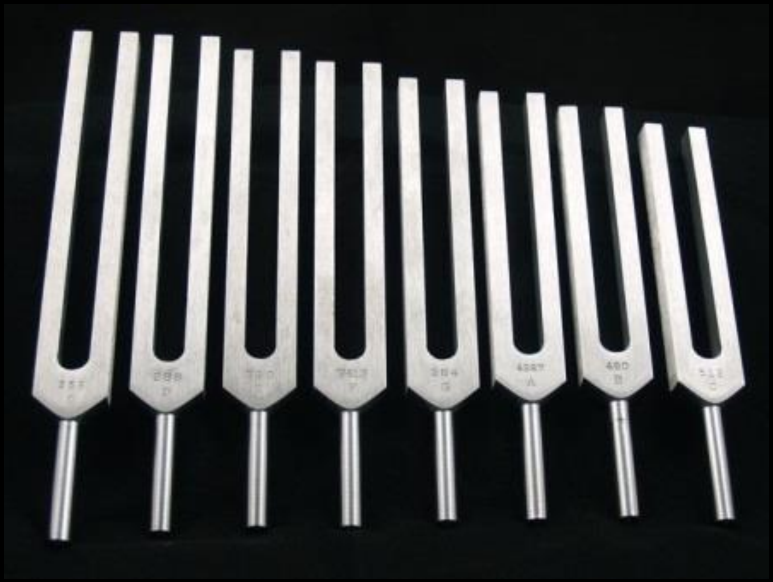
Self-Tuning Under the Microscope



Last Chance to Be Wrong About

What the LHC Will Find

Cliff Burgess

w R.Diener, D.Hoover, H.M.Lee, Q.Matias, L.van Nierop, S.Parameswaran, F.Quevedo, C.de Rham, A.Salvio, G.Tasinato, A.Tolley, M Williams,…

SOUND OF LOVE
SOUND & METAPHYSICAL STORE

These special tuning fork combinations assist people in *becoming more attuned to the vibratory nature of our magnificent universe*. It is like saying to the universe " let me hear and feel you more closely as we play in the Music of the Spheres".

These tuning fork sets are very unique in that they are *backed by years of scientific and historical research into the unified field of sound*, Sacred Geometry, color, ancient music traditions, and the harmonic proportions found in nature.

Preamble: Naturalness

Light scalars are unnatural

….so LHC will see:

- Lots of SUSY particles, or
- A complicated Higgs sector, or
- Extra dimensions in your face

Patron Saint of All Things Natural

Preamble: Naturalness

Naturalness: The Dog that Didn't Bark

- Gregory (Scotland Yard detective): *"Is there any other point to which you would wish to draw my attention?"*
- Holmes: *"To the curious incident of the dog in the night-time."*
- Gregory: *"The dog did nothing in the night-time."*
- Holmes: *"That was the curious incident."*

Sir Arthur Conan Doyle – *Silver Blaze*

Preamble: Naturalness

The Cosmological Constant Problem:

A small vacuum energy is also unnatural

Preamble: Naturalness

The cosmological constant problem is only a useful clue if there's a solution. *Need we give up?*

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The cosmological constant problem is only a useful clue if there's a solution. *Need we give up?*

Will argue in this talk

- There is a broad direction in which a solution might yet be *(but has not yet been)* found; *Also no no-go*
- At very least a useful rephrasing of the problem
- Useful spin-off technology: eg back reaction
- Why I think it may yet work

Preamble: Naturalness

The co

useful

Will ar

- Broad direction has many observational tests, independent of the details of any one model
  - *Points towards a very supersymmetric (eV scale) gravity sector coupled to a non supersymmetric particle physics sector (no MSSM)*

- There is a broad direction in which a solution might yet be *(but has not yet been)* found; *Also no no-go*
- At very least a useful rephrasing of the problem
- Useful spin-off technology: eg back reaction
- Why I think it may yet work

Outline

- Naturalness
  - *What is the problem?*
- Roads well travelled
  - *Symmetries and No-Go Results*
- A way forward?
  - *The broad direction*
  - *Where the Devil is*
  - *How would we know?*

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NATURALNESS

"I ought to know by this time that when a fact appears to be opposed to a long train of deductions it invariably proves to be capable of bearing some other interpretation."

Sherlock Holmes in *A Study in Scarlet*

What is the problem?

Electroweak Hierarchy vs Cosmological Constant

NATURALNESS

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Hierarchy problems

The Standard Model

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

Most general renormalizable theory possible given the particle content

Hierarchy problems

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

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

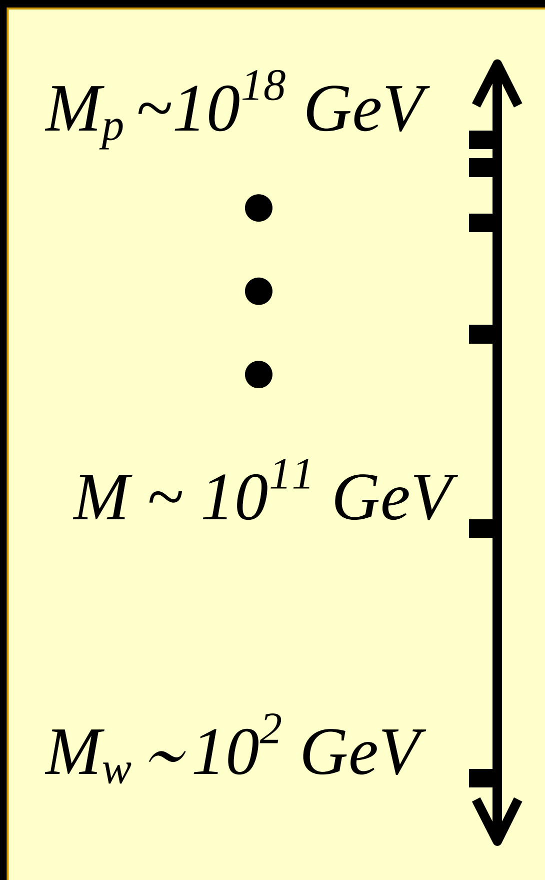
$$m^2 = {m^2}_0 + higher\ order \sim (126\ GeV)^2$$

Hierarchy problems

Model

ss'.

theory.



BUT: effective theory can be defined at many scales

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

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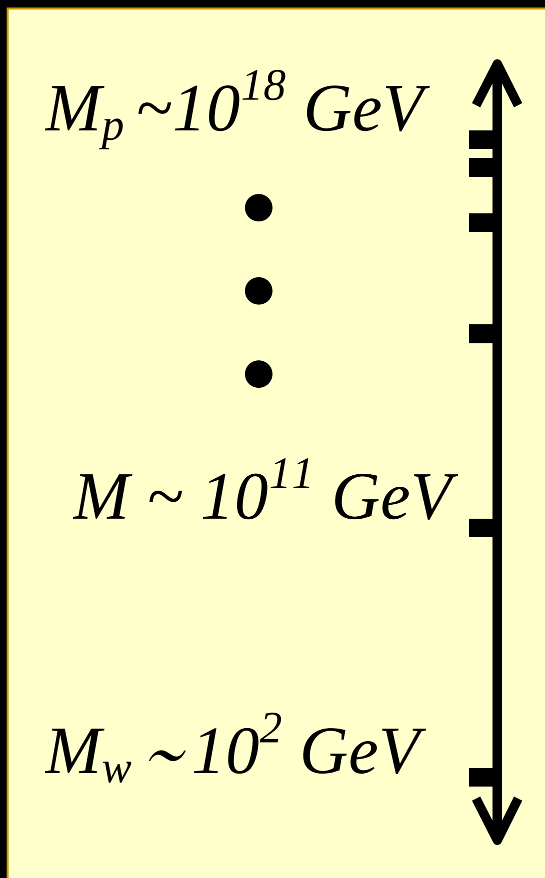

BUT: effective theory can be defined at many scales

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

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

Hierarchy problems

Model

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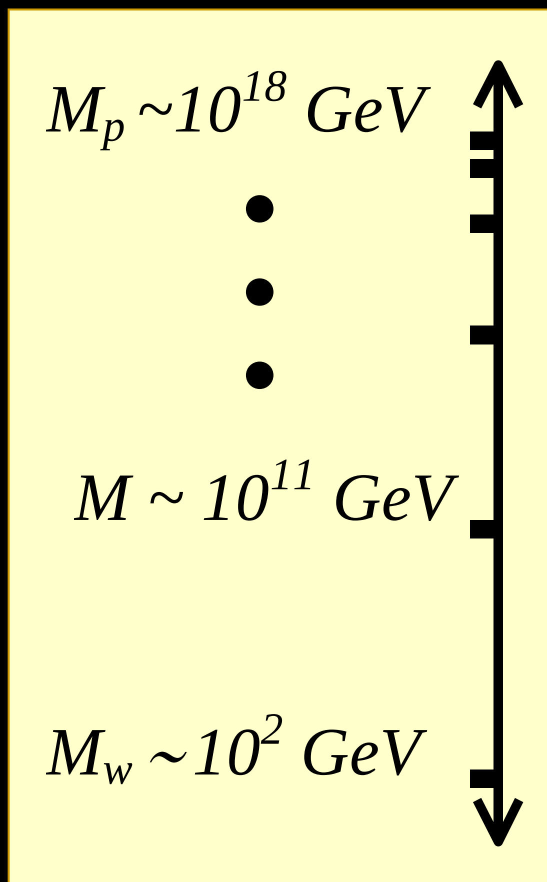

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$$m^2 \approx m_1^2 + kM^2 + \cdots$$

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

Must cancel to 20 decimal places!!

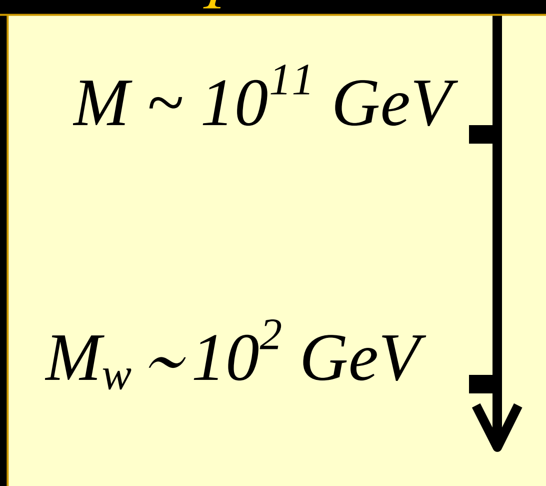
Hierarchy problems

WAYS OUT: #1

Composite Higgs: there is no m_1 parameter if there is no Higgs field in the higher-energy EFT

Compositeness should arise at accessible energies

Didn't expect a vanilla Higgs



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

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

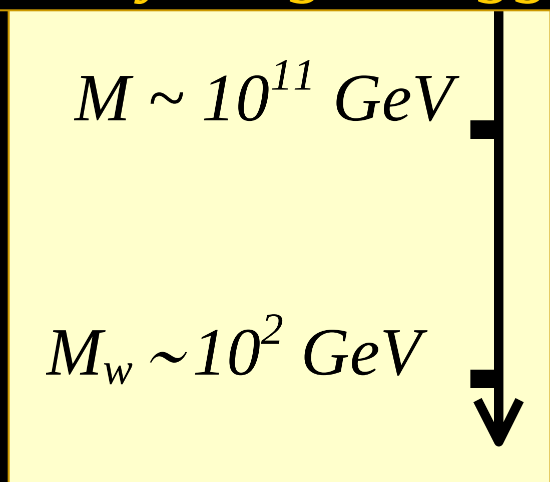
Hierarchy problems

WAYS OUT: #2

Supersymmetry: bosons and fermions cancel to give small contributions to m_1 in the higher-energy EFT

Superpartners should arise at accessible energies

Usually a light Higgs



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

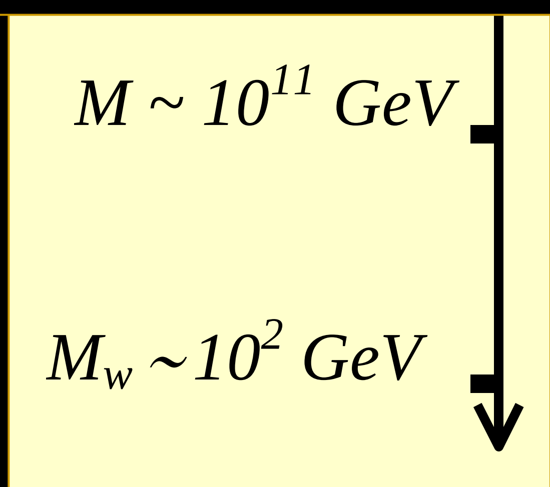
$$m^2 \approx m_0^2 + \cdots$$

Hierarchy problems

WAYS OUT: #3

Extra dimensions: the fundamental scale of gravity may not be too different from the Higgs mass

Should see missing energy and perhaps string states at the LHC, perhaps deviations from Newton's $1/r^2$ law



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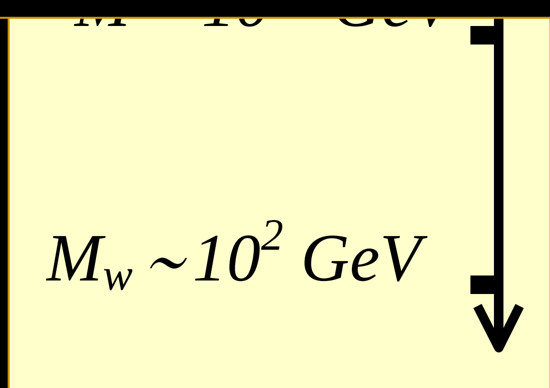
Hierarchy problems

WAYS OUT: #3

Extra dimensions: the fundamental scale of gravity may not be too different from the Higgs mass

Must stabilize the size of extra dimensions to explain hierarchy



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Hierarchy problems

WAYS OUT: #3

Extra dimensions: the fundamental scale of gravity may not l

Must stal hierarchy

M ~ 1

$M_W \sim 1$

For 2 extra dims: two kinds of bounds:

1. Energy-loss bounds imply gravity scale must be above ~10 TeV
2. There are stronger bounds that can require the gravity scale be *much* higher

The stronger bounds are model dependent inasmuch as they require KK modes to decay into visible states; can be evaded.

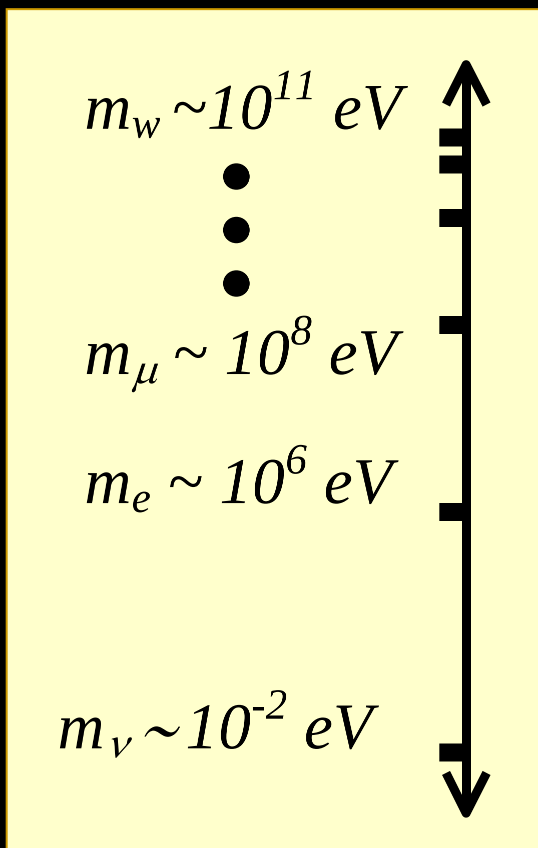
CC Problem

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

$$L_{SM} = \lambda_0 + m^2{}_0\, H^* H + dimensionless$$

$$\lambda = \lambda_0 + higher\ order \sim (3 \times 10^{-3}\ eV)^4$$

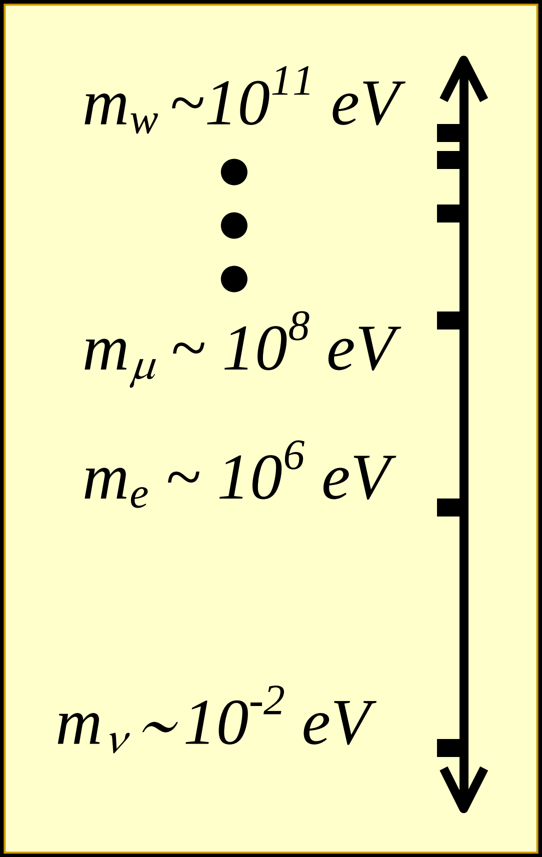
CC Problem



Modern picture: no unique 'classical' theory; instead many 'effective' theories

$$\rho_{vac} = \lambda_0 + k_\upsilon m_\upsilon^4$$

CC Problem



Modern picture: no unique 'classical' theory; instead many 'effective' theories

$$\rho_{vac} = \lambda_1 + k_e m_e^4 + k_\nu m_\nu^4$$

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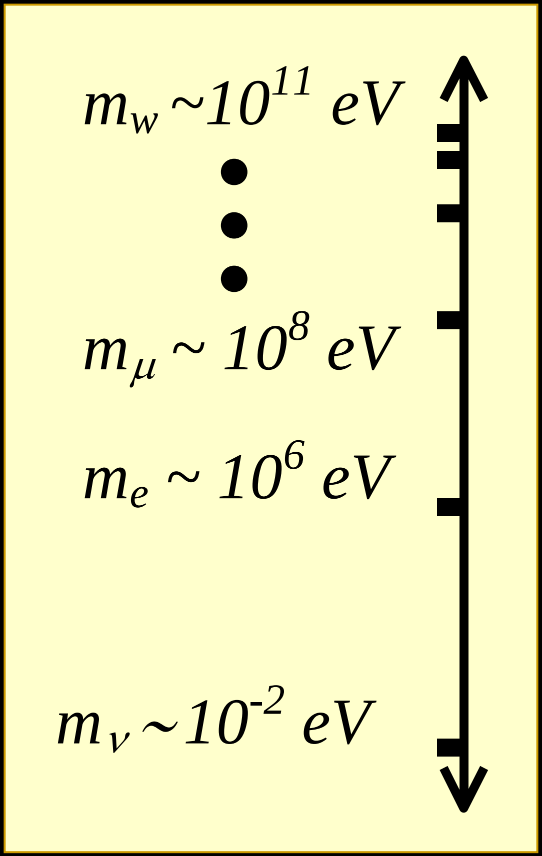
CC Problem



Modern picture: no unique 'classical' theory; instead many 'effective' theories

$$\rho_{vac} = \lambda_1 + k_e m_e^4 + k_\nu m_\nu^4$$

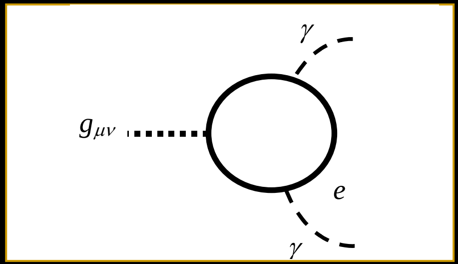
$$\rho_{vac} = \lambda_0 + k_\nu m_\nu^4$$

Must cancel to 32 decimal places!!

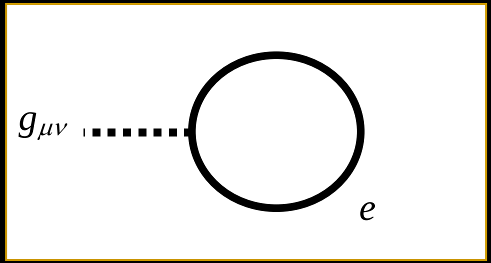
CC Problem

- But the SM has another unnatural parameter

Why this?



But not this?



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

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

Proposals

"Circumstantial evidence is a very tricky thing," answered Holmes thoughtfully.
"It may seem to point very straight to one thing, but if you shift your own point of view a little, you may find it pointing in an equally uncompromising manner to something entirely different."
Sherlock Holmes in *The Boscombe Valley Mystery*

What a solution would look like

Roads well travelled

Symmetries and no-gos

Proposals

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- Apply at energies larger than the cosmological constant scale
  - *Quantum effects are not a problem until particles included with masses heavier than the vacuum energy.*

What Must a Solution Do?

- Go beyond the classical approximation
  - *Hard to beat a cosmological constant at classical level*

- Apply at energies larger than the cosmological constant scale
  - *Quantum effects are not a problem until particles included with masses heavier than the vacuum energy.*

- Do no harm
  - *Do not screw up particle physics or cosmology.*

Popular Proposals

- Denial
  - *Work on something else and hope Dark Energy doesn't affect it.*
- Anthropic Arguments
  - *Multiverse explanations for why naturalness might not be needed*
- Modify Gravity I
  - *'New' CC problem: try to generate acceleration IF CC not present*
- Modify Gravity II
  - *Screening: try to screen CC using graviton mass* (still missing: nonlinear proof of screening; and UV completion above the CC scale)

Can Symmetries Help?

- Supersymmetry
  - *Can suppress a vacuum energy, but only by SUSY breaking scale*

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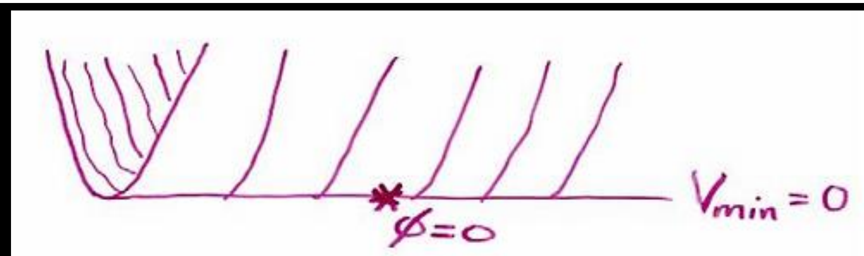
- Scale Invariance
  - *Can suppress a vacuum energy even if spontaneously broken*

Can Symmetries Help?

- Su
- Sca

- Scale invariance and Weinberg's no-go theorem:
  - Scale invariance kills the cc (and all masses) if unbroken
  - It kills the cc (but *not* masses) *even if spontaneously broken*

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



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  - *Weinberg's no-go: if spontaneously broken, scale invariance in itself cannot keep the flat direction from being lifted*

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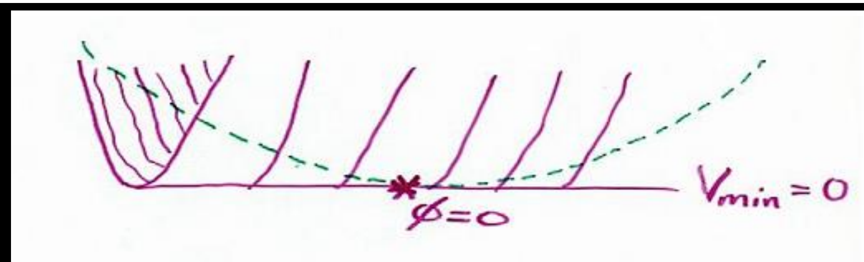

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For later: *Weinberg's no-go does not say anything at all about the* size *of this correction.*

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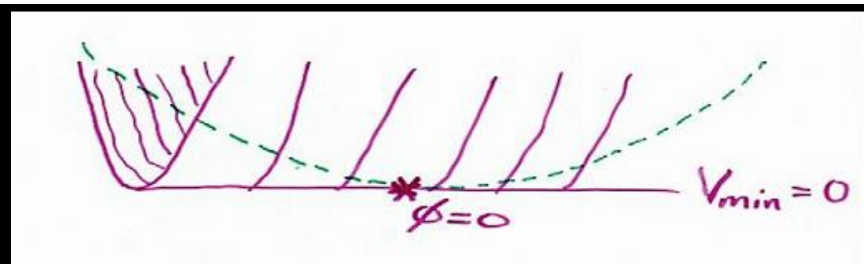

A Way Forward?

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

Sherlock Holmes in *A Study in Scarlet*

A broad direction

Where the Devil is

How would we know?

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A Loophole

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

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

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

A Loophole

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

- The Problem:
  - Einstei
    energy
    a close

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

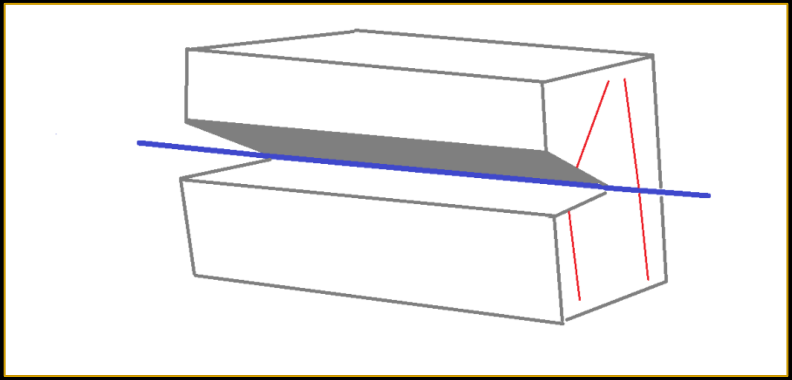
$$T_{\mu\nu} = -\lambda \, g_{\mu\nu}$$

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

A Loophole

Vilenkin et al

- *Why not?*
  - Extra dimensions need not be lorentz invariant
  - *Vacuum energy might curve extra dimensions, rather than the ones we see in cosmology*

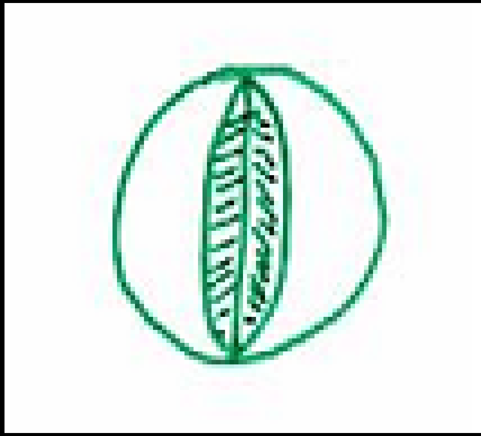


e.g. gravitational field of a cosmic string

A Loophole

Carroll & Guica
Aghababaie et al

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball and related solutions*
  - 'Brane-world' Picture: *we are trapped on a 4D brane within 6 (or more) dimensions*



A Loophole

Carroll & Guica
Aghababaie et al

- A higher-dimensional analog:

brane in
d related

4D brane

To be useful extra dimensions must be present already at the cc scale: micron sized. *(limit is: 45 microns)*

Notice particle physics remains 4 dimensional and only gravitational response sees the extra dimensions!

But…

- But cosmic strings in de Sitter space are *not* flat
- Why can't there be a cosmological constant *in the extra dimensions?*

Doubling Down

- Supersymmetry *can* forbid a cosmological constant in higher dimensions
  - Much as more than one supersymmetry can do in 4D

Doubling Down

- Supersymmetry *can* forbid a cosmological constant in higher
  - Much as more than

Does NOT mean particle physics (brane) should look supersymmetric

only gravity (bulk) need be

Doubling Down

- Supersymmetry *can* forbid a cosmological constant in higher dimensions
  - Much as more than one supersymmetry can do in 4D
  - Higher-dimensional supergravity tends to be scale invariant

Doubling Down

- Supersymmetry *can* forbid a cosmological constant in higher
  - Much as more than
  - Higher-dimensional variant

Typically:

$$L = e^{-2\phi}\sqrt{-g}\, f(\psi, \partial\phi)$$

so $L \to \lambda^2 L$ *when* $e^{-\phi} \to \lambda e^{-\phi}$

Doubling Down

- Supersymmetry *can* forbid a cosmological constant in higher dimensions
  - Much as more than one supersymmetry can do in 4D
  - Higher-dimensional supergravity tends to be scale invariant
- Novel mechanism available (for bulk loops):
  - Can be that at least one supersymmetry is unbroken *locally* everywhere in extra dimensions, but all broken *globally* once all branes are viewed together.

Shortest wavelength that 'knows' that SUSY is broken is size of extra dimensions, giving $\lambda \sim 1/r^4$

Good Things

- Can the numbers work?
  - *Radius, r, as large as microns since* $\lambda \sim 1/(4\pi r)^4$

Good Things

Adelberger et al

- Can the numbers work?
  - *Radius, r, as large as micr*

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

Good Things

- Can the numbers work?
  - *Radius, r, as large as microns since* $\lambda \sim 1/(4\pi r)^4$
  - *At most two dimensions can be this large*

Good Things

Arkani-Hamed et al

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  - *Radius, r, as large as microns since* $\lambda \sim 1/(4\pi r)^4$
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Otherwise the high-D Planck scale, M_g, must be too low to get 4D Planck scale right.

Remarkably: same size, *r*, needed by EW Hierarchy Problem as for vacuum energy, since $M_p = M_g^2\, r$,

Good Things

- Can the numbers work?
  - *Radius, r, as large as microns since* $\lambda \sim 1/(4\pi r)^4$
  - *At most two dimensions can be this large*
  - *Must include 'back-reaction' of branes on the extra dimensions.*

Good Things

Aghababaie et al

- Can the numb
  - *Radius, r, as*
  - *At most two d*
  - *Must include 'back-reaction' of branes on the extra dimensions.*

Extra-dimensional curvature cancels brane tension in 4D vacuum energy.

This is hard to do, and why these models were not studied to death earlier.

A broad direction

Where the Devil is

How would we know?

A Way Forward?

Explicit examples

- Ge

- Ar

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

Explicit examples

Nishino, Sezgin

- Ge
- Ar

- 6D Einstein-Maxwell-scalar system

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

Two cases (both with flat directions):

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

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

Explicit examples

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dS sign

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Explicit examples

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

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

then

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

Explicit examples

Aghababaie et al
Gibbons, Guven & Pope

- Ge

- Exact classical resu

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

In particular,

$$\hat{R} = 0 \;\; if \;\; n\cdot\nabla\phi = 0$$

at the brane positions
(All such solutions
are explicitly known)

then

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

- An

Explicit examples

CB, Maharana, van Nierop & Quevedo

- Ge
- Exact classical resu

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

General feature of high dim sugra that $\hat{R}$ is set by bc's at brane posns: *(Must know to vanish if bc's are supersymm.)*

then

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

- An

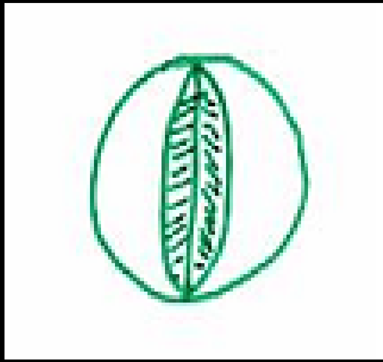
Explicit examples

Carroll & Guica
Aghababaie et al

- Simple solution

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

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



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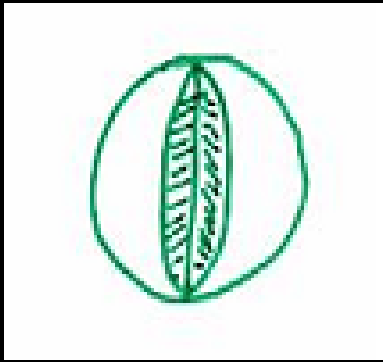

Magnetic flux required to stabilize extra dimensions against gravitational collapse

Explicit examples

Carroll & Guica
Aghababaie et al

- Simple solution

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

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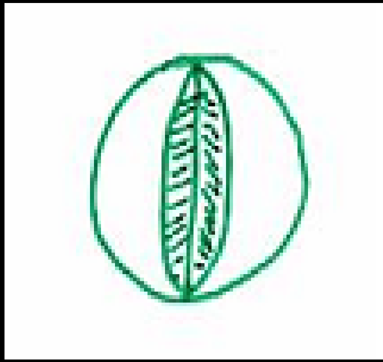

Labels flat direction *(which exists due to shift symmetry or scale invariance)*

Explicit examples

Carroll & Guica
Aghababaie et al

- Simple solution

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

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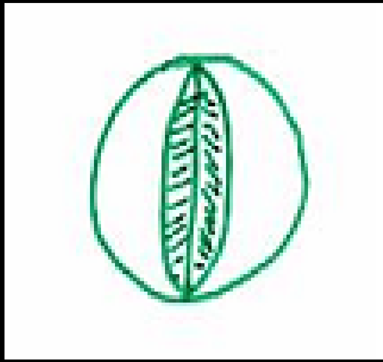

For later: notice radius is exponential in the flat direction ϕ_0 in the SUSY case

Explicit examples

- Simple solution (including back-reaction)

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

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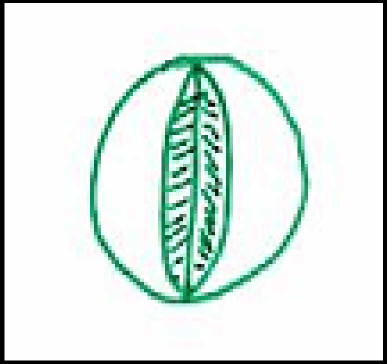

$$1 - \alpha = \frac{\kappa^2 T}{2\pi}$$

Explicit examples

Carroll & Guica

- Simple solution (non-SUSY case)

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

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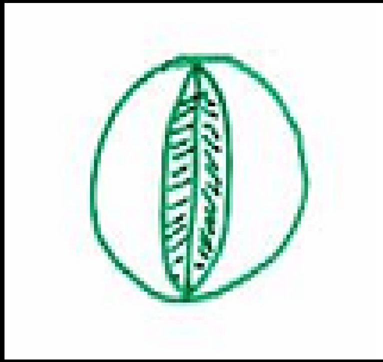

Field equations

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

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

Flux quantization

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

Explicit examples

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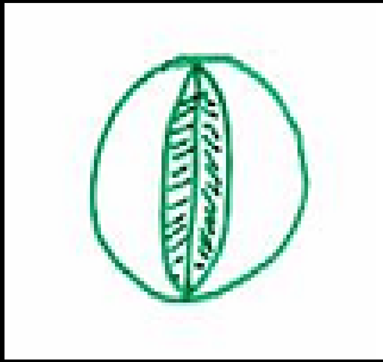

$$Q = \frac{n}{2\alpha g L^2} \qquad \hat{R} = \kappa^2 (Q^2 - 2\Lambda)$$

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

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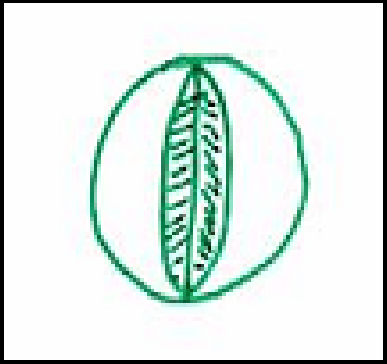

Tune $\Lambda = \frac{Q^2}{2}$ so $\hat{R} = 0$

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

Explicit examples

Aghababaie et al

- Simple solution (SUSY case)

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

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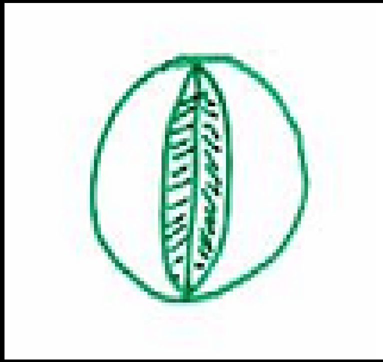


Field equations

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

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

Flux quantization

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

Explicit examples

Salam & Sezgin

- Simple solution

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

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

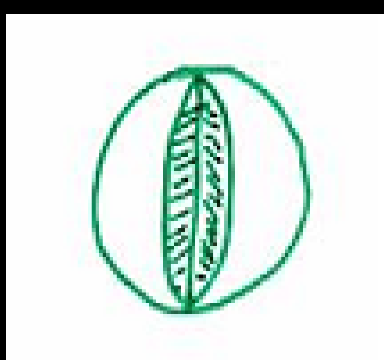
On-source geometry is always flat.

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

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

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

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



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

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Explicit examples

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

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

Obstructs T to δT

Explicit examples

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

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

- On other hand, general argument:

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

Explicit examples

CB & van Nierop

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

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

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

- New function Φ has interpretation as brane-localized flux

Explicit examples

- SUSY result:

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

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

Explicit examples

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Agrees with general result given earlier

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

Explicit examples

CB, Diener & Williams

- So absence of brane coupling to ϕ implies flatness
- But robust flatness also requires brane coupling to bulk flux.
  - *Are these compatible, given that ϕ is the gauge coupling for the bulk gauge field?*
- In detail, it appears generically not. In scale invariant case get Weinberg's runaway: $V(\phi) = Ae^{2\phi}$

Explicit examples

- Ge
- Ar

- What about loops?
  - Pure brane loops just change tension and cannot in themselves generate a dilaton coupling to the brane not already present

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- What about loops?
  - Pure brane loops just change tension and cannot in themselves generate a dilaton coupling to the brane not already present
  - Each bulk loop comes with a factor of $e^{2\phi}$ (since this is the loop-counting parameter), but flux stabilization relates this to the radius by $e^{2\phi} = 1/r^4$ making the cc equal the KK scale.

Explicit examples

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

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

and source actions

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

Explicit examples

Short-
both t

and sc

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

$$V(r) = A_{-1} M^6 r^2 + A_0 M^4 + \frac{A_1 M^2}{r^2} + \frac{A_2}{r^4} + \cdots$$

with

$$A_{-1} \cong a_1 e^{3\phi} \cong \frac{a_1}{(Mr)^6},$$

$$A_0 \cong b_1 e^{2\phi} \cong \frac{b_1}{(Mr)^4},$$

$$A_1 \cong c_1 e^{\phi} \cong \frac{c_1}{(Mr)^2}$$

and so on

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

A Way Forward?

A broad direction

Where the Devil is

How would we know?

Surprises?

- Required spectrum:
  - *Particle sector (always 4D)*

Gravity sector

$M_g \sim 10 - 30\, TeV$

(gravity 6D and SUSY)

SM particles

$\frac{1}{r} \sim 0.1 - 0.01\, eV$

gravity becomes 4D

neutrino masses

a new very light scalar?

Surprises?

Newton's Law $\Phi = -k/r$ *applies for* $r > 1$ micron

Converts to 6D form $\Phi = -k''/r^3$ *for* $r < 1$ micron

Likely a scalar-tensor theory, m ~ H, over longest scales

$\frac{1}{r} \sim 0.1 - 0.01\, eV$

neutrino masses

gravity becomes 4D

a new very light scalar?

Surprises?

No MSSM! ✓

Vanilla Higgs!

- Required spectrum:
  - *Particle sector (always 4D)* | *Gravity sector*

$M_g \sim 10 - 30\,TeV$

SM particles | *(gravity 6D and SUSY)*

$\frac{1}{r} \sim 0.1 - 0.01\,eV$

neutrino masses | *gravity becomes 4D*

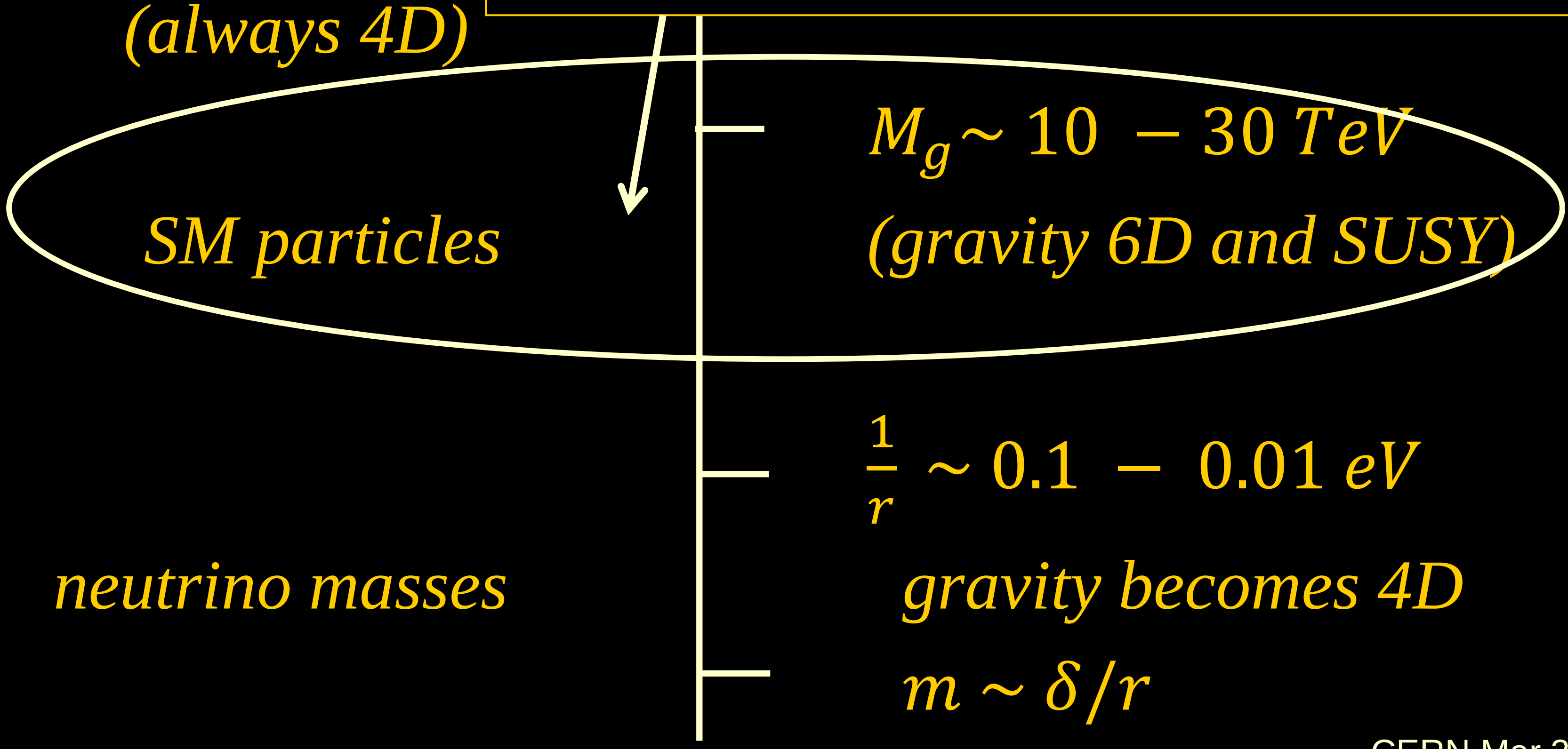
$m \sim \delta / r$

Surprises?

- Required spec
  - *Particle secto*
    (always 4D)

Missing energy, *not* just to gravitons since also other fields in bulk (eg Higgs can mix with bulk scalars)

String excited versions of all SM particles (eg Z' searches) BELOW M_g



Surprises?

- Required spect
  - *Particle sector*
    (always 4D)

Sterile neutrinos: many KK towers of 6D fermions in extra dimensions, massless because tied to graviton by SUSY

DARK MATTER: what is it?

WIMP? (nonstandard thermal evolution)

AXION? OTHER BRANE? .....

SM particles

(gravity 6D and SUSY)

$\frac{1}{r} \sim 0.1 - 0.01\ eV$

neutrino masses

gravity becomes 4D

$m \sim \delta/r$

Opportunities & Concerns

- If true, many striking implications:

  - Micron deviations from inverse square law
  - *Missing energy at the LHC and in astrophysics: requires M_g > 10 TeV*
  - *Probably a vanilla SM Higgs*
  - Excited string states (or QG) at LHC *below* 10 TeV
  - *Low energy SUSY without the MSSM*
  - Very light Brans-Dicke-like scalars
  - *Sterile neutrinos from the bulk?*

Opportunities & Concerns

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  - Excited string states (or QG) at LHC below 10 TeV
  - ✓ *Low energy SUSY without the MSSM*
  - Quite light Brans-Dicke-like scalars
  - Sterile neutrinos from the bulk?
  - New massless states (axion, gauge boson)

Opportunities & *Concerns*

S Weinberg

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

Postscript: Naturalness

Light scalars *and vacuum energy* are unnatural

….so LHC will see:

- Extra dimensions in your face *….and supersymmetric (yet without MSSM superpartners at the LHC)*

Patron Saint of All Things Natural

Summary

- Brane backreaction is largely unexplored with more than one transverse dimension:
  - Many cool features in 1 dimension (RS models)
  - Requires renormalizing singularities at sources

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  - Parameterically small on-brane curvatures
  - de Sitter solutions to higher dimensional sugra

Summary

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

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

A. Conan Doyle

Fin