Title: Explorations in Supersymmetric Large Extra Dimensions

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Abstract: Brane worlds may provide insight into the cosmological constant problem because a large vacuum energy on the brane can curve the extra dimensions rather than the local 4D spacetime. Moreover, such models with supersymmetric large extra dimensions reveal a tantalizing numerology, in which the size of the two extra dimensions can lead not only to the electroweak hierarchy but also to the observed dark energy scale. I will review this proposal, its promises and problems, and then describe some of the novel physics that can arise in 6D brane worlds. The dynamical stability of models in 6D supergravity constrains the matter content of the theory, but surprisingly this can be relaxed with negative tension branes. Meanwhile, the Kaluza-Klein mass gap can remain finite even in the infinite volume limit.

Explorations in Supersymmetric Large Extra Dimensions

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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 '05
Kachru, Schulz & Silverstein '05

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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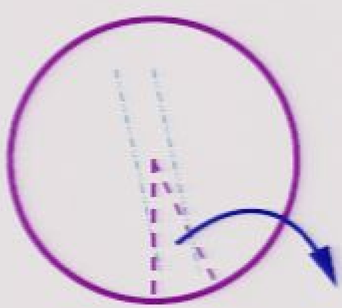


Tantalizing Numerology

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:

$$M_W \sim 10\,TeV$$

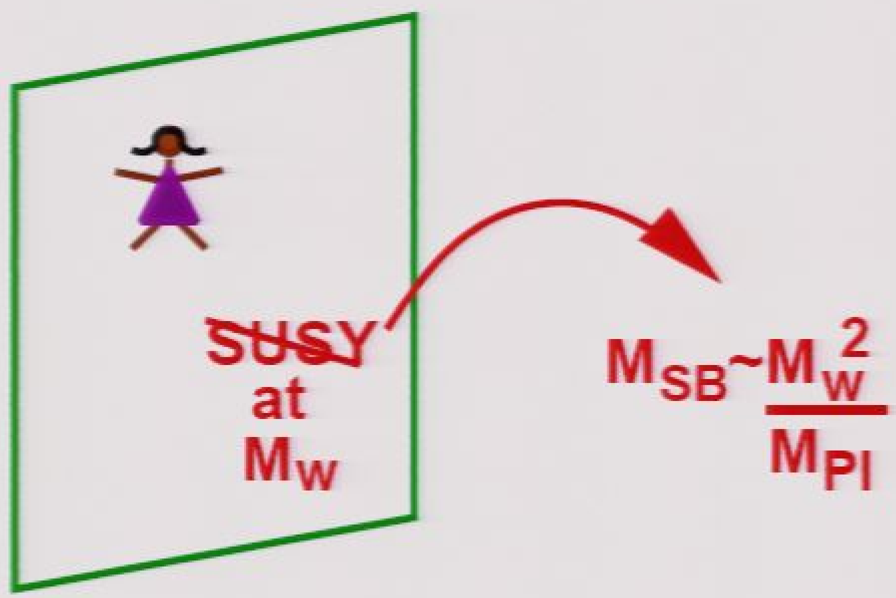
and:

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

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:

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

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 & Stradthdee '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:

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

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:

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

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

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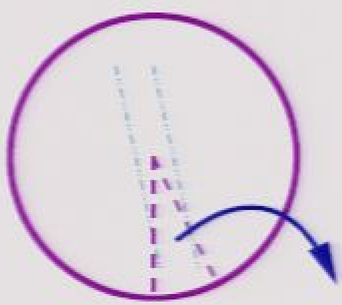

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&= \ldots \\
&= 0
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Cancellations do not depend on details of the solutions nor on the tensions!

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

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

$$\mathcal{A} = \mathcal{A}_\varphi(r)\,Q\,d\varphi\,, \qquad \sigma = \sigma(r)$$

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

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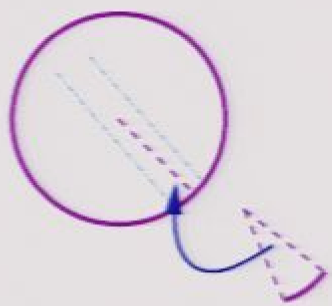
Solution has conical defects at $r = 0$ and $r = \bar{r}$ with deficit angles:

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

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

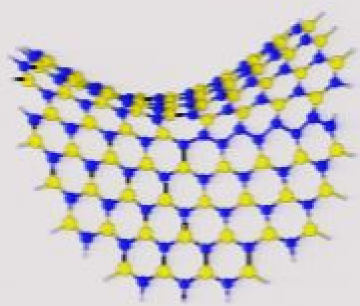
Negative Tension Branes

Negative deficit angles are also possible:



Like nanocones with negative disclination angles in condensed matter physics:

Azevedo, Mazzoni, Chacham & Nunes '04



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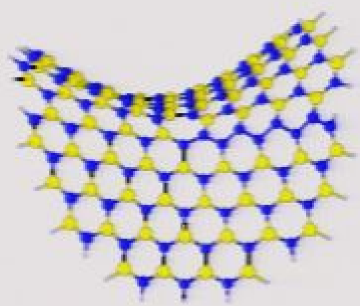
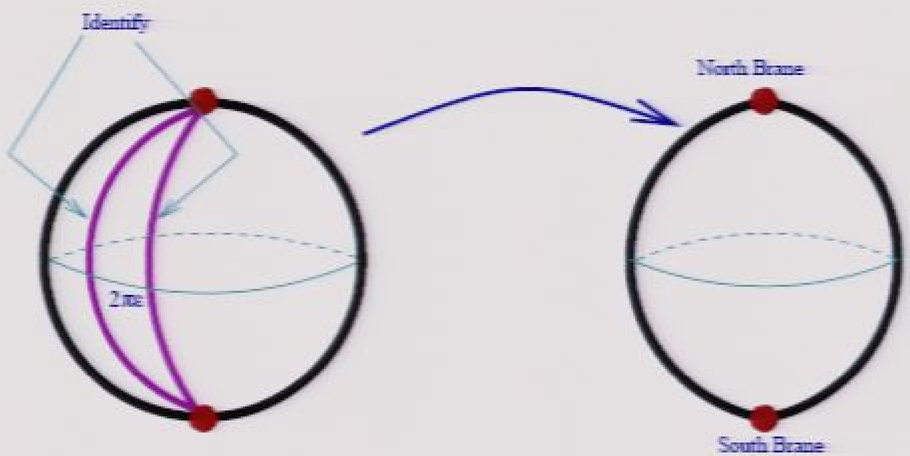


Sphere Limit

As $\omega \to \bar{\omega}$ 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 $\bar{\omega} \to 1$ 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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  Burgess, Quevedo, Tasinato & Zavala '04
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Stability: Scalar Fluctuations

Before gauge fixing:

(I) Minimal model: $\{\delta G^\mu_\mu, \delta G_{\rho\rho}, \delta G_{\varphi\varphi}, \delta G_{\rho\varphi}, \delta\sigma, \delta\zeta, \delta B_{\rho\varphi}, \delta\mathcal{A}_\rho Q, \delta\mathcal{A}_\varphi Q\}$

(II) Anomaly cancelling matter multiplets: $\{\delta A_\rho T^I, \delta A_\varphi T^I, \delta\Phi\}$

(III) Brane bending modes: $\{\delta Y^M\}$

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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:

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

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

Stability: Mass Spectrum II

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

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

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

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

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

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

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

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

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

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

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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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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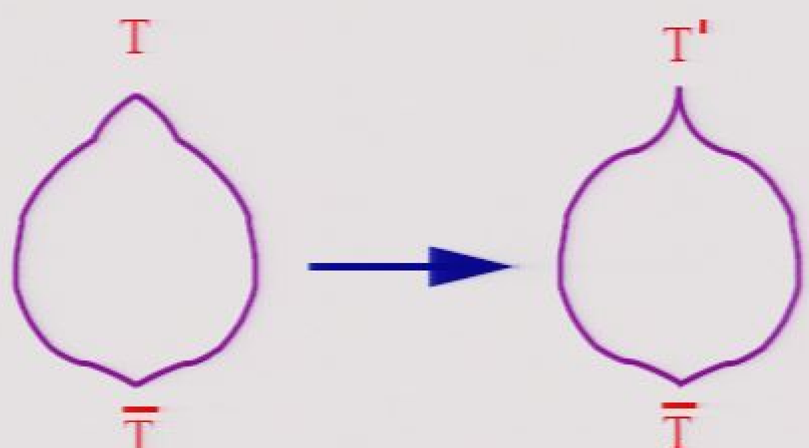
With monopole in drone $U(1)$ there is no Dirac Quantization

$\rightarrow$ 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 $\delta \leq -\pi$ stabilizes models with $|N^I| \leq 2$.

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 $\to \infty$ by taking $\bar{\omega} \to 0$ 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 Rahm & 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

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

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

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

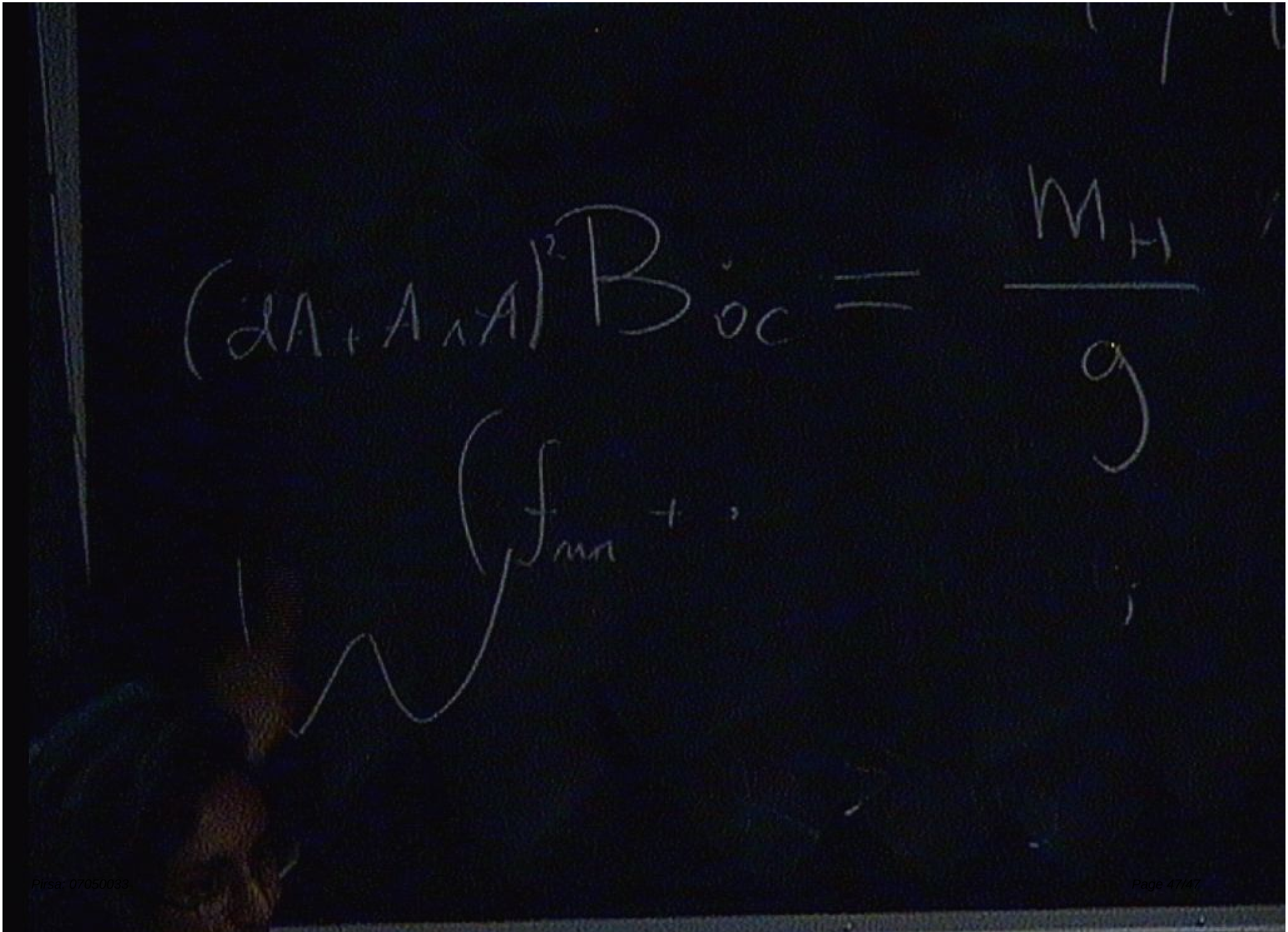
$\Rightarrow$ Time-dependent dark energy with a Albrecht-Skordis dynamical potential

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 & Stradthdee '85
Avramis, Kehagias & Randjbar-Daemi '05
Avramis & Kehagias '05
Suzuki & Tachikawa '05


(dA + A∧A)² B oc = mH / g
fmn +