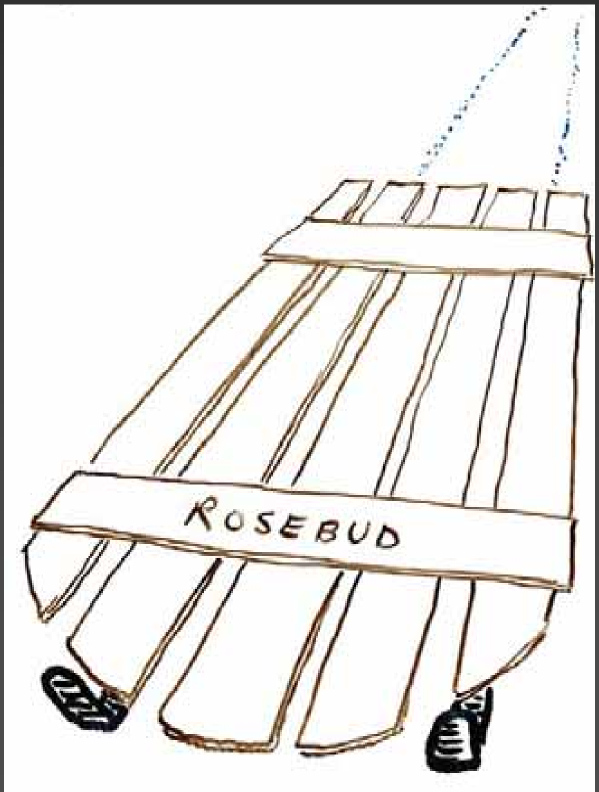
SLED: an update

Supersymmetric Large Extra Dimensions



Cliff Burgess

Moriond 2007

Partners in Crime

CC Problem:

Y. Aghababaie, J. Cline, C. de Rham, H. Firouzjahi, D. Hoover, S. Parameswaran, F. Quevedo, G. Tasinato, A. Tolley, I. Zavala

Phenomenology:

G. Azuelos, P.-H. Beauchemin, J. Matias, F. Quevedo

Cosmology:

Albrecht, F. Ravndal, C. Skordis

On the shoulders of giants

A. Salam, E. Sezgin, H. Nishino,G. Gibbons, S. Kachru E. Silverstein, R. Guven, C. Pope, K. Maeda, M. Sasaki, V. Rubakov, R. Gregory, I. Navarro, J. Santiago, S. Carroll, C. Guica, C. Wetterich, S. Randjbar-Daemi, F. Quevedo, Y. Aghababaie, S. Parameswaran, J. Cline, J. Matias, G. Azuelos, P-H. Beauchemin, A. Albrecht, C. Skordis, F. Ravndal, I. Zavala, G. Tasinato, J. Garriga, M. Porrati, H.P. Nilles, A. Papazoglou, H. Lee, N. Arkani-Hamad, S. Dimopoulos, N. Kaloper, R. Sundrum, D. Hoover, A. Tolley, C. de Rham, S. Forste, Z. Lalak, S. Lavingnac, C. Grojean, C. Csaki, J. Erlich, T. Hollowood, H. Firouzjahi, J. Chen, M. Luty, E. Ponton, P. Callin, D. Ghilencea, E. Copeland, O. Seto, V. Nair, S. Mukhoyama, Y. Sendouda, H. Yoshigushi, S. Kinoshita, A. Salvio, J. Duscheneau, J. Vinet, M. Giovannini, M. Graesser, J. Kile, P. Wang, P. Bostok, G. Kofinas, C. Ludeling, A. Nielsen, B. Carter, D. Wiltshire. C. K. Akama, S. Appleby, F. Arroja, D. Bailin, M. Bouhmadi-Lopez, M. Brook, R. Brown, C. Byrnes, G. Candlish, A. Cardoso, A. Chatterjee, D. Coule, S. Creek, B. Cuadros-Melgar, S. Davis, B. de Carlos, A. de Felice, G. de Risi, C. Deffayet, D. Easson, A. Fabbri, A. Flachi, S. Fujii, L. Gergely, C. Germani, D. Gorbunov, I. Gurwich, T. Hiramatsu, B. Hoyle, K. Izumi, P. Kanti, S. King, T. Kobayashi, K. Koyama, D. Langlois, J. Lidsey, F. Lobo, R. Maartens, N. Mavromatos, A. Mennim, M. Minamitsuji, B. Mistry, S. Mizuno, A. Padilla, S. Pal, G. Palma, L. Papantonopoulos, G. Procopio, M. Roberts, M. Sami, S. Seahra, Y. Sendouda, M. Shaeri, T. Shiromizu, P. Smyth, J. Soda, K. Stelle, Y. Takamizu, T. Tanaka, T. Torii, C. van de Bruck, D. Wands, V. Zamarias, H. Ziaeepour

The Plan

- Motivation
  - Reading the Tea Leaves
- The SLED Proposal
  - Changing how the vacuum energy gravitates
- Worries
  - Naturalness; Runaways; Stabilizing dimensions; No-Go arguments; pre-BBN cosmology; Constraints on new forces,…
- Observational Tests
  - Cosmology; Tests of Gravity; LHC; Particle Phenomenology; Neutrino Oscillations?…
- Summary

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The Motivation

- Hierarchy Problems
- Why Extra Dimensions?

The Motivation

- *Hierarchy Problems*
- Why Extra Dimensions

- Ideas for what lies beyond the Standard Model are largely driven by 'technical naturalness'.

The Motivation

- *Hierarchy*
  Problems

- W
  Di

- Ideas for what lies beyond the Standard Model are largely driven by 'technical naturalness'.

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

Hierarchy problem: *Since the largest mass dominates, why isn't m ~ M_{GUT} or M_p ??*

The Motivation

- *Hierarchy*
  Problems
- Why Extr
  Dimensio

- Three approaches to solve the Hierarchy problem:
  - Compositeness: *H is not fundamental at energies E À M_w*
  - Supersymmetry: *there are new particles at E À M_w and a symmetry which ensures cancellations so $m^2 \sim M_B^2 - M_F^2$*
  - Extra Dimensions: *the fundamental scale is much smaller than M_p , much as*
    $G_F^{-1/2} > M_w$

The Motivation

- *Hierarchy*
  Problems

- Ideas for what lies beyond the Standard Model are largely driven by 'technical naturalness'.

$$L_{SM} = \mu^4 + m^2 H^* H + \textit{dimensionless}$$

- W
  Di

Cosmological constant problem: *Why is $\mu \sim 10^{-3}$ eV rather than m_e , M_w , M_{GUT} or M_p?*

The Motivation

- *Hier*
  Prol

- W
  Di

Harder than the Hierarchy problem:

Integrating out the electron already gives too large a contribution!!

Cosmological constant problem: *Why is $\mu \sim 10^{-3}$ eV rather than m_e , M_w , M_{GUT} or M_p?*

The Motivation

- *Hierarchy ... Problems*
- Why Extr... Dimensio...

- Which approaches also address the Cosmological Constant problem?

The Motivation

- *Hierarchy*
  Problems

- Why Extr
  Dimensio

- Which approaches also address the Cosmological Constant problem?
  - Compositeness: *H is not fundamental at energies* $E \gg M_w$

The Motivation

- *Hierarchy*
  Problems
- Why Extr
  Dimensio

- Which approaches also address the Cosmological Constant problem?
  - Compositeness: *H is not fundamental at energies E À M_w*
  - Supersymmetry: *there are new particles at E À M_w and a symmetry which ensures cancellations so $m^2 \sim M_B^2 - M_F^2$*

The Motivation

- *Hierarchy*
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- Why Extr
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- Which approaches also address the Cosmological Constant problem?
  - ⊗ Compositeness: *H is not fundamental at energies E À M_w*
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  - ?? Extra Dimensions: *the fundamental scale is much smaller than M_p, much as* $G_F^{-1/2} > M_w$

The Motivation

- Hierarchy Problems

- *Why Extra Dimensions?*

The Motivation

- Hierarchy
  Problems

- *Why Extra*
  Dimension

- In 4D a nonzero vacuum energy (*which we think should be large*) is equivalent to the curvature of spacetime (*which cosmology measures to be small*).

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \approx 8\pi G\, \mu^4 g_{\mu\nu}$$

The Motivation

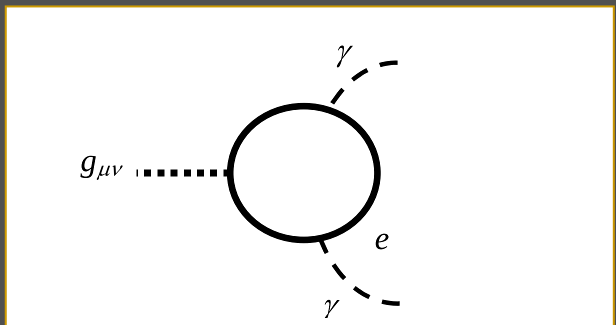
- H…
  P…

- In 4D a nonzero vacuum energy … *e*) is … *ieasures* … $g_{\mu\nu}$

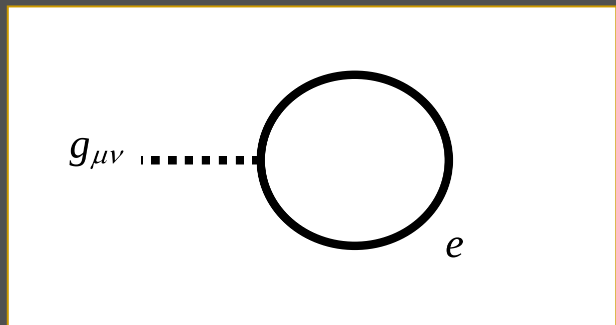
- *W…*
  D…

- And we know vacuum fluctuations gravitate, because they contribute to binding energies, to which equivalence principle tests show gravity couples

Why this?



But not this?



The Motivation

Arkani-Hamad et al
Kachru et al,
Carroll & Guica
Aghababaie, et al

- Hierarchy
  Problems

- *Why Extr*
  Dimensio

- In higher dimensions a 4D vacuum energy need not imply *4D* curvature

The Motivation

Gibbons, Guven & Pope

- Hierarchy
  Problems

- *Why Extra*
  Dimension

$$ds^2 = \mathcal{W}^2(\eta)\,\eta_{\mu\nu}\,dx^\mu dx^\nu + \mathcal{A}^2(\eta)\Big[\mathcal{W}^8(\eta)\,d\eta^2 + d\theta^2\Big]$$

$$F_{\eta\theta} = \left(\frac{q\mathcal{A}^2}{\mathcal{W}^2}\right) e^{-\lambda_3\eta} \qquad \text{and} \qquad e^{-\phi} = \mathcal{W}^2\, e^{\lambda_3\eta}\,,$$

$$\mathcal{W}^4 = \left(\frac{\kappa^2 q\lambda_2}{2g\lambda_1}\right) \frac{\cosh[\lambda_1(\eta-\eta_1)]}{\cosh[\lambda_2(\eta-\eta_2)]}$$

$$\mathcal{A}^{-4} = \left(\frac{2\kappa^2 q^3 g}{\lambda_1^3\lambda_2}\right) e^{-2\lambda_3\eta}\cosh^3[\lambda_1(\eta-\eta_1)]\cosh[\lambda_2(\eta-\eta_2)]\,,$$

- Most general 4D flat solutions to chiral 6D supergravity, without matter fields.
- λ_3 nonzero gives curvature singularities

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The SLED Proposal

Aghababaie, CB,
Parameswaran & Quevedo

- Suppose physics is extra-dimensional above the 10^{-2} eV scale.

- Suppose the physics of the bulk is supersymmetric.

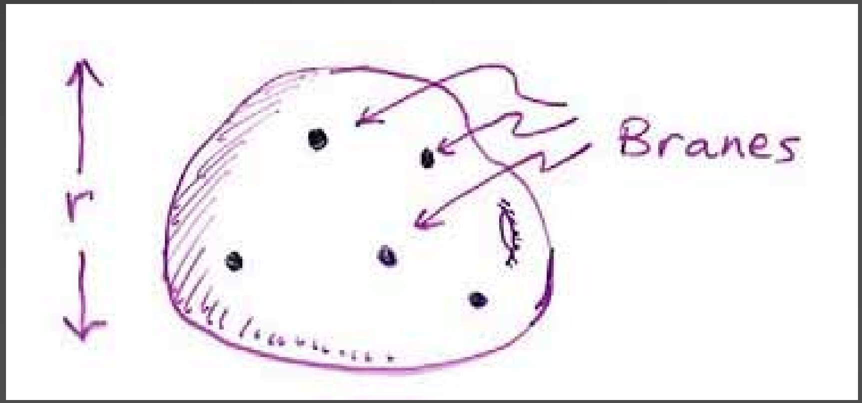
The SLED Proposal

Arkani-Hamad, Dimopoulos & Dvali

- *Suppose physics is extra-dimensional above the 10^{-2} eV scale.*

- Suppose the physics of the bulk is supersymmetric.

- *Experimentally possible:*
  - *There are precisely two extra dimensions at these scales;*
  - *We are brane bound;*



The SLED Proposal

Arkani-Hamad, Dimopoulos & Dvali

- *Suppose physics is extra-dimensional above the 10^{-2} eV scale.*
- Suppose the physics of the bulk is supersymmetric.

- *Experimentally possible:*
  - *There are precisely two extra dimensions at these scales;*
  - *We are brane bound;*
  - *The 6D gravity scale is in the TeV region.*

$$M_p = M_g^2\, r$$

The SLED Proposal

- Suppose physics is extra-dimensional above the 10^{-2} eV scale.

the bulk is *supersymmetric.*

- *Bulk supersymmetry*
  - *Graviton has many partners in the extra dimensions*

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2\kappa^2}\, g^{MN}\left[R_{MN} + \partial_M\phi\,\partial_N\phi\right] - \frac{1}{4}\, e^{-\phi}\, F_{MN}F^{MN} - \frac{2g^2}{\kappa^4}\, e^{\phi}$$

The SLED Proposal

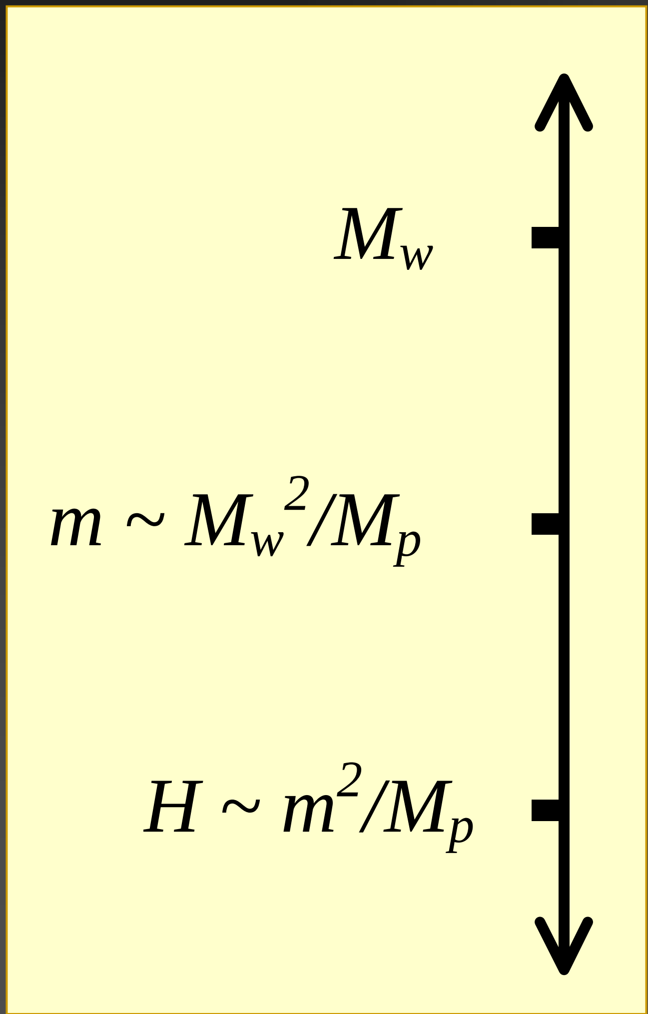
- Suppose physics is extra-dimensional above the 10^{-2} eV scale.

- *Suppose the physics of the bulk is supersymmetric.*

- *Bulk supersymmetry*
  - *SUSY breaks at scale M_g on the branes;*
  - *Trickle-down of SUSY breaking to the bulk is:*

$$m_{SB} \approx \frac{M_g^2}{M_p} \approx \frac{1}{r} \approx 10^{-2}\,\mathrm{eV}$$

The SLED Proposal



Particle Spectrum:

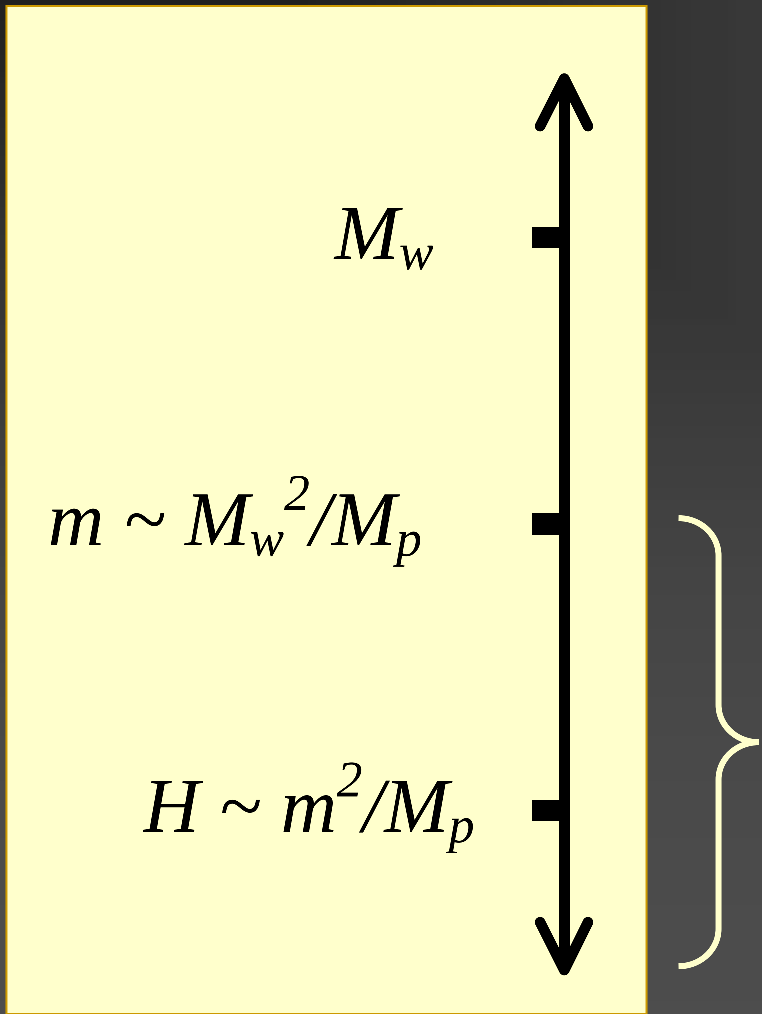
SM on brane – no partners

Many KK modes in bulk

4D scalar: $e^{\phi} r^2 \sim const$

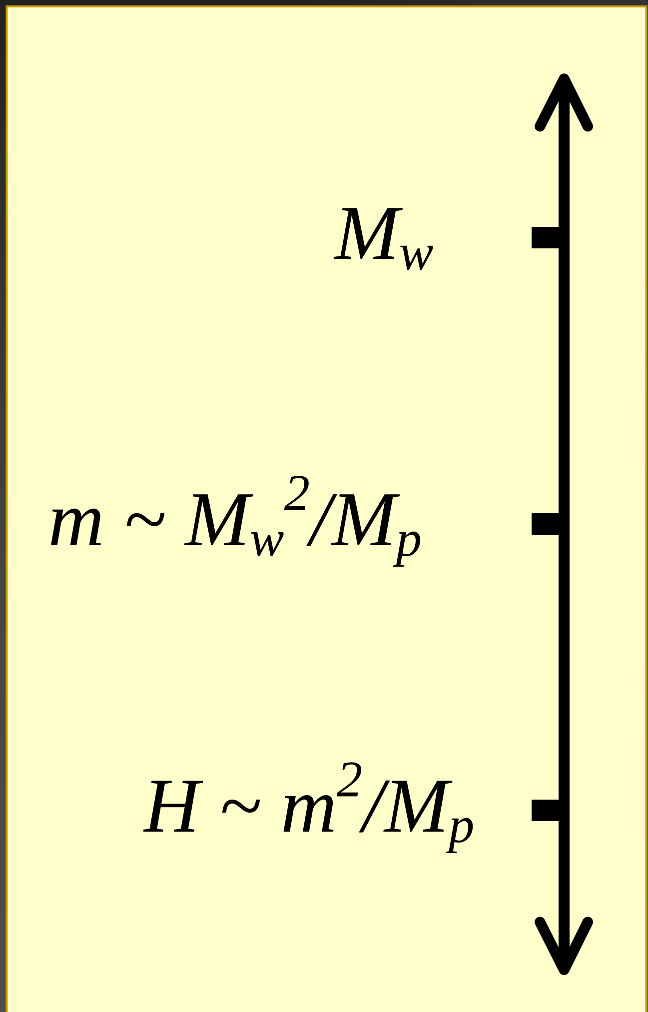
4D graviton

The SLED Proposal



These scales are natural using standard 4D arguments.

The SLED Proposal



Must rethink how the vacuum gravitates in 6D for these scales.

SM interactions do not change at all!

These scales are natural using standard 4D arguments.

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The Worries

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

- *‘Technical N*
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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

- *'Technical N*
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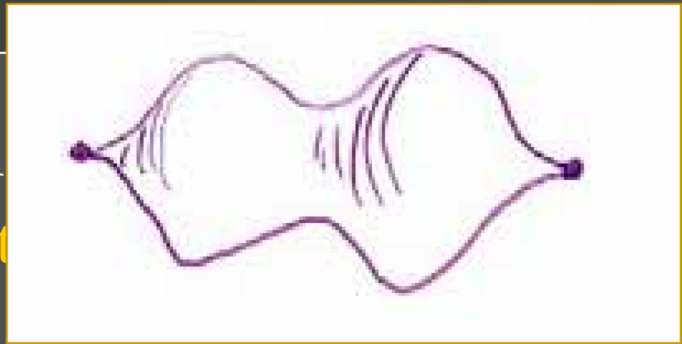

Now understand how 2 extra dimensions respond to presence of 2 branes having arbitrary couplings.

- *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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- Quantum part of the argument:
  - Are these choices stable against renormalization?

So far so good, but not yet complete

- *Brane loops cannot generate dilaton couplings if these are not initially present*
- *Bulk loops can generate such couplings, but are suppressed by 6D supersymmetry*

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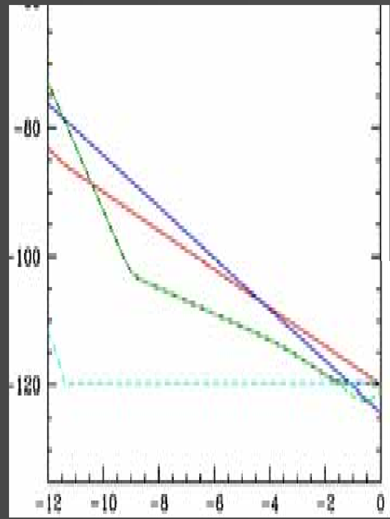
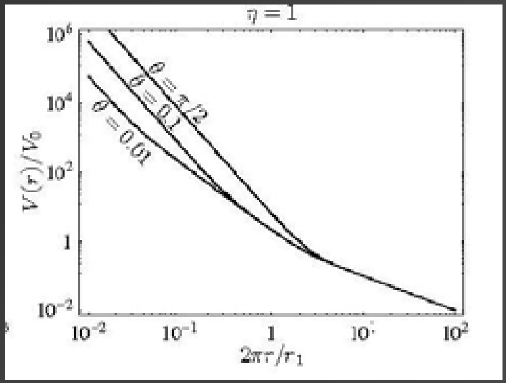
The Observational Tests

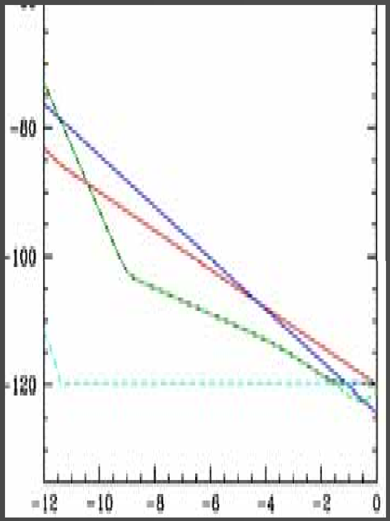
- Quintessence cosmology



The Observational Tests

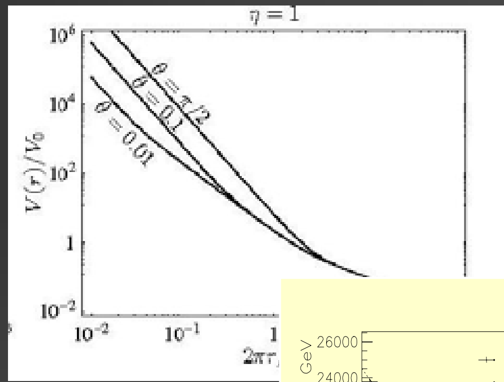
- Quintessence cosmology
- Modifications to gravity

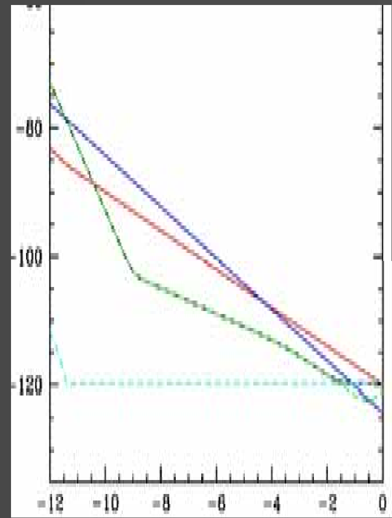


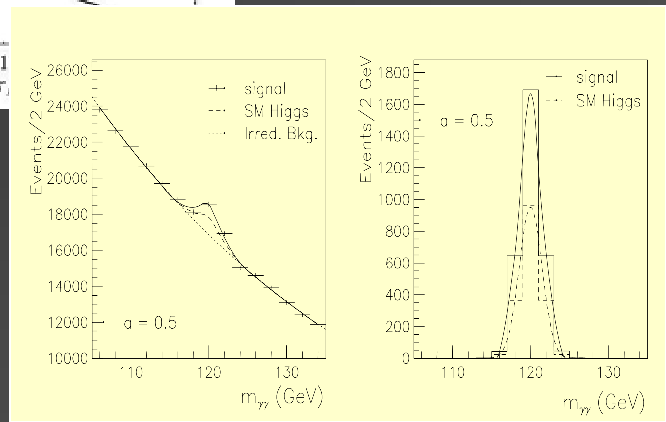


The Observational Tests

- Quintessence cosmology
- Modifications to gravity
- Collider physics







The Observational Tests

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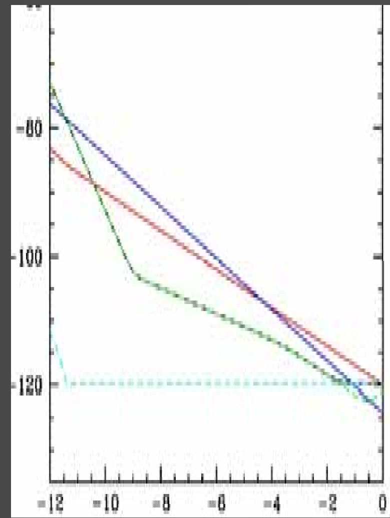
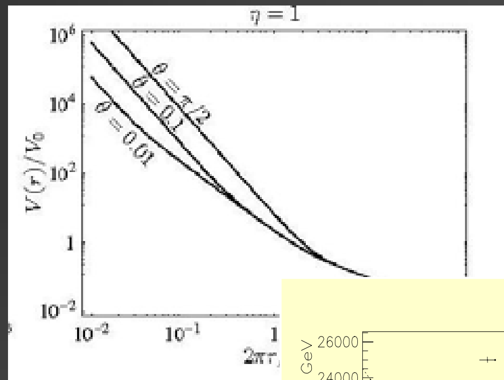
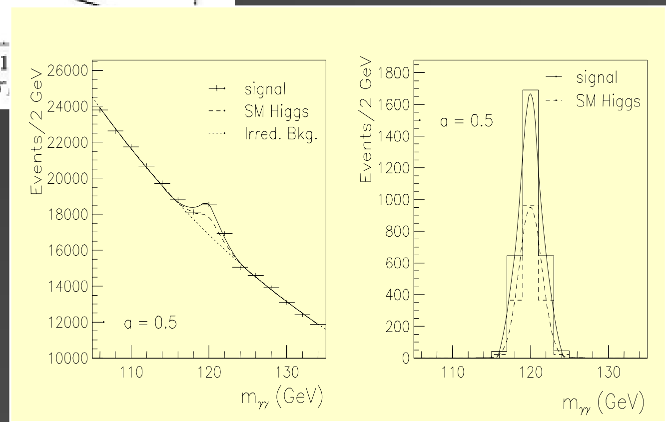
SUSY broken at the TeV scale,
but not the MSSM!







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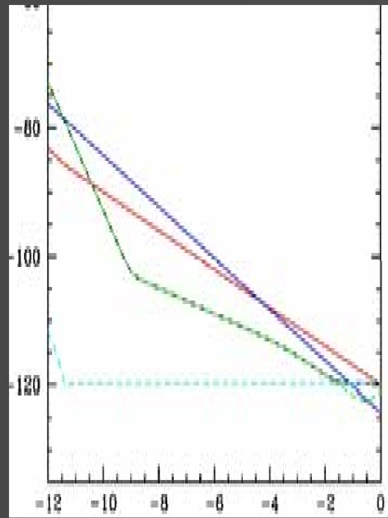
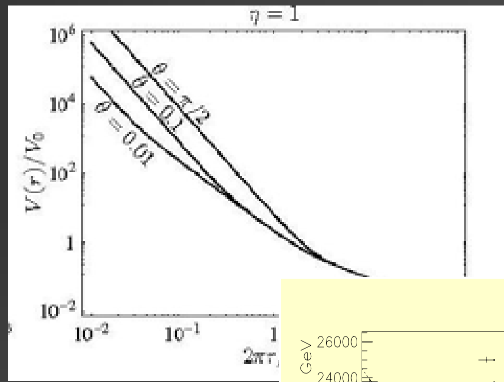
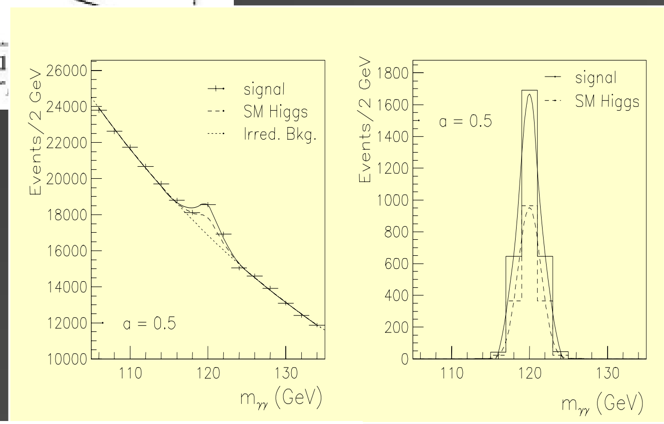
- Neutrino physics?



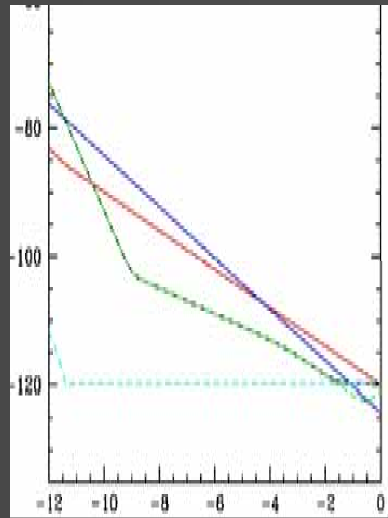


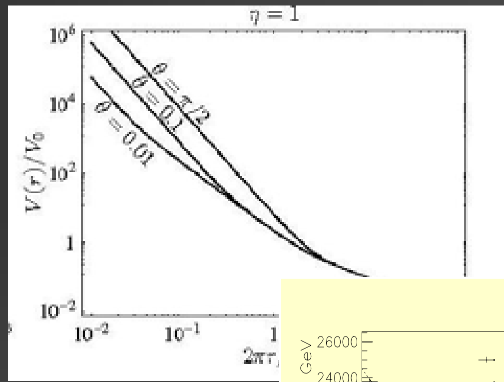


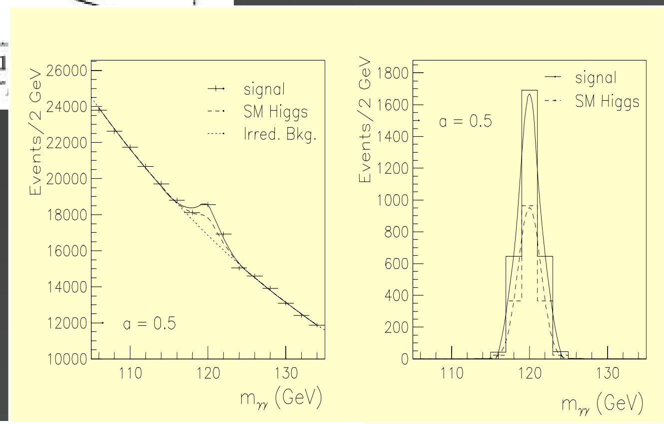
$$U \approx \begin{pmatrix} c_s(-1/\sqrt{2}-\delta/4) & c_s(1/\sqrt{2}-\delta/4) & 0 \\ c_s(1/2-\delta/4\sqrt{2}) & c_s(1/2+\delta/4\sqrt{2}) & 1/\sqrt{2} \\ c_s(1/2-\delta/4\sqrt{2}) & c_s(1/2+\delta/4\sqrt{2}) & -1/\sqrt{2} \end{pmatrix}$$

The Observational Tests

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







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- 6D braneworlds allow progress on the cosmological constant problem:
  - Vacuum energy not equivalent to curved 4D
  - ‘Flat’ choices stable against renormalization?

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  - Vacuum energy not equivalent to curved 4D
  - ‘Flat’ choices stable against renormalization?
- Tuned initial conditions
  - Much like for the Hot Big Bang Model..

Summary

- 6D braneworlds allow progress on the cosmological constant problem:
  - Vacuum energy not equivalent to curved 4D
  - ‘Flat’ choices stable against renormalization?
- Tuned initial conditions
  - Much like for the Hot Big Bang Model..
- Enormously predictive, with many observational consequences.
  - Cosmology at Colliders! Tests of gravity…

Detailed Worries and Observations

- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- Famous No-Go Arguments
- Problems with Cosmology
- Constraints on Light Scalars
- Quintessence cosmology
- Modifications to gravity
- Collider physics
- Neutrino physics?

Backup slides

The Worries

- ‘Technical Naturalness’
- *Runaway Behaviour*
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The Worries

Albrecht, CB, Ravndal, Skordis
Tolley, CB, Hoover & Aghababaie
Tolley, CB, de Rham & Hoover

- ‘Technical N
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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

- 'Technical Naturalness'
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- Problems with Cosmology
- Constraints on Light Scalars

The Worries

Salam & Sezgin

- ‘Technical N
- Runaway Bel
- *Stabilizing th*
- Famous No-G
- Problems wit
- 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

- ‘Techn
- Runaw
- *Stabiliz*
- Famou
- Probler
- Constra

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

Potential domination when:

$$V' \approx 0 \quad if \quad r\,M \approx \exp(a/b)$$

Canonical Variables:

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

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

The Worries

Albrecht, CB, Ravndal, Skordis

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Canonical Variables:

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

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

The Worries

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

The Worries

- ‘Technical N
- Runaway Bel
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- *Famous No-G*
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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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- *Famous No-G*
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- Constraints on Light Scalars

- *Weinberg’s No-Go Theorem*:

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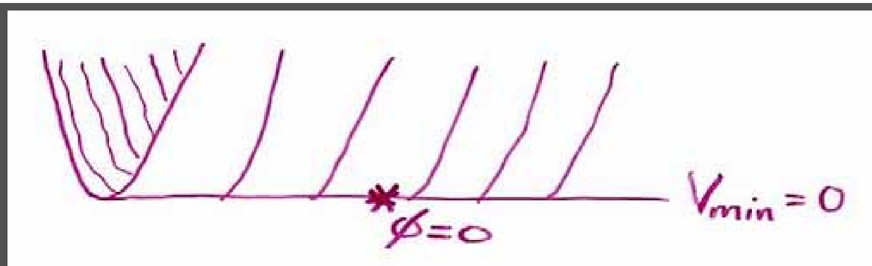
eg: $V_{eff} = \lambda_{ijkl}\, \phi^i \phi^j \phi^k \phi^l$ with flat dir^n.



The Worries

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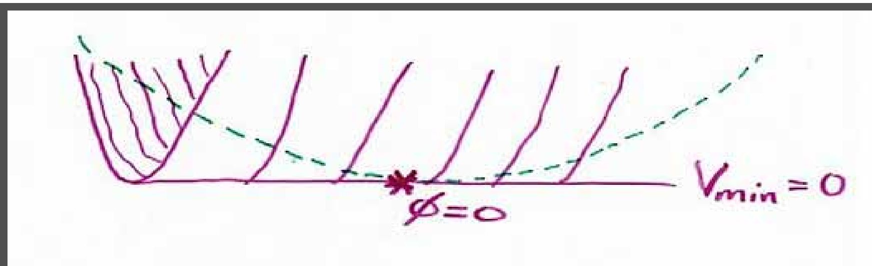

$\approx \lambda\,\phi^4$

The Worries

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

- *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
- *Fa*
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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 \mu 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
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- *Problems with Cosmology*
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The Worries

- ‘Technical N
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- Constraints o

- *Post BBN*:

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

The Worries

- ‘Technical N
- Runaway Be
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- Famous No-G
- *Problems wit*
- Constraints o

- *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

- ‘Technical N
- Runaway Be
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- *Problems wit*
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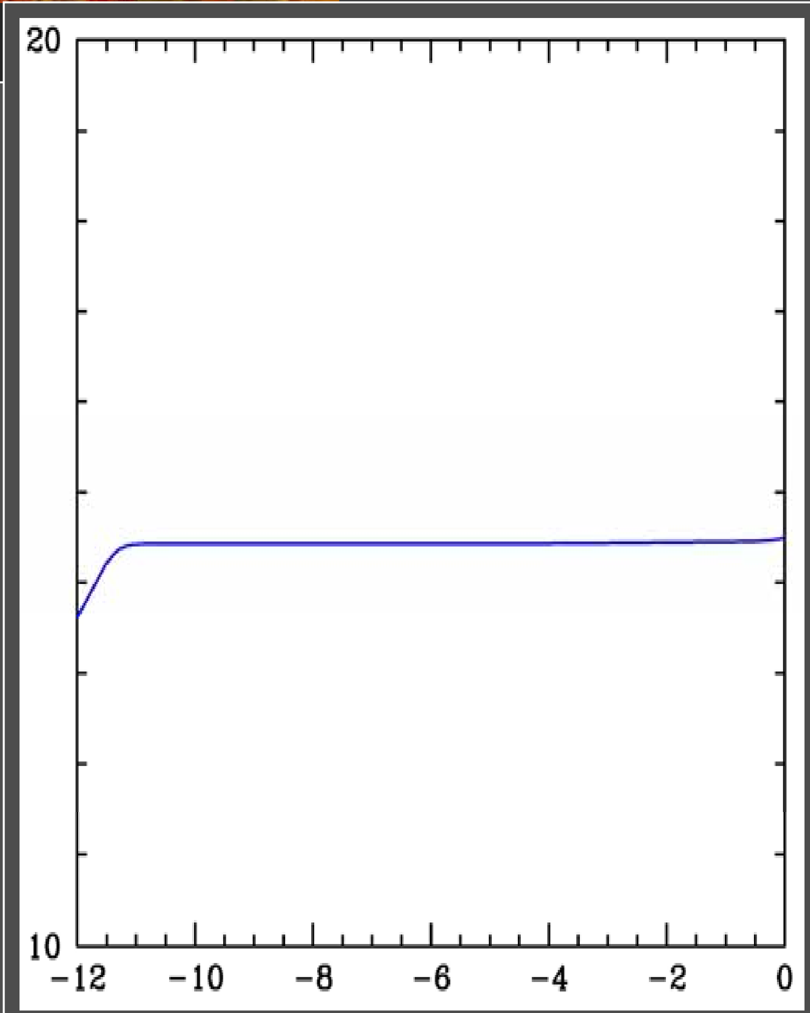

log *r* vs log *a*

The Worries

- 'Technical N
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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

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

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

The Worries

- ‘Technical Naturalness’
- Runaway Behaviour
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The Worries

- ‘Technical N
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- Problems wit
- *Constraints c*

- *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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- *Constraints o*

- *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.*

The Worries

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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 Worries

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- *Constraints c*

- *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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- Problems wit
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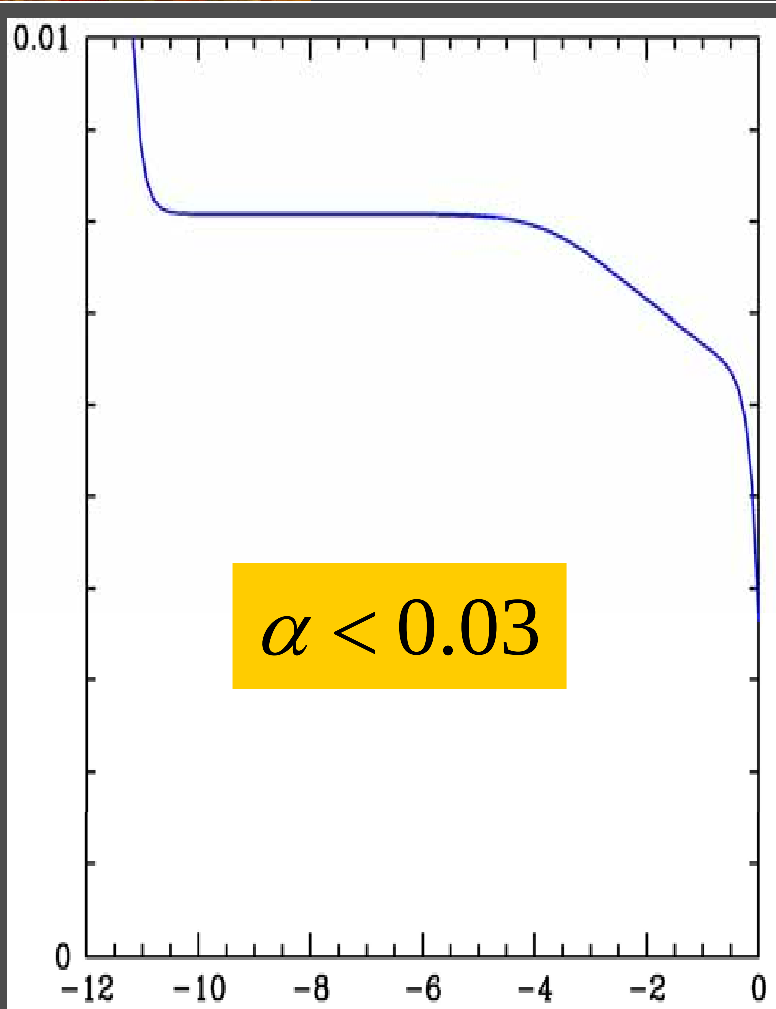

α *vs* log *a*

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

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.

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* ... *energy*
- Modifications t ... *calar*
- Collider physic
- Neutrino physi
- Astrophysics

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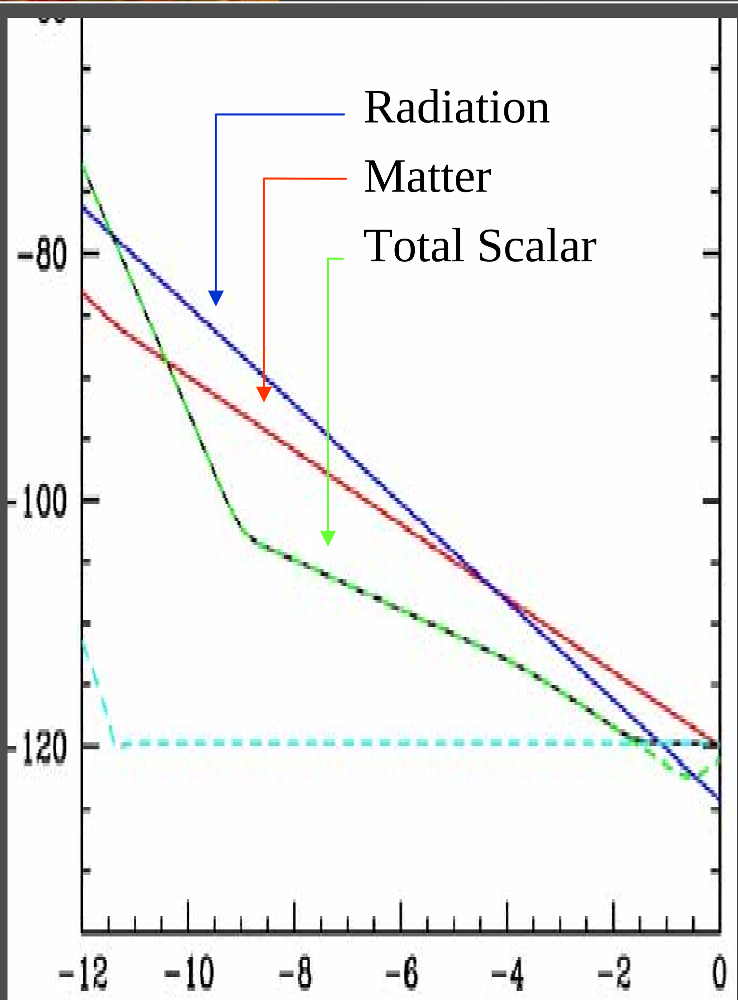
Observational Consequences

Albrecht, CB, Ravndal & Skordis

- *Quintessence c* ... *uum energy* ... *tion.*
- Modifications t ... *of scalar* ... *ire*
- Collider physic
- Neutrino physi
- Astrophysics

Albrecht- ... *of potential* ... *tudies* ... *possible to* ... *osmology:* ... *; BBN;…*



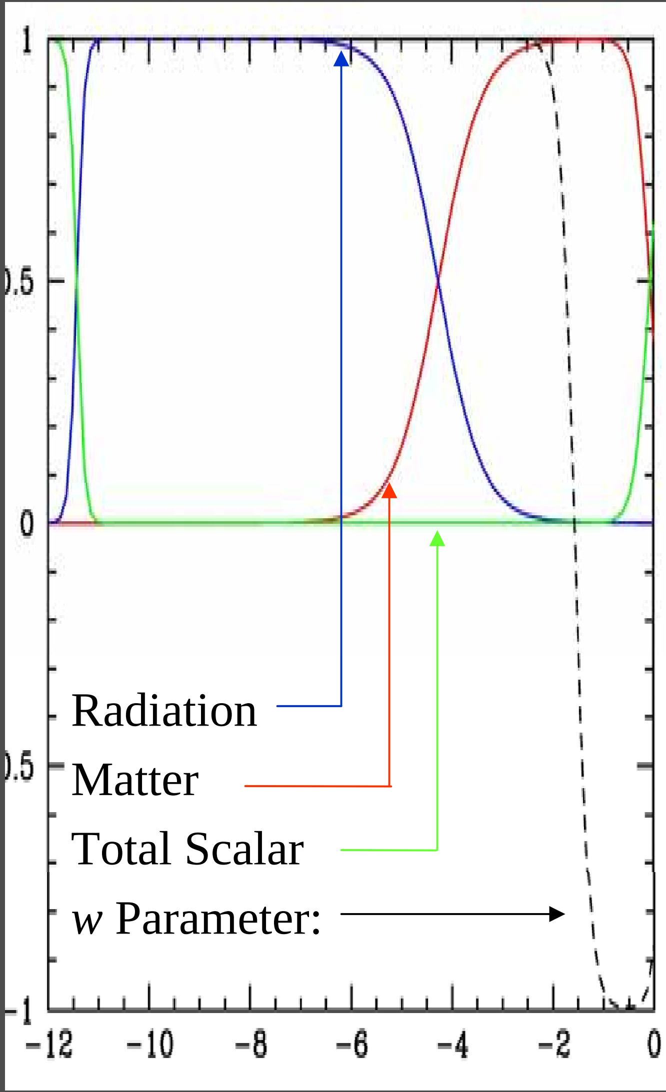
log ρ *vs* log *a*

Observational Consequences

Albrecht, CB, Ravndal & Skordis

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

Ω and w vs log a



$\Omega_\Lambda \sim 0.7$

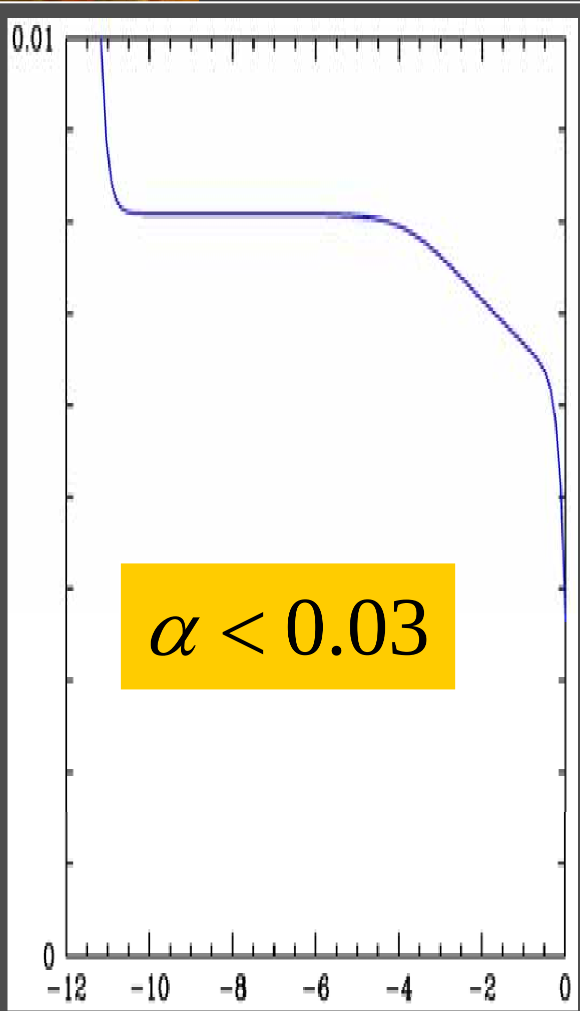
$\Omega_m \sim 0.25$

$w \sim -0.9$

Observational Consequences

Albrecht, CB, Ravndal & Skordis

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



α *vs* log *a*

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Observational Consequences

Albrecht, CB, Ravndal & Skordis

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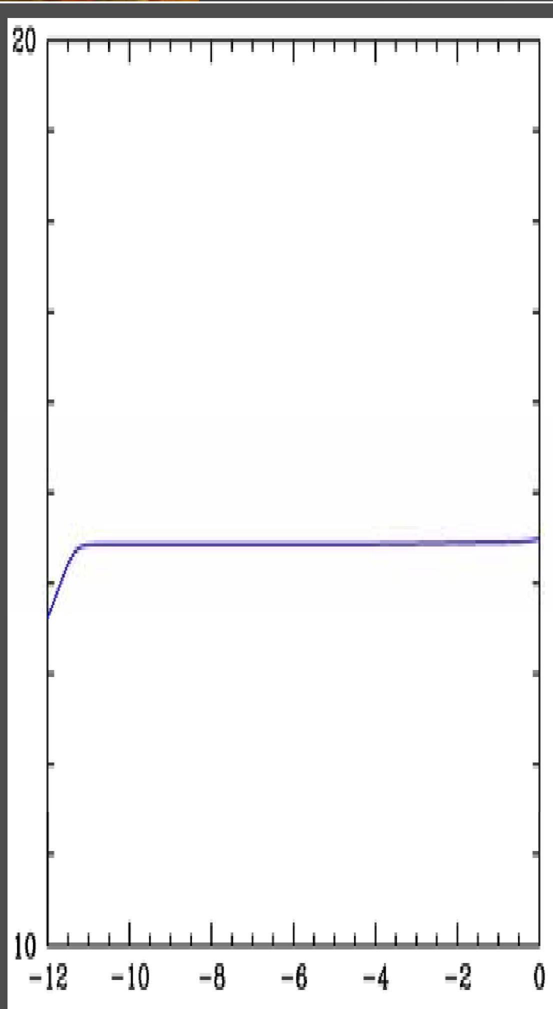

log *r* vs log *a*

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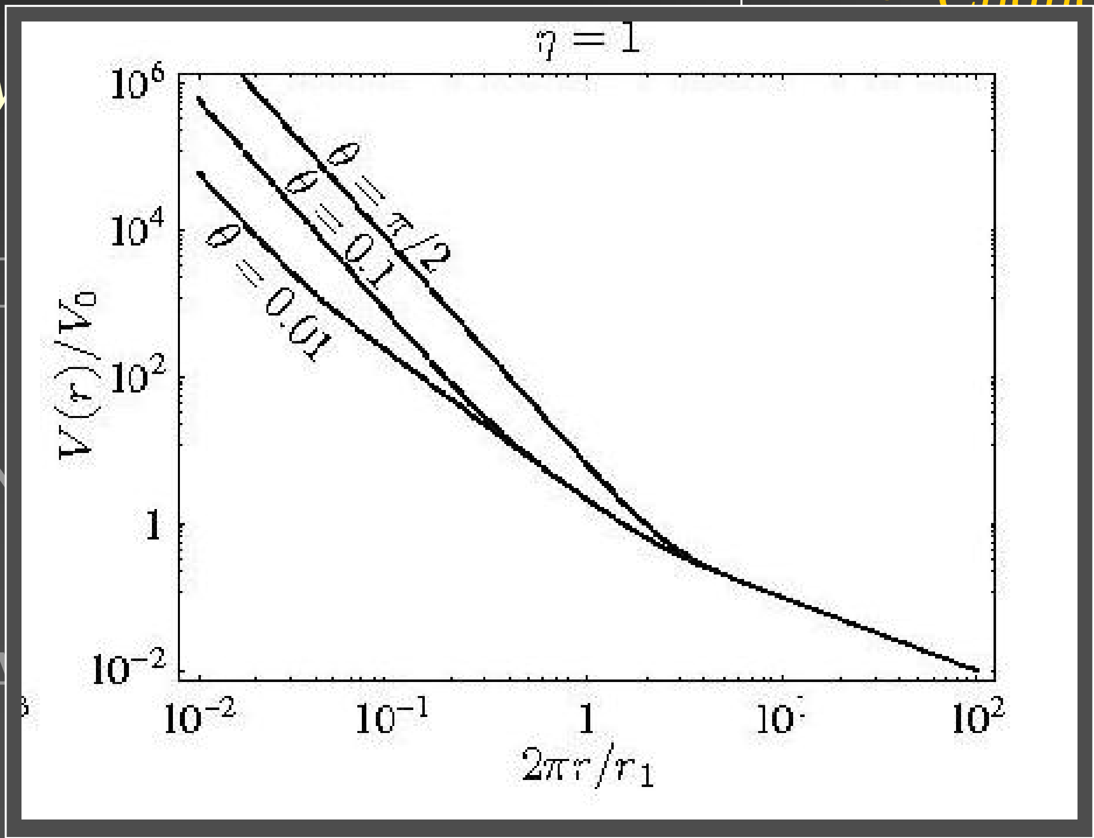
Observational Consequences

- 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*
  - *-tensor theory out*
  - *ances of order H_0.*

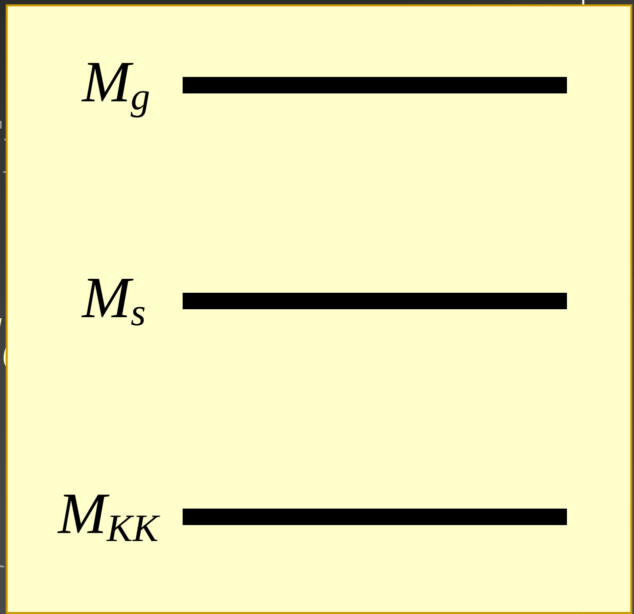
Observational Consequences

- 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

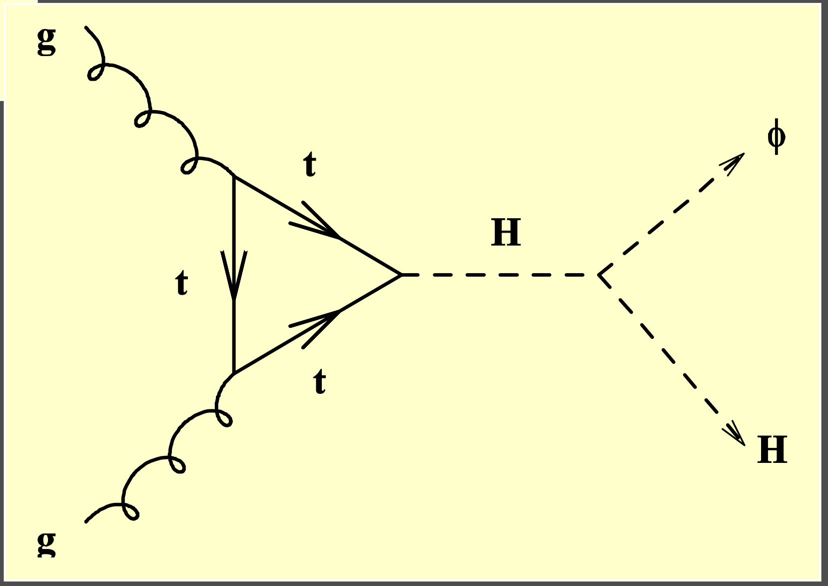
Observational Consequences

Azuelos, Beauchemin & CB

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

Dimensionless coupling!
O(0.1-0.001) from loops

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



Observational Consequences

Azuelos, Beauchemin & CB

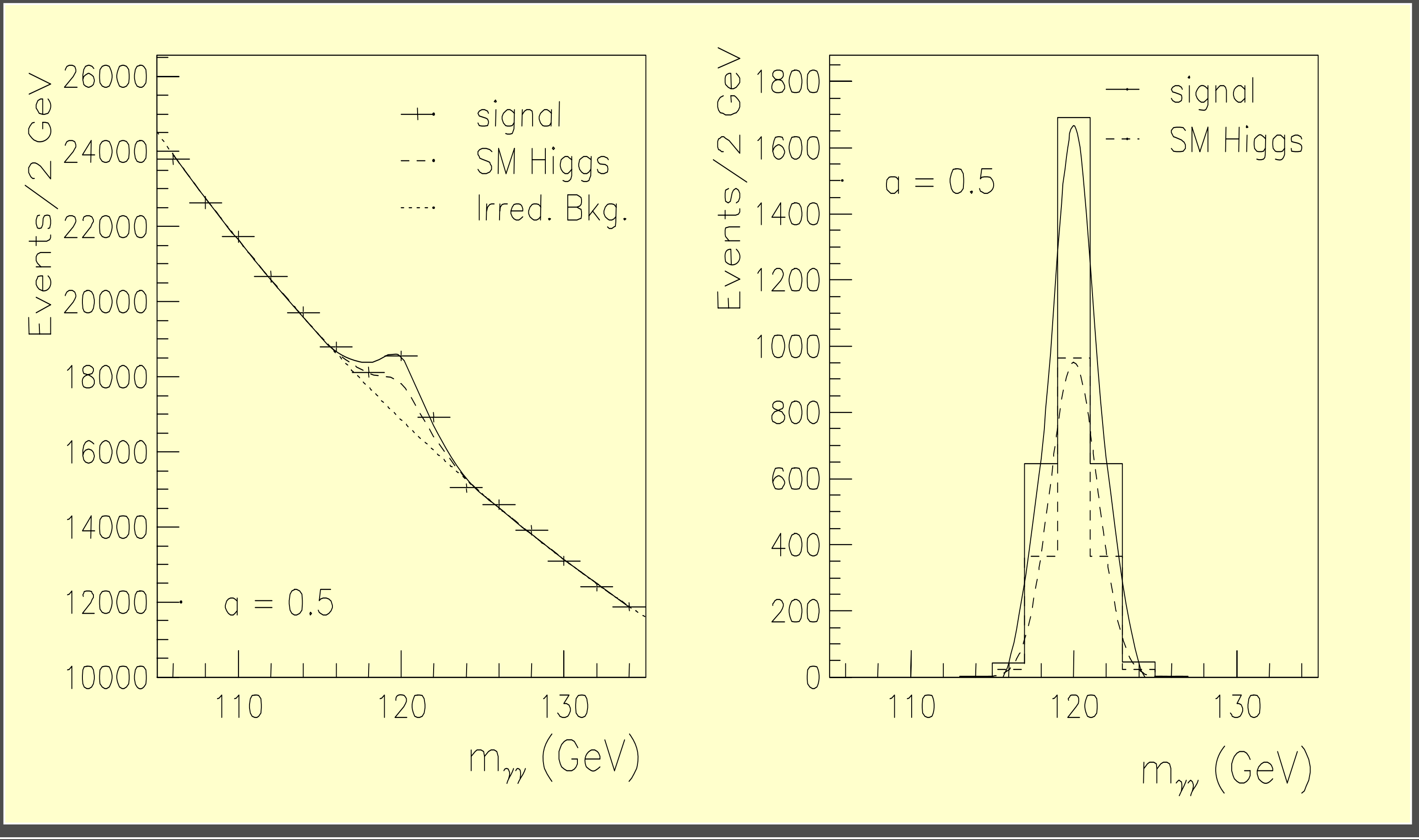
Table 2. SM backgrounds to the production of bulk scalars in association with the Higgs particle at ATLAS, their cross-section (for an $E_T^{\rm cut}$ of 23 GeV) and the total number of events expected at ATLAS for an integrated luminosity of 100 fb^{-1} (after application of rejection factors).

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*

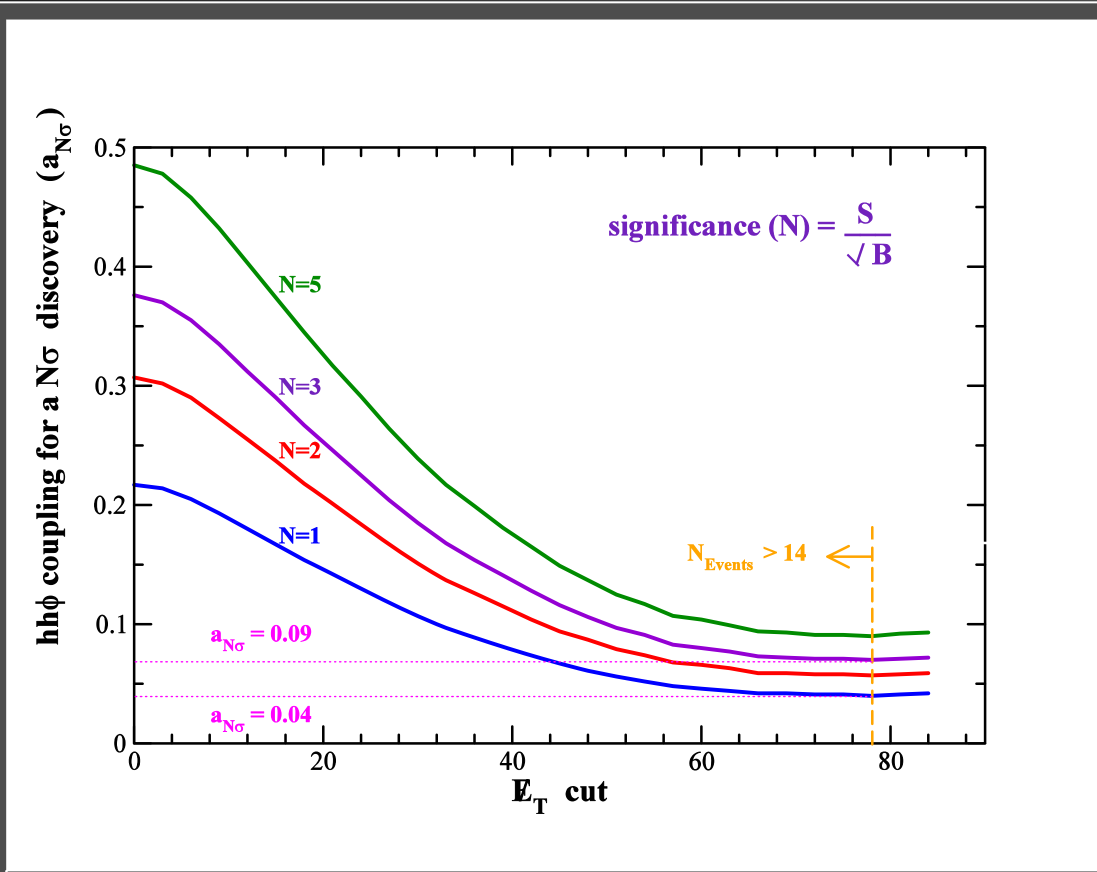
Observational Consequences

Azuelos, Beauchemin & CB



Observational Consequences

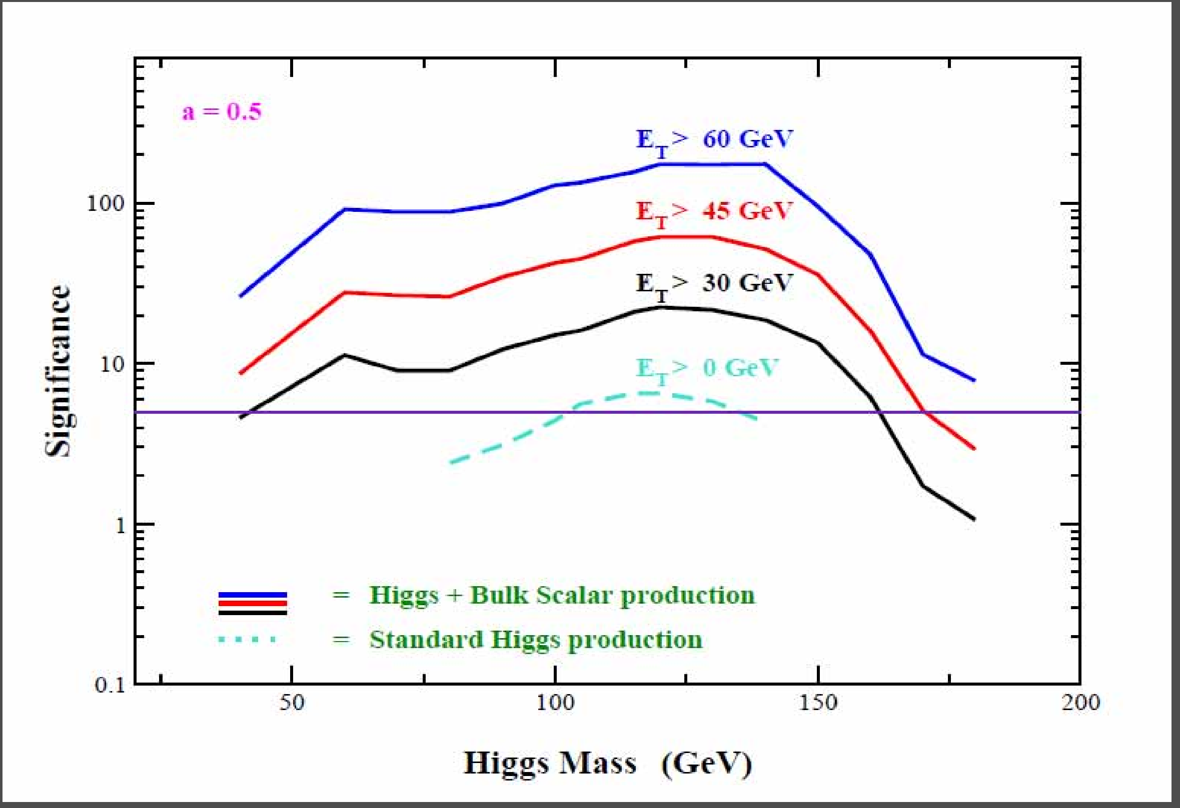
Azuelos, Beauchemin & CB



- *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
$\boldsymbol{\lambda \sim 1/M_g}$

Observational Consequences

Matias, CB

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

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

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

Dimensionful c
$\lambda \sim 1/M_g$

Constrained by bounds on sterile neutrino emission

Require observed masses and large mixing.

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

Observational Consequences

Matias, CB

- 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.

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

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

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 ($\theta_i \sim g/c_i$).

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

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

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

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;…*