126 GeV Goldstone Boson Higgs

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1110.1613 + 1205.0232
1208.6013 with A. Strumia

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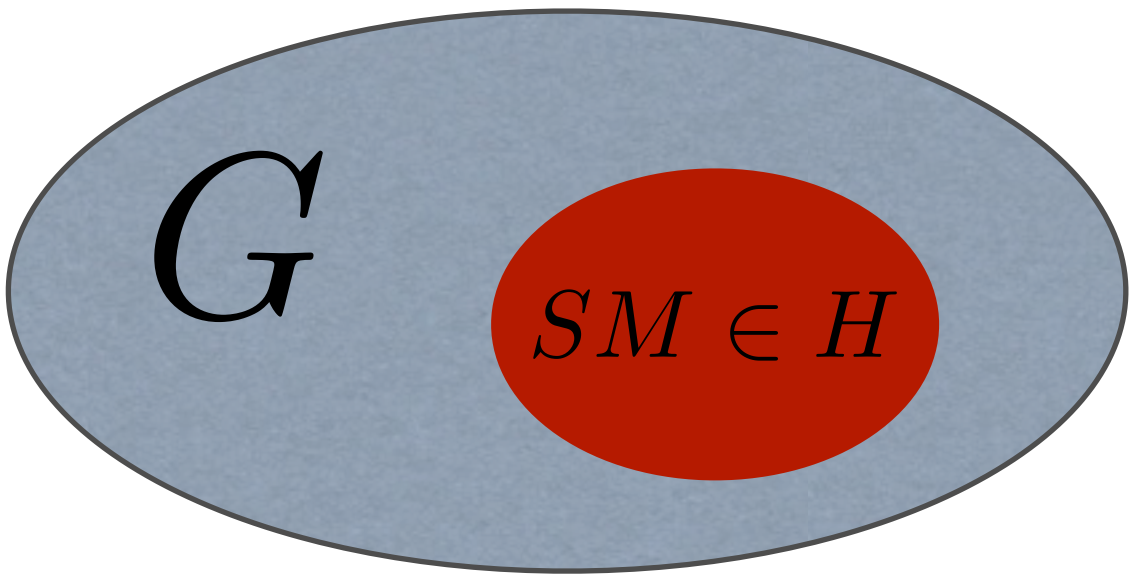
Georgi, Kaplan ‘80s

The Higgs could be a remnant of strong dynamics.

Most compelling Higgs as Nambu-Goldstone boson:



$$\mathrm{NGB} = \frac{G}{H}$$

$g_\rho \qquad m_\rho$

$$\delta m_h^2 \sim N_c \frac{y_t^2}{8\pi^2} m_\rho^2$$

Ex:

$$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \xrightarrow{f = \frac{m_\rho}{g_\rho}} GB = (2,2)$$

Agashe , Contino, Pomarol, ’04

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

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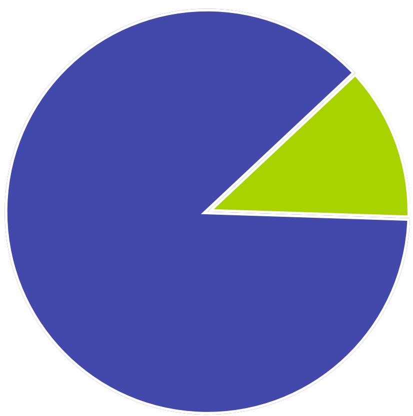
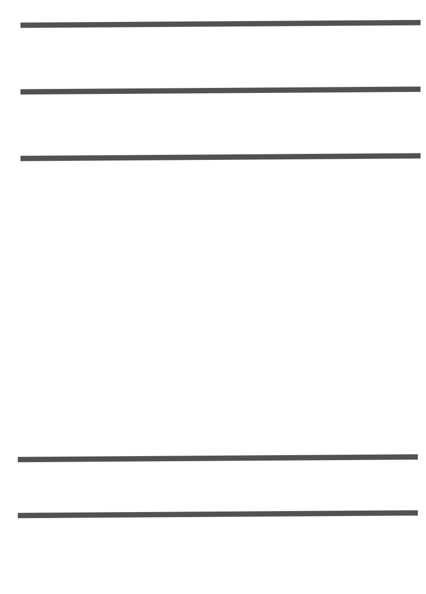
Higgs is an angle,



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

Natural 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:

D. B. Kaplan '92
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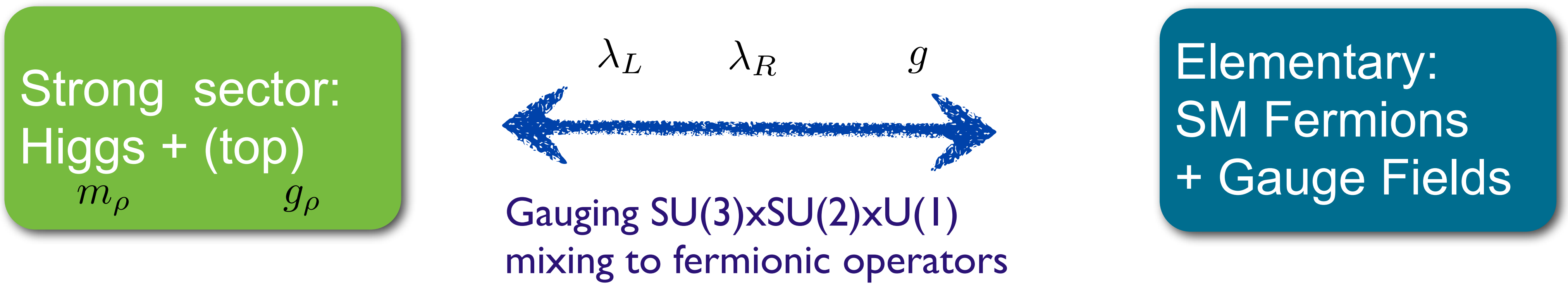


They talk through linear couplings:

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

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

+ phenomenology greatly ameliorated
- big dynamical assumptions

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:

$$v \ll f \quad \longrightarrow \quad a_i \text{ must be tuned}$$

Higgs mass is then "predicted".

Coleman-Weinberg effective potential:

$$V(h)_{gauge} = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \ln\left[1 + \frac{1}{4}\frac{\Pi_1(p^2)}{\Pi_0(p^2)} \sin^2\frac{h}{f}\right]$$

$$\langle J^a_\mu(q) J^a_\mu(-q)\rangle = (\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2})\,\Pi^a(q^2)$$

$$\langle J^{\hat{a}}_\mu(q) J^{\hat{a}}_\mu(-q)\rangle = (\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2})\,\Pi^{\hat{a}}(q^2)$$

$$\Pi_0 = \Pi^a$$

$$\Pi_1 = 2(\Pi^{\hat{a}} - \Pi^a)$$

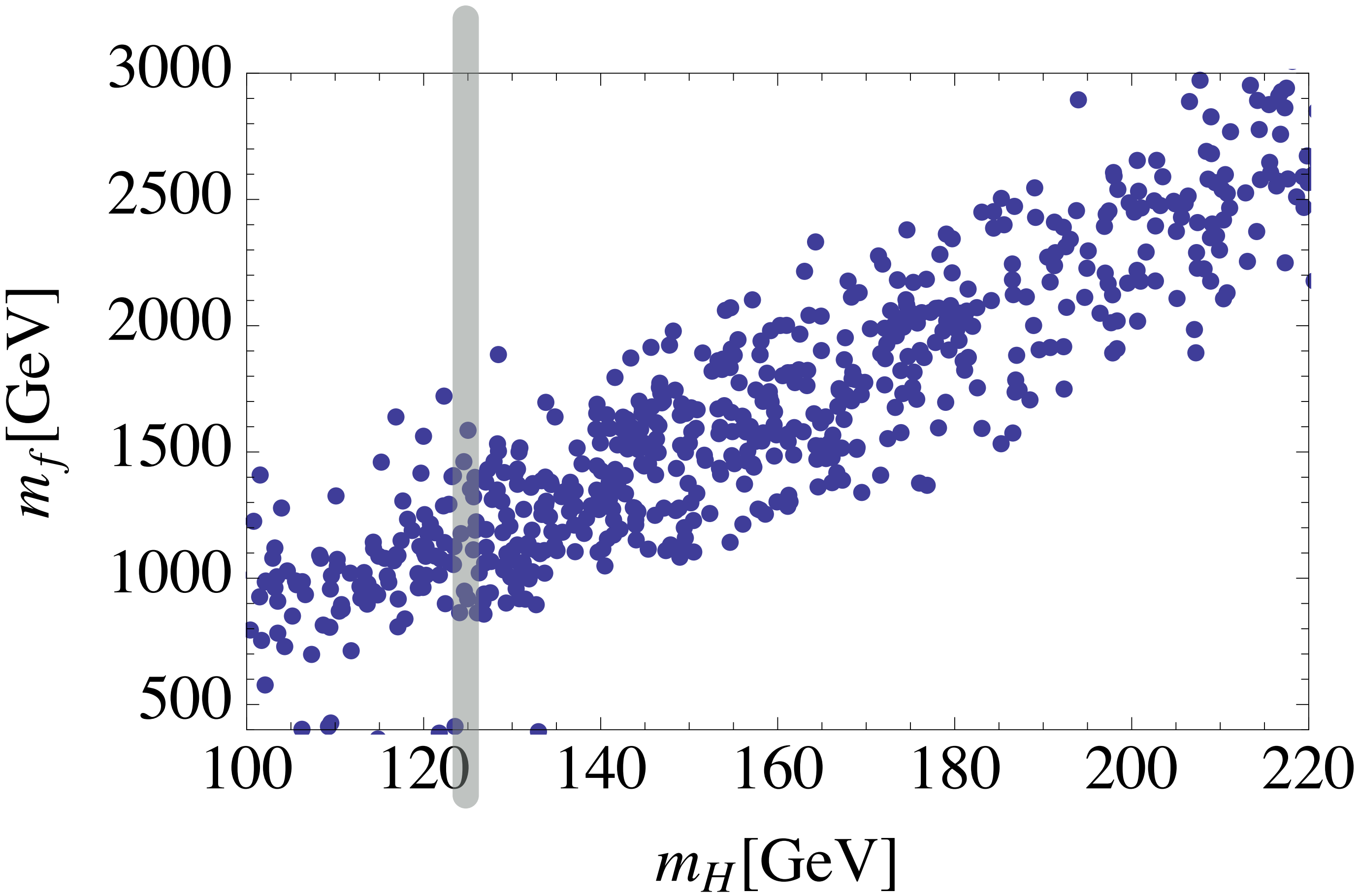
Potential is finite with a single SO(5) multiplet:

$$V(h)_{gauge} \approx \frac{9}{4}\frac{g^2}{(4\pi)^2}\frac{m_\rho^4}{g_\rho^2}\log\left[\frac{m_a^2}{m_\rho^2}\right]\sin^2\frac{h}{f}$$

Divergences effectively cut-off by resonances

CHM5:

De Curtis, MR, '11
MR, Tesi, '12



$$f = 800\,\mathrm{GeV}$$

$$m_h \sim \sqrt{\frac{N_c}{2}\frac{y_t}{\pi}\frac{m_f}{f}}v$$

Partners around ~ 1 TeV

Many challenges:

- flavor

$$m_\rho > 20\,\mathrm{TeV}$$

- direct exclusion

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

- smart model building

Many challenges:

- flavor

$$m_\rho > 20\,\text{TeV}$$

- precision tests

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

- direct exclusion

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

- smart model building

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

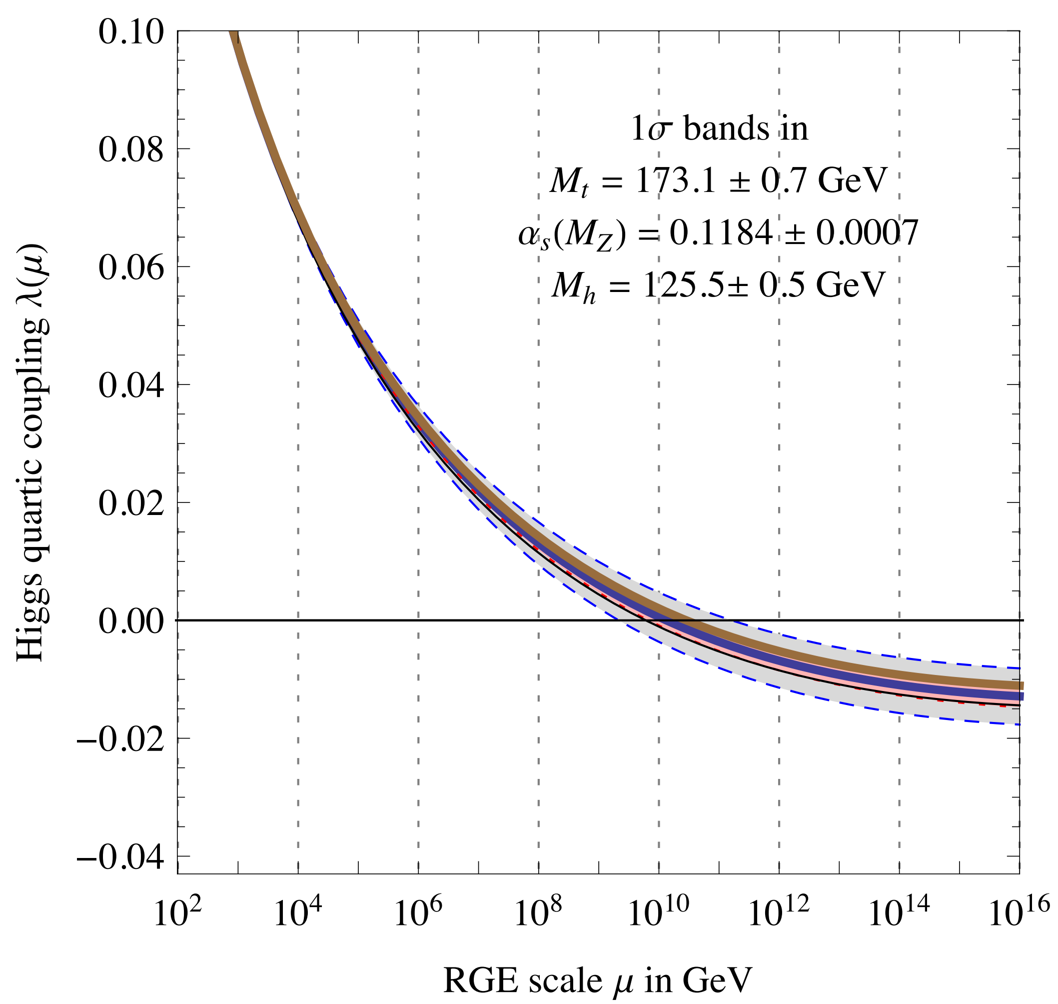
- 126 GeV Higgs can be explained

- Axions + Higgs can be unified

1208.6013 with A. Strumia

HINTS ?

- Running:



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

De Grassi et al. '12

Quartic almost zero at high scale for 125 GeV Higgs

- Strong CP problem:

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

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Elegant solution with axions

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

Axions are Goldstone bosons of a symmetry anomalous under QCD

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

$$f > 10^9\,\text{GeV} \longrightarrow m_a < 10^{-3}\,\text{eV}$$

Axions can be dark matter

$$\frac{\rho_a}{\rho_{\text{DM}}} \approx \theta_i^2 \left(\frac{f}{2-3\times 10^{11}\,\text{GeV}}\right) \xrightarrow{\theta_i \sim 1} f \approx 10^{11}\,\text{GeV}$$

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- Neutrino masses

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

- Unification

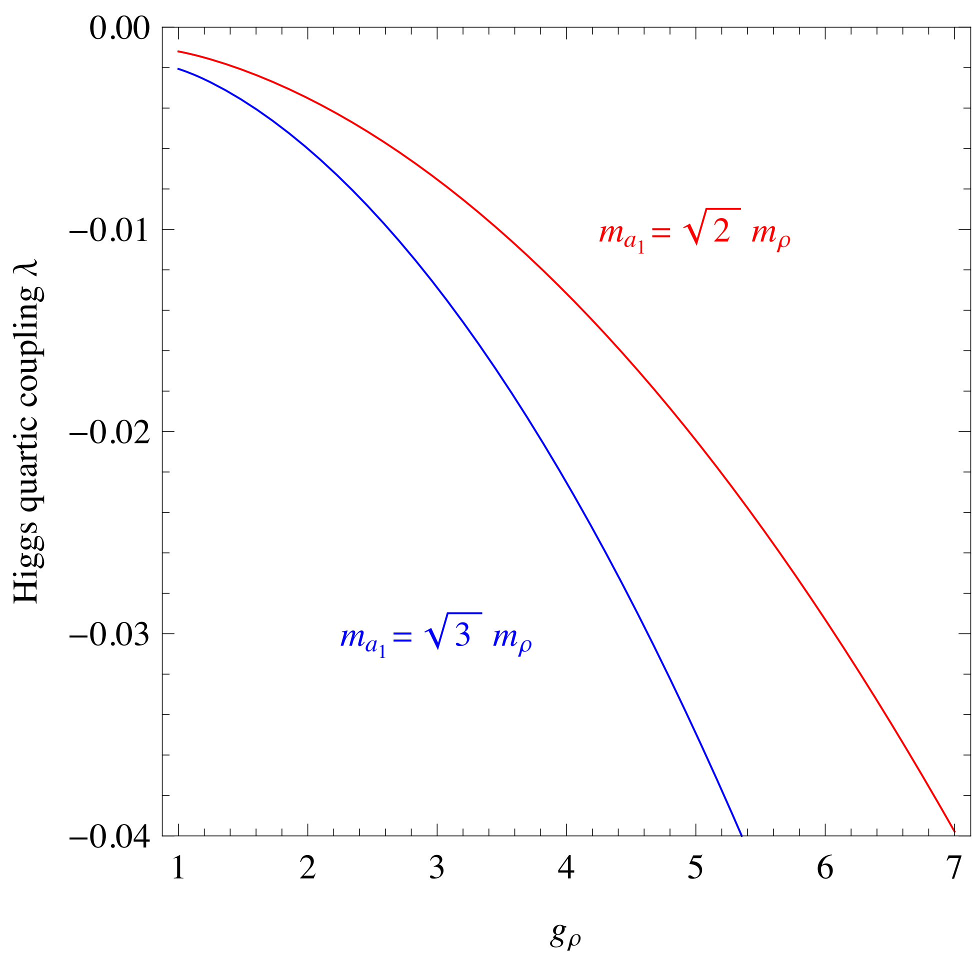
$$\Lambda < M_{GUT}$$

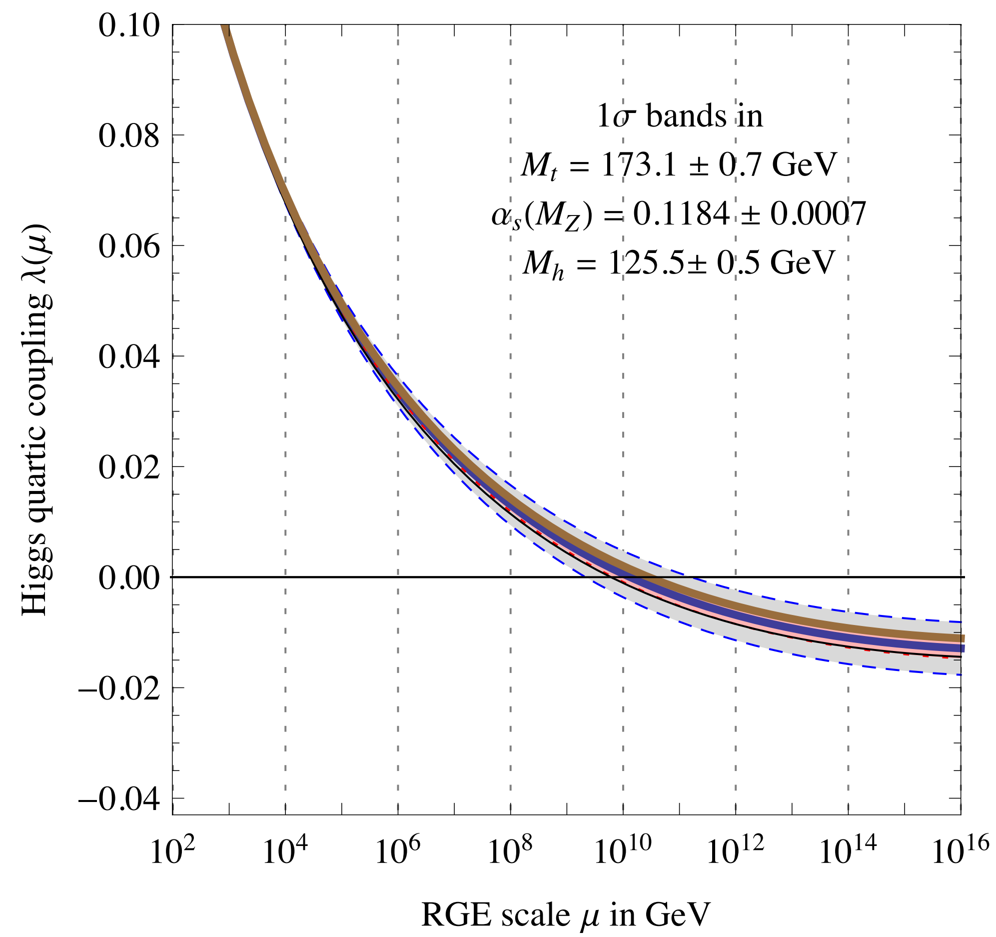
Quartic boundary condition:

$$V(h, m_\rho)_{gauge} = \frac{9}{2}\int_{m_\rho}^{\infty} \frac{d^4p}{(2\pi)^4} \ln\left[1 + \frac{1}{4}\frac{\Pi_1(p^2)}{\Pi_0(p^2)}\sin^2\frac{h}{f}\right]$$

$$= \int_{m_\rho}^{\infty} \frac{d^4p}{(2\pi)^4}\left[\frac{9}{8}\frac{\Pi_1(p^2)}{\Pi_0(p^2)}\sin^2\frac{h}{f} - \frac{9}{64}\frac{\Pi_1(p^2)^2}{\Pi_0(p^2)^2}\sin^4\frac{h}{f} + \dots\right]$$

$$\lambda(m_\rho) = -3\, a_1\, g_{SM}^2 \frac{g_\rho^2}{(4\pi)^2} + O\left(\frac{g_{SM}^4}{(4\pi)^2}\right)$$





Quartic contributions:

$$\cancel{\frac{g_\rho^4}{(4\pi)^2}} \qquad \frac{g_{SM}^2\, g_\rho^2}{(4\pi)^2} \qquad \frac{g_{SM}^4}{(4\pi)^2}$$

- **Leading order cancellation:**

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

125 GeV Higgs requires weak coupling (large n)

- **Subleading order cancellation:**

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

AXION-HIGGS

Composite Axion:
Choi Kim ’85

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

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

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- QCD anomaly from new fermions (KSVZ)

- QCD anomaly from SM fermions (DFSZ)

HIGGS + KSVZ AXION

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

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	$\bar{n}$

$$(\bar{5}+1, n) \oplus (5+1, \bar{n})$$

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$$(\bar{5}+1, n) \oplus (5+1, \bar{n})$$

$$\langle D\bar{D}\rangle = \langle L\bar{L}\rangle = \langle N\bar{N}\rangle \approx \Lambda^3 \qquad H \sim (L\bar{N}) - (\bar{L}N)^*$$

Singlets:

$$D\bar{D} \qquad L\bar{L} \qquad N\bar{N}$$

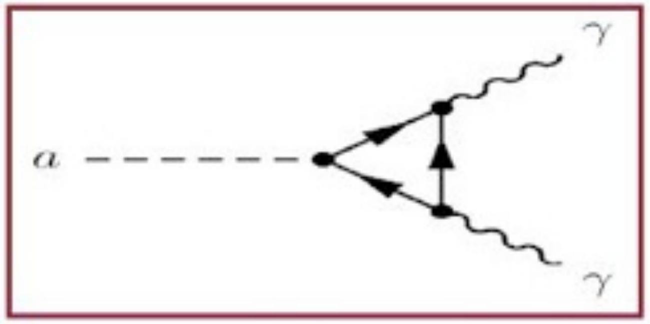
$$D\bar{D} + L\bar{L} + N\bar{N} \xrightarrow{U(1)\times SU(n)^2_{TC} \text{ anomaly}} \frac{g_{TC}}{4\pi}\Lambda$$

Axions couple to photon and gluons through anomalies

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

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

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



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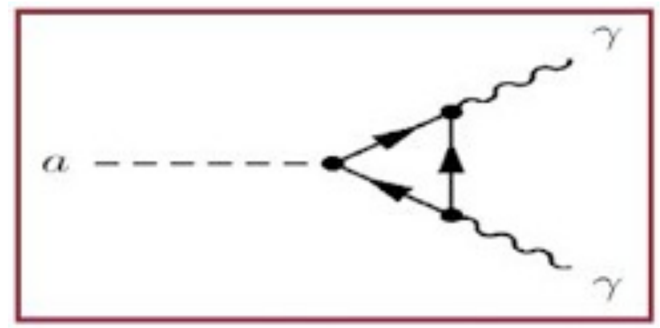
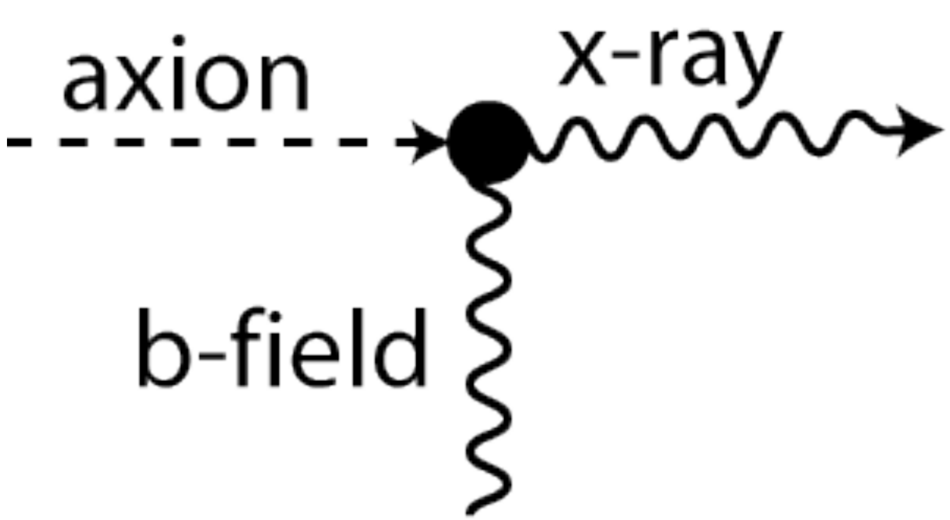
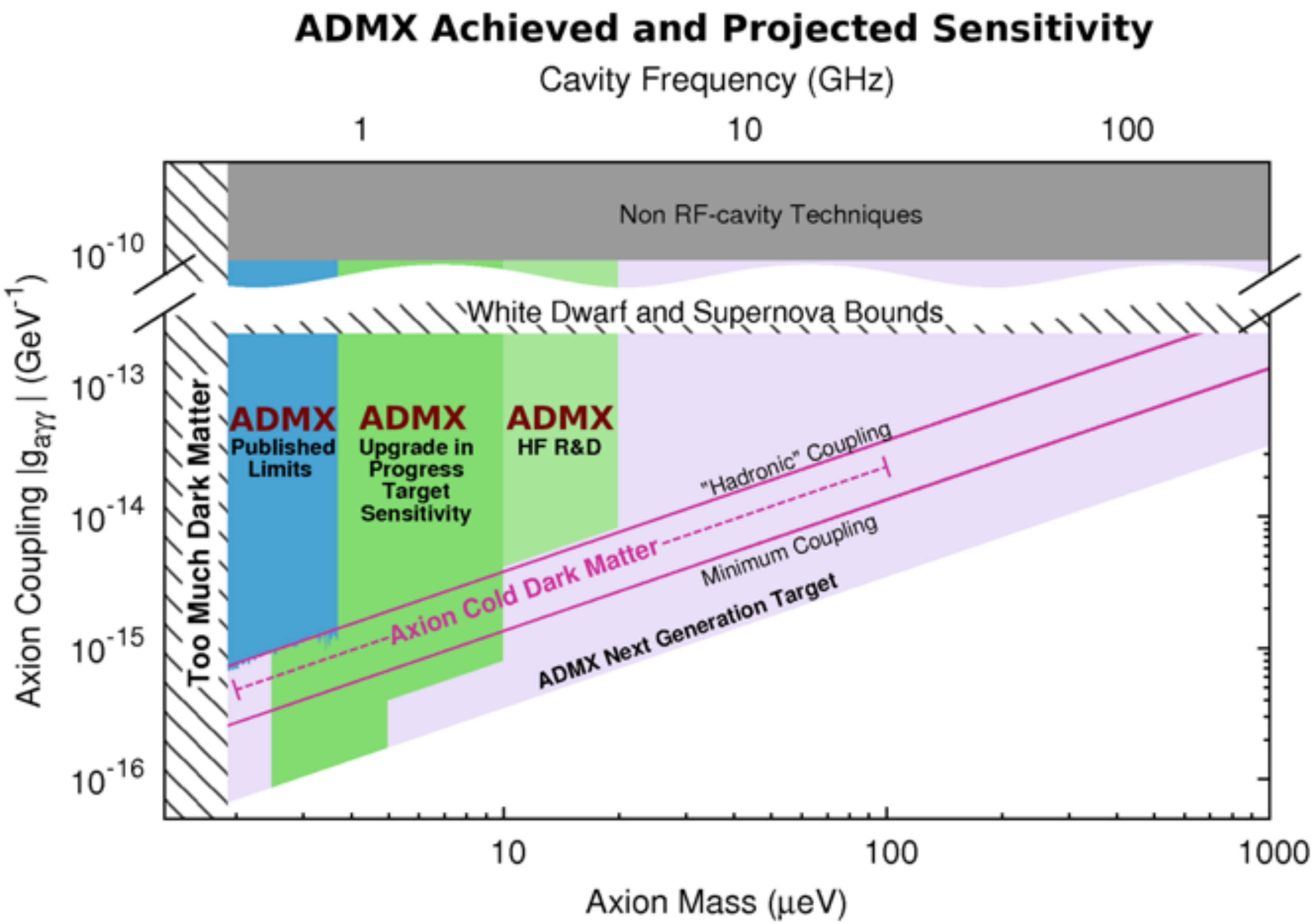


Experiments measure conversion of axion to photons



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

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



$$\frac{E}{N} < 1.92 + 3.5\sqrt{\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{DM}}}$$

$$(m_a = 1.9 - 3.55 \times 10^{-6}\,\mathrm{ev})$$

Flavor:

$$\frac{1}{\Lambda_1^2}(qu)(L\bar{N}) \qquad \frac{1}{\Lambda_2^2}(\bar{q}\bar{u})(\bar{L}N)$$

Flavor: $\frac{1}{\Lambda_1^2}(qu)(L\bar{N})$ $\frac{1}{\Lambda_2^2}(\bar{q}\bar{u})(\bar{L}N)$

a) If UV interactions respect singlets symmetry

$$\frac{4D-3L-6N}{\sqrt{102}}, \qquad \frac{L-2N}{\sqrt{3}} \qquad\qquad \frac{E}{N}=-\frac{5}{6}$$

b) If all Yukawas allowed

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

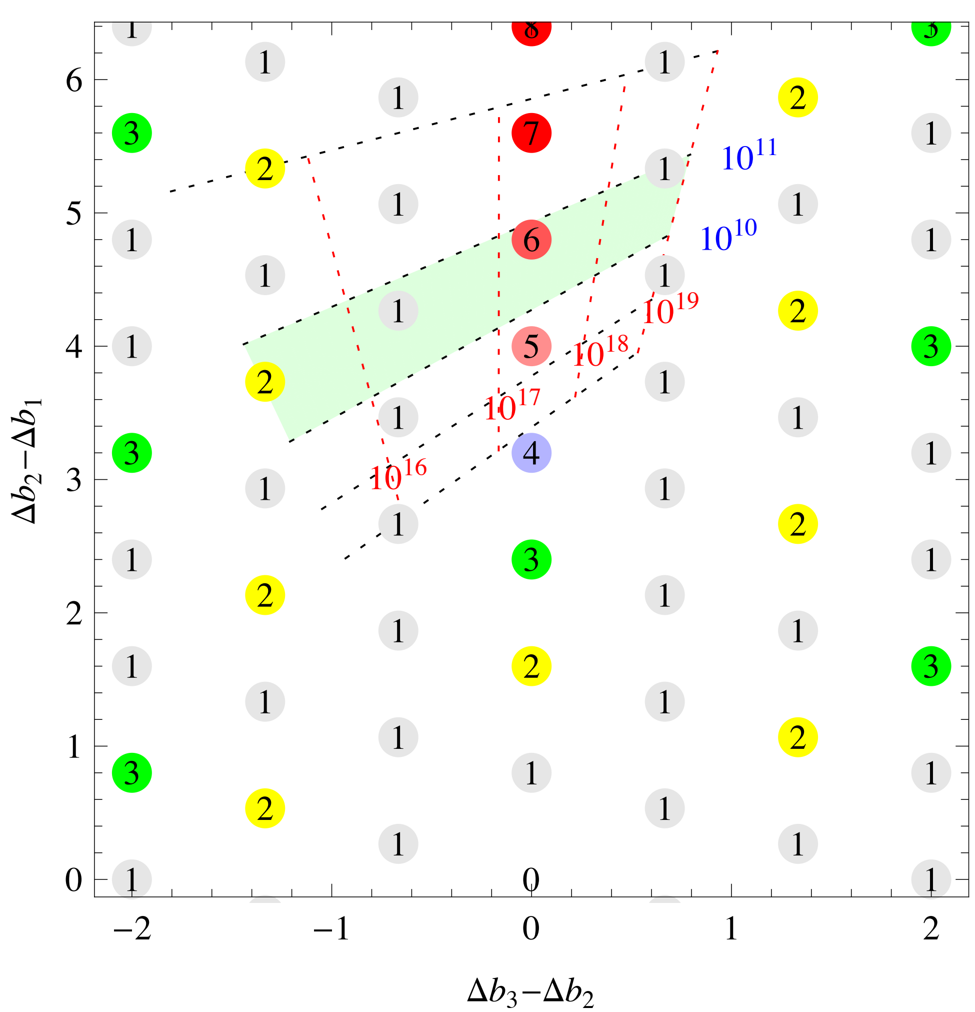
c) SU(5) is gauged

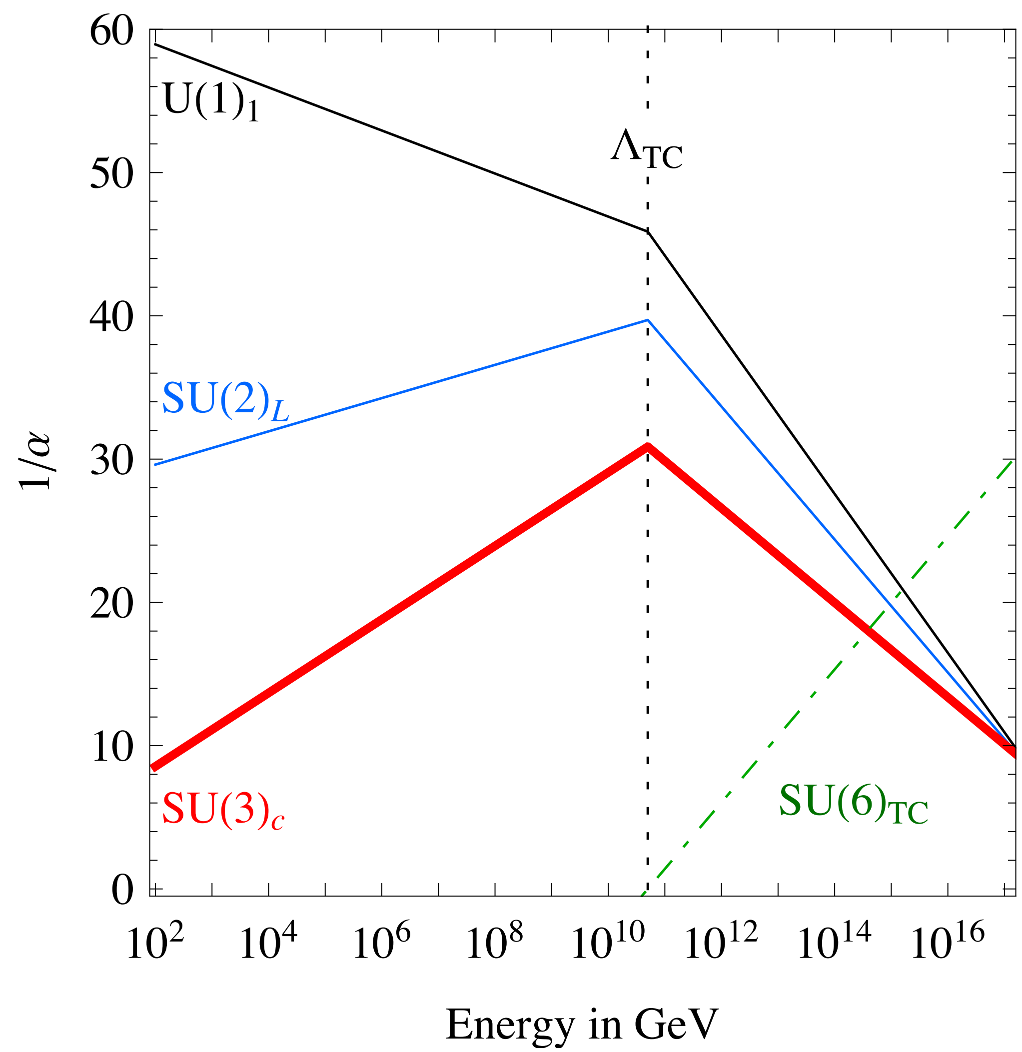
$$\frac{D+L-5N}{\sqrt{30}} \qquad\qquad \frac{E}{N}=\frac{8}{3}$$

Incomplete SU(5) multiplets can improve unification ("unificaxion")

Giudice, Rattazzi, Strumia '12

Ex: D, L, Q, U, N





HIGGS + DFSZ AXION

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

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

5 GBs:

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

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5 GBs:

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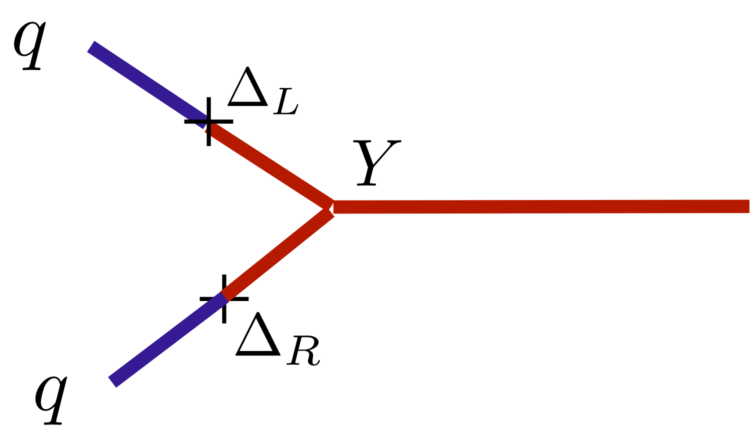
Gauging of SM gauge symmetry preserves

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

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

Partial compositeness



$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

$$\psi_{SM}\Psi_{comp}$$

$$\Psi_{comp} \in G$$

We can choose

$$10 = (2,2) + (3,1) + (1,3)$$

Mixing induces a PQ charge on the SM fermions.

$$\delta q_L = 0 \qquad \delta u_R = -\frac{1}{\sqrt{2}} u_R \qquad \delta d_R = -\frac{1}{\sqrt{2}} d_R \qquad \delta e_R = -\frac{1}{\sqrt{2}} e_R$$

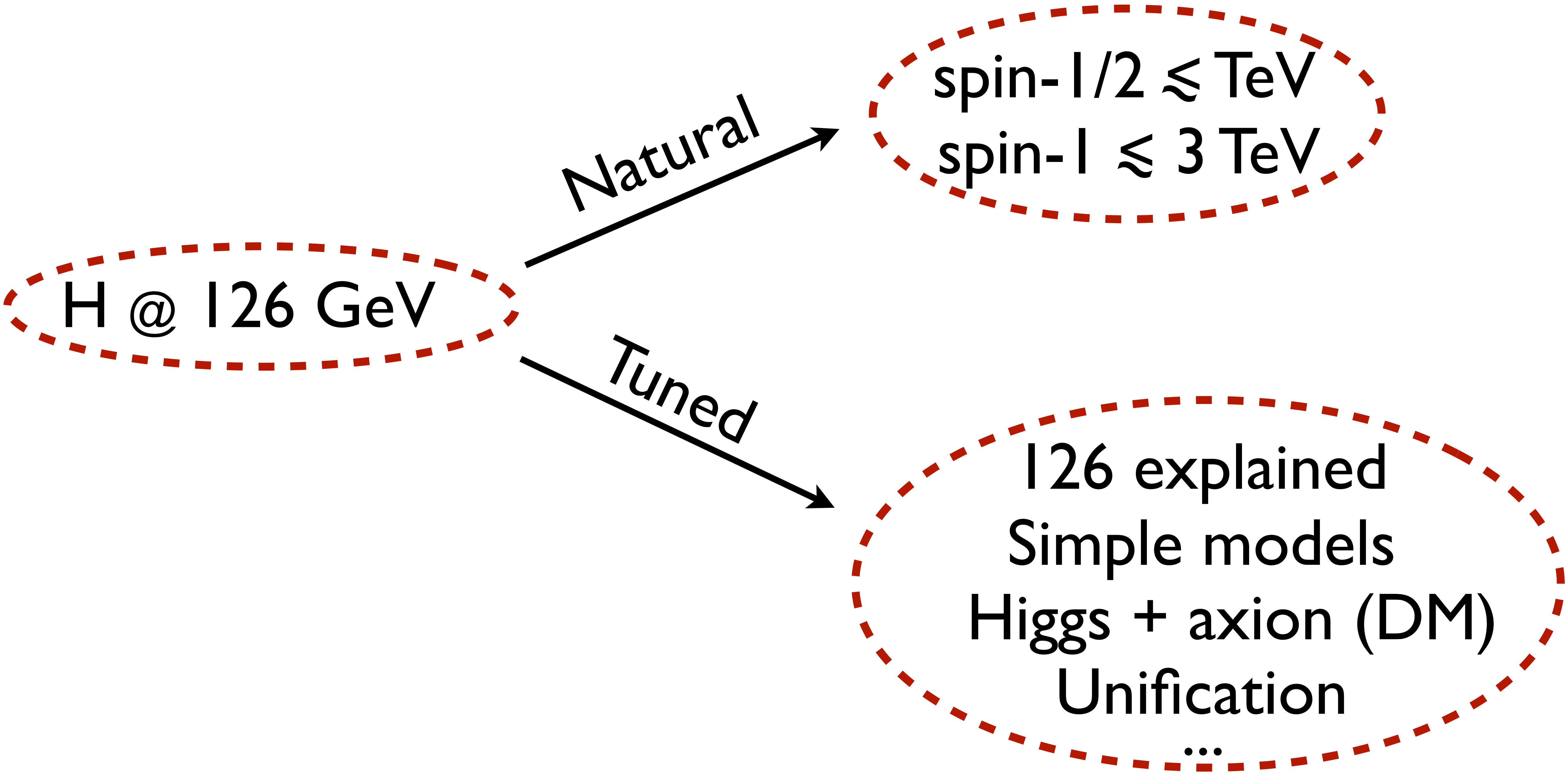
PQ symmetry is anomalous due to uR, dR, eR rotations

$$N = 2N_F$$

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

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

GOLDSTONE HIGGS



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

Fermions	$U(1)_Y$	$SU(2)_L$	$SU(3)_c$	$SO(n)_{TC}$	$U(1)_{PQ}$
L	$-\frac{1}{2}$	2	1	n	0
$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	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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$$\langle L\bar{L}\rangle = \langle N\bar{N}\rangle = \Lambda^3$$

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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:

$$E_{TC} = 0$$

$$\frac{E}{N} = \frac{8}{3}$$

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

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

Leptogenesis?

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

Sp(n) theories with 4 flavors

Fermions	$\mathrm{U}(1)_Y$	$SU(2)_L$	$SU(3)_c$	$\mathrm{Sp}(n)_{\mathrm{TC}}$	$\mathrm{U}(1)_{\mathrm{PQ}}$
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S	$+\frac{1}{2}$	1	1	n	-1
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Difficult to generate QCD anomaly

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

We can be build models with partial compositeness

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

ESTIMATES

Panico, MR, Tesi, Wulzer '12

$$\mathcal{L} = \left(1 + \epsilon_L^2 \sum_i I_L^{(i)}(s_h)\right) \bar{q}_L \partial q_L + \left(1 + \epsilon_R^2 \sum_i I_R^{(i)}(s_h)\right) \bar{t}_R \partial t_R$$
$$+ y_t f\, M(s_h) \bar{t}_L t_R + h.c.\,,$$

$$s_h \equiv \sin\frac{h}{f} = \frac{v}{f}$$

Loops of SM fields generate:

$$V_{\text{leading}} \sim \frac{N_c}{16\pi^2} m_\psi^4 \sum_i \left[\epsilon_L^2\, I_L^{(i)}(s_h) + \epsilon_R^2\, I_R^{(i)}(s_h)\right]$$

$$V_{\text{sub-leading}} \sim \frac{N_c}{16\pi^2} m_\psi^2 f^2\ \left[y_t^2\, M^2(s_h) + \ldots\right]$$

$$\left(y_t \sim \epsilon_L \epsilon_R \frac{m_\psi}{f}\right)$$

Two different trigonometric structures needed to tune.

- Tuning at leading order

$$m_h \sim 500\,\mathrm{GeV}\left(\frac{m_\psi}{3\,f}\right)^{\frac{3}{2}} \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$

- Tuning with sub-leading terms (CHM5, CHM10...)

$$m_h \sim 300\,\mathrm{GeV}\left(\frac{m_\psi}{3\,f}\right) \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{m_\psi}{y_t f} \times \frac{f^2}{v^2}$$

- Composite tR

$$m_h \sim 300\,\mathrm{GeV}\left(\frac{m_\psi}{3\,f}\right) \longrightarrow \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$

Minimum ingredients for semi-natural composite Higgs:

- partial compositeness

- custodial symmetry

- L-R symmetry

- split spectrum

- luck with precision tests

- miracle with flavor