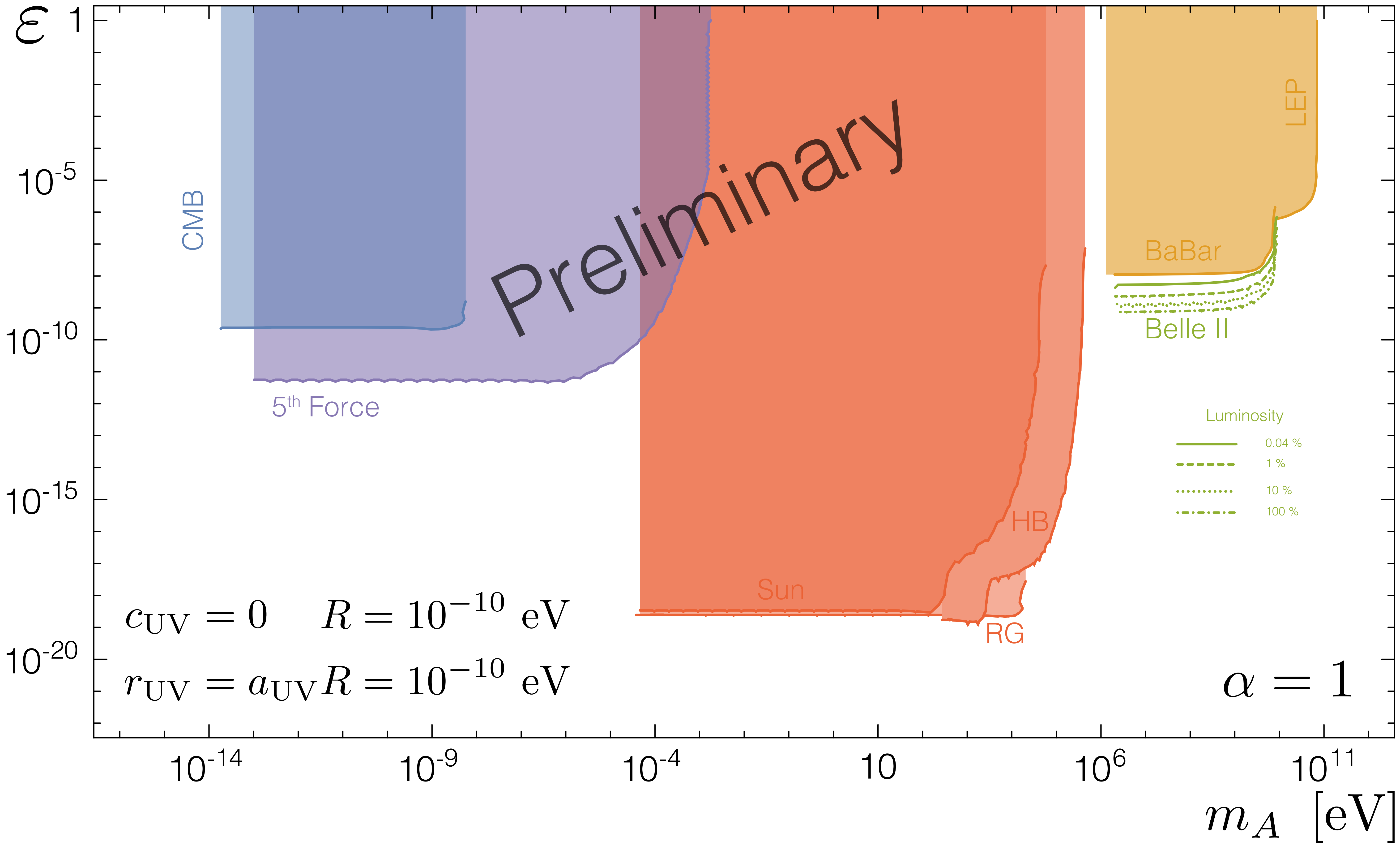
$$N_{\max} = \mathcal{L} \left(\varepsilon_{5D}^{\max}\right)^2 \int d\mu^2 \rho(\mu^2) \sigma_0(\mu^2)$$

Adapting 4D Bounds to a Continuum

Equating both expressions for the max number of events we find

$$(\varepsilon_{5D}^{\max} C)^2 = \left[\int d\mu^2 \frac{\rho(\mu^2)}{\varepsilon_{\max}^2(\mu^2)} \right]^{-1}$$

We find that for larger AdS curvature, the bounds are enhanced



Conclusions

A bulk gauge boson with a bulk mass resulting from the SSB of a U(1) symmetry by bulk scalar with a brane localized potential results in several possibilities for the UV brane-to-brane propagator/Holographic self-energy

The form of the spectrum produced (gapped/ungapped/discrete) will affect the phenomenology

We find the four momentum scaling of the holographic self-energy runs logarithmically with momentum for $\alpha = d/2$

Increasing the AdS curvature enhances constraints on the kinetic mixing parameter

More work to be done to fully determine phenomenology

IR Stability

To see where in IR the backreaction to the vev becomes important, we compare the cosmological constant to the matter term in the Einstein equation

$$\Lambda = -\frac{d(d-1)}{2R^2} \qquad T_{MN} = -2\frac{\partial \mathcal{L}}{\partial g^{MN}} + g_{MN}\mathcal{L} = \left(-\eta_{MN}\frac{d}{2}\left(\frac{d}{2}-\alpha\right) - \delta_{zM}\delta_{zN}\left(\frac{d}{2}-\alpha\right)^2\right)\frac{v_0^2}{R^2}\left(\frac{z}{R}\right)^{d-2-2\alpha}$$

We find the backreaction becomes important for

$$z_b \sim R\left(\frac{(d-1)M_*^{d-1}}{(\frac{d}{2}-\alpha)v_0^2}\right)^{\frac{1}{d-2\alpha}} \qquad \alpha < \frac{d}{2}$$

d+1 dimensional Planck Mass

For larger values of the bulk mass parameter, the vev vanishes in the IR and the backreaction can be neglected