Title: The Cosmological Constant Problem and Extra Dimensions

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Abstract: TBA

The Cosmological Constant Problem and Extra Dimensions

Cliff Burgess

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The Cosmological Constant Problem and Extra Dimensions

Last chance to be wrong about what will be found at the LHC

Cliff Burgess

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, P. Brax, 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

- The Cosmological Constant problem
  - Technical Naturalness in Crisis
- How extra dimensions might help
  - Changing how the vacuum energy gravitates
  - Re-posing the question
- Prognosis
  - Technical worries
  - Observational tests

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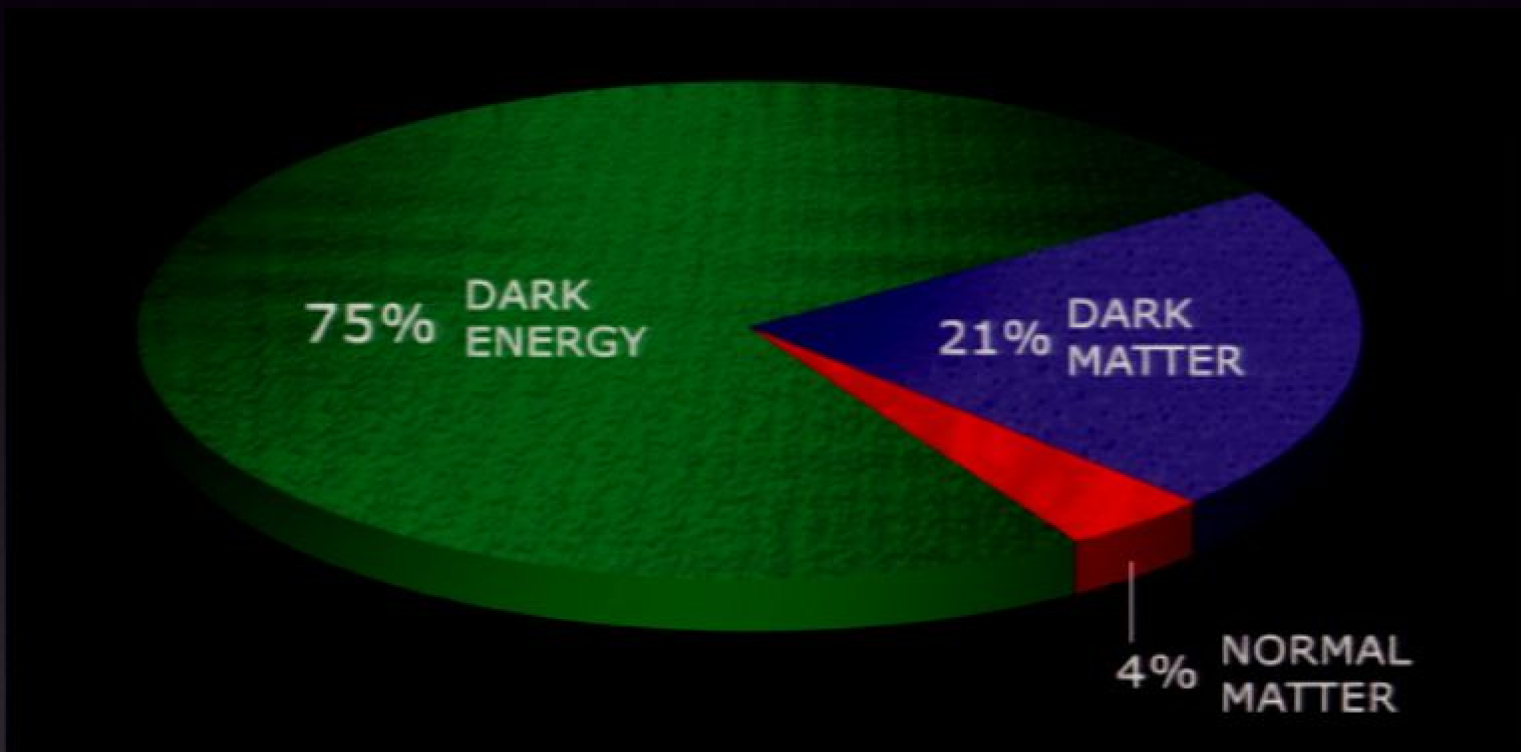
Prologue

- Dar



The Universe appears to contain two types of unknown forms of matter

Prologue

- Dar

Evidence for Dark matter and Dark Energy comes from several sources

CMB

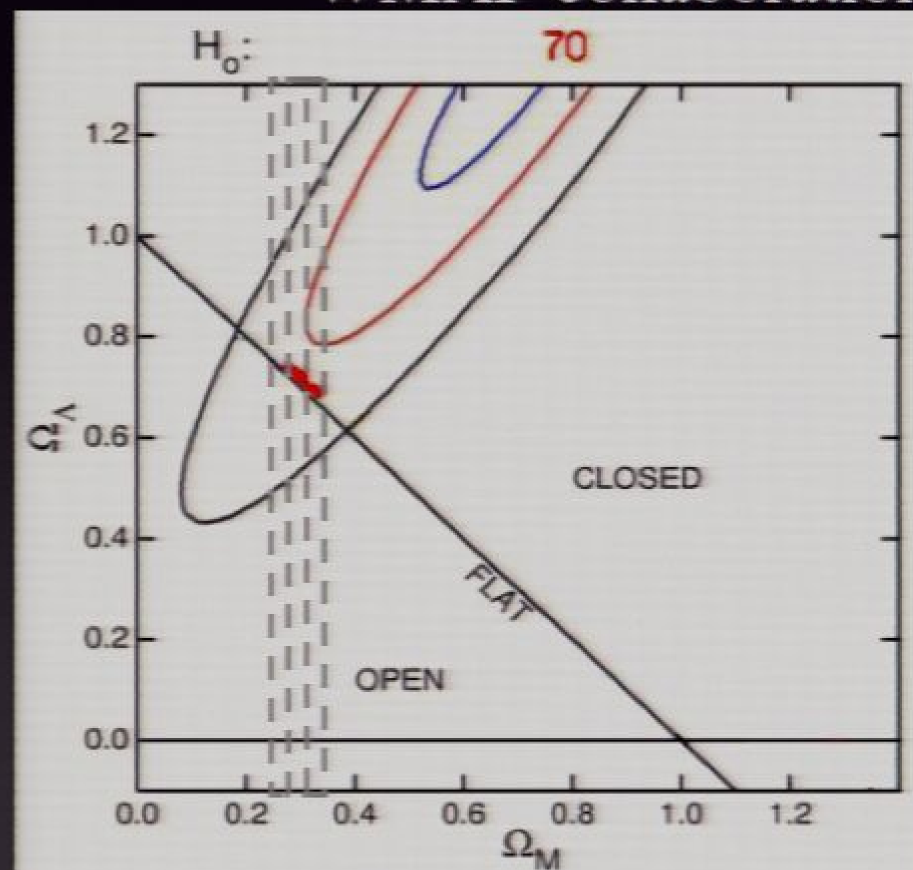
Hubble meas.

Type IA SN

Dark Matter

WMAP collaboration

Amount of Dark Energy



Amount of Dark Matter

Prologue

- Dark I

The dark energy is well-described by a *cosmological constant* (equivalently, by a Lorentz invariant *vacuum energy* of size $\mu \sim 3 \times 10^{-3}\ eV$)

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

vs

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

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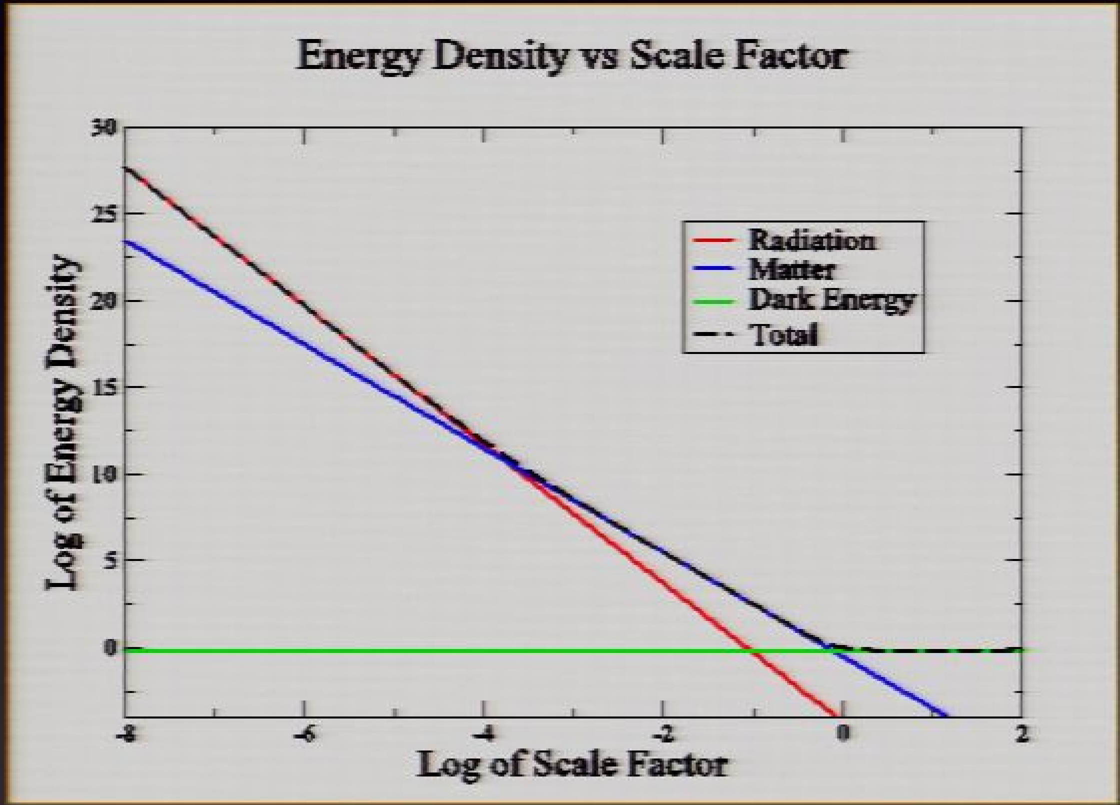
Quantum puzzle:

why isn't μ much larger?

Prologue

- Dar

Dark Energy density is constant in time if it is a vacuum energy.



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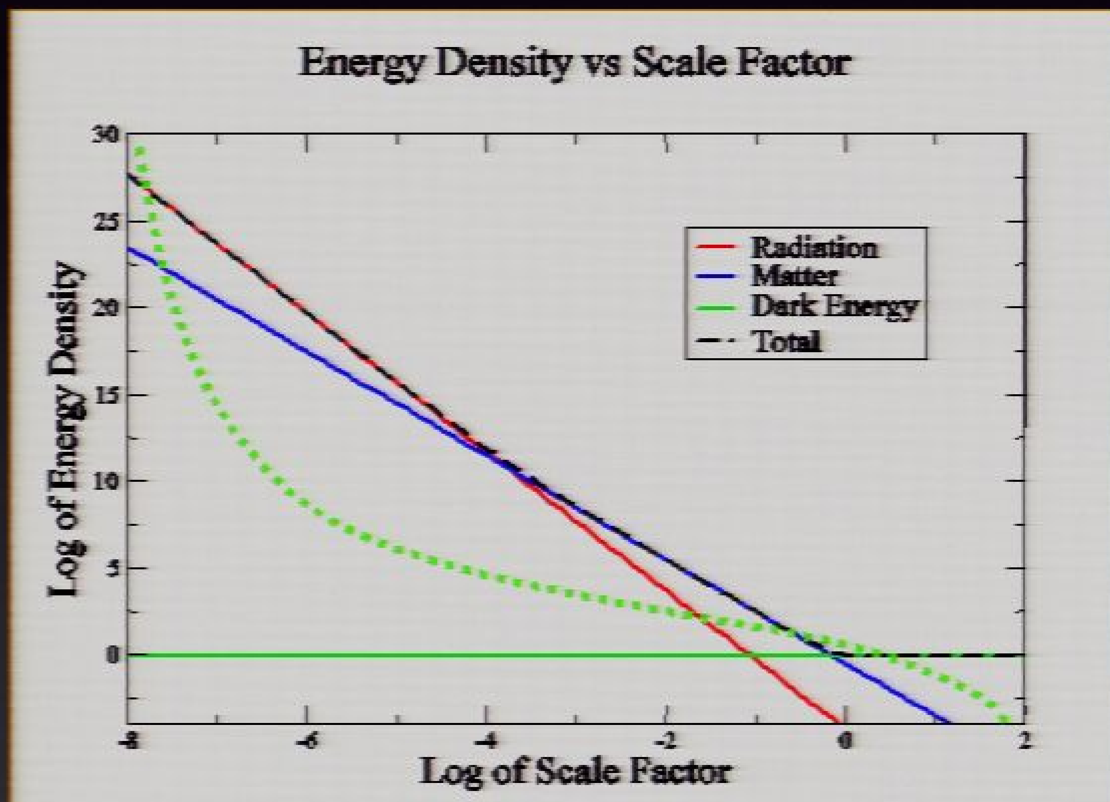
Prologue

- Dar

But other models are possible for which the Dark Energy density evolves in time.



Prologue

- Dar

These other models include:

- 'Quintessence' models: new scalar fields
  (require scalars having mass ~ $H \sim 10^{-32}$ eV)
- '*f(R)*' and other changes to Einstein's gravity
- 'Self-acceleration' and 'self-tuning' models

... and so on.

Prologue

- Dar

These other models include:

BUT: *time-dependent models introduce new problems:*

** Why Now? problem;*

** Sensitivity to initial conditions/history;*

** Issues associated with very light scalars…*

Prologue

- **Dar**

These other models include:

Any models working purely within the classical approximation must:

** Justify the validity of the classical approximation;*

Prologue

- Dar

These other models include:

'Quintessence' models ... scalar fields

Any models working purely within the classical approximation must:

** Justify the validity of the classical approximation;*

** Acknowledge that Occam's Razor prefers a cosmological constant at the purely classical level.*

Technical Naturalness

- The Standard Model

$$L = \bar{E}DE + \bar{L}DL + \bar{Q}DQ + \bar{U}DU + \bar{D}DD$$
$$+ B_{\mu\nu}B^{\mu\nu} + W^{a}_{\mu\nu}W^{\mu\nu}_{a} + G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha} + G^{\alpha}_{\mu\nu}\tilde{G}^{\mu\nu}_{\alpha}$$
$$+ H\left(\bar{L}y_l E\right) + H\left(\bar{Q}y_d D\right) + H^*\left(\bar{Q}y_u U\right)$$
$$+ D_\mu H^* D^\mu H + \lambda\left(H^* H - m^2\right)^2$$

A theory only a mother could love….

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A theory only a mother coul

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Prologue

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The Beauty of the SM: it is the ***most general*** description possible for the given particles and symmetries at low energies!!

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SM is a low-energy limit of a more fundamental theory.

Technical Naturalness

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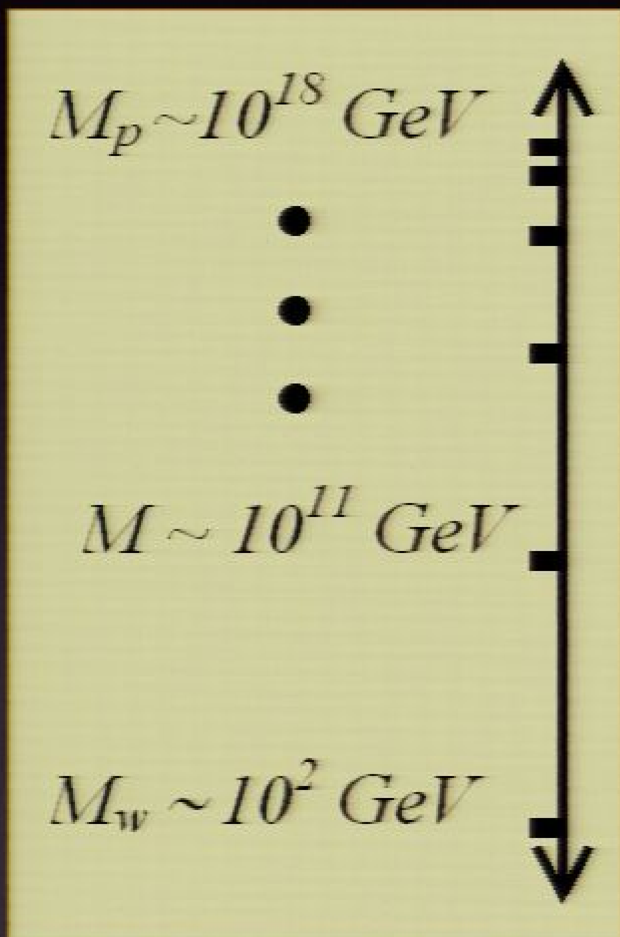


Higher scales almost certainly exist:

eg Planck scale

$$M_p^2 = \hbar c / G_N$$

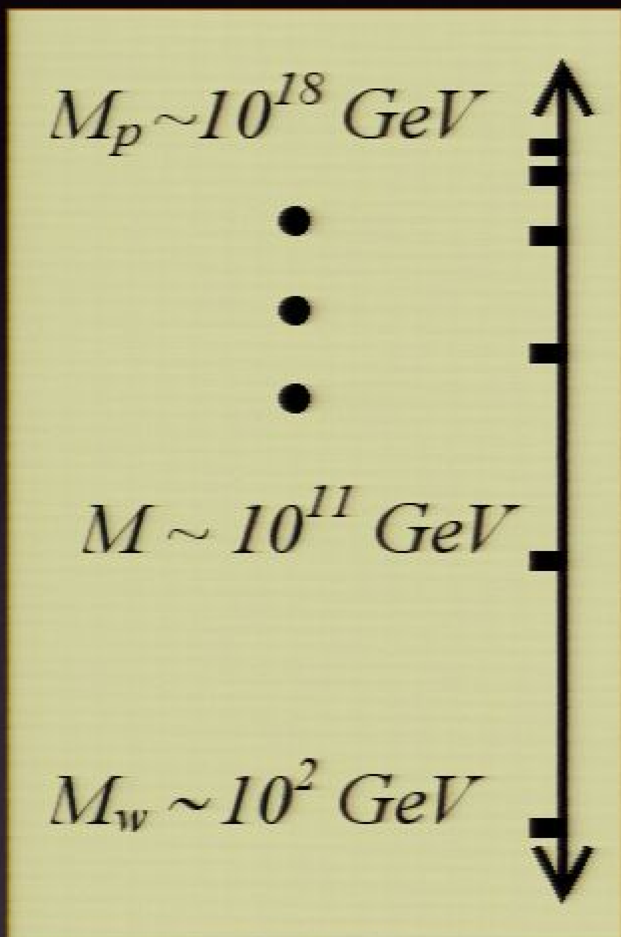
Technical Naturalness

- One feature of the SM seems unlikely if the SM really is the low-energy limit of something more fundamental

$$L_{SM} = m_0^2 H^* H \quad + \quad dimensionless$$

Technical Naturalness

- On … really is t… fun…

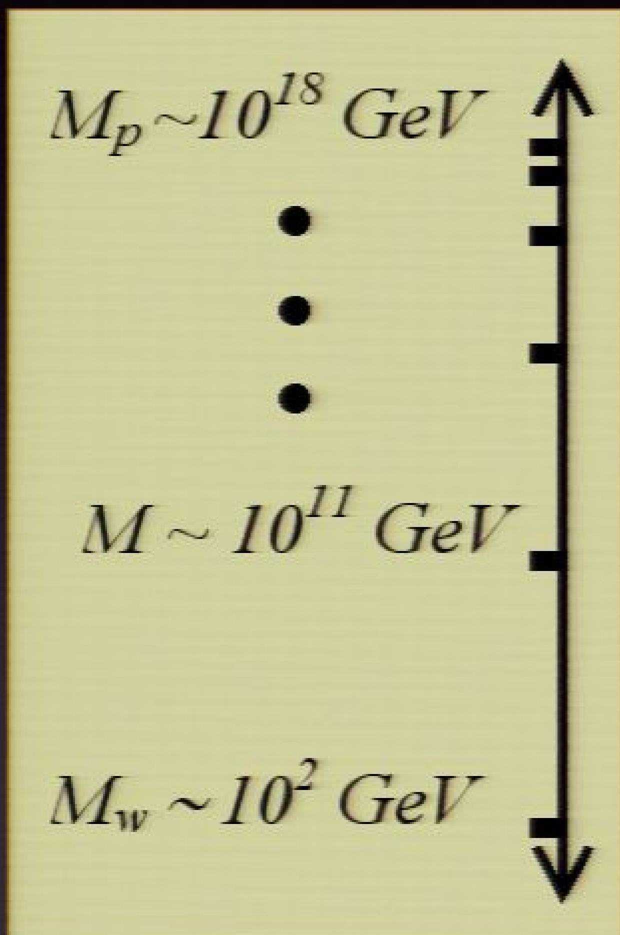


effective theory can be defined at many scales

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

Technical Naturalness

- Or … really
  is t…
  fur…



effective theory can be defined at many scales

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

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

Technical Naturalness

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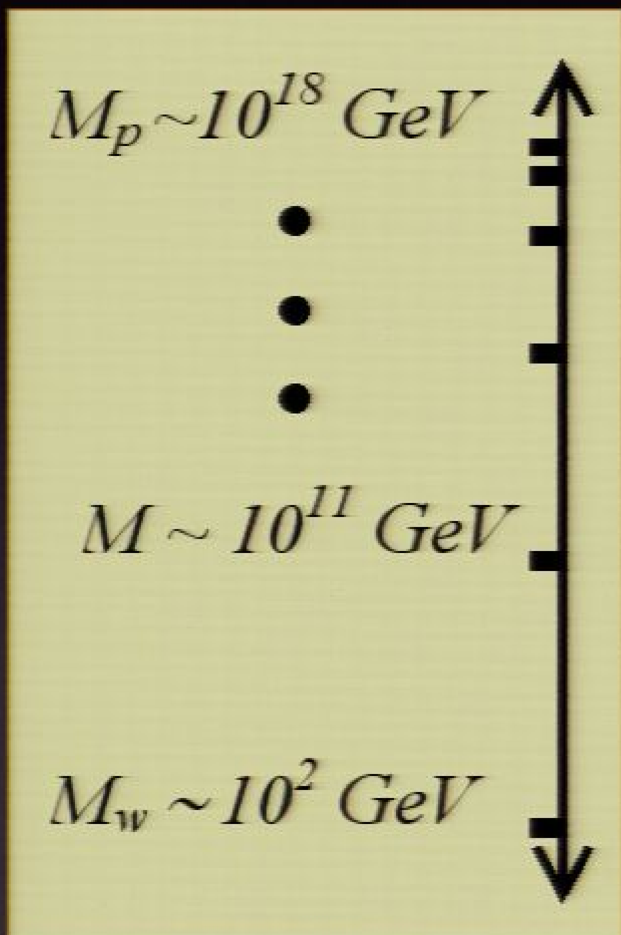

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$$m^2 \approx m_0^2$$

Must cancel to 20 decimal places!!

Technical Naturalness

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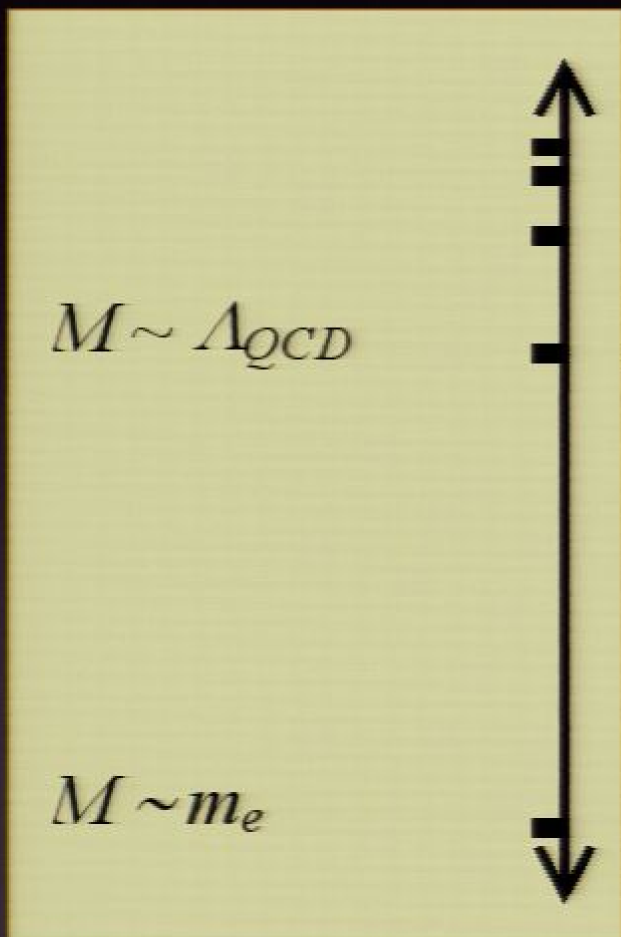

Not the way hierarchies usually arise

eg: why are atoms larger than nuclei?

$$\alpha m_e << \Lambda_{QCD}$$

$$\alpha m_e << m_p$$

Technical Naturalness

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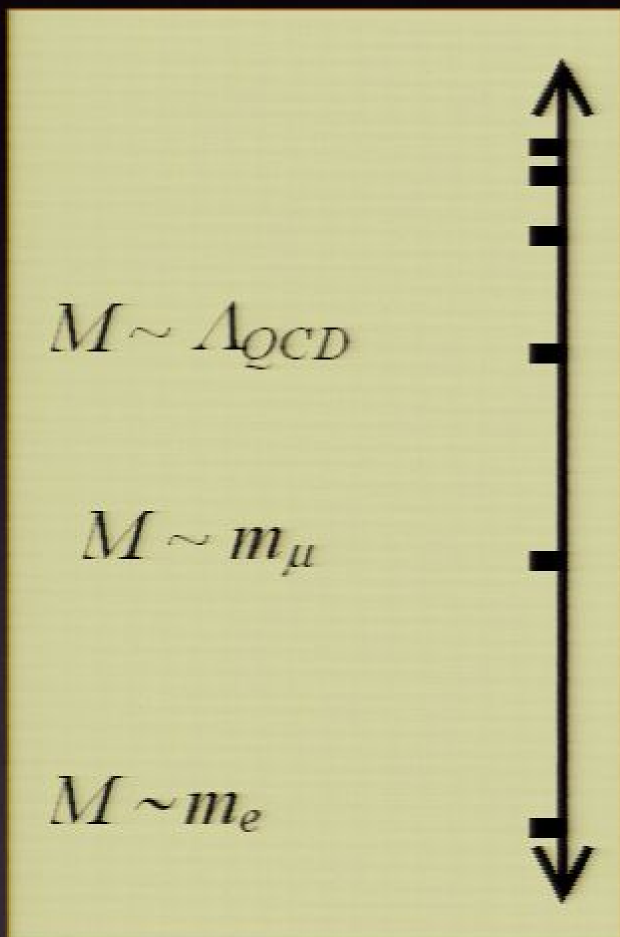

Not the way hierarchies usually arise

eg: why are atoms larger than nuclei?

$$\alpha m_e << \Lambda_{QCD}$$

$$\delta m_e \approx \left(\frac{\alpha}{4\pi}\right)\log\left(\frac{m_\mu}{m_e}\right)$$

$$\alpha m_e << m_p$$

Technical Naturalness

- One feature of the SM seems unlikely if the SM really is the low-energy limit of something more fundamental.

$$L_{SM} = m_0^2 H^* H \quad + \quad dimensionless$$

Hierarchy problem: *should be able to understand why m_0 is small, at any scale we choose to ask the question.*

Spinless particles are rarely systematically light.

Technical Naturalness

- On… really is t… fur…

- Three approaches to solve the Hierarchy problem:

  Compositeness: *H is not fundamental at energies* $E \gg M_w$

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- Three approaches to solve the Hierarchy problem:
  - **Compositeness:** *H is not fundamental at energies* $E \gg M_w$
  - **Supersymmetry:** *there are new particles at* $E \gg M_w$ *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*
    $G_F^{-1/2} \sim 246\,GeV > M_w \sim 80\,GeV$

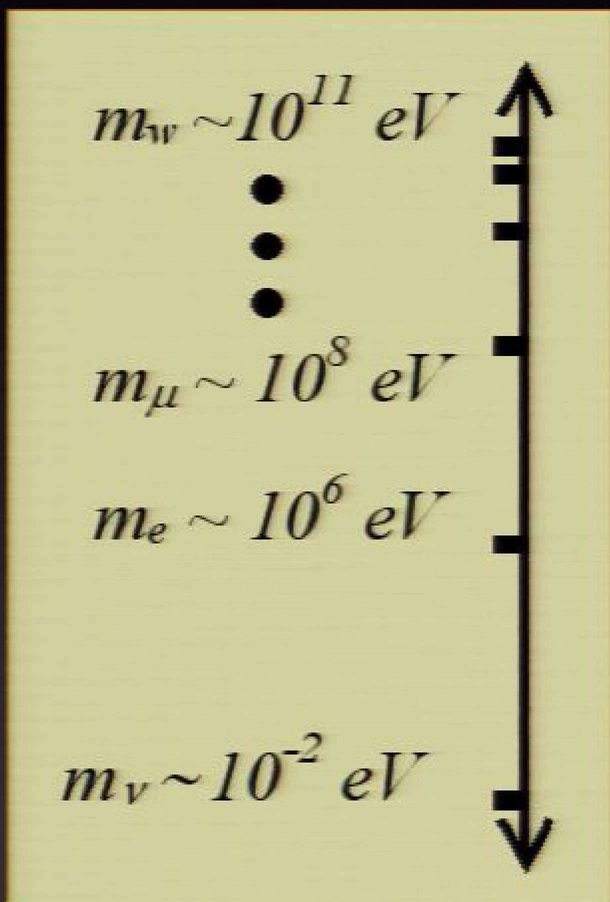
Naturalness in Crisis

- One feature of the SM seems unlikely if the SM really is the low-energy limit of something more fundamental.

$$L_{SM} = \mu_0^4 + m_0^2 H^* H + \; dimensionless$$

Naturalness in Crisis

- ly



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

$$\mu^4 \approx \underbrace{\mu_1^4 + k_e m_e^4}_{} + k_\nu m_\nu^4$$

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

Naturalness in Crisis

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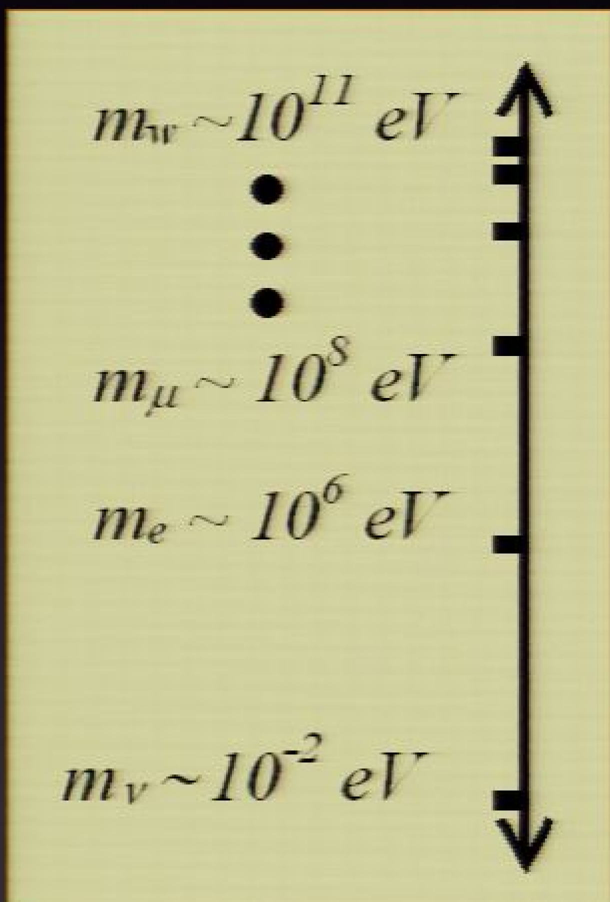

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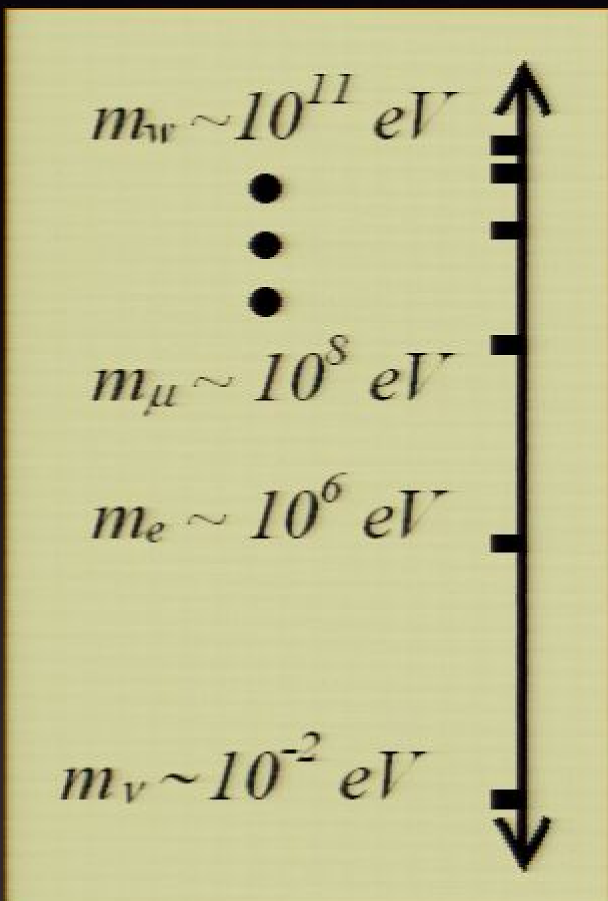
$$\mu^4 \approx \mu_1^4 + k_e m_e^4 + k_\nu m_\nu^4$$

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

Must cancel to 32 decimal places!!

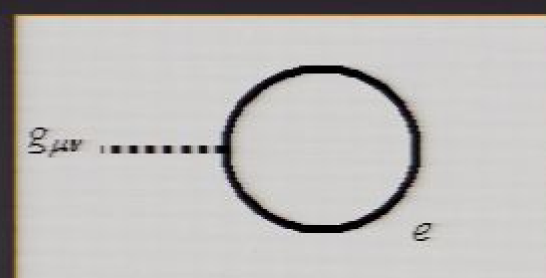
Naturalness in Crisis



- 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 seem to gravitate in atoms!*

Why this?

But not this?



Naturalness in Crisis

- One feature of the SM seems unlikely if the SM really is the low-energy limit of something more fundamental.

$$L_{SM} = \mu_0^4 + m_0^2 H^* H \; + \; dimensionless$$

Cosmological constant problem:

Why $\mu_0 \sim 10^{-3}$ *eV rather than* m_e, M_w, M_{GUT} *or* M_p*?*

Naturalness in Crisis

- Or[…]
  is[…]
  fu[…]

L[…]

Cos[…]
W[…]

Anthropic point of view:

Although cancellation of μ_1^4 with $k_e m_e^4$ seems unlikely, it can be possible if:

i. μ_1 is a field that varies with position;

ii. there are sufficiently many vacua; and if

iii. observers only exist when the cancellation occurs.

‘Naturalness’ as an Opportunity

- Cosmology alone cannot distinguish amongst the various models of Dark Energy.

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‘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*

The Plan

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- How extra dimensions might help
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How Extra Dimensions Might Help

- 4D CC *vs* 4D vacuum energy
- Branes and scales

How Extra Dimensions Might Help

- *4D CC*
  vacuu
- Brane

A *cosmological constant*

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

How Extra Dimensions Might Help

- *4D CC*
  vacuu
- Brane

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

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vs

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

vs

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* *in 4 dimensions ...*

How Extra Dimensions Might Help

- 4D
  vac
- *Bra*

Degravitation:

- *In 4D a graviton mass can suppress the curvature caused by a cosmological constant;*
- *Graviton masses can arise within higher-dimensional brane-world models.*

Dvali, Hofmann & Khoury
de Rham, Hofmann, Khoury & Tolley

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Supersymmetric large extra dimensions:

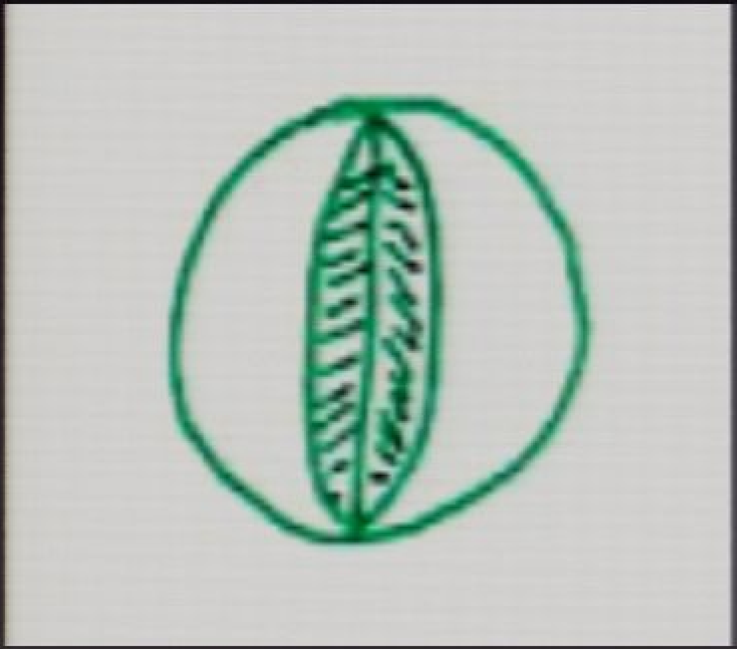
- *In higher dimensions 4D vacuum energy need not curve the dimensions we see.*

How Extra Dimensions Might Help

- 4D
vac

- *Bra*

In higher dimensions a 4D vacuum energy, *if localized in the extra dimensions (such as on a brane)*, can curve the extra dimensions instead of the observed four.



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

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How Extra Dimensions Might Help

- 4D
vac

- *Bra*

To be useful it must be that extra dimensions can be as large as the observed Dark Energy density:

$$\hbar c/r \sim 10^{-2}\ eV \quad or \quad r \sim 1\ \mu\text{-metre}$$

This is possible: provided all known particles except gravity are trapped on a brane, since tests of Newton's law allow

Arkani Hamed, Dvali, Dimopoulos

$$r < 50\ \mu\text{-metre}$$

Adelberger et al

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Arkani Hamed, Dvali, Dimopoulos

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If there are extra dimensions as large as $r \sim 1\ \mu$*-metre* then there can only be two of them (although others could exist if they are much smaller), or else the observed strength of gravity would require the scale of extra-dimensional physics to be too small to have been missed

$$M_p \approx M_g \left(rM_g\right)^{n/2}$$

with n extra dimensions

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

when $n = 2$.

How Extra Dimensions Might Help

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  vac
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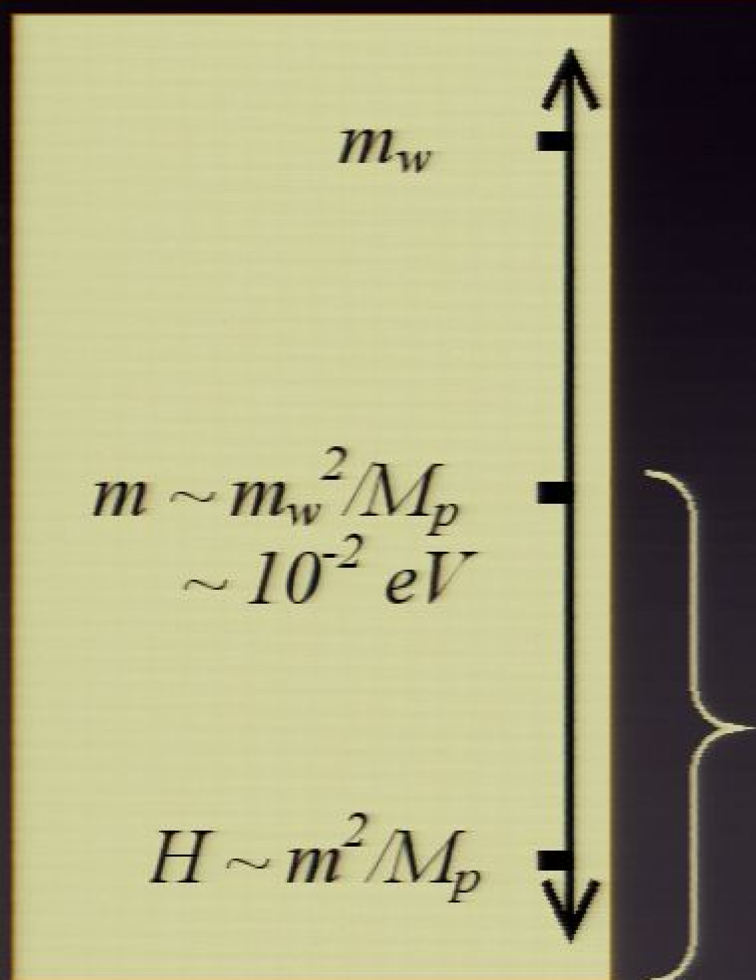

These scales are natural using standard 4D arguments.

How Extra Dimensions Might Help

Arkani Hamed, Dvali, Dimopoulos

- 4D
  vac
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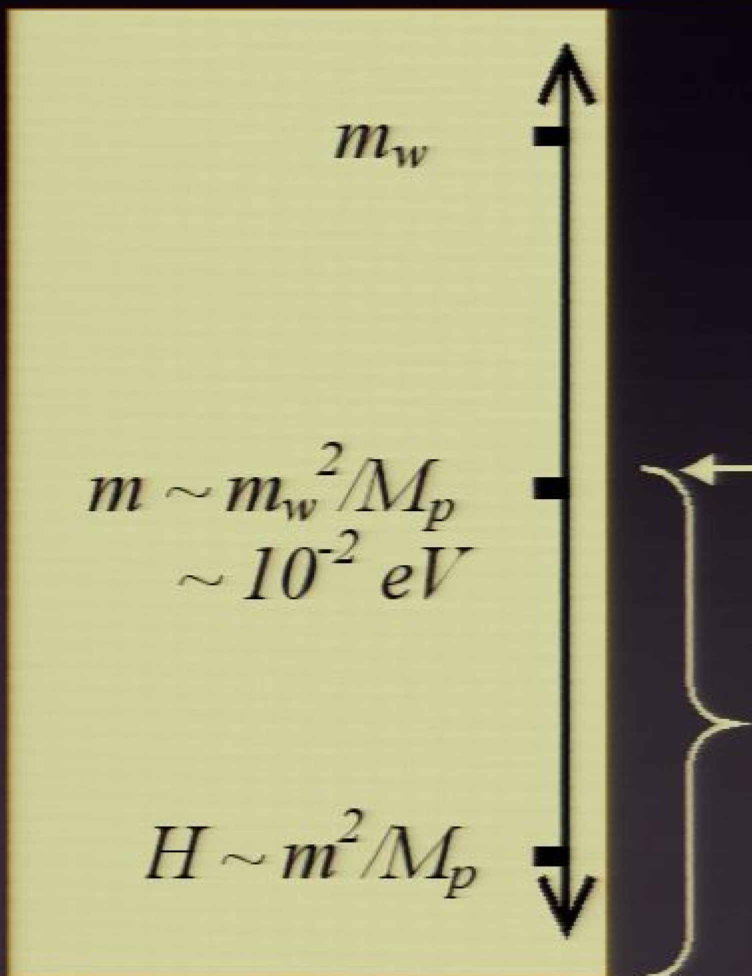
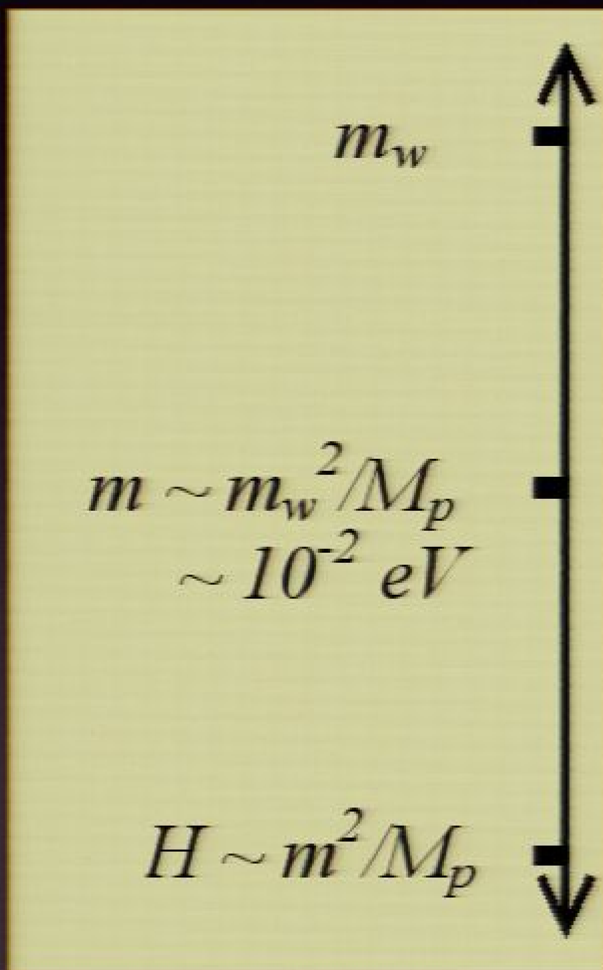


Extra dimensions could start here, if there are only two of them.

These scales are natural using standard 4D arguments.

How Extra Dimensions Might Help

- 4D
  vac
- *Bra*



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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A Concrete Example

- The basic model
- What choices make the 4D geometry flat?
- Are these choices stable?

A Concrete Example

Aghababaie, CB,
Parameswaran & Quevedo

- *The basic model*

- What choices make the 4D geometry flat?

- Are these choices stable?

A Concrete Example

Nishino & Sezgin

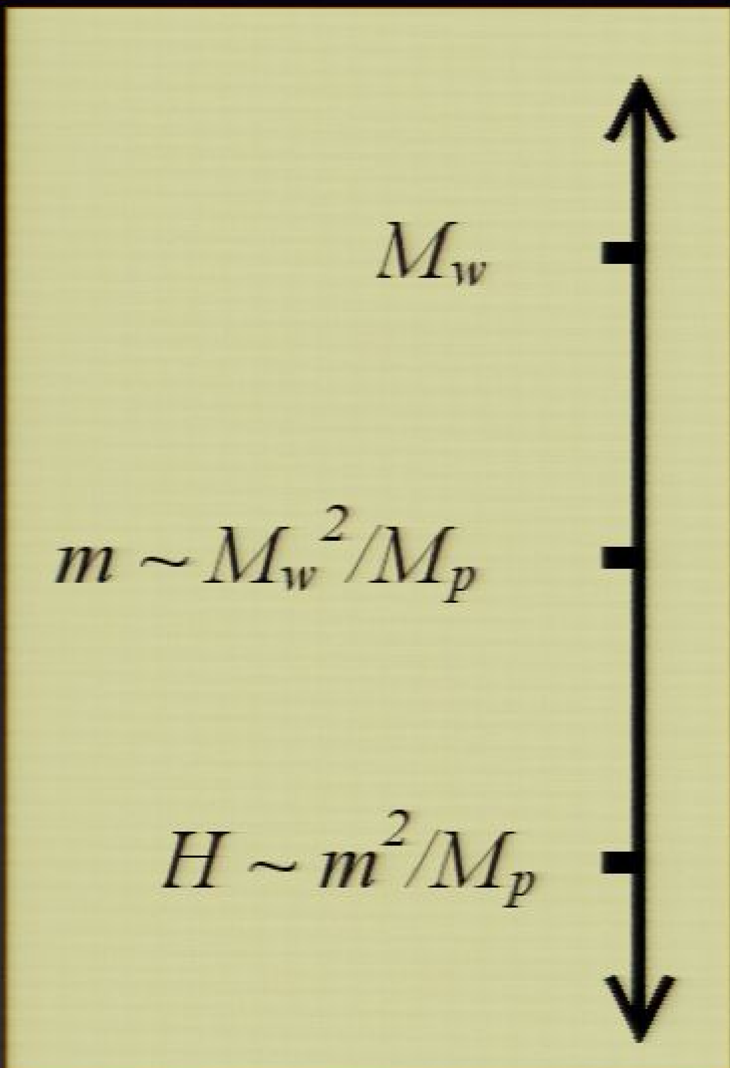
- *The basic*
- What choi
  4D geome

- 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)

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

A Concrete Example

- *The*
- Wha
  4D g
- Are



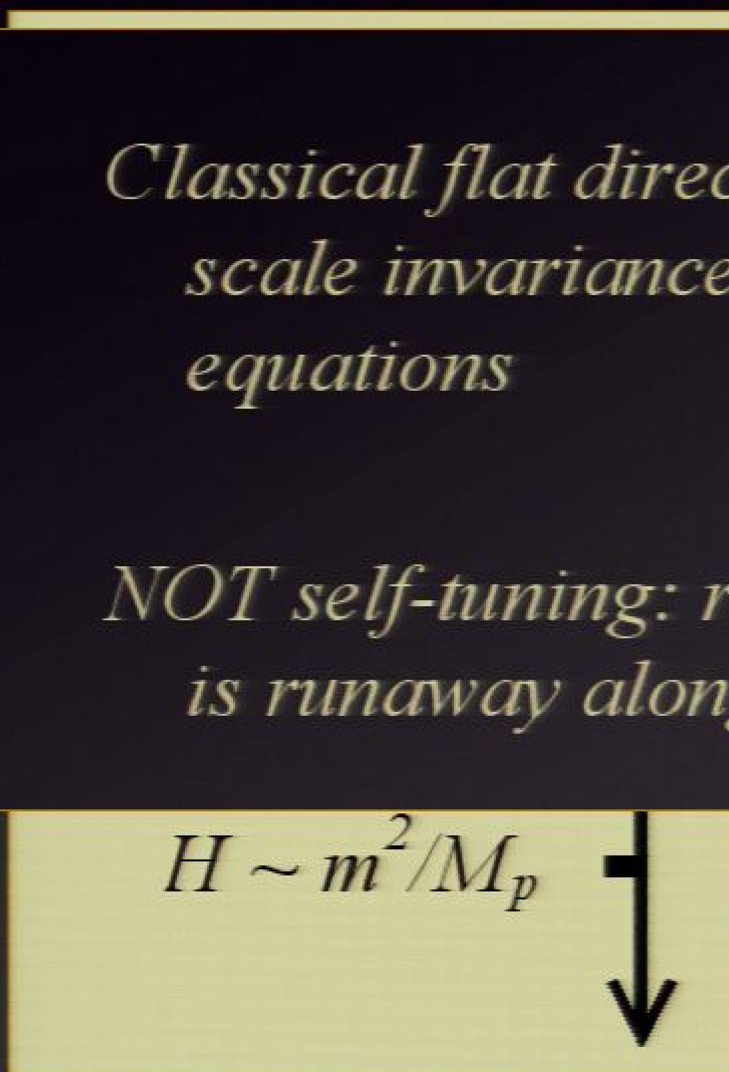
Particle Spectrum:

SM on brane
No superpartners on brane
Many KK modes in bulk

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

A Concrete Example

- *The*
- Wh
  4D
- Are



m:

n brane

bulk

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

4D graviton

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

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

A List of Detailed Worries (Preview)

- ‘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?

A Concrete Example

- The basic model
- *What choices make the 4D geometry flat?*
- Are these choices stable?

A Concrete Example

- The
- *Wha*
  4D g
- Are

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

A Concrete Example

- The

- Search for solutions to 6D supergravity:

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

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

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

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

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

- W
4

- A

A Concrete Example

- The

- Search for solutions to 6D supergravity:

- Salam Sezgin ansatz:

  maximal symmetry in 4D and in 2D

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}\, dy^m\, dy^n$$

$$F = f\, \varepsilon_{mn}\, dy^m\, dy^n\,; \quad \partial_m \phi = 0$$

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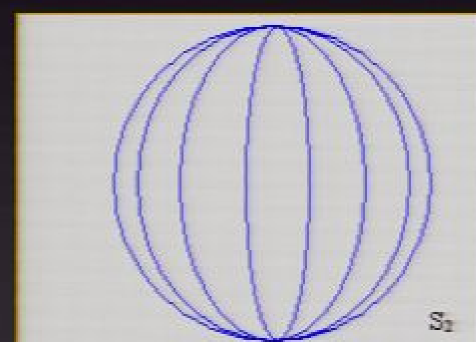

- *Implies:*

  1. $g_{\mu\nu} = \eta_{\mu\nu}$
  2. *spherical extra dimensions*
  3. *dilaton stabilization:* $g^2\, e^\phi = 1/r^2$

- A

A Concrete Example

- The
- *W*
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- *A*

- *Search for solutions to 6D supergravity:*

- *Why a flat solution?*

80's: Unit magnetic flux leaves SUSY unbroken…

$$V = \sqrt{g}\left[\frac{R}{2} + \frac{e^{-\phi}F^2}{4g^2} + 2g^2e^{\phi}\right]$$

$$= \frac{1}{r^2}\left[-\frac{2}{r^2} + \frac{e^{-\phi}}{g^2r^4} + g^2e^{\phi}\right]$$

$$= \frac{g^2e^{\phi}}{r^2}\left[1 - \frac{1}{g^2r^2e^{\phi}}\right]^2$$

A Concrete Example

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…but: turns out to be 4D flat for higher fluxes as well!

$$= \frac{g^2 e^{\phi}}{r^2}\left[1 - \frac{1}{g^2 r^2 e^{\phi}}\right]^2$$

A Concrete Example

- *Search for solutions to 6D supergravity:*

- The

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4

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- *Can include branes:*

Aghababaie, CB, Parameswaran & Quevedo

Cut-and-paste solutions have equal-sized conical singularities at both poles;

Interpret singularity as due to back-reaction of branes located at this position

Branes break supersymmetry

A Concrete Example

Chen, Luty & Ponton
Aghababaie et al

- *Yet geometry on the branes remains flat*

$$4D\ cc = \sum_i T_i + \int d^2x \sqrt{g}\left(R + \ldots\right)$$

$$R = -\sum_i T_i\, \delta^2\left(x - x_i\right) + smooth$$

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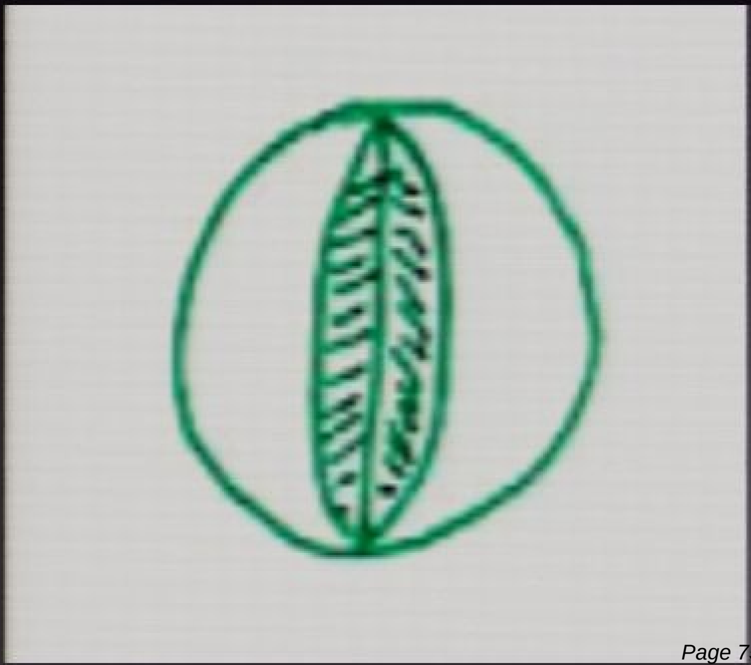

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A Concrete Example

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- *Search for solutions to 6D supergravity:*

- *General solns with two conical singularities:*

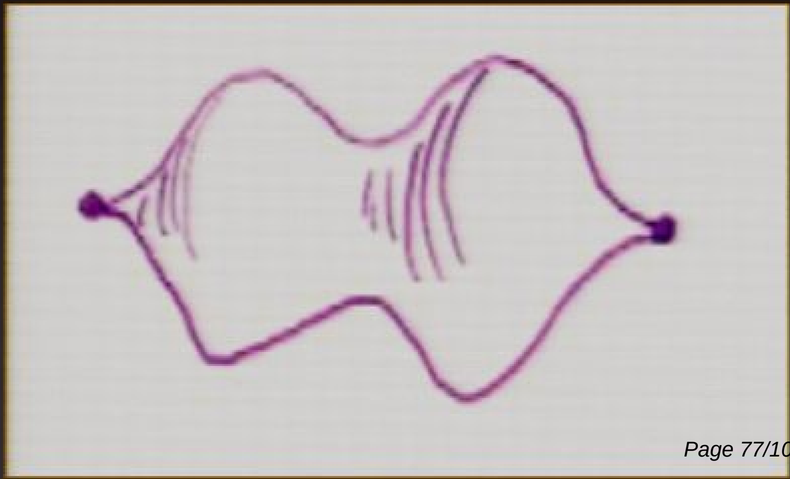
Gibbons, Guven & Pope

Aghababaie, CB, Cline, Firouzjahi, Parameswaran, Quevedo Tasinato & Zavala

- *W*
  4

Unequal defects have warped geometries in the bulk;

All of these solutions are flat



- A

Solutions also known with curvature singularities, time dependent evolution, *etc.*

A Concrete Example

- The
- *Wha*
  4D g
- Are

- *Summary of axially symmetric solutions:*
  Properties of 2-brane geometries are governed by the ϕ-dependence of the brane tensions: $T(\phi)$
- T independent of ϕ suffices to ensure that branes are flat and back-react to give conical singularities
- Static solutions also exist which are 4D dS.
- Runaways are generic.

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

A Concrete Example

- The basic model

- What choices make the 4D geometry flat?

- *Are these choices stable?*

A Concrete Example

- The basic model

- W…
  4…

- A…

- *Q: Is existence of flat solution stable against perturbations of branes?*
  A: Can be.

  So long as the brane tensions remain independent of ϕ there always exists a flat solution.

Aghababaie et. al.

A Concrete Example

- The basic model

- *Q: Is existence of flat solution stable against perturbations of branes?*
  A: Can be.

  Cursory inspection can make it *seem* as if tensions must be tuned.

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

Aghababaie et. al.

- W
  4

- A

A Concrete Example

- The basic model
- W
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  Cursory inspectio
  tensions must be t

  $$4G\sum_b$$

Being topological, this is *always* preserved by continuous deformations (like renormalization).

If ΣT_b becomes nonzero then R becomes nonzero

Aghababaie et. al.

A Concrete Example

- The basic model

- W
  4

- A

- *Q: Is flatness stable to perturbations of initial conditions? A: No.*

Solutions are marginally stable against perturbations that do not change the brane sources; *de Rham et. al.* *Papazoglou et. al.*

Generic situation is a runaway, so arbitrary change to branes starts a time-dependent roll. *Tolley et. al.*

Technical Naturalness

- 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?

A Concrete Example

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Technical Naturalness

- *Key feature of 6D solutions:*

  A sufficient condition for flatness is the absence of a coupling between brane and the bulk scalar ϕ in the tension $T(\phi)$

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- Qua
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Technical Naturalness

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- *Quantum effects away from the brane are small due to supersymmetry*
- *Quantum effects on the brane itself do not curve the observed dimensions appreciably*
- *Quantum effects near the brane are under investigation, and appear of order $e^{2\phi} \sim 1/r^4$.*

Technical Naturalness

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- *UV sensitive loop corrections can be organized into a curvature and dilaton expansion:*

$$L_B = \sqrt{-g}\left[A + B\,R + CR^2 + DR^3 + \dots\right]$$

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CC @ PI, May 2009

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- *UV sensitive loop corrections can be organized into a curvature and dilaton expansion:*

$$A_0 = 0 \quad (\text{no 6D cc allowed by susy})$$

$$B_0 = \text{Newton's constant renorm}$$

$$C_0 = 0 \text{ if summed on 6D supermult.}$$

$$\text{loops} \propto e^{2\phi} \approx \frac{1}{r^4}$$

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The Plan

- The Cosmological Constant problem
  - Why is it so hard?
- How extra dimensions might help
  - Changing how the vacuum energy gravitates
  - Re-posing the question
- Prognosis
  - Technical worries
  - Observational tests

Prognosis

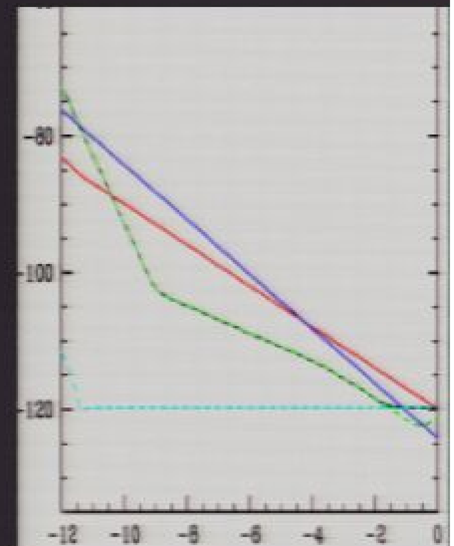
- Theoretical worries
- Observational tests

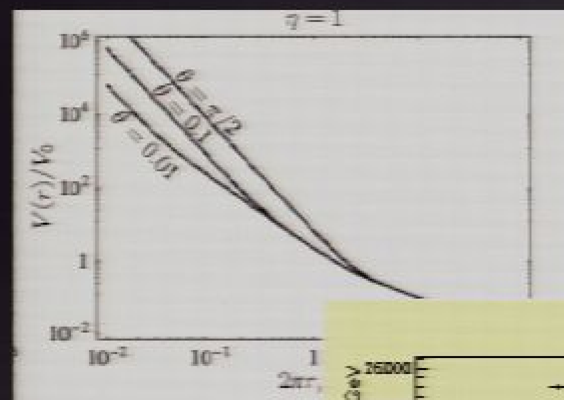
The Worries

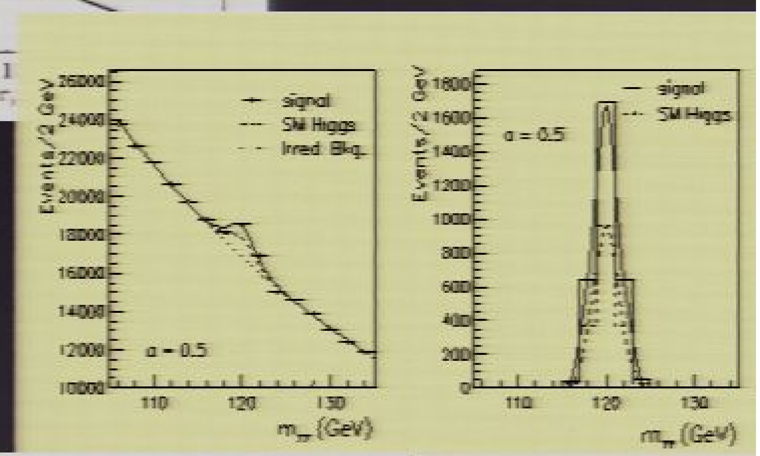
- ‘Technical Naturalness’
- Runaway Behaviour
- Stabilizing the Extra Dimensions
- Famous No-Go Arguments
- Problems with Cosmology
- Constraints on Light Scalars

The 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

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  - Much like for the Hot Big Bang Model.
- Enormously predictive, with many observational consequences.
  - Cosmology at Colliders! Tests of gravity…

Detailed Worries and Observations

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