

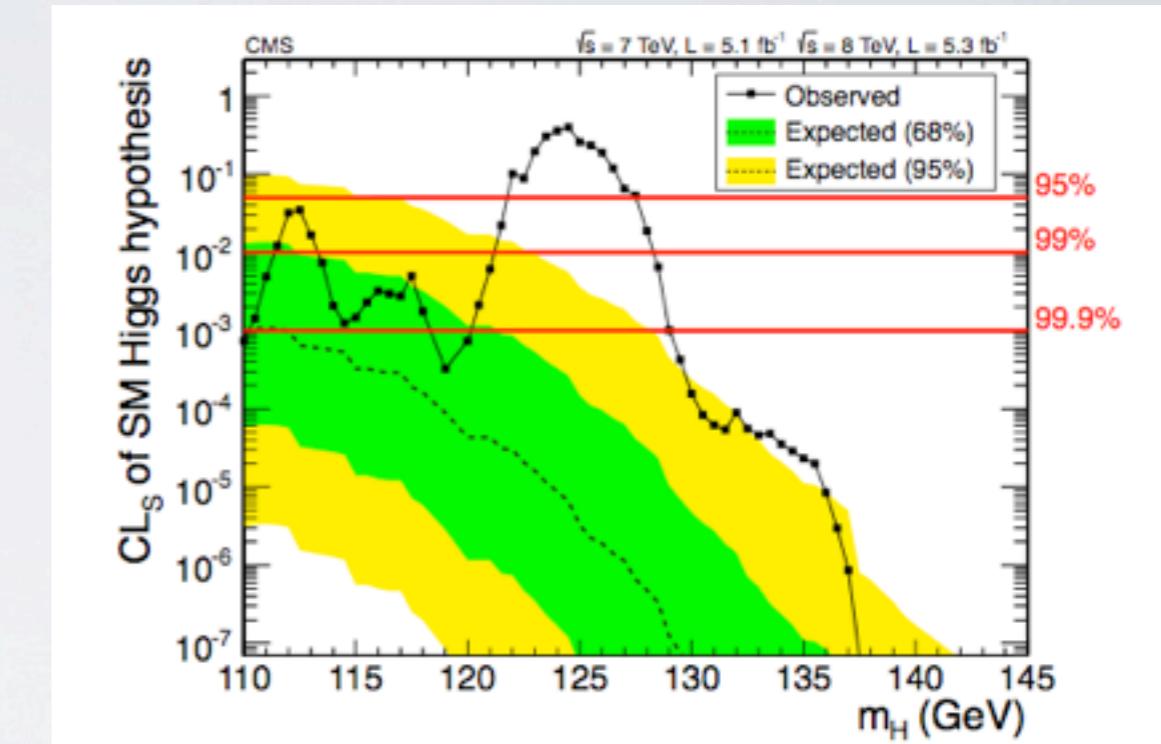
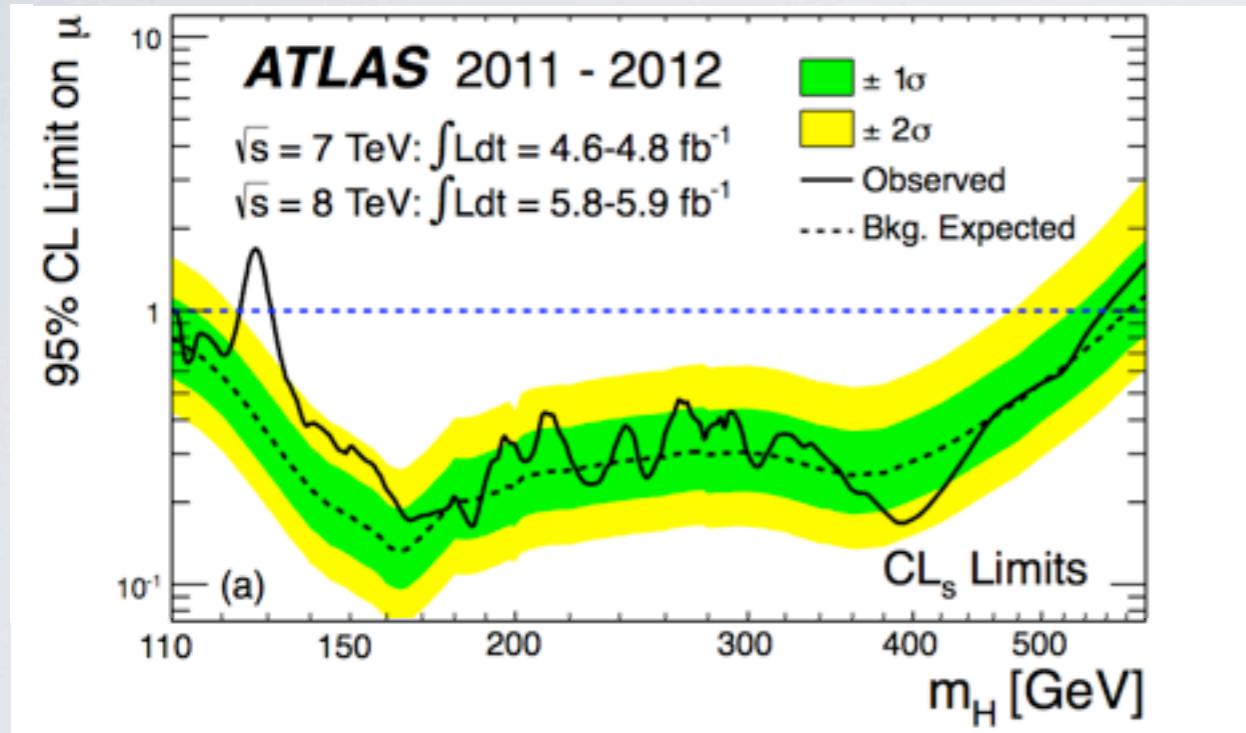
# Axion-Higgs Unification

Michele Redi



1208.6013 with A. Strumia

Brussels, 12 December



Observation of a new particle in the search for the Standard Model Brout-Englert-Higgs boson with the ATLAS and the CMS Detector at the LHC

FLAVOR HAS FOUND NOTHING

$$\Lambda > 10^5 \text{ TeV}$$

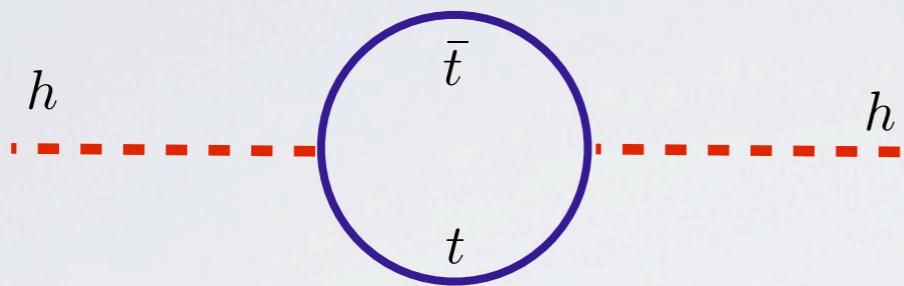
LEP HAS FOUND NOTHING

$$\Lambda > 5 - 10 \text{ TeV}$$

LHC HAS FOUND THE HIGGS  
+ NOTHING

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

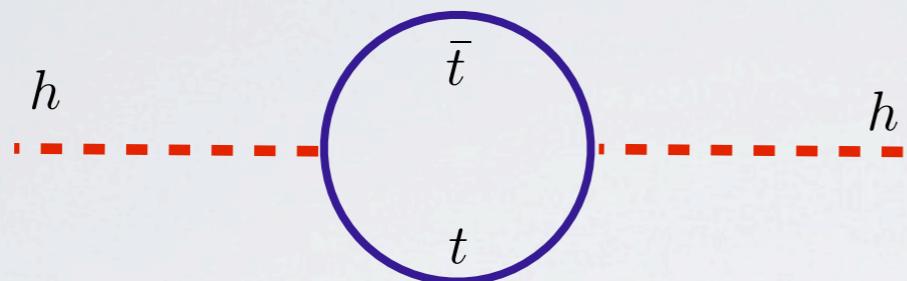
## Hierarchy Problem:



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

$$\Lambda < 1 \text{ TeV}$$

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A circular loop diagram representing a loop correction to the Higgs mass. The loop is drawn with a blue circle. Inside the circle, at the top, is the symbol  $\bar{t}$ , and at the bottom is the symbol  $t$ . Two red dashed horizontal lines extend from the left and right sides of the circle to the left and right respectively, each ending with the letter  $h$ .

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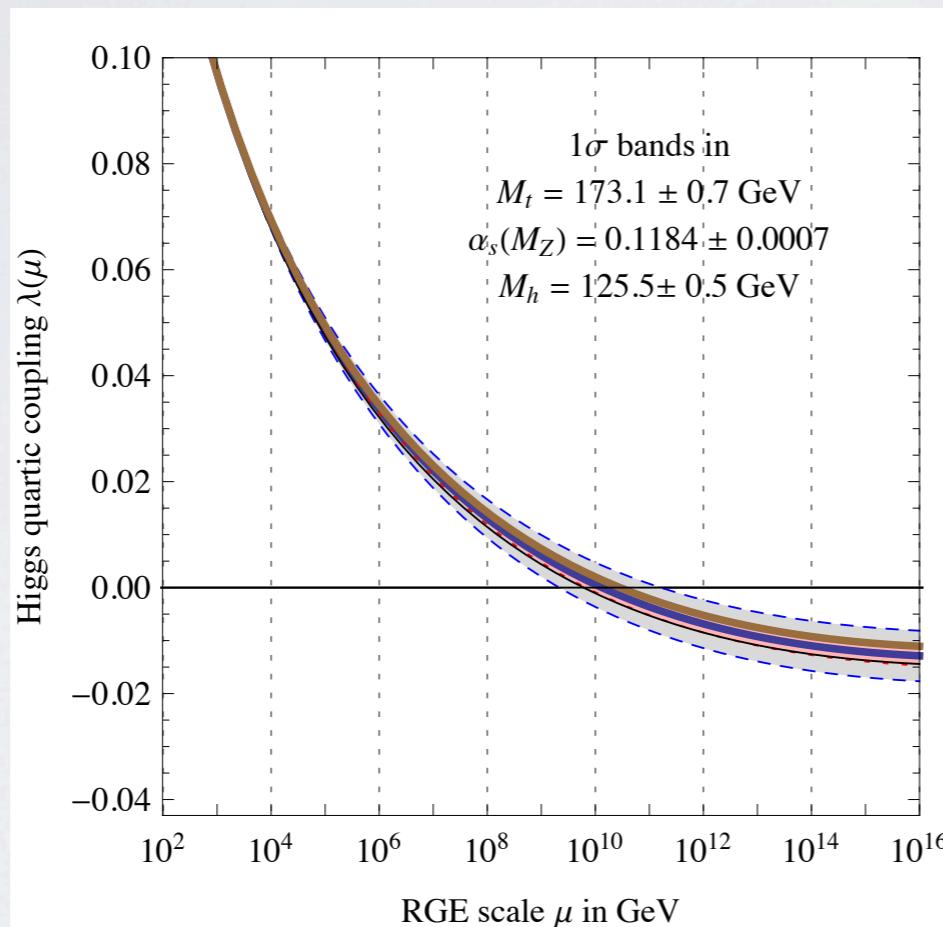
$$\Lambda < 1 \text{ TeV}$$

Suspicion:

Perhaps naturalness was not a good guide

# 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:

$$\frac{\theta}{32\pi^2} \int d^4x \epsilon^{\mu\nu\rho\sigma} Tr[G_{\mu\nu}G_{\rho\sigma}] \quad \theta < 10^{-9}$$

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Most elegantly solved by axions

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

Axions are Goldstones of a symmetry anomalous under QCD

$$m_a \sim \frac{\Lambda_{QCD}^2}{f}$$

Experimentally:

$$f > 10^9 \text{ GeV}$$

Axions can be dark matter

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

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- Neutrino masses

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

# GOLDSTONE HIGGS

Georgi, Kaplan '80s

Higgs could be a Goldstone boson of 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  $v$ .

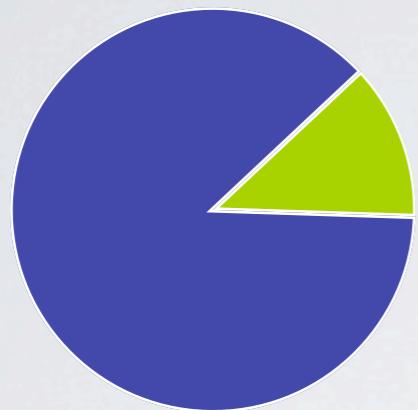
Deviation from SM:

$$\mathcal{O}\left(\frac{v^2}{f^2}\right)$$

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Higgs is an angle,



$$0 < h < 2\pi f$$



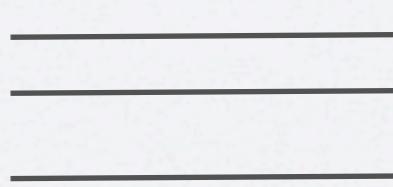
$$\text{TUNING} \propto \frac{f^2}{v^2}$$

Typical spectrum:

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



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



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

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

$$0$$

# Partial compositeness:

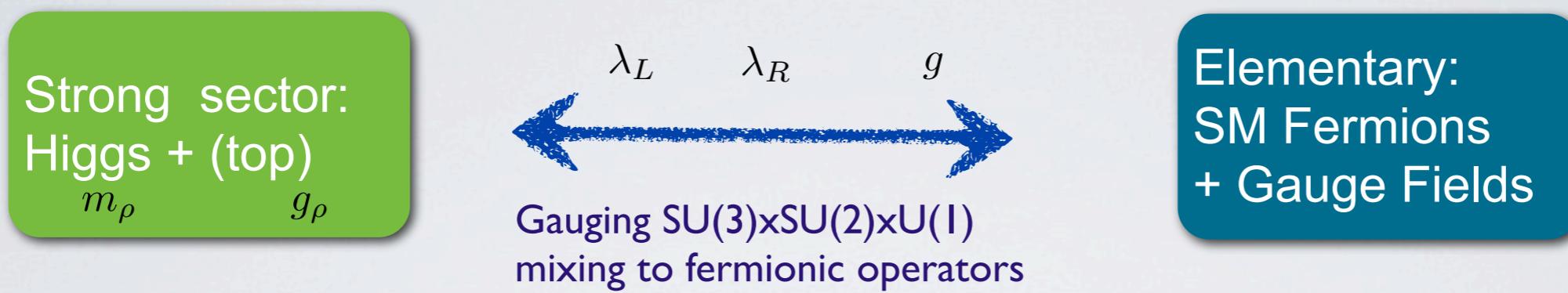
D. B. Kaplan '92  
Contino-Pomarol, '04

Strong sector:  
Higgs + (top)  
 $m_\rho$        $g_\rho$

Elementary:  
SM Fermions  
+ Gauge Fields

# Partial compositeness:

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



They talk through linear couplings:

$$\begin{aligned} \mathcal{L}_{gauge} &= g A_\mu J^\mu \\ \mathcal{L}_{mixing} &= \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \end{aligned} \quad \xrightarrow{\epsilon \sim \frac{\lambda}{Y}} \quad y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

- + phenomenology greatly ameliorated
- big dynamical assumptions

Despite smart theorists difficulties remain:

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- direct exclusion

$$m_f > 0.7 \text{ TeV} \quad m_\rho > 1.5 \text{ TeV}$$

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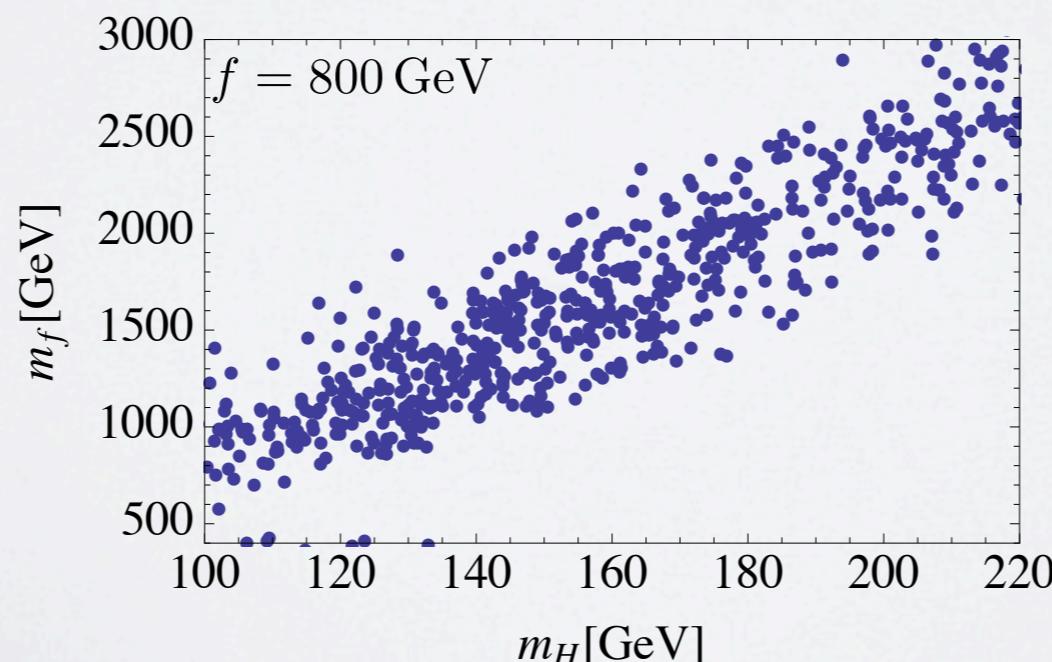
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- Higgs mass



Redi,Tesi '12

$$f \approx 10^{11} \text{ GeV}$$

# 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.

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

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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

$$\Psi_Q \rightarrow e^{i\alpha_Q \gamma_5} \Psi_Q, \quad \sigma \rightarrow e^{-2i\alpha_Q} \sigma$$

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

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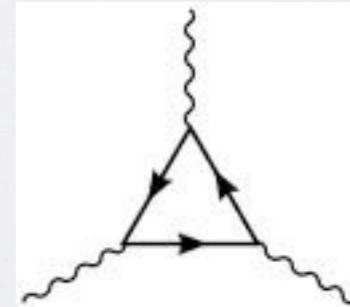
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Spontaneous PQ symmetry breaking

$$f \approx \langle \sigma \rangle$$

$$a = \sqrt{2} \operatorname{Im}[\sigma]$$

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.

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	$\bar{n}$

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

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

FLAVOR:

$$(qu)(L\bar{N})$$

$$(\bar{q}\bar{u})(\bar{L}N)$$

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

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

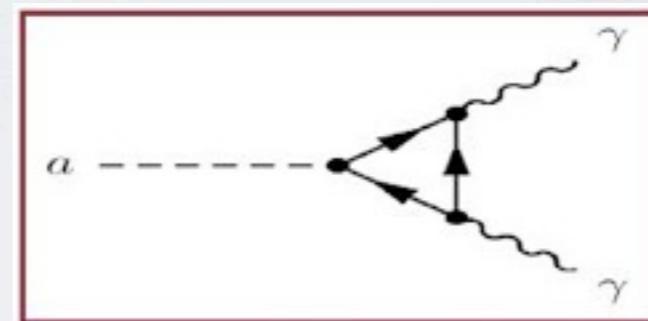
Axions couple to photon and gluons through anomalies

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

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

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

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



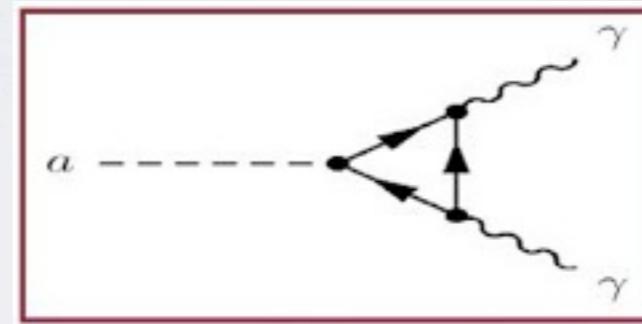
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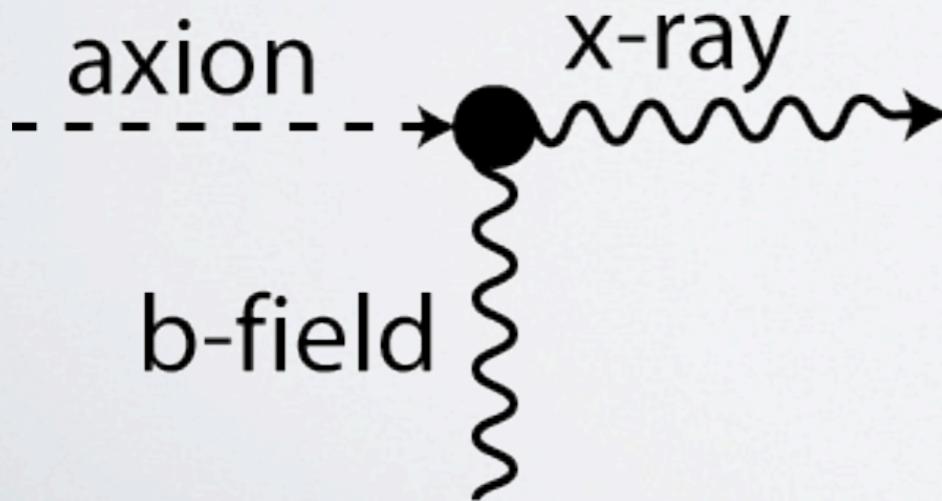
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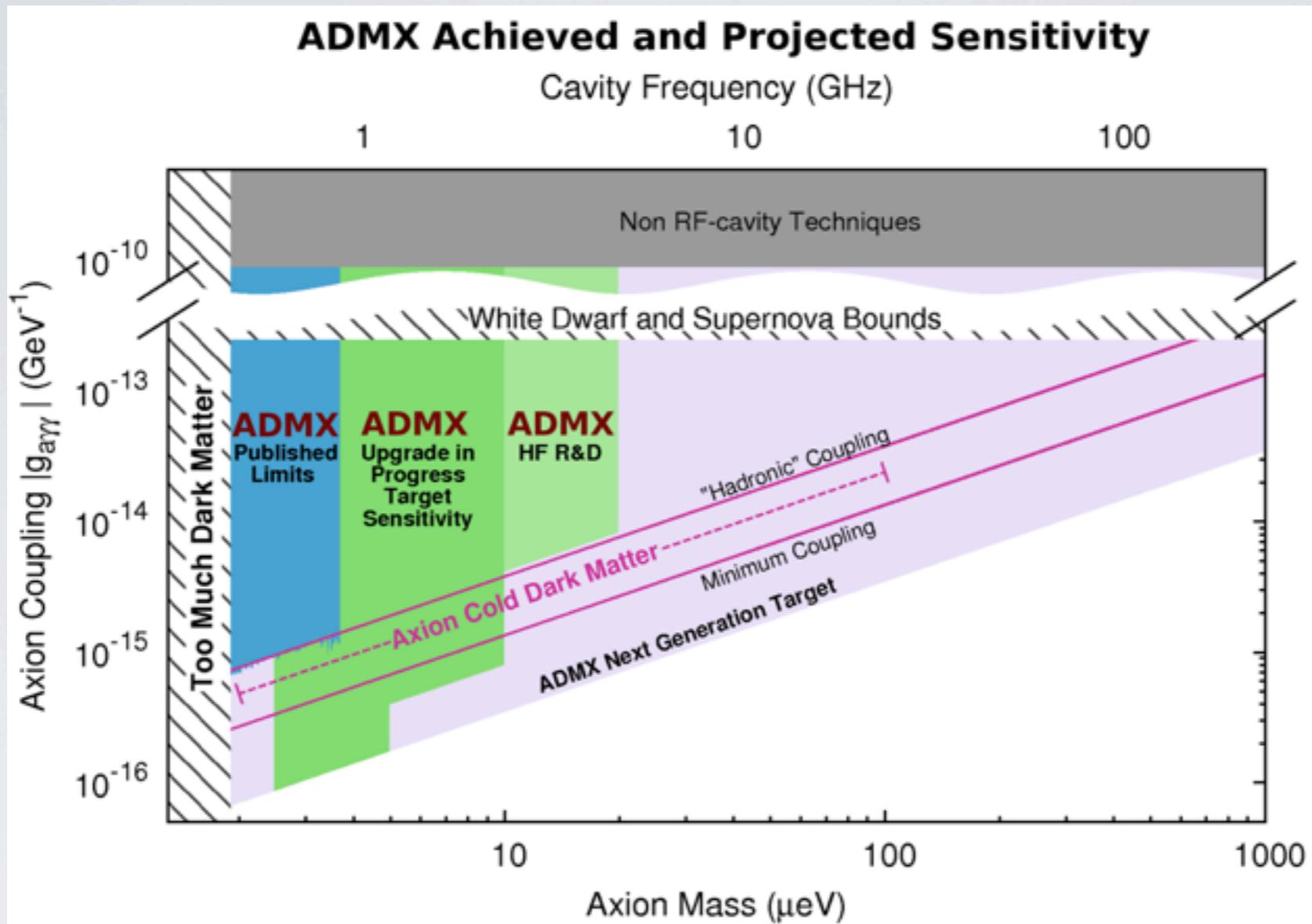


Experiments measure conversion of axion to photons



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

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



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

a) If UV interactions respect singlets symmetry

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

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

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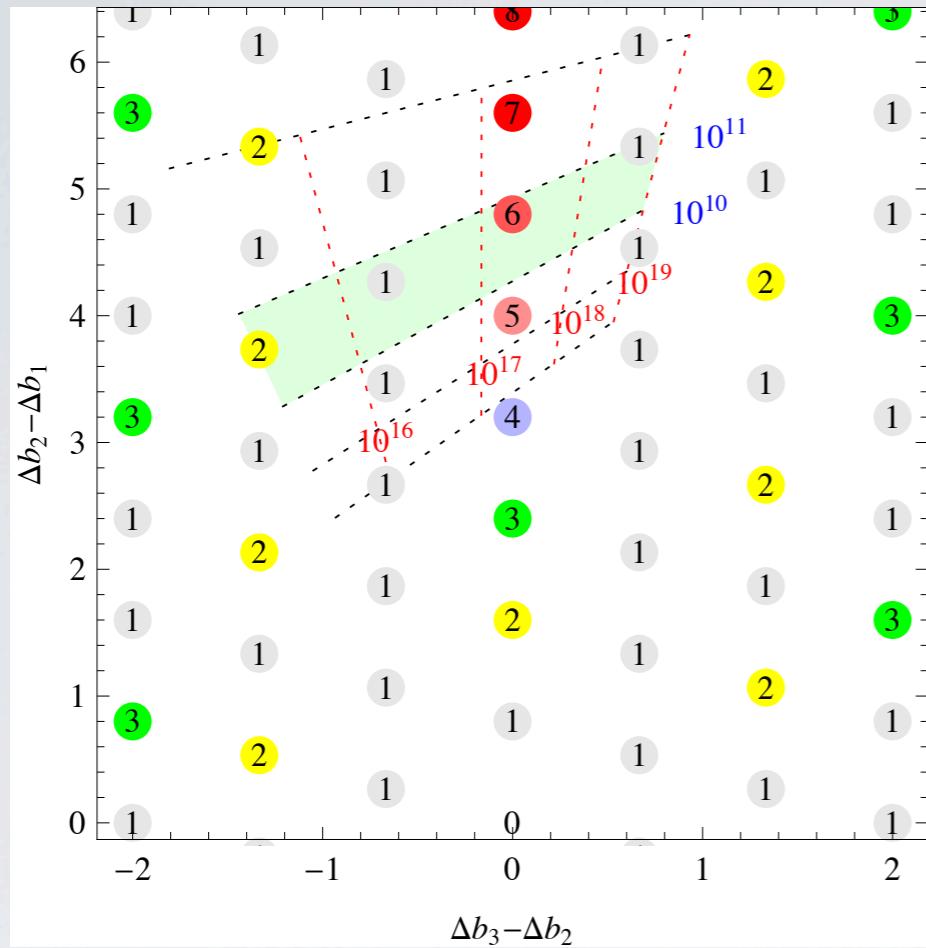
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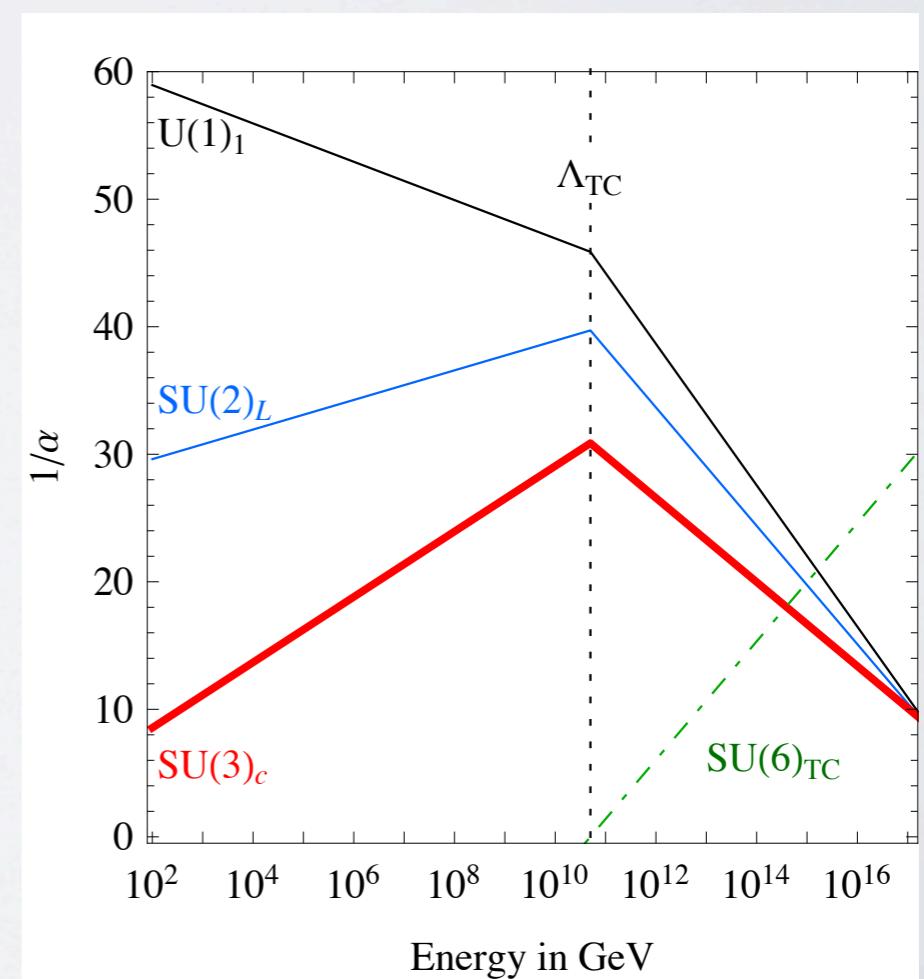
c) If all Yukawas allowed

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

# 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

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

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

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Ex:

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

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

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

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$$H_1 \sim LN$$

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

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

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

Yukawas must respect PQ

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

Anomalies:

$$E_{TC} = 0$$

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

Neutrino masses can be generated by see-saw mechanism

$$\frac{1}{\Lambda_\nu^2} (L \nu_R^c)^\dagger (\bar{L} \bar{N}) + m^2 (\nu_R^c)^2 + h.c.$$

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

If no right-handed neutrinos

$$\frac{1}{\Lambda_\nu^4} (\ell \bar{L})^2 N^2 \rightarrow \frac{1}{\Lambda_\nu^3} (\ell H_u)^2 \sigma^2 + \dots$$

Same order of magnitude.

# 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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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.

# Sp(n) theories with 4 flavors

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

# $\text{Sp}(n)$ theories with 4 flavors

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Difficult to generate QCD anomaly

$(qu)(DS)$

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

We can build models with partial compositeness

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

Fermions can couple to  $6 = (2,2) + 2 \times 1$

$$q_L \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix}$$

$$t_R \rightarrow \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i \cos \theta t_R \\ \sin \theta t_R \end{pmatrix}$$

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For  $\theta = \frac{\pi}{4}$  singlet becomes exact GB  
PQ symmetry is anomalous due to tR rotations

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

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

# HIGGS MASS

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

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

Electro-weak scale:

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

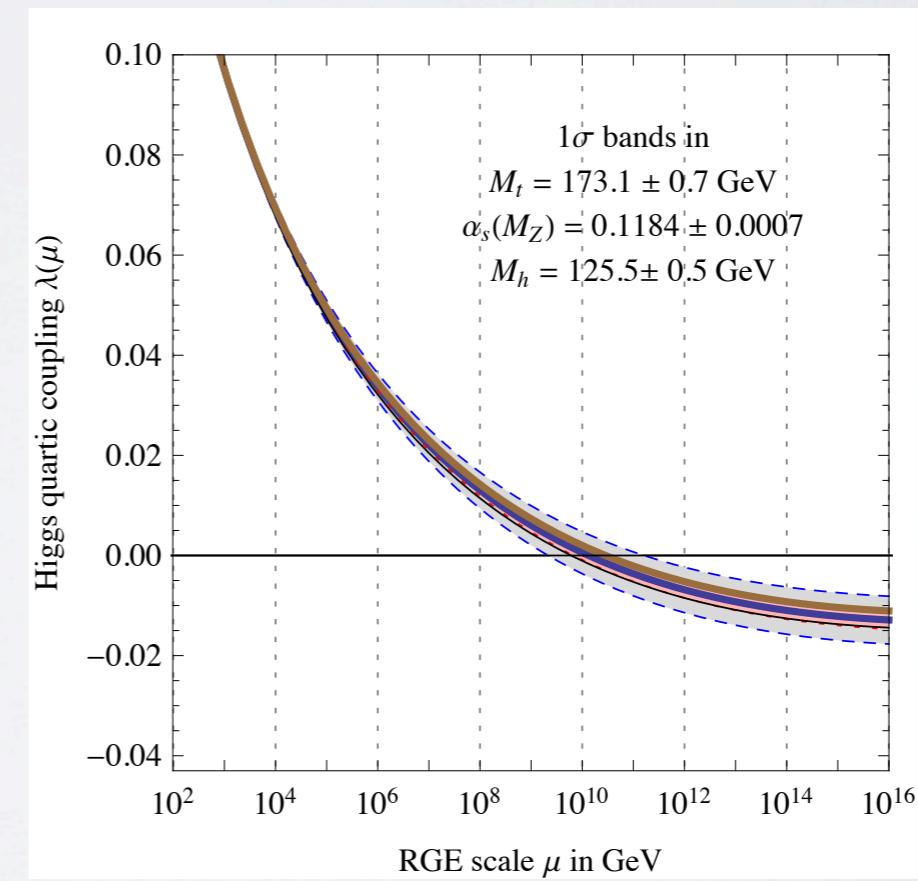
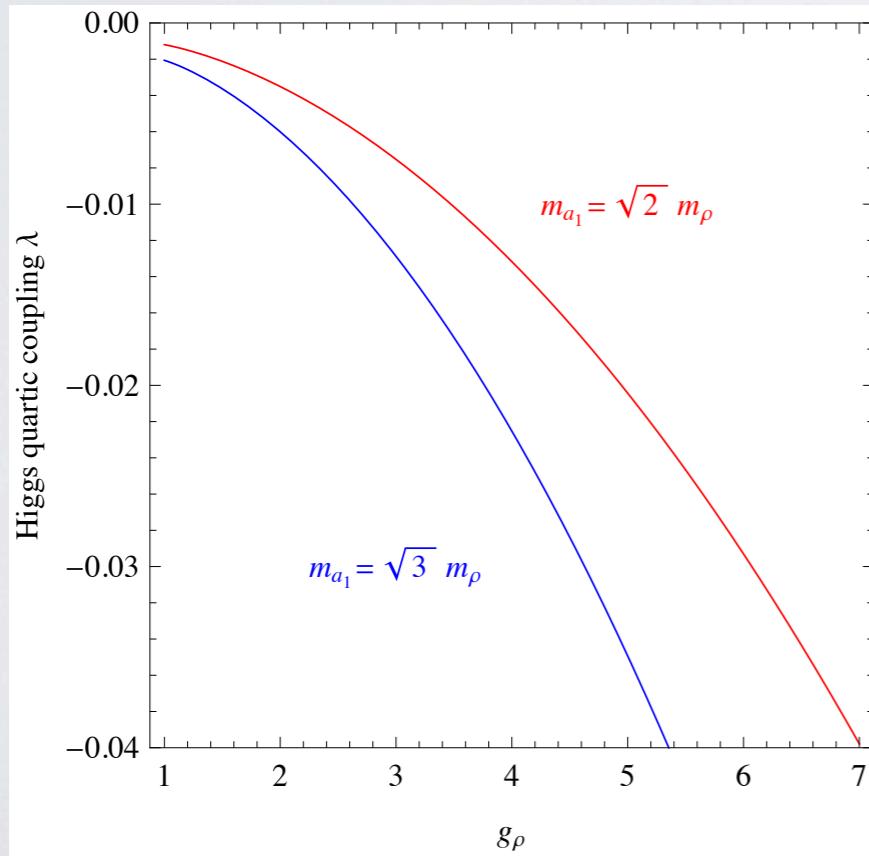
Higgs mass is then “predicted”.

# Gauge contribution:

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

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

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



- Leading order tuning

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

125 GeV Higgs implies weak coupling (large n)

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| 125 GeV Higgs implies weak coupling (large n)

- Subleading order tuning

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

Model I:

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

# CONCLUSIONS

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- So far everything is consistent with the SM being valid up to a very large a scale.

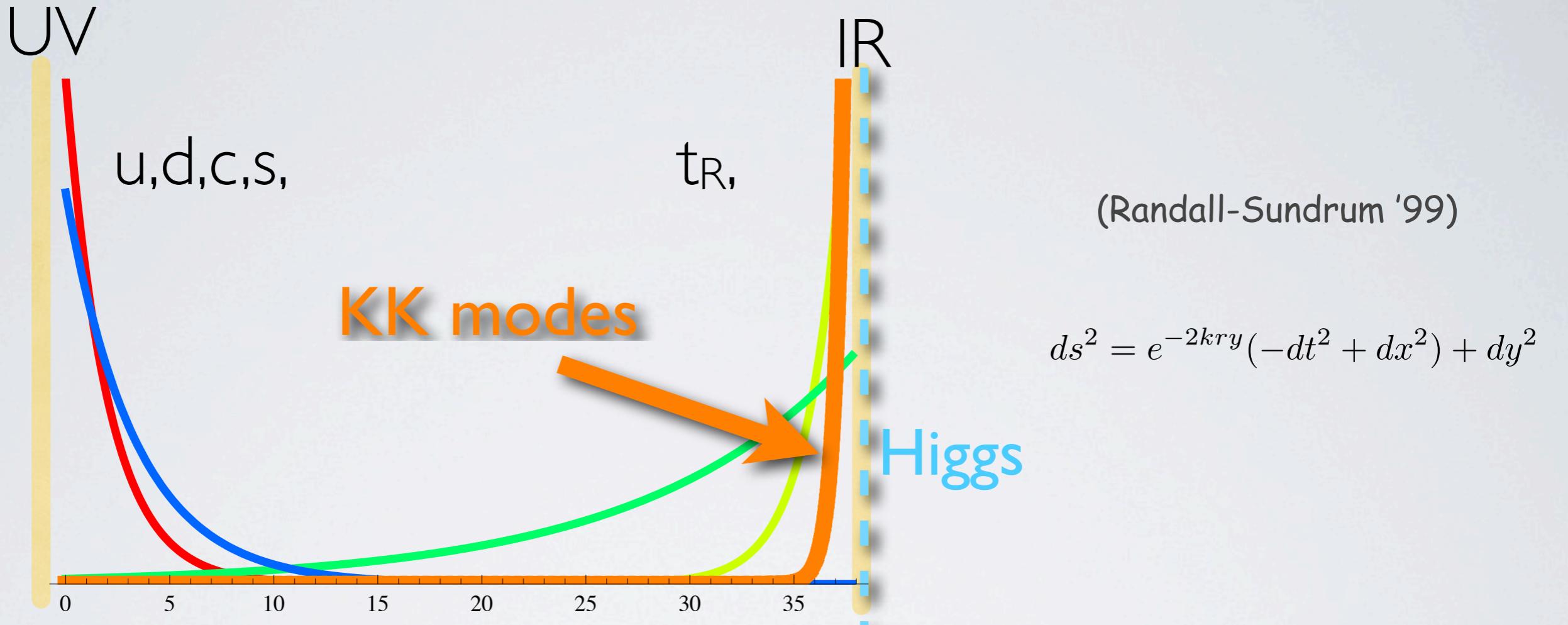
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- The idea of the Higgs as Goldstone boson can be naturally merged with axions if  $\Lambda \sim 10^{11} \text{ GeV}$
- Giving up naturalness, strong CP, dark matter, Higgs mass can be explained. Unification and neutrino masses could also fit into the picture.

Possible to realize it in Randall-Sundrum scenarios.



Through AdS/CFT correspondence dual to 4D CFTs.  
Relevant physics dominated by the lowest modes.