Title: Explorations in Supersymmetric Large Extra Dimensions

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Abstract:

Explorations in Supersymmetric Large Extra Dimensions

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In collaboration with:
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The 6D Brane World

Vacuum energy on brane worlds can curve the extra dimensions rather than their instrinsic 4D spacetime.

Rubakov & Shaposhnikov '83
...
Arkani-Hamed, Dimopoulos, Kaloper & Sundrum '00
Kachru, Schulz & Silverstein '00

A 3-brane in 6D induces a conical defect in the transverse dimensions:

Sundrum '98
Chen, Luty & Ponton '00

$$\Delta\varphi = \frac{T_3}{M_6^2}$$

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Tantalizing Numerology

Sundrum '98

Chen, Luty & Ponton '00

Observed scale of Dark Energy:

$$\Lambda \sim \left(\frac{M_W^2}{M_{Pl}}\right)^4 \sim \frac{1}{r^4}$$

with:

$$M_W \sim 10\,TeV$$

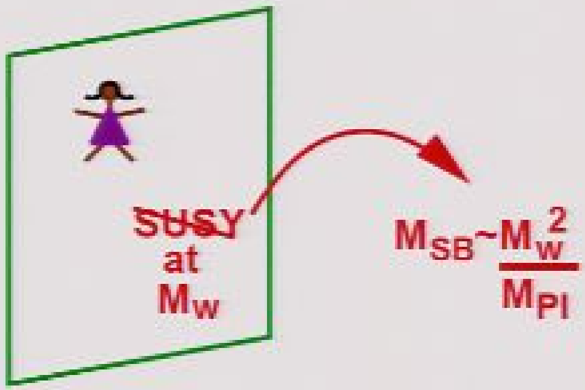
and:

$$r \sim 10\,\mu m$$

Supersymmetric Large Extra Dimensions I

Aghababaie, Burgess, S.L.P & Quevedo '02
Burgess '04

- Change gravity at the scale of Λ
- Separation of SUSY breaking scales



Supersymmetric Large Extra Dimensions II

Explain not only why the cosmological constant is zero, but why it is $(10^{-120} M_{Pl})^4$!

- Supersymmetry is badly broken on the brane:

$$T_3 \sim M_W^4$$

This localized vacuum energy is absorbed by the bulk curvature.

- Bulk susy-breaking is gravitationally suppressed:

$$M_{SB} = \frac{M_W^2}{M_{Pl}}$$

If bulk contribution to vacuum energy is $\mathcal{O}(M_{SB}^4)$ then we are there...

Overview

- 6D Supergravity and SLED
- Explicit Solutions
- Stability Issues
- Mass Gaps
- Open Questions
- Cosmology at Colliders!
- Conclusions

6D Supergravity

6D chiral gauged supergravity in the bulk:

$$S_{bulk} = \int d^6X\sqrt{-g}\Big[\frac{1}{4}R - \frac{1}{4}\partial_M\sigma\,\partial^M\sigma - \frac{1}{4}G_{\alpha\beta}(\Phi)D_M\Phi^\alpha D^M\Phi^\beta$$
$$- \frac{e^{-2\sigma}}{12}G_{MNP}\,G^{MNP}\frac{e^{-\sigma}}{4}F^I_{MN}\,F^{I\,MN} - 2g_1^2\,v(\Phi)\,e^\sigma$$
$$+ \text{ fermions}\Big]$$

Nishino & Sezgin '84

Points to note:

- Gauged R-symmetry $\Rightarrow$ positive-definite scalar potential, with minimum at $\Phi = 0$ where $v(0) = 1$.
- Chiral fermions $\Rightarrow$ in general anomolous.

Anomaly Cancellation

For special gauge groups and hyperino reps ($n_H - n_V + 244$) the anomalies cancel via a Green-Schwarz mechanism:

Gauge Group	Hyperino Rep
$E_7 \times E_6 \times U(1)_R$	$(\mathbf{912}, \mathbf{1})_0$
$E_7 \times G_2 \times U(1)_R$	$(\mathbf{56}, \mathbf{14})_0$
$F_4 \times Sp(9) \times U(1)_R$	$(\mathbf{52}, \mathbf{18})_0$
$E_6 \times Sp(1)_R$	$325\,(\mathbf{1}, \mathbf{1})$
$SU(2) \times U(1)_R$, $SU(2) \times U(1)_{R+}$, $U(1) \times Sp(1)_{R+}$, $SU(2) \times Sp(1)_{R+}$, $Sp(1)_{R+}$, $SU(3) \times U(1)_R$	*many anomaly cancelling reps*
many models with drone U(1)'s e.g. $E_7 \times U(1)^{22} \times U(1)_R$	$2\,(\mathbf{133})_0 + 2\,(\mathbf{56})_0$

Randjbar-Daemi, Salam, Sezgin & Strathdee '85
Avramis, Kehagias & Randjbar-Daemi '05
Avramis & Kehagias '05
Suzuki & Tachikawa '05

The Brane

Solve Einstein's equation in the presence of 3-brane source:

$$S_{brane} = -T_3 e^{\lambda\,\sigma} \int d^4 y \sqrt{-\det\left(g_{MN} \partial_\alpha Y^M \partial_\beta Y^N\right)}$$

where we take dilaton coupling $\lambda = 0$.

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$\Rightarrow$

$$R_2 = R_2^{smth} + 2\sum_i T_3^i \frac{\delta^{(2)}(y - y_i)}{\sqrt{g_2}}$$

4D Effective Vacuum Energy

Classical

Integrate out fields using their EOMs:

$$\begin{aligned}\rho_{eff} &= \int_{\mathcal{M}_2} d^2y\sqrt{g_2}\left[\frac{1}{2}R_2 + \ldots\right] + \sum_i T_3^i \\ &= \ldots \\ &= 0\end{aligned}$$

Cancellations do not depend on details of the solutions nor on the tensions!

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Cancellations do not depend on details of the solutions nor on the tensions!

Do depend on:

- classical scaling symmetry (*á la Weinberg*)
- choice for brane-bulk couplings ($\lambda = 0$)

4D Effective Vacuum Energy II

Quantum

Casimir energy from integrating out bulk loops with SUSY down to $1/r$:

Burgess & Hoover '05
Ghilencea, Hoover, Burgess & Quevedo '05

$$V(r) = c_2 \frac{M_6^2}{r^2} + \frac{c_3}{r^4} \left[\text{Log}\left(M_6^2 r^2\right) + c\right]$$

If SUSY cancellations are such that $c_2 = 0$ then vacuum energy is of correct order to explain Λ!

$\rightarrow$ Time-dependent dark energy with a Albrecht-Skordis dynamical potential

Explicit Solutions

A general class of solutions with:

Gibbons, Guven & Pope '03

Aghababaie, Burgess, Cline, Firouzjahi, S.L.P., Quevedo, Tasinato & Zavala '03

1. Maximal symmetry in 4D
2. Axial symmetry in 2D
3. At most conical defects

$$ds^2 = e^{A(r)}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu + dr^2 + e^{B(r)}\,d\varphi^2$$

$$A = A_\varphi(r)\,Q\,d\varphi\,, \qquad \sigma = \sigma(r)$$

$$G_{MNP} = 0\,, \qquad \Phi^\alpha = 0$$

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\end{aligned}
$$

Solution has conical defects at $r = 0$ and $r = \bar{r}$ with deficit angles:

$$\delta = 2\pi\left(1 - \frac{1}{\omega}\right) \qquad \text{and} \qquad \bar{\delta} = 2\pi\left(1 - \frac{1}{\bar{\omega}}\right)$$

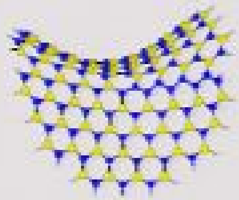
where $\omega, \bar{\omega} > 0$ are integration constants.

Negative Tension Branes

Negative deficit angles are also possible:

Like nanocones with negative disclination angles in condensed matter physics:

Azevedo, Mazzoni, Chacham & Nunes '03



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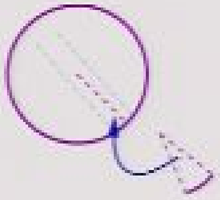

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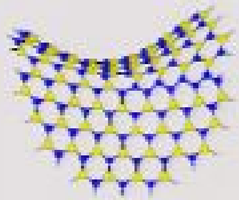
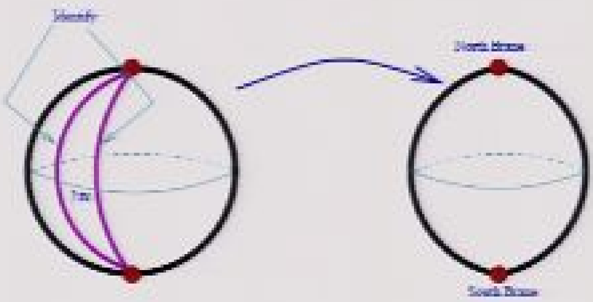


Explorations in SLED – p.13/25

Sphere Limit

As $\omega \to \tilde{\omega}$ the warp factor goes to one $\Rightarrow$ **unwarped rugby ball.**

Carroll & Guica '02
Navarro '02
Aghababaie, Burgess, S.L.P & Quevedo '02



As both $\omega \to 1$ and $\tilde{\omega} \to 1$ the deficit angles go to zero $\Rightarrow$ **classic sphere-monopole compactification.** Supersymmetric for monopole in $U(1)_R$.

Randjbar-Daemi, Salam & Strathdee '83
Salam & Sezgin '84

Topological Constraints

Dirac quantization condition:

$$e^i \frac{g_{bk}}{g_1} \frac{1}{(\omega\bar{\omega})^{1/2}} = N^i$$

where e^i are the charges of fields under the monopole background.

Relates tensions and bulk gauge couplings via a topological quantity.

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- For monopole embeddings in $U(1)_R$ at least one of the branes must be negative. Burgess, Quevedo, Tasinato & Zavala '04
- Can we describe arbitrary brane tensions with a conical-GGP solution? Aghababaie, Burgess, SLP & Quevedo '02

Stability: Scalar Fluctuations

Before gauge fixing:

(I) Minimal model: $\left\{\delta G^{\nu}_{\mu}, \delta G_{\rho\rho}, \delta G_{\varphi\varphi}, \delta G_{\rho\varphi}, \delta\sigma, \delta\zeta, \delta B_{\rho\varphi}, \delta A_{\rho}Q, \delta A_{\varphi}Q\right\}$
(II) Anomaly cancelling matter multiplets: $\left\{\delta A_{\rho}T^{I}, \delta A_{\varphi}T^{I}, \delta\Phi\right\}$
(III) Brane bending modes: $\left\{\delta Y^{M}\right\}$

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Project out (III) with orbifolding.

(I) gives rise to:

- massless mode due to spontaneously broken global classical scaling symmetry.
- massless mode due to unbroken Kalb-Ramond gauge symmetry
- Kaluza-Klein towers of heavy modes with $M^2 > 0$

Burgess, de Rham, Hoover, Mason & Tolley '06
S.L.P, Randjbar-Daemi & Salvio soon

Stability: Mass Spectrum

We know from the classic sphere-monopole compactification that embedding the monopole in a Yang-Mills sector generically leads to instabilities.

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Scalar fluctuations of gauge fields orthogonal to monopole bkgd:

$$\mathcal{A}^I = \langle \mathcal{A}^I \rangle + V^I$$

Kaluza-Klein expansion:

$$V_j(X) = \sum_{n=0}^{\infty} \sum_{m=-\infty}^{\infty} V_{jmn}(x) f_n(r) e^{im\varphi}$$

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Linearized dynamics leads to Mass Spectrum:

S.L.P. Randjbar-Daemi & Salvio soon

$$M^2 = \frac{4}{r_0^2}\left[l(l+1) - \left(\frac{P}{2}\right)^2\right]$$

with $P = m\omega - (m - N)\tilde{\omega}$ and $l = k(m, \omega, \tilde{\omega}) + |1 \pm P/2| + n$

Stability: Mass Spectrum II

S.L.P. Randjbar-Daemi & Salvio soon

- For $m \leq -1/\omega$ and $m \leq N + 1/\bar{\omega}$

$$M^2 = \frac{4}{r_0^2}\left\{n(n+1) - \left(n+\frac{1}{2}\right)[m\omega + (m-N)\bar{\omega}] + m(m-N)\omega\bar{\omega}\right\}.$$

- For $-1/\omega < m \leq N + 1/\bar{\omega}$

$$M^2 = \frac{4}{r_0^2}\left\{\left(n+\frac{3}{2}\right)^2 - \frac{1}{4} + \left(n+\frac{3}{2}\right)[m\omega - (m-N)\bar{\omega}]\right\}$$

- For $N + 1/\bar{\omega} < m \leq -1/\omega$

$$M^2 = \frac{4}{r_0^2}\left\{n(n-1) - \left(n-\frac{1}{2}\right)[m\omega - (m-N)\bar{\omega}]\right\}$$

- For $m > -1/\omega$ and $m > N + 1/\omega$

$$M^2 = \frac{4}{r_0^2}\left\{n(n+1) + \left(n+\frac{1}{2}\right)[m\omega + (m-N)\bar{\omega}] + m(m-N)\omega\bar{\omega}\right\}.$$

for $n = 0, 1, 2, \ldots$

Stability Conditions

For stability we require $M^2 > 0$

Exact and complete mass spectrum $\Rightarrow$

- stability if:

  $$|N^I| \leq 1$$

  warping and brane defects do not introduce new instabilities
- with positive tension branes only, stability *iff*: $|N^I| \leq 1$

Therefore:

- if we embed the monopole in an Abelian factor, then the compactification is stable.
- if we embed the monopole in a non-Abelian factor, then it is generically unstable.

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Dirac quantization condition:

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Stable Models with Positive Tension Branes

For example, consider the anomaly free models

Recall positive tension branes forbid the $U(1)_R$ monopole embedding

Then the only stable models are:

- $E_7 \times E_6 \times U(1)_R$ with monopole lying in E_6
- $SU(2) \times U(1)_R$ and $7(\mathbf{3}) + 2(\mathbf{5}) + 31(\mathbf{7})$
- Any of the drone $U(1)$ models

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Gauge Group	Hyperino Rep
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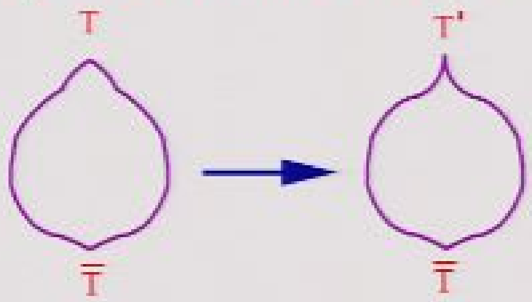
With monopole in drone $U(1)$ there is no Dirac Quantization

→ simple explicit realization of self-tuning?



Negative Tensions and Stability

Negative tensions can relax the stability constraint!

For example:

- For $T < 0$ and $\overline{T} = 0$ stability *iff*:

$$|N^I| \leq 1 + \frac{1}{3\omega}$$

- For $T - \overline{T} < 0$ stability if:

$$|N^I| \leq \frac{4}{3\omega}$$

For example:

A rugby ball with deficit angle $\delta < -\pi$ stabilizes models with $|N^I| < 2$.

Mass Gaps

S.L.P. Randjbar-Daemi & Salvio '06

Conical defects give rise to non-conventional behaviour for mass gaps:

Volume of internal manifold:

$$V_2 = 4\pi \frac{1}{\bar{\omega}} \left(\frac{r_0}{2}\right)^2$$

Take volume $\rightarrow \infty$ by taking $\bar{\omega} \rightarrow 0$ and mass gap remains finite!

Same behaviour observed for:

- vector fluctuations descending from the gauge fields
- gaugino and hyperino fluctuations.

Standard Model could arise from the bulk in large extra dimensions.

Open Questions

Classical dynamics: Tolley, Burgess, de Rham & Hoover '06

- 6D Landscape and initial conditions:
  - (singular) static solutions with 4D Poincaré, de Sitter or Anti de Sitter slicings
  - (singular and conical) time-dependent solutions with scaling behaviour
- Are there flat solutions for arbitrary brane tensions?
- Scaling solutions: fast-rolling attractors to marginal or unstable directions?

Quantum dynamics: Burgess '04

- Are the choices required for 4D flat cosmologies stable against renormalization?
- Do bulk contributions to the vacuum enery cancel down to M_{SB}^4?

Cosmology at Colliders!

Dynamical Dark Energy *and*:

Burgess '04
Burgess, Matias & Quevedo '04

- Deviations from inverse square law for gravity at $r/2\pi \sim 1\,\mu m$
- A particular scalar-tensor theory of gravity at large distances
- Potential atrophysical signals (and bounds) due to energy loss into extra dimensions by stars and supernovae.
- Distinctive missing energy signals at the LHC due to emission of particles into the extra dimensions

Predictions at the bounds of experiments in gravity, cosmology, astrophysics and accelerators!

Conclusions

- Supersymmetric Large Extra Dimensions may provide a technically natural solution to the cosmological constant problem:
  - change gravity at the scale of Λ
  - SUSY helps in non-conventional way
- 6D supergravity provides a laboratory in which to explore these ideas and codimension two branes in general
- Self-tuning solutions are stable only in a few special models: drone $U(1)'$s...
- Explicit calculations reveal surprising dynamics for 6D brane worlds:
  - negative tension branes can relax stability constraints
  - conical defects allow a large mass gap for large volume compactifications
- Several open questions...
- Many and diverse predictions within reach of upcoming experiments

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$E_6 \times Sp(1)_R$	$325\,(\mathbf{1}, \mathbf{1})$
$SU(2) \times U(1)_R$, $SU(2) \times U(1)_{R+}$, $U(1) \times Sp(1)_{R+}$, $SU(2) \times Sp(1)_{R+}$, $Sp(1)_{R+}$, $SU(3) \times U(1)_R$	*many anomaly cancelling reps*
many models with drone U(1)'s e.g. $E_7 \times U(1)^{22} \times U(1)_R$	$2\,(\mathbf{133})_0 + 2\,(\mathbf{56})_0$

Randjbar-Daemi, Salam, Sezgin & Strathdee '85
Avramis, Kehagias & Randjbar-Daemi '05
Avramis & Kehagias '05
Suzuki & Tachikawa '05