Aspects of Vector-like Confinement

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with O. Antipin, A. Strumia 1410.1817
+ work in progress with E. Vigiani

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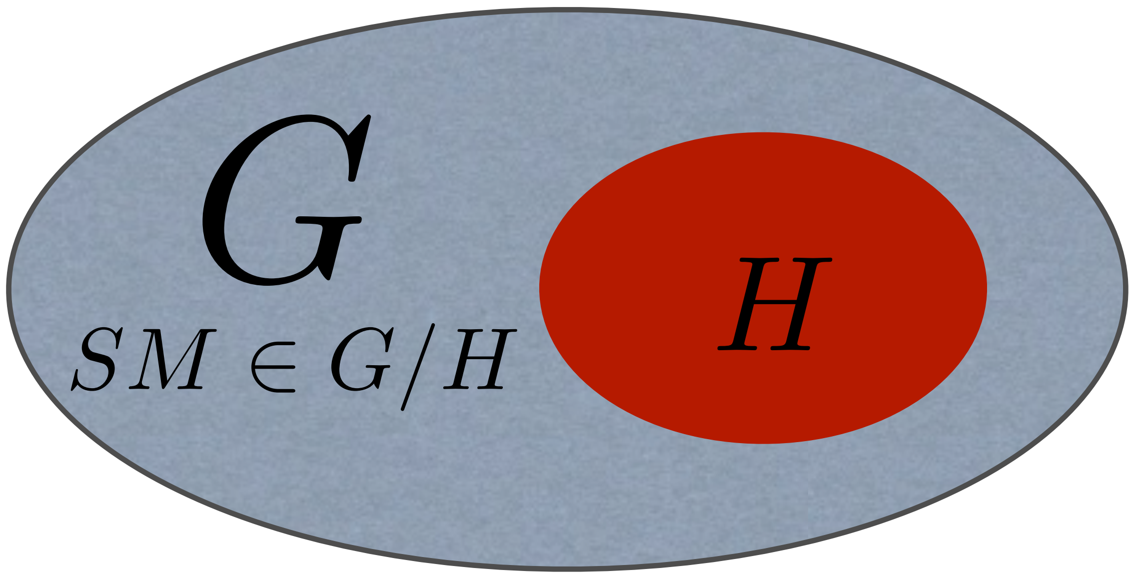
Strong dynamics is a plausible possibility for BSM

In origin it was technicolor:



$$f = v$$

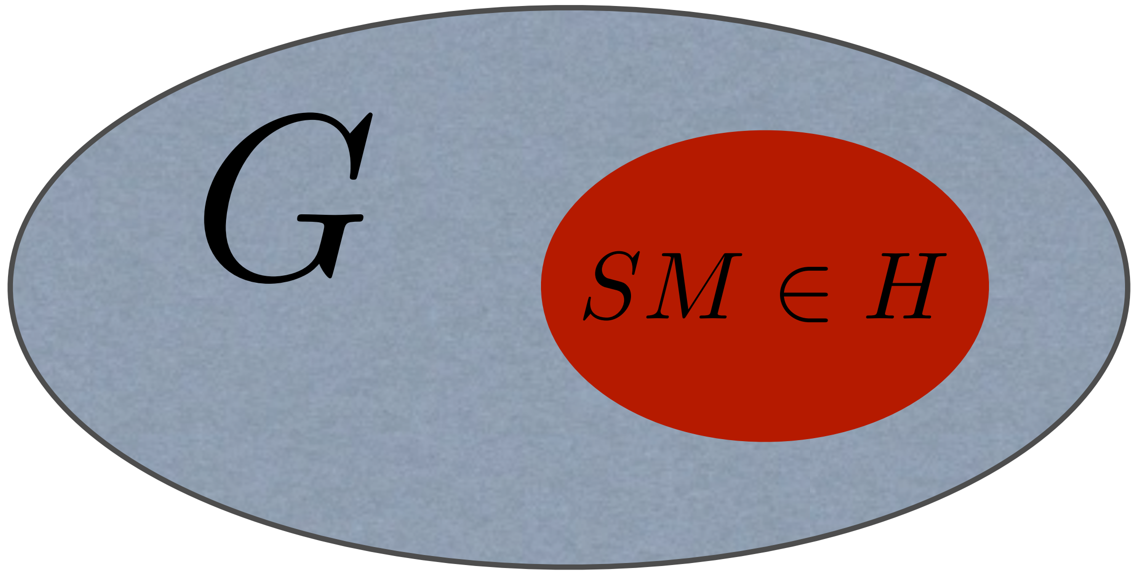
Completely natural theory. No need for the Higgs scalar.

Already in trouble before LHC, now dead.

Next it was the composite Higgs

Georgi, Kaplan '80s

Higgs could be an approximate GB



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

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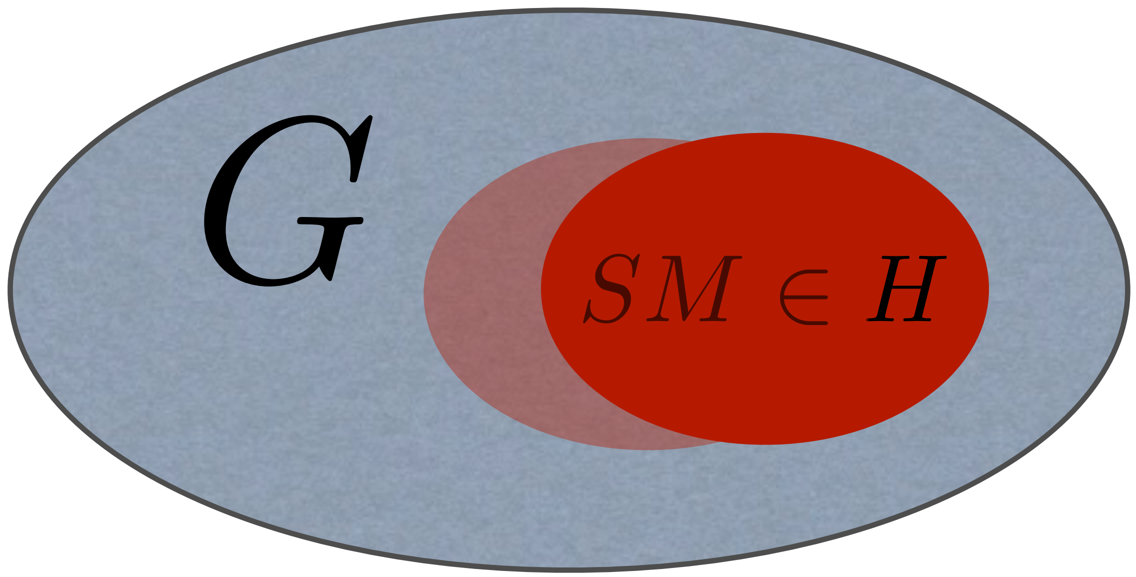


$$m_\rho = g_\rho f$$

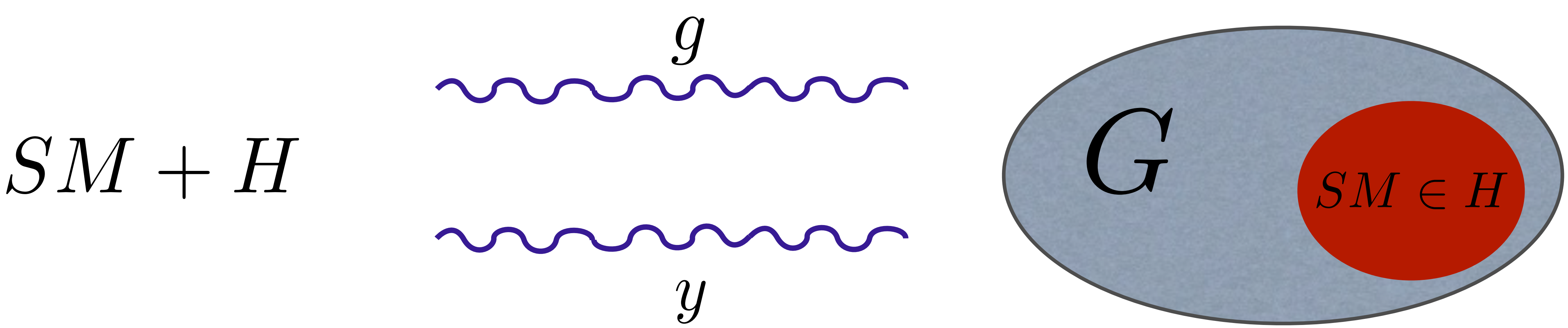
Electro-weak scale determined by vacuum alignment.

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

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

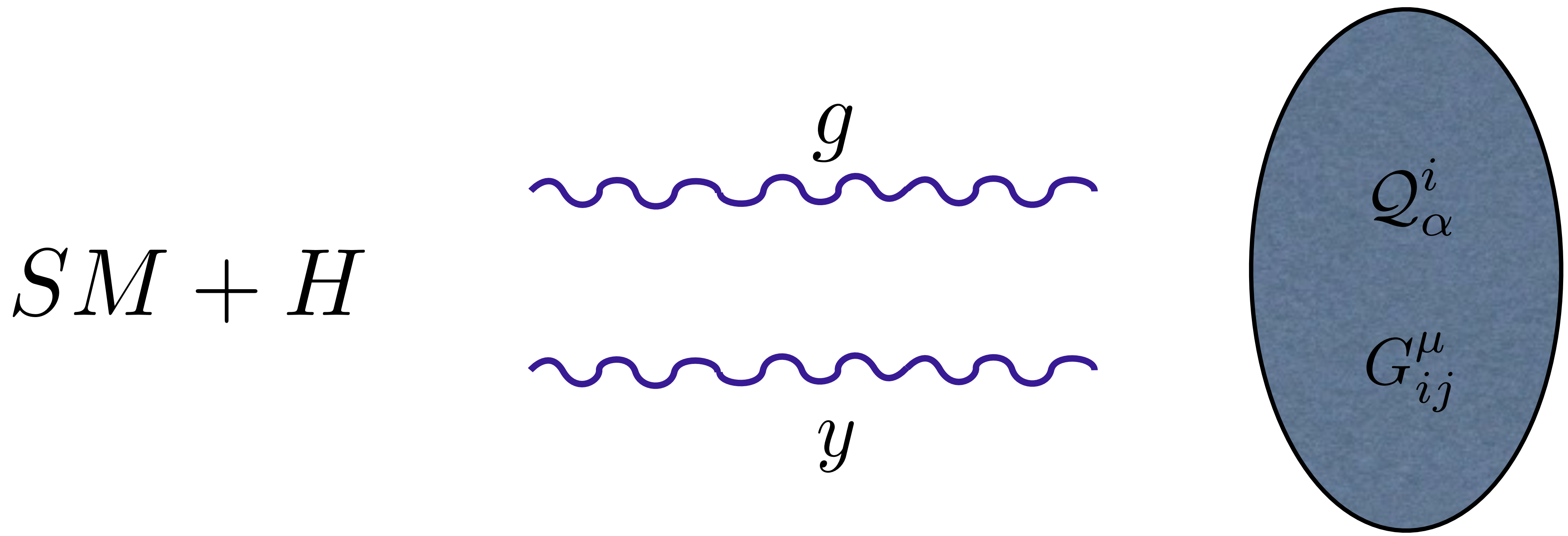
Electro-weak preserving strong sector:

Kilic, Okui, Sundrum '09



Electro-weak preserving strong sector:

Kilic, Okui, Sundrum '09



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

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4g_{\rm TC}^2}\mathcal{G}_{\mu\nu}^2 + \bar{\Psi}^i i\gamma^\mu(\partial_\mu - iA_\mu - iG_\mu)\Psi^i - m_i\bar{\Psi}^i\Psi^i$$

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

COLLIDER SIGNATURES

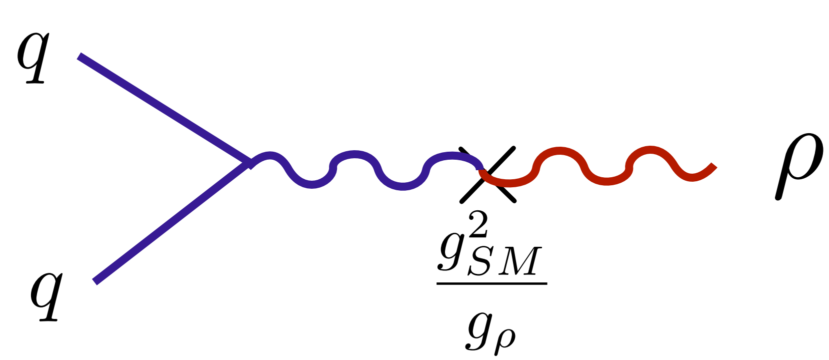
Kilic, Okui, Sundrum '09

Frameworks predicts Goldstone bosons and vector bosons with SM charges:

$$\langle 0|\bar{\Psi}\gamma^\mu T^a \Psi|\rho^b\rangle = -\delta^{ab}\, m_\rho f_\rho \epsilon^\mu$$

$$\langle 0|\bar{\Psi}\gamma^\mu \gamma^5 T^a \Psi|\pi^b\rangle = -i\delta^{ab}\, f\, p^\mu$$

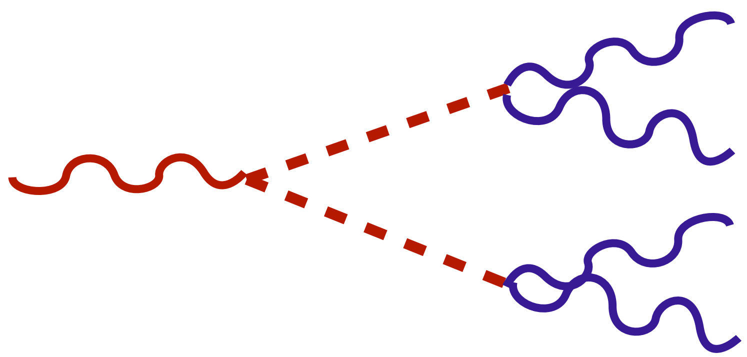
Heavy vectors mix with SM gauge bosons



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

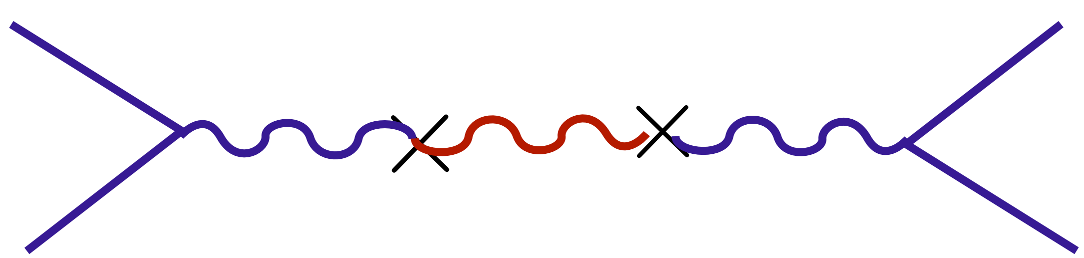
Unlike composite Higgs fermions are elementary.

Decay to hidden pions and back to SM gauge bosons,



Pions can also be stable or long lived.

Compositeness bounds:



$$\sim \frac{g_{SM}^4}{g_\rho^2} \frac{1}{m_\rho^2}$$

$$\mathcal{L}_{4-Fermi} = \frac{2\pi}{\Lambda^2} \left(\bar{q}_L \gamma^\mu q_L\right)^2 \qquad \Lambda > 6\,\mathrm{TeV} \qquad \longrightarrow \qquad m_\rho > \frac{2 g_{SM}^2}{g_\rho} \mathrm{TeV}$$

- **Models**

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

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

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

$$\langle \bar{\Psi}^i \Psi^j \rangle \sim 4\pi f^3 \delta^{ij}$$

Vacuum does not break electro-weak symmetry.
Goldstone bosons:

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

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

Accidental symmetries:

- Techni-Baryon number

$$U(1)_{TB} \qquad \Psi^i \to e^{i\alpha}\Psi^i$$

- Species number

$$U(1)_{F_i} \qquad \Psi^i \to e^{i\alpha_i}\Psi^i \qquad \sum_i^K \alpha_i = 0$$

- G-parity

$$\Psi \to e^{-i\pi J_2}\Psi^c$$

Broken by hypercharge.

Automatic dark matter candidates:

- **Pions**

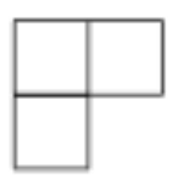
Stable due to G-parity or species symmetry.

- **Baryons**

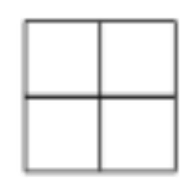
$$B = \epsilon^{i_1 i_1 \ldots i_n} Q_{i_1}^{\{\alpha_1} Q_{i_2}^{\alpha_2} \ldots Q_{i_n}^{\alpha_n\}}$$

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,...

Flavor multiplets are split by quark masses and gauge interactions:

- **quark masses**

$$\delta m_\pi^2 \sim g_\rho \, m \, m_\rho$$

$$\delta m_B \sim m$$

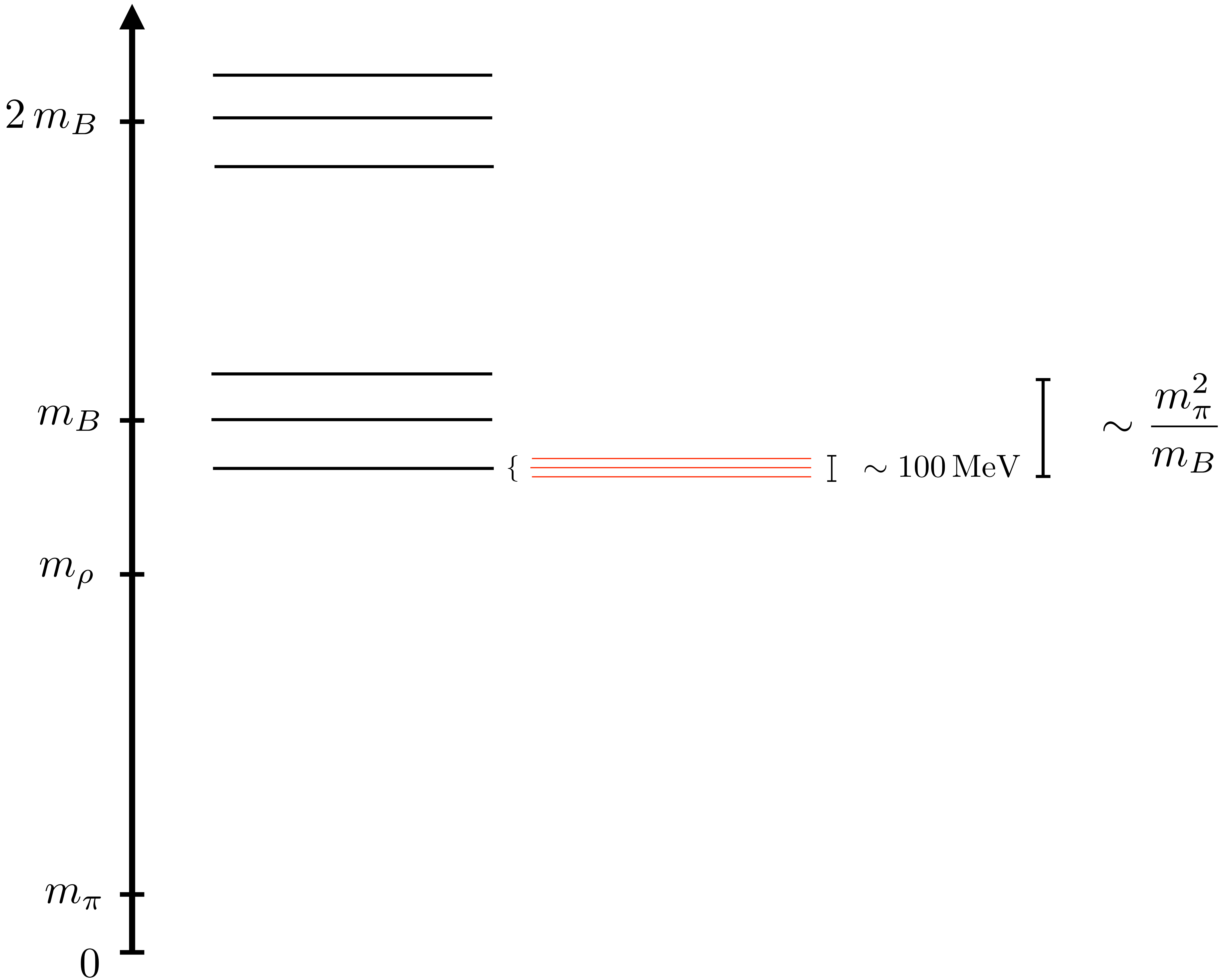
- **gauge interactions**

Charged pions acquire positive mass.

$$m_\pi^2 = \frac{3 g_i^2}{(4\pi)^2} C_2(\pi) m_\rho^2$$

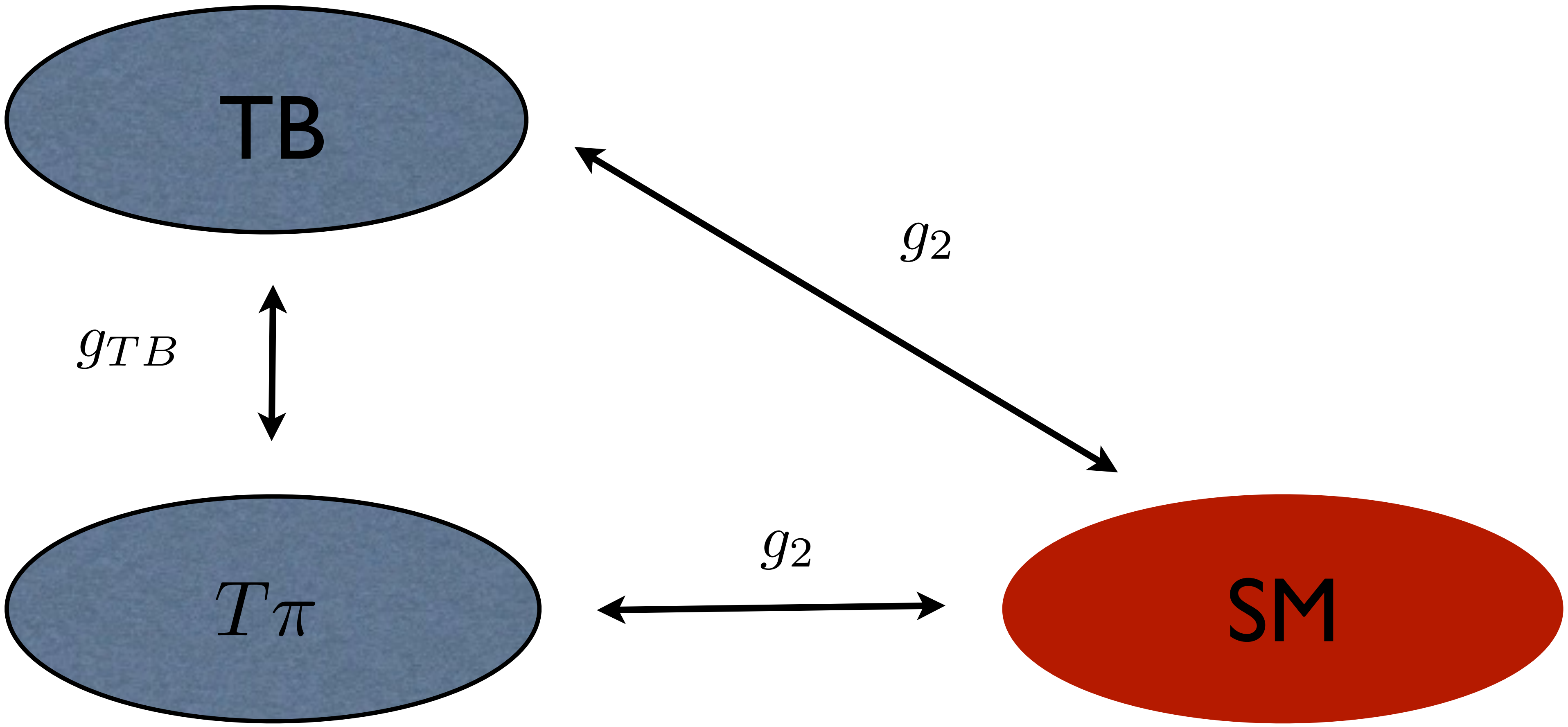
After electro-weak symmetry breaking multiplets further split. Neutral component is the lightest. For triplets:

$$m^+ - m^0 = 166 \, \mathrm{MeV}$$



$2\,m_B$
m_B
m_ρ
m_π
0
$\sim 100\,\mathrm{MeV}$
$\sim \dfrac{m_\pi^2}{m_B}$

Baryons-anti-baryon annihilate mostly into pions



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

THERMAL ABUNDANCE

$$m_B \sim 50 - 100\,\mathrm{TeV}$$

Consider branches of unified representations

SU(5)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	charge	name
1	1	1	0	0	N
$\bar{5}$	$\bar{3}$	1	$-1/3$	$-1/3$	D
	1	2	$1/2$	$0, 1$	L
10	$\bar{3}$	1	$-2/3$	$-2/3$	U
	1	1	1	1	E
	3	2	$1/6$	$-1/3, 2/3$	Q
15	3	2	$1/6$	$-1/3, 2/3$	Q
	1	3	1	$0, 1, 2$	T
	6	1	$-2/3$	$-2/3$	S
24	1	3	0	$-1, 0, 1$	V
	8	1	0	0	G
	$\bar{3}$	2	$5/6$	$1/3, 4/3$	X
	1	1	0	0	N

$R = (N, \mathrm{SM}) \oplus (\overline{N}, \overline{\mathrm{SM}})$ or $\tilde{R} = (N, \overline{\mathrm{SM}}) \oplus (\overline{N}, \mathrm{SM})$

Sample models for N=3

SU(3) techni-color. Techni-quarks	Yukawa couplings	Techni-pions	Techni-baryons	under
$N_{\rm TF} = 3$		8	8	$\mathrm{SU}(3)_{\rm TF}$
$\Psi = V$	0	3	$VVV = 3$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L$	1	unstable	$NNN^* = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 4$		15	$\overline{20}$	$\mathrm{SU}(4)_{\rm TF}$
$\Psi = V \oplus N$	0	3×3	$VVV, VNN = 3,\ VVN = 1$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L \oplus \tilde{E}$	2	unstable	$NNN^* = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 5$		24	$\overline{40}$	$\mathrm{SU}(5)_{\rm TF}$
$\Psi = V \oplus L$	1	unstable	$VVV = 3$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L \oplus \tilde{L}$	2	unstable	$NL\tilde{L} = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 6$		35	70	$\mathrm{SU}(6)_{\rm TF}$
$\Psi = V \oplus L \oplus N$	2	unstable	$VVV, VNN = 3, VVN = 1$	$\mathrm{SU}(2)_L$
$\Psi = V \oplus L \oplus \tilde{E}$	2	unstable	$VVV = 3$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L \oplus \tilde{L} \oplus \tilde{E}$	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E} = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 7$		48	112	$\mathrm{SU}(7)_{\rm TF}$
$\Psi = L \oplus \tilde{L} \oplus E \oplus \tilde{E} \oplus N$	4	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N = 1$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L \oplus \tilde{E} \oplus V$	3	unstable	$VVV, VNN = 3,\ VVN = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 9$		80	240	$\mathrm{SU}(9)_{\rm TF}$
$\Psi = Q \oplus \tilde{D}$	1	unstable	$QQ\tilde{D} = 1$	$\mathrm{SU}(2)_L$
$N_{\rm TF} = 12$		143	572	$\mathrm{SU}(12)_{\rm TF}$
$\Psi = Q \oplus \tilde{D} \oplus \tilde{U}$	2	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U} = 1$	$\mathrm{SU}(2)_L$

$$n = N_F = 3$$

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

Rescale QCD:

$$\frac{m_\rho}{f} \sim 7 \qquad \frac{m_B}{m_\rho} \approx 1.3 \qquad \frac{m_\pi}{m_\rho} \approx 0.1\sqrt{J(J+1)}$$

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

Scalar triplet is stable and is dominant dark matter.

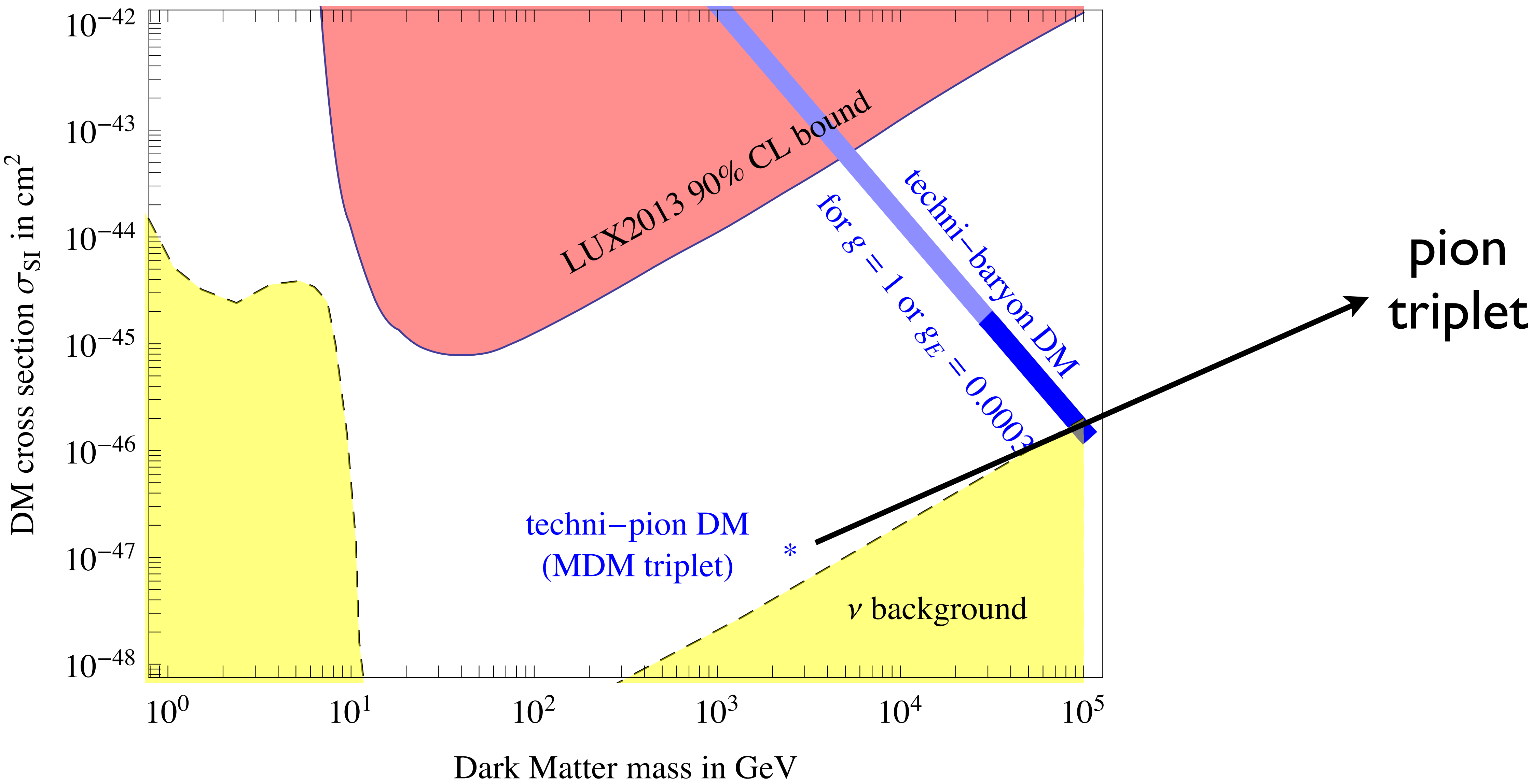
- $SU(2)_L \times U(1)_Y \subset SU(3)_F$

Q=L+E

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

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

Dark matter is a the singlet technibaryon with mass
200 TeV.



Dipole interactions:

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

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

- **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:

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

- **Unification**

Incomplete SU(5) reps modify SM running

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

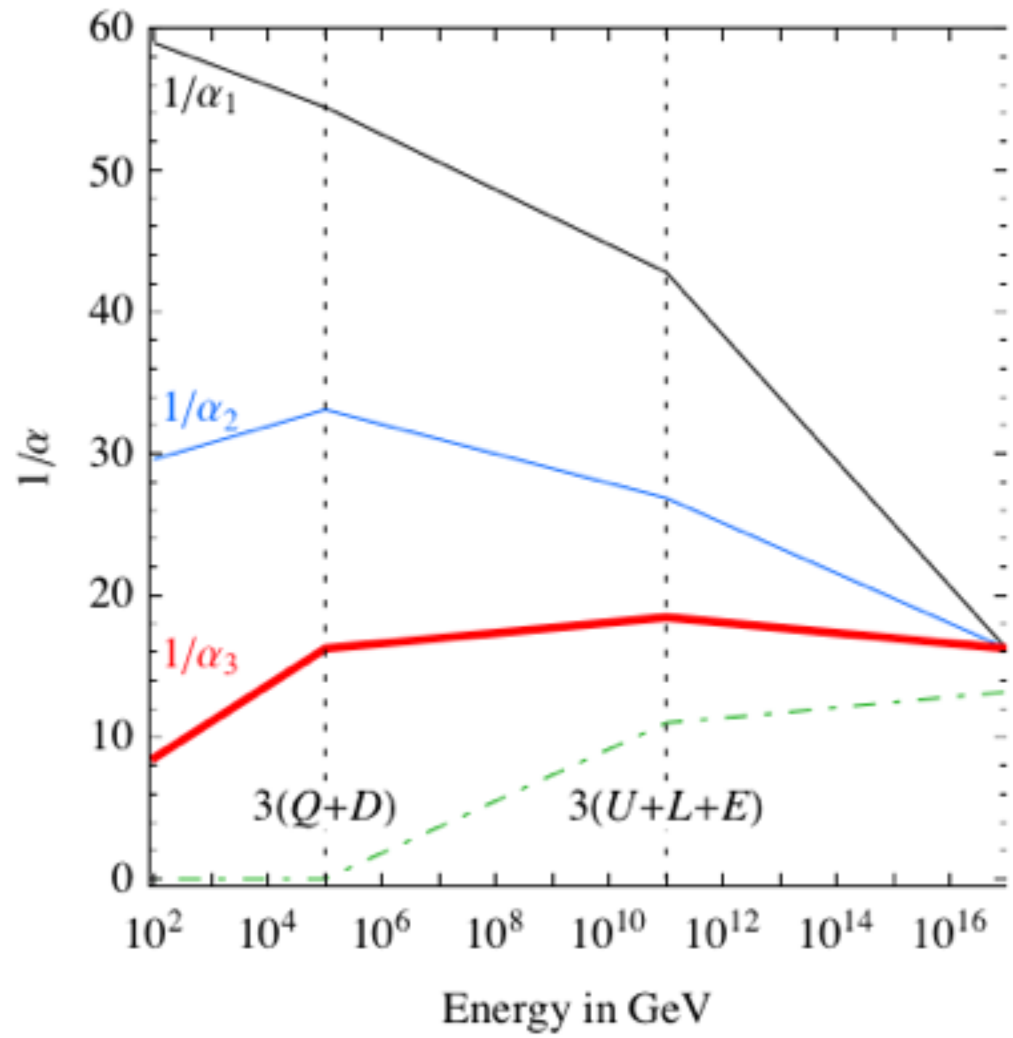
$$\frac{1}{\alpha_G(m_G)} - \frac{1}{\alpha_i(m_Z)} = -\frac{b_i^{SM}}{2\pi}\log\frac{m_\rho}{m_Z} - \frac{b_i^A}{2\pi}\log\frac{m_1}{m_\rho} - \frac{b_i^B}{2\pi}\log\frac{m_G}{m_1}$$

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

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

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

TC multiplicity typically requires intermediate treshold to achieve unification:



Ex:

$Q + \tilde{D} \subset 5 + 10$

NTC=3

$\alpha_G = 0.075$

$m_1 \sim 10^{10}\,\mathrm{GeV}$

$m_G \sim 10^{17}\,\mathrm{GeV}$

- **SO(N) models**

With NF fundamental flavors:

$$\langle 0|q_i^a q_i^b|0\rangle \sim 4\pi f^3 \delta^{ab} \longrightarrow \frac{SU(N_F)}{SO(N_F)}$$

Fermions are in a real representation:

- No difference between baryons and anti-baryons.
Two baryons can annihilate into N pions

$$\epsilon^{i_1 i_2 \ldots i_N} \epsilon^{j_1 j_2 \ldots j_N} = (\delta_{i_1 j_1} \delta_{i_2 j_2} \ldots \delta_{i_N j_N} \pm \text{permutations})$$

- Majorana masses are possible for real SM reps.

NN $\quad$ VV $\quad$ GG

Majorana DM ("Higgsino dark matter"):

$$\mathcal{L} = M_L \tilde{L}_B L_B + M_N N_B N_B + \lambda'_1 \tilde{L}_B H N_B + \lambda'_2 L_B H^\dagger N_B$$

$$M = \begin{pmatrix} M_N & \lambda'_1 v & \lambda'_2 v \\ \lambda'_1 v & 0 & M_L \\ \lambda'_2 v & M_L & 0 \end{pmatrix}$$

$M_L < M_N$

$$\Psi_M \sim \frac{1}{2}(L + \tilde{L})$$

$$M_1 \approx M_L - \frac{2\lambda^2 v^2}{\Delta M} \qquad M_2 = M_L \qquad M_3 \approx M_N + \frac{2\lambda^2 v^2}{\Delta M}$$

Lightest state has suppressed couplings to Z.
Direct detection bound:

$$M_2 - M_1 = \frac{2\lambda^2 v^2}{\Delta M} > \mathcal{O}(100 \text{ keV})$$

In SO(N) theories baryons in real reps have Majorana masses. Higgs couplings then realize Majorana DM.

$\mathrm{SO(N_F)}$	Yukawa	TCπ	$N=3$	$N=4$
$N_F=5$		14	35	35
$\mathcal{Q}=L\oplus\tilde{L}\oplus N=(1,2)_{\pm 1/2}\oplus(1,1)_0$	Yes	$3_{\pm1,0}\oplus 2_{\pm1/2}\oplus 1_0$	B_5^3	B_5^4
$N_F=7$		27	105	168
$\mathcal{Q}=L\oplus\tilde{L}\oplus V=(1,2)_{\pm 1/2}\oplus(1,3)_0$	Yes	$5_0\oplus 4_{\pm1/2}\oplus 3_{\pm1,0}\oplus 2_{\pm1/2}\oplus 1_0$	B_7^3	B_7^4

- **NF=5**

$$B_5^3=B_5^4=\mathbf{35}=4_{\pm1/2}\oplus 3_{\pm1,0}\oplus 2_{\pm3/2}\oplus 2\times 2_{\pm1/2}\oplus 1_{\pm1,0}$$

$$\lambda_1\tilde{L}HN \qquad\qquad \lambda_2 LH^\dagger N$$

Spectrum almost degenerate.

$$\Delta M=\mathcal{O}(\mathrm{TeV}) \longrightarrow \lambda>10^{-3}$$

CONCLUSIONS

- A strongly coupled sector that does not break electro-weak symmetry is a plausible possibility for new physics compatible with what we know and perhaps observable.

- Explicit models can be realised in term of well known gauge dynamics. Dark matter is very naturally a technibaryon (or techni-pion) stable due to accidental symmetries.

- Technibaryons should be heavy for thermal production. New EDM signature. Techni-pion dark matter similar to minimal dark matter.

$$n = N_F = 3$$

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

$$\mathcal{L}_B \sim \bar{B}(i\gamma^\mu D_\mu - m_B)B - 2b_1 \mathrm{Tr}[\bar{B}\tilde{\chi}B] - 2b_2 \mathrm{Tr}[\bar{B}B\tilde{\chi}] + \ldots$$
$$-\frac{D}{2f}\mathrm{Tr}[\bar{B}\gamma^\mu\gamma^5\{D_\mu\Pi, B\}] - \frac{F}{2f}\mathrm{Tr}[\bar{B}\gamma^\mu\gamma^5[D_\mu\Pi, B]] + \ldots$$

Rescale QCD:

$$\frac{m_\rho}{f} \approx 7 \qquad \frac{m_B}{m_\rho} \approx 1.3 \qquad \Delta^g m_\pi^2 \approx \alpha_2 J(J+1) m_\rho^2$$

$$b_2 \sim -2b_1' \sim -0.3\, m_B^{-1} \qquad D = 0.6 \qquad F = 0.4$$

Technibaryon thermal abundance:

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

$$\Delta m_N = \quad 2(b_1\mu_L^2\cos\phi_L + b_2\mu_E^2\cos\phi_E)\,, \qquad \Delta m_\Xi = 2(b_2\mu_L^2\cos\phi_L + b_1\mu_E^2\cos\phi_E)$$
$$\Delta m_\Sigma = \quad 2(b_1+b_2)\mu_L^2\cos\phi_L\,, \qquad \Delta m_{B_1} = 2/3(\mu_L^2\cos\phi_L + 2\mu_E^2\cos\phi_E)(b_1+b_2)$$

Triplet is never lightest. Singlet can be DM:

$$m_L \sim m_E \longrightarrow \phi_L \simeq \phi_E \simeq \frac{\theta}{3}$$

Dipole interactions:

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

$$g_M \sim \mathcal{O}(1) \qquad\qquad g_E \sim \frac{\theta}{10}\frac{1}{16\pi^2}\frac{m_\pi^2}{f^2}\log\frac{m_B^2}{m_\pi^2}$$

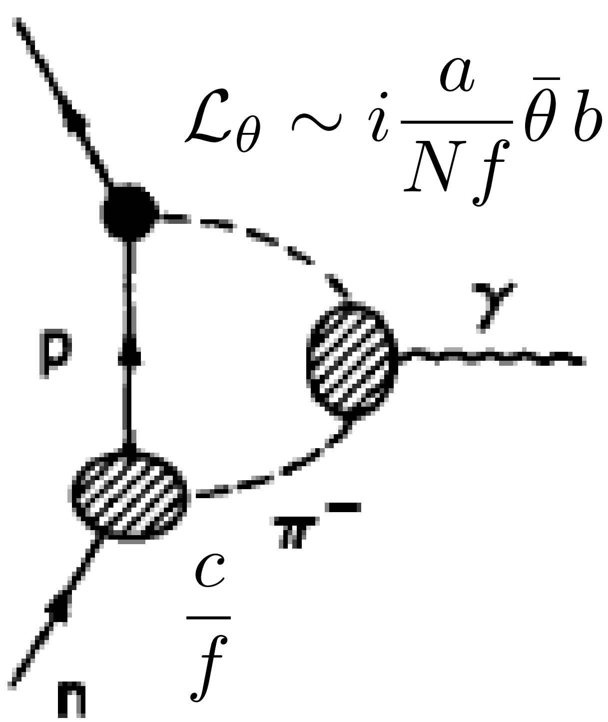
Crewther et al. '79
Pich, de Rafael '91

Baryons action depends on θ

$$\mathcal{L}_B \sim \bar{B}(i\gamma^\mu D_\mu - m_B)B - b\,\mathrm{Tr}\bar{B}\tilde{\chi}B + \frac{c}{f}D_\mu \Pi\,\bar{B}\gamma^\mu\gamma^5 B$$

$$\tilde{\chi} = v_0\,\xi^\dagger M \xi \qquad\qquad U = \xi^2$$

CP violating interactions from mass terms.
As for the neutron EDM is generated:



$$\mathcal{L}_\theta \sim i\frac{a}{Nf}\bar{\theta}\,b\,\bar{B}\pi B$$

$$i\frac{d_{DM}}{2}\bar{B}\sigma_{\mu\nu}\gamma_5 B\ F_{\mu\nu}$$

$$d_{DM} \sim \frac{e}{16\pi^2}\frac{a\,b\,c}{N\,f^2}\,\bar{\theta}\log\frac{m_B^2}{m_\pi^2}$$

Heavier baryons

$$B_3^{heavy} = \Box\Box\Box \qquad \text{or} \qquad B_4^{heavy} = \begin{array}{l}\Box\Box\Box\\ \Box\end{array} \oplus \Box\Box\Box\Box$$

$$s = \frac{3}{2} \qquad\qquad s = 1 \qquad s = 2$$

$$M_B \sim N m_0 + m_1 + \frac{J(J+1)}{N} m_2 + \mathcal{O}\left(\frac{1}{N^2}\right)$$

Baryons with species number can also be stable

Ex:

$$\Omega^-(sss) \to \Xi^0(uss) + K^-(\bar{u}s)$$

Forbidden by phase space in QCD.

Baryon number can be broken by dimension 6 operators

$$\tau_B \sim \frac{8\pi\, M^4}{m_B^5} \sim \left(\frac{M}{10^{16}\,\mathrm{GeV}}\right) \times \left(\frac{10^5\,\mathrm{GeV}}{m_B}\right) \times 10^{10}\,\mathrm{years}$$

Species symmetry and G-parity can be broken by Yukawa couplings or dim 5 operators

$$\frac{1}{M}\bar{\mathcal{Q}}\mathcal{Q}HH\,, \qquad\qquad \frac{1}{M}\bar{\mathcal{Q}}\sigma^{\mu\nu}\mathcal{Q}B_{\mu\nu}$$

Within EFT baryons more likely cosmologically stable.