Firing Missiles at Right Angles to Reality:
The Search for Hidden Dimensions of Nature

An ex-Higgs-Hunter's Guide to Extra Dimensions and the Quest for Physics Beyond the Standard Model

Physics Colloquium
Syracuse University
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“..anyone who has been to the higher dimensions will know that they're a pretty nasty heathen lot up there who should just be smashed and done in, and would be, too, if anyone could work out a way of firing missiles at right-angles to reality.”

-Douglas Adams

Hitchhiker’s guide to the galaxy

Take me to your leader

Take me to your ~~leader~~

Take me to your ~~leader~~

RULER

Feynman: We can use hydrogen atoms as our common ruler

Units

Use fundamental constants to work in terms of single unit

Mass/Energy

Speed of light - convert meters to seconds, kg to GeV

$$c = 3 \cdot 10^8 \mathrm{m/s} \qquad E = mc^2$$

Planck's constant - convert seconds to GeV

$$\hbar = 6.6 \cdot 10^{-25} \mathrm{GeV} \cdot \mathrm{s}$$

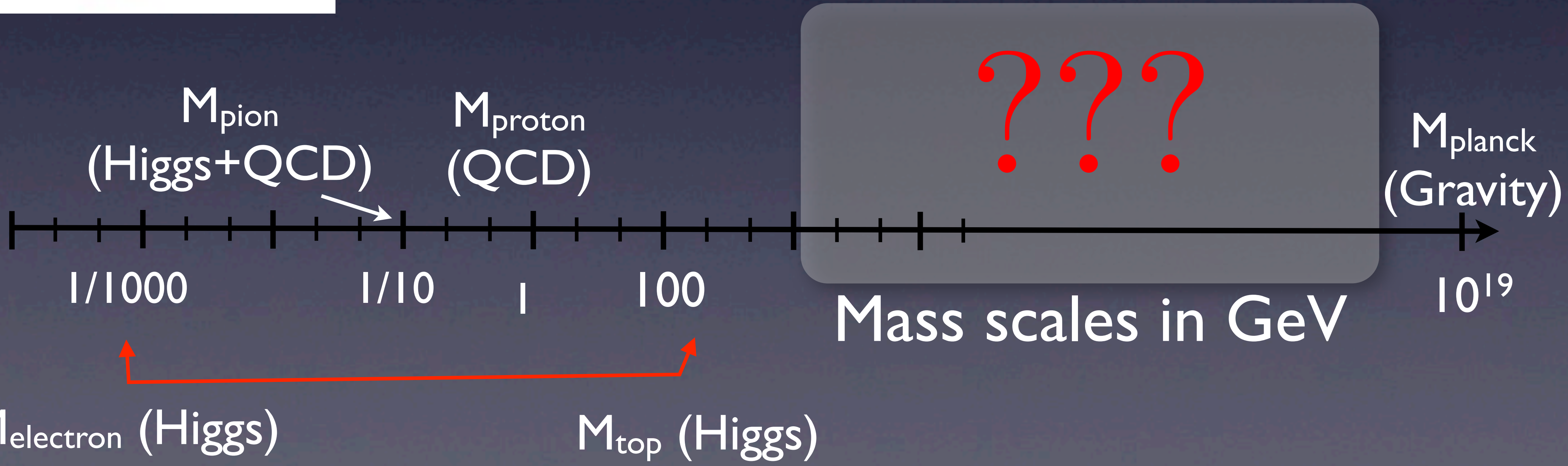
Everything can be measured in terms of GeV ~ 1 M_{Proton}

We have lots of Rulers

You can't just make things bigger and expect them to work the same way

Nature is full of different length scales

The scales we observe follow from violations of scale invariance at the shortest distances



Chemistry
Materials
Biology
& all that.

M_{pion} (Higgs+QCD)

M_{proton} (QCD)

???

M_{planck} (Gravity)

1/1000

1/10

1

100

Mass scales in GeV

10^{19}

M_{electron} (Higgs)

M_{top} (Higgs)

Gravity plays a role as well

Some physics in Feynman's answer

Height:

Bohr Radius: $a_0 = \frac{4\pi}{e^2 m_e}$

Electron Charge   Electron mass (Higgs)

Mass:

M_{Proton}~1 GeV

set by physics of Quantum Chromodynamics

theory of quarks and gluons

Two very different dynamical phenomena contribute to volume-mass relations of every-day objects our local universe

some other
hospitable corner
of the multiverse

What’s a hydrogen atom?

One Ruler to Rule them all

We both live in spacetime - should both have gravity

$$V = -\frac{G_N M_1 M_2}{r}$$

$$\mathrm{GeV} = [V] = [G_N]\mathrm{GeV}^3 \rightarrow [G_N] = \frac{1}{\mathrm{GeV}^2}$$

$$G_N = \frac{1}{M^2_{\mathrm{Planck}}}$$

$$M_{\mathrm{Planck}} = \sqrt{\frac{\hbar c}{G_N}} \approx 10^{19}\mathrm{GeV} \qquad L_{\mathrm{Planck}} \approx 10^{-35}\mathrm{m}$$

We're $3\text{x}10^{105}$ Planck lengths in volume

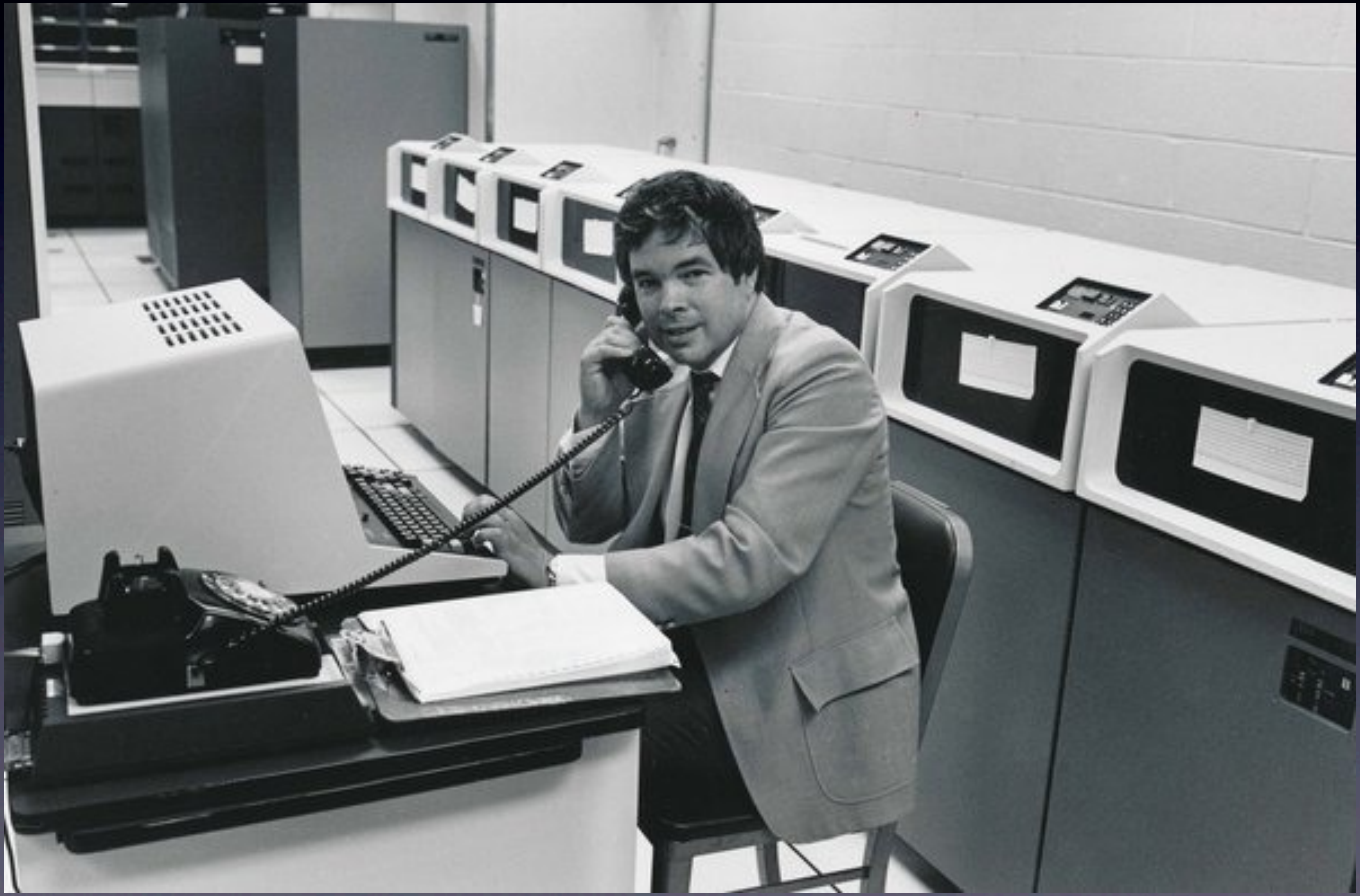
Our mass is $4\text{x}10^{29}$ Planck masses

What will their response be?

What are the ways in which you can move?

Effective Field Theory

Ken Wilson (1936-2013)



The greatest physicist the average person has never heard of

Effective Field Theory

systems w/ fluctuations at all scales

Quantum Field Theory

sum over all possible fluctuations

long and short wavelength included

$$\boxed{Z = \int D\phi \exp\left[\frac{i}{\hbar} S\right]}$$

Function S (the action) contains all the physics

Z is generating function for QM amplitudes

Useful in condensed matter - approach to phase transitions

Effective Field Theory

Parameters

Relationship between parameters in action and physical observables is complicated

e.g. a very simple quantum field theory:

$$S = \int d^4x \left[\frac{1}{2}(\partial_\mu \phi)^2 - m^2\phi^2 - \lambda\phi^4 \right]$$

$$m^2_{\text{obs}} = m^2_{\text{obs}}(m^2, \lambda)$$

Parameters in action wildly different from observables

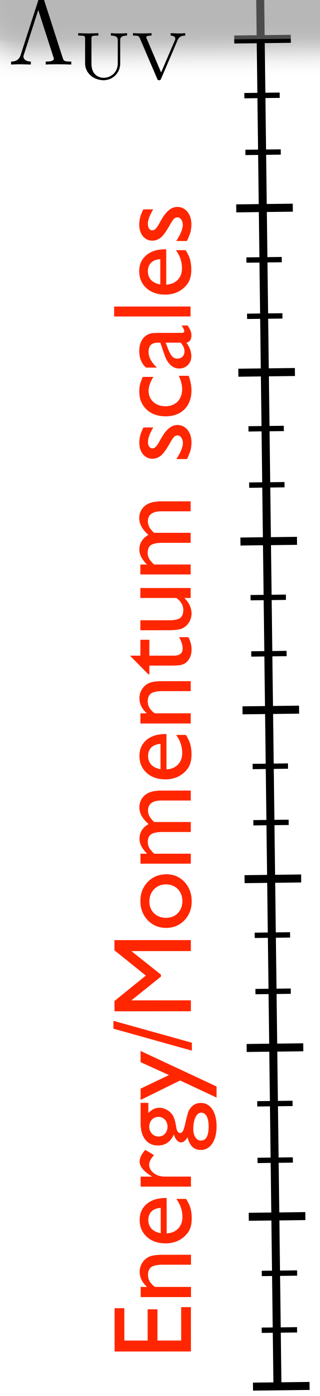
Summing over all scales:

m^2 and λ must both be infinite to get finite m^2_{Obs}

Cumbersome juggling of infinities to get out real physics

“Dragons” at high momentum:

infinities, string theory/quantum gravity, GUT’s, stuff that might solve SM problems...



Don’t sweat the small stuff

Perform integral over high momentum fields first!

$$Z = \int [D\phi_<][D\phi_>] \exp\left[\frac{i}{\hbar} S\right] = \int [D\phi_<] \exp\left[\frac{i}{\hbar}\tilde{S}\right]$$

$\tilde{S}$ is “effective” action valid for all scales below $\Lambda_{\rm UV}$

You don’t need to know what’s going on up there! Your mission is to construct an **effective** action with **finite** parameters describing what you **do** see

$$\alpha(\Lambda_{UV}), M_{\rm Higgs}(\Lambda_{\rm UV}), \text{etc}\ldots$$

The Wilsonian Ruler

$1/\Lambda_{\mathrm{UV}}$ is a **length scale**

we can measure all of our dimensionful parameters in units of it

$$M^2_{\mathrm{Higgs}} = c_{\mathrm{Higgs}} \Lambda^2_{\mathrm{UV}} \qquad \Lambda_{\mathrm{CC}} = c_\Lambda \Lambda^4_{\mathrm{UV}}$$

This ruler is fictitious when you already know S

a convention

BUT

when curtain nears a threshold where there is new physics

UV cutoff takes on physical meaning

Example: Scale at which gravitational coupling grows big!

Lifting the Veil

As we push the boundaries of the **energy frontier**, we push the UV cutoff ever higher

finite parameters of effective action change

Wilsonian view of renormalization group:

$$\alpha(\Lambda_{UV}) \to \alpha(\Lambda'_{\mathrm{UV}}) \qquad M_{\mathrm{Higgs}}(\Lambda_{UV}) \to M_{\mathrm{Higgs}}(\Lambda'_{\mathrm{UV}})$$

$$\frac{c_i^{(n)}(\Lambda_{\mathrm{UV}})}{\Lambda_{UV}^n} \to \frac{c_i^{(n)}(\Lambda'_{\mathrm{UV}})}{\Lambda'^n_{\mathrm{UV}}}$$

Rule:

all predictions for the low energy processes you've already probed must remain identical

Lifting the Veil

"Dragons" hide in parameters with negative mass dimension: $\frac{c_i^{(n)}(\Lambda_{\mathrm{UV}})}{\Lambda_{UV}^n}$

$$\frac{c_i^{(n)}(\Lambda_{\mathrm{UV}})}{\Lambda_{UV}^n} \to \frac{c_i^{(n)}(\Lambda'_{\mathrm{UV}})}{\Lambda'^n_{\mathrm{UV}}}$$

If you measure a c $\neq$ 0, it grows **quickly**
signals onset of non-perturbativity/New Physics

Fermi Theory $\Longrightarrow$ Electroweak theory

Dragons = $W^\pm$, Z bosons

Bad behavior of W scattering $\Longrightarrow$ Higgs discovery

Dragon = Higgs boson

As we push the boundaries of the **intensity frontier**, we push the c's ever smaller (or discover non-zero ones!)

Lifting the Veil

$$S = \int d^4x \left[\frac{1}{2} (\partial_\mu \phi)^2 - m^2 \phi^2 - \lambda \phi^4 \right]$$

action must be dimensionless to be in exponential

$$Z = \int D\phi \exp \left[\frac{i}{\hbar} S \right]$$

$$[\partial_\mu] = \text{GeV} \qquad [dx] = \text{GeV}^{-1}$$

so: $[\phi] = \text{GeV}$ $[\phi^4] = \text{GeV}^4$

and: $[\lambda] = 1$ Right?

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and: $[\lambda] = 1$

WRONG (but close if λ is small)

“Unlike for everyone else, 1+1 isn’t 1, for us it is more like 4.”

-Yuval Grossman

Lifting the Veil

Naive dimensional analysis doesn't capture all the physics

$$\frac{d\lambda}{d\log\Lambda_{\rm UV}} = \beta(\lambda) \longleftarrow \text{small}$$

$$\lambda(\Lambda_{\rm UV}) = \lambda_0 \Lambda_{\rm UV}^{\beta(\lambda_0)/\lambda_0}$$

"Dimensionless" coupling constants change with scale

If β is positive, λ grows (like the c's)
If β is negative, λ shrinks

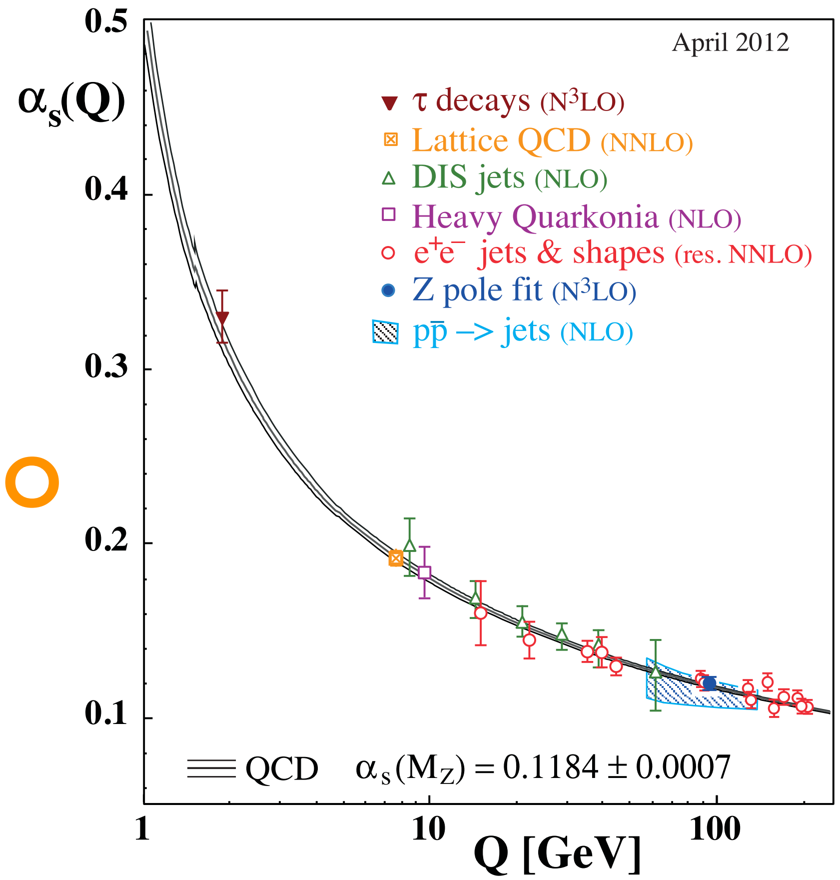
“Emergent” scales

For theory of quarks and gluons β is negative

Running the procedure in reverse - lowering the curtain:

Quantum Chromodynamics & the proton mass

proton, neutron, pions, + rest of zoo



quarks & gluons

Standard Model vs Wilsonian Standard Model

As a fundamental theory:

$$\mathcal{L} = -\frac{1}{4\underset{\substack{\uparrow\\ \log\infty}}{g_s^2}}G^2 - \frac{1}{4\underset{\substack{\uparrow\\ \log\infty}}{g_w^2}}W^2 - \frac{1}{4\underset{\substack{\uparrow\\ \log\infty}}{g_y^2}}B^2 + \underset{\substack{\uparrow\\ \text{depends...}\\ \log\infty \text{ or } \infty^2}}{\mu^2}|H|^2 - \underset{\substack{\uparrow\\ \text{0? +NAN? -NAN?}}}{\lambda}|H|^4 + \text{fermions}$$

Pathologies all in “bare” parameters
cumbersome order by order (in perturbation theory)
subtraction of infinities

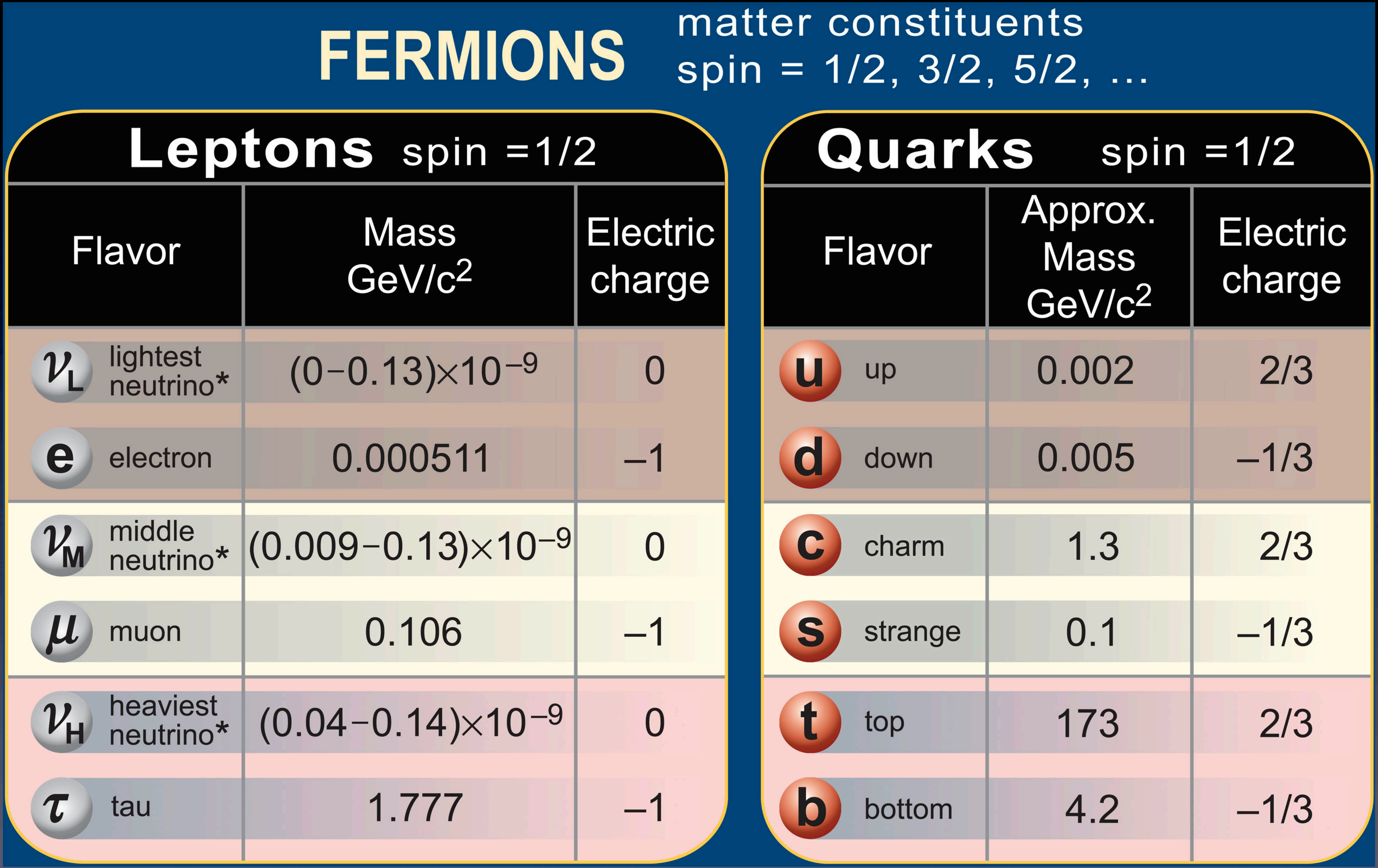
Standard Model vs Wilsonian Standard Model

As a Wilsonian Effective Field Theory

$$\mathcal{L}_\Lambda = -\frac{1}{4g_s^2(\Lambda)}G^2 - \frac{1}{4g_w^2(\Lambda)}W^2 - \frac{1}{4g_y^2(\Lambda)}B^2 + \mu^2(\Lambda)|H|^2 - \lambda(\Lambda)|H|^4 + \text{fermions}$$
$$+\sum_i \frac{c_i(\Lambda)\mathcal{O}_i(\Lambda)}{\Lambda^n}$$

All parameters are finite - study approach to pathologies in controlled and phenomenologically motivated way and they have real physical meaning!

The Standard Model Fermions



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

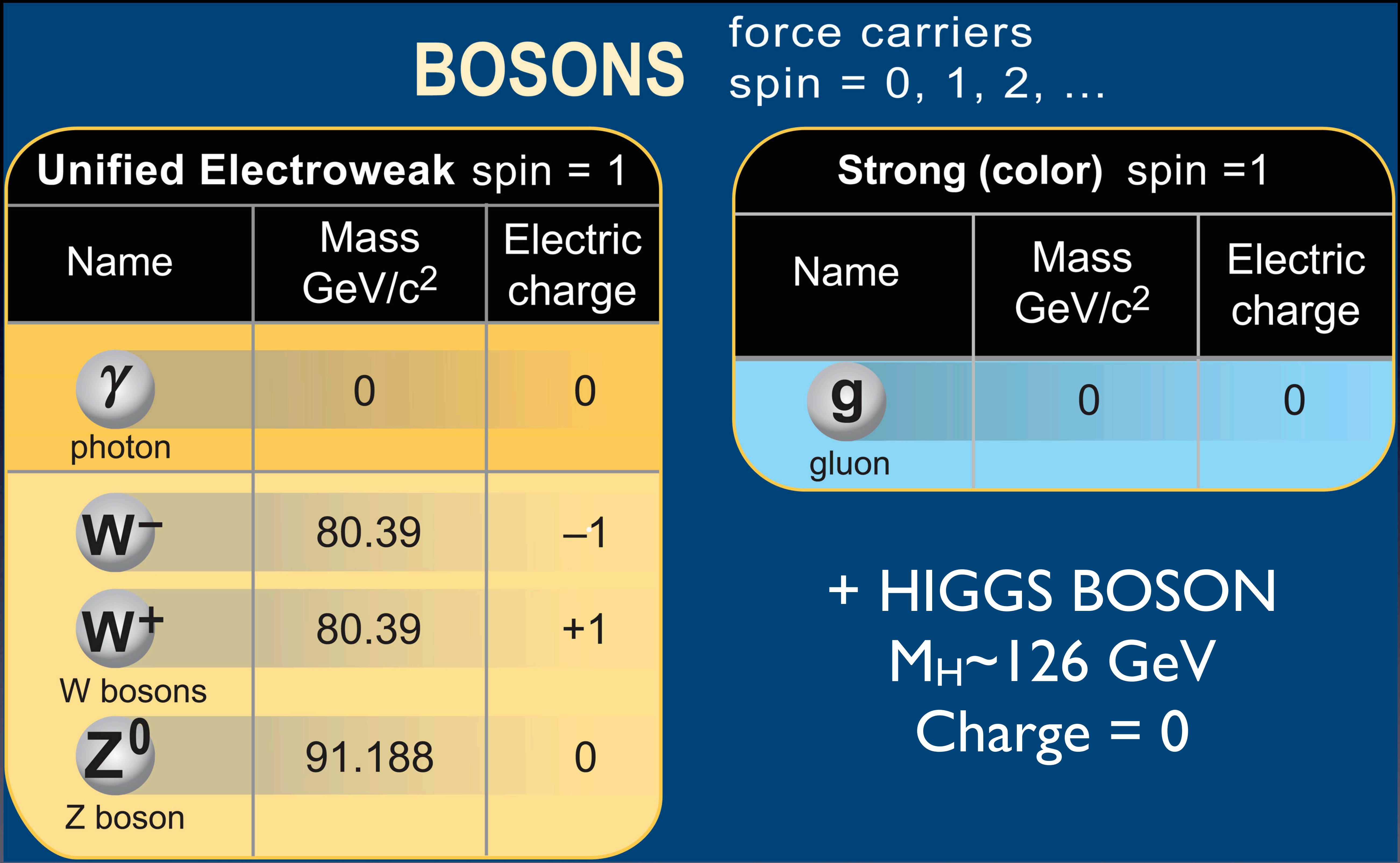
Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Standard Model Bosons



BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

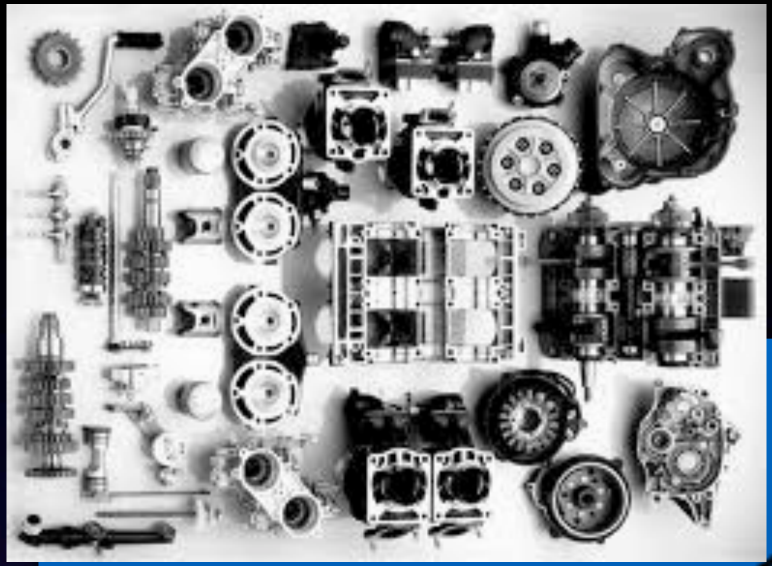
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

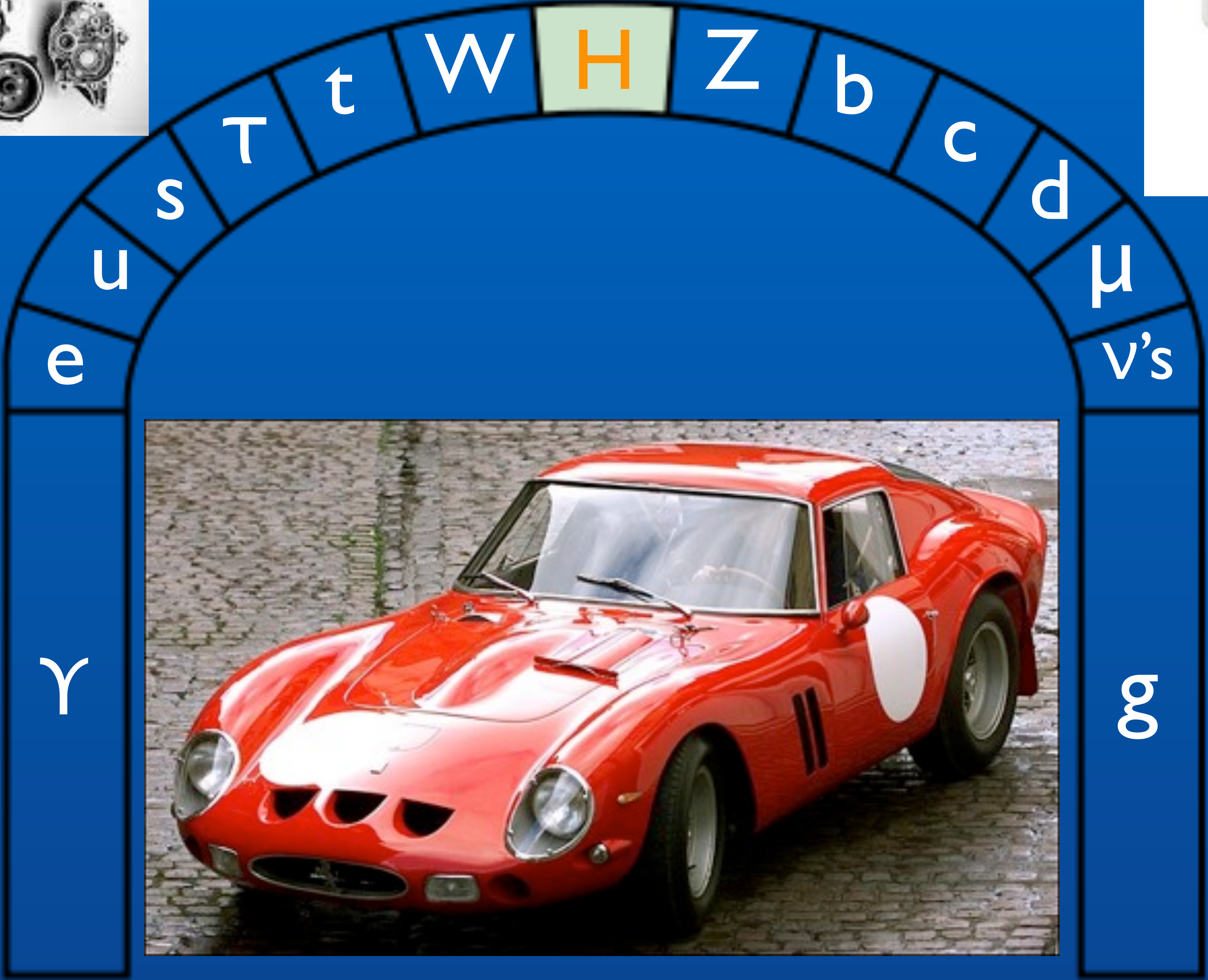
Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

+ HIGGS BOSON
M_H~126 GeV
Charge = 0

The Standard Model Keystone





No nearby obvious pathologies

“The Standard Model is a really good effective theory”

-Simon Catterall

Almost every hep-ex paper:

"The data are consistent with Standard Model expectations, and limits are set..."

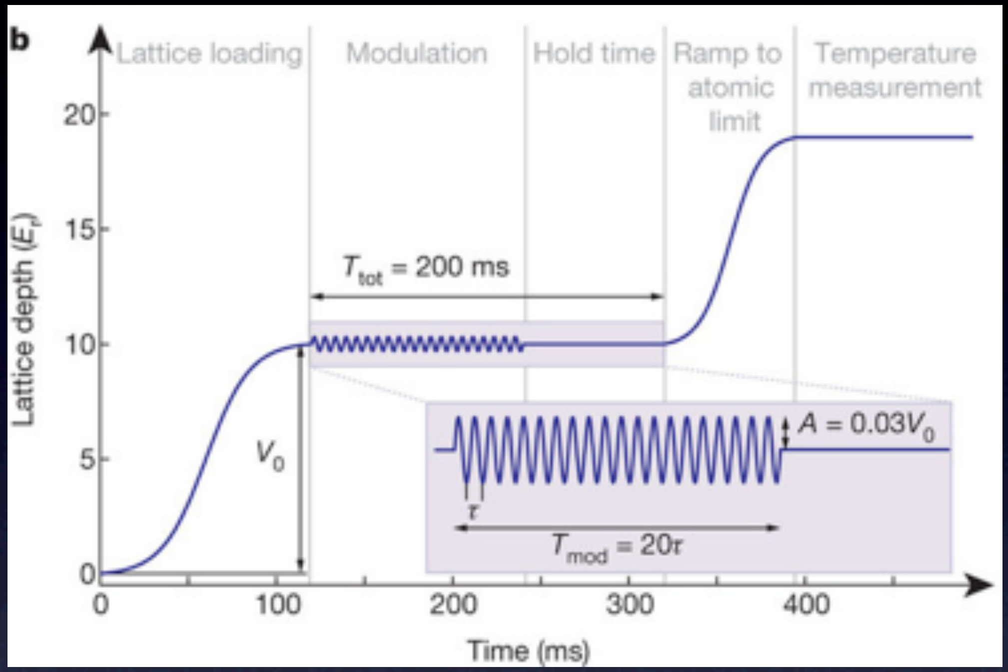
“I think you ought to know I’m feeling very depressed”
-Marvin the paranoid android

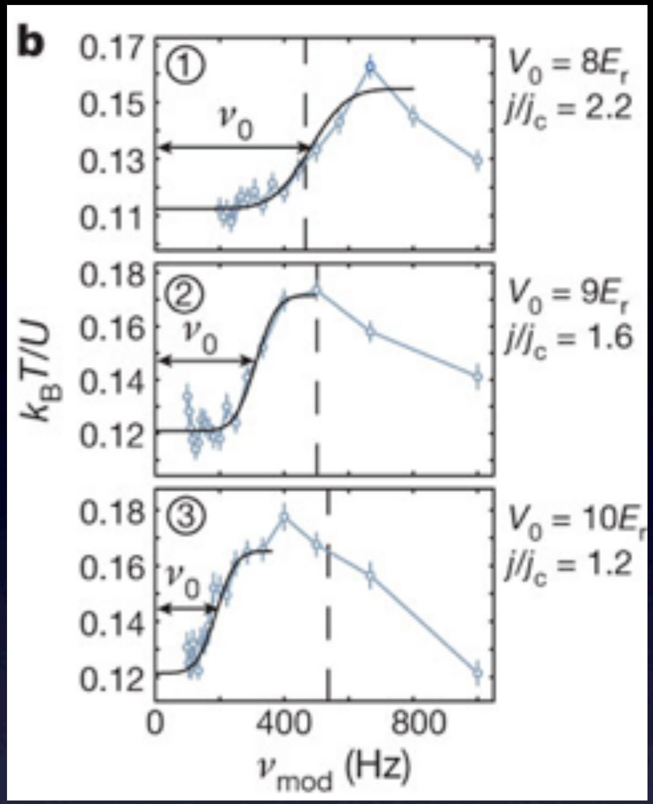
"Incredible... It's even worse than I thought it would be."

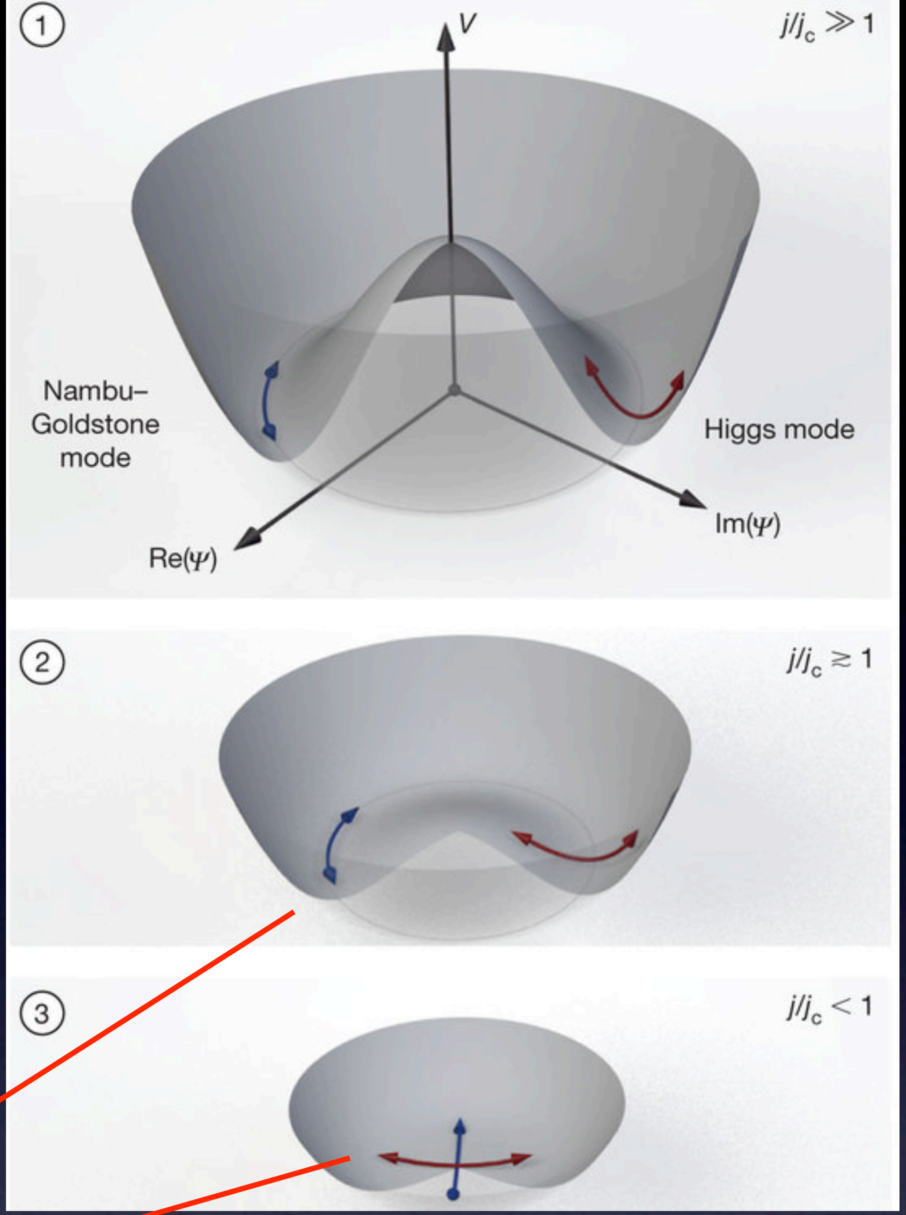
DON'T PANIC

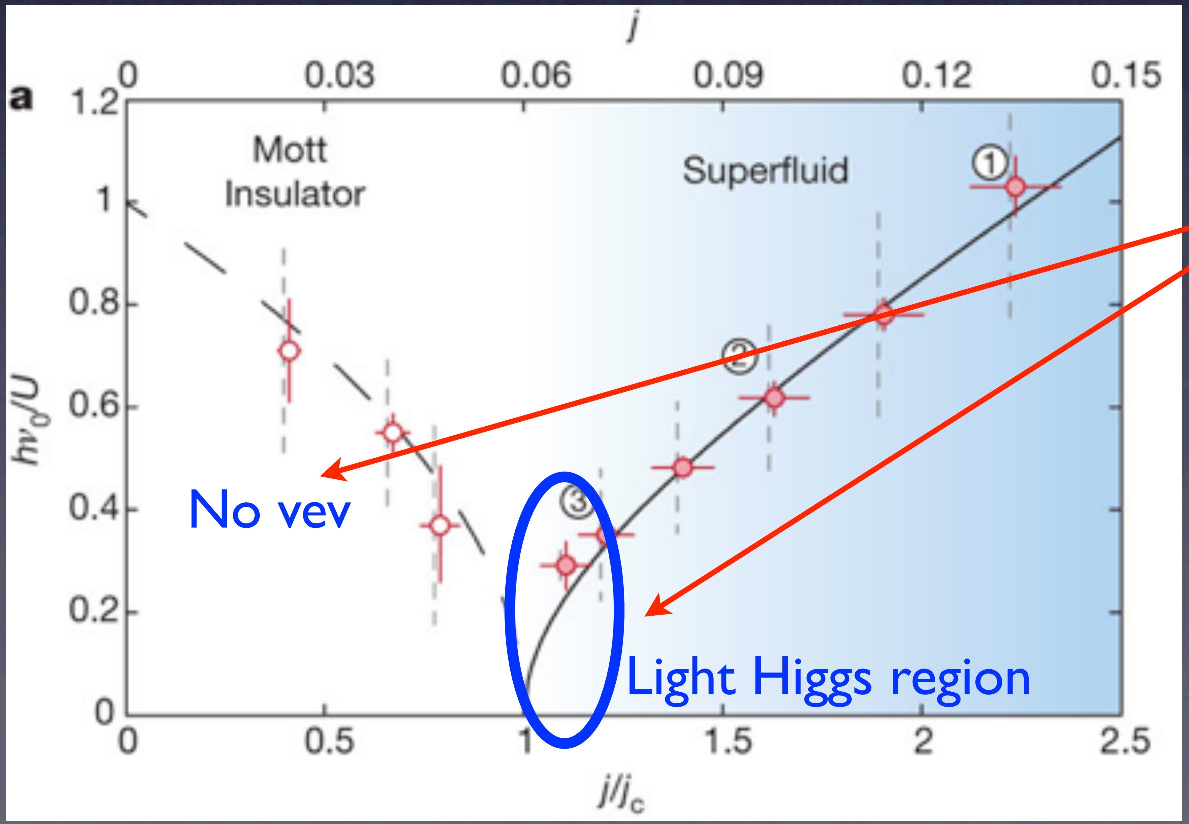
Fine Tuning

In Condensed matter, you get to play “God”:









In particle physics:

$$\frac{j}{j_c} - 1 \sim 10^{-32} \sim \left(\frac{M_{\rm weak}}{M_{\rm planck}}\right)^2$$

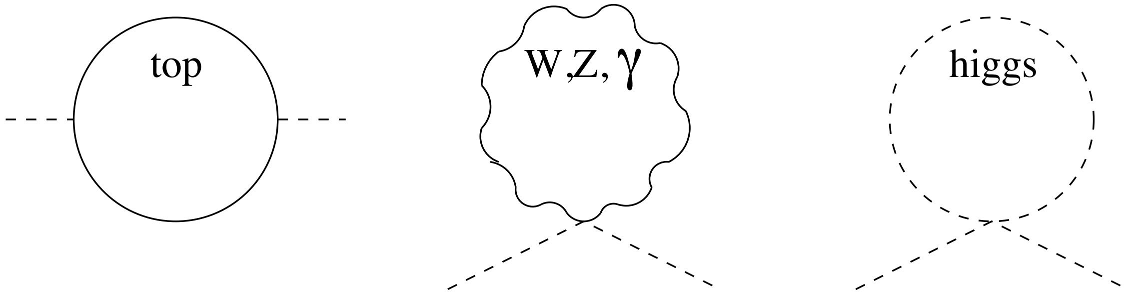
Masses would generically be of order $M_{\rm Planck}$ or $M_{\rm GUT}$

Nature **487**, 454–458 (26 July 2012)

Fine Tuning in Wilsonian Picture

$$M^2_{\rm Obs} = c_{\rm Higgs}\Lambda^2_{\rm UV} +$$ sum over all fluctuations relevant for this measurement up to scale $\Lambda_{\rm UV}$

microscopics above the curtain



top loop	$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$
$SU(2)$ gauge boson loops	$\frac{9}{64\pi^2}g^2\Lambda^2$
Higgs loop	$\frac{1}{16\pi^2}\lambda^2\Lambda^2$

$c_{\rm Higgs}$ tuned to part in $M_{\rm Higgs}^2/\Lambda_{\rm UV}^2$

Strong CP Problem

QCD "should" have violated CP

neutron electric dipole moment - sensitive to both strong and weak CP violating phases

$$\mathcal{L}_{\text{CP}} = \theta G \cdot \tilde{G}$$

$$\bar{\theta} = \theta - \arg\det M_q \xleftarrow{\hspace{2em}}$$ This part is from the Higgs!

must be < 10^{-11}!

One of the best solutions so far

New particle: Axion

V_{axion} minimized when strong CP violation vanishes

→ only QCD can contribute...another tuning!

(Planck scale is actually ***TOO SMALL*** here)

Cosmological Constant

$\Lambda_{cc} \simeq (10^{-12} \text{ GeV})^4$

Just as the Higgs fills the vacuum with weak-charge, it also fills it with an energy density

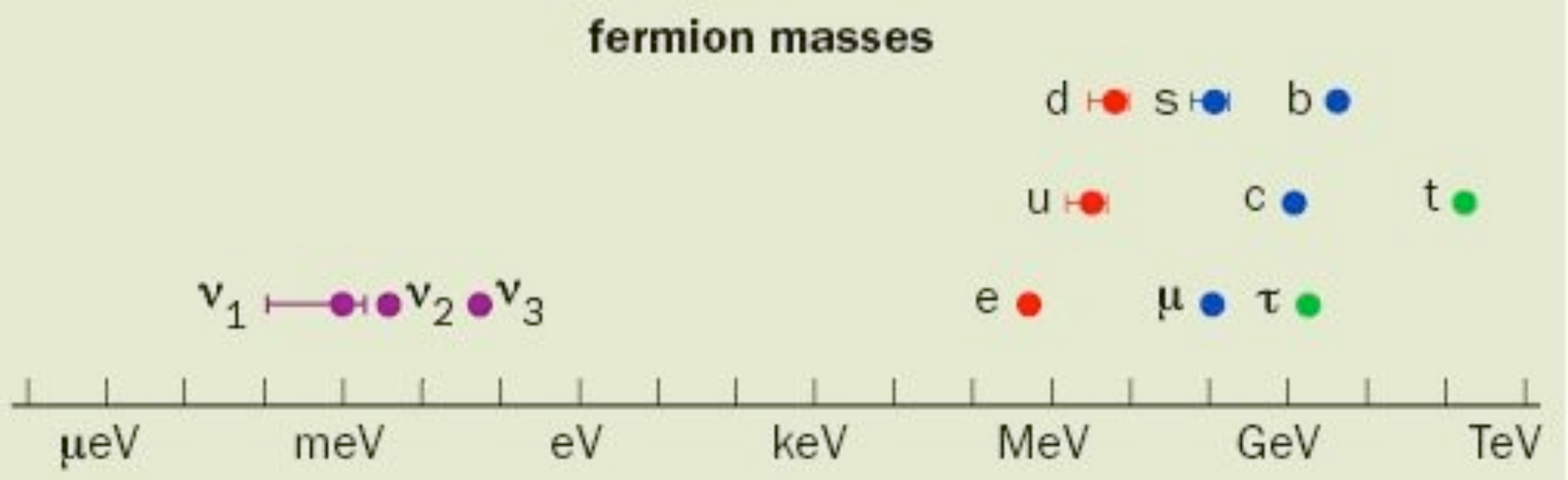
$$V(\langle H \rangle) = V_0 - \frac{\mu^4}{4\lambda} \simeq (10^2 \text{ GeV})^4$$

56 orders of magnitude!!??

There are also a bunch of quantum contributions that seem to greatly exacerbate the problem

also other contributions of similar style (i.e. QCD)

Fermion masses



These come from the Higgs

$$\sum \lambda_{ij} H \psi_L^i \psi_R^j$$

Neutrinos are special

$$\sum \frac{1}{\Lambda} \lambda_{ij} \nu_i^T H i\tau 2 H \nu_j$$

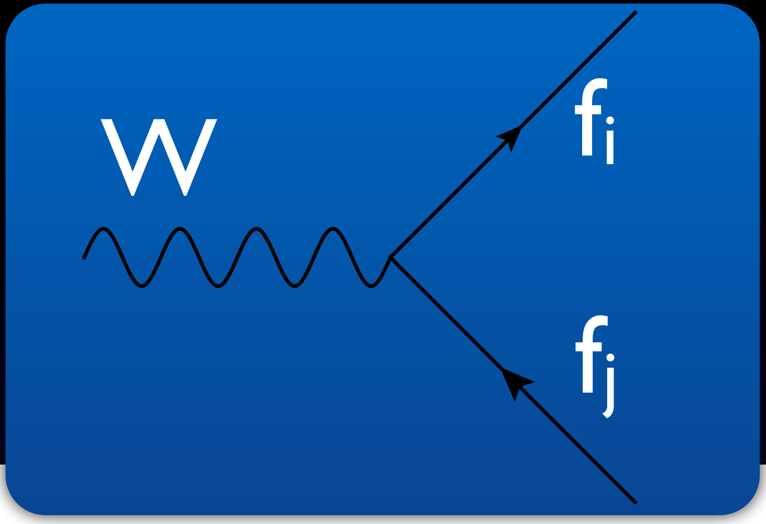
very small #'s

or

very high scale

Flavor

Weak interactions are not diagonal



e.g. top-bottom, top-strange, top-down

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

$J = (2.91^{+0.19}_{-0.11}) \times 10^{-5}$ - weak CP violation

This is close to the identity, and very hierarchical
off-diagonals quantify amount of flavor changing in weak interactions

weak charge and masses **almost** simultaneously diagonalizable...why?

What does the Higgs not do?

- It doesn't give masses of order M_{Planck}
  - It should
- It doesn't give huge contribution to E_{vacuum}
  - It should
- It doesn't give huge contribution to strong CP violation
  - It should
- It doesn't give generically large flavor changing couplings
  - It should

We seem to have some parts left-over/missing

e u s T t W H Z b c d μ ν's

γ

g

Dark matter?

CP violation?

Flavor?

Neutrino masses?

Dark Energy?

Strong CP?

Gravity?

A New Mechanism for

Hierachical Scale Generation, Naturally Light Scalar Fields, and Naturally Suppressed CC

Bellazzini, Csaki, JH, Serra, Terning

arXiv:1305.3919 "A Naturally Light Dilaton and a small Cosmological Constant"
Eur.Phys.J. C73 (2013) 2333 "A Higgs-like Dilaton"
and ongoing research

Moving about

Recall how we formally move about in physics

e.g. rotations

Finite Rotations:

$$M = e^{i\sum_i \alpha_i J_i}$$

$$\text{e.g. } M_x = e^{i\theta J_1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Obey commutation relations:

$$[J_i, J_j] = i\epsilon_{ijk} J_k$$

$$J_1 = \frac{i}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$J_2 = \frac{i}{2}\begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$J_3 = \frac{i}{2}\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

commutation relations specify the actions

Can construct theories symmetric under these actions

In space-time

Turn

J_i

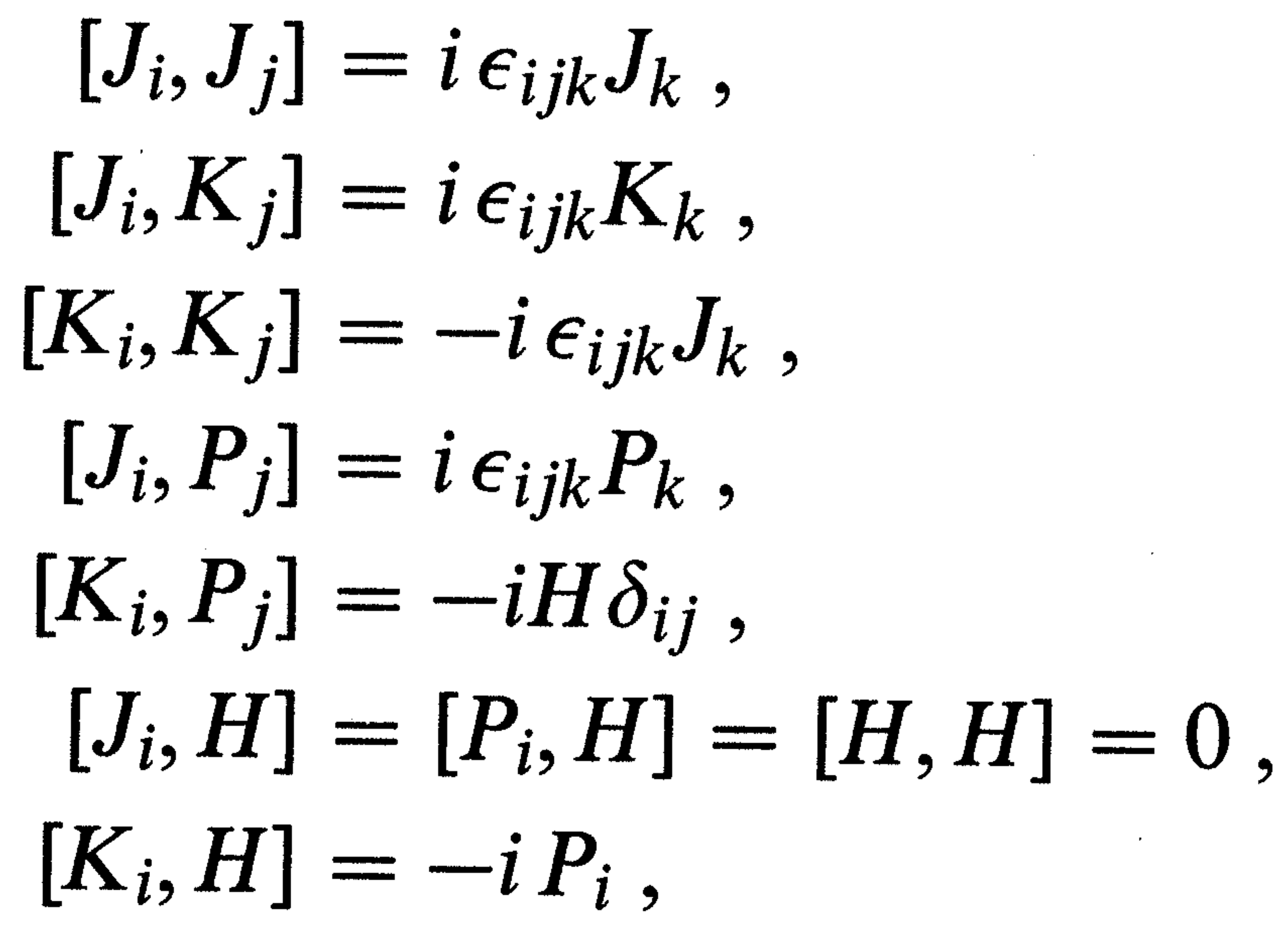
Translate

in space: P_i

in time: H

Boost

K_i



$$[J_i, J_j] = i\,\epsilon_{ijk} J_k \ ,$$
$$[J_i, K_j] = i\,\epsilon_{ijk} K_k \ ,$$
$$[K_i, K_j] = -i\,\epsilon_{ijk} J_k \ ,$$
$$[J_i, P_j] = i\,\epsilon_{ijk} P_k \ ,$$
$$[K_i, P_j] = -iH\,\delta_{ij} \ ,$$
$$[J_i, H] = [P_i, H] = [H, H] = 0 \, ,$$
$$[K_i, H] = -i\,P_i \ ,$$

More possibilities in QFT? Coleman-Mandula Theorem says NO

Scale invariance

(aka conformal invariance)

A way to avoid Coleman-Mandula:

Give up on having an analytic scattering matrix

$$
\begin{aligned}
[J_i, J_j] &= i\,\epsilon_{ijk} J_k \;, \\
[J_i, K_j] &= i\,\epsilon_{ijk} K_k \;, \\
[K_i, K_j] &= -i\,\epsilon_{ijk} J_k \;, \\
[J_i, P_j] &= i\,\epsilon_{ijk} P_k \;, \\
[K_i, P_j] &= -iH\delta_{ij} \;, \\
[J_i, H] &= [P_i, H] = [H, H] = 0 \,, \\
[K_i, H] &= -i\,P_i \;,
\end{aligned}
$$

+ Generator for changing rulers

$$[D, P_\mu] = P_\mu$$

+special conformal

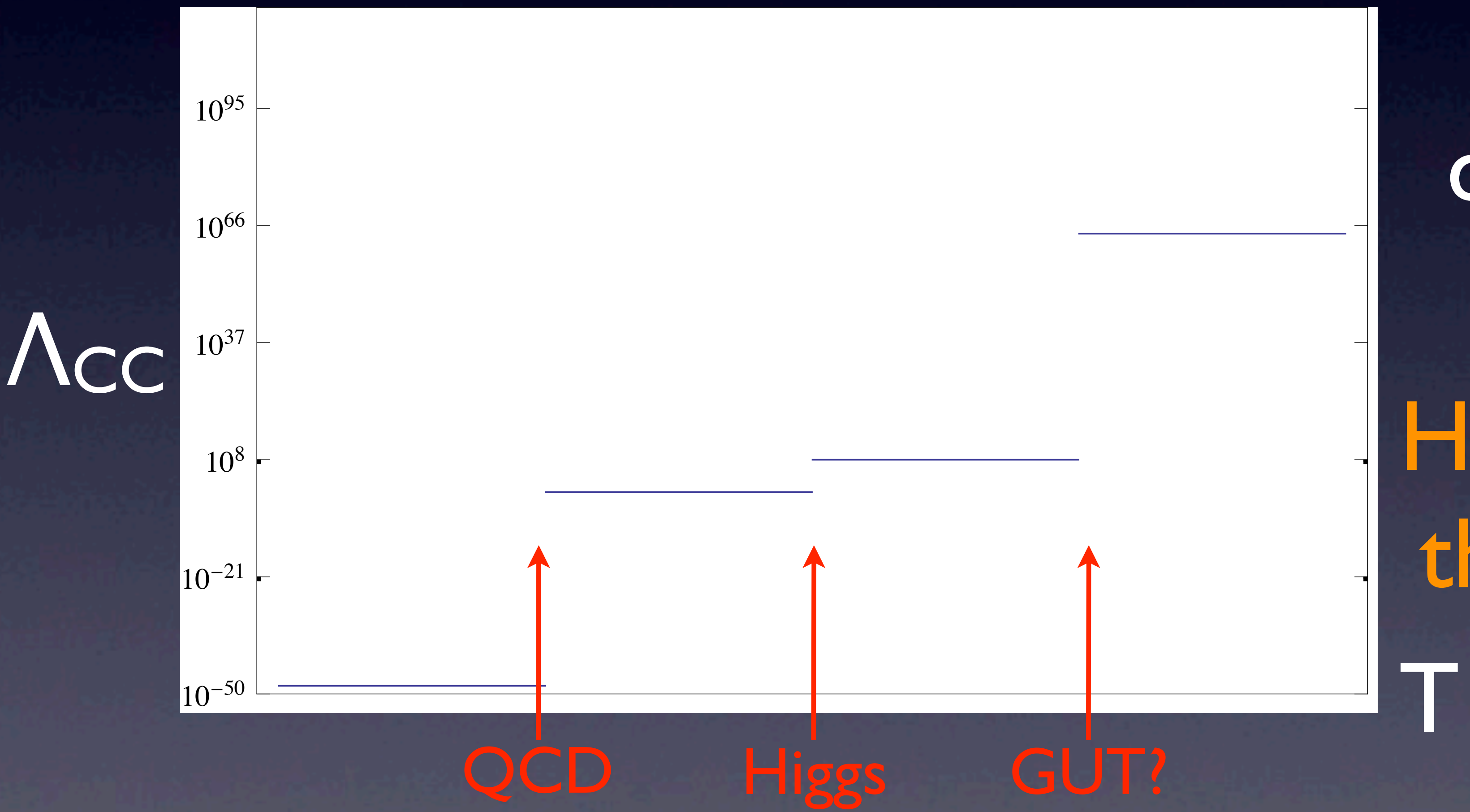
$$e^{i\lambda D} x_\mu = e^{\lambda} x_\mu$$

At energies above m_{Higgs} the SM is nearly scale invariant

“Biggest” Problem:

When QCD phase transition occurs
(or any other PT’s occur in early universe - e.g. Higgs)
vacuum filled with energy density (cosmological constant)

History of the CC:



somehow when the dust settles end result is near zero CC

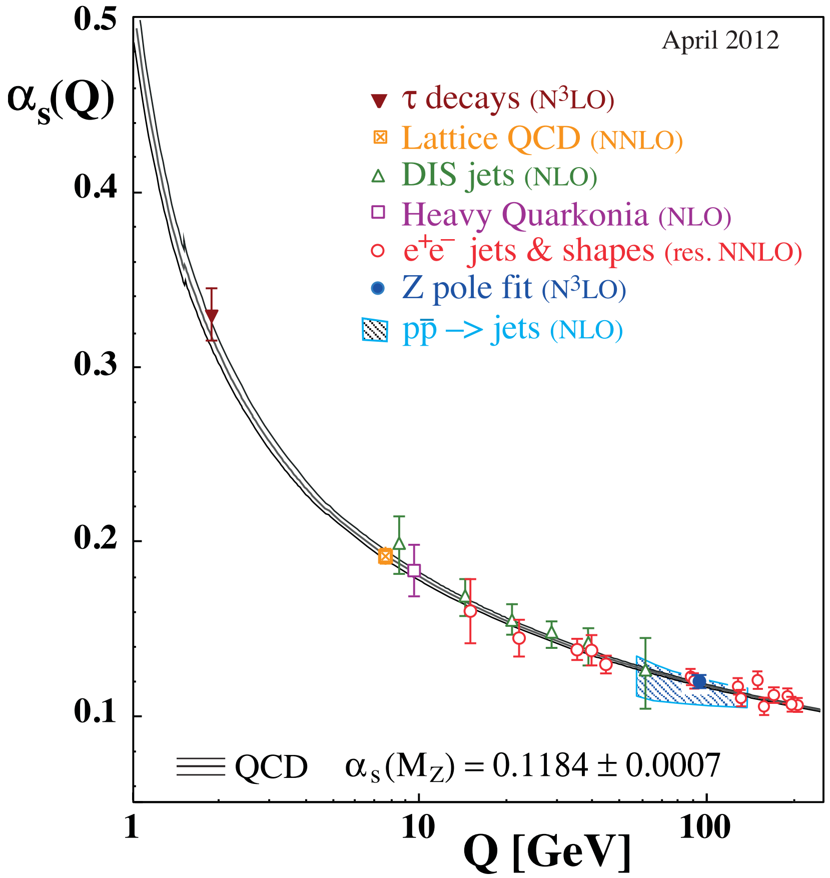
How did UV know what the IR was going to do?

Supersymmetry really can’t do much about this one

Revisit QCD

$$\alpha_S(\mu) = \frac{\alpha_S(\Lambda_{\rm UV})}{1 - \alpha_S(\Lambda_{\rm UV})\beta \log \frac{\mu}{\Lambda_{\rm UV}}}$$

Pathology manifests when denominator vanishes



approach to phase transition

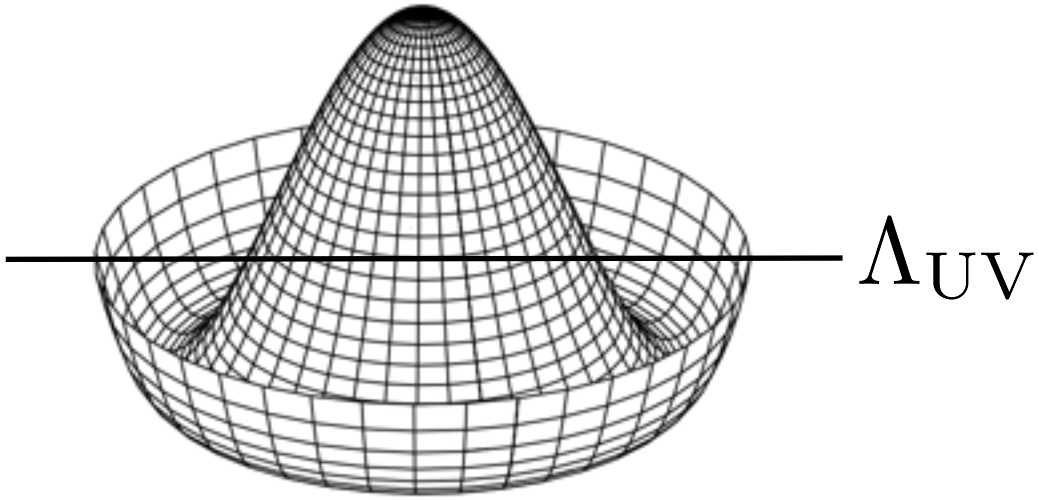
Scale invariance very broken near 1 GeV!

Determined by value of QCD coupling constant at the highest scales (e.g. $M_{\rm GUT}$ or $M_{\rm Planck}$)

UV boundary conditions determine IR scale

Could there be a theory where the IR scale is sensitive to the eventual value of the CC itself? An adjustment mechanism?

Spontaneously broken symmetries



Symmetry appears as "mysterious" relations among parameters in effective action & conspicuously light particles

Example:

Below QCD phase transition

Light pions and $g_{\pi NN} f_{\pi} = G_{N^0} M_N$ (to about 10%)

pion-nucleon coupling

decay rate of neutron

We have since developed procedures to construct effective theories where symmetry is manifest

Spontaneously broken Scale Invariance?

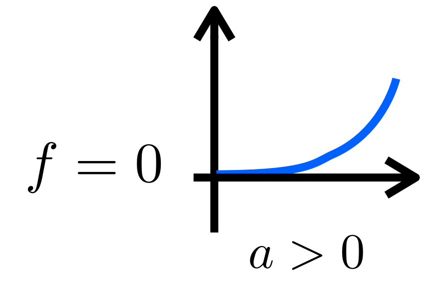
$$S_{\text{eff}} = \int d^4x \frac{1}{2}(\partial\chi)^2 - a\chi^4$$

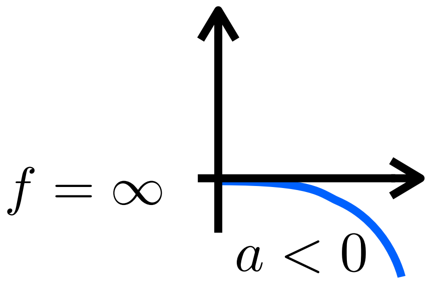
$$\langle\chi\rangle = f$$

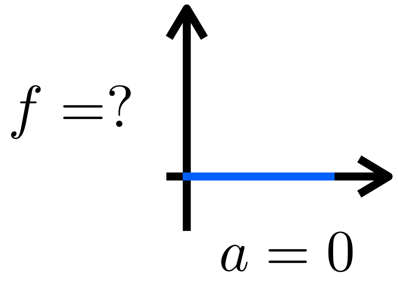
Obstruction:

Fubini '76

- a > 0 → f = 0 (no breaking)
- a < 0 → f = ∞ (runaway)
- a = 0 → f = anything (flat potential)
  (massless particle - no symmetry)







a is cosmological constant in units of f!
CC problem - it's usually big

Hard to realize

Spontaneously broken almost scale invariance

quartic coupling "a" depends on parameters of UV theory

a(λ) is function with zero for some value of λ

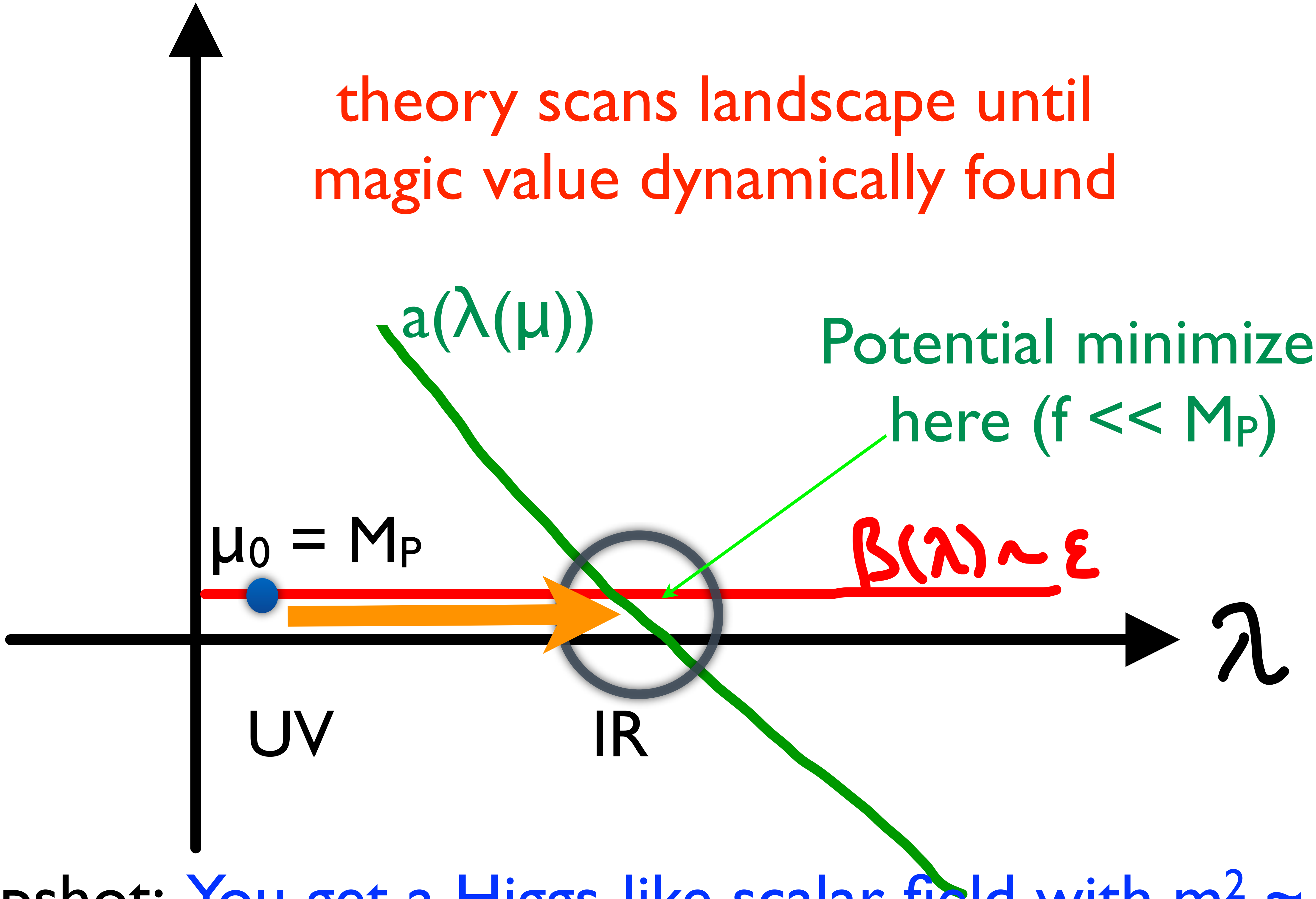
If theory is not quite scale invariant, coupling λ can change slowly

$$\frac{d\lambda}{d\log\mu} = \epsilon$$

so quartic (Cosmological constant) changes with scale!

$a(\lambda(\chi))\chi^4$

No longer a simple quartic potential



Upshot: You get a Higgs-like scalar field with $m^2 \sim \epsilon f^2$

(somewhat: Eur.Phys.J. C73 (2013) 2333 “A Higgs-like Dilaton”)

Cosmological constant is $\Lambda_{CC} \sim \epsilon f^4$

Where do extra dimensions come in?

$$
\begin{aligned}
[J_i, J_j] &= i\,\epsilon_{ijk} J_k \,, \\
[J_i, K_j] &= i\,\epsilon_{ijk} K_k \,, \\
[K_i, K_j] &= -i\,\epsilon_{ijk} J_k \,, \\
[J_i, P_j] &= i\,\epsilon_{ijk} P_k \,, \\
[K_i, P_j] &= -iH\delta_{ij} \,, \\
[J_i, H] &= [P_i, H] = [H, H] = 0 \,, \\
[K_i, H] &= -i\,P_i \,,
\end{aligned}
$$

+ Generator for changing rulers

$$[D, P_\mu] = P_\mu$$

+special conformal

$$e^{i\lambda D} x_\mu = e^\lambda x_\mu$$

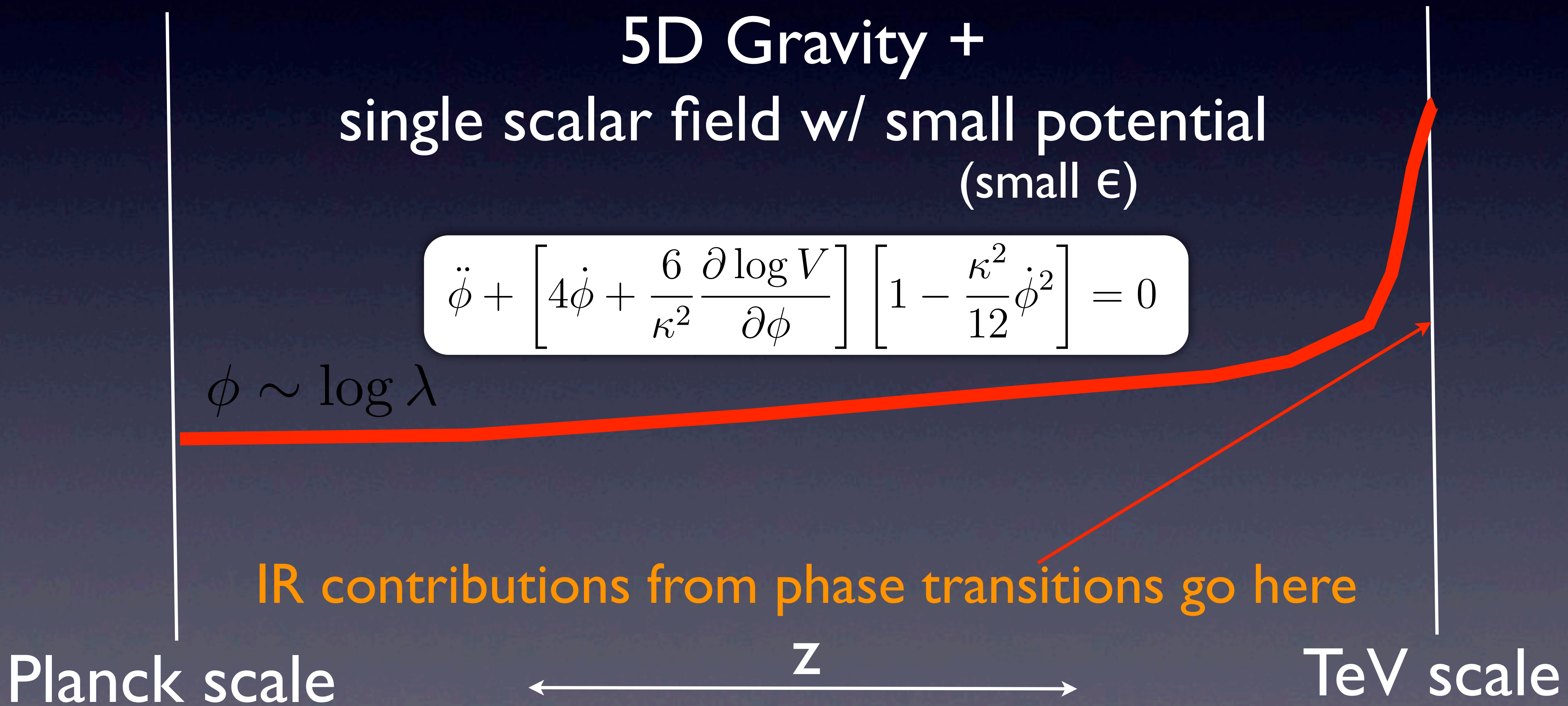
These are the **same** as the movements in a 5D space with constant negative curvature

quantum field theories in these 5D spaces share properties with certain scale invariant 4D theories (AdS/CFT)

Changes in scale = translations in 5th dimension

5D Model that implements ideas of cartoon

arXiv:1305.3919 “A Naturally Light Dilaton and a small Cosmological Constant”



5D Gravity +

single scalar field w/ small potential

(small ϵ)

$$\ddot{\phi} + \left[4\dot{\phi} + \frac{6}{\kappa^2}\frac{\partial \log V}{\partial \phi}\right]\left[1 - \frac{\kappa^2}{12}\dot{\phi}^2\right] = 0$$

$\phi \sim \log \lambda$

IR contributions from phase transitions go here

Planck scale

z

TeV scale

system responds by **shifting Planck scale** - CC stays zero

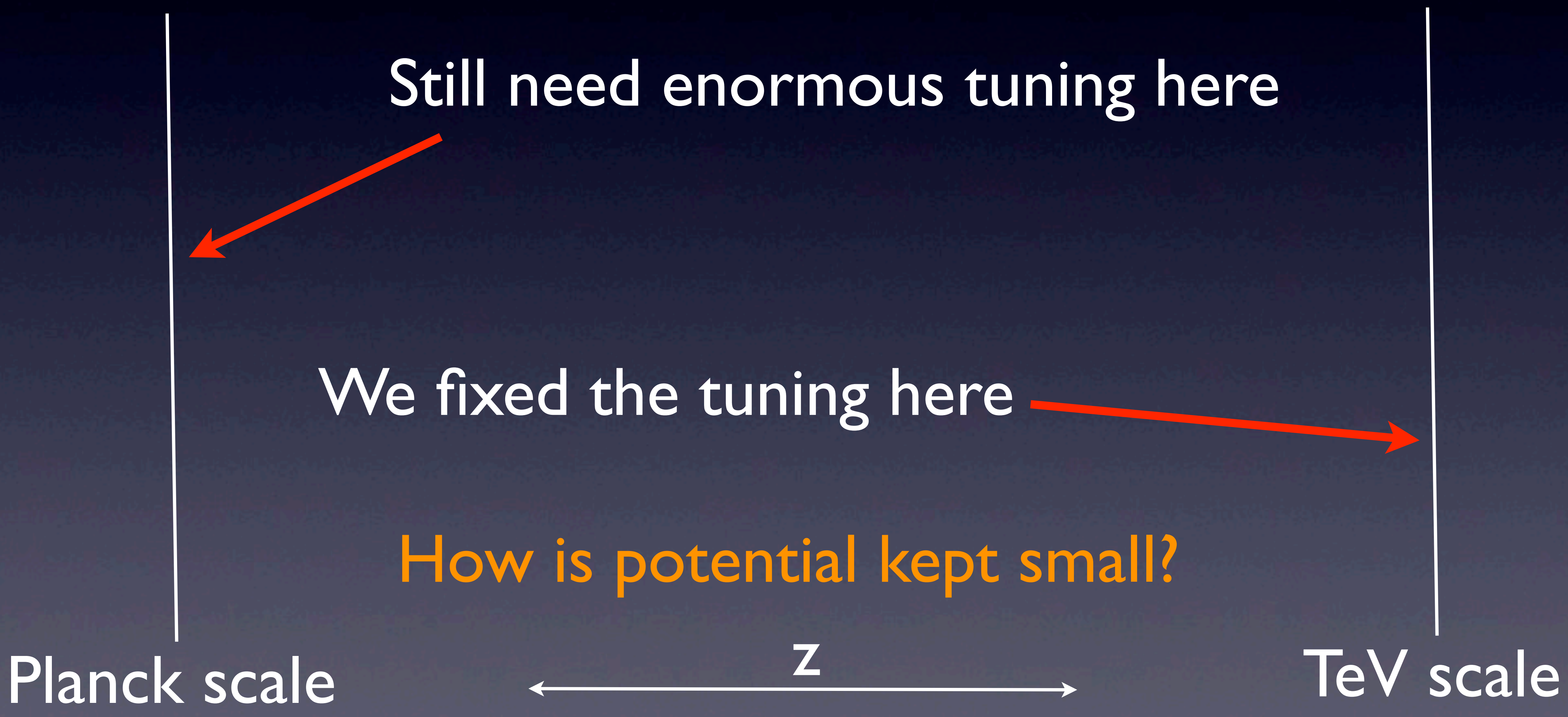
Can we observe this?

Some speculation/outlook:

- Gravity waves/CMB: phase transitions in early universe
  - dynamics of true vacuum bubble collisions sensitive to this mechanism!
- Neutron stars: Seems like there should be order 1 change in energy density in exotic phases in core
  - mass-radius relations and/or limits may be affected!
- Dark-Matter: Light scalar may undergo coherent oscillations after phase transitions
  - correspondence between Dark Matter and Dark Energy?

Strong tie-in to cosmic frontier

Problem One



Still need enormous tuning here

We fixed the tuning here

How is potential kept small?

Planck scale

z

TeV scale

Another Coleman-Mandula Loophole:

$$
\begin{aligned}
[J_i, J_j] &= i\,\epsilon_{ijk} J_k \ , \\
[J_i, K_j] &= i\,\epsilon_{ijk} K_k \ , \\
[K_i, K_j] &= -i\,\epsilon_{ijk} J_k \ , \\
[J_i, P_j] &= i\,\epsilon_{ijk} P_k \ , \\
[K_i, P_j] &= -iH\,\delta_{ij} \ , \\
[J_i, H] &= [P_i, H] = [H, H] = 0 \, , \\
[K_i, H] &= -i\,P_i \ ,
\end{aligned}
$$

All commutation relations

anti-commutation relations?

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$$

truly quantum dimensions:

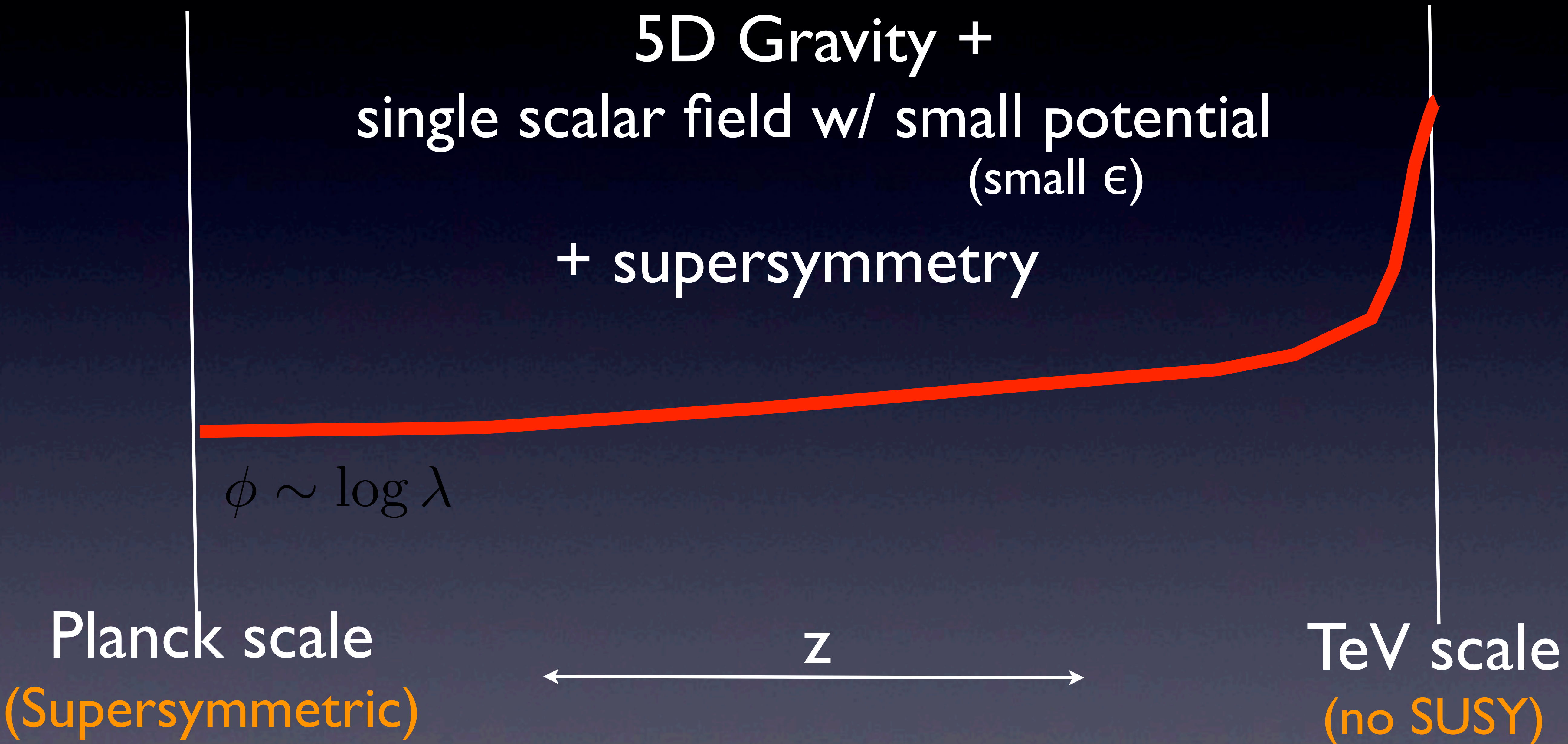
can only take one step in each one

Supersymmetry is an extra-dimensional theory

Easy Solution

5D Gravity +
single scalar field w/ small potential
(small ϵ)

+ supersymmetry



$\phi \sim \log \lambda$

Planck scale
(Supersymmetric)

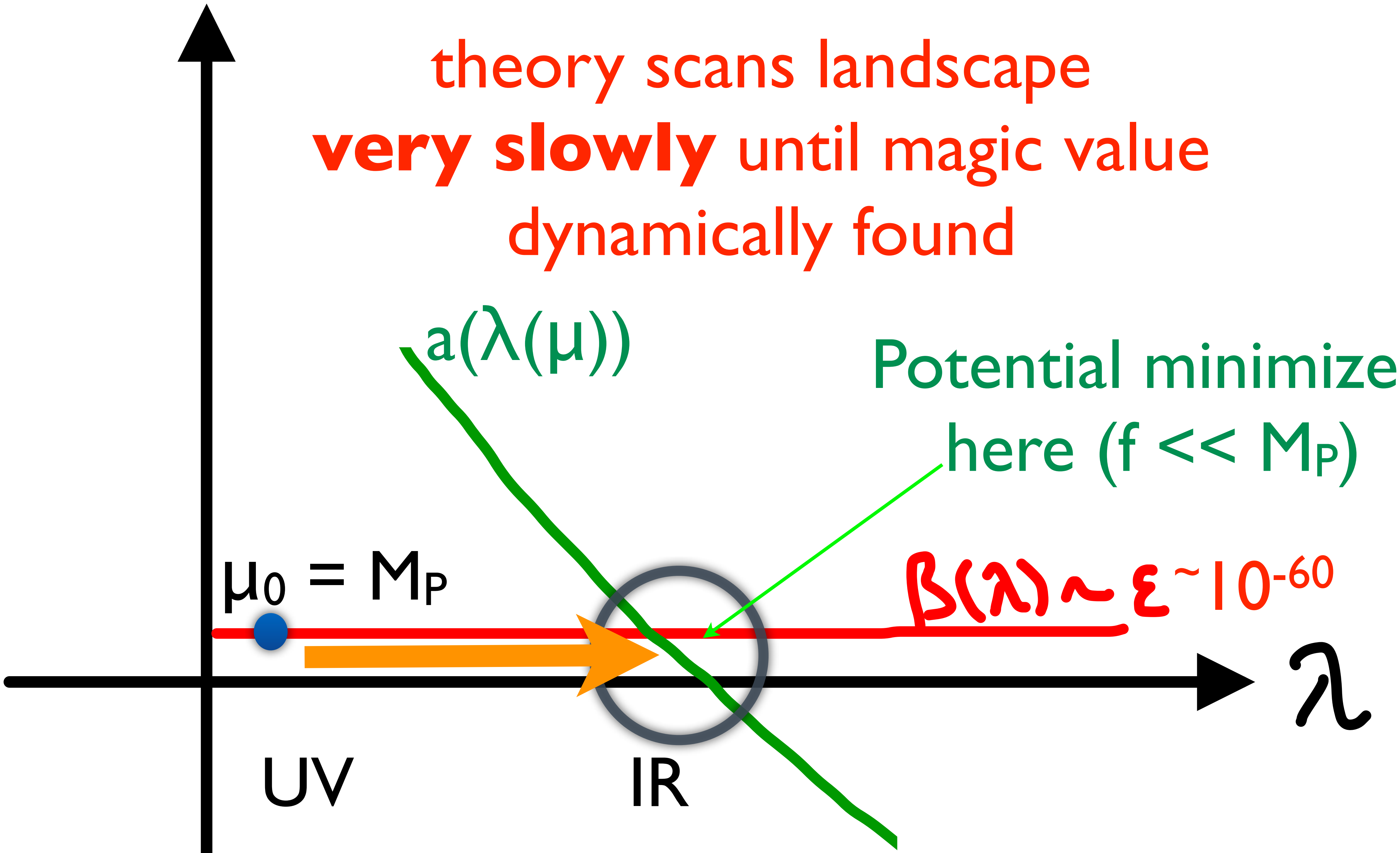
z

TeV scale
(no SUSY)

system responds by **shifting Planck scale** - CC stays zero

Problem Two

The Planck scale is ***TOO SMALL***



Recall our best solution to the strong CP problem has same issue!

What don’t these 5D Models do?

- They don’t give masses of order M_{Planck}
  - Randall, Sundrum ’99
- The don’t give huge contribution to E_{vacuum}
  - (Bellazzini, Csáki, JH, Serra, Terning 2013)
- They don’t give huge contribution to strong CP violation
  - Adding SUSY may give axion for strong CP
  - also see (Bunk, JH 2010)
- They don’t give fermion masses all at weak scale
  - Grossman, Neubert ’99
- They don’t give generically large flavor changing couplings
  - many interesting works on flavor (Cornell, Harvard, Maryland)

Phenomenological Consequences

Energy Frontier: New resonances associated with extra dimensional dynamics, changes in Higgs physics
(e.g. ongoing work with Jain, Bunk
+ many new features given most recent work)

Intensity Frontier: Flavor physics predictions are affected
(will be different in our new construction - future work)

Cosmic Frontier: Gravity waves, observations of neutron stars, dark matter puzzle, general cosmological evolution
(ongoing research Bellazzini, Csáki, JH, Redi, Serra, Terning)

We seem to slowly be getting better at painting our own self portrait

We're 3×10^{105} Planck lengths in volume Our mass is 4×10^{29} Planck masses
and we move in 3 space dimensions, 1 time....

"Whoa...you are a very spacious species"

OR....

...plus one curved dimension
and a couple intrinsically quantum dimensions
plus ....

"Sounds about par for the course."

Thank You!