SUPERSYMMETRIC LARGE EXTRA DIMENSIONS and the Cosmological Constant

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OUTLINE

- MOTIVATION

  Branes and Naturalness

- SUPERSYMMETRIC LARGE EXTRA DIMENSIONS (SLED)

- BRANE LOOPS + BULK RELAXATION

  Classical Scale Invariance

- BULK LOOPS?

  Bulk Susy and m_s^4 vs $M_s^2 M^2$

- HIDDEN FINE TUNINGS? (Where's Waldo?)

  Topological Constraints

- RADIUS STABILIZATION / WARPING?

- OBSERVATIONAL CONSTRAINTS?

  Astrophysics, Cosmology....

  Colliders, Neutrinos

THE MESSAGE

★ **SLED PROPOSAL:**

Can have naturally small dark energy IF:

* there are 2 dimensions whose size is $\sim 10\mu m$.
* the bulk physics is supersymmetric

LARGER

- <u>NATURALNESS</u>: makes low energy theory predictive and rich in observational consequences

- <u>BRANES:</u> have identified hidden assumptions about the low-energy world

- <u>CAVEAT EMPTOR</u> look closely for hidden tunings and pitfalls

NATURALNESS + DARK ENERGY

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

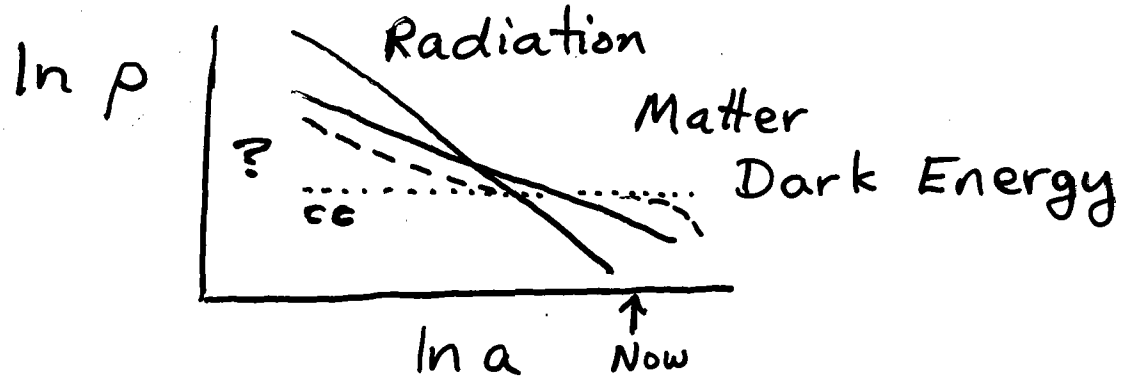
  Why doesn't the electron generate too large a c.c.?

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

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

  or m_{ss}^4

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



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

Even if so, why isn't there an observable long-range force?

WISH LIST

(1) IN THE FUNDAMENTAL MICROSCOPIC THEORY, WHY IS λ_0 SMALL?

(2) GIVEN THAT λ_0 IS SMALL, WHY DOES IT STAY SMALL AS ONE INTEGRATES OUT THE SCALES TO WHERE λ 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 we understand !!

SLED

- SUPPOSE PHYSICS IS EXTRA DIMENSIONAL ABOVE THE CC SCALE:

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

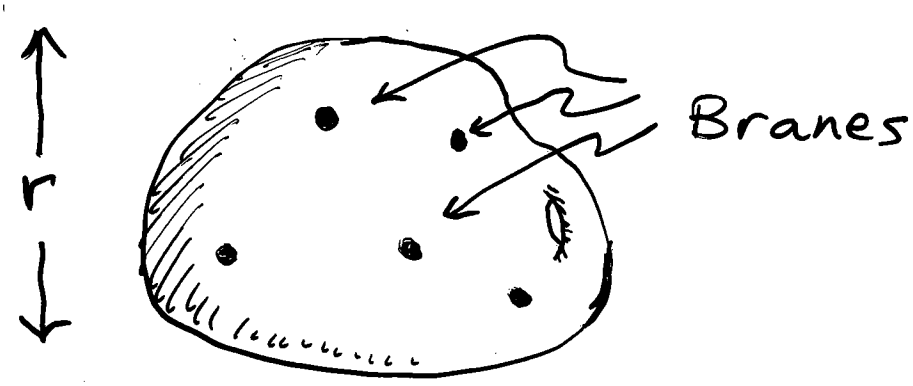
    * 6D World at these scales
    * $M_g^2 \sim \frac{M_p}{r} \sim (10^4\,GeV)^2$

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 $m_{sb} \sim \frac{M_g^2}{M_p} \sim \frac{1}{r}$



CC IN 6 DIMENSIONS

- SUSY FORBIDS A C.C. IN 6D

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

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

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

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

  $\rightarrow$ a <u>local</u> 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 <u>CLASSICALLY</u> INTEGRATING OUT BULK:

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

$\sum T_i$ cancels R_{sing}

R_{smooth} cancels $(\partial\phi)^2 + \cdots$

Chen, Luty, Ponton
th/0003067

ABPQ
th/0304256

e.g.: # SS SOLUTION

- Fluxes (Freund-Rubin ansatz): Salam, Sezgin PLB 147 (84) 47

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

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

(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
* $s = \dfrac{r^2}{g^2 e^{\phi}}$ flat
* flat 4D space!

- PRESERVES $N=1$ $D=4$ SUSY

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

$$\xi_{FI} = \text{const}$$

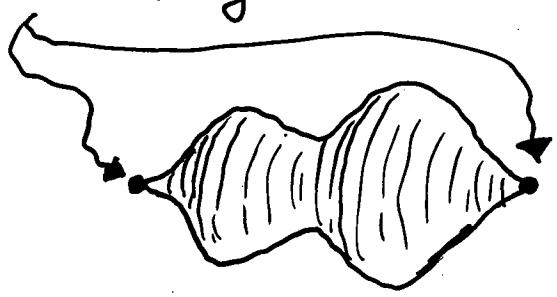
Aghababaie, CB, Parameswaran + Quevedo

th/0212091

GENERAL ARGUMENTS

- **GIBBONS, GUVENS + POPE:** th/0307238

  - FIND MOST GENERAL SOLUTION TO NISHINO-SEZGIN SUPERGRAVITY WITH:
    - ★ 4D Maximal symmetry
    - ★ Axisymmetric extra dimensions
    - ★ Nonsingular dilaton and warp factor



  - ALL of these solutions have FLAT 4D!

- **WHAT IS GOING ON?** ABCFQTZ th/0308064

The flatness of solutions is attributable to classical scale invariance of bulk supergravity plus brane action:

$$\mathcal{L}_{SF} = \int d^6x\, e^{-2\phi}\left[-\tfrac{1}{2}R + \dots\right] + \int d^4x\, e^{-2\phi}\left[T + \dots\right]$$

BULK LOOPS

- QUANTUM BULK INTEGRATION DOES NOT RESPECT SCALE INVARIANCE AND SO GENERATES A NONZERO 4D CC.

  Bulk susy requires $\lambda_{eff} \sim m_{sb}^2 M_g^2$ (bad)
  or m_{sb}^4 ?? (good)

- Antoniadis + Angelantonj: 1-loop string calculation with susy breaking by branes and bc's gives $\lambda_{eff} \sim m_{sb}^4$

- A POWER-COUNTING CARTOON:

  Integrating out scales near $M_g \gg m_{KK}$ generates local 6D interactions:

$$\mathcal{L}_6 \sim M^6 + M^4 R + M^2 R^2 + (\log M^2) R^3 + \cdots$$

$$\Rightarrow V(r) \simeq M^6 r^2 + M^4 + M^2/r^2 + (\log M^2)/r^4 + \cdots$$

tree: $* \, e^{-2\phi}$

1-loop: $* \, e^{0}$ ← Dangerous terms

2-loop: $* \, e^{2\phi} \sim 1/r^4$

OK FOR 6D SOLNS OF 10D SUGRA

CB, Hoover

X X

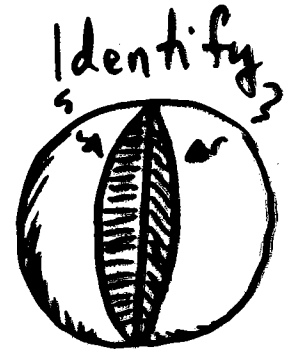
X X

susy classical...

TUNING?

- SIMPLEST EXPLICIT SOLUTIONS SEEM TO REQUIRE TUNING OF COUPLINGS

$$\frac{1}{\hat{g}} = \frac{N}{g(1-\epsilon)}$$



"Rugby Ball"

- Navarro
- Carroll + Guica
- Aghababaie, CB, Parameswaran Quevedo

$$\frac{q_+ - q_-}{2\pi} +$$

BUT!

- THESE ARE TOPOLOGICAL CONSTRAINTS ON SOURCE CHARGES

$$S_i = -\frac{1}{2} T \int d^4x \, e^{\lambda\phi} \sqrt{-\det\gamma} + q \int {}^*F \, e^{\xi\phi}$$

– A, B, P, Q, Cline, Tasinato, Zavala

ARE THESE STABLE AGAINST RENORMALIZATION OF SCALES $\lambda \ll r$?? (Possible since topological)

TOPOLOGY VS TUNING

- Topological constraints must be satisfied 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:

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

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

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

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

Arkani Hamed, Hall, Smith + Weiner ph/9912453

DYNAMICAL ISSUES

- EVEN GIVEN $\lambda \sim m_{KK}^4$ MUST ANSWER:
  - What stabilizes r at $10\mu m$?
    (ie: why is $M_P/M_W \sim 10^{16}$?)
  - Why don't extra dimensions warp?
    (ie: why is $m_{KK} \sim 1/r$?)
    (eg if $T_1 \neq T_2$ then bulk warps)
- RADION STABILIZATION: CASIMIR ENERGY

$$V(r) = \frac{-A}{r^4}\left[1 - \epsilon \ln r\right] + \cdots$$

  - $V' = 0 \longrightarrow r \sim e^{1/\epsilon} \rightarrow \epsilon \sim \frac{1}{70}$
  - $V_{min} = \frac{A\epsilon}{4r^4} \longrightarrow A = o(1)$
  - Radion mass <u>naturally</u> of order $m_\phi \sim \frac{1}{M_P r^2} \sim 10^{-33}\,eV$!

    Albrecht, CB, Raundal + Skordis th/0105261
- WARPING? Require $V(r, \omega, \ldots)$

  (Unwarped bulk is supersymmetric....)

OBSERVATIONAL BOUNDS

- FROM ASTROPHYSICS:
  - * SN energy loss to KK modes:

    $M_g \gtrsim 10$ TeV ; $r \lesssim 10\,\mu m$

  - * Production of γ's by KK modes:

    Model dependent

- FROM TESTS OF GRAVITY'S $1/r^2$ LAW:

  $$\frac{r}{2\pi} \lesssim 100\,\mu m$$

- FROM COSMOLOGY:
  - * Absence of change in r since BBN

    $V(r) \simeq \frac{1}{r^4}(-A + B \log r) + \cdots$ OK bcs of friction

  - * Absence of long-range scalar forces

    Can be OK since couplings evolve cosmologically.

    Albrecht, CB, Ravndal, Skordis
    astro-ph/0107573

REQUIRES CLOSER STUDY ONCE $V(r)$ IS KNOWN IN DETAIL

COSMOLOGY AT COLLIDERS!

- MINIMAL SLED:

  (1) OUR BRANE: THE STANDARD MODEL

  (2) BULK: 6D SUPERGRAVITY

  (3) OTHER BRANES: ?

- ▶ MANY COLLIDER SIGNALS, SIMILAR TO LED
  - MISSING ENERGY INTO BULK:

    gravitons, gravitini, dilaton....

    Atwood et al, ph/0007178

    Azuelos et al, ph/0401125
  - GRAVITY PHYSICS:

    black holes, strings?

- ▶ NON ACCELERATOR IMPLICATIONS
  - Neutrino Masses?
  - Dark Matter?

CONCLUSIONS

- SLED MAY HELP REDUCE THE CC PUZZLE: can achieve $\lambda_{eff} \ll M_g^4$

- IF SO, OBSERVATIONAL CONSEQUENCES ABOUND:
  - * SN/ASTRO ENERGY LOSS
  - * QUINTESSENCE COSMOLOGY?
  - * LONG/SHORT RANGE TESTS OF GRAVITY ($r < 10\,\mu m$)
  - * ACCELERATOR PHYSICS @ LHC:

mSLED: $\mathcal{L} \sim$ SM + 6D SUGRA + OTHER BRANE

  - * DARK MATTER? (Not the MSSM!)
  - * Neutrino Masses?

- MUST BETTER UNDERSTAND LOOPS IN BULK, RENORMALIZATIONS OF TOPOLOGICAL CONSTR.s, (technology exists!) AND DYNAMICS OF WARPING.