Beyond the Standard Model

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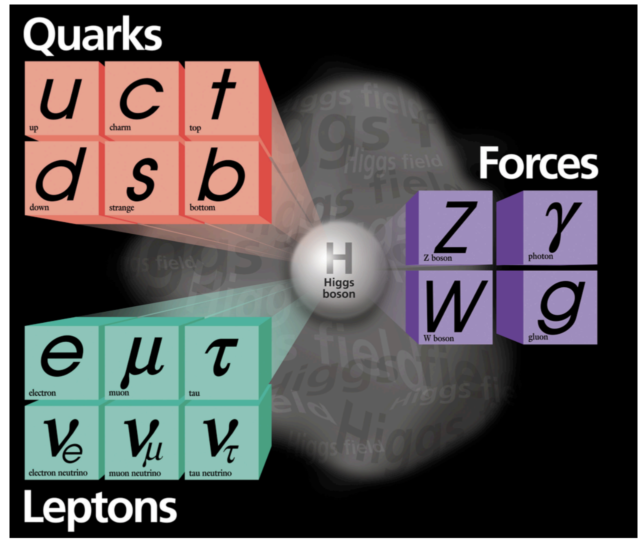
Outline:

- The Standard Model: symmetries, consistency, and reasons for improvement
- Grand Unified Theories
- The strong CP-problem and axions
- The hierarchy problem
- Supersymmetry
- Composite/PGB Higgs and Higgsless models
- Extra dimensions

What you must know:

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

The SM:



Gauge symmetry: SU(3)xSU(2)xU(1)

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

$Q=Y/2+T_3$

\+ **Gravity** (General Relativity)

Relatively simple lagrangian for the SM:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4g'^2}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4g^2}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4g_s^2}G^{\mu\nu}G_{\mu\nu}$$

$$+i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{l}^i_L \not{D} l^i_L + i\bar{e}^i_R \not{D} e^i_R$$

$$+|D_\mu H|^2$$

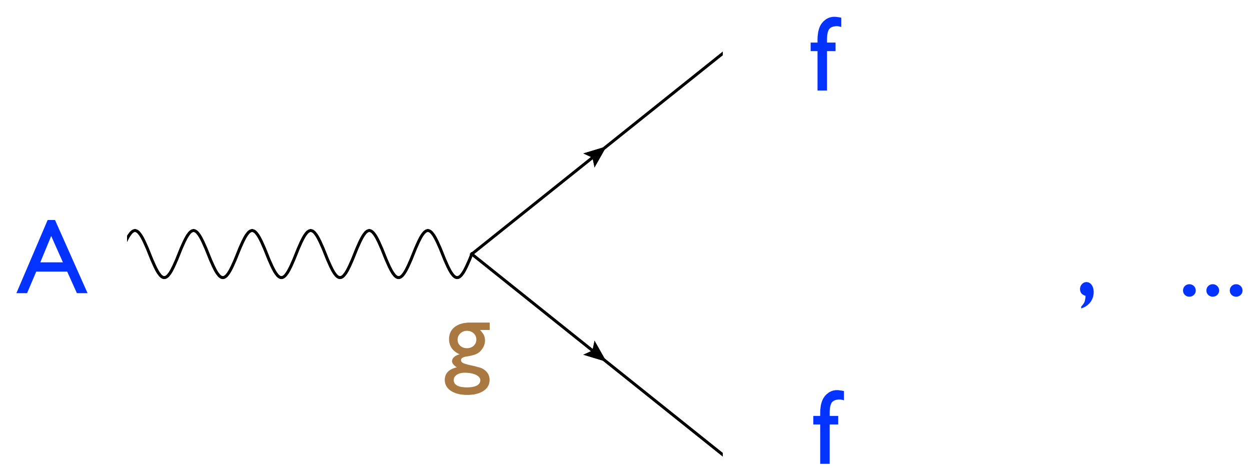
$$+Y_u^{ij}\bar{Q}^i_L \tilde{H} u^j_R + Y_d^{ij}\bar{Q}^i_L H d^j_R + Y_e^i \bar{l}^i_L H e^i_R + h.c.$$

$$+V(H)$$

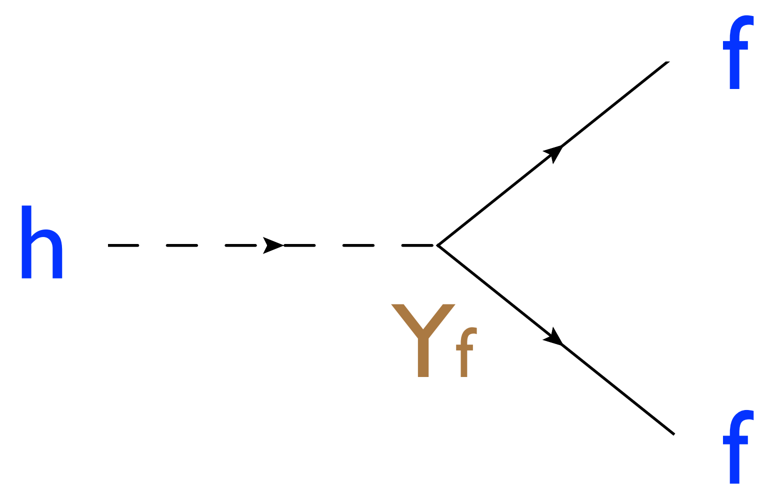
+ we are, for the moment, neglecting neutrino masses!

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

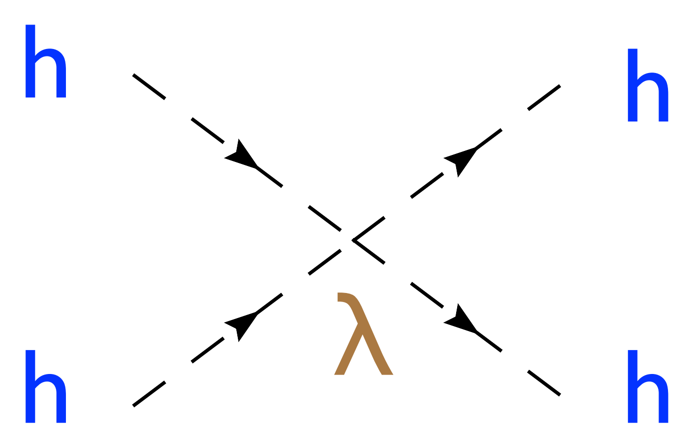
Gauge:



Yukawa:



Self-Higgs:



g, Y_f, λ = dimensionless couplings

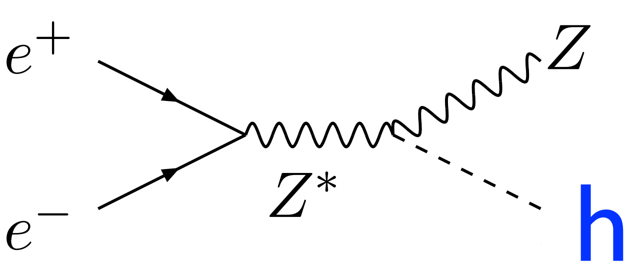
Only one unknown parameter:

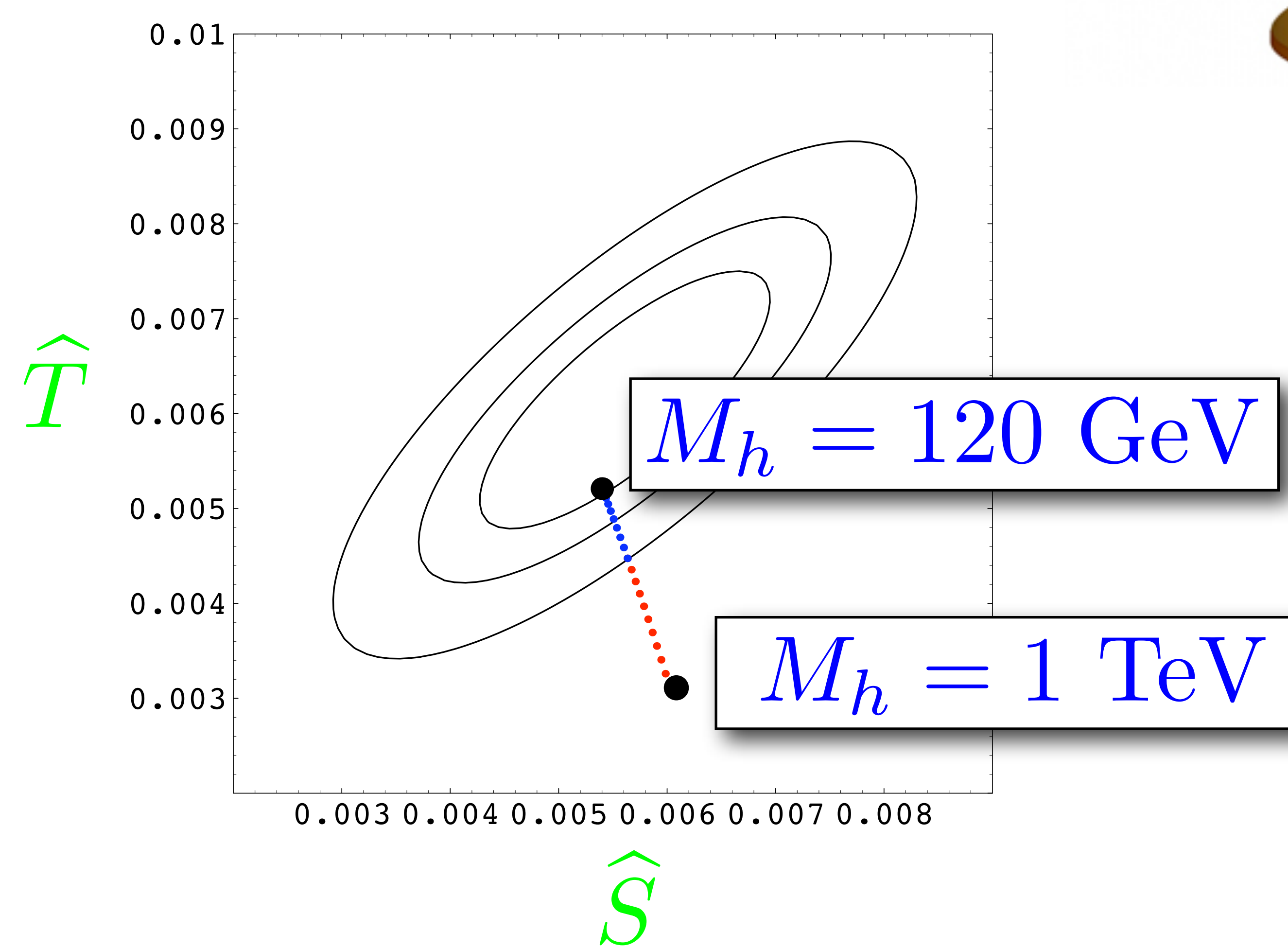
The Higgs mass

(or λ)

Experimental bounds:

LEP searches + EW Precision Tests





➥ 114 GeV $< M_h <$ 186 GeV (95%CL)

SM Lagrangian dictated by symmetries:
Gauge + (local) **Poincare** symmetries

when gravity is included

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

"Symmetries are the keystone of the universe"

The SM has also extra **"accidental" symmetries**:

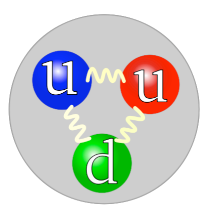
We didn't ask for them, but they are there!

Are Global Symmetries: $\psi \rightarrow e^{iB\theta}\psi$

1) Baryon number B:

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), $L_\mu=1$,(for μ), $L_\tau=1$,(for τ) (zero for the rest)

→ μ cannot decay to e+photon

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

1) Custodial symmetry:

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

Extra global SU(2): H being a doublet

when it gets a VEV: $SU(2)_L \times SU(2) \to SU(2)_c$

(W^+, W^-, Z) are a triplet of $SU(2)_c$ ➠ $m_W = m_Z$

- 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:

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

➠ Small K-$\bar{K}$ mixing

...but these **accidental symmetries** of the SM are only symmetries of the dimension-4 operators:

Dimensional analysis ($\hbar = c = 1$) tell us that

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

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

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

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

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

} All SM terms in the Lagrangian have dimension 4

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

This new terms spoil the predictivity of the SM:

We have infinite of them!

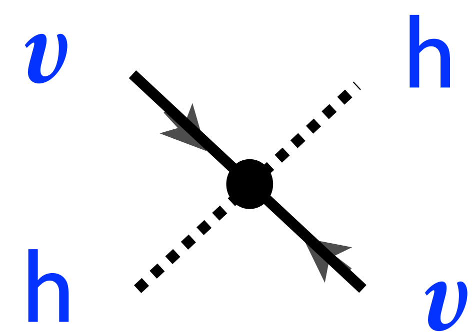
It's OK, for physics at scales smaller than Λ:

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

... but, even worse, higher-dim terms don't respect the accidental symmetries of the SM:

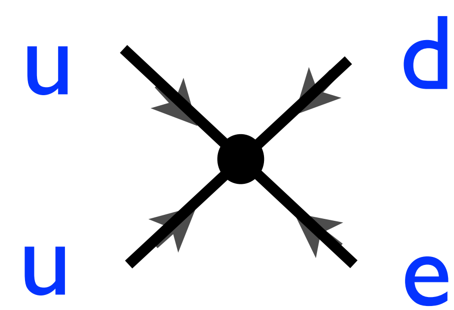
L violation:

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

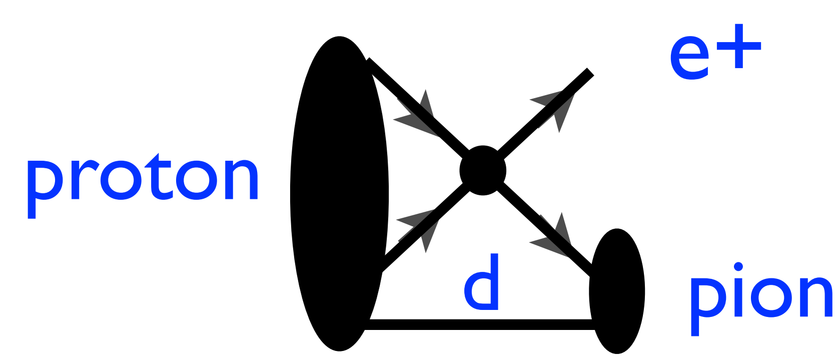


B violation:

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



↪ **Proton decay:** $p \rightarrow \pi^0 e^+$



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

Lessons so far:

- The SM Lagrangian (based on local symmetries) has extra global symmetries (B,L,...)

- Extra terms (suppressed by Λ) could be added (preserving local symmetries) but are dangerous since break the symmetries (B,L,...)

We have to require Λ be very large

➥ **can we take it to be infinity?**

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

Theoretical: Consistency of the theory?

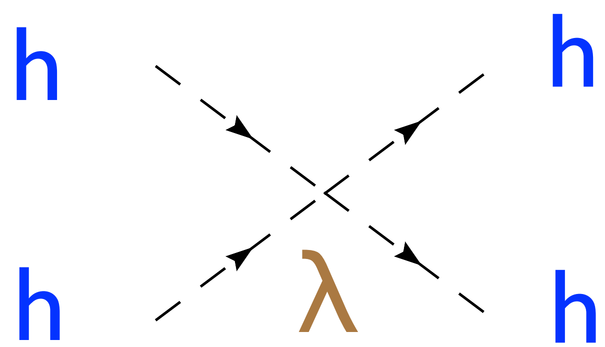
Experimental: Data that cannot be explained?

TH **Could it be the the SM the final theory?**

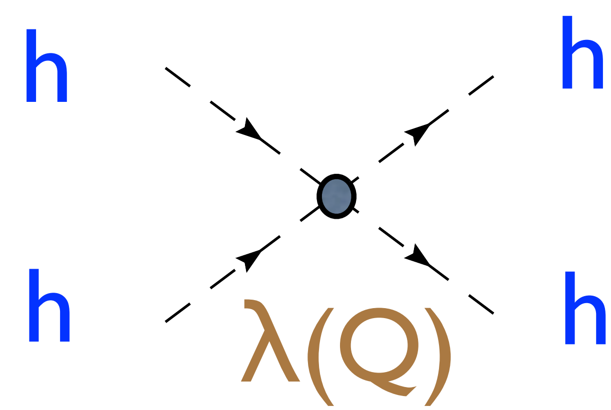
We must use Einstein "Gedankenexperiment"
(thought experiments):

"...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

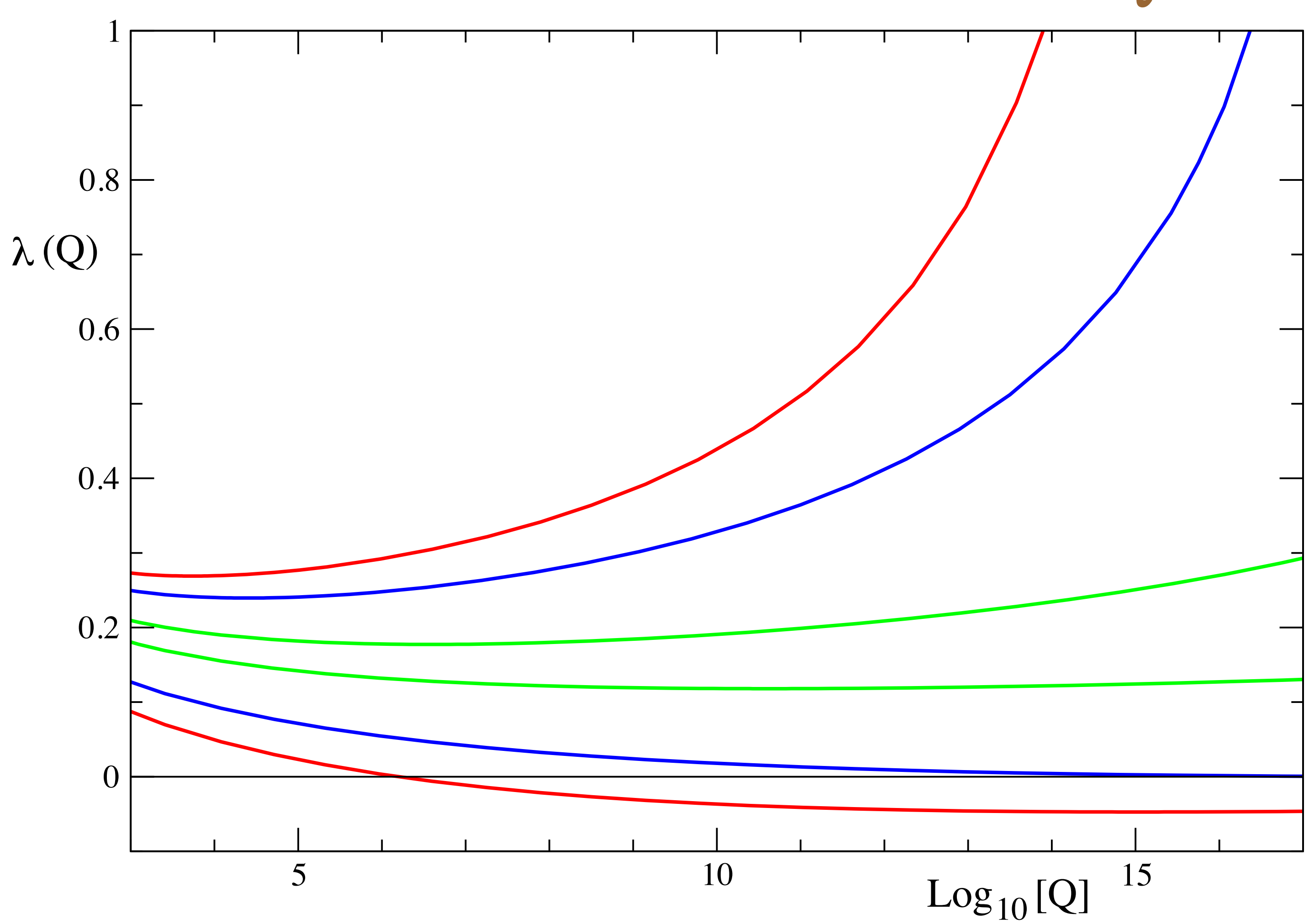


+ loops ~



where Q ~ E_{cm}

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



"velocity" of growth of λ(Q)

Espinosa

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

  λ(Q=Λ) ~ π

  (perturbation theory not valid anymore)

- If λ(Q) decreases, it can become negative at some scale Q = Λ:

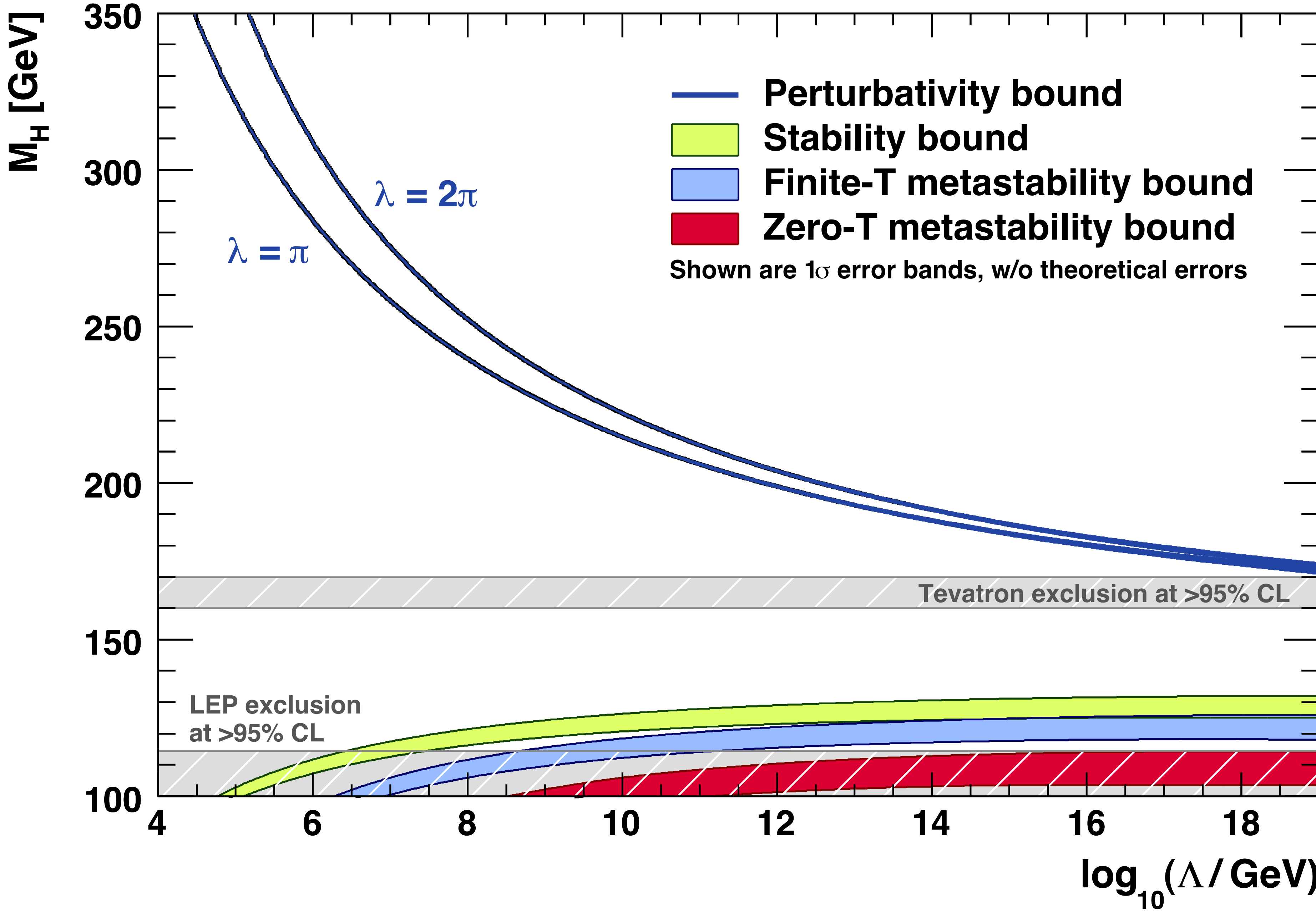
  ➥ Unstable Higgs potential

Λ ≡ "Cut-off scale" ☛ I cannot trust my theory at Q > Λ

Since $M_h^2 = 2\lambda(Q = M_H)v^2$

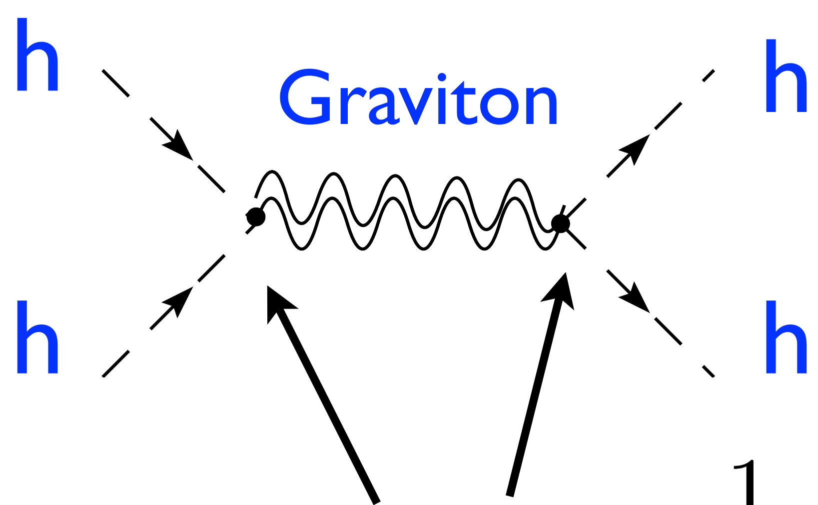
for each Higgs mass there is a scale Λ

Ellis et al



$\Lambda = 10^{19}$ GeV

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



$\sim G_N Q^2$

at Q > M_P violation of unitarity
~ quantum loops of gravitons
important

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

G_N = Newton's constant

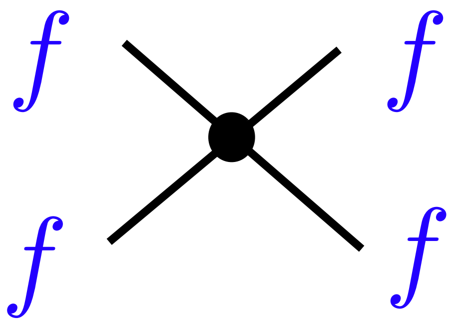
M_P = Planck's mass ~ 1.2 x 10^{19} GeV

SM+GR not a consistent quantum theory at Q> M_P!

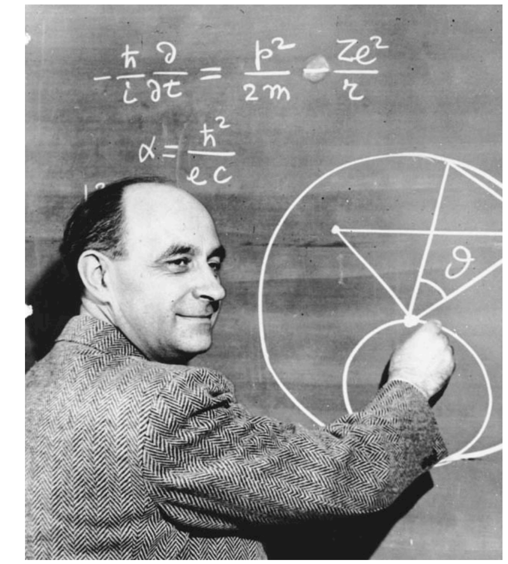
New physics expected (at least)

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

Very similar to Fermi's theory:



$\sim G_F Q^2$



G_F = Fermi's constant

We know what happened at $Q \sim 1/\sqrt{G_F} \sim 300$ GeV:

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

We discovered the W/Z particles, the SM!

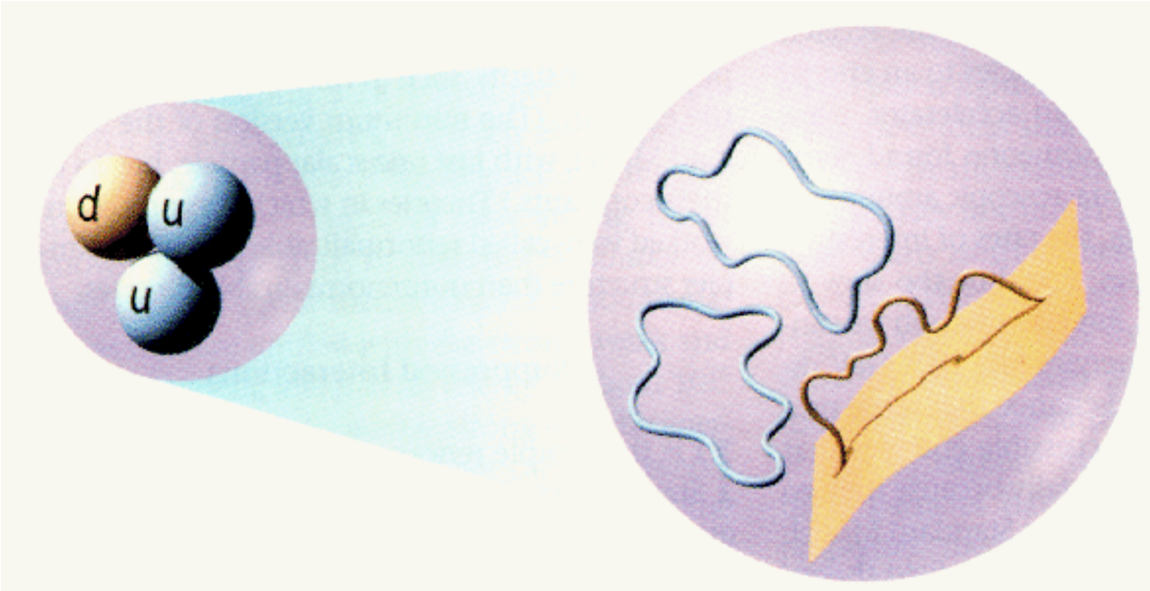
TH

Could it be the SM the final theory?

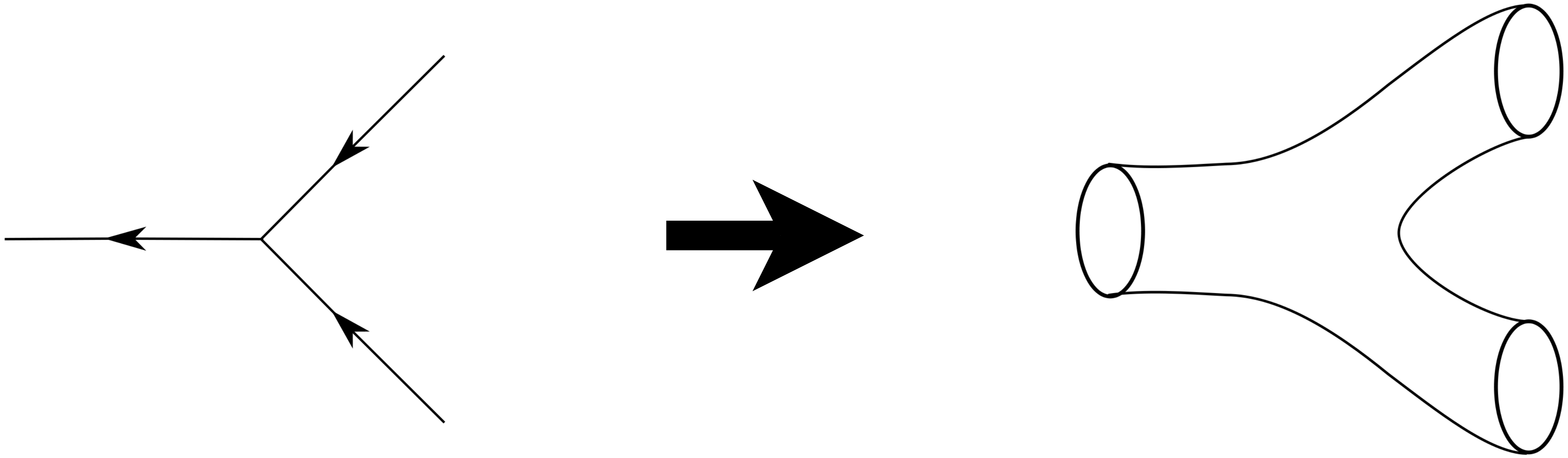
NO !

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

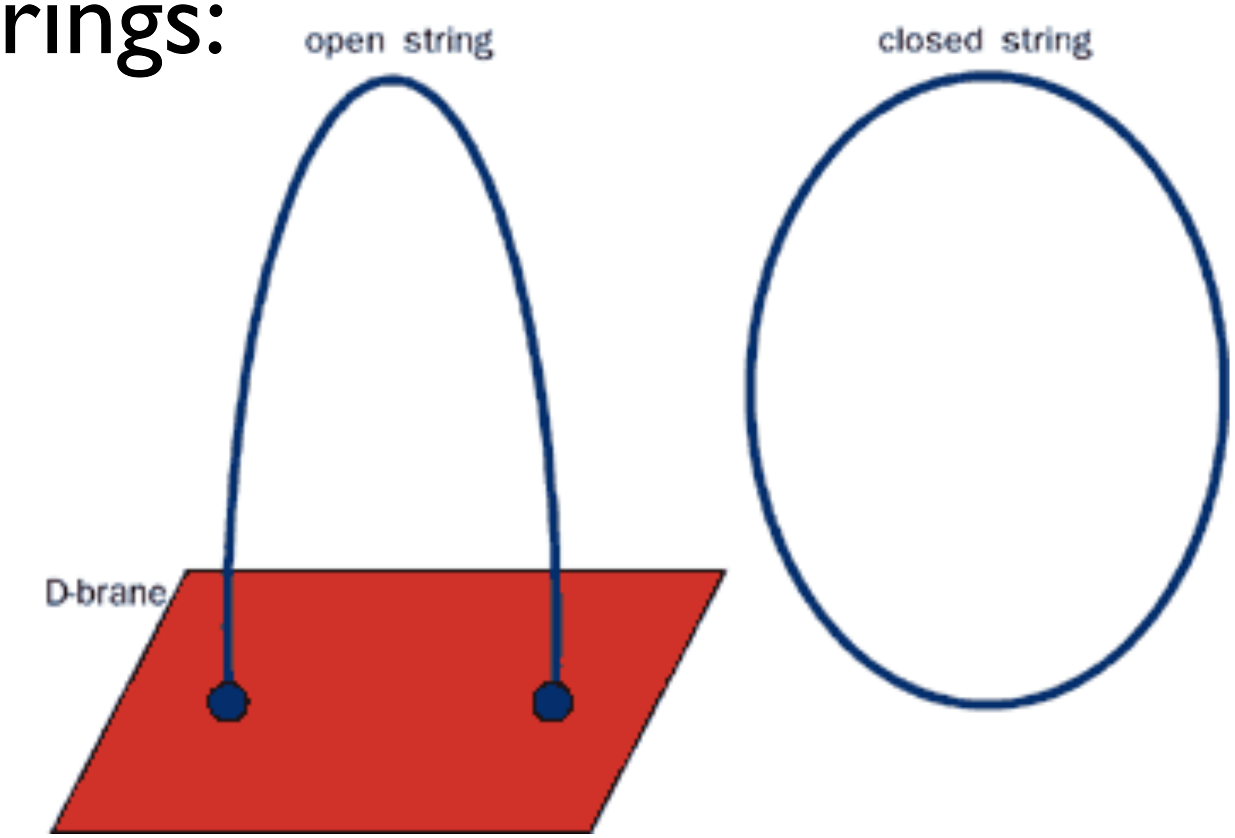
A possibility (the only one?): **STRINGS**



Particles are the lowest-energy modes of a string



Two types of strings:



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

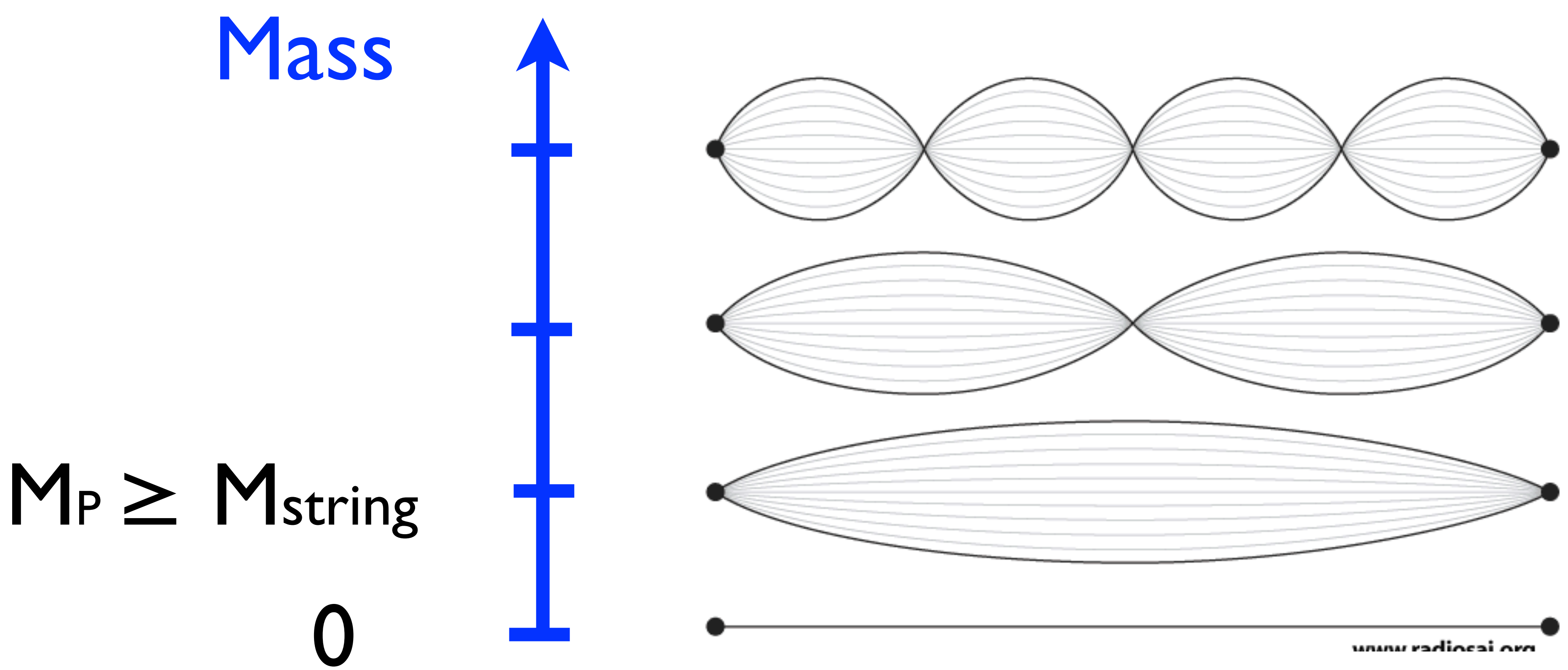
➠ **theory of unification**

Predictions:

"The only prediction of string theory is that there are no predictions"
Anonymous

1) The space must be 1+9 dimensional

2) There are string excitations of higher-energy:



... we will come back later to further explore these implications!

EX

Data unexplained by the SM

1) Neutrino masses

2) Dark matter

3) Cosmological Inflationary epoch

4) Matter/Antimatter asymmetry in the universe

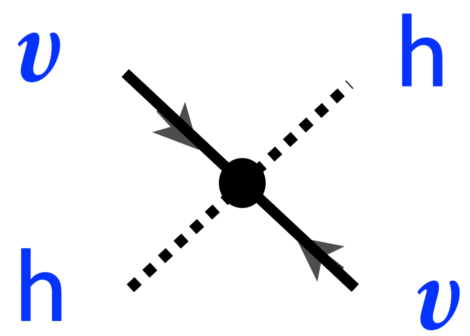
↓

Nevertheless all these evidences **could be** explained by physics close to the Planck Scale

No **deep** reasons for a lower value of $\Lambda \sim M_P$

e.g. neutrino masses:

$$\frac{1}{\Lambda} l_L H C l_L H$$



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

But there are other important reason to go beyond the SM

↓

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

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

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

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

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

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

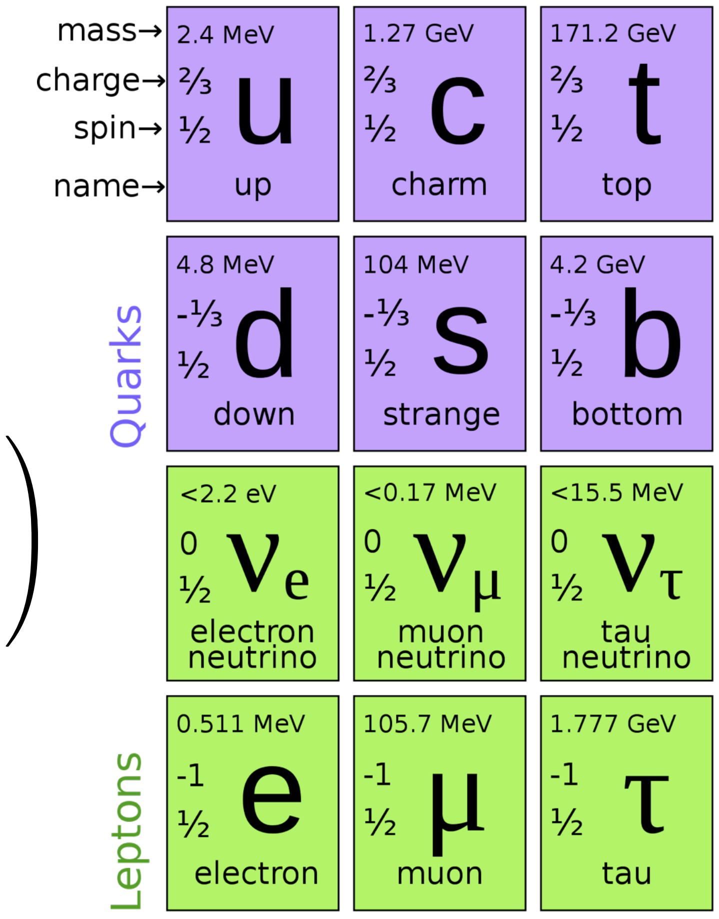
3) Charge quantization:

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

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:

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

7) Number of families:

$N_f = 3$

Search for a “natural” explanation

	New physics scale
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

	New physics scale
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: $Q_p = - Q_e$

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

$$Q = Y/2 + T_3$$

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

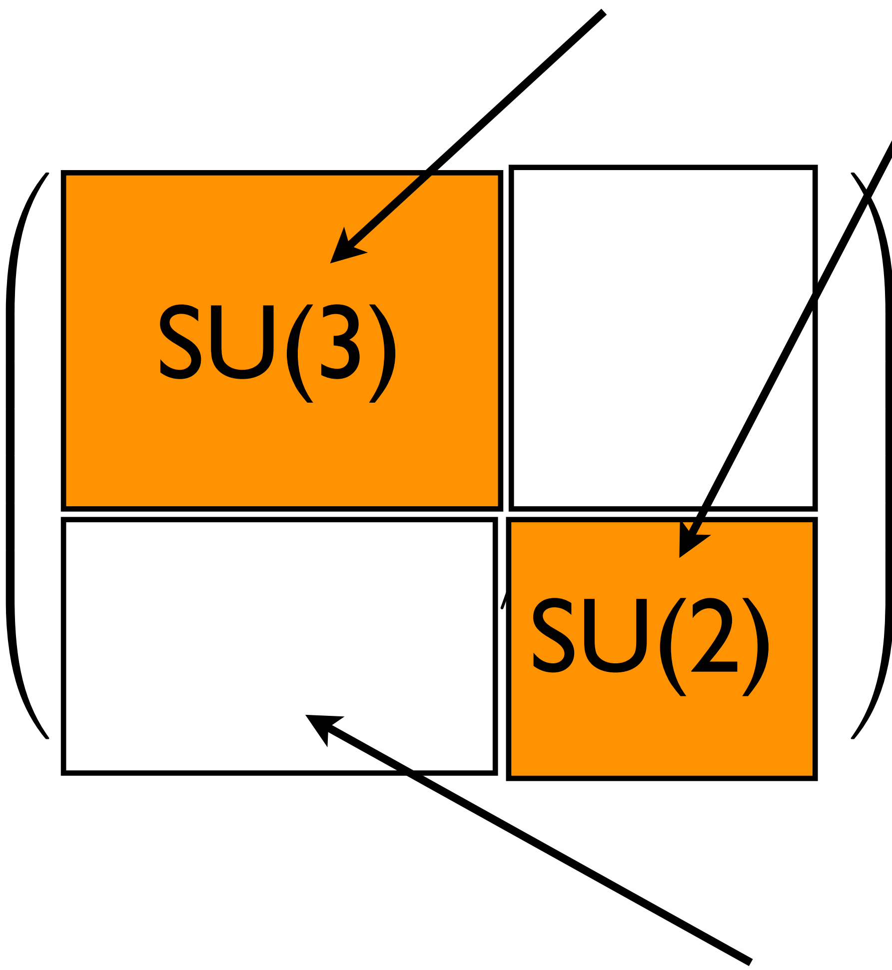
The U(1) hypercharges will be quantized if it is embedded in a **non-abelian group:**

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

Simple group: SU(5) Glashow,Georgi 74

SU(5) model

Embedding : SU(3)xSU(2)xU(1) ⊂ 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 $\subset$ $\mathbf{\bar{5}+10}$

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

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

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) → SU(3)xSU(2)xU(1)

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

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

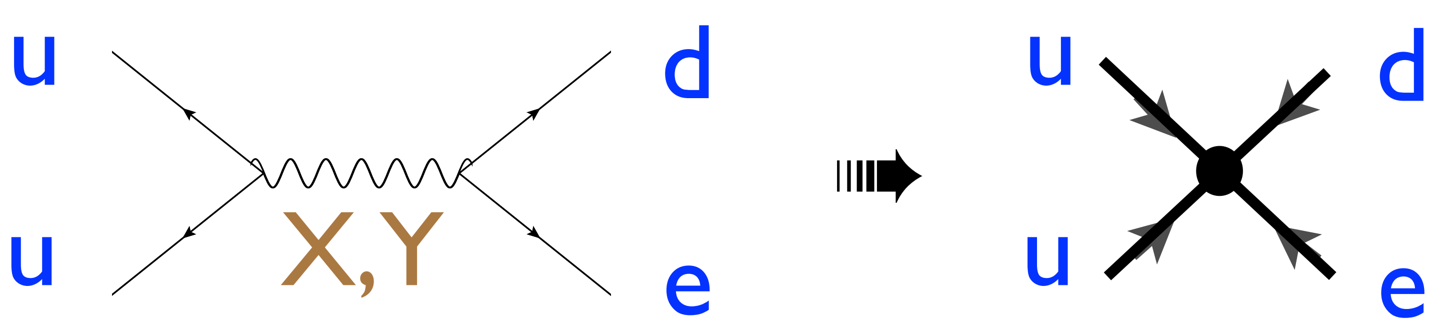
SU(5) predictions:

1) Charge quantization

2) Gauge-coupling unification:

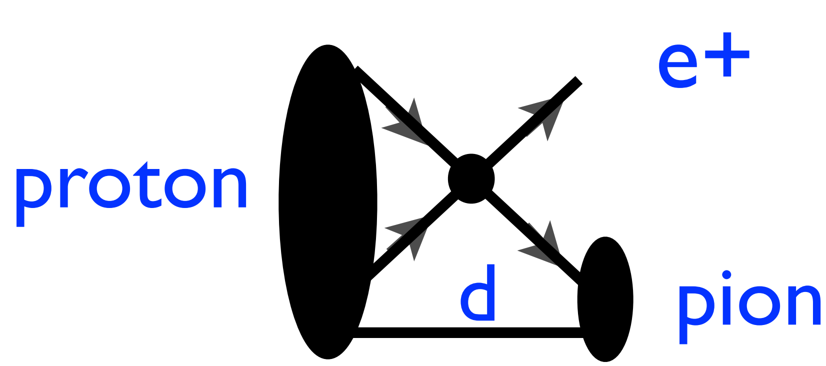
$$g_5 = g_s = g = \sqrt{5/3}\, g' \quad \text{at} \quad Q \geq M_{GUT}$$

3) Proton decay:



where $\Lambda \sim M_{GUT}$

$p \rightarrow \pi^0 e^+$:



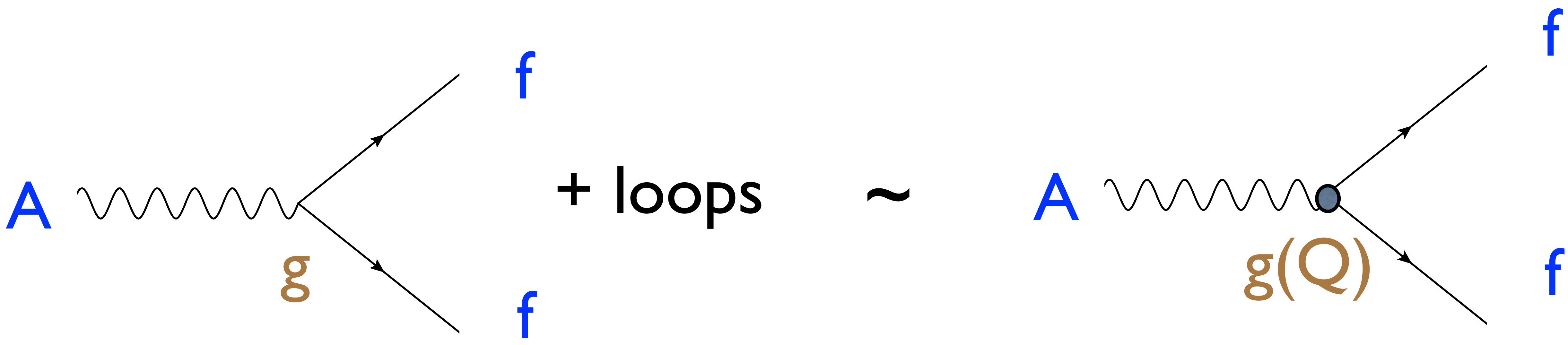
Exp. $\tau_p > 10^{34}$ years

$\Rightarrow$ $M_{GUT} > 3\times10^{15}$ GeV

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?

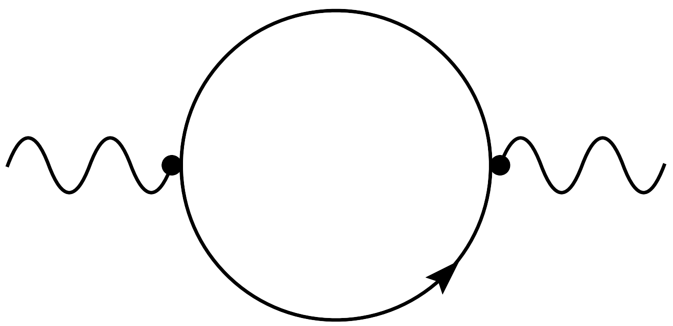


g dependence with Q
dictated by the SM spectrum
➥ can be calculated

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

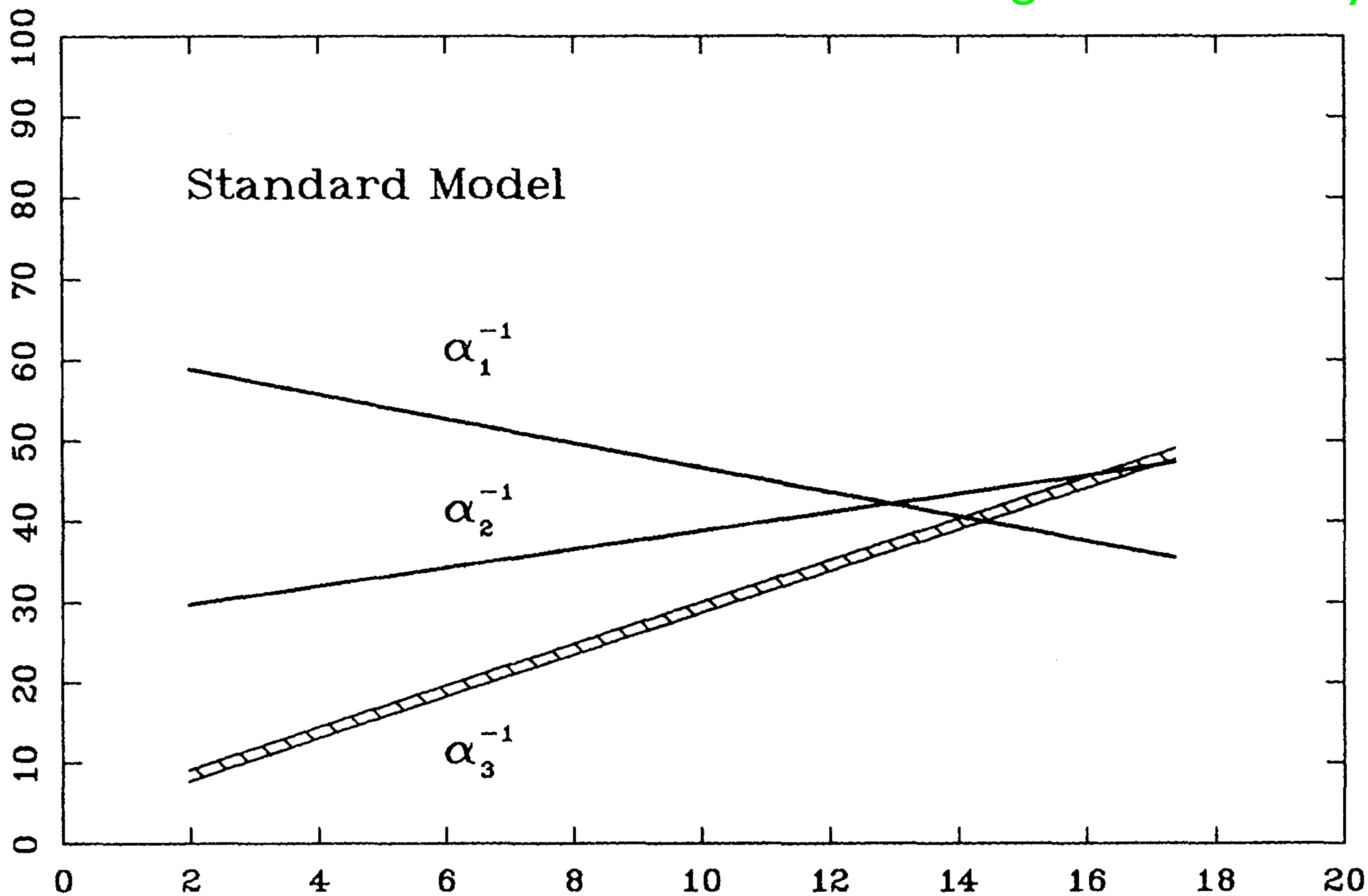


	SM	MSSM
b_i	$\begin{pmatrix} \frac{41}{10} \\ -\frac{19}{6} \\ -7 \end{pmatrix}$	$\begin{pmatrix} \frac{66}{10} \\ 1 \\ -3 \end{pmatrix}$

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

Langacker, Polonsky 93

$$\alpha = \frac{g^2}{4\pi}$$

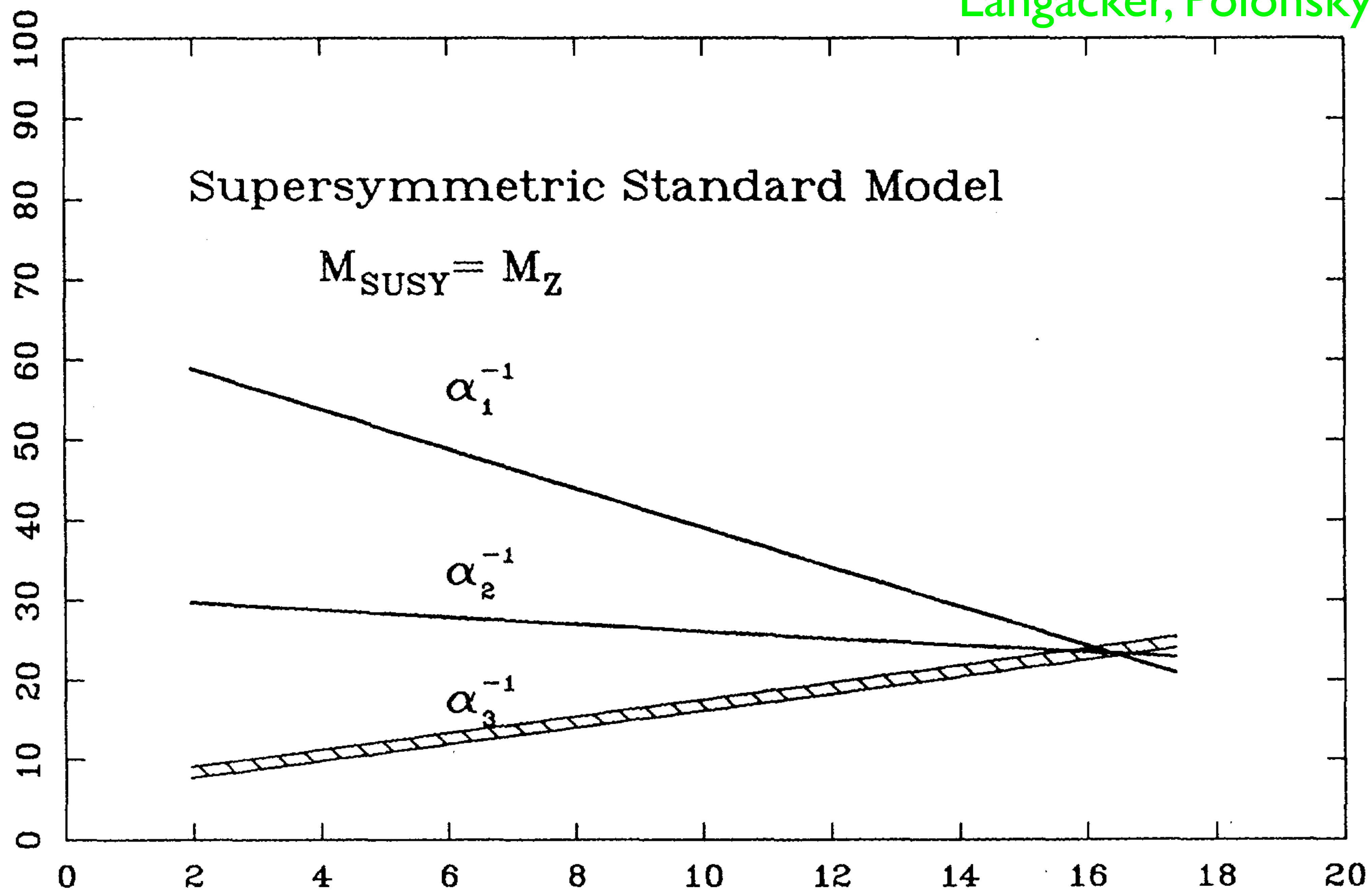


$\log_{10}(Q/\mathrm{GeV})$

SM+SUSY partners (to be discussed later):

Langacker, Polonsky 93

$\alpha = \frac{g^2}{4\pi}$



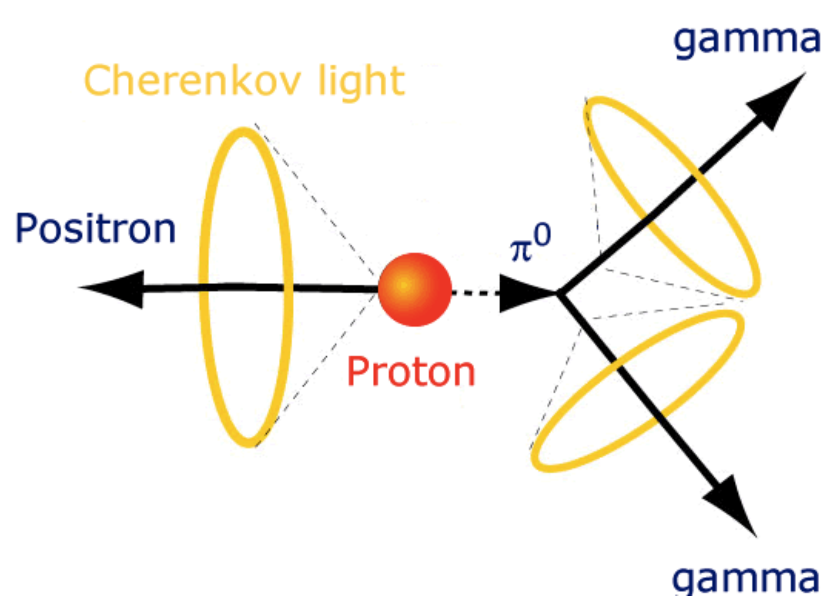
$\log_{10}(Q/\mathrm{GeV})$

Too good to be true?

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 limit:

$\tau_p > 10^{34}$ years

➥ $M_{GUT} > 3 \times 10^{15}$ GeV

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 $\mathbf{16=\bar{5}+10+1}$

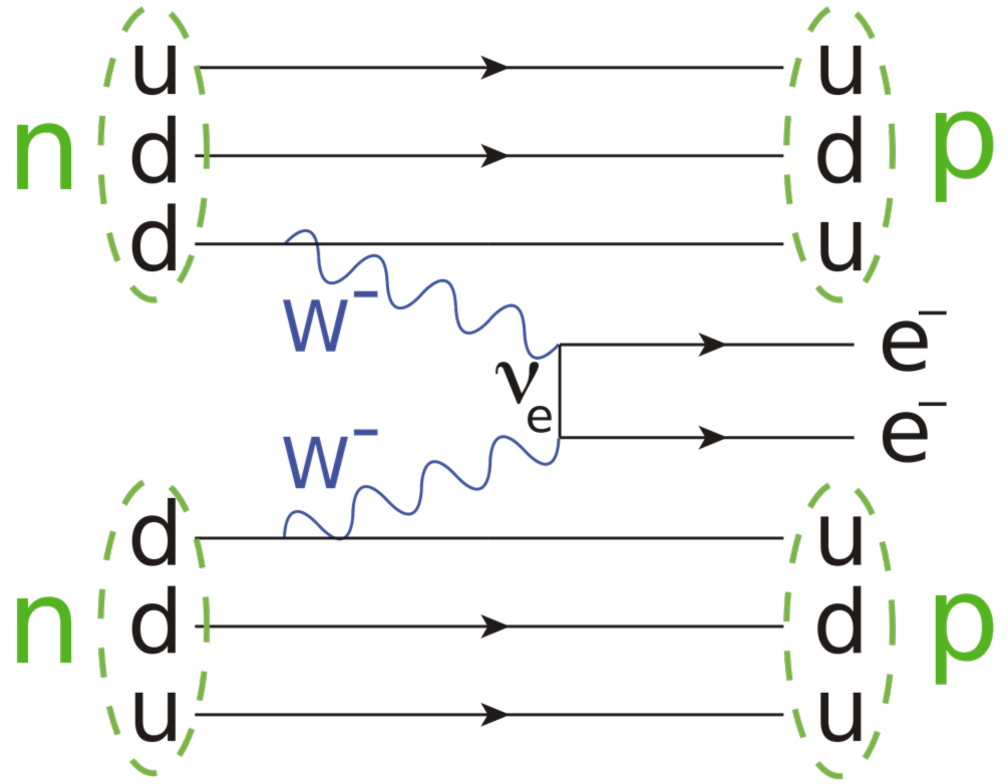
left-handed neutrino

right-handed neutrino

see-saw mechanism for neutrino masses

Implications: Majorana masses for neutrino

➟ Neutrinoless Double Beta Decay:



The strong CP Problem

Dimension 4 operator allowed in QCD:

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

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

$$\theta \lesssim 10^{-10}$$

Why so small?

Peccei-Quinn axion

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

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

No other couplings (possible by global symmetries: a=PGB)

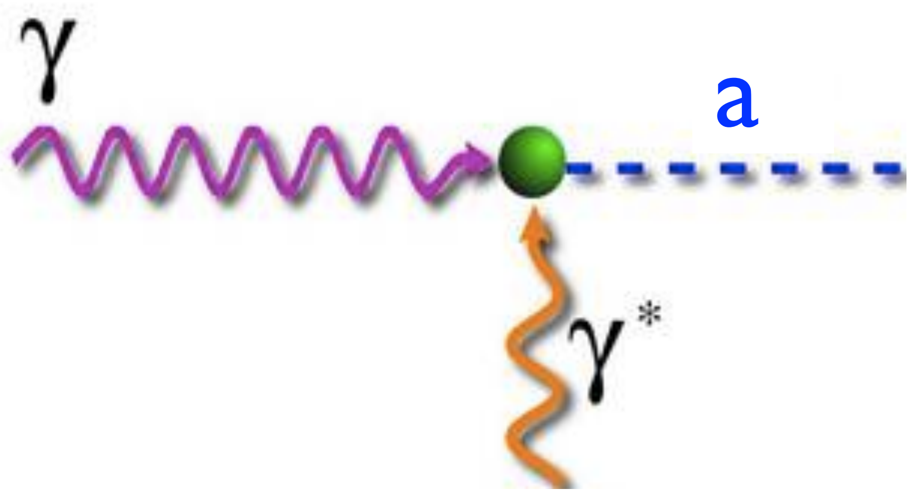
At low-energies (~GeV) a potential will be generated:

$$V(a) \propto a(x)^2 + \cdots \;\longrightarrow\; a(x) = 0 \;\rightarrow\; \boxed{\theta=0}$$

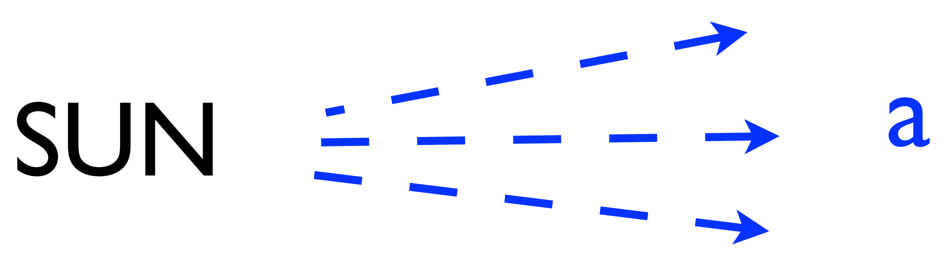
The axion gets also a mass: $m_a = \frac{f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u+m_d}m_\pi$

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

Main searches through its coupling to 2 photons:



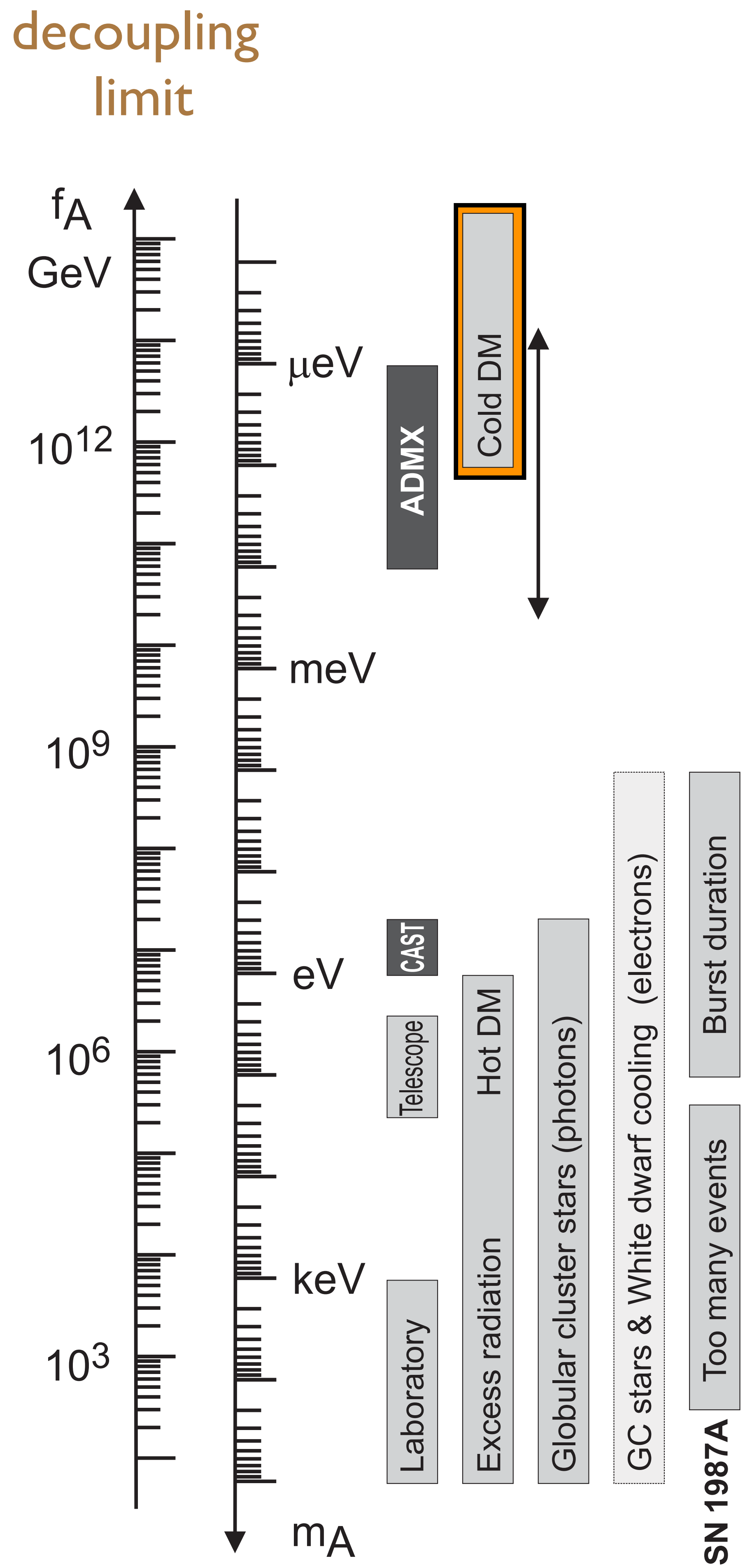
Strong constraints from limits on energy looses in stars, SN,...



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

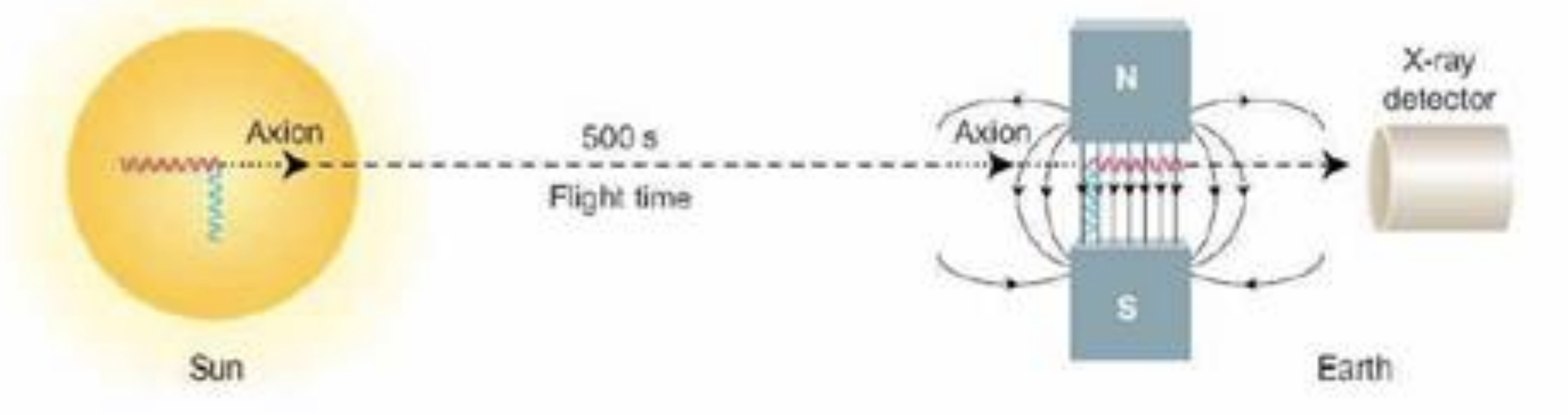
Excluded regions:

(slightly model dependent)



CAST Experiment

Detecting axions coming from the sun



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