# More Effective Field Theory

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# Effective Field Theories

- Very useful to have a low energy description
- Basic premise in all of physics that you can relate parameters of low energy/large distance theories even without detailed knowledge of more fundamental physics
  - More efficient for calculations and often for understanding physical mechanisms
- **However: obvious point is that you need the correct effective theory**
  - **We know eft can break down,** but generally through small discrepancies at limits of validity of allowed and tested parameter range
- But sometimes not all the EFT variables are evident
- Will consider a few such examples here
  - Based on extra dimensions; RS and KKLT
  - **Need to account for stabilization, all light modes, and consequences of consistent gravitational solutions; also of course model dependence**

# Why Bother (after one or two decades)?

- Two main threads for me
  - Theoretical: In particular peculiar aspects of higher-dimensional theories
    - Deriving low energy theory of warped compactifications (eg KKLT) and warped geometry (RS with GW) have some puzzling features
      - Behavior of radion mode
      - Energy in low energy theory
      - Supersymmetry realization
      - Cosmology from extra dimensions
      -             with shououts to many in audience here

  - Second is phenomenological
    - LHC results have discouraged research into naturalness
      - Current bounds at TeV to few TeV seem to rule out natural theories
      - How tied to specific models is this?
- **But also more general question: how do field theory and gravity interact and when do we have to pay attention?**
- In other words when is it subtle to find an EFT?
- After all sometimes inconsistencies best way to look for new ideas

# B(efore)BBSM

- Understand our theories better

- Interaction between gravity and PP?

- Extra dimensions are nice probe of physics beyond SM but in controllable regime

- Often elucidate physical phenomena of string theory for example

# Outline

- RS, KKLT "review"
- State puzzles; prelude to resolutions
- More details on puzzles
- Conclude

# Warped Geometry: RS Refresher

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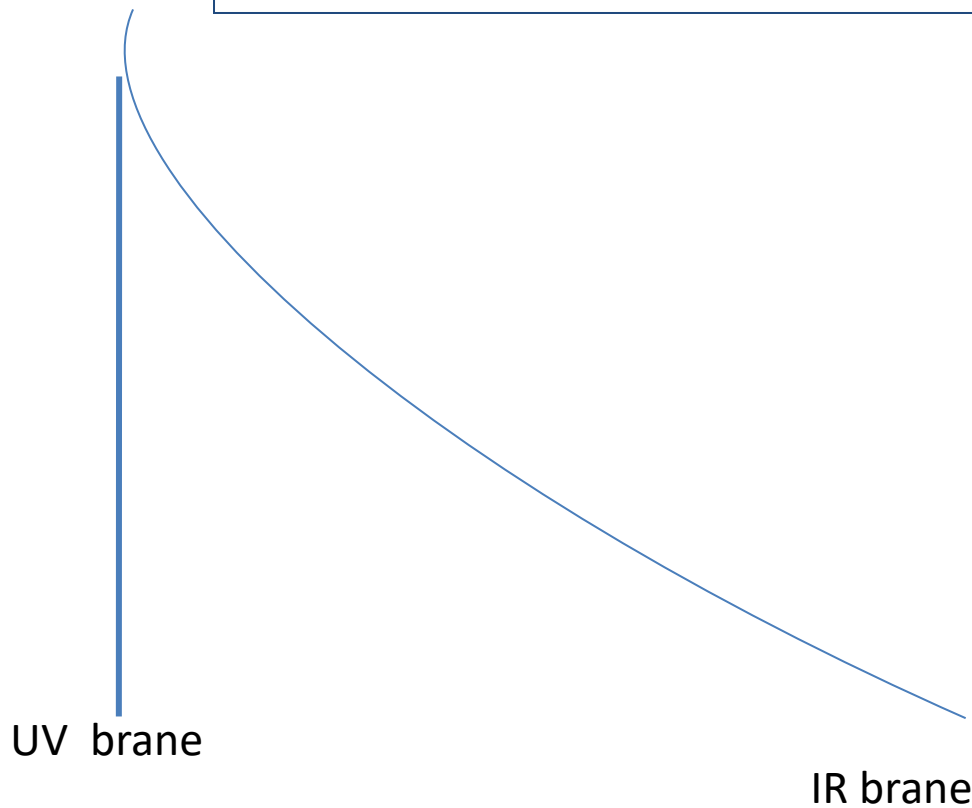
UV  brane

IR brane

From 5d perspective space extends over fifth dimension but metric (and graviton wf) scaled significantly with composite states on IR brane and fundamental on UV brane

From 4d CFT perspective strong renormalization group scaling of some operator leading to compositeness in IR

# 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

# 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

# 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

•IR set by S
•Conifold deformation parameter

redshift

Calabi-Yau:
UV
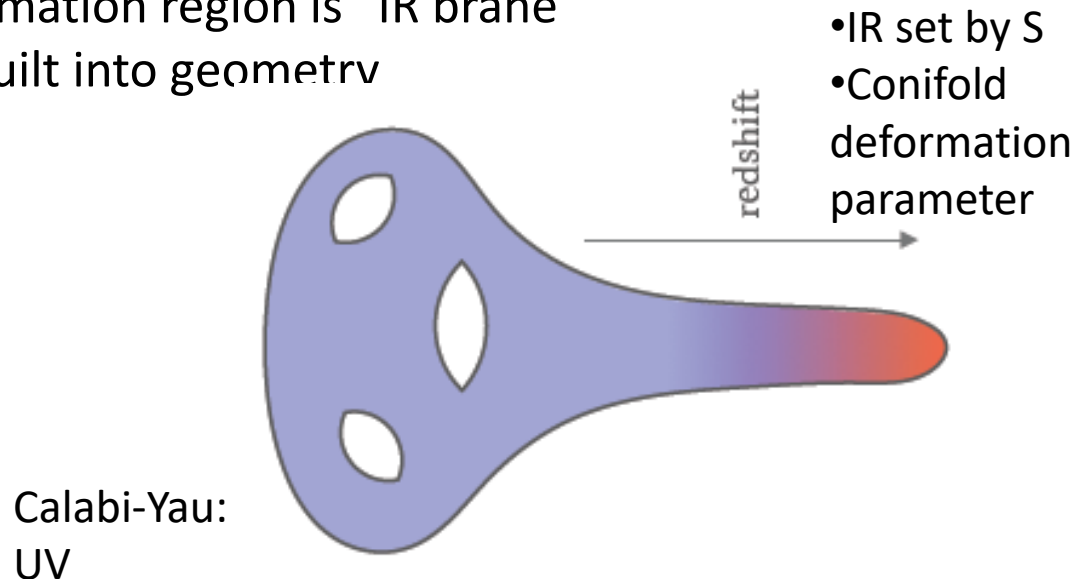
# EFT Puzzles

# I: Effective Field Theory From Higher Dimensions: Warped compactifications

$$ds_{10}^2 = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}(y)dy^m dy^n$$

- Need a radion/GW field in low energy theory S(x)
- In original KKLT we showed S was the conifold deformation parameter; fixed value before uplif
- But with uplift S(x) needs to be a field
- So warping really A(y, S(x)) g(y, S(x)) where S(x) is a radion field allowed to go off shell
- With naïve potential in literature, seemed S was a runaway
  - But how can adding perturbation destroy conifold
  - Restore supersymmetry
- We will see  not all forms of potential allowed; becasuse of S(x), metric has to confront higher dimensional constraints

# EFT Perspective: Related to Kaluza-Klein Modes in RS Geometry

- Usually we just integrate out heavy fields
- But in RS even heavy fields can have light KK modes
- Suppose bulk mass
- Zero mode mass is warped down and KK modes on top of that
  - Modes are discrete; mass gap determined by IR scale
  - Warped version of Planck scale; eg TeV
- BUT if UV mass only zero mode heavy
- BUT KK modes stay light
  - Less than mass of "zero" mode

Mass
on
brane

x
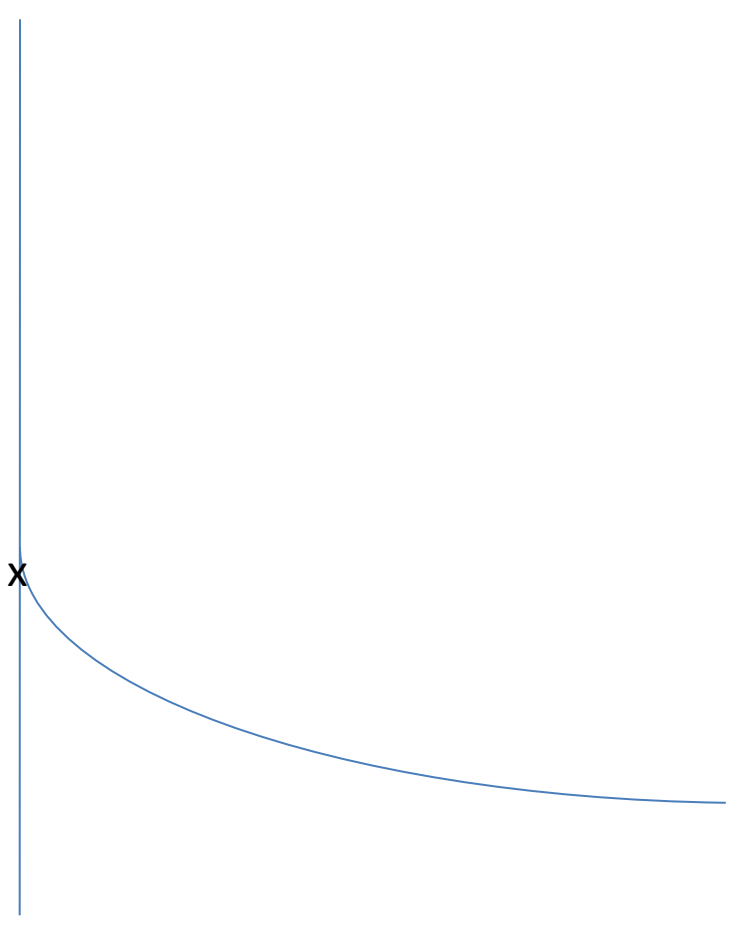
Mass on uv brane only
Take mass big
Acts as Dirichlet boundary
condition
Get essentially same KK
spectrum
KK modes localized in IR
Only marginally affected by
mass in UV

# RS EFT: Simple failure mode

- Omission of light degrees of freedom
- eg Bulk field gets heavy mass on UV brane
- Mass (taken to infinity) acts as a Dirichlet boundary condition

The masses of gauge KK modes with $(-,+)$ boundary condition and a bulk mass $M$ are given by

Agashe,Degado, May, Sundrum

$$\frac{J_\nu\left(m_{gauge}^{(n)}z_h\right)}{Y_\nu\left(m_{gauge}^{(n)}z_h\right)} = \frac{\tilde{J}_\nu\left(m_{gauge}^{(n)}z_v\right)}{\tilde{Y}_\nu\left(m_{gauge}^{(n)}z_v\right)}$$

(D.3)

so that, for $m_{gauge}^{(n)}z_h \ll 1$, we get $m_{gauge}^{(n)}z_v \approx$ zeroes of $J_0 + M^2/(4k^2) + O\left(\left[z_h m_{gauge}^{(n)}\right]^2, M^4/k^4\right)$.

- Spectrum of light KK modes is essentially same as for massless field
  - From dual perspective fundamental field not influencing mass of composite
- This has been done properly in studying RS models
- **However string theorists integrate out heavy moduli fields but neglect light KK modes in warped throat**

  - **In addition to "radion" essential to stabilization**

# UV Mass and EFT

- However, it is very easy to forget those modes
- Standard EFT: integrate out heavy fields
  - Include higher-dimension operators
  - But otherwise forget them
- Here we integrate out heavy modes but need to still include KK modes in EFT!
- If KK modes associated with shape or volume it means shape or volume can still vary over extra dimension
- Turns out it is essential to consistency

# Puzzle II: Effective Field Theory From Warped Metric

- $ds^2 = e^{\wedge}f(y) \, g_{\mu\nu} \, x_\mu \, x_\nu - dy^2$
- We simply solve 5d eq of motion with a stabilizing field
- And put in 4d boundary conditions
- 5d: four constraints (two boundary conditions on scalar and warp factor), four unknowns ($r_c$, $\Lambda_4$, and two additional integration constants from stabilizing field)
- Leads to different EFT answers than in literature; with radion mass set by $\epsilon$ in low energy, however cc set by $\epsilon\delta T$ or just $\delta T$
- That is (naïve) theory of radion incomplete in EFT

- Resolution: To get an EFT implicitly imposing constraint that you have 4d dynamics
  - Third constraint: Amounts to constant 4d curvature, Hubble
- Resolution: Also we need to explicitly integrate out heavy fields

# Another related puzzle

- If I stabilize extra dimension by pinning down values at boundary, how do I see parameters of that potential in low energy theory

- In general, Dirichlet and Neumann

- Nontrivial to derive dependence

- Again disagreed with naïve effective theory with only radion included

- Answer here is you need to more carefully integrate out high energy parameters

# Why Bother?

- Relevant to cc in low energy theory

- Relevant to consistency of description

- Also get  better understanding supersymmetry with boundaries

# Puzzle III: EFT of Supersymmetric Theory

- How does supersymmetry communicate between branes?
- Standard answer is anomaly-mediation and sequestering (and gaugino or other mediation with fields in the bulk)
- But… if consistent in higher d
- Need to equilibrate curvature
  - implies energy redistributes
- Seems to imply large communication from GW field
  - Would imply direct supersymmetry communication
- But susy breaking generally quadratic in order parameter
  - No sequestering?
- In fact reason I started down this rabbit hole
  - KKLT says IR SUSY breaking
  - But consistent slicing says even UV must change its 4d mettric

- But…CFT sequestering, lots of results saying it is

- Resolution:  boundary terms essential to consistency of susy theory

# IV: Cosmology of extra dimensions

- Disturbing (to me) (old) paper by Creminelli, Nicolis, Rattazzi
- Argue first order phase transition from black brane phase to RS
- Because radiion potential very flat bubble action very suppressed
- Leads to strong constraints on dual SU(N) version of theory (small N)

- "Resolution" (w Mishra) we argue highly model-dependent
  - Add cubic GW interaction
  - Alternatively, add additional field; more closely related to what is actuallly happening
    - IR brane  standin for some relevant CFT dynamics
    - Not really included in original argument
  - Model seems to really matter
  - Not exactly eft failure but in general better to have eft that captures range of dynamics
    - Here we think reasonable ways to evade conclusion

- Our goal; When and how does high energy theory affect effective theory?
  - Really question is when do you need to know more about high-energy theory
    - Higher-dimensional wavefunctions
    - Stabilization
    - Energy and metric variation over the extra dimension
- Put it all together
  - Some surprising results
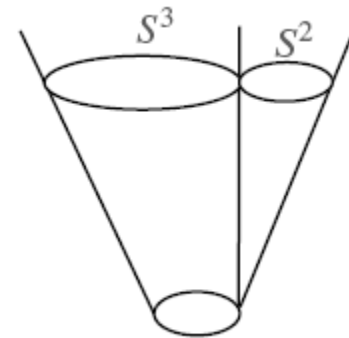  - (But not all results: work in progress)

# Resolutions

# Puzzle I:
# Warped Compactification

LR w/S. Luest

# Can Identify "Radion" in KKLT

$S$: Conifold deformation parameter

$$\sum_{a=1}^{4} \omega_a^4 = S \,. \qquad (3.10)$$

$S^3$  $S^2$

$S \sim vol(S^3)$

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.

$$\int_A \Omega_3 = S \,, \qquad (3.11)$$

## Potential for S Douglas Shelton Torroba

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

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

where $g_s$ is the stabilized vev of the dilaton, $Im\rho = (Vol_6)^{3/2}$, $c$ 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 $c' \approx 1.18$.

# "Radion" Potential
# Radion is Condifold Deformation Parameter

- Fluxes generate a potential for S <sub>Douglas, Shelton, Torriba</sub>

$$V_{KS} \sim \underbrace{\frac{|S|^{4/3}}{g_s(\alpha' M)^2}}_{G^{S\bar{S}}} \underbrace{\left| \frac{M}{2\pi i} \log \frac{\Lambda_0^3}{S} + i \frac{K}{g_s} \right|^2}_{D_S W}$$
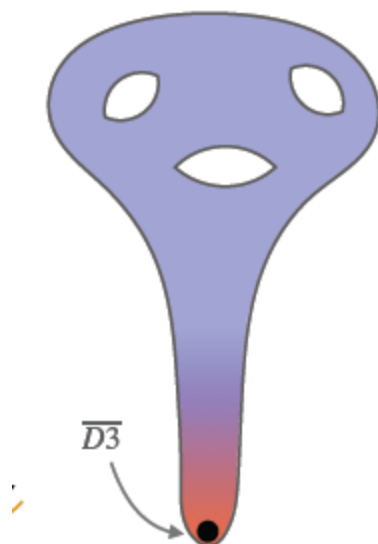
$$e^{-4A(\tau)} \sim \frac{g_s(\alpha' M)^2}{|S|^{\frac{4}{3}}} I(\tau)$$

- Kahler Metric

$$G_{S\bar{S}} = \partial_S \partial_{\bar{S}} K \sim \int e^{-4A} \chi_S \wedge \bar{\chi}_{\bar{S}} \approx e^{-4A(\tau=0)} \sim \frac{g_s(\alpha' M)^2}{|S|^{\frac{4}{3}}}$$

- But when we add antibrane, will take S away from initial minimum

- Spoiler alert: We will need metric off shell

# Add Potential from Antibrane



The antibrane contributes a perturbation

$$V_{\overline{D3}} = \frac{\pi^{1/2}}{\kappa_{10}} \frac{1}{(Im\rho)^3} \frac{2^{1/3}}{I(\tau)} \frac{|S|^{4/3}}{g_s(\alpha'M)^2} \, .$$

# "Conifold" instability Runaway Radion

The general form of the potential (we factor out $\lambda_1^2 \pi g_s/c'$) 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 $\delta$ type perturbation above) yields the potential proportional to the above with $\delta = c''c'g_s/\pi K^2$ and $|\epsilon| = Mg_s/2\pi K$. By writing it this way we keep $\epsilon$ and $\delta$ as small parameters. This gives precisely the stability condition found in [59], namely

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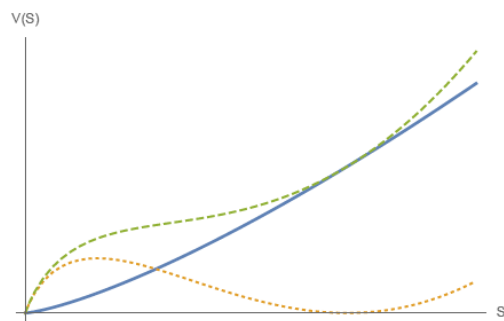


Figure 2: The contribution $V_{\overline{D3}}$ (solid blue line) of an $\overline{D3}$-brane placed in the Klebanov-Strassler throat to the potential for $S$. The two other lines represent the original potential $V_{KS}$ (dotted orange line) for the specific value $\sqrt{g_s}M = 6$ as well as the superposition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

# Puzzle Restated

- Why is there an instability when we are adding only a single antibrane (compared to M branes)

- If I look at this from a dual perspective, we had gaugino condensation breaking supersymmetry

- If this result true,  supersymmetry and condensate would never happen

# Resolution

- Gravitational constraints from higher-dimensional theory
  - Required because it is a warped compactification
  - Compactification depends on coordinate of low-energy theory
  - Einstein equations mix dependence on extra and "physical" coordinates
- (Alternatively, because wrong low-energy theory when KK modes omitted)

# Resolution: Need to impose constraints

- 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

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

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

# First: Constraints without warping

➤ First: understand gauge fixing without warping:

$$ds^2_{10} = ds^2_4 + ds^2_{DC}$$

➤ Gauge fixing of Calabi-Yau deformations:

$$g_{ij} \to g_{ij} + \delta g_{ij} \qquad \text{[Candelas, de la Ossa}$$

$$\Rightarrow \qquad g^{ij}\delta g_{ij} = 0 \qquad\qquad \nabla^i \delta g_{ij} = 0$$

$$\text{(traceless)} \qquad\qquad\qquad \text{(harmonic)}$$

*(will get modified in the presence of warping!)* [Giddings, Maharana '05],
[Shiu et al. '08],
[Douglas, Torroba '08]

➤ Deformed conifold:

$$\delta g_{ij} = \partial_S g_{ij} \sim \frac{1}{S} g_{ij} \qquad \text{harmonic but not traceless!}$$

$$\delta_S G_{\mu\nu} = \partial_\mu \partial_\nu S \left( 4\delta_S A - \frac{1}{2} g^{mn} \delta_S \tilde{g}_{mn} \right) + \mathcal{O}(S^2) + \eta_{\mu\nu} [\dots] \,,$$

$$\delta_S G_{\mu m} = \partial_\mu S \left[ 2\partial_m \delta_S A - \frac{1}{2}\partial_m \delta_S \tilde{g} - 8\partial_m A \delta_S A + \partial_m A \delta_S \tilde{g} - 2\partial^p A \delta_S \tilde{g}_{mn} + \frac{1}{2}\nabla^p \delta_S \tilde{g}_{mp} \right] \,.$$

# Constraints Cont'd

I   $$\delta_S A = \frac{1}{8}\delta_S \tilde{g} \, ,$$  Or warped volume conserved

$$V_w = \int d^6 y \sqrt{\tilde{g}_6}\, e^{-4A}$$

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

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

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]

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

# Can fix with diffeomorphism

➤ Add compensating diffeomorphism:

$$\delta g_{ij} = \partial_S g_{ij} + 2 \nabla_{(i} \eta_{j)}$$

Ansatz:

$$\eta = \left( \eta^{\tau}(\tau), 0, 0, 0, 0, 0 \right)$$

Solution:

$$\eta^{\tau}(\tau) = -\frac{1}{2S} \frac{\sinh(2\tau) - 2\tau}{\sinh^2 \tau}$$

➤ Interpretation:

Replace $\tau$ with "new" $S$-dependent radial variable:    $\tau \to T(\tau, S)$

$$\frac{dT}{dS} = \eta^{\tau}\left( T(\tau, S), S \right) \qquad \longrightarrow$$

Analytic solution:

$$T(\tau, S) = F\left[ F^{-1}(\tau) - \frac{1}{4} \log \frac{S}{S_0} \right]$$

with   $F(x) = \frac{1}{2} \log \left[ \sinh(2x) - 2x \right]$

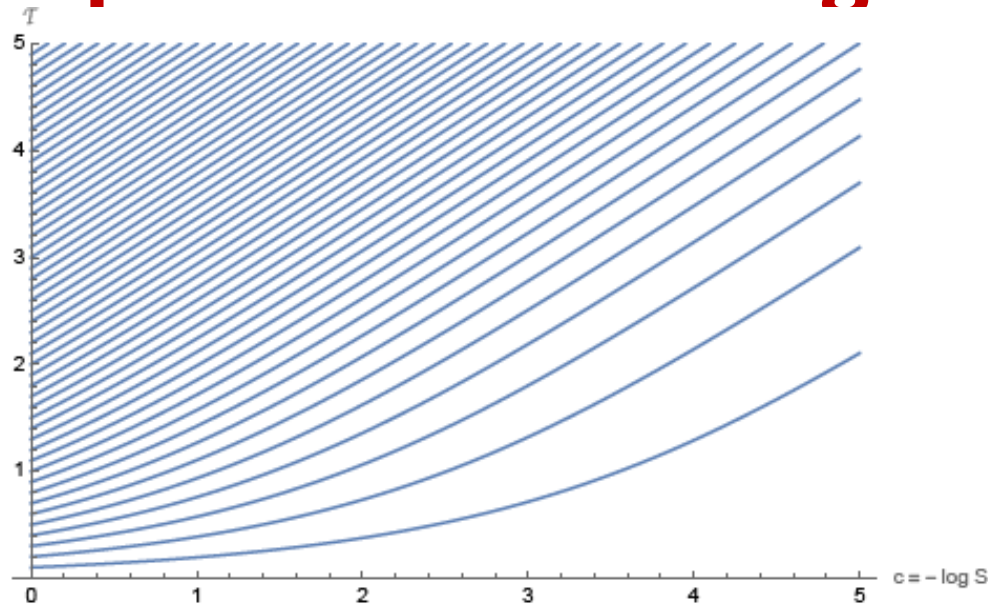# Result: Strong Change to metric, potential in IR region



Figure 1: The radial coordinate $\mathcal{T}$ as a function of $\log S$ (for $S_0 = 1$), where $S$ is the conifold deformation parameter.

$$\mathcal{T}(\tau, S) \rightarrow \tau - \log \frac{S}{S_0}.$$

In IR: $\quad \mathcal{T}(\tau, S) = \tau \left( \frac{S_0}{S} \right)^{2/3} + \mathcal{O}(\tau^3)$

In UV $\quad ds_6^2 \rightarrow \frac{3}{2^{5/3}} S^{2/3} e^{2\mathcal{T}/3} \left[ \frac{1}{9} \left( d\mathcal{T}^2 + (g^5)^2 \right) + \frac{1}{6} \sum_{i=1}^{4} (g^i)^2 \right],$

$$S^{2/3} e^{2\mathcal{T}/3} \rightarrow S_0^{2/3} e^{2\tau/3}$$

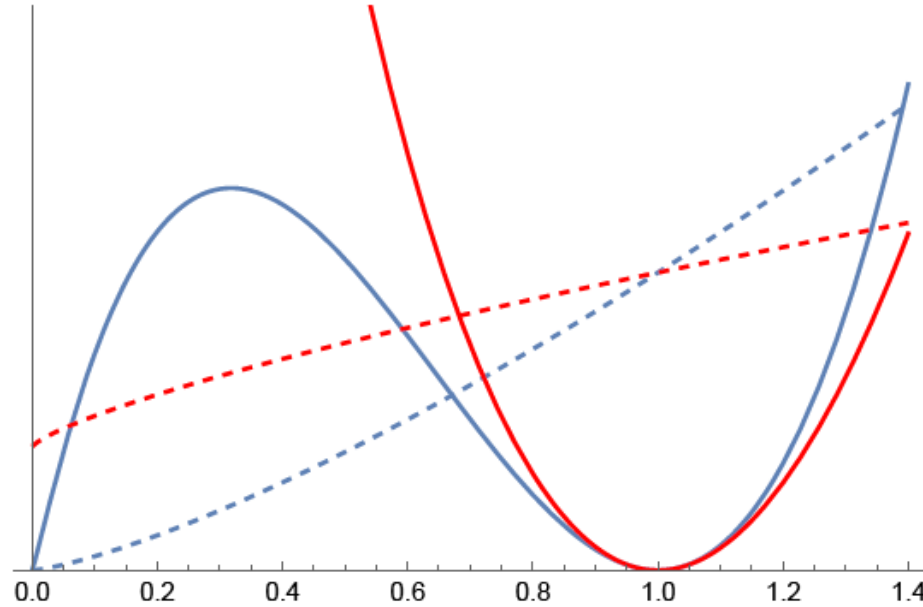# Result of Imposing Constraints: No Second Minimum



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.

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

$$+ \tanh^2 (\mathcal{T}/2) \frac{\cosh^2(\tau/2)}{\sinh^6(\tau/2)} (\sinh \tau + \tau)^2 + 16 \left[ 1 + \frac{3 + 2\tau - 6t \coth \tau + 3\tau^2 \operatorname{csch}^2 \tau}{\sinh^2 \tau} \right] \partial_\tau \mathcal{T}$$

$$+ 8 \left[ 1 + 2\operatorname{csch}^2 \mathcal{T} - 4\frac{\cosh \mathcal{T}}{\sinh^2 \mathcal{T}} \operatorname{csch} \tau + \frac{(\tau \coth \tau - 1)^2 + \tau^2(1 + 2\operatorname{csch}^2 \mathcal{T})}{\sinh^2 \tau} \right] (\partial_\tau \mathcal{T})^2 \left. \right\}.$$

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

# What About EFT?

- Working on this
- But presumably it is precisely omission of light modes I mentioned earlier
- Masses for moduli from CY/UV part of throat
- Still have light KK modes for all moduli
  - Volume moduli in particular
- Light modes allow IR region to deform
- And that is what happens

# Puzzle II

- Suppose a warped geometry with two branes
  - Assume only gravity in the bulk
- How does energy perturbation communicate from one brane to the other?
- With Raman had worked on exactly this scenario: sequestering
  - Hadn't accounted for warping
  - Or backreaction of gravity
  - Others have since

- Many people worked on related issues
- Luty, Rattazzi, Geller, Bellanzini, and Pomarol, Gherghetta, Sundrum, Csaki, Terning
- Interested in susy breaking communication
- Some did anomaly mediation
- Also radion interactions
- But needed to put it together
- Some disagreements between full theory and EFT
- Lots of models for warped susy communication but no warped susy with boundaries

# To address more generally we need back reaction on geometry: "Slicings" of AdS

negative cosmological constant $\Lambda^{5d} = -3/L^2$ coupled to a brane of tension $\lambda$:

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

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 $A(r)$,

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

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

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

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

# Boundary Matching

brane and the horizon, whereas in the AdS case $c$ is the distance to the turn around point in the warp factor. As is well known, in order to have a Minkowski solution, one has to fine-tune $\lambda$ relative to $L$; in our conventions $\lambda = \frac{3}{L}$. Since $\coth(x) > 1$ and $\tanh(x) < 1$ for any $x$, we see that, $\lambda > \frac{3}{L}$ implies that the effective 4d cosmological constant is positive and $\lambda < \frac{3}{L}$ implies a negative 4d cosmological constant. The 4d cosmological constant in 4d Planck units is given by

$$4\pi \int dr\, e^{2\left(A(r) - \frac{1}{2} \ln |\Lambda|\right)} \tag{4}$$

and is hence determined by $c$ alone, that is by the mismatch of brane tension and bulk cosmological constant. Since only the combination $\Lambda e^{2A}$ appears in the equations of motion, not both, $\Lambda$ and $A$, will be determined independently. One can use this freedom to set $A(0) = 0$, as in [1]. This way the cosmological constant becomes

$$\Lambda_{dS} = \frac{1}{L^2 \sinh^2 \frac{c}{L}}, \quad \Lambda_{AdS} = \frac{-1}{L^2 \cosh^2 \frac{c}{L}}. \tag{5}$$

Using the value of $c$ determined by the jump equations one finds that the 4d cosmological constant is indeed only given by the detuning

$$M = \frac{\lambda L}{3} \tag{6}$$

of the brane tension without any exponential surpression:

$$\Lambda_{dS} = \frac{1}{L^2}(M^2 - 1), \quad \Lambda_{AdS} = \frac{1}{L^2}(1 - M^2). \tag{7}$$

# NO Stabilizing Field

$$dS_4: \quad \bar{\Lambda} > 0$$

$$e^A = \sqrt{\bar{\Lambda}} L \sinh \frac{r_1 - r}{L} , \quad \lambda_1 = \frac{3}{L} \coth \frac{r_1}{L} , \quad \lambda_2 = -\frac{3}{L} \coth \frac{r_1 - r_0}{L}$$

$$AdS_4: \quad \bar{\Lambda} < 0$$

$$e^A = \sqrt{-\bar{\Lambda}} L \cosh \frac{r_1 - r}{L} , \quad \lambda_1 = \frac{3}{L} \tanh \frac{r_1}{L} , \quad \lambda_2 = -\frac{3}{L} \tanh \frac{r_1 - r_0}{L}$$

- Can rewrite as $e^{-kr} (1 +/- \Lambda L e^{2kr})$
- A' matches energy on brane through jump condition
- Interesting in that induced energy density on IR brane down by only 2 warp factors (not 4)
- Gravity mediated masses will be of the same size since M_Pl warped too

# So What Happens if Energy Added Only on One Brane

- Clearly not a solution

- Need (eg) de Sitter everywhere

- Really need appropriately warped de Sitter everywhere

- Only consistent if there is a stabilizing field that can adjust so that boundary "jump" conditions will be satisfied

# Goldberger-Wise Stabilization

Imagine adding to the model a scalar field $\Phi$ with the following bulk action

$$S_b = \frac{1}{2} \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{G} \left( G^{AB} \partial_A \Phi \partial_B \Phi - m^2 \Phi^2 \right),$$

where $G_{AB}$ with $A, B = \mu, \phi$ is given by Eq. (1). We also include interaction terms on hidden and visible branes (at $\phi = 0$ and $\phi = \pi$ respectively) given by

$$S_h = - \int d^4x \sqrt{-g_h} \lambda_h \left( \Phi^2 - v_h^2 \right)^2,$$

and

$$S_v = - \int d^4x \sqrt{-g_v} \lambda_v \left( \Phi^2 - v_v^2 \right)^2,$$

# Find minimum

$$V_\Phi(r_c) = k\epsilon v_h^2 + 4ke^{-4kr_c\pi}(v_v - v_h e^{-\epsilon kr_c\pi})^2\left(1 + \frac{\epsilon}{4}\right) - k\epsilon v_h e^{-(4+\epsilon)kr_c\pi}(2v_v - v_h e^{-\epsilon kr_c\pi}) \quad (13)$$

where terms of order $\epsilon^2$ are neglected (but $\epsilon kr_c$ is not treated as small). Ignoring terms proportional to $\epsilon$, this potential has a minimum at

$$kr_c = \left(\frac{4}{\pi}\right)\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right]. \quad (14)$$

With $\ln(v_h/v_v)$ of order unity, we only need $m^2/k^2$ of order $1/10$ to get $kr_c \sim 10$. Clearly, no extreme fine tuning of parameters is required to get the right magnitude for $kr_c$. For instance, taking $v_h/v_v = 1.5$ and $m/k = 0.2$ yields $kr_c \simeq 12$.

What happens when you perturb it?

# But this ignores gravity

- With third constraint, if we plug back in we just get integrated cc
  - Clearly more subtle
  - Not only radion, but $\Lambda$, and GW field adjust
- So 4 parameters
- 4 constraints…
- We are doing full theory; not EFT

# More general: Third Constraint

$$V_{\text{eff}} = \frac{1}{\kappa_{10}^2} \int d^d y \sqrt{\tilde{g}} e^{4A} \left[ -\frac{1}{2} R\left[\tilde{g}\right] + 4\tilde{\nabla}^2 A + 10(\tilde{\nabla}A)^2 - \mathcal{L}_{\text{mat}} \right]$$

Definitions

$$V_{\text{eff}} = \int d^d y \left[ v_{\text{int}}(y) + \sqrt{\tilde{g}}\,\tilde{\nabla}^i \left( e^{4A}\nabla_i A \right) \right]$$

$$\kappa_4^2 V_{\text{eff}} = e^{2A} \left[ -\frac{1}{2} R\left[\tilde{g}\right] + 3\tilde{\nabla}^2 A + 6(\tilde{\nabla}A)^2 - \mathcal{L}_{\text{mat}} \right]$$

Constraint from 10d, 4d EE

$$\frac{\kappa_4^2}{\kappa_{10}^2} \sqrt{\tilde{g}(y)} e^{2A(y)} V_{\text{eff}} = v_{\text{int}}(y) ,$$

- All the y dependence in the warp factor and the higher-dimensional (internal) metric
- Strong constraint that implies consistent slicing
  - For de 4d de Sitter space amounts to consistent slicing with a 4d de Sitter metric
- Otherwise time-dependent solution
  - https://arxiv.org/pdf/2006.10061.pdf Karch Randall

# Third Constraint: Interpretation

$$\frac{\kappa_4^2}{\kappa_{10}^2} \sqrt{\tilde{g}(y)} e^{2A(y)} V_{\text{eff}} = v_{\text{int}}(y) \, ,$$

- Ignore compact metric
- We see two (not four) warp factors
- Essentially constant curvature, constant Hubble over 5d space
  - Otherwise dynamics would allow branes to move with time
  - Consistent 4d dynamics requires no such motion
- Why two factors? Essentially energy divided by MPl2.
  - Two warp factors associated with local Planck scale
- This constraint very important
- Means we can't adjust IR neglecting UV
- Also is reason Lambda4 is parameter of our theory

# Metric With GW Field

- Need to satisfy third constraint

- How does energy distribute itself in space?

- We consider two different models
  - Original GW  $\alpha_i (\Phi^2 - v_i^2)^2$ on both branes
  - Quartic UV, Quadratic in IR: $\alpha_i (\Phi^2 - v_i^2)$

- Also we consider adding energy in UV vs IR

# With Metric and Back Reaction

We start with the five-dimensional gravitational action

$$S = \int d^5 x \sqrt{g} \left[ -\frac{1}{4} R + \frac{3}{L^2} \right] ,$$

in $+----$ signature. The most general five-dimensional metric with four-dimen Poincaré symmetry is

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

The five-dimensional Ricci tensor and the equations of motion are

$$R_{ij} = e^{2A} \left( 4A'^2 + A'' - 3\bar{\Lambda} e^{-2A} \right) \bar{g}_{ij} , \qquad R_{55} = -4A'^2 - 4A'' ,$$

$$\phi'' + 4A'\phi' = \frac{\partial V(\phi)}{\partial \phi} + \sum_\alpha \frac{\partial \lambda_\alpha(\phi)}{\partial \phi} \delta(r - r_\alpha) ,$$

$$A'' + \bar{\Lambda} e^{-2A} = -\frac{2}{3}\phi'^2 - \frac{2}{3}\sum_\alpha \lambda_\alpha(\phi)\delta(r - r_\alpha) ,$$

$$A'^2 - \bar{\Lambda} e^{-2A} = -\frac{1}{2}V(\phi) + \frac{1}{6}\phi'^2 .$$

Bulk equations

By integrating the first two equations on a small interval $(r_\alpha - \epsilon, r_\alpha + \epsilon)$ one can derive the jump conditions

$$A'\Big|_{r_\alpha - \epsilon}^{r_\alpha + \epsilon} = -\frac{2}{3}\lambda_\alpha(\phi(r_\alpha)) , \qquad \phi'\Big|_{r_\alpha - \epsilon}^{r_\alpha + \epsilon} = \frac{\partial \lambda_\alpha}{\partial \phi}(\phi(r_\alpha)) . \qquad (7)$$

Equations at boundaries

# Energy Distribution Depends on GW Model

- 4 parameters, 4 constraints
  - 2 boundaries (value and derivative)
  - Lambda, rc, A, B (GW field has two free parameters)
- We generally want perturbative solutions
- Here answers for two models
  - Original GW
  - Modified IR potential with quadratic, not quartic in IR
- Three possibilities
  - UV "susy breaking"
  - IR "susy breaking"
  - IR with compensating UV energy to keep space flat
    - Really a small cc

# I: UV breaking

- Suppose $\delta T_{UV}$ on UV brane
- $\delta \Lambda \sim 2k/3 \, \delta \, T_{UV}$
- But what about IR?
  - GW adjusts; small $\epsilon$, large $\alpha$ limit
- $\delta E_{IR} \sim e^{2 k \Pi i \, r} k \delta T_{UV}/\alpha_{IR}$
  - Suppressed by stabilizing potential parameter but exponentially enhanced
- $\delta \Phi(\Pi) \sim e^{2\Pi kr} \delta T_{UV}/v_{uv}^2 \, \alpha_{IR}$
- But this means $\delta \Phi'(\Pi)$ can compensate
- $\delta \, r \sim e^{2\Pi kr} dT_{UV}/ (8\Pi i \, k^2 \, v_{uv}^2 \, \epsilon)$
- Cancelling $\Lambda$ term in warp factor at leading order

# Basic Lesson

- $\Lambda$ must exist throughout the bulk
  - Either IR boundary condition has to adjust or
  - Warp factor in IR has to adjust
- Requires shift to produce eg de Sitter on opposite boundary too
- But r shifts as well; not usual EFT result!
- Notice r-dependence through c1, c2
- Only after integrating out full GW field can we get the radion potential

# IR Symmetry Breaking

- $\delta\Lambda \sim 2/3 e^{-4\Pi k} r\ k\ \delta_{IR}$

- $\delta T_{UV} \sim e^{-4\Pi kr}\ k\delta_{IR}/\alpha_{uv}\ v_{uv}^2$
  - Induced energy through change in stabilizing field
  - Suppressed but for finite alpha could be important

- $\delta r \sim \delta_{IR}/(8\ \Pi\ k^2\ v_{uv}^2\ \epsilon)$
  - Similar to before

- $\Phi(0) \sim e^{-4\Pi kr}\ \delta\ ir/(2^{5/2}\ v_{uv}\ \alpha_{uv}\epsilon)$

- Approximate cancellation of A' in presence of suppressed IR energy

# More exact expressions

- Large α: result as expected
- Otherwise opposite sign
- Need to redo with small α

$$\delta\Lambda = e^{-4k\pi r}\frac{2k(4k - \alpha_{IR})(2k - v_{UV}^2\alpha_{UV})}{3v_{UV}^2(4k + \alpha_{IR}\alpha_{UV}}\delta T_{IR}$$

$$\delta R = e^{2k\pi r\epsilon}\frac{(-4k + \alpha_{IR})^2}{8k^2\pi v_{UV}^2\alpha_{IR}(4k + \alpha_{IR)}}\delta T_{IR}$$

# IR Symmetry Breaking With Cancelling UV Energy

- $\delta_{IR} + k/\alpha$ (suppressed) in IR
- $e^{-4\Pi kr} \delta_{IR} + k/\alpha_{uv} v_{uv}^2$ suppressed in UV
- $\delta \Lambda \sim 0$ (by design)
- $\delta \Phi(0), \delta \Phi(\Pi)$ similar to before
- Results very similar to before
- GW field acts to adjust locally in IR and UV separately
- Only difference is that $-\delta T\, e^{-4\Pi kr}$ in UV

- Also parametrically suppressed energies

# Comparison to EFT

- EFT: $\delta T \ \Phi^4 + \epsilon \ \Phi^{4+\epsilon}$

- As with all racetrack models, $\epsilon$ suppressed energy

- For us, we generate EFT for radion by first solving and then integrating out heavy modes

- Recall

$$\delta A'(\phi) = -\frac{e^{2kr\phi} r}{2k}\Lambda - \frac{1}{12kr}\Phi'(\phi)^2 + \frac{r}{3k}m^2\Phi(\phi)^2 .$$

After inserting (37) this can be straightforwardly integrated and we find

$$A(\phi) = -kr\phi - \frac{\Lambda}{4k^2}e^{2kr\phi} - \frac{1}{6}e^{4kr\phi}\left(C_1^2 e^{4kr\phi\sqrt{1+\epsilon}} + C_2^2 e^{-4kr\phi\sqrt{1+\epsilon}} - 2C_1 C_2 \epsilon\right) + C_3$$

can argue potential comes from boundary terms; eg A'

# Net result

- $\Lambda_4$ $(1-e^{-2kr})$ as it has to be to get curvature
- Also same form of potential but with k/α terms from integrating out GW field
- So radion is still light
- But cc is generated
- Also α dependent potential

# Relevant to KKLT?

- We found radion adjusts

- If conifold fixed does that mean "UV" brane adjusts

- Recall volume modulus of CY is light (lighter than radion even)

- In progress

# Puzzle III: Supersymmetry Breaking and EFT

- Calabi-Yau (aka UV brane) has negative energy, antibrane in throat has positive warped energy
  - Add together to generate small cc
- IR energy breaks supersymmetry
  - How is susy breaking communicated to rest of space
    - Assuming no additional bulk fields
- Obvious answer: anomaly mediation
  - Also radion mediation
  - Volume modulus mediation ($M\_Pl$ depends on modulus)
- But how does third constraint get satisfied?
- Need energy change in UV
- If supersymmetric, why doesn't this break SUSY directly in UV?

# Rewrite 5d susy in 4d superspace

Arkani-hamed, Gregoire, Wacker

## 2.1 Free Hypermultiplets

The superfield formulation of the $\mathcal{D} = 5$ hypermultiplet has been described in [11]. In $\mathcal{N} = 1, \mathcal{D} = 4$ superspace, the 5D hypermultiplet consists of a collection of 4D chiral superfields $H(x_5), H^c(x_5)$ labeled by the 5'th co-ordinate $x_5$. Its free action is given by

$$S_5^{\text{Hyp.}} = \int d^5x \left\{ \int d^4\theta \left( \bar{H}^c H^c + \bar{H} H \right) + \left( \int d^2\theta H^c \left( \partial_5 + m \right) H + \text{h.c.} \right) \right\} \quad (1)$$

Expanding in components and integrating out the auxilliary $F$ components, the action (1) describes an $\mathcal{N} = 1$ $\mathcal{D} = 5$ supersymmetric theory containing two complex scalar and one Dirac fermion $\Psi_5^T = (\psi, \bar{\psi}^c)$ composed of the 2 component fermions $\psi$ and $\bar{\psi}^c$:

$$S_5^{\text{Hyp.}} = -\partial_M H^\dagger \partial^M H - \partial_M H^{c\dagger} \partial^M H^c - i\bar{\psi}\bar{\sigma}^m \partial_m \psi - i\bar{\psi}^c \bar{\sigma}^m \partial_m \psi^c - \psi^c \partial_5 \psi - \bar{\psi}^c \partial_5 \bar{\psi}$$
$$- m^2(|H^c|^2 + |H|^2) - m(\psi^c\psi + \bar{\psi}^c\bar{\psi})$$
$$= -\partial_M H^\dagger \partial^M H - \partial_M H^{c\dagger} \partial^M H^c - m^2(|H^c|^2 + |H|^2) + \bar{\Psi}_5(i\gamma^M \partial_M - m)\Psi_5$$

$$(2)$$

# But…Boundary terms

- Turns out requires surprising boundary terms
- "F" terms in bulk essentially $d_5 H_c + (dW/dH)$
- Square of this quantity appears
  (This is flat space: modified in warped space)
- Requires term on boundary
- $H^+ (d_5 H_c + (dW/dH))$
- Notice this is nonholomorphic term
  - Proportional to single power of "F"
- This is in addition to usual 4d superpotential
- Note: boundary so can be just values
- But if we want it to correctly adjust with perturbations should be field-dependent

# So "F" Term for GW field

- But set by $\delta T$
- Not **F** (sqrt $\sqrt{}$ $\delta$ T)
- Allows space energy to adjust
- Without communicating SUSY breaking (at leading order)
- Subtle, but can show in higher-dimensional theory that anomaly-mediation still generally effective
- So SUSY communication agrees with EFT
  - But for subtle reason from higher dimensional perspective

# Puzzle IV
# Cosmology of RS

# Phase Transition from Black Brane to RS

$$\beta^{-1} = \frac{\rho_h}{\pi L^2} \equiv T_h$$

$$ds^2 = \left(\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}} + \frac{\rho^2}{L^2}\sum_i dx_i^2$$

for $\rho_h \leq \rho < \infty$. For $\rho_h = 0$ this reduces to the pure AdS metric

$$ds^2 = \frac{\rho^2}{L^2}\left(dt^2 + \sum_i dx_i^2\right) + \frac{L^2}{\rho^2}d\rho^2 \,,$$

$$
\begin{aligned}
F_{\mathrm{RS}} &= \left[(4+2\epsilon)\mu^4(v_1 - v_0(\mu/\mu_0)^\epsilon)^2 - \epsilon v_1^2 \mu^4\right] + \mathcal{O}(T^4) \\
F_{\mathrm{AdS-S}} &= 6\pi^4(ML)^3 T_h^4 - 8\pi^4(ML)^3 T T_h^3 - \epsilon\frac{\pi^{4+2\epsilon}}{2}v_0^2 T_h^4\left(\frac{T_h}{\mu_0}\right)^{2\epsilon}
\end{aligned}
$$

$$T_c = \left(\frac{8\epsilon^{3/2}v_1^2}{\pi^2}\right)^{1/4}\frac{1}{\sqrt{N}}\mu_{\mathrm{TeV}} \qquad\qquad T_c \ll \mu_{\mathrm{TeV}}$$

$$\frac{S_3}{T} \simeq 0.13 \times \frac{N^{7/2}}{\epsilon^{9/8} v_1^{3/2}} \times \frac{(T_c/T)}{\left[1 - (T/T_c)^4\right]^2}$$

Requiring $\Gamma > H^4_{T \sim T_c}$ we have

$$0.13 \frac{N^{7/2}}{\epsilon^{9/8} v_1^{3/2}} \lesssim 137 \quad \Rightarrow \quad \frac{N}{\epsilon^{9/28} v_1^{3/7}} \lesssim 7 \, , \qquad ($$

where we used the fact that $(T_c/T)/\left[1 - (T/T_c)^4\right]^2 > 1$ for $T < T_c$ [8]. Taking $\epsilon \simeq 1/20$ we finally

$$\frac{N}{v_1^{3/7}} \lesssim 3 \, . \qquad ($$

Good news: first order phase transition—can possibly see in gravity waves at LISA
Bad news: model seems severely constrained
Good news (current work): seems strongly dependent on simple model of GW field, brane

# New Models for Cosmology

- Old analysis based on GW field inducing IR brane

- Dynamics such that still scaling slowly in IR

- We consider
  - Adding cubic term
    - Allows for "strong dynamics" –different powers of GW field balancing so radion mass not order epsilon
  - "Mimic" CFT; add dynamics responsible for IR brane
    - We mimic KKLT by putting in a curvature term that blows up
    - Treat as additional Brans-Dicke scalar

# (Preliminary) Results

- Cubic leads to less strong first order phase transition

- But easier to achieve

- New model leads to peculiar results—
  - Even absence of black brane phase at low tempertaure

- Why should we care?
  - Relevant to gravity wave predictions
  - Viability of model

# More detail

$$V_b(\chi) = \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{6}\eta\chi^3 \equiv 2\epsilon_2\chi^2 + \frac{4}{3}\epsilon_3\chi^3$$

$$V_{\text{uv}}(\chi) = \beta_{\text{uv}}(\chi - v_{\text{uv}})^2 \,, \quad \beta_{\text{uv}} \to \infty$$

$$V_{\text{ir}}(\chi) = 2\alpha_{\text{ir}}\chi \,.$$

$$S = \int d^4x\sqrt{g}\left(-12M_5^3\left(\partial\varphi\right)^2 - V(\varphi)\right) \,,$$

$$V(\varphi) = 24M_5^3\,\kappa\,\varphi^4\left(1 + \frac{a_2}{24M_5^3\kappa}\frac{\lambda\varphi^{\epsilon_2}}{1 - \lambda\varphi^{\epsilon_2}} - \frac{a_3}{24M_5^3\kappa}\log(1 - \lambda\varphi^{\epsilon_2})\right) \,,$$

$$\lambda = \frac{v_{\text{uv}}\epsilon_{32}}{1 + v_{\text{uv}}\epsilon_{32}}, \ \epsilon_{32} = \frac{\epsilon_3}{\epsilon_2}, \ a_2 = -\frac{1}{32}\epsilon_2\alpha_{\text{ir}}^2 - \frac{\epsilon_2}{\epsilon_3}\alpha_{\text{ir}} + 2\alpha_{\text{ir}}, \ a_3 = \frac{1}{2}\frac{\epsilon_2}{\epsilon_3}\alpha_{\text{ir}} \,. \tag{3.1}$$

The details of the computation are given in app. B. In the limit of $\lambda\varphi^{\epsilon_2} \ll 1$ (note that for this we need $\lambda \sim \mathcal{O}(v_{\text{uv}}) \ll 1$, since $\varphi^{\epsilon_2}$ can be $\mathcal{O}(1)$, for $\epsilon_2 < 0$), the potential can be expanded in a power series:

$$V(\varphi) = \varphi^4\left(b_0 + b_1\lambda\varphi^{\epsilon_2} + b_2\lambda^2\varphi^{2\epsilon_2} + b_3\lambda^3\varphi^{3\epsilon_2} + \cdots\right) \,, \tag{3.2}$$

$$V(\varphi) = b_0\,\varphi^4\,P(\varphi^{\epsilon_2})\,,  \qquad (3.4)$$

where $P(x)$ is a polynomial in $x$ of some given order, with the first term 1 (since we have factored out an overall constant in eq. (3.4)). Expanding eq. (3.1), some of the terms in $P(x)$ are explicitly given as

$$b_0\,P(x) = b_0 + \sum_{i \geq 1} b_i x^i\,, \qquad b_0 = 24 M_5^3\,\kappa\,,$$

$$b_1 = -v_{\rm uv}\left(\frac{1}{2}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-1}\,,$$

$$b_2 = -v_{\rm uv}\left(\frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)\left(\frac{3}{4}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-2}\,,$$

$$b_3 = -v_{\rm uv}\left(\frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^2\left(\frac{3}{4}\alpha_{\rm ir} - 2\alpha_{\rm ir}\frac{\epsilon_3}{\epsilon_2} + \frac{1}{32}\alpha_{\rm ir}^2\epsilon_3\right)\left(1 + \frac{v_{\rm uv}\epsilon_3}{\epsilon_2}\right)^{-2}\,,$$

$$\vdots \qquad\qquad (3.5)$$

|   | $\kappa$ | $\epsilon_2$ | $\epsilon_3$ | $\alpha_{\rm ir}$ | $v_{\rm uv}$ | $\varphi_{\rm min} \times 10^{16}$ | $V''(\varphi_{\rm min})/\varphi_{\rm min}^2$ | $-V(\varphi_{\rm min})/\varphi_{\rm min}^4$ |
|---|---|---|---|---|---|---|---|---|
| A | 1/10 | -1/25 | 0 | 1/10 | 1/14 | 1.47 | 0.002 | $10^{-4}$ |
| B | 1/10 | -1/25 | -1/100 | 5/2 | 1/14 | 1.09 | 0.005 | $3 \times 10^{-4}$ |
| C | 1/10 | -1/25 | -1/90 | 5/2 | 1/5 | 0.86 | 0.032 | $2 \times 10^{-3}$ |
| D | 1/10 | -1/25 | -1/81 | 5/2 | 1/3 | 0.59 | 0.135 | $8 \times 10^{-3}$ |

Table 1: Benchmark choice of parameters to show the effect of self-interaction.
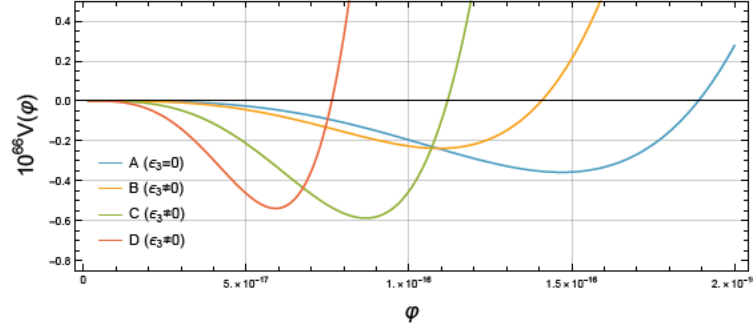
(a) Potentials near the minimum, for the parameter choices in table 1. A deeper potential results from a non-zero $\epsilon_3$.
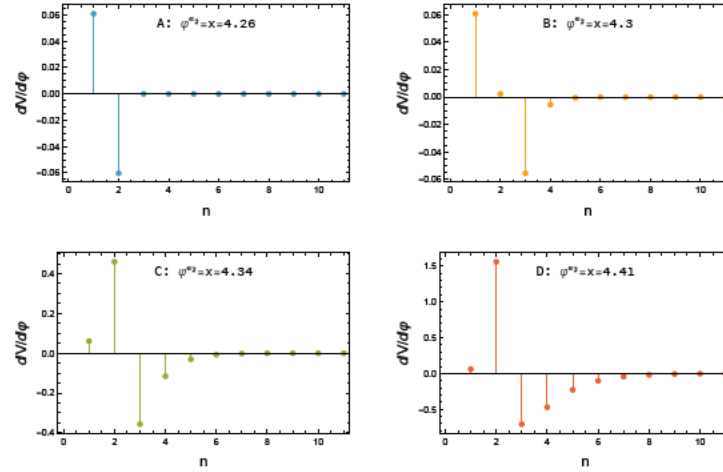


(b) Various terms in the series expansion of the derivative of the potential, for the parameter choices in table 1. The terms balancing near the minimum are, top left: first and second, top right: first and third, bottom left: second and third, and bottom right: second, third and fourth.

Figure 2: Radion potentials, for the parameter choices in table 1.
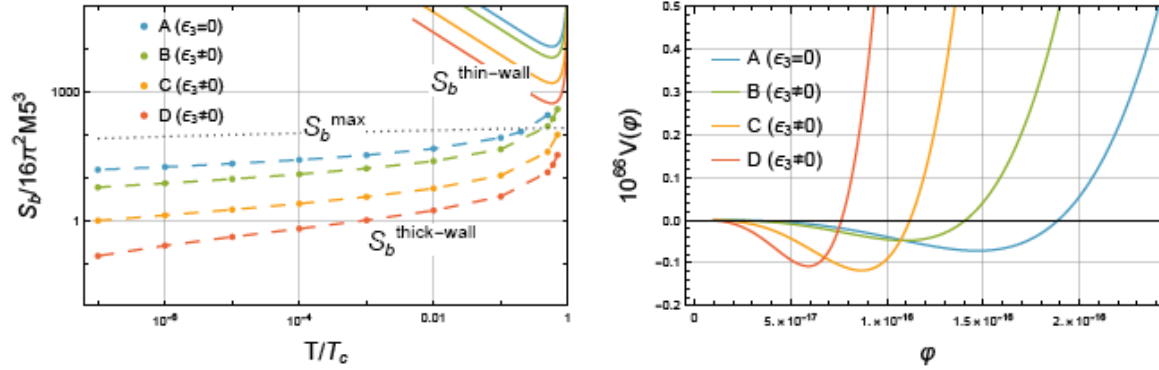
(a) The bounce action (left) normalized by $16\pi^2 M_5^3 = N_c^2$, and the radion potential for parameter choice in table 1. Both thin wall (solid lines) and thick wall (dashed lines) estimates for the bounce action are shown. Also shown in dotted is the maximum value of bounce action $S_b^{\mathrm{max}}$, beyond which the phase transition rate to too small to compete with the Hubble expansion.
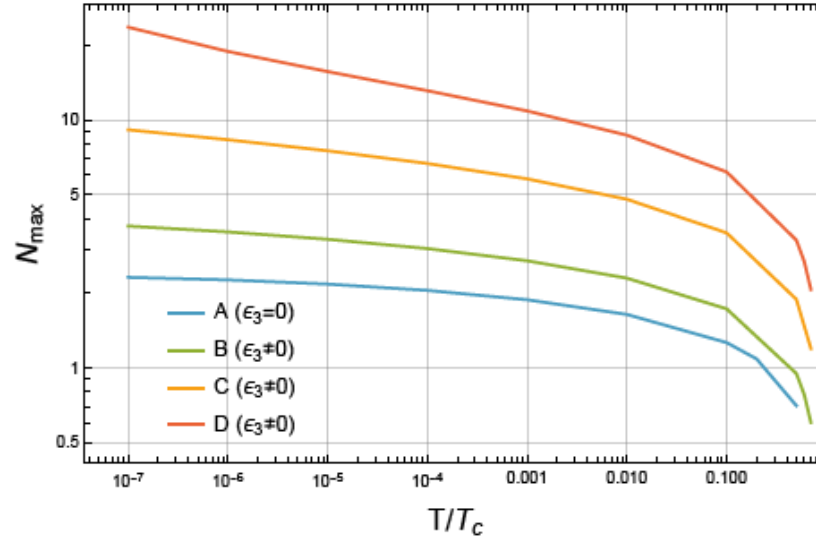


(b) Maximum number of colors for the phase transition to complete, as a function of $T/T_c$, for the parameter choice in table 1.

Figure 3: Bounce action, potential, and the maximum number of colors for the phase transition to complete, for the parameter choice in table 1.

# Point

- Strong dynamics can evade or minimize $\epsilon$-suppression
- Two roles for $\epsilon\epsilon$ in standard GW
    - One is scaling
- The other is IR dynamics
- For real strong dynamics we expect them to be separate
- $\epsilon_3$ is enough to mimic that by turning on in IR where field value has grown sufficiently

# Alternative; additional scalar

For a geometry with a black brane, this would imply that as the horizon falls too far beyond the would-be IR brane location, the contribution from the back reaction of the growing potential would likely make it thermodynamically unfavorable, or even unstable. The back-reaction can allow a small movement in the IR but not sufficiently large to give a large supercooling while the theory remains five-dimensional.

To capture this physics, we start with the action for the scalar and gravity in a general Jordan frame.

$$
\begin{aligned}
S &= S_{\mathrm{GR}} + S_\phi + S_{\mathrm{bdy}} \,, \\
S_{\mathrm{GR}} &= 2M_5^3 \int \mathrm{d}^5x \sqrt{-g}\Big( \left(1 - \phi/\phi_c\right)^n R - 2\left(1 - \phi/\phi_c\right)^m \Lambda \Big) \,, \\
S_\phi &= 2M_5^3 \int \mathrm{d}^5x \sqrt{-g}\Big( -a(\partial\phi)^2 - v(\phi) \Big) \,.
\end{aligned}
\tag{2.1}
$$

where $R$ is the 5D Ricci scalar, $\Lambda$ is the bulk cosmological constant, and we have included a scalar that changes the coefficient of $R$ and $\Lambda$, as it evolves. The scalar is given a bulk potential $v(\phi)$, that can be chosen appropriately to give $\phi$ a non-trivial profile. Note that

# Another scalar

- Presumably more closely mimics actual dynamics

- Need strong dynamics in IR

- Presumably space bounded in both RS and black brane phases

- We find (preliminary) black brane phase disappears at a critical temperature

# Summary: Inadequate EFTs

- Warped compactifications
  - Compactifications where internal metric depend on coordinate of lower-dimensional theory

  $$ds_{10}^2 = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}(y)dy^m dy^n$$

  - Need to include constraints on consistency of high energy theory
- Usual warped compactifications
  - Need to include third constraint
- Supersymmetry
  - Need to include boundary terms
- Cosmology
  - Need to consider more general GW potentials

- Need to keep **all** light degrees of freedom  (KK modes)

# More to be done

- CC

- Understand KKLT better?

- Certainly more rigorous SUSY analysis

- Better understanding cosmology phases

# CU at B BBBBB SM?

# Surprisingly (but not perfectly) Effective Field Theory

1. ## Stability of 4d theory

    - Breaking supersymmetry at arbitrarily high scale decouples from IR
        - Supergravity->supersymmetry

2. ## Consistent slicing aka third constraint

    - Cannot just add energy in IR
    - Need consistent distribution for four-dimensional theory
        - Anomaly mediation via chiral compensator

3. ## Better understanding of radion?

4. ## Better understanding of cc?

# Conclude

- If EFT means just integrating out high energy we need details of stabilizing potential to get the correct results

- Can do this with EFT but not necessarily easier

- Also need shapes of wavefunctions in extra dimension
  - Are fields uv or ir localized?
  - Is susy IR or UV localized

# Conclusion <span style="color:red">maybe</span>

- Stability critical to analyzing SUSY breaking
- With stabilization fields adjust so hubble same everywhere in fifth dimension
- But with IR SUSY breaking, seems potential very important
  - **Determines net cc**
- With strong stability susy breaking everywhere
  - Including anomaly mediation
- If less strong, results less determined
  - Not clear cc even has same sign
  - Generally anomaly mediation but depends on stabilizing part
- Not clear what EFT interpretation is
  - Potential itself changes when cc turns on
  - Not just perturbation to flat metric?

# KKLT and
# Warped RS Geometry

- Observations are rooted in detailed studies of the above theories

  - However, results more general

- These are useful calculable models that provide some interesting puzzles

- Puzzles that get resolved with a combination of top-down and bottom-up thinking

# Big Lesson

- Kahler moduli appearing in string construction stabilized
  - Was big point of KKLT construction
- But in warped geometries their KK modes are still light
- Metric, warp factor can be modified in IR
- Comparable in mass to conifold deformation parameter
- Runaway behavior goes away
- And IR (EFT) potential significantly modified

# Examples Where Important Features Omitted

- Warped Compactifications

- Supersymmetry Breaking and Anomaly-Mediated SB
  - Generally a UV brane and an IR brane
  - SUSY sequestered on one and transferred to the other (in progress)
  - Assumed to be an IR effect so high energy theory irrelevant
  - Not true if strong scaling/higher-dimensional warped geometry

# Conclusion

- EFT obviously ineffective if done incorrectly
- Which is why effective field theorists
- These are subtle issues and the models are hard to completely calculate in some cases
- Helps to have guideposts to what answers should be
- In case of susy, not at all obvious what spectrum is
- And turns out it's a richer playing field than previously acknowledged
- New SUSY models
  - More compatible with current limits and testable with new machine?
- Also relevant to QCD with AMSB and confinement
- Can be important for string model stability
  - Stability and slicing constraints

# Important for…

- Getting correct EFT for Warped Compactifications
  - Need to modify "GW" of KKLT –really flux
  - Need to modify matching to CY
- Significant phenomenological consequences
  - Nonstandard spectra much more generic
  - Investigating now
- Using AMSB as a way of using nontrivial SUSY theories to analyze non-SUSY dynamics
  - At least in warped theory, SUSY breaking decouples so efficiently that gravitino removed but supersymmetry otherwise intact
  - Calls into question use of AMSB to investigate gauge dynamics

# Failure of Naive EFT

- 1) Chiral compensator independent at different points
  - But single 5d superpotential; should follow warp factor
- 2) From a dual perspective the UV can decouple from composite states

- For general supersymmetry breaking:

Gherghetta and Pomarol

https://arxiv.org/pdf/hep-ph/0302001.pdf

- For AMSB (with some restrictions)

Luty https://arxiv.org/pdf/hep-th/0205077.pdf

# Luty and AMSB

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

$$\mathcal{L}_{4,\text{eff}} = -\frac{3M_5^3}{k}\int d^4\theta \left(\phi^\dagger\phi - \omega^\dagger\omega\right) + \int d^4\theta \left(\phi^\dagger\phi\, K_{\text{UV}} + \omega^\dagger\omega\, K_{\text{IR}}\right)$$

$$+ \left[\int d^2\theta \left(\phi^3\, W_{\text{UV}} + \omega^3\, W_{\text{IR}}\right) + \text{h.c.}\right].$$

$$\omega = \phi e^{-kT}, \qquad T = \pi r + \cdots$$

$$\left|\frac{\langle F_\omega \rangle}{\langle \omega \rangle}\right| = \frac{|c_{\text{IR}}|}{M_{\text{P}}^2}|\langle\omega\rangle|, \qquad |\langle F_\phi\rangle| = \frac{|c_{\text{UV}}|}{M_{\text{P}}^2} = \frac{F_{\text{UV}}}{\sqrt{3}M_{\text{P}}},$$

# Caveat: "Easy" Cases

- Supersymmetry broken in IR and energy cancelled in IR
  - Then geometry remains flat space
- Expect usual contributions
  - Gaugino mediation (if bulk gauge boson)
  - Anomaly mediation ???
- No anomaly mediation aside from where $W_0$ resides
- (But complication: Need to find stable radion consistent with susy breaking)

# Simple cases to consider; always add small energy

1. Add in UV, cancel in UV
    1. Clearly no tree level effect away from UV
2. Add in IR, cancel in IR
    1. Tricker since radion potential changes
3. Add in IR, cancel in UV
    1. We will see in that case there is SUSY breaking in UV too
    2. Compensating energy directly on brane or in warp factor (by jump condition)
    3. We will check if anomaly-mediation works as expected by EFT

# What about IR Symmetry Breaking?

- $\delta\Lambda \sim 2/3\ \delta T_{IR}$
- $\delta T_{UV} \sim^{e\text{-}4k\Pi r}\ k/v_{uv}^2\ \alpha_{UV}\ \delta T_{IR}$
- $\delta T_{IR}$ only moderately changed by GW
- This was for de Sitter space
  - If cc cancelled in IR won't affect rest of metric
  - But challenging since radion potential changed
- What if cc cancelled in UV?