Physics Beyond the Standard Model III: Composite Higgs and/or Extra Dimensions

David E Kaplan

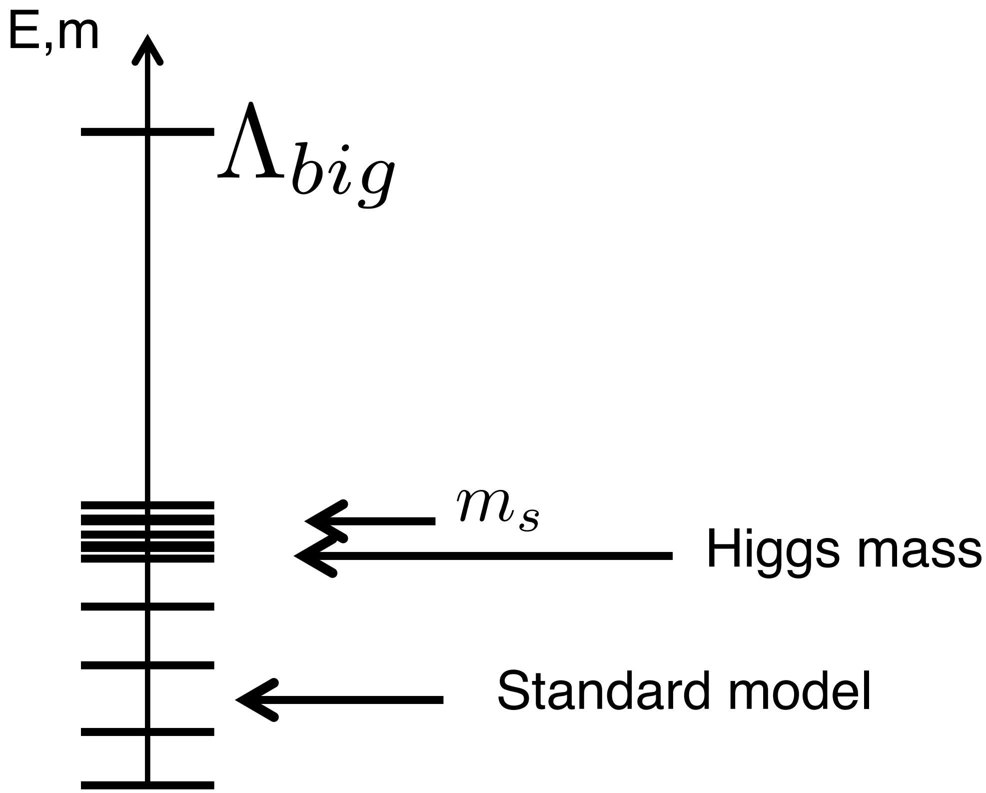
HCP Summer School 2007

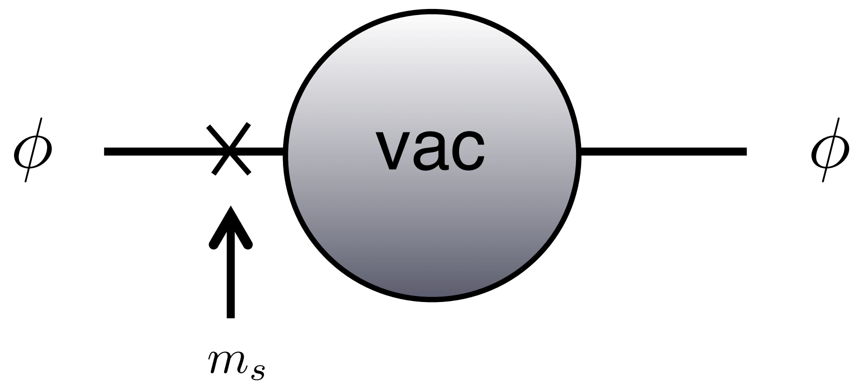
CERN

Supersymmetry

Superpartner masses: m_s

The symmetry is “softly broken”, with $m_s \ll \Lambda_{big}$





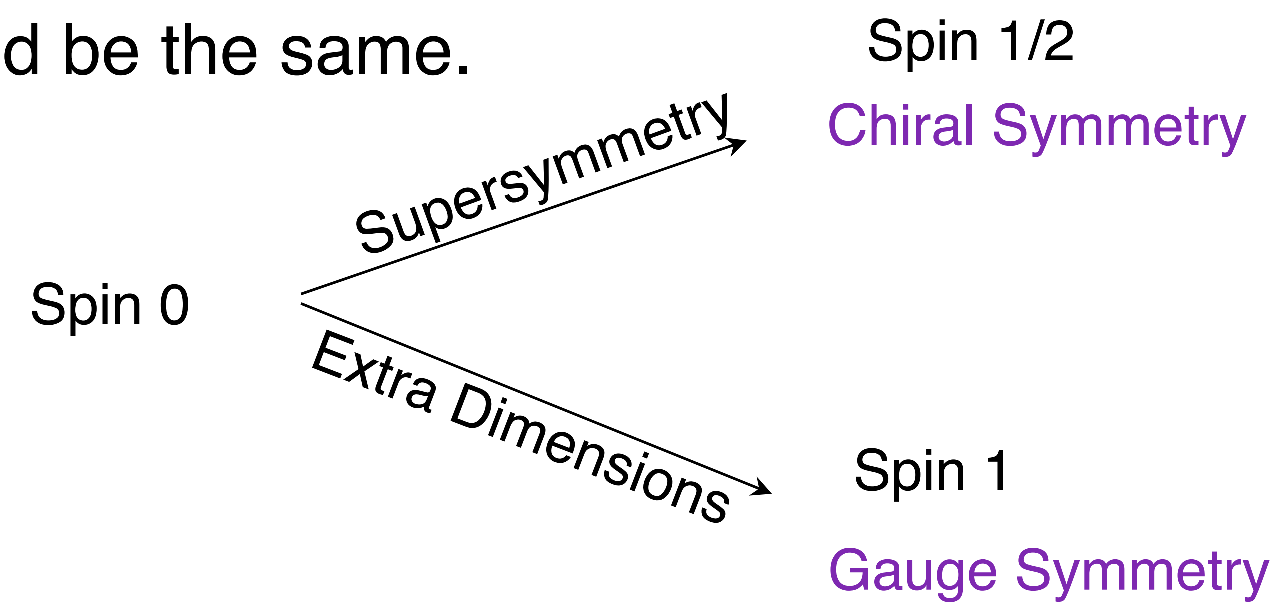
Do perturbation theory

In the superpartner masses

Symmetries Between Particles with Different Spins

Masses and scattering cross sections

would be the same.



Spin 0 $\longleftrightarrow$ 1

A massless spin 1 field (e.g., the electromagnetic field) can be described by a 4-vector:

$$\mu = 0, 1, 2, 3 \qquad A_\mu \;\longrightarrow\; \Phi, \vec{A}$$

After imposing gauge invariance, and the equation of motion,

there are two physical polarizations.

Spin 0 $\longleftrightarrow$ 1

A massless spin 1 field in *4 space dimensions* can be described by a 5-vector:

$$M = 0, 1, 2, 3, 5 \qquad A_M \;\rightarrow\; \Phi, \vec{A}, A_5$$

After imposing gauge invariance, and the equation of motion,

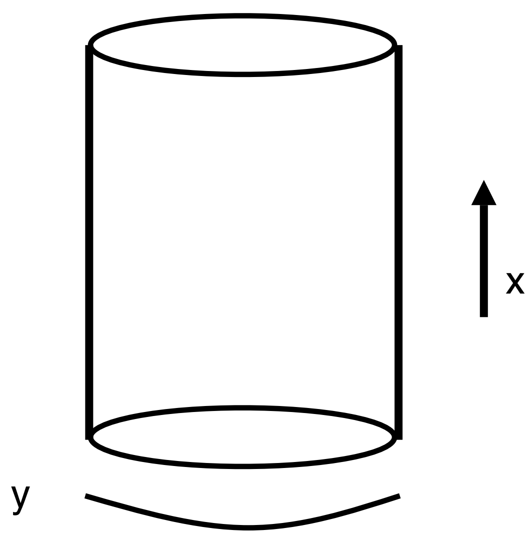
there are *three* physical polarizations.

Spin 0 ⟷ 1

A massless spin 1 field in *4 space dimensions* can be described by a 5-vector:

$$M = 0, 1, 2, 3, 5 \qquad A_M \;\rightarrow\; \Phi, \vec{A}, A_5$$

Now compactify.



At distances much larger than the circumference, L, the new field A_5 is not associated with a direction - it is a scalar (spinless) field.

Spin 0 ⟷ 1

A massless spin 1 field in *4 space dimensions* can be described by a 5-vector:

$$M = 0,1,2,3,5 \qquad A_M \;\rightarrow\; \Phi, \vec{A}, A_5$$

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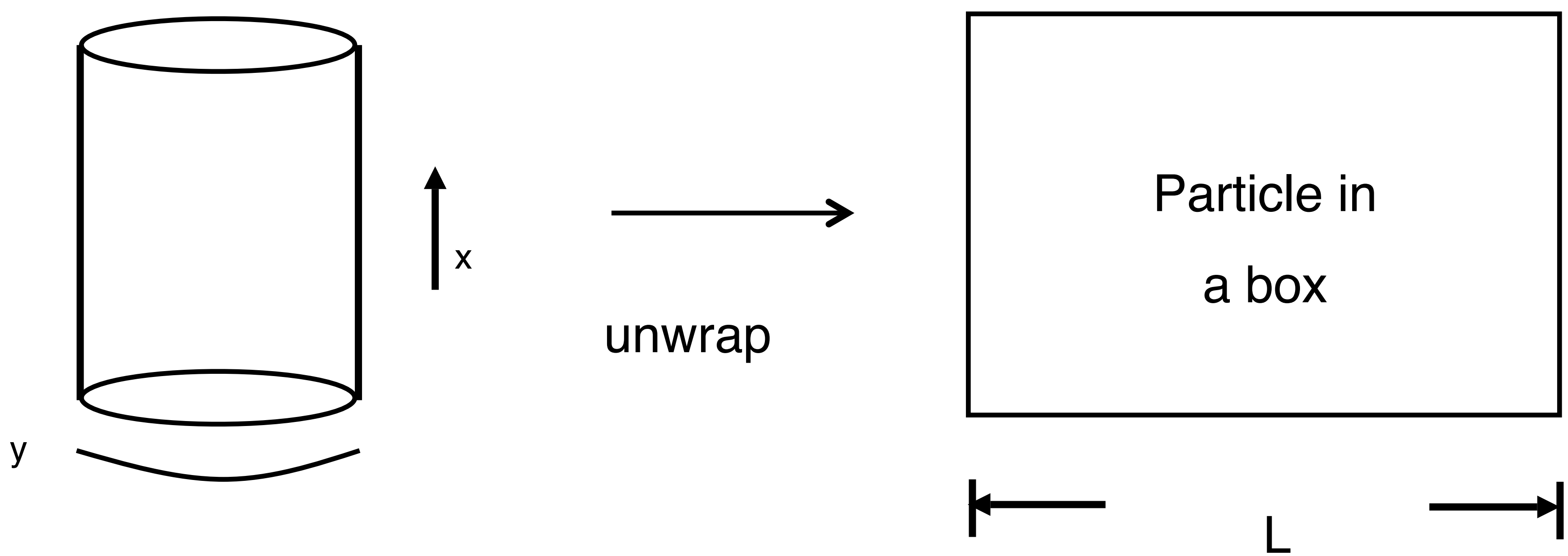
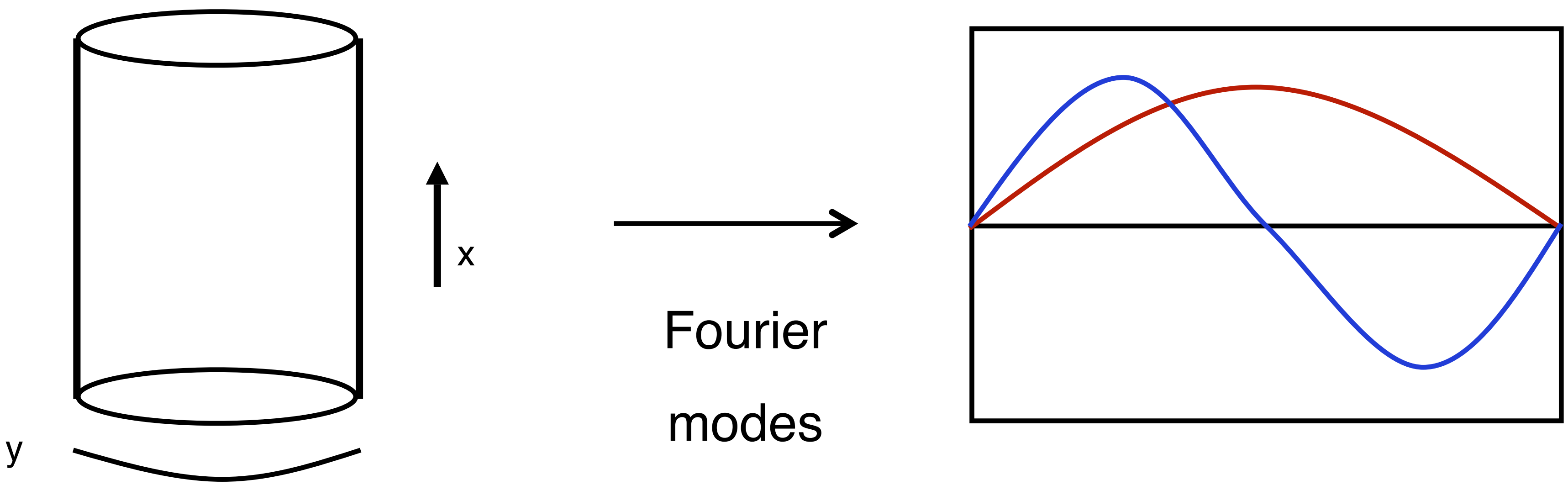


Spin 0 ⟷ 1

At short distances, 4-dimensional rotational invariance appears intact.

At long distances, the vector potential breaks up into a 3-vector and a scalar.



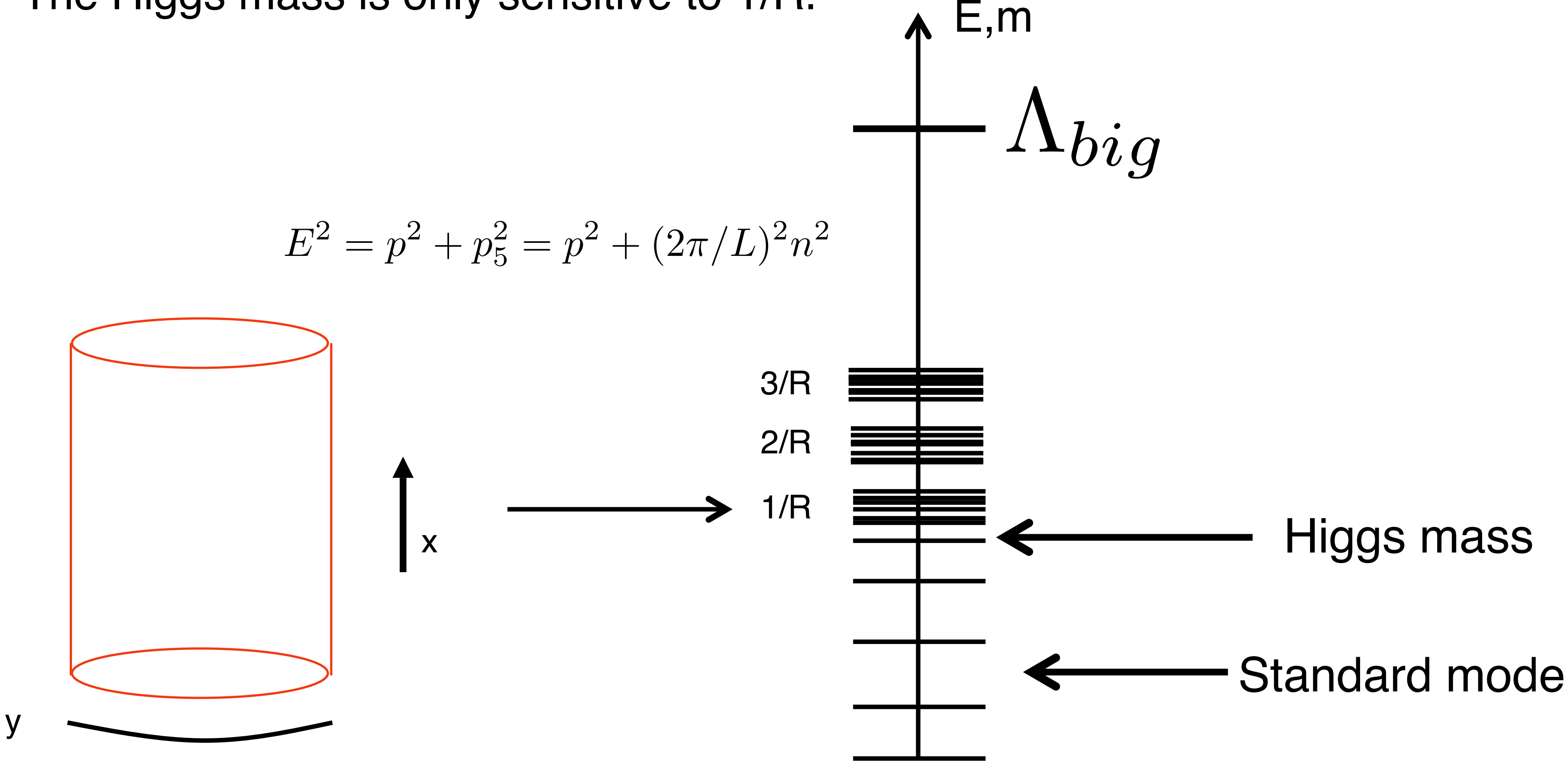
Spin 0 ⟷ 1

At short distances, 4-dimensional rotational invariance appears intact.

At long distances, 4-dimensional rotational invariance is softly broken.

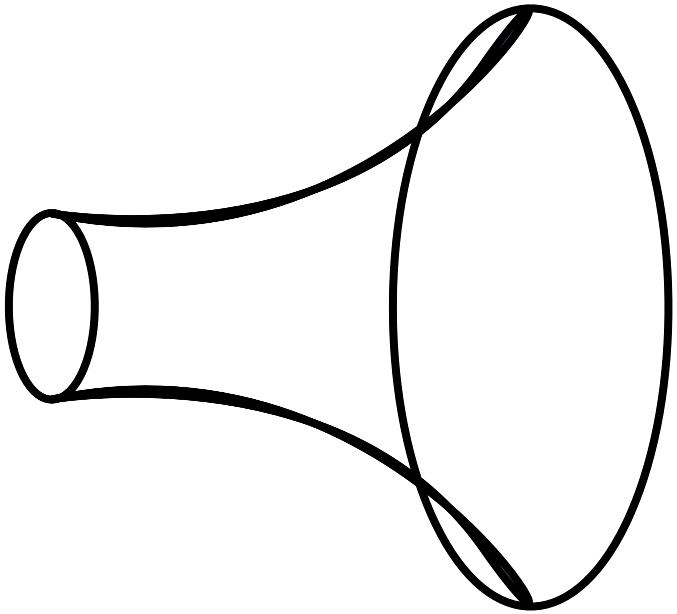
The Higgs mass is only sensitive to 1/R.

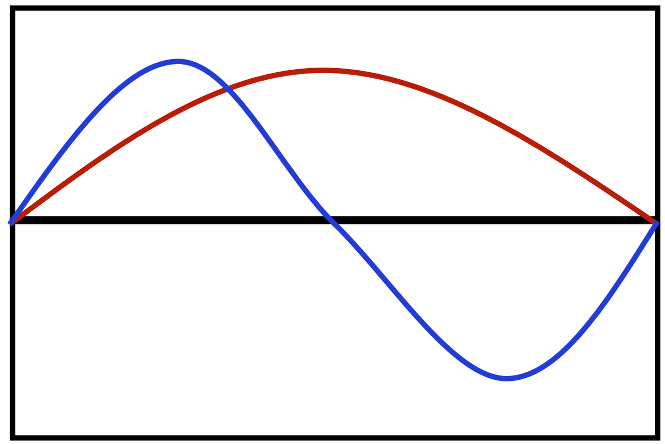
$$E^2 = p^2 + p_5^2 = p^2 + (2\pi/L)^2 n^2$$



Some separation required between the Higgs mass and 1/R.

RS Models - A Warped Extra Dimension





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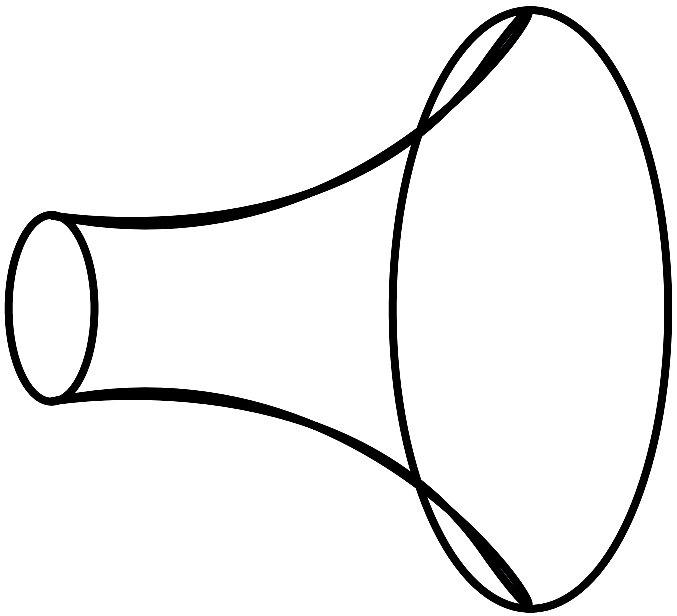

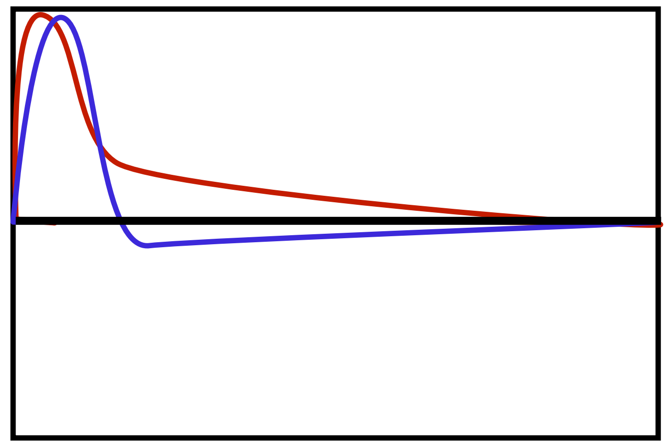

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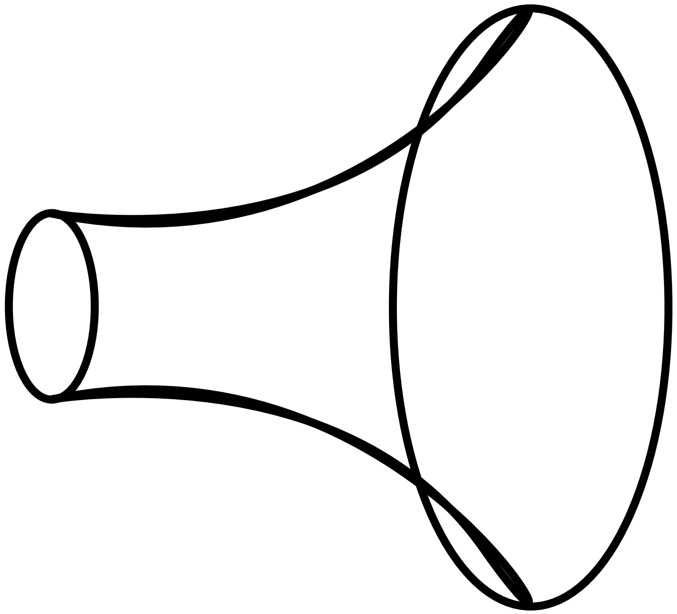

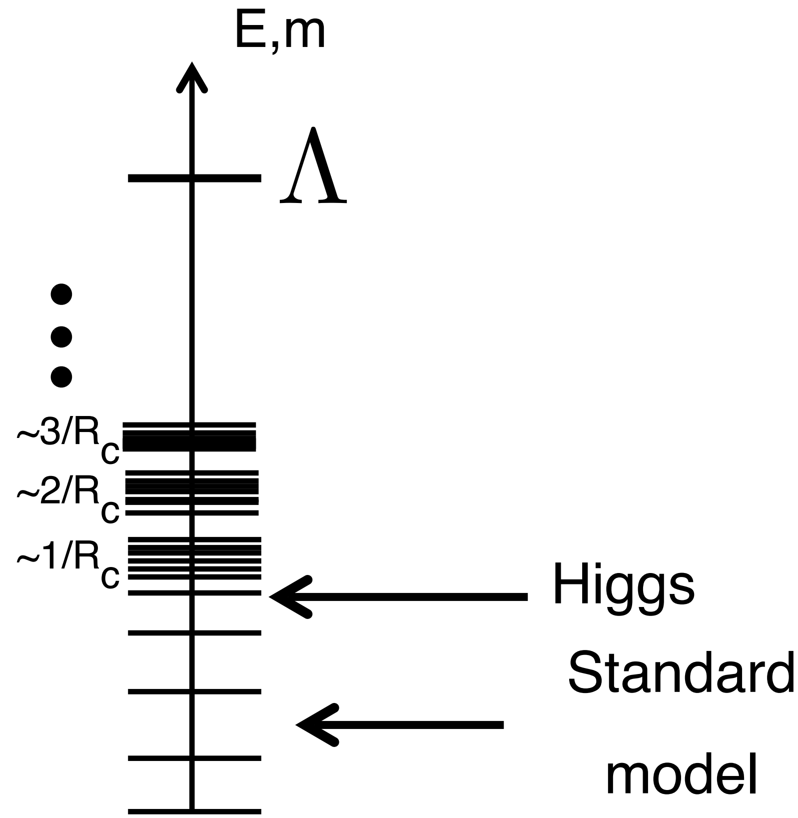

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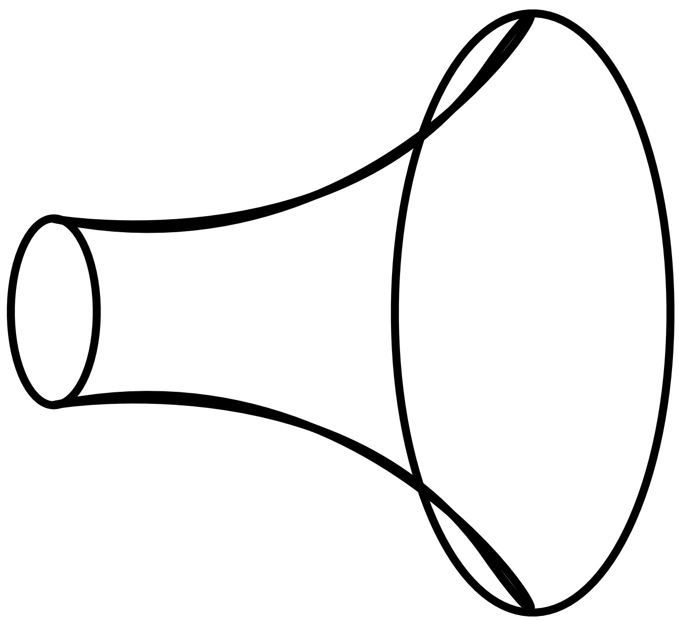

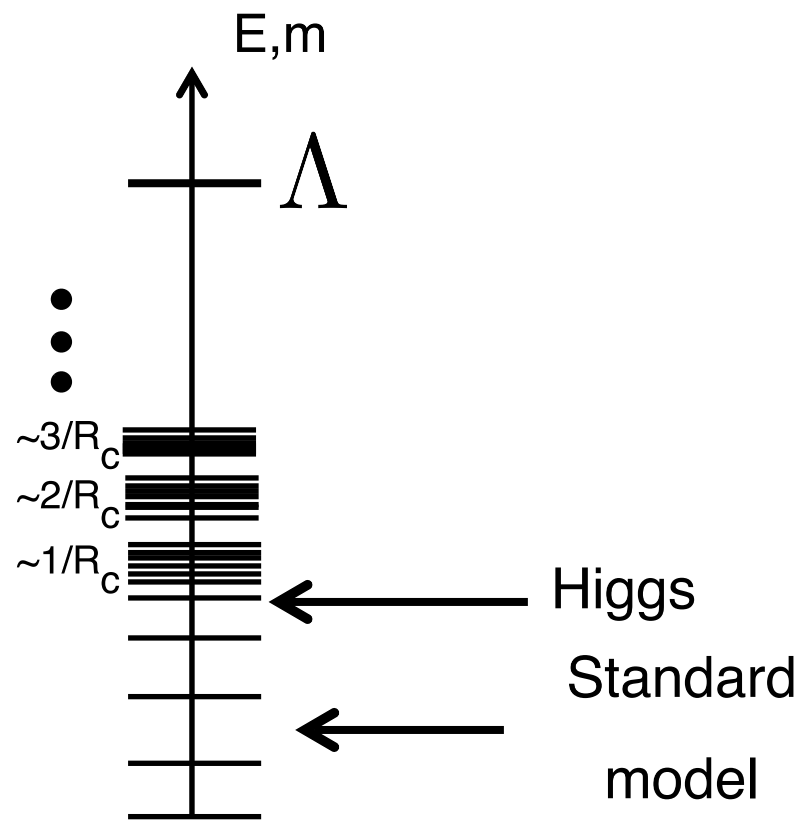

This 4D-5D “duality” also compares strong coupling with weak coupling.

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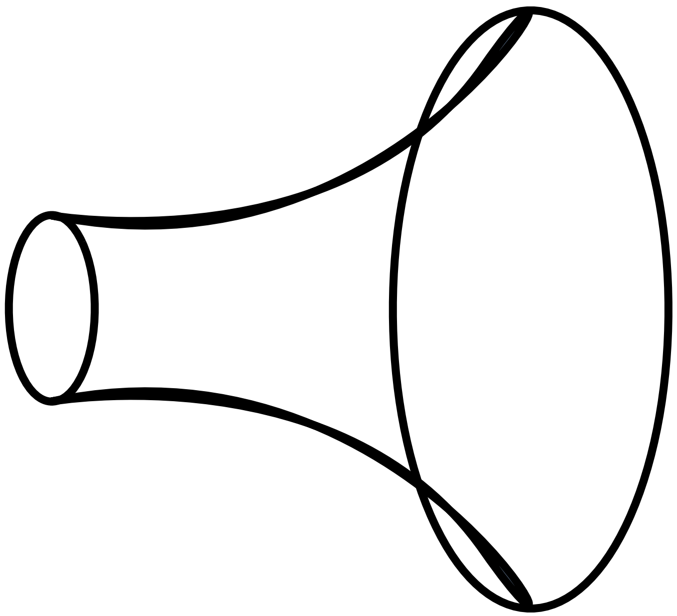
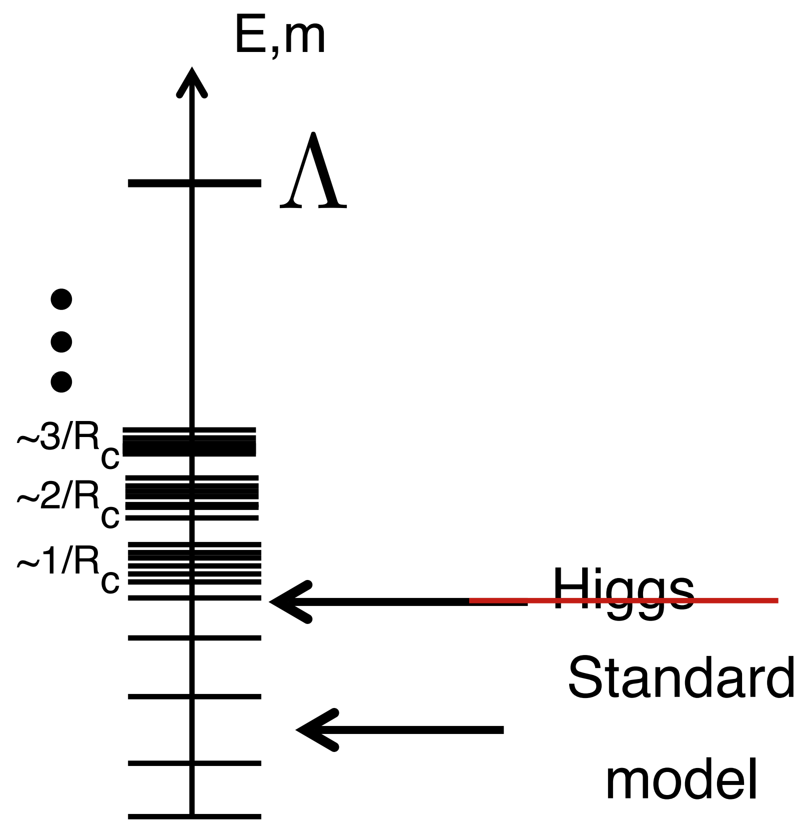


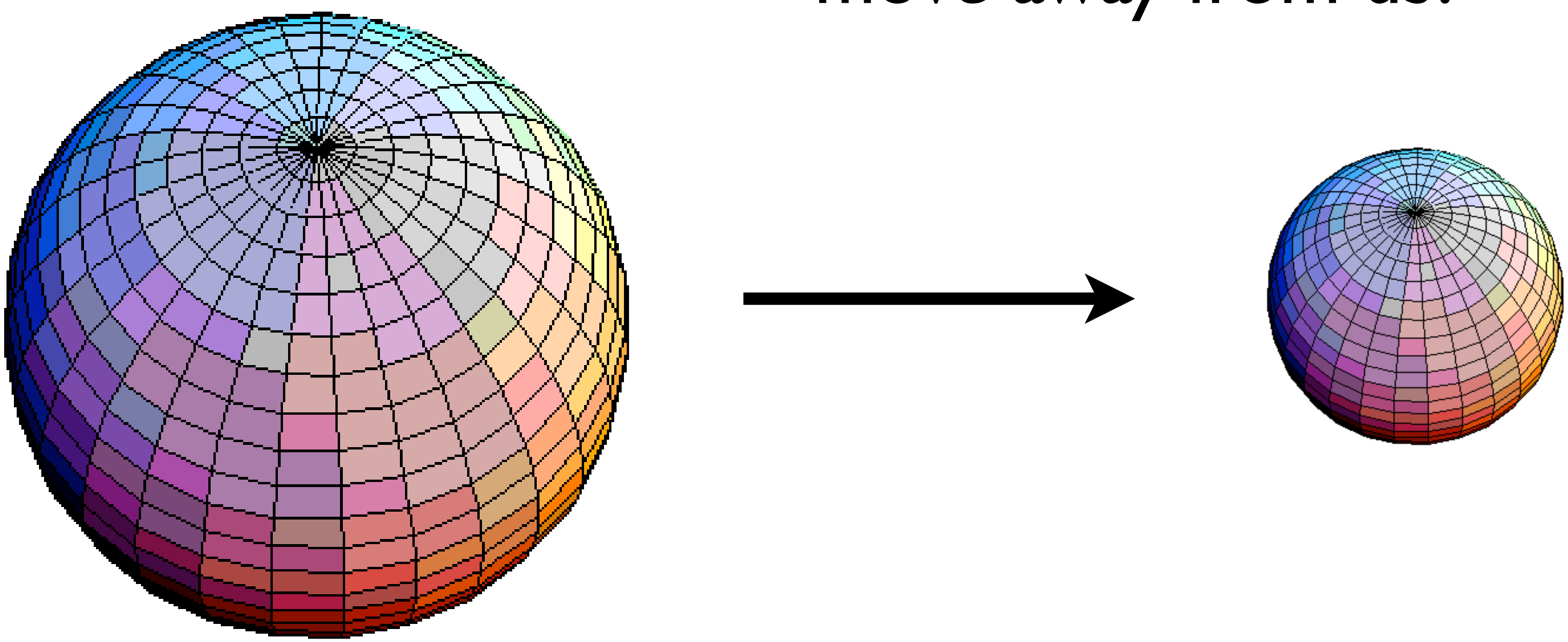
This 4D-5D "duality" also compares strong coupling with weak coupling.

The theory should resemble Technicolor



AdS/CFT

Did this object shrink or
move away from us?



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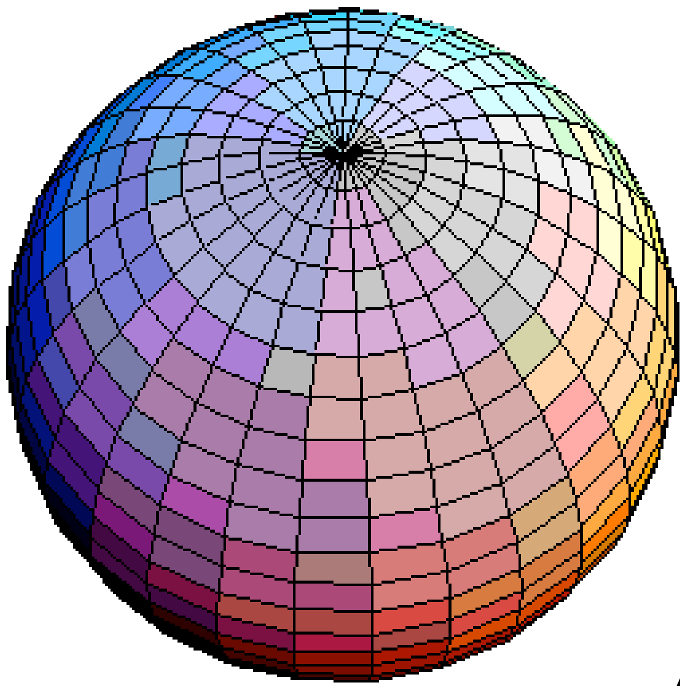
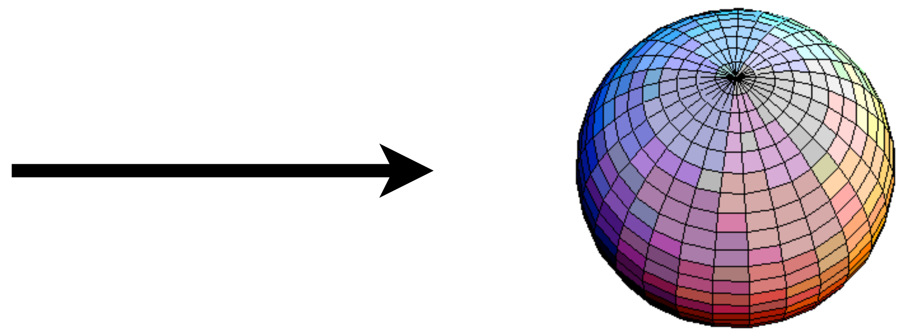
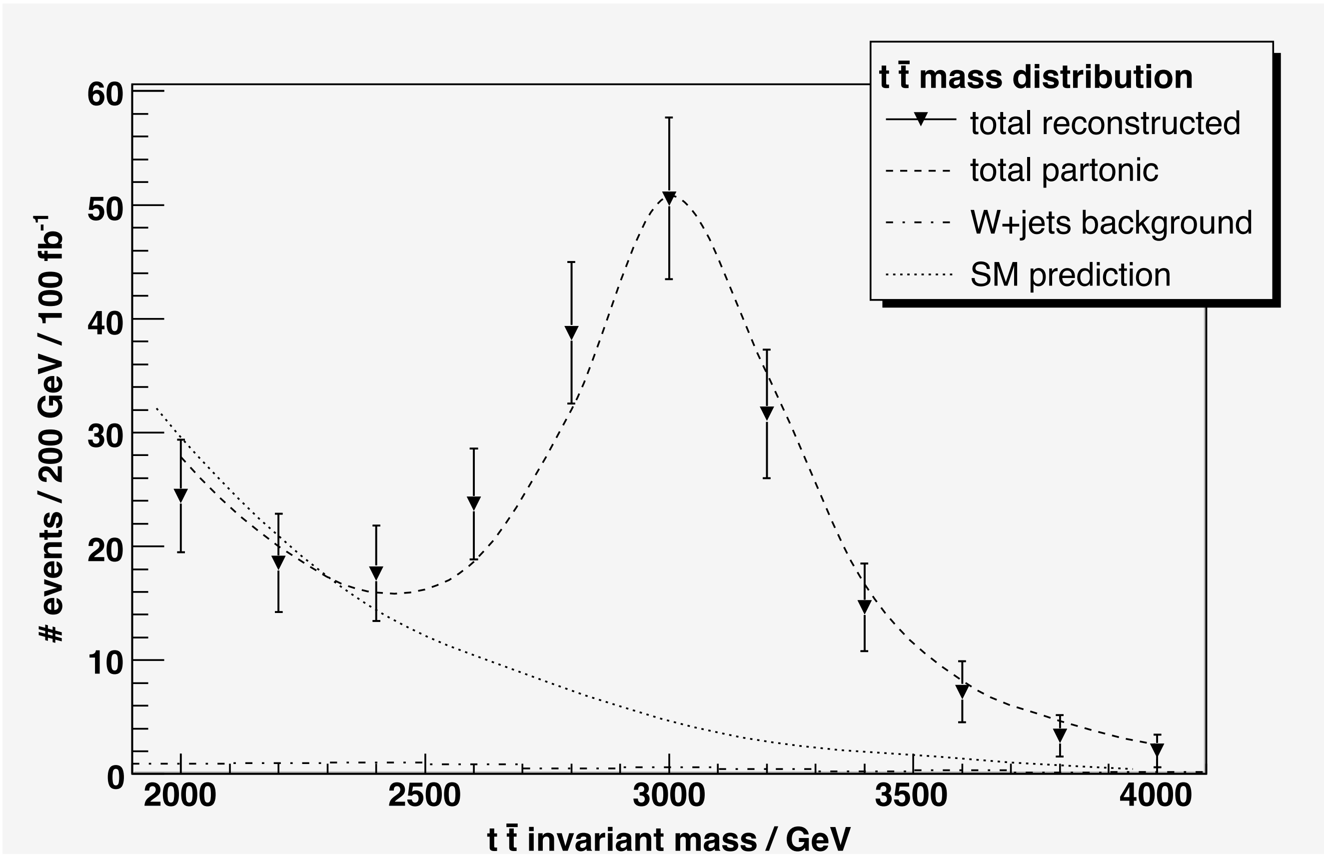




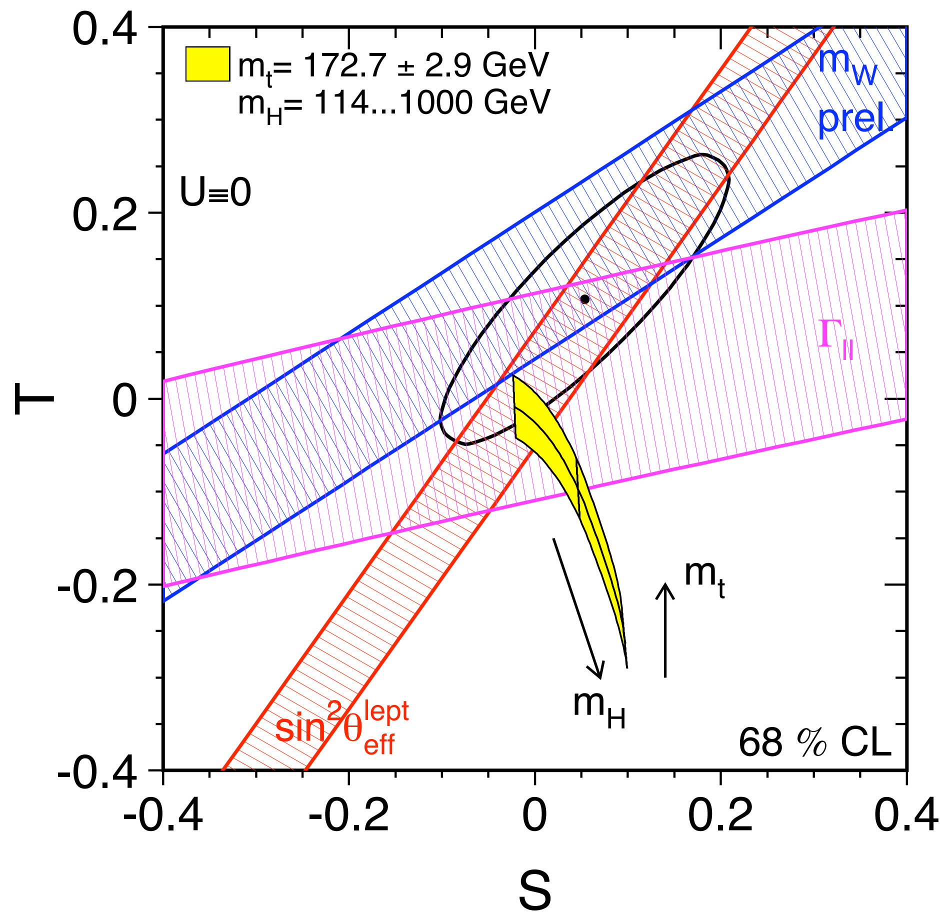
A type of 5-dimensional theory can
be described as a 4-dimensional
“scale-invariant” theory.

KK-gluon at the LHC



Agashe, Belyaev, Krupovnickas, Perez, Virzi

What was wrong with Technicolor?



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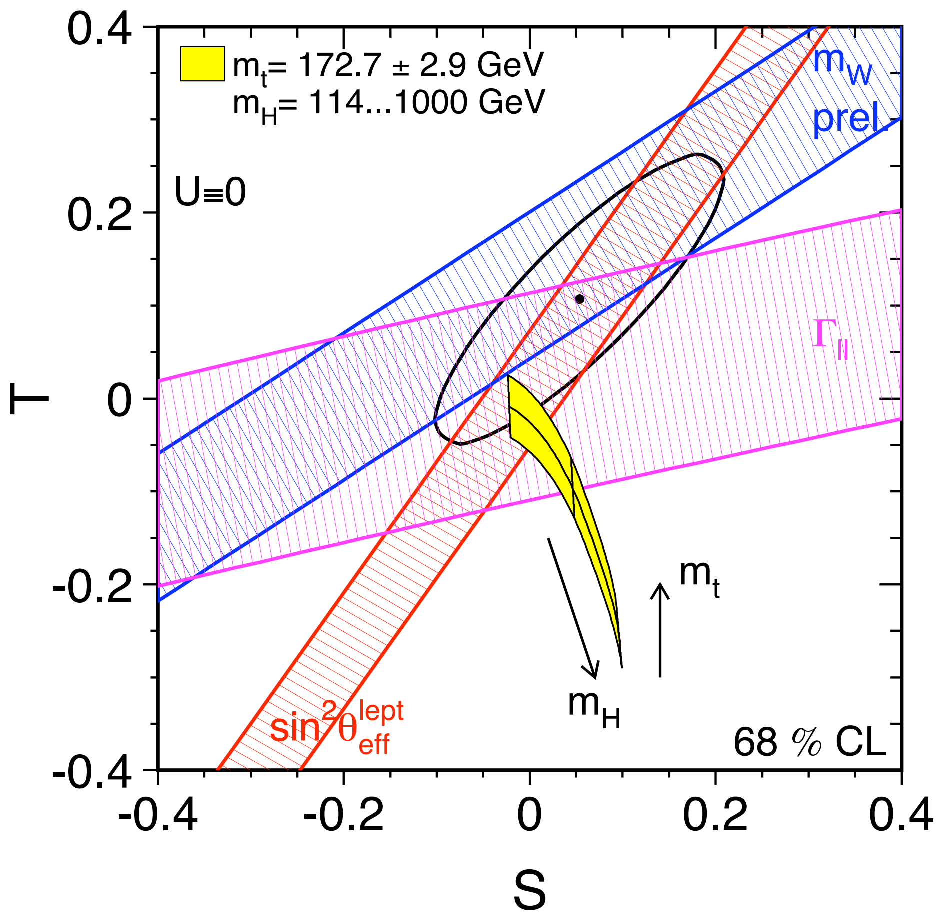

How About Strong Coupling *With* a Higgs?

Pions are light, spinless composite particles.

How do they do that?

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Pions are light, spinless composite particles.

How do they do that?

There is ample evidence that they are approximate Goldstone bosons from chiral-symmetry breaking in the theory of the strong nuclear force (QCD).

Goldstone Bosons

A “continuous” symmetry of the Lagrangian which is broken by
The ground state of the theory (the vacuum) is said to be
“spontaneously broken”

A spontaneously broken (internal) symmetry always produces
a massless scalar particle.

If the symmetry is only approximate, the particle won’t be massless,
but can be very light.

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but can be very light.

Do thing with the wire now.

Goldstone Bosons

Let's see the classical phenomenon using the wave description.

An infinite straight rope breaks translation invariance in directions perpendicular to the rope. The transverse waves are the Goldstone modes.

$$\mathcal{L} = \frac{1}{2}\sigma\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2}\tau\left(\frac{\partial\phi}{\partial x}\right)^2 \longrightarrow \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\partial^2\phi}{\partial x^2}$$

Fourier transform:

$$\phi(x,t) = \int \frac{dk\, d\omega}{4\pi^2}\tilde{\phi}(k,\omega)\, e^{i(kx-\omega t)} \longrightarrow \omega^2 = k^2c^2$$

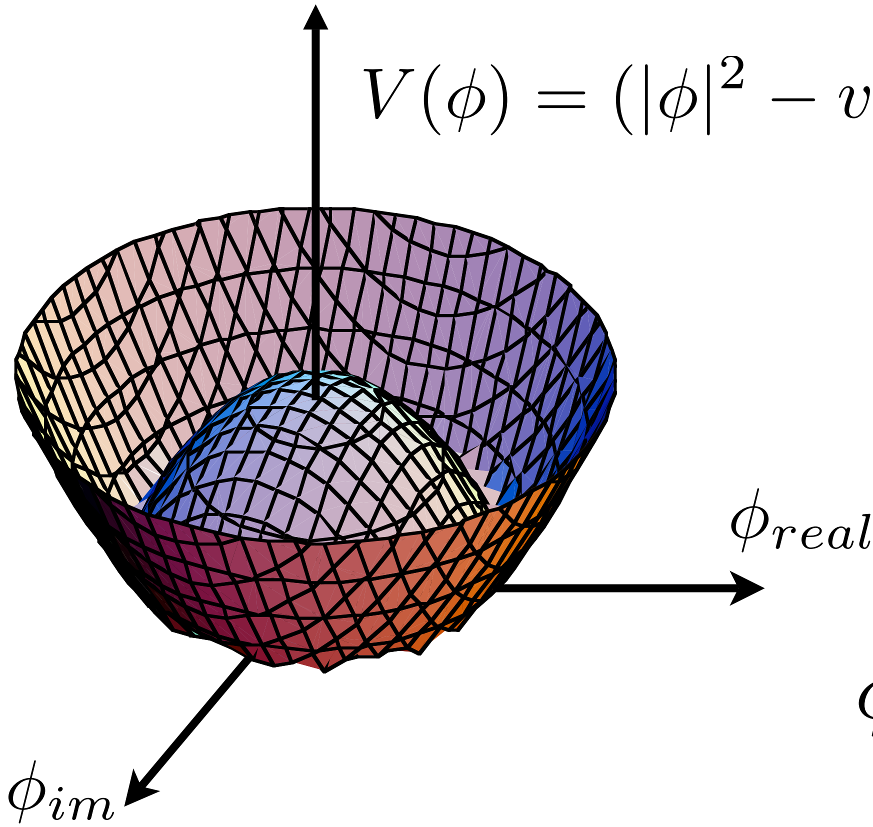
Can have waves with arbitrarily low frequency.

quantize: Particles with arbitrarily low energy $\longrightarrow$ massless particles

$$E^2 = p^2$$

Internal Symmetry Breaking

$$V(\phi) = (|\phi|^2 - v^2)^2$$



$$\phi \to e^{i\alpha}\phi(x)$$

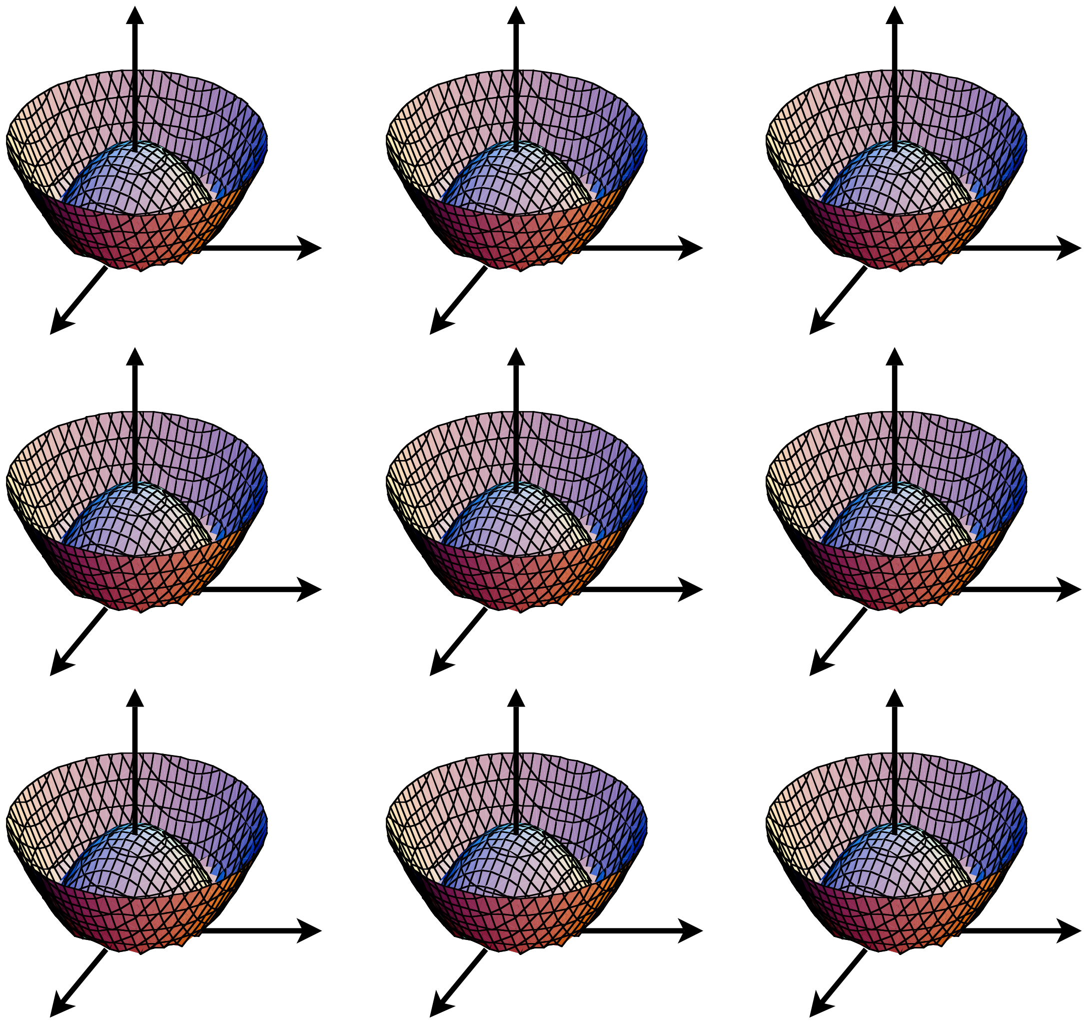
$$|\phi_{min}| = v$$

$$\phi(x) = (v + \rho(x))e^{i\theta(x)}$$

The potential is independent of theta.

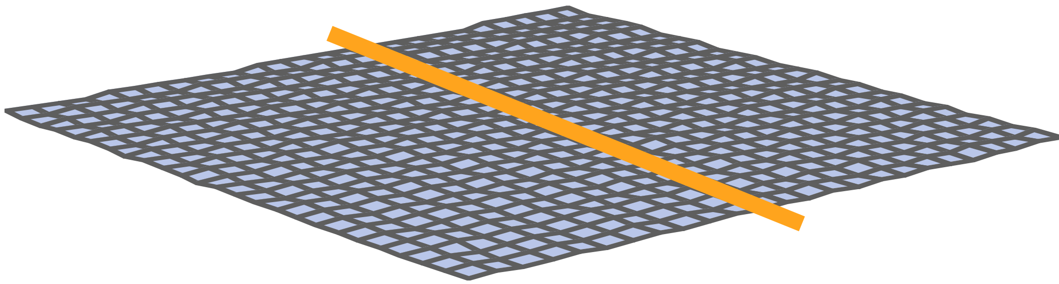
$$V = (2v\rho + \rho^2)^2$$

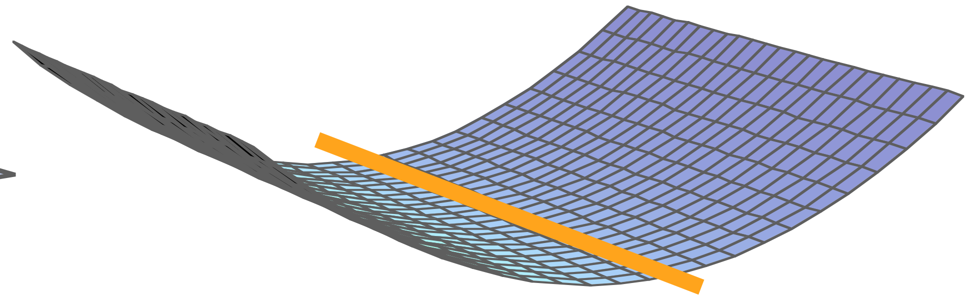
Internal Symmetry Breaking



The potentials live at every point in space and waves of fluctuations between vacua move through space

Pseudo-Goldstone Bosons



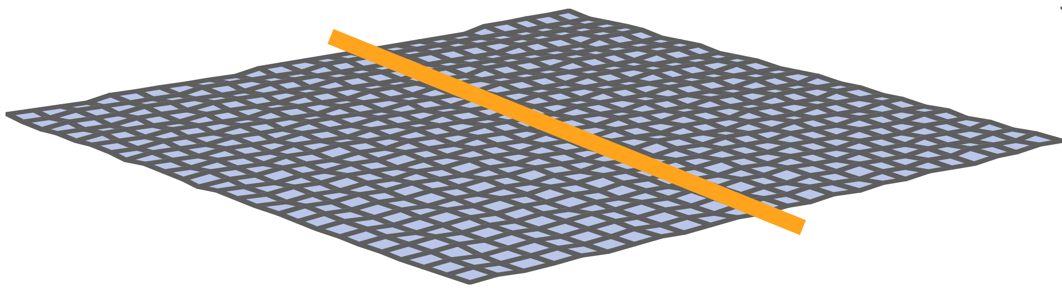


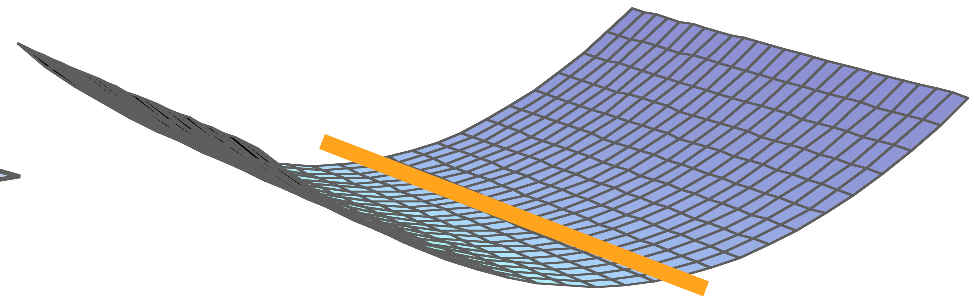
$$\mathcal{L} = \frac{1}{2}\sigma\left(\frac{\partial y}{\partial t}\right)^2 - \frac{1}{2}\tau\left(\frac{\partial y}{\partial x}\right)^2 - \frac{1}{2}\eta^2 y^2$$

Equation of motion:

$$\frac{1}{c^2}\frac{\partial^2 y}{\partial t^2} = \frac{\partial^2 y}{\partial x^2} - \mu^2 c^2 y^2$$

Pseudo-Goldstone Bosons





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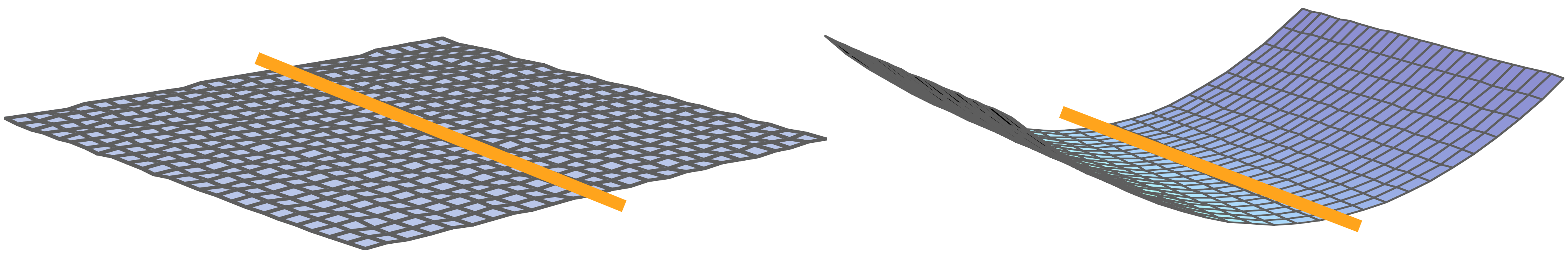
A mass gap appears:

$$\omega^2 = k^2 + \mu^2$$

19

Pseudo-Goldstone Bosons



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This is what we think a pion is.

19

Technicolor vs. Composite Higgs

Q_i, Q_i^c = techniquarks

$$\langle Q_i Q_j^c \rangle \sim \Lambda_{TC}^3 \delta_{ij}$$

$$Q = \left(\begin{array}{c} U \\ D \end{array} \right), \; Q_i^c = U^c, D^c$$

$$SU(2)_L \times SU(2)_R$$

$$\Pi = \left(\begin{array}{cc} \pi^0 & \pi^+ \\ \pi^- & -\pi^0 \end{array} \right)$$

without the Higgs, QCD breaks Electroweak symmetry, and the pions are eaten

$$M_W = g f_\pi$$

Technicolor vs. Composite Higgs

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Georgi, Kaplan

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Georgi, Kaplan

$$\equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

Then include weak couplings to give it a vev

The Higgs as a Pion
(Composite Higgs)

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The naturally light pion has significant couplings (e.g., electro-magnetic).

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Just what we need for the Higgs

The Higgs as a Pion (Composite Higgs)

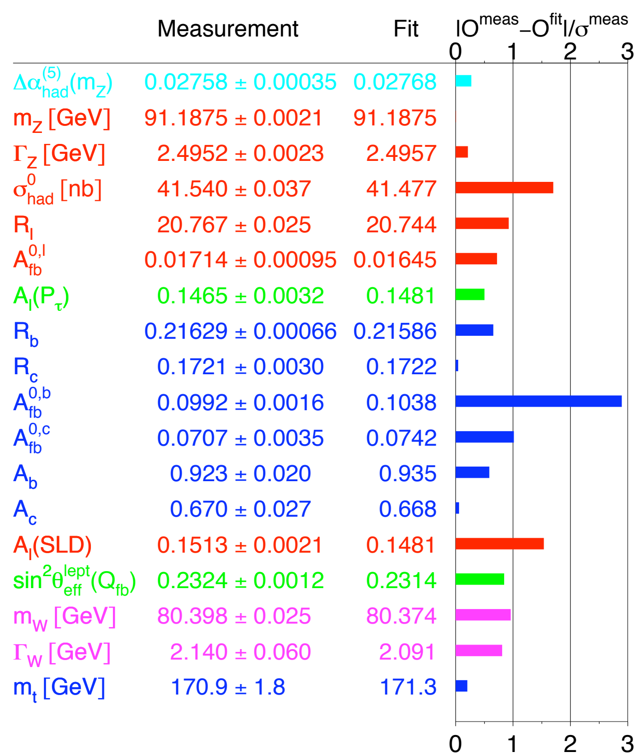
The naturally light pion has significant couplings (e.g., electro-magnetic).

Just what we need for the Higgs

heuristically:

$$\left(\frac{m_\pi}{m_\rho}\right)^2 \sim \left(\frac{m_\pi}{\Lambda}\right)^2 \sim \left(\frac{140\ \mathrm{MeV}}{770\ \mathrm{MeV}}\right)^2 \sim 4\%$$

but per mil required:

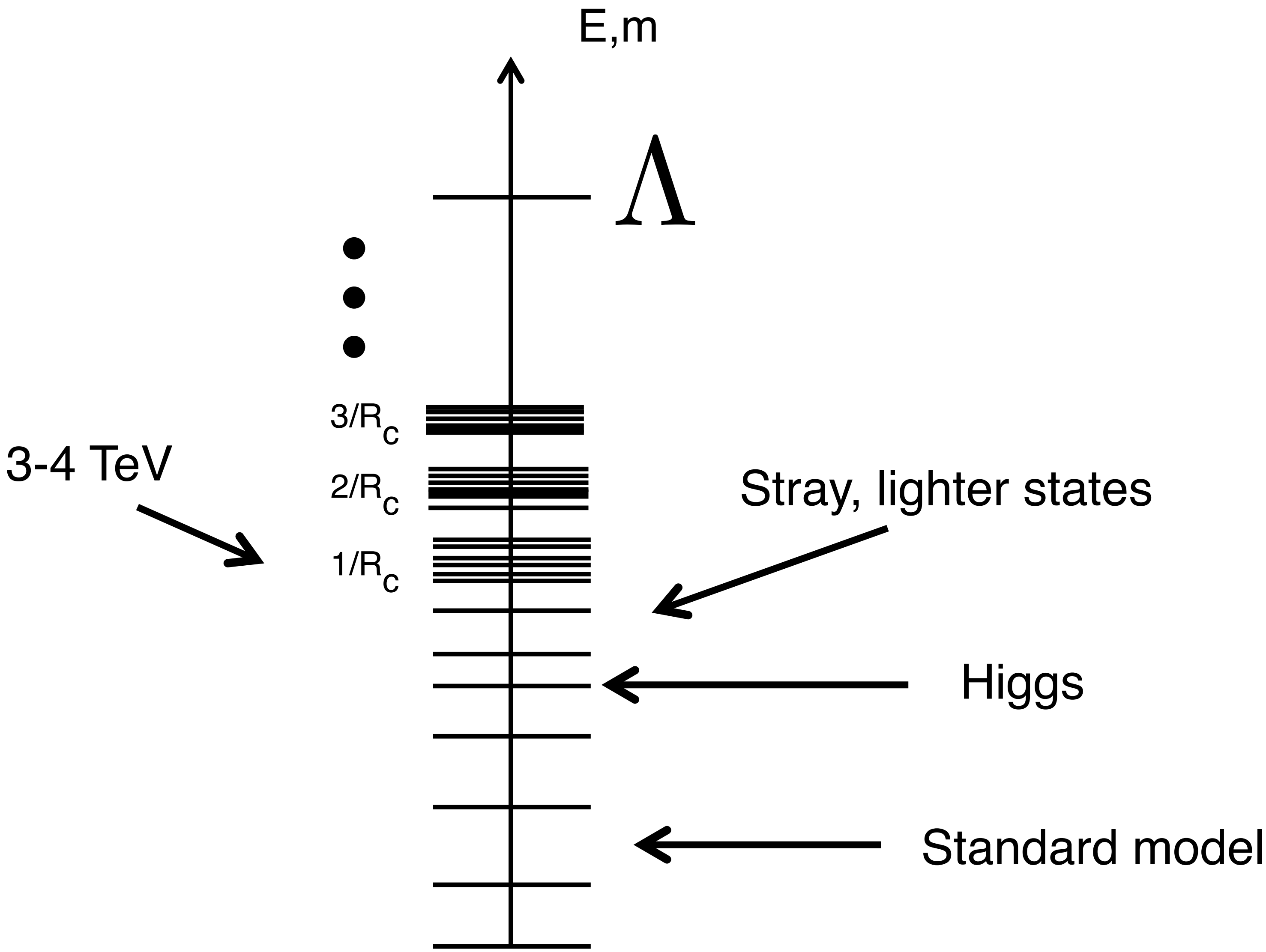


Answer - Some Tuning

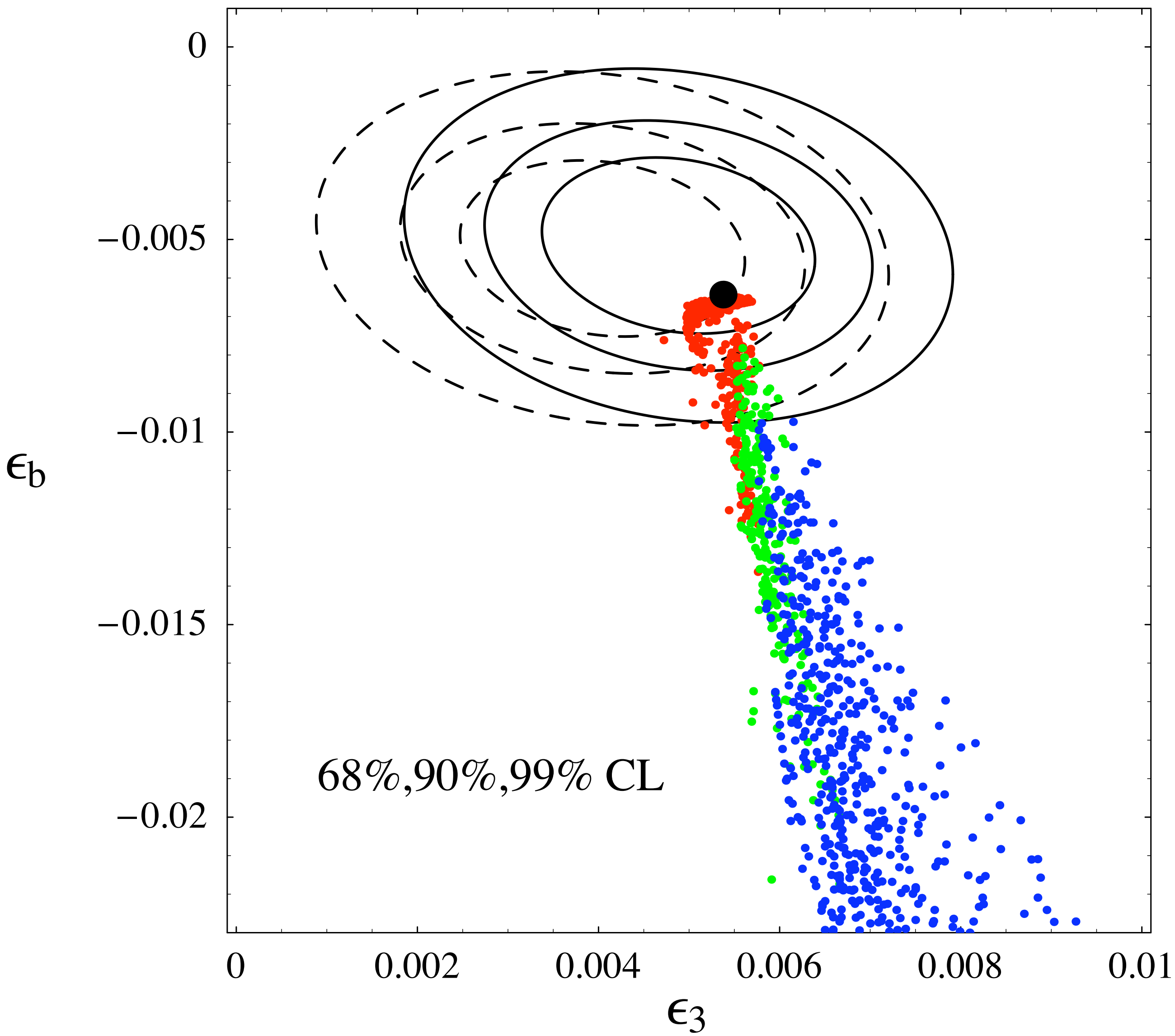
Worst problem is a contribution to $Z \to b\bar{b}$

In current models, must push the "Techni-"rho mass to 3-4 TeV, requiring a fine-tuning in the Higgs mass of ~5%.

Answer - Some Tuning



RS w/ composite Higgs

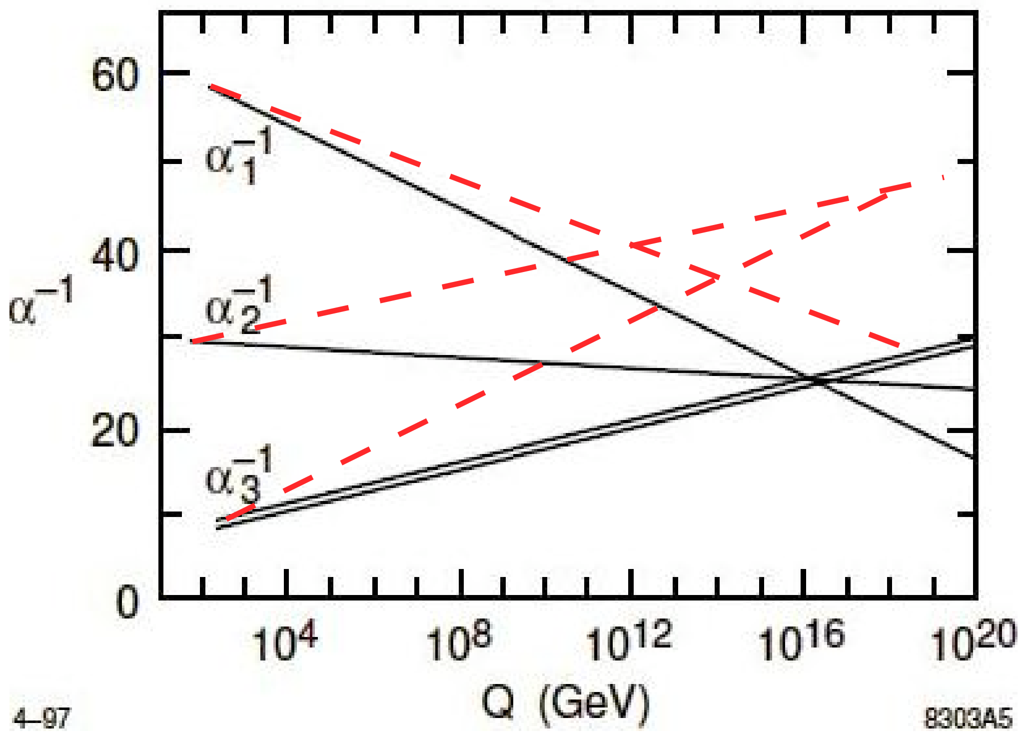


< 4%
<10%, >4%
> 10%

Agashe, Contino

Unification?

$$\alpha(M_Z) = \alpha_{unified} + \text{SM} + \text{superpartners}$$



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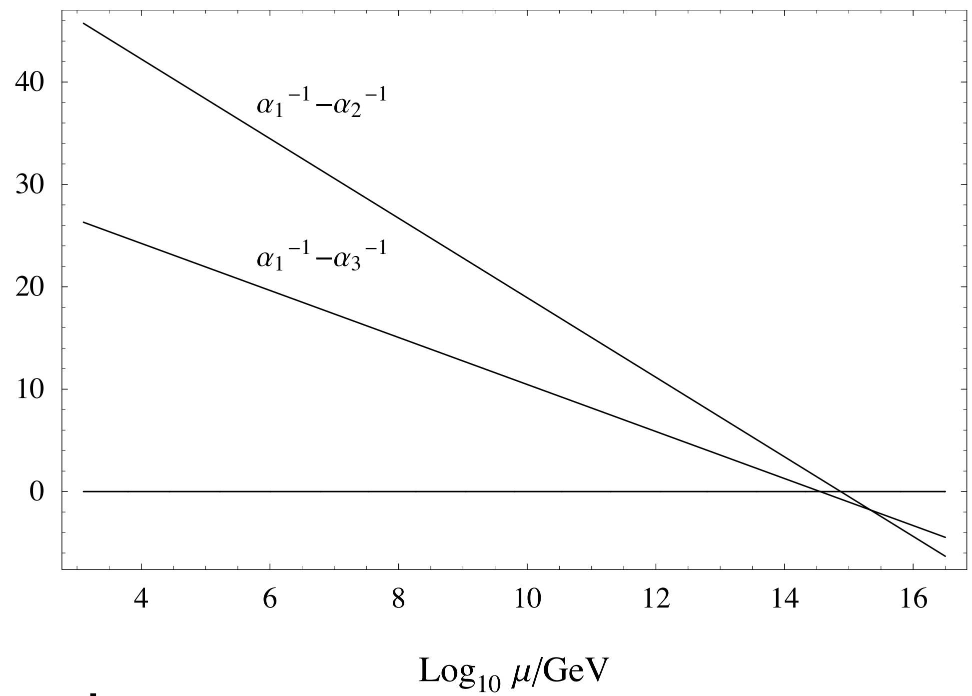

Agashe, Contino, Sundrum

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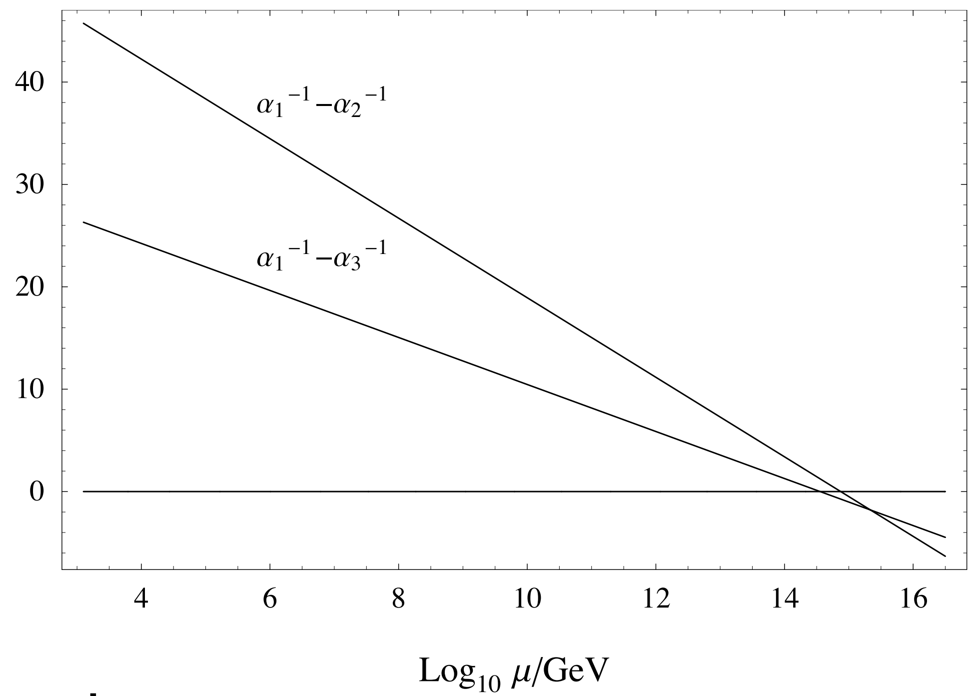


Agashe, Contino, Sundrum

Beautiful Flavor Structure Too

RS summary

Strongly coupled theories are making a comeback as AdS/CFT suggests more theoretical control

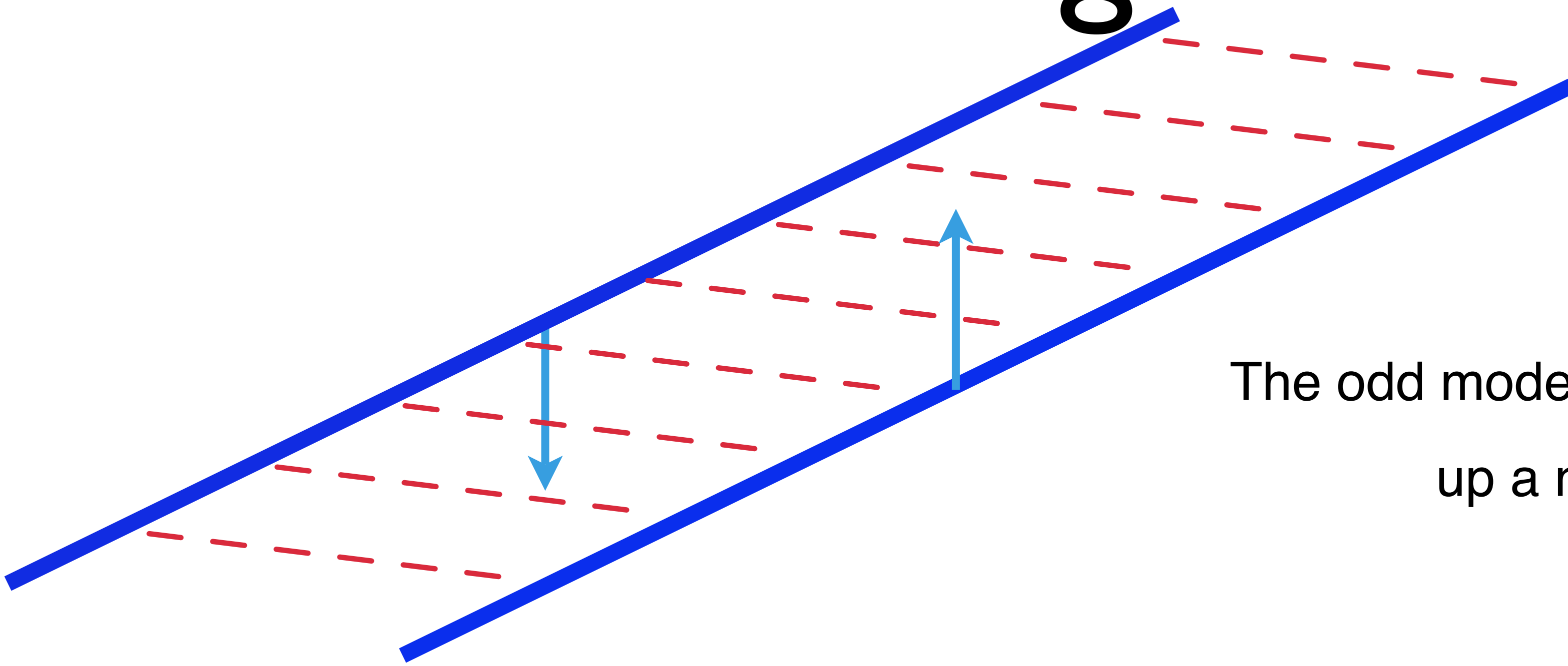
Best versions are when the Higgs is a pseudo-Goldstone boson similar to the pion (Composite Higgs Theories)

Significant effort made to simplify the phenomenology:
Contino, Kramer, Son, Sundrum; hep-ph/0612180

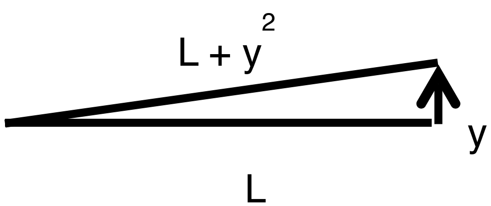
Little Higgs

The goal of the Little Higgs models is to remove that last bit of tuning in composite Higgs theories - at the price of complicating the models.

Collective Symmetry Breaking



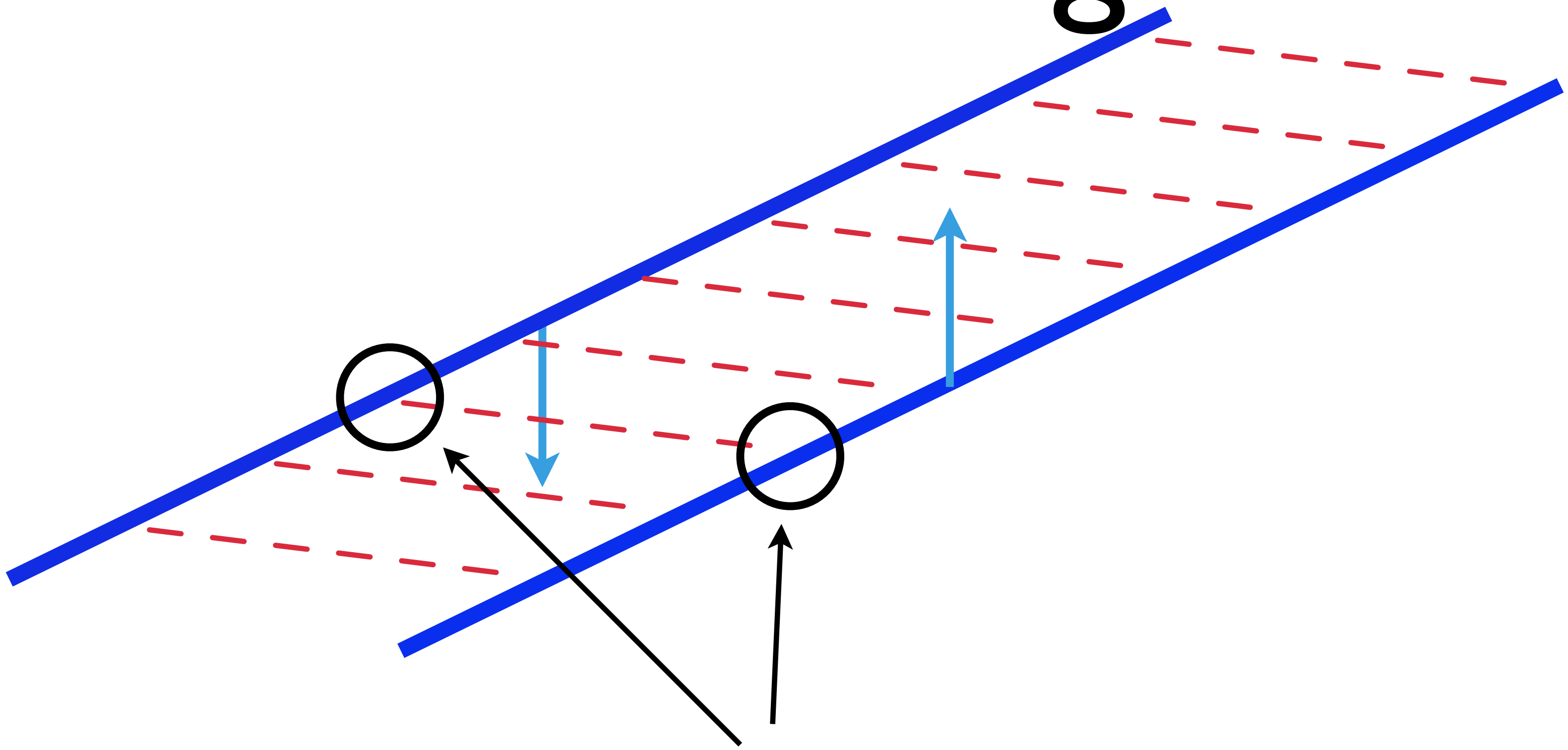
The odd mode does not pick up a mass!



Force goes like displacement y^4

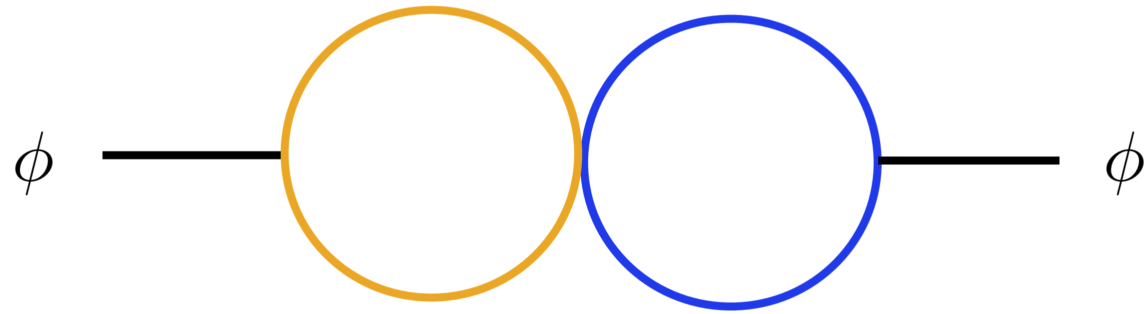
Higher order effect - no mass gap!   Quantum corrections induce

Collective Symmetry Breaking



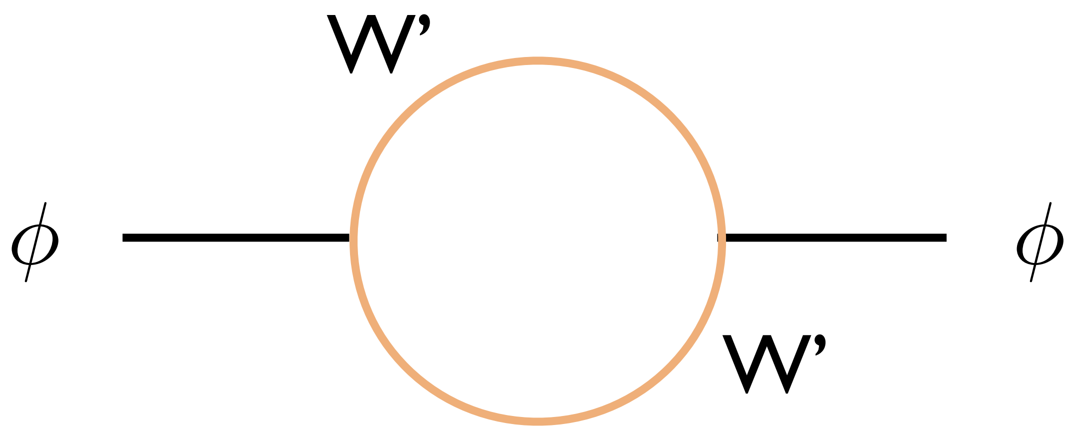
Two couplings required

The "Little Higgs"



$$m_\phi \sim \epsilon^2 \Lambda$$

The "Little Higgs"



New particles in the loop

Copies of Standard Model fields required for collective symmetry breaking. Will look similar to XD, SUSY.

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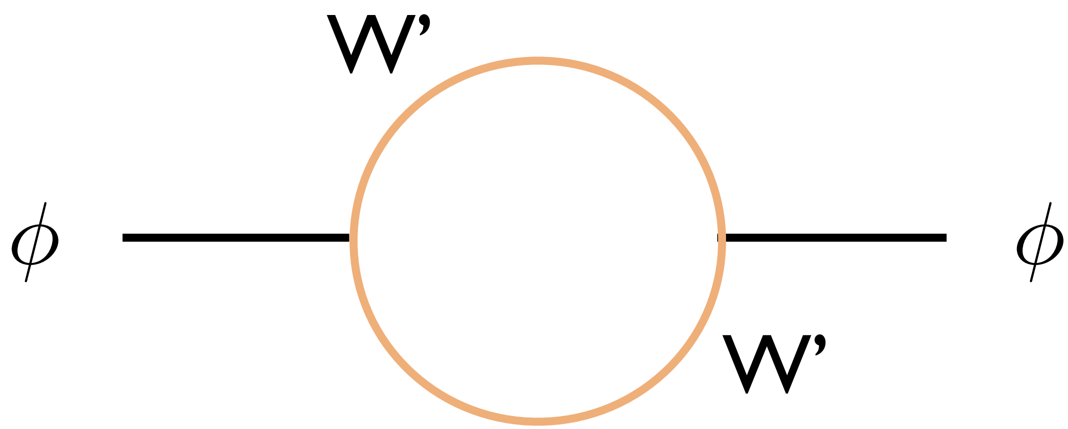

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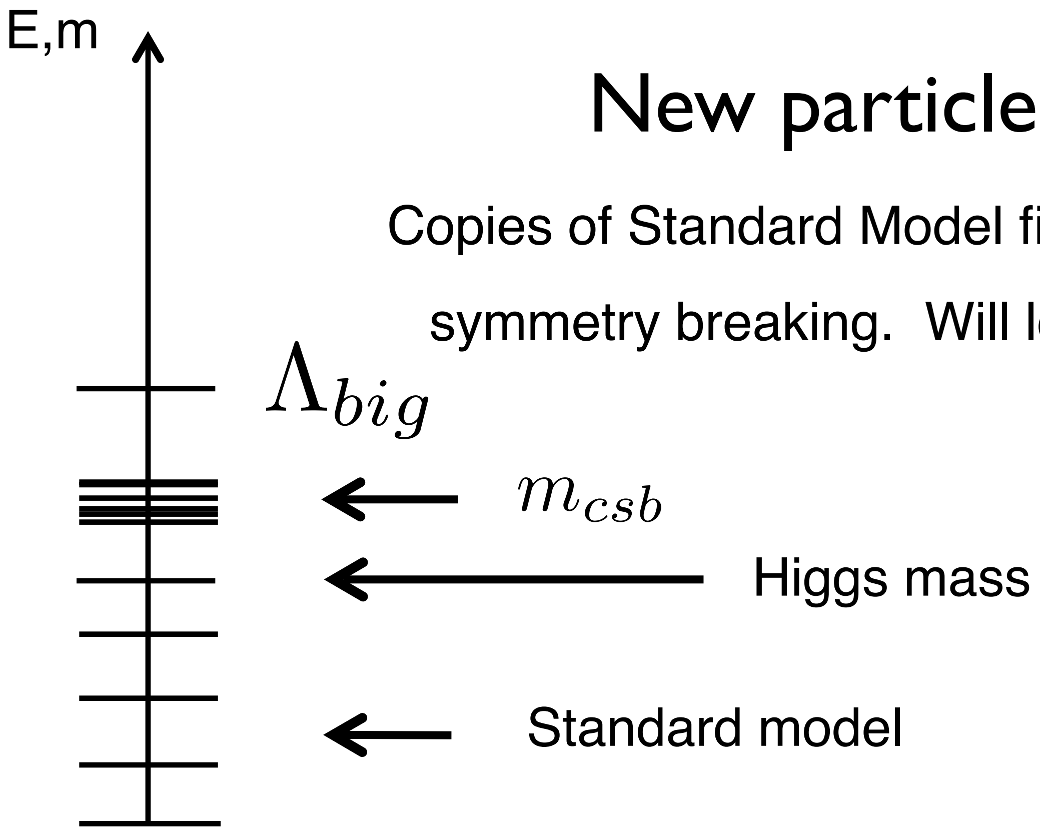
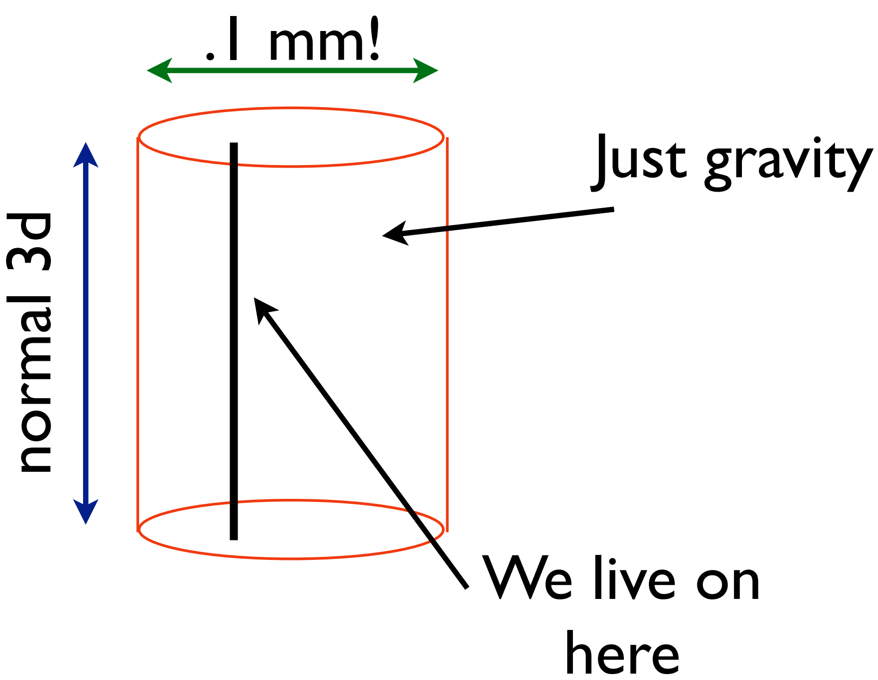


Large Extra Dimensions

$$M_{pl}^2 = M_G^{D-2} V_{D-4}$$

Perhaps M_G ~ 1 TeV!



D=6 severely constrained by short-dist. gravity tests and supernova 1987A

only D=6 has a nice stabilization mechanism

$$q\bar{q} \rightarrow \gamma + invisible\ gravitons$$
$$gg \rightarrow g + invisible\ gravitons$$

Should the world be "Natural"?

$$(m_h^{phys})^2 = M_{planck}^2 + M_{qtm\,corr}^2$$

Cancellation of one part in 10^{34}

This doesn't happen in condensed matter system unless we force it to happen.

The Cosmological Constant

Fine tuning of one part in 10^{120}!

(one part in 10^{60} with SUSY)

In 1987 Weinberg suggested that if our universe was one of a large selection, we would live in one where the cosmological constant was *just small enough* to allow for structure to form, and if we don't measure one, we can rule out the anthropic principle.

The Cosmological Constant

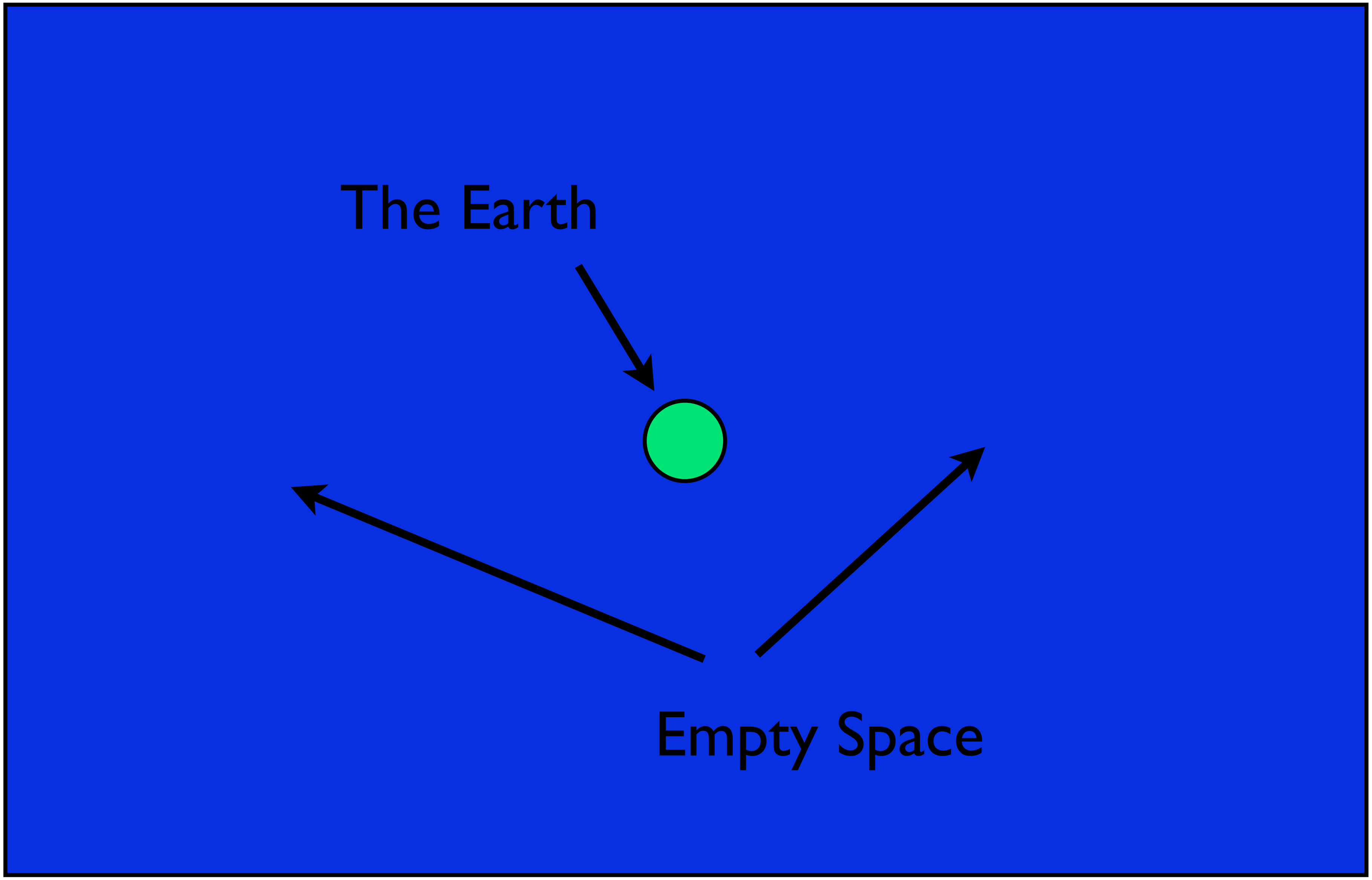
Fine tuning of one part in 10^{120}!

(one part in 10^{60} with SUSY)

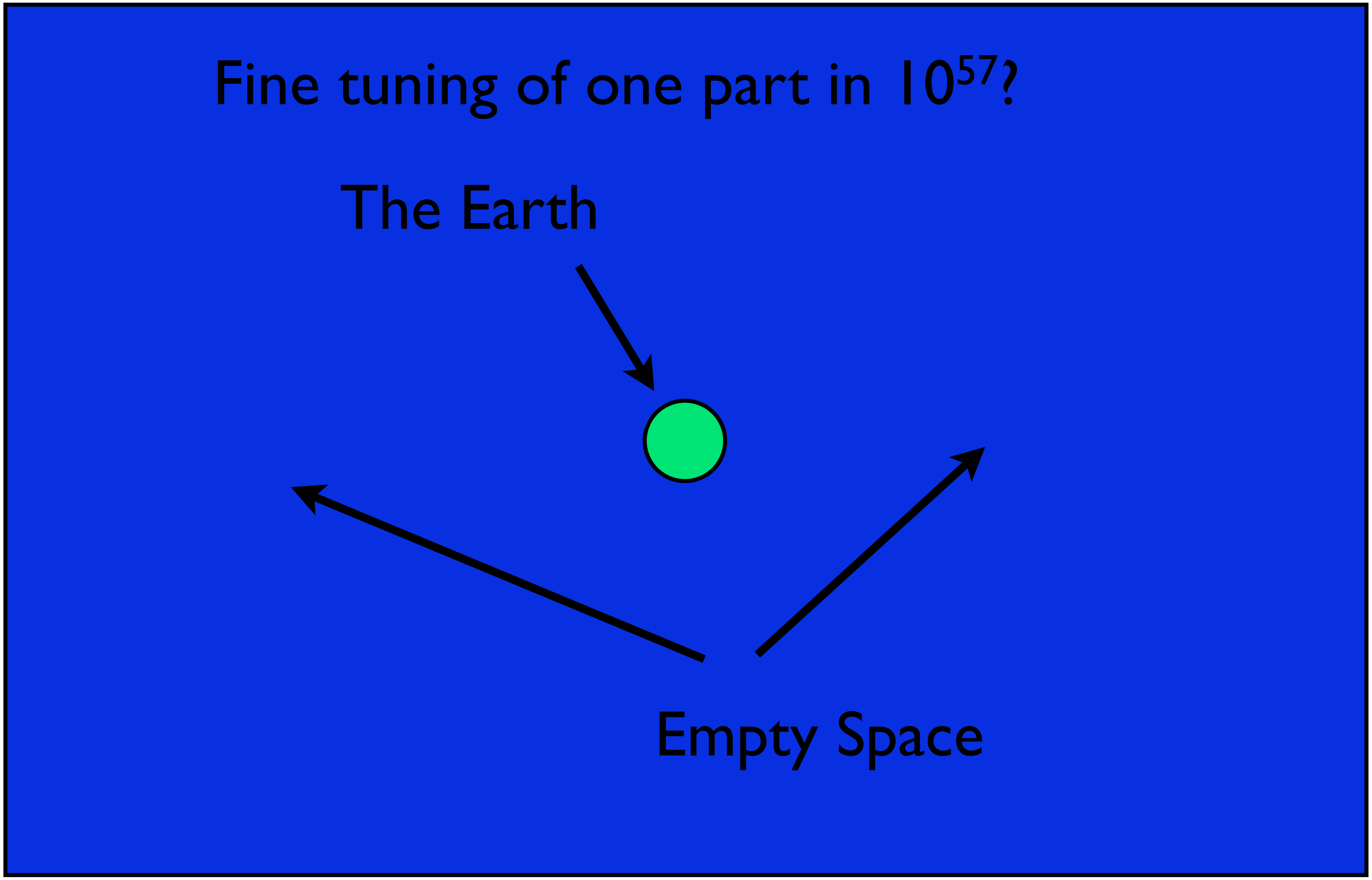
In 1987 Weinberg suggested that if our universe was one of a large selection, we would live in one where the cosmological constant was *just small enough* to allow for structure to form, and if we don't measure one, we can rule out the anthropic principle.

But then we did measure one...

Environmental Selection



Environmental Selection



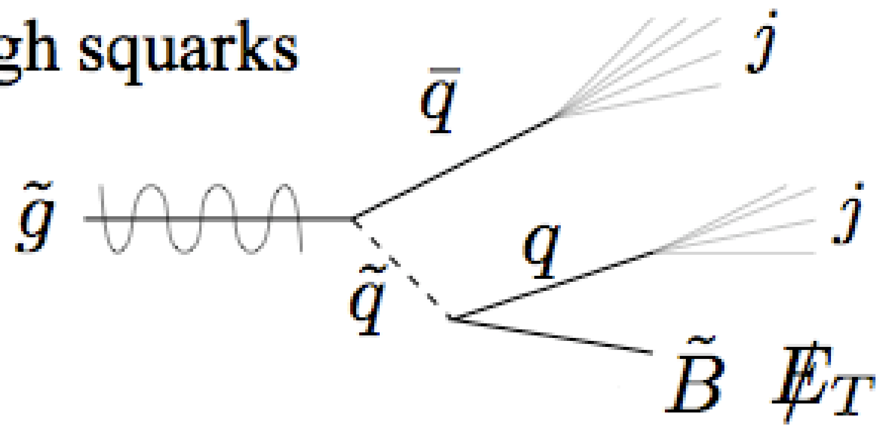
Split Supersymmetry

	$M_{\text{Pl.}}$	10^{16} TeV
Scalars (Squarks, sleptons, ...)	M_{susy}	? { 10^{15} TeV 10 TeV
Fermions (Higgsinos, gauginos) +SM Higgs	M_{weak}	~1 TeV
	M_{CC}	10^{-15} TeV

Preserves Unification and Dark Matter

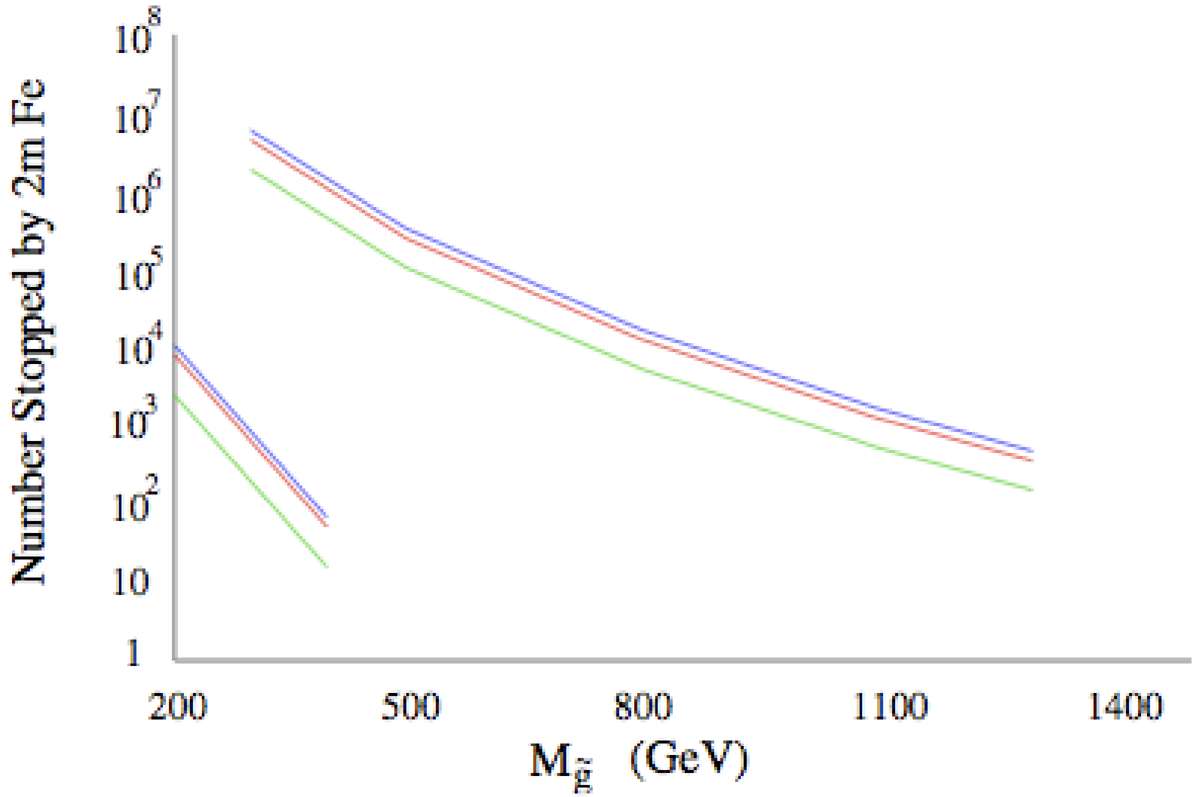
Gluinos are Long-Lived

Must decay through squarks



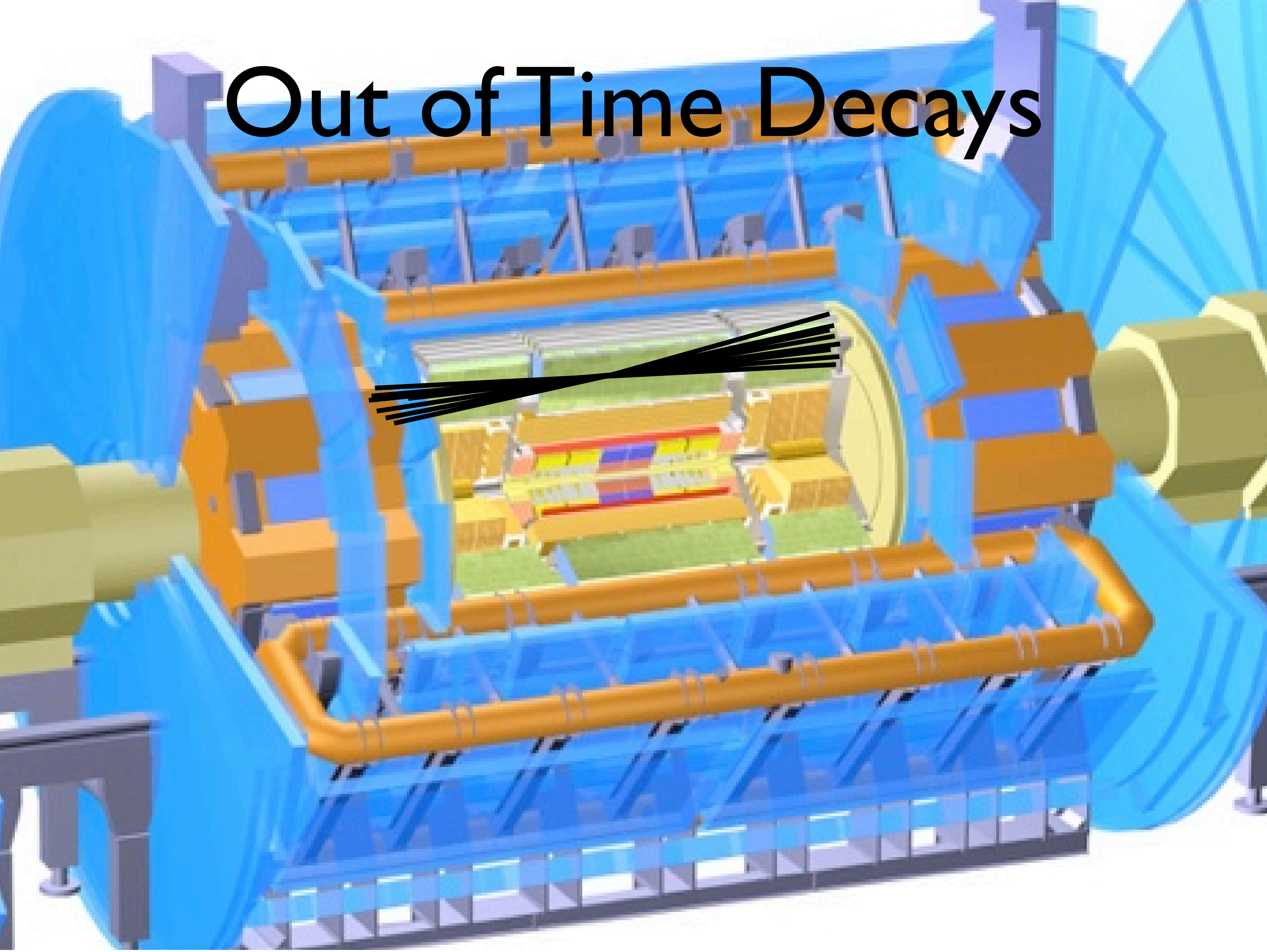
$$\tau_{\tilde{g}} \simeq 2 \text{ sec.} \left(\frac{350 \text{ GeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\text{Susy}}}{10^6 \text{ TeV}}\right)^4$$

Stopped Gluinos



$2\ fb^{-1}$	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
$100\ fb^{-1}$	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2

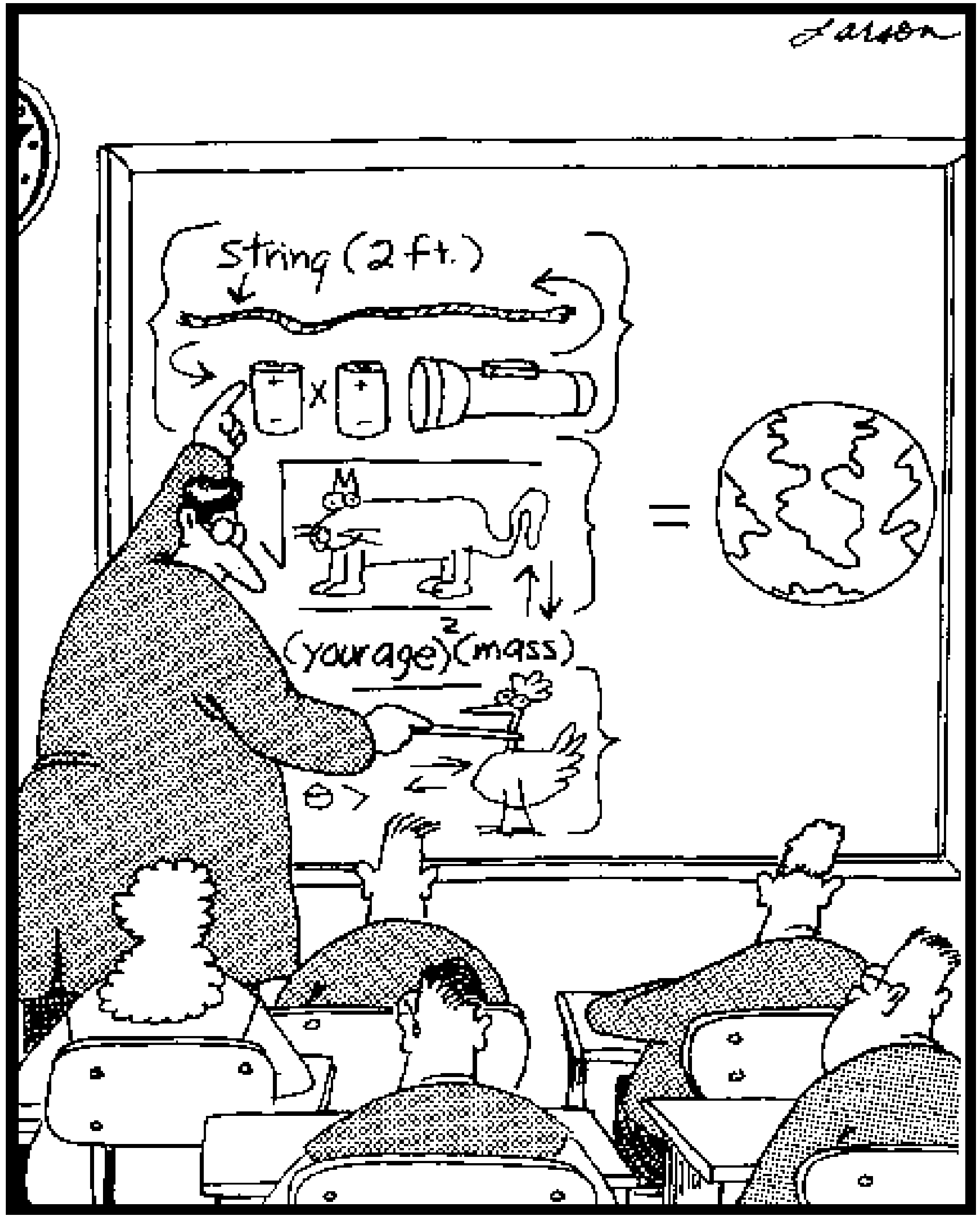
Out of Time Decays



Even if you HATE use of the anthropic principle...

It points us to a new signal to look for - very long lived stopped particles.

Time to figure out what is going on



Creationism Explained