Composite dark matter

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Partially based on: arxiv 1503.08749 and 1508.01112

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Outline

- Vector-like confinement model-building and viable models
- Predictions for Dark Matter
- Phenomenology
- Conclusions

Vector-like confinement framework

- We take SM with elementary Higgs and add NF new "hyperquarks" Ψ charged under new "hypercolor" interactions

- We also assume that hyperquarks lie in a real representation under the SM so that their condensate does not break EW

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\Psi}_i (i\not{D} - m_i)\Psi_i - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm TC}} + \frac{\theta_{\rm TC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + [H\bar{\Psi}_i(y^L_{ij}P_L + y^R_{ij}P_R)\Psi_j + \text{h.c.}]$$

$$\supset |D_\mu H|^2 - \lambda(H^\dagger H)^2 + m^2 H^\dagger H$$

Why bother?

- Natural DM candidates (hyperbaryons and hyperpions) to be probed in the next round of DM experiments
- Each model predicts concrete set of hypermesons to be probed at LHC 13
- Deviations in the Higgs couplings and EDMs
- Automatic MFV to avoid all flavor bounds
- Naturalness may be solved via relaxion mechanism
- η' can be 750 di-photon resonance

Our model-building rules

- We study SU(N) and SO(N)* "hypercolor" gauge theories with fermionic hyperquaks in the fundamental reps

* Sp(N) models don't have stable baryons

- Under SM, hyperquark reps are embeddable in unified SU(5) multiplets

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

- Demand that HC gauge group is asymptotically free and SM gauge couplings do not develop Landau poles below Planck scale

Accidental symmetries

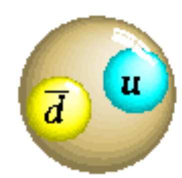
U(1) hyperbaryon number

<u>Leads to stable HyperBaryons (HB)</u>

"Species" number

The NF hyperflavors organize themselves into S SM-multiplets

<u>This leads to stable hyper-pions made of different species</u> $\psi_1, \psi_2 ..., \psi_{N_F}$ $\Psi_1, \Psi_2 ... \Psi_S$

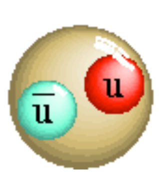
Example: in QCD + QED 

π^+ would be stable

G-parity

Modified version of the charge conjugation $\Psi \to \exp(i\pi T^2)\Psi^c$

Even (odd) weak isospin hyperpions are even (odd) under G-parity
<u>This leads to lightest odd weak isospin hyperpions stable</u>

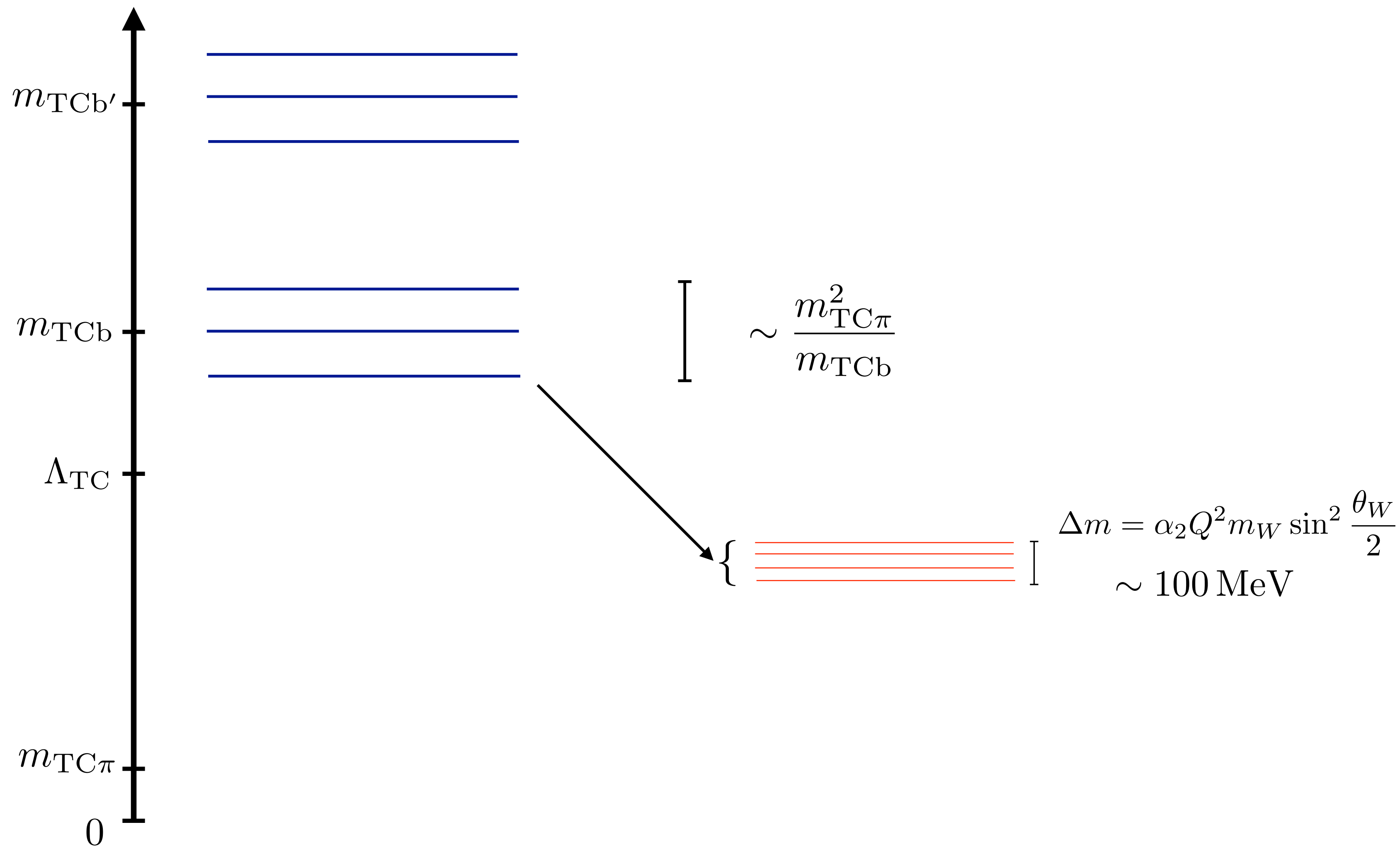
Example: 

π^0 would be stable

SU(N) composite DM models

Dynamics is QCD-like :

$$SU(N_F)_L \otimes SU(N_F)_R \to SU(N_F)_V \quad \Rightarrow \quad N_F^2 - 1 \ \ \text{hyperpions}$$



Model has viable DM candidates (hyperbaryons and hyperpions) if all stable particles have zero charge, hypercharge and QCD color

⇒ DM should belong to the multiplets with integer weak isospin J=0,1,2,..

Viable renormalizable SU(N) models

We scan over combinations of HC quarks and impose constraints to obtain viable DM candidates

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
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

$SU(N)$ techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{TF} = 3$			8	$8, \bar{6}, \ldots$ for $N = 3, 4, \ldots$	$SU(3)_{TF}$
$\Psi = V$	0	3	3	$VVV = 3$	$SU(2)_L$
$\Psi = N \oplus L$	1	3, .., 14	unstable	$N^{N*} = 1$	$SU(2)_L$
$N_{TF} = 4$			15	$\overline{20}, 20', \ldots$	$SU(4)_{TF}$
$\Psi = V \oplus N$	0	3	3×3	$VVV, VNN = 3,\ VVN = 1$	$SU(2)_L$
$\Psi = N \oplus L \oplus \tilde{E}$	2	3, 4, 5	unstable	$N^{N*} = 1$	$SU(2)_L$
$N_{TF} = 5$			24	$\overline{40}, \overline{50}$	$SU(5)_{TF}$
$\Psi = V \oplus L$	1	3	unstable	$VVV = 3$	$SU(2)_L$
$\Psi = N \oplus L \oplus \tilde{L}$	2	3	unstable	$NL\tilde{L} = 1$	$SU(2)_L$
=	2	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L} = 1$	$SU(2)_L$
$N_{TF} = 6$			35	$70, \overline{105'}$	$SU(6)_{TF}$
$\Psi = V \oplus L \oplus N$	2	3	unstable	$VVV, VNN = 3, VVN = 1$	$SU(2)_L$
$\Psi = V \oplus L \oplus \tilde{E}$	2	3	unstable	$VVV = 3$	$SU(2)_L$
$\Psi = N \oplus L \oplus \tilde{L} \oplus \tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E} = 1$	$SU(2)_L$
=	3	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}, N\tilde{E}\tilde{L}\tilde{L} = 1$	$SU(2)_L$
$N_{TF} = 7$			48	112	$SU(7)_{TF}$
$\Psi = L \oplus \tilde{L} \oplus E \oplus \tilde{E} \oplus N$	4	3	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N = 1$	$SU(2)_L$
$\Psi = N \oplus L \oplus \tilde{E} \oplus V$	3	3	unstable	$VVV, VNN = 3,\ VVN = 1$	$SU(2)_L$
$N_{TF} = 9$			80	240	$SU(9)_{TF}$
$\Psi = Q \oplus \tilde{D}$	1	3	unstable	$QQ\tilde{D} = 1$	$SU(2)_L$
$N_{TF} = 12$			143	572	$SU(12)_{TF}$
$\Psi = Q \oplus \tilde{D} \oplus \tilde{U}$	2	3	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U} = 1$	$SU(2)_L$

Exemplary SU(N) model

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF} = 3$			8	$8, \bar{6}, \ldots$ for $N = 3, 4, \ldots$	$\mathrm{SU}(3)_{\rm TF}$
$\Psi = V$	0	3	3	$VVV = 3$	$\mathrm{SU}(2)_L$
$\Psi = N \oplus L$	1	3, .., 14	unstable	$N^{N*} = 1$	$\mathrm{SU}(2)_L$

1) $SU(N)_{\rm HC}$ model with $\Psi = V$

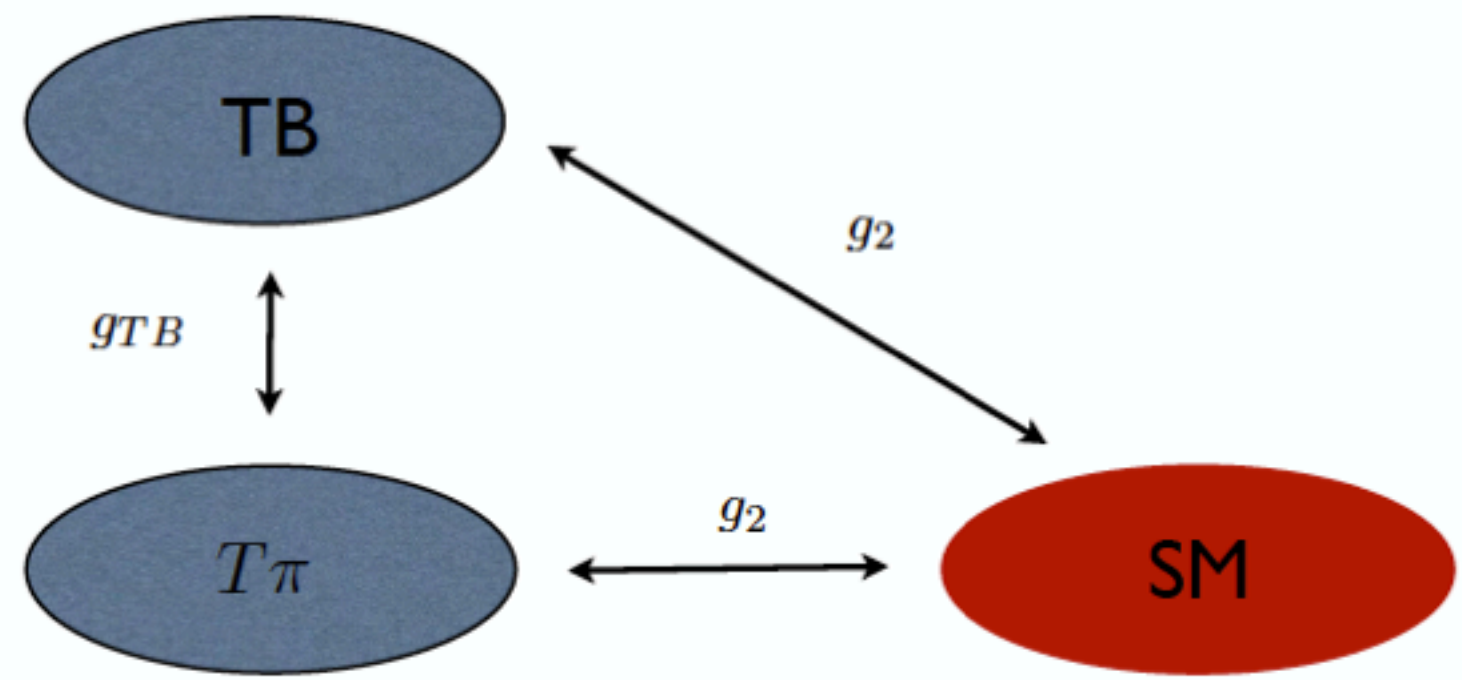
- One specie of hyperquark in the adjoint of SU(2) so that NF=3
- No Yukawa with the Higgs is allowed (because 3⊗3⊗2 contains no singlets)
- If N>3, the SU(2) coupling becomes non-perturbative below the Planck scale
- HB and Hπ lie in 8 of hyper-flavor SU(3): $8 = 3_0 \oplus 5_0$ under $SU(2)_L \otimes \mathrm{U}(1)_Y$
- The Hπ triplet is stable because of G-parity (J=1 odd) and the HB triplet is stable because of HB number

HyperBaryon DM

Crucially depends on the HBaryon mass:

$$M_{\rm DM} \approx \begin{cases} 100\,{\rm TeV} & \text{if DM is a thermal relic,} \\ 3\,{\rm TeV} & \text{if DM is a complex state with a TCb asymmetry} \end{cases}$$

Relic abundance determined by non-relativistic annihilation xsec of HB into hyperpions rescaling the measured QCD pp xsec



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

THERMAL ABUNDANCE

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

Direct detection of complex HB DM

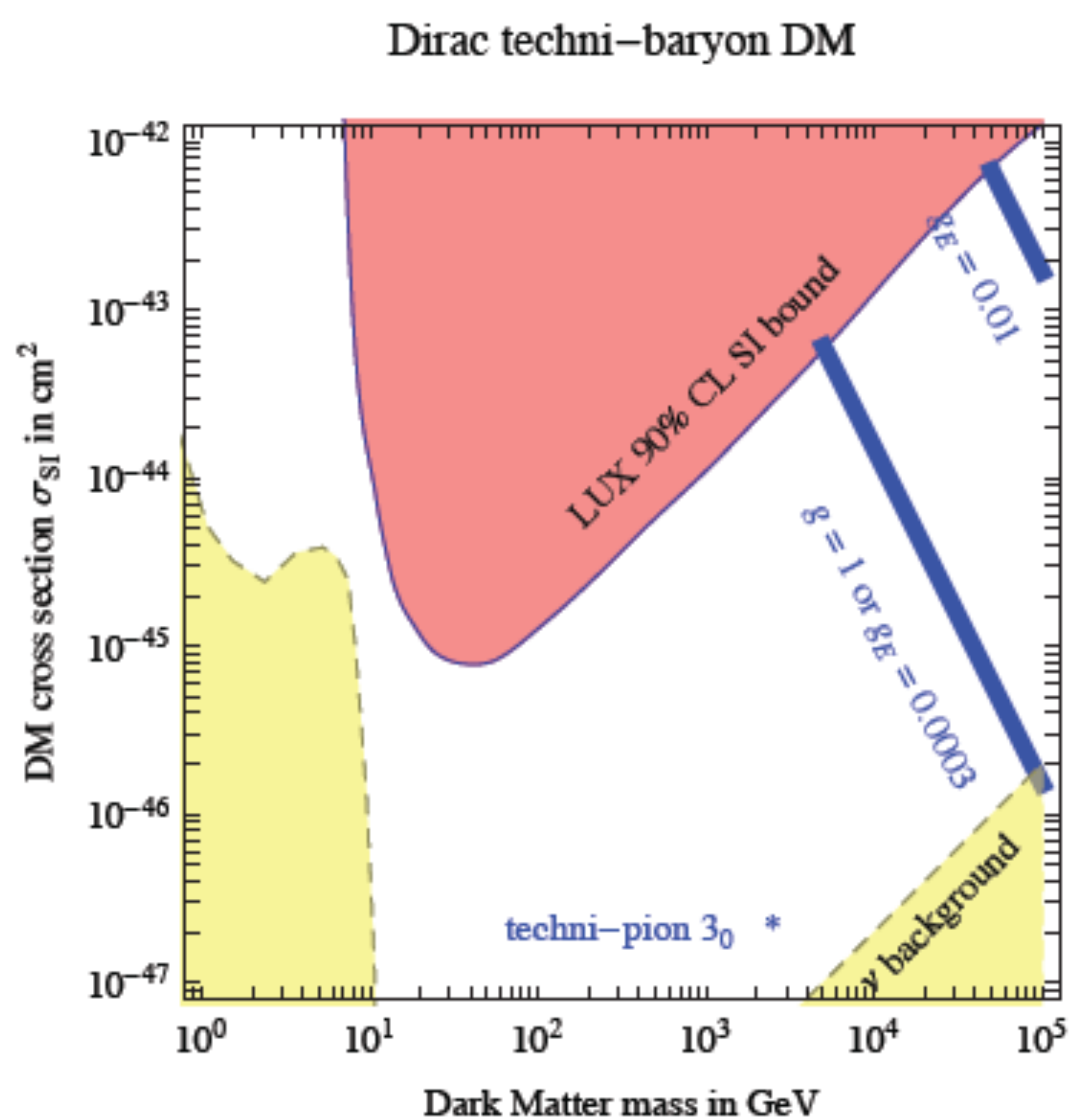
Weak interactions lead to the too small direct detection xsec for 100 TeV DM

Main hope for direct detection of the fermionic DM is the dipole interactions with the photon :

$$\bar{\Psi}\gamma_{\mu\nu}(\mu_M + i d_E \gamma_5)\Psi \; F_{\mu\nu}/2$$

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{4\pi E_R}\left(\mu_M^2 + \frac{d_E^2}{v^2}\right)$$

In models with QCD-colored hyperquarks we also have chromo-dipole moments



HyperBaryon EDM in models **with** Higgs coupling

Example

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{TF} = 3$			8	$8, \bar{6}, \ldots$ for $N = 3, 4, \ldots$	$SU(3)_{TF}$
$\Psi = V$	0	3	3	$VVV = 3$	$SU(2)_L$
$\Psi = N \oplus L$	1	3, .., 14	unstable	$N^{N*} = 1$	$SU(2)_L$

Add lepton doublet L and singlet N in the fundamental of new QCD'

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

$$\text{CP phase :} \qquad \text{Im}(m_L m_N y^* \tilde{y}^*)$$

After χSB, octet of SU(3) GB decompose under EW as:

$$8 = 3_0 \oplus 2_{\pm 1/2} \oplus 1_0$$

$$\Pi = \begin{pmatrix} \pi_3^0/\sqrt{2} + \eta/\sqrt{6} & \pi_3^+ & K_2^+ \\ \pi_3^- & -\pi_3^0/\sqrt{2} + \eta/\sqrt{6} & K_2^0 \\ K_2^- & \bar{K}_2^0 & -2\eta/\sqrt{6} \end{pmatrix} + \frac{\eta'}{\sqrt{3}} \mathbb{1}_3 .$$

Hyperpions low energy effective theory

Yukawas and explicit masses

$U(1)_A$ anomaly

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[D_\mu U D^\mu U^\dagger] + (g_\rho f_\pi^3 Tr[MU] + h.c) + \frac{f_\pi^2}{16}\frac{a}{N}\left[\ln(\det U) - \ln(\det U^\dagger)\right]^2$$

$$- \frac{N}{16\pi^2 f_\pi}\sum_{G_1,G_2} g_{G_1} g_{G_2} Tr[\pi^a T^a F^{(G_1)}\tilde{F}^{(G_2)}] + \frac{3g_2^2 g_\rho^2 f_\pi^4}{2(4\pi)^2}\sum_{i=1..3}\mathrm{Tr}[UT^iU^\dagger T^i]$$

Anomaly with SM vectors

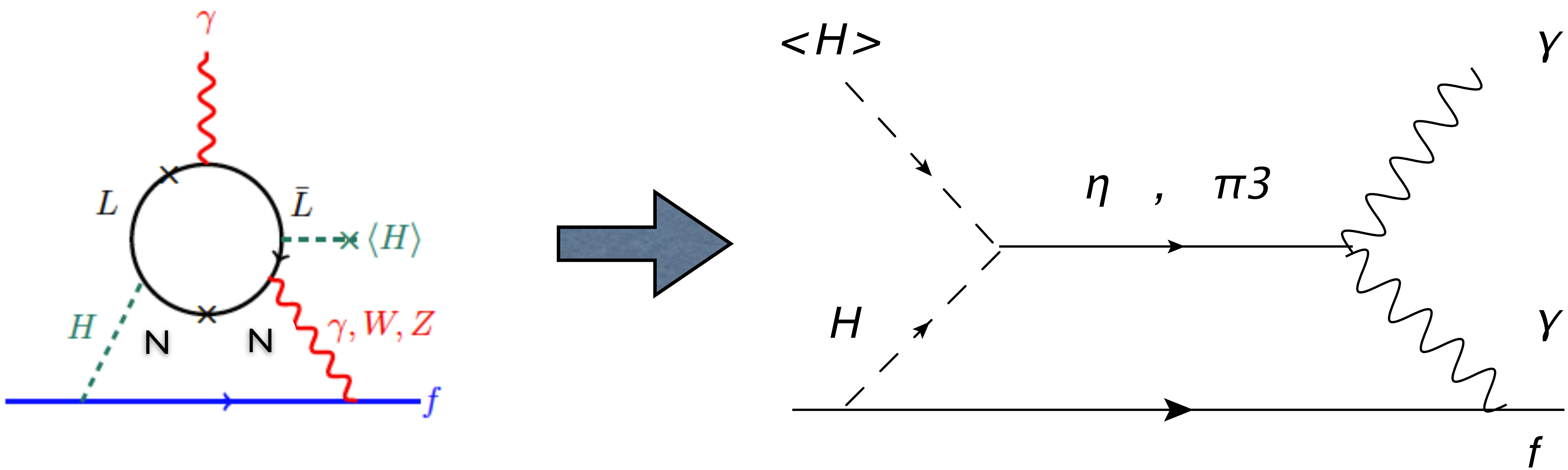
1-loop gauge contribution

$$M = \begin{pmatrix} m_L & 0 & yh^+ \\ 0 & m_L & yh^0 \\ \tilde{y}h^- & \tilde{y}h^{0\dagger} & m_N \end{pmatrix}$$ and $$U \equiv e^{i\sqrt{2}\Pi/f_\pi}$$

HyperBaryon EDM with Higgs coupling

CP phase : $\mathrm{Im}(m_L m_N y^* \tilde{y}^*)$

Heavy fermions　　　　　　　　Light fermions



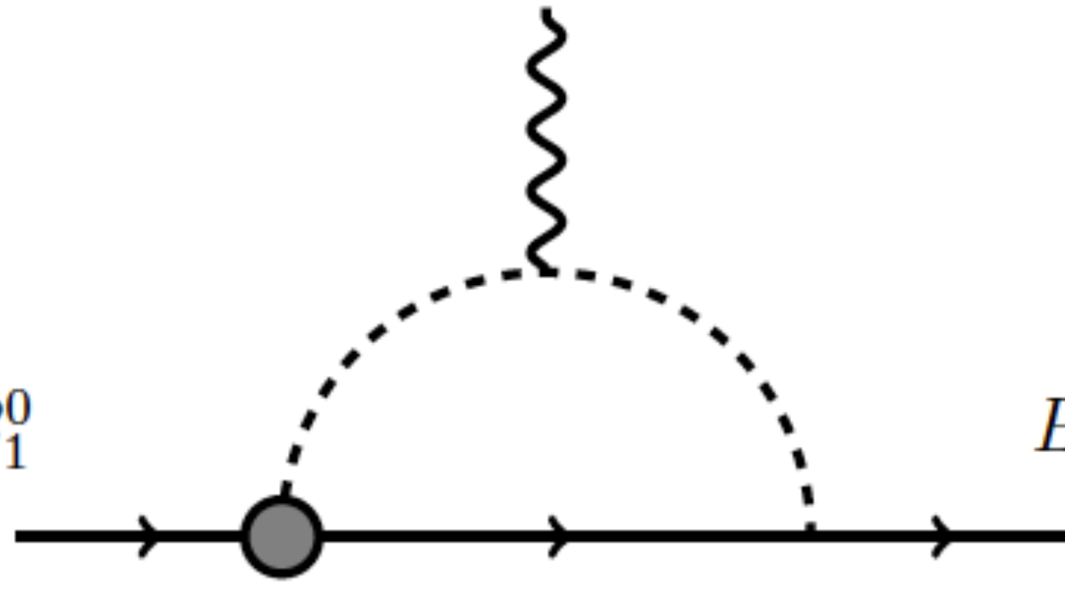
Integrating out η, π3 :

$$L^{\mathrm{eff}}_{\mathrm{EDM}} \subset -\frac{e^2 N}{48\pi^2}\frac{\mathrm{Im}(y\tilde{y})(3m_\eta^2 - 2m_{\pi_3}^2)m_\rho^2}{m_{\pi_3}^2 m_\eta^2 m_{K_2}^2} F\tilde{F} h^{0\dagger} h^0$$

$$d_e \approx 10^{-27}\,\mathrm{e\,cm} \times \mathrm{Im}[y\tilde{y}] \times \frac{N}{3} \times \left(\frac{\mathrm{TeV}}{m_{\pi_3,\eta}}\right)^4 \times \left(\frac{m_\rho}{\mathrm{TeV}}\right)^2$$

HyperBaryon EDM without Higgs coupling

- Hypercolor CP phase leads to EDM for HyperBaryons



$$\mathscr{L}_{BB\Pi,\theta} = -\frac{2\sqrt{2}a}{3f}\left(\theta_{\rm TC} - 2\phi_L - \phi_E\right)\left(b_1 {\rm Tr}[\bar{B}\Pi B] + b_2 {\rm Tr}[\bar{B}B\Pi]\right) + \ldots ,$$

$$\mathscr{L}_{BB\Pi} = -\frac{D+F}{\sqrt{2}f}{\rm Tr}[\bar{B}\gamma^\mu\gamma_5(D_\mu\Pi)B] - \frac{D-F}{\sqrt{2}f}{\rm Tr}[\bar{B}\gamma^\mu\gamma_5 B(D_\mu\Pi)] + \ldots ,$$

$$d_E = \frac{e g_E}{2M_{\rm DM}} \qquad g_E^{B_1} \simeq -0.15\,\frac{m_{\pi_2}^2}{f^2}\log\frac{m_B^2}{m_\pi^2} \times \theta_{\rm TC}$$

HyperPion DM

- If DM is charged under SM, it behaves as a minimal DM with mass ~ 3 TeV (SM vectors give DM annihilation xsec)
- If DM Π is SM-neutral and assuming η(750):

Redi, Strumia, Tesi, Vigiani: 1602.07297

$U(1)_A$ anomaly

$$\mathscr{L}_{\rm DM} = C_{\eta\Pi\Pi}\frac{\eta\Pi^2}{2} - \frac{g_3^2}{16\pi^2} c_G \frac{\eta}{f} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + \frac{g_3^2}{16\pi^2} C_{\Pi\Pi gg}\frac{\Pi^2}{f^2} G^a_{\mu\nu}G^{a,\mu\nu}$$

Chromo-Rayleigh interactions

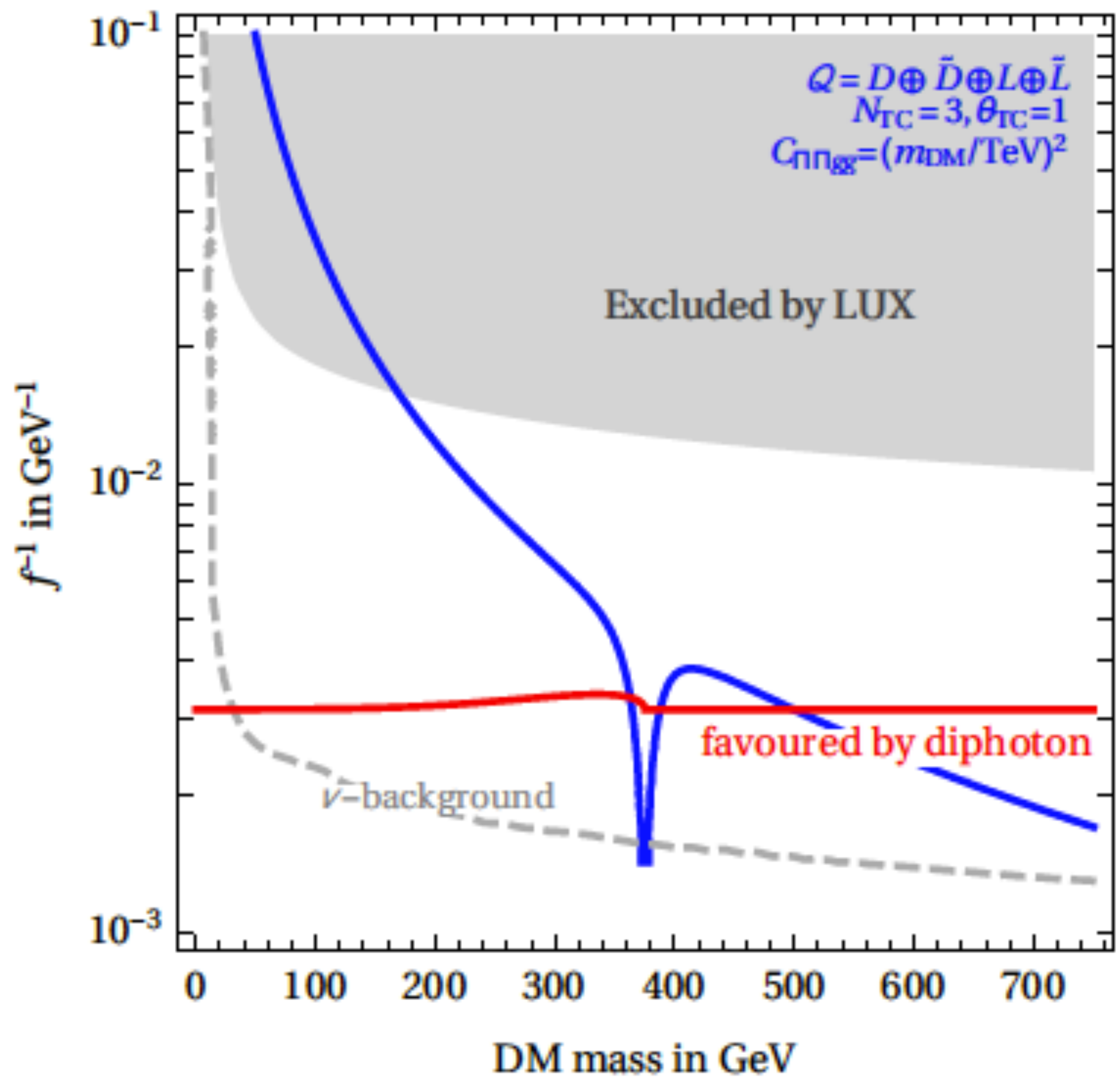
$$C_{\Pi\Pi gg} \sim N_{\rm TC}\frac{m_\Pi^2}{\Lambda_{\rm TC}^2}, \qquad C_{\eta\Pi\Pi} \sim \frac{m_\Pi^2}{f}\theta_{\rm TC}$$

$$\langle\sigma v\rangle = \frac{\alpha_3^2}{\pi^3}\frac{m_\Pi^2}{f^4}\left[4C^2_{\Pi\Pi gg} + \frac{C^2_{\eta\Pi\Pi}c_G^2 f^2}{(M_S^2 - 4m_\Pi^2)^2 + M_S^2\Gamma_S^2}\right]$$

Redi, Strumia, Tesi, Vigiani: 1602.07297

Relic density is reproduced for :

$$m_\Pi \approx 500 \text{ GeV} \left(\frac{f}{200 \text{ GeV}}\right)^2 \left(\frac{0.1}{C_{\Pi\Pi gg}}\right) \qquad \text{(Rayleigh interactions only)}$$



LHC phenomenology and other constraints

LHC Phenomenology and Constraints

Very weak bounds:

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

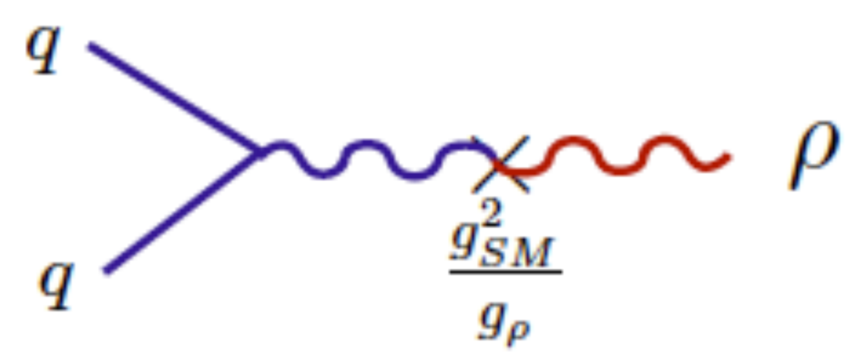
Interesting phenomenology:

- Plausible at LHC13
- Automatic dark matter candidates
- Simple UV models

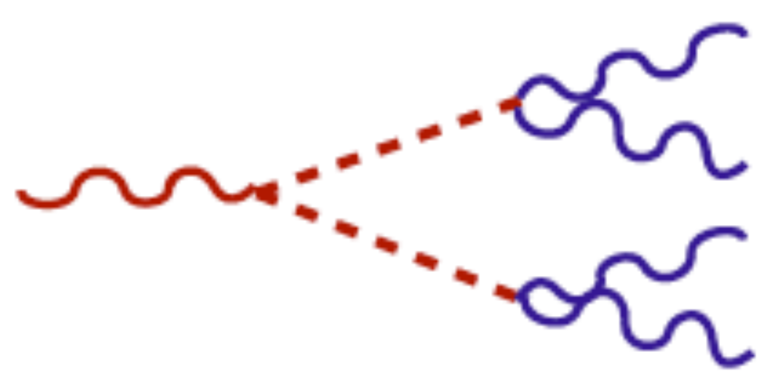
COLLIDER SIGNATURES

Kilic, Okui, Sundrum '09

Vector resonances with SM quantum numbers predicted



Decay to hidden pions and back to SM gauge bosons,



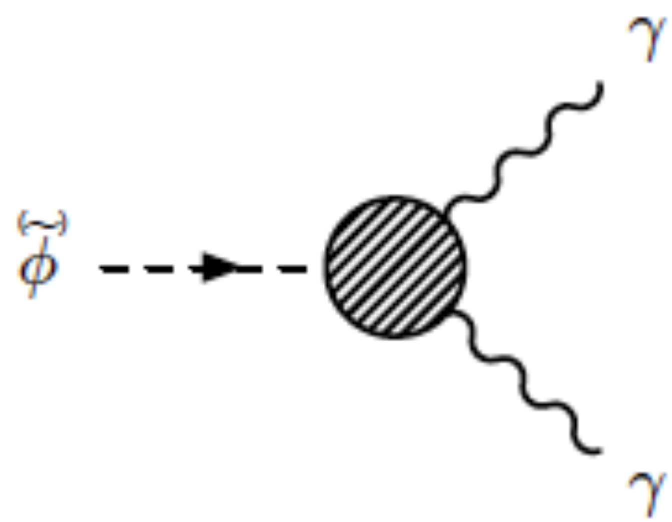
Pions can also be stable or long lived.

In conclusions...

- We discussed electroweak-preserving strong sector
- We showed that these theories are consistent with all present bounds and naturally feature DM candidates to be probed in the next round of DM experiments
- Each model predicts concrete set of hyperpions to be probed at LHC 13 and some models allow for unification of SM gauge couplings (back up)
- Among other predictions are gravity waves (back up) and electron EDM which are also within the reach of the upcoming experiments

Back up slides

Connections with 750 GeV ?



Redi, Strumia, Tesi, Vigiani: 1602.07297

- Hyperquarks charged under QCD leads to large cosets
- Qcd-colored Goldstone bosons
- CP-violating decays of hyperpions allow 750 GeV to decay into lighter hyperpions

Low energy effective theory

Expand around the origin of fields space to cubic order:

$$\mathcal{L}_m = g_\rho f_\pi^3 Tr[MU] + h.c + \frac{3g_2^2 g_\rho^2 f_\pi^4}{2(4\pi)^2} \sum_{i=1..3} \mathrm{Tr}[UT^iU^\dagger T^i]$$

$\approx$ **mass terms**

$$\mathrm{Re}[4m_L + 2m_N] g_\rho f_\pi^3 + m_{K_2}^2 K_2^\dagger K_2 - \frac{m_{\pi_3}^2}{2}\pi_3^a\pi_3^a - \frac{m_\eta^2}{2}\eta^2$$

$+$ **mixing and trilinear**

$$i\sqrt{2} g_\rho f_\pi^2 B K_2^\dagger H - \frac{g_\rho}{\sqrt{2}} A f_\pi \left(K_2^\dagger \sigma^a \pi_3^a - \frac{\eta K_2^\dagger}{\sqrt{3}} \right) H + h.c.$$

$$- \frac{g_\rho(\mathrm{Im}(m_L) - \mathrm{Im}(m_N))\eta}{\sqrt{3}} \left(4f_\pi^2 - \frac{2\eta^2}{9}\right) - \frac{2g_\rho \eta}{\sqrt{3}} \left(K_2^\dagger K_2 \mathrm{Im}(m_N) - \frac{1}{2}\pi_3^a\pi_3^a \mathrm{Im}(m_L) \right)$$

$+$ **η-tadpole**

$$\frac{2}{3} g_\rho (2\mathrm{Im}(m_L) + \mathrm{Im}(m_N)) K_2^\dagger \sigma^a K_2 \pi_3^a$$

$$A \equiv (y + \tilde{y}^*) \qquad B \equiv (y - \tilde{y}^*)$$

Direct detection of real HB DM

In most of SO(N) models there is Yukawa interaction with the Higgs and therefore, after EWSB, HB DM candidates with Y=0 mix with Y≠0 HB

Example:

SO(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF} = 5$			14	5, 1...	$\mathrm{SO}(5)_{\rm TF}$
$\Psi = L \oplus N$	1	3, 4, .., 14	unstable	$L\bar{L}N = 1,$	$\mathrm{SU}(2)_L$

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

The resulting lightest HB is a Majorana fermion for N-odd and real scalar for N-even

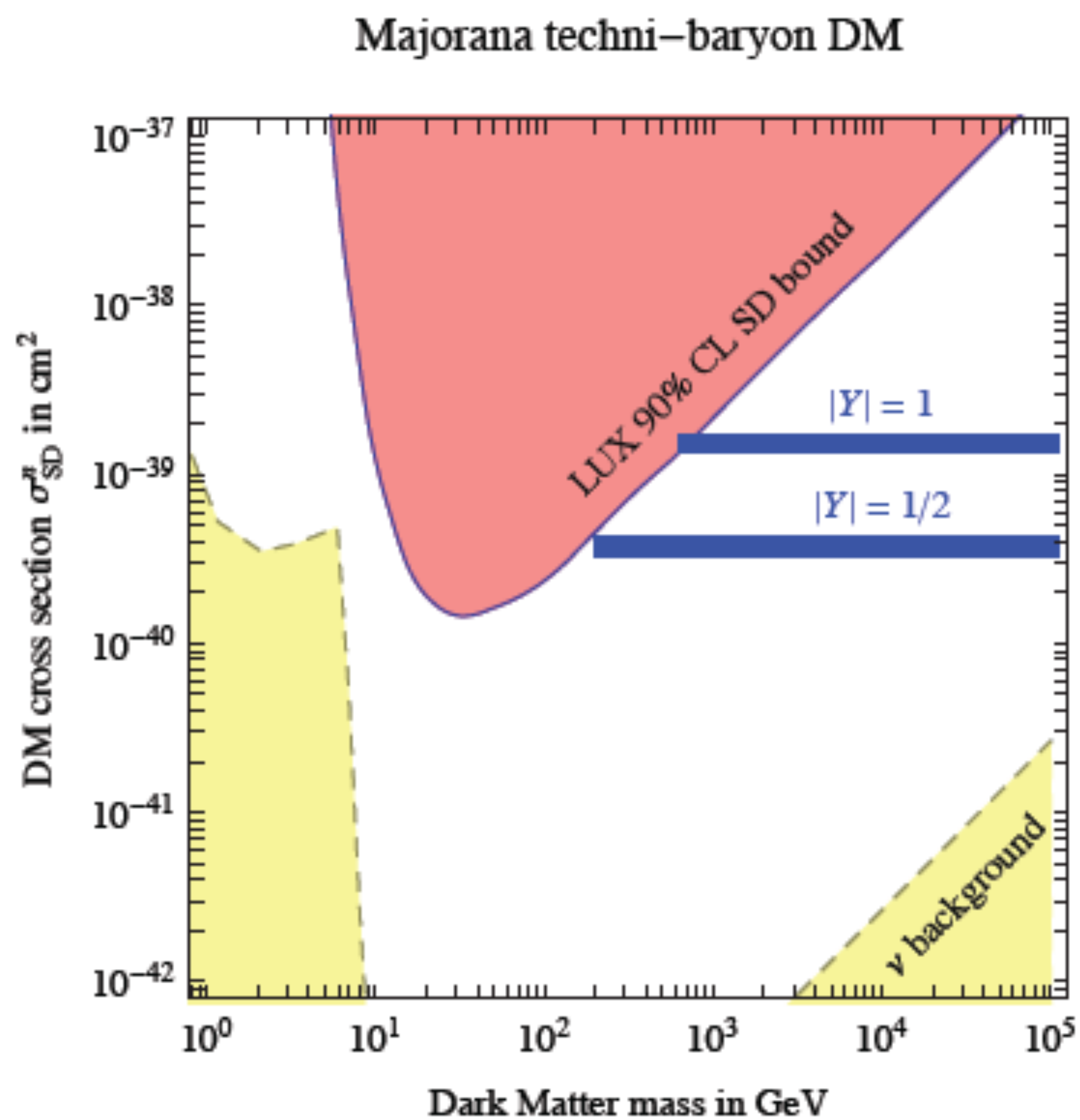
Majorana fermion can neither have vector coupling to Z nor dipole moments

Axial coupling to Z : $-g_A Z_\mu \frac{g_2}{\cos\theta_{\rm W}} \frac{\bar{\chi}\gamma_\mu\gamma_5\chi}{2}$ ⇒ spin-dependent xsec with nuclei

Direct detection of real HB DM

Using the present LUX bound : $\sigma^n_{\rm SD} < 1.7\ 10^{-39}\ \frac{M_{\rm DM}}{\rm TeV}$

$$|g_A| < 1.2 \frac{M_{\rm DM}}{\rm TeV}$$



Exemplary SO(N) model

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	$V^N = 3, 1, \ldots$	$\mathrm{SU}(2)_L$

$SO(N)_{\rm HC}$ model with $\Psi = V$

- One specie of hyperquark in the adjoint of SU(2) so that NF=3
- No Yukawa with the Higgs is allowed (because 3⊗3⊗2 contains no singlets)
- If N>7, the SU(2) coupling becomes non-perturbative below the Planck scale
- Hπ are unstable and lie in 5 SU(2)
- HB: for N=3 is a fermion triplet while for N=4 is a scalar singlet

Viable renormalizable SO(N) models

Again, scan over combination of HC quarks and impose constraints to obtain viable DM candidates

Discussed later for DM → $\Psi = L \oplus N$

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 $L \oplus E \oplus V + NN(L\bar{L}+E\bar{E}+VV) = 1$	$\mathrm{SU}(2)_L$

Vectorial hyperquarks Ψ are defined as

$$\Psi \equiv \begin{cases} C_N \oplus \bar{C}_N & \text{for complex SM representations } C \in \{E, L, D, U, Q, S, T, X\} \\ R_N & \text{for real SM representations } R \in \{N, V, G\} \end{cases}$$

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
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

Symmetry breaking pattern is :

$$SU(N_F) \to SO(N_F) \otimes Z_2$$

$$\langle C_N \bar{C}_N \rangle = 2\langle R_N R_N \rangle \sim 4\pi\Lambda^3_{\mathrm{HC}}$$

$N_F(N_F+1)/2 - 1$ hyperpions in $\Box\Box$ of $SO(N_F)$

$$\mathrm{HB} = \mathrm{anti-HB}$$

Two HB can annihilate into hyperpions

(HB stability follows from the Z2 symmetry)

Gravitational waves (GW)

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

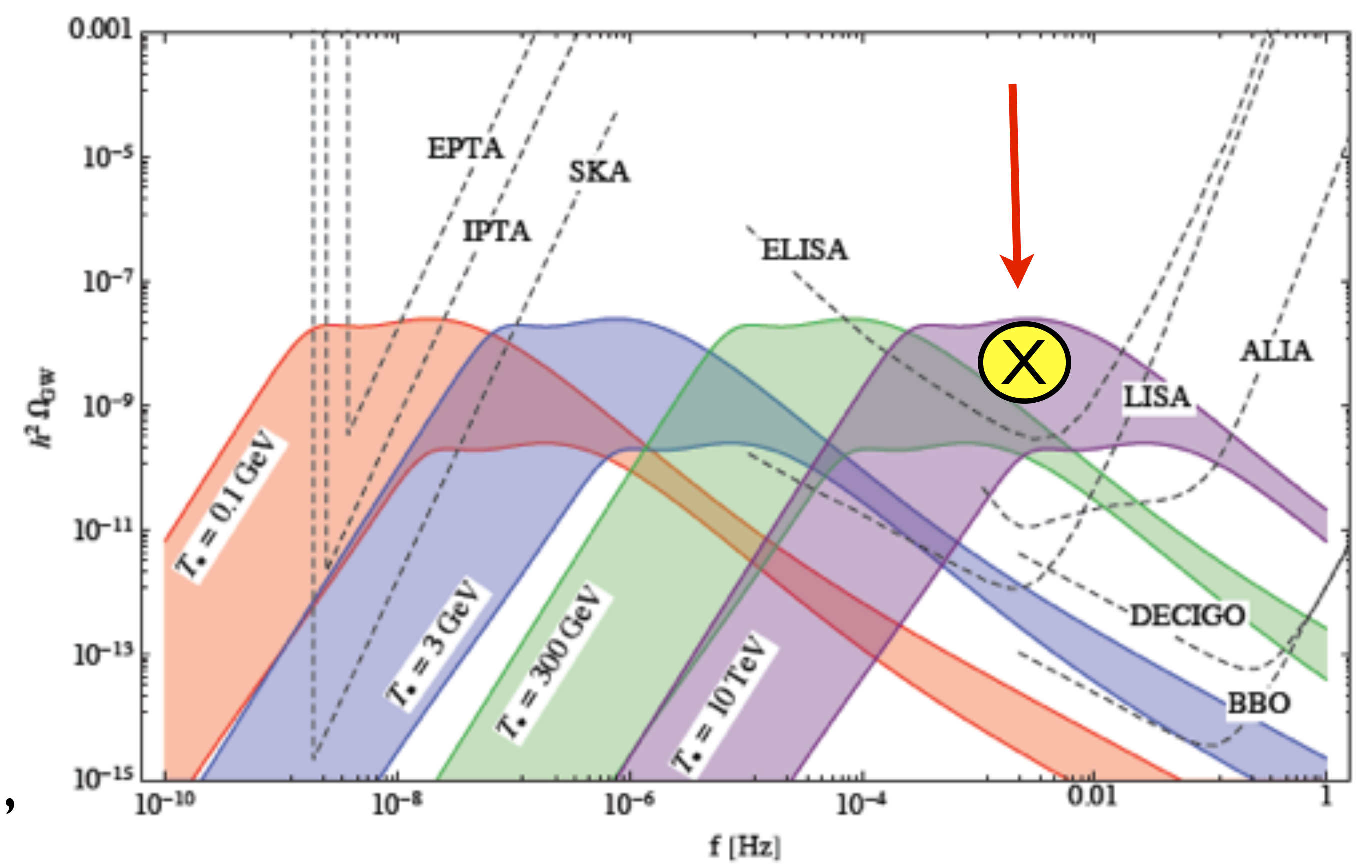
$$3 \leq N_F \leq 4N \quad \text{and} \quad N > 3$$

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'

Unification of the SM gauge couplings

Incomplete SU(5) multiplets modify SM running

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

Examples :

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=9$			80	240	SU(9)$_{\rm TF}$
$\Psi = Q\oplus\tilde D$	1	3	unstable	$QQ\tilde D = 1$	SU(2)$_L$

$$\alpha_{\rm GUT}\approx 0.06,\qquad M_{\rm GUT}\approx 2\times 10^{17}\ {\rm GeV},$$

1

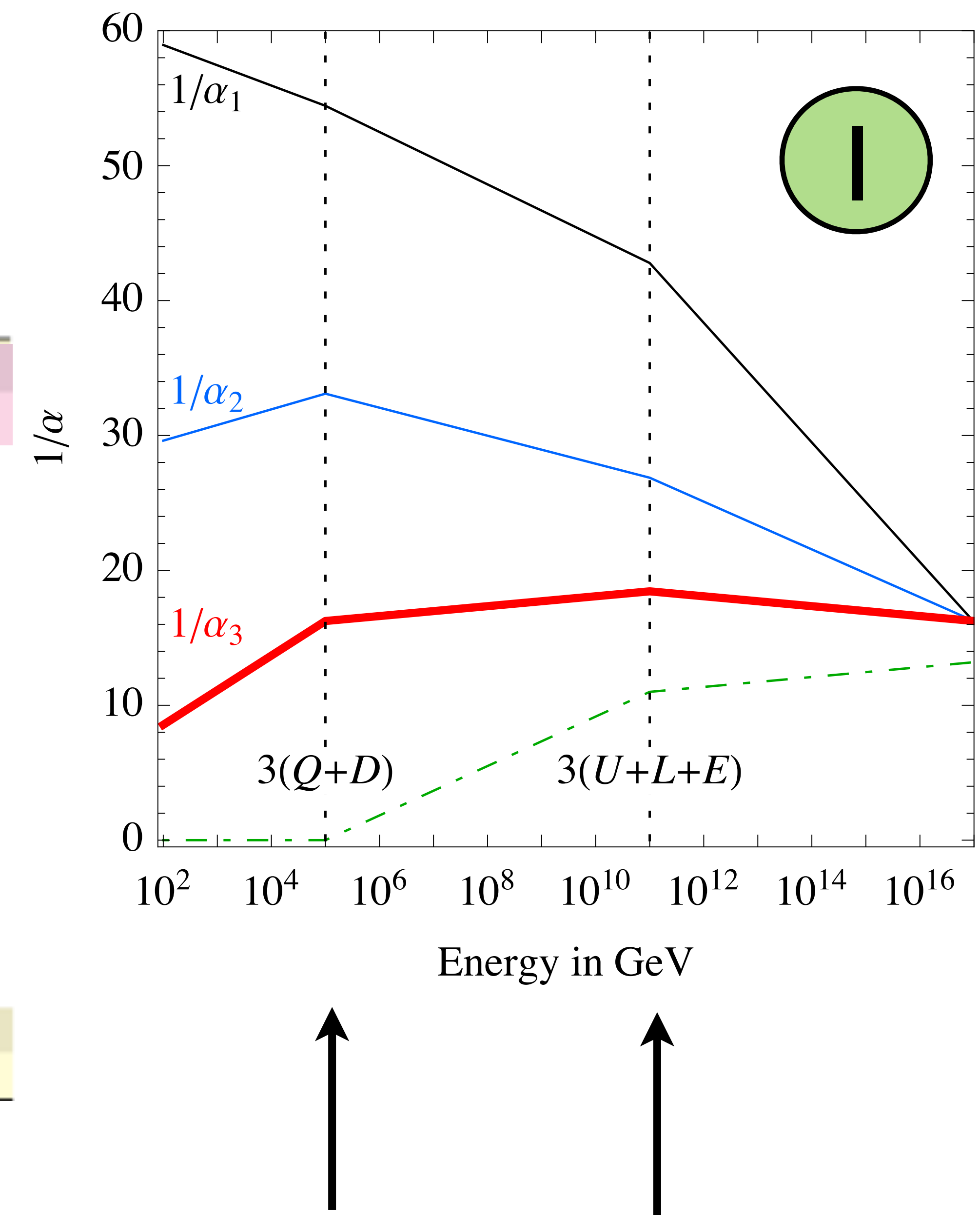
$$M_X \approx 2\times 10^{11}\ {\rm GeV}\times\frac{\Lambda_{\rm HC}}{100\ TeV}$$

SO(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			5	3, 1, ... for $N=3,4,...$	SO(3)$_{\rm TF}$
$\Psi = V$	0	3, 4, .., 7	unstable	$V^N = 3, 1, ...$	SU(2)$_L$

$$\alpha_{\rm GUT}\approx 0.065,\qquad M_{\rm GUT}\approx 3\times 10^{14}\ {\rm GeV},$$

2

$$M_X \approx 4\times 10^{7}\ {\rm GeV}\times\frac{\Lambda_{\rm HC}}{100\ TeV}$$



$\Lambda_{\rm HC} = 100\ {\rm TeV}$ $M_X\approx 2\times 10^{11}\ {\rm GeV}$

Breaking of accidental symmetries

The above symmetries can be violated by various effects

- Yukawa interactions, if allowed, break "species symmetry" and G-parity $\bar{\Psi}_I H \Psi_J$
- Dim-5 operators break "species" number and G-parity:

$$\frac{1}{M}\bar{\Psi}\Psi H H\,, \qquad \frac{1}{M}\bar{\Psi}\sigma^{\mu\nu}\Psi B_{\mu\nu}$$

- U(1) hyperbaryon and "species" symmetry can be broken by dim-6 operators :

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

Within EFT hyperbaryons (HB) are more likely to be cosmologically stable

Hyperpions in SU(N) models

Hyperpions belong to the adjoint reps and decompose under SM as:

$$\bar{\Psi}\Psi \quad \text{states}: \quad \text{Adj}_{SU(N_F)} = \left[\sum_{i=1}^{N_S} R_i\right] \otimes \left[\sum_{i=1}^{N_S} \bar{R}_i\right] \ominus 1$$

Charged pions acquire positive mass.

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

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

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

Hyperpions may be stable due to “species” symmetry or G-parity

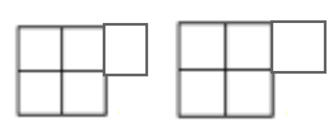
Hyperbaryons in SU(N) models

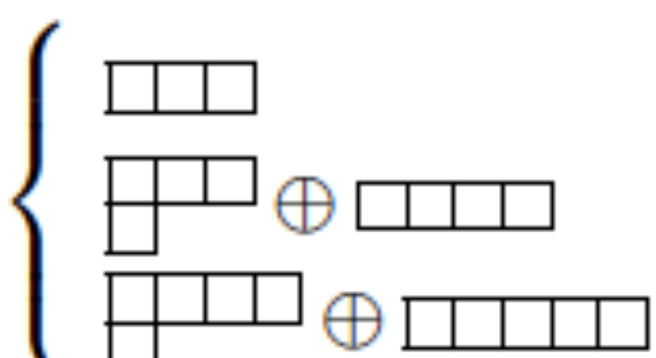
Hypercolor (HC) singlets constructed with N hyperquarks.
Fermions (scalars) for odd (even) N

Lightest HB w.f.	=	HC	x	spatial	x	spin x flavour
↑ antisymm (Fermi statistics)		↑ antisymm		↑ symmetric (s-wave)		has to be symmetric

spin x flavor =() N=3 (spin=1/2)

spin x flavor =() N=4 (spin=0)

spin x flavor = () N=5 (spin=1/2)

heavier HB = 

for $N = 3$ (spin=3/2)

for $N = 4$ (spin=1,2)

for $N = 5$ (spin=3/2, 5/2)

Hyperbaryons in SO(N) models

Start from the SU(NF) HB 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 HB

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

similarly for the heavier spin-3/2 HB :

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