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# Exponential expansion through decaying Anti-de Sitter

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Based on: 1807:01570 & 1907.04268 in collaboration with S. Banerjee, U. Danielsson,  
G. Dibitetto, and S. Giri.

# Ideology

- String theory is very hard but very necessary
  - The early universe and inflation need to be studied using string theory — **we don't have enough data to make EFT predictive.**
  - There are several promising embeddings of inflation in string theory, however **a fully explicit model in a stable compactification remains an open area of research and debate.**
  - Recent work highlights obstacles to proposed de Sitter constructions and motivate the **de Sitter Swampland conjecture, which states that the observed late-time acceleration cannot be due to a CC and is in tension with single field slow roll inflation.**

See Will Kinney's talk
  - We present an **alternative embedding of an accelerating cosmology in string theory that side-steps the difficulty of finding an explicit, scale separated, compactified de Sitter vacuum.**

# Inspiration: Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa:  
hep-th/0601001

- The WGC states that if an EFT with a massless gauge boson descends from string theory, there must exist a charged particle whose charge-to-mass ratio is greater than or equal to that of a semiclassical extremal black hole:

$$Q^2 M_{(d)}^{d-4} \geq \frac{d-3}{d-2} \left( \frac{m}{M_{(d)}} \right)^2 \quad \text{for a } U(1) \text{ gauge field and } d \geq 4$$

$M_{(d)} = d\text{-dimensional Planck Mass}$

- We have strong circumstantial evidence: the electron, absence of counter-examples in string theory, and several “proofs” in certain set-ups.

Hod: 1705.06287 || Fischer, Mogni: 1706.08257 || Cheung, Liu, Remmen: 1801.08546 ||  
Hamada, Noumi, Shiu: 1810.03637 || Urbano: 1810.05621 || Montero: 1812.03978

- Immediate extension to higher dimensional charged objects: for every gauge field  $A_{p+1}$  there is a p-brane state whose charge-to-tension ratio is greater or equal to the extremal black brane:

Heidenreich, Reece, Rudelius: 1509.06374

$$Q_p^2 M_{(d)}^{d-2(p+2)} \geq \frac{(p+1)(d-p-3)}{d-2} \left( \frac{\tau_p}{M_{(d)}^{p+1}} \right)^2$$

# WGC for branes in AdS

- The WGC applied to higher dimensional gauge fields precisely indicates that non-supersymmetric AdS supported by flux can decay. Ooguri, Vafa: 1610.01533  
Freivogel, Kleban: 1610.04564

- The decay channel is a [Brown-Teitelboim instanton \(1987\)](#) describing the creation of spherical membranes which discharge the cosmological constant.

- [Energy conservation](#) — the (energy density in the field)\*volume has to pay for the (membrane tension)\*area of the brane. This fixes the critical radius of the instanton to be:

$$R_* = \left[ \frac{2\Lambda_O}{(d-1)(d-2)} + \tau_p^{-2} \left( \frac{1}{d-1} \left( Q_p E_O - \frac{1}{2} Q_p^2 \right) - \frac{M_{(d)}^{2-d} \tau_p^2}{2(d-2)} \right)^2 \right]^{-1/2}$$

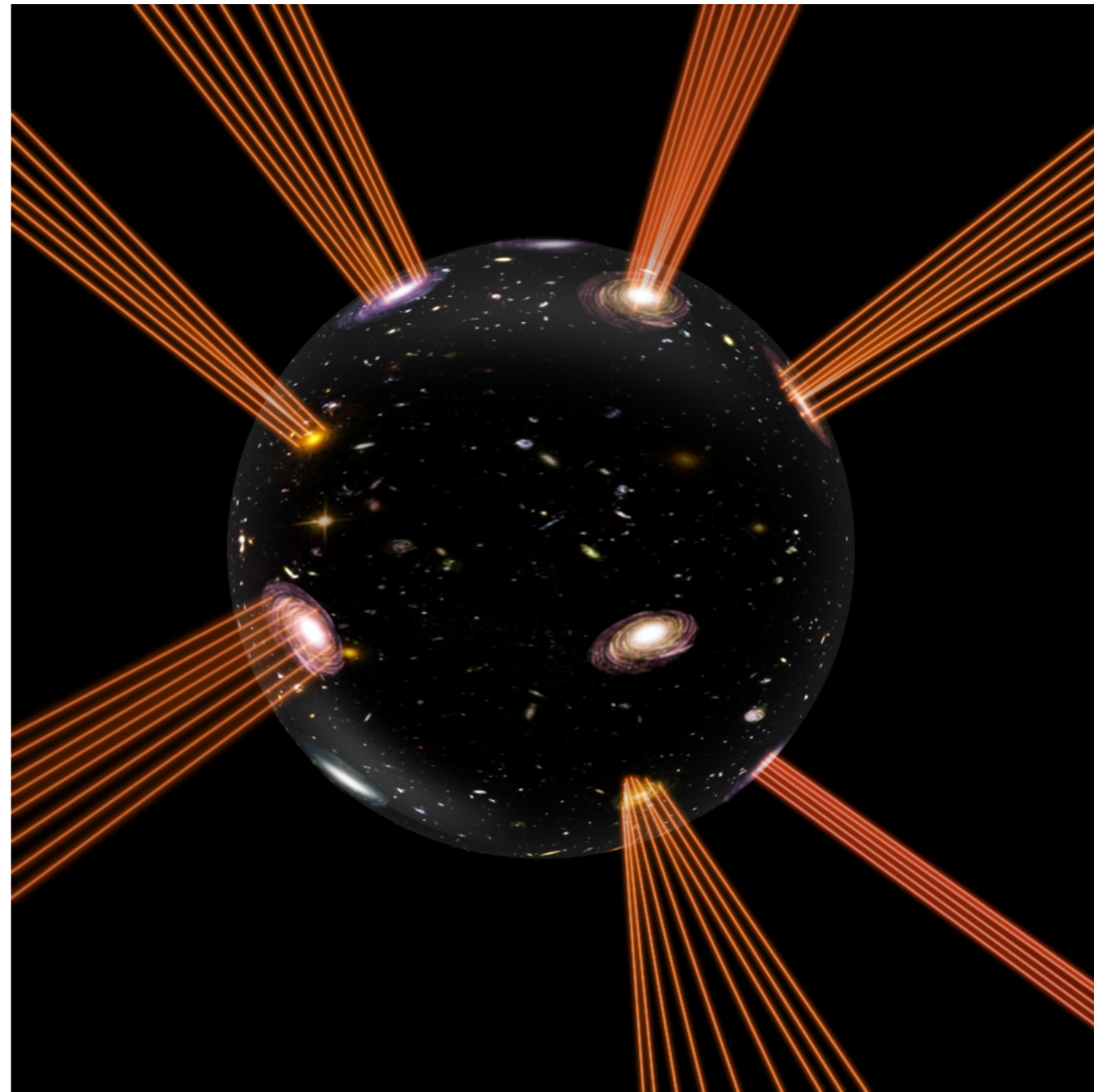
- In AdS, the condition  $R_*^2 > 0$  gives:  $\tau_p^2 < \frac{d-2}{d-1} Q_p^2 M_{(d)}^{d-2} + \mathcal{O}\left(\frac{Q_p}{E_O}\right)$

- This matches the WGC for higher forms in the case  $p = d - 2$ .

- [We will use this instanton for our Braneworld.](#)

# Braneworlds

- Braneworlds were first popularized by [Randall and Sundrum](#) 20 years ago.  
[hep-ph/9905221](#)  
[hep-th/9906064](#)
- In a Braneworld scenario observed [matter fields](#) *and* [gravity](#) are confined to a brane (co-dimension  $\geq 1$  surface.)
- In these scenarios our observed universe lives on a surface in a higher dimensional bulk, [avoiding the need to compactify extra dimensions at very small length scales.](#)



artwork by Suvendu Giri

# Braneworld Phenomenology

- Assume the decay channel exists **what does cosmology on the brane look like?**

- The brane separates two regions with different negative vacuum energy:

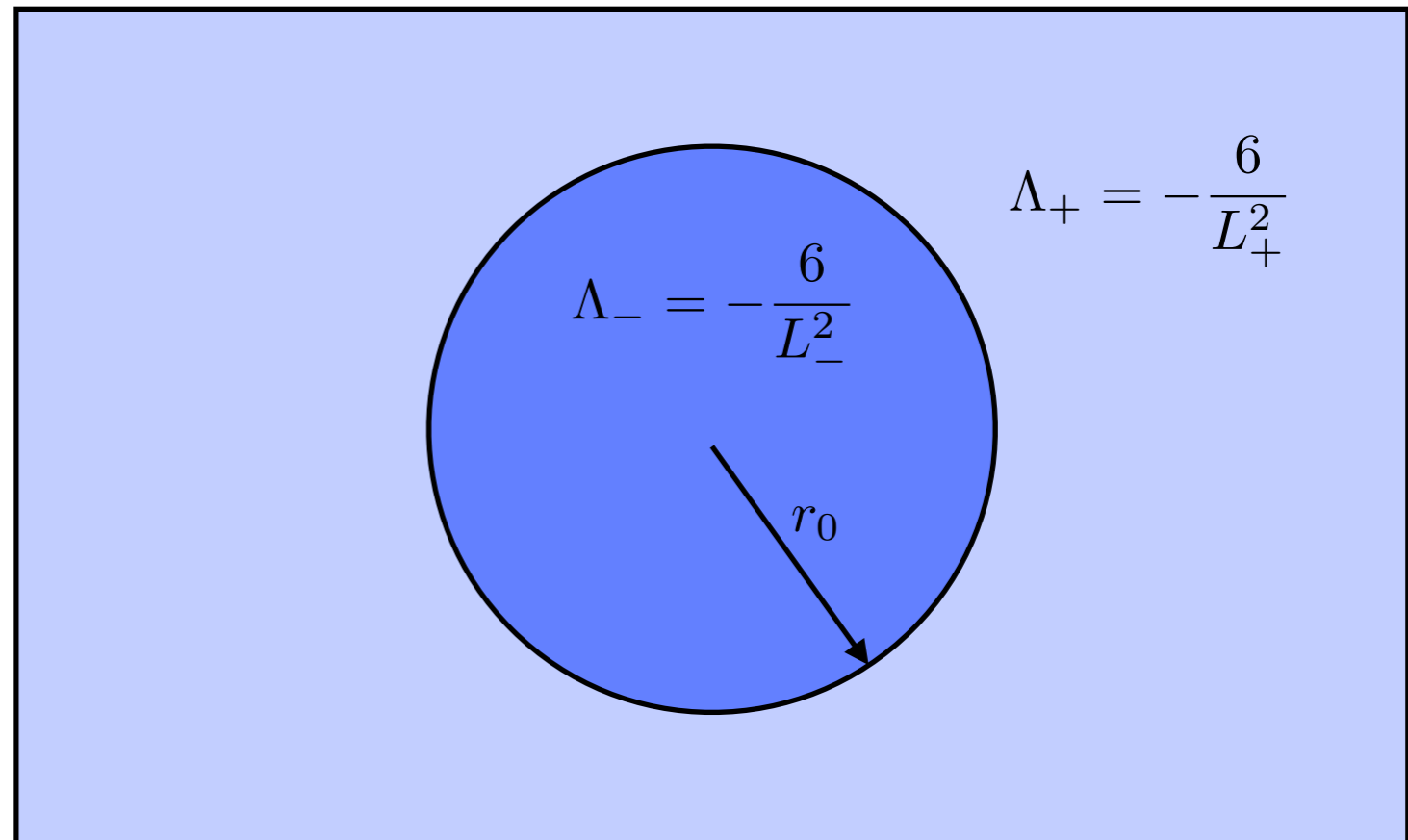
$$ds^2 = - \left( 1 + \frac{r^2}{L_{\pm}^2} \right) dt^2 + \frac{dr^2}{\left( 1 + \frac{r^2}{L_{\pm}^2} \right)} + r^2 d\Omega_3^2 \quad L_+ > L_-$$

- The induced metric on a spherical bubble located at  $r = r_0$  is:

$$ds_{ind}^2 = -d\tau^2 + r_0(\tau)^2 d\Omega_3^2$$

FLRW cosmology with positive spatial curvature

$$r_0(\tau) \equiv a(\tau)$$



# Braneworld Phenomenology

- The **Israel Junction conditions** describe the requirements for a sharp domain wall to join two spacetimes. For a relativistic brane with constant tension,  $\sigma$ :

$$\sigma = 3M_{(5)}^3 \left( \sqrt{\frac{1}{L_-^2} + \frac{1 + \dot{a}^2}{a^2}} - \sqrt{\frac{1}{L_+^2} + \frac{1 + \dot{a}^2}{a^2}} \right)$$

- Solve for  $H = \frac{\dot{a}}{a}$ :

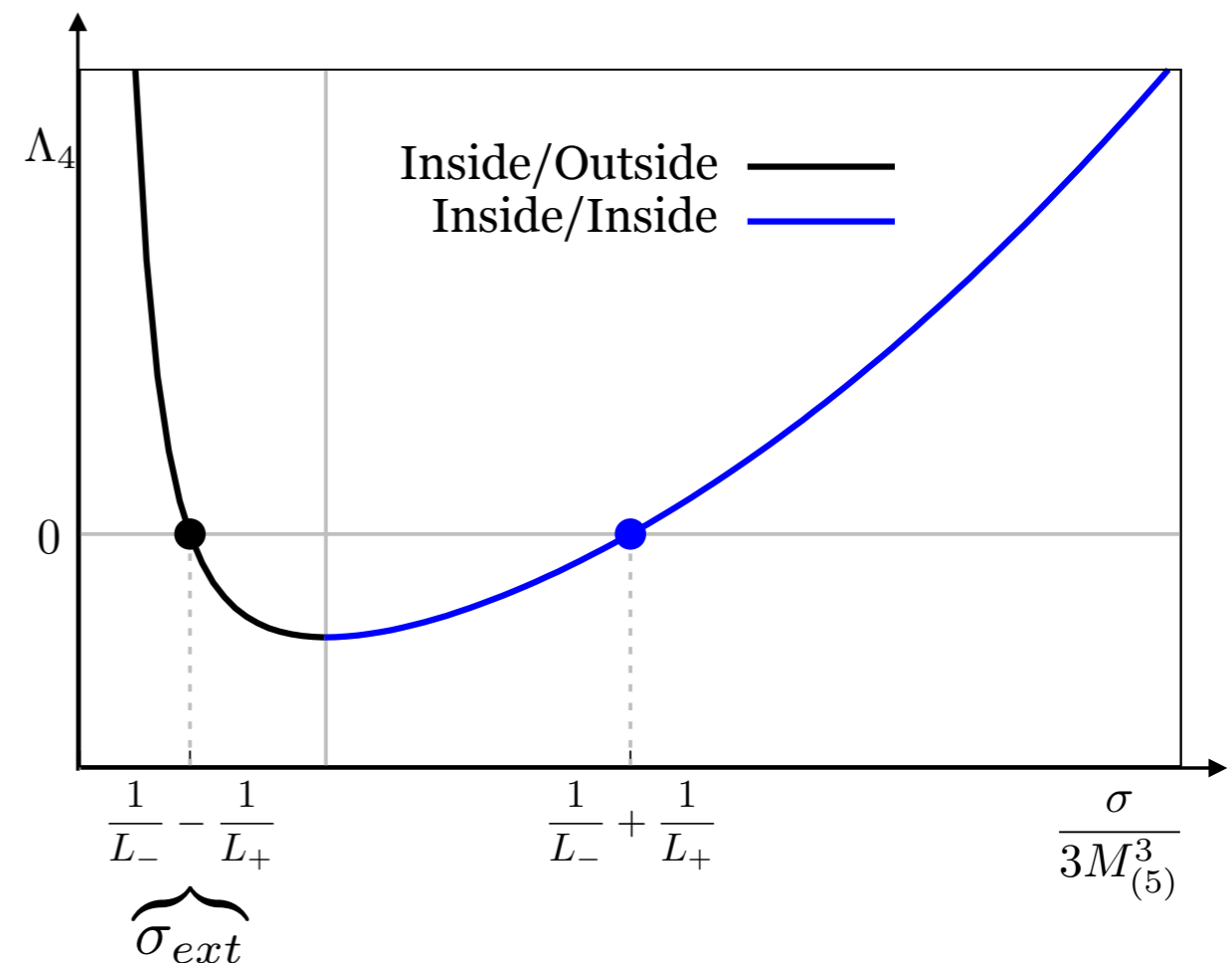
$$H^2 = -\frac{1}{a^2} + \frac{1}{3M_{(4)}^2} \Lambda_4 + \mathcal{O}(1 - \sigma/\sigma_{ext})^2$$

- Obtain Friedmann equation the identifications

$$M_{(4)}^2 = \frac{1}{2} M_{(5)}^3 (L_+ - L_-)$$

$$\Lambda_4 = \sigma_{ext} - \sigma$$

- Note: **corrections are time-independent!** Cosmology is exact dS + curvature for  $\sigma < \sigma_{ext}$ .



# Matter on a non-RS Braneworld

- Consider effects of modified 5D geometry, *e.g.* AdS-Schwarzschild:

$$ds^2 = - \left( 1 + \frac{r^2}{L_{\pm}^2} + \frac{2M_{(5)}^{-3}m_{\pm}}{r^2} \right) dt^2 + \frac{dr^2}{\left( 1 + \frac{r^2}{L_{\pm}^2} + \frac{2M_{(5)}^{-3}m_{\pm}}{r^2} \right)} + r^2 d\Omega_3^2$$

- The resulting Friedmann equation is:

$$H^2 = -\frac{1}{a^2} + \frac{1}{3M_{(4)}^2} \left( \Lambda_4 + 3 \frac{m_+ L_+ - m_- L_-}{a^4} \right) + \dots$$

- A **black hole** in the bulk results in an energy density scaling like **radiation**:

$$m_+ = m_-, \quad \rho_{rad} = 3m(L_+ - L_-)a^{-4}$$

- An open **string** cloud gives an energy density scaling like **matter**:

$$m_- = 0, \quad m_+ = T_s r \quad \rho_{mat} = 3T_s L_+ a^{-3}$$

# Predictions

- **No initial singularity.**
- **Positive spatial curvature.** (Note this is opposite the prediction of Coleman-de Luccia instanton from scalar field bubble formation.)
- **Modifications to gravity:** both at high energy, where we probe the extra dimensions, and very low energy small graviton mass tied to spatial curvature.
- **Collisions with other bubbles: doomsday in 9 billion years** (subject to initial conditions.)

# Future Work

- **Inflation**: exciting model building opportunities coming from bubble collisions, phase transition, and open string production (reheating).
- Black holes: there are long-standing issues regarding embedding **black holes** in braneworlds.
- Phenomenology: **particle spectrum** from open strings given brane intersections.
- Phenomenology: **Modifications to gravity** and interactions beyond the Newtonian limit.
- String embedding: finding the precise brane embedding and probe action.
- Holography: implications for specific decay channels in a dual CFT?

**Thank you for your attention!**

# Randall Sundrum

hep-ph/9905221  
hep-th/9906064

- An Alternative to Compactification: warping

$$\text{AdS}_5 \text{ with a } \mathbb{Z}_2 \text{ orbifold: } ds^2 = e^{-2|y|/L} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

- Despite infinite extra dimension, 4D Planck mass is finite:

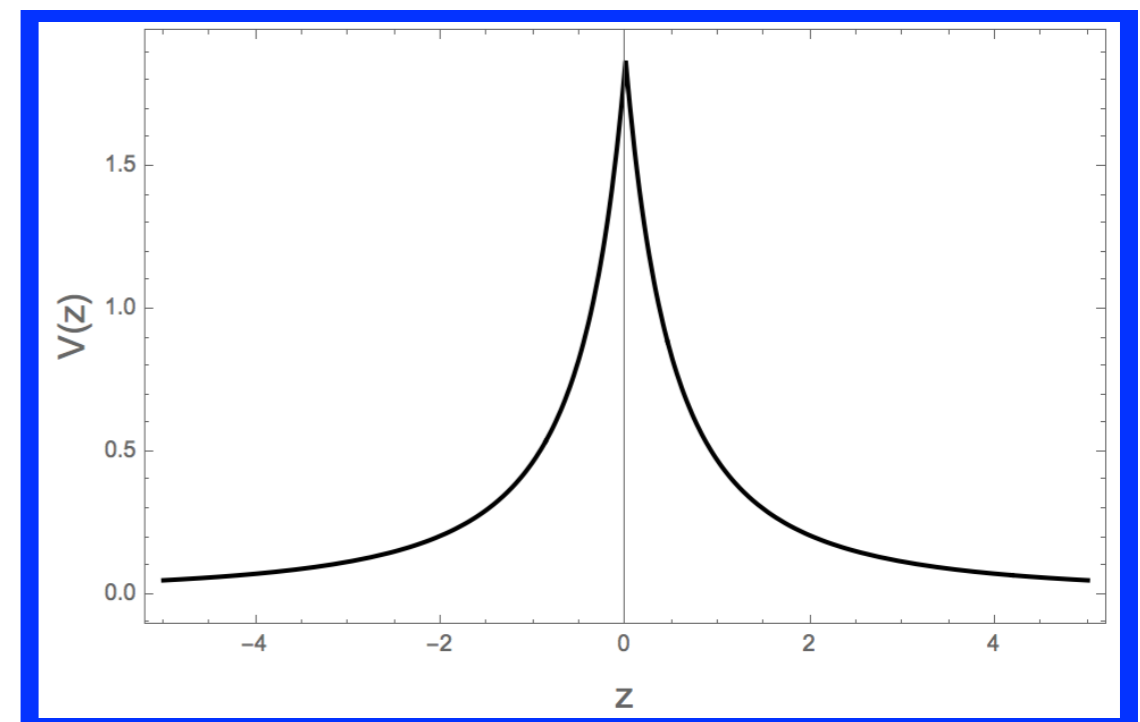
$$\frac{M_{(5)}^3}{2} \int dy d^4x \sqrt{g_{(5)}} R_{(5)} \supset M_{(5)}^3 \int_0^\infty dy e^{-2y/L} d^4x \sqrt{g_{(4)}} R_{(4)} = \frac{M_{(5)}^3 L}{2} \int d^4x \sqrt{g_{(4)}} R_{(4)}$$

- Linearized 4D graviton satisfies Schrödinger equation with delta function potential: single normalizable bound state and a continuum of KK modes.

$$g_{\mu\nu} = e^{-2|y|/L} \eta_{\mu\nu} + \psi_{\mu\nu} e^{ip \cdot x}$$

$$z = \frac{L|y|}{y} \left( e^{|y|/L} - 1 \right)$$

$$\left[ -\frac{1}{2} \partial_z^2 + \left( \frac{15}{8L^2 \left( \frac{|z|}{L} + 1 \right)^2} - \frac{3}{2L} \delta(z) \right) \right] \psi(z) = m^2 \psi(z)$$



# Randall Sundrum

- On the brane:  $\psi_{\mu\nu}$  mediates Newtonian gravitational interactions+ corrections:

$$V(r) = \frac{1}{M_{(4)}^2} \frac{m_1 m_2}{r} \left( 1 + \frac{L^2}{r^2} \right) \quad M_{(4)}^2 = M_{(5)}^3 L$$

- Extensions/Generalizations to  $ds^2 = e^{-2|y|/L} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$ 
  1. Go beyond a Minkowski brane.
  2. Allow different AdS vacua on either side.
  3. Remove absolute value: study an inside/outside rather than inside/inside

# Fun Fact

- The **de Sitter temperature** on the braneworld is identified with the **Unruh temperature** of the accelerating brane in AdS

Deser, Levin: gr-qc/9706018

$$\begin{aligned} T_U &= \frac{1}{2\pi} \sqrt{a^2 - L_{AdS}^{-2}} \\ &= \frac{1}{2\pi} \left( H + \mathcal{O}(e^{-2H\tau}) \right) \end{aligned}$$

- This relies on the geodesic equation and the relationship between global time and de Sitter time. This is given by the condition that the bubble follow a timelike trajectory.

$$a^\mu = \ddot{x}^\mu + \Gamma_{\rho\lambda}^\mu \dot{x}^\rho \dot{x}^\lambda$$

$$\partial_\tau t_0 = \frac{\sqrt{f(r_0) + (\partial_\tau r_0)^2}}{f(r_0)}$$

# 4D Gravity Sourced by Strings

- In what sense is gravity 4-dimensional? Switch to the Poincare patch where the brane is located at  $y = 0$ :

Giddings, Katz, Randall: [hep-th/0002091](https://arxiv.org/abs/hep-th/0002091)

Karch, Randall: [hep-th/0011156](https://arxiv.org/abs/hep-th/0011156)

Padilla: [hep-th/0410033](https://arxiv.org/abs/hep-th/0410033)

$$ds^2 = dy^2 + \left( e^{2y/L_{\pm}} \eta_{\mu\nu} + h_{\mu\nu} \right) dx^{\mu} dx^{\nu}$$

- Solving the Einstein Equations for the transverse traceless metric component

$$h_{\mu\nu}^{(TT)}(x, y) = h_p(y) e^{ip \cdot x} \quad h_p = C_1 I_2 \left( e^{-y/L_{\pm}} L_{\pm} p \right) + C_2 K_2 \left( e^{-y/L_{\pm}} L_{\pm} p \right)$$

- Boundary conditions at  $y \rightarrow -\infty$  select  $h_p^- = C_- K_2 \left( e^{-y/L_-} L_- p \right)$

- In the presence of strings, which **act as a source** at all  $y$ , both solutions are present as  $y \rightarrow \infty$

$$h_p^+ = C_1 I_2 \left( e^{-y/L_+} L_+ p \right) + C_2 K_2 \left( e^{-y/L_+} L_+ p \right)$$

# 4D Gravity Sourced by Strings

- Solving the junction conditions fixes the integration constants and we find the propagator on the brane:

$$h_p^b = -M_{(4)}^{-2} \frac{\Sigma_{matter} + \Sigma_{string}}{p^2 + \mathcal{O}(pL_{\pm})}$$

$$\Sigma_{matter} = T_{\mu\nu} - \frac{1}{3}T\gamma_{\mu\nu}$$

$$\Sigma_{string} = -\frac{2M_{(5)}^{-3}m}{r}(3\delta_0^\mu + \delta_j^i)$$

- The correct gravitational coupling  $M_{(4)}^{-2}$  is independently reproduced.
  - Matter localized on the brane gives the **wrong sign** as expected from the Friedmann equation
  - Longitudinal string sources provide precisely a delta function matter source with the correct sign giving the correct Newtonian gravitational interactions for matter.
- Chamblin, Hawking, Reilly: hep-th/9909205
- There will be corrections due to: KK modes at large energy and curvature at large scales.