Title: Colloquium - Insights from Warped Extra Dimensions - VIRTUAL

Speakers: Lisa Randall

Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

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Abstract: Warped extra dimensions were originally introduced as a way of addressing the hierarchy problem. But insights from these scenarios have extended to black hole physics, cosmology, and even mechanisms for addressing issues in purely four dimensions. We investigate this scenario and some compelling lessons.

The presenter will be joining via Zoom for this talk.

Insights from Warped Extra Dimensions

Lisa Randall

For Conference

Puzzles in the Quantum Gravity Landscape

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Baby Steps to Quantum Gravity?

- Many physicists have ambitious goals to "solve" quantum gravity
- Increasingly clear that is an elusive goal
- Top-down approach: top keeps receding
- Bottom-up approach: puzzles related to cc and black holes require low-energy mechanisms only distantly related to fundamental theories

Extra Dimensions/Warped Ex D

- Extra dimensions very useful in this context
  - Provide solvable extensions of usual theories
  - Provide new gravitational solutions
- Warped extra dimensions in particular provide new insights
  - Holographically dual to lower-dimensional conformal field theories
  - New mechanisms for 4d problems due to changing gravitational coupling
  - Better understand constraints on low energy theory that depend on higher energy theory

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Outline: Review

- Simplest warped geometry
  - Extensions: with surprising properties
- Insights into black hole information
- Useful for string realization of positive cc universe
  - But importation insights about constraints
- Current work on effective theory and cosmological constant

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Origin

- Two things I thought I wouldn't work on because they were too faddish at the time
  - Extra dimensions
  - AdS/CFT
- We set out to work on SUSY flavor problem…
  - GIM mechanism works when no other sources of flavor violation aside from masses
  - But SUSY gives ample room to violate this assumption
  - Why would scalar masses (from SUSY breaking) align?
- But Raman and I came across an interesting metric

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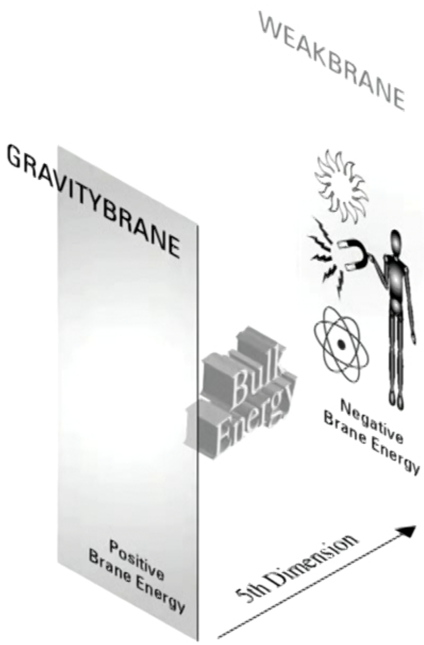
RS1 "Multiverse:"
Warped Spacetime Geometry

With Raman Sundrum



- Two branes
- Bulk energy
- Brane energies to guarantee fla brane:
- Gravity/Planck and Weakbrane/TeV Branes
- Also known as UV and IR branes as we will see

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Setup and Solution

w/Sundrum

- Nonfactorizalbe metric

warping

$$ds^2 = e^{-2\sigma(\phi)}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2.$$

$$\begin{aligned} S &= S_{gravity} + S_{vis} + S_{hid} \\ S_{gravity} &= \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{-G}\{-\Lambda + 2M^3 R\} \\ S_{vis} &= \int d^4x \sqrt{-g_{vis}}\{\mathcal{L}_{vis} - V_{vis}\} \\ S_{hid} &= \int d^4x \sqrt{-g_{hid}}\{\mathcal{L}_{hid} - V_{hid}\}. \end{aligned}$$

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

Negative tension worriesome,
But orbifolds

$$\sigma = r_c|\phi|\sqrt{\frac{-\Lambda}{24M^3}}$$

Flat branes: AdS space...

$$V_{hid} = -V_{vis} = 24M^3 k, \quad \Lambda = -24M^3 k^2$$

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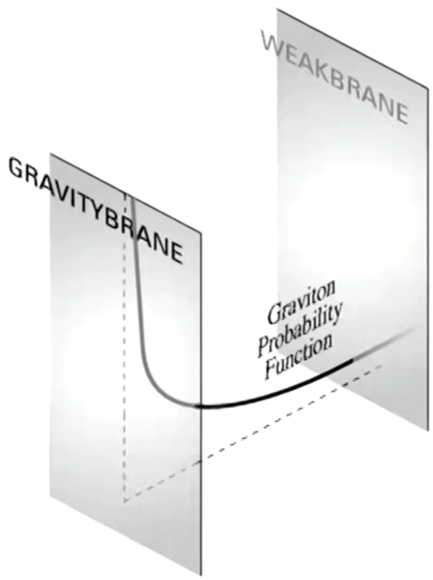
Natural for gravity to be weak!



- Small probability for graviton to be near the Weakbrane
- If we live anywhere but the Gravitybrane, gravity will seem weak
- Natural consequence of warped geometry

$$ds^2 = g_{MN}\, dx^M dx^N = e^{-2\sigma}\eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2\,,$$

$$S_{vis} \supset \int d^4x \sqrt{-g_{vis}} \{ g^{\mu\nu}_{vis} D_\mu H^\dagger D_\nu H - \lambda(|H|^2 - v_0^2)^2 \}, \qquad (17)$$

which contains one mass parameter v_0. Substituting Eq. (3) into this action yields

$$S_{vis} \supset \int d^4x \sqrt{-\overline{g}} e^{-4kr_c\pi} \{ \overline{g}^{\mu\nu} e^{2kr_c\pi} D_\mu H^\dagger D_\nu H - \lambda(|H|^2 - v_0^2)^2 \}, \qquad (18)$$

After wave-function renormalization, $H \to e^{kr_c\pi} H$, we obtain

$$S_{eff} \supset \int d^4x \sqrt{-\overline{g}} \{ \overline{g}^{\mu\nu} D_\mu H^\dagger D_\nu H - \lambda(|H|^2 - e^{-2kr_c\pi} v_0^2)^2 \}. \qquad (19)$$

A remarkable thing has happened. We see that the physical mass scales are set by a symmetry-breaking scale,

$$v \equiv e^{-kr_c\pi} v_0. \qquad (20)$$

This result is completely general: any mass parameter m_0 on the visible 3-brane in the fundamental higher-dimensional theory will correspond to a physical mass

$$m \equiv e^{-kr_c\pi} m_0 \qquad (21)$$

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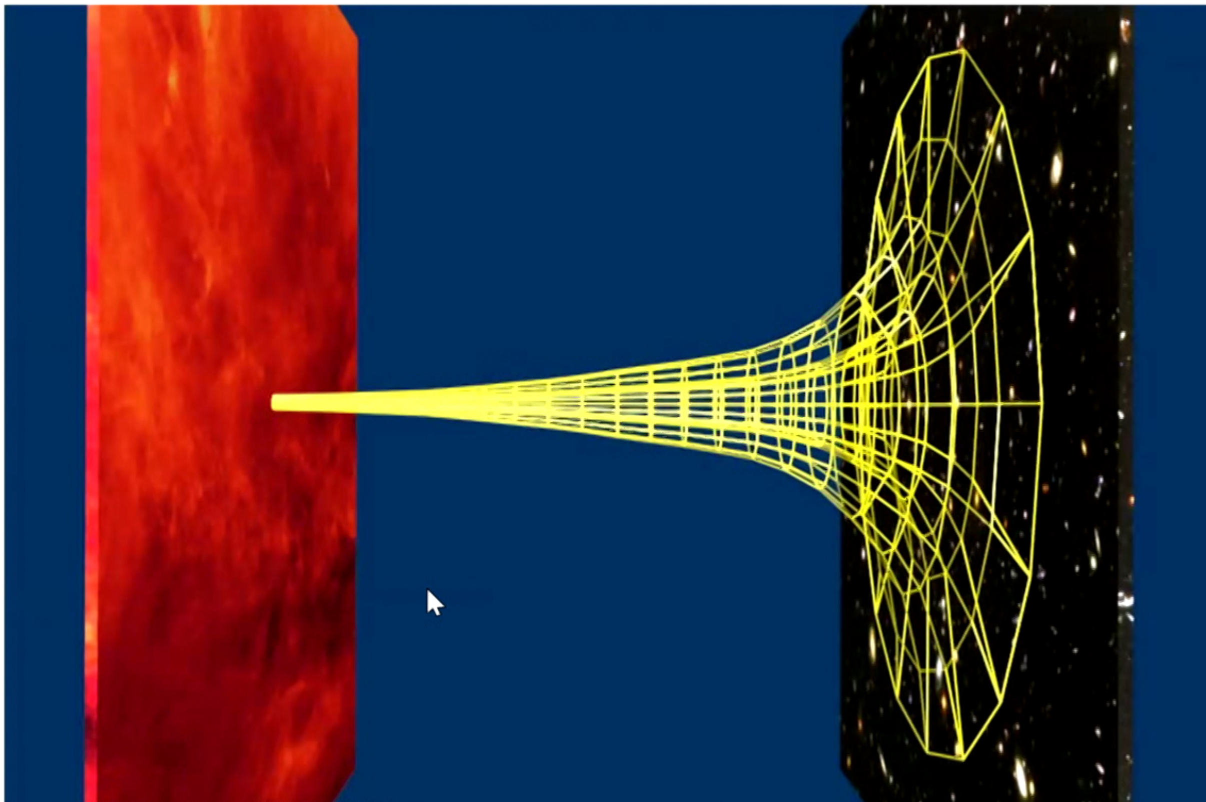
Solves Hierarchy!



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(Goldberger and Wise)

Implications
Many Unanticipated

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2.$$

- Can rescale on weak brane
  - But doesn't eliminate high scales
- Individual resonances: gravitons don't just disappear
  - Only a few
  - So had to be more strongly coupled to match onto 5 d expectation
  - And indeed, rescaling of interaction strength too
    - So finite number of resonances, but weakly coupled
      - Not gravitationally
  - **Means experimental implication is resonances**
  - Might be only hope to see a graviton

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Metric held even more surprises

- Planck scale only weakly depends on compactification radius
- With such weird dependence on "compactification" scale
- Don't actually need it
- Seemed that space can be infinite

$$S_{eff} \supset \int d^4x \int_0^{\pi r_c} dy \; 2M^3 r_c e^{-2k|y|} \sqrt{\overline{g}} \; \overline{R}.$$

$$M_{Pl}^2 = 2M^3 \int_0^{\pi r_c} dy e^{-2k|y|} = \frac{M^3}{k}[1 - e^{-2kr_c\pi}].$$

- Even when r is infinite, well-defined 4d gravity

Interpretation?

- Volume of extra dimensional space is finite
  - Even though coordinate takes infinite values
- Physical distance is infinite
- But volume determining M_{Pl} is not

- $M_{Pl}^2 = M^3/k$
- Note this also determines normalization of would-be zero mode
- Finite because of "UV" brane

Result

- Graviton bound state
  - Exponentially peaked
- Potential sum of all contributions

$$V(r) \sim G_N \frac{m_1 m_2}{r} + \int_0^\infty dm \frac{G_N}{k} \frac{m_1 m_2 e^{-mr}}{r} \frac{m}{k}$$

Extra wave function suppression

$$V(r) = G_N \frac{m_1 m_2}{r} \left(1 + \frac{1}{r^2 k^2}\right)$$

Generalize away from (4d) flat space

w/Karc

- Some big surprises
- Biggest surprise:
- for negative curvature –AdS –space:
- 4d gravity even though volume of extra dimension is infinite
- **No normalizable zero mode!!** Would-be graviton
- **But can 4d gravity really disappear with an arbitrarily small negative energy?**
- Another major insight:
  - **Appearance of a massive graviton**
    - Scaling with cc to sufficient power
  - Consistent with all 4d phenomena

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Before saying in a bit more detail

- This means we can see 4d gravity
- Even though space is truly higher-dimensional
- 4d Gravity can be a local phenomenon!
- Graviton can be massive

- Neither anticipated and genuinely new features that warped geometry shows possible

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Equations with 4d CC

$$S = \int d^5x \sqrt{g}\left[-\frac{1}{4}R - \Lambda^{5d}\right] - \lambda \int d^4x\, dr \sqrt{|\det g_{ij}|}\,\delta(r), \tag{1}$$

where g_{ij} is the metric induced on the brane by the ambient metric $g_{\mu\nu}$.

We use the ansatz for the solution to be a warped product with warp factor $A(r)$,

$$ds^2 = e^{2A(r)}\bar{g}_{ij}dx^i dx^j - dr^2 , \tag{2}$$

allowing for the 4d metric to be Minkowski, de Sitter or anti-de Sitter with the 4d cosmological constant Λ being zero, positive or negative respectively following the conventions of [2].

The solutions to Einstein's equations* are [2, 5, 6, 7]:

A is warp factor Determines overall scaling

$$\begin{aligned} dS_4 : A &= \log(\sqrt{\Lambda}L \sinh\frac{c-|r|}{L}) , \quad \lambda = \frac{3}{L}\coth\frac{c}{L} \\ M_4 : A &= \frac{c-|r|}{L} , \quad \lambda = \frac{3}{L} \\ AdS_4 : A &= \log(\sqrt{-\Lambda}L \cosh\frac{c-|r|}{L}) , \quad \lambda = \frac{3}{L}\tanh\frac{c}{L} . \end{aligned} \tag{3}$$

$$M = \frac{\lambda L}{3}$$

nsion without any exponential surpression:

$$\Lambda_{dS} = \frac{1}{L^2}(M^2 - 1), \quad \Lambda_{AdS} = \frac{1}{L^2}(1 - M^2).$$

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Warp Factors

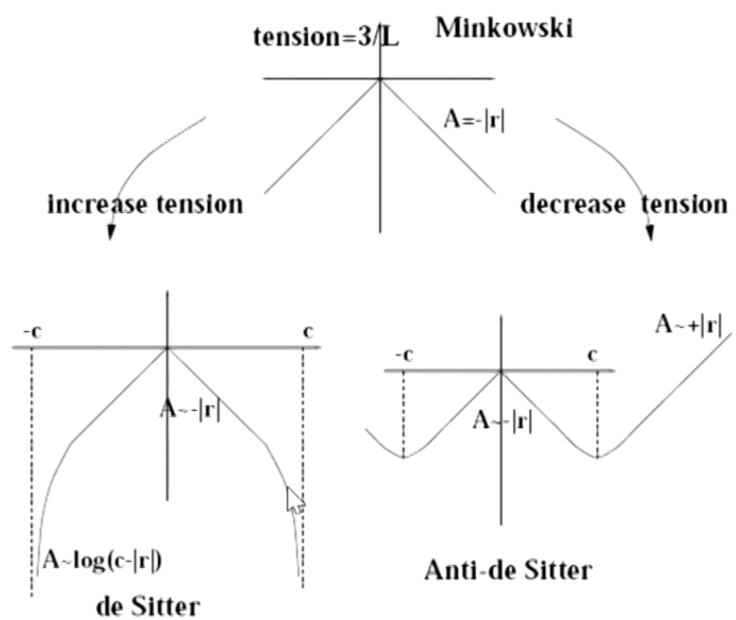

Figure 1: The behavior of the warp-factor for $\Lambda = -1$, 0 and 1.

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dS and Minkowski

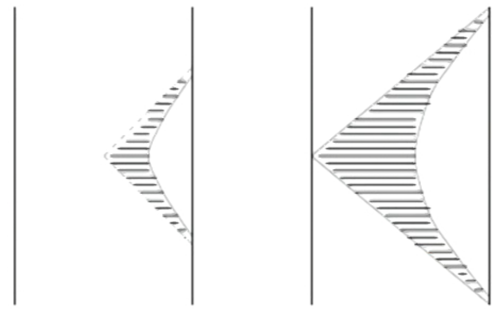

Figure 5: Schematics of the Penrose diagrams of the dS and Minkowski. The spacetime one is instructed to keep is shaded. Since the branes are accelerated, they have their own horizon, only for the Minkowski brane does this coincide with the Poincare patch horizon. The spacetime one wants to keep is between the brane and the horizon. The dS brane really is a full hyperboloid, the part drawn corresponding to the static slice of dS. In the case of the AdS brane the brane falls through the horizon of the Poincare patch. It is more useful to study the embedding in terms of an constant time slice through global AdS.

AdS

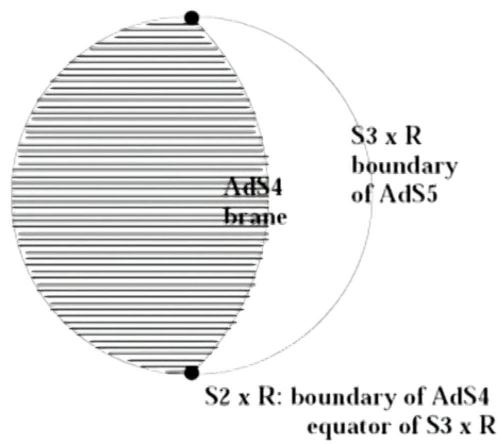

Figure 6: Constant time slice through AdS_5, with the AdS_4 brane included and again the region of spacetime we are instructed to keep shaded. Global time on the brane is global time in AdS_5, the picture does not evolve in time.

So AdS very different/but similar!

- You do reproduce 4d gravity—to an extent
- But eventually at low energy you are sensitive to modes that mix with another sector
- There are two CFTs with two different theories—one dual to a theory of 4d gravity and one dual to the nongravitational boundary theory
- From CFT point of view "leaky boundary conditions" allow energy to pass from one to the other

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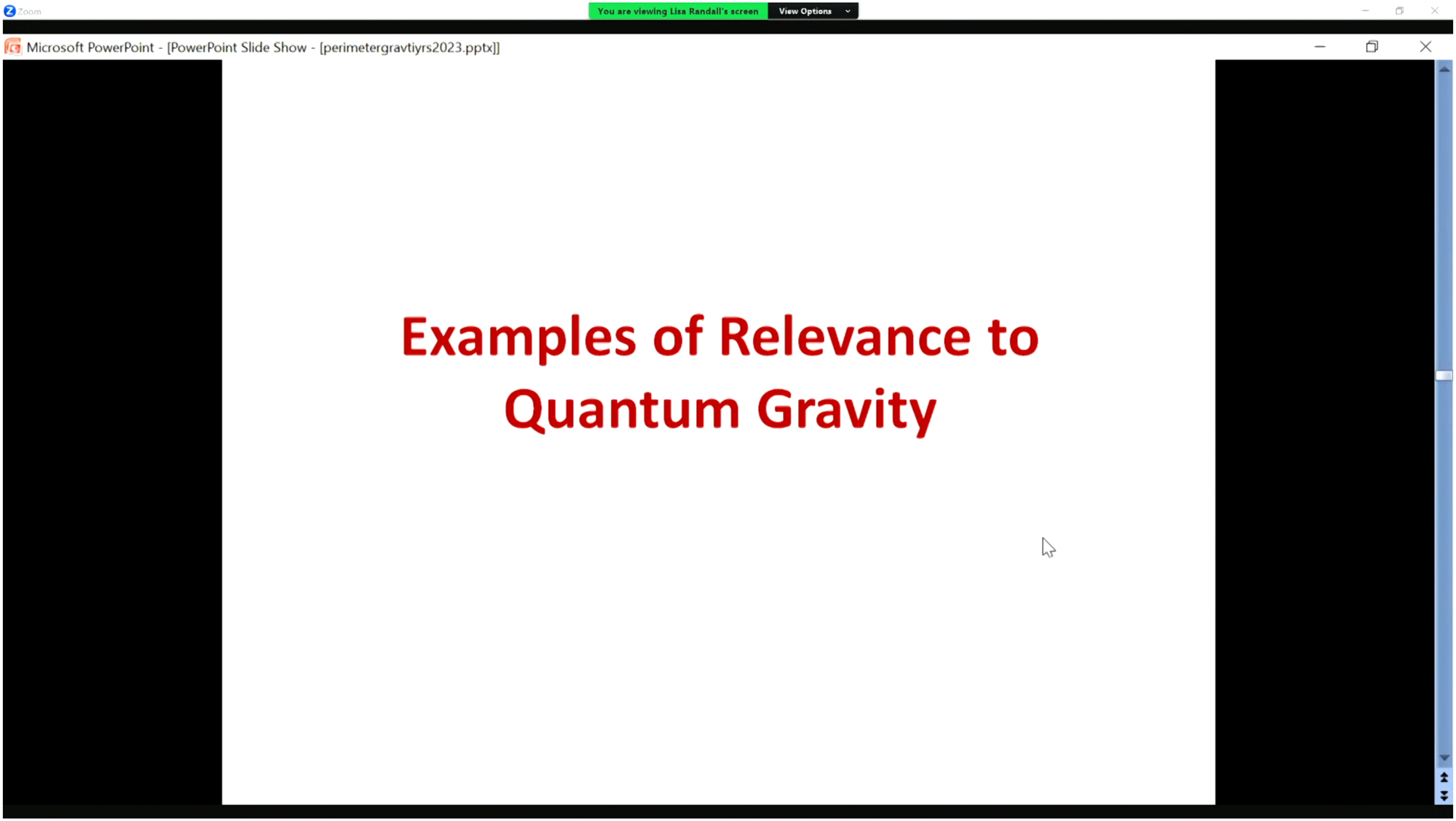
Massive graviton

- Resolution comes from detailed study of KK modes
  - Though more sophisticated understanding subsequently
- KK modes discrete; generally separated by mass of order $\sqrt{\Lambda}$
- But there is a special light mode with mass scaling as Λ
- This mode plays the role of the graviton

Massive Gravity in AdS

- Turns out VVdZ discontinuity is not an issue for such a small mass w/Karch, Katz
- For sufficiently high energies, theory acts as a theory of massless gravity
- Ultimately in IR (or after a long time) “leakage” of 4d gravitational theory becomes apparent
- Was beginning of renaissance of work on massive gravity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Examples of Relevance to
Quantum Gravity

What else does AdS_5/AdS_4 teach us?

- Lots of work on understanding resolution to black hole information paradox
- Proposed advance involves “islands” which are regions (entanglement wedges) spatially disconnected from the asymptotic boundary.
- However, in theories of long-range-gravity, excitations in the island can be detected outside
- But operators in the entanglement wedge should commute with those outside

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Hao Geng[a,b], Andreas Karch[b,c], Carlos Perez-Pardavila[c], Suvrat Raju[a], Lisa Randall[a], Marcos Riojas[c] and Sanjit Shashi[c]

Schematic 5d

brane

Boundary (meets brane)

horizon

Thermal double

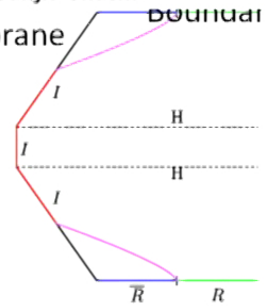

Figure 1: *A cartoon of a constant-time slice of a black hole with a brane embedded. R is the union of regions on two asymptotic boundaries and $\overline{R}$ is its complementary region. The horizons in the bulk are marked by H. The separation between horizons is meant to convey that the Cauchy slice under examination is a late-time slice on which the wormhole is of a finite length. The dominant RT surface for the region R is shown in purple. The region on the brane marked I becomes the "island" in the lower-dimensional picture of Figure 2. In this figure, both the horizontal and the vertical directions are spatial.*

4D (Includes time)

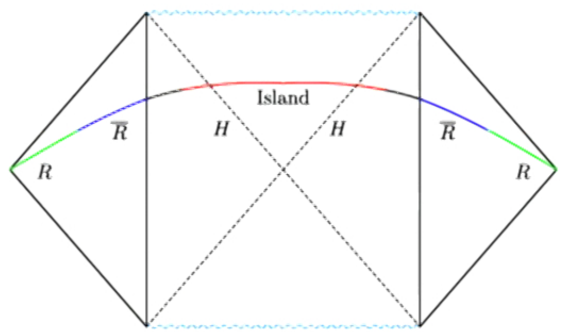

Figure 2: *A spacetime diagram of the same system of branes in a black hole in the d dimensional description. The entanglement wedge for the region R is now an "island". In this figure, the horizontal direction is spatial and time runs along the vertical direction.*

- The fine-grained entropy of a part of the bath—the radiation region—is computed through an "island rule" generating a Page curve
- Operators in the island should be reconstructable in part of the boundary in the same way that bulk can be reconstructed through the boundary CFT with the AdS/CFT correspondence

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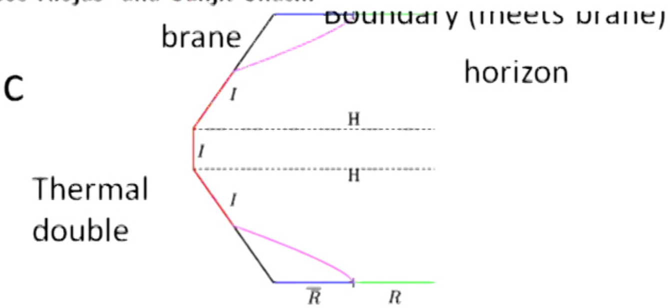
Hao Geng[a,b], Andreas Karch[b,c], Carlos Perez-Pardavila[c], Suvrat Raju[a], Lisa Randall[a], Marcos Riojas[c] and Sanjit Shashi[c]

Schematic 5d



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4D (Includes time)

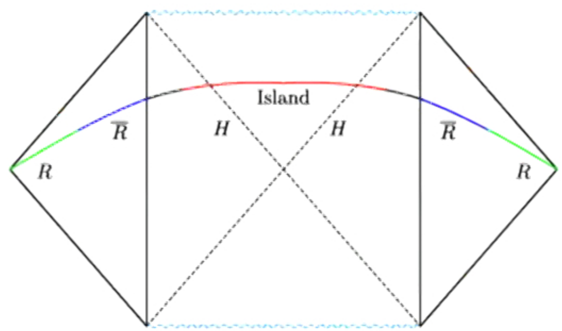

Figure 2: *A spacetime diagram of the same system of branes in a black hole in the d dimensional description. The entanglement wedge for the region R is now an "island". In this figure, the horizontal direction is spatial and time runs along the vertical direction.*

Contradiction

- The problem is that every local operator must be “dressed” to the boundary
- Ordinarily connected components of the entanglement wedge contain a piece of the boundary so this can be readily made to be consistent
- But if the wedge does not contain the boundary, any unitary operator creating energy in the island will not commute with the complement of the island since the energy of the island could be measureable from the falloff of the metric in the asymptotic region using Gauss’ Law

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4d a problem

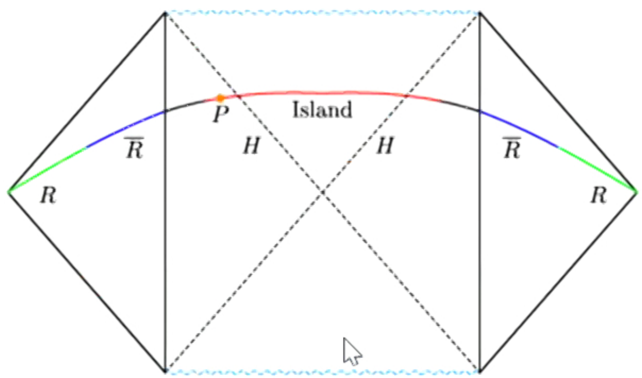

Figure 6: *A lower-dimensional picture of the setup of Figure 5. This is a spacetime diagram like Figure 2. In the lower-dimensional description, an operator at point P in the island cannot be dressed to the boundary without affecting the region outside the island. So the island cannot constitute a consistent entanglement wedge in a theory where the Gauss law applies. The lower-dimensional description of Figure 5 involves massive gravity where the Gauss law does not hold. In this figure, the horizontal direction is spatial and time runs along the vertical direction.*

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Resolution: Gauss' Law with Mass

- Gauss' Law doesn't apply (or applies in a modified fashion) because of the mass term

$$\frac{1}{16\pi G}\int_B d^{d-1}x\; n_j(\partial_i h_{ij} - \partial_j h_{ii}) = \int_V d^d x\; \rho.$$

$$-\partial_j\partial_j h_{ii} + \partial_j\partial_i h_{ij} + m^2 h_{ii} = 16\pi G\rho.$$

Two important distinctions
NOT a total derivative so can't simply integrate to the surface
And NOT a constraint—relates metric to a new longitudinal component

Big lesson from Karch-Randall (AdS version of RS)
Graviton has mass which is why islands are consistent!

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One Other Application for Quantum Gravity: KKLT (Kachru, Kallosh, Linde, Trivedi)

- KKLT is proposed model for a background in de 4d Sitter space from string theory
- We present cartoon version of the model
  - Emphasize role of warped geometry
- And emphasize an interesting (unanticipated) lesson about gravitational constraints

KKLT: deSitter String Theory Construction

- Stable string vacua much easier to construct with supersymmetry
- But supersymmetry consistent only with flat (critical energy density) or Anti de Sitter (negative energy density) space
- Measurements however support positive cosmological constant
  - Albeit tiny
- Idea of KKLT was to construct a stable configuration with smallish negative energy
- Add an antibrane to cancel that energy and provide de Sitter
- Use warped throat to explain smallness of antibrane energy
  - Natural scale is string scale which is too big

KKLT Construction

- Used fluxes to generate stable compactification where moduli have mass
- One field left massless: volume modulus
- Supersymmetric condensate generates a potential (breaks no-scale form of superysymmetric Lagrangian)
- Leaves a stable AdS solution
- Uplift from an antibrane
  - But too high an energy density
- Warped throat (generated by branes) so that antibrane energy density comparable to that of the AdS solution

KKLT: de Sitter String Construction

$$V = \frac{aAe^{-a\sigma}}{2\sigma^2}\left(\frac{1}{3}\sigma aAe^{-a\sigma} + W_0 + Ae^{-a\sigma}\right) + \frac{D}{\sigma^3}$$

- Calabi-Yau /F-theory compactification
  - Fluxes stabilize all complex structure moduli
  - But Kahler (volume) modulus σ remains undetermined
- KKLT resolution
  - Break no-scale structure with nonperturbative gauge contributions to stabilize Kahler modulus at large volume
    - Yields AdS_4 as low-energy theory
- Uplift energy using warped throat
  - Anti D3 brane
  - In warped geometry (KS) throat
    - Suppresses uplift
    - Warped geometry gives smaller energy density to match AdS
    - Resulting in desired dS geometry

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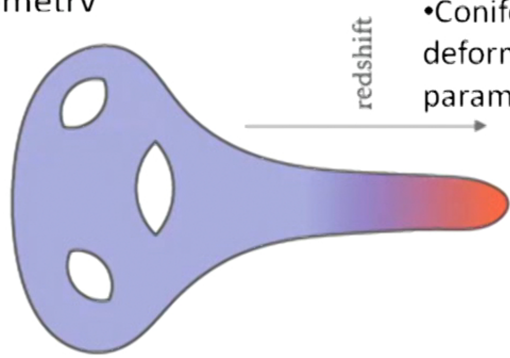
String Theory Version of RS

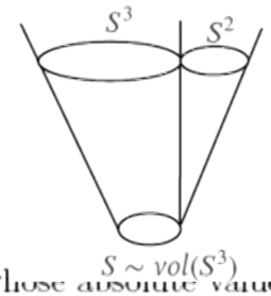
(Kachru, Polchinski, Verlinde)

- Cartoon: RS warped AdS throat glued onto CY
- CY **compactification** acts as UV brane
- But Klebanov-Strassler AdS space
  - Constantly changing (increasing) AdS curvature
  - AdS_5 but with "running N_{eff}"
    - N_{UV}=MK; N_{IR}= M; hierarchy from $e^{-2\pi K/Mg_s}$
- Caps off at a critical length
- Conifold deformation region is "IR brane"
- Stabilization built into geometry



Can Identify "Radion" in KKLT LR

S: Conifold deformation parameter



$$\sum_{a=1}^{4} \omega_a^4 = S \, . \tag{3.10}$$

The deformation parameter S is the complex structure modulus whose absolute value corresponds to the size of the 3-sphere at the tip of the cone.

$$\int_A \Omega_3 = S \, , \tag{3.11}$$

Potential for S Douglas Shelton Torroba

The supersymmetric potential for this field induced by the Klebanov-Strassler geometry is

$$V_{KS} = \frac{\pi^{3/2}}{\kappa_{10}} \frac{g_s}{(Im\rho)^3} \left[c \log \frac{\Lambda_0^3}{|S|} + c' \frac{g_s(\alpha' M)^2}{|S|^{4/3}} \right]^{-1} \left| \frac{M}{2\pi i} \log \frac{\Lambda_0^3}{S} + i \frac{K}{g_s} \right|^2 , \tag{3.12}$$

where g_s is the stabilized vev of the dilaton, $Im\rho = (\mathrm{Vol}_6)^{3/2}$, c as we argue below is not relevant here (and is in any case suppressed in the small S region), whereas the constant c', multiplying the term coming solely from the warp factor, denotes an order one coefficient, whose approximate numerical value was determined in [46] to be $c' \approx 1.18$.

"Conifold" instability Runaway Radion

Bena, Dudas, Grana, Lust; LR

The general form of the potential (we factor out $\lambda_1^4 \pi g_s / c'$) is

$$V = S^{4/3}\left(1 + \epsilon \log \frac{S}{\Lambda_0^3}\right)^2 + \delta S^{4/3} \tag{3.28}$$

The barrier disappears when $\delta/\epsilon^2 = 9/16$.

We see that the perturbation from the antibrane (yielding the δ type perturbation above) yields the potential proportional to the above with $\delta = c'' c' g_s / \pi K^2$ and $|\epsilon| = M g_s / 2\pi K$. By writing it this way we keep ϵ and δ as small parameters. This gives precisely the stability condition found in [59], namely

$$\sqrt{g_s} M > M_{\min} \qquad \text{with} \qquad M_{\min} = \frac{8}{3}\sqrt{\pi c' c''} \approx 6.8\sqrt{p}\,. \tag{3.29}$$

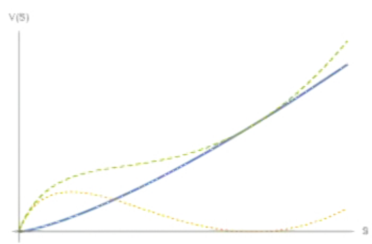


Figure 2: The contribution $V_{\overline{D3}}$ (solid blue line) of an $\overline{D3}$-brane placed in the Klebanov-Strassler throat to the potential for S. The two other lines represent the original potential V_{KS} (dotted orange line) for the specific value $\sqrt{g_s}M = 6$ as well as the superposition $V_{KS} + V_{\overline{D3}}$ (dashed green line).

] I. Bena, E. Dudas, M. Graña and S. Lüst, "Uplifting I
(2019) no.1-2, 1800100 [arXiv:1809.06861 [hep-th]].

L. Randall, "The Boundaries of KKLT," Fortsch. Phys. **68** (2020) no.3-4, 1900105 [arXiv:1912.06693 [hep-th]].

Good and Bad?

- You can identify radion
- And radion potential
- Has expected form: slow running from UV to IR corresponding to small bulk “mass”
- BUT…
- Radion runs off to infinity
- Not expected; especially since antibrane a small perturbation?

Resolution: Need to impose constraints/higher D EE

- Potential not correct! (off shell)
  - Need off-shell potential
- Consider a one parameter family of metrics labeled by S(x)
- You then have $A(y^m, S)$ and $\tilde{g}_{mn}(y^m, S)$.
- Which renders the metric x-dependent

$$G_{MN} = R_{MN} - \frac{1}{2} g_{MN} R,$$

- So consistent only with constraints from higher-dimensional Einstein Equations

Constraints Cont'd
Analog of Traceless Transverse
But with Warped Compactification

I $\qquad \delta_S A = \frac{1}{8}\delta_S \tilde{g}\,,$ Or warped volume conserved $\qquad V_w = \int d^6y \sqrt{\tilde{g}_6}\, e^{-4A}$

$$\delta_S \tilde{g} = g^{mn}\delta_S \tilde{g}_{mn}.$$

II $\qquad \tilde{\nabla}^n\left[\delta_S\tilde{g}_{nm} - \tilde{g}_{mn}\left(\delta_S\tilde{g} - 4\delta_S A\right)\right] - 2\tilde{g}^{nk}\,\partial_n A\left[\delta_S\tilde{g}_{km} - \tilde{g}_{km}\left(\delta_S\tilde{g} - 8\delta_S A\right)\right] = \delta_S T_m$

or

$$\tilde{\nabla}^n\left(\delta_S\tilde{g}_{nm} - \frac{1}{2}\tilde{g}_{mn}\delta_S\tilde{g}\right) - 4\tilde{g}^{nk}\,\partial_n A\,\delta_S\tilde{g}_{km} = \delta_S T_m$$

When A is zero the constraints (3.8) and (3.12) readily reduce to the familiar gauge-fixing conditions [73]

$$\nabla^m\delta g_{mn} = 0\,, \qquad g^{mn}\delta g_{mn} = 0\,. \qquad (4.3)$$

Result of Imposing Constraints: No Second Minimum

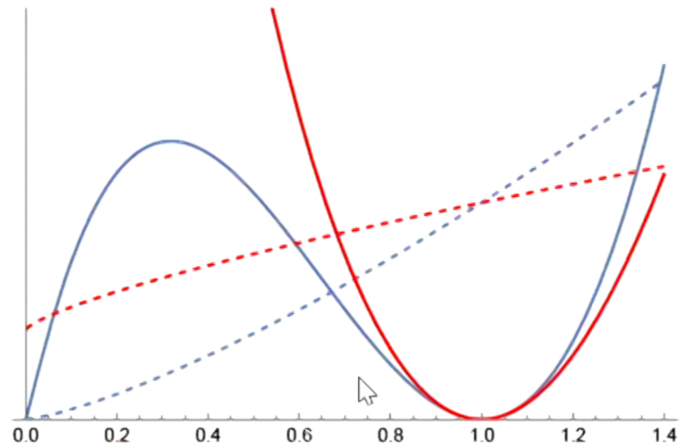


Figure 3: Comparison of the potential computed by [10] (blue) and our potential (red). The solid line is the potential for the conifold modulus S and the dashed line the contribution from the antibrane. Their superposition is illustrated in Figure 4.

$$V_{\text{flux}} = T_3 \frac{g_s M^2}{32\pi} \int d\tau \frac{e^{4A}}{\partial_\tau \mathcal{T}} \left\{ 8\frac{(\tau \coth\tau - 1)^2}{\sinh^2\tau} + \coth^2(\mathcal{T}/2) \frac{\sinh^2(\tau/2)}{\cosh^6(\tau/2)} (\sinh\tau + \tau)^2 \right.$$
$$+ \tanh^2(\mathcal{T}/2) \frac{\cosh^2(\tau/2)}{\sinh^6(\tau/2)} (\sinh\tau + \tau)^2 + 16\left[1 + \frac{3 + 2\tau - 6t\coth\tau + 3\tau^2 \operatorname{csch}^2\tau}{\sinh^2\tau}\right] \partial_\tau \mathcal{T}$$
$$\left. +8\left[1 + 2\operatorname{csch}^2\mathcal{T} - 4\frac{\cosh\mathcal{T}}{\sinh^2\mathcal{T}} \operatorname{csch}\tau + \frac{(\tau\coth\tau - 1)^2 + \tau^2(1 + 2\operatorname{csch}^2\mathcal{T})}{\sinh^2\tau}\right] (\partial_\tau \mathcal{T})^2 \right\}.$$

$$V_{\overline{D3}}(S) = 2N_{\overline{D3}} T_3 e^{4A(0,S)}$$

General Lessons

- IR theory depends on UV theory
- In warped models in particular, KK mode masses get warped down
- This means even a heavy UV field can have KK modes present in IR theory
- This allows shape of extra dimensions to adjust in IR
- And effects potential of light field

Current Work

EFT of Higher Dimensions Luest, LR

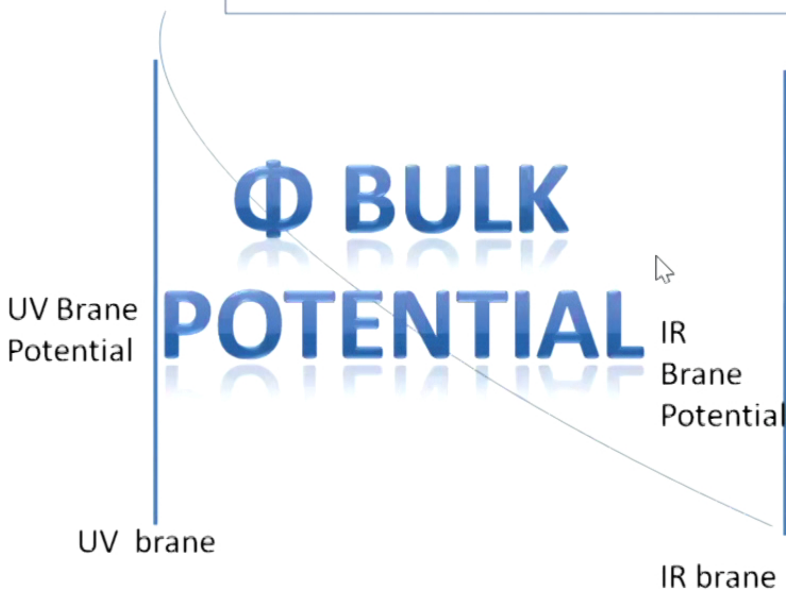
- Why?
  - Worth knowing if there are hidden mechanisms in higher-dimensional theories (generally UV theories)
  - We certainly want 4d to reproduce usual physics
  - But have we been too cavalier about potential deviations
- My motivation was understanding how susy is broken in IR yet gives consistent metric throughout space
- To address needed to track energy in more detail than we usually do
- Also need to track stabilization –low energy theory critically relies on that
- Does it modify low energy in any interesting way

One Interesting New Result

- Third constraint: for a stable 5d (or higher d) solution
- Need constant lower-dimensional cc at each higher-dimensional point
- Otherwise time-dependence in extra dimensions
- Like previous constraints, just a consequence of higher-dimensional EE
  - – But here true even without compact space

Warped Geometry: RS Refresher

$$ds^2 = e^{-2kr|\vartheta|}\eta_{\mu\nu}dx^\mu dx^\nu + r^2 d\vartheta^2, \qquad -\pi < \vartheta \leq +\pi.$$



Need to stabilize distance between branes

Goldberger and Wise suggested a mechanism that is general enough in spirit to cover options

Essentially put in UV and IR bc
And b
ulk potential
Competition stabilizes field

EFT of Higher Dimensions: Potentially Interesting Result

- For a potential

$$S = \int d^4x dr \sqrt{g_5}\left[\frac{1}{4}R - \frac{1}{2}(\partial\Phi)^2 - V(\Phi)\right] - \sum_\alpha \int_{B_\alpha} d^4x \sqrt{g_4}\lambda_\alpha(\Phi)$$

$$\lambda_1 = 3k + \Delta T_{UV} + \lambda_{UV}(\Phi)\,, \qquad \lambda_2 = -3k + \Delta T_{IR} + \lambda_{IR}(\Phi)$$

$$\lambda(\Phi) = \alpha\,(\Phi - v)^2\,.$$

- We find low-energy (4d) cosmological constant when perturbed in IR is

$$\delta\Lambda = e^{-4k\pi r_c}\frac{2k(\alpha_{IR} - 4k)(\alpha_{UV} - 8k)}{3\alpha_{UV}(\alpha_{IR} + 4k)}\delta T_{IR}\,.$$

In the large α_{IR} and α_{UV} limit this reduces to

$$\delta\Lambda = \frac{2k}{3}e^{-4k\pi r_c}\delta T_{IR}\,.$$

- This means UV parameters determine how efficiently IR energy transfers to the low-energy theory
- Implications for cc?
  - Long shot but worth understanding

Why

- Previous attempts at potential ignored dependence on UV; assumed cc set to zero and all remaining interesting physics in IR
- We find yet another gravitational constraint for system with 4d dynamics
  - Static in extra dimension
- Requires same (4d) cc at every extra-dimensional slice
- Consequence is radion field adjusts to allow for consistent warping

Why Interesting if correct)

- This means even though energy deposited in IR the net energy change can be sensitive to UV parameters
- Suggests interesting deviation from purely 4d physics
- And also suggests again gravity holds some calculable surprises we should understand

Summary of Lessons (general)

- We can debate nature of quantum gravity
- We can try to see what are consequences of gravity theory we know
- Clear is we don't fully understand even that
- Solutions to Einstein's Equations are tricky
- Time-dependent warped solutions challenging
- But until we better understand full consequences might be difficult to determine what underlies it

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Lots more didn't have time to discuss

- Cosmology
  - Phase transition to RS from black brane phase
  - First order
  - Yields potentially observable gravity waves
  - But too much supercooling and constraint on dual theory
- BUT
  - We find model dependent
  - IR matters (and can change with higher-order interactions)
  - But model matters too
  - Phase transition in KKLT different
  - We are modeling with additional scalar and find minimum temperature

New Ways of Searching

- Lots of new models
- Combining with supersymmetry
- How supersymmetry breaking is communicated

Big lesson and Conclusion

- Combination top-down and bottom-up often best approach
- Hard to fully appreciate new ideas without more detailed specific questions
- Extra dimensional models often tractable
- And reveal many new phenomena
- Useful tool
- And who knows? Might even be right!