Axion-Higgs Unification

Michele Redi

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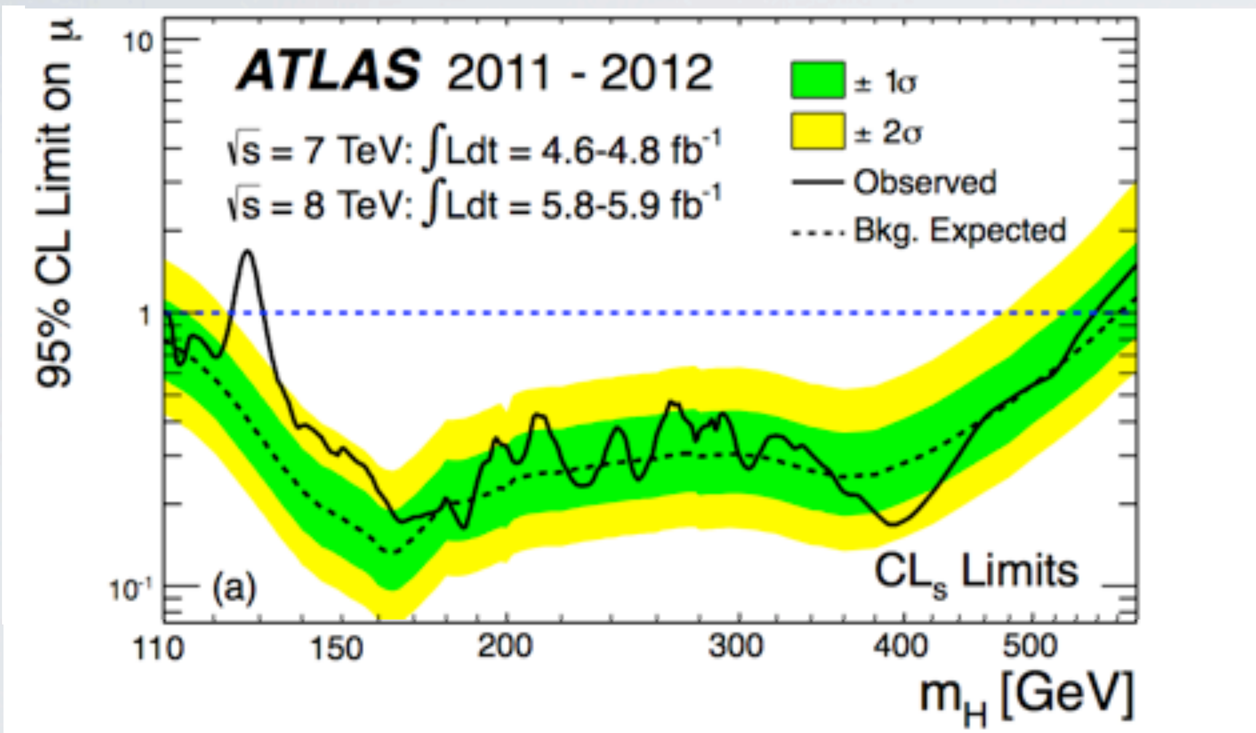
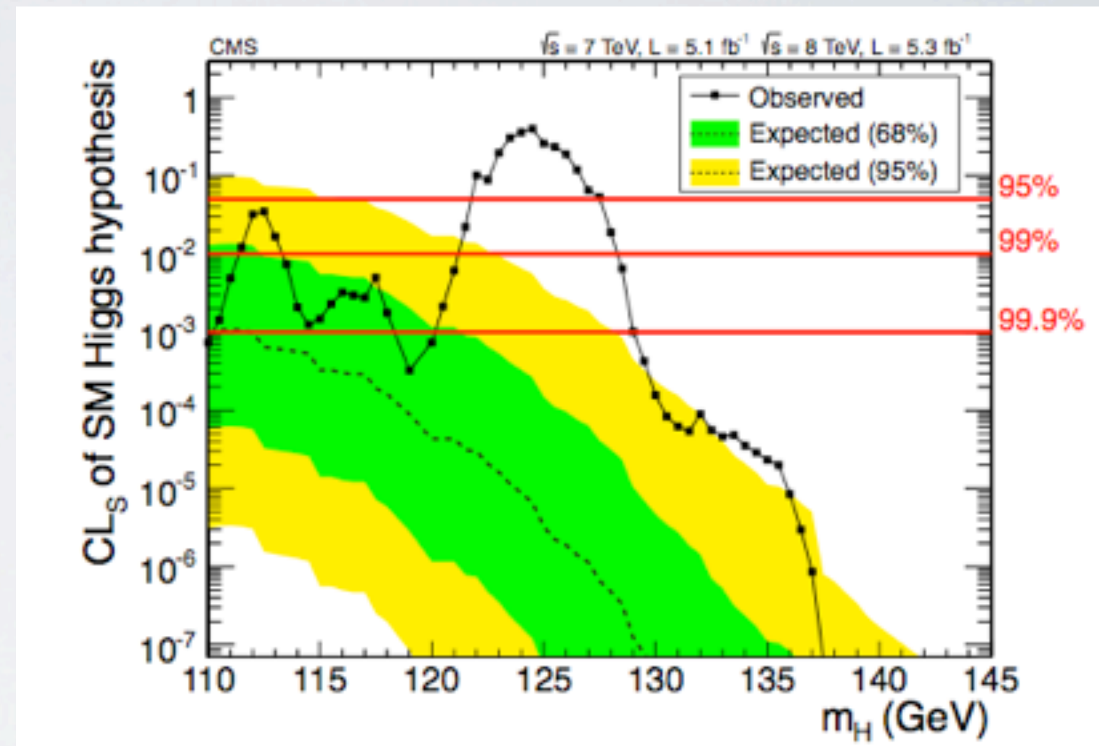




$$m_h \approx 125\,\mathrm{GeV}$$

FLAVOR HAS FOUND NOTHING

$$\Lambda > 10^5\,\mathrm{TeV}$$

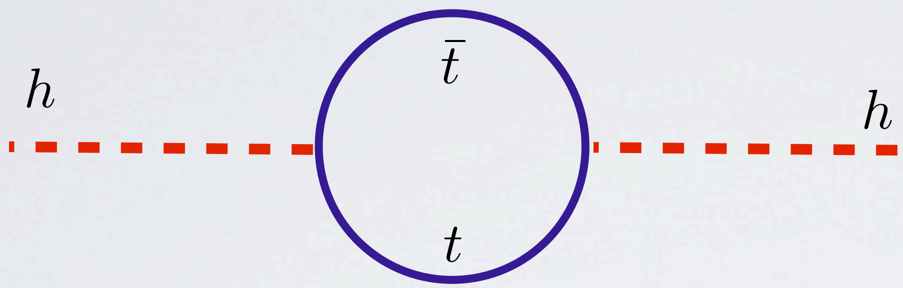
LEP HAS FOUND NOTHING

$$\Lambda > 5 - 10\,\mathrm{TeV}$$

LHC HAS FOUND THE HIGGS + NOTHING

$$\Lambda > \text{few} \times \text{TeV}$$

Hierarchy Problem:



$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2$$

$$\Lambda < 1\,\mathrm{TeV}$$

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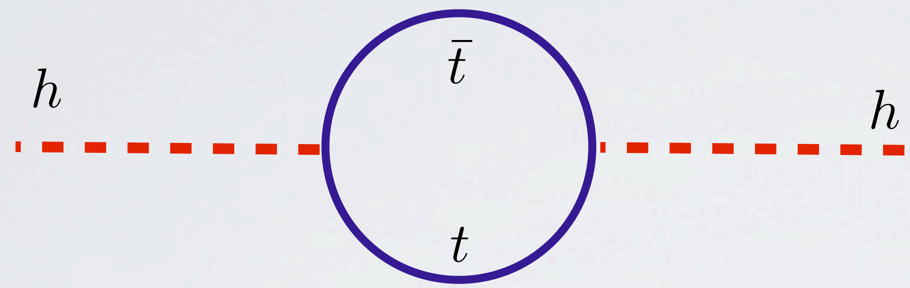

$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2$$

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Suspicion:
Perhaps naturalness was not a good guide

$$\Lambda \gg \mathrm{TeV}?$$

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- Explains why we have not seen anything

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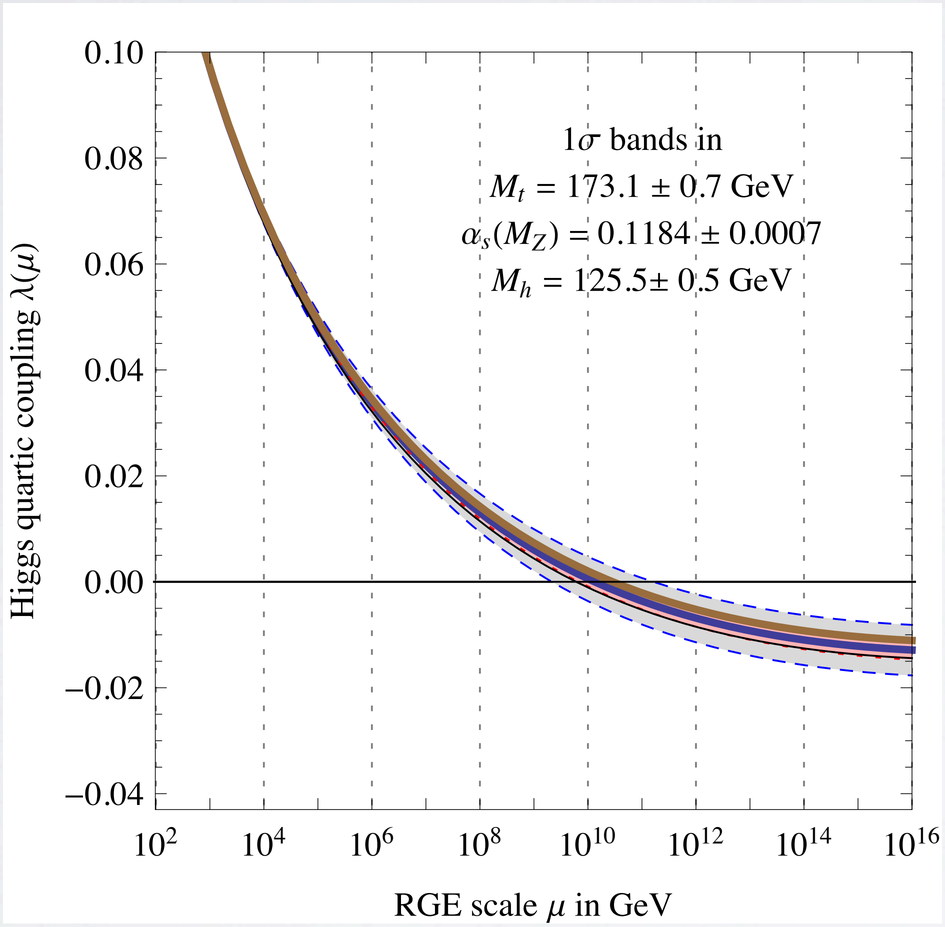
- Higgs could be tuned anthropically (as c.c.)

HINTS ?

- Running:



$$V(h) = m^2 h^2/2 + \lambda h^4/4$$

De Grassi et al. ’12

Quartic almost zero at high scale for 125 GeV Higgs

- Strong CP problem:

$$\frac{\theta}{32\pi^2} \int d^4x\, \epsilon^{\mu\nu\rho\sigma}\, Tr[G_{\mu\nu} G_{\rho\sigma}] \qquad \theta < 10^{-10}$$

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Axions are most elegant solution

$$\theta \rightarrow \frac{a(x)}{f}$$

Axions are Nambu-Goldstone bosons of a symmetry anomalous under QCD

$$m_a \sim \frac{m_\pi f_\pi}{f}$$

Experimentally:

$$f > 10^9\,\mathrm{GeV}$$

Axions can be dark matter

$$\frac{\rho_a}{\rho_{\mathrm{DM}}} \approx \theta_i^2 \left(\frac{f}{2 - 3 \times 10^{11}\,\mathrm{GeV}} \right) \longrightarrow f \approx 10^{11}\,\mathrm{GeV}$$

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- Neutrino masses

$$\frac{1}{\Lambda}(LH)^2 \qquad m_\nu \propto \frac{v^2}{\Lambda}$$

NGB HIGGS

Georgi, Kaplan '80s

Higgs could be a Nambu-Goldstone boson of new strong dynamics

$$\frac{G}{H} \xrightarrow{SM \in H} \mathcal{L} = f^2 D_\mu^{\hat{a}} D^{\mu \hat{a}}$$

$$m_\rho \sim g_\rho f$$

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Massless at leading order.

Ex: $$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$$

Agashe , Contino, Pomarol, '04

Main difference from technicolor is that f is not linked to v.

Deviation from SM: $\mathcal{O}\left(\frac{v^2}{f^2}\right)$

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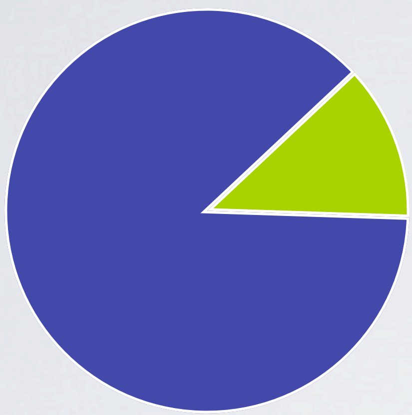
Higgs is an angle,



$0 < h < 2\pi f$ $\longrightarrow$ $\text{TUNING} \propto \frac{f^2}{v^2}$

Small Tuning $f < TeV$

Typical spectrum:

$m_\rho \sim 3\,\text{TeV}$

$f = 0.5 - 1\,\text{TeV}$

$m_h = 125\,\text{GeV}$

$m_W = 80\,\text{GeV}$

0

Partial compositeness:

D. B. Kaplan '92
Contino-Pomarol, '04

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

Partial compositeness:

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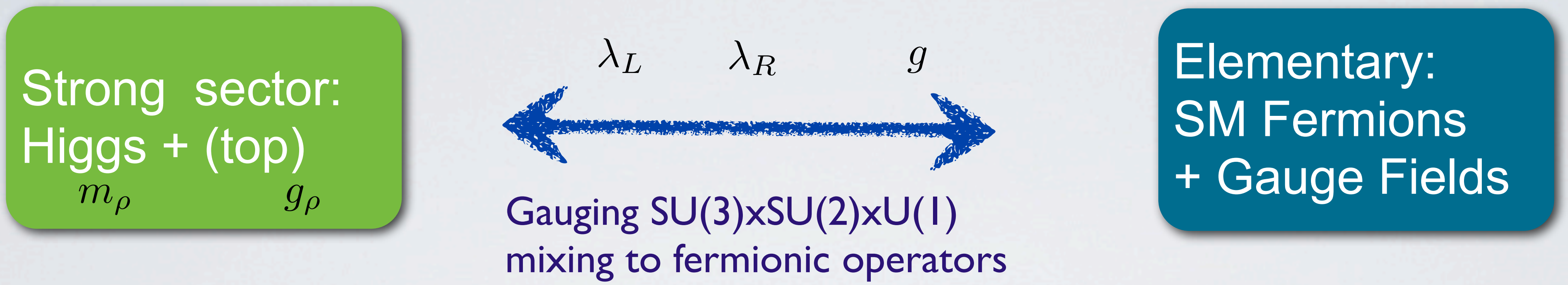

They talk through linear couplings:

$$\mathcal{L}_{gauge} = g\, A_\mu J^\mu$$

$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \xrightarrow{\epsilon \sim \frac{\lambda}{Y}} y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

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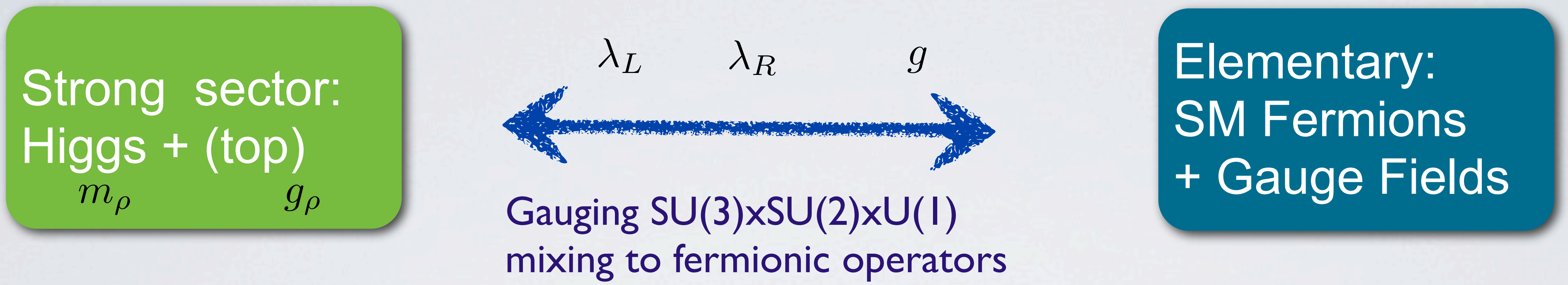

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\+ phenomenology greatly ameliorated

\- big dynamical assumptions

Despite smart theorists difficulties remain:

- flavor

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- direct exclusion

$$m_f > 0.7\,\mathrm{TeV} \qquad m_\rho > 2\,\mathrm{TeV}$$

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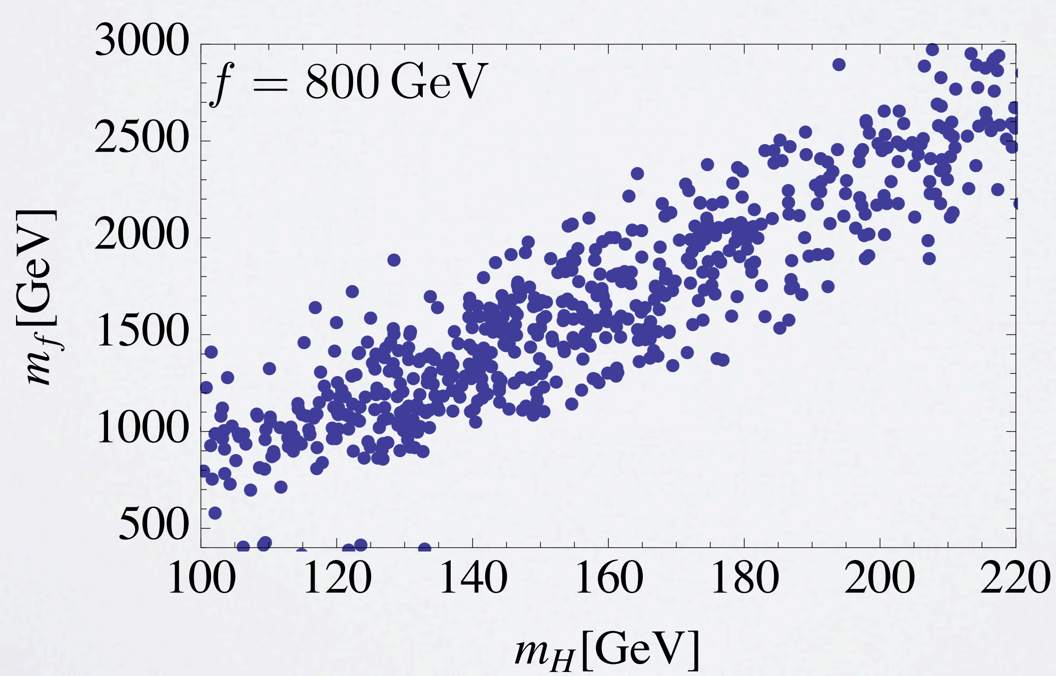
- Higgs mass



Redi, Tesi '12

$$f \approx 10^{11}\,\mathrm{GeV}$$

AXION-HIGGS

Basic idea:
Axion and Higgs originate from the same dynamics.
f is fixed by dark matter and the electro-weak scale is tuned.

$$\frac{G}{H} \xrightarrow{f \approx 10^{11}\,\text{GeV}} \text{Higgs} + \text{singlet}$$

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- Axion anomaly from new fermions (KSVZ)
- Axion anomaly from SM fermions (DFSZ)

HIGGS + KSVZ AXION

Kim-Shifman-Vainstein-Zakharov:

Add new colored fermions + complex scalar

$$\Psi_Q \to e^{i\alpha_Q \gamma_5}\Psi_Q, \qquad \sigma \to e^{-2i\alpha_Q}\sigma$$

$$L = L_{\rm SM} + \bar{\Psi}_Q \partial \Psi_Q + |\partial_\mu \sigma|^2 + (\lambda\,\sigma\,\bar{\Psi}_Q \Psi_Q + {\rm h.c.}) - V(\sigma)$$

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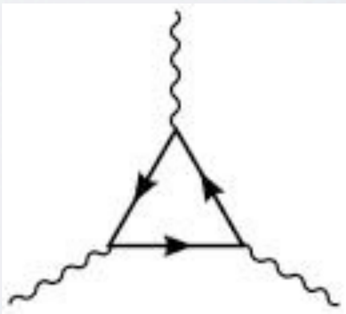
Spontaneous PQ symmetry breaking

$$f \approx \langle \sigma \rangle \qquad\qquad a = \sqrt{2}\, {\rm Im}[\sigma]$$

PQ symmetry anomalous under QCD



$$\frac{G}{H} = \frac{SU(6)_L \times SU(6)_R}{SU(6)_{L+R}}$$

Under $SU(5)_{SM}$

$$\mathbf{35} = \mathbf{24} \oplus \mathbf{5} \oplus \bar{\mathbf{5}} \oplus \mathbf{1}$$

One Higgs doublet.

Two massless singlets are axion candidates.

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Under SM 33 charged scalars acquire mass.

$$m \approx \frac{g_{SM}}{4\pi}\Lambda$$

UV realization: SU(n) gauge theory with 6 flavors

Fermions	$U(1)_Y$	$SU(2)_L$	$SU(3)_c$	$SU(n)_{TC}$
D	$\frac{1}{3}$	1	$\bar{3}$	n
L	$-\frac{1}{2}$	2	1	n
N	0	1	1	n
$\bar{D}$	$-\frac{1}{3}$	1	3	$\bar{n}$
$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	1	$\bar{n}$
$\bar{N}$	0	1	1	$\bar{n}$

$$\langle D\bar{D}\rangle = \langle L\bar{L}\rangle = \langle N\bar{N}\rangle \approx \Lambda^3$$

$$H \sim (L\bar{N}) - (\bar{L}N)^*$$

$U(1) \times SU(n)^2_{TC}$ anomaly

$$D\bar{D} + L\bar{L} + N\bar{N} \longrightarrow \frac{g_{TC}}{4\pi}\Lambda$$

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FLAVOR: $\frac{1}{\Lambda^2}(qu)(L\bar{N})$ $\frac{1}{\Lambda^2}(\bar{q}\bar{u})(\bar{L}N)$

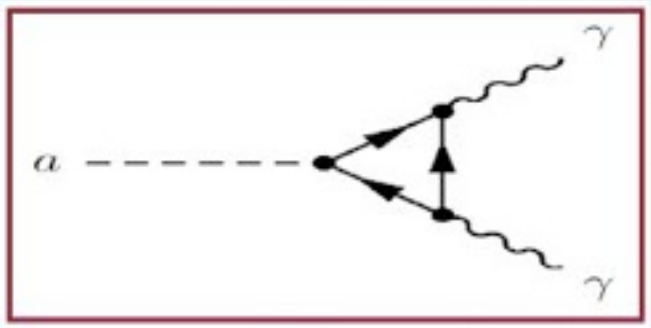
Axions couple to photon and gluons through anomalies

$$\frac{a\,E}{32\pi^2 f}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

$$\frac{aN}{32\pi^2\,f}\epsilon^{\mu\nu\rho\sigma}Tr[G_{\mu\nu}G_{\rho\sigma}]$$

$$E = \sum Q_{PQ}Q_{em}^2$$

$$N = \sum Q_{PQ}T_{SU(3)}^2$$



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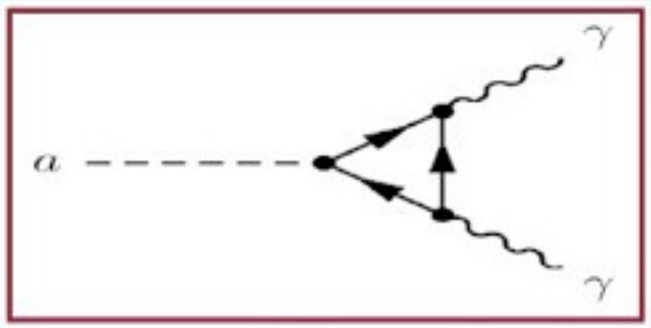
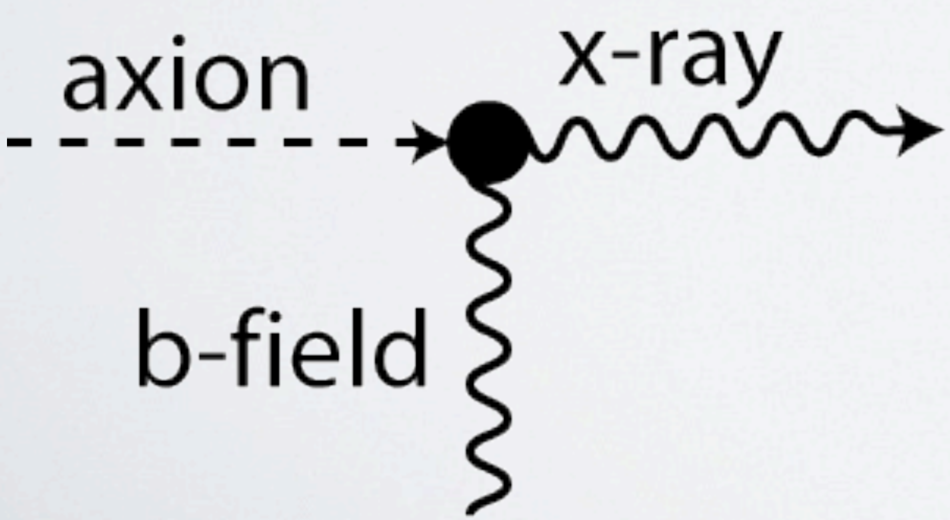
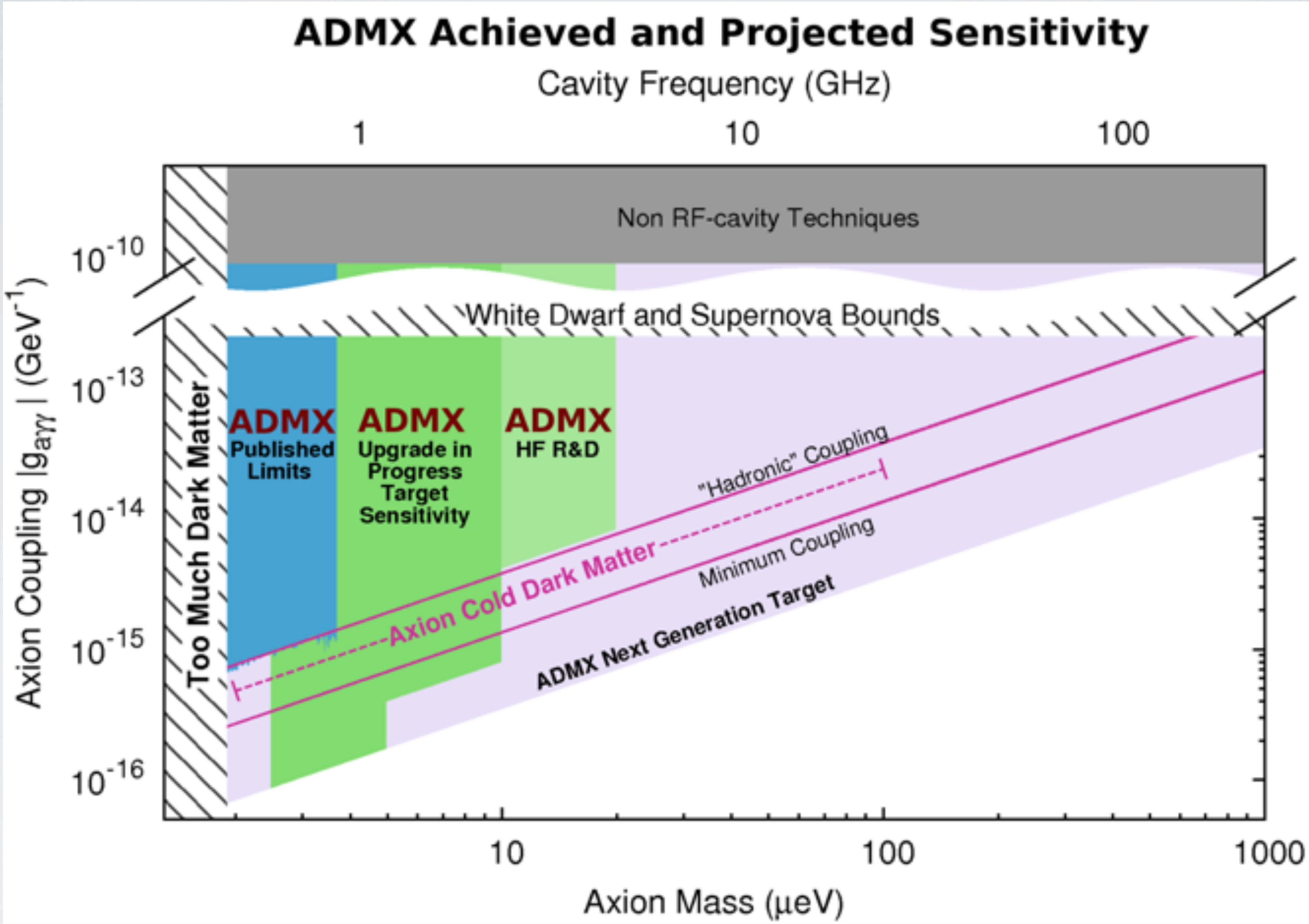


Experiments measure conversion of axion to photons



$$g_{a\gamma\gamma} = \frac{2(E/N - 1.92)}{10^{16}\,\mathrm{GeV}}\frac{m_a}{\mu\mathrm{eV}}$$

$$m_a \sim \frac{N f_\pi m_\pi}{2f}\frac{\sqrt{m_u m_d}}{m_u + m_d}$$



$$\frac{E}{N} < 1.92 + 3.5\sqrt{\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{DM}}} \qquad (m_a = 1.9 - 3.55 \times 10^{-6}\,\mathrm{ev})$$

a) If UV interactions respect singlets symmetry

$$\frac{4D-3L-6N}{\sqrt{102}}, \qquad \frac{L-2N}{\sqrt{3}}$$

$$\frac{E}{N}=-\frac{5}{6}$$

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$$\frac{D + L - 5N}{\sqrt{30}} \qquad\qquad \frac{E}{N} = \frac{8}{3}$$

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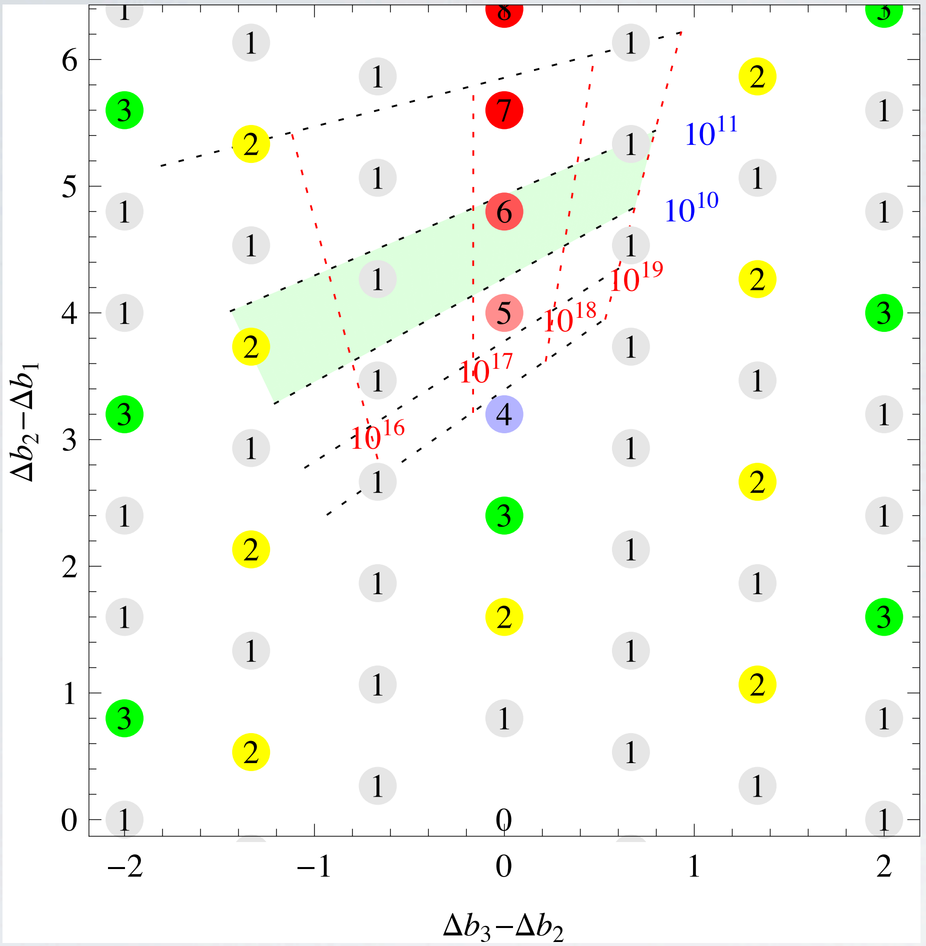
b) If SU(5) is gauged

$$\frac{D + L - 5N}{\sqrt{30}} \qquad\qquad \frac{E}{N} = \frac{8}{3}$$

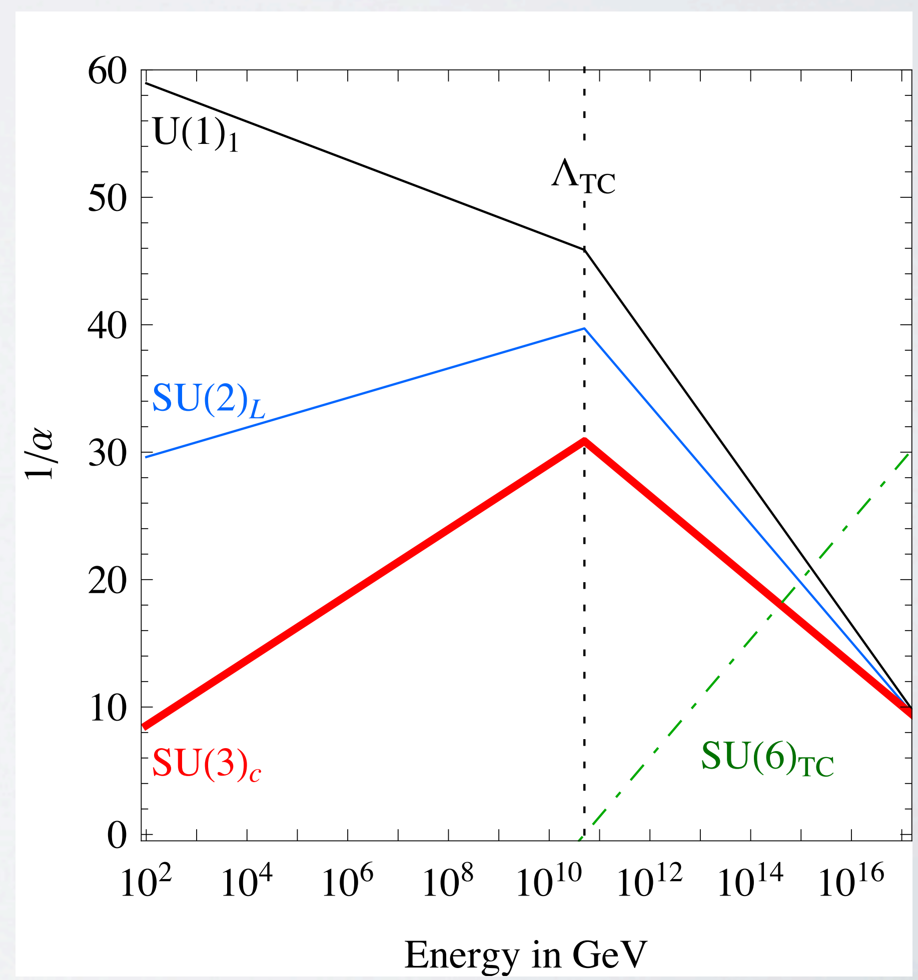
c) If all Yukawas allowed

$$\frac{D - 3L + 3N}{\sqrt{30}} \qquad\qquad \frac{E}{N} = -\frac{16}{3}$$

Incomplete SU(5) multiplets can improve unification



Ex: D, L, Q, U, N



HIGGS + DFSZ AXION

Dine-Fischler-Srednicki-Zhitnitsky:
Two Higgs doublets and complex singlet

$$\sigma \to e^{4i\alpha}\sigma, \qquad q_{L,R} \to e^{i\alpha} q_{L,R} \qquad H_u \to e^{-2i\alpha} H_u, \qquad H_d \to e^{-2i\alpha} H_d$$

$$f = \sqrt{v_u^2 + v_d^2 + |\sigma|^2}$$

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Ex:

$$\frac{G}{H} = \frac{SU(6)}{SO(6)} \qquad SO(6) \supset SO(4) \otimes \mathrm{U}(1)_{\mathrm{PQ}}$$

$$\mathbf{20'} = (\mathbf{2},\mathbf{2})_{\pm\mathbf{2}} \oplus (\mathbf{1},\mathbf{1})_{\pm\mathbf{4}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{0}} \oplus (\mathbf{3},\mathbf{3})_{\mathbf{0}}$$

UV realization: SO(n) gauge theory with 6 flavors

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$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	1	n	0
N	0	1	1	n	2
$\bar{N}$	0	1	1	n	-2

$$\langle L\bar{L}\rangle = \langle N\bar{N}\rangle = \Lambda^3$$

$$H_1 \sim LN$$

$$H_2 \sim \bar{L}\bar{N}$$

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Yukawas must respect PQ

$$\frac{1}{\Lambda_t^2}(q_L t_R^c)^\dagger (L\,N) + \frac{1}{\Lambda_b^2}(q_L b_R^c)^\dagger (\bar{L}\,\bar{N}) + \text{h.c.}$$

Anomalies:

$$E_{TC} = 0 \qquad \frac{E}{N} = \frac{8}{3}$$

Neutrino masses can be generated by see-saw mechanism

$$\frac{1}{\Lambda_\nu^2}(l\nu_R^c)^\dagger(LN) + m(\nu_R^c)^2 + h.c \longrightarrow \lambda\, l H_1 \nu_R^c + m(\nu_R^c)^2 + h.c.$$

$$m_\nu \sim \frac{\lambda^2 v^2}{m}$$

If no right-handed neutrinos

$$\frac{1}{\Lambda_\nu^5}(l\bar{L})^2 N^2 \longrightarrow \frac{1}{\Lambda_\nu^3}(lH_u)^2\sigma^2 + \ldots$$

Leptogenesis?

PARTIAL COMPOSITENESS

$$\frac{G}{H} = \frac{SO(6)}{SO(5)} \simeq \frac{SU(4)}{\mathrm{Sp}(4)}$$

Gripaios, Pomarol, Riva, Serra '09
Redi, Tesi '12
Galloway et. al. '10

5 GBs:

$$5 = (2,2) + 1$$

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Gauging of SM gauge symmetry preserves

$$SU(2)_L \times U(1)_Y \times U(1)_{PQ}$$

Under $U(1)_{PQ}$ singlet shifts.

Sp(n) theories with 4 flavors

Fermions	$\mathrm{U}(1)_Y$	$SU(2)_L$	$SU(3)_\mathrm{c}$	$\mathrm{Sp}(n)_\mathrm{TC}$	$\mathrm{U}(1)_\mathrm{PQ}$
D	0	2	1	n	$+1$
S	$+\frac{1}{2}$	1	1	n	-1
$\bar{S}$	$-\frac{1}{2}$	1	1	n	-1

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Difficult to generate QCD anomaly

$(qu)(DS)$ $\qquad$ $(qu)(DS)(S\bar{S})$

We can be build models with partial compositeness

$$m\psi\Psi + M\Psi\Psi + g_{\mathrm{TC}}\Psi\Psi H$$

Fermions can couple to 6=(2,2)+2 × 1

$$q_L \to \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} \qquad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\cos\theta\, t_R \\ \sin\theta\, t_R \end{pmatrix}$$

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For $\theta = \frac{\pi}{4}$ singlet becomes exact GB

PQ symmetry is anomalous due to tR rotations

$$E = 2\left[\left(\frac{4}{9}+\frac{1}{9}\right)3+1\right]N_F + E_{\rm TC}$$

$$\frac{E}{N} = \frac{8}{3} + \frac{E_{\rm TC}}{6} \qquad E_{TC} \sim n$$

HIGGS MASS

Higgs potential is generated by the couplings that break the global symmetry. Minimally gauge and Yukawa couplings.

$$V(h) = \sum_i a_i \sin^{2i}\left(\frac{h}{f}\right)$$

Electro-weak scale:

$v \ll f$ ⟶ a_i must be tuned

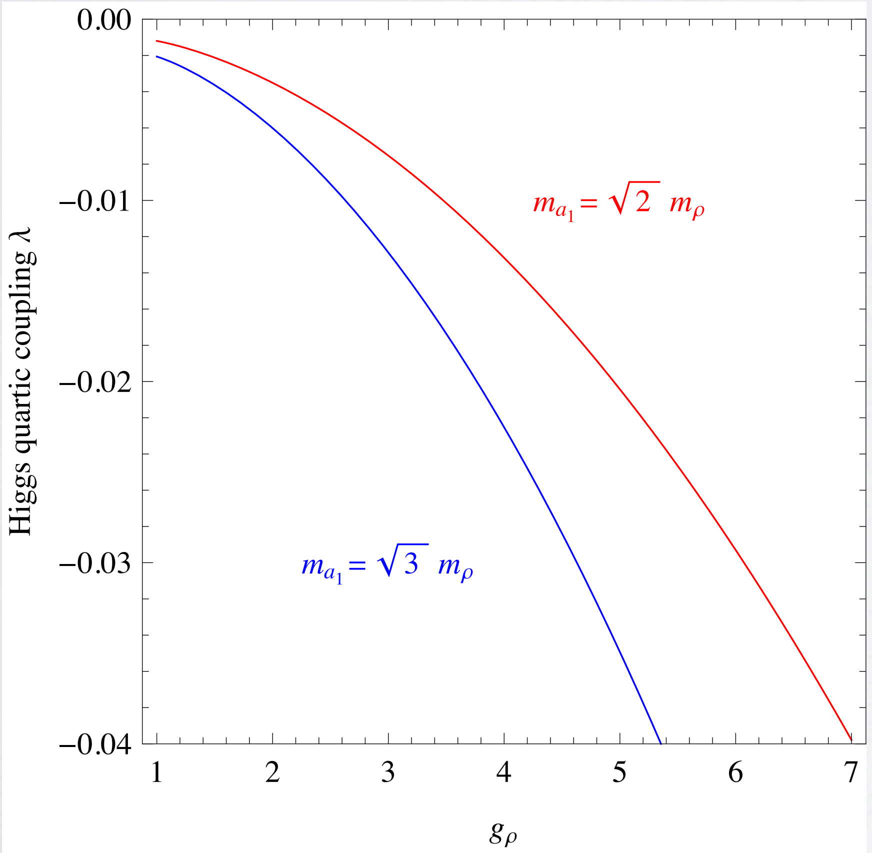
Higgs mass is then "predicted".

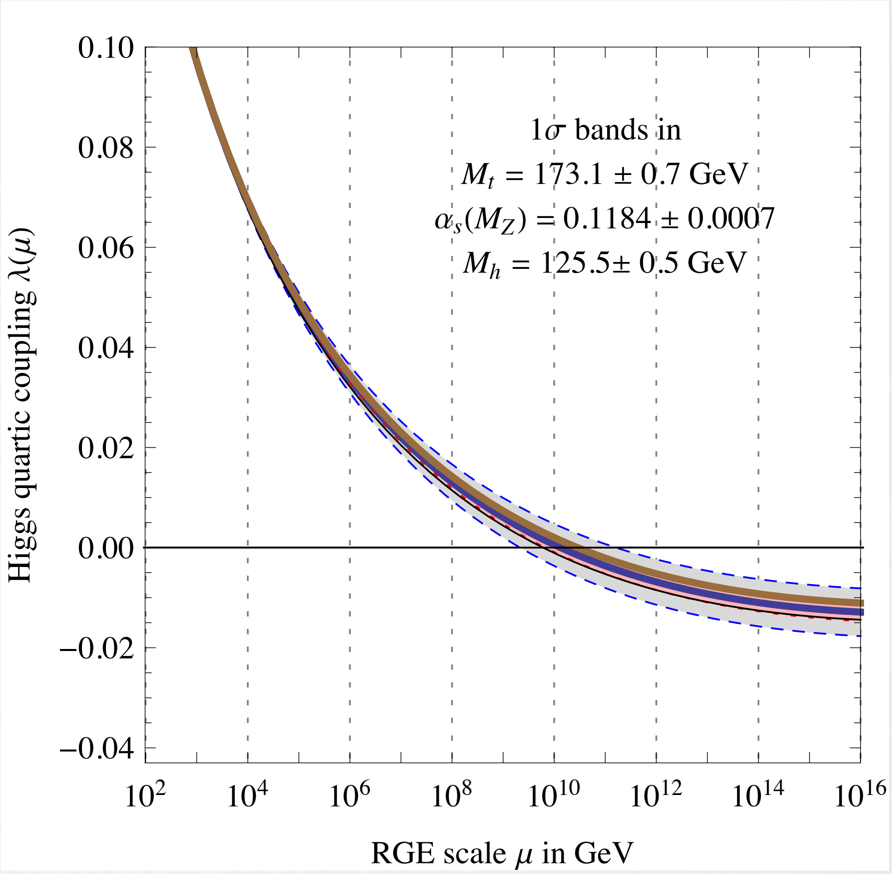
Gauge contribution:

$$V(h)_{\rm gauge} = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \ln\left[1 + F(p^2)\,\sin^2\frac{h}{f}\right]$$

$$V(h)_{\rm gauge} \approx \frac{9}{4}\frac{g^2}{16\pi^2}\frac{m_\rho^4}{g_\rho^2}\ln\left[\frac{m_\rho^2 + m_{a_1}^2}{2m_\rho^2}\right]\sin^2\frac{h}{f}$$

$$\lambda(m_\rho)^{\rm leading}_{\rm gauge} \approx -3g^2 \log\frac{3}{2}\frac{g_\rho^2}{(4\pi)^2}$$





- Leading order tuning

$$\lambda(\Lambda) \sim g_{\rm SM}^2 \frac{g_\rho^2}{(4\pi)^2} \sim {\rm few}\, 10^{-2}$$

125 GeV Higgs implies weak coupling (large n)

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$$\lambda(\Lambda) \sim g_{\rm SM}^2 \frac{g_\rho^2}{(4\pi)^2} \sim \text{few}\, 10^{-2}$$

125 GeV Higgs implies weak coupling (large n)

- Subleading order tuning

$$\lambda(\Lambda) \sim \frac{g_{\rm SM}^4}{(4\pi)^2} \sim 10^{-3}$$

Model I:

$$V_{\rm fermions} \sim \frac{N_c\, \lambda_t^2}{16\pi^2} \Lambda^2 f^2 \sum_{\alpha=1}^{2} |{\rm Tr}[\Pi_t^\alpha \cdot U]|^2 \qquad \propto \sin^2 \frac{h}{f}$$

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- So far everything is consistent with the SM being valid up to a very large a scale.
- The idea of the Higgs as Nambu-Goldstone boson can be naturally merged with axions if $\Lambda \sim 10^{11}\,\mathrm{GeV}$
- Giving up naturalness, strong CP, dark matter, Higgs mass can be explained. Unification and neutrino masses could also fit into the picture.