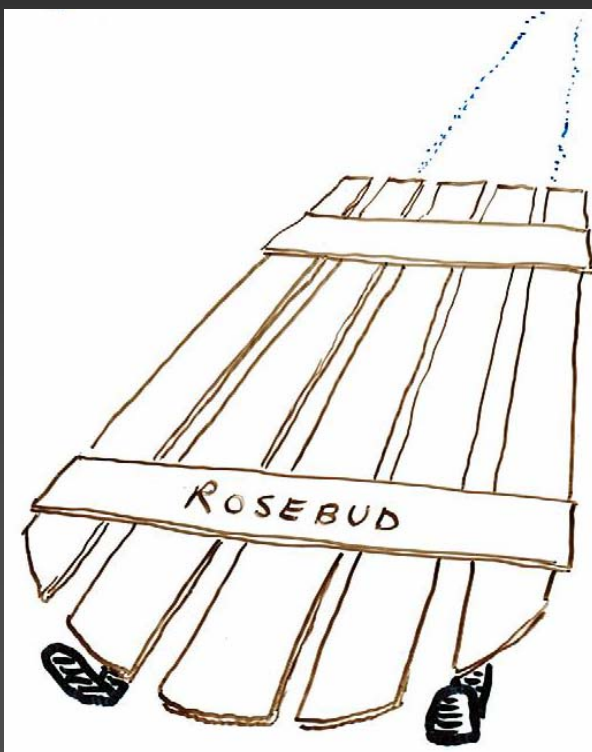
SLED Neutrinos

Neutrino Oscillations and the Cosmological Constant Problem

Cliff Burgess

…More Obsessing About SLEDs



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CC Problem:

Y. Aghababaie, J. Cline, H. Firouzjahi, D. Hoover, S. Parameswaran, F. Quevedo, G. Tasinato, I. Zavala

Phenomenology:

*G. Azuelos, P.-H. Beauchemin, **J. Matias**, F. Quevedo*

Cosmology:

A. Albrecht, F. Ravndal, C. Skordis

The Plan

- 6D Supergravity and the Cosmological Constant
  - Classical: Weinberg’s theorem and all that…
  - Quantum: Loops, SUSY and LEDs
- But what about…..
  - Hidden fine tunings, UV sensitive loops, brane phase transitions, new forces, radius stabilization, dynamical warping, time-varying G, SN bounds…
- Have we been MSLED?
  - Colliders; Newton’s Law; Neutrino Oscillations…

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Naturalness and Dark Energy

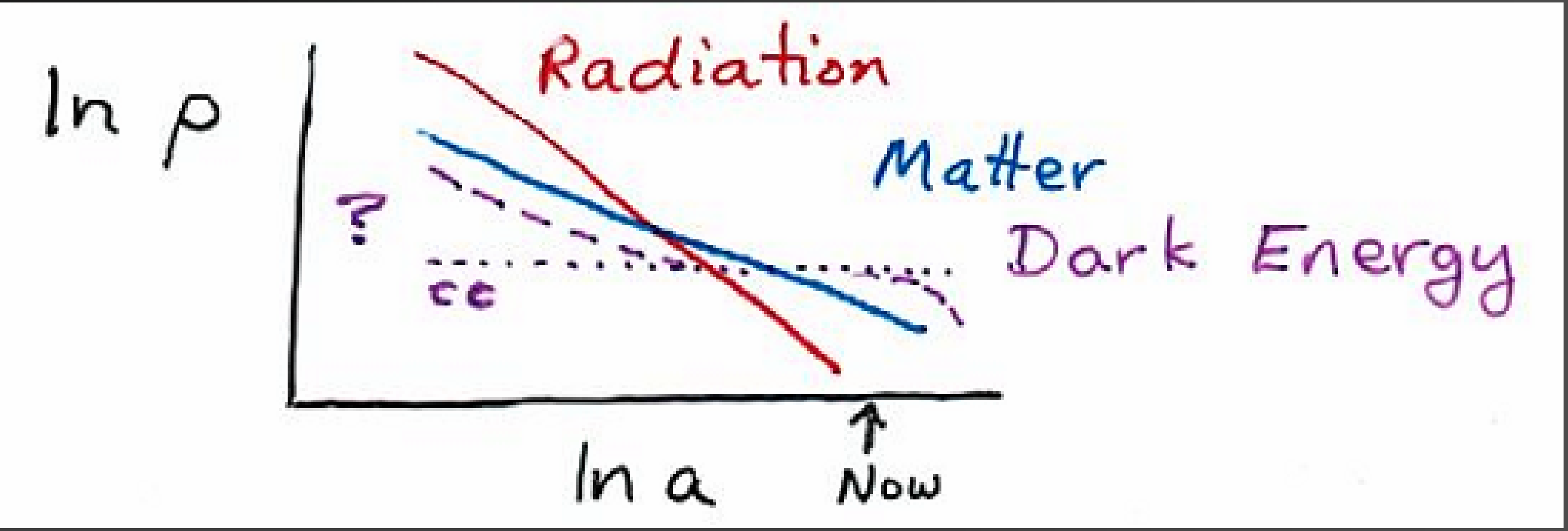
$\delta\lambda \sim m^4$ (non supersymmetric)

$\delta\lambda \sim m_{ss}^2 M^2$ or m_{ss}^4 (supersymmetric)

$$\lambda_{\rm obs} \approx (10^{-3}\ \text{eV})^4$$

- Why doesn't the *electron* contribute too large a zero-point energy to the cosmological constant?

Naturalness and Dark Energy



$$m_\phi \approx H_0 \approx 10^{-33}\ \text{eV}$$

- Why is such a small mass stable against radiative corrections?
- Even if so, why doesn't it mediate a new long-range force?

Technical Naturalness

- Given a small quantity $\lambda = \lambda_0 + \delta\lambda$:
  - In the fundamental theory, why should λ_0 be small?
  - Given that λ_0 is small, why does it *stay small* as one integrates out physics up to the scales for which λ is measured?

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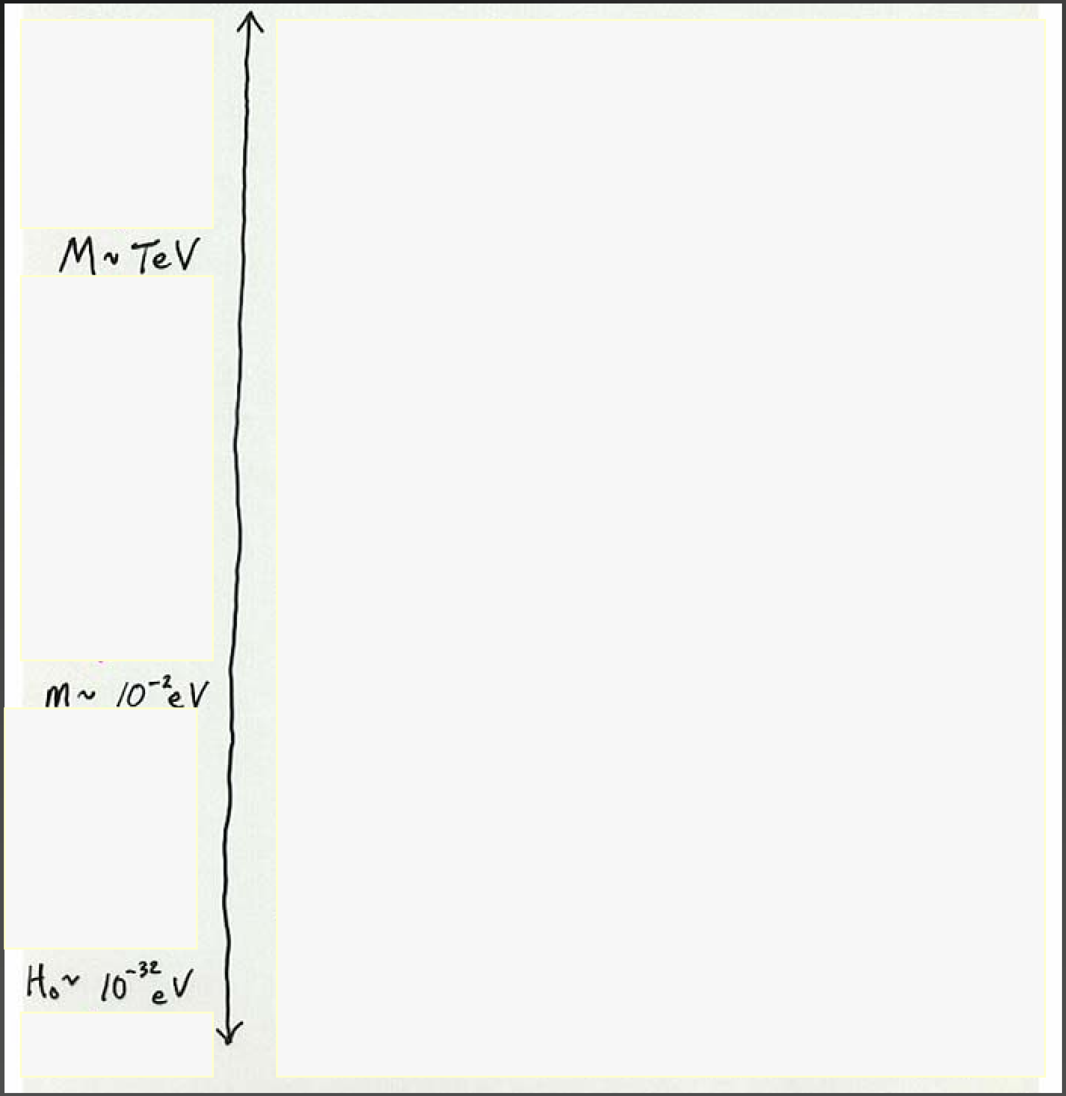
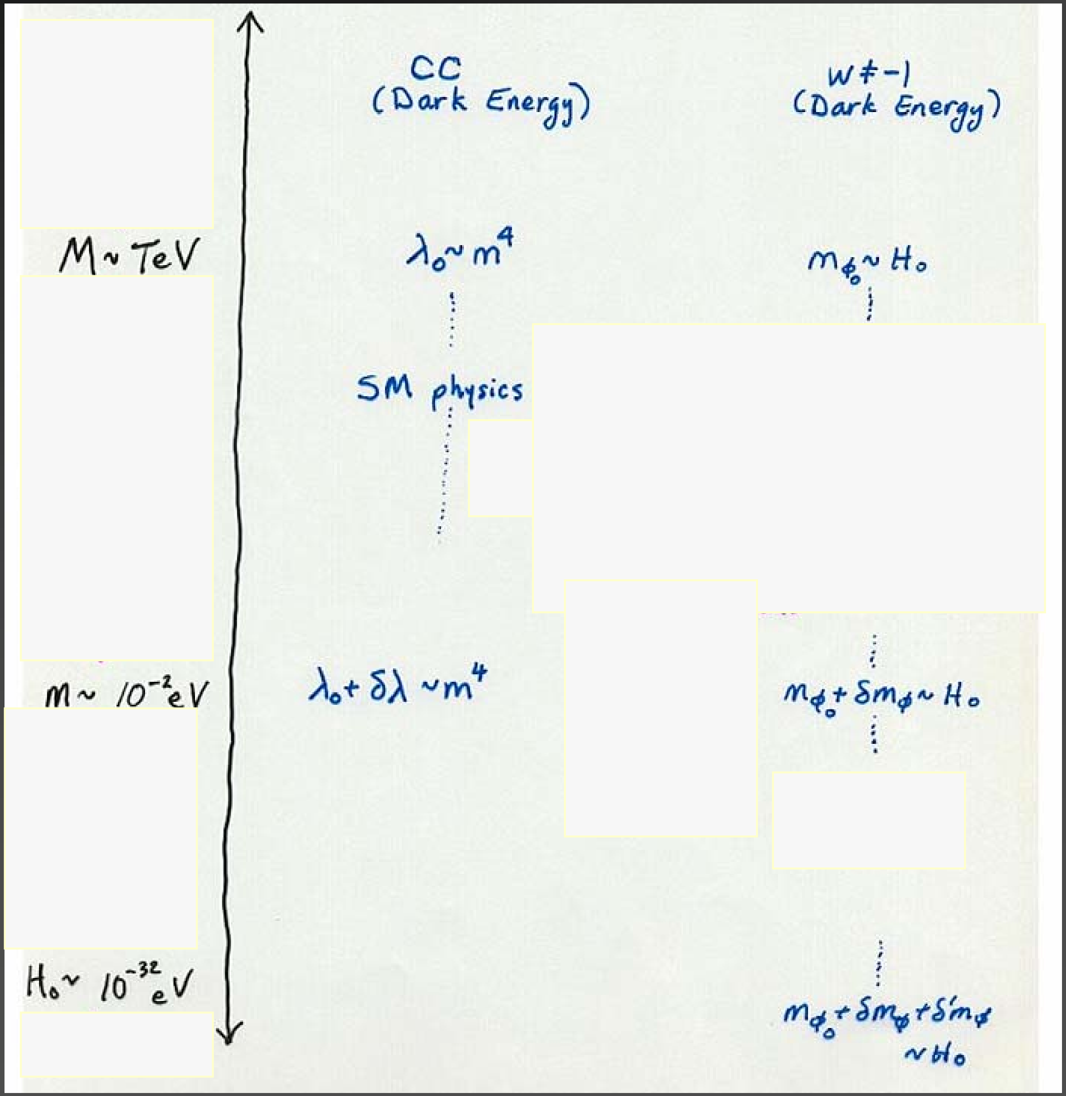
This is serious because it involves physics we think we understand…

Scales

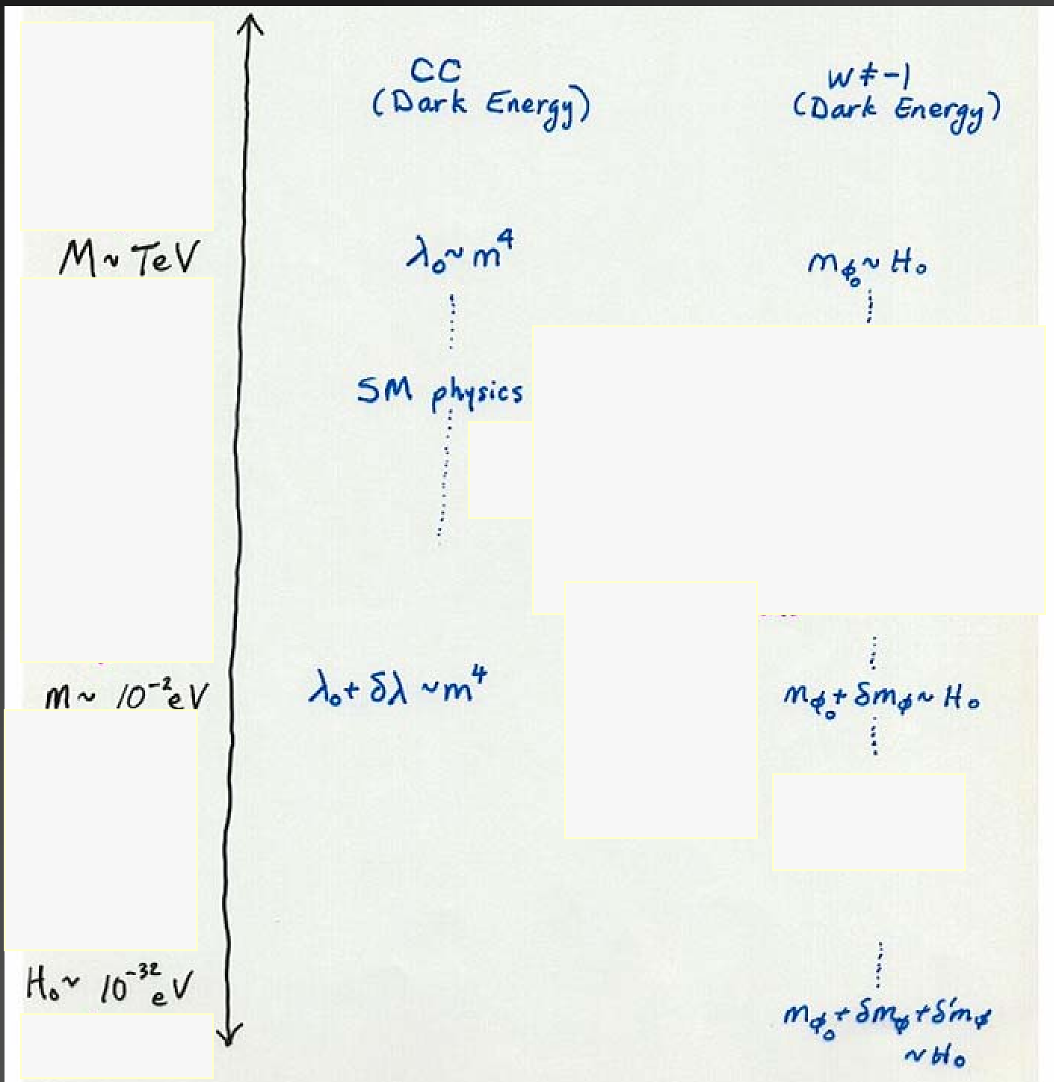


Scales



These scales are natural using standard 4D arguments.

Scales



How can these scales be changed to give a small vacuum energy?

These scales are natural using standard 4D arguments.

The SLED Proposal

- Suppose physics is extra-dimensional above the 10^{-2} eV scale.

- Suppose the physics of the bulk is supersymmetric.

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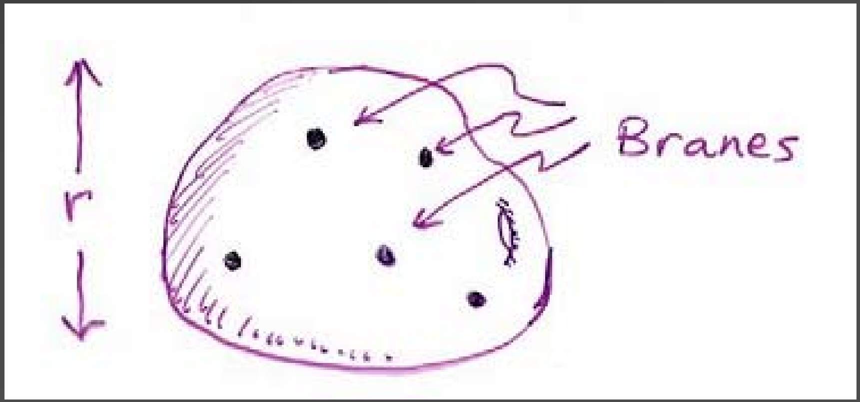
- Suppose the physics of the bulk is supersymmetric.

- *Experimentally possible:*
  - *There are precisely two extra dimensions at these scales;*
  - *We are brane bound;*



The SLED Proposal

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- Suppose the physics of the bulk is supersymmetric.

- *Experimentally possible:*
  - *There are precisely two extra dimensions at these scales;*
  - *We are brane bound;*
  - *The 6D gravity scale is in the TeV region.*

$$M_p = M_g^2 \, r$$

The SLED Proposal

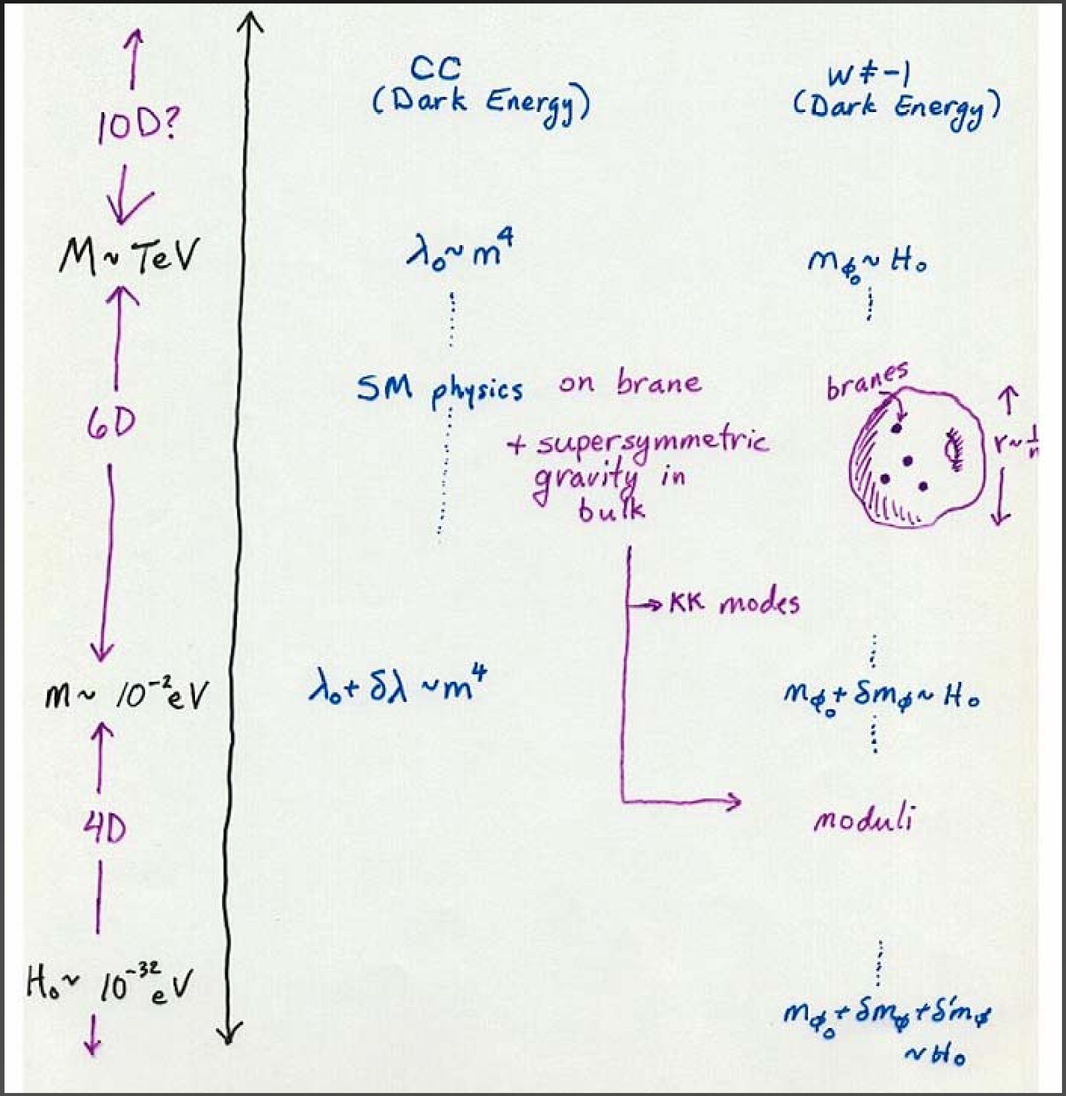
- Suppose physics is extra-dimensional above the 10^{-2} eV scale.

- Suppose the physics of the bulk is supersymmetric.

- *Experimentally possible provided:*
  - *SUSY breaks at scale M_g on the branes;*
  - *Trickle-down of SUSY breaking to the bulk is:*

$$m_{SB} \approx \frac{M_g^2}{M_p} \approx \frac{1}{r}$$

Scales



Naturalness for these scales must be rethought in 6D.

These scales are natural using standard 4D arguments.

The CC Problem in 6D

- The 6D CC
- Integrate out brane physics
- Integrate out bulk physics
  - *Classical contribution*
  - *Quantum corrections*

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  - *None have a 6D CC.*

The CC Problem in 6D

Nishino & Sezgin

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- Integ… phys…
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  - *Quantum corrections*

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  - *None have a 6D CC.*

$$e_6^{-1}\mathcal{L}_B = -\frac{1}{2}R - \frac{1}{2}\partial_M\varphi\,\partial^M\varphi - \frac{1}{2}G_{ab}(\Phi)\,D_M\Phi^a\,D^M\Phi^b - \frac{1}{12}e^{-2\varphi}\,G_{MNP}G^{MNP} - \frac{1}{4}e^{-\varphi}\,F^\alpha_{MN}F_\alpha^{MN} - e^\varphi\,v(\Phi)$$

The CC Problem in 6D

- The 6D CC
- Integrate out brane physics
- Integrate out bulk physics
  - *Classical contribution*
  - *Quantum corrections*

- *Generates large vacuum energy*
- *This energy is* localized *in the extra dimensions (plus higher-derivatives)*

$$\sum_i T_i \, \delta^2(y - y_i)$$

The CC Problem in 6D

- The 6D CC
- Integrate out brane physics
- Integrate out bulk physics
  - *Classical contribution*
  - *Quantum corrections*

- *Solve classical equations in presence of branes*
- *Plug back into action*

$$R = -\sum_i T_i \, \delta^2\left(y - y_i\right) + R_{smooth}$$

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$$\lambda_{eff} = \sum_i T_i + \int d^2 y \sqrt{g}\left(R + \dots\right)$$

The CC Problem in 6D

Chen, Luty & Ponton

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Tensions cancel between brane and bulk!!

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Smooth parts also cancel for supersymmetric theories!!

The CC Problem in 6D

- The 6D CC
- Integrate out brane physics
- Integrate out bulk physics
  - *Classical contribution*
  - *Quantum corrections*

- *Bulk is a supersymmetric theory with $m_{sb} \sim 10^{-2}$ eV*
- *Quantum corrections can be right size in absence of $m_{sb}^2 M_g^2$ terms!*
  - *Lifts flat direction.*

$$\delta\lambda \approx m_{sb}^4$$

Present Status

- Classical part of the argument:
  - Adjustment of the bulk to brane properties.

- Quantum part of the argument:
  - Absence of M^4 or $m_{sb}^2 M^2$ UV sensitivity.

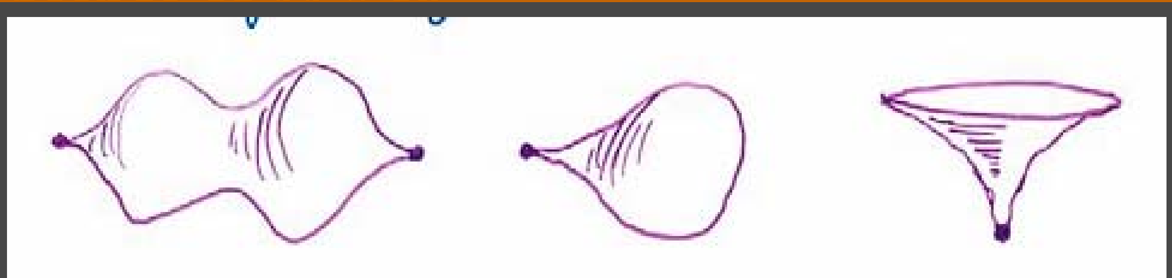
Present Status

**Gibbons, Guvens & Pope*

- Classical part of the argument:
  - Adjustment of the bulk to brane properties.

- Quantum part of the argument:
  - Absence of M-4 or

- *Bulk solutions generically have a classically flat direction.*
- *General 2D axially-symmetric solutions are known and are 4D flat.**
  - *Assume 4D maximal symmetry.*
  - *Not restricted to conical singularities.*



Present Status

**CB, Quevedo, Tasinato & Zavala*
Cline & Vinet

- Classical part of the argument:
  - Adjustment of the bulk to brane properties.
- Quantum part of the argument:
  - Absence of M_g^4 or $m_{sb}^2 M_g^2$ UV sensitivity.

- *Bulk solutions generically have a classically flat direction.*
- *General 2D axially-symmetric solutions are known and are 4D flat.*
  - *Assume 4D maximal symmetry.*
  - *Not restricted to conical singularities.*
- *There are known choices of branes for which no static bulk solutions exist.**

Present Status

- Classical part of the argument:
  - Adjustment of the bulk to brane properties.
- Quantum part of the argument:
  - Absence of M^4 or $m_{sb}{}^2M^2$ UV sensitivity.

- *UV sensitivity may be computed for general background fields.*
  - *Integration over bulk KK modes can give $m_{sb}{}^2M^2$ terms, in bulk and on branes, but these cancel when summed over 6D supermultiplets.*
- *Higher-derivative brane-localized counterterms can exist from brane loops.*
  - *These can make the nature of bulk singularities at brane positions more than conical.*

Observational Consequences

- Quintessence cosmology
- Modifications to gravity
- Collider physics
- Neutrino physics
- Astrophysics

Observational Consequences

Matias & CB

- Quintessence cosmology
- Modifications to gravity
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- *SLED predicts there are 6D fermions in the bulk, as well as their properties*
  - *Masses, chirality, couplings, …*
- *Masses and mixings can be chosen to agree with terrestrial oscillation data.*
  - *Most difficult: bounds from cosmology and supernovae.*

Bulk Fermions in SLED

- 6D supergravities contain many bulk fermions:
  - Gravity: $(g_{mn}, \psi_m, B_{mn}, \chi, \varphi)$
  - Gauge: (A_m, λ)
  - Hyper: (Φ, ξ)
- Bulk couplings dictated by supersymmetry
  - In particular: 6D fermion masses must vanish
- Brane back-reaction removes KK zero modes
  - eg: boundary condition due to conical defect at brane position

Bulk-Brane Fermion Couplings

$$S_{\text{int},N} = \int d^4x \left[\lambda_{aI\alpha}(L_a^u N_{u\alpha}^I)H + \text{c.c.}\right]$$

- Natural coupling size: $\lambda \sim M_g^{-1}$
  - Naïvely expect flavour independence at TeV scale
- Brane Goldstino naturally mixes in this way with the bulk gravitino
- Extra-dimensional (2D) chirality as lepton number
  - Brane-bulk couplings invariant if brane fermions transform, but this is a symmetry of SM brane interactions only if identified as L_e, L_μ, L_τ (or some linear combination).
  - Chirality generically broken in the bulk at KK scale: *1/r*

4D Left-handed Mass Matrix

$$M_\nu = \frac{1}{r}\begin{pmatrix} 0 & 0 & 0 & g_{11}^{(+)} & g_{11}^{(-)} & g_{12}^{(+)} & g_{12}^{(-)} & g_{13}^{(+)} & g_{13}^{(-)} & \cdots \\ 0 & 0 & 0 & g_{21}^{(+)} & g_{21}^{(-)} & g_{22}^{(+)} & g_{22}^{(-)} & g_{23}^{(+)} & g_{23}^{(-)} & \cdots \\ 0 & 0 & 0 & g_{31}^{(+)} & g_{31}^{(-)} & g_{32}^{(+)} & g_{32}^{(-)} & g_{33}^{(+)} & g_{33}^{(-)} & \cdots \\ g_{11}^{(+)} & g_{21}^{(+)} & g_{31}^{(+)} & 0 & c_\ell^{I=1} & 0 & 0 & 0 & 0 & \cdots \\ g_{11}^{(-)} & g_{21}^{(-)} & g_{31}^{(-)} & c_\ell^{I=1} & 0 & 0 & 0 & 0 & 0 & \cdots \\ g_{12}^{(+)} & g_{22}^{(+)} & g_{32}^{(+)} & 0 & 0 & 0 & c_\ell^{I=2} & 0 & 0 & \cdots \\ g_{12}^{(-)} & g_{22}^{(-)} & g_{32}^{(-)} & 0 & 0 & c_\ell^{I=2} & 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Rows 1–3: ν_e, ν_μ, ν_τ

Rows 4–7: KK ν

$$g^s{}_{aI} = \lambda^s{}_{aI}\,\mathrm{v}$$

$$m_\ell^{KK} = \frac{c_\ell}{r}$$

Example Mass Spectrum

- Simplest assumption: g's independent of flavour and 2D chirality. Leads to:
  - 2 massless neutrinos having no overlap with bulk;
  - For each KK mode one state with mass c_l/r having no overlap with brane;
  - One state for each root of a transcendental eq:

$$z = -6g^2 \sum_{\ell} \frac{1}{c_\ell - z}$$

Each KK mode: $c_l/r + O(g)$

One state: $6g^2 \, \Sigma_l \, c_l^{-1}$

The Naturalness Issue

- Large number of KK modes can overpower smallness of *g* and *1/r* due to divergent mode sums.
- These renormalize neutrino masses on branes, so must understand why these are small.
- Suggests requiring lepton-number invariance for *g*'s.

$$\mathcal{S} \equiv \sum_{\ell} \frac{1}{c_\ell}$$

$$h_{ab} \sim M_g^{-1}$$

Possible Pitfalls for LED Neutrinos

- Sterile Oscillations:
  - Low-lying states: very light KK modes can strongly mix with active brane modes.
  - Higher states: KK tower of sterile states can resonantly oscillate with neutrinos in stars and SN.
- Incoherent emission:
  - Energy loss to all bulk states gravitons
  - Active-neutrino distortion due to bulk neutrino emission
  - Cannot tolerate many KK states at BBN, or for closure of late universe.

A Model

- Imagine lepton-breaking terms are suppressed.
  - Possibly generated by loops in running to low energies from M_g.
- Acquire desired masses and mixings with a mild hierarchy for g'/g and ε'/ε.
  - Build in approximate $L_e - L_\mu - L_\tau$, and Z_2 symmetries.

$$g^{(+)} = \begin{pmatrix} g' \\ g \\ g \end{pmatrix} \qquad g^{(-)} = \begin{pmatrix} \varepsilon \\ \varepsilon' \\ \varepsilon' \end{pmatrix}$$

$$\varepsilon, \varepsilon' \approx \frac{m_{KK}}{M} \approx \frac{k m_{KK}}{M_g} \approx kS^{-1}$$

$$\frac{\varepsilon'}{\varepsilon} \approx \frac{g'}{2g} \approx 10\%$$

Lightest Mass Eigenstates

- 1 massless state
- 2 next- lightest states have strong overlap with brane.
  - Inverted hierarchy.
- KK states mix weakly with lighter 3 states.

$$\mu_{\pm} = \mu_{\pm}^{0} \left[1 \pm \sqrt{2} \left(\frac{\epsilon'}{\epsilon} - \frac{g'}{g} \right) + \left(\frac{\epsilon'}{\epsilon} \right)^2 + \left(\frac{g'}{g} \right)^2 + \cdots \right]$$

$$\mu_{\pm}^{0} = \frac{\sqrt{2}\,\epsilon g \mathcal{S}}{r}$$

Lightest Mass Eigenstates

- 1 massless state
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Worrisome: once we choose $g \sim 10^{-4}$, good masses for the light states require:

$\varepsilon S = k \sim 1/g$

Must get this from a real compactification.

$$\mu_\pm = \mu_\pm^0 \left[1 \pm \sqrt{2} \left(\frac{\epsilon'}{\epsilon} - \frac{g'}{g} \right) + \left(\frac{\epsilon'}{\epsilon} \right)^2 + \left(\frac{g'}{g} \right)^2 + \cdots \right]$$

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Mixings

$$U \approx \begin{pmatrix} c_s(-1/\sqrt{2} - \delta/4) & c_s(1/\sqrt{2} - \delta/4) & 0 \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & 1/\sqrt{2} \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & -1/\sqrt{2} \end{pmatrix}$$

$$\delta = 2\left(\frac{\epsilon'}{\epsilon} + \frac{g'}{2g}\right)$$

- Lightest 3 states can have acceptable 3-flavour mixings.
- Active sterile mixings can satisfy incoherent bounds provided $g \sim 10^{-4}$ or less ($\theta_i \sim g/c_i$).
  - *Resonant oscillations within supernovae?*

$$\sum_{i=1}^{3} |U_{ai}|^2 = \cos^2\theta_i$$

$$\tan^2\theta_s \approx g^2\mathcal{P}$$

$$\mathcal{P} = \sum_{\ell} \frac{1}{c_\ell^2}$$

The Good News

- Technically natural solution to the cosmological constant problem may be possible.
- Unconventional realization of weak-scale supersymmetry breaking.
- Enormously predictive, with many observational consequences.
  - Cosmology at Colliders! Neutrinos? Tests of gravity…

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Current Worries

- Understanding self-tuning dynamics of bulk.
- Pin down M^2 contributions from branes.
- What controls scalar-tensor bounds.
- How contrived is post-BBN cosmology? (Robustness to initial conditions, etc)
- Large-extra dimensional pre-BBN cosmology?
- Dynamics of volume and warping.
- Connection to string theory?

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Some References

- Cosmological Constant proposal using 6D supersymmetric large extra dimensions:
  - *Aghababaie, CB, Parameswaran & Quevedo*, hep-th/0304256;
  - *CB, Quevedo, Tasinato & Zavala*, hep-th/0408109;
  - *Aghababaie, CB, Cline, Firouzjahi, Quevedo, Tasinato & Zavala*, hep-th/0308064;
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  - *Albrecht, CB, Ravndal & Skordis*, astro-th/0107573.
- Particle Physics Implications:
  - *CB, Matias & Quevedo*, hep-ph/0404135;
  - *Azuelos, Beauchemin & CB*, hep-ph/0401125; hep-ph/0407196.
- Reviews:
  - *CB*, hep-th/0402200; hep-th/0411140.