Extra Dimensions and the Cosmological Constant Problem

Cliff Burgess

Stockholm 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:**
  - *A. Albrecht, F. Ravndal, C. Skordis*

The Plan

- The Cosmological Constant problem
  - Technical Naturalness in Crisis
- How extra dimensions might help
  - Changing how the vacuum energy gravitates
- Making things concrete
  - 6 dimensions and supersymmetry
- Prognosis
  - Technical worries
  - Observational tests

‘Naturalness’ as an Opportunity

- Cosmology alone cannot distinguish amongst the various models of Dark Energy.
- The features required by cosmology are difficult to sensibly embed into a fundamental microscopic theory.
- *Progress will come by combining both*

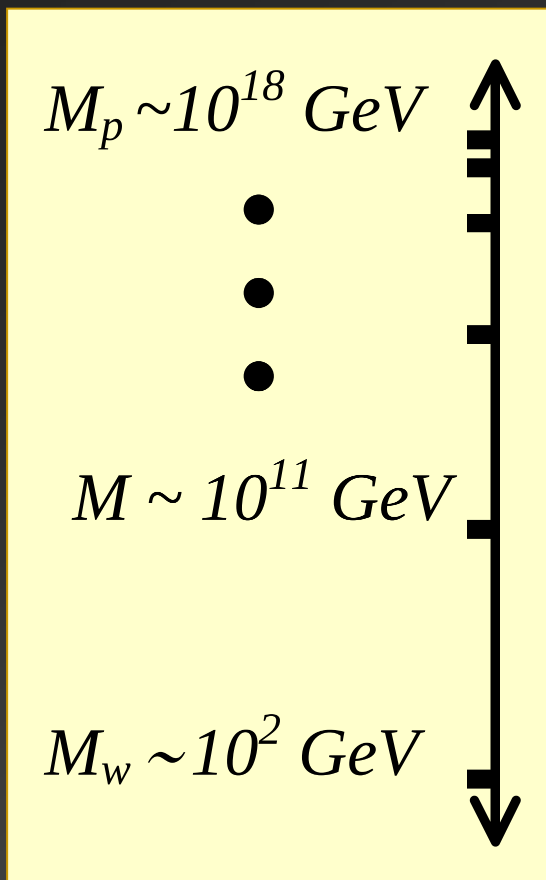
Naturalness

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

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

Naturalness

- Ide… are
  lar…
  - …ory.



BUT: effective theory can be defined at many scales

$$m^2 \approx m_1^2 + kM^2 + \cdots$$

$$m^2 \approx m_0^2 + \cdots$$

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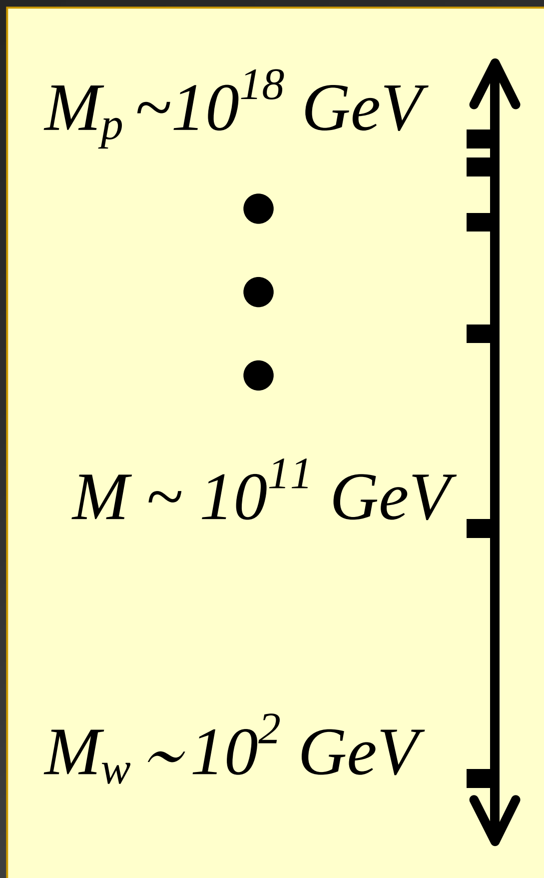

BUT: effective theory can be defined at many scales

$$m^2 \approx m_1^2 + kM^2 + \cdots$$

$$m^2 \approx m_0^2$$

Must cancel to 20 decimal places!!

Naturalness

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…?

- 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 $m^2 \sim M_B^2 - M_F^2$*

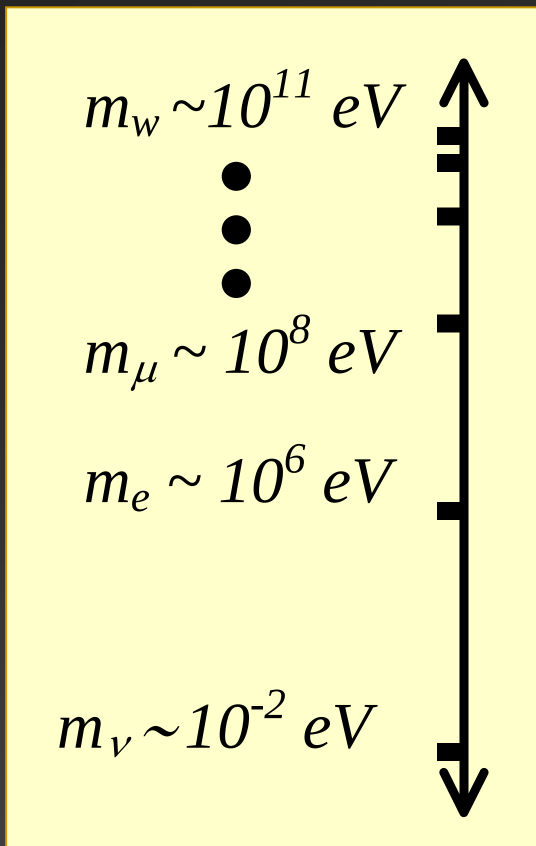
  Extra Dimensions: *the fundamental scale is much smaller than M_p, much as*
  $G_F^{-1/2} > M_W$

Naturalness in Crisis

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

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

Naturalness in Crisis



- Can apply same argument to scales between TeV and sub-eV scales.

$$\mu^4 \approx \mu_1^4 + k_e m_e^4 + k_\nu m_\nu^4$$

$$\mu^4 \approx \mu_0^4 + k_\nu m_\nu^4$$

Must cancel to 32 decimal places!!

Naturalness in Crisis

- Id
  lar
  -

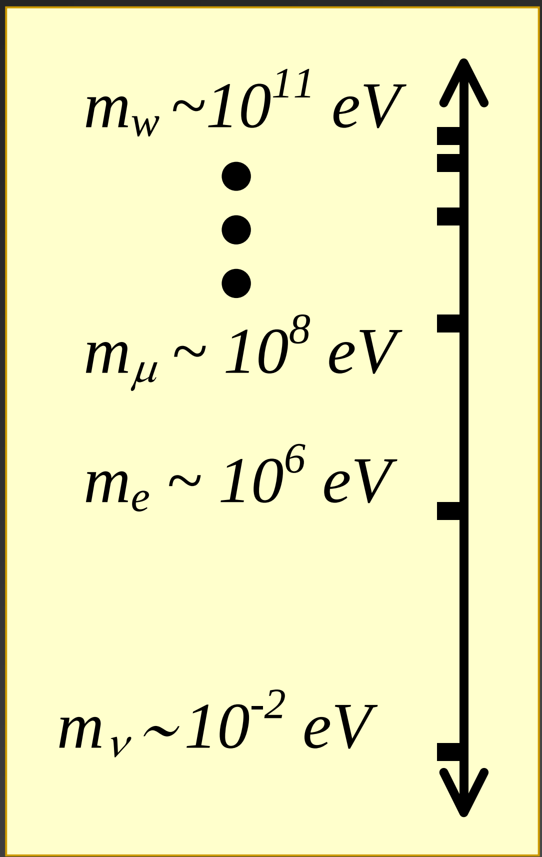
L

Harder than the Hierarchy problem:

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

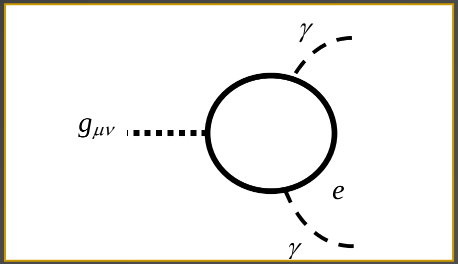
Cosmological constant problem: *Why is $\mu \sim 10^{-3}$ eV rather than m_e , M_w , M_{GUT} or M_p?*

Naturalness in Crisis

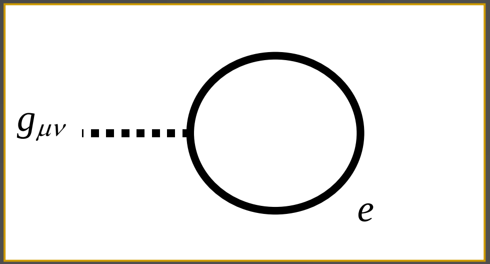
- 

Seek to 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!*

- *Why this?*



But not this?



Naturalness in Crisis

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??

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  - 6 dimensions and supersymmetry
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  - Observational tests

How Extra Dimensions Help

- 4D CC *vs* 4D vacuum energy

- Branes and scales

How Extra Dimensions Help

- *4D C*[partially hidden] *vacuu*[partially hidden]
- Brane[partially hidden]

A *cosmological constant*

$$G_{\mu\nu} + \underline{\Lambda g_{\mu\nu}} = 8\pi G\, T_{\mu\nu}$$

How Extra Dimensions Help

- *4D CC*
  vacuu

- Brane

A *cosmological constant* is not distinguishable from a Lorentz invariant *vacuum energy*

$$G_{\mu\nu} + \underline{\Lambda g_{\mu\nu}} = 8\pi G\, T_{\mu\nu}$$

vs

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

How Extra Dimensions Help

- *4D CC ... vacuu...*
- Brane...

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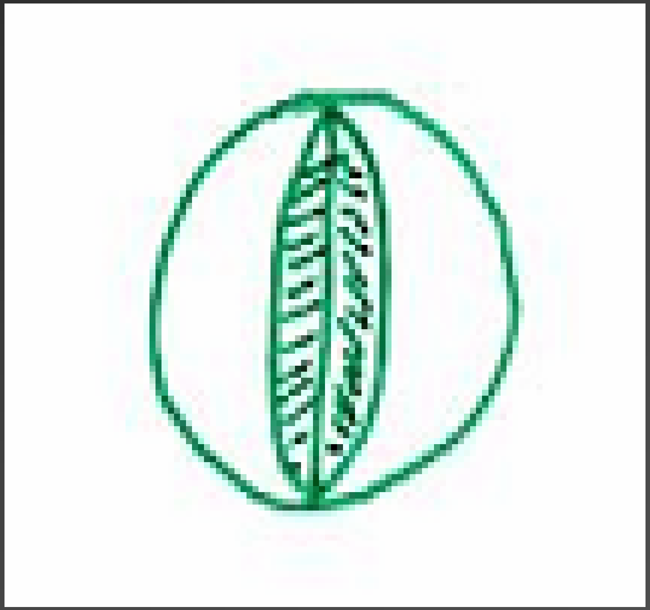
* *in 4 dimensions…*

How Extra Dimensions Help

- 4D ...
  vac...
- *Bro...*

In higher dimensions a 4D vacuum energy, *if localized in the extra dimensions*, can curve the extra dimensions instead of the observed four.

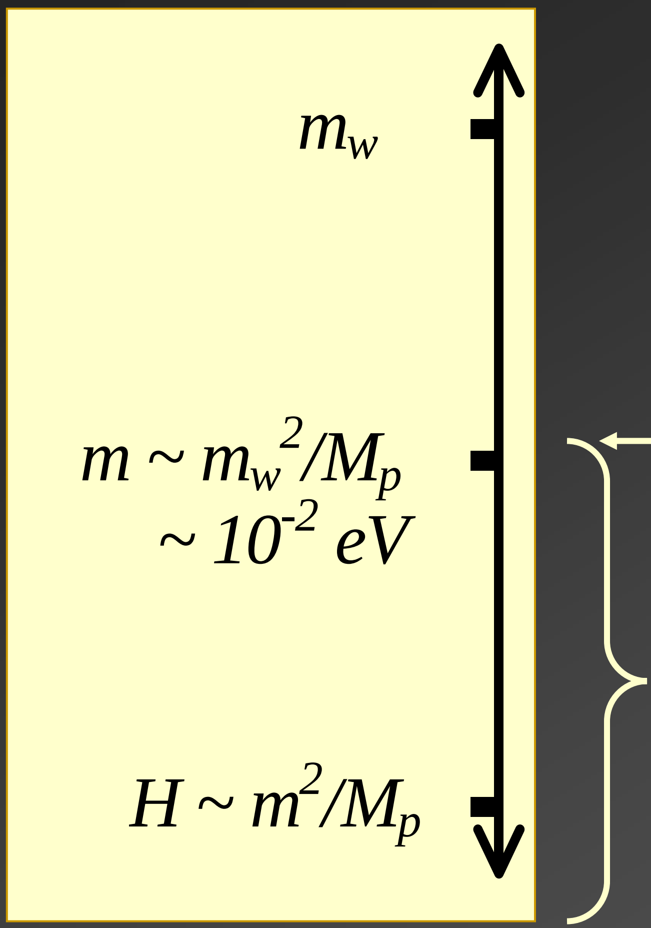


Arkani-Hamad et al
Kachru et al,
Carroll & Guica
Aghababaie, et al

How Extra Dimensions Help

Arkani Hamed, Dvali, Dimopoulos

- 4D vac
- *Br*

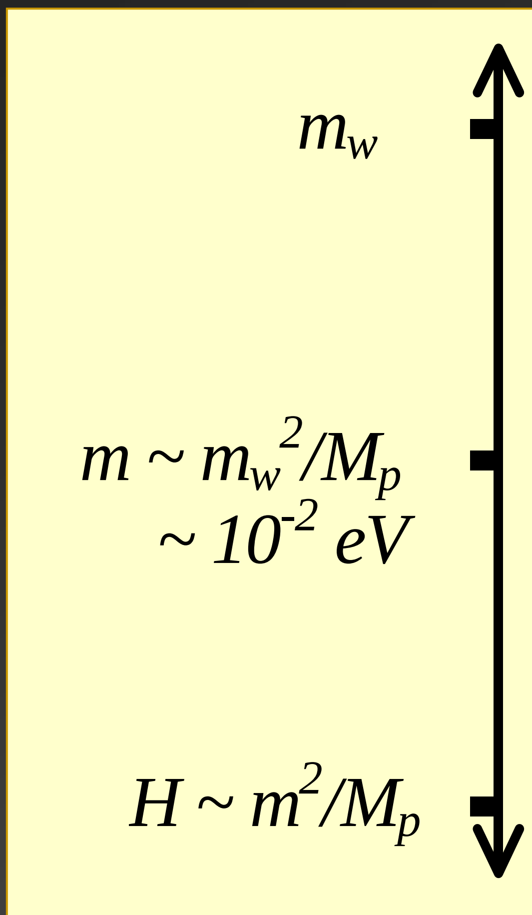


Extra dimensions could start here, if there are only two of them.

These scales are natural using standard 4D arguments.

How Extra Dimensions Help

- 4D
  vac
- *Bro*



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

SM interactions do not change at all!

Only gravity gets modified over the most dangerous distance scales!

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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.

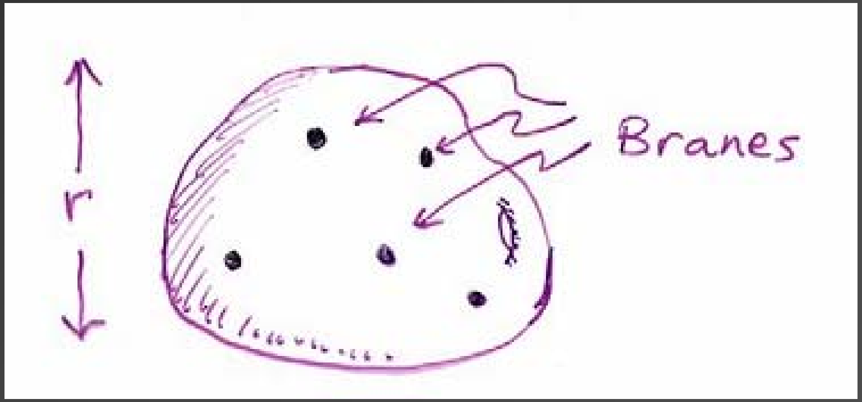
The SLED Proposal

Arkani-Hamad, Dimopoulos & Dvali

- *Suppose p*
  extra-dime
  above the

- Suppose t
  the bulk is
  supersymm

- 6D gravity scale: $M_g \sim 10$ TeV
- KK scale: $1/r \sim 10^{-2}$ eV
- Planck scale: $M_p \sim M_g^2\, r$



The SLED Proposal

Nishino & Sezgin

- Suppose p
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- 6D gravity scale: $M_g \sim 10$ TeV
- KK scale: $1/r \sim 10^{-2}$ eV
- Planck scale: $M_p \sim M_g^{\,2}\, r$
- Choose bulk to be supersymmetric
(no 6D CC allowed)

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

The SLED Proposal

- Suppose p
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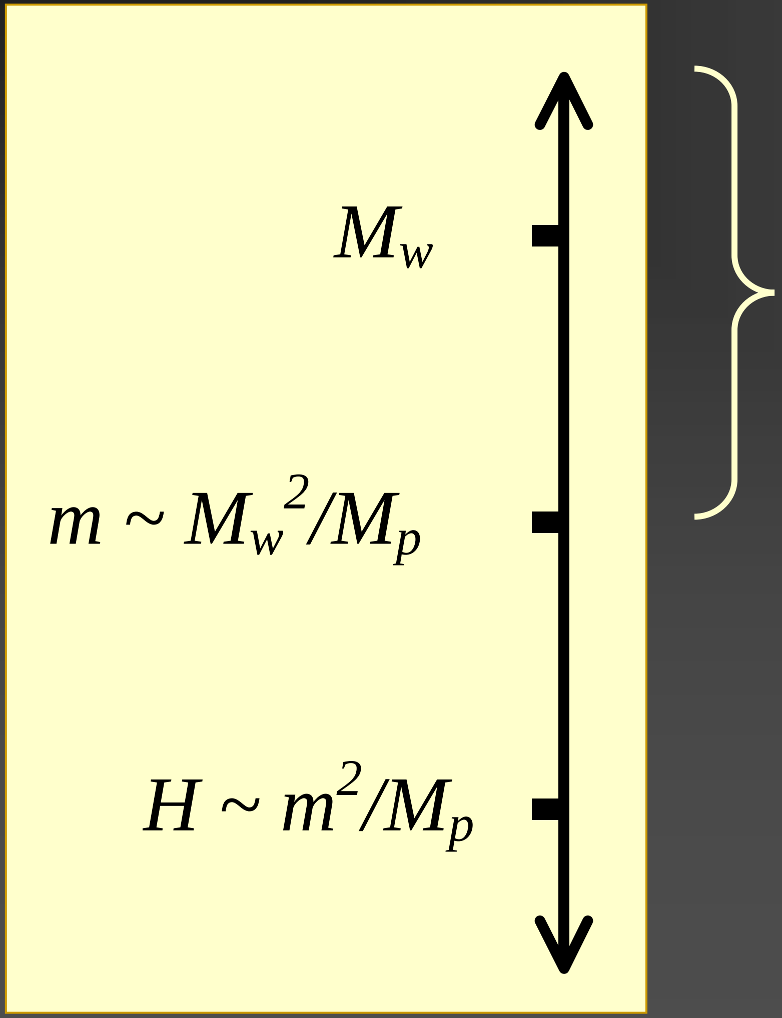
- Suppose th

- 6D gravity scale: $M_g \sim 10$ TeV
- KK scale: $1/r \sim 10^{-2}$ eV
- Planck scale: $M_p \sim M_g^2\, r$
- SUSY Breaking on brane: TeV
  in bulk: $M_g^2/M_p \sim 1/r$

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

The SLED Proposal

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

Classical flat direction due to a scale invariance of the classical equations

NOT self-tuning: response to a kick is runaway along flat direction.

rum:

no partners

es in bulk

$H \sim m^2/M_p$

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

4D graviton

What Needs Understanding

- 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?

What Needs Understanding

- Clas
  argu
  - W
    m
    fl
- Qua
  argu
  - A
    ag

- *Search for solutions to 6D supergravity:*
  - *What bulk geometry arises from a given brane configuration?*
  - *What is special about the ones which are 4D flat?*

What Needs Understanding

- Clas
  argu

- C
  a

- *Search for solutions to 6D supergravity:*

$$\Box\,\varphi + \frac{1}{6}\,e^{-2\varphi}\,G_{MNP}\,G^{MNP} + \frac{1}{4}\,e^{-\varphi}\;F^{\alpha}_{MN}F^{MN}_{\alpha} - e^{\varphi}\,v(\Phi) = 0$$

$$D_M\left(e^{-2\varphi}\,G^{MNP}\right) = 0$$

$$D_M\left(e^{-\varphi}\,F^{MN}_{\alpha}\right) + e^{-2\varphi}\,G^{MNP}\,F_{\alpha MP} = 0$$

$$D_M D^M \Phi^a - G^{ab}(\Phi)\,v_b(\Phi)\,e^{\varphi} = 0$$

$$R_{MN} + \partial_M\varphi\,\partial_N\varphi + G_{ab}(\Phi)\,D_M\Phi^a\,D_N\Phi^b + \frac{1}{2}\,e^{-2\varphi}\,G_{MPQ}\,G_N{}^{PQ}$$
$$+\,e^{-\varphi}\,F^{\alpha}_{MP}F_{\alpha N}{}^{P} + \frac{1}{2}\,(\Box\varphi)\,g_{MN} = 0,$$

What Needs Understanding

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- Search for solutions to 6D supergravity:

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$$\ldots G_{MPQ} G_N{}^{PQ}$$

- Chiral gauged supergravity chosen to allow extra dimensions topology of a sphere:

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

What Needs Understanding

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- Many classes of axially symmetric solutions known
  - Up to two singularities, corresponding to presence of brane sources
  - Brane sources characterized by:

$$S = \int \mathrm{d}^4 x \sqrt{g}\, T(\phi)$$

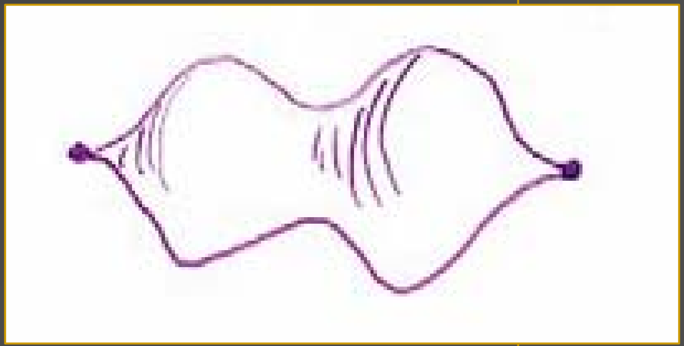
- Asymptotic near-brane behaviour is related to properties of $T(\phi)$.
  - $dT/d\phi$ nonzero implies curvature singularity

What Needs Understanding

- Clas argu
  - W m fl
- Qua argu
  - A ag

- Static solutions having only conical singularities are all 4D flat
  - Unequal defect angles imply warping.
- Flat solutions with curvature singularities exist. *Gibbons, Guvens & Pope*
- Static solutions exist which are 4D dS.
- Runaways are generic.

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



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- *When both branes have conical singularities all static solutions have 4D minkowski geometry.*

What Needs Understanding

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- *When both branes have conical singularities all static solutions have 4D minkowski geometry.*
- *Conical singularities require vanishing dilaton coupling to branes (and hence scale invariant)*

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- *Bulk loops can generate brane-dilaton coupling but TeV scale modes are suppressed at one loop by 6D supersymmetry*
- *Each bulk loop costs power of $e^{\phi} \sim 1/r^2$ and so only a few loops must be checked…..*

The Plan

- The Cosmological Constant problem
  - Why is it so hard?
- How extra dimensions might help
  - Changing how the vacuum energy gravitates
- Making things concrete
  - 6 dimensions and supersymmetry
- Prognosis
  - Technical worries
  - Observational tests

Prognosis

- Theoretical worries
- Observational tests

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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The Worries

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

- ‘Technical N
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- Constraints on Light Scalars

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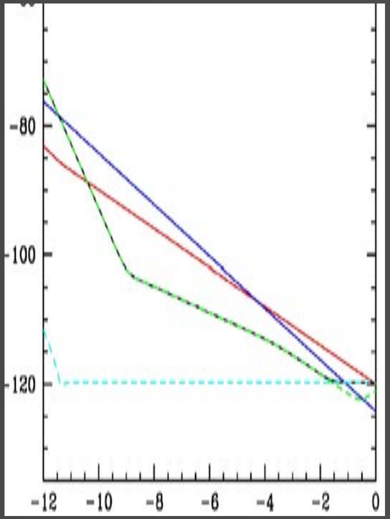
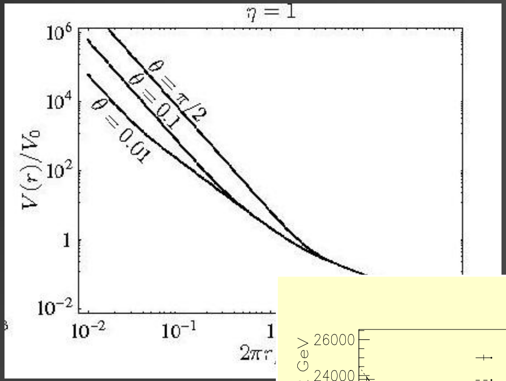
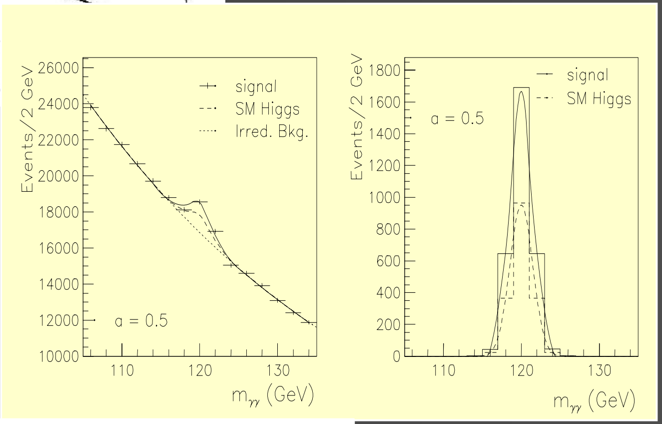
- Most brane properties and initial conditions do not lead to anything like the universe we see around us.
  - For many choices the extra dimensions implode or expand to infinite size.
- *Initial condition problem:* much like the Hot Big Bang, possibly understood by reference to earlier epochs of cosmology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

The Observational Tests

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







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

Summary

- It is the interplay between cosmological phenomenology and microscopic constraints which will make it possible to solve the Dark Energy problem.
  - Technical naturalness provides a crucial clue.
- 6D brane-worlds allow progress on technical naturalness:
  - Vacuum energy not equivalent to curved 4D
  - Are ‘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
- *Stabilizing the Extra Dimensions*
- Famous No-Go Arguments
- Problems with Cosmology
- Constraints on Light Scalars

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

- ‘Techn
- Runaw
- *Stabiliz*
- Famous
- 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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Hubble damping can allow potential domination for exponentially large r, even though r is not stabilized.

The Worries

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The Worries

Nilles et al
Cline et al
Erlich et al

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- *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:

$$T_1 + T_2 = 0$$

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Nilles et al
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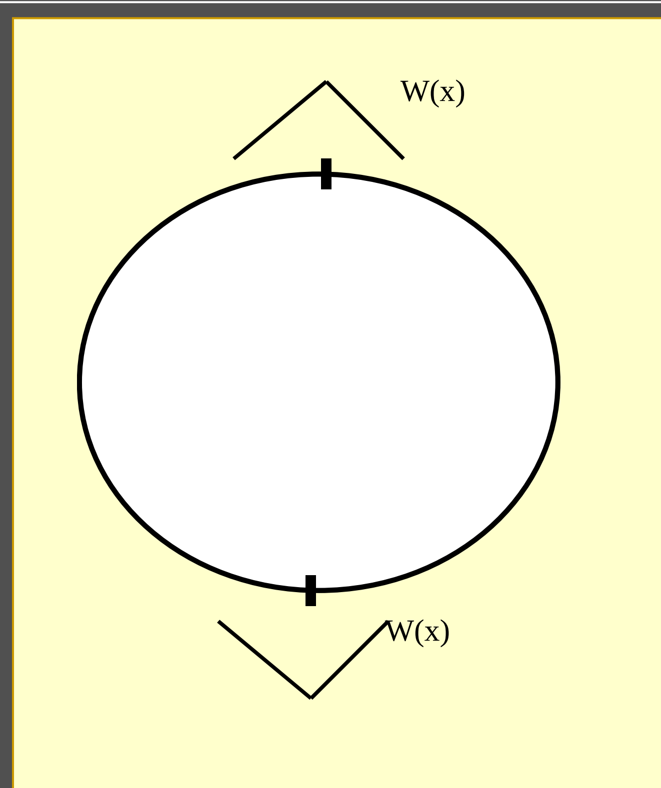

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$$T_1 + T_2 = 0$$

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

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

The Worries

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- *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 ΣT_b nonzero then R becomes nonzero*

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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

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

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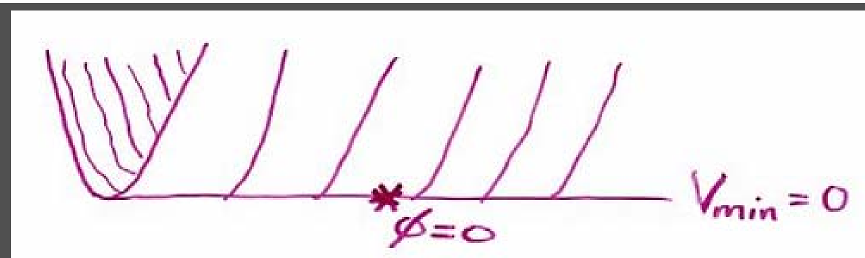
Steven Weinberg has a general objection to self-tuning mechanisms for solving the cosmological constant problem that are based on scale invariance

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



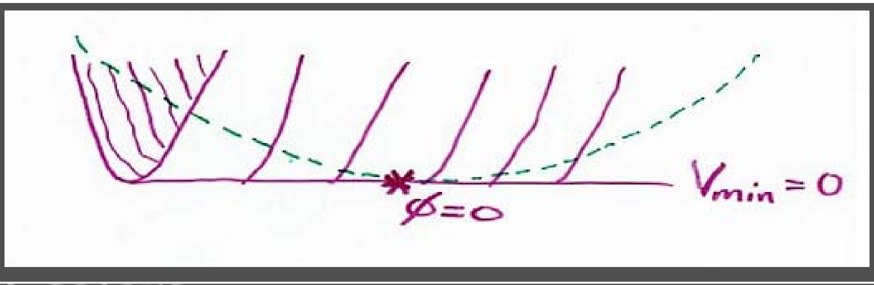
The Worries

- ‘Technical N
- Runaway Be
- Stabilizing th
- *Famous No-G*
- Problems wit
- Constraints on Light Scalars

- *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

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



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

The Worries

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- *Famous No-G*
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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
- *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 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*
- Constraints on Light Scalars

The Worries

- ‘Technical N
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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*.

The Worries

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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*.

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 Bel
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- *Problems wit*
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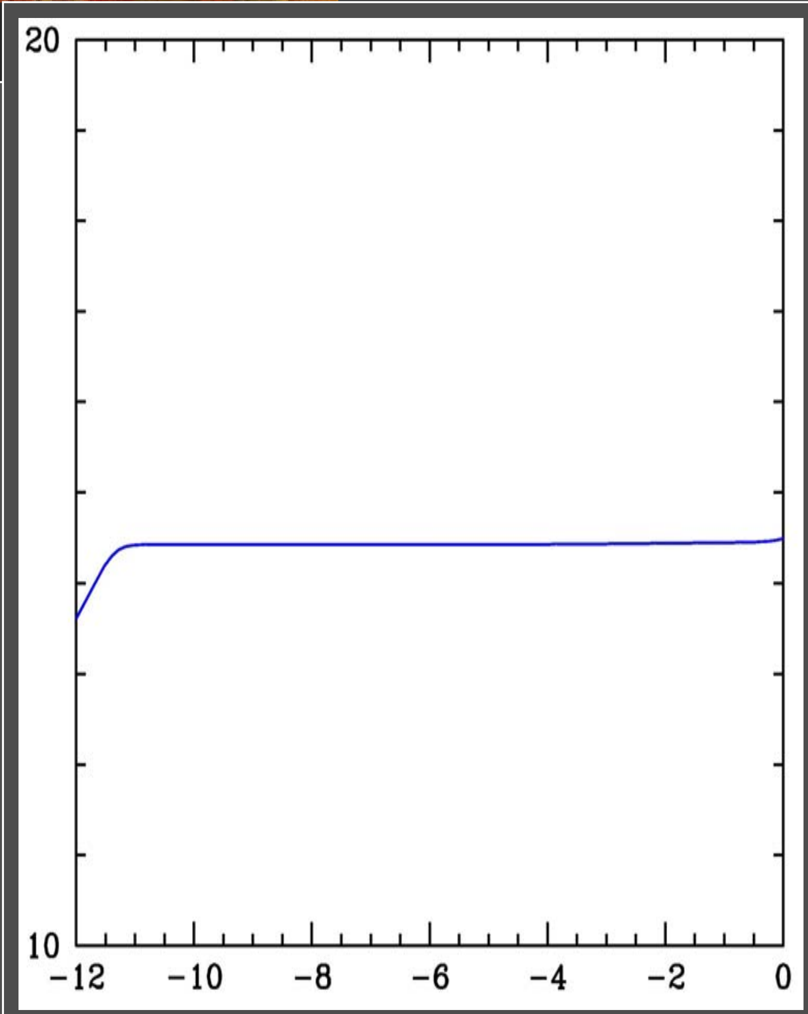

log *r vs* log *a*

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
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- Problems with Cosmology
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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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- Famous No-G
- 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?

Given a potential of the form

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

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?

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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

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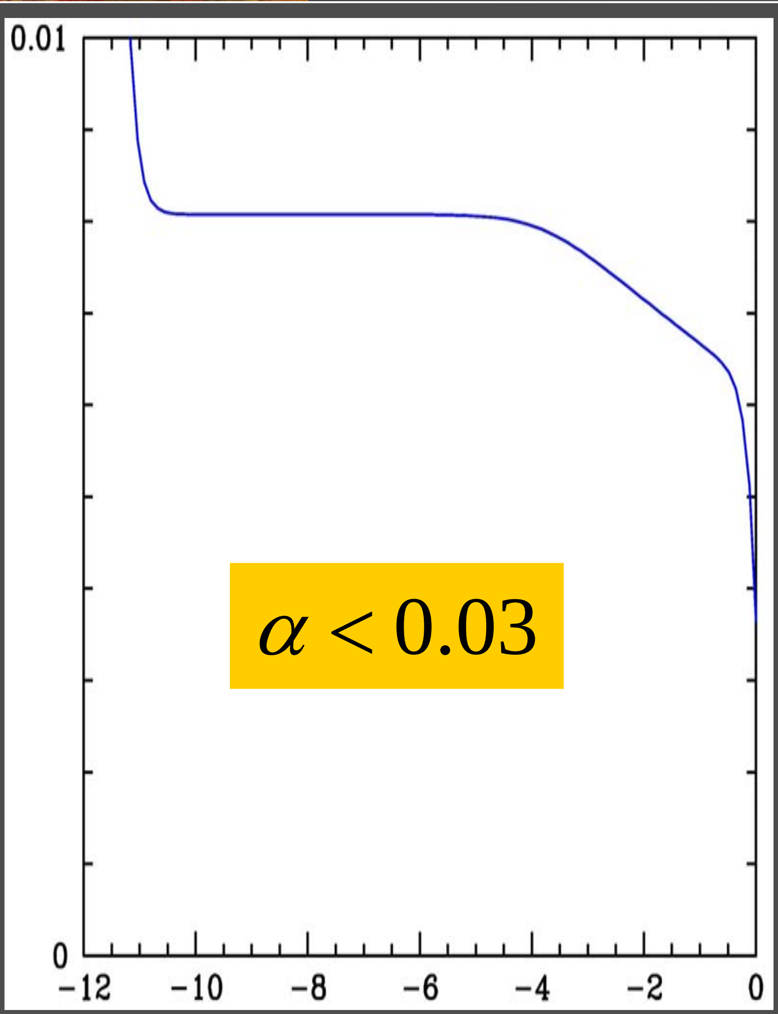

α *vs* log *a*

The Worries

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

Potential domination when:

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

Canonical Variables:

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

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

Observational Consequences

Albrecht, CB, Ravndal & Skordis

- *Quintessence c*
- Modifications t
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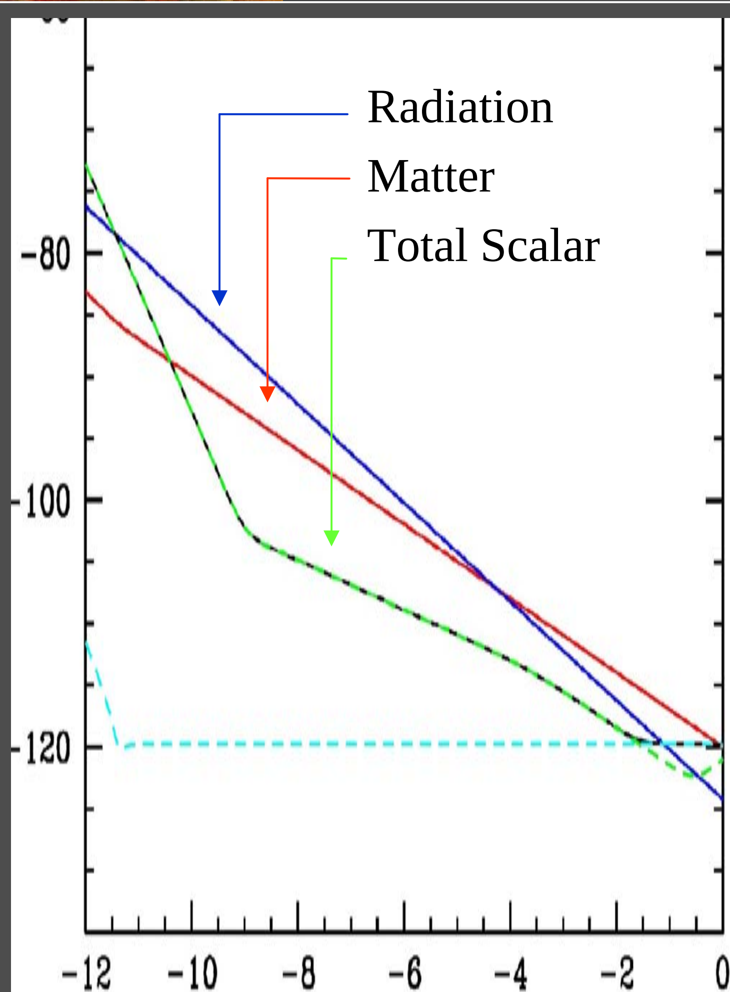

log ρ *vs* log *a*

Observational Consequences

Albrecht, CB, Ravndal & Skordis

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- C
- N
- A

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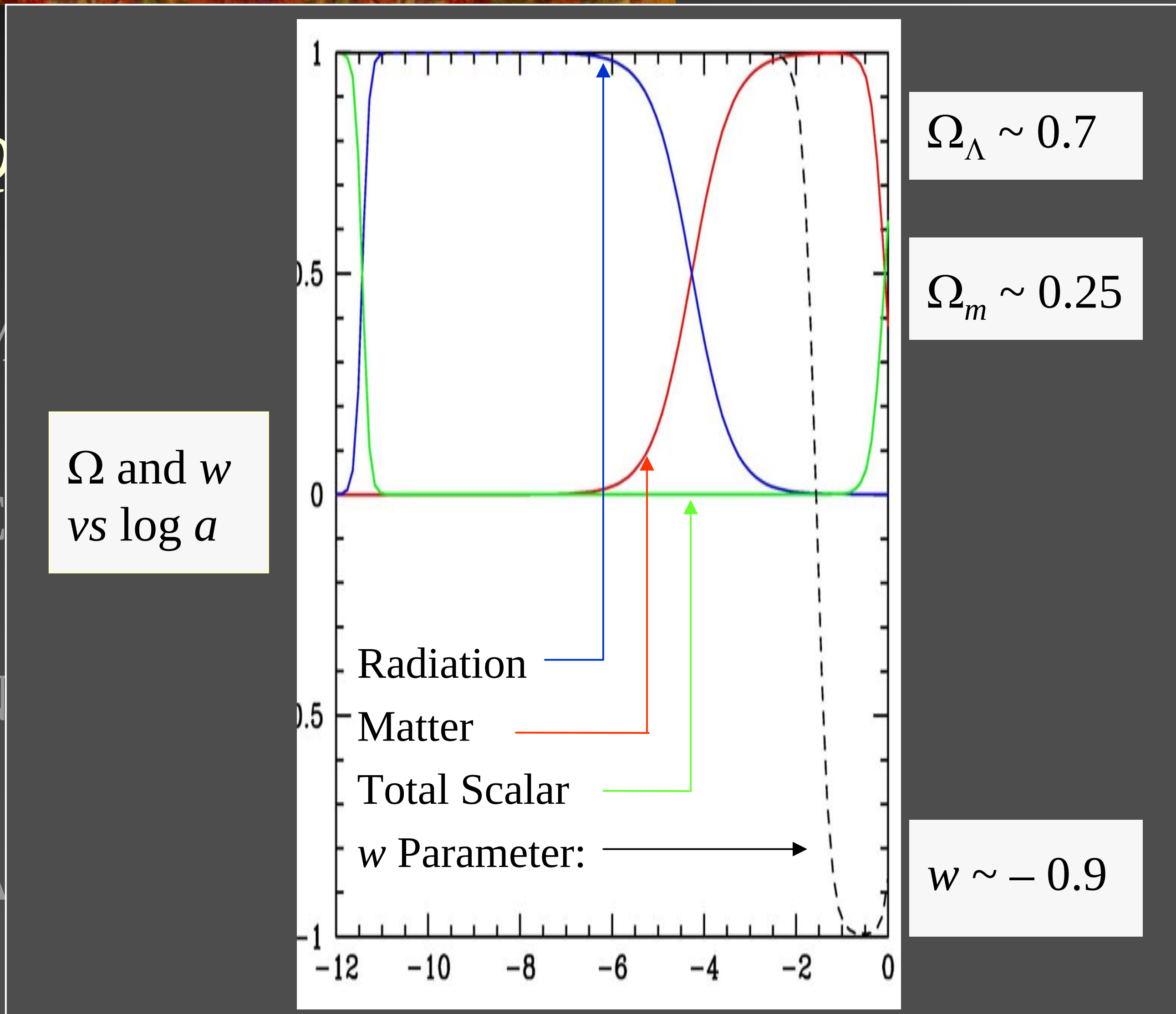
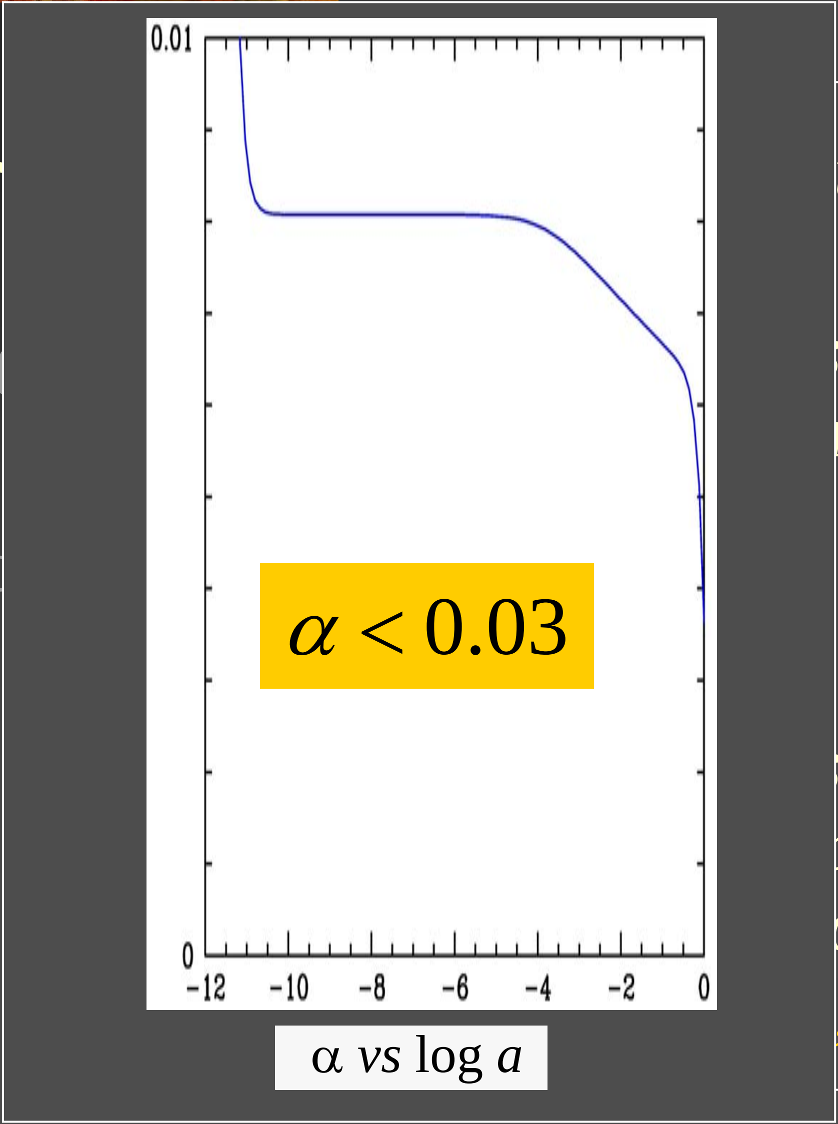


Observational Consequences

Albrecht, CB, Ravndal & Skordis

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



α *vs* log *a*

Observational Consequences

Albrecht, CB, Ravndal & Skordis

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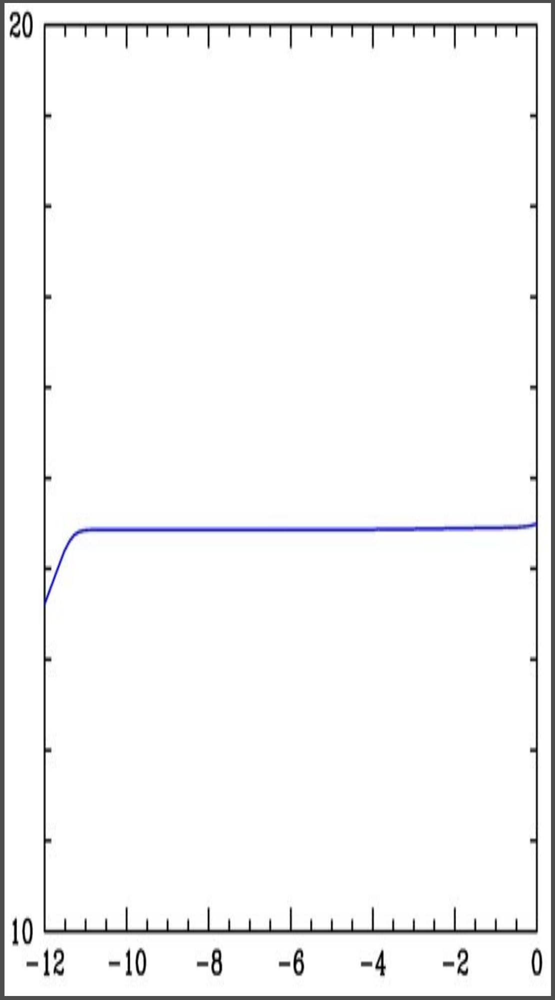
- Astrophysics



log r *vs* log a

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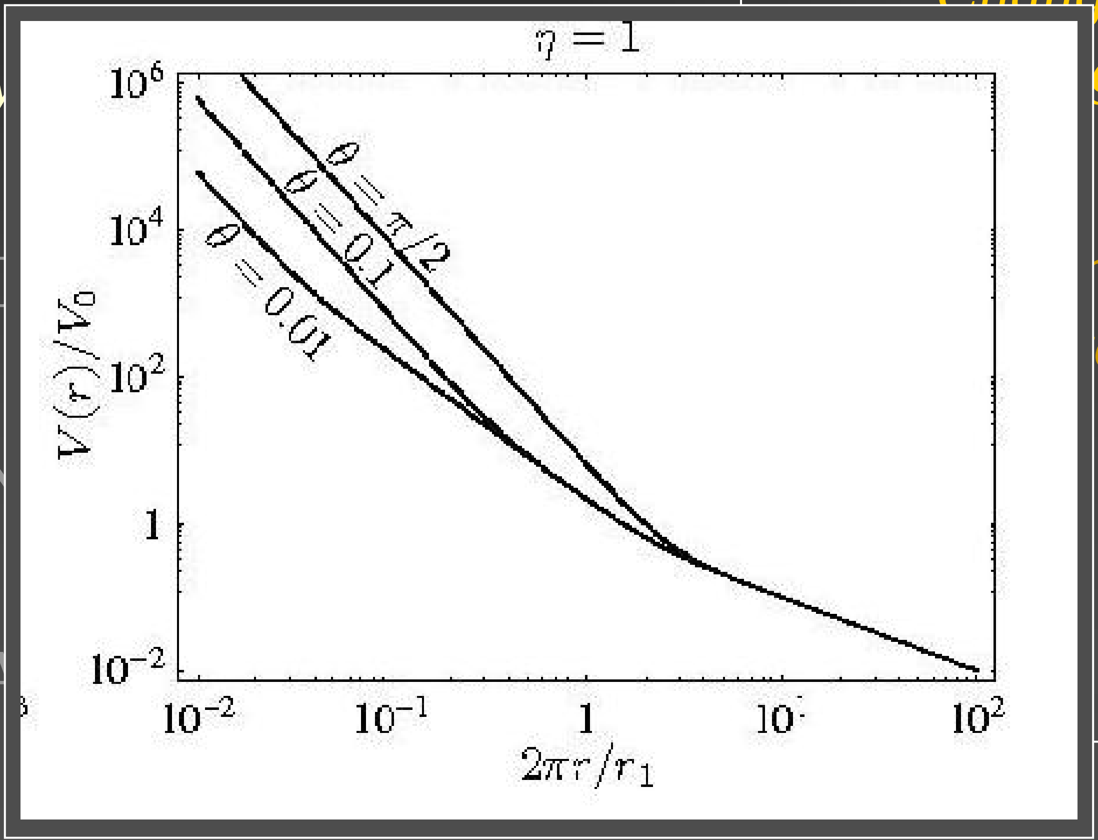
Observational Consequences

- 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 $r/2\pi \sim 1$ μm.*
- *distances*
  - *r-tensor theory out*
  - *ances of order H_0.*

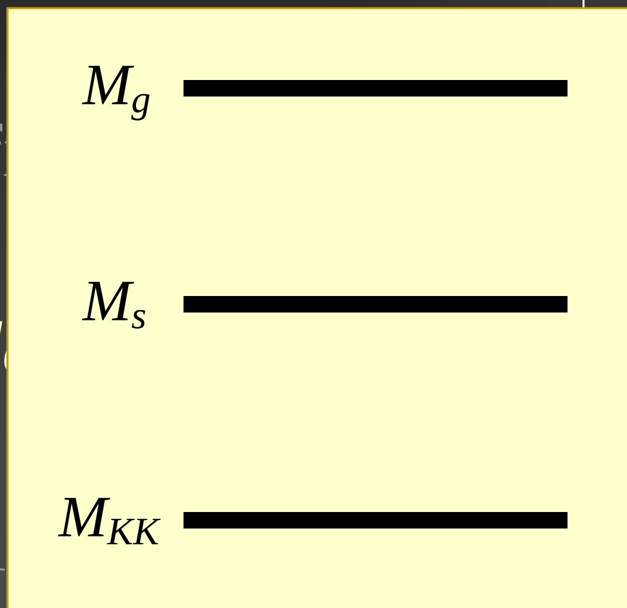
Observational Consequences

- 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
- Modifi
- *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

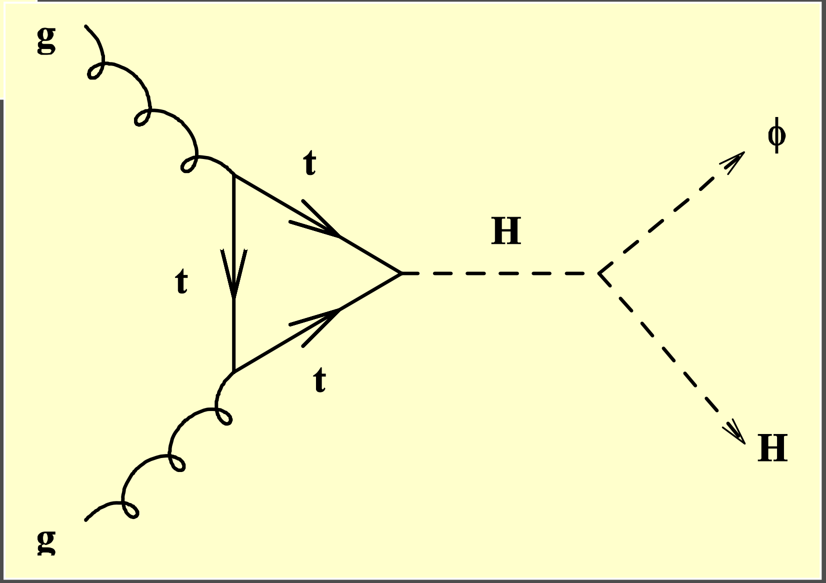
Observational Consequences

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

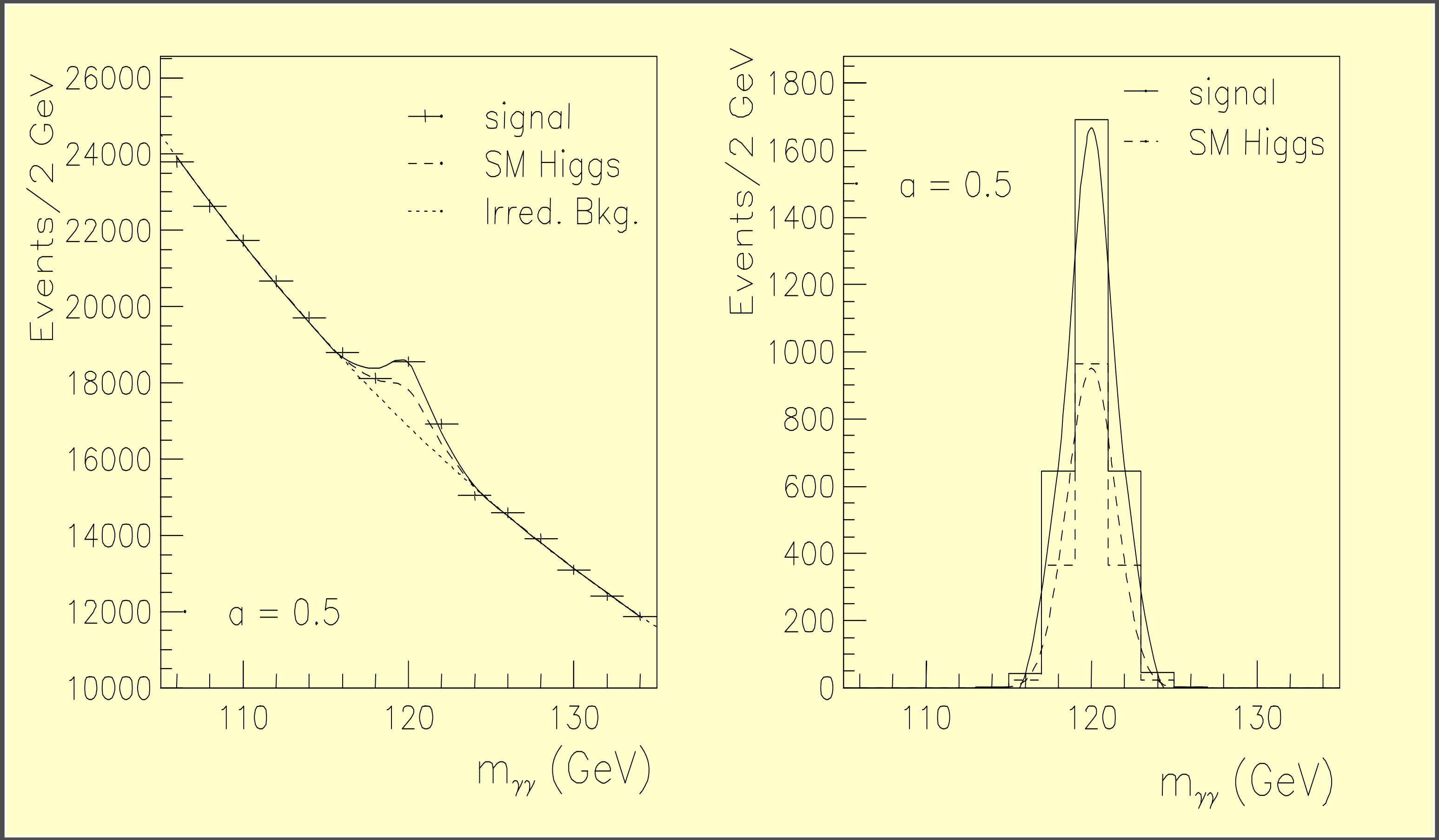
Table 2. SM backgrounds to the production of bulk scalars in association with the Higgs particle at ATLAS, their cross-section (for an E_T^{cut} of 23 GeV) and the total number of events expected at ATLAS for an integrated luminosity of 100 fb^{-1} (after application of rejection factors).

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*

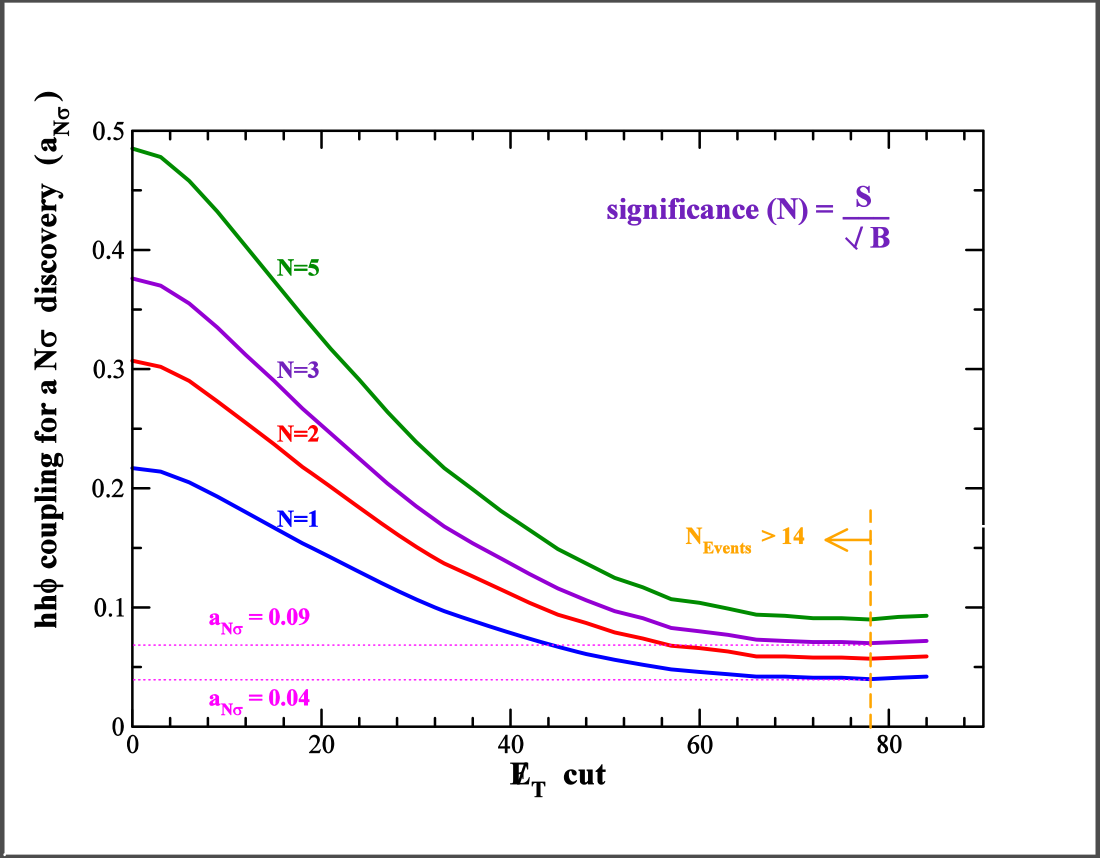
Observational Consequences

Azuelos, Beauchemin & CB



Observational Consequences

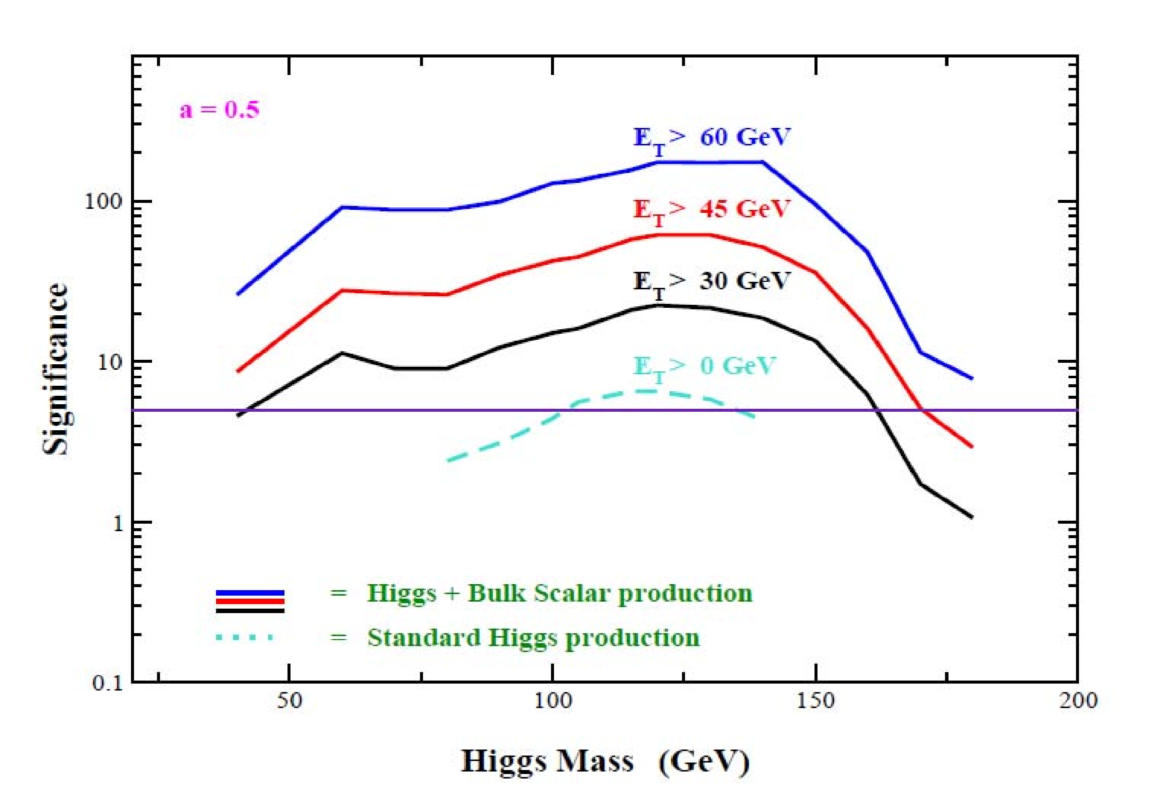
Azuelos, Beauchemin & CB



- *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

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

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;…*