Extra Dimensions, the LHC & the Cosmological Constant Problem

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Why extra dimensions must be large *and supersymmetric*

w Leo van Nierop

idea: hep-th/0304256, hep-ph/0404135

mechanism: 1012.2638; 1101.0152; 1108.0345

some implications: 1103.4556; 1108.2553

The message:

- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)

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- These dimensions must be supersymmetric (but need *NOT* require the MSSM)

"…when you have eliminated the impossible, whatever remains, however improbable, must be the truth."

A. Conan Doyle

The message:

- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)
- These dimensions must be supersymmetric (but need *NOT* require the MSSM)
- *More generally: back-reaction for higher codimension objects is a very promising, but largely unexplored area*

Outline

- Hierarchy problems in nature
  - Cosmological constant: the dog that didn't bark

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  - Cosmological constant: the dog that didn’t bark
- How extra dimensions can help
  - Why they must be big and supersymmetric
  - An explicit realization

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- Hierarchy problems in nature
  - Cosmological constant: the dog that didn’t bark
- How extra dimensions can help
  - Why they must be big and supersymmetric
  - An explicit realization
- Opportunities and concerns

Hierarchy problems

Hierarchy problems

- Th
- Th

- Ideas for what lies beyond the Standard Model are largely driven by 'technical naturalness'.
  - Motivated by belief SM is an effective field theory.

$$L_{SM} = m^2{}_0 H^* H + dimensionless$$

$$m^2 = m^2{}_0 + higher\ order \sim (126\ GeV)^2$$

Hierarchy problems

- Th
- Th

- But the SM has another unnatural parameter
  - Even more unnatural than the EW hierarchy.

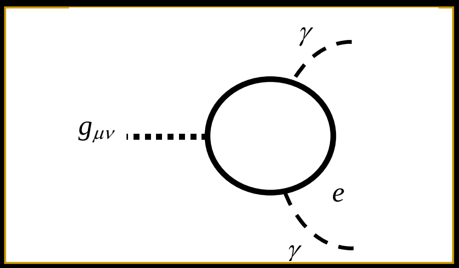
$$L_{SM} = \mu^2{}_0 + m^2{}_0\, H^* H + dimensionless$$

$$\mu^2 = \mu^2{}_0 + higher\ order \sim (3 \times 10^{-3}\ eV)^4$$

Hierarchy problems

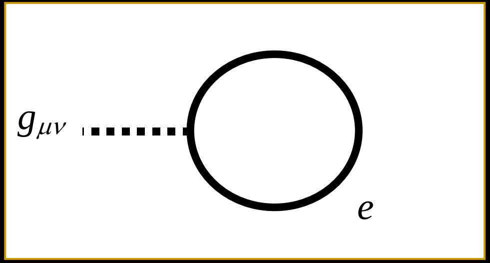
- But the SM has another unnatural parameter

Why this?



How do you change properties of *low-energy* particles (like the electron) so that their zero-point energy does not gravitate, *even though quantum effects do gravitate in atoms!*

But not this?



Must change only gravity and not any of their other well-tested properties.

Hierarchy problems

- Th

- Th

- But the SM has another unnatural parameter

- Where does absence of a technically natural cc take us as a field?
  - Abandon naturalness as a criterion (and along with it motivations for supersymmetry, technicolour, etc…)?

Extra dimensions can help

Helpful extra dimensions

- General arguments
- An explicit realization

Helpful extra dimensions

- General arguments

- An explicit realization

Helpful extra dimensions

- Ge
- An

- The Problem:
  - Einstein's equations make a lorentz-invariant vacuum energy *(which is generically large)* an obstruction to a close-to-flat spacetime *(which we see around us)*

$$T_{\mu\nu} = \lambda \, g_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

Helpful extra dimensions

Arkani-Hamed et al
Kachru et al
Carroll & Guica
Aghababaie et al

- Ge
- Ar

- The Problem:
  - Einstein's equations make a lorentz-invariant vacuum ene
    a cl

But this need not be true if there are more than 4 dimensions!!

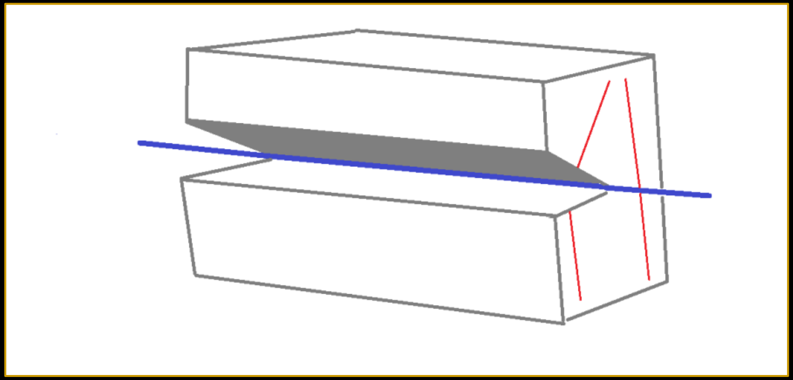
$$T_{\mu\nu} = \lambda\, g_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Helpful extra dimensions

Vilenkin et al

- Ge
- Why not?
  - Need not be lorentz invariant in the extra dimensions
  - Vacuum energy might curve extra dimensions, rather than the ones we *see (eg gravity field of a cosmic string)*



- Ar

Helpful extra dimensions

Carroll & Guica
Aghababaie et al

- Ge
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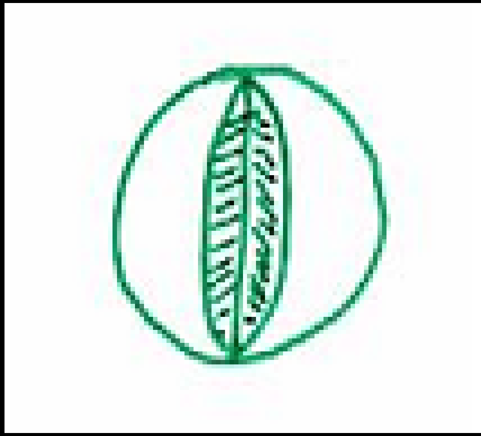
- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball and related solutions*



Helpful extra dimensions

Rubakov & Shaposhnikov
Polchinski

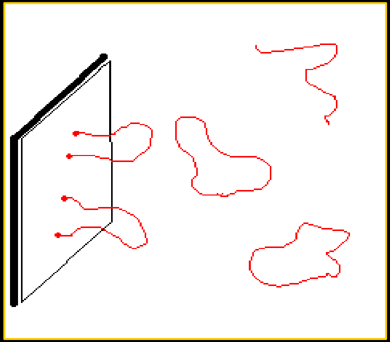
nalog:

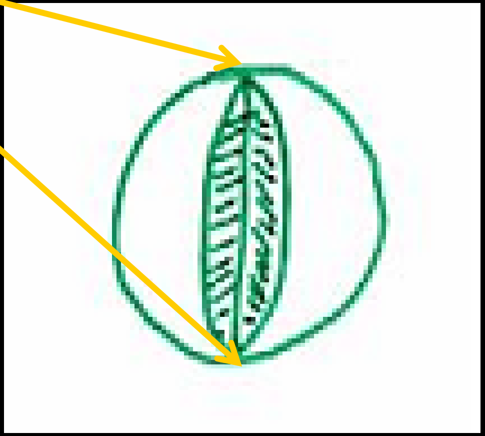
ples also with a 4D brane in

g. the rugby ball and related

Particles can be localized on surfaces (branes, or defects) within the extra dimensions

Gravity is not similarly localized

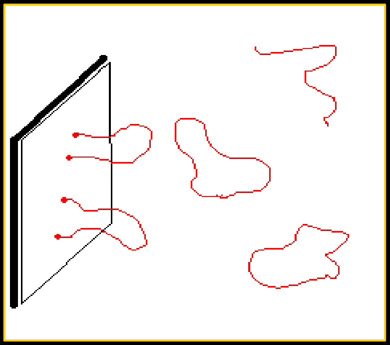




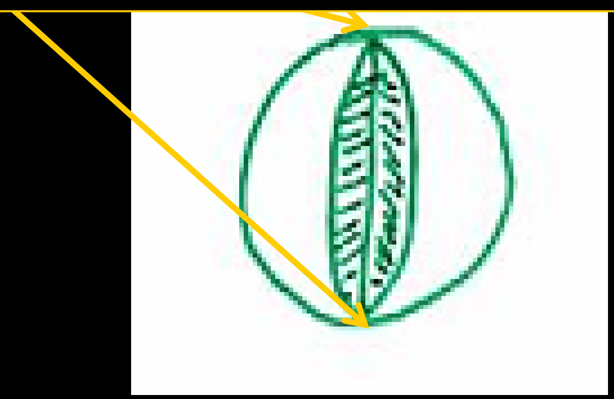
Helpful extra dimensions

- Particles can be localized on surfaces (branes, or defects) within the extra dimensions

  Gravity is not similarly localized



Notice: *this framework manages to modify how things gravitate without strongly modifying other interactions*



Helpful extra dimensions

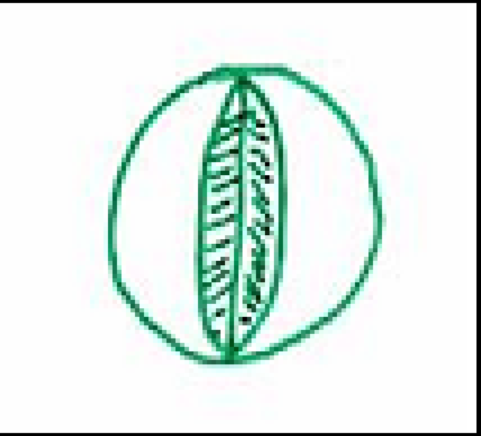
Chen, Luty & Ponton

- Ge
- A

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball and related solutions*

$$R = -2\kappa^2 \sum T_i \;\; \delta^2(x_i)$$

$$\text{4D cc} = \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, R$$
$$= 0 \;\; \text{for all } T_i$$



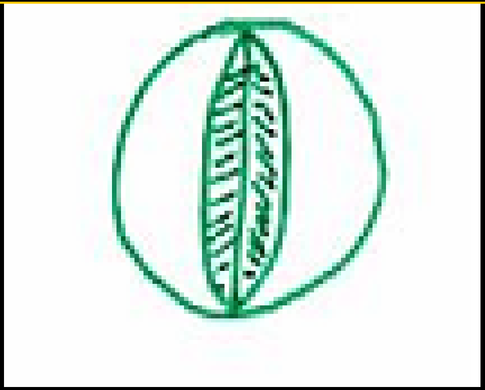
Helpful extra dimensions

Adelberger et al

- Ge
- Ar

- A higher-dimensional a
  - Similar *(classical)* exam
    two extra dimensions: *e.*
- *Requires:*
  - *Radius as large as microns*

Remarkably: *this is possible* if *they are smaller than 45 μm* and *particles stuck on branes*



Helpful extra dimensions

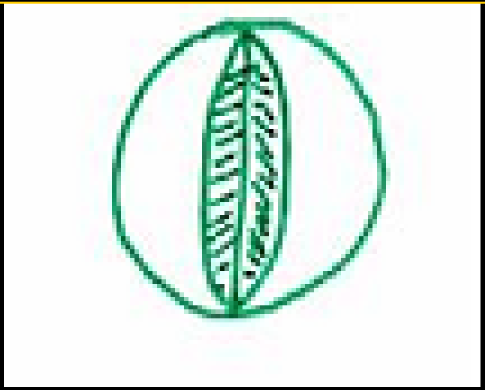
Arkani-Hamed et al

- Ge
- Ar

- A higher-dimensional a
  - Similar *(classical)* exam
    two extra dimensions: *e.*

- *Requires:*
  - *Radius as large as microns*
  - *At most two dimensions*

Remarkably: *consistent with EW hierarchy if precisely two dimensions this large since $M_p = M_g^2 r$*



Helpful extra dimensions

Golberger & Wise
CB, de Rham,
van Nierop, Tasinato

- Ge
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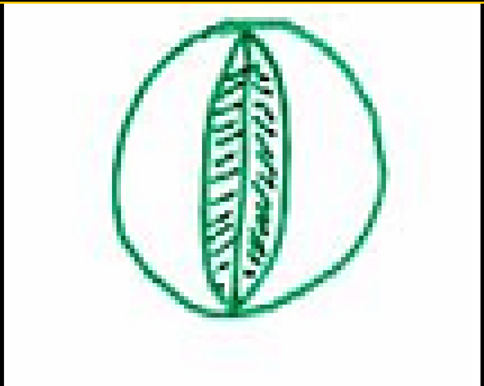
- A higher-dimensional a
  - Similar *(classical)* exam
    two extra dimensions: *e.*
- *Requires:*
  - *Radius as large as microns*
  - *At most two dimensions*
  - *Back-reaction of the branes*

Otherwise bulk cannot respond to branes. *Technical difficulty: bulk fields diverge at brane positions*



Helpful extra dimensions

Aghababaie et al

- Ge
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- A higher-dimensional a
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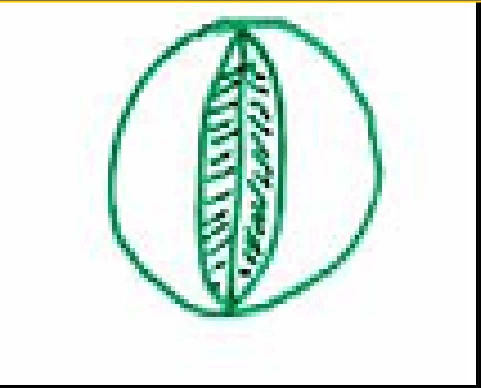
    two extra dimensions: *e.*
- *Requires:*
  - *Radius as large as microns*
  - *At most two dimensions*
  - *Back-reaction of the branes*
  - *Supersymmetry in extra dims*

For several reasons, including forbidding a cosmological constant in higher dimensions



Helpful extra dimensions

- General arguments

- An explicit realization

Helpful extra dimensions

- Must re-ask the cosmological constant problem:
  - Some choices for the branes make the resulting on-brane geometry flat (classically), but other known choices do not: must identify the ‘flat’ choices.
  - Once flat choices are made in UV, *do they stay made* at the quantum level as successive scales are integrated out?

- Ge
- Ar

Helpful extra dimensions

Nishino, Sezgin

- Ge
- An

- 6D Einstein-Maxwell-scalar system

$$L = \frac{1}{2\kappa^2}[R + (\partial\phi)^2] + e^{-a\phi} F_{mn}F^{mn} + V(\phi)$$

Two cases (both with flat directions):

6D sugra: choose $a = 1$ and $V = \frac{2{g_R}^2}{\kappa^2} e^{\phi}$

6D axion with ~~SUSY~~: $a = 0$ and $V = \lambda$

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dS sign

6D sugra: choose $a = 1$ and $V = \frac{2{g_R}^2}{\kappa^2} e^{\phi}$

6D axion with ~~SUSY~~: $a = 0$ and $V = \lambda$

Helpful extra dimensions

Aghababaie et al

- Ge
- Ar

- Exact classical result (for SUSY case): *if*

$$ds^2 = e^{2W}\hat{g}_{\mu\nu}\, dx^\mu dx^\nu + dr^2 + e^{2B} d\theta^2$$

then

$$\hat{R} = \frac{1}{\kappa^2}\int d^2x \ \nabla^2\phi$$

Helpful extra dimensions

Aghababaie et al
Gibbons, Guven & Pope

- Ge
- Ar

- Exact classical resu

$$ds^2 = e^{2W}\hat{g}_{\mu\nu}\, dx$$ ... 2

In particular,
$\hat{R} = 0$ *if* $n \cdot \nabla\phi = 0$
at the brane positions
(All such solutions are explicitly known)

then

$$\hat{R} = \frac{1}{\kappa^2}\int d^2x\; \nabla^2\phi$$

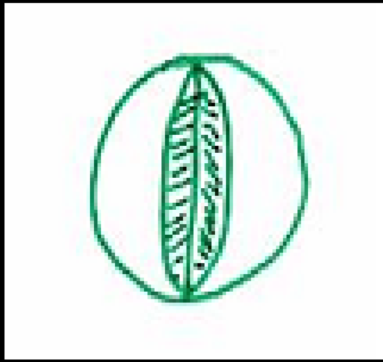
Helpful extra dimensions

Carroll & Guica
Aghababaie et al

- Simple solution

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + [dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2] e^{-a\phi_0}$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) e^{-a\phi_0} \qquad \phi = \phi_0$$



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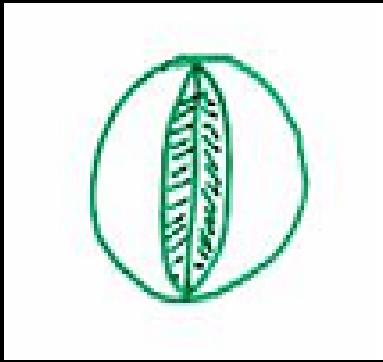

Magnetic flux required to stabilize extra dimensions against gravitational collapse

Helpful extra dimensions

Carroll & Guica
Aghababaie et al

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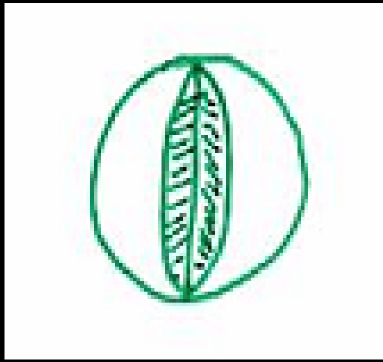

Labels flat direction *(which exists due to shift symmetry or scale invariance)*

Helpful extra dimensions

Carroll & Guica
Aghababaie et al

- Simple solution

$$ds^2 = \hat{g}_{mn} dx^m\, dx^n + [dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2] e^{-a\phi_0}$$

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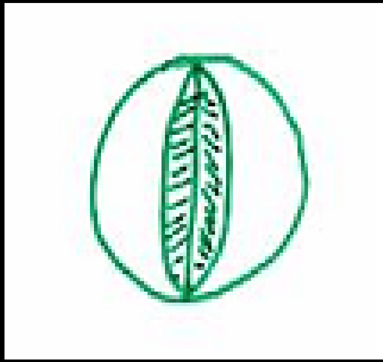


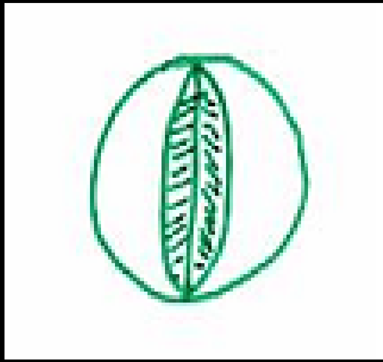
For later: notice radius is exponential in the flat direction ϕ_0 in the SUSY case

Helpful extra dimensions

- Simple solution (including back-reaction)

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + [dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2] e^{-a\phi_0}$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) e^{-a\phi_0} \qquad \phi = \phi_0$$



$$1 - \alpha = \frac{\kappa^2 T}{2\pi}$$

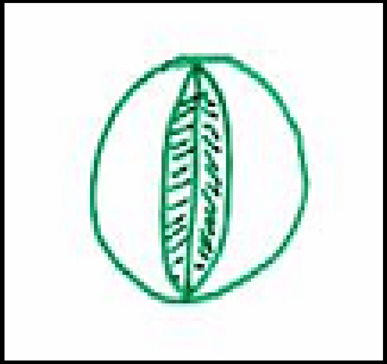
Helpful extra dimensions

Carroll & Guica

- Simple solution (non-SUSY case)

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) \qquad \phi = \phi_0$$



Field equations

$$\frac{2}{L^2} = \kappa^2\left(\frac{3Q^2}{2} + \Lambda\right)$$

$$\hat{R} = \kappa^2(Q^2 - 2\Lambda)$$

Flux quantization

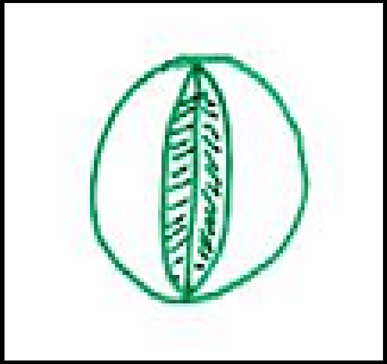
$$\frac{n}{g} = 2\alpha L^2 Q$$

Helpful extra dimensions

- Simple solution (non-SUSY case)

$$ds^2 = \hat{g}_{mn} dx^m\, dx^n + dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) \qquad \phi = \phi_0$$



$$Q = \frac{n}{2\alpha g L^2} \qquad \hat{R} = \kappa^2 (Q^2 - 2\Lambda)$$

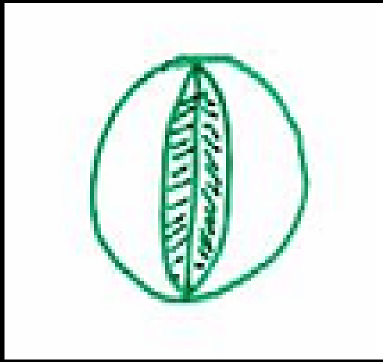
$$\frac{1}{L^2} = \frac{8\alpha^2 g^2}{3n^2\kappa^2}\left[1 \mp \sqrt{1 - \left(\frac{3n^2\kappa^4\Lambda}{8\alpha^2 g^2}\right)}\right]$$

Helpful extra dimensions

- Simple solution (non-SUSY case)

$$ds^2 = \hat{g}_{mn} dx^m \, dx^n + dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) \qquad \phi = \phi_0$$



Tune $\Lambda = \frac{Q^2}{2}$ so $\hat{R} = 0$

If $T \to T + \delta T$ then $\hat{R} \to -\frac{\kappa^2 \rho}{\pi \alpha L^2}$ where $\rho = 2\,\delta T$

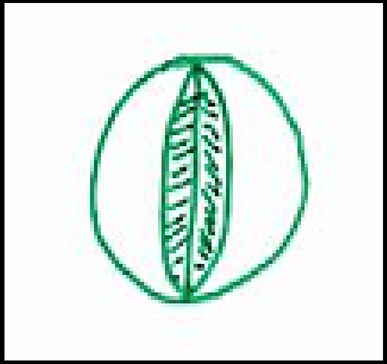
Helpful extra dimensions

Aghababaie et al

- Simple solution (SUSY case)

$$ds^2 = \hat{g}_{mn} dx^m\, dx^n + [dr^2 + \alpha^2 L^2 \sin^2\left(\frac{r}{L}\right) d\theta^2] e^{-\phi_0}$$

$$F_{r\theta} = Q\alpha L \sin\left(\frac{r}{L}\right) e^{-\phi_0} \qquad \phi = \phi_0$$



Field equations

$$\frac{2g_R^2}{\kappa^2} = \frac{\kappa^2 Q^2}{2}$$

$$\kappa^2 Q^2 L^2 = 1 \qquad \hat{R} = 0$$

Flux quantization

$$\frac{n}{g} = 2\alpha L^2 Q = \frac{\alpha}{g_R}$$

Helpful extra dimensions

Salam & Sezgin

- Simple solution

$$ds^2 = \hat{g}_{mn} dx^m d$$

$$F_{r\theta} = Q \alpha L \sin\left(\frac{r}{L}\right.$$

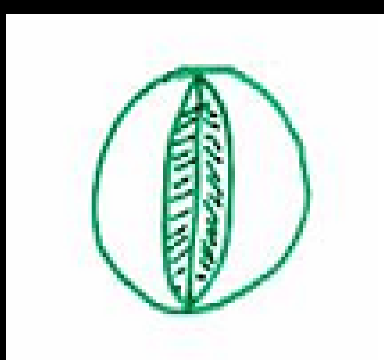
On-source geometry is always flat.

Noticed in mid-80s in special case where $n = \alpha = 1$, in which case:

$$L = \sqrt{g}\left[R + e^{-\phi} F^2 + e^{\phi}\right]$$

with $R = -1/r^2$ and $F = 1/r^2$

gives $L = r^2 e^{-\phi}\left[e^{\phi} - {}^1\!/_{r^2}\right]^2$



F

$$\frac{2 g_R^2}{\kappa^2} = \frac{\kappa^2 Q^2}{2}$$

$$\kappa^2 Q^2 L^2 = 1$$

$$\hat{R} = 0$$

$$\frac{n}{g} = 2 \alpha L^2 Q = \frac{\alpha}{g_R}$$

Helpful extra dimensions

- In SUSY case, how does system respond to changes in brane tension?

Flux quantization: $$\frac{n}{g} = 2\alpha L^2 Q = \frac{\alpha}{g_R}$$ Obstructs T to δT

Helpful extra dimensions

- In SUSY case, how does system respond to changes in brane tension?

Flux quantization: $$\frac{n}{g} = 2\alpha L^2 Q = \frac{\alpha}{g_R}$$ Obstructs T to δT

- On other hand, general argument:

$$\rho = \int dV\, L_{bulk} = -\frac{1}{2\kappa^2}\int dV\ \partial^2\phi = \oint dS\, n \cdot \partial\phi \propto \frac{\partial T}{\partial \phi}$$

Helpful extra dimensions

CB & van Nierop

- Resolution: subdominant effects in the brane action are important for flux quantization

$$\text{if } L_b = T_b(\phi) + \Phi_b(\phi)\ {}^*F + \ldots$$

$$\frac{n}{g} = \int F + \frac{1}{2\pi}\sum_b \Phi_b\, e^{\phi}$$

- New function Φ has interpretation as brane-localized flux

Helpful extra dimensions

- Energetics of perturbations: *explore the ansatz*

$$ds^2 = e^{2W}\hat{g}_{mn}dx^m\,dx^n + dr^2 + e^{2B}d\theta^2$$

$$F_{r\theta} = Qe^{B-4W} \qquad\qquad \phi = \phi(r)$$

Helpful extra dimensions

- Perturb brane properties

$$T \to T + \delta T(\phi)$$

- To evade time-dependence add current

$$\Delta L_{bulk} = J\phi \qquad \text{or} \qquad \Delta L_{bulk} = J$$

- Find general solution to linearized equations

$$\kappa^2 J L^2 \ll 1$$

Helpful extra dimensions

- Sample solutions

$$\delta W = W_0 + W_1 \cos\left(\frac{r}{L}\right)$$

$$\delta\phi = \phi_0 + \phi_1 \ln\left(\frac{1-\cos(r/L)}{\sin(r/L)}\right) - \kappa^2 J L^2 \ln\left[\sin\left(\frac{r}{L}\right)\right]$$

and so on

Helpful extra dimensions

CB, Hoover & Tasinato
Bayntun, CB, van Nierop

- Brane-bulk boundary conditions:

$$(e^B \phi')_b = \frac{\kappa^2}{2\pi}\left(\frac{\partial L_b}{\partial \phi}\right)$$

$$(e^B W')_b = \frac{\kappa^2}{4\pi}\left(\frac{\partial L_b}{\partial g_{\theta\theta}}\right) = U_b$$

$$(e^B B' - 1)_b = -\frac{\kappa^2}{2\pi}\left[\left(\frac{\partial L_b}{\partial \phi} + \frac{3}{2}\frac{\partial L_b}{\partial g_{\theta\theta}}\right)\right]$$

$$\text{Constraint:}\quad 4U_b[2 - 2L_b - 3U_b] - \left(\frac{\partial L_b}{\partial \phi}\right)^2 = 0$$

Helpful extra dimensions

- Non-SUSY result:

$$V_{eff}(\phi) = \phi \int \frac{d\phi}{\phi^2} \left[\frac{\pi \alpha L^2 \hat{R}(\phi)}{\kappa^2} \right]$$

$$\left[\frac{\partial}{\partial \phi} \sum_b \delta T_b - Q \delta \Phi_b \right]_{\phi_*} = 0$$

$$\rho = \left[\sum_b \delta T_b - 2Q \delta \Phi_b \right]_{\phi_*}$$

This is δL_b
while
this is *not*

Helpful extra dimensions

- SUSY result:

$$\left[\delta T_b - 2Q\delta\Phi_b + \frac{1}{2}\frac{\partial}{\partial\phi}\sum_b \delta T_b - Q\delta\Phi_b\right]_{\phi_*} = 0$$

ie Einstein frame potential: $V = U(\phi)e^{2\phi}$

Helpful extra dimensions

- SUSY result:

$$\left[\delta T_b - 2Q\delta\Phi_b + \frac{1}{2}\frac{\partial}{\partial\phi}\sum_b \delta T_b - Q\delta\Phi_b\right]_{\phi_*} = 0$$

$$\rho = [\delta T_b - 2Q\delta\Phi_b] = \left[-\frac{1}{2}\frac{\partial}{\partial\phi}\sum_b \delta T_b - Q\delta\Phi_b\right]_{\phi_*}$$

Helpful extra dimensions

- SUSY result:

$$\left[\delta T_b - 2Q\delta\Phi_b + \frac{1}{2}\frac{\partial}{\partial\phi}\sum_b \delta T_b - Q\delta\Phi_b\right]_{\phi_*} = 0$$

Agrees with general result given earlier

$$\rho = [\text{[illegible]}] = \left[-\frac{1}{2}\frac{\partial}{\partial\phi}\sum_b \delta T_b - Q\delta\Phi_b\right]_{\phi_*}$$

Helpful extra dimensions

- Three intriguing choices:

Case 1: scale invariant:

if δT independent of ϕ and $\delta\Phi = Ce^{-\phi}$ then $V(\phi) = Ae^{2\phi}$

Helpful extra dimensions

- Three intriguing choices:

Case 1: scale invariant:

if δT independent of ϕ and $\delta\Phi = Ce^{-\phi}$ then $V(\phi) = Ae^{2\phi}$

As required by Weinberg's no-go theorem

Helpful extra dimensions

- Three intriguing choices:

Case 1: scale invariant:

if δT independent of ϕ and $\delta\Phi = Ce^{-\phi}$ then $V(\phi) = Ae^{2\phi}$

Case 2: exponentially large volume:

$\delta T_b = A + B\,(\phi + v)^2$ with v ~ 50 then $r = Le^{-\phi/2} \gg L$

Helpful extra dimensions

- Three intriguing choices:

Case 3: parametrically small vacuum energy:

If brane action completely independent of ϕ then $\rho = 0$

and ϕ_* adjusts to satisfy flux quantization condition

$$\frac{n}{g} = \int F + \frac{1}{2\pi} \sum_b \Phi_b \, e^{\phi}$$

Helpful extra dimensions

- Ge
- Ar

- What about loops?
  - Pure brane loops have no effect on curvature because they cannot generate a dilaton coupling to the brane

Helpful extra dimensions

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- Ar

- What about loops?
  - Pure brane loops have no effect on curvature because they cannot generate a dilaton coupling to the brane
  - Each bulk loop comes with a factor of $e^{2\phi}$ (since this is the loop-counting parameter), but flux stabilization relates this to the radius by $e^{2\phi} = 1/r^4$ making the cc equal the KK scale.

Helpful extra dimensions

Short-wavelength loops in the bulk (*eg* particle of mass *M*) generate local terms in both the bulk effective action

$$L_B + \delta L_B = \left[\frac{2{g_R}^2}{\kappa^2} e^{\phi} + a_1 M^6 e^{3\phi} + \cdots\right] + \left[\frac{1}{2\kappa^2} + b_1 M^4 e^{2\phi} + \cdots\right] R + \left[c_1 M^2 e^{\phi} + \cdots\right] R^2 + \cdots$$

and source actions

$$L_b + \delta L_b = T_0 + t_1 M^4 e^{2\phi} + \cdots$$

Helpful extra dimensions

- (
- A

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and so

This generates the following potential as a function of the zero mode, $e^{\phi} = 1/r^2$

$$V(r) = A_{-1}M^6r^2 + A_0M^4 + \frac{A_1M^2}{r^2} + \frac{A_2}{r^4} + \cdots$$

with
$$A_{-1} \cong a_1 e^{3\phi} \cong \frac{a_1}{(Mr)^6},$$
$$A_0 \cong b_1 e^{2\phi} \cong \frac{b_1}{(Mr)^4},$$
$$A_1 \cong c_1 e^{\phi} \cong \frac{c_1}{(Mr)^2}$$
and so on

and so $$V(r) \cong \frac{k}{r^4} + \cdots$$

Opportunities and concerns

Opportunities & Concerns

- Observational opportunities

- Where is the catch?

Opportunities & Concerns

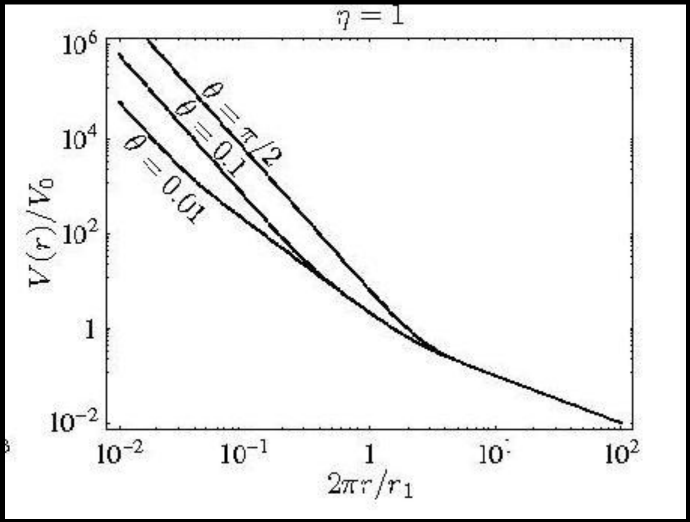
- Observational opportunities
- Where is the catch?

Opportunities & Concerns

Callin et al

- Ol
- W

- If true, many striking implications:
  - Deviations from Newton's inverse square law at distances of order 1 – 10 microns



Opportunities & Concerns

Hannestad & Raffelt
CB, Matias & Quevedo

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Opportunities & Concerns

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- If true, many striking implications:
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  - *Probably a vanilla SM Higgs*

Opportunities & Concerns

Lust et al

- Ol
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Opportunities & Concerns

Lust et al

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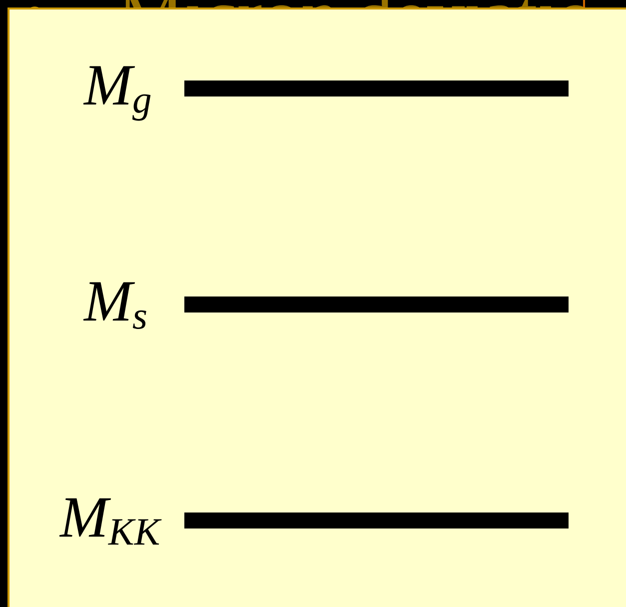

- W

- *Are there observable effects if M_g ~ 10 TeV?*
  - *Must hit new states* before $E \sim M_g$.
  - *eg: string and KK states (for 'other' 4 dimensions) have $M_{KK} < M_s < M_g$*

Opportunities & Concerns

CB, Matias & Quevedo

- Ol
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- If true, many striking implications:
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CB, Matias & Quevedo

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- W

Opportunities & Concerns

Albrecht et al

- Ol

- W

- If true, m… …nplications:
  - Micron… …inverse square law
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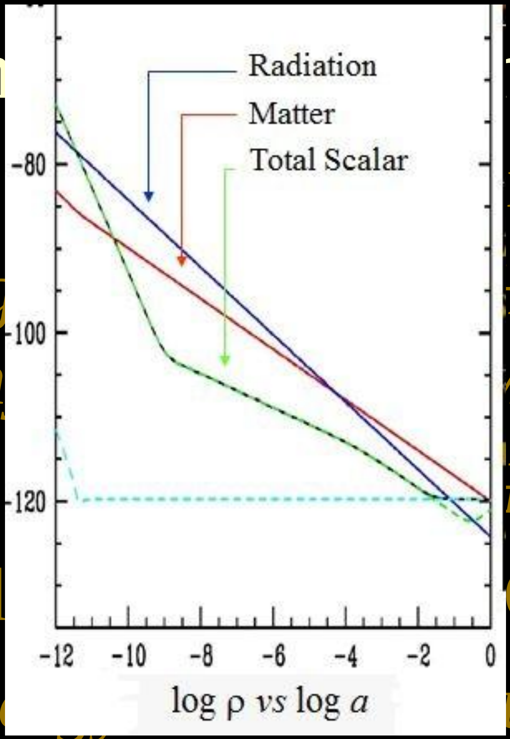
  - *Probab… …Higgs*
  - Excited… …QG) at the LHC
  - *Low ene… …ut the MSSM*
  - Very light Brans-Dicke-like scalars and quintessence cosmology



Opportunities & Concerns

CB & Matias

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- If true, many striking implications:
  - Micron deviations from inverse square law
  - *Missing energy at the LHC and in astrophysics; requires M > 10 TeV*
  - *P*

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

  - E … C
  - *Low energy SUSY without the MSSM*
  - Very light Brans-Dicke-like scalars and quintessence cosmology
  - *Sterile neutrinos from the bulk?*
- W

Opportunities & Concerns

- Observational opportunities
- Where is the catch?

Opportunities & Concerns

S Weinberg

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Opportunities & Concerns

- Ol
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- If you claim to solve the cosmological constant problem, aren't you crazy?
  - Weinberg's no-go theorem?
  - Didn't we see this all before in 5D?
  - What about Nima's argument against x dims
  - What stops proton decay?
  - How is inflation possible?
  - Long range scalars are unnatural/ruled out?
  - Don't constraints already force $(1/r)^4 > cc$?

Summary

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  - Many cool features in 1 dimension (RS models)
  - Requires renormalizing singularities at sources

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Summary

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Potentially wide-ranging observational implications for Dark Energy cosmology, the LHC and elsewhere…

"…when you have eliminated the impossible, whatever remains, however improbable, must be the truth."

A. Conan Doyle

Opportunities & Concerns

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- W

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Fin

Backup slides

The Worries

- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- *Famous No-Go Arguments*
- Problems with Cosmology
- Constraints on Light Scalars

The Worries

Nilles et al
Cline et al
Erlich et al

- 'Technical N
- Runaway Bel
- Stabilizing th
- *Famous No-*
- Problems wit
- Constraints on Light Scalars

- *Why isn't this killed by what killed 5D self-tuning?*

In 5D models, presence of one brane with nonzero positive tension T_1 implied a singularity in the bulk.

Singularity can be interpreted as presence of a second brane whose tension T_2 need be negative. This is a hidden fine tuning:

$$T_1 + T_2 = 0$$

The Worries

Nilles et al
Cline et al
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- ‘Technical N
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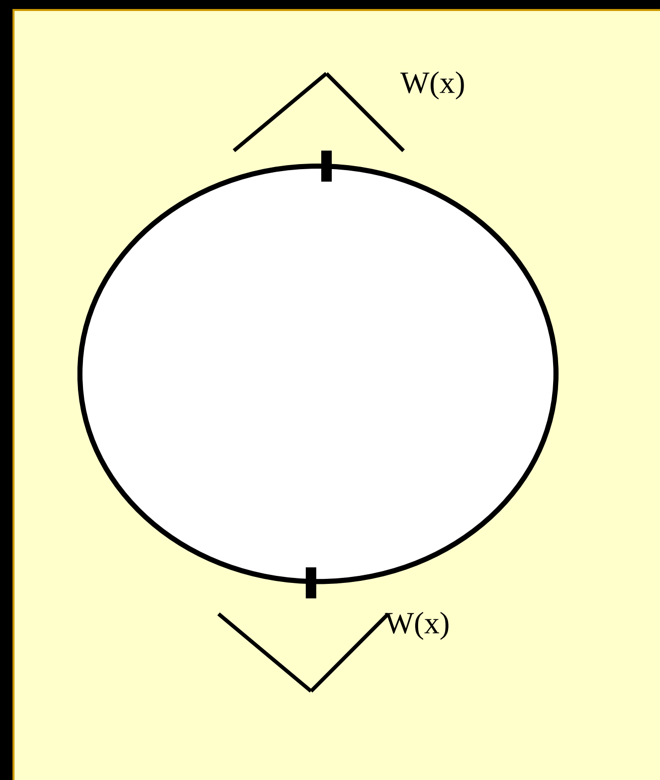

The Worries

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- *Fan*
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$$T_1 + T_2 = 0$$

- *6D analog corresponds to the Euler number topological constraint:*

$$4G\sum_b T_b + \frac{1}{4\pi}\int d^2x\sqrt{g}\,R = \chi$$

The Worries

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g:

- *6D analog corresponds to the Euler number topological constraint:*

$$4G\sum_b T_b + \frac{1}{4\pi}\int d^2x\sqrt{g}\,R = \chi$$

- *Being topological, this is preserved under renormalization. If $\Sigma\, T_b$ nonzero then R becomes nonzero*

The Worries

- ‘Technical N
- Runaway Bel
- Stabilizing th
- *Famous No-(*
- Problems wit
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- *Weinberg’s No-Go Theorem*:

Steven Weinberg has a general objection to self-tuning mechanisms for solving the cosmological constant problem that are based on scale invariance

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

The Worries

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

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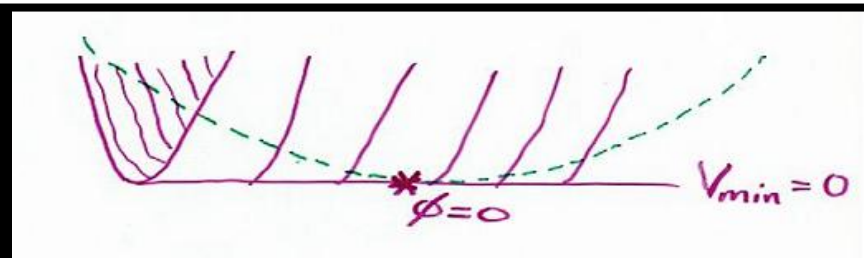

$\approx \lambda\,\phi^4$

The Worries

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- *Nima's No-Go Argument*:

One can have a vacuum energy μ^4 with μ greater than the cutoff, provided it is turned on adiabatically.

So having extra dimensions with $r \sim 1/\mu$ does not release one from having to find an intrinsically 4D mechanism.

The Worries

- ‘Technical N
- Runaway Bel
- Stabilizing th
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- *Nima's No-Go Argument*:

One can have a vacuum energy μ^4 with μ greater than the cutoff, provided it is turned on adiabatically.

- Scale invariance precludes obtaining μ greater than the cutoff in an adiabatic way:

$$V_{eff} = \mu^4 \, e^{\lambda\phi} \quad \text{implies} \quad \dot{\phi}^2 \approx \mu^4$$

The Worries

- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- Famous No-Go Arguments
- *Problems with Cosmology*
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The Worries

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- *Post BBN*:

  Since *r* controls Newton’s constant, its motion between BBN and now will cause unacceptably large changes to *G*.

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- *Post BBN*:

  Since *r* controls Newton’s constant, its motion between BBN and now will cause unacceptably large changes to *G*.

  Even if the kinetic energy associated with r were to be as large as possible at BBN, Hubble damping keeps it from rolling dangerously far between then and now.

The Worries

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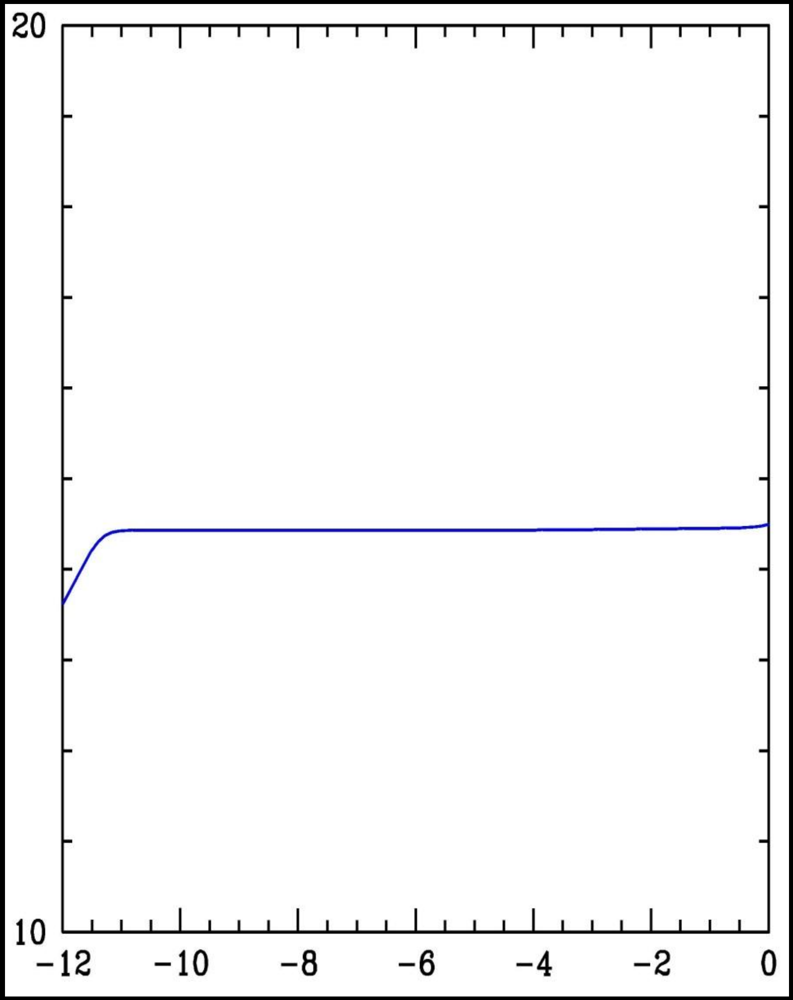

log *r vs* log *a*

The Worries

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- *Pre BBN*:

  There are strong bounds on KK modes in models with large extra dimensions from:

  * their later decays into photons;
  * their over-closing the Universe;
  * their light decay products being too abundant at BBN

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- *Pre BBN*:

There are strong bounds on KK modes in models with large extra dimensions from:

* their later decays into photons;

* their over-closing the Universe;

* their light decay products being too abundant at BBN

Photon bounds can be evaded by having invisible channels; others are model dependent, but eventually must be addressed

The Worries

- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- Famous No-Go Arguments
- Problems with Cosmology
- *Constraints on Light Scalars*

The Worries

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- *A light scalar with mass m ~ H has several generic difficulties*:

  What protects such a small mass from large quantum corrections?

The Worries

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- *A light scalar with mass m ~ H has several generic difficulties*:

What protects such a small mass from large quantum corrections?

Given a potential of the form

$$V(r) = c_0 M^4 + c_1 M^2/r^2 + c_2/r^4 + \ldots$$

then $c_0 = c_1 = 0$ *ensures* both *small mass and small dark energy.*

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Isn’t such a light scalar already ruled out by precision tests of GR in the solar system?

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- *A light scalar with mass m ~ H has several generic difficulties*:

Isn’t such a light scalar already ruled out by precision tests of GR in the solar system?

The same logarithmic corrections which enter the potential can also appear in its matter couplings, making them field dependent and so also time-dependent as ϕ rolls.

Can arrange these to be small here & now.

The Worries

- ‘Technical N
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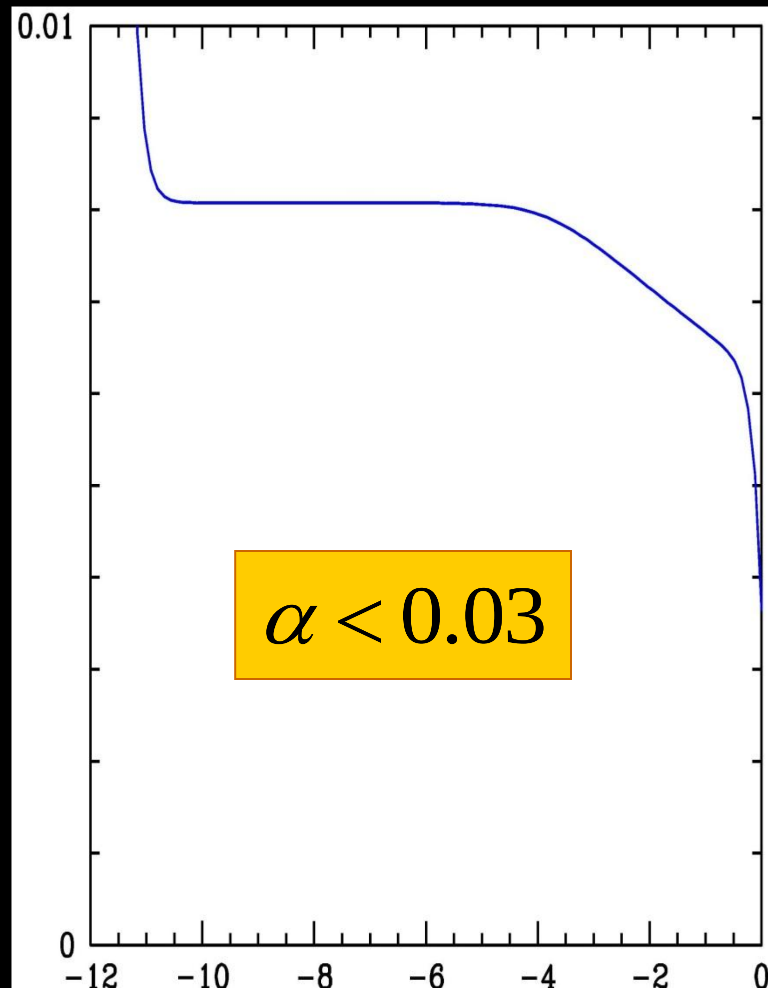

α *vs* log *a*

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Shouldn't there be strong bounds due to energy losses from red giant stars and supernovae? (Really a bound on LEDs and not on scalars.)

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Shouldn't there be strong bounds due to energy losses from red giant stars and supernovae? (Really a bound on LEDs and not on scalars.)

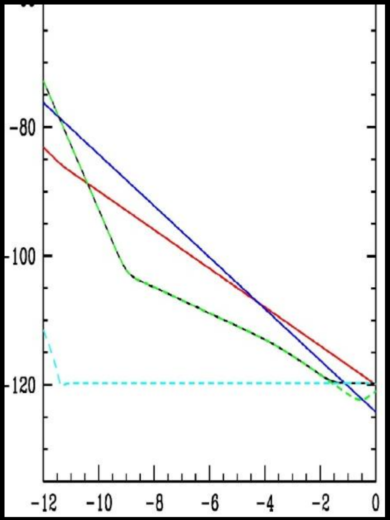
Yes, and this is how the scale M ~ 10 TeV for gravity in the extra dimensions is obtained.

Prognosis

- Theoretical worries
- *Observational tests*

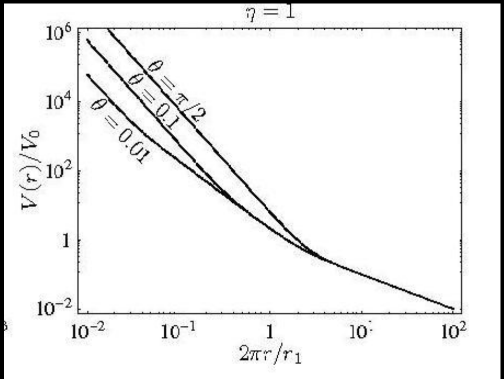
The Observational Tests

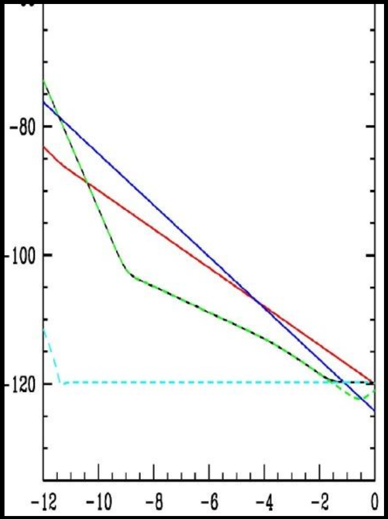
- Quintessence cosmology



The Observational Tests

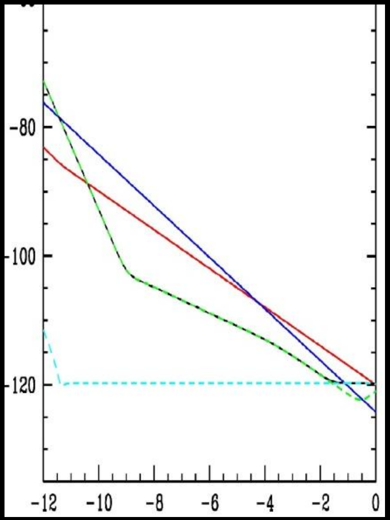
- Quintessence cosmology
- Modifications to gravity

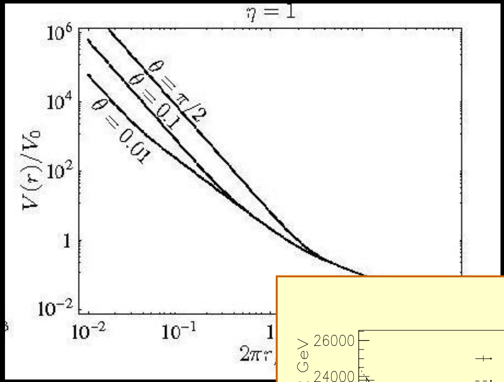


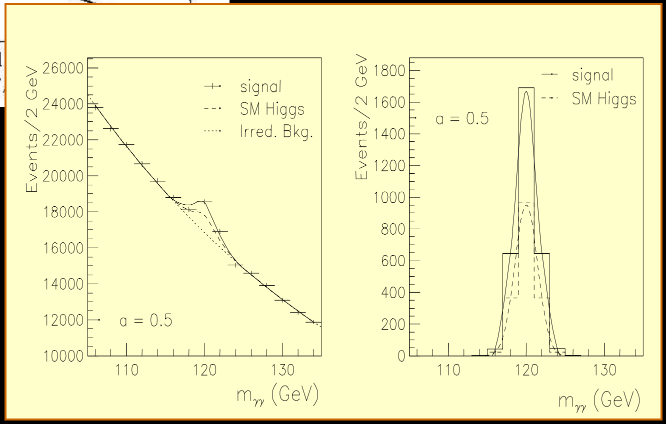


The Observational Tests

- Quintessence cosmology
- Modifications to gravity
- Collider physics



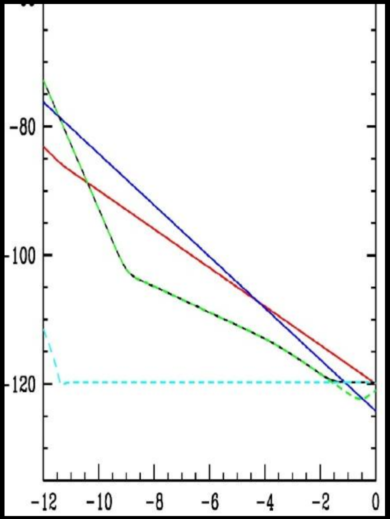


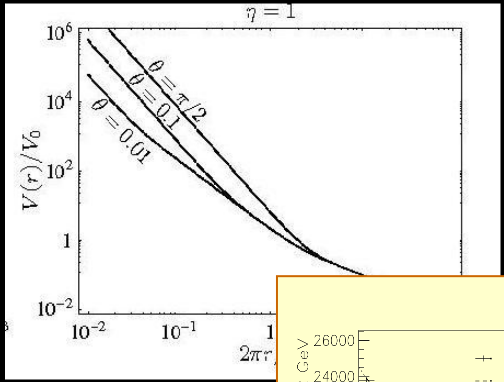


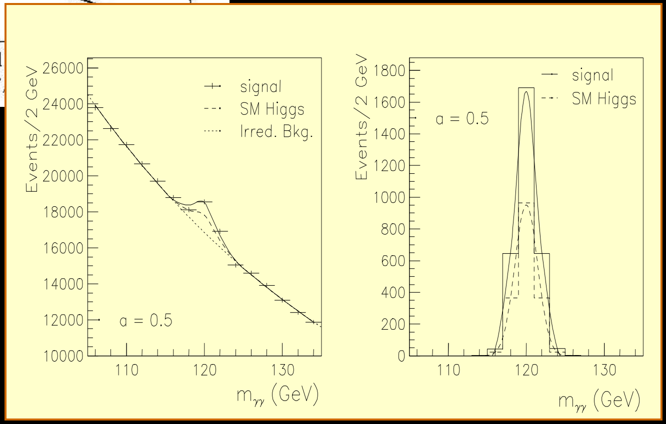
The Observational Tests

- Quintessence cosmology
- Modifications to gravity
- Collider physics

SUSY broken at the TeV scale,
but not the MSSM!

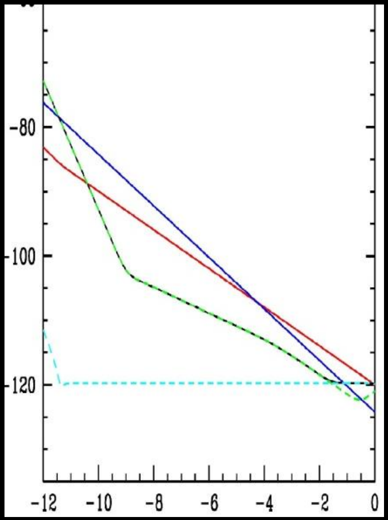


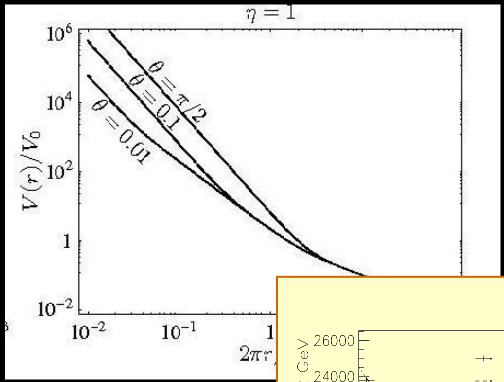


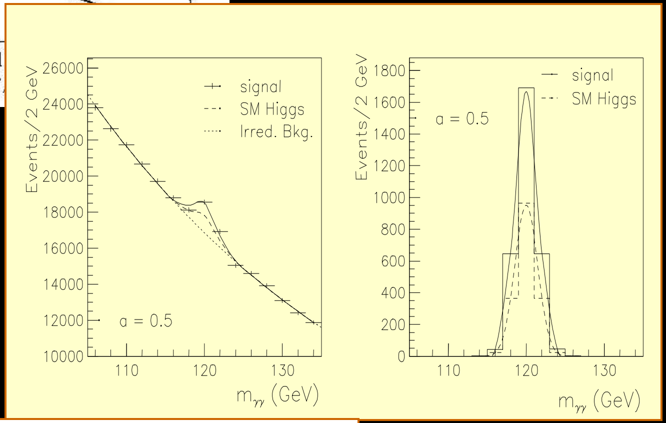


The Observational Tests

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



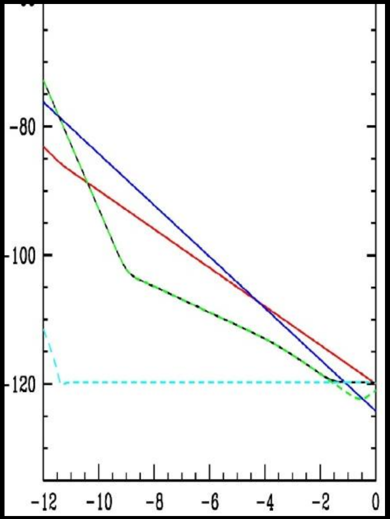


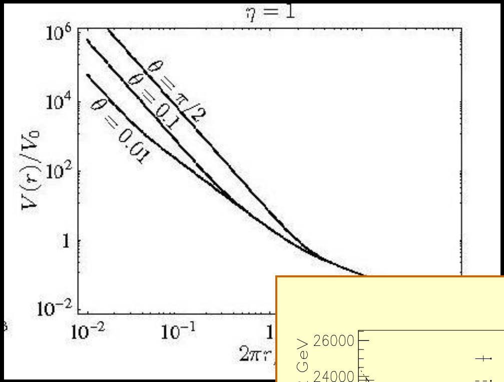


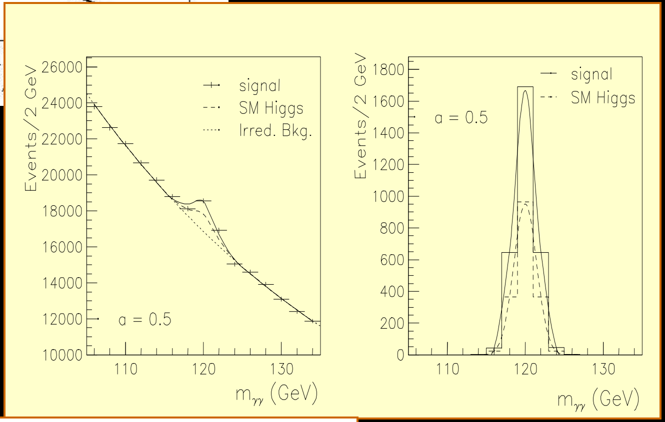
$$U \approx \begin{pmatrix} c_s(-1/\sqrt{2} - \delta/4) & c_s(1/\sqrt{2} - \delta/4) & 0 \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & 1/\sqrt{2} \\ c_s(1/2 - \delta/4\sqrt{2}) & c_s(1/2 + \delta/4\sqrt{2}) & -1/\sqrt{2} \end{pmatrix}$$

The Observational Tests

- Quintessence cosmology
- Modifications to gravity
- Collider physics
- Neutrino physics?
- *And more!*







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Observational Consequences

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

Observational Consequences

Albrecht, CB, Ravndal & Skordis
Kainulainen & Sunhede

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

- *Quantum vacuum energy lifts flat direction.*
- *Specific types of scalar interactions are predicted.*
  - *Includes the Albrecht-Skordis type of potential*
- *Preliminary studies indicate it is possible to have viable cosmology:*
  - *Changing G; BBN; …*

Observational Consequences

Albrecht, CB, Ravndal & Skordis

- *Quintessence c*
- Modifications t
- Collider physic
- Neutrino physi
- Astrophysics

$$V = [a + b\log(rM) + c\log^2(rM)]\left(\frac{1}{r^4}\right)$$

Potential domination when:

$$V' \approx 0 \quad \textit{if} \quad rM \approx \exp(a/b)$$

Canonical Variables:

$$L_{kin} = M_p^2 \frac{(\partial r)^2}{r^2}$$

$$V = (a + b\phi + c\phi^2)\exp[-\lambda\phi]$$

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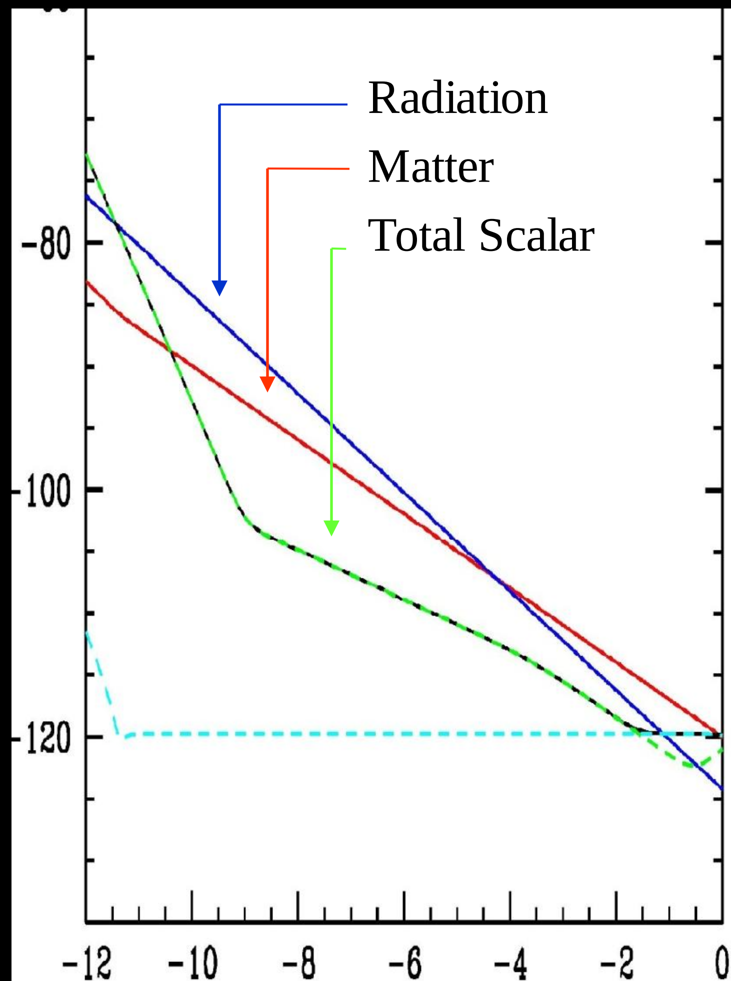
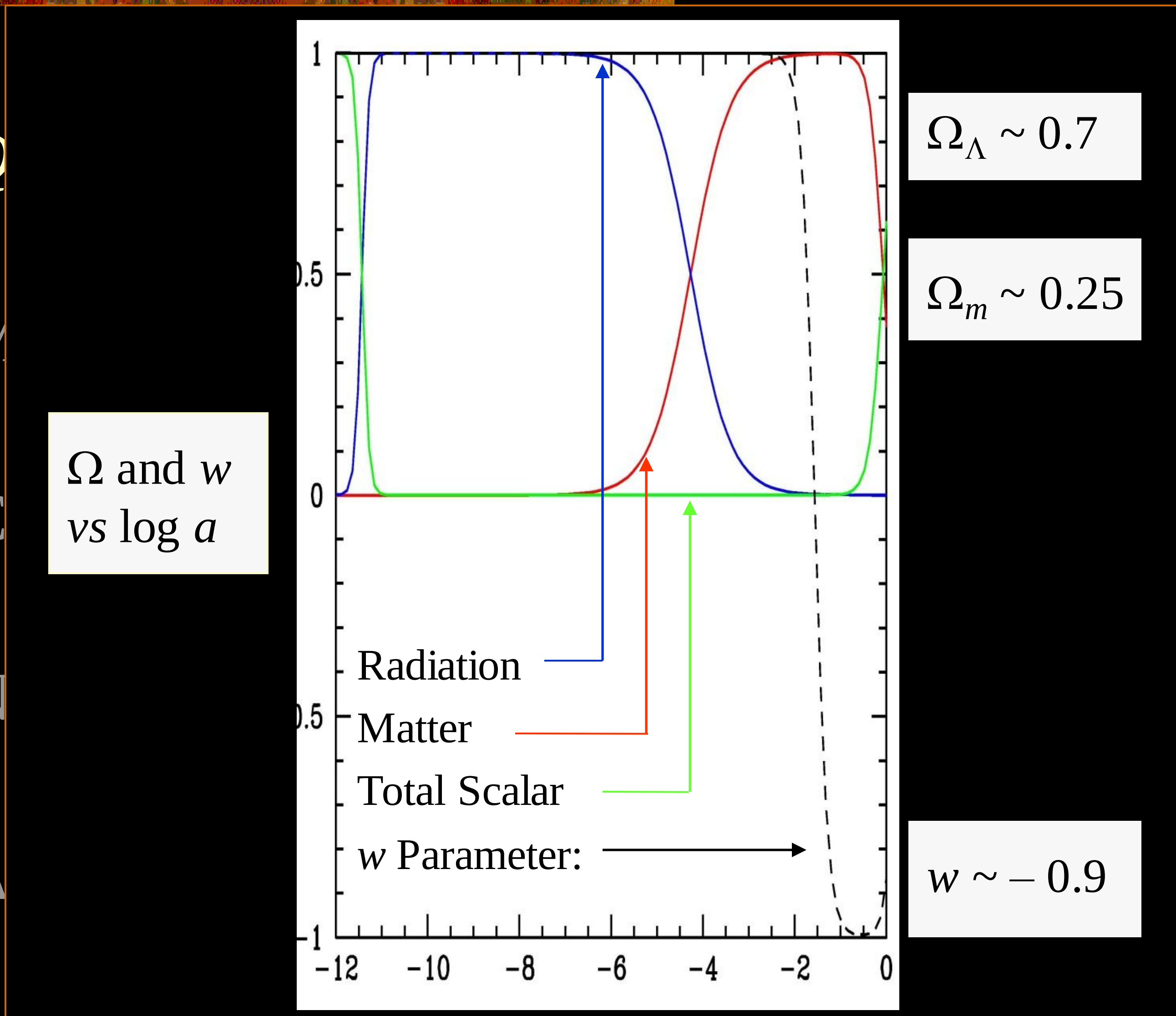


log ρ *vs* log *a*

Observational Consequences

Albrecht, CB, Ravndal & Skordis



- *Q … um energy … on.*
- M … *f scalar*
- C … *lbrecht- … f potential*
- N … *dies*
- A … *ssible to … mology: … BBN; …*

Observational Consequences

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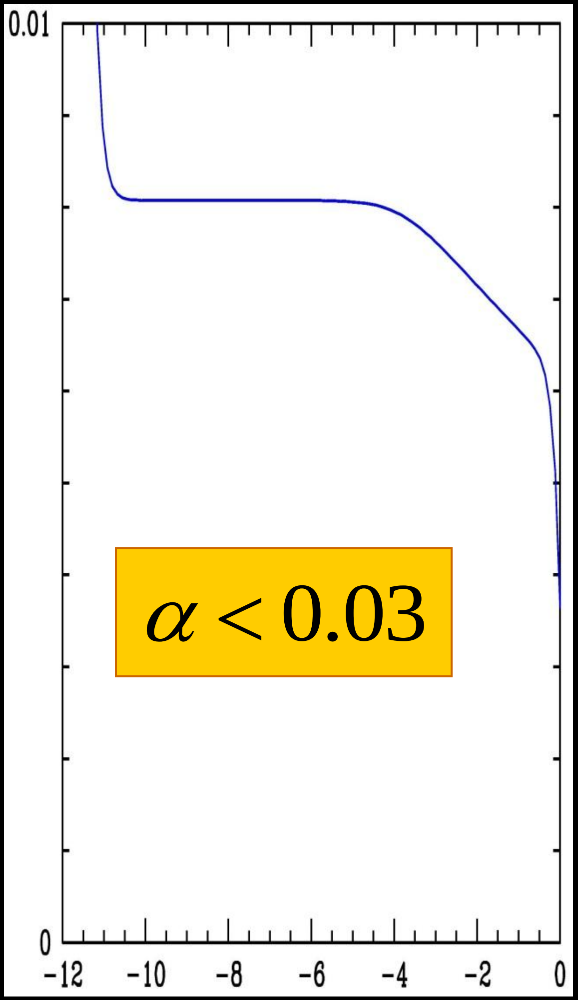
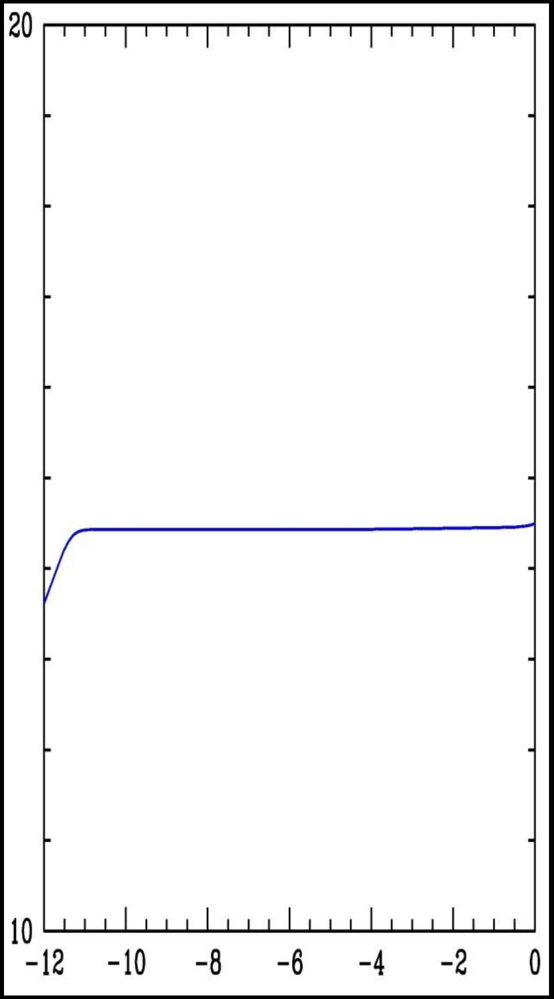


α *vs* log *a*

Observational Consequences

Albrecht, CB, Ravndal & Skordis

- *Quintessence c* *uum energy* *tion.*
- Modifications t *of scalar* *ire*
- Collider physic *Albrecht-* *of potential*
- Neutrino physi *studies* *possible to* *osmology:*
- Astrophysics *; BBN; …*



log r *vs* log a

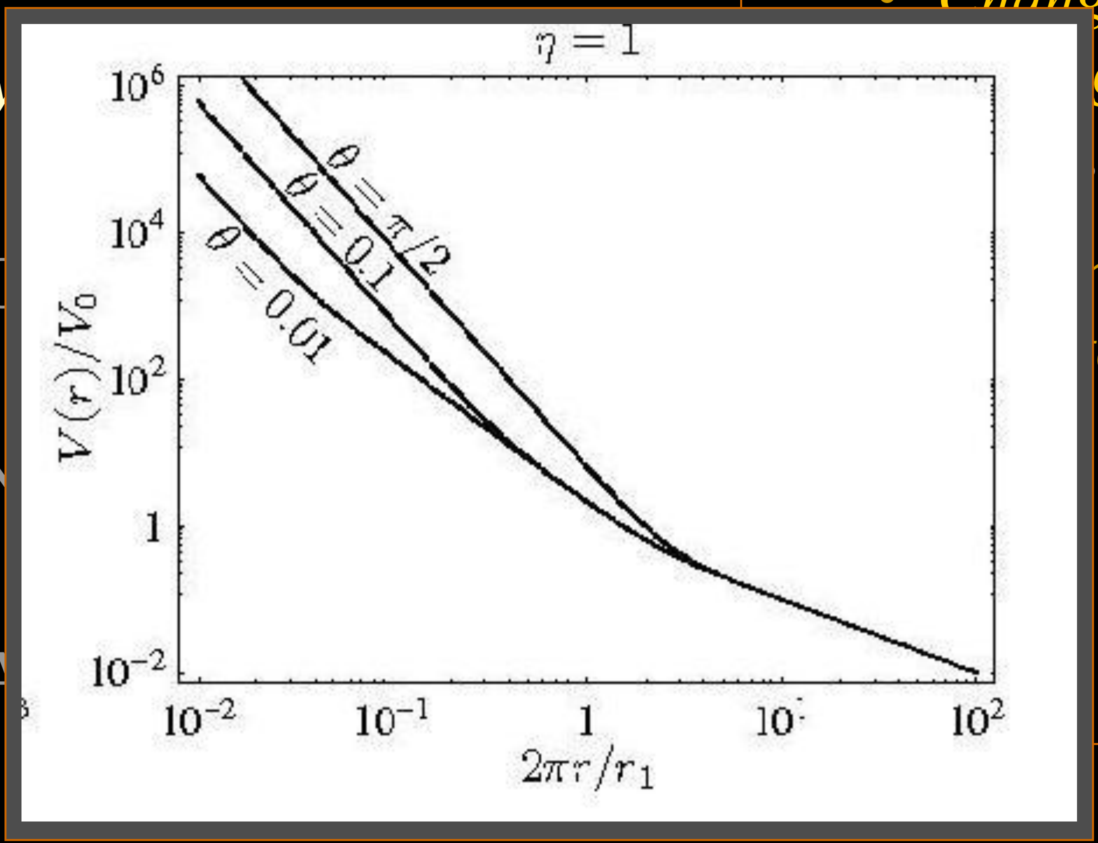
Observational Consequences

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

- *At small distances:*
  - *Changes Newton's Law at range $r/2\pi \sim 1\ \mu m$.*
- *At large distances*
  - *Scalar-tensor theory out to distances of order H_0.*

Observational Consequences

- Quintessence cosmology
- M
- C
- N
- A



- *At small distances:*
  - *Changes Newton's Law*
  - *ge $r/2\pi \sim 1\ \mu m$.*
- *distances*
  - *r-tensor theory out*
  - *ances of order H_0.*

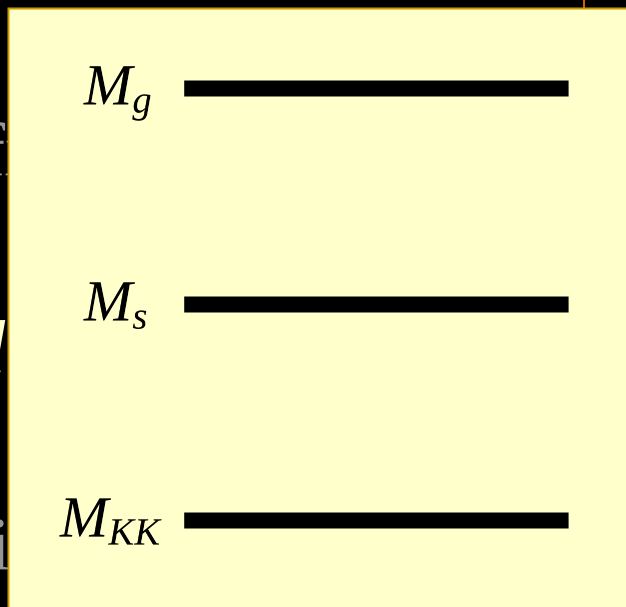
Observational Consequences

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

- *Not the MSSM!*
  - *No superpartners*
- *Bulk scale bounded by astrophysics*
  - $M_g \sim 10$ *TeV*
- *Many channels for losing energy to KK modes*
  - *Scalars, fermions, vectors live in the bulk*

Observational Consequences

- Quintessence cosmology
- Modif
- *Collid*
- Neutri
- Astrophysics



- *Can there be observable signals if $M_g \sim 10$ TeV?*
  - *Must hit new states* before *$E \sim M_g$. Eg: string and KK states have $M_{KK} < M_s < M_g$*
  - *Dimensionless couplings to bulk scalars are unsuppressed by M_g*

Observational Consequences

Azuelos, Beauchemin & CB

$$S = a \int d^4x \left(H^* H\right) \Phi\left(x, y_b\right)$$

Dimensionless coupling!
O(0.1-0.001) from loops

Observational Consequences

Azuelos, Beauchemin & CB

$$S = a\int d^4x\left(H^*H\right)\Phi\left(x, y_b\right)$$

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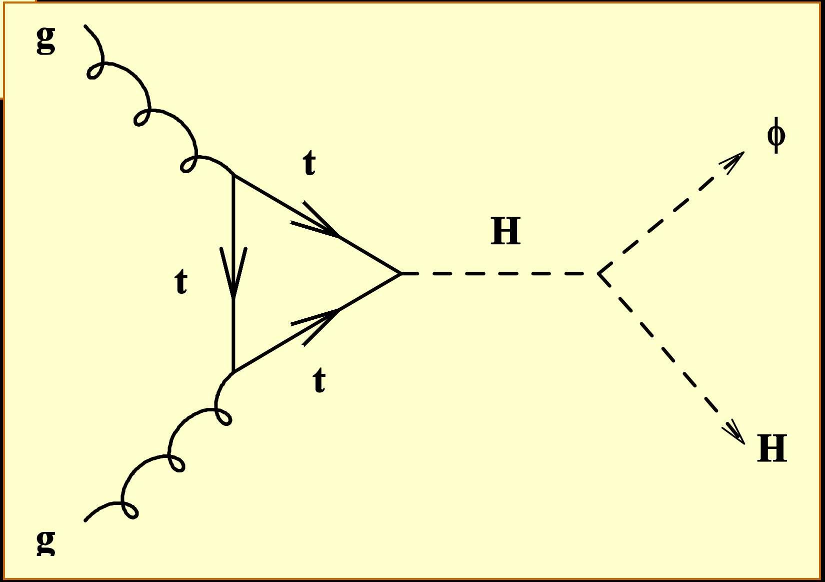
- *Use H decay into $\gamma\gamma$, so search for two hard photons plus missing E_T.*



Observational Consequences

Azuelos, Beauchemin & CB

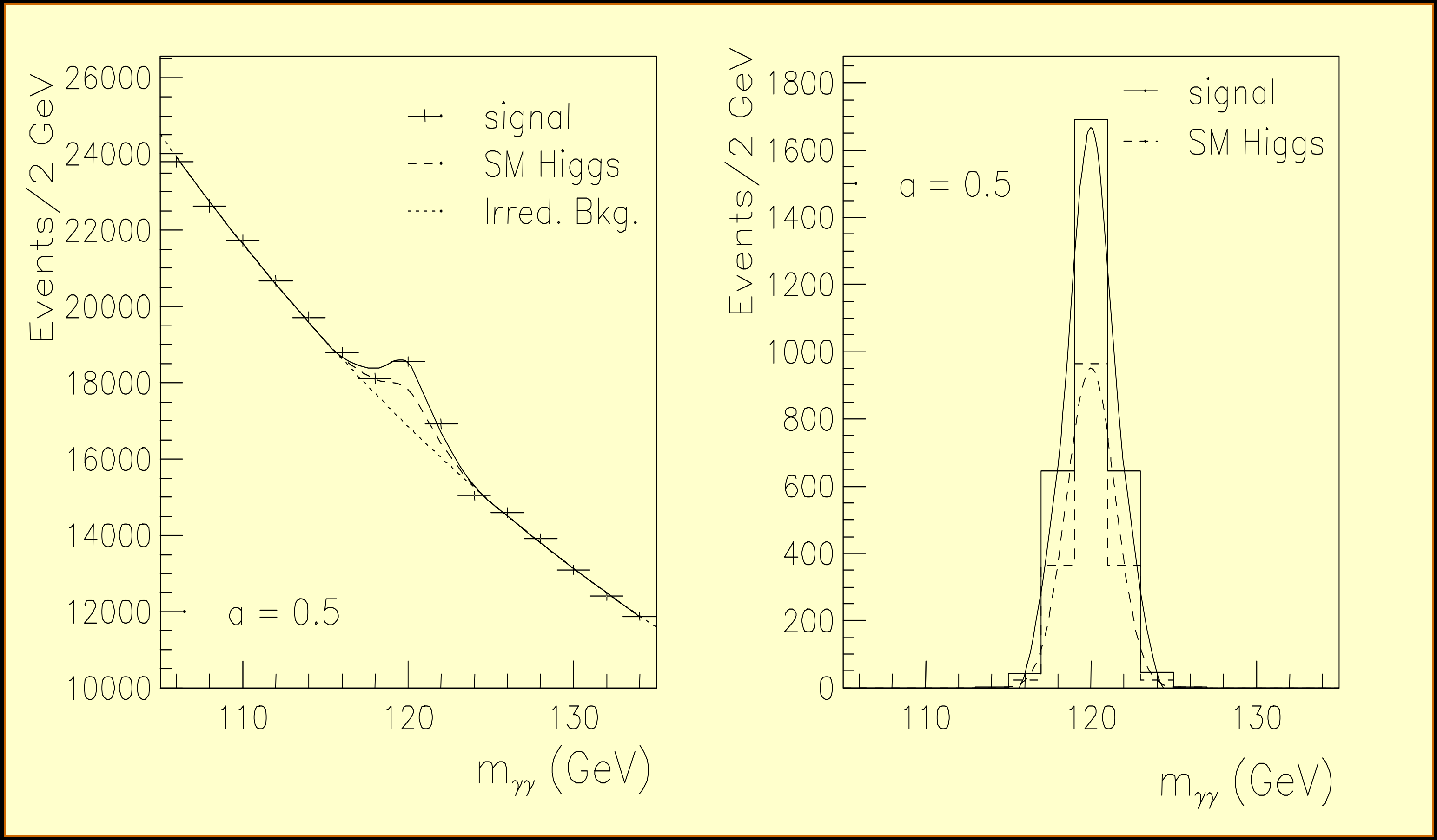
Table 2. SM backgrounds to the production of bulk scalars in association with the Higgs particle at ATLAS, their cross-section (for an E_T^{cut} of 23 GeV) and the total number of events expected at ATLAS for an integrated luminosity of 100 fb^{-1} (after application of rejection factors).

Processes	Cross-section (pb)	Number of events
$pp \to \gamma\gamma$ (Born)	56.2	5.62×10^6
$pp \to \gamma\gamma$ (box)	49.0	4.90×10^6
$pp \to$ jet+jet	4.9×10^8	2.50×10^6
$pp \to$ jet+γ	1.2×10^5	1.50×10^6
$pp \to h \to \gamma\gamma$	4.63×10^{-2}	4630
$pp \to Zh, Wh, t\bar{t}h$		
$Z \to \nu\bar{\nu}, W \to \ell\nu, h \to \gamma\gamma$	2.5×10^{-3}	250
$pp \to Z\gamma; Z \to \nu\bar{\nu}$	3.3	3.3×10^5
$pp \to W\gamma; W \to \ell\nu$	5.6	5.6×10^5

- *Standard Model backgrounds*

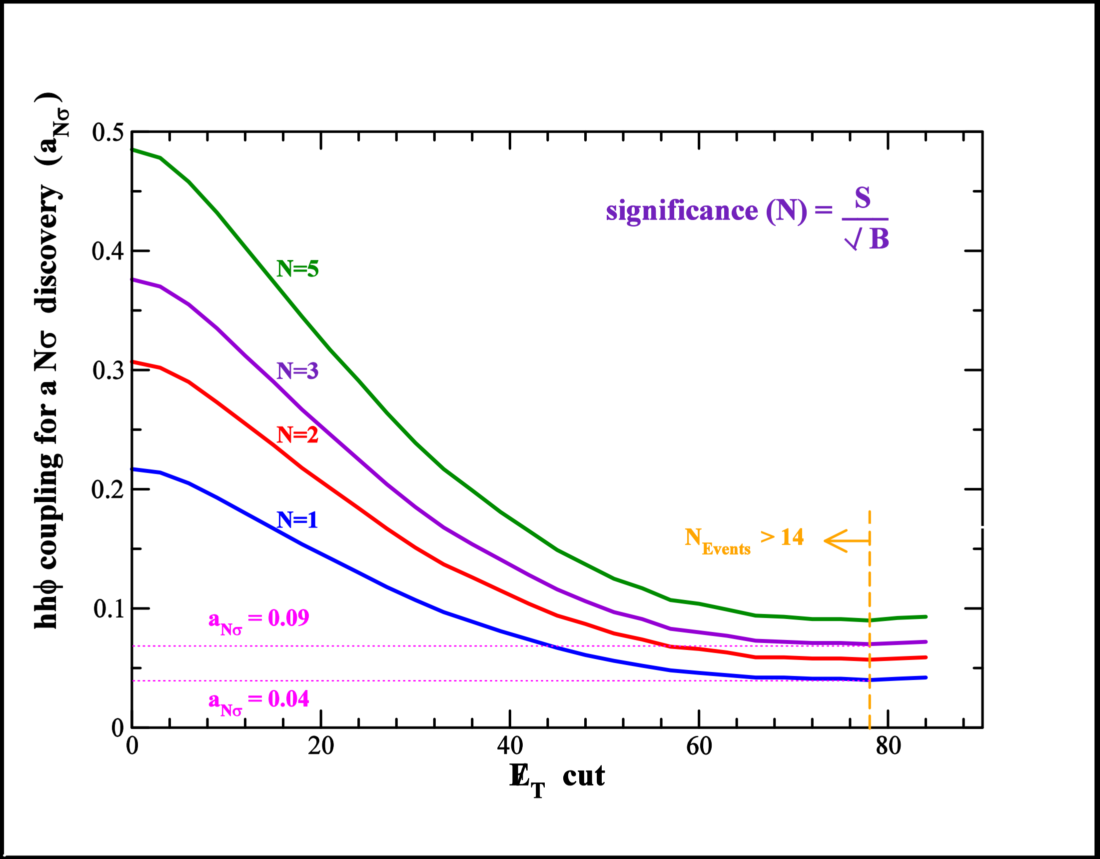
Observational Consequences

Azuelos, Beauchemin & CB



Observational Consequences

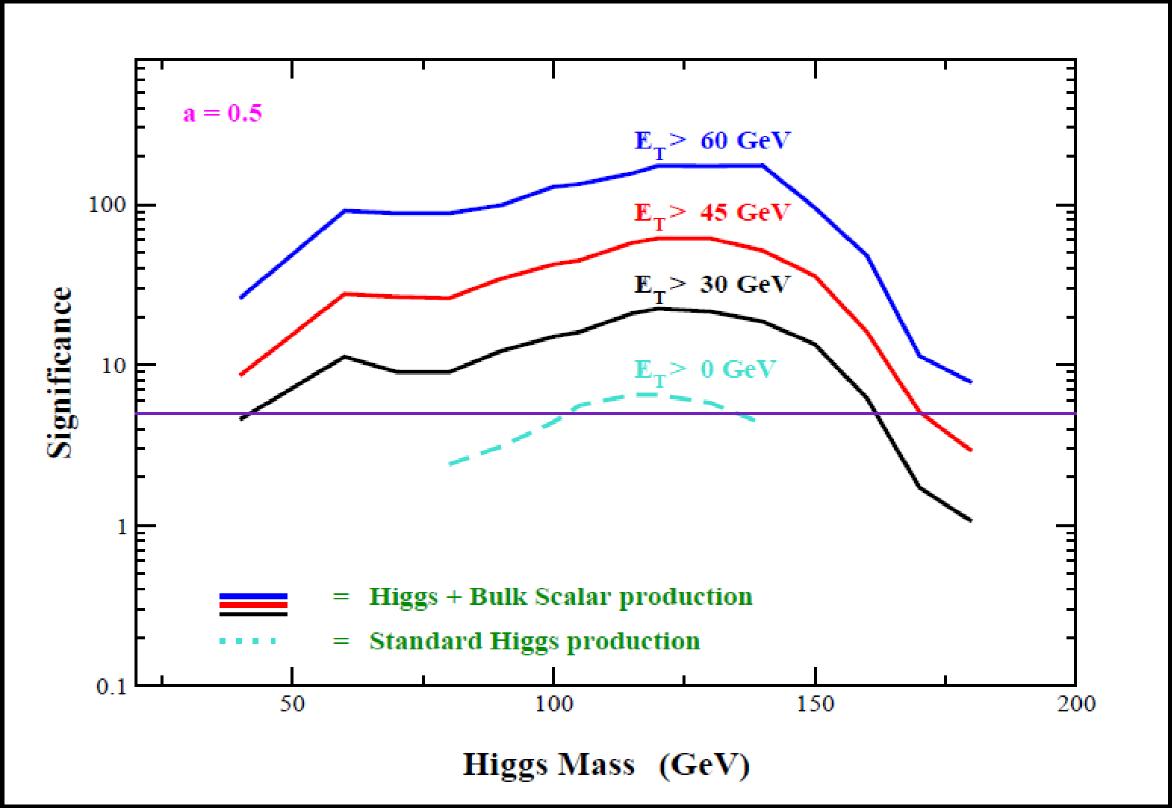
Azuelos, Beauchemin & CB



- *Significance of signal vs cut on missing E_T*

Observational Consequences

Azuelos, Beauchemin & CB



- *Possibility of missing-E_T cut improves the reach of the search for Higgs through its $\gamma\gamma$ channel*

Observational Consequences

Matias, CB

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

- *SLED predicts there are 6D massless fermions in the bulk, as well as their properties*
  - *Massless, chiral, etc.*
- *Masses and mixings can be chosen to agree with oscillation data.*
  - *Most difficult: bounds on resonant SN oscillilations.*

Observational Consequences

Matias, CB

- 6D supergravities have 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
- Back-reaction removes KK zero modes
  - eg: boundary condition due to conical defect at brane position

Observational Consequences

Matias, CB

$$S = \lambda_u \int d^4x \left(L_a^i H_i\right) N_{au}\left(x, y_b\right)$$

Dimensionful coupling
$\lambda \sim 1/M_g$

Observational Consequences

Matias, CB

$$S = \lambda_u \int d^4x \left(L_a^i H_i \right) N_{au}(x, y_b)$$

Dimens
λ ~ 1/M

SUSY keeps N massless in bulk;

Natural mixing with Goldstino on branes;

Chirality in extra dimensions provides natural L;

Observational Consequences

Matias, CB

$$S = \lambda_u \int d^4x \left(L_a^i H_i\right) N_{au}\left(x, y_b\right)$$

Dimensionful c
$\lambda \sim 1/M_g$

$$M = \frac{1}{r}\left(\begin{array}{ccc|ccc} 0 & 0 & 0 & \lambda_e^+ v & \lambda_e^- v & \cdots \\ 0 & 0 & 0 & \lambda_\mu^+ v & \lambda_\mu^- v & \cdots \\ 0 & 0 & 0 & \lambda_\tau^+ v & \lambda_\tau^- v & \cdots \\ \hline \lambda_e^+ v & \lambda_\mu^+ v & \lambda_\tau^+ v & 0 & 2\pi c_1 & \cdots \\ \lambda_e^- v & \lambda_\mu^- v & \lambda_\tau^- v & 2\pi c_1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{array}\right)$$

Observational Consequences

Matias, CB

$$S = \lambda_u \int d^4x \left(L_a^i H_i\right) N_{au}(x, y_b)$$

Dimensionful c
$\lambda \sim 1/M_g$

Constrained by bounds on sterile neutrino emission

Require observed masses and large mixing.

$$M = \frac{1}{r}\begin{pmatrix} 0 & 0 & 0 & \lambda_e^+ v & \lambda_e^- v & \cdots \\ 0 & 0 & 0 & \lambda_\mu^+ v & \lambda_\mu^- v & \cdots \\ 0 & 0 & 0 & \lambda_\tau^+ v & \lambda_\tau^- v & \cdots \\ \lambda_e^+ v & \lambda_\mu^+ v & \lambda_\tau^+ v & 0 & 2\pi c_1 & \cdots \\ \lambda_e^- v & \lambda_\mu^- v & \lambda_\tau^- v & 2\pi c_1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Observational Consequences

Matias, CB

- Bounds on sterile neutrinos easiest to satisfy if $g = \lambda v < 10^{-4}$.
- Degenerate perturbation theory implies massless states strongly mix even if g is small.
  - This is a problem if there are massless KK modes.
  - This is good for 3 observed flavours.
- Brane back-reaction can *remove* the KK zero mode for fermions.

Observational Consequences

Matias, CB

- 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.

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

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

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

$$S \sim M_g\, r$$

Observational Consequences

Matias, CB

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

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

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

Observational Consequences

Matias, CB

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

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.

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

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

Observational Consequences

Matias, CB

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

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

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

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

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

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

Observational Consequences

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

- *Energy loss into extra dimensions is close to existing bounds*
  - *Supernova, red-giant stars,…*
- *Scalar-tensor form for gravity may have astrophysical implications.*
  - *Binary pulsars;…*

The Worries

- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- Famous No-Go Arguments
- Problems with Cosmology
- Constraints on Light Scalars

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- Famous No-G
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- Constraints on Light Scalars

- Classical part of the argument:
  - What choices must be made to ensure 4D flatness?
- Quantum part of the argument:
  - Are these choices stable against renormalization?

The Worries

Tolley, CB, Hoover & Aghababaie
Tolley, CB, de Rham & Hoover
CB, Hoover & Tasinato

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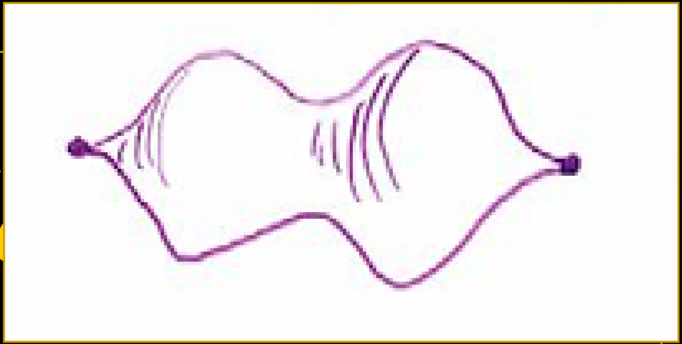

Now understand how 2 extra dimensions respond to presence of 2 branes having arbitrary couplings.

- *Not all are flat in 4D, but all of those having only conical singularities are flat.*

(Conical singularities correspond to absence of dilaton couplings to branes)

The Worries

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  - Are these choices stable against renormalization?

So far so good!!

- *Brane loops cannot generate dilaton couplings if these are not initially present*
- *Bulk loops can generate such couplings, but are suppressed by 6D supersymmetry*
- *Bulk loops counted by $e^{2\phi} = 1/r^4$*

The Worries

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- Most brane properties and initial conditions do not lead to anything like the universe we see around us.
  - For many choices the extra dimensions implode or expand to infinite size.

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- Most brane properties and initial conditions do not lead to anything like the universe we see around us.
  - For many choices the extra dimensions implode or expand to infinite size.
- *Initial condition problem:* much like the Hot Big Bang, possibly understood by reference to earlier epochs of cosmology (eg: inflation)

The Worries

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The Worries

Salam & Sezgin

- ‘Technical N
- Runaway Bel
- *Stabilizing th*
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- Constraints on Light Scalars

- Classical flat direction corresponding to combination of radius and dilaton:
  $$e^{\phi} r^2 = constant.$$
- Loops lift this flat direction, and in so doing give dynamics to ϕ and r.

The Worries

Kantowski & Milton
Albrecht, CB, Ravndal, Skordis
CB & Hoover
Ghilencea, Hoover, CB & Quevedo

- 'Techni
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Hubble damping can allow potential domination for exponentially large r, even though r is not stabilized.