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Accidental Composite Dark Matter

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+ work in progress

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Motivation

In the SM, all observed global symmetries arise
as accidental symmetries of the renormalizable Lagrangian.
This explains why the proton is stable. It also explains flavour.

We need at least one more stable particle for Dark Matter…

New gauge theory:
DM is an accidentally stable “dark”-baryon

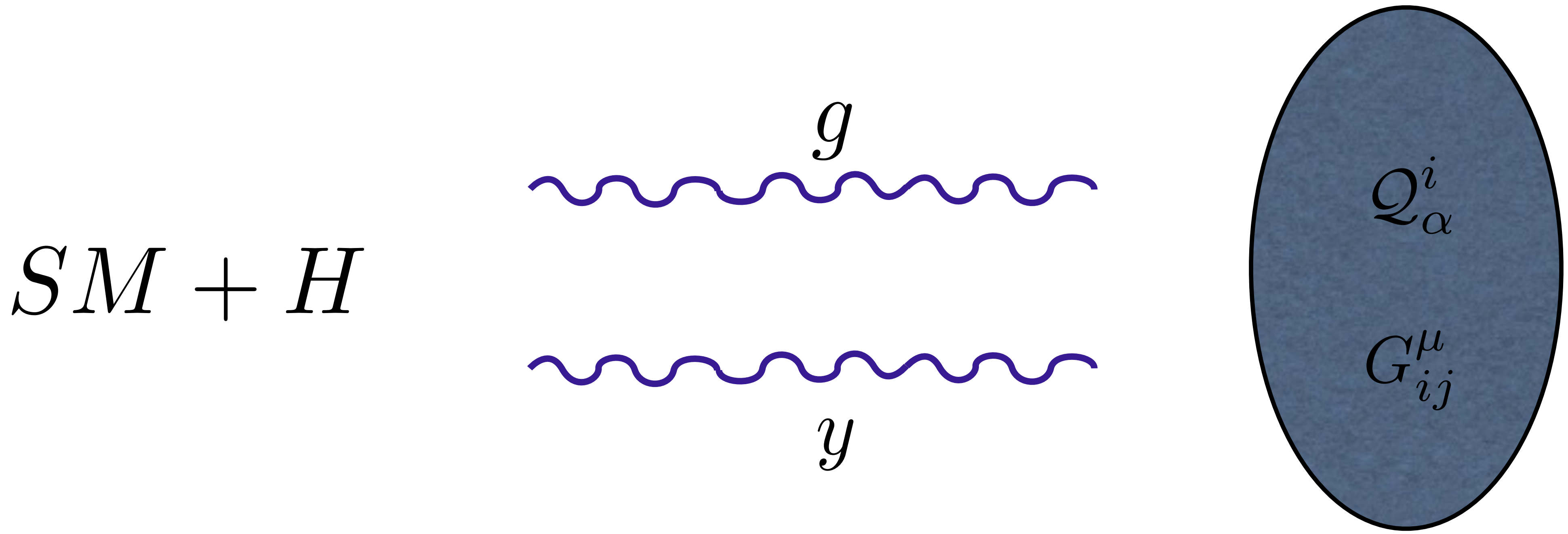
Vector-like confinement:

Kilic, Okui, Sundrum '09

New confining gauge theory with fermions vectorial under SM

Vector-like confinement:

Kilic, Okui, Sundrum '09



New confining gauge theory with fermions vectorial under SM

SM including elementary Higgs couples to the strong sector with renormalizable couplings:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{Q}_i(i\gamma^\mu D_\mu - m_i)Q_i - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm DC}} + \frac{\theta_{\rm DC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + [H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j + \text{h.c.}]$$

Very weak bounds:

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

Interesting phenomenology:

- Accidental dark matter candidates
- Plausible signatures for LHC and cosmology
- (Rel)axions & composite Higgs
- Explained di-photon excess

Accidental symmetries:

- Dark-Baryon number

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

- 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

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

- Light Dark Quarks: $(m_Q < \Lambda_{DC})$

Strongly coupled dynamics.

- Heavy Dark Quarks: $(m_Q > \Lambda_{DC})$

$$\Lambda_{DC} \sim m_Q \exp\left[-\frac{6\pi}{11 C_2(G)\alpha_{DC}}\right] \qquad r_{DC} \sim (\alpha_{DC} m_Q)^{-1}$$

Effective coupling is perturbative.
Vastly different phenomenology varying the coupling.

- $r_{DC} < \Lambda_{DC}^{-1}$ $\qquad \Delta E \sim \alpha_{DC}^2 m_Q$
- $r_{DC} > \Lambda_{DC}^{-1}$ $\qquad \Delta E \sim \Lambda_{DC}$

Light Quarks

- with O. Antipin, A. Strumia, E. Vigiani

SU(N) Models

SU(N) gauge theory with NF light flavors.
Dark-quarks are vectorial with respect to SM.

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

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

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

Nambu-Goldstone bosons:

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

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

Vacuum does not break electro-weak symmetry.

Dark matter candidates:

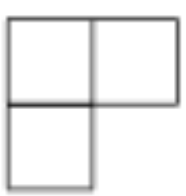
- Dark-Baryons

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

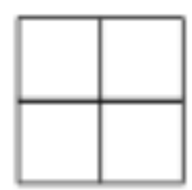
$$m_B \sim N \Lambda_{DC}$$

Lightest multiplet has minimum spin among reps.

$N_{DC} = 3$



$N_{DC} = 4$



DM candidate:

$$Q_{DB} = T^3_{DB} + Y_{DB} = 0$$

$$Y_{DB} = 0$$

⇒ I=0,1,2,...

- **Dark-Pions**

Bai, Hill '10

Pions can be stable due to G-parity or species number:

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

$$W^a_\mu J^a \to W^a_\mu J^a$$

$$S = e^{i\pi J_2}$$

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

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

Triplet is stable. Behaves as minimal dark matter.

Strumia, Cirelli '05

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

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

Symmetry breaking effects:

Baryon number can be broken by dimension 6 operators

$$\tau \sim \frac{8\pi \, M^4}{M_{\rm DM}^5} \sim 10^{26}\,{\rm sec} \times \left(\frac{M}{\bar{\rm M}_{\rm Pl}}\right)^4 \left(\frac{100\,{\rm TeV}}{M_{\rm DM}}\right)^5$$

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

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

Dark baryons more robustly cosmologically stable

Flavor multiplets are split by fermion masses and gauge interactions:

- **quark masses**

$$\delta m_\pi^2 \sim m\,\Lambda_{DC} \qquad\qquad \delta m_B \sim m$$

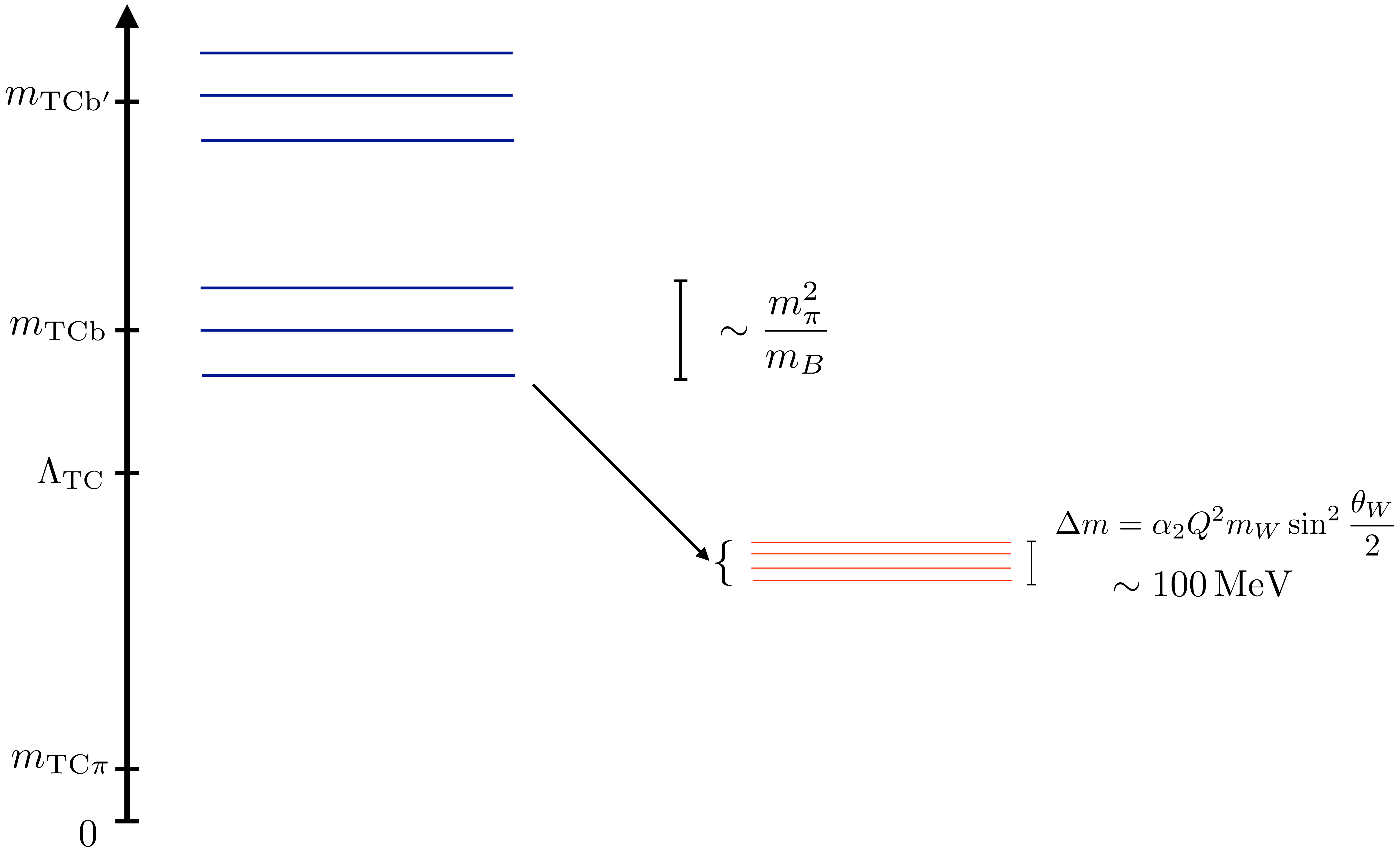
- **gauge interactions**

Charged pions acquire positive mass:

$$\delta m_\pi^2 \sim \frac{3g_i^2}{(4\pi)^2} C_2(\pi)\Lambda_{DC}^2$$

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

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



$m_{\mathrm{TCb}'}$
m_{TCb}
Λ_{TC}
$m_{\mathrm{TC}\pi}$
0
$\sim \frac{m_\pi^2}{m_B}$
$\Delta m = \alpha_2 Q^2 m_W \sin^2 \frac{\theta_W}{2}$
$\sim 100\,\mathrm{MeV}$

We take branches of unified representations

$$R = (N, SM) \oplus (\bar{N}, S\bar{M})$$

$$\tilde{R} = (N, S\bar{M}) \oplus (\bar{N}, SM)$$

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

- SU(N) asymptotically free
- No Landau poles below the Planck scale.
- Lightest dark-baryon with Q=Y=0
- No unwanted stable particles

Two classes of models:

- **Golden**

No unwanted stable states exist

Ex:

$N_{DC} = 3$ Q=V DM=VVV

- **Silver**

Extra sources of breaking of accidental symmetries needed:

Ex:

$N_{DC} = 3$ Q=L+E DM=LLE

Golden models:

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			8	$8, \bar{6}, \dots$ for $N=3,4,\dots$	$\mathrm{SU}(3)_{\rm TF}$
$\Psi=V$	0	3	3	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L$	1	3, .., 14	unstable	$N^{N*}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=4$			15	$\overline{20}, 20', \dots$	$\mathrm{SU}(4)_{\rm TF}$
$\Psi=V\oplus N$	0	3	3×3	$VVV, VNN=3,\ VVN=1$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{E}$	2	3, 4, 5	unstable	$N^{N*}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=5$			24	$\overline{40}, \overline{50}$	$\mathrm{SU}(5)_{\rm TF}$
$\Psi=V\oplus L$	1	3	unstable	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{L}$	2	3	unstable	$NL\tilde{L}=1$	$\mathrm{SU}(2)_L$
$=$	2	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=6$			35	$70, \overline{105'}$	$\mathrm{SU}(6)_{\rm TF}$
$\Psi=V\oplus L\oplus N$	2	3	unstable	$VVV, VNN=3, VVN=1$	$\mathrm{SU}(2)_L$
$\Psi=V\oplus L\oplus\tilde{E}$	2	3	unstable	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{L}\oplus\tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E}=1$	$\mathrm{SU}(2)_L$
$=$	3	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}, N\tilde{E}\tilde{L}\tilde{L}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=7$			48	112	$\mathrm{SU}(7)_{\rm TF}$
$\Psi=L\oplus\tilde{L}\oplus E\oplus\tilde{E}\oplus N$	4	3	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	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	3	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	3	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U}=1$	$\mathrm{SU}(2)_L$

- **Unification**

Incomplete SU(5) reps modify SM running

SU(5)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	charge	name	Δb_3	Δb_2	Δb_Y
1	1	1	0	0	N	0	0	0
$\bar{5}$	$\bar{3}$	1	1/3	1/3	D	1/3	0	2/9
	1	2	−1/2	0, −1	L	0	1/3	1/3
10	$\bar{3}$	1	−2/3	−2/3	U	1/3	0	8/9
	1	1	1	1	E	0	0	2/3
	3	2	1/6	2/3, −1/3	Q	2/3	1	1/9
15	3	2	1/6	2/3, −1/3	Q	2/3	1	1/9
	1	3	1	0, 1, 2	T	0	4/3	2
	6	1	−2/3	−2/3	S	5/3	0	8/9
24	1	3	0	−1, 0, 1	V	0	4/3	0
	8	1	0	0	G	2	0	0
	$\bar{3}$	2	5/6	4/3, 1/3	X	2/3	1	25/9
	1	1	0	0	N	0	0	0

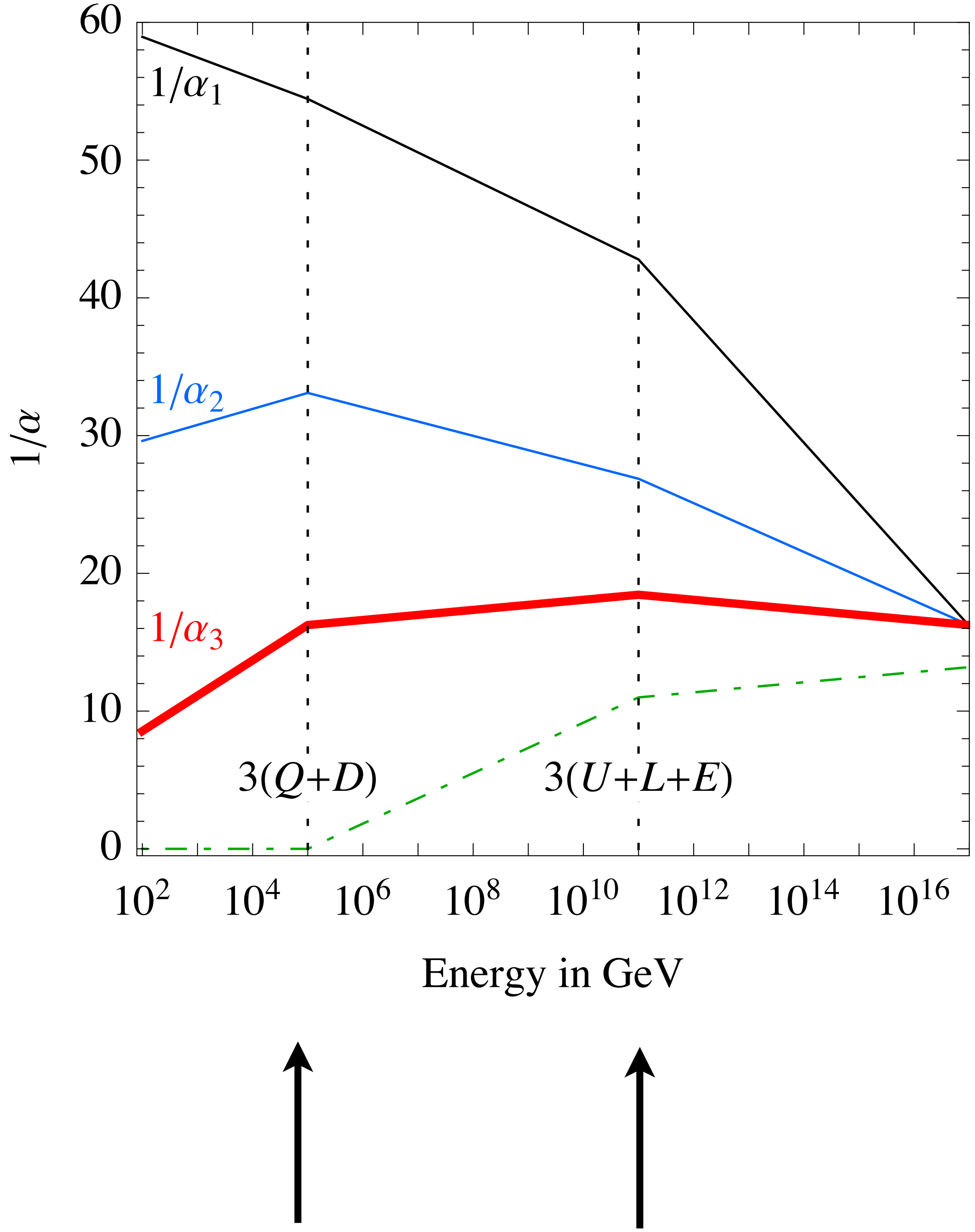
$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{\rm GUT}} + \frac{b_i^{\rm SM}}{2\pi}\log\frac{M_{\rm GUT}}{M_Z} + \frac{\Delta b_i}{2\pi}\log\frac{M_X}{\Lambda_{\rm TC}} + \frac{\Delta b}{2\pi}\log\frac{M_{\rm GUT}}{M_X}$$

$$\ln\frac{M_X}{\Lambda_{\rm TC}} = \frac{68}{\Delta b_{21} - 1.9\Delta b_{32}}, \qquad \ln\frac{M_{\rm GUT}}{M_X} = \frac{35.3\Delta b_{21} - 49.2\Delta b_{32}}{\Delta b_{21} - 1.9\Delta b_{32}}$$

Ex:

$Q + \tilde{D}$

$\mathrm{DM} = QQ\tilde{D}$

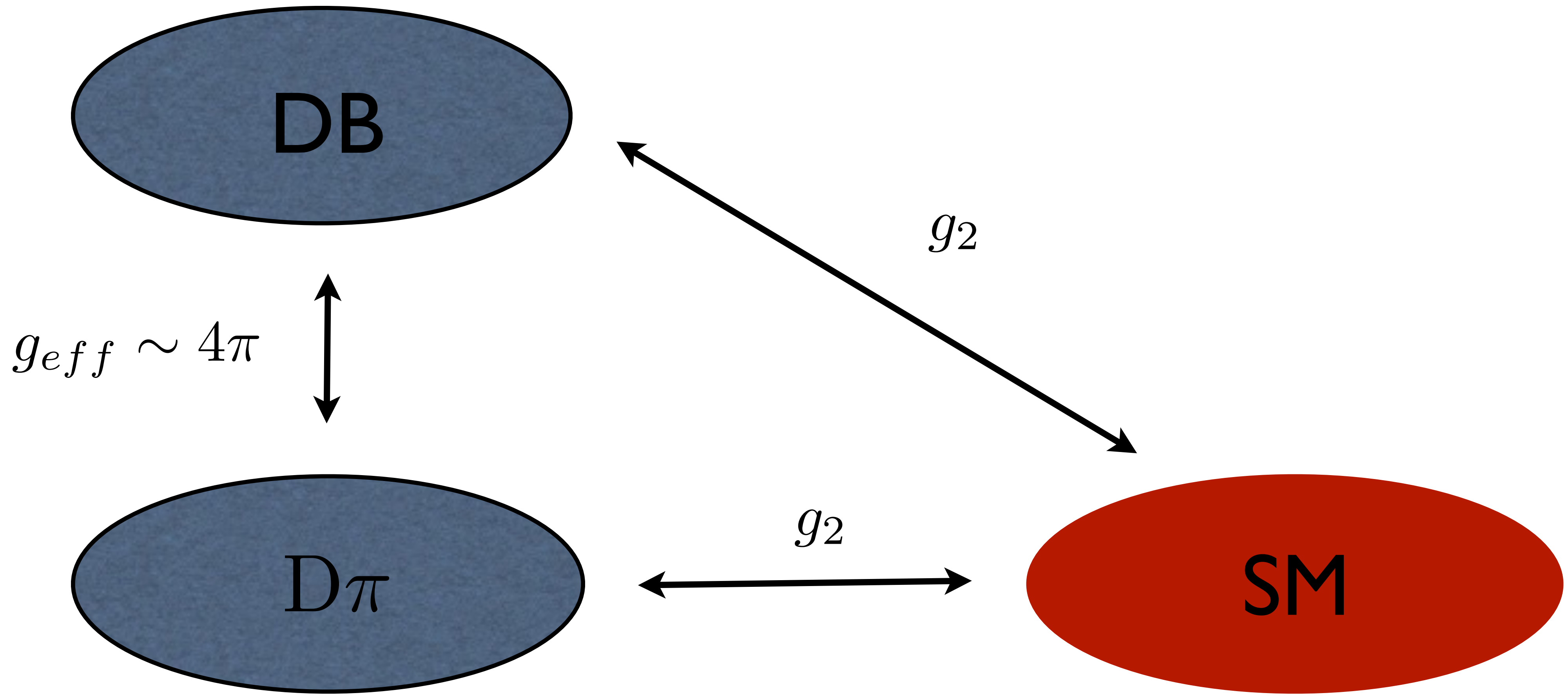


$\Lambda_{DC} = 100\,\mathrm{TeV}$ $M_X \approx 2 \times 10^{11}$ GeV

$\alpha_{\mathrm{GUT}} \approx 0.06$

$M_{\mathrm{GUT}} \approx 2 \times 10^{17}\,\mathrm{GeV}$

Relic abundance:



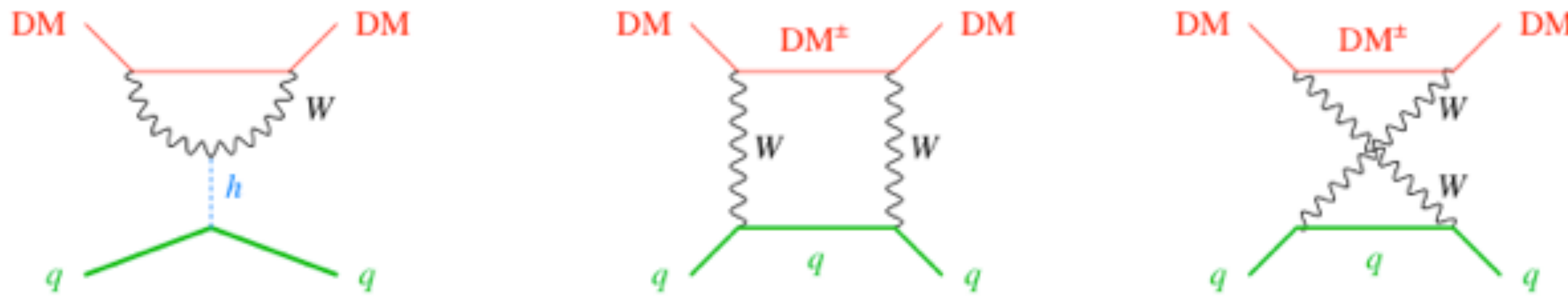
$$\langle \sigma_{B\bar{B}}^{ANN} v \rangle \sim \frac{4\pi}{m_B^2}$$

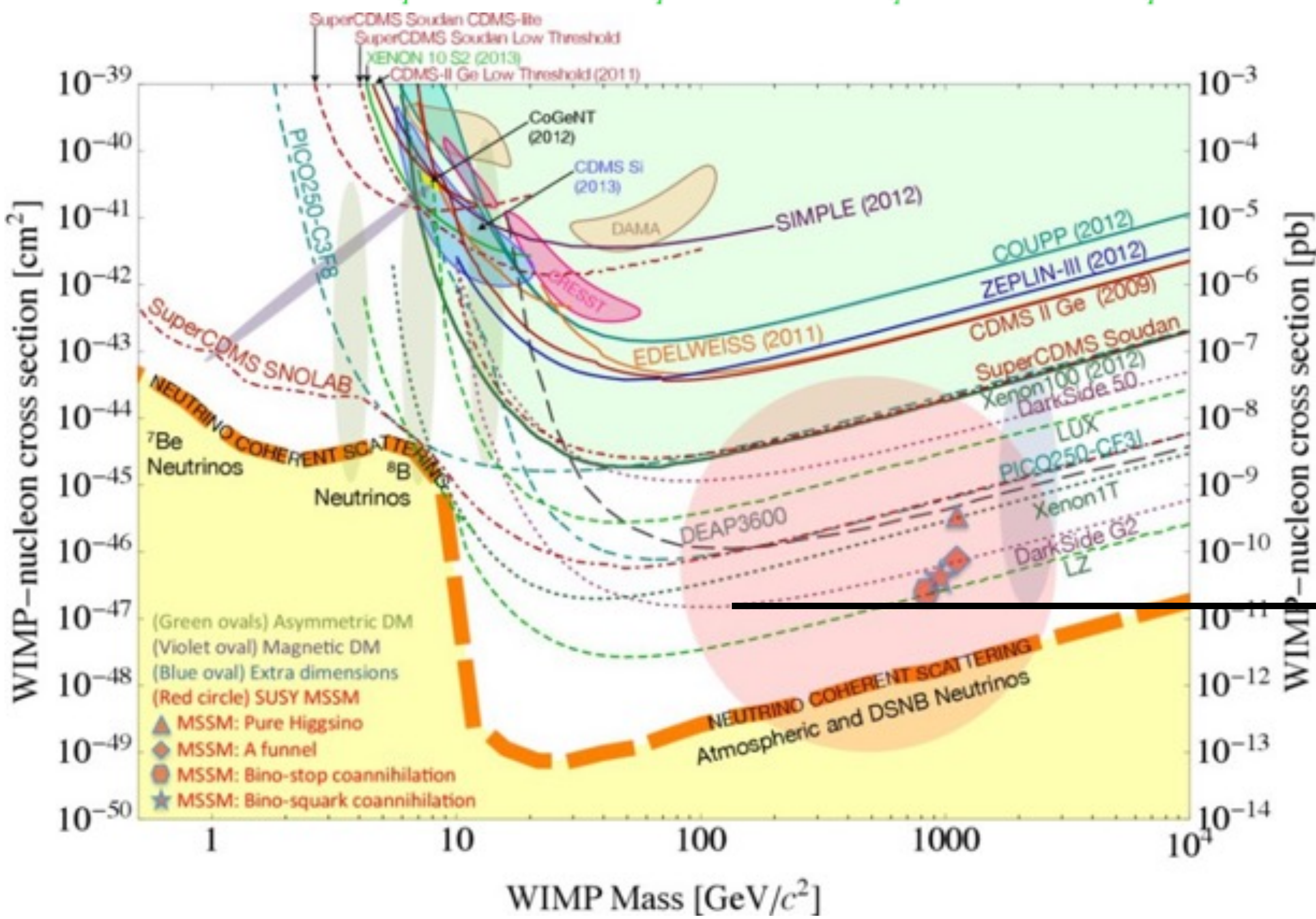
THERMAL ABUNDANCE

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

Alternatively DM could be produced asymmetrically.

If DB has SM charges it interacts as WIMPS.





$$\sigma_{SI}^3 = 0.12 \times 10^{-46}\,\mathrm{cm}^2$$

Yukawa couplings very constrained.

Even if DB is a SM singlet can have dipole interactions

$$\frac{e}{2m_B}\bar{\Psi}\gamma_{\mu\nu}(g_M + i g_E \gamma_5)\Psi \; F_{\mu\nu}.$$

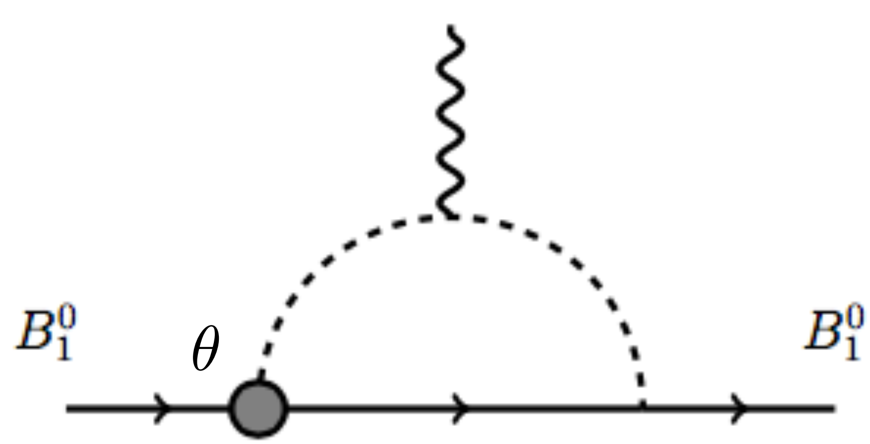
- **Magnetic**

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

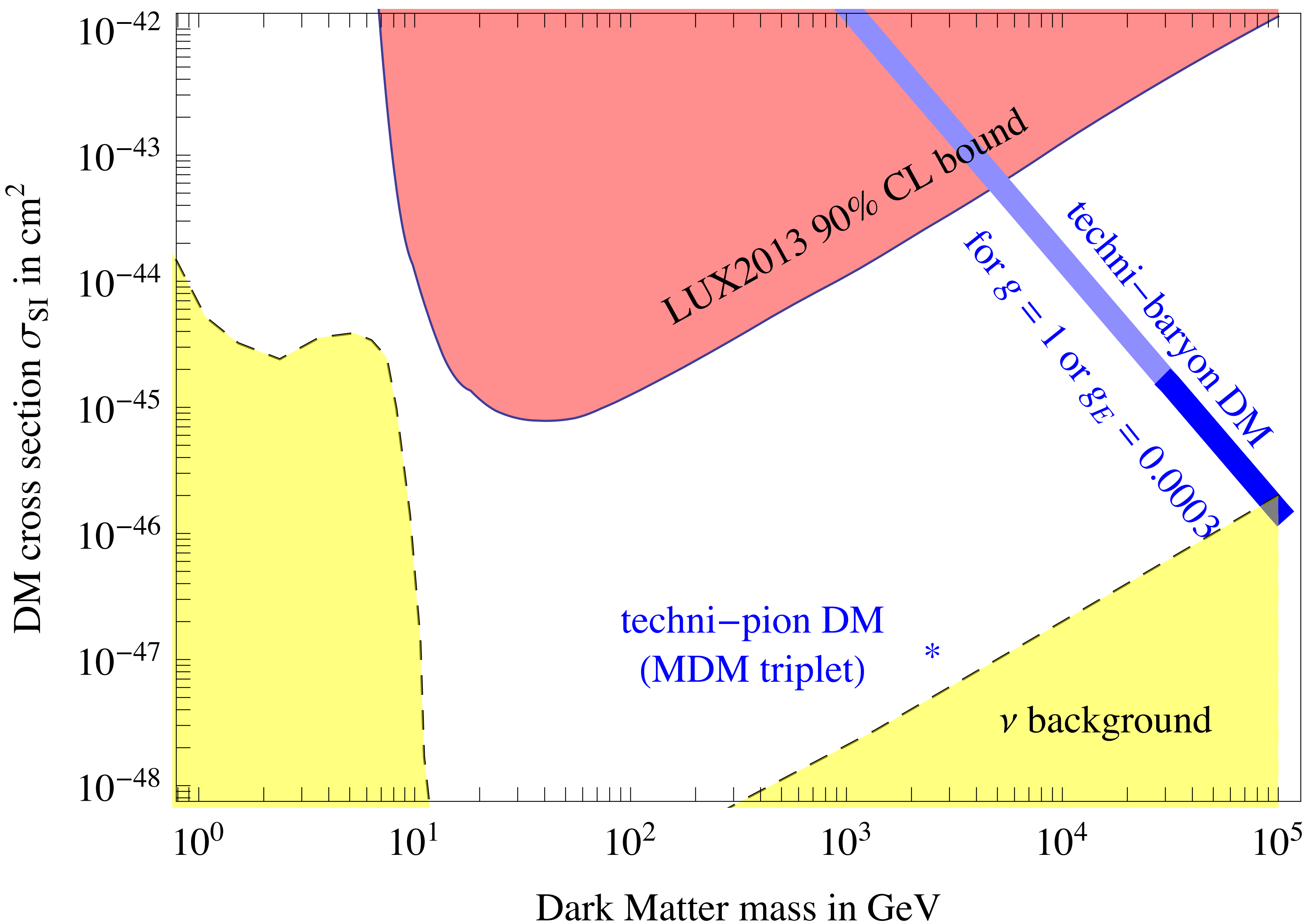
- **Electric**

Need CP violation:

$$\frac{\theta_{TC}}{32\pi^2}\mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}$$



$$g_E \sim \frac{e\,\theta_{\rm TC}\,\min[m_Q]}{M_{\rm DM}}$$



Dipole interactions:

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

SO(N) Models

With NF flavors in the vector rep:

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

Fermions are in a real dark color rep:

- 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

After electro-weak symmetry breaking neutral states with hyper-charge mix with Majorana ones. Analogous to SUSY neutralinos.

SO(N) baryons are Majorana fermions or real scalars:

- **production**

  Cannot be produced through an asymmetry.
  Thermal abundance:

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

- **detection**

  There are no vector couplings with Z eliminating spin independent bounds. No dipole interactions.

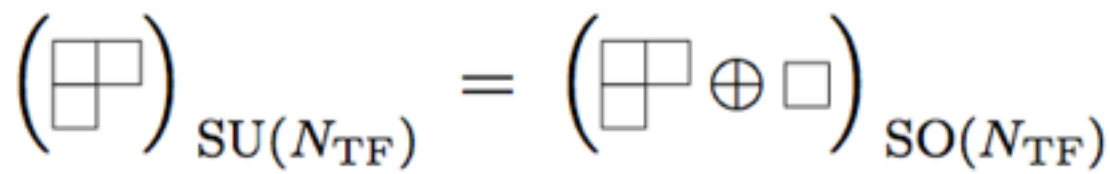
Golden models:

SO(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			5	$3,1,\ldots$ for $N=3,4,\ldots$	$\mathrm{SO}(3)_{\rm TF}$
$\Psi=V$	0	$3,4,..,7$	unstable	$V^N=3,1,\ldots$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=4$			9	$4,1,\ldots$	$\mathrm{SO}(4)_{\rm TF}$
$\Psi=N\oplus V$	0	$3,4,..,7$	3	$VVN=1, V(VV+NN)=3,$	$\mathrm{SU}(2)_L$
				$VV(VV+NN)=1,\ldots$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=5$			14	$5,1\ldots$	$\mathrm{SO}(5)_{\rm TF}$
$\Psi=L\oplus N$	1	$3,4,..,14$	unstable	$L\bar{L}N=1,$	$\mathrm{SU}(2)_L$
				$L\bar{L}(L\bar{L}+NN)=1,\ldots$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=7$			27	$1,\ldots$	$\mathrm{SO}(7)_{\rm TF}$
$\Psi=L\oplus V$	1	4	unstable	$(L\bar{L}+VV)^2=1$	$\mathrm{SU}(2)_L$
$\Psi=L\oplus E\oplus N$	2	$4,5$	unstable	$(E\bar{E}+L\bar{L})^2+NN(L\bar{L}+E\bar{E})=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=8$			35	1	$\mathrm{SO}(8)_{\rm TF}$
$\Psi=G$	0	4	unstable	$GGGG=1$	$\mathrm{SU}(2)_L$
$\Psi=L\oplus N\oplus V$	2	4	unstable	$(L\bar{L}+VV)^2+NN(L\bar{L}+VV)=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=9$			44	1	$\mathrm{SO}(9)_{\rm TF}$
$\Psi=L\oplus E\oplus V$	2	4	unstable	$(E\bar{E}+L\bar{L}+VV)^2=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=10$			54	1	$\mathrm{SO}(10)_{\rm TF}$
$\Psi=L\oplus E\oplus V\oplus N$	3	4	unstable	as $L\oplus E\oplus V+NN(L\bar{L}+E\bar{E}+VV)=1$	$\mathrm{SU}(2)_L$

Q=L+N

$$m_L \bar{L} L + \frac{m_N}{2} N N + y_L H^\dagger L N + y_R^* H \bar{L} N + h.c$$

$N = 3$:



Lightest baryons are likely a quintuplet of SO(5):
"Higgsino" + "bino"

$$\begin{array}{c} \\ 1_0 \\ 2_{1/2} \\ 2_{-1/2} \\ \vdots \end{array} \begin{array}{c} \begin{array}{cccc} 1_0 & 2_{1/2} & 2_{-1/2} & \cdots \end{array} \\ \begin{pmatrix} m_N & y_L v & y_R v & \cdots \\ y_L^* v & 0 & m_L & \cdots \\ y_R^* v & m_L & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \end{array}$$

- "Higgsino DM" $\quad m_L < m_N$

$$\Delta m_M \sim \frac{y^2 v^2}{m_N} \qquad \qquad \alpha \sim \frac{y v}{m_N}$$

- spin-independent x-sec

$$\sigma^{SI} \approx 10^{-42} \left(\frac{(y_L - y_R^*)v}{m_L + m_N} \right)^2 \mathrm{cm}^2 \qquad \sigma^{SI}_{LUX} < 2 \times 10^{-45}\,\mathrm{cm}^2 \frac{M_{DM}}{\mathrm{TeV}}$$

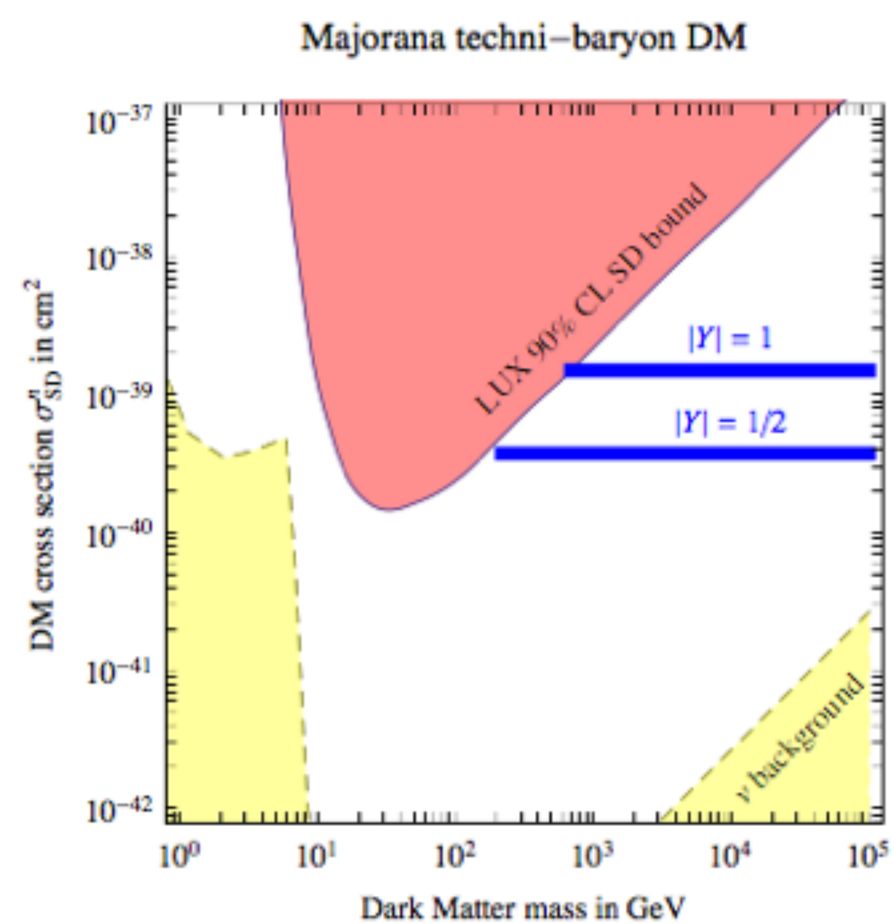
- inelastic x-sec

$$\sim \frac{g_2 Y}{\cos\theta_W} \bar{\Psi}^+_M \gamma^\mu \Psi^-_M Z_\mu \xrightarrow{\Delta m_M > 100\ \mathrm{KeV}} y > 10^{-2} \times \sqrt{\frac{m_N}{100\,\mathrm{TeV}}}$$

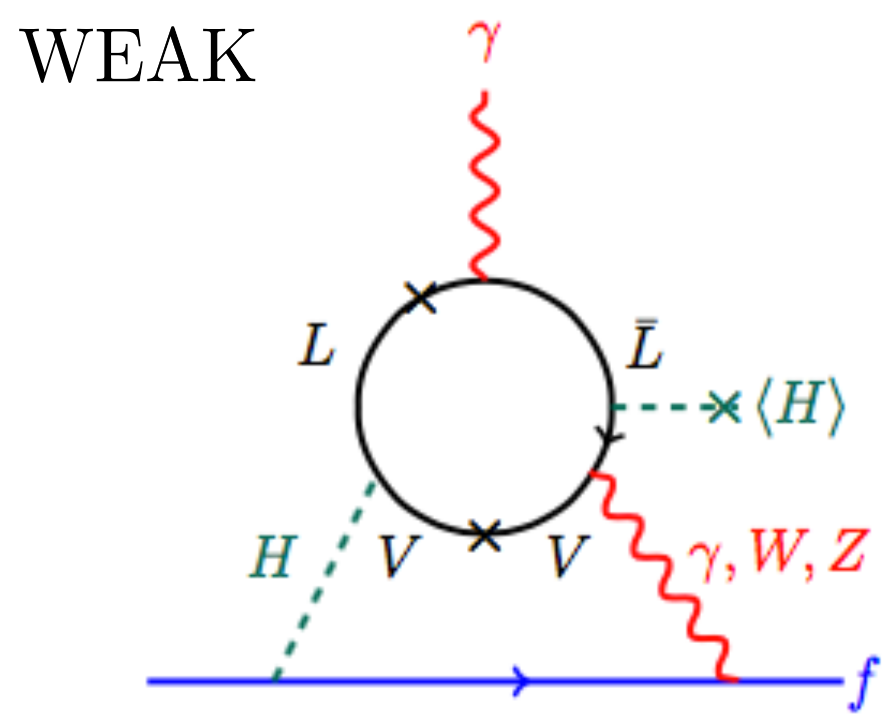
- spin-dependent x-sec

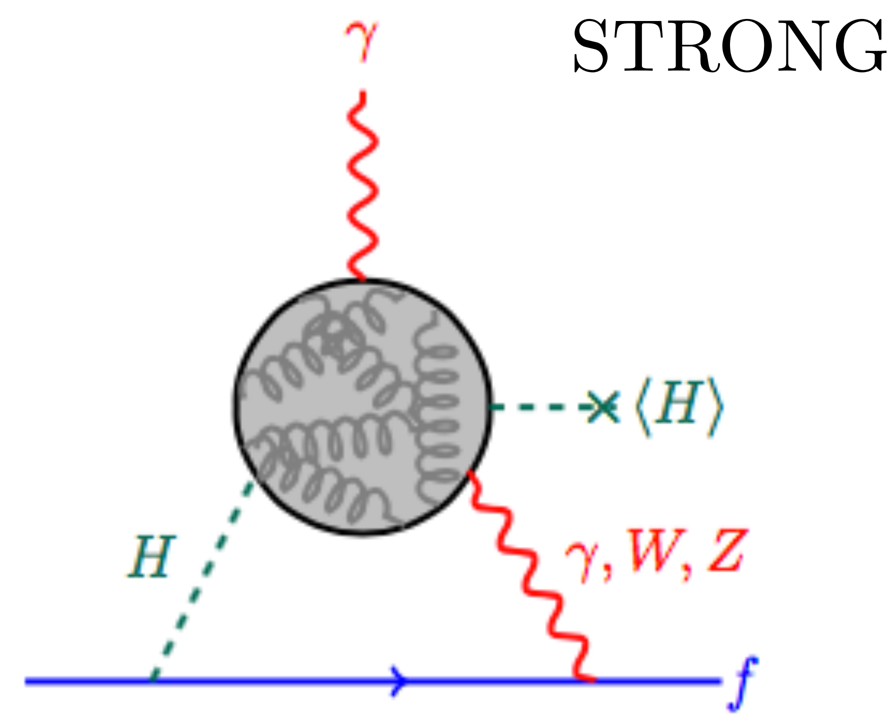
$$g_A Z_\mu \frac{g_2}{\cos\theta_W} \frac{\bar{\chi}\gamma^\mu\gamma^5\chi}{2} \qquad g_A < \frac{M_{DM}}{\mathrm{TeV}}$$

$$g_A \sim \frac{y^2 v^2}{m_N^2} \ll 1$$



EDM for SM particles generated with complex Yukawas:





$$d_e \approx 10^{-27}\,\mathrm{e}\cdot\mathrm{cm} \times \mathrm{Im}(y_L y_R) \times \frac{N_{DC}}{3} \times \left(\frac{\mathrm{TeV}}{m_{\pi,\eta}}\right)^2 \times \left(\frac{\Lambda_{DC}}{\mathrm{TeV}}\right)^2$$

$$d_e < 8.7 \times 10^{-29}\ \mathrm{e\,cm} \qquad @\,90\%\ \mathrm{C.L.}$$

Heavy quarks

- with A. Mitridate

Baryons are non-relativistic bound states N fermions

$$m_B \sim N m_Q$$

Binding energy

$$\Delta E \sim \mathrm{Max}(\alpha_{DC}^2 m_Q,\ \Lambda_{DC})$$

Lightest baryons are typically made of a single specie.

- $SU(3)$

$$\Psi = N \oplus \dots \qquad \mathrm{DM} = NNN\,, \qquad I(J^P) = 0\left(\frac{3}{2}^+\right)$$

$$\Psi = V \oplus \dots \qquad \mathrm{DM} = VVV\,, \qquad I(J^P) = 1\left(\frac{1}{2}^+\right)$$

- $SO(3)$

$$\Psi = L \oplus N \oplus V + \dots \qquad DM = LL\bar{L} \qquad I(J^P) = \frac{1}{2}\left(\frac{1}{2}^+\right)$$

At freeze out dark quarks can be free:

$$\Delta E < T_{f.o.} \sim \frac{m_B}{30} \qquad \langle \sigma v \rangle = \frac{1}{d} \frac{2 - 3N_{DC}^2 + N_{DC}^4}{8N_{DC}^3} \frac{\pi \alpha_{DC}^2}{m_Q^2} + \frac{1}{N_{DC}} \langle \sigma v \rangle_{SM}$$

Quarks eventually recombine into mesons and baryons.
Unstable mesons will decay to SM or dark gluons.

$$\Omega_{DM} = \lambda \Omega_Q \qquad 0.001 < \lambda < 0.1$$

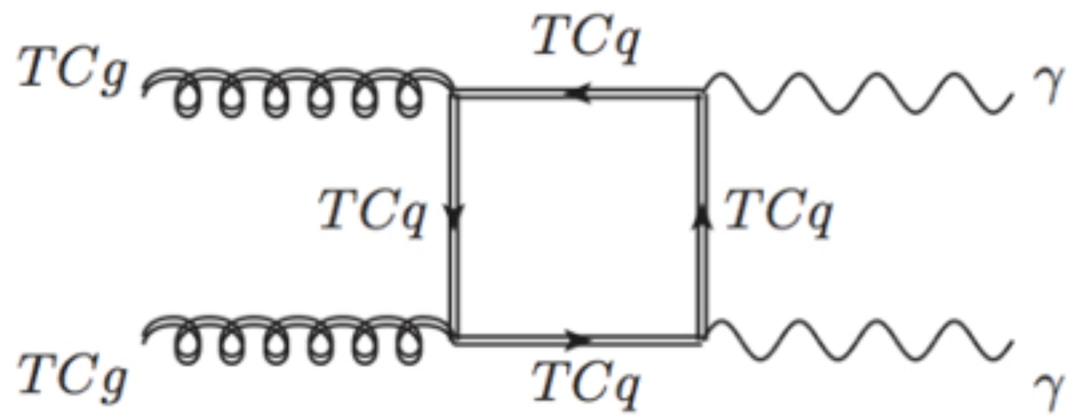
If dark quarks are bound:

$$\Delta E > T_{f.o.} \qquad \langle \sigma v \rangle = \frac{4\pi \alpha_{eff}^2}{m_B^2} + \langle \sigma v \rangle_{SM}$$

With perturbative couplings thermal abundance of DM is obtained for masses at the TeV scale.

- $\Lambda_{DC} < T_0$ $\left(10^{-6} < \alpha_{DC} < \frac{0.05}{N_{DC}}\right)$

Dark gluons never confine but kept in equilibrium



$$\Delta N_{eff} = \frac{8}{7}(N_{DC}^2 - 1)\left(\frac{T_{dg}}{T_\nu}\right)^4 \qquad \left(\frac{T_{dg}}{T_\nu}\right) = \left(\frac{g_*^\nu}{g_*^{dg}}\right)^{\frac{1}{3}}$$

Constrained by Neff

$$\Delta N_{eff} < \frac{1}{2} \qquad N_{DC} < 4$$

- $T_0 < \Lambda_{DC} < T_{f.o.}$ $\quad\left(\frac{0.05}{N_{DC}} < \alpha_{DC} < 0.1\right)$

As before freeze out takes place before confinement. Unstable hadrons cannot decay into dark gluons. Possible late time decay of dark glueballs.

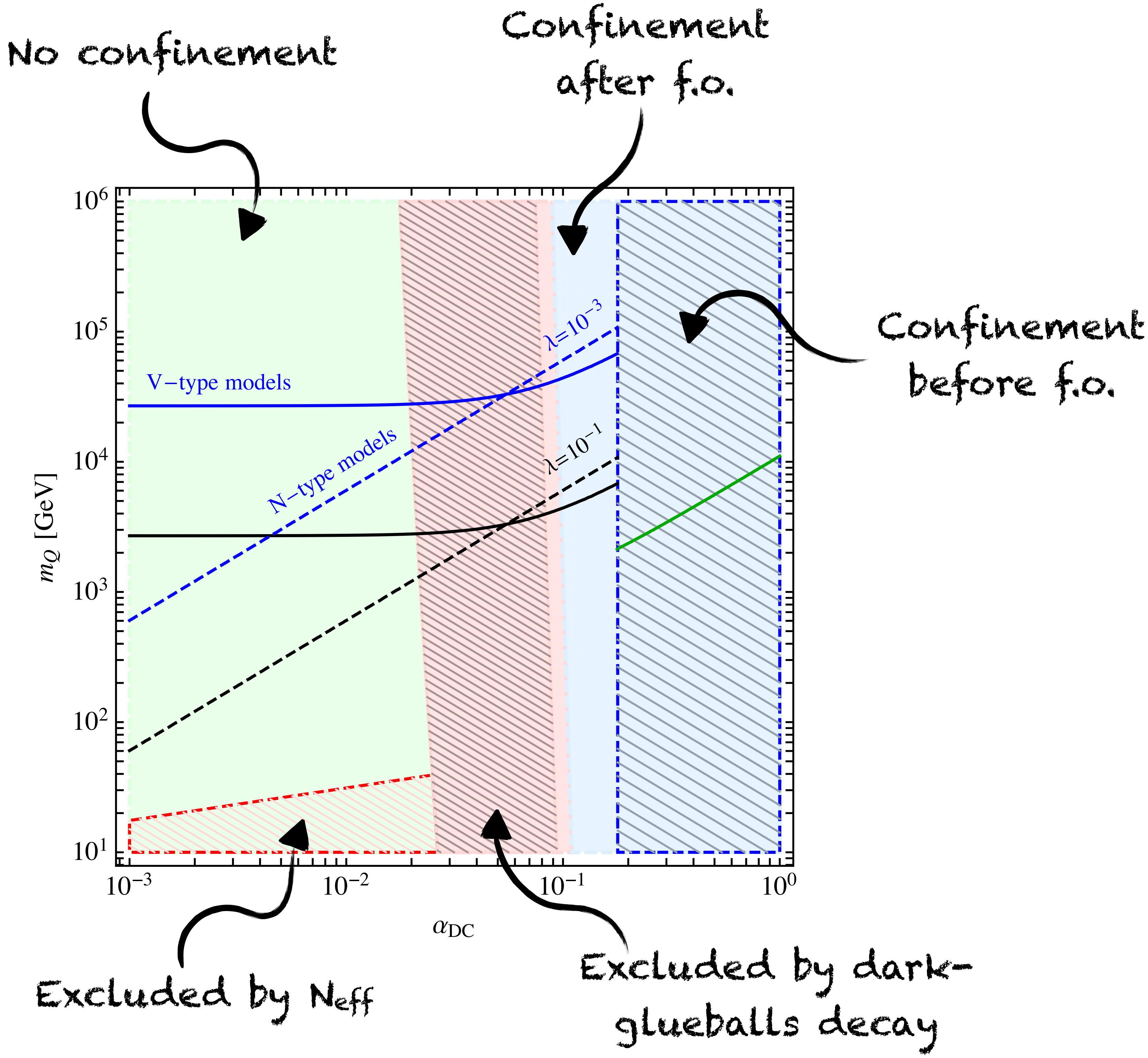
- $\Lambda_{DC} > T_{f.o.}$ $\quad(\alpha_{DC} > 0.1)$

Bound states form before freeze out. Similar to light quarks regime. No cosmological bounds.

DM is point-like for direct detection:

$$\Delta E > 100\,\mathrm{KeV} \qquad \alpha_{DC} > 10^{-4}\sqrt{\frac{10\,\mathrm{TeV}}{m_Q}}$$

$SU(3) \qquad m_{V,N} > \Lambda_{DC}$



CONCLUSIONS

- Stability of DM suggests the existence of accidental symmetries beyond the SM. DM can be simply realised as baryons of a new gauge theory with vectorial fermions.

- SU(N) models generate complex DM with sizeable dipole moments. SO(N) models give Majorana DM with pheno similar to neutralinos.

- Thermal abundance of DM is obtained for masses 1-100 TeV depending on the confinement scale.

- These models could be accessible to other experiments. Interesting effects include: new resonances, EDMs, gravitational waves, unification…

OTHER PHENO

(O. Antipin, MR, arxiv:1508.01112
Agugliaro, Antipin, Becciolini, De Curtis, Redi, to appear)

COLLIDER SIGNATURES

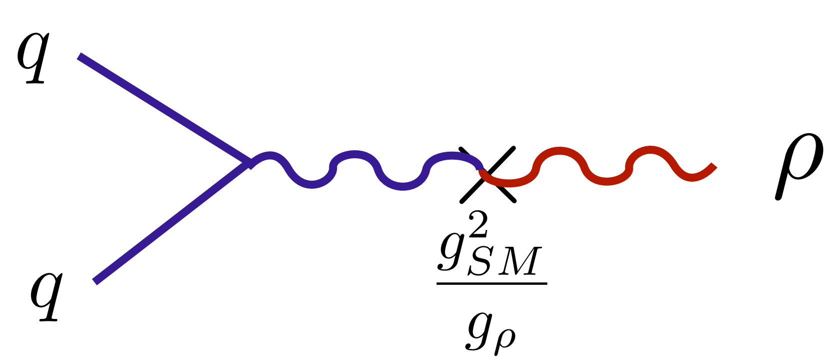
Kilic, Okui, Sundrum '09

Framework predicts Goldstone bosons and vector bosons with SM charges:

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

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

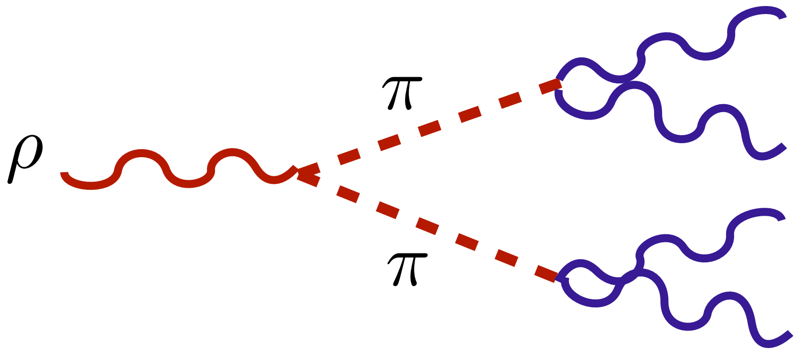
Heavy vectors mix with SM gauge bosons

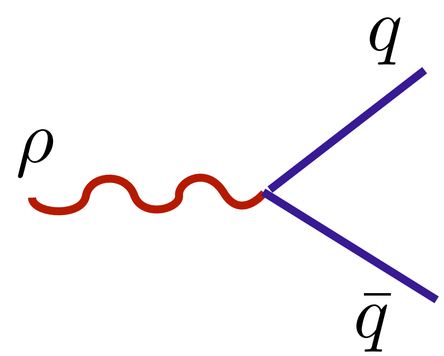


$$m_\rho \sim g_\rho f$$

Unlike composite Higgs fermions are elementary.

Decay to hidden pions and back to SM gauge bosons through anomalies or qqbar





$$\mathrm{Br}(\rho \to q\bar{q}) \propto \frac{g_2^4}{g_\rho^4}$$

Pions can also be collider stable or long lived.

Pions can also be produced through SM interactions

$$pp \to W^\pm \to \pi_3^\pm \pi_3^0 \to 3\gamma \;+\; W^\pm$$

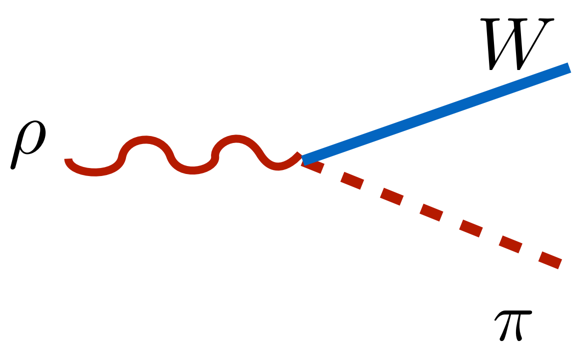
Only search from CDF!

$$m_{\pi_3} > 230\,\mathrm{GeV}$$

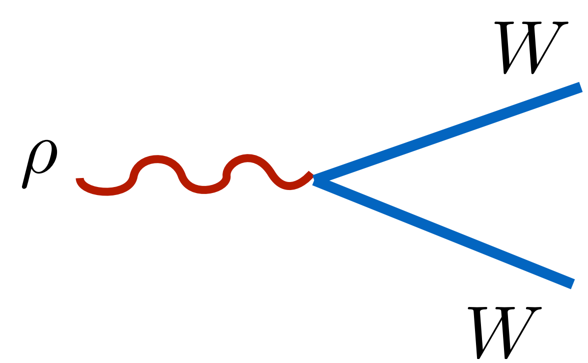
New features arise with Yukawa couplings

$$H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j \longrightarrow y\, m_\rho f\, H\pi_2 + \ldots$$

$$\text{MIXING :} \qquad \epsilon \sim y\frac{m_\rho f}{m^2_{\pi_2}}$$



$$\text{BR}(\rho \to \pi W) \sim \epsilon^2$$



$$\text{BR}(\rho \to WW) \sim \epsilon^4$$

- Pions with species number decay through Higgs:

$$\pi_{2_{1/2}} \to H\pi_{1_0}, \qquad \pi_{1_1} \to HH\pi_{1_0}$$

- Small effects in precision tests, Higgs couplings etc…

$$\delta\hat{T} \sim \frac{v^2}{f^2}\epsilon^4 \qquad \delta\hat{S} \sim \frac{m^2_W}{m^2_\rho}\epsilon^2 \qquad \frac{h_{WW}}{h^{SM}_{WW}} \sim \epsilon^3\frac{v^2}{f^2}$$

COMPOSITE HIGGS

Antipin, Redi '15
+ work in progress

$$M^2 = \begin{pmatrix} m_0^2 & \epsilon\, m_{\pi_2}^2 \\ \epsilon\, m_{\pi_2}^2 & m_{\pi_2}^2 \end{pmatrix}$$

Electro-weak VEV

$$m_0^2 - \epsilon^2 m_{\pi_2}^2 \approx 0$$

- $\epsilon < 1$ Elementary Higgs
- $\epsilon > 1$ Composite Higgs

Elementary Higgs generates vacuum misalignment of composite Higgs!

$$\lambda\, H \bar{q}_L q_R \longrightarrow y^{SM} \approx \frac{\lambda}{\epsilon}$$

Viable UV completion of composite Higgs.
Not natural… supersymmetry? relaxion?

Gravitational waves (GW)

$SU(N)$ confining theories with N_F massless flavours give rise to a 1st order P.T. for

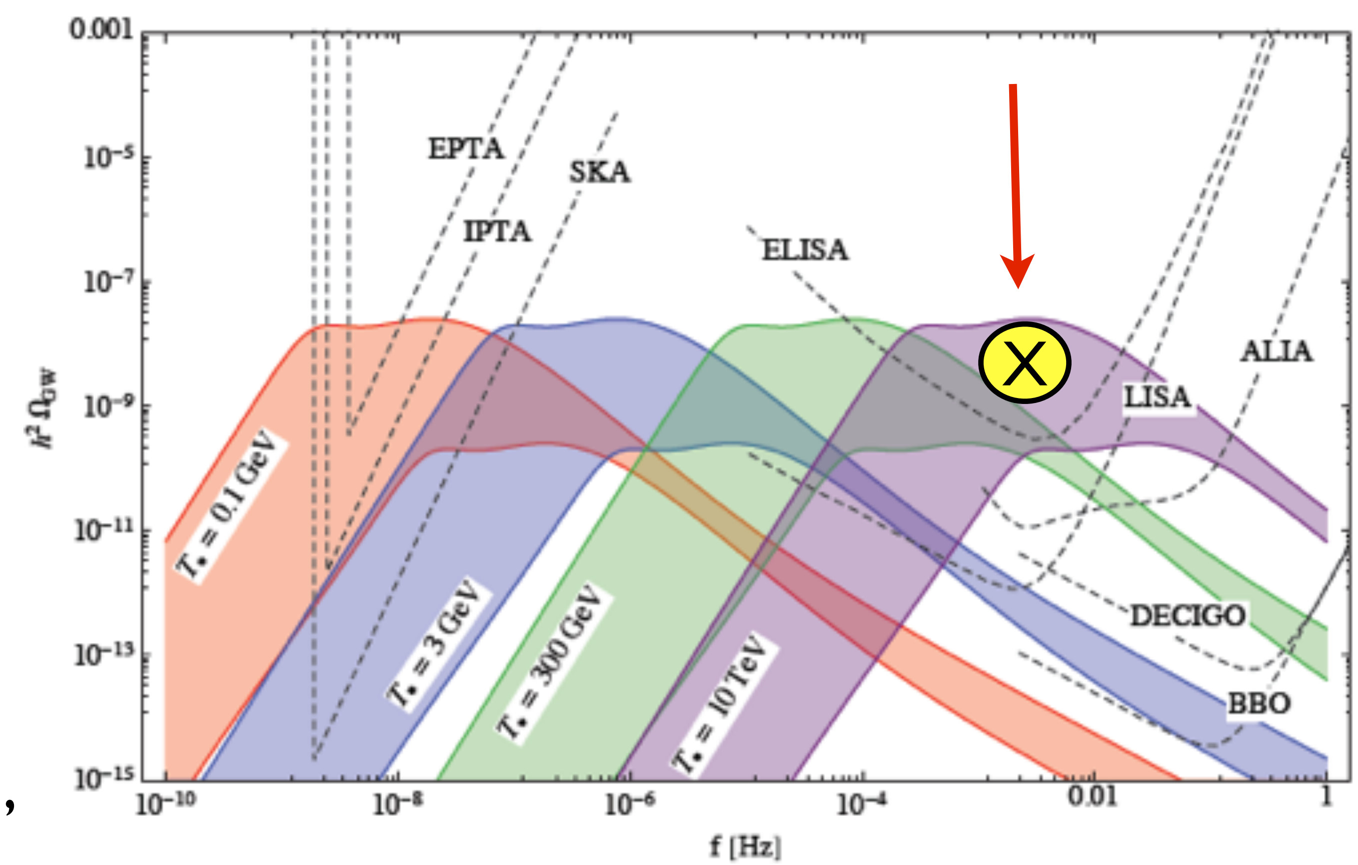
$$3 \leq N_F \leq 4N \quad \text{and} \quad N > 3$$

P.T. occurs at : $T \sim \Lambda_{\rm TC} \sim \mathcal{O}(10 \text{ TeV})$

Peak frequency of the GW signal : $$f_{\rm peak} = 3.3 \times 10^{-3} \text{ Hz} \times \left(\frac{T}{10\,\text{TeV}}\right) \times \left(\frac{\beta}{10H}\right)$$

Amplitude of the GW signal :

$$h^2\Omega_{\rm GW} \sim 10^{-9}$$



P. Schwaller 15'

Baryons in SO(N) models

Start from the SU(NF) DB and decompose under SO(NF)

$$N=3 \quad : \qquad \left(\ydiagram{2,1}\right)_{\mathrm{SU}(N_{\mathrm{TF}})} = \left(\ydiagram{2,1} \oplus \ydiagram{1}\right)_{\mathrm{SO}(N_{\mathrm{TF}})}$$

$$N=4 \quad : \qquad \left(\ydiagram{2,2}\right)_{\mathrm{SU}(N_{\mathrm{TF}})} = \left(\ydiagram{2,2} \oplus \ydiagram{2} \oplus 1\right)_{\mathrm{SO}(N_{\mathrm{TF}})}$$

$$N=5 \quad : \qquad \left(\ydiagram{3,2}\right)_{\mathrm{SU}(N_{\mathrm{TF}})} = \left(\ydiagram{3,2} \oplus \ydiagram{2,1} \oplus \ydiagram{3} \oplus \ydiagram{1}\right)_{\mathrm{SO}(N_{\mathrm{TF}})}$$

Example: QCD "eightfold way" splits spin-1/2 DB

$$8 = \left(\ydiagram{2,1}\right)_{\mathrm{SU}(3)} = \left(\ydiagram{2,1} \oplus \ydiagram{1}\right)_{\mathrm{SO}(3)} = 5 \oplus 3$$

similarly for the heavier spin-3/2 DB :

$$10 = \left(\ydiagram{3}\right)_{\mathrm{SU}(3)} = \left(\ydiagram{3} \oplus \ydiagram{1}\right)_{\mathrm{SO}(3)} = 7 \oplus 3$$

Electron EDM

Q=L+N

$$\mathcal{L}_M = m_L L L^c + m_N N N^c + y H L N^c + \tilde{y} H^\dagger L^c N + h.c.$$

Anomalies:

$$L^{\rm EDM} = -\frac{m_{\pi_3}^2}{2}(\pi_3^a)^2 - \frac{m_\eta^2}{2}\eta^2 + \frac{4{\rm Im}(y\tilde{y})g_\rho^2 f_\pi^3}{m_{K_2}^2}\left(H^\dagger\sigma^a H\pi_3^a - \frac{1}{\sqrt{3}}\eta H^\dagger H\right)$$
$$+ \frac{g_1 g_2 N}{64\pi^2 f_\pi}\pi_3^a W_{\mu\nu}^a \tilde{B}^{\mu\nu} - \frac{N}{64\sqrt{3}\pi^2 f_\pi}\eta\left[g_2^2\tilde{W}^{i\mu\nu}W_{\mu\nu}^i + g_1^2\tilde{B}^{\mu\nu}B^{\mu\nu}\right]$$

Integrate out GBs:

$$L^{\rm EDM} = -\frac{m_{\pi_3}^2}{2}L_{\rm EDM}^{\rm eff} \subset -\frac{e^2 N}{48\pi^2}\frac{{\rm Im}(y\tilde{y})(3m_\eta^2 - 2m_{\pi_3}^2)m_\rho^2}{m_{\pi_3}^2 m_\eta^2 m_{K_2}^2}F\tilde{F}h^{0\dagger}h^0 \equiv -\frac{c_H}{\Lambda^2}F\tilde{F}h^{0\dagger}h^0$$

$$\longrightarrow \qquad d_e \approx \frac{e m_e c_H}{4\pi^2\Lambda^2}\log\frac{\Lambda^2}{m_h^2}$$

$$N = N_F = 3$$

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

Rescale QCD:

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

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

Dark-baryon thermal abundance:

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

Q=L+E

$$\Delta m_N \approx 4 m_\rho (b_1 m_L + b_2 m_E) \qquad \Delta m_\Xi \approx 4 m_\rho (b_2 m_L + b_1 m_E)$$

$$\Delta m_\Sigma \approx 4 m_\rho (b_1 + b_2) m_L \qquad \Delta m_\Lambda \approx \frac{4}{3} m_\rho (b_1 + b_2)(m_L + 2 m_E)$$

Triplet is never lightest. Singlet can be DM:

$$m_L \sim m_E$$

Dipole interactions:

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

$$g_M \sim \mathcal{O}(1) \qquad g_E^{B_1} \sim -0.15 \, \frac{m_\pi^2}{f^2} \log \frac{m_B^2}{m_\pi^2} \times \theta_{\rm TC}.$$