Title: Supersymmetric large extra dimensions and dark energy.

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Abstract:

# OUTLINE

- 6D SUGRA AND THE COSMOLOGICAL CONSTANT
  - * Classical Scale Invariance and Self Tuning (Weinberg's No Go)
  - Loops, SUSY and LEDs
- ..... BUT WHAT ABOUT:
  - * Hidden Fine Tunings; UV-sensitive Loops; Brane Phase Transitions; New Forces; Dynamical Warping; Radius Stabilization; Time-Varying G; ED Energy Loss.....
- ARE WE MSLED?
  - * NOT the MSSM

# NATURALNESS + DARK ENERGY

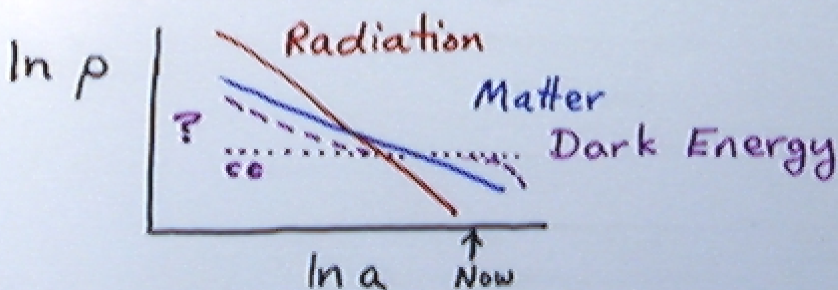
- **COSMOLOGICAL CONSTANT:** $\left(\lambda_{obs} \sim (10^{-3}\,eV)^4\right)$

  Why doesn't the electron generate too large a c.c.?

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

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

- **DARK ENERGY:** $\left(m_\phi \lesssim H_0 \sim 10^{-33}\,eV\right)$




How can such a light scalar be stable against loop corrections?

Even if so, why isn't there an

# WISH LIST

(1) IN THE FUNDAMENTAL MICROSCOPIC THEORY, WHY IS $\lambda_0$ SMALL?

(2) GIVEN THAT $\lambda_0$ IS SMALL, WHY DOES IT STAY SMALL AS ONE INTEGRATES OUT THE SCALES TO WHERE $\lambda$ IS MEASURED?

ALL KNOWN HIERARCHIES SATISFY BOTH (eg atom/nucleus ; superconductor/electron..)

* Solutions to (1) may need to await discovery of microscopic fundamental theory. (string theory?...)

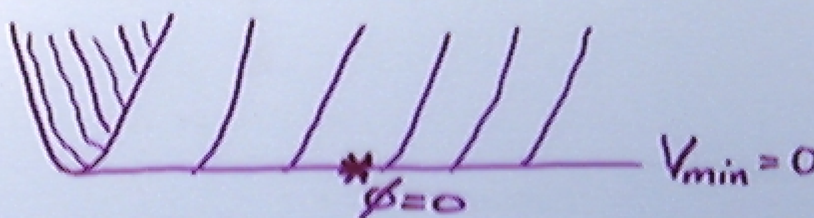
* Solutions to (2) must change LOW ENERGY physics we think

# WEINBERG'S NO-GO

- DYNAMICAL RELAXATION + SPONTANEOUSLY BROKEN SCALE INVARIANCE.

$$g^{\mu\nu}\frac{\delta S}{\delta g^{\mu\nu}} \propto \frac{\delta S}{\delta \phi} \longleftrightarrow \hat{g}_{\mu\nu} = \phi\, g_{\mu\nu}$$

- e $V_{eff} = \lambda_{ijkl}\,\phi^i\phi^j\phi^k\phi^l$ with flat dir$^n$.




▶ Scale invariant point $(\phi=0)$: $V_{min} = 0$

▶ Scale invariance of $V \Rightarrow V_{trough}(\phi) \equiv 0$.

# SLED

- SUPPOSE PHYSICS IS EXTRA DIMENSIONAL ABOVE THE CC SCALE:

  - Experimentally possible if $r < 100\,\mu m$ (so $1/r > 0.01\,eV$) provided:

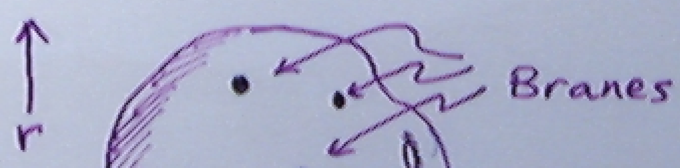
    * 6D World at these scales
    * $M_g^2 \sim \frac{M_p}{r} \sim (10^4\,GeV)^2$

    ADD

- IN STRING VERSION WOULD EXPECT SUPERSYMMETRY, BUT:

  - Must be broken at scale $M_g$ on the branes

  - Implies susy breaking scale in bulk is of order $m_{sb} \sim \frac{M_g^2}{M_p} \sim \frac{1}{r}$



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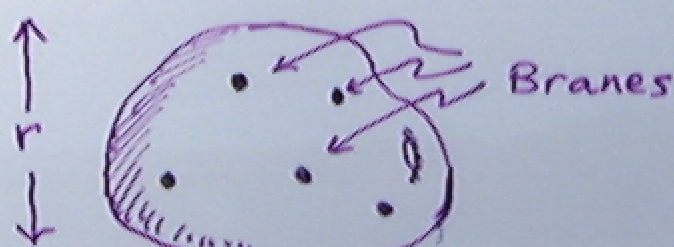


# CC IN 6 DIMENSIONS

- SUSY FORBIDS A C.C. IN 6D

$$\mathcal{L} = -\tfrac{1}{2}R - \tfrac{1}{2}(\partial\phi)^2 - \tfrac{1}{12}e^{-2\phi}G_3^2 - \tfrac{1}{4}e^{-\phi}F_2^2 \pm^{*} g^2 e^{\phi} + \dots$$

$*$ $+ \rightarrow$ ROMAN'S SUGRA (NON CHIRAL)

$- \rightarrow$ NISHINO-SERGIN SUGRA (CHIRAL)

- INTEGRATING OUT BRANE PARTICLES GIVES $O(M_g^4)$ CONTRIBUTION TO BRANE TENSION.

  $\rightarrow$ a local energy distribution: $T_i\,\delta^2(x-x_i)$

- CLASSICAL BULK RESPONSE: $R_{sing} = -2\sum_i T_i\,\delta^2(x-x_i)$ + smooth parts

- EFFECTIVE 4D VACUUM ENERGY AFTER CLASSICALLY INTEGRATING OUT BULK:

$$\lambda_{eff} = \sum_i T_i + \frac{1}{2}\int d^2y\left[R + (\partial\phi)^2 + \dots\right] = 0$$

$\Sigma T_i$ cancels $R_{sing}$

Chen, Luty, Ponton

# e.g.: SS SOLUTION

– Salam, Sezgin; PLB 147 (84)

- Fluxes (Freund–Rubin ansatz):

$$F_{mn} = f\,\epsilon_{mn} \quad (n=1 \text{ monopole})$$

$$ds^2 = g_{\mu\nu}(x)\,dx^\mu dx^\nu + g_{mn}(y)\,dy^m dy^n$$

(maximal symmetry)

- STABILIZATION WITH A SURPRISE

$$\sqrt{g}\left[-\tfrac{1}{2}R - \frac{1}{4g^2}e^{-\phi}F^2 - 2g^2 e^{\phi}\right]$$

$$\Downarrow$$

$$V_{eff} \sim \frac{1}{r^2}\left[-\frac{2}{r^2} + \frac{e^{-\phi}}{g^2 r^4} + g^2 e^{\phi}\right]$$

$$\Downarrow$$

$$= \frac{g^2 e^{\phi}}{r^2}\left[1 - \frac{1}{g^2 r^2 e^{\phi}}\right]^2$$

* $t = g^2 r^2 e^{\phi}$ fixed

* $s = \frac{r^2}{g^2 e^{\phi}}$ flat

* flat 4D space!

- PRESERVES N=1 D=4 SUSY

$f_{ab} = S\delta_{ab} + \ldots \quad K = -\ln(S+S^*) - \ln(T+T^* + V)$

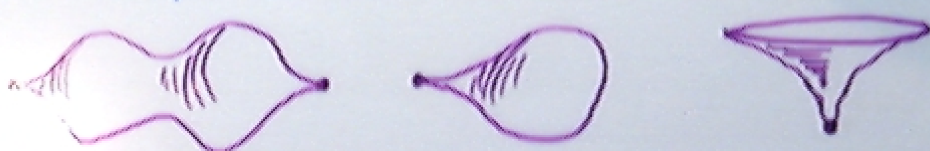
$\xi_{FI} = \text{const}$ Aghababaie, CB, Parameswaran

# GENERAL SOLUTIONS

- MOST GENERAL SOLUTION TO CHIRAL GAUGED SUGRA — Gibbons, Guvens + Pope th/0307238

    * 4D Maximal Symmetry

    * Axisymmetry in Extra Dimensions



* ALL of these solutions have FLAT 4D *

* Tensions can be positive

- WHY ARE THEY ALL FLAT?

ABCFQTZ th/0308064

* Classical Scale Invariance!

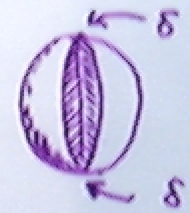
$$S = \int d^6x\, e^{-2\phi}\left[-\tfrac{1}{2}R + \cdots\right] + \sum_i \int d^4x\, e^{-2\phi}\left[T_i + \cdots\right]$$

# SELF TUNING?

- RUGBY BALL TENSIONS MUST BE EQUAL:

  WHAT HAPPENS IF ONE

  BRANE TENSION CHANGES?




$\star$ Time-dependent transients must preserve topological constraints + conservation laws.

$\star$ CANNOT be addressed using truncated 4D theory: $\phi(x)$, $ds^2 = a(x)\,ds_4^2 + b(x)\,ds_2^2$

MASS OF $t = r^2 e^{\phi}$ SAME AS KK MASS

Garriga + Porrati

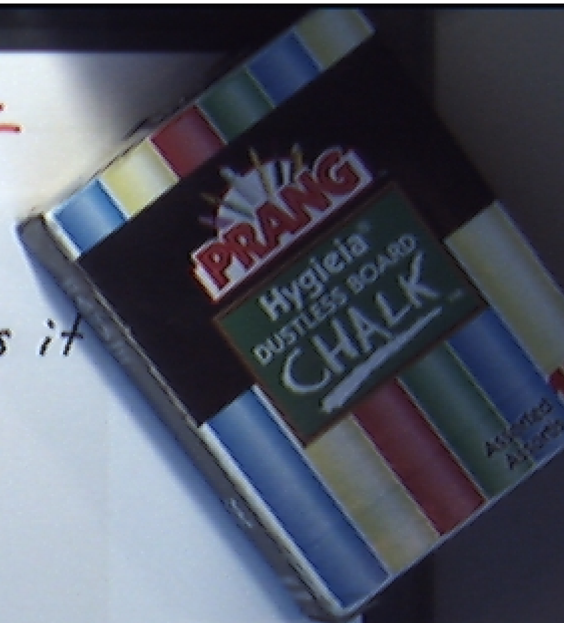
- IS EVOLUTION TOWARDS ANOTHER FLAT GGP SOLUTION? Yes, for small enough $\delta T$ BQTZ th/0408109

  $\star$ All conical singularity solutions satisfy:

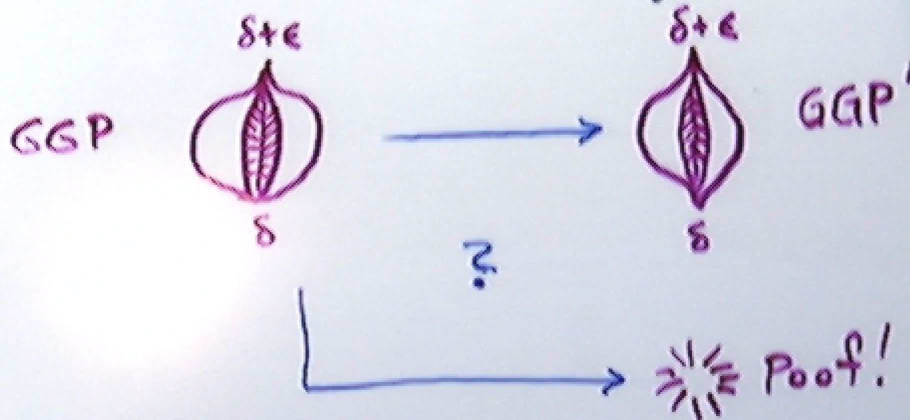
$$\frac{T_+ - T_-}{2\pi} + \frac{1}{g}\left(1 + \frac{T_+}{2\pi}\right)\left(1 + \frac{T_-}{2\pi}\right) = 0$$

ABCFQTZ th/0308064

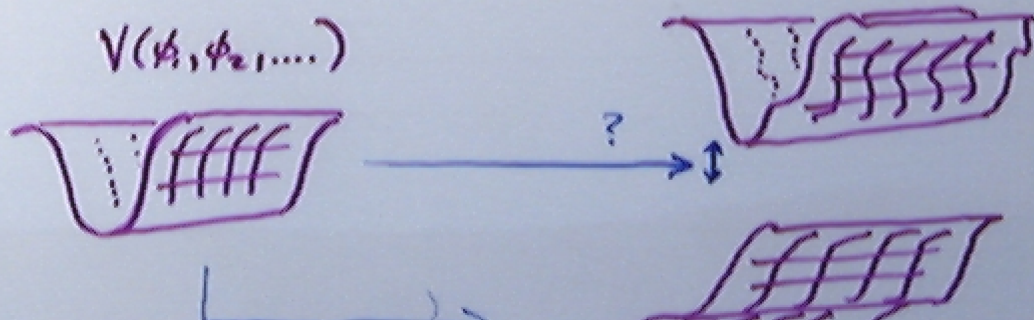
# GGP SOLUTIONS + STABILITY




- Since GGP assume maximal 4D symmetry (Mink, AdS, dS), what does it say about self tuning?




- Regarded as 4D theory with many KK modes:



# BULK LOOPS

- INTEGRATING OUT BULK MASSLESS 6D FIELDS: (1-Loop)

  * On spheres and rugby balls: $V(r) = \frac{\alpha}{r^4}\left[\ln\left(\frac{r}{r_0}\right) + \beta\right]$

    $r_0$: UV cutoff

  * On torii and orbifolds: $V(r,U) = \frac{W(U,U^*)}{r^4}$

    $U$: shape moduli

    Poppitz Ponton
    Poppitz Peloso
    BGHQ

- ULTRAVIOLET DIVERGENCES: (1-Loop)

  * In bulk (dim reg):

$$S_\infty = \int d^6x \left[ c_1 R^3 + c_2 e^{\phi} R^2 + c_3 e^{2\phi} R + c_4 e^{3\phi} + \cdots \right]$$

  * On branes (dim reg):

$$S_\infty = \int d^4x \left[ b_1 R^2 + b_2 e^{\phi} R + b_3 e^{2\phi} + \cdots \right]$$





Recall: $R \sim \frac{1}{r^2}$ $\int d^2x \sim r^2$ $e^{\phi} \sim \frac{1}{r^2}$

# BULK LOOPS (2)

- INTEGRATE OUT MASSIVE 6D MODES:
  (eg: 10D-6D KK modes; .... ) $M \sim \text{TeV}$

  * Sensitivity to $M$ arises for local effective terms in 6D and on branes

$$S_{bulk} = \int d^6x \left[ M^6 + M^4(R + e^{\phi} \ldots) + M^2 (R^2 + e^{\phi} R + \ldots) \right]$$

$$S_{brane} = \int d^4x \left[ M^4 + M^2 (R + e^{\phi} + \ldots) \right]$$

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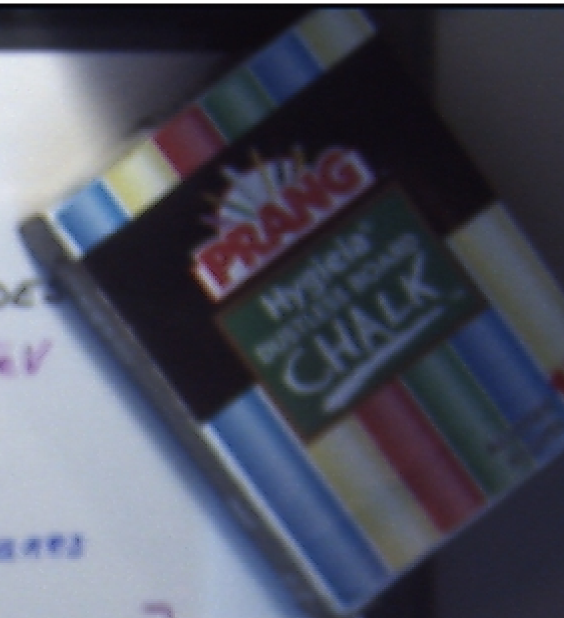


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⊗ : 6D SUSY

↗ : Renormalisations of classical action

! : Dangerous terms : $\delta V(r) \sim \frac{M^2}{r^4} \left[ 1 + \underbrace{e^{\phi} + \cdots}_{\text{higher loops}} \right]$

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# Topology vs Tuning

- Topological constraints must be satisfie[d] in order for solutions to classical eqns to exist.

  eg: $\sum_i Q_i = 0$ for Coulomb's Law in compact space

- Once existence is ensured, general solution shows it is necessarily flat in 4D.

- Easy to confuse this with fine tuning of c.c. IF internal dimensions are flat:

$$\blacktriangleright \frac{1}{4\pi}\int d^2y\,\sqrt{g}\,R = \sum_i \frac{\delta_i}{2\pi} = \chi = \begin{cases} 2 & \text{(sphere)} \\ 0 & \text{(torus)} \\ \vdots & \end{cases}$$

$$\lambda_{eff} = \sum_i T_i - \frac{1}{2}\int d^2y\,\sqrt{g}\,R = \sum_i T_i - 2\pi\chi$$

$$= \sum_i T_i \quad \text{(torus)}$$

many....

$$= \sum_i T_i - 4\pi \quad \text{(sphere)}$$

Arkani Hamed, Hall, Smith + Weiner

## CONCLUSIONS

- SLED HAS PROMISE AS AN UNDERSTANDIN OF DARK ENERGY IN A NATURAL WAY.
  - ★ Hidden Tunings of Couplings?
  - ★ Too Large UV Loops?
  - ★ Response to tension Changes?
  - ★ Why Don't 2D Warp Strongly?
    Why Are 2D So Large?
  - ★ Sensible Post BBN Cosmology?
  - ★ New Light Scalar Bounds?
  - ★ SN + Phenomenology Bounds?

- NOVEL REALIZATION OF WEAK SCALE SUSY BREAKING:
  - ★ POSSIBLY NO SUSY PARTNERS EXCEPT FOR THE GRAVITON!
  - ★ LED AT COLLIDERS AND MORE!

- ENORMOUSLY PREDICTIVE, WITH MANY

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