UV complete composite Higgs models

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Partially based on: arxiv 1503.08749, 1508.01112 and 1609.07122
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Outline

- Model-building framework and viable models
- Predictions for Dark Matter
- Phenomenology
- Conclusions

Framework

In SM, all observed global symmetries (B and L) are understood as accidental symmetries of the renormalizable Lagrangian. This leads to the proton stability

We need at least one more stable particle to explain DM ...
let's assume DM stability is due to new accidental symmetries

- We take SM with elementary Higgs and add NF new "hyperquarks" Ψ charged under new "hypercolor" interactions
- We assume that "hypercolor" confines and hyperquarks condensate is formed ~ TeV scale
- We also assume that hyperquarks lie in a real representation under the SM so that their condensate does not break EW

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

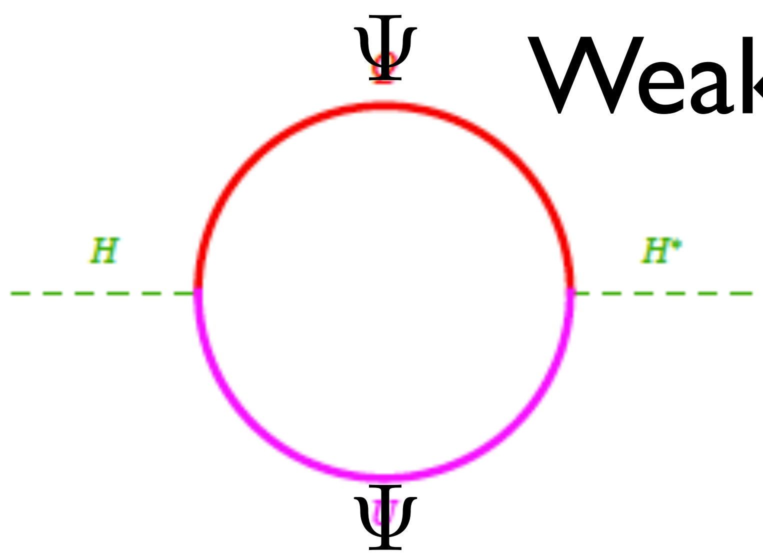
$$\supset |D_\mu H|^2 - \lambda (H^\dagger H)^2 + m^2 H^\dagger H$$

SM Higgs

(models **with** Higgs coupling)

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

Weak coupling



Strong coupling

The models will always contain “half-composite” 2HDM sector (due to elementary and composite doublets).

Depending on the mixing induced by Yukawa (y), the 125 GeV Higgs can be mainly elementary or composite

What do we gain?

- 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 (since SM quarks couple only to the elementary Higgs)
- Naturalness is solved via relaxion mechanism
or by hypothesis of scale invariance

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

"Species"

$$R \equiv R_N \oplus \bar{R}_{\bar{N}}$$

$$\langle \psi_R^{(N)} \psi_{\bar{R}}^{(\bar{N})} \rangle \neq 0$$

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

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

Accidental symmetries

1) U(1) hyperbaryon number

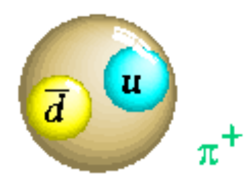
Leads to stable HyperBaryons (HB)

2)“Species” number

The NF hyperflavors organize themselves into S “species”

$\psi_1, \psi_2 ..., \psi_{N_F}$
$\Psi_1, \Psi_2 ... \Psi_S$

Leads to stable hyper-pions made of different species

Example: in QCD + QED  would be stable

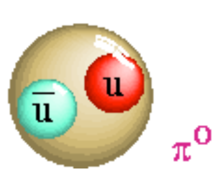
3) G-parity

Bai, Hill ’10

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

Leads to lightest odd weak isospin hyperpions stable

Example:  would be stable

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

SU(N) composite DM models

Dynamics is QCD-like :

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

We assume the standard large-N scaling :

$$\Lambda_{\rm HC} \sim \frac{4\pi}{\sqrt{N}} f \qquad m_{HB} \sim N\Lambda_{\rm HC}$$

Model has viable DM candidates 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,..

Hyperpions in SU(N) models

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

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

Charged pions acquire positive mass.

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

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

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

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 $=(\ydiagram{2,1}, \ydiagram{2,1})$ N=3 (spin=1/2) QCD octet (p, n, Σ, Ξ, Λ)

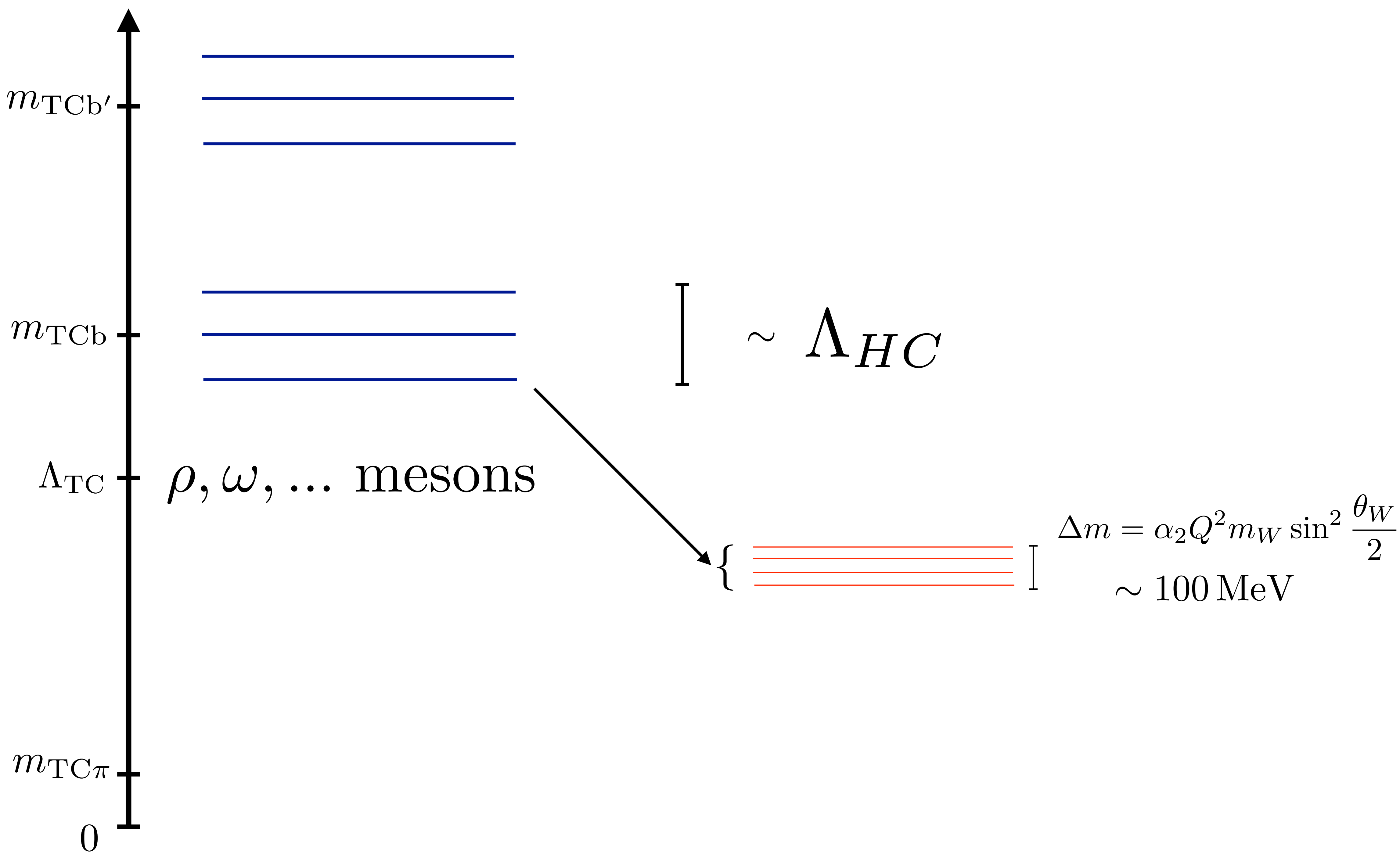
spin x flavor $=(\ydiagram{2,2}, \ydiagram{2,2})$ N=4 (spin=0)

spin x flavor $=(\ydiagram{3,2}\ \ydiagram{3,2})$ N=5 (spin=1/2)

$$\text{heavier HB} = \begin{cases} \ydiagram{3} & \text{for } N=3 \quad \text{(spin=3/2)} \\ \ydiagram{3,1} \oplus \ydiagram{4} & \text{for } N=4 \quad \text{(spin=1,2)} \\ \ydiagram{4,1} \oplus \ydiagram{5} & \text{for } N=5 \quad \text{(spin=3/2, 5/2)} \end{cases}$$

QCD decuplet

Final spectrum in SU(N) models



Viable renormalizable SU(N) models

We scan over combination of HC quarks and impose constraints to obtain viable DM candidates (multiplet with integer weak isospin)

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

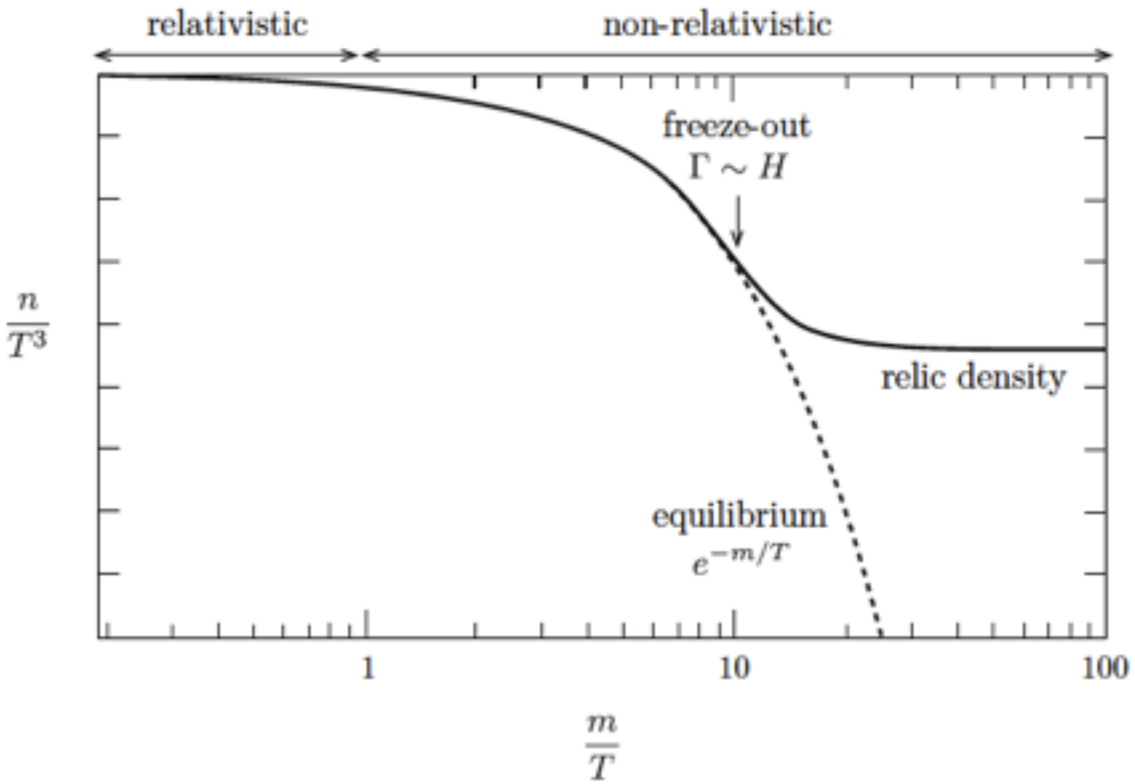
Exemplary SU(N) model

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 $N = 3, 4, \ldots$	SU$(3)_{\rm TF}$
$\Psi = V$	0	3	3	$VVV = 3$	SU$(2)_L$
$\Psi = N \oplus L$	1	3, .., 14	unstable	$N^{N*} = 1$	SU$(2)_L$

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

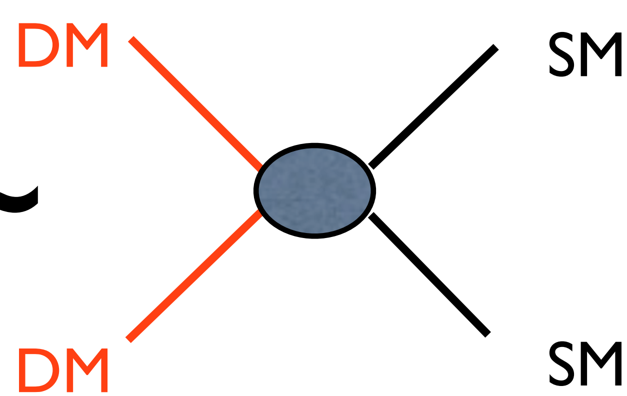
Dark Matter (WIMP)



Cirelli, Fornengo, Strumia ' 05

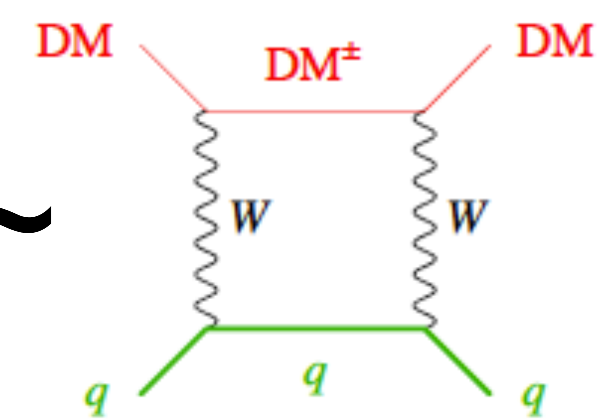
Hyperpion DM : behave as minimal DM

Annihi lation ~



Direct detection

$\sigma(\mathrm{DM}\mathcal{N} \to \mathrm{DM}\mathcal{N})$ ~



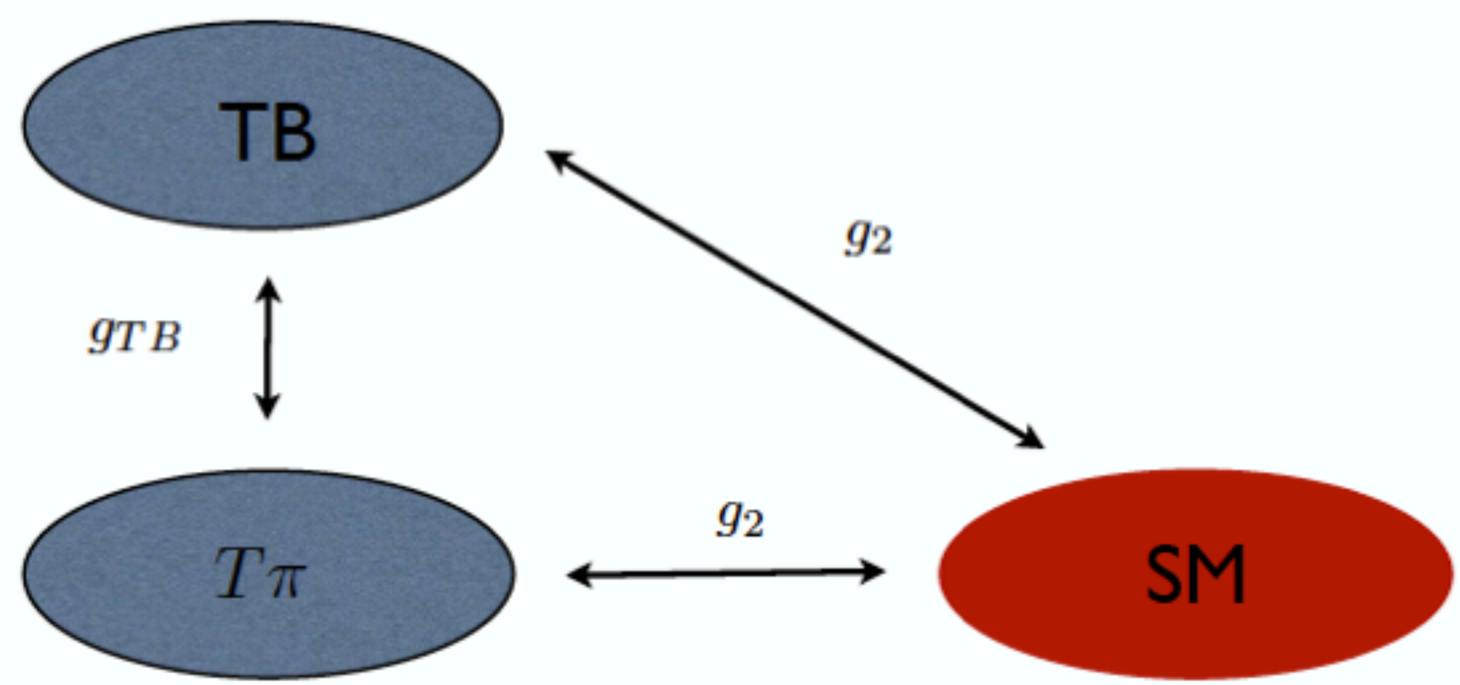
Let's concentrate on....

HyperBaryon DM

Crucially depends on the HBaryon mass:

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

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



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

THERMAL ABUNDANCE

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

$(\; m_B \sim N\Lambda_{HC} \Longrightarrow \Lambda_{HC} \sim 10 \; TeV \;)$

Direct detection of HBaryon 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 :

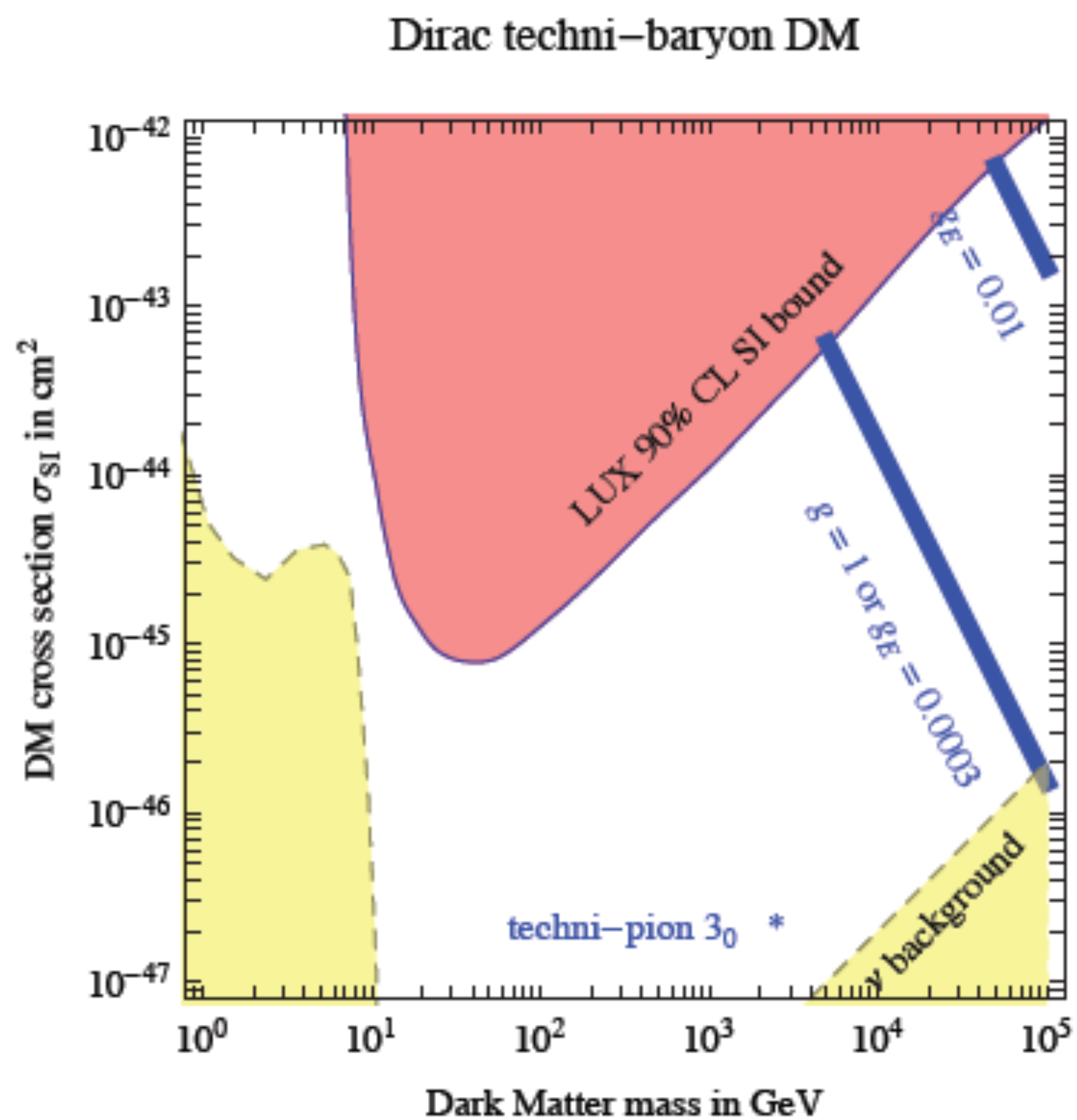
$$\bar{\Psi}\gamma_{\mu\nu}(\mu_M + i d_E \gamma_5)\Psi \; F_{\mu\nu}/2$$

$$\mu_M = \frac{e g_M}{2M_{\rm DM}} \qquad d_E = \frac{e g_E}{2M_{\rm DM}}$$

$$\Downarrow$$

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

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



Additional effects in theories with Yukawa coupling

Example

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	$N^{N*}=1$	$\mathrm{SU}(2)_L$

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

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

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

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

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

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

Low energy effective theory of hyperpions

Yukawas and explicit masses

$U(1)_A$ anomaly

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

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

Anomaly with SM vectors

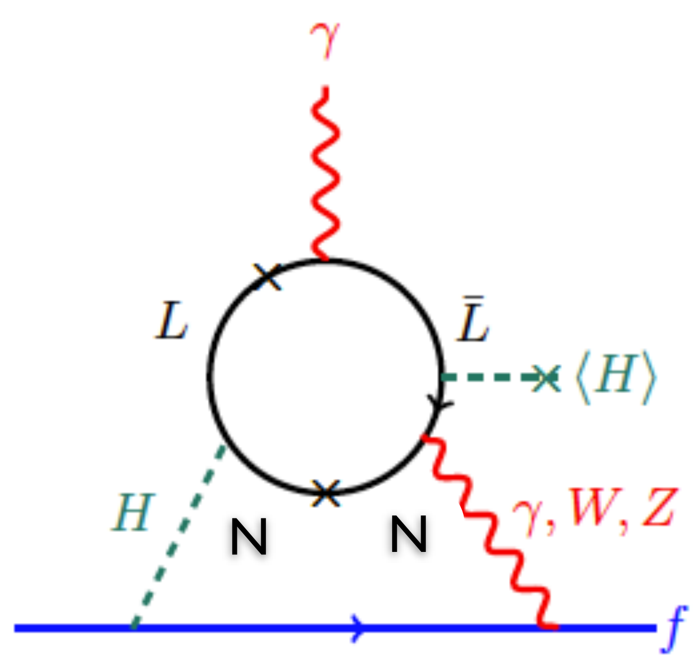
1-loop gauge contribution

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

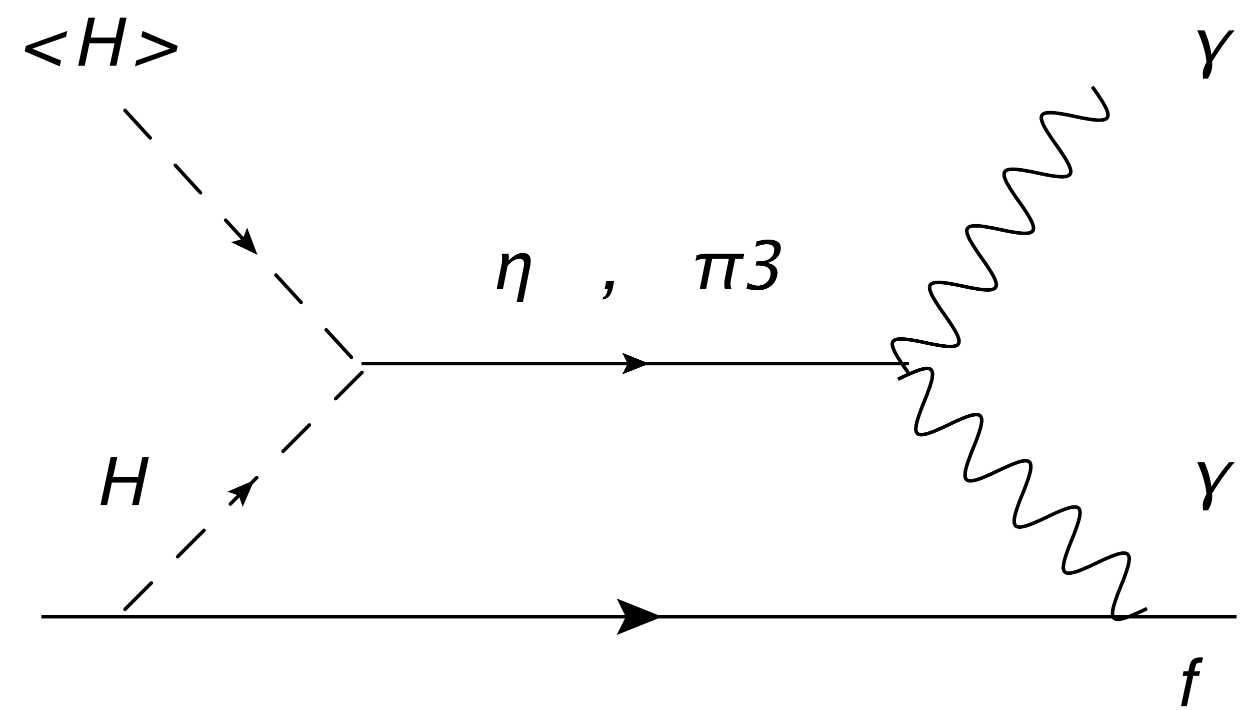
Electron EDM

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

Heavy fermions



Light fermions



Integrating out η, π3 :

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

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

LHC phenomenology and other predictions

LHC Phenomenology and Constraints

Very weak bounds:

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

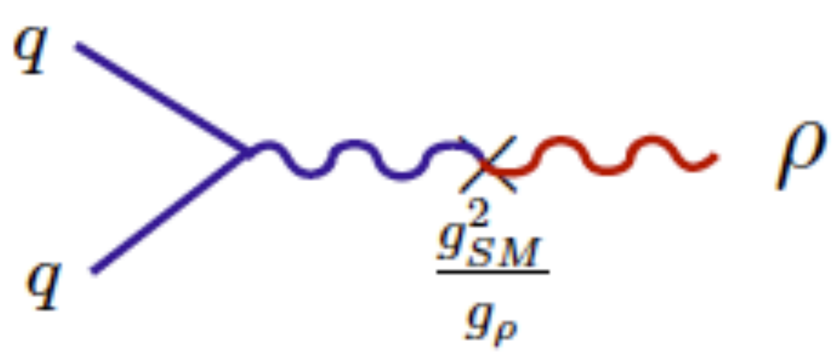
Interesting phenomenology:

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

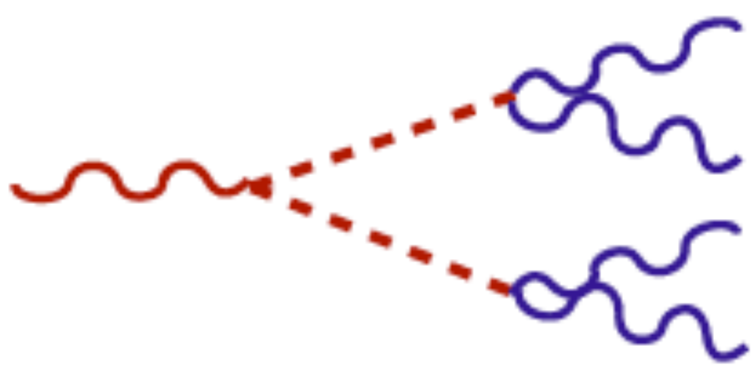
COLLIDER SIGNATURES

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.

Gravitational waves (GW)

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

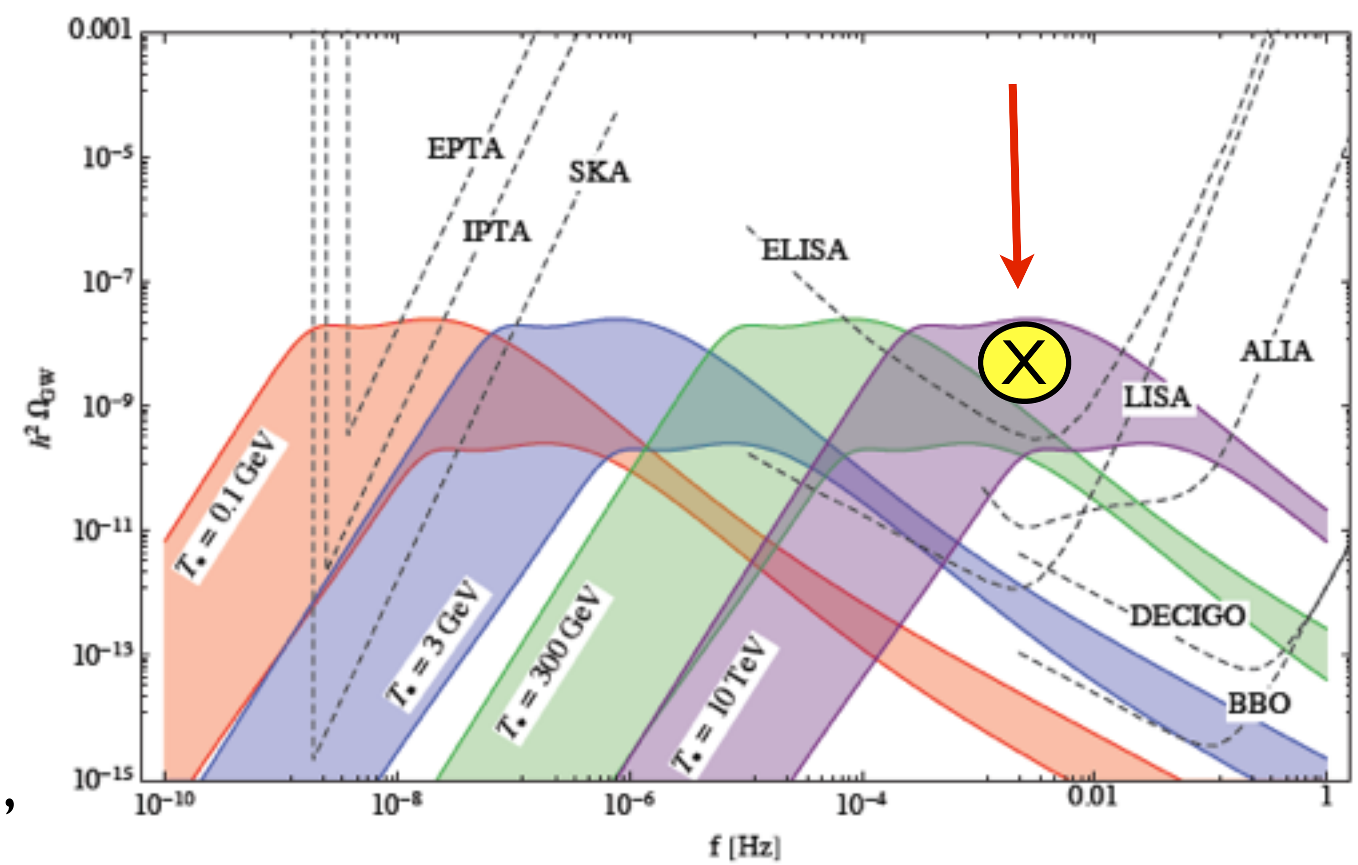
$$3 \leq N_F \leq 4N \quad \text{and} \quad N > 3$$

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

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

Amplitude of the GW signal :

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



P. Schwaller 15'

Unification of the SM gauge couplings

Incomplete SU(5) multiplets modify SM running

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

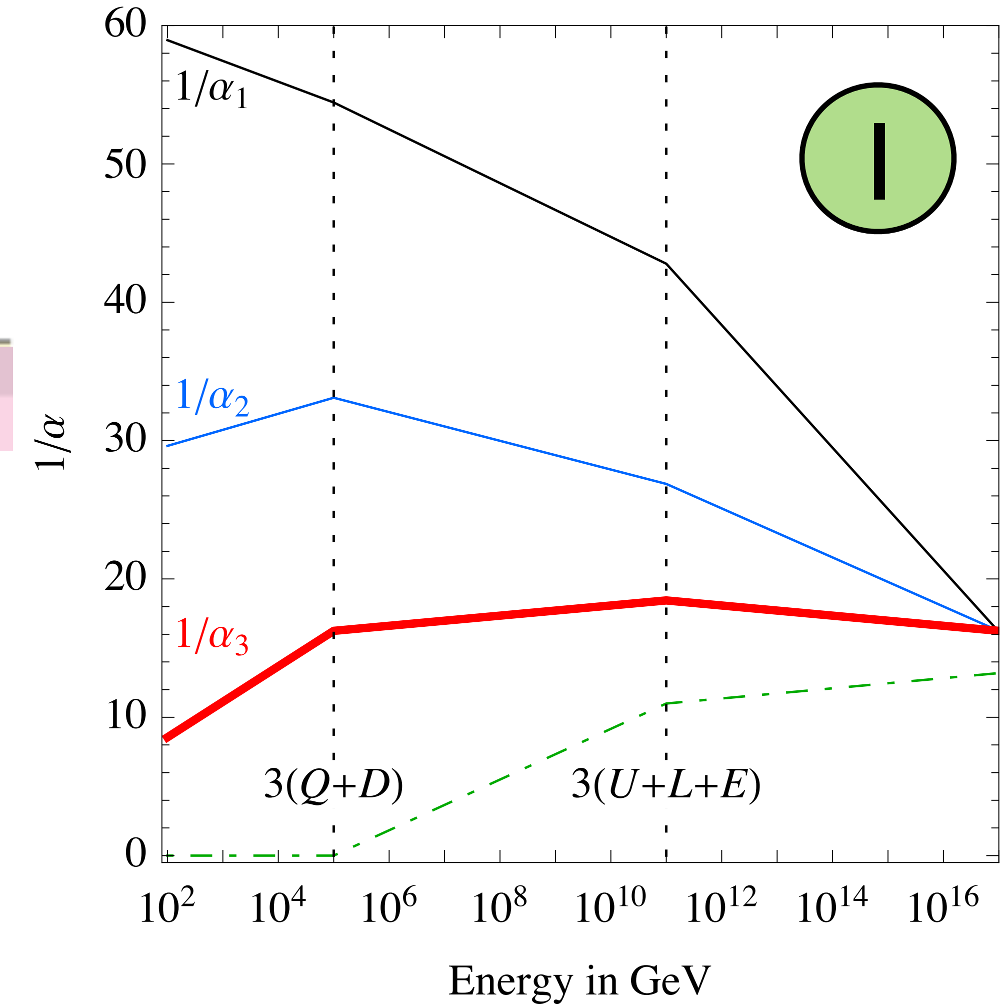
Examples :

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)$_L$

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

1

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



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

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

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

2

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

What about naturalness?

Relaxion mechanism

1504.07551

Minimal model: SM + QCD axion + inflaton

$$\mathsf{L} = (-M^2 + g\phi)|h|^2 + gM^2\phi + \frac{\phi}{f}\tilde{G}'_{\mu\nu}G'^{\mu\nu}$$

- Soft-breaking of shift symmetry (via coupling to Higgs)
- Large (non-compact) axion field excursions

How it works?

- During inflation axion slow-rolls and scans Higgs mass
- Once mass gets negative, Higgs obtains a vev
- Axion potential barriers (linear in the vev) grow and stop scanning

$$m_\pi^2 \sim m_q f_\pi \sim y_q < h > f_\pi \quad \Rightarrow \quad y_q f_\pi^3 < h > \cos\frac{\phi}{f}$$

Relaxion mechanism

1504.07551

Minimal model: SM + QCD axion + inflaton

$$\mathrm{L} = (-M^2 + g\phi)|h|^2 + gM^2\phi + f_\pi^2 m_\pi^2 \cos\frac{\phi}{f}$$

- Soft-breaking of shift symmetry (via coupling to Higgs)
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How it works?

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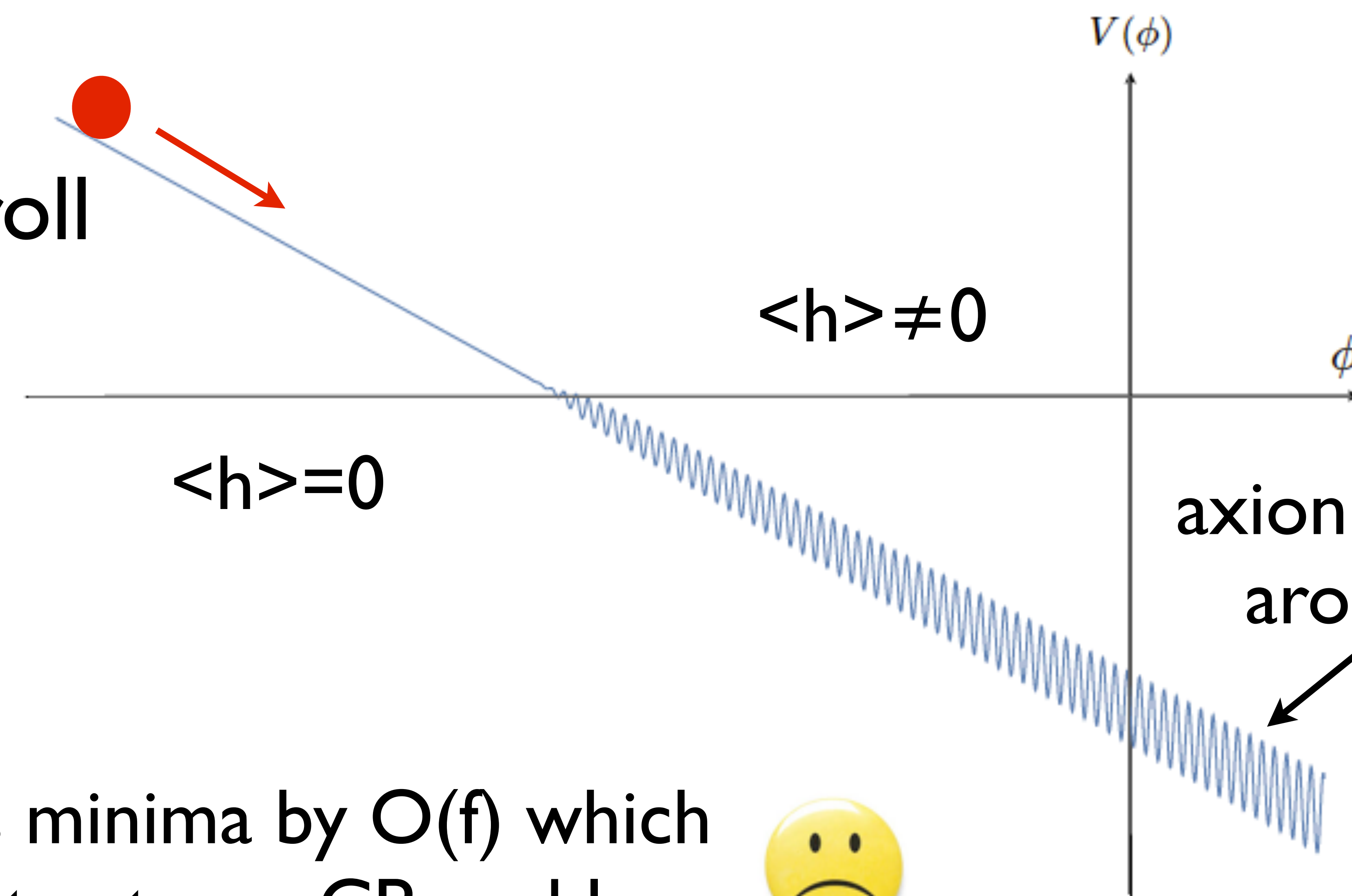
$$m_\pi^2 \sim m_q f_\pi \sim y_q < h > f_\pi \quad \Longrightarrow \quad y_q f_\pi^3 < h > \cos\frac{\phi}{f}$$

Relaxion mechanism

Rolling stops when slopes match :

$$gM^2 \sim \frac{m_\pi^2 f_\pi^2}{f}$$



Slope shifts minima by O(f) which leads back to strong CP problem

Solution : barriers for axion arise from a new strong group (QCD')

$$\frac{\phi}{f}\tilde{G}'_{\mu\nu}G'^{\mu\nu}$$ and this is precisely our framework

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

Compared to original paper, our vector-like fermions are lighter than confinement scale leading to parametric enhancement of the cutoff

Scales to be tested at the LHC 13 :

$$m_{K_2} \sim f_\pi \sim \ 500 \text{ GeV and } m_\rho \sim 5 \text{ TeV}$$

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
- Among other predictions are gravity waves and electron EDM which are also within the reach of the upcoming experiments

Back up slides

Low energy effective theory

Expand around the origin of fields space to cubic order:

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

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

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

$+$ **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	$L\bar{L}N = 1,$	$\mathrm{SU}(2)_L$

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

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

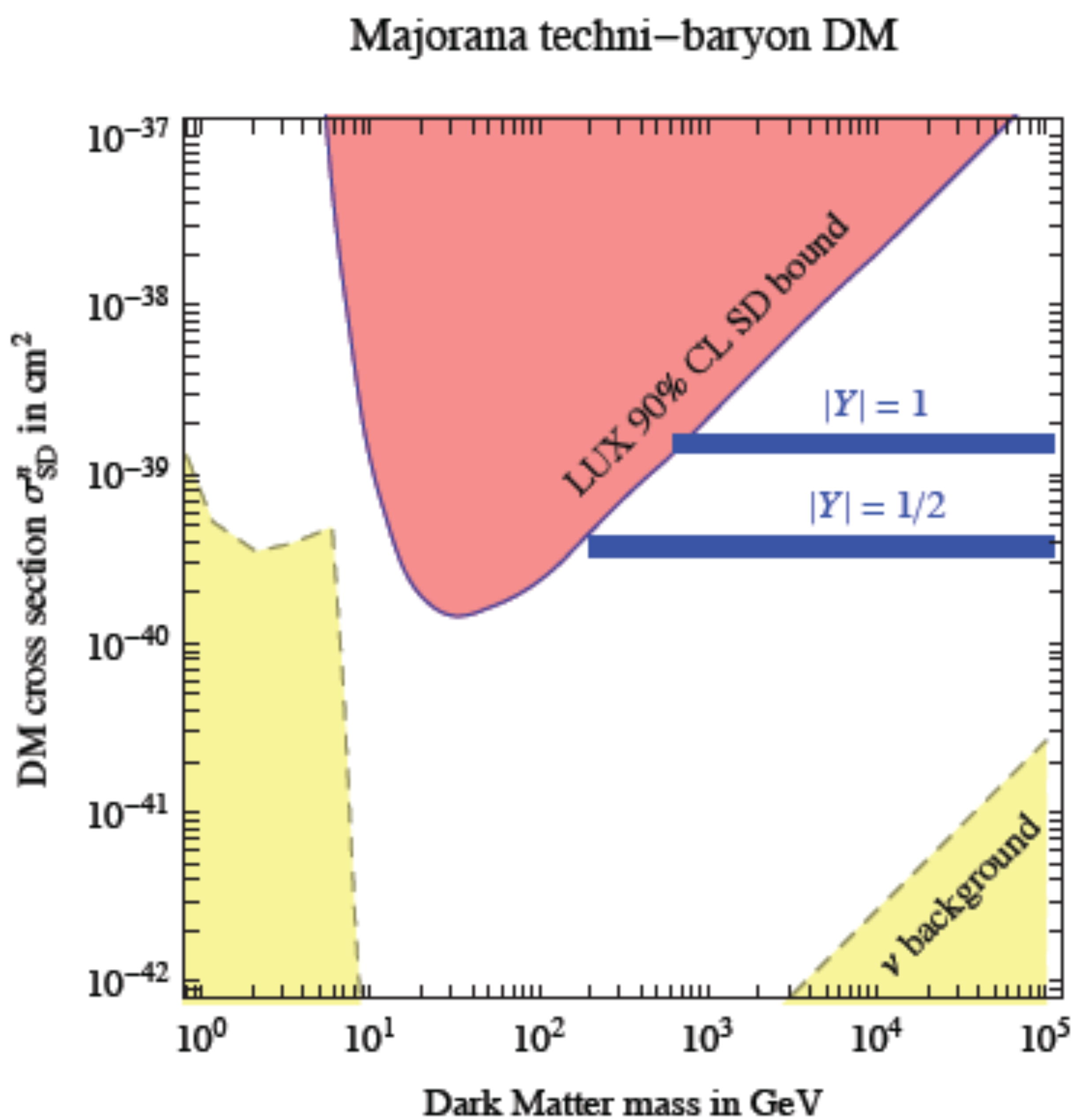
Axial coupling to Z : $-g_A Z_\mu \frac{g_2}{\cos\theta_{\rm W}} \frac{\bar{\chi}\gamma_\mu\gamma_5\chi}{2}$

spin-dependent xsec with nuclei

Direct detection of real HB DM

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

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



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

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

Discussed later for DM

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 :

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

$$\langle C_N \bar{C}_N \rangle = 2 \langle R_N R_N \rangle \sim 4\pi \Lambda_{\rm HC}^3$$

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

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

Two HB can annihilate into hyperpions
(HB stability follows from the Z2 symmetry)

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

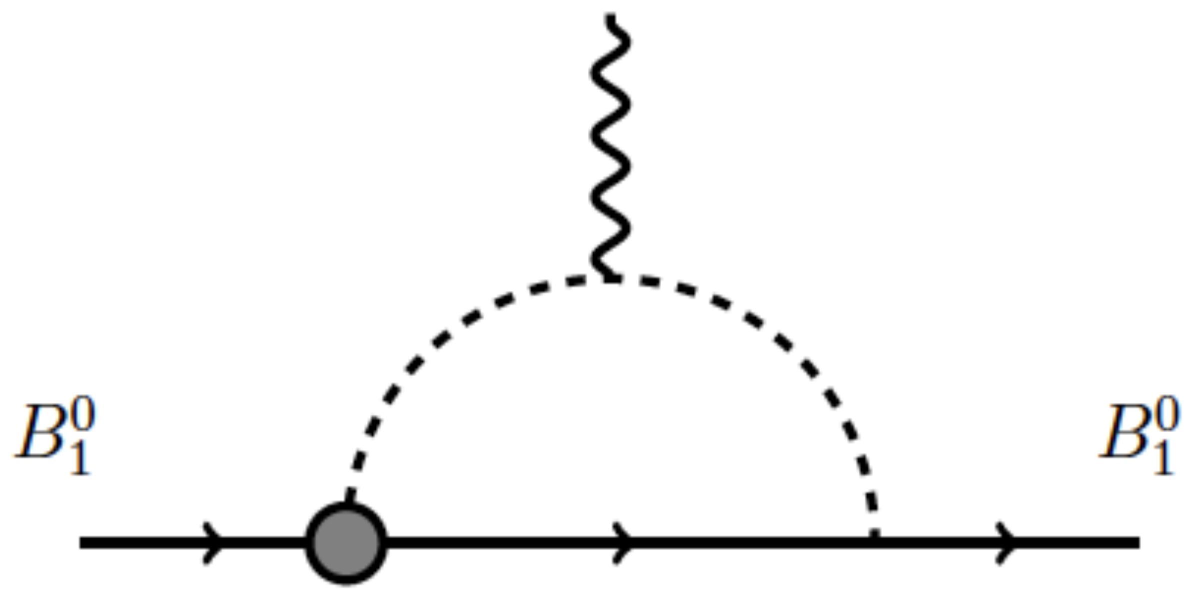
$$8 = \left(\ydiagram{2,1}\right)_{\mathrm{SU}(3)} = \left(\ydiagram{2,1} \oplus \ydiagram{1}\right)_{\mathrm{SO}(3)} = 5 \oplus 3$$

similarly for the heavier spin-3/2 HB :

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

HyperBaryon EDM

- HC CP phase leads to EDM for HBaryons



Pich, Rafael ’91

$$\begin{aligned}
\mathscr{L}_{BB\Pi,\theta} &= -\frac{2\sqrt{2}a}{3f}\left(\theta_{\mathrm{TC}} - 2\phi_L - \phi_E\right)\left(b_1 \mathrm{Tr}[\bar{B}\Pi B] + b_2 \mathrm{Tr}[\bar{B}B\Pi]\right) + \dots\,, \\
\mathscr{L}_{BB\Pi} &= -\frac{D+F}{\sqrt{2}f}\mathrm{Tr}[\bar{B}\gamma^\mu\gamma_5(D_\mu\Pi)B] - \frac{D-F}{\sqrt{2}f}\mathrm{Tr}[\bar{B}\gamma^\mu\gamma_5 B(D_\mu\Pi)] + \dots\,,
\end{aligned}$$

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