Thermal Dark Matter from Strong Interactions

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With O. Antipin and A. Strumia
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Strong dynamics is a very plausible possibility for BSM

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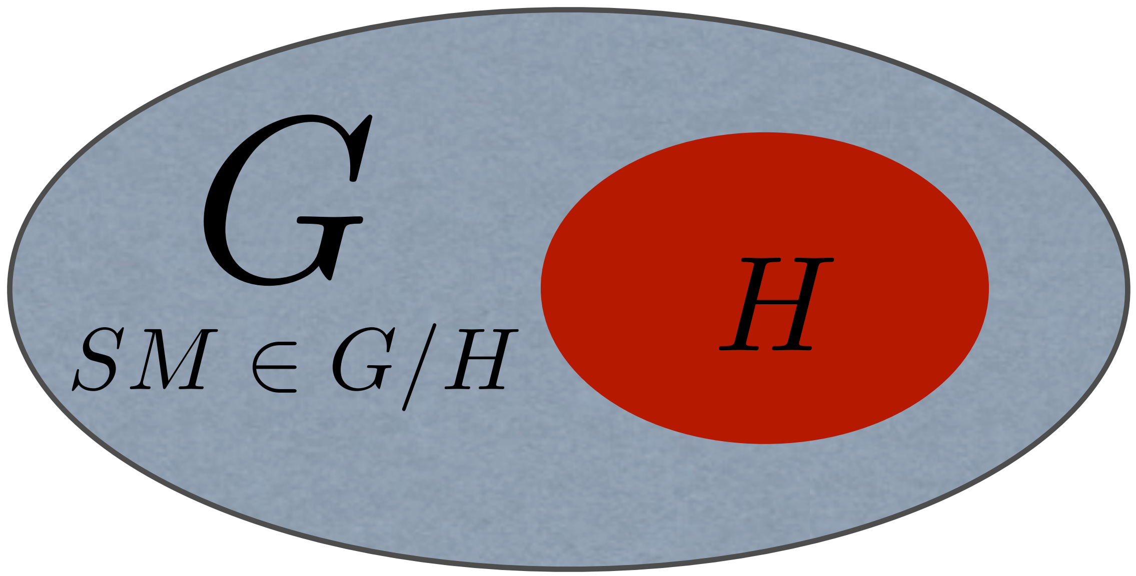
In origin it was technicolor:



$$f = v$$

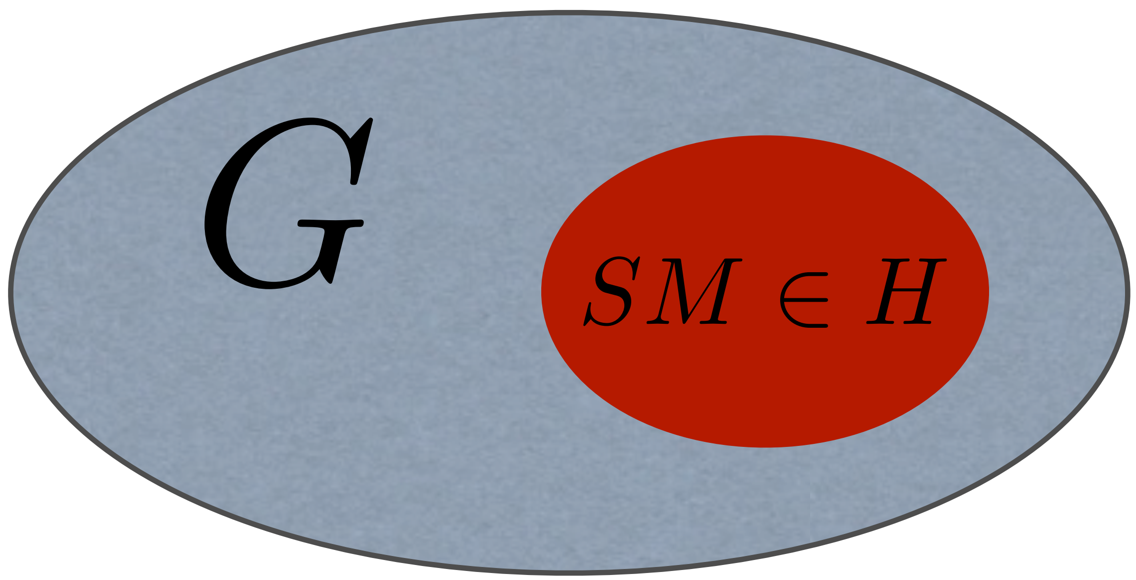
Completely natural theory. No need for the Higgs scalar.

Already in trouble before LHC, now dead.

Next it was the composite Higgs

Georgi, Kaplan '80s

Higgs could be an approximate GB



$$m_\rho = g_\rho f$$

Ex:

Agashe , Contino, Pomarol, '04

$$\frac{SO(5)}{SO(4)} \xrightarrow{f > v} \mathrm{GB} = 4$$

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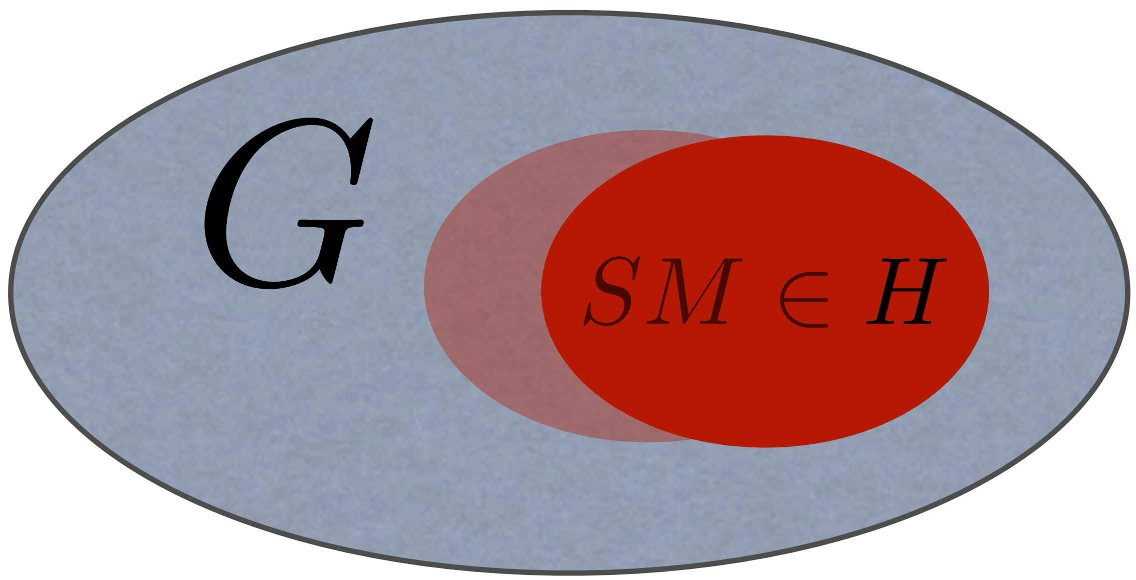

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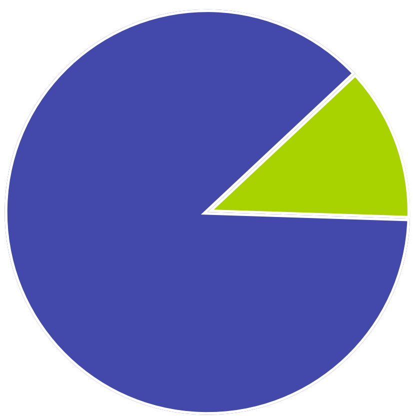
Electro-weak scale determined by vacuum alignment.

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

Higgs is an angle,



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

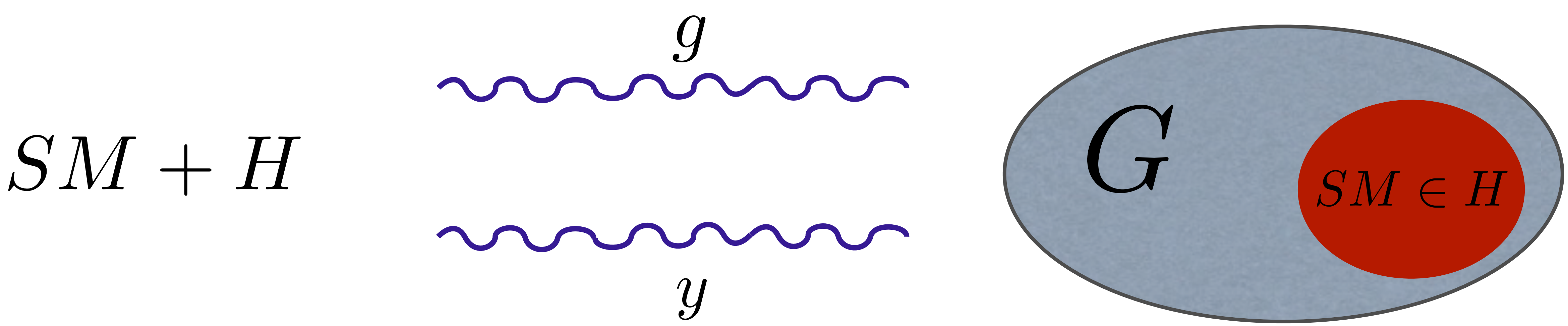
Small Tuning $\quad f < TeV$

- Natural models are constrained by flavor, precision tests and now LHC.

- Hard to construct UV theories.
  Typically postulate effective theories with correct features.

Electro-weak preserving strong sector:

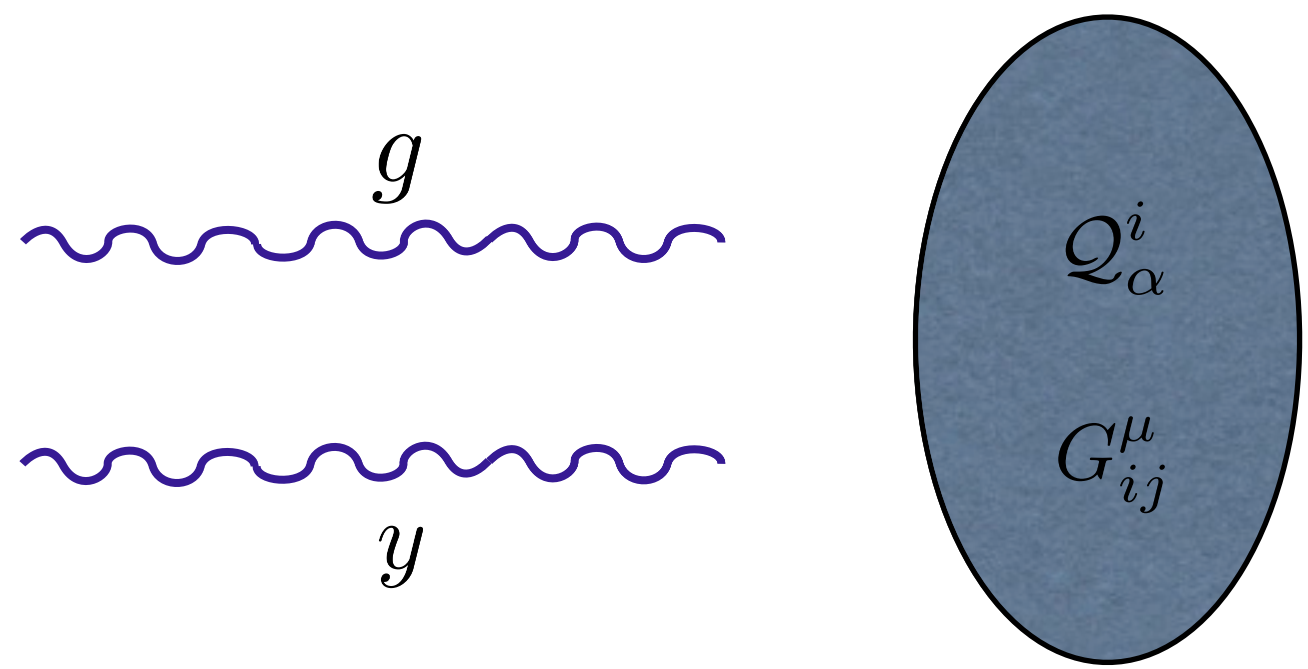
Kilic, Okui, Sundrum '09



Electro-weak preserving strong sector:

Kilic, Okui, Sundrum '09

$$SM + H$$



Higgs is elementary and couples to strong dynamics with renormalizable couplings:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4\, g_{TC}^2} G^a_{\mu\nu} G^{a\,\mu\nu} + i\bar{\mathcal{Q}}\gamma_\mu(\partial_\mu - iA_\mu - iG_\mu)\mathcal{Q} + \bar{\mathcal{Q}} M \mathcal{Q}$$

Very weak bounds:

- Automatic MFV
- Precision tests ok
- LHC: $m_\rho > 1 - 2\,\mathrm{TeV}$

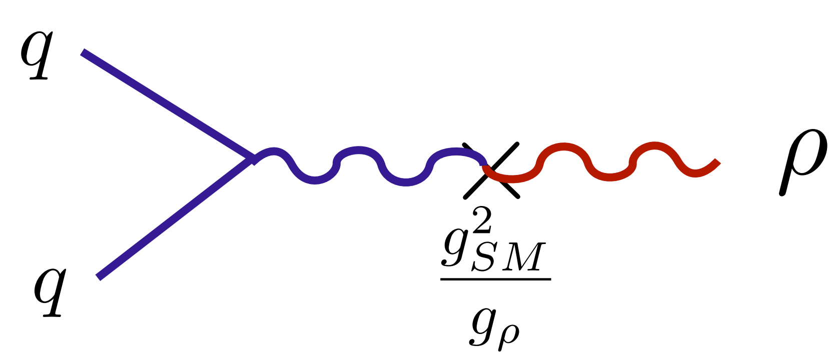
Interesting phenomenology:

- Plausible at LHC13
- Automatic dark matter candidates
- Simple UV models
- Can generate the electro-weak scale

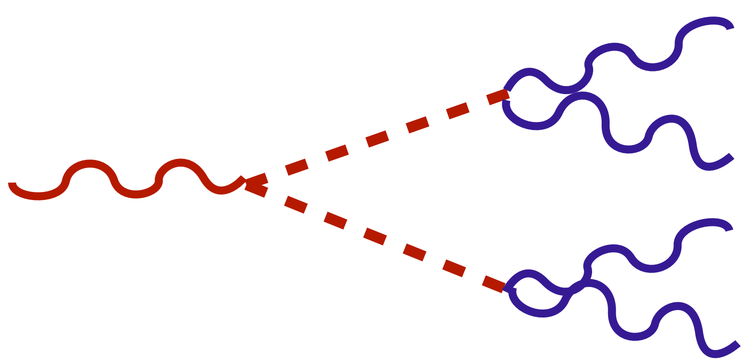
COLLIDER SIGNATURES

Kilic, Okui, Sundrum '09

Vector resonances with SM quantum numbers predicted



Decay to hidden pions and back to SM gauge bosons,



Pions can also be stable or long lived.

- **Models**

SU(n) gauge theory with NF flavors.
Techni-quarks are vectorial with respect to SM.

Fermions	SM	$SU(n)_{\mathrm{TC}}$
Ψ_L	$\sum_i r_i$	n
Ψ_R	$\sum_i \bar{r}_i$	$\bar{n}$

$$\sum_i d[r_i] = N_F$$

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Fermions	SM	$SU(n)_{\mathrm{TC}}$
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$$\sum_i d[r_i] = N_F$$

Vacuum respects electro-weak symmetry.
Massless Goldstone bosons:

$$\frac{SU(N_F)\times SU(N_F)}{SU(N_F)}$$

$$\mathrm{Adj}[SU(N_F)] = \mathrm{Adj}[SM] + R(\pi)$$

Charged pions acquire positive mass from gauge interactions

$$m_\pi^2 \approx \frac{3\,g_2^2}{(4\pi)^2} J(J+1) m_\rho^2$$

These models have automatic dark matter candidates:

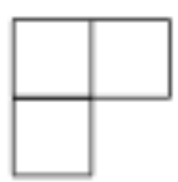
- Baryons

$$B = \epsilon^{i_1 i_1 \ldots i_n} Q_{i_1}^{\{\alpha_1} Q_{i_2}^{\alpha_2} \ldots Q_{i_n}^{\alpha_n\}}$$

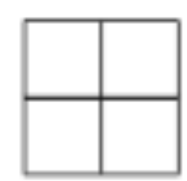
$$m_B \sim N m_\rho$$

Lightest multiplet has minimum spin among reps.

$n = 3$



$n = 4$



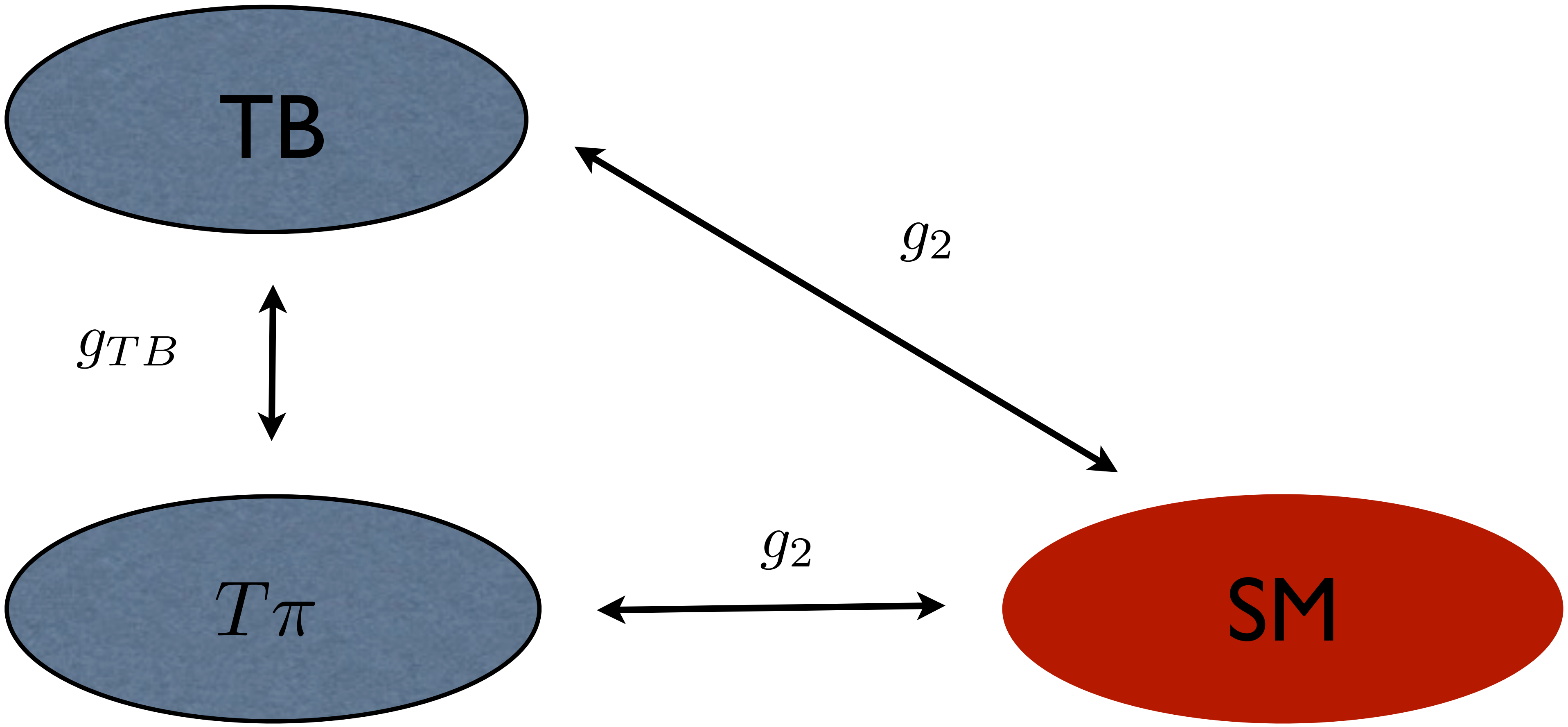
DM candidate:

$$Q_{TB} = T_3 + Y_{TB} = 0$$

$$Y_{TB} = 0$$

J=0,1,2,...

Baryons-anti-baryon annihilate mostly into pions



$$\langle \sigma^{ANN}_{B\bar{B}} v \rangle \sim \frac{4\pi}{m_B^2}$$

THERMAL ABUNDANCE

$$m_B \sim 50 - 100 \text{ TeV}$$

- **Pions**

Bai, Hill '10

Pions can be stable due to G-parity:

$$\psi \to S\,\psi^C$$

$$W^a_\mu J^a \to W^a_\mu J^a \qquad\qquad S^\dagger J^a S = -J^{a*}$$

$$A^a t^a \to A^a (-t^a)^*$$

$$\Pi^J \to (-1)^J \Pi^J$$

Triplet is stable. Behaves as minimal dark matter. Strumia, Cirelli '05

$$m_{J=1} \sim 2.5\,\mathrm{TeV}$$

$$\sigma_{SI} = 0.12 \pm 0.03 \times 10^{-46}\,\mathrm{cm}^2$$

With reducible SM reps pions can also be stable due to species symmetry.

$$\mathrm{Adj}_{SU(N_F)} = \sum_{i=1}^{K} r_i \times \sum_{i=1}^{K} \bar{r}_i - 1$$

$$\bar{\Psi}_I \Psi_J \qquad\qquad I \neq J$$

K-1 singlets do not acquire mass from gauge interactions. Anomalous under the SM:

$$\frac{e^2}{(4\pi)^2 f} \eta F \tilde{F}$$

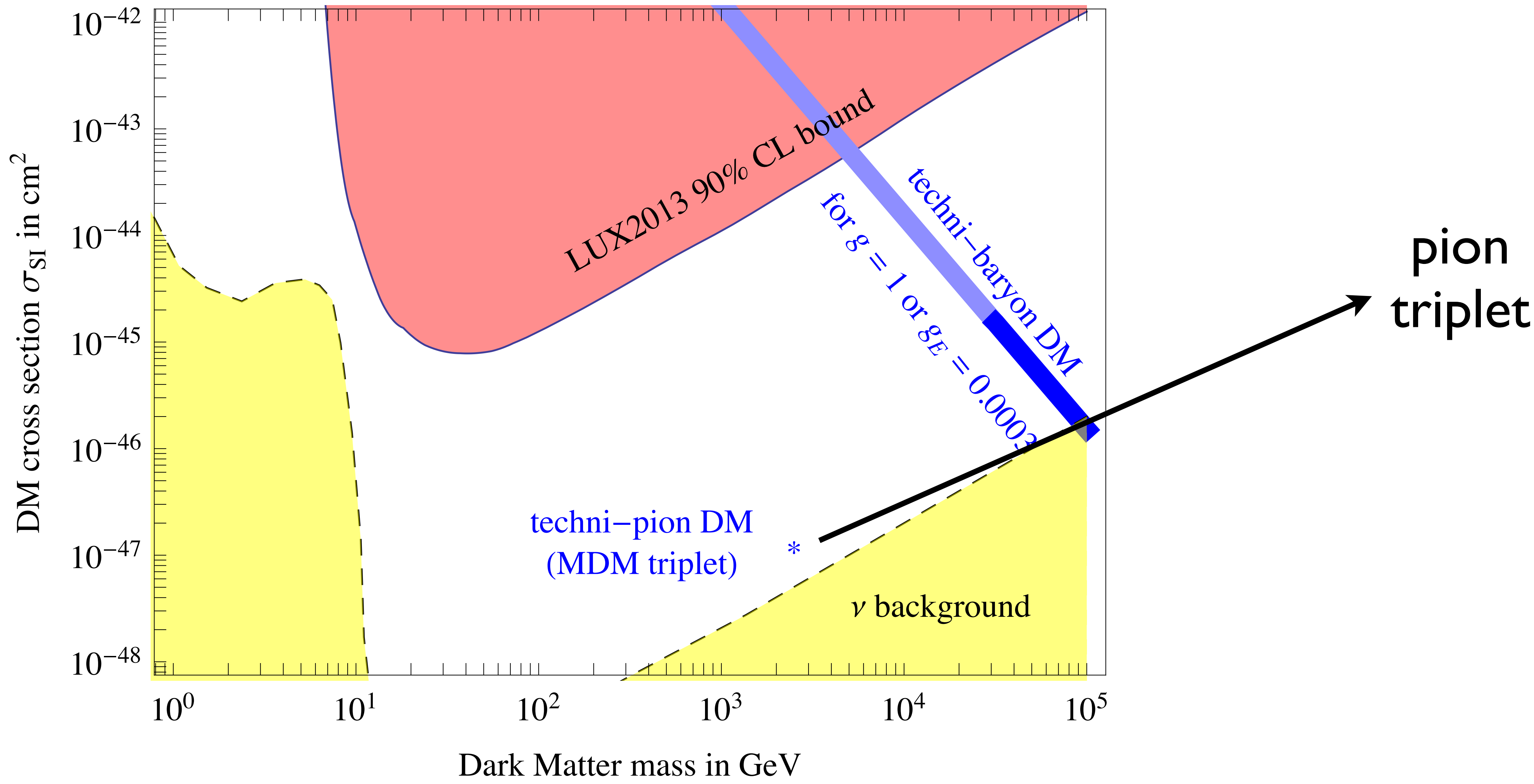
Singlets can be very light.

DM summary (M=0):

number of techni-flavors	Yukawa	TCπ	TCb N=3	TCb N=4	TCb N=5	DM under $SU(N_F)_V / SU(2)_L$
$N_F = 2$		3	2	1	2	$SU(2)_F$
M1: $Q = 2_{Y=0}$	N	3	charged	1	charged	$SU(2)_L$
$N_F = 3$		8	8	$\bar{6}$	$\overline{15}$	$SU(3)_F$
M1: $Q = 1_Y + 2_{Y'}$	Y	N	1	1	1	$SU(2)_L$
M2: $Q = 3_{Y=0}$	N	3	3	1	3	$SU(2)_L$
$N_F = 4$		15	$\overline{20}$	$20'$	60	$SU(4)_F$
M1: $Q = 4_{Y=0}$	N	3	charged	1	charged	$SU(2)_L$
M2: $Q = 2_Y + 2_Y$	N	4×3	charged	1	charged	$SU(2)_L$
M3: $Q = 3_{Y=0} + 1_{Y=0}$	N	3×3	1	1	1	$SU(2)_L$
$N_F = 5$		24	$\overline{40}$	$\overline{50}$	$175'$	$SU(5)_F$
M1: $Q = 2_Y + 3_{Y'}$	Y	N	1	charged	charged	$SU(2)_L$
M2: $Q = 5_{Y=0}$	N	3	3	1	1	$SU(2)_L$

Often DM has two components.

If Yukawas are allowed pions are not stable.
Quark masses may change the lightest baryon.



Dipole interactions:

$$\frac{1}{4\,m_B}\bar{B}\sigma_{\mu\nu}(g_M + i g_E \gamma_5)B\ F_{\mu\nu}$$

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{16\pi\, m_B^2\, E_R}\left(g_M^2 + \frac{g_E^2}{v^2}\right) \longrightarrow g_M^2 + 10^7 g_E^2 < \left(\frac{m_B}{5\,\mathrm{TeV}}\right)^3$$

- Magnetic Dipoles

$$g_M \sim \mathcal{O}(1)$$

- Electric dipoles

Needs CP violation. Naturally generated by θ_{DARK}

$$g_E \sim \frac{\theta}{10}\frac{1}{16\pi^2}\frac{m_\pi^2}{f^2}\log\frac{m_B^2}{m_\pi^2}$$

Interesting ball park for experiments. In QCD:

$$g_E \sim 10^{-2} \times \theta$$

Spectrum is also modified:

$$V(U) = -\frac{f_\pi^2}{2}\left(\mathrm{Tr}[MU + M^\dagger U^\dagger] - \frac{a}{N}(-i\log\det U - \theta)^2\right)$$

$$U = U_0 V \qquad\qquad U_0 = \mathrm{Diag}[e^{\phi_1}, e^{\phi_2}, \ldots, e^{i\phi_{N_F}}]$$

$$m_i^2 \sin\phi_i = \frac{a}{N}(\theta - \sum \phi_i) \qquad\qquad i = 1, ..., N_F \ .$$

In QCD:

$$m_{\pi^+}^2 = m_{\pi^0}^2 = \frac{4v}{f_\pi^2}[m_u\cos\phi_u + m_d\cos\phi_d]$$

$$m_{K^+}^2 = \frac{4v}{f_\pi^2}[m_u\cos\phi_u + m_s\cos\phi_s]$$

$$m_{K^0}^2 = \frac{4v}{f_\pi^2}[m_d\cos\phi_d + m_s\cos\phi_s]$$

$$m_{\eta^0}^2 = \frac{4v}{3f_\pi^2}[m_u\cos\phi_u + m_d\cos\phi_d + 4m_s\cos\phi_s]$$

$$n = N_F = 3$$

Pions and lightest baryons are adjoint of SU(3).

Rescale QCD:

$$\frac{m_B}{m_\rho} \approx 1.3 \qquad \frac{m_\pi}{m_\rho} \approx 0.1\,\sqrt{J(J+1)}$$

Technibaryon thermal abundance:

$$\sigma_{p\bar{p}}^{QCD} \sim 100\,\mathrm{GeV}^{-2} \longrightarrow \frac{\Omega_{DM}}{\Omega_{DM}^c} \sim \left(\frac{M_B}{200\,\mathrm{TeV}}\right)^2$$

- $SU(2)_L \subset SU(3)_F$

Q=3

$$\mathbf{8} = \mathbf{3} + \mathbf{5}$$

Scalar triplet is stable and is dominant dark matter.

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- $SU(2)_L \times U(1)_Y \subset SU(3)_F$

Q=2+1

$$\mathbf{8} = \mathbf{2}(\mathrm{p}, \mathrm{n}) + \mathbf{3}(\Sigma^{\pm,0}) + \mathbf{2}(\Xi^0, \Xi^-) + \mathbf{1}(\Lambda_0)$$

$$\mathbf{8} = \mathbf{2}(\mathrm{K}^0, \mathrm{K}^+) + \mathbf{3}(\pi^{\pm,0}) + \mathbf{2}(K^-, \bar{K}^0) + \mathbf{1}(\eta)$$

Quantum numbers allow for Yukawa interactions.
Singlet GB acquires mass and triplet decays.

Dark matter is a technibaryon.


PARENTAL
ADVISORY
ADULT CONTENT

DYNAMICAL GENERATION OF THE WEAK SCALE

Assumption: the fundamental theory has no scales.

Practically discard uncalculable quadratic divergences.
SM is natural ("finite naturalness"):

Farina, Pappadopulo, Strumia, '14

$$\delta m_h^2 \sim -\frac{3\,y_t^2}{(4\pi)^2} m_h^2 \log \frac{m_t^2}{\mu^2}$$

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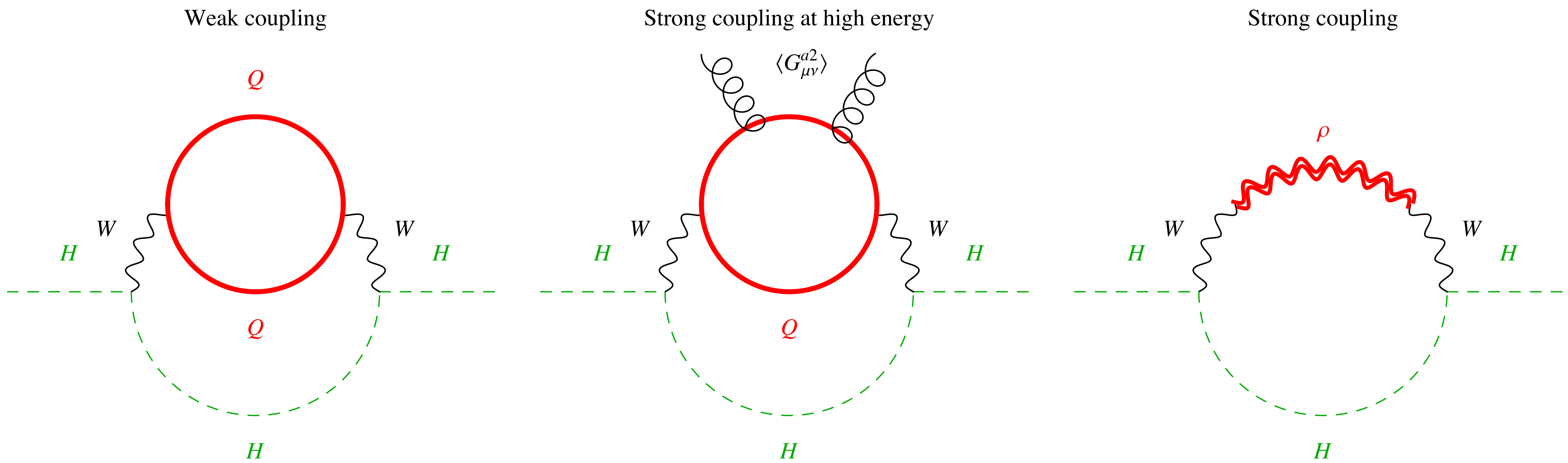
With no masses electro-weak scale determined by the confinement scale of strong sector.
Gauge (Yukawa) interactions trigger electro-weak symmetry breaking:

$$m_h \sim \alpha_2 f$$

- # Gauge Interactions



Strong dynamics modifies SM propagators

$$G^{VV}_{\mu\nu}(q) = -i\frac{\eta_{\mu\nu}}{q^2}(1+g_2^2\Pi_{VV}(q^2)) + i\xi_V\frac{q_\mu q_\nu}{q^2}$$

$$i\int d^4x\, e^{iq\cdot x}\langle 0|\mathrm{T}J^a_\mu(x)J^b_\nu(0)|0\rangle \equiv \delta^{ab}(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi_{VV}(q^2)$$

Higgs mass:

$$\boxed{\Delta m^2 = \frac{9g_2^4}{4(4\pi)^2}\int dQ^2\Pi_{VV}(-Q^2)}$$

Contributions is finite. OPE:

$$\Pi_{VV}(q^2) \overset{q^2 \gg \Lambda_{\rm TC}^2}{\simeq} c_1(q^2) + c_2(q^2)\langle 0|m_Q Q_L Q_R|0\rangle + c_3(q^2)\langle 0|\frac{\alpha_{\rm TC}}{4\pi} G_{\mu\nu}^{A2}|0\rangle + \cdots$$

$$c_1 = C\frac{\alpha_2}{3\pi}\ln(-q^2) + \cdots \qquad\qquad c_3 = -C'\frac{g_2^2}{3q^4}$$

$$\Delta m^2|_{\rm UV} \simeq -\frac{3C' g_2^4}{4(4\pi)^2}\langle 0|\frac{\alpha_{\rm TC}}{4\pi}G_{\mu\nu}^{A2}|0\rangle \int_{Q_{\rm min}^2}^{\infty}\frac{dQ^2}{Q^4} \qquad \left(\text{in QCD} \quad \langle 0|\frac{\alpha_s}{4\pi}G_{\mu\nu}^{A2}|0\rangle = 0.03\,{\rm GeV}^4\right)$$

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Sign is negative:

$$\frac{\partial \Delta m^2}{\partial \Lambda_{\rm TC}^2} = \frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{\partial \Pi_{VV}}{\partial \Lambda_{\rm TC}^2} = -\frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{Q^2}{\Lambda_{TC}^2}\frac{\partial \Pi_{VV}}{\partial Q^2}$$

$$= \frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{1}{\pi}\frac{Q^2}{\Lambda_{TC}^2}\int_0^\infty ds \frac{\mathrm{Im}\,\Pi_{VV}(s)}{(s+Q^2)^2} < 0$$

Estimate:

$$\Pi_{VV}(q^2) = \frac{f^2}{(q^2 - m_\rho^2)}$$

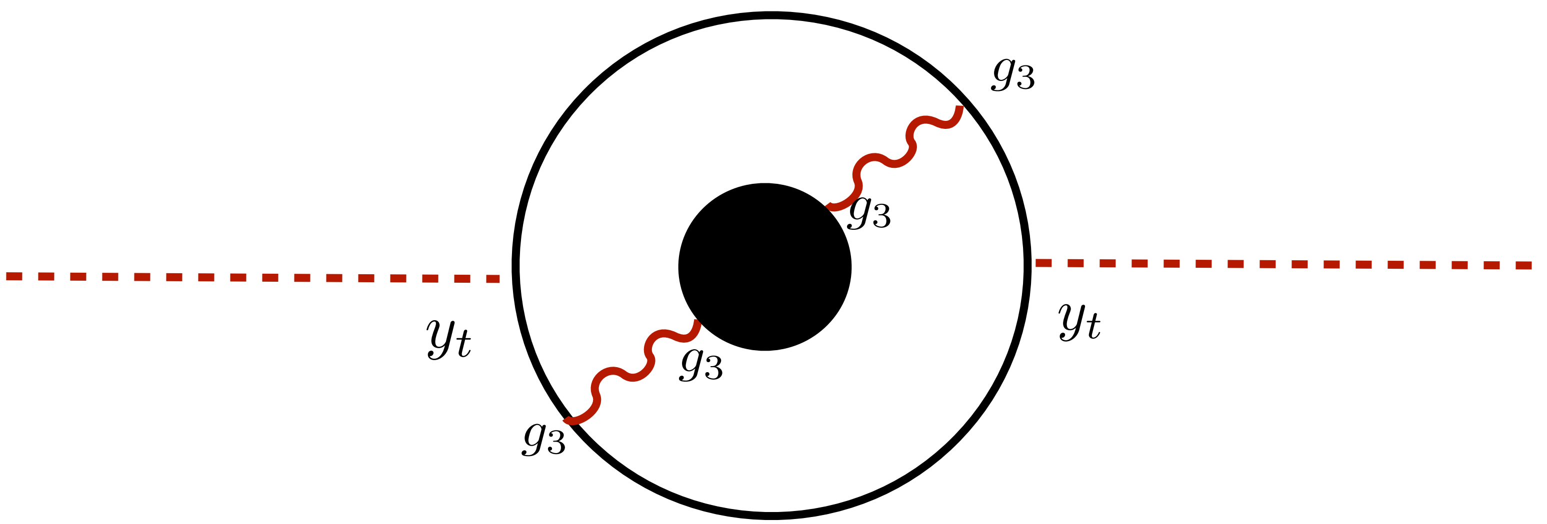
$$\Delta m^2 \approx -\frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{f^2}{(Q^2 + m_\rho^2)} \sim -\alpha_2^2 f^2$$

We obtain the following scales

$$f \sim \frac{m_H}{\alpha_2} \sim \text{few} \times \text{TeV}$$

$$m_\pi \sim 2\,\text{TeV}, \qquad m_\rho \sim 20\,\text{TeV}, \qquad m_B \sim 50\,\text{TeV}$$

- **3-loops**



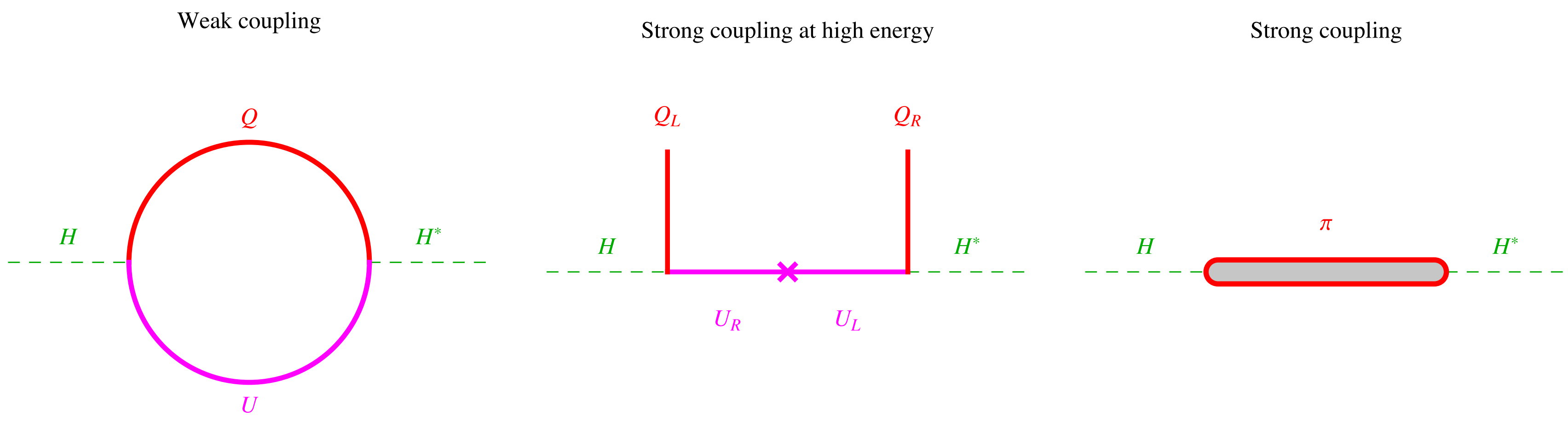
Positive Higgs mass:

$$\boxed{\Delta m^2 = -\frac{64 y_t^2 g_3^4}{(4\pi)^4}\int dQ^2 \Pi_{GG}(-Q^2) \sim \frac{y_t^2 g_3^4}{(4\pi)^4} f^2}$$

Gravitational corrections can be related to 2-point function of energy momentum tensor

$$\Delta m^2 \sim \frac{y_t^2 m_\rho^4 f^2}{(4\pi)^4 M_p^4}$$

- # Yukawa Interactions



$$yHQ_LQ_R$$

Chiral lagrangian,

$$y\,\frac{N}{(4\pi)^2}m_\rho^3\mathrm{Tr}[HU]$$

2 Higgs doublets mix:

$$\begin{array}{cc} & \begin{array}{cc} \pi^* & H^* \end{array} \\ \begin{array}{c} \pi \\ H \end{array} & \begin{pmatrix} (\mathcal{O}(g^2) \pm \mathcal{O}(y^2))m_\rho^2/(4\pi)^2 & \mathcal{O}(y)m_\rho^2\sqrt{N}/(4\pi) \\ \mathcal{O}(y)m_\rho^2\sqrt{N}/(4\pi) & -\mathcal{O}(y^2))m_\rho^2 N/(4\pi)^2 \end{pmatrix} \end{array}$$

Mixing induces negative Higgs mass

$$\Delta m^2 \approx -\frac{y^2\,N}{(4\pi)^2}\frac{m_\rho^4}{m_\pi^2}$$

The singlet acquires a mass

$$m_\eta \sim y\frac{m_\rho}{m_\pi}v$$

CONCLUSIONS

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- Within finite naturalness electro-weak symmetry breaking could be induced from the technicolor dynamical scale. Scales and signs roughly work out.

- **SO(N) models**

With NF fundamental flavors:

$$\frac{SU(N_F)}{SO(N_F)}$$

Baryons are stable but two baryons can annihilate.
Pions are in the symmetric rep

$$\mathrm{Sym}_{SO(N_F)} = \left[\sum_{i=1}^{K} r_i \times \sum_{i=1}^{K} \bar{r}_i\right]_{\mathrm{Sym}} - 1$$

SO(N_F)	Yukawa	$T\pi$	$N=3$	$N=4$
$N_F=3$		5	5	–
3_0	0	no	5	
$N_F=4$		9	16	10
2_0+1_Y	1	no	1	1
2_0+2_0	0	$3+3_{IJ}$	charged	1
3_0+1_0	0	3	3	5

- # Unification

Assume that new fermions are in complete reps.

SU(5)	SU(3) ⊗ SU(2) ⊗ U(1)			n_3	$\bar{n}_3$	n_2	z	name	Δb_3	Δb_2	Δb_1
$5 \oplus \bar{5}$	$\bar{3}$	1	$1/3$	0	1	0	0	D	2/3	0	4/15
$5 \oplus \bar{5}$	1	2	$1/2$	0	0	1	0	L	0	2/3	2/5
$10 \oplus \overline{10}$	$\bar{3}$	1	$-2/3$	0	1	0	1	U	2/3	0	16/15
$10 \oplus \overline{10}$	1	1	-1	0	0	0	1	E	0	0	4/5
$10 \oplus \overline{10}$	3	2	$1/6$	1	0	1	0	Q	4/3	2	2/15
$15 \oplus \overline{15}$	3	2	$1/6$	=	=	=	=	Q	=	=	=
$15 \oplus \overline{15}$	1	3	1	0	0	2	0	T	0	8/3	12/5
$15 \oplus \overline{15}$	6	1	$-2/3$	2	0	0	0	S	10/3	0	32/15
24	1	3	0	0	0	2	1	V	0	4/3	0
24	8	1	0	1	1	0	0	G	2	0	0
24	$\bar{3}$	2	$5/6$	0	1	1	0	X	4/3	2	10/3

Giudice, Rattazzi, Strumia, '12

a) $L + E \subset \mathbf{5} + \mathbf{10}$

b) $L + T \subset \mathbf{5} + \mathbf{15}$

c) $E + T \subset \mathbf{10} + \mathbf{15}$

d) $V \subset \mathbf{24}$

$$\frac{1}{\alpha_G(m_G)} - \frac{1}{\alpha_i(m_Z)} = -\frac{b_i^{SM}}{2\pi}\log\frac{m_\rho}{m_Z} - \frac{b_i^A}{2\pi}\log\frac{m_1}{m_\rho} - \frac{b_i^B}{2\pi}\log\frac{m_G}{m_1}$$

$$b_3 = \frac{1}{3}(4N_g - 33) + \Delta b_3$$

$$b_2 = \frac{1}{3}(4N_g - 22 + \frac{1}{2}) + \Delta b_2$$

$$b_1 = \frac{1}{3}(4N_g + \frac{3}{10}) + \Delta b_1$$

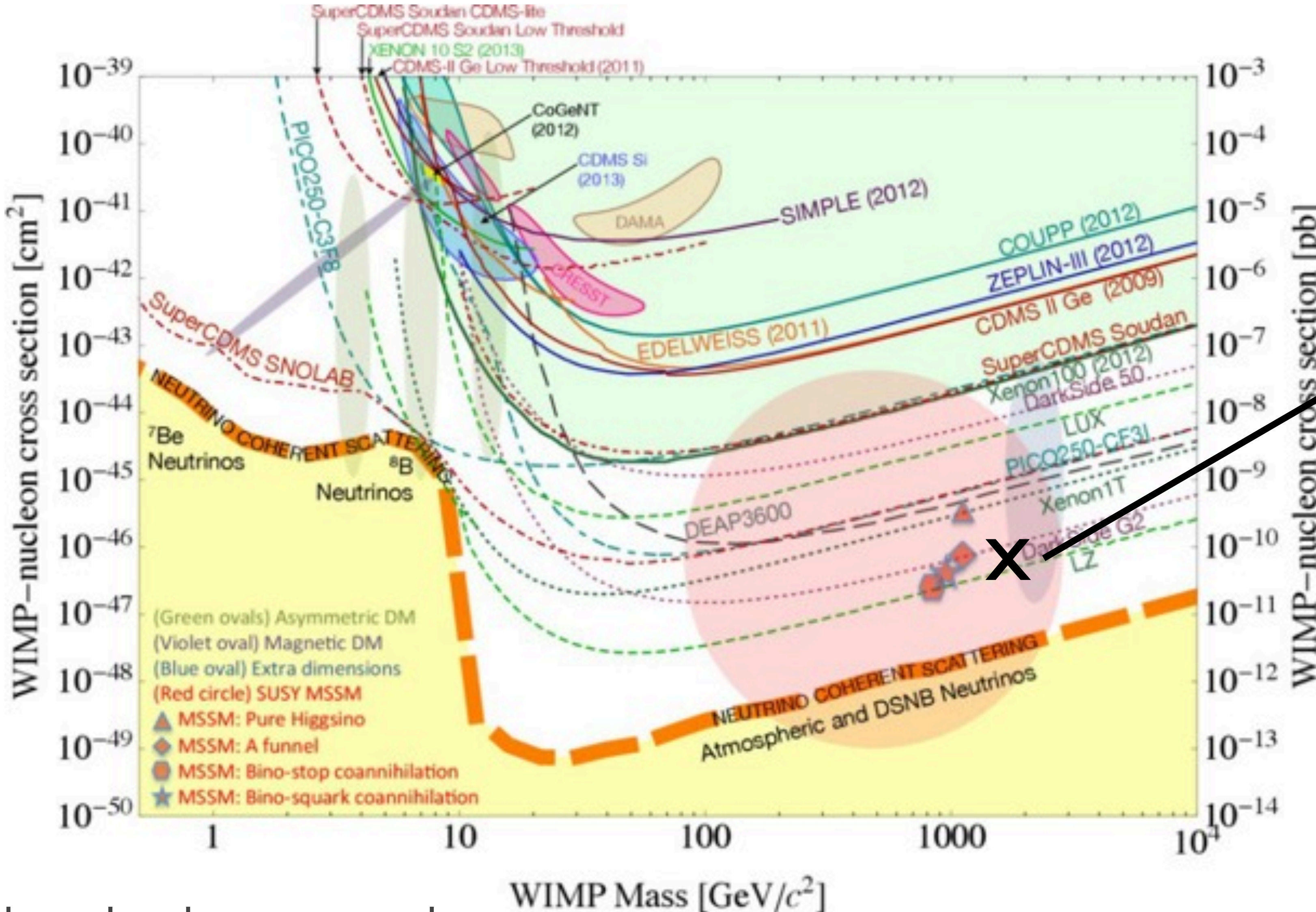
Ex:

$$V = (1,3)_0 \subset 24 \quad \xrightarrow{\text{NTC=3}}$$

$$\alpha_G \approx 0.085$$

$$m_1 \approx 4 \times 10^6\,\mathrm{GeV}$$

$$m_G \approx 3 \times 10^{14}\,\mathrm{GeV}$$



pion
triplet

Dipole interactions:

$$\frac{1}{4\,m_B}\bar{B}\sigma_{\mu\nu}(g_M + i g_E \gamma_5)B\ F_{\mu\nu}$$

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{16\pi\, m_B^2\, E_R}\left(g_M^2 + \frac{g_E^2}{v^2}\right) \longrightarrow g_M^2 + 8\times 10^6 g_E^2 < \left(\frac{m_B}{5.8\,\mathrm{TeV}}\right)^3$$