Beyond the Standard Model

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Outline:

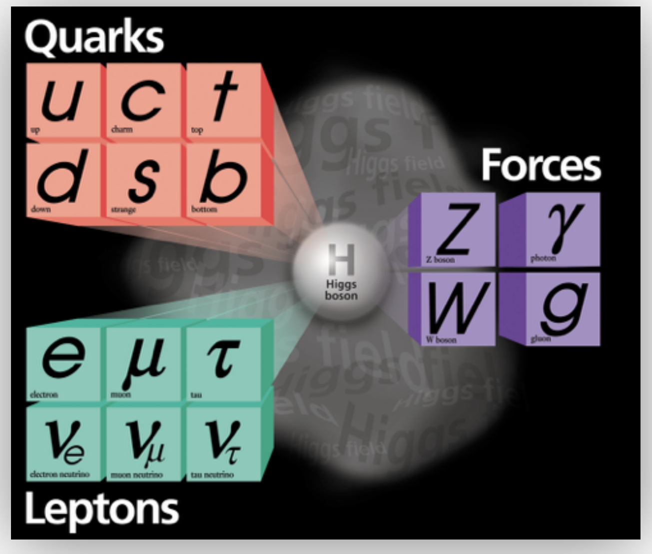
- The Standard Model: symmetries, consistency, and reasons for improvement
- Grand Unified Theories
- The strong CP-problem and axions
- The hierarchy problem and possible solutions:

  Supersymmetry, Composite Higgs, Extra Dimensions, …

What you must know:

There is a relatively simple **QFT** that explains "almost" all data:

The SM:



Determined by Lorentz + Dynamics!

- Vector bosons: Introduced by a gauge sym.: **SU(3)xSU(2)xU(1)**
- Fermions (Matter): 3 families of

$$\left\{ \begin{array}{rl} Q_L: & (3,2,1/3) \\ u_R: & (3,1,4/3) \\ d_R: & (3,1,-2/3) \\ l_L: & (1,2,-1) \\ e_R: & (1,1,-2) \end{array} \right.$$

- Scalar: $H: \ (1,2,1)$

$Q_{EM}=Y/2+T_3$

\+ **Gravity (General Relativity)**

Weinberg's Book 1, page 246:

To have 2 DOF of a spin=1 object properly transforming under the Lorentz Group ➠ **Gauge Symmetry**

To have 2 DOF of a spin=2 object properly transforming under the Lorentz Group ➠ **Invariance under x-transformations**

Apart from Spacetime Symmetries, in the SM symmetries are not imposed

Relatively simple Lagrangian for the SM:

$$\mathcal{L}_{\rm SM} = \boxed{-\frac{1}{4g'^2}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4g^2}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4g_s^2}G^{\mu\nu}G_{\mu\nu} + i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{l}^i_L \not{D} l^i_L + i\bar{e}^i_R \not{D} e^i_R + |D_\mu H|^2}$$

$$\boxed{+Y_u^{ij}\bar{Q}^i_L \tilde{H} u^j_R + Y_d^{ij}\bar{Q}^i_L H d^j_R + Y_e^{i}\bar{l}^i_L H e^i_R + h.c.}$$

$$\boxed{+V(H)}$$

Only terms whose dimensions are ≤ 4

in fact, not all of them!!

Using dimensional analysis with $\hbar = c = 1$

Using dimensional analysis with $\hbar = c = 1$

$$[S = \int \mathcal{L}\, d^4x] = M^0$$

$$[\mathcal{L}] = M^4$$

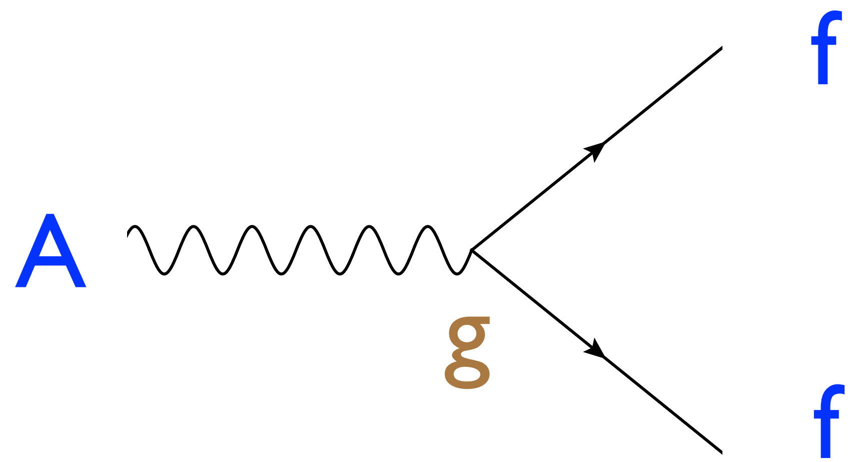
$$[\partial_\mu] = M$$

$$[H] = [A_\mu] = M$$

$$[\psi] = M^{3/2}$$

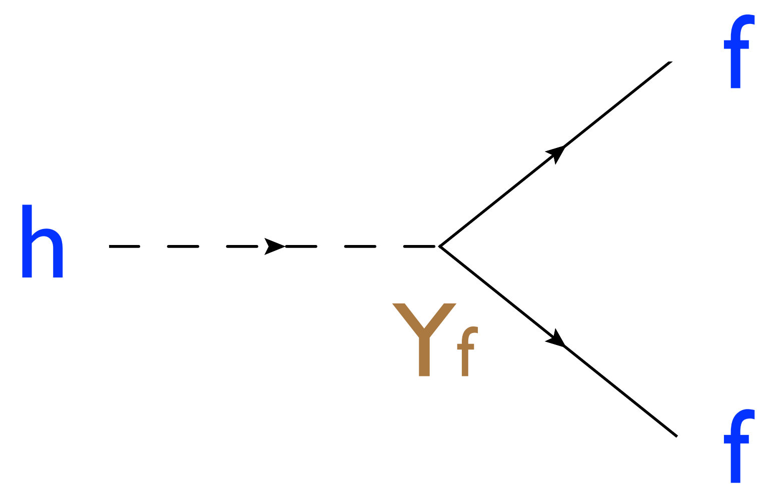
Apart from kin. terms + masses, it gives interactions:

Gauge:

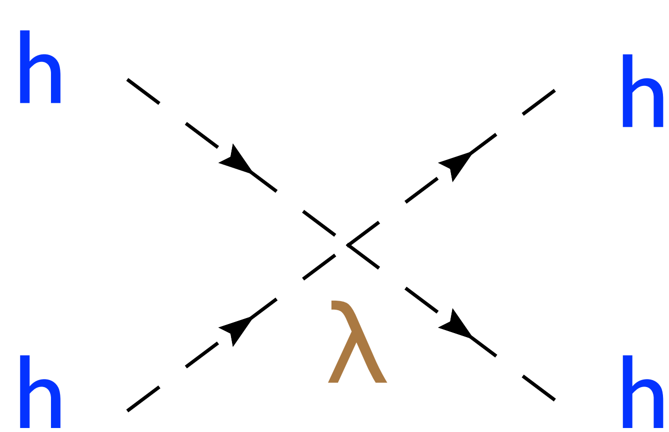


, ...

Yukawa:



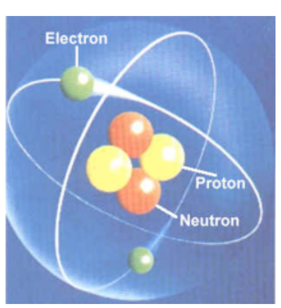
Self-Higgs:



g, Y_f, λ= dimensionless couplings

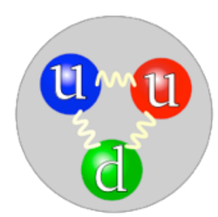
Nature has been very kind to us
providing interactions in 3 different "phases"
at large distances

EM interaction	**Strong interaction**	**Weak interaction**
"Coulomb phase"	**"Confining phase"**	**"Higgs phase"**
$\mathbf{V(r) \sim \frac{1}{r}}$	$\mathbf{V(r) \sim r}$	$\mathbf{V(r) \sim e^{-r}}$

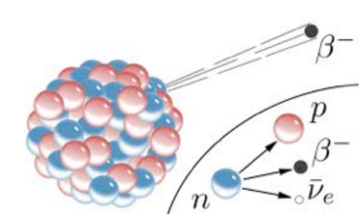


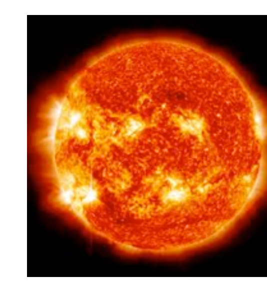
responsible for atoms, ...

& Gravity



responsible for nuclei





$pp \rightarrow D + e^+ + \nu_e$

responsible for sun's ignition

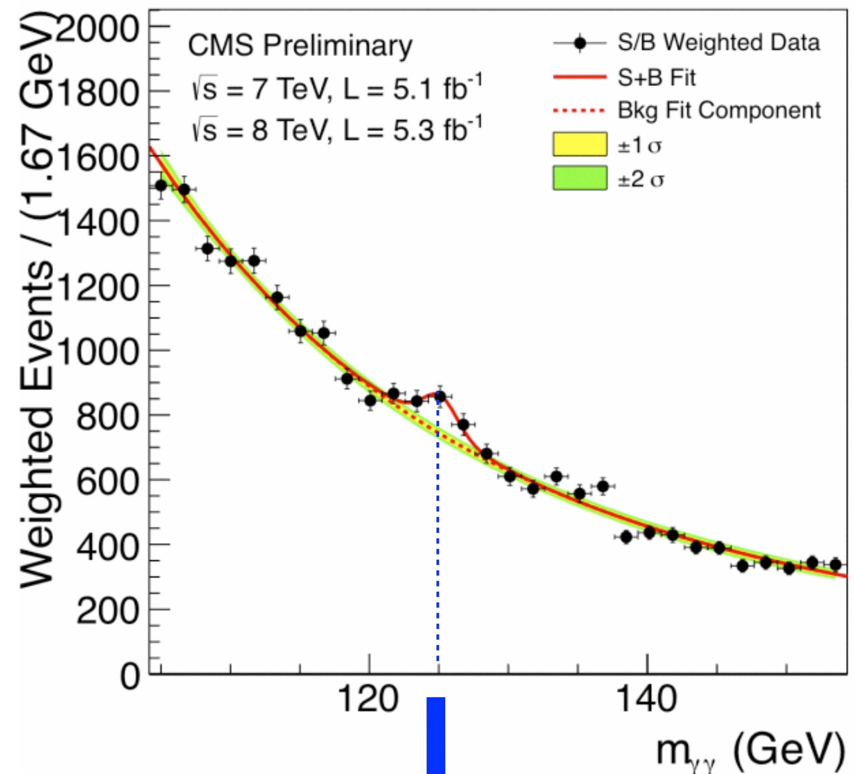
Before LHC:

Only one unknown parameter:

The Higgs mass (or λ)

4th of July of 2012
LHC marked a milestone in particle physics

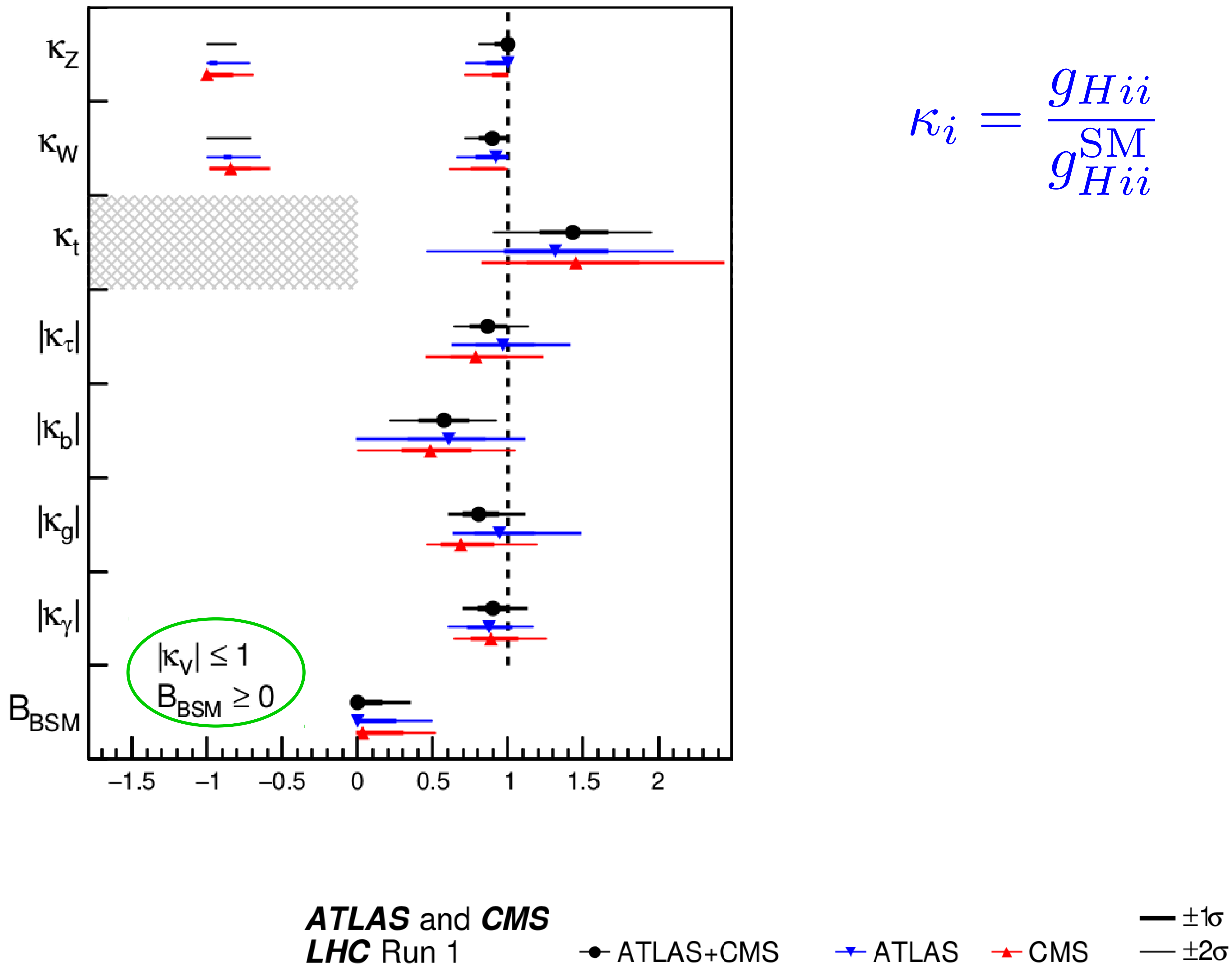
A Higgs-like state discovered:



LHC most **relevant** piece of data so far: $\mathbf{m_H \approx 125\ GeV}$

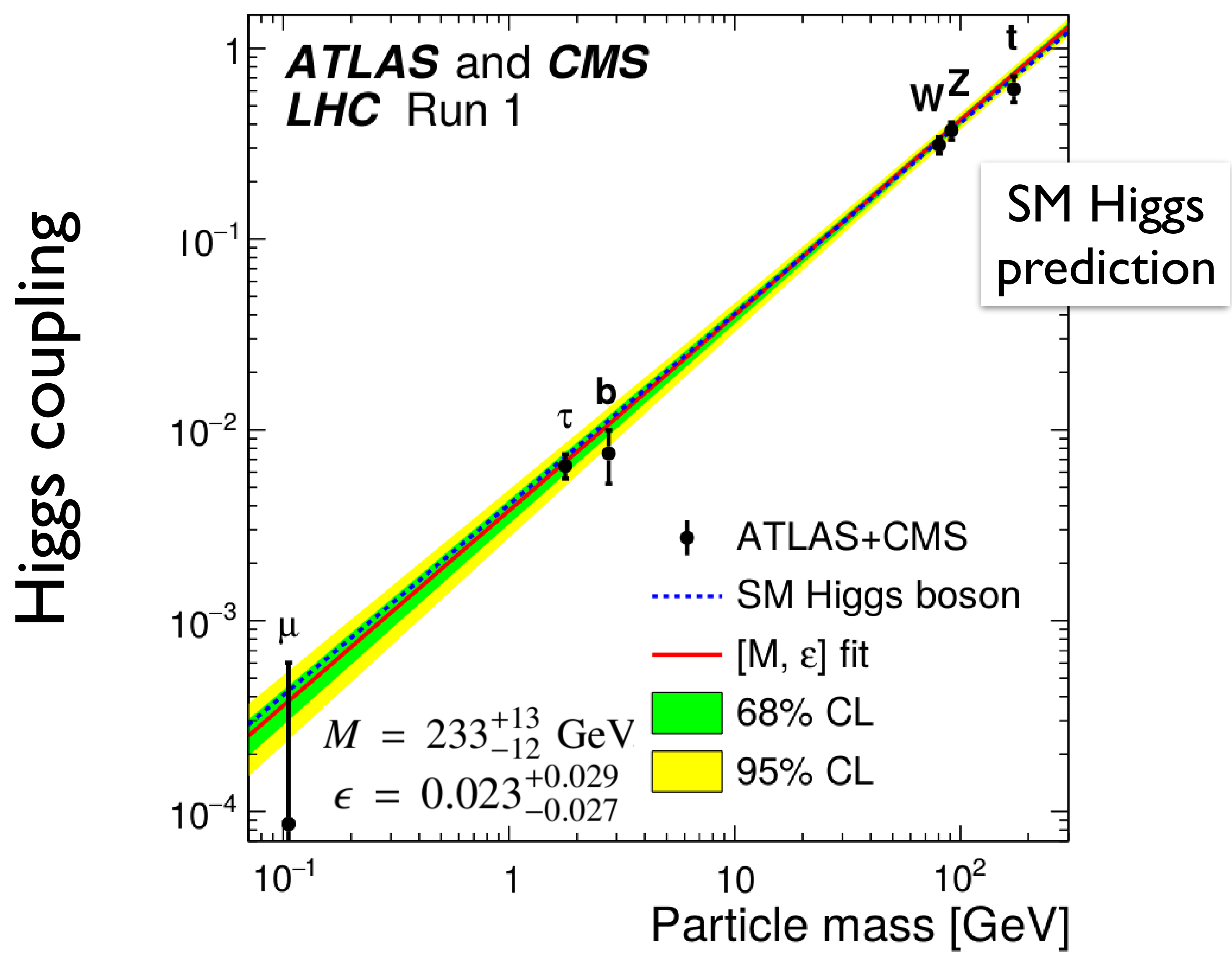
Really shook the theory community

All data quite compatible with the SM Higgs predictions

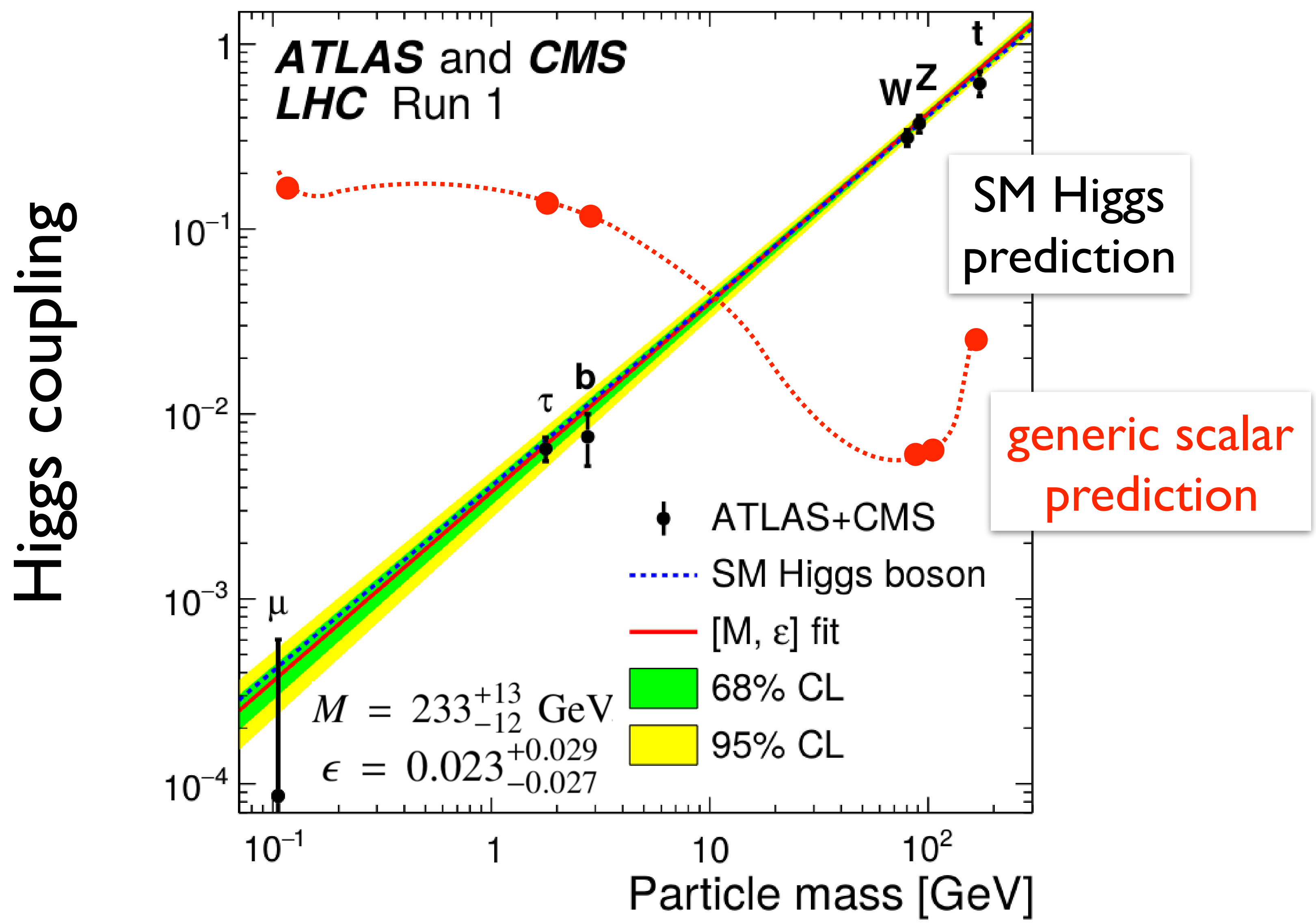


$$\kappa_i = \frac{g_{Hii}}{g_{Hii}^{\mathrm{SM}}}$$

A better perspective to understand how close experimental data is to the SM Higgs predictions:



A better perspective to understand how close experimental data is to the SM Higgs predictions:




Like Ulysses that revealed himself
by shooting an arrow through twelve axe rings

$$\mathbf{m_H^2 = \lambda v^2}$$

$\sim$ 0.26 (perturbative coupling)

Accidental global symmetries of the SM

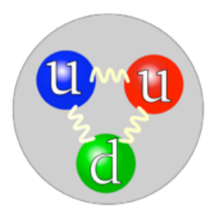
(symmetries of the dimension-4 operators)

We didn't ask for them, but they are there!

1) Baryon number B: $\psi \to e^{iB\theta}\psi$

B=1/3 (quarks), B=0 (leptons, Higgs)

→ Proton B=1: Cannot decay to leptons



caveat: This symmetry is "anomalous" and proton could decay but with an extremely small rate

2) Lepton number L_e, L_μ, L_τ:

L_e =1 (for e), L_μ=1,(for μ), L_τ =1,(for τ) (zero for the rest)

→ μ cannot decay to e+photon

Some **accidental** symmetries are approximate (broken by small couplings)

1) *Custodial* **symmetry:**  $\mathbf{\frac{m_W^2}{m_Z^2 c_{\theta_W}^2} \simeq 1.0}$ 

- In the limit $Y_f = 0$ and $g' = 0$

  Extra global SU(2): $(\mathbf{H}, i\boldsymbol{\sigma}_2 \mathbf{H}^*)$ being a doublet

  when **H** gets a VEV: $SU(2)_L \times SU(2) \to SU(2)_{custodial}$

  (W^+, W^-, Z) are a triplet of $SU(2)_{custodial}$ ➠ $m_W = m_Z$

- For $Y_f \neq 0$ and $g' \neq 0$: $$\frac{m_W^2}{m_Z^2 c_{\theta_W}^2} \equiv \rho \simeq 1.0$$

2) Family symmetry:

In the limit all $Y_f = 0$:

$$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$$

In the limit $Y_f = 0$ for 1st + 2nd family:

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(2)_L \times U(2)_e$$

➠ Reason for small $\bar{K}$-K mixing

Higher-dimensional operators

Why not?

Why we don't include terms like e.g. $(W^{\mu\nu}W_{\mu\nu})^2$ **?**

They are allowed by symmetries!

It has dim=8, so in the Lagrangian should be written as

$$\frac{1}{\Lambda^4}(W^{\mu\nu}W_{\mu\nu})^2$$

Λ = some scale suppressing the higher-dim terms

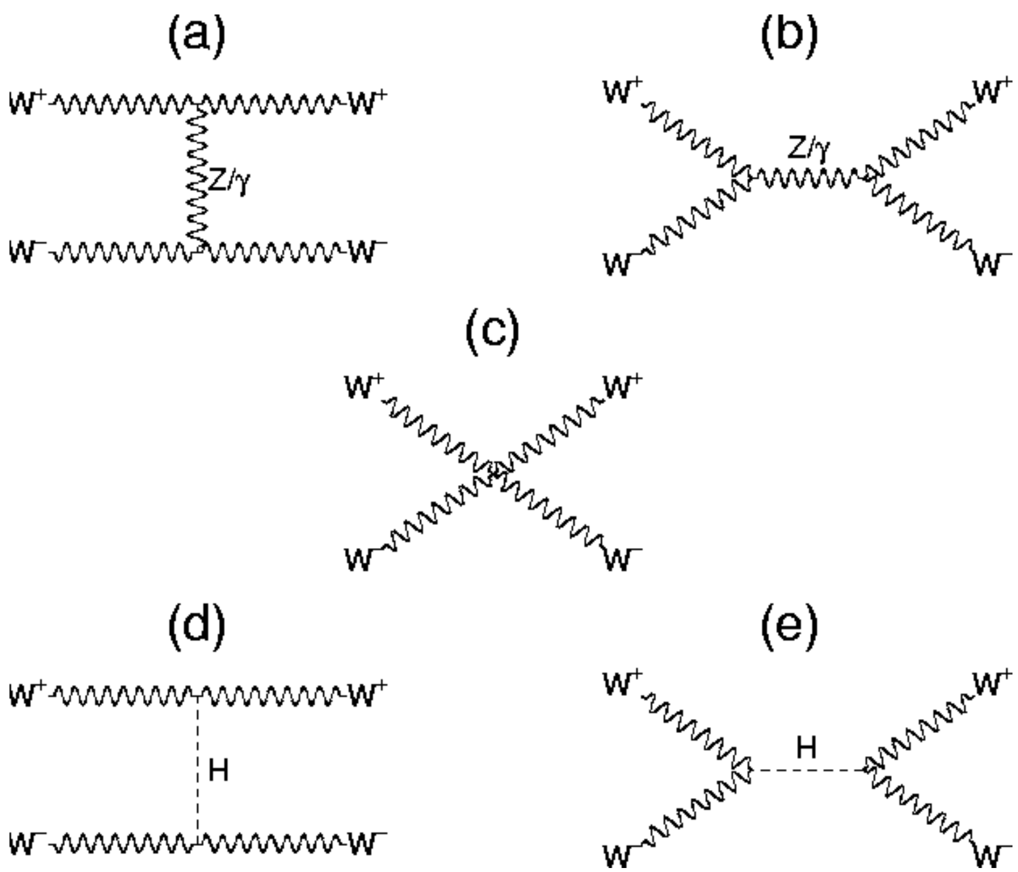
These new terms spoil the predictivity of the SM:

We have infinite of them!

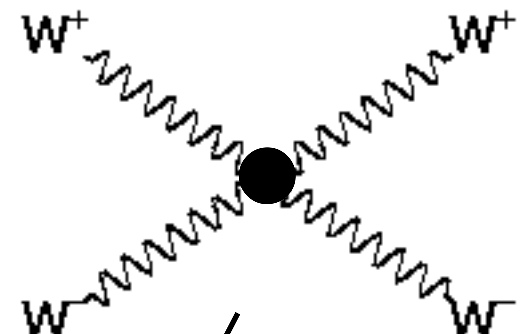
$\Lambda \equiv$ "Cut-off scale" ☛ Calculability lost at $E > \Lambda$

Fortunately, they are **irrelevant** at energies smaller than Λ:

For example, in WW-scattering:



+



$$\mathcal{M} = c_1 + c_2 \frac{E^4}{\Lambda^4}$$

small effects at E≪Λ

Then, we can think of **The SM**
as an **Effective Field Theory** (EFT),
valid below some scale Λ
that suppresses all higher-dimensional operators

This demystifies the SM!

How large can we take Λ ?

➥ **can we take it to be infinity?**

Related (but deeper) question:

Is there any need to go beyond the SM ($\Lambda \neq \infty$)?

Theoretical: Consistency of the theory?

Experimental: Data that cannot be explained?

TH

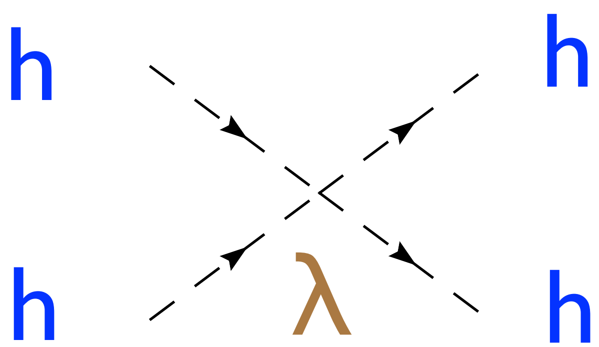
Could it be the SM the final theory?

We must use Einstein "Gedankenexperiment"
(thought experiments):

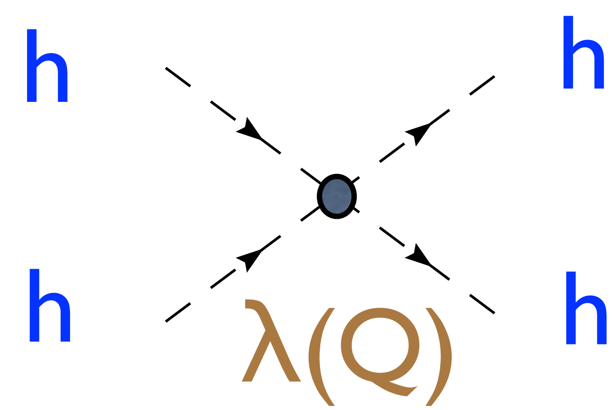
At the age of sixteen:

"If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing..."

Scattering at high-energies >> M_W



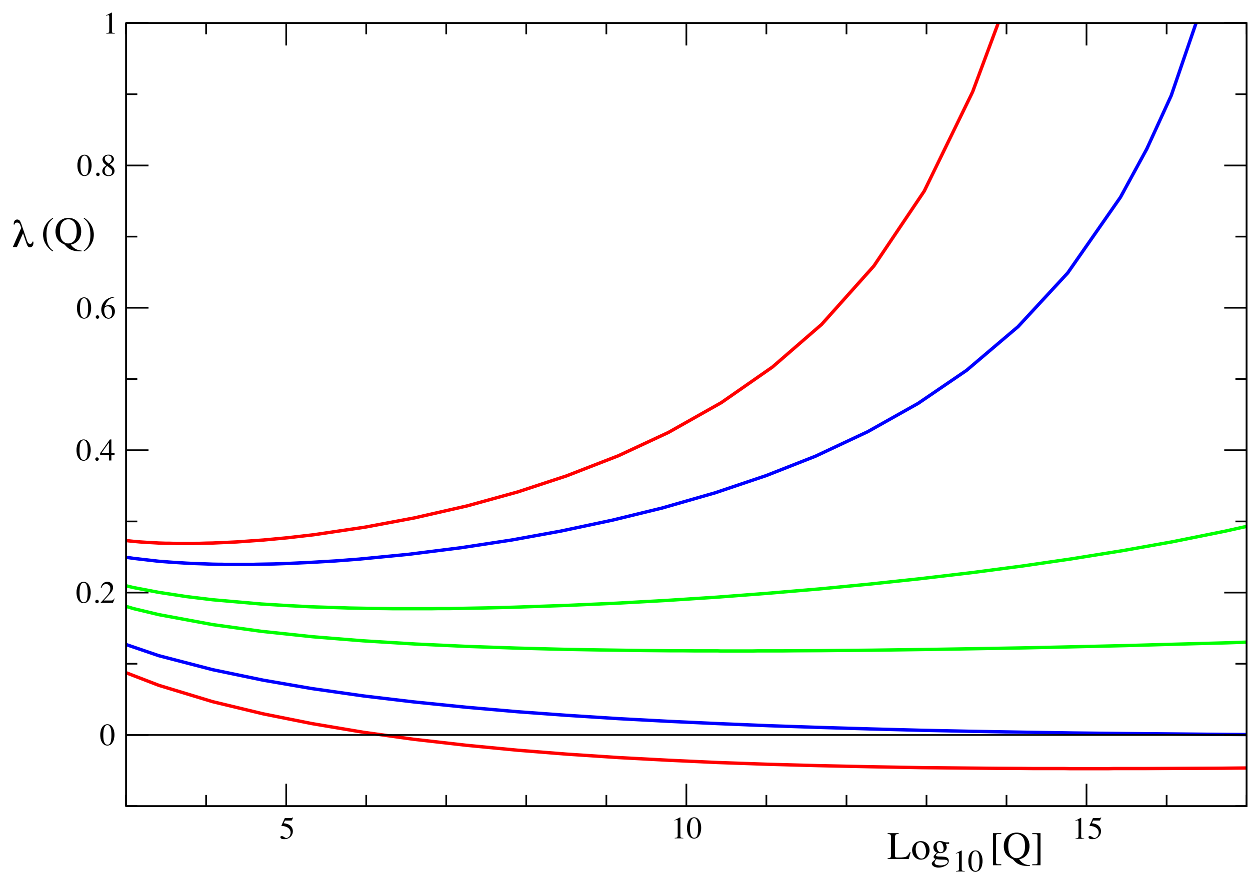
+ loops ~



λ(Q)≡"Running coupling constant" where Q ~ E_{cm}

Dictated by the RG Equation: $$\frac{d\lambda}{d\ln Q} = \frac{1}{16\pi^2}\left(24\lambda^2 + \underbrace{12\lambda Y_t^2 - 6Y_t^4}\right) + \cdots$$

"velocity" of growth of λ(Q)



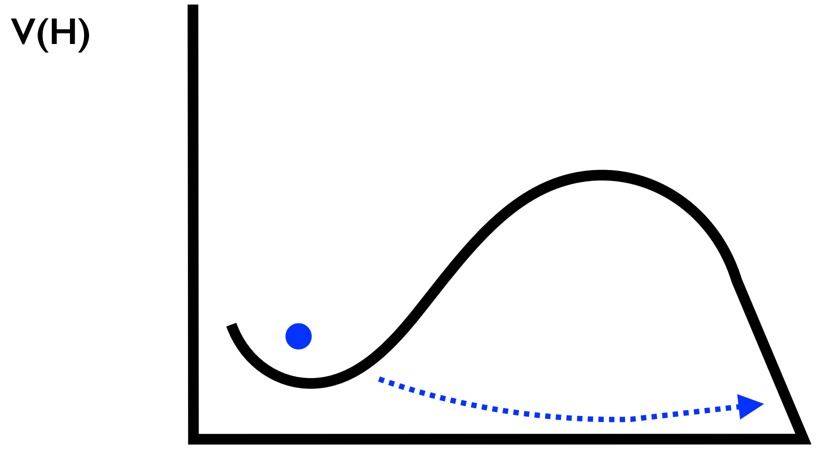
From Espinosa

- If $\lambda(Q)$ grows, as we increase Q, it can become too large at some scale Λ:

$$\lambda(Q=\Lambda) \sim 16\pi^2$$ ➥ Perturbation theory not valid anymore

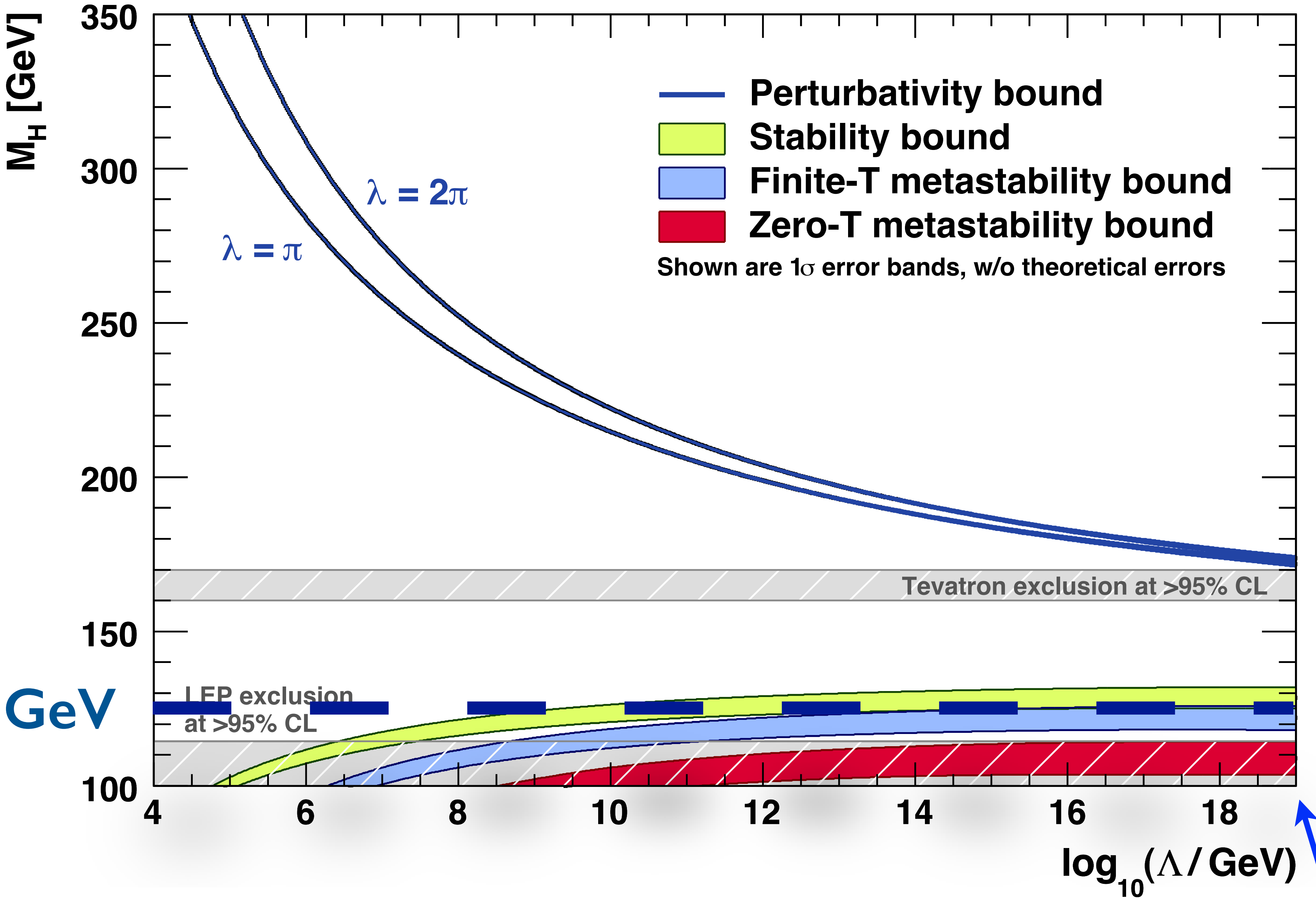
- If $\lambda(Q)$ decreases, it can become negative at some scale Λ:

➥ Unstable Higgs potential



I cannot trust my theory at $Q > \Lambda$ ☛ Λ =Cut-off scale

Since $M_h^2 = 2\lambda(Q = M_H)v^2$ for each Higgs mass value we can find a Λ

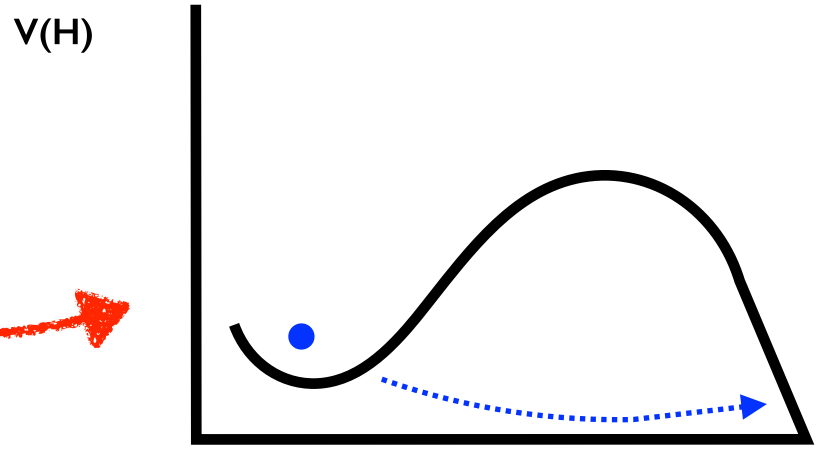


Ellis et al

125 GeV

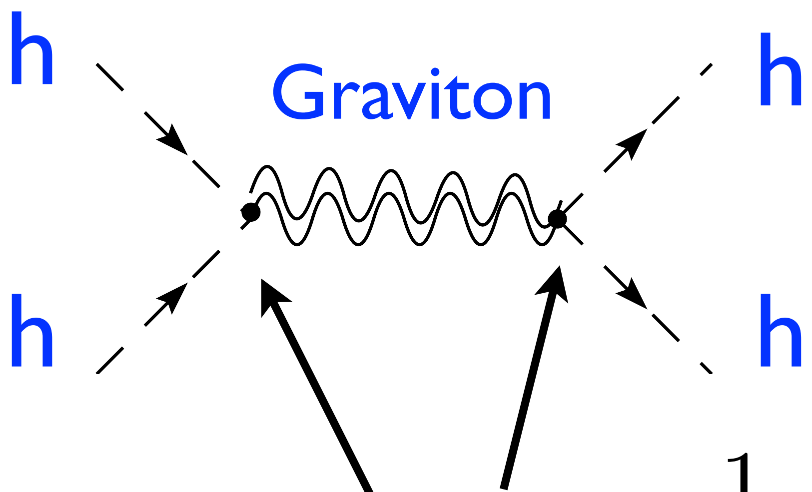
$\Lambda = 10^{19}$ GeV

taking $\Lambda = 10^{19}$ GeV



meta-stable vacuum

... but as $Q \sim 10^{19}$ GeV, gravitons are also important:



$\sim G_N Q^2$

$$G_N = \frac{1}{M_P^2}$$

larger than one for $Q > M_P$
~ quantum loops of gravitons important

also higher-dim operators suppressed by M_P are important

G_N = Newton's constant

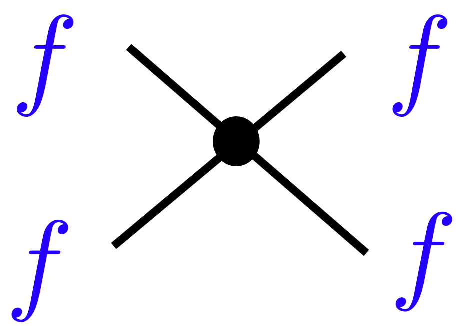
M_P = Planck's mass ~ 1.2×10^{19} GeV

Not known a consistent quantum treatment of SM+GR at $Q>M_P$!

New physics expected (at least)

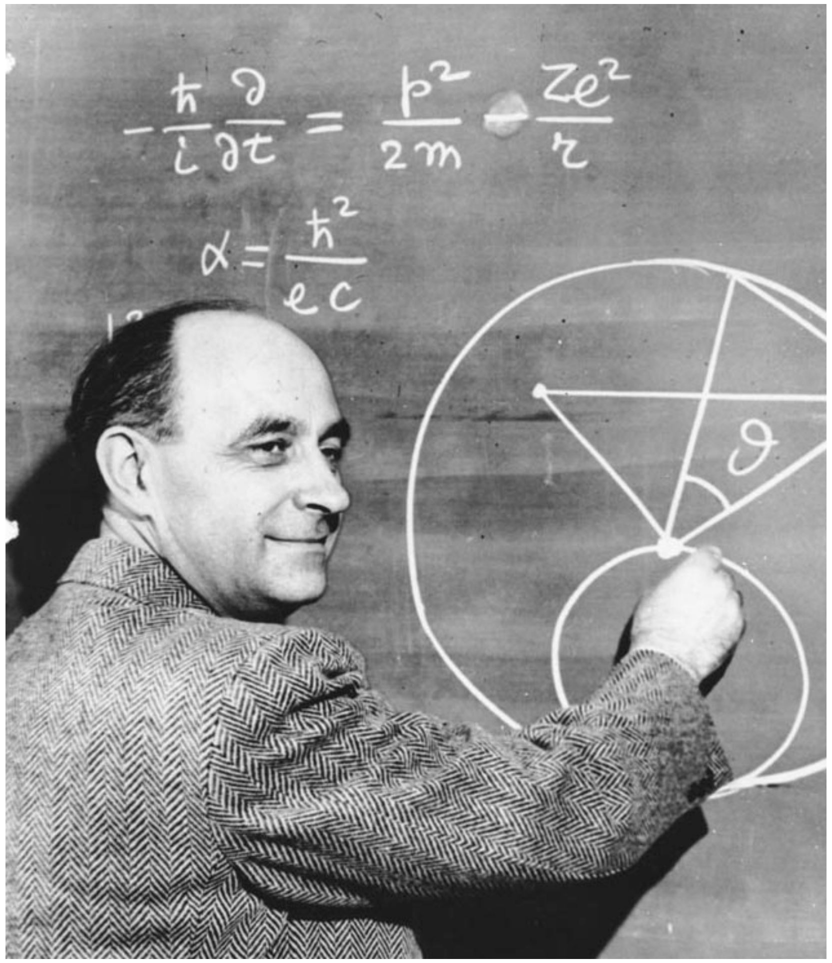
at energies ~ **10^{19} GeV !**

Very similar to Fermi's theory:



$\sim G_F Q^2$

G_F = Fermi's constant



The strength of the interaction is larger than one for

$Q > 1/\sqrt{G_F}$ ➠ $\Lambda_F \sim 1/\sqrt{G_F}$

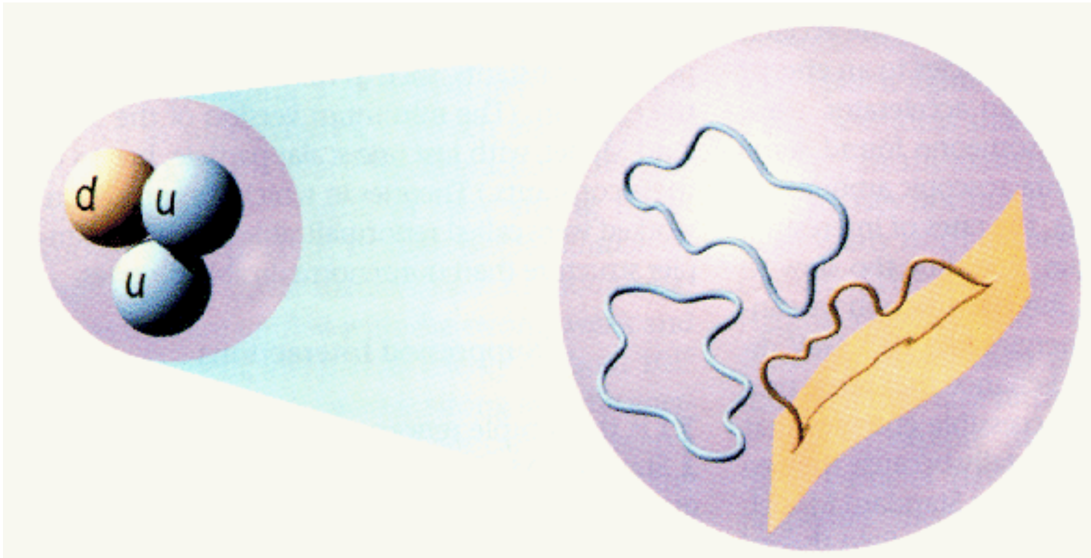
Now, we know what happened below $1/\sqrt{G_F} \sim 300$ GeV:

There was "**New physics**" (beyond Fermi's theory):

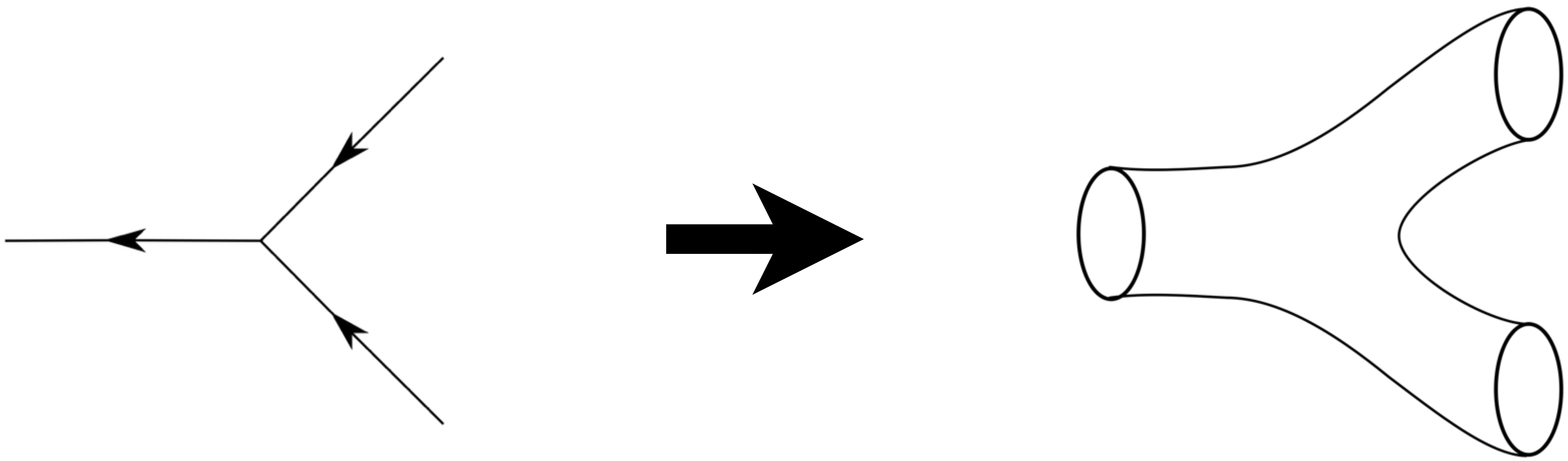
We discovered the W/Z particles, the SM!

What could we find around $M_P \sim 10^{19}$ GeV ?

A possibility (the only one?): **STRINGS**

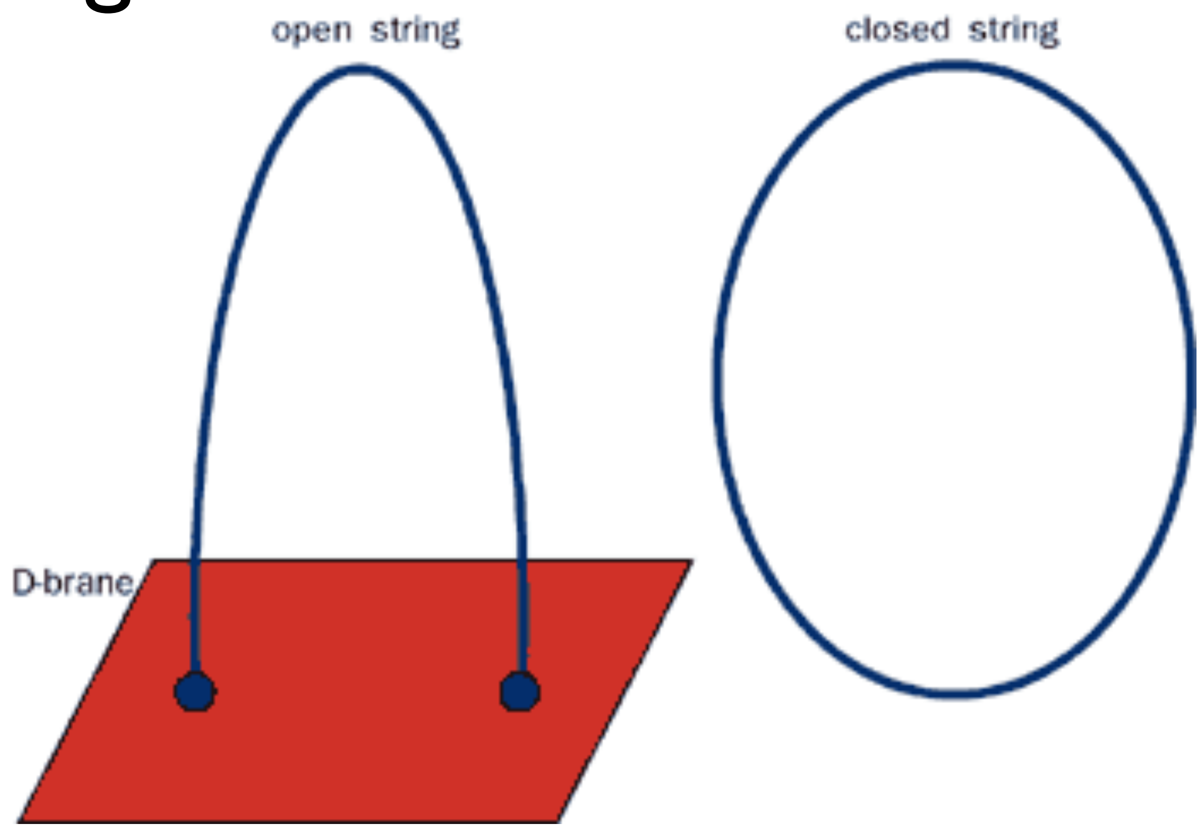


Particles are the lowest-energy modes of a string



The interactions are not anymore in a space-time point, but smears out over the string world-sheet

Two types of strings:



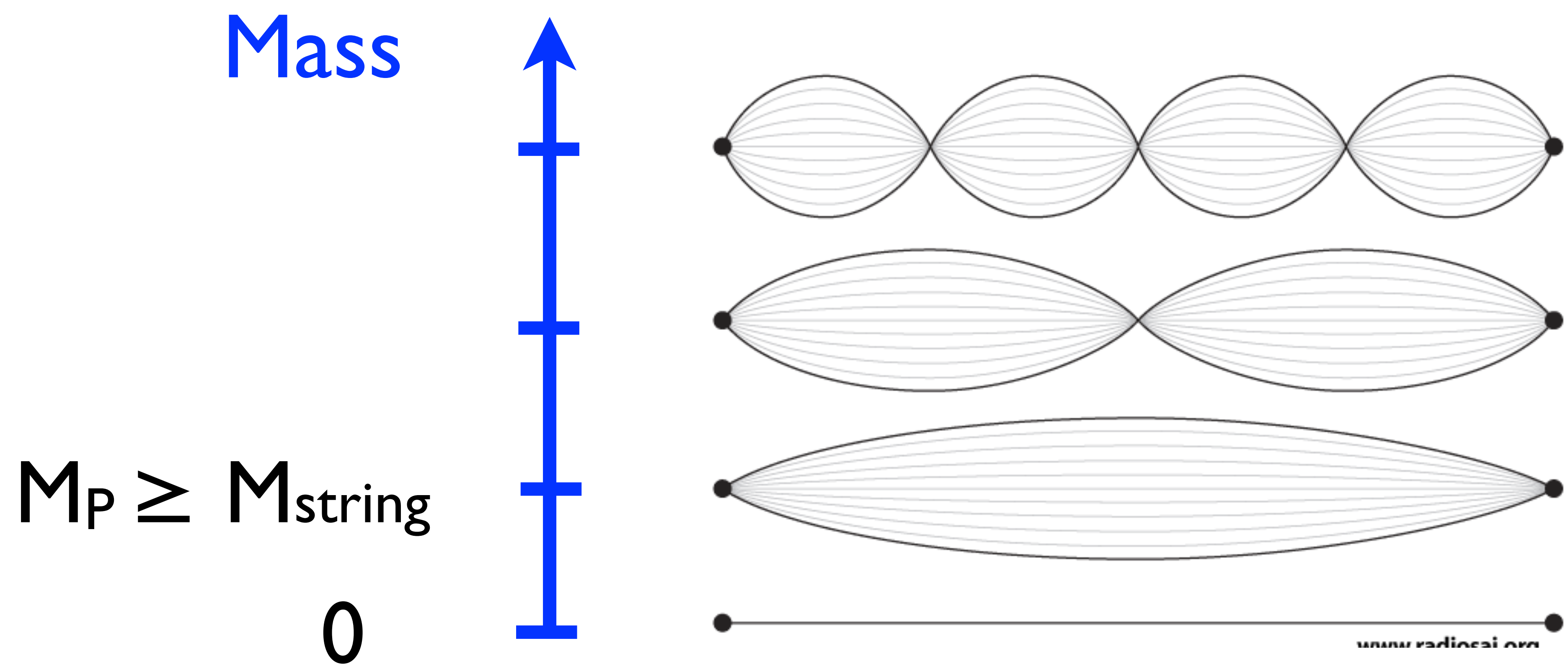
gravitons, gauge bosons and matter appear as massless excitations of the strings

➠ **theory of unification**

Generic Predictions:

1) The space must be 1+9 dimensional

2) There are string excitations of higher-energy:



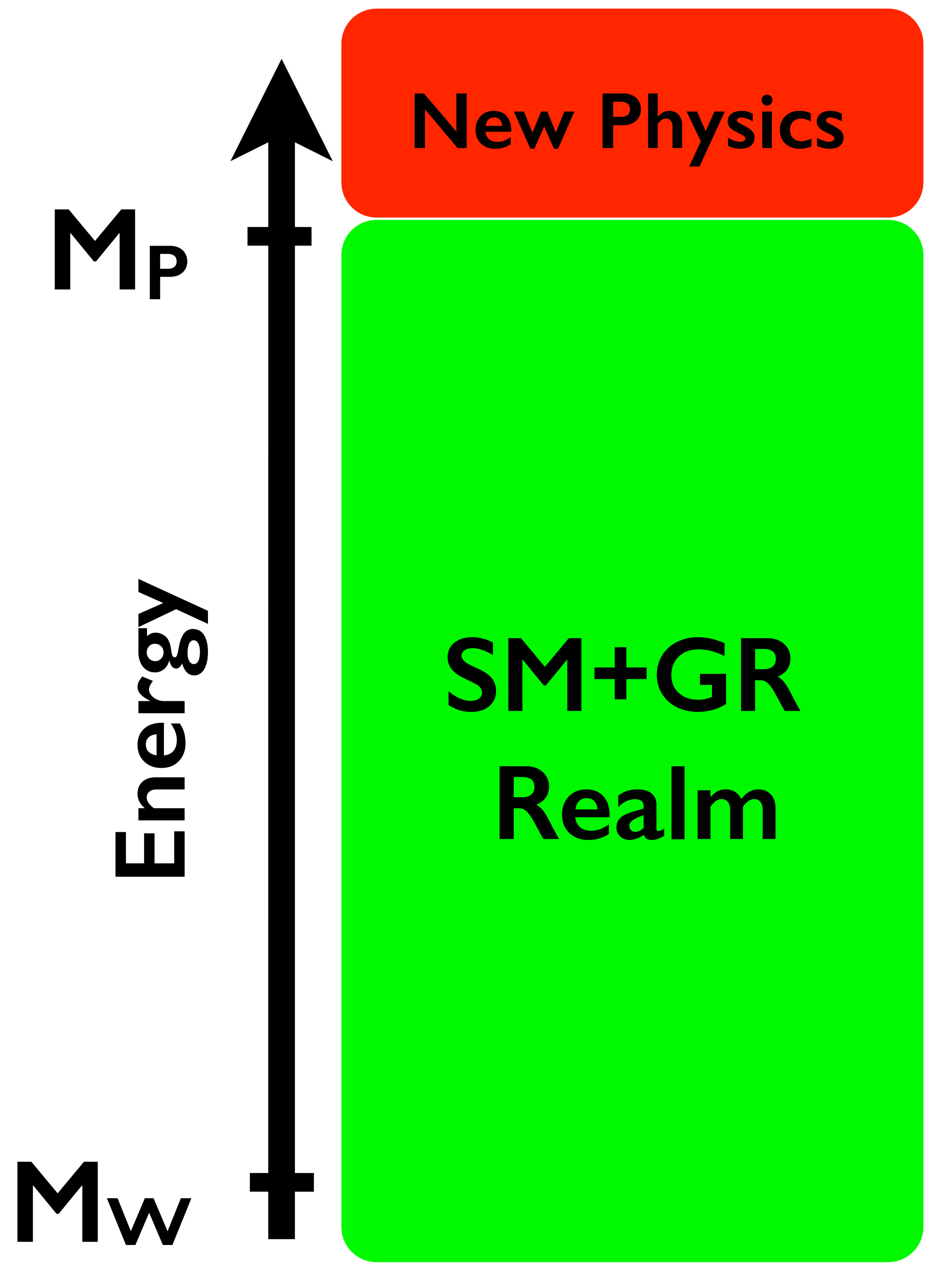
Expected very heavy to be detected at present colliders

Indirect effects? Virtual effects of the strings generate higher-dimensional operators for the SM

TH End of understanding at

$$\Lambda \sim M_P \sim 10^{19}\ \mathrm{GeV}$$

Most **conservative** approach:



SM = Effective field Theory below M_P

$$\mu^2 |H|^2$$

$\mu \sim m_W$

Dim O_i = 2

$$\mathcal{L}_{SM} = -\frac{1}{4g^2} F^{\mu\nu} F_{\mu\nu} + i\bar{f}_L \not{D} f_L + i\bar{f}_R \not{D} f_R$$
$$+ |D_\mu H|^2 - \lambda |H|^4 + Y_f \bar{f}_L H f_R + h.c$$

Dim O_i = 4

$$\frac{1}{\Lambda} H \bar{l}^c_L l_L H$$

$\Lambda \sim M_P$

Dim O_i = 5

$$\frac{c_1}{\Lambda^2} |H|^2 |D_\mu H|^2 + \frac{c_2}{\Lambda^2} (\bar{f}_L \gamma^u f_L)^2$$
$$+ \frac{c_3}{\Lambda^2} (D_\mu F^{\mu\nu})^2 + \cdots$$

Dim O_i = 6

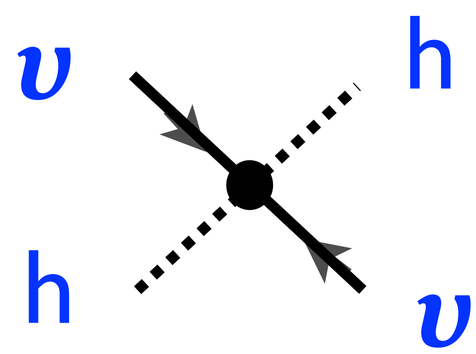
$\vdots$ $\vdots$

Important consequences:

Higher-dimensional operators do not preserve B & $L_{e,\mu,\tau}$

L violation:

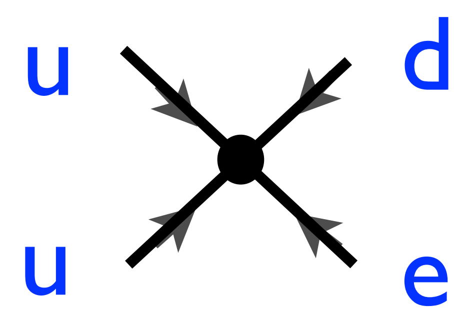
$$\frac{1}{\Lambda}\bar{l}^{c\,i}_{L} H_i\, H_j l^j_L$$



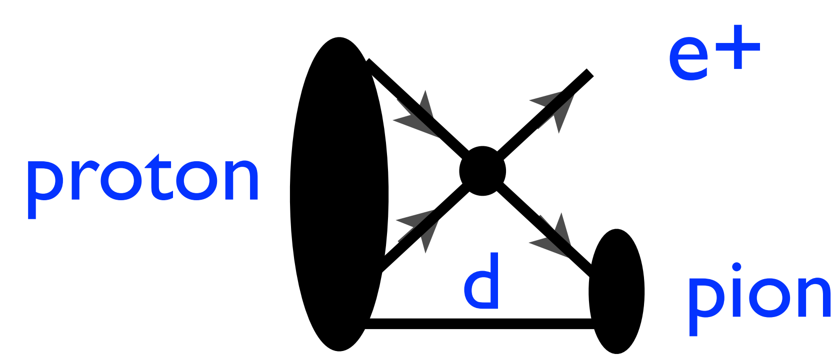
➥ **Neutrino masses**

B violation:

$$\frac{1}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\bar{Q}^{c\,i}_{L\alpha}\gamma^\mu u_{R\beta}][\bar{d}^c_{R\gamma}\gamma_\mu l_{L\,i}]$$



➥ **Proton decay:** $p \to \pi^0 e^+$



Exp. $\tau_p > 10^{34}$ years ➠ $\Lambda > 10^{15}$ GeV

EX

SM+GR

Can explain "almost" everything from the biggest to the smallest...

EX

Data unexplained by the SM

1) Neutrino masses

2) Dark matter

3) Cosmological Inflationary epoch

4) Matter/Antimatter asymmetry
in the universe

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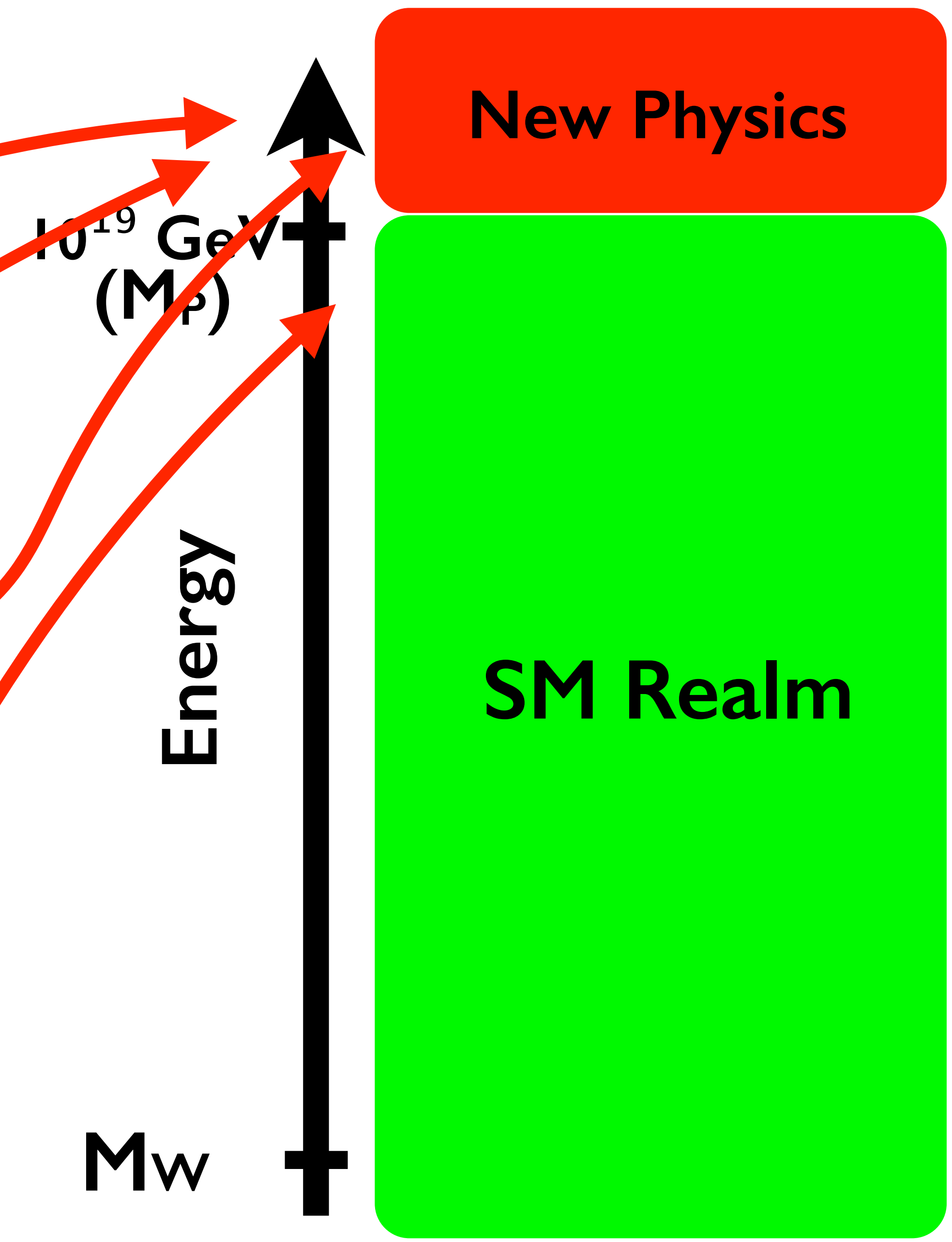


No clear idea where this **BSM** should show up!

It could well be related to new-physics near $\sim M_P$

If so, very difficult to detect this physics (only indirectly by astro/cosmo experiments)

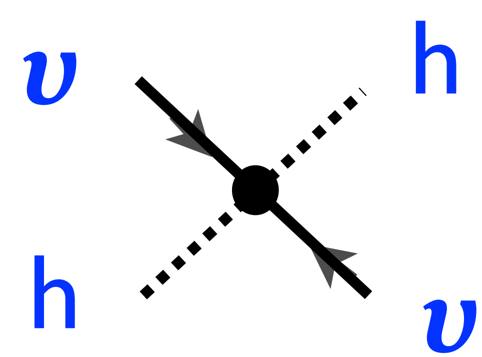
e.g. Neutrino Masses:

Mandatory as Lepton Number L <u>not</u> respected
by higher-dimensional operators

It was just an **accident** of the SM!

Leading one: Dimension-5 operators:

$$\frac{1}{\Lambda}\bar{l}_L^{c\,i} H_i\, H_j l_L^j$$



taking smallest value
from oscillations:
$\Delta m \sim m$

$$\hookrightarrow \quad m_\nu \sim \frac{v^2}{\Lambda} \sim 0.06\ \mathrm{eV}\left(\frac{10^{15}\mathrm{GeV}}{\Lambda}\right)$$

close (but below) M_P

But there are other important reason to go beyond the SM

Not building the theory anymore, but trying to understand the present one: The SM

Searching for a “natural” explanation of the SM parameters

Search for a "natural" explanation of SM coupling-constants and masses:

1) Cosmological constant: $\int \Lambda_{cosmo} \sqrt{g}\, d^4x$

$$\Lambda_{cosmo} \sim 10^{-47}\ \mathrm{GeV}^4 << M_P^4 \sim 10^{76}\ \mathrm{GeV}^4$$

2) Higgs mass term: $V(H) = -\mu^2|H|^2+\ldots$

$$\mu^2 \sim v^2 \sim 10^4\ \mathrm{GeV}^2 << M_P^2 \sim 10^{38}\ \mathrm{GeV}^2$$

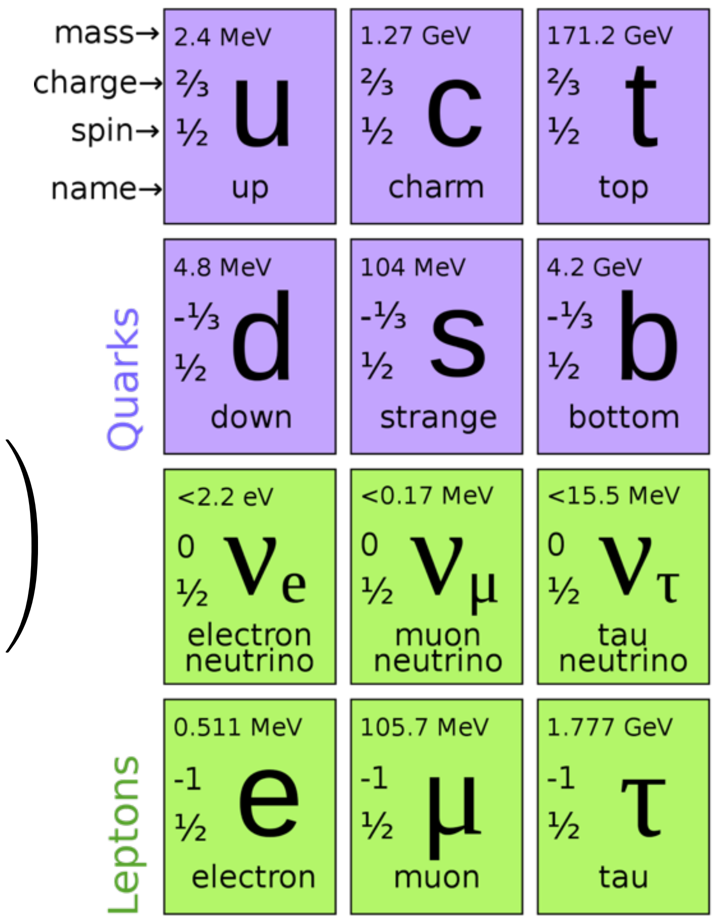
3) Charge quantization:

$$Q_e+Q_P < 10^{-21}$$

4) Strong CP problem: $\int \theta F\tilde{F}\, d^4x$

$$\theta < 10^{-13}$$

5) Fermion masses and mixing angles:



$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

6) Gauge couplings:

$g' \sim 0.35 \quad g \sim 0.65 \quad g_s \sim 1.12 \quad$ at $Q \sim M_Z$

7) Number of families:

$N_f = 3$

Search for a “natural” explanation

	Scale of New physics
Cosmological constant	?
Higgs potential	~ TeV
Charge quantization	~ 10^{15} GeV
Strong CP problem	~ 10^{12} GeV
Fermion masses/mixing angles	TeV - M_P
Gauge couplings	~ 10^{15} GeV
Number of families	?

Search for a “natural” explanation

To be discussed here

	Scale of New physics
Cosmological constant	?
Higgs potential	~ TeV
Charge quantization	~ 10^{15} GeV
Strong CP-problem	~ 10^{12} GeV
Fermion masses/mixing angles	TeV - M_P
Gauge couplings	~ 10^{15} GeV
Number of families	?

Grand Unified Theories

(GUT)

We want to explain:

$$|q_p + q_e|/e$$

See DYLLA 73 for a summary of experiments on the neutrality of matter.
See also "n CHARGE" in the neutron Listings.

VALUE	*DOCUMENT ID*		*COMMENT*
$<1.0 \times 10^{-21}$	[8] DYLLA	73	Neutrality of SF_6
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<3.2 \times 10^{-20}$	[9] SENGUPTA	00	binary pulsar
$<0.8 \times 10^{-21}$	MARINELLI	84	Magnetic levitation

[8] Assumes that $q_n = q_p + q_e$.

[9] SENGUPTA 00 uses the difference between the observed rate of of rotational energy loss by the binary pulsar PSR B1913+16 and the rate predicted by general relativity to set this limit. See the paper for assumptions.

➥ suggest that the charge is quantized: $Q_p = - Q_e$

$Q = Y/2 + T_3$ $\quad$ u_R, d_R, Q_L, e_L, e_R: $\quad Y = (4/3, -2/3, 1/3, -1, -2)$

$$Q = Y/2 + T_3$$

Quantized since it comes from a non-abelian group SU(2)

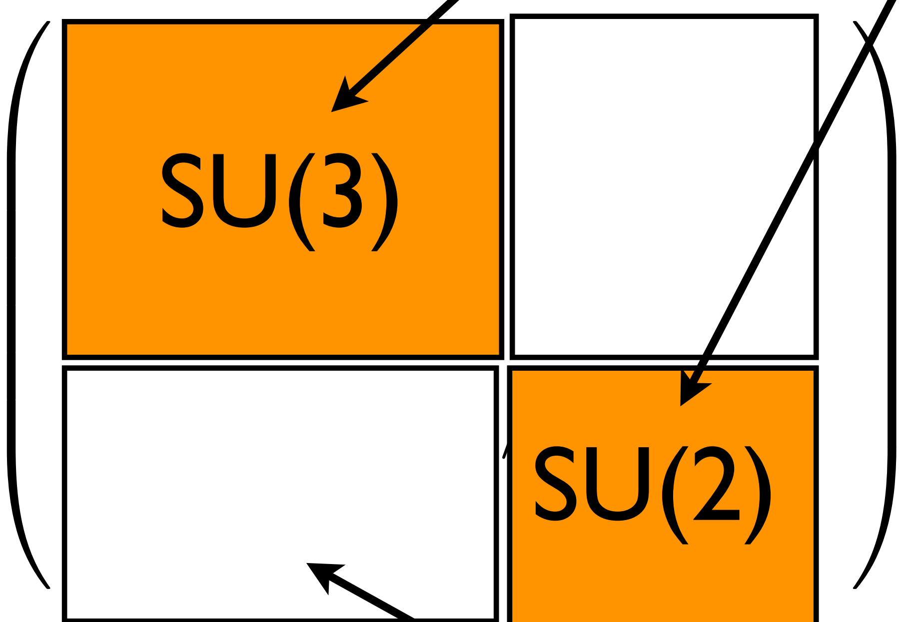
The U(1) hypercharges will be quantized if it is embedded in a **non-abelian group:**

Minimal case: SU(4)xSU(2)xSU(2) Pati-Salam 74

Simple group: SU(5) Glashow,Georgi 74

SU(5) model

Embedding : $SU(3) \times SU(2) \times U(1) \subset SU(5)$



$$\begin{pmatrix} e^{i\theta\frac{2}{3}} & & & & \\ & e^{i\theta\frac{2}{3}} & & & \\ & & e^{i\theta\frac{2}{3}} & & \\ & & & e^{-i\theta} & \\ & & & & e^{-i\theta} \end{pmatrix}$$

➥ Quantized!

Extra gauge bosons X,Y associated to the new generators: 24-8-3-1=12 fields

Complex fields of SM charges = (3, 2, -5/3)

Not seen → must be massive: mass = M_{GUT}

Matter embedding: 15 fields $\subset$ $\bar{\mathbf{5}}+\mathbf{10}$

$\mathbf{10}=(\mathbf{5}\mathrm{x}\mathbf{5})_{\text{Antisymmetric}}$

$$\bar{5} = \begin{pmatrix} {d^c}_1 \\ {d^c}_2 \\ {d^c}_3 \\ e^- \\ -\nu_e \end{pmatrix} \qquad 10 = \begin{pmatrix} 0 & {u^c}_3 & -{u^c}_2 & -u_1 & -d_1 \\ & 0 & {u^c}_1 & -u_2 & -d_2 \\ & & 0 & -u_3 & -d_3 \\ & & & 0 & -e^c \\ & & & & 0 \end{pmatrix}$$

Fit like a glove!

Not the same simplicity for the Higgs

(Doublet-triplet splitting problem)

The GUT-gauge symmetry must be broken (not seen in nature the X,Y bosons):

$$SU(5) \rightarrow SU(3)\times SU(2)\times U(1)$$

Extra "Higgs" in **24** getting VEV

Give mass only to X,Y bosons: $M_{X,Y} = M_{GUT}$

SU(5) predictions:

1) Charge quantization

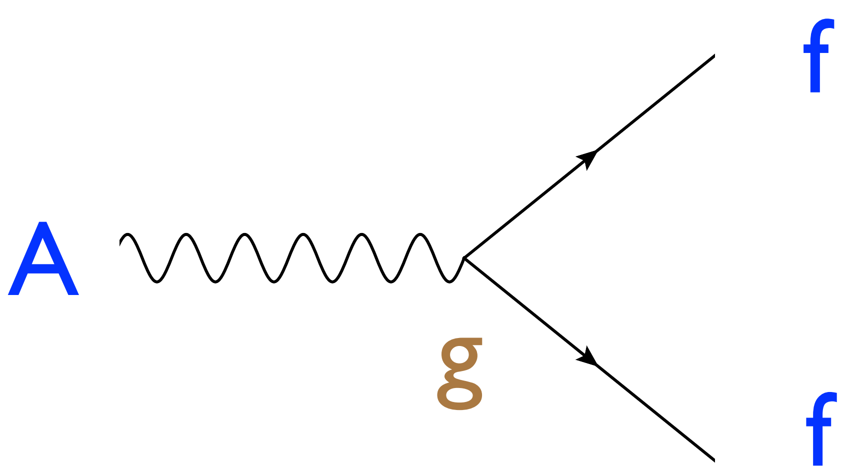
2) Gauge-coupling unification

3) Proton decay

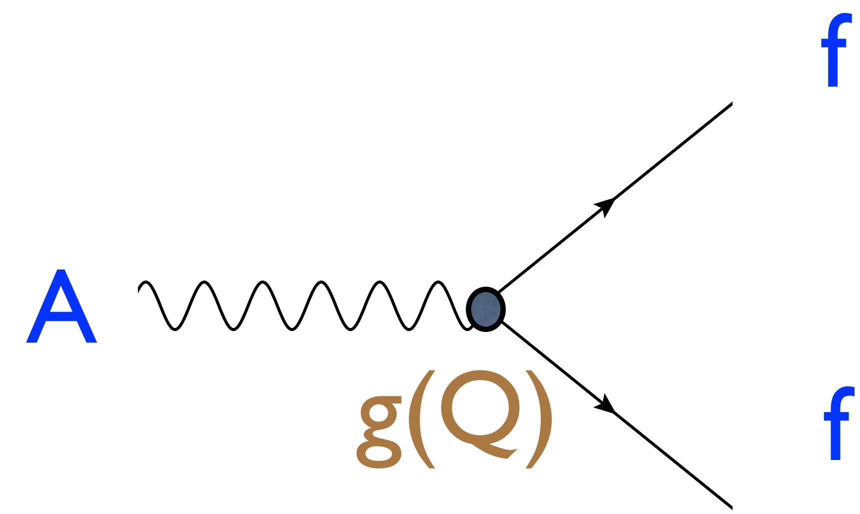
2) Gauge-coupling unification:

$$g_5 = g_s = g = \sqrt{5/3}\, g' \quad \text{at} \quad Q \geq M_{GUT}$$

What are the values of the SM gauge-couplings at high-energies?



+ loops ~

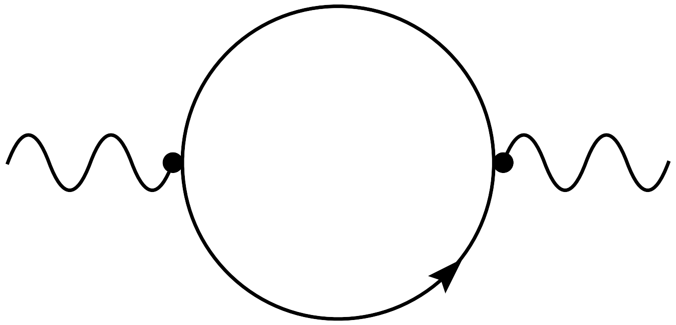


g dependence with Q
dictated by the SM spectrum
➥ can be calculated

RG Equations: $$\frac{dg_i^{-2}}{d\ln Q} = -\frac{b_i}{8\pi^2}$$

$$g_1 = \sqrt{5/3}\, g'$$
$$g_2 = g$$
$$g_3 = g_s$$

b-coefficients depend on the particle spectrum

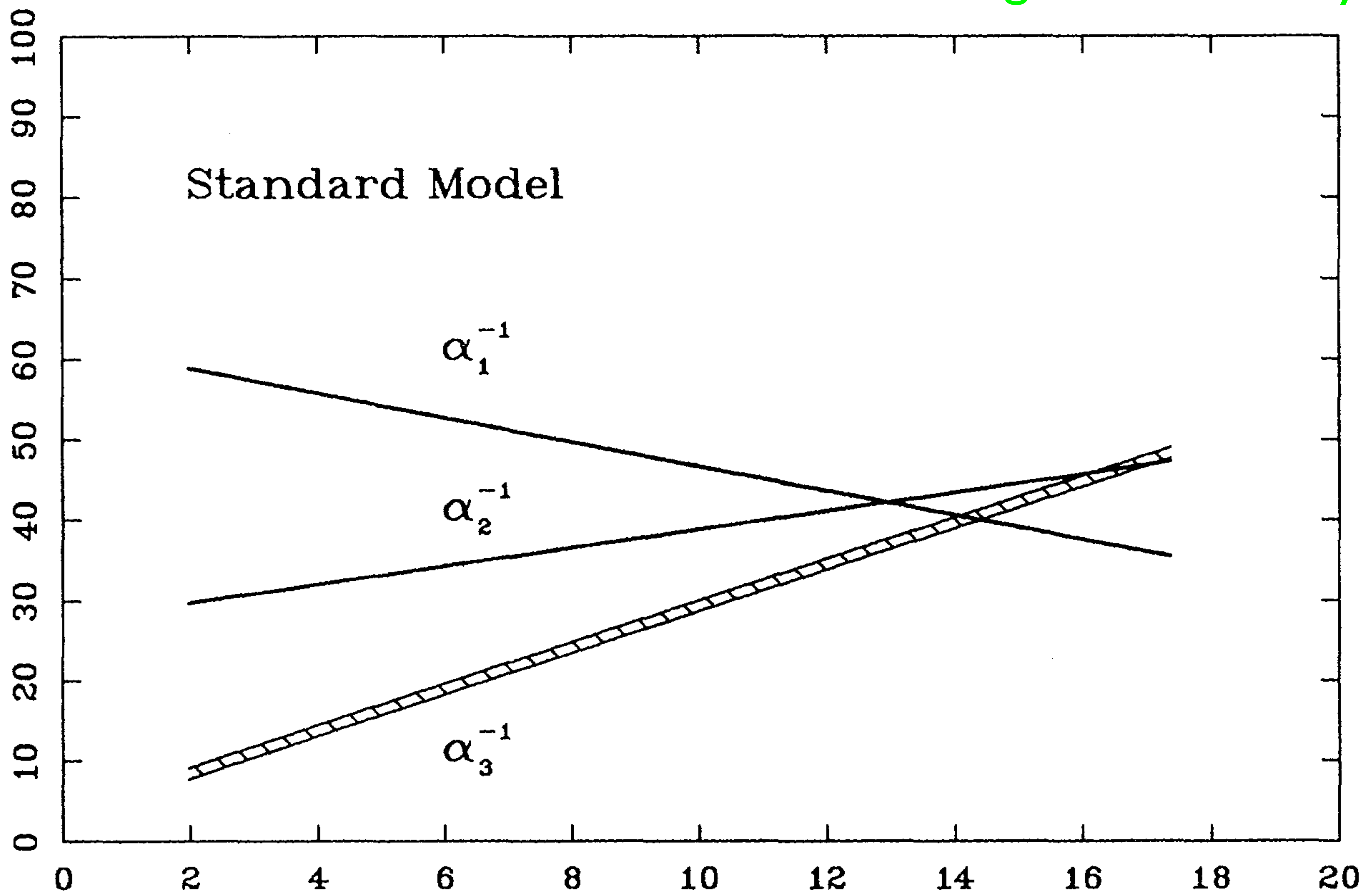


	SM	MSSM
b_i	$\begin{pmatrix} \frac{41}{10} \\ -\frac{19}{6} \\ -7 \end{pmatrix}$	$\begin{pmatrix} \frac{66}{10} \\ 1 \\ -3 \end{pmatrix}$

$$g_1 = \sqrt{5/3}\, g'$$
$$g_2 = g$$
$$g_3 = g_s$$

$$\alpha_i = \frac{g_i^2}{4\pi}$$

Langacker, Polonsky 93

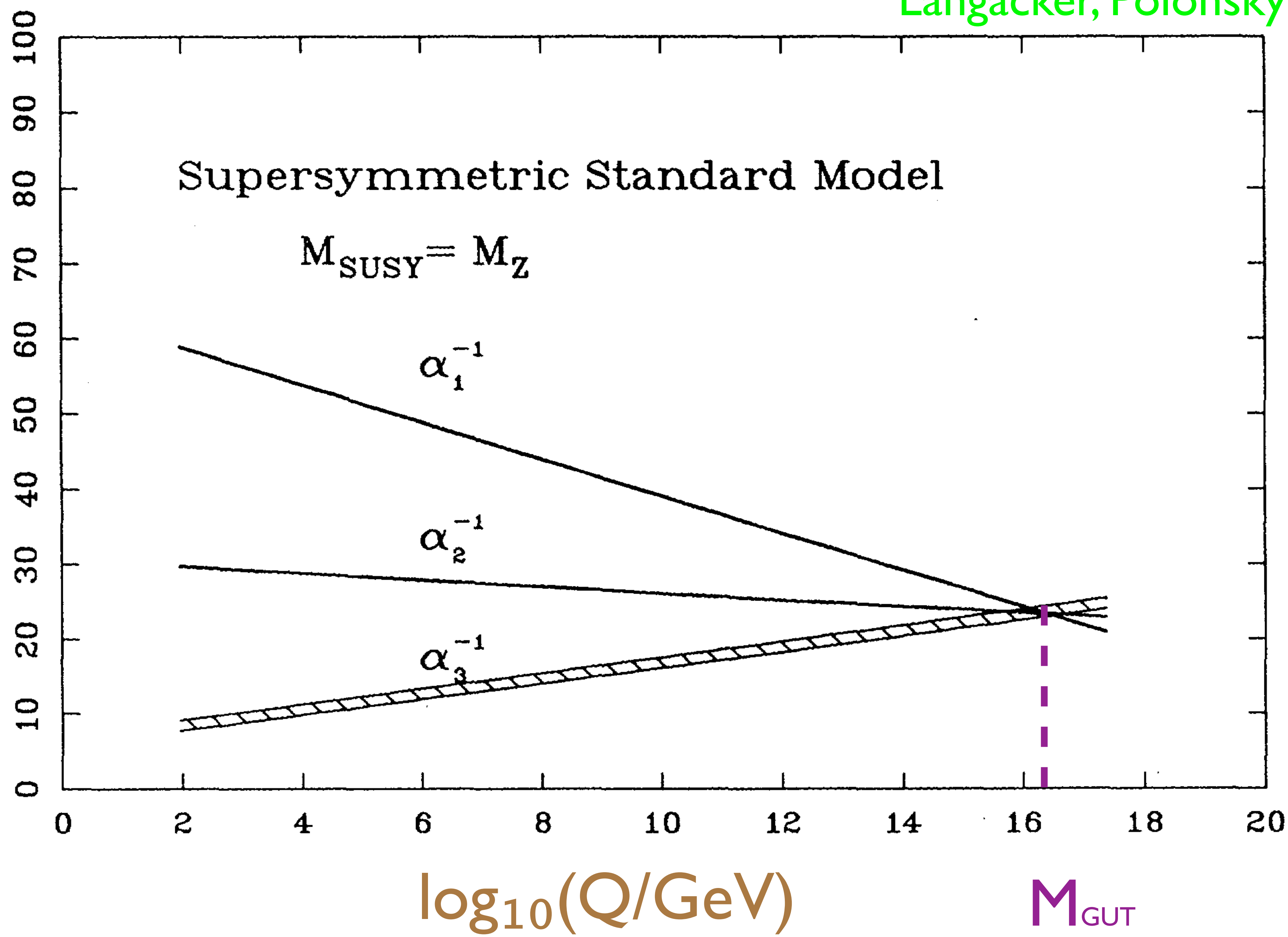


$\log_{10}(Q/\mathrm{GeV})$

SM+SUSY partners (to be discussed later):

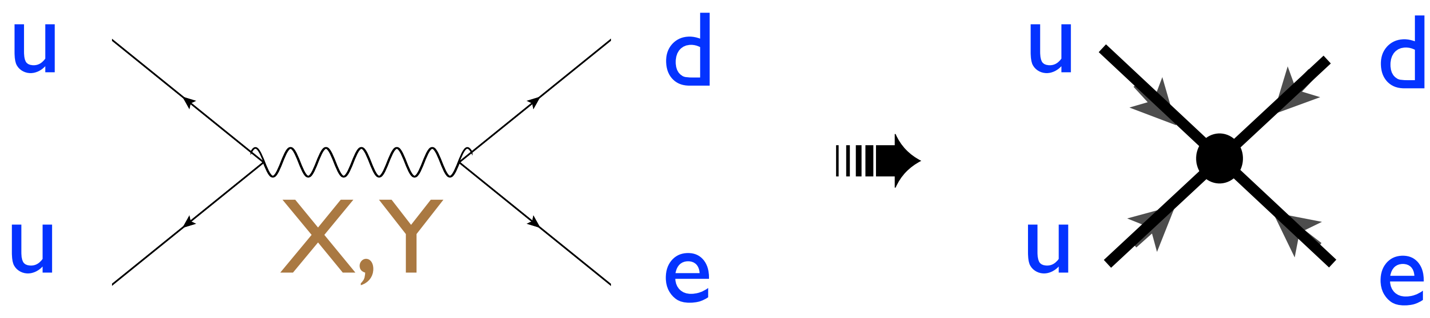
Langacker, Polonsky 93

$$\alpha_i = \frac{g_i^2}{4\pi}$$



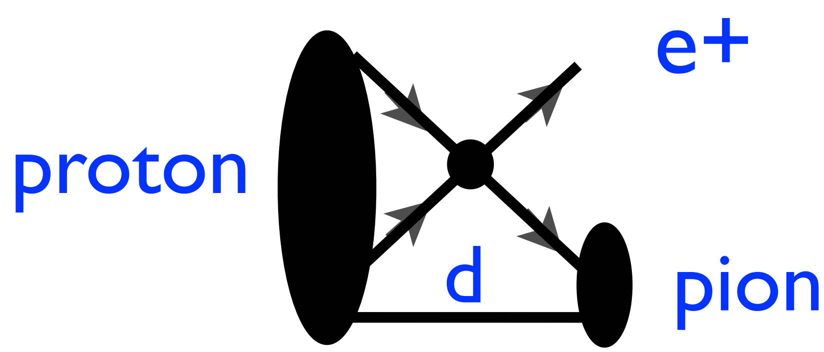
Too good to be true?

3) Proton decay:



where $\Lambda \sim M_{GUT}$

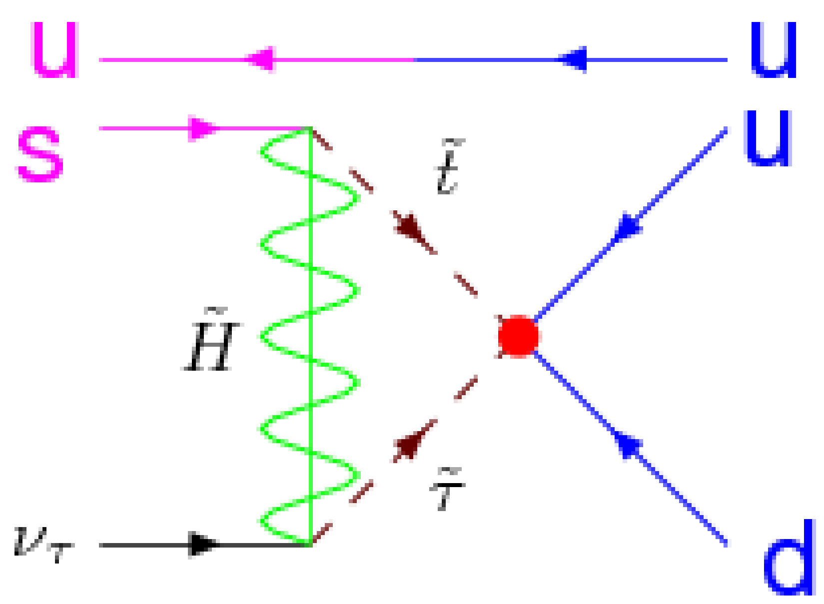
Leads to $\mathbf{p \rightarrow \pi^0 e^+}$:



The absence of observing the proton decaying gives a lower-bound on M_{GUT}

In supersymmetric GUT there are other decay modes more important:

$$p \rightarrow K^{+} + \bar{\nu}_{\tau}$$

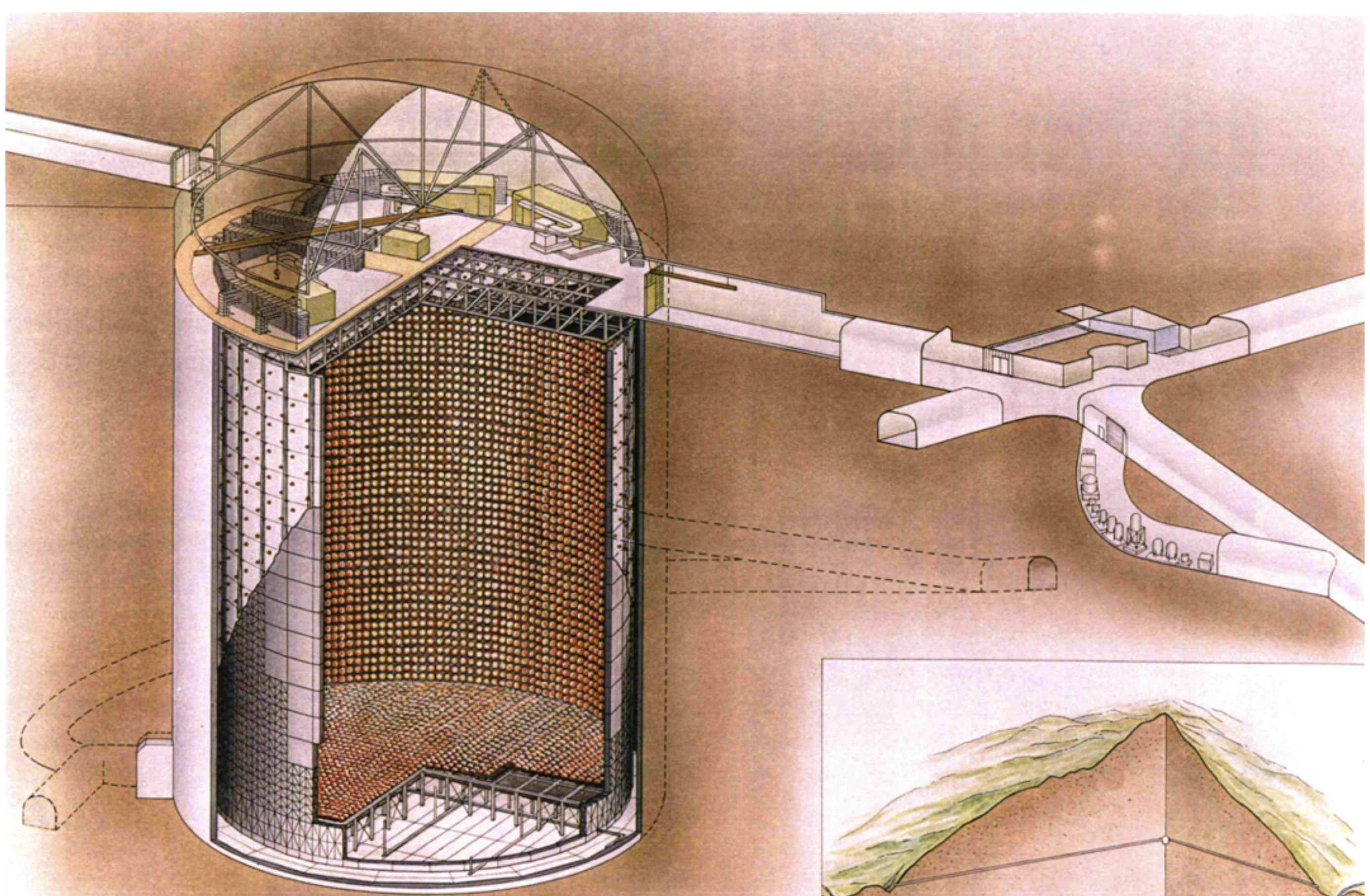


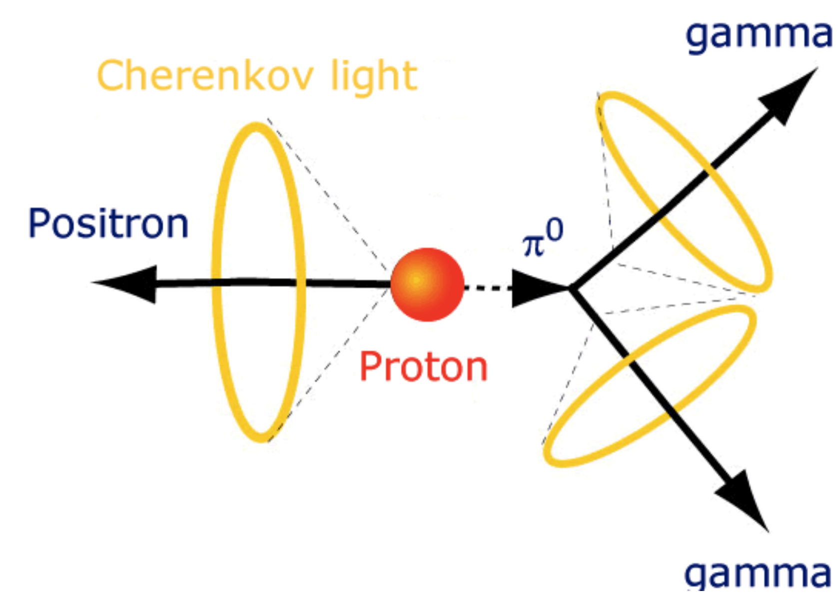
arXiv:hep-ph/0608183

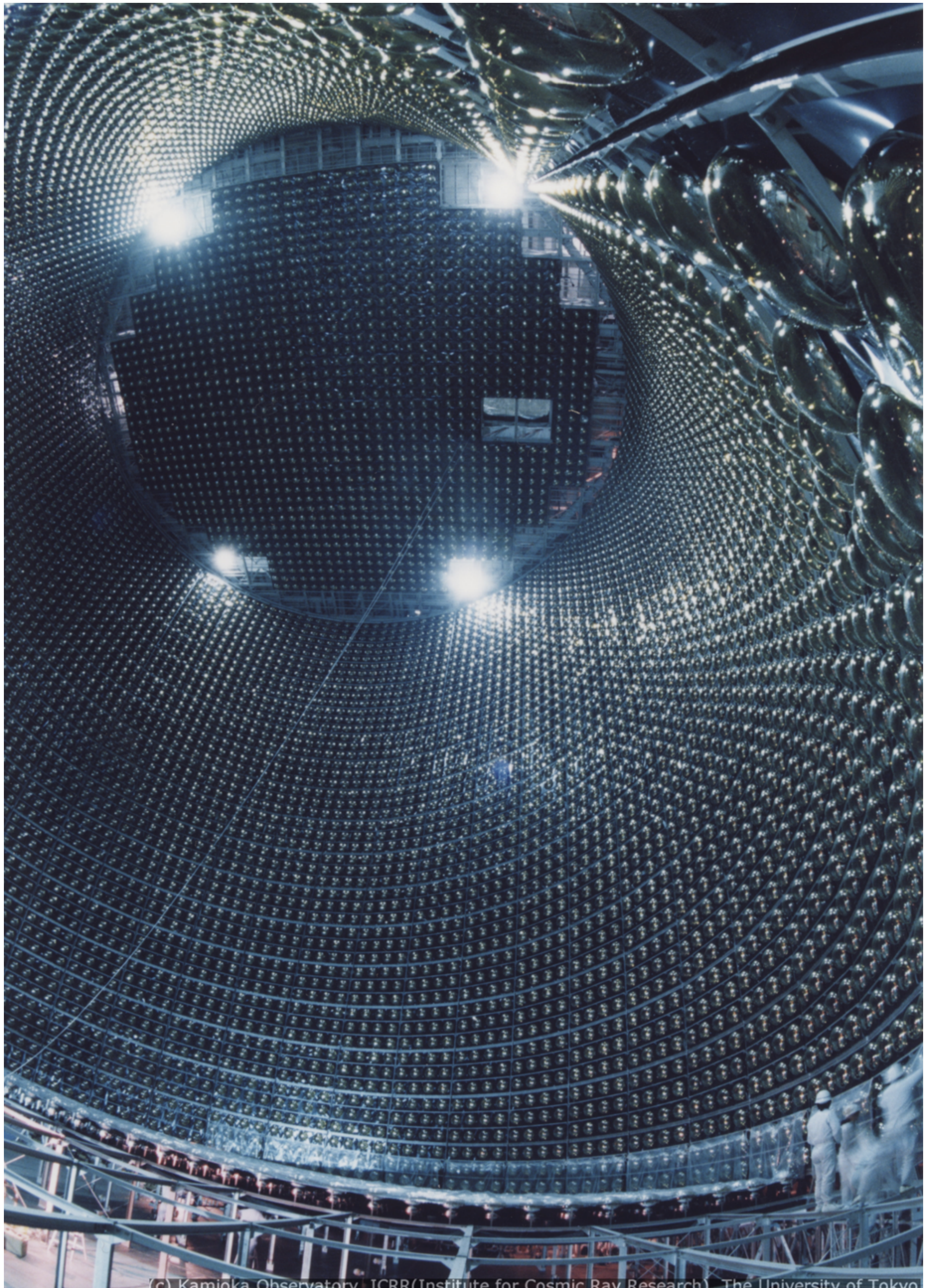
Search for proton decay

The Super-Kamiokande detector

- Stainless-steel tank
- 39m diameter and 42m tall
- Filled with 50,000 tons of ultra pure water.
- About 13,000 photo-multipliers on the tank wall
- At 1000 meter underground in the Kamioka-mine, Hida-city, Gifu, Japan.







Present experimental limits:

$\tau_p(p \to \pi^0 e^+) > 10^{34}$ years

➡ $\boxed{M_{GUT} > 3 \text{x} 10^{15}\ \text{GeV}}$

$\tau_p(p \to K^+ \upsilon) > 2.3\ 10^{33}$ years

Already ruling out some SU(5) models

Other GUT's beauties:

- Bottom-tau unification: **$M_b = M_\tau$** at $Q \geq M_{GUT}$

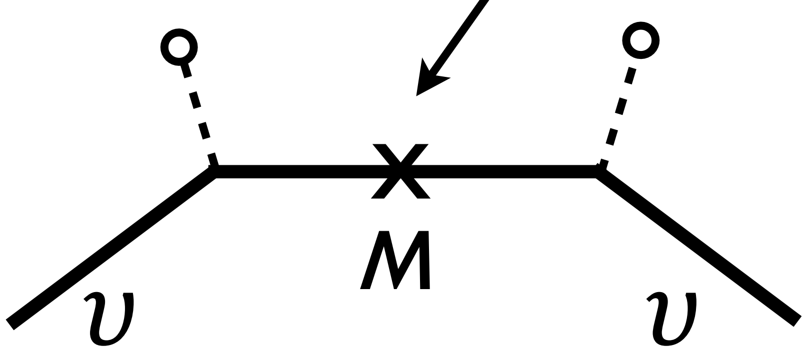
  works reasonably well in the Supersymmetric SM

  ...but don't work for other fermions

- **SO(10)** model: Matter **16=$\bar{5}$+10+1**

left-handed neutrino

right-handed neutrino

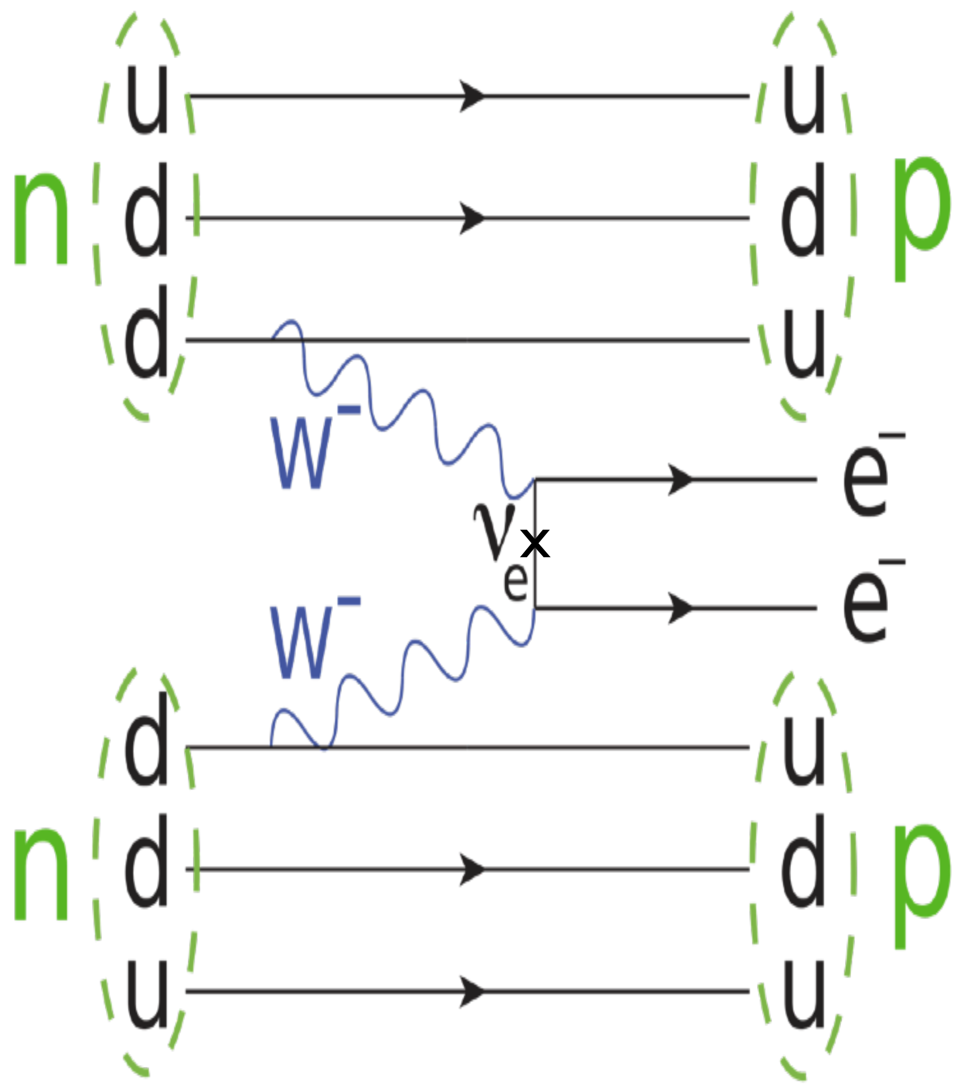


$$m_\nu \sim \frac{v^2}{M}$$

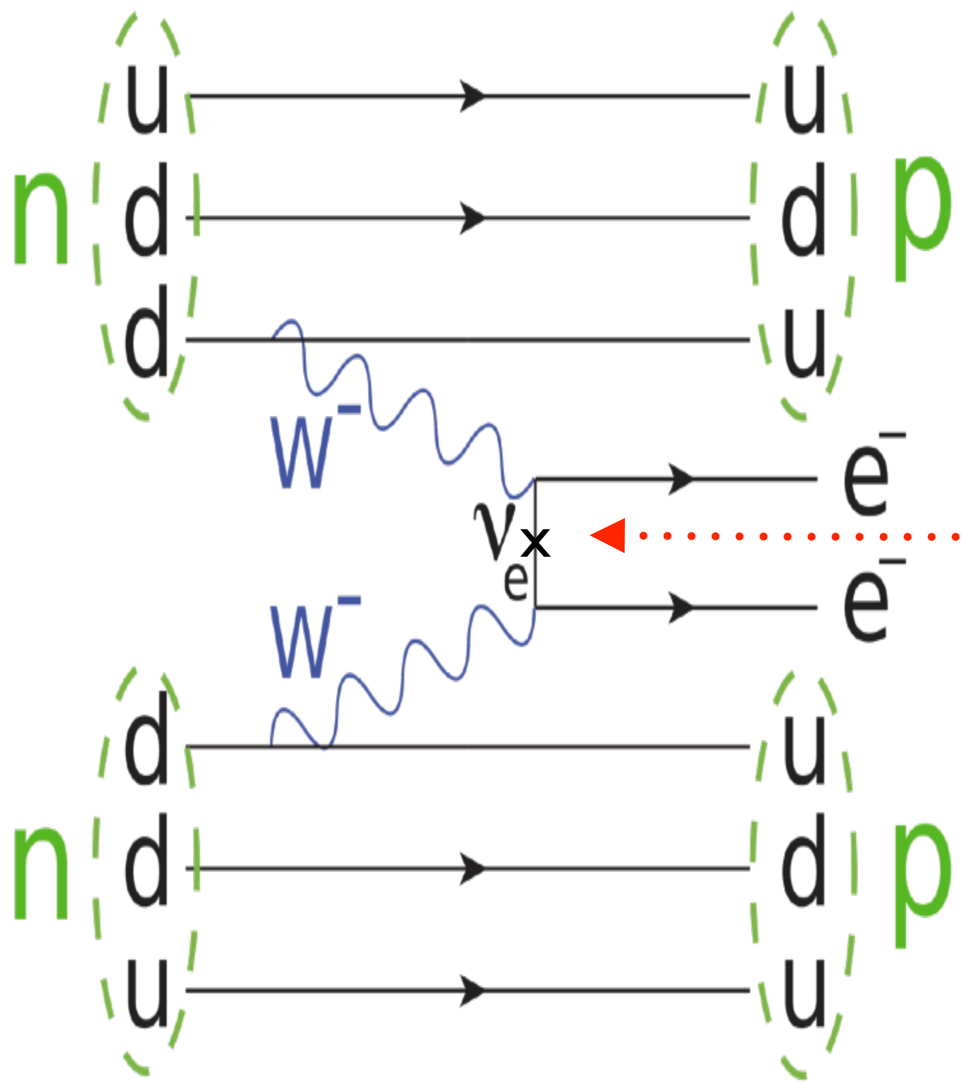
see-saw mechanism for neutrino masses

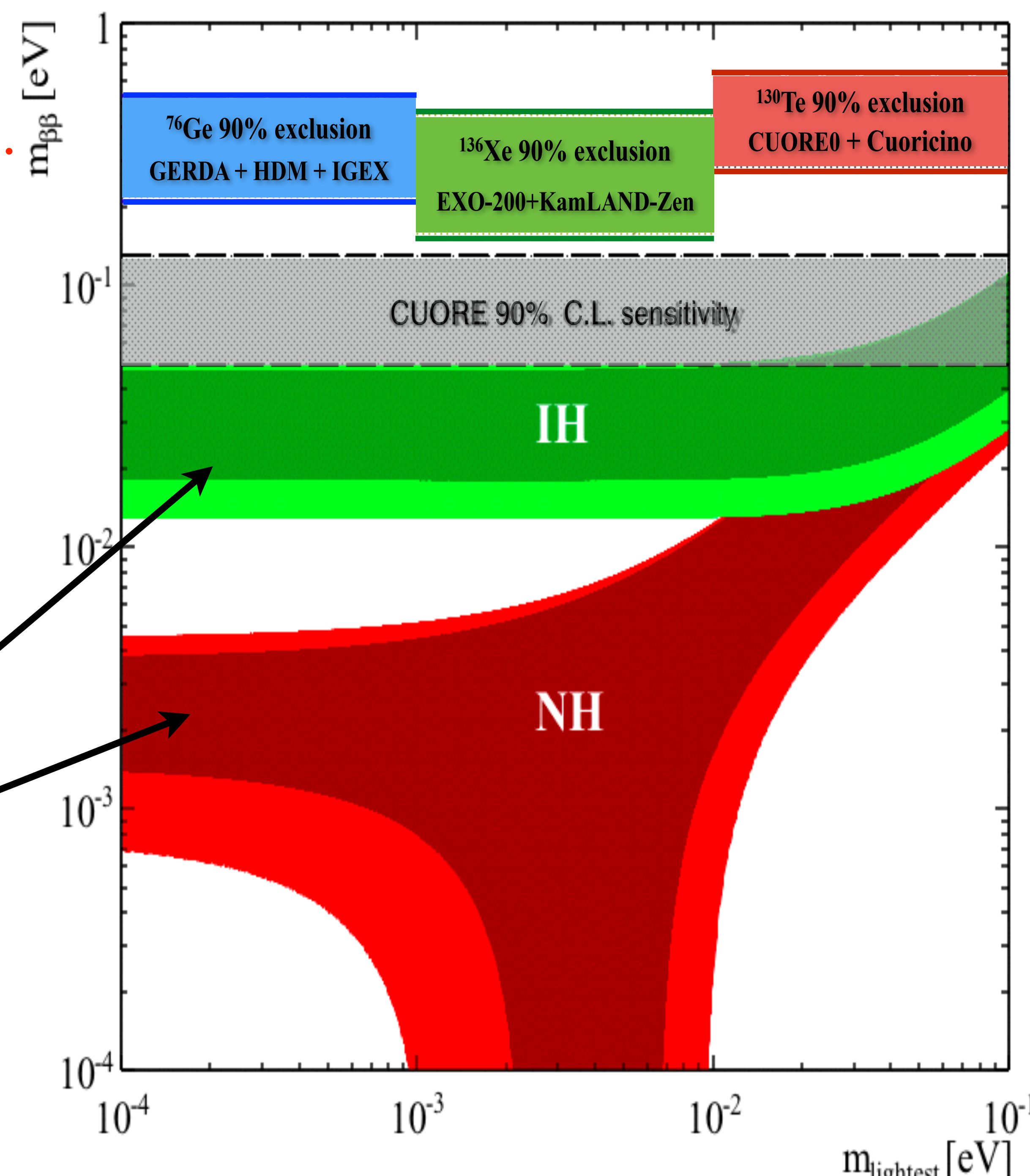
Implications: Majorana masses for neutrino

➠ Neutrinoless Double Beta Decay:



Implications: Majorana masses for neutrino
➠ Neutrinoless Double Beta Decay:





expected values

The strong CP Problem

Dimension-four operator allowed in QCD:

$$\theta \frac{g_s^2}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu} \cdot G_{\rho\sigma}$$

(by a phase rotation of the quarks, it can be removed (due to anomalies) and put into the quark masses.
The only physical parameter is

$$\theta + \mathrm{Arg\,Det}\ M_q$$
)

Violates CP and induce a large EDM for the neutron.
Experimental limits give:

$d_n < 2.9 \cdot 10^{-26}\, e\, cm$ ☛ $\theta \lesssim 10^{-10}$ **Why this parameter is so small in the SM?**

This is the strong CP Problem

Are we getting more symmetries in the SM if $\theta \to 0$?

CP?

No, as CP is also violated by the CKM phase (~O(1))

Peccei-Quinn axion

Promote θ to a scalar-field a(x) ≡ **axion:**

$$a(x)\frac{g_s^2}{32\pi^2 f_a}\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}\cdot G_{\rho\sigma} \qquad + \text{ kinetic term}$$

$$\Big\downarrow$$

The value of θ is now dynamical:

Determined by minimizing the energy

One finds: $\boxed{\theta=0}$

Simple argument to see
that the energy minimizes for θ=0

$$
\begin{aligned}
e^{-V_4 E(\theta)} &= \int \delta[\phi] e^{-S_0 + i\theta Q} \\
&= \left| \int \delta[\phi] e^{-S_0 + i\theta Q} \right| \\
&\leq \int \delta[\phi] \left| e^{-S_0 + i\theta Q} \right| \\
&= e^{-V_4 E(0)}
\end{aligned}
$$

Vafa Witten '84

Villadoro

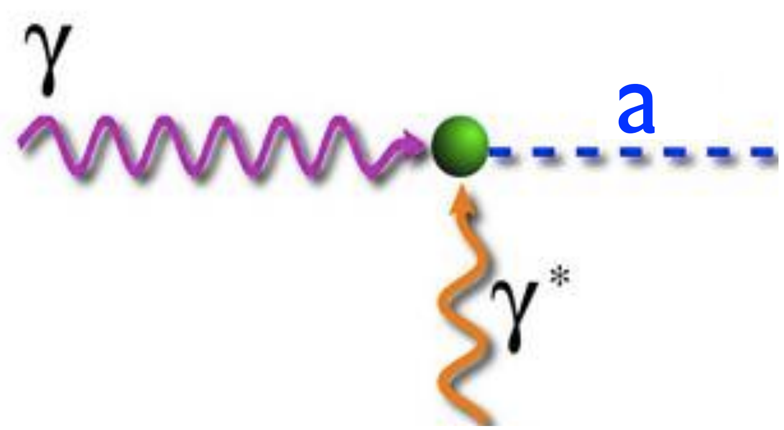
$$a(x)\frac{g_s^2}{32\pi^2 f_a}\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}\cdot G_{\rho\sigma} \longrightarrow m_a = \frac{f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u+m_d}m_\pi$$

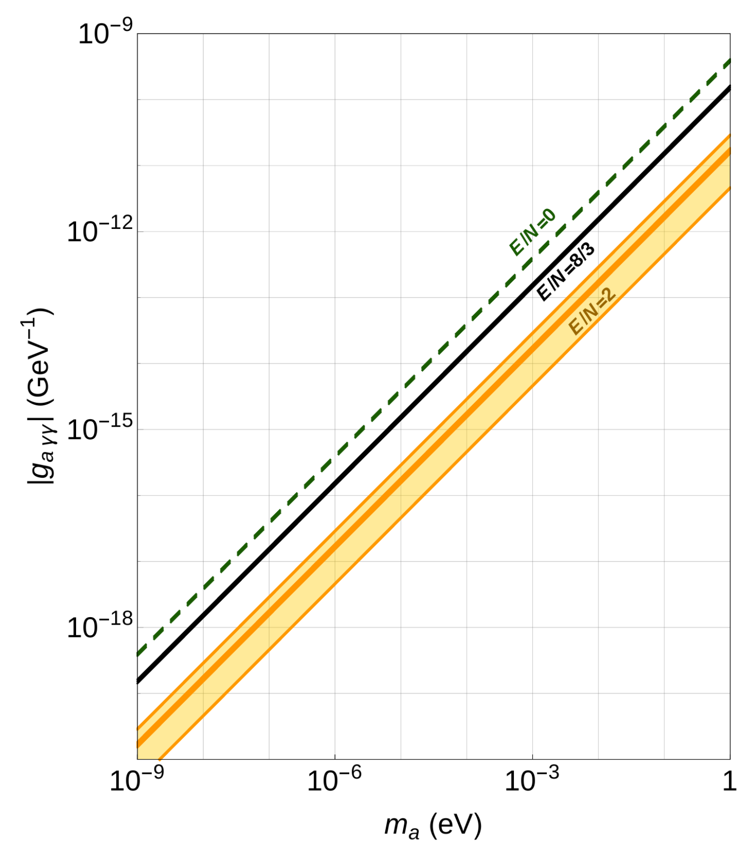
Coupling to photon

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left\{\frac{E}{N} - \frac{2}{3}\frac{4m_d+m_u}{m_d+m_u}\right\}$$

model-dependent term

by mixing with the pion

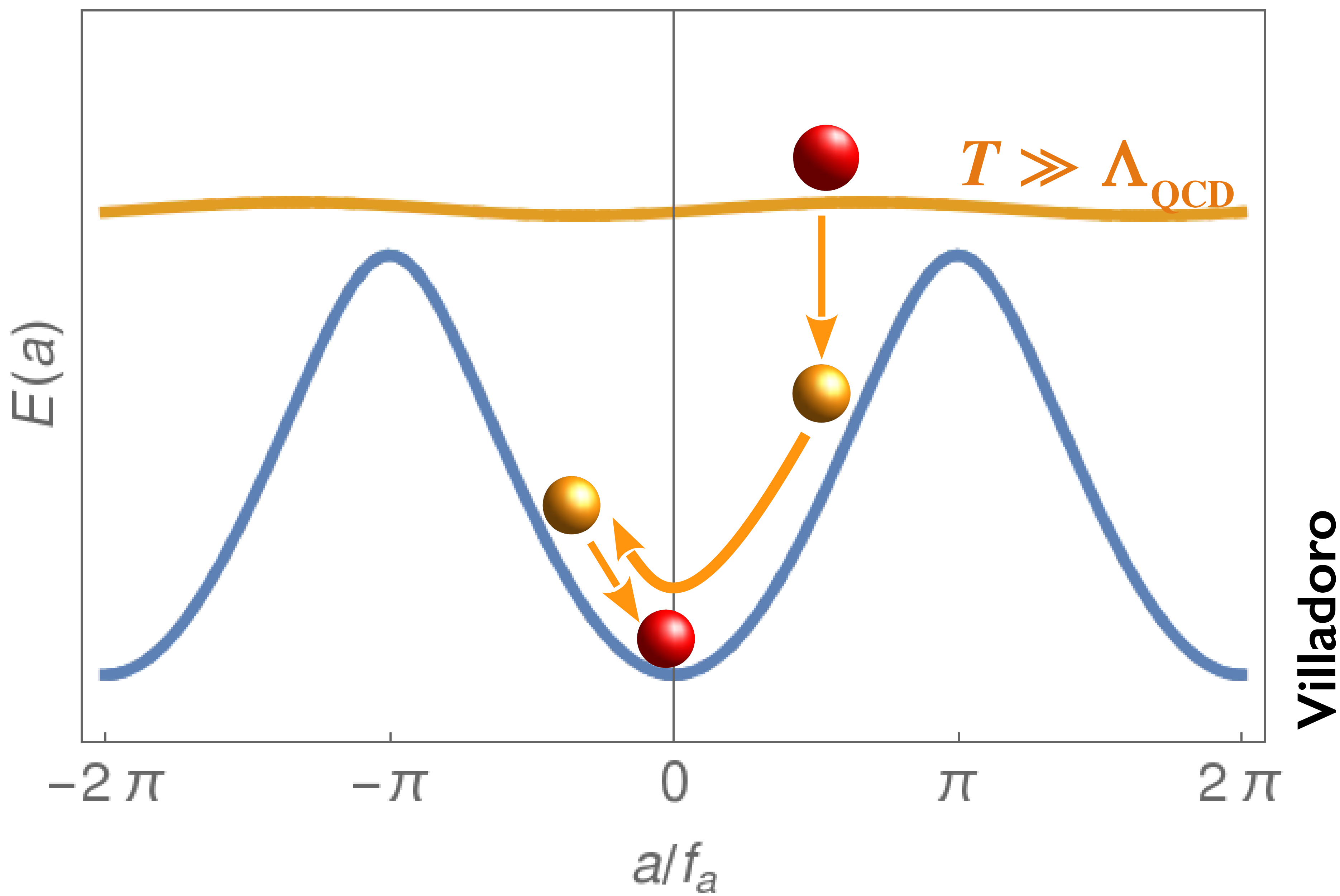




Villadoro

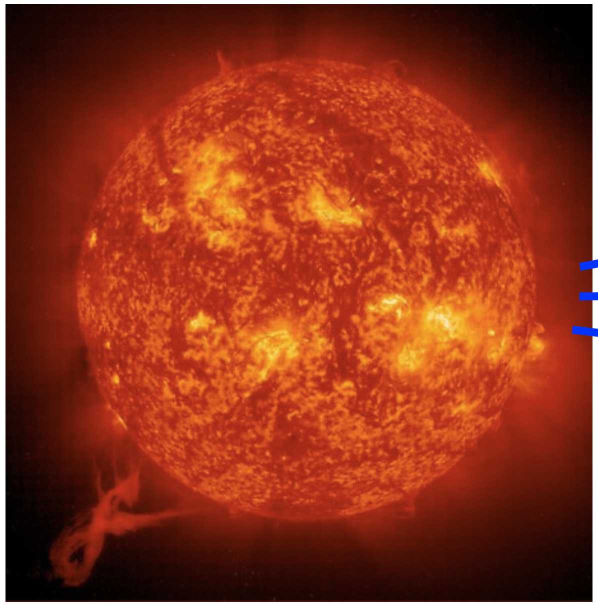
the larger f_a,
the smaller its coupling to SM states,
and the smaller its mass

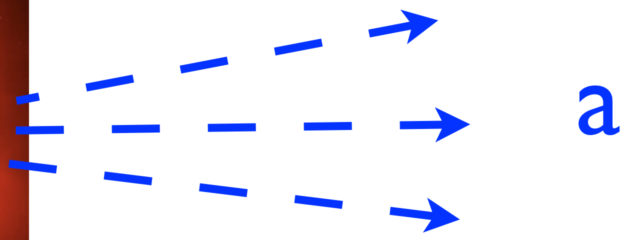
the QCD axion: *as dark matter*



Energy store in oscillations around the minimum
Looks like cold dark matter

Strong constraints from limits on energy looses in stars, SN,...



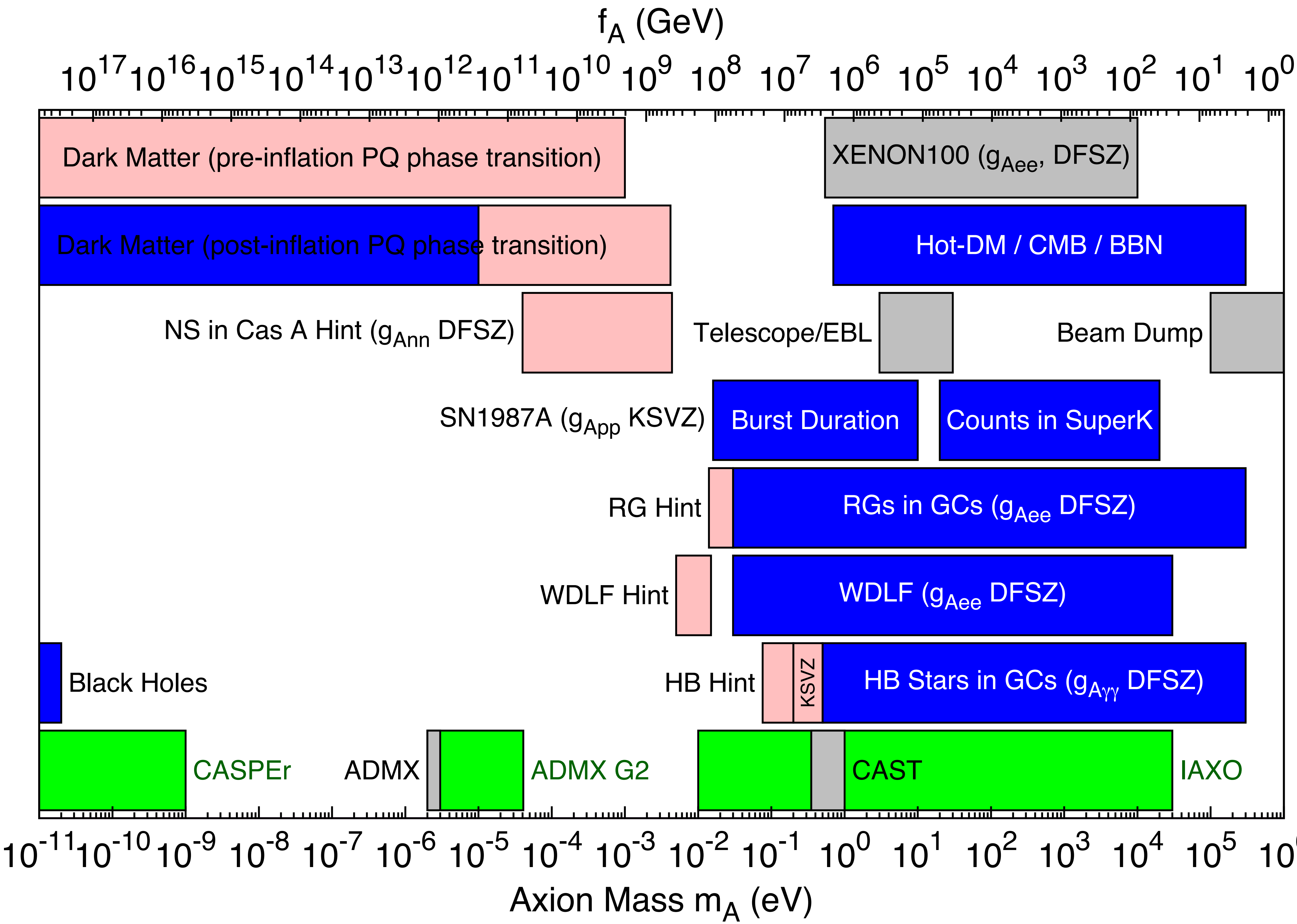


If a exists,
the sun will loose energy
by emitting it

Excluded regions:

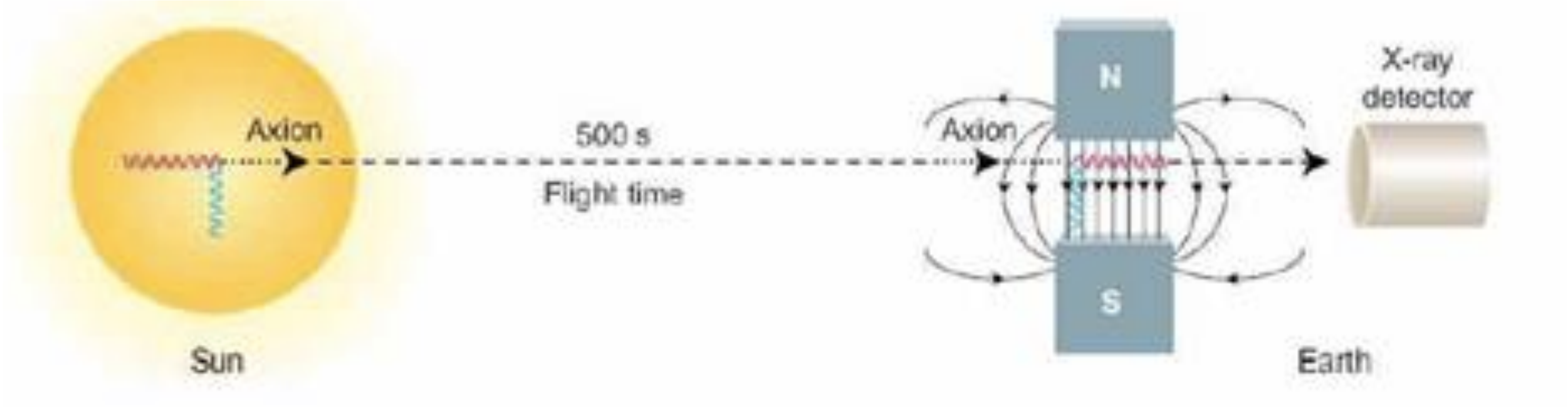
(slightly model dependent)

decoupling limit



CAST (IAXO) Experiment

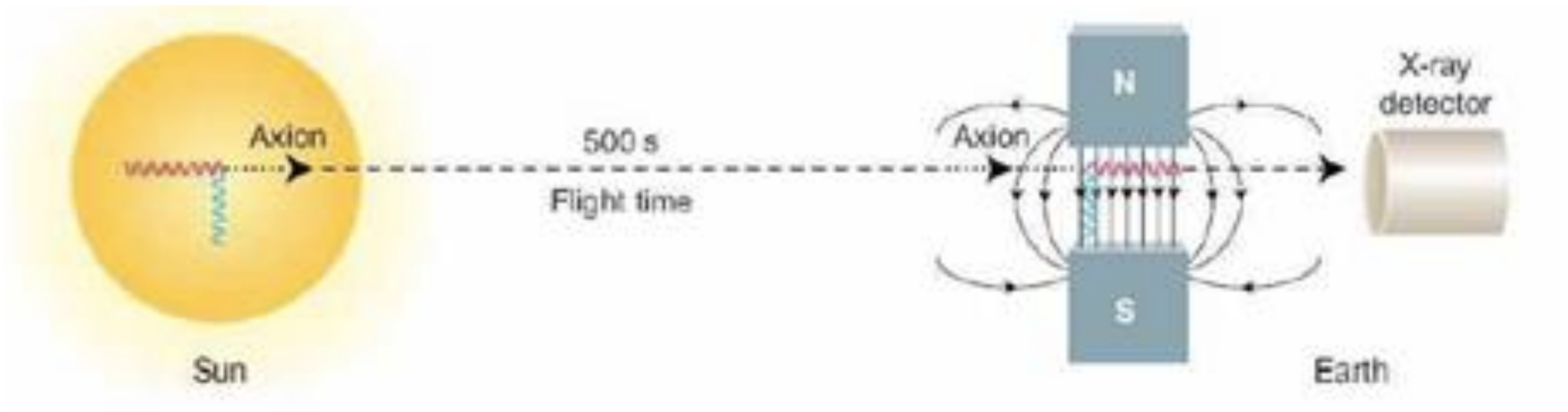
Detecting axions coming from the sun



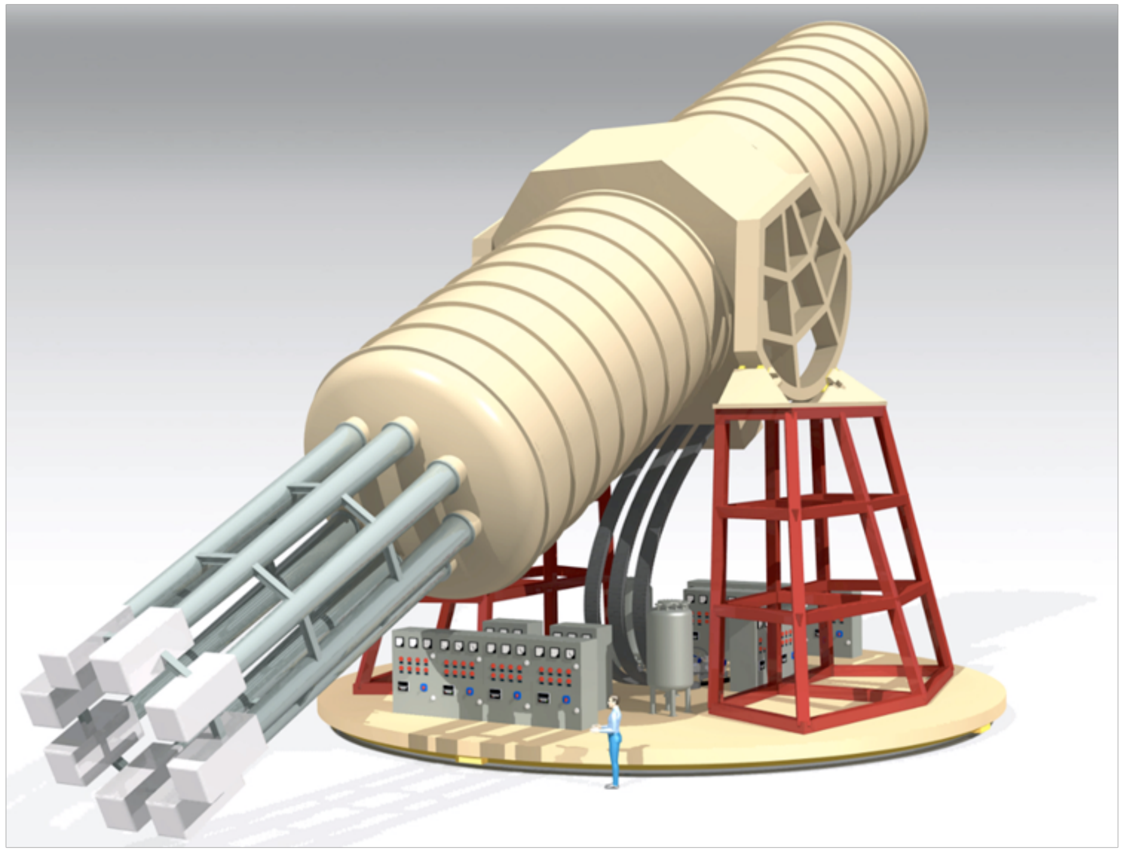
CAST

CAST (IAXO) Experiment

Detecting axions coming from the sun

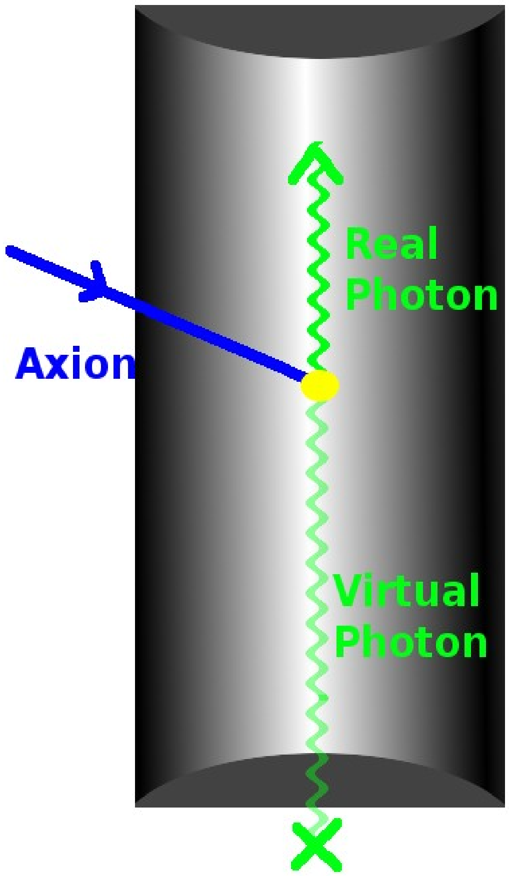


Future:
IAXO



ADMX Experiment

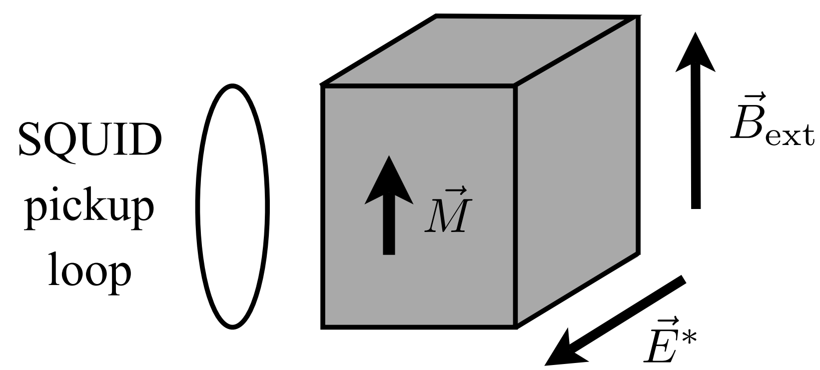
If axions are DM:



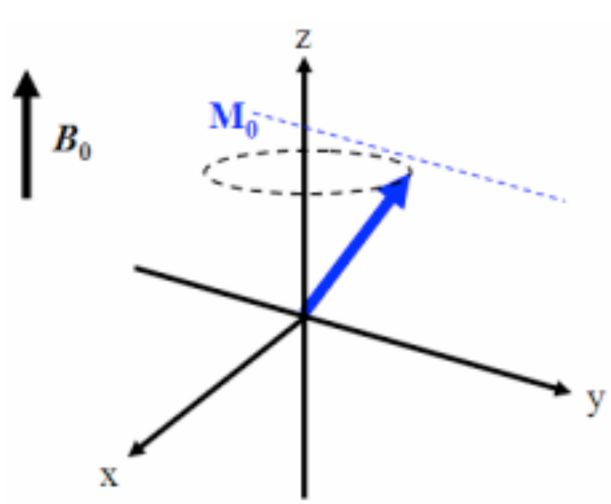
- Halo axions enter cavity
- Axions scatter off B field
- Resonantly convert to microwave photons
- Excess photons observed above thermal noise

Cosmic Axion Spin Precession Experiment (CASPEr)

- Oscillating DM axion induces an oscillating nuclear EDM
- This produces a precession of the nuclear spin in a nucleon spin polarized sample in a E-field



- Transverse magnetization can be searched by magnetic resonance



$$M(t) \approx np\mu E^* \epsilon_S d_n \frac{\sin\left[\left(\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}\right) t\right]}{\frac{2\mu B_{\text{ext}} - m_a c^2}{\hbar}} \sin\left(2\mu B_{\text{ext}} t\right)$$

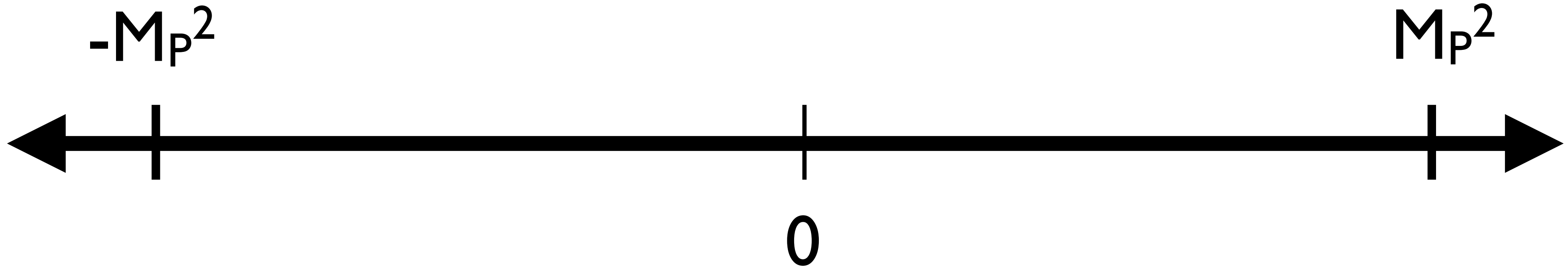
The hierarchy problem

(On the origin of the Higgs potential)

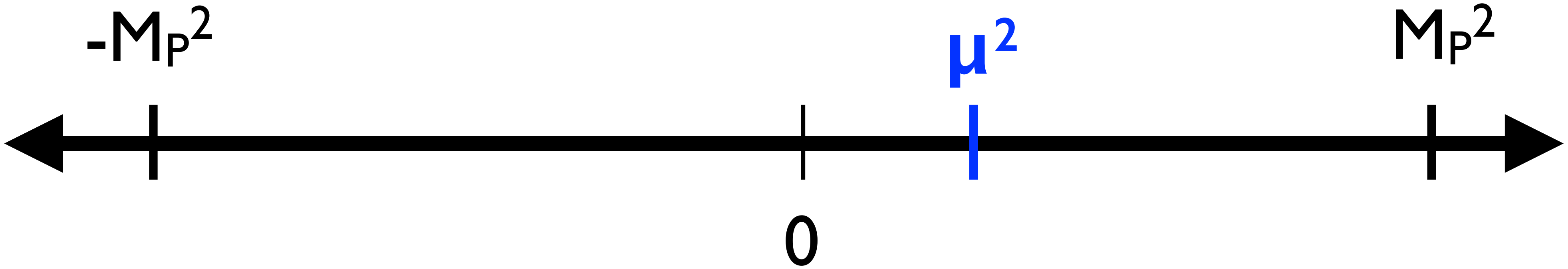
$$V(h) = -\frac{1}{2}\boxed{\mu^2}h^2 + \frac{1}{4}\lambda h^4$$

The only dimension-full parameter of the SM

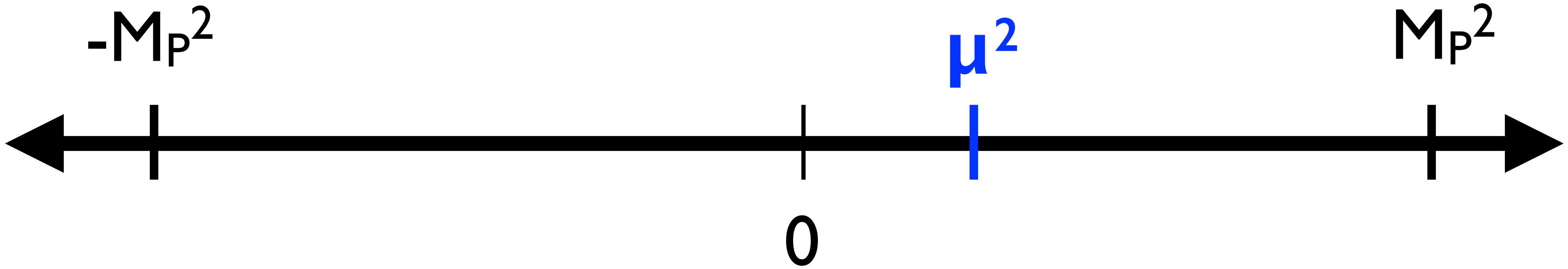
Where would you expect the Higgs mass (μ^2) to be?



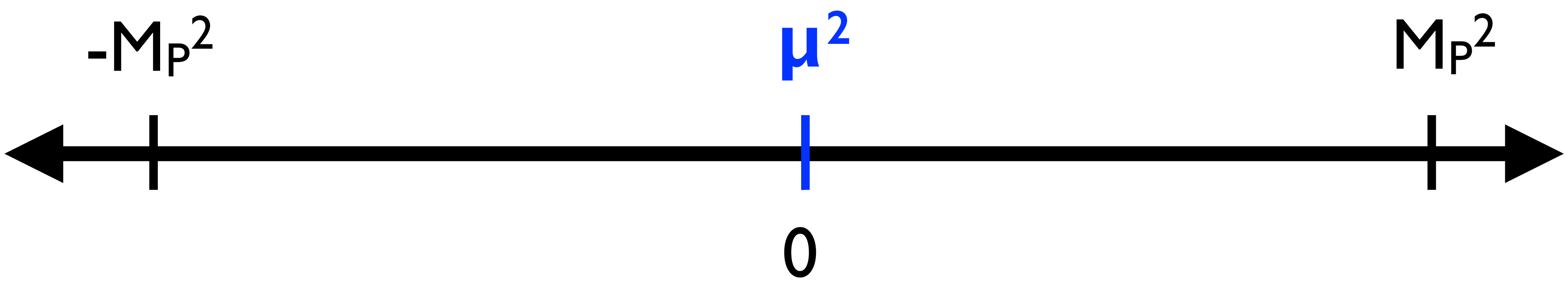
Where would you expect the Higgs mass (μ^2) to be?



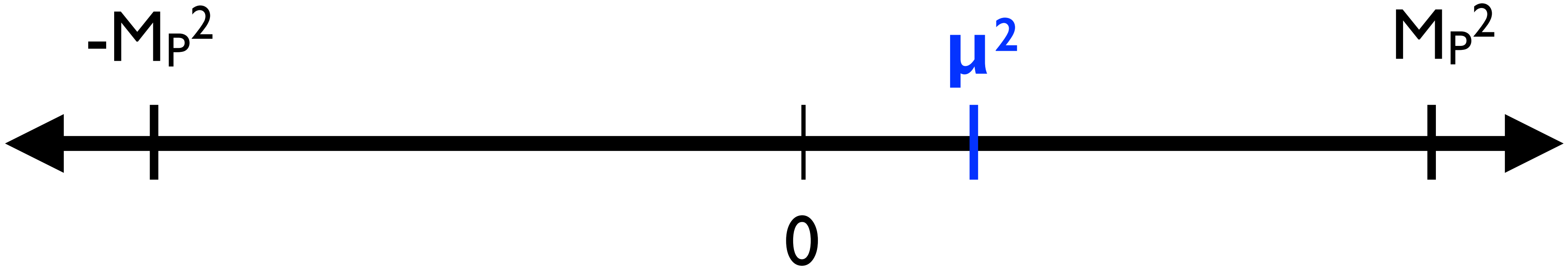
Where would you expect the Higgs mass (μ^2) to be?



What we found:



Where would you expect the Higgs mass (μ^2) to be?



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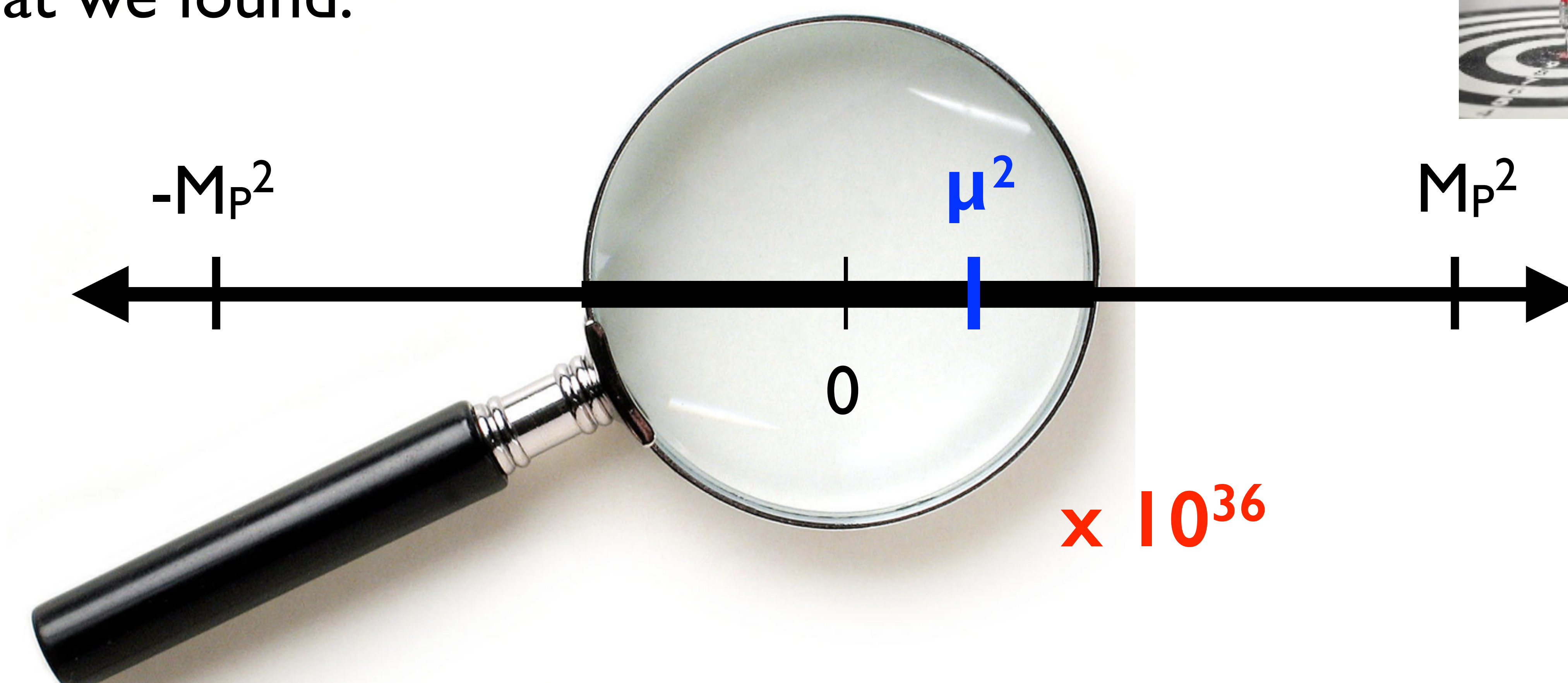
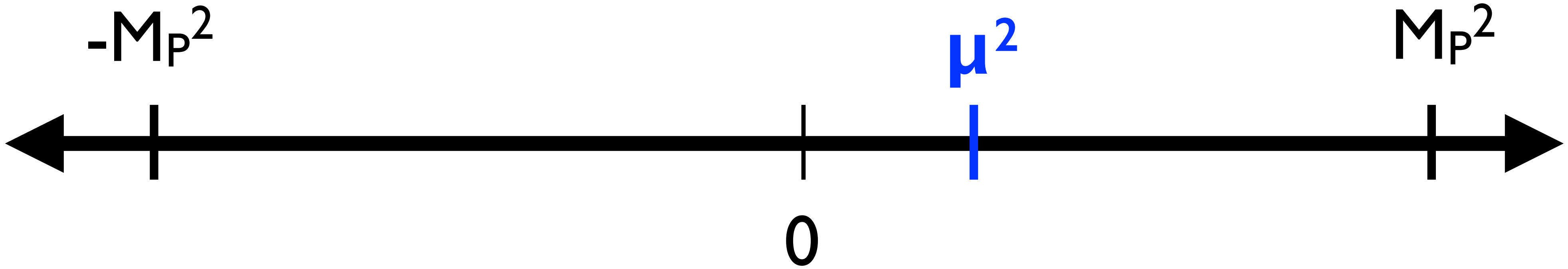
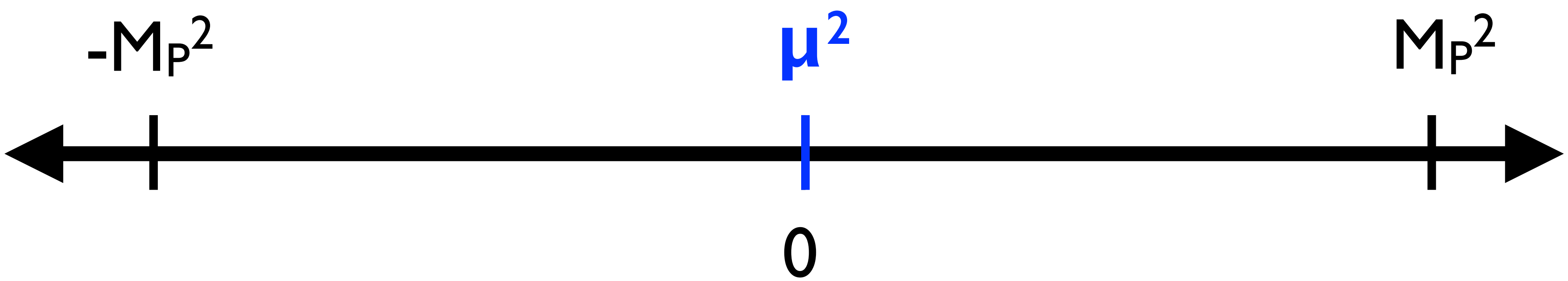


Very close to zero (as compared to M_P)

Where would you expect the Higgs mass (μ^2) to be?



What we found:



Why is the EW scale "almost" zero?

Is it a special point? More symmetrical?

Gaining symmetries in the massless limit

Dirac fermion mass: $\mathbf{m_\Psi \rightarrow 0}$ Chiral-symmetry recovered:

$m_\Psi \bar{\Psi}_L \Psi_R$

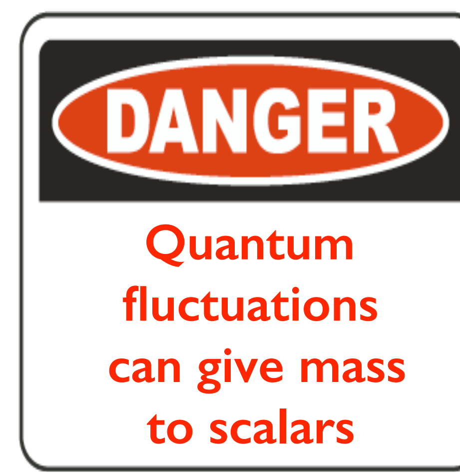
$$\Psi_R \longrightarrow e^{i\theta}\Psi_R$$

Higgs mass: $\boldsymbol{\mu^2 \rightarrow 0}$ **No extra symmetry in the SM**

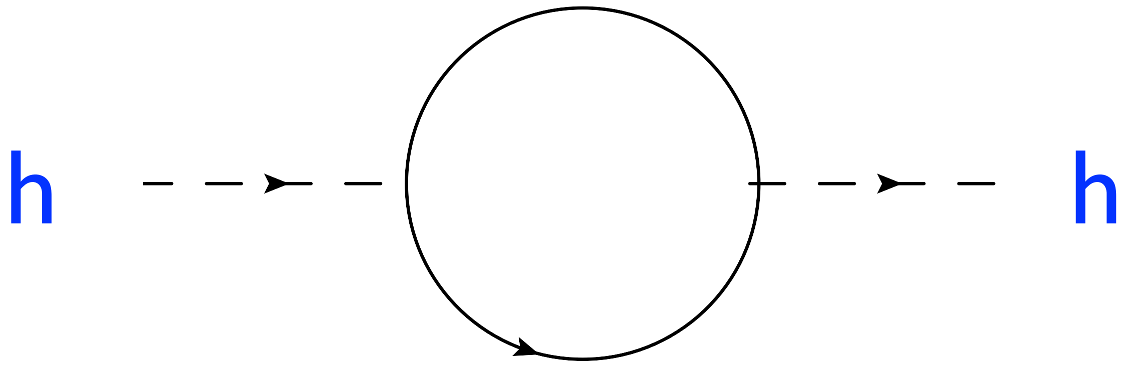
$\boldsymbol{\mu^2}$=0 not a special point!

Problems for massless scalars:

	Massless	Massive	
Vector $\mathbf{A}_\mu$	2 *dof* (+,-)	3 *dof* (+,0,-)	*2≠3* ✔ *Massless vectors are save*
Fermion (charged)	2 *dof* Ψ_L	4 *dof* Ψ_L , Ψ_R	*2≠4* ✔ *Massless fermions are save*
Scalar	1 *dof*	1 *dof*	*1=1 Problem!*



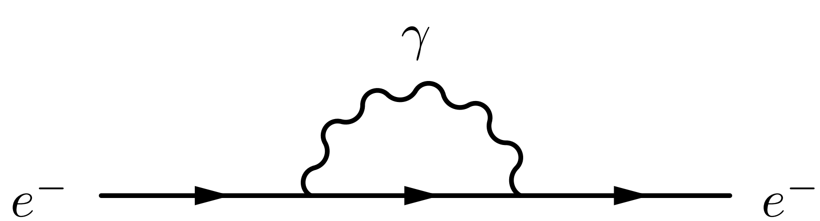
Quantum corrections to masses from heavy particles

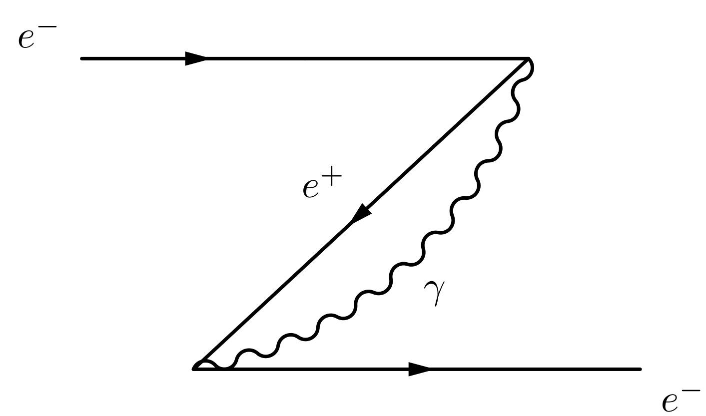


$$\sim \frac{1}{16\pi^2} M^2$$

mass of the particle
in the loop

Not the same for fermions:





$$\Delta m_e \propto m_e$$

“OLD” possibilities that theorists envisage to tackle the Hierarchy Problem:

1) **Supersymmetry**:

Making $\mu^2 \to 0$ a special point! Gaining a symmetry!

2) **Composite Higgs:** The Higgs is not elementary:

As pions in QCD $\sim \bar{q}q$ Made of fermions!

3) **Large extra dimensions**:

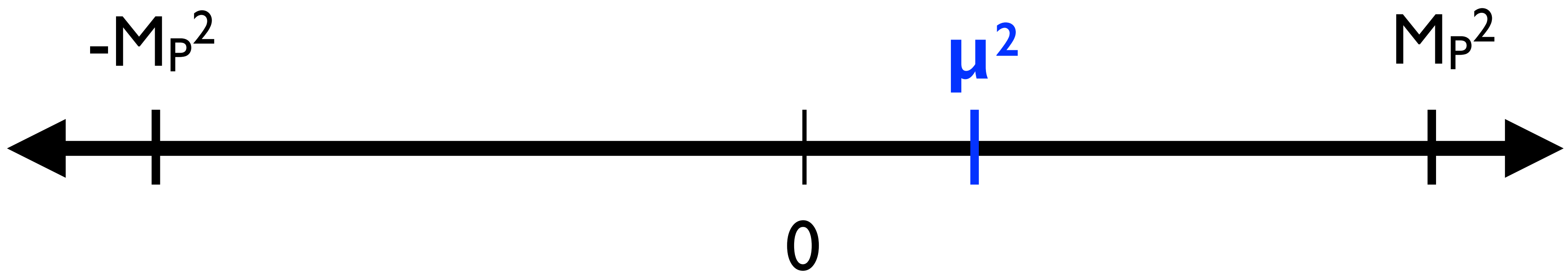
M_P not a fundamental scale! G_N small because gravity propagates in extra dimensions

➡ In all cases New Physics at ~TeV

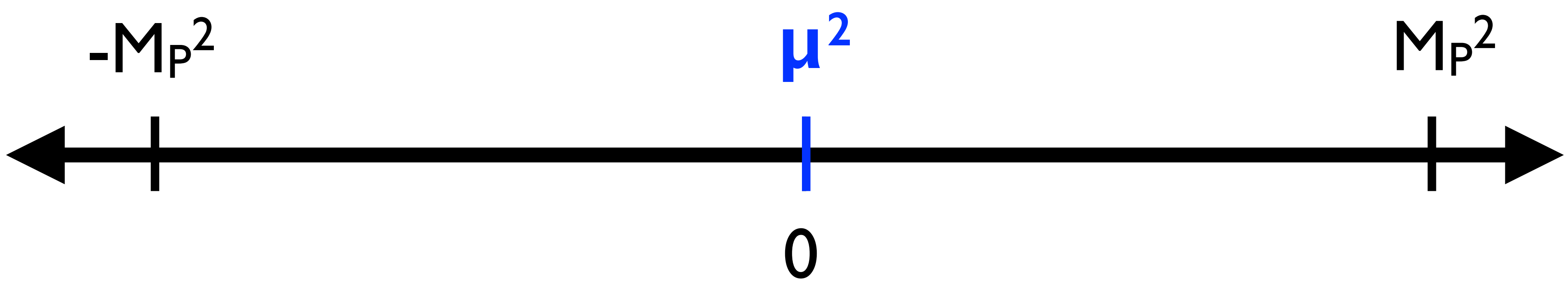
Best motivation for the LHC program!

Supersymmetry

Where would you expect the Higgs mass (μ^2) to be?



What we found:



Why is the EW scale “almost” zero?

Is it a special point?   More symmetrical?

Yes, it is supersymmetric!

Idea: Scalar $\xrightarrow[\text{symmetry trans.}]{}$ Fermion

from which
$m_\Psi \to 0$
is a special point

It exists, it is a ***Super***symmetry:

Simplest case:

$$\mathcal{L} = |\partial_\mu \Phi|^2 + i\frac{1}{2}\bar{\Psi}\partial\!\!\!/\Psi$$

Ψ = Majorana fermion

Φ = Complex scalar

Invariant under:

$$\Phi \to \Phi + \delta\Phi \qquad \delta\Phi \to \bar{\xi}(1-\gamma_5)\Psi$$

$$\Psi \to \Psi + \delta\Psi \qquad \delta\Psi \to -i(1-\gamma_5)\gamma^\mu \xi \partial_\mu \Phi$$

Parameter of the trans.
being a Majorana fermion

The scalar must be massless!!

Supersymmetry Algebra

(Maximal extension of Poincare in a QFT)

Minimal SUSY (*N*=*1*): One extra generator Q

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

Schematic form:

$$\boxed{\begin{aligned}
&[Q, M_{\mu\nu}] = Q \\
&\{Q, Q^\dagger\} = P^\mu, \\
&\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \\
&[P^\mu, Q] = [P^\mu, Q^\dagger] = 0,
\end{aligned}}$$

Q commutes with P^2 and any generator of the gauge symmetries:

The Fermion and Boson have <u>equal</u> masses and charges

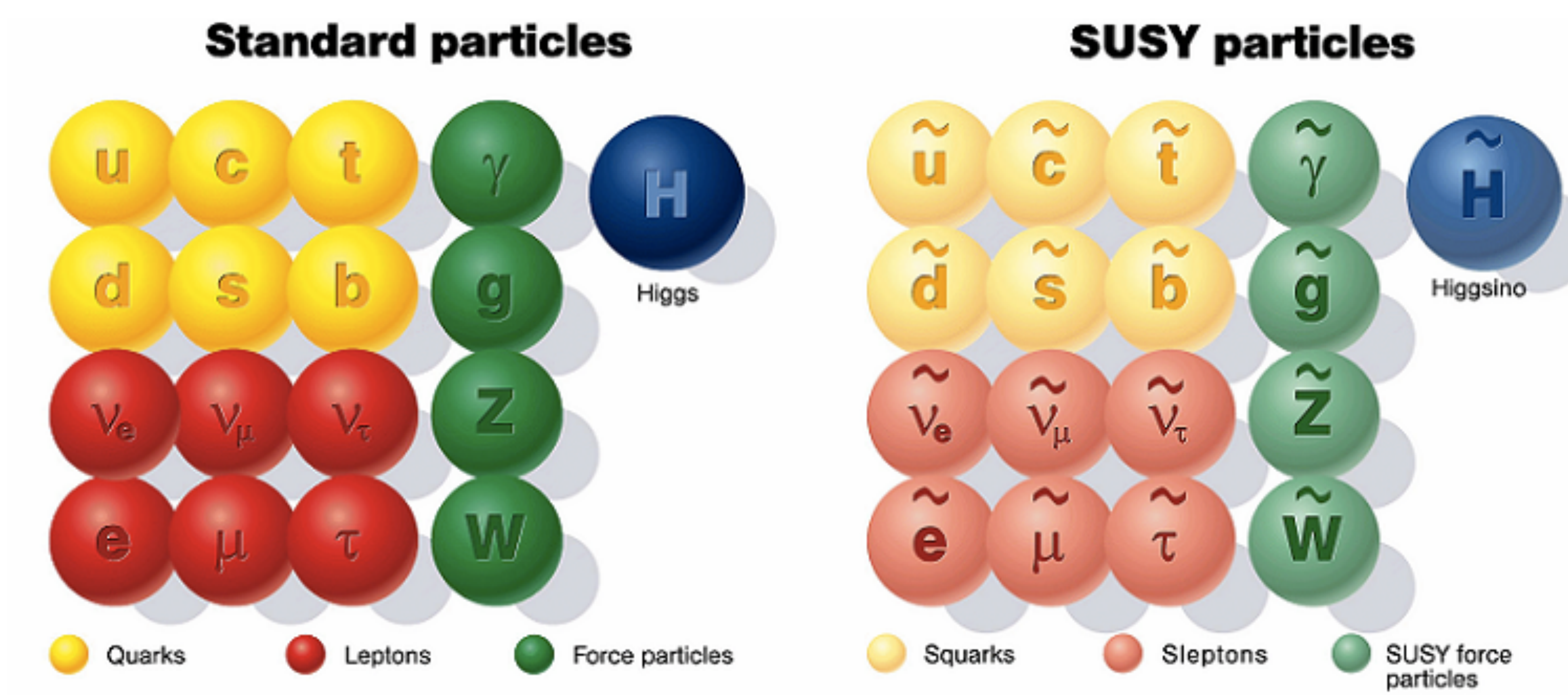
Minimal Supersymmetric SM (MSSM)

Imposing supersymmetry to the **SM** ➡ **MSSM**

The spectrum is doubled:

SM fermion ➡ New scalar (s-"…")

SM boson ➡ New majorana fermion ("…"-ino)



... but not yet realistic:

The model has a quantum anomaly (due to the Higgsino) and the down-quarks and leptons are massless

Extra Higgs needed

➡ Two Higgs doublets:

$H_u : \ (1,2,1)$ → give mass to the up quarks

$H_d : \ (1,2,-1)$ → give mass to the down quarks and leptons

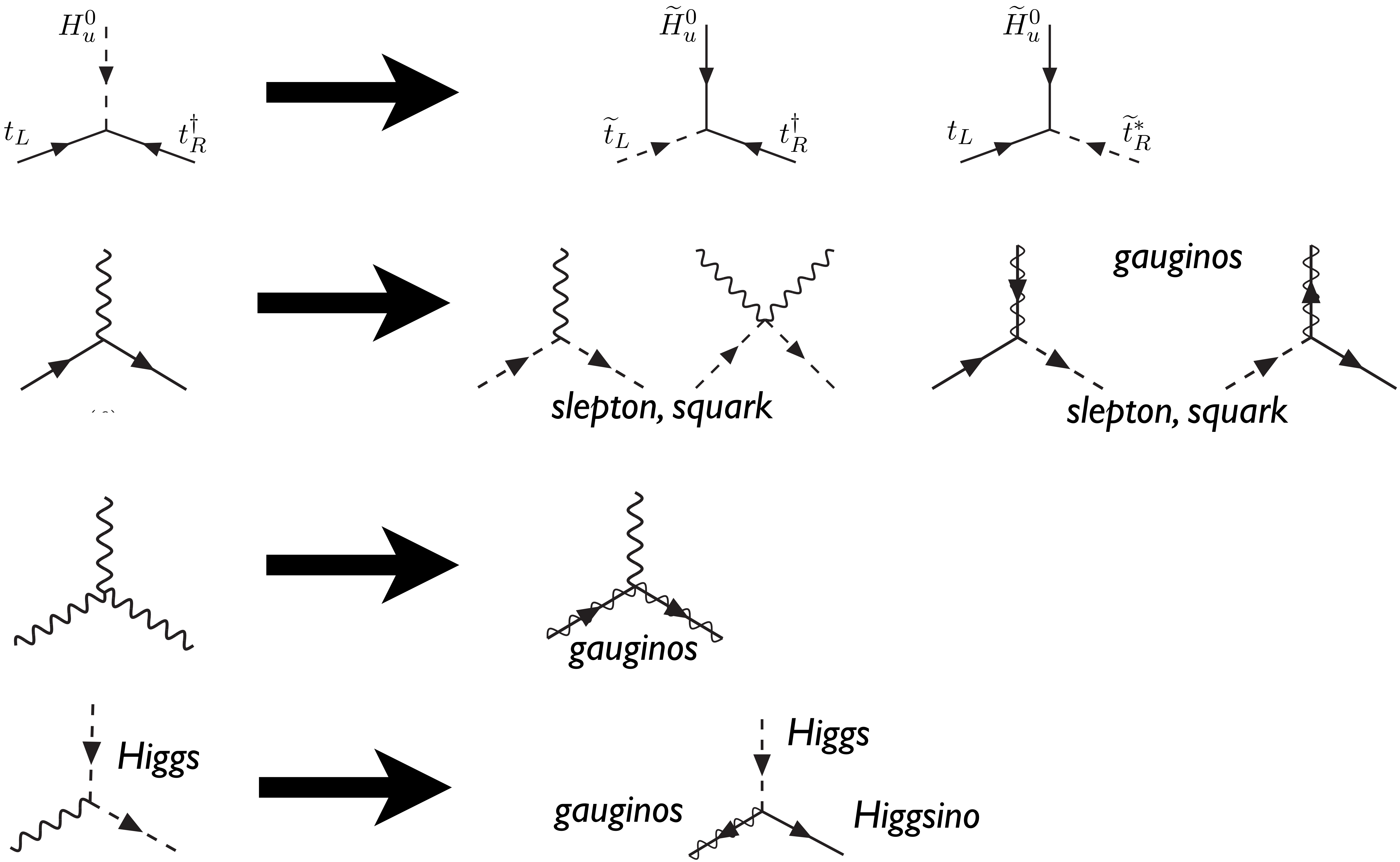
+ two Higgsino doublets:

$$\widetilde{H}_u : \ (1,2,1)$$

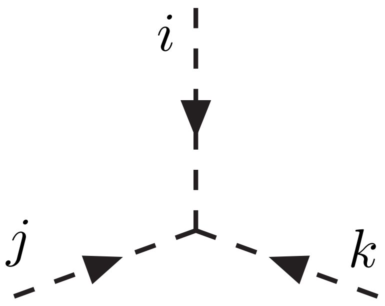
$$\widetilde{H}_d : \ (1,2,-1)$$

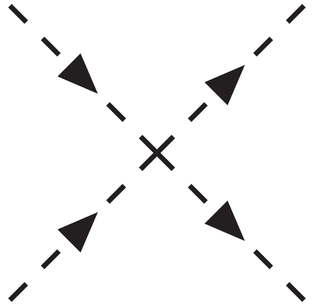
Type of interactions

Getting them from "supersymmetrization":

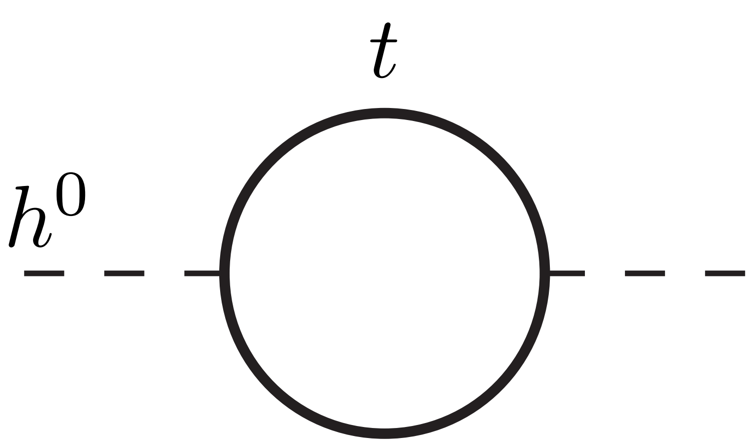


Up to scalar trilinear and quartics:

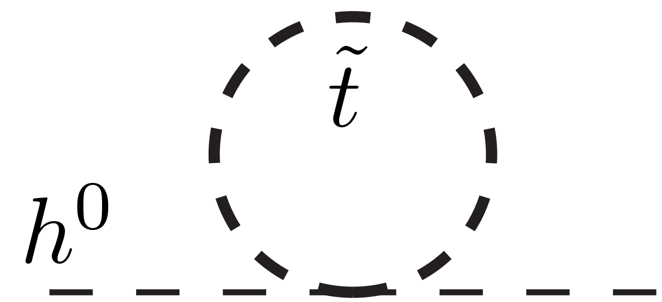




How supersymmetry works?



+



Fermion loop

$\mu^2 = +A$

Boson loop

$\mu^2 = -A$

$\mu^2_{total} = 0$

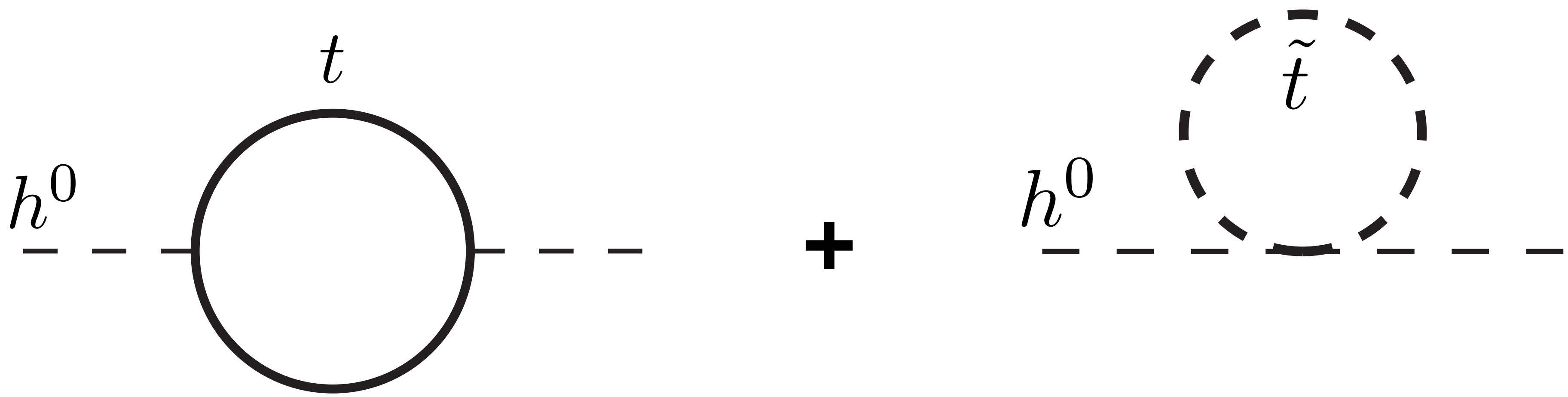
But if supersymmetry is exact:

$M_F = M_B$ ➡ e.g. $M_e = M_{\tilde{e}}$

It must be broken (as weak interactions)
to give masses to the superpartners

How supersymmetry works?

(including soft-masses)



Fermion loop

Boson loop

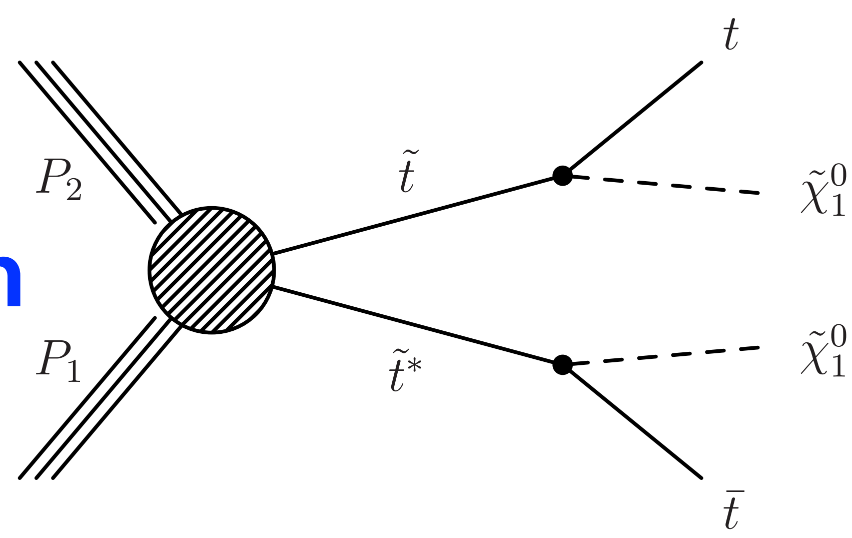
$\mu^2 = +A$

$\mu^2 = -A + m_{stop}^2\ B$

$\mu^2_{total} \sim m_{stop}^2$

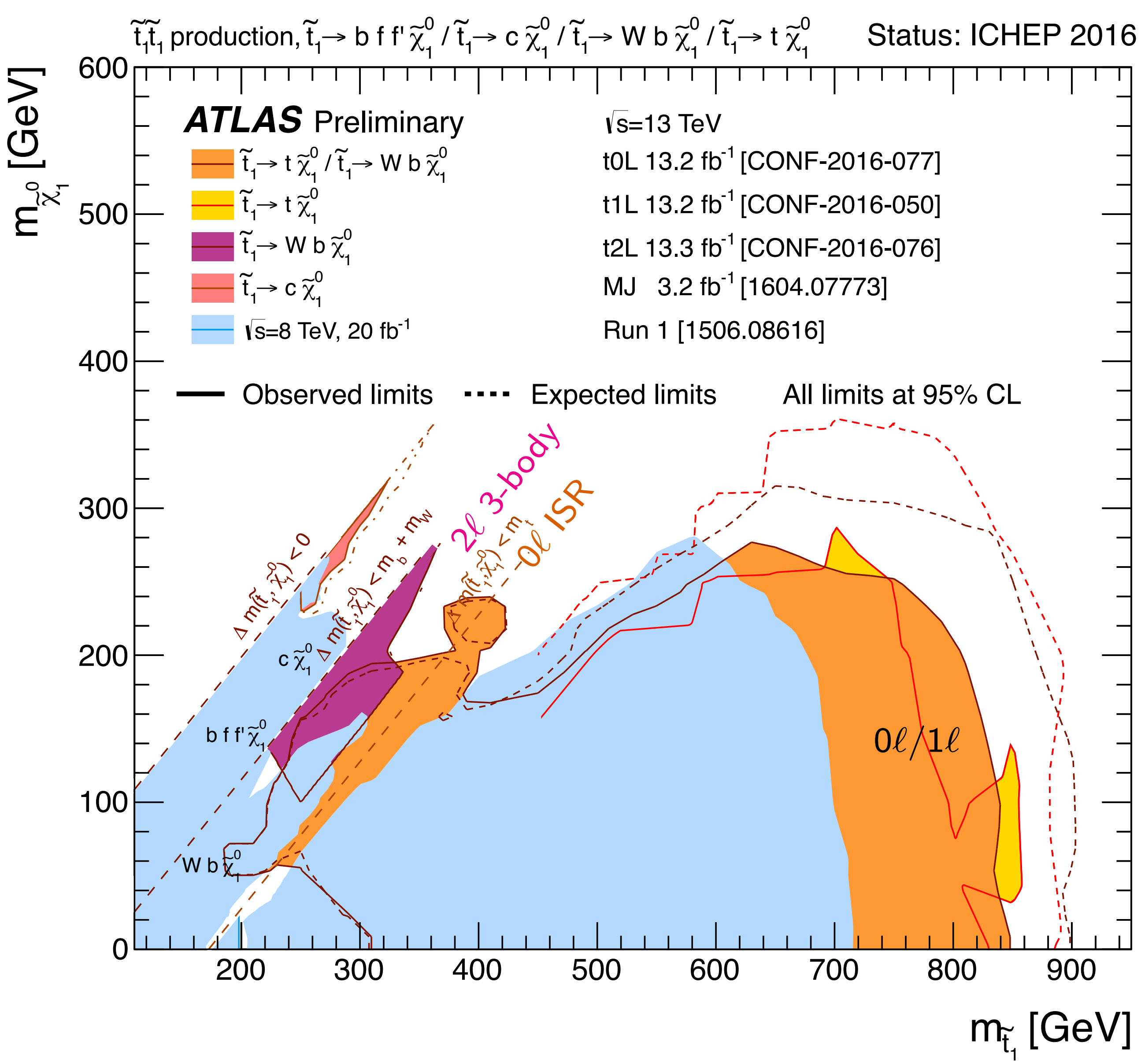
Superpartners expected around v ~ 246 GeV

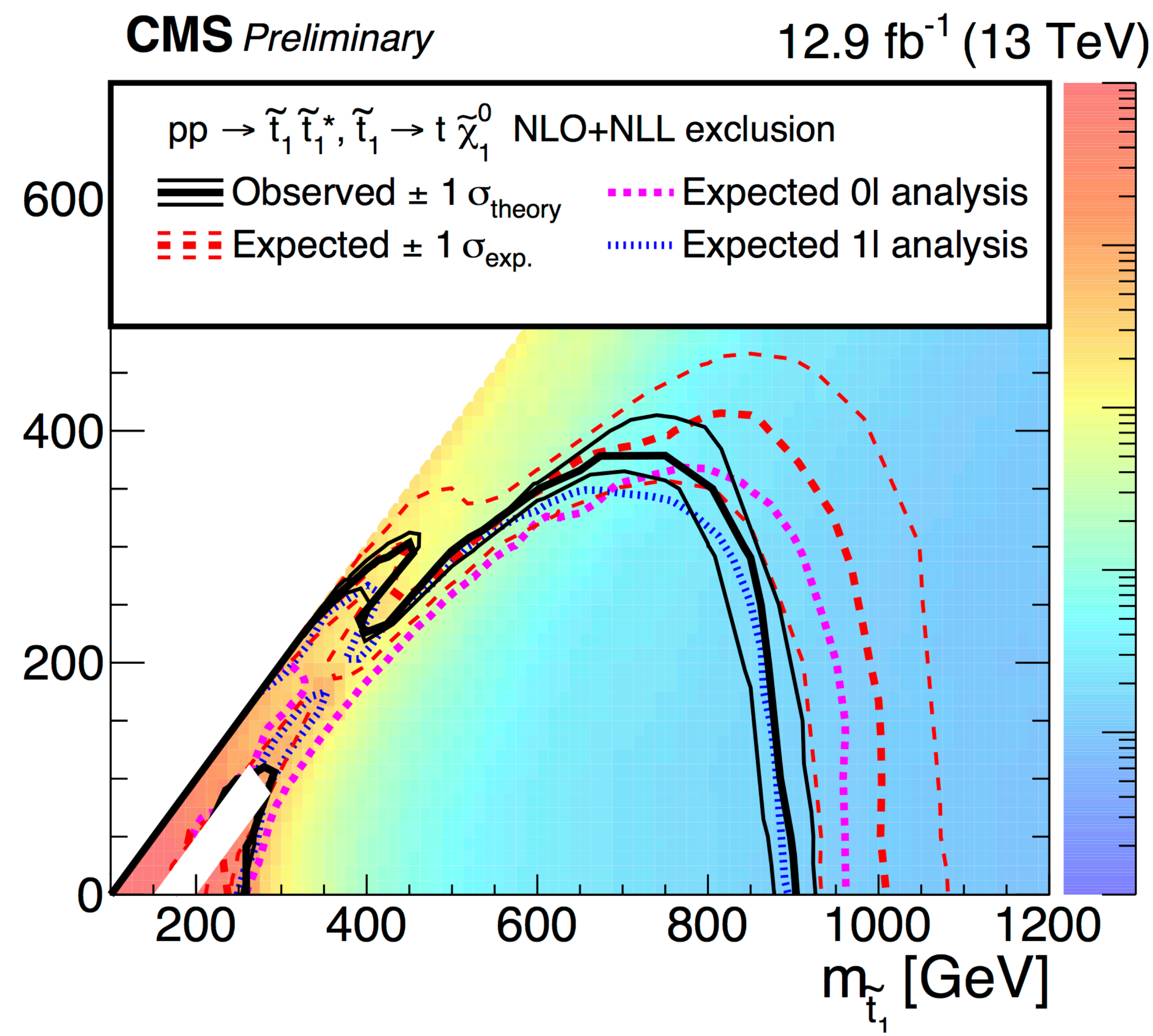
Stop production



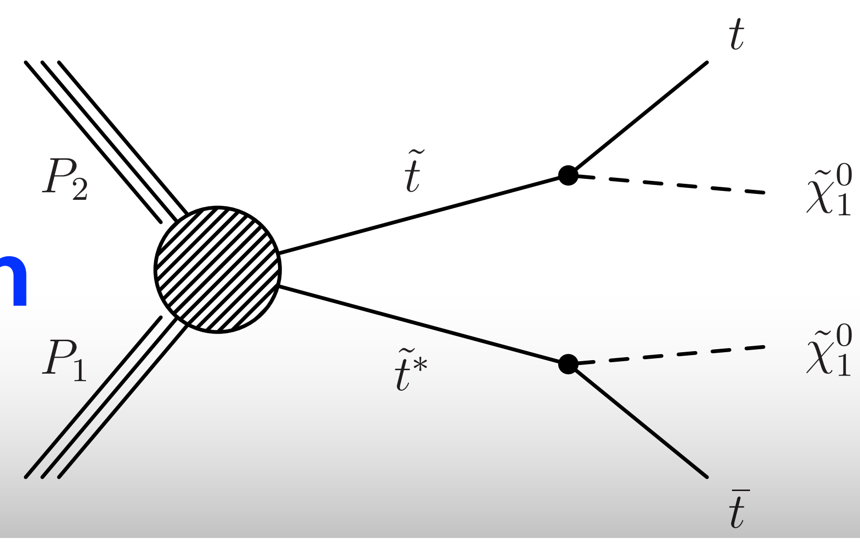
stable

↳missing-E_T

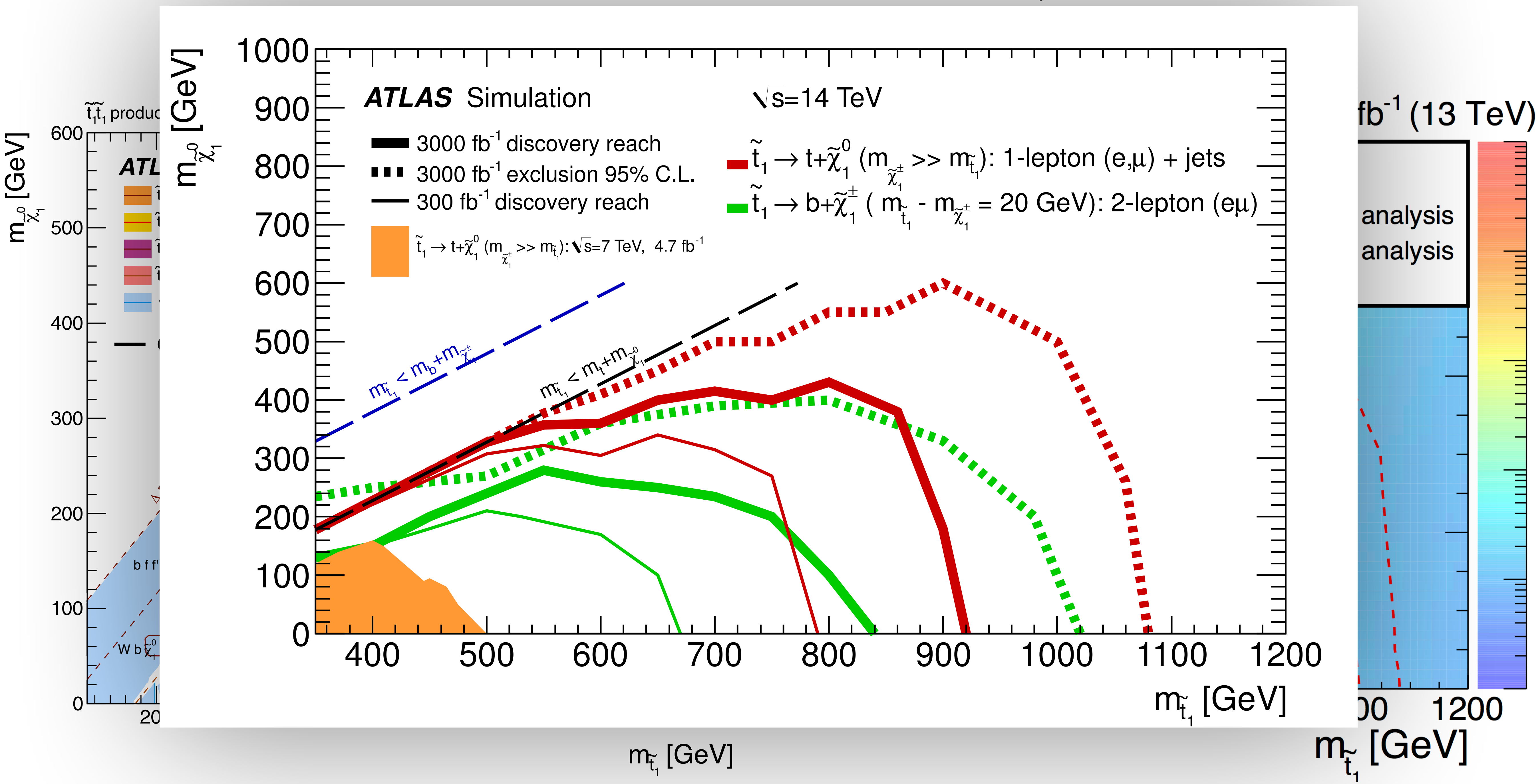




Stop production



stable
↳missing-E_T



There is a nice prediction from supersymmetry:

The Higgs quartic is related to gauge couplings!

$$\mathbf{M_h^2 \leq M_Z^2}$$

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susy breaking term
(at one-loop)

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The Higgs quartic is related to gauge couplings!

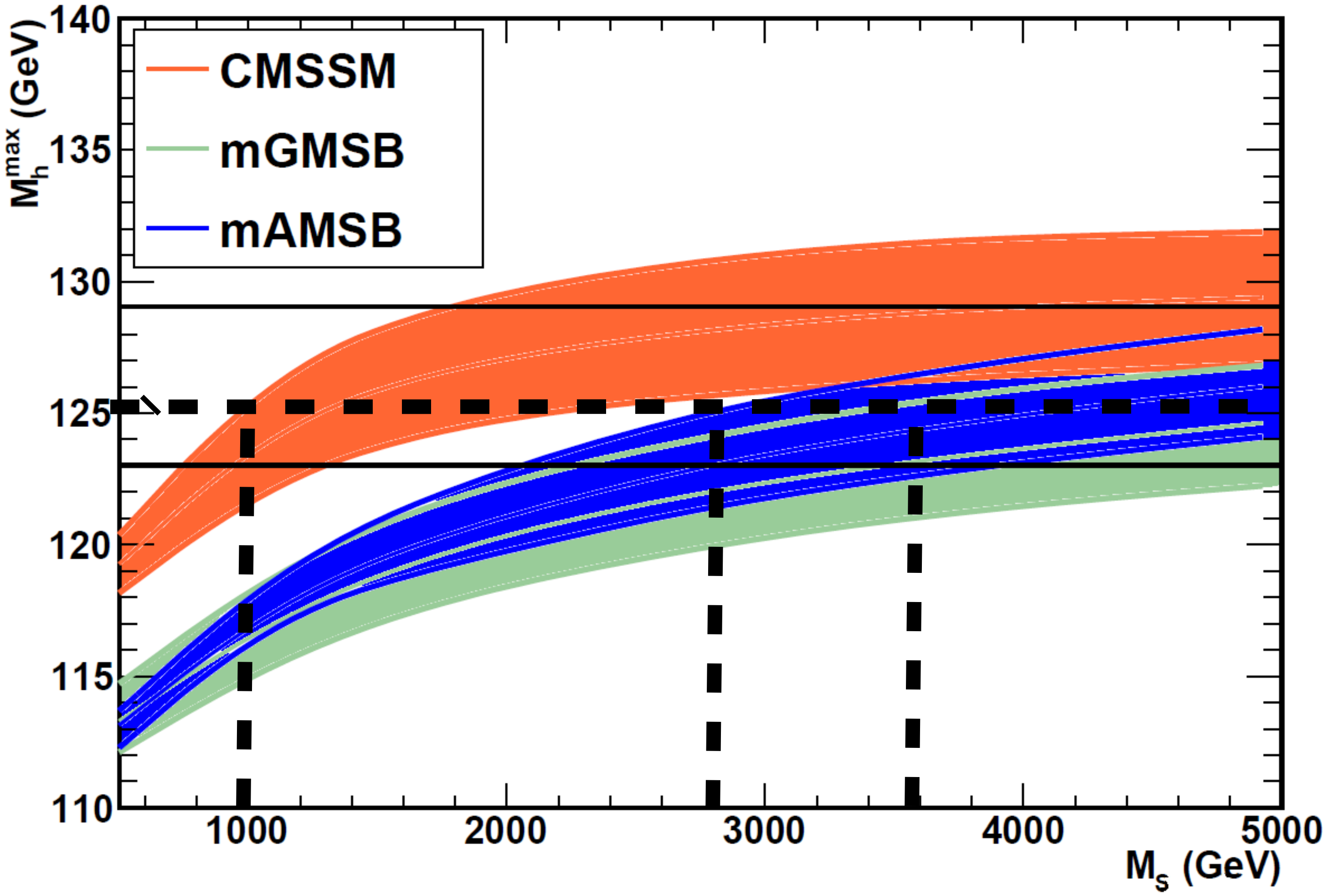
$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

susy breaking term (at one-loop)

$$\mathbf{(125\ GeV)^2} \qquad \mathbf{(91\ GeV)^2} \qquad \mathbf{(86\ GeV)^2}$$

both have similar size:
Non-small Susy breaking effects

Higgs mass in particular models of susy breaking:



from arXiv:1207.1348

This implies that most superpartners are beyond present LHC searches!

The MSSM in the aftermath of $M_H \sim 125$ GeV

- Big chunks of the parameter space are excluded
- Main simple models: GMSB, Gravity/String mediated SB, in trouble as are forced to have a high scalar susy-spectrum

SUSY is unnatural,

but simple

SUSY is natural

but not minimal:

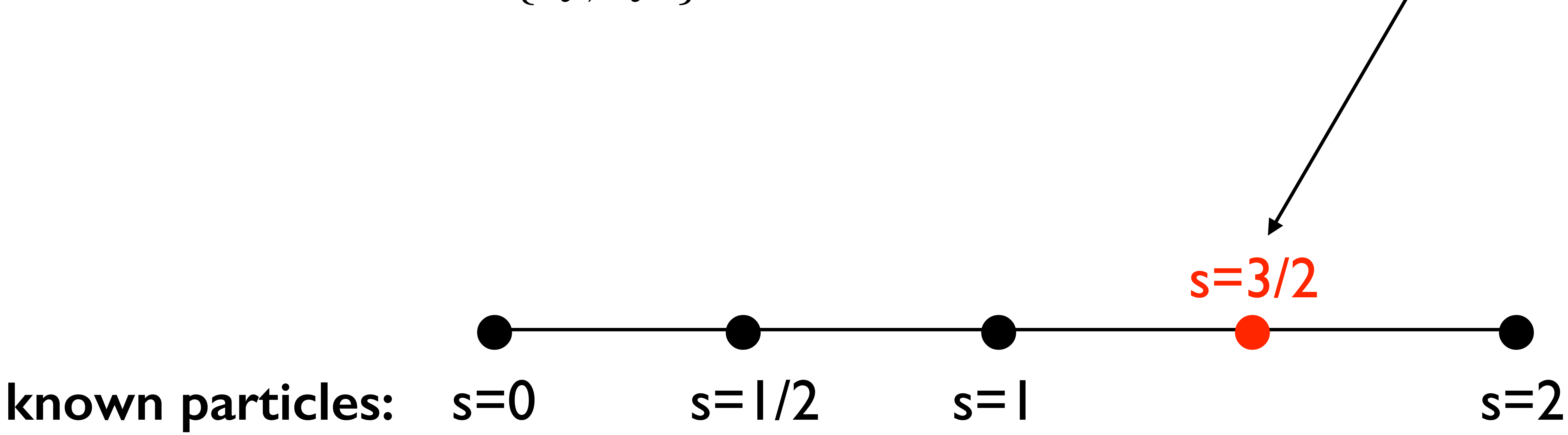
- Extra states (singlets): **NMSSM**
- New sources of Susy breaking

SUSY is dead

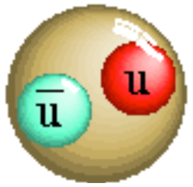
Other MSSM goodies:

- Gauge coupling unification
- The lightest supersymmetric particle (LSP) can be Dark matter
- Local supersymmetry must incorporate gravity:

$$\{Q, Q^\dagger\} = P^\mu$$



Composite Higgs

H = 

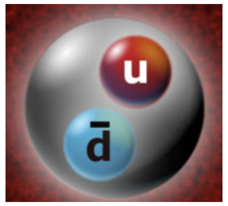
"dead dogs don't bite":

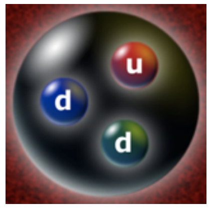
If no elementary Higgs, μ^2 not anymore a fundamental parameter

Indeed, in **QCD** we see **light scalars** without problems of naturalness:

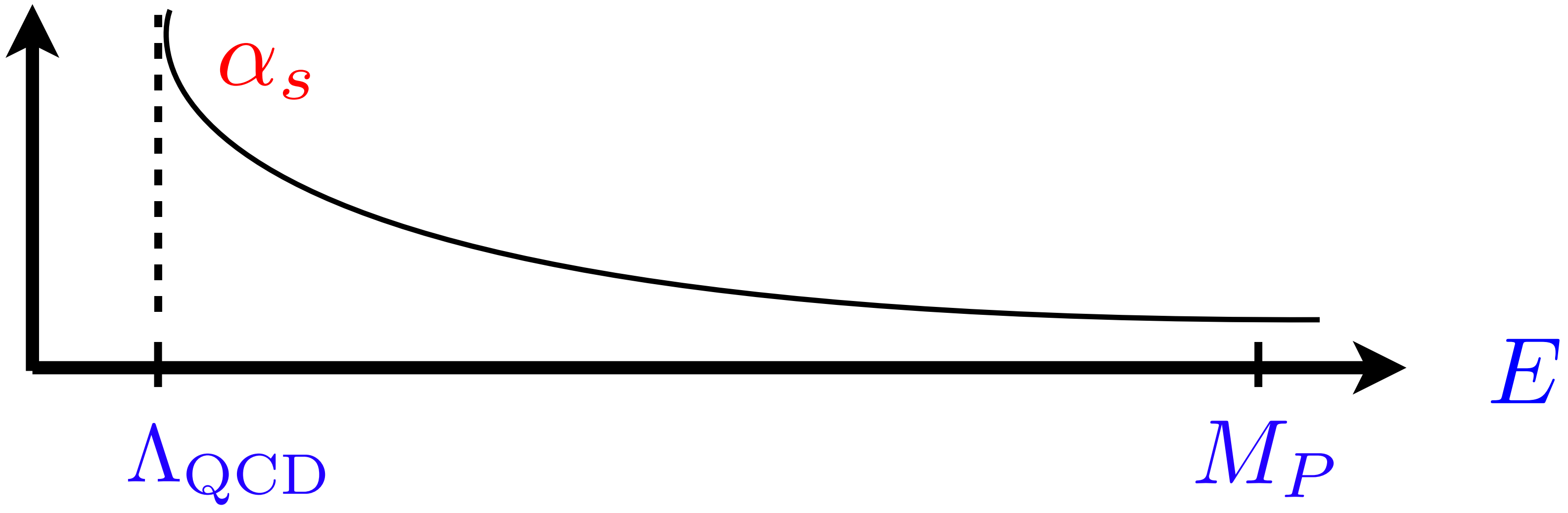
$$m_\pi,\ m_K,\ m_{a_0}, \ldots << M_P$$

Reason: they are <u>composite</u> states at $\Lambda_{\rm QCD} << M_P$,





defined by the scale at which the strong gauge-coupling becomes large:

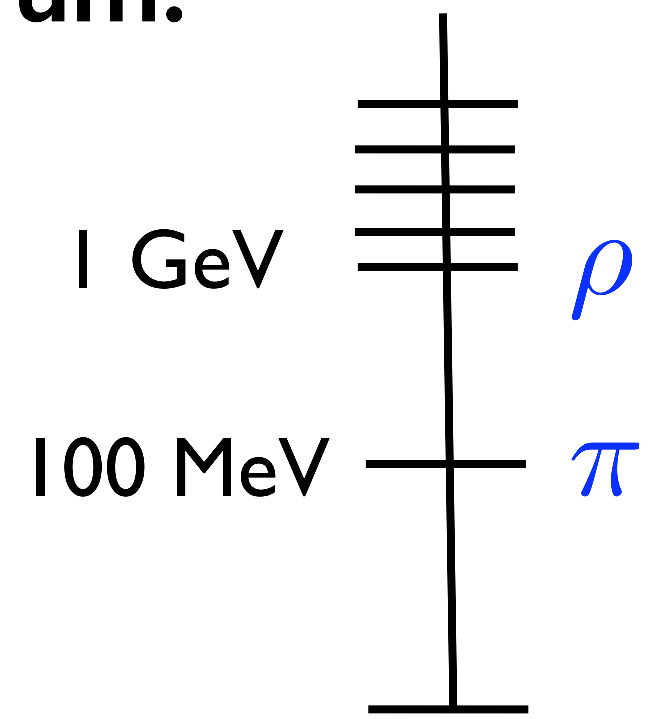


Furthermore,

the lightest states in **QCD** are the (pseudo) **scalars**

(spin=0 particles like the Higgs)

QCD Spectrum:



Why the lightest?

Because they are
Pseudo-Goldstone bosons (PGB)

Pseudo-Goldstone bosons (PGB) in QCD

QCD, considering only two quarks in the massless limit,

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

has an accidental global symmetry:

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

It is broken by the quark condensate: $\langle q\bar{q} \rangle \neq 0$

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \quad \textit{Isospin}$$

3 Goldtones:

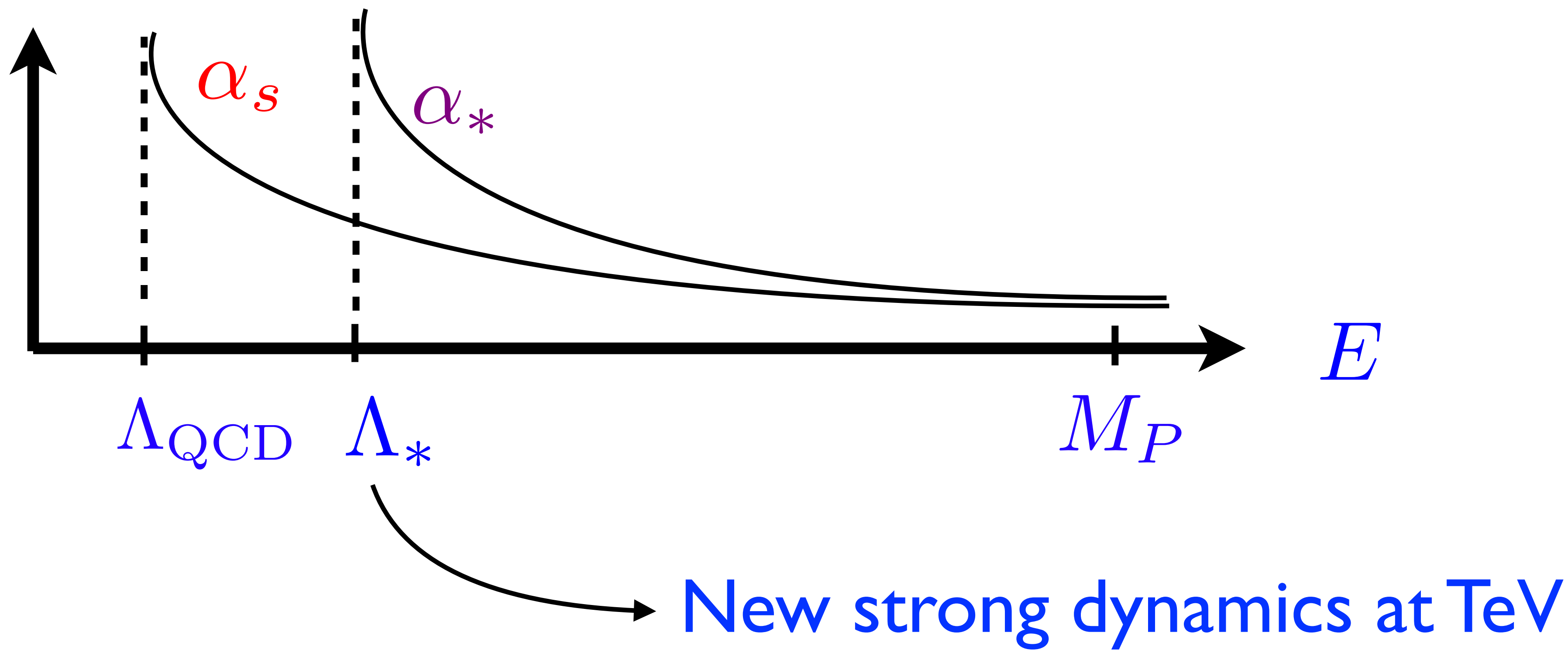
π^+, π^-, π^0 **Massless!!**

In reality, they are not massless since quark masses break explicitly $SU(2)_L \times SU(2)_R$ giving the pions a mass:

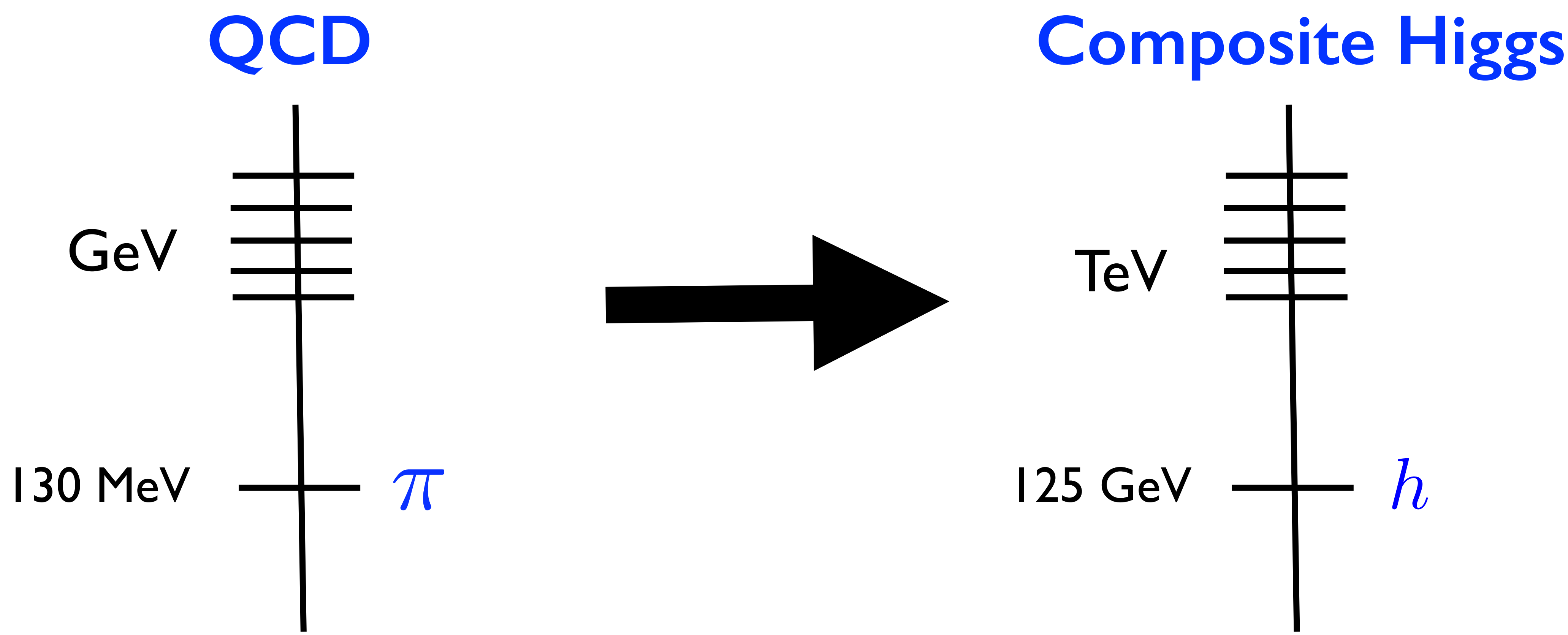
$$m_\pi^2 \propto m_q$$

Lets try the same for the Higgs

➠ Assume that there is a **New Strong sector** (QCD-like) at around the TeV-scale:



The **Higgs, the lightest** of the new strong resonances, as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)



E.g.: **SO(6) → SO(4)**

5 Goldstones = Higgs doublet
+ Singlet

Galloway, Evans, Luty, Tacchi 10

Example: Just take QCD (with two flavors)
replace $\mathbf{SU(3)_c}$ by $\mathbf{SU(2)_c}$

	$\mathbf{SU(3)_c}$	$\mathbf{SU(2)_c}$
Global symmetry:	$\mathbf{SU(2)_L \otimes SU(2)_R}$	$\mathbf{SU(4) \sim SO(6)}$
	$\langle\psi\psi\rangle\neq 0$ $\downarrow$	$\downarrow$ $\langle\psi\psi\rangle\neq 0$
	$\mathbf{SU(2)_V}$	$\mathbf{SO(5)}$
	3 Golstones = π^0, π^+, π^-	5 Goldstones = **Higgs doublet + singlet**

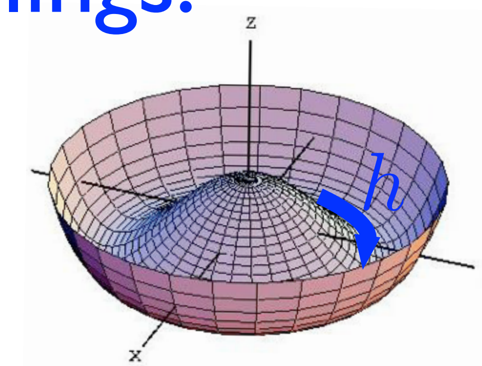
since $\mathbf{2 \sim \bar{2}}$

$\mathbf{4} = 2_L + 2_R$

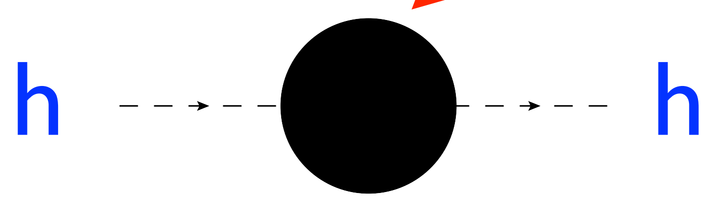
ψ_L, ψ_R^c

Main difference with QCD pions → Higgs must get a VEV

The **Higgs** is a **Pseudo-Goldstone** as the global symmetry is broken due to the SM couplings:

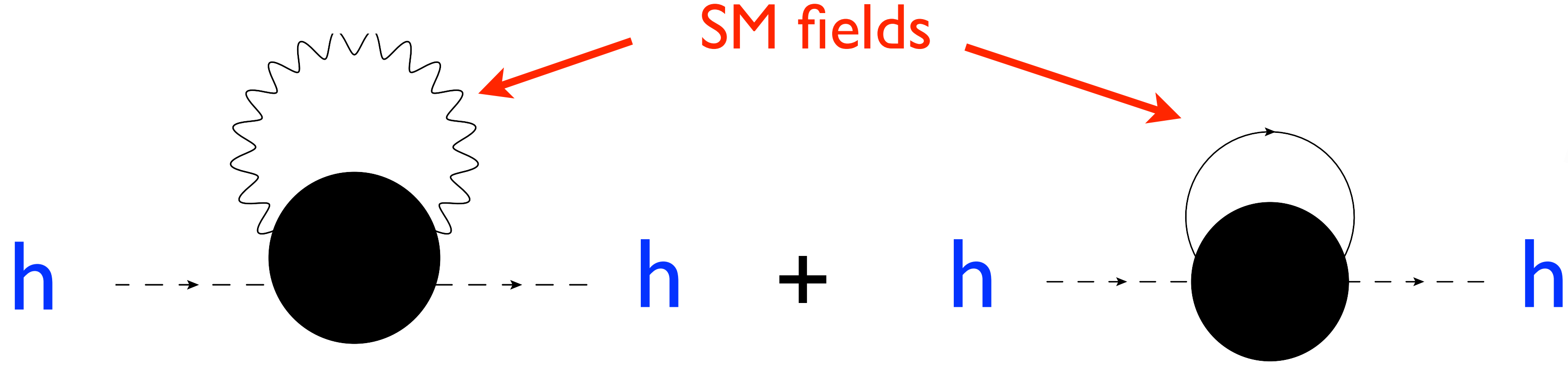


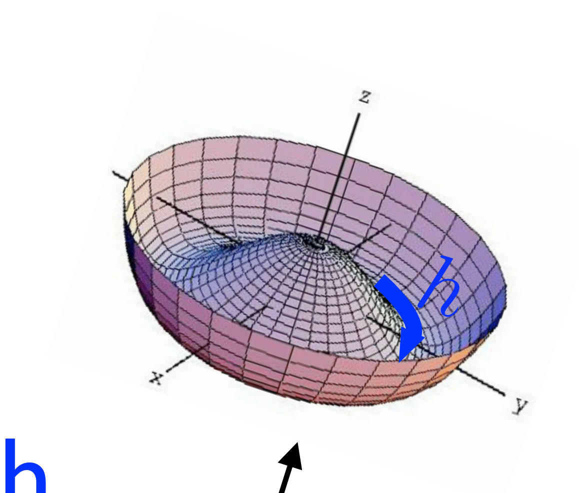
contribution from the strong sector



= 0 it's a Goldstone

SM fields

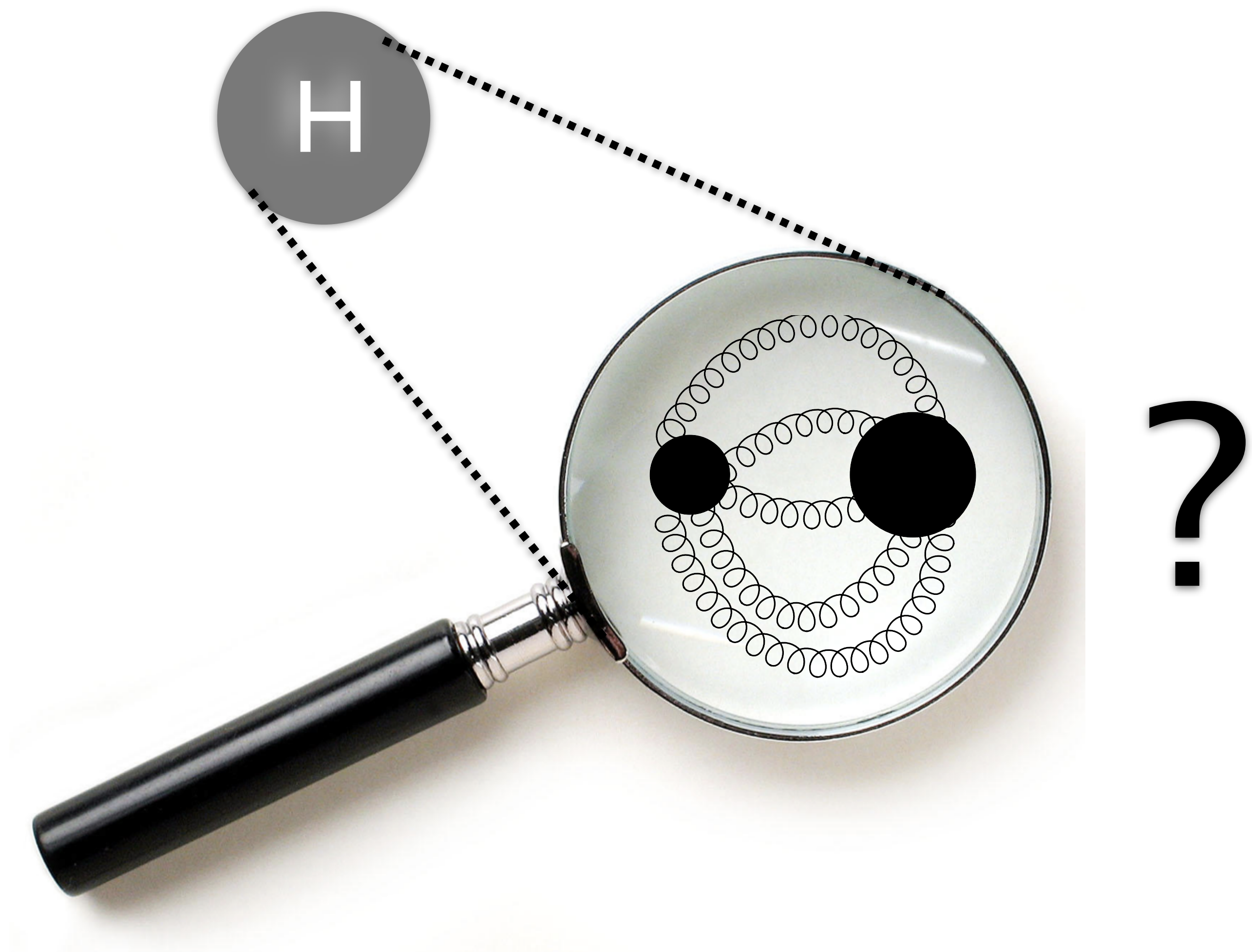




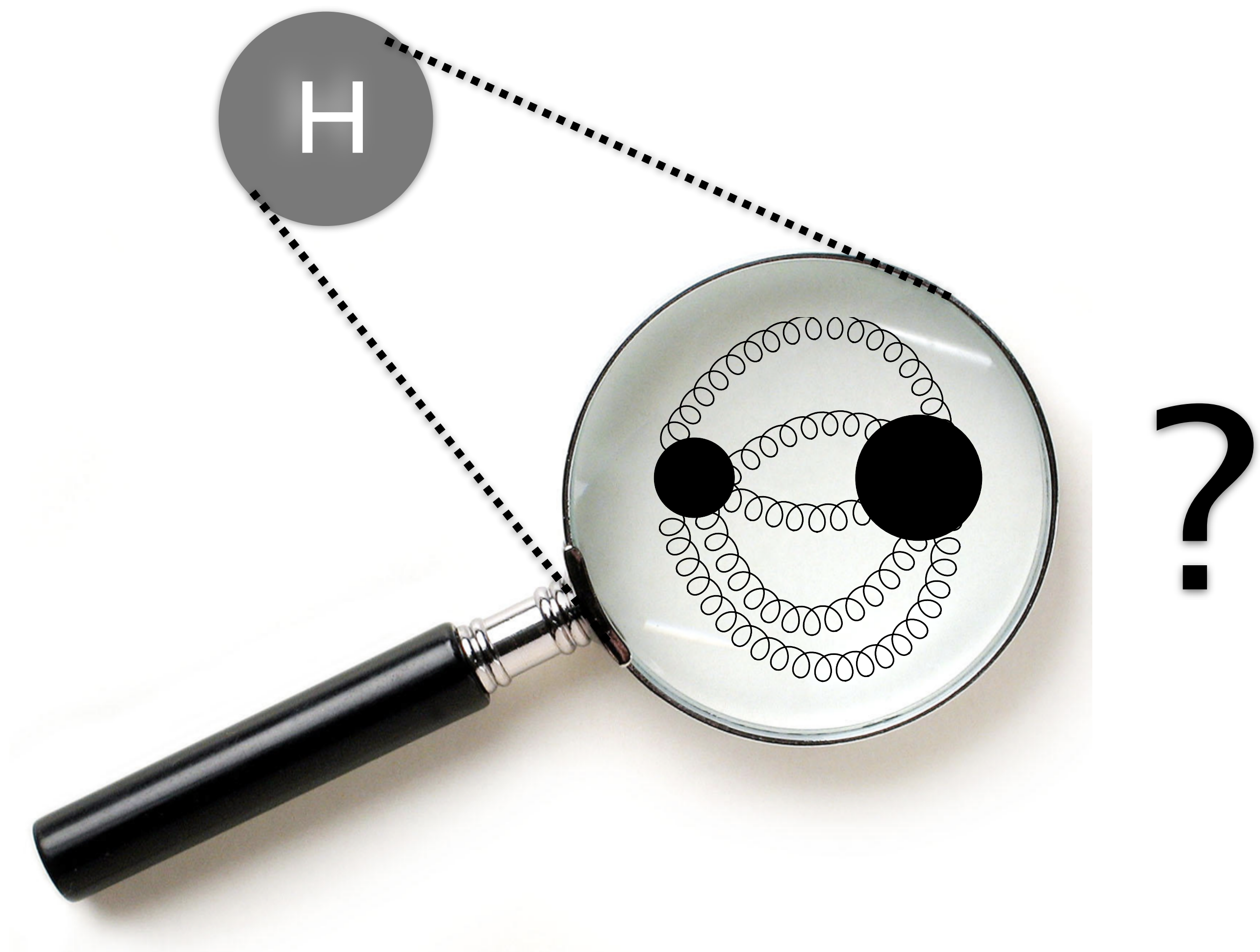
Tilt the potential

$$m_h^2 \sim \frac{(\mathrm{TeV})^2}{16\pi^2} \sim (100\ \mathrm{GeV})^2$$

How to unravel the composite nature of the Higgs?



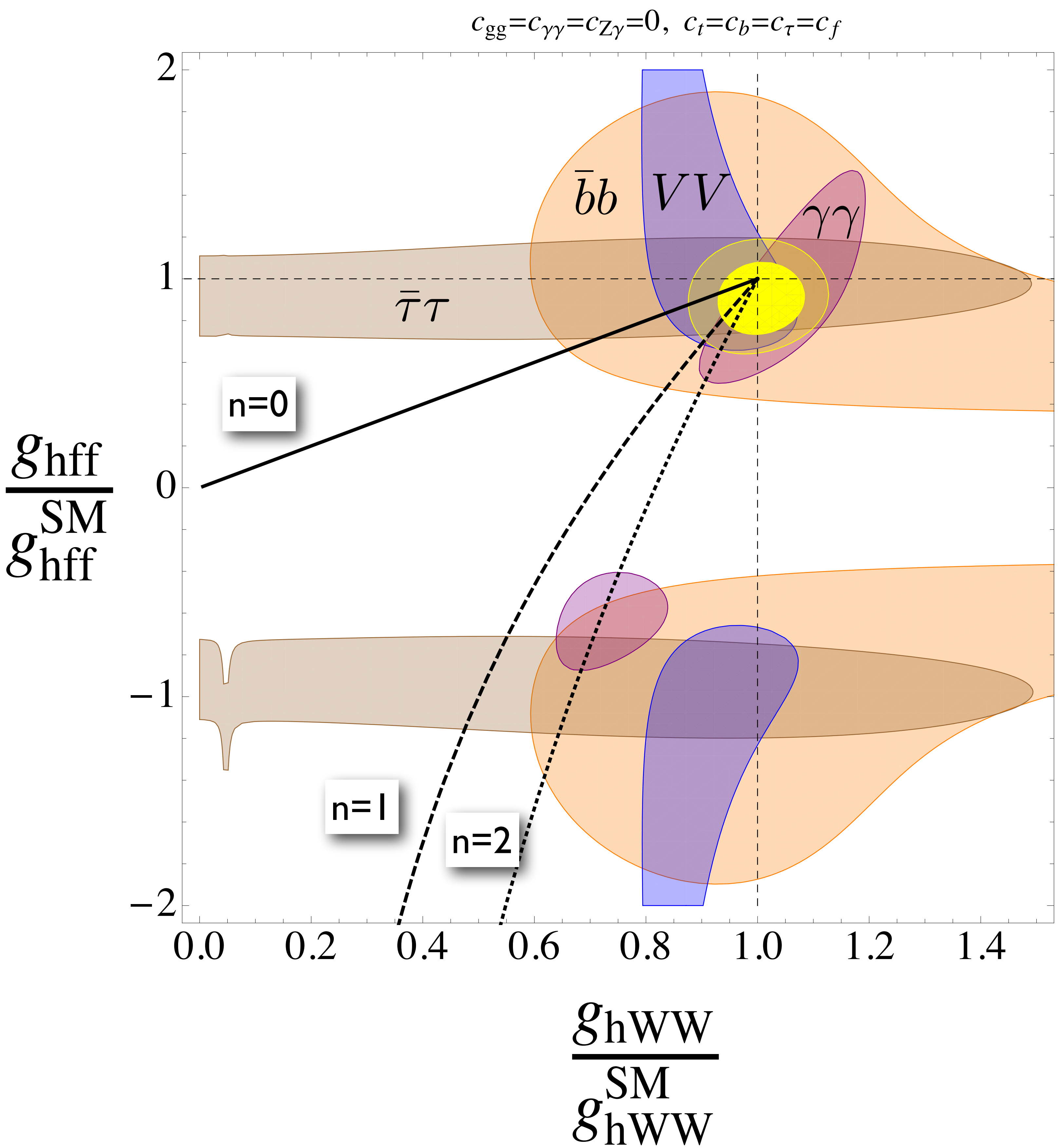
How to unravel the composite nature of the Higgs?



Measuring its couplings!

The higher the energy, the better

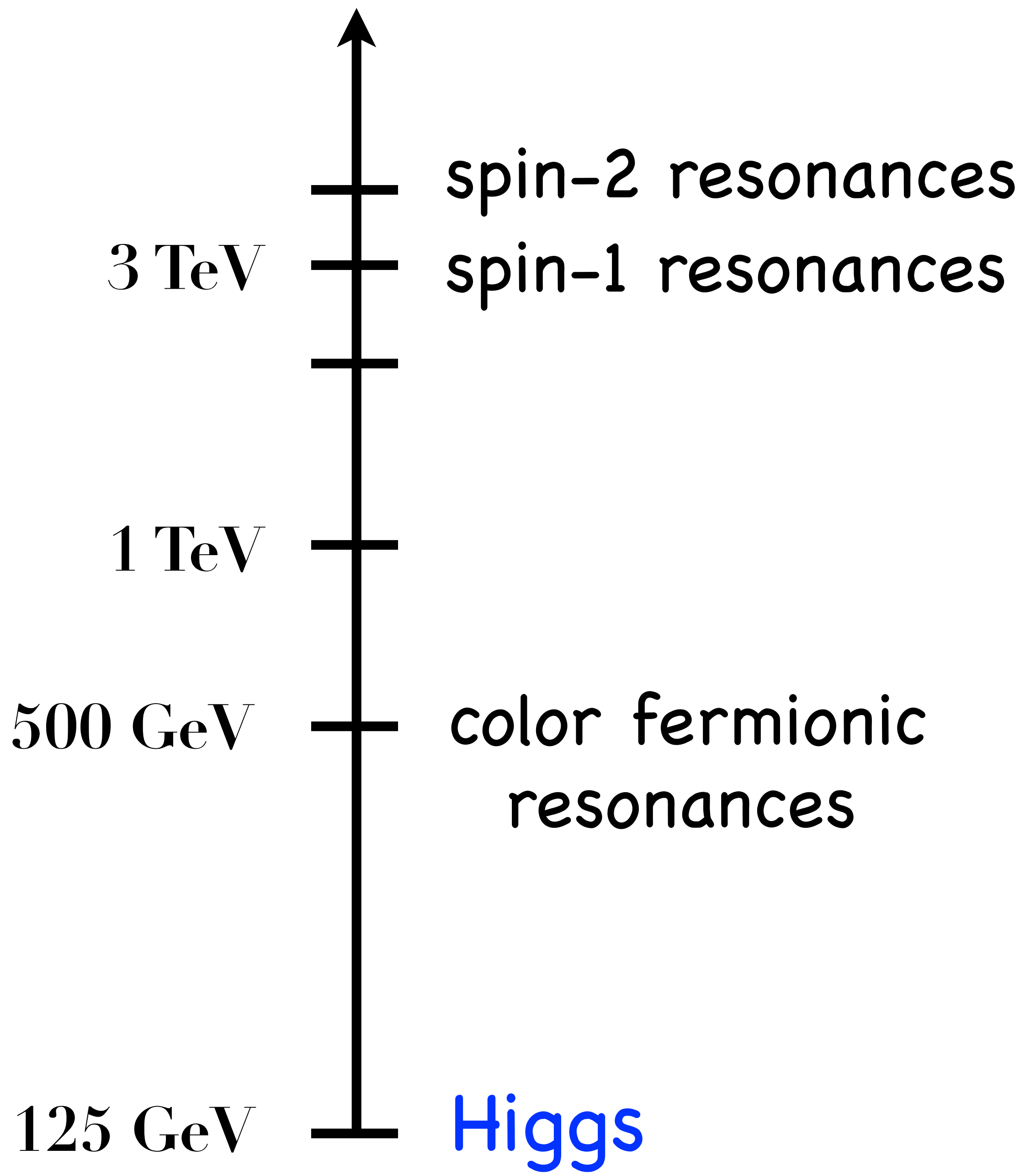
ATLAS+CMS:



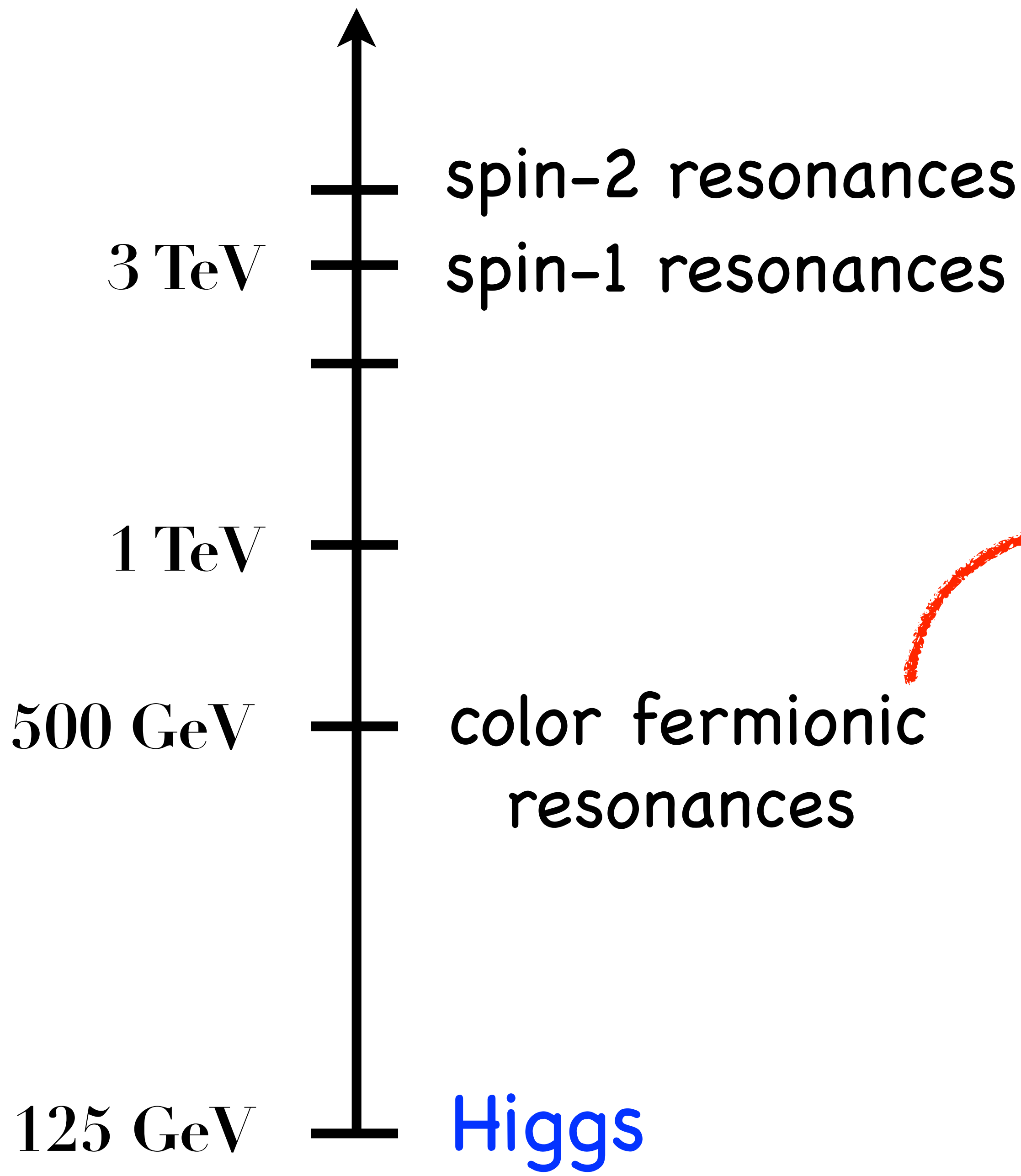
arXiv:1303.1812

No indication of such deviations!

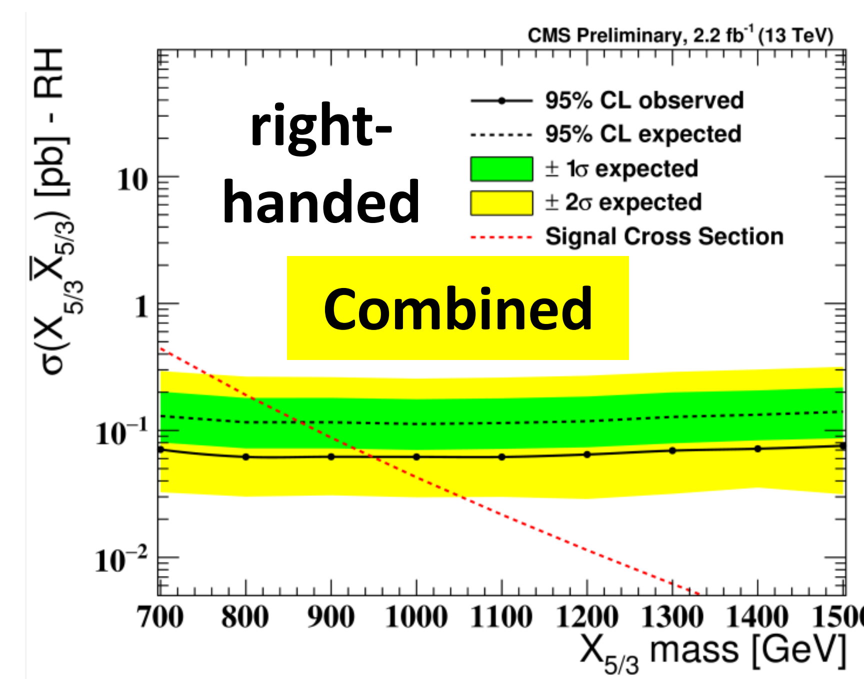
As in QCD, many other resonances expected:



As in QCD, many other resonances expected:



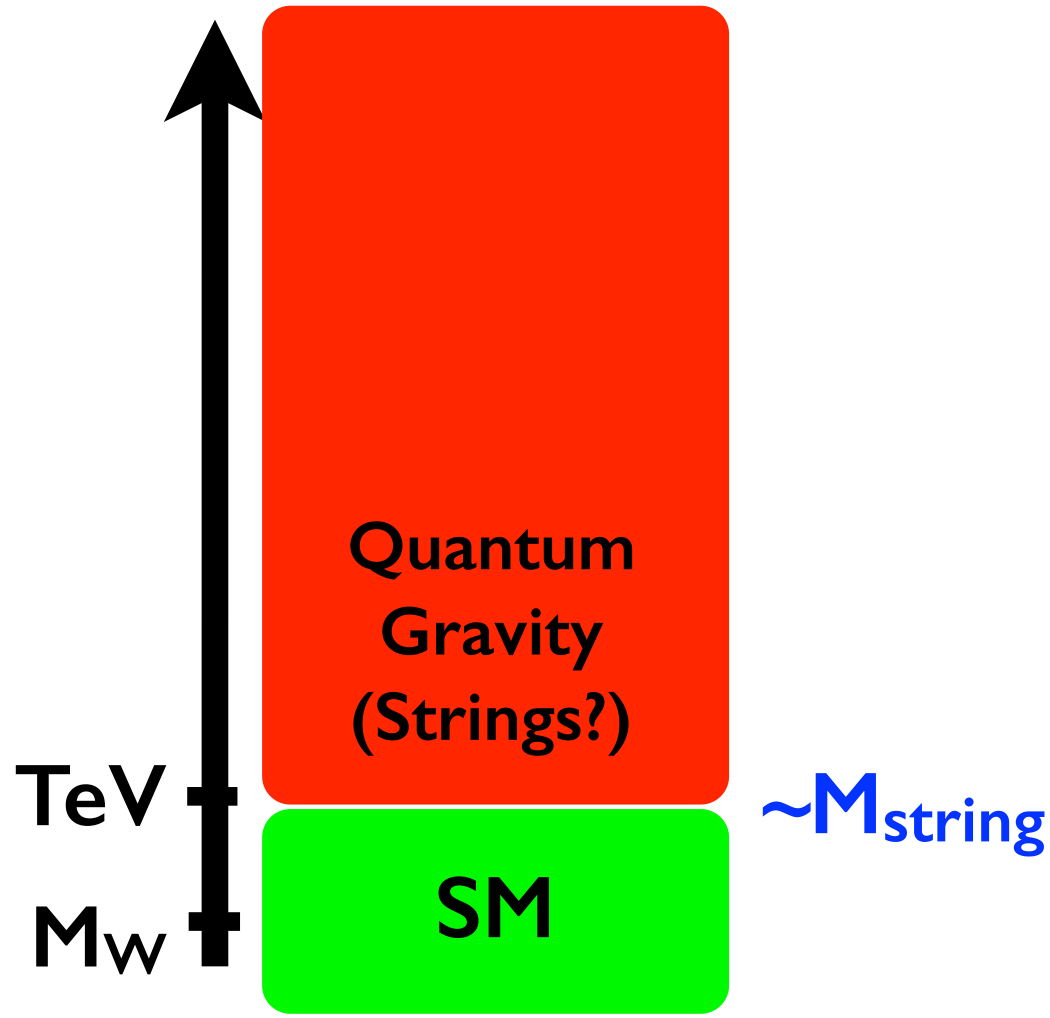
no sign
at 13 TeV!



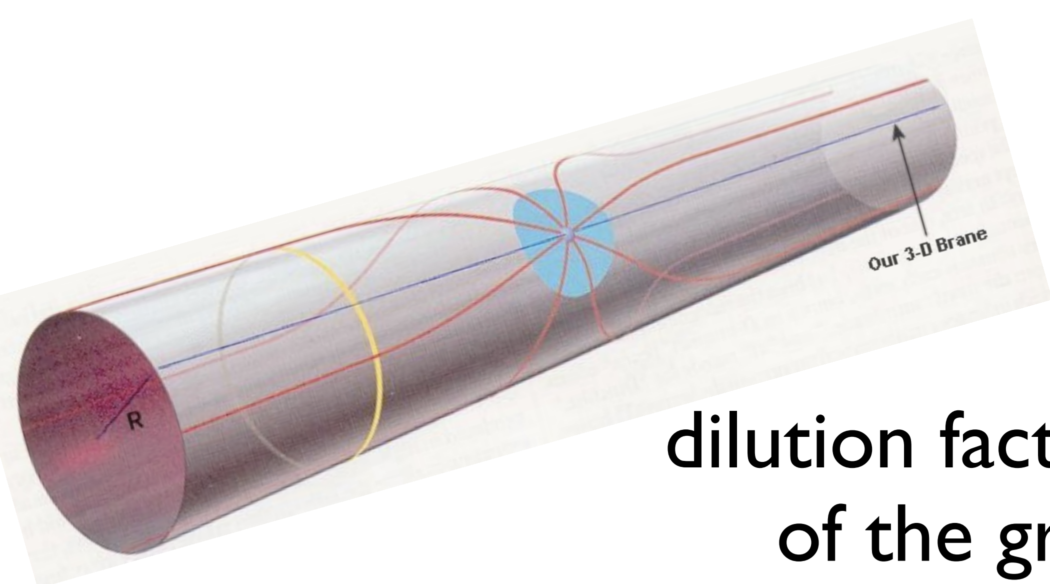
$$m(X_{5/3}) > 960\ \mathrm{GeV}$$

Extra dimensions

In 1998 Arkani-Hamed, Dimopoulos and Dvali (ADD) proposed the following scenario:



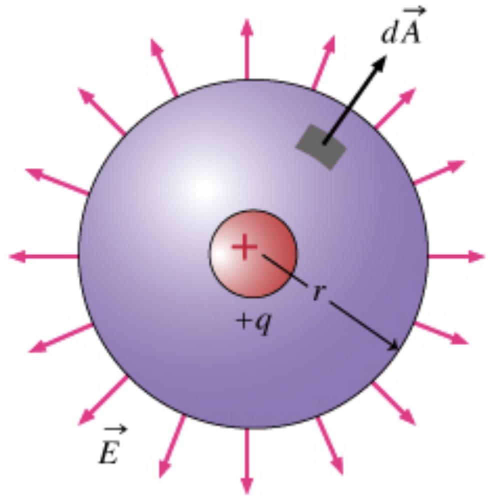
$$G_N = \frac{1}{M_P^2} \sim \frac{1}{M_{string}^2} \boxed{\frac{1}{(M_{string} 2\pi R)^d}}$$



dilution factor due to the spreading
of the gravitational field lines
in *d* compactified extra dimensions

R=size of extra-dim

Gauss's law in higher-dimensions:



$$\oint_S d\Phi \sim Q_{int}$$

4 dim

$$V \sim \frac{Q_{int}}{r}$$

4+d dim

$$V \sim \frac{Q_{int}}{r^{1+d}}$$

$$S \sim r^{2+d}$$

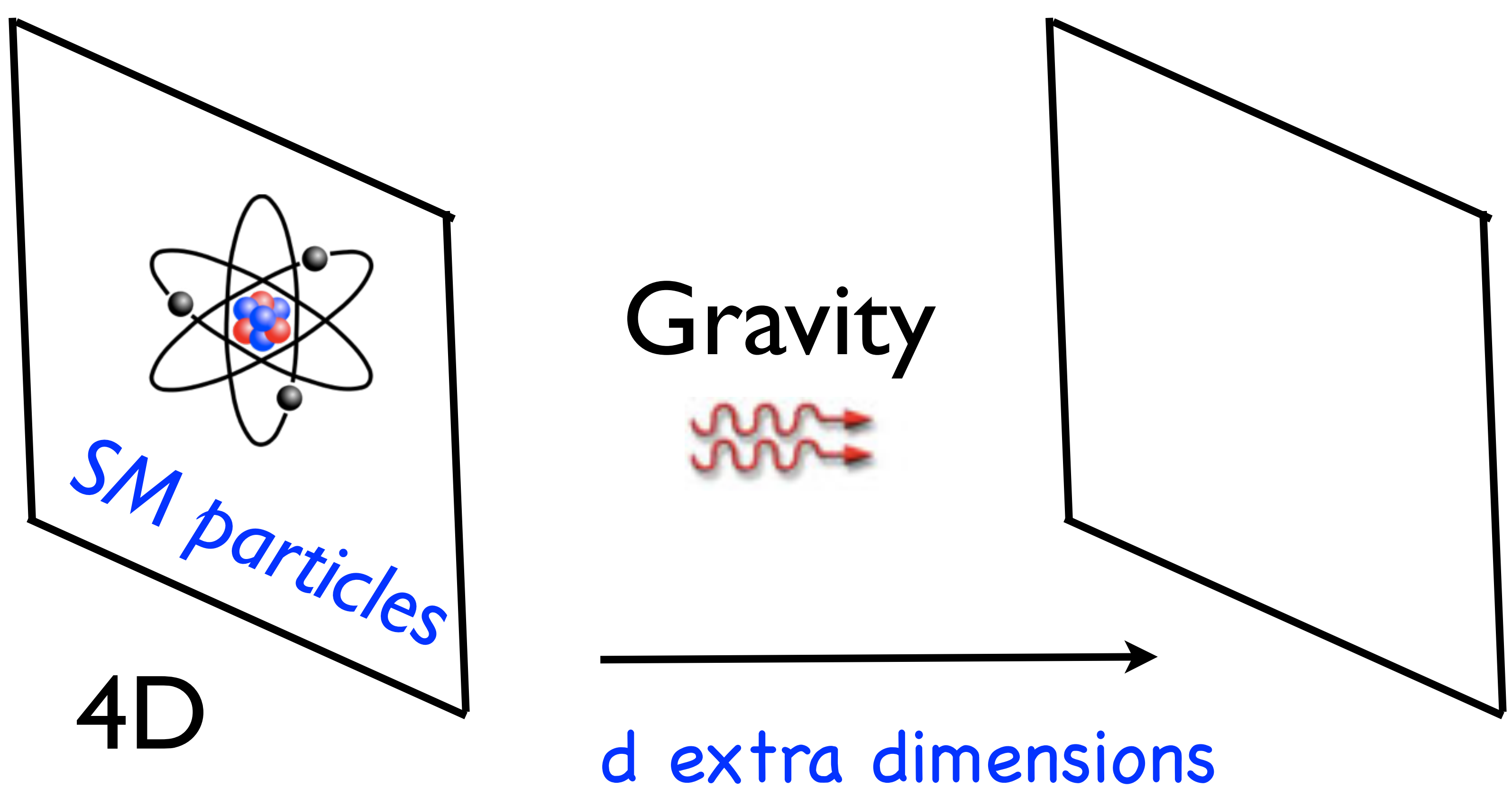
d = number of extra dimensions

At large distances, the strength of a force becomes smaller in higher dimensions

BUT:

1) Only gravity could propagate in these extra dimensions (otherwise all forces will be weak)

Possible in “Brane Worlds” (String constructions):



$$G_N = \frac{1}{M_P^2} \sim \frac{1}{M_{string}^2} \frac{1}{(M_{string} 2\pi R)^d}$$

$\Big\downarrow$ $M_{string} \sim \text{TeV}$

$d=1 \rightarrow R \sim 10^8$ Km — Not possible

$d=2 \rightarrow R \sim 0.1$ mm — ~ at the verge of the exp. bounds

...

$d=6 \rightarrow R \sim 1/$ MeV — OK

Predictions:

1) **For d=2**, we expect deviations from Newtonian gravity at distances smaller than ~ 0.1mm

2) **String theory at the reach of the LHC**

Two generic predictions:

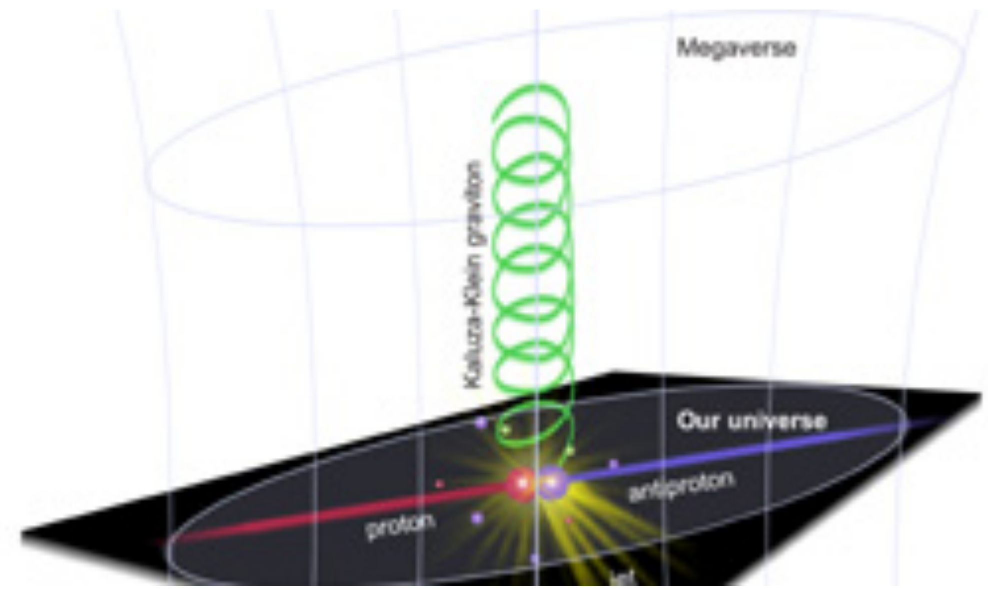
a) The space must be 1+9 dimensional

b) There are string excitations of higher-energy

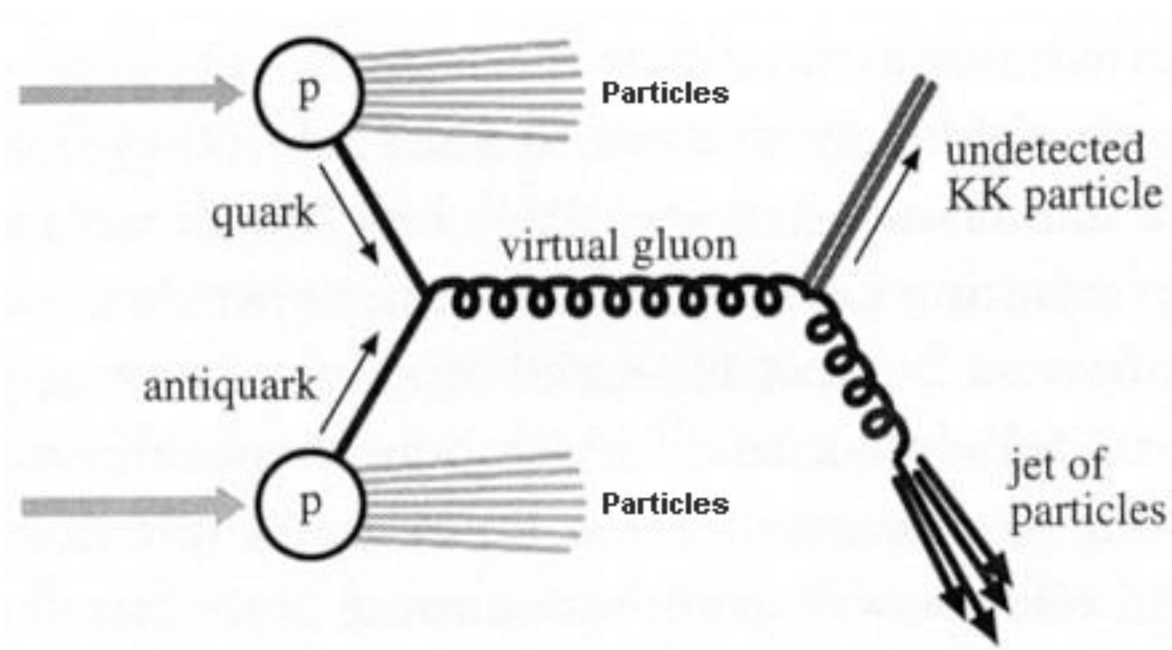
3) **Gravitons at the reach of the LHC**

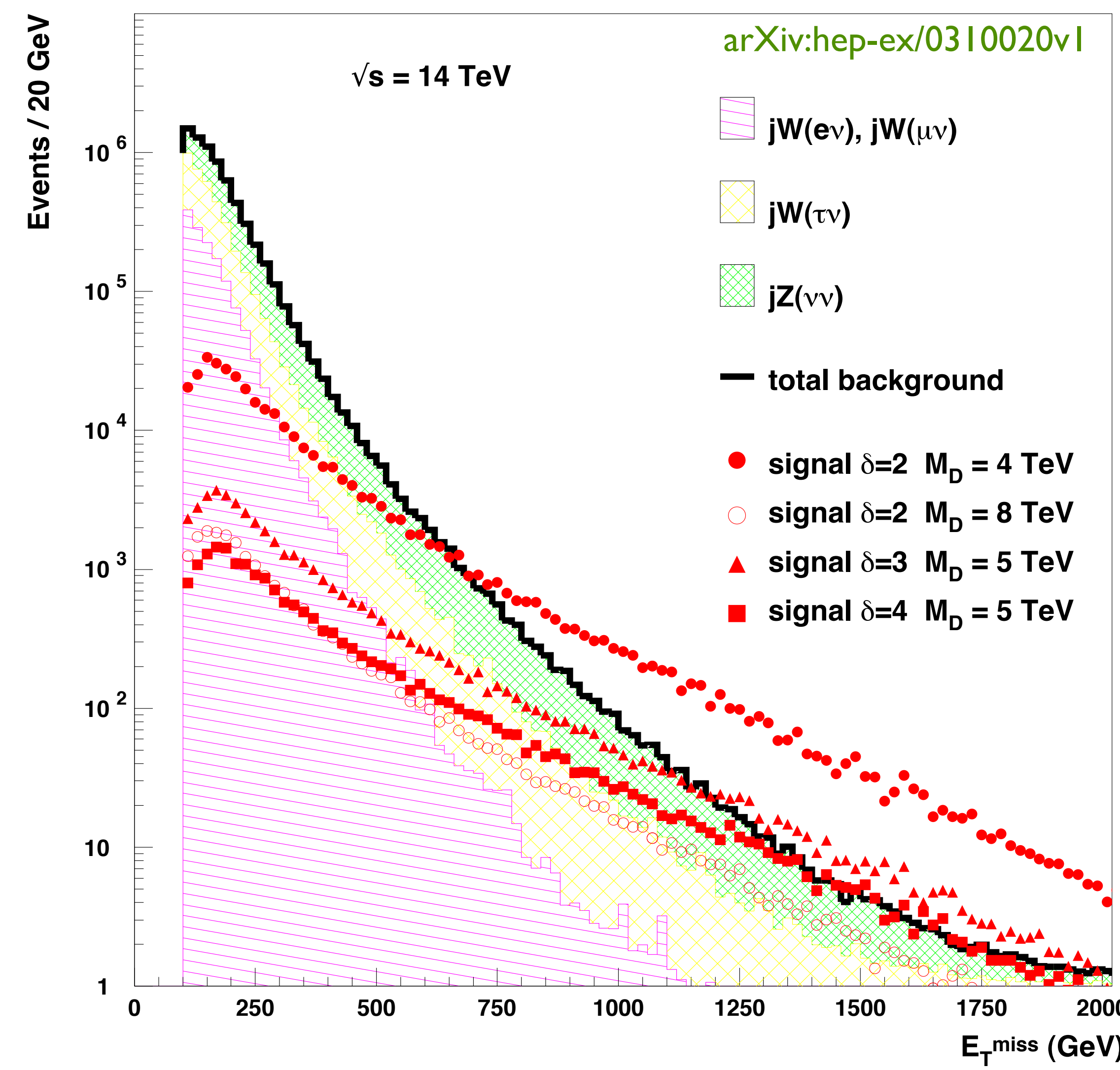
Model-independent signals from gravity at ~TeV

Graviton production:

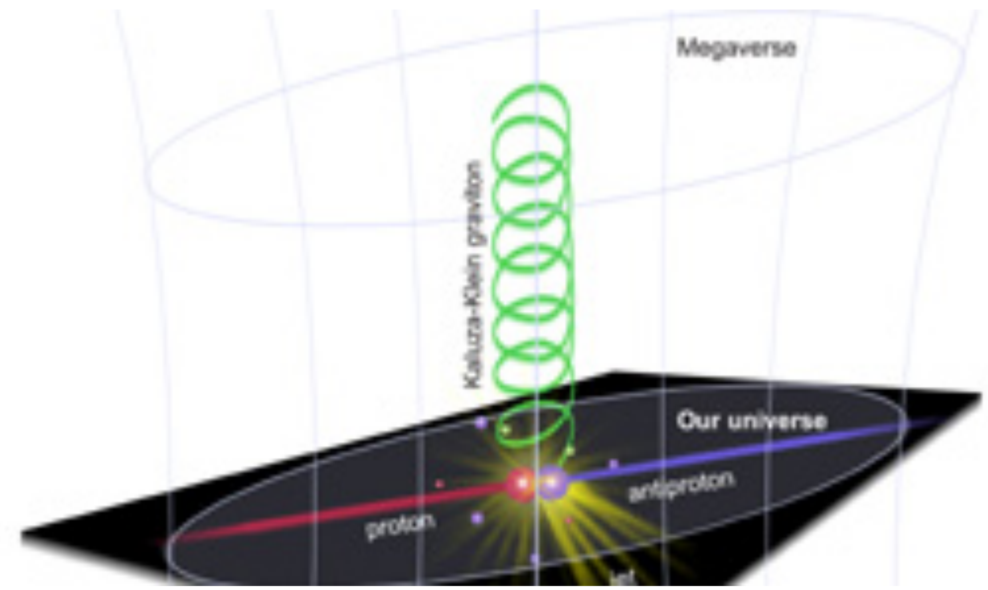


Search for:
Mono-jet + Missing energy





Model-independent signals from gravity at ~TeV



Graviton production:

Search for:
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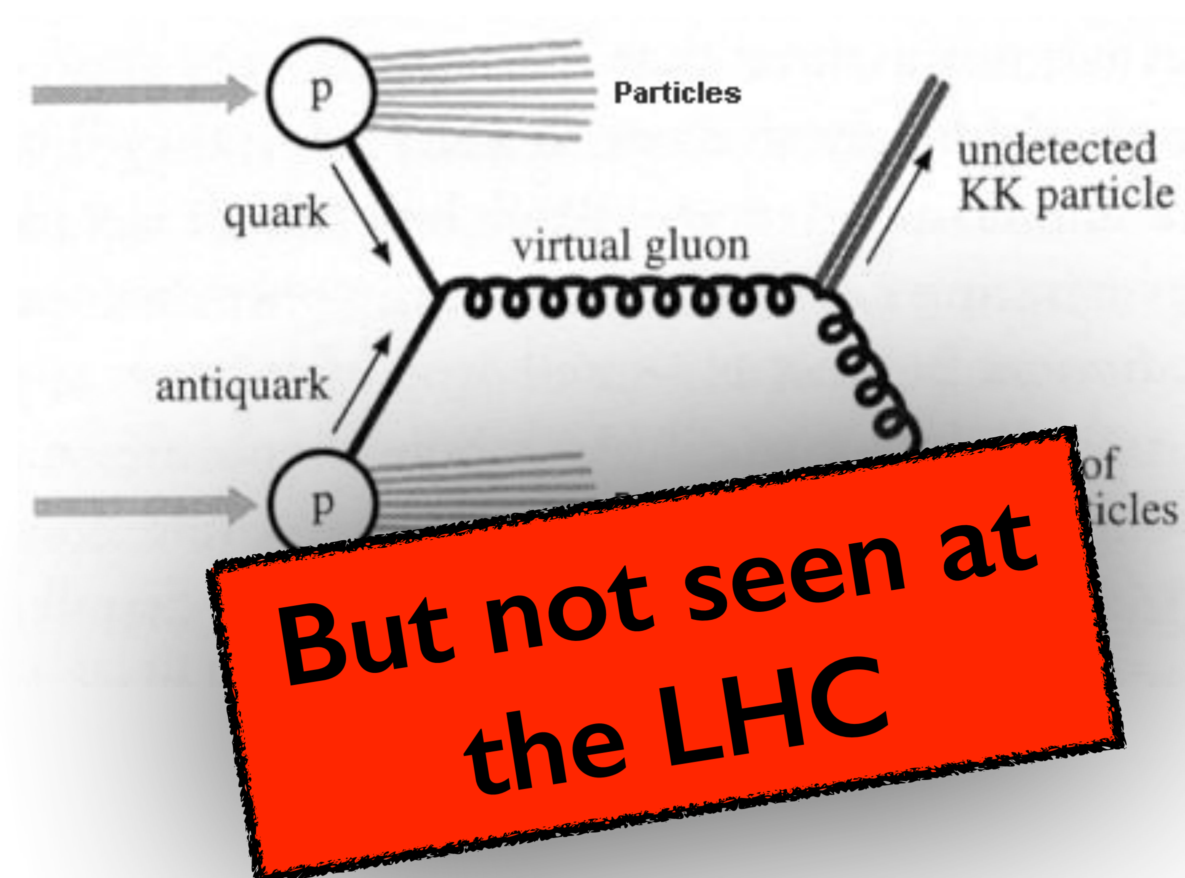

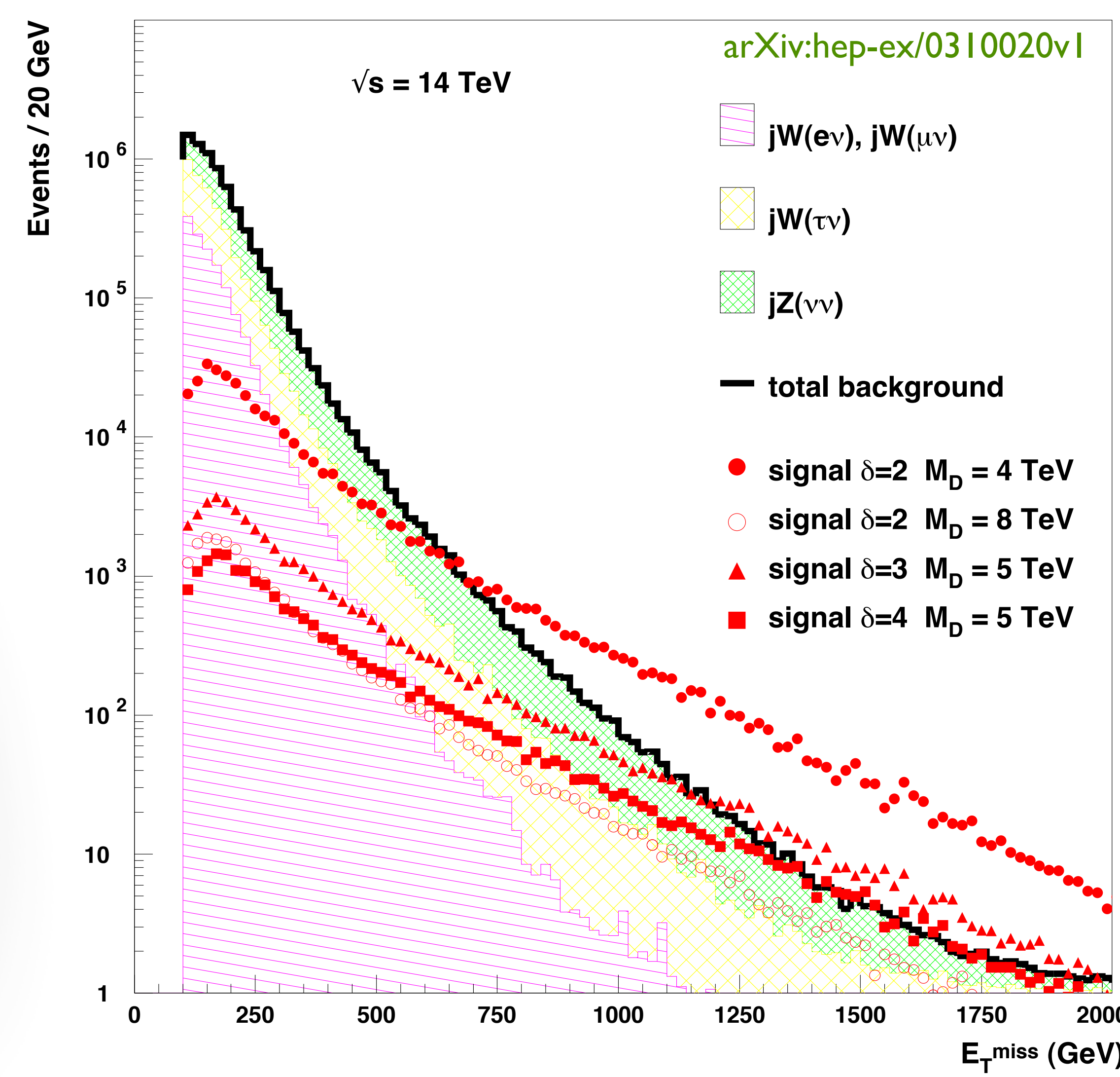

Present situation on New-Physics at the TeV

Pros

Could explain the origin of the EW scale

Cons

No new particles seen,
No new flavor-violations seen,
No deviations on Higgs couplings seen,
No deviations on Z/W couplings seen,
No WIMP detected,
No EDMs seen,

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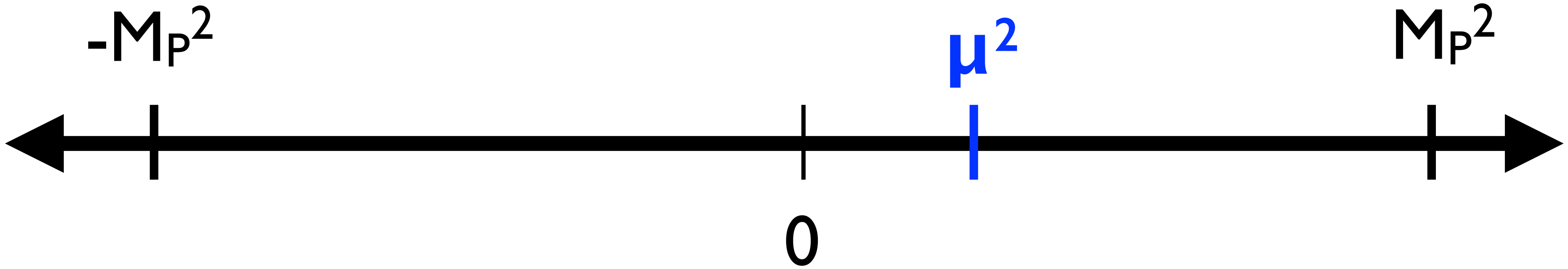
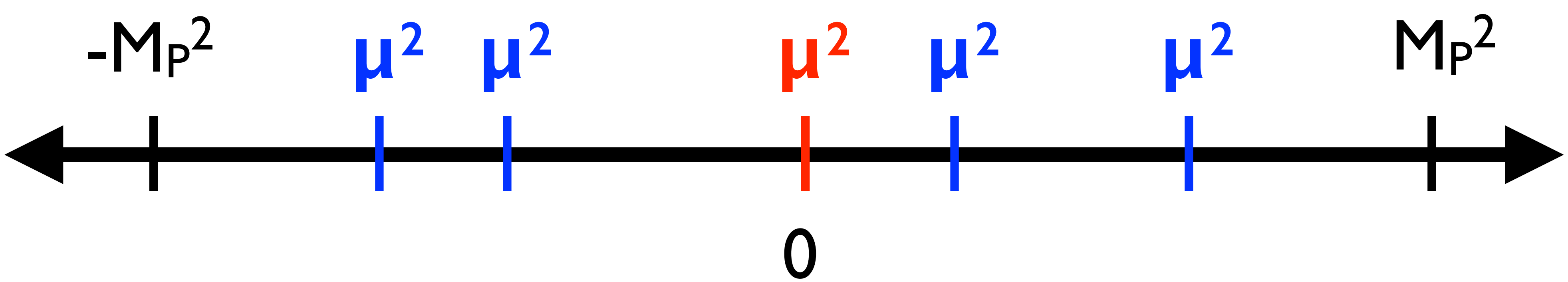
paradigm shift?

We need new ideas!

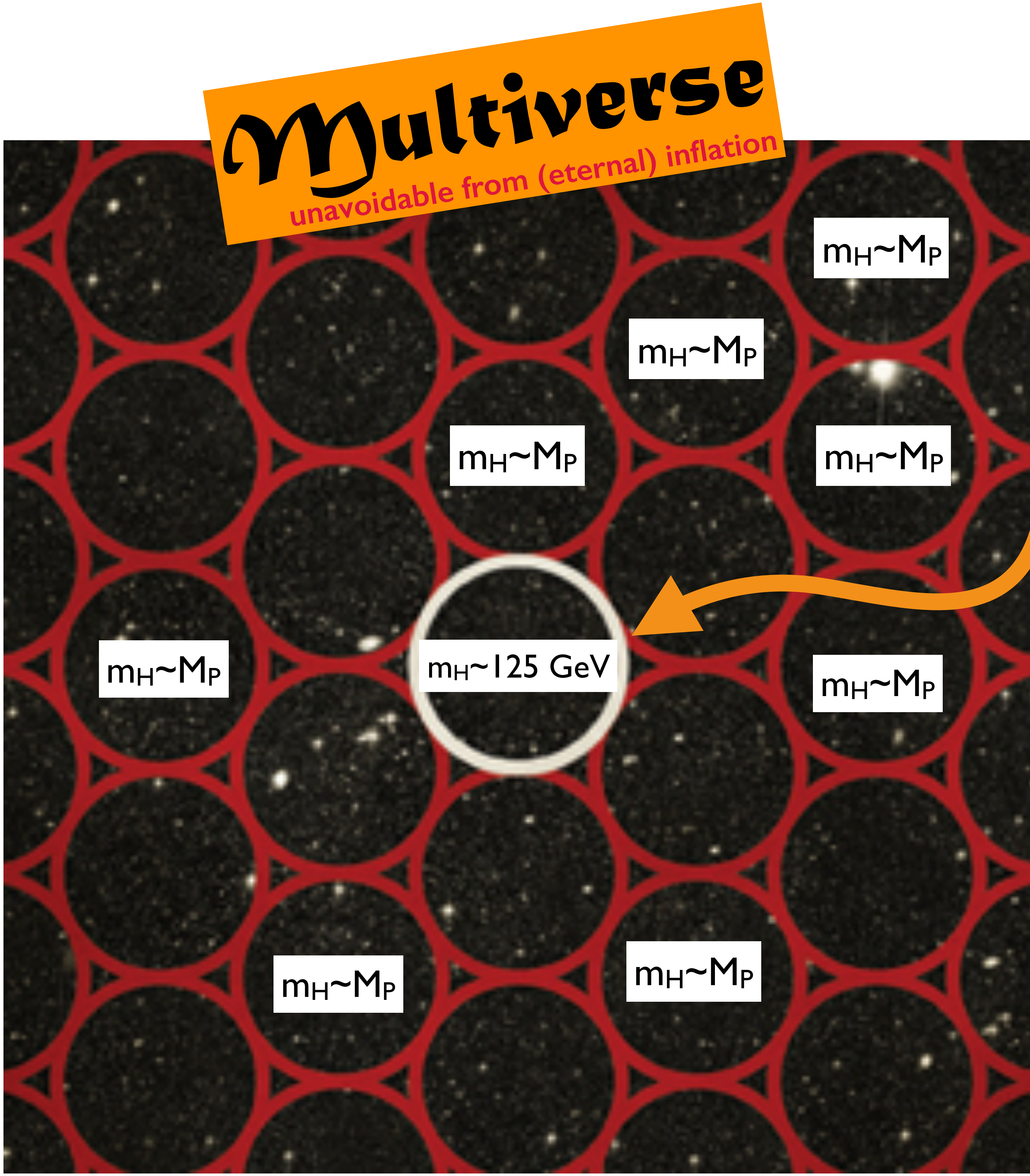
Where would you expect the Higgs mass (μ^2) to be?



But if one can “through many darts”:



One will hit the center!

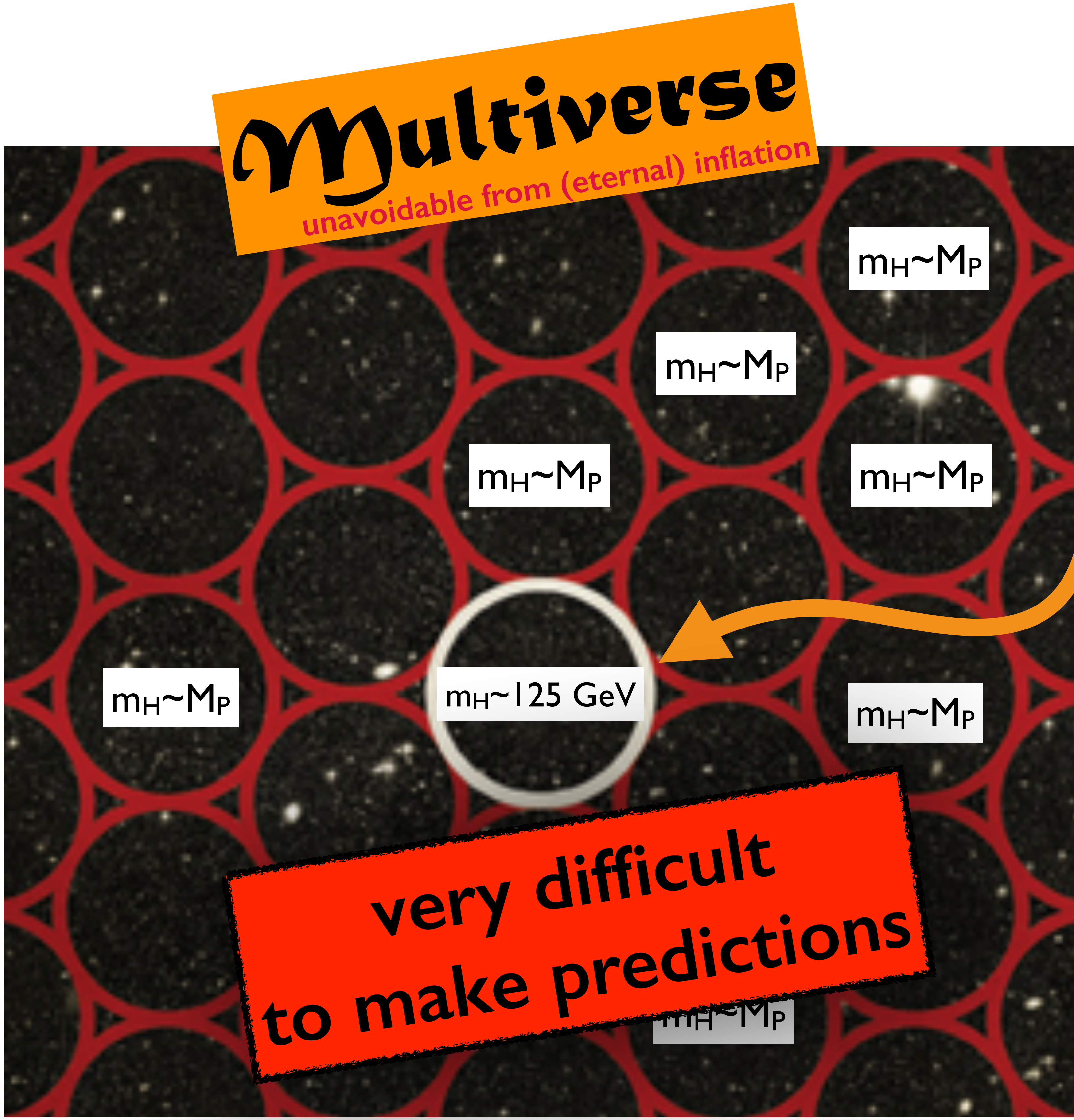


Our **Universe** is very delicate:
Change the SM parameters and could be uninhabitable

"Natural", since only we can "live" in a Universe with these "fine-tuned" parameters

$\Downarrow$

<u>No new physics at the TeV!</u>
(new physics in another universes)



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parameters

↓

<u>No new physics</u>
<u>at the TeV!</u>
(new physics in
another universes)

At present, the only scenario that could "explain"
the present smallness of the cosmological constant!

2) “Relaxation” mechanism:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

Higgs-mass parameter → Field-dependent Higgs mass

$$m_H^2|H|^2 \qquad\qquad m_H^2(\phi)|H|^2$$

minimum of $\boldsymbol{\phi}$ where

$$m_H^2(\phi) \ll M_P^2$$

Breakthrough:

An axion-like ϕ can have the following (natural) potential:

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

P.W. Graham, D.E. Kaplan, S.Rajendran
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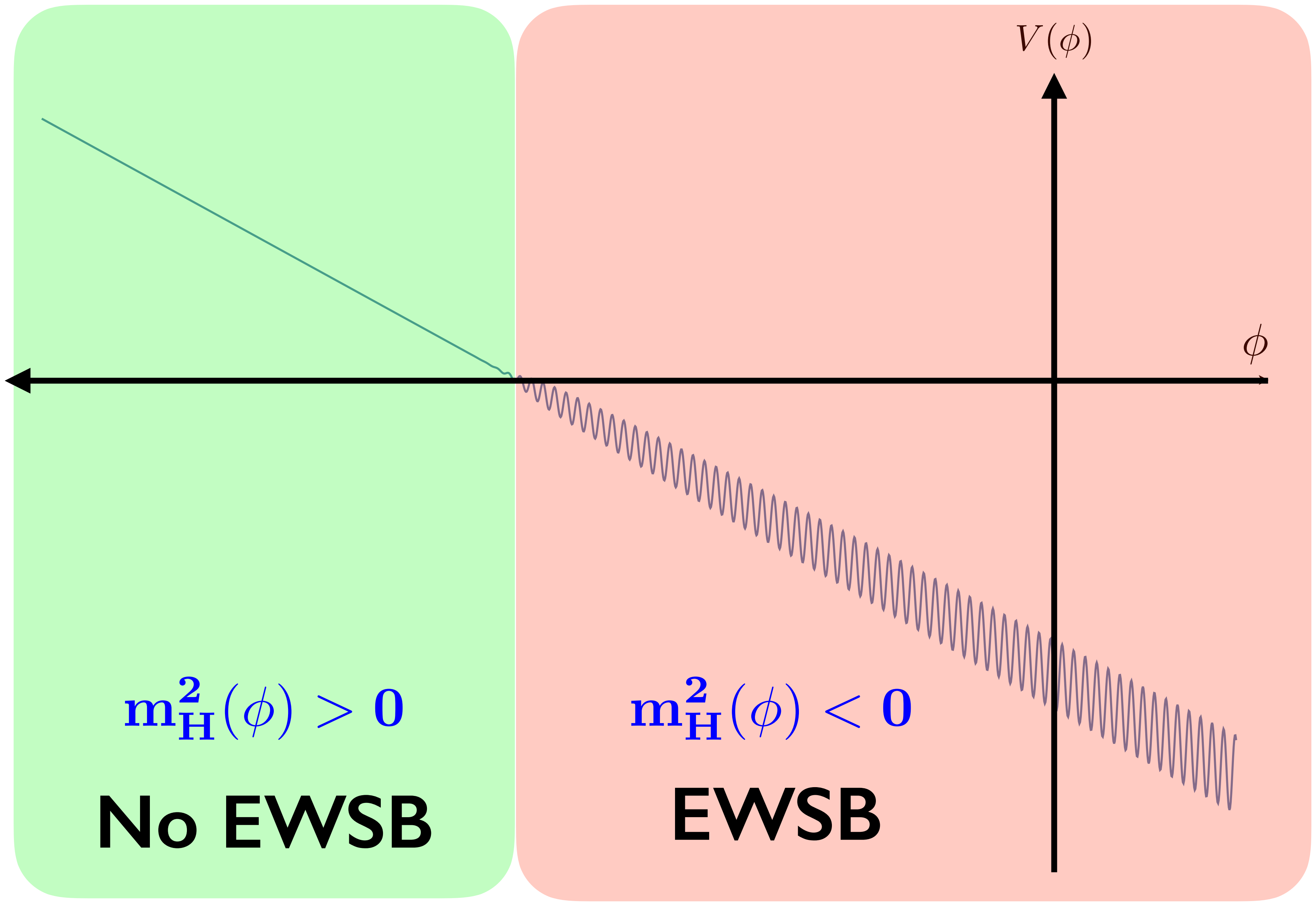

Cosmological evolution can lead to a small EW scale

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

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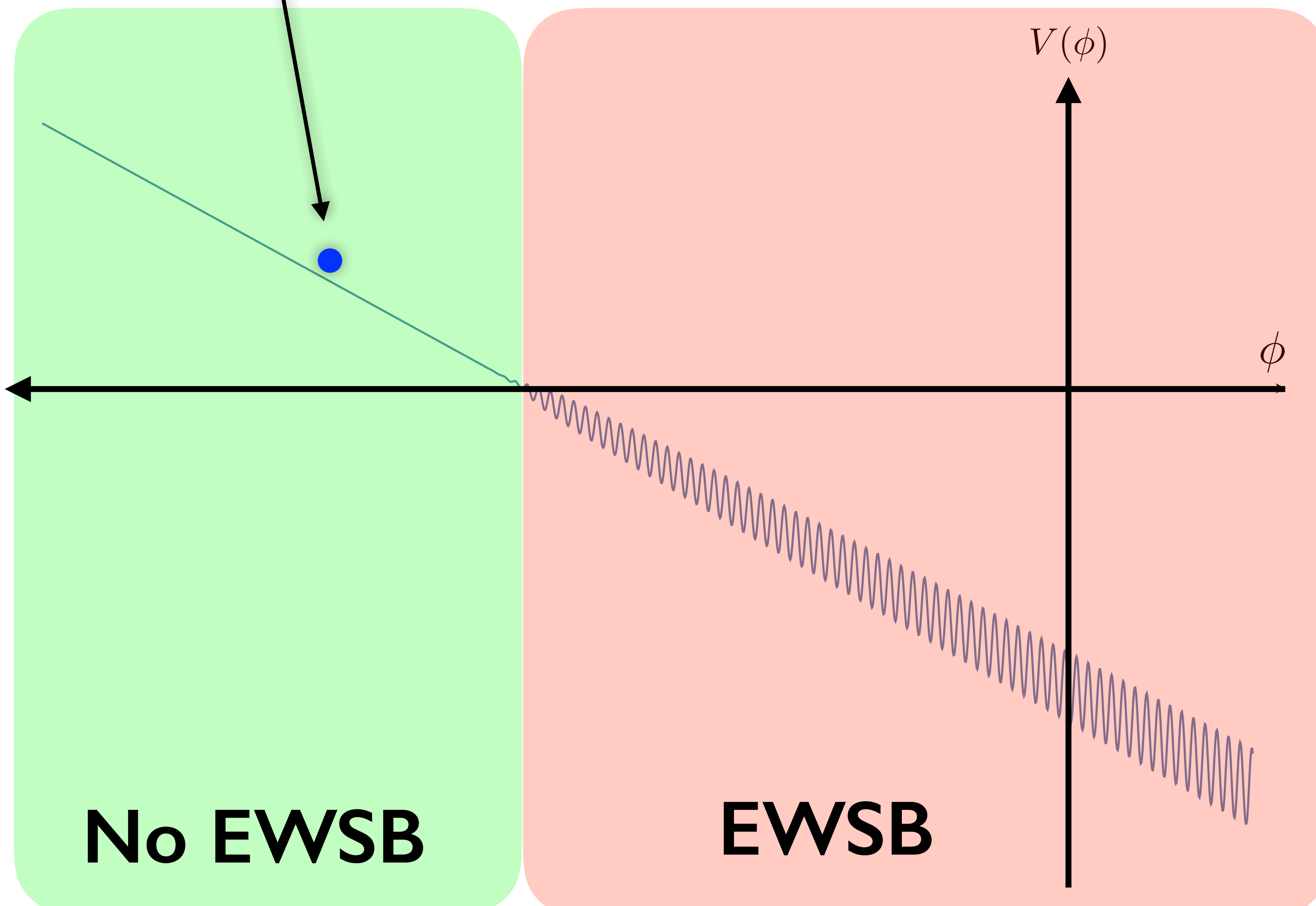
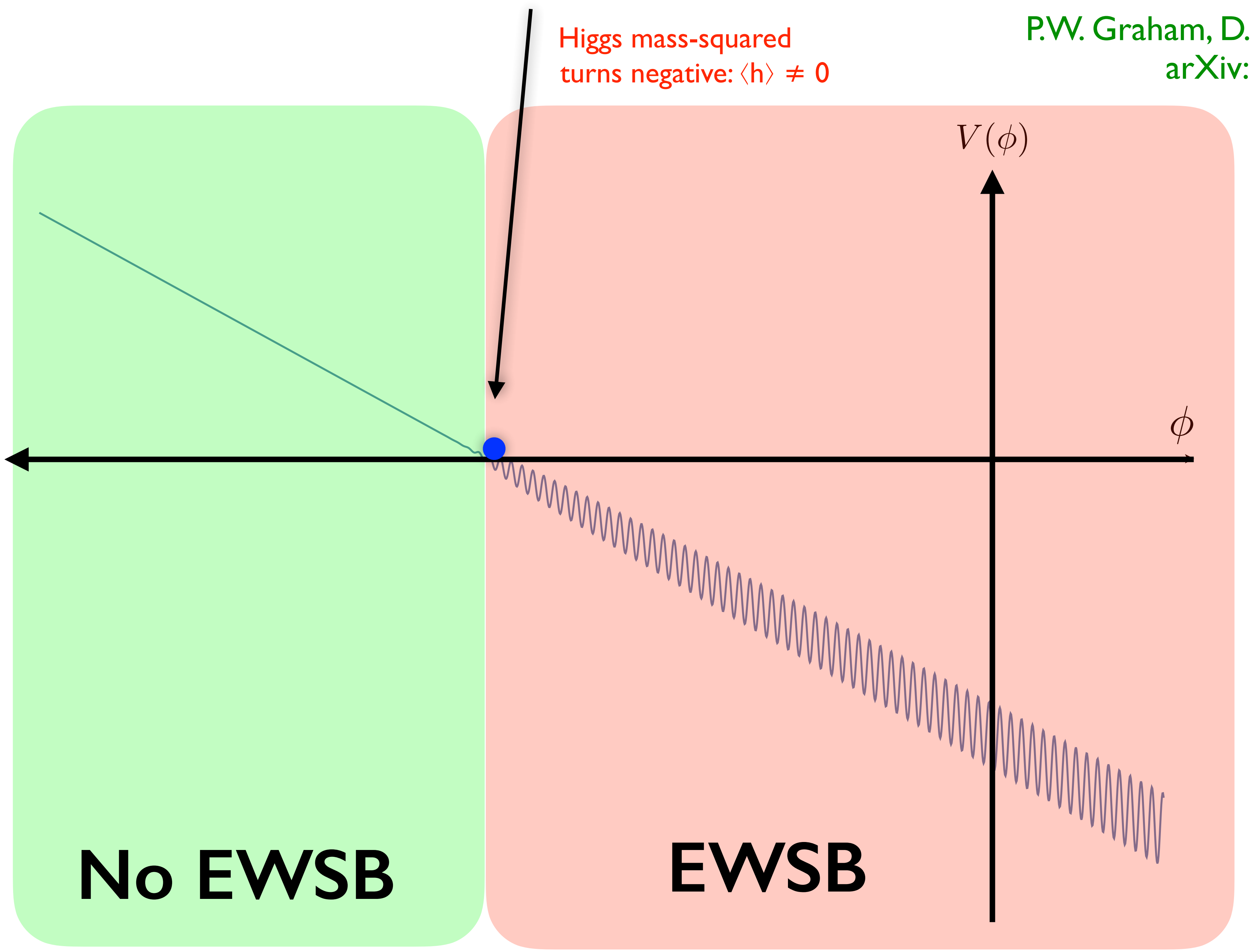


Cosmological evolution can lead to a small EW scale

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551



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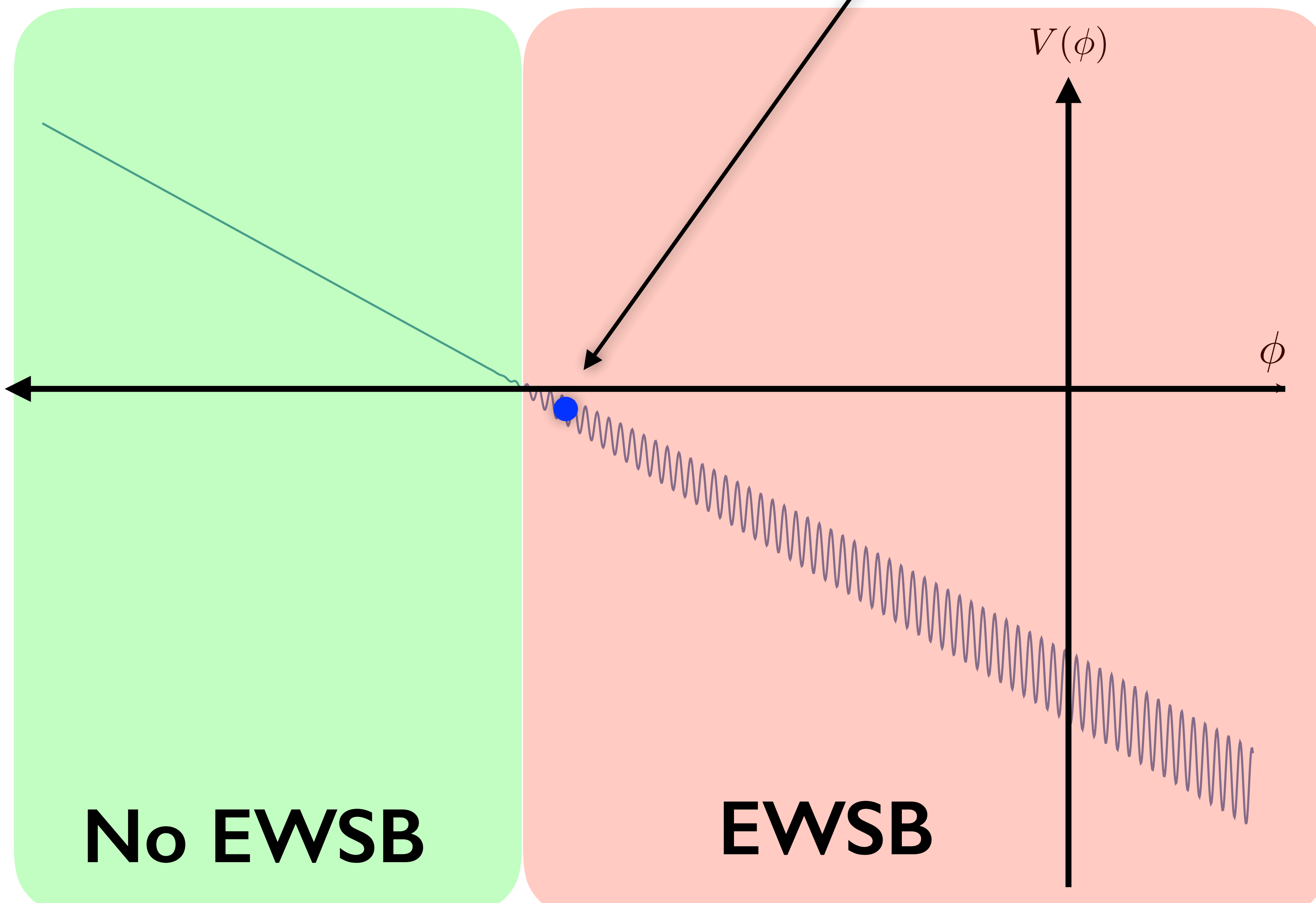
becomes
more & more
important

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551



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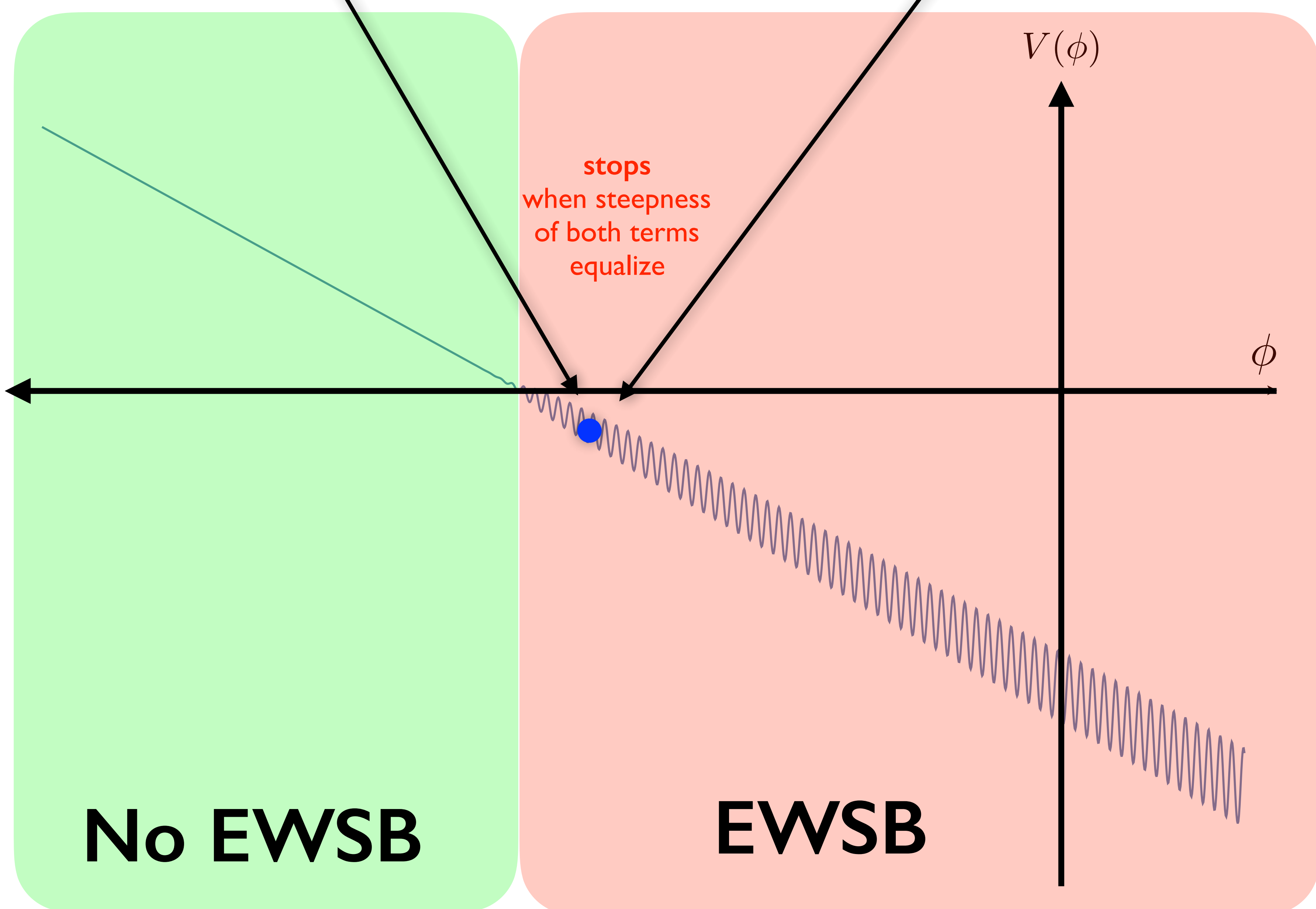

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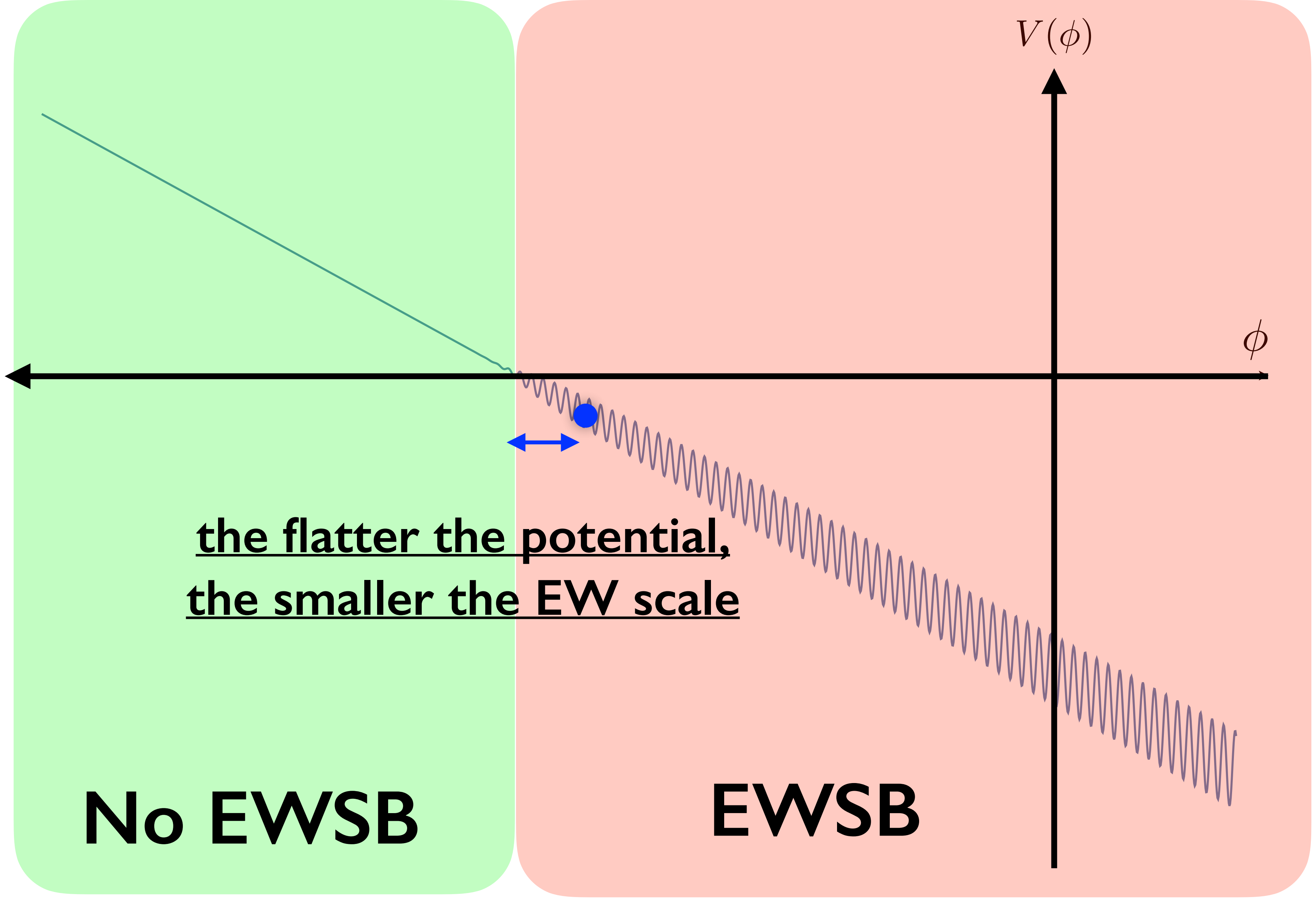
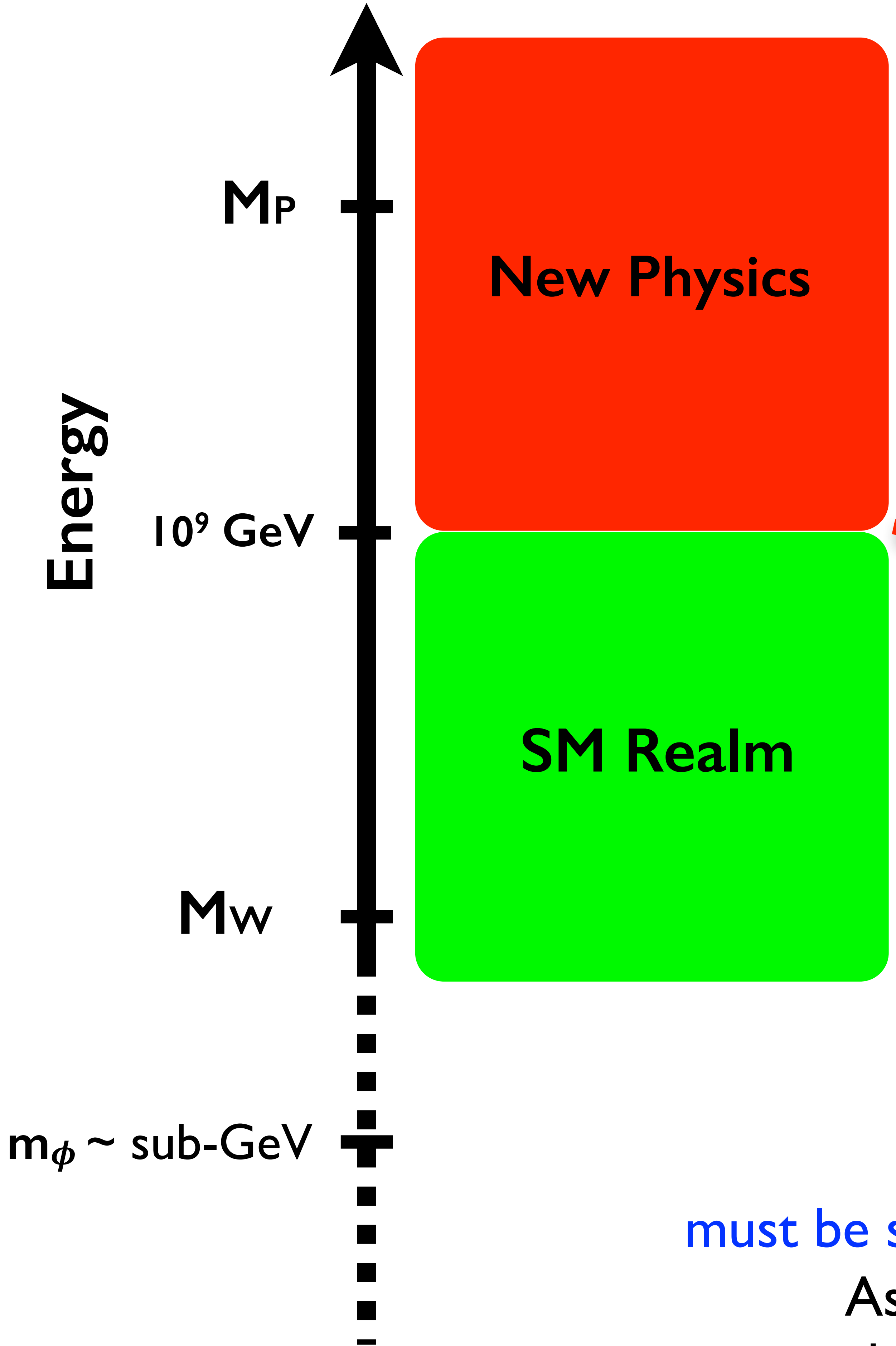




New physics scale can be pushed up naturally to at least 10^9 GeV

see for example, J.R.Espinosa,C.Grojean,G.Panico,A.P., O.Pujolàs,G.Servant 15

<u>Main prediction:</u>

ϕ's: very light & extremely weakly-coupled states (*axion-like*)

must be searched in different type of experiments:

Astro (γ-rays, pulsar timing, …), CMB, table-top (fifth-force searches, EPV), …

Conclusion

- Big achievement at LHC run I

  ➥ **the SM has been completed**

  ➥ **No need** for anything else
  (at least) up to around the **Planck scale**

End of <u>no-lose theorems</u> for discovery at the nearby energy frontier

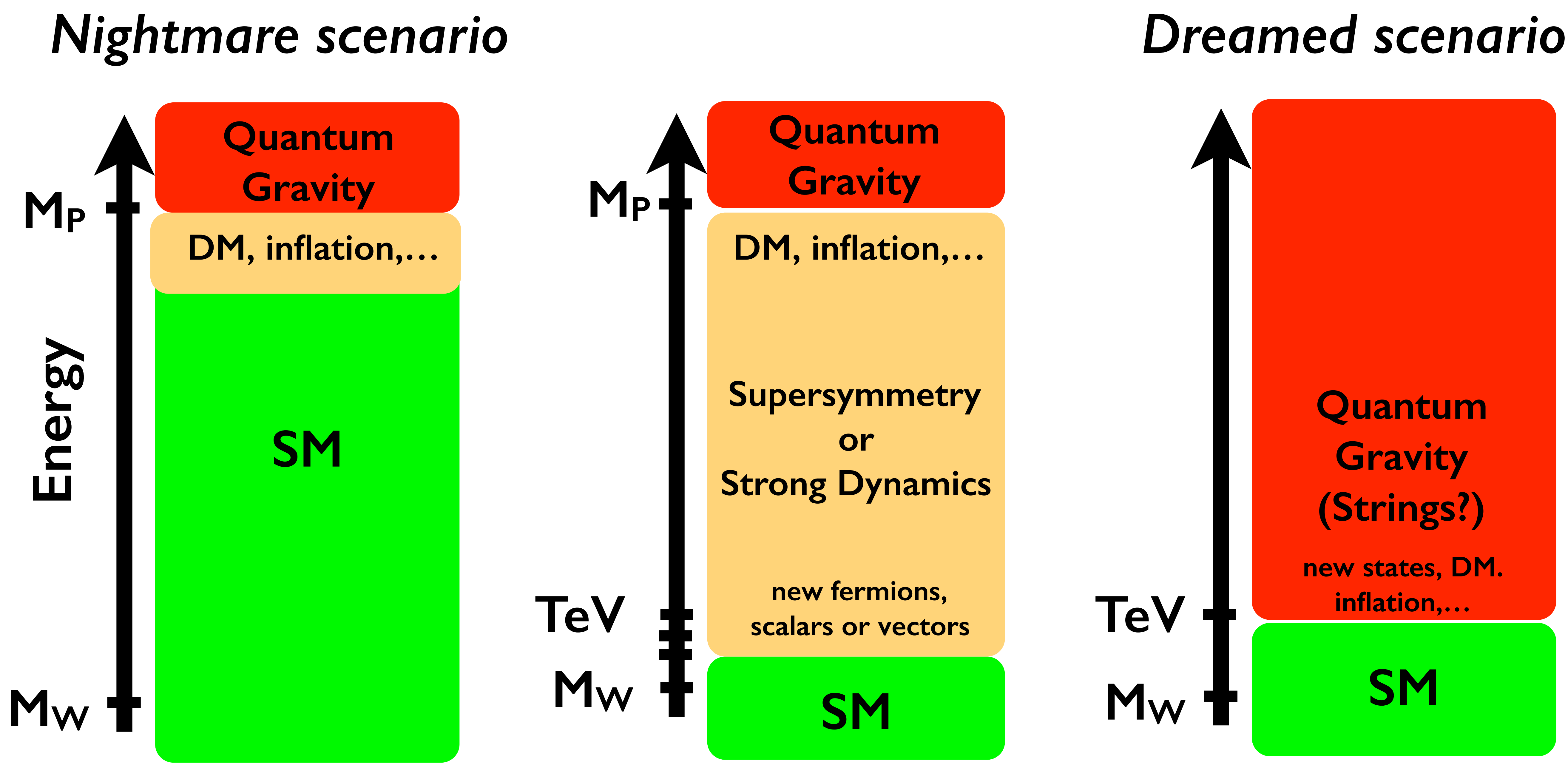
- We start a very different **phase** in particle physics:

Discovery is not anymore guaranteed !

We could discover plenty,
we could discover nothing…

It was the best of times,
It was the worst of times,
…
It was the spring of hope,
It was the winter of despair
A Tale of Two Cities

BSM scenarios from pessimistic to optimistic



Not much to learn in the near future

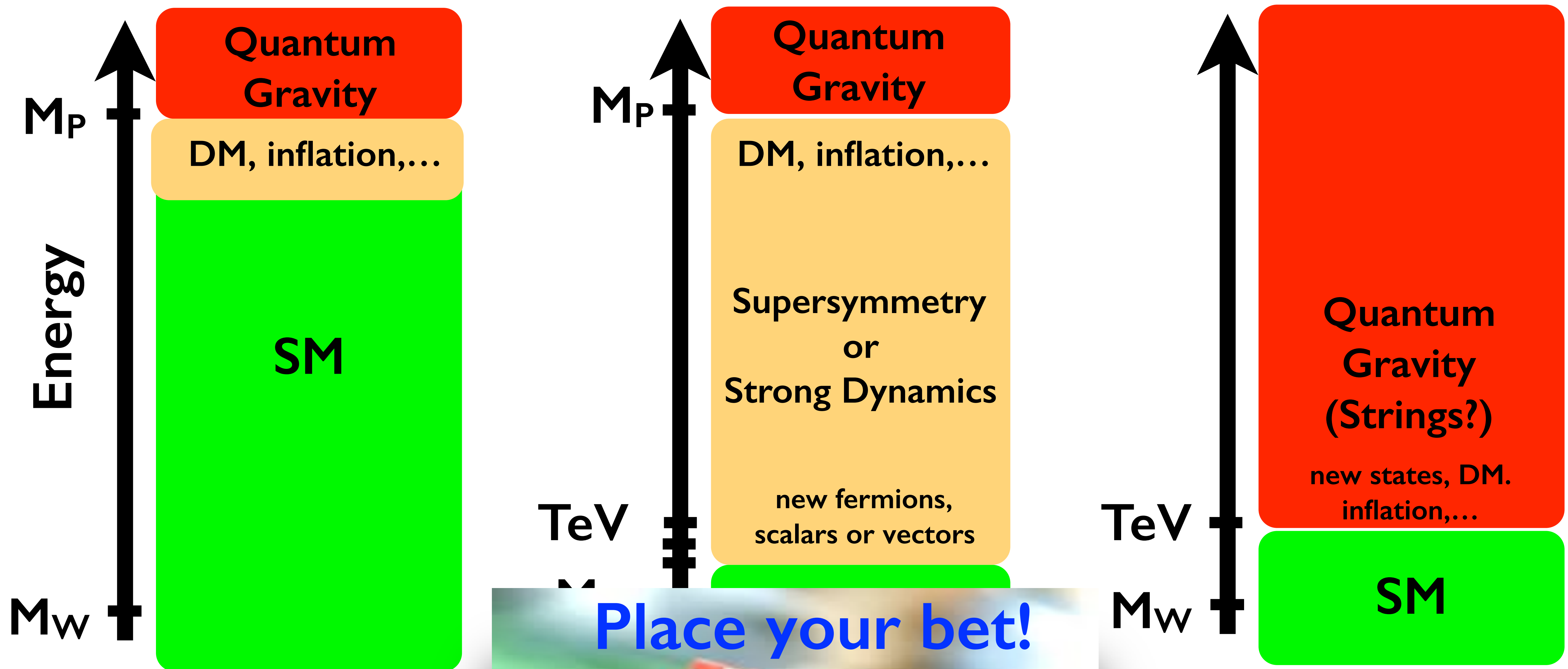
proton decay?

We learn on the **origin** of the EW scale in the near future

We learn on **everything** in the near future

BSM scenarios from pessimistic to optimistic

Nightmare scenario | *Dreamed scenario*



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