Composite Higgs and Dark Matter

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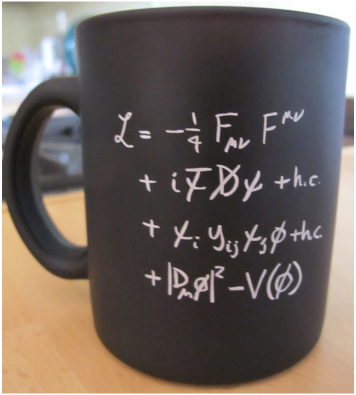
The Standard Model

What we know from the Standard Model (SM):

- Fermionic fields: q, l, $\nu \longrightarrow$ **Matter**,
- Vector fields: γ, $W^{\pm}$, Z, $g \rightsquigarrow$ **Force**,
- Scalar fields: $H \dashrightarrow$ **origin of mass**.



What we don't know from the SM:

- Why $m_h \ll \Lambda_{GUT}$? (Hierarchy problem),
- Dark energy, **dark matters**,
- Neutrino masses and oscillation,
- Matter—antimatter asymmetry,
- Strong CP problem,...

New physics are needed!

Dark matter

Evidences for dark matter (DM):

- Galaxy rotation curve,
- CMB,
- Bullet cluster,...

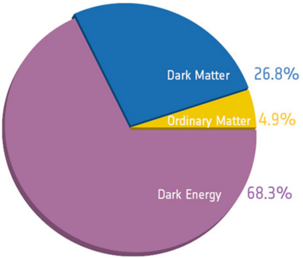
Properties of DM:

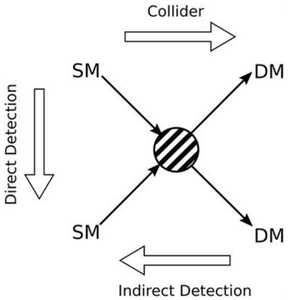
- Weakly interacting,
- Massive, probably cold,
- Stable.

Detections:

- Direct detection, indirect detection, collider.

A famous candidate: WIMP





Fundamental Composite Higgs Model

- $2N_f$ Weyl spinors ψ^i charged under some gauge Group G_{TC}.
- Global symmetry $G_F = \text{SU}(2N_f)$ or $\text{SU}(N_f) \times \text{SU}(N_f)$,
- Non-abelian G_{TC}, asymptotic freedom $\Rightarrow \psi^i$ condensates in the IR,

$$\langle \psi^i \psi^j \rangle \sim \Sigma^{ij} \neq 0 \quad \Rightarrow \quad G_F \to H \tag{1}$$

where H is a subgroup of G_F.

  - ψ^i: real reps. of $G_{TC} \Rightarrow \text{SU}(2N_f) \to \text{SO}(2N_f)$,
  - ψ^i: pseudo-real reps. of $G_{TC} \Rightarrow \text{SU}(2N_f) \to \text{Sp}(2N_f)$.
  - ψ^i: complex reps. of $G_{TC} \Rightarrow \text{SU}(N_f) \times \text{SU}(N_f) \to \text{SU}(N_f)$.
- If Higgs doublet $\subset$ pNGBs, protected by shift symmetry
- SU(4)/Sp(4): minimal model [E. Katz (2005), B. Gripaio (2009), M. Frigerio (2012), G. Cacciapaglia, F. Sannino (2014)],
- SU(6)/Sp(6): 2 types.

$SU(6) \to Sp(6)$ composite model

- 6 left-handed Weyl spinors ψ, fundamental reps of G_{TC} =SU(2).
- In the IR, $\langle\psi^i\psi^j\rangle \sim \Sigma^{ij}$ antisymmetric, SU(6) →Sp(6).
- NGBs: d.o.f $= 35 - 21 = 14$, decomposition: $(SU(2)_1, SU(2)_2, SU(2)_3)$

$$14_{Sp(6)} \to (2,2,1) \oplus (2,1,2) \oplus (1,2,2) \oplus (1,1,1) \oplus (1,1,1) \qquad (2)$$

Case		$SU(2)_L$	$U(1)_Y$	$SU(2)_L$	Y	Higgs
A	ψ_1	**2**	0	SU(2)$_1$	$T_2^3 + T_3^3$	$(2,2,1)+(2,1,2)$
	ψ_2	**1**	$\pm 1/2$			
	ψ_3	**1**	$\pm 1/2$			
B	ψ_1	**2**	0	SU(2)$_1$ + SU(2)$_3$	T_2^3	$(2,2,1)+(1,2,2)$
	ψ_2	**1**	$\pm 1/2$			
	ψ_3	**2**	0			

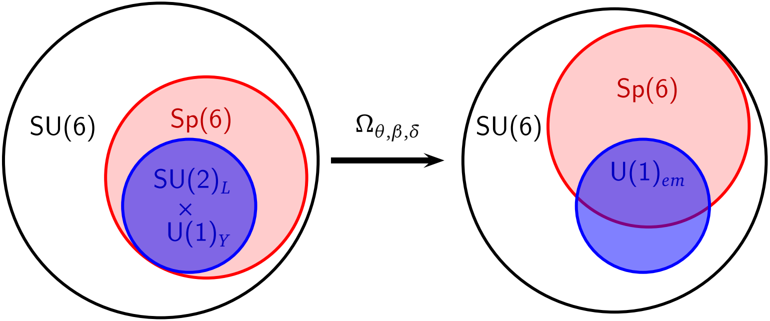
[C. Cai, G.Cacciapaglia, H.H. Zhang, JHEP01(2019)130]

The Model A

- Before EW symmetry breaking,

$$i\Pi(\phi')\cdot\Sigma_0=\frac{1}{2}\begin{pmatrix} S_1 & H_1 & H_2\\ -H_1^T & S_2 & G\\ -H_2^T & -G^T & S_3\end{pmatrix} \quad (3)$$

- $H_1\sim(2,2,1)$, $H_2\sim(2,1,2)$; $G\sim(1,2,2)$; $S_{1,2,3}$: $(1,1,1)\oplus(1,1,1)$.



Composite inert 2HDM

- A special vacuum: all fermions couple to the same $\mathrm{SU}(2)_{R1}$ leading to

$$\beta = 0, \quad \delta = 0, \quad \theta \neq 0 \tag{4}$$

- $\mathrm{SU}(2)_{R2}$ is only broken by gauging $T^3_{R2} \sim Y$, to a remnant $\mathrm{U}(1)_{DM}$.

$$Q_{DM} = 1 \text{ fields}: \quad (H_2^+, H_2^0) \in (2,1,2), \quad \eta^+, \ \eta^0 \in (1,2,2) \tag{5}$$

- A mixture of H_2^0 and η^0 can be DM candidate.
- Direct detection bound: $\sigma_{\chi N} \sim 10^{-45}$ cm^2 for $m_\chi \sim 1$ TeV (XENON1T,PANDAX-II,LUX).
- $\chi\chi Z$ coupling leads to a $\chi - N$ scattering cross-section:

$$\sigma_{Z,\chi N} \approx \frac{(1-c_\theta)^2 g^4 m_N^4}{16\pi c_W^2 m_Z^2} \frac{1}{2} \left(\frac{1}{4}\right)^2 \sim 5 \cdot 10^{-40} (1-c_\theta)^2 \mathrm{cm}^2 \Rightarrow s_\theta \lesssim 0.01 \tag{6}$$

The Model B: Higgs boson emerging from the dark

- 6 technifermions are assigned with quantum number of $SU(2)_{L,1} \times SU(2)_R \times SU(2)_{L2} \subset Sp(6)$ as follows

$$\Psi^1 = \begin{pmatrix} \psi^1 \\ \psi^2 \end{pmatrix} \sim (2,1,1), \Psi^2 = \left(\chi^1, \chi^2\right) \sim (1,2,1), \Psi^3 = \begin{pmatrix} \psi^3 \\ \psi^4 \end{pmatrix} \sim (1,1,2),$$

- $\mathcal{G}/\mathcal{H}$ coset structure

$$\left(\begin{array}{c|c} \mathcal{G}_0/\mathcal{H}_0 & \begin{array}{c}\mathbb{Z}_2\text{–odd} \\ \text{pNGBs}\end{array} \\ \hline \begin{array}{c}\mathbb{Z}_2\text{–odd} \\ \text{pNGBs}\end{array} & \begin{array}{c}\mathbb{Z}_2\text{–even} \\ \text{pNGBs}\end{array} \end{array} \right),$$

where $\mathcal{G}_0/\mathcal{H}_0 = \mathrm{SU}(4)/\mathrm{Sp}(4)$ in this case.

[C. Cai, H-H. Zhang, G. Cacciapaglia, M. Rosenlyst, M.T. Frandsen, PRL.125.021801]

pNGB contents in different phases

- An EW anomalous $U(1)_X \Rightarrow$ Asymmetric DM
- High-T: $\theta = \pi/2$, $U(1)_X$ is preserved, DM annihilation, frozen.
- Low-T: $0 < \theta < \pi/2$, $U(1)_X$ is broken, DM splits $\Rightarrow$ loose DD bound.

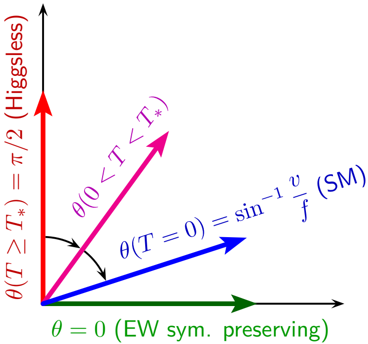
	Higgs vacuum $\theta \sim 0$	HL vacuum $\theta = \pi/2$	Q_X
$\mathcal{G}_0$	$H_1 = 2_{1/2}$	$\phi_X = (h + i\eta)/\sqrt{2}$	1
$\mathcal{H}_0$	$\eta = 1_0$	$\omega^\pm,\ z^0$	0
$\mathbb{Z}_2$–odd pNGBs	$H_2 = 2_{1/2}$ $\Delta = 3_0$ $\varphi = 1_0$	$\Theta_1 = -H_2^0 + \frac{\Delta_0 + i\varphi_0}{\sqrt{2}}$ $\Theta_2 = (H_2^0)^* + \frac{\Delta_0 - i\varphi_0}{\sqrt{2}}$ $\Theta_1^- = \Delta^- - H^-$ $\Theta_2^+ = \Delta^+ + H^+$ +c.c.	$\frac{1}{2}$
$\mathbb{Z}_2$–even pNGBs	$\eta' = 1_0$	η'	0

Temperature dependent vacuum

The vacuum alignment is temperature dependent if the potential has a form

$$V(\theta,T) = -a(T)\ \sin^2\theta + \frac{1}{2}b(T)\ \sin^4\theta\,. \tag{7}$$

If $a(T)/b(T) > 1$ in high T, the $\sin\theta$ is stuck at 1 and $v(T) = f$ (HL vac.).
If $a(T)/b(T) < 1$ in low T, $\sin\theta < 1$ and $v(T) \to v_{SM}$ in the present T_0.

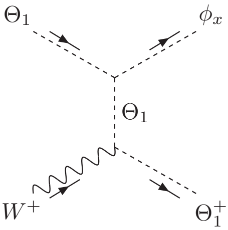


A simplified situation

- Assuming $m_W^{HL} < M_{\Theta_1} \ll M_{\Theta_2}$, Θ_2, Θ_2^+ decouples much earlier.
- Relevant fields and couplings

$$\mathcal{L} \supset -i\frac{g}{\sqrt{2}} W_\mu^+ (\Theta_1^* \overleftrightarrow{\partial^\mu} \Theta_1^-) + \frac{\xi}{2} f \ \phi_X^* \Theta_1 \Theta_1 + \text{h.c.}$$
$$-\frac{g^2}{2} \phi_X^* \phi_X \left(W_\mu^+ W^{-,\mu} + \frac{1}{2} Z_\mu Z^\mu \right) + ... \quad (8)$$

- Dominant Θ# changing process, $\Theta_1 + W^+ \to \phi_x + \Theta_1^+$ etc. decouples at T_{dc}.



The equations of chemical potential

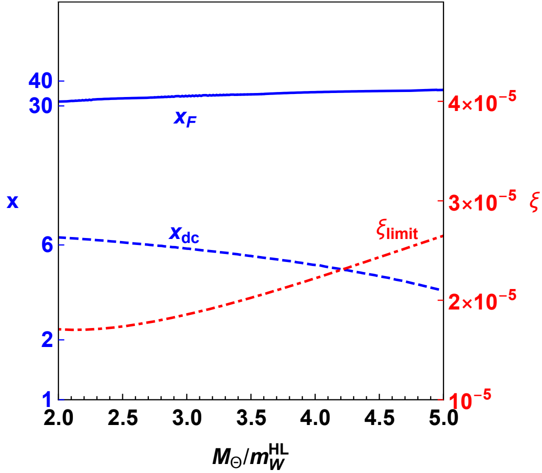
- The charges

$$B = 2(5+\sigma_t)\mu_{uL} + 6\mu_W \quad (9)$$
$$L = 3\mu_l - 3\mu_W \quad (10)$$
$$X = \left(2N_{TC}\sigma_\psi + 4\sigma_x + \sigma_+ + \sigma_- + \sigma_1 + \sigma_2\right)\mu_\Theta - (\sigma_+ - \sigma_-)\mu_W \quad (11)$$
$$0 = \mu_1 + \mu_2 + 3(\mu_{uL} + 2\mu_{dL}) + \sum_f \mu_{\nu_f L} \quad (12)$$

- Solution: $\frac{X}{B} = -4, \quad \frac{L}{B} = \frac{3}{4}$.
- Most of X number is stored in ϕ_x, which will finally decay.
- The temperature T_{dc} can be fixed by the DM relic density for each M_Θ :

$$\frac{\Omega_\Theta}{\Omega_b} \approx \frac{M_\Theta}{m_p}\left|\frac{X}{B}\right|\frac{\Delta n_\Theta(T_{dc})}{n_X(T_{dc})} \approx \frac{M_\Theta}{1\ \mathrm{GeV}} \times 4 \times e^{-M_\Theta/m_W^{\mathrm{HL}}} \times 6\left(\frac{x_{dc}}{2\pi}\right)^2 e^{-x_{dc}} \approx 5, \quad (13)$$

Estimating the coupling ξ



Explaining XENON1T data by the ALP η

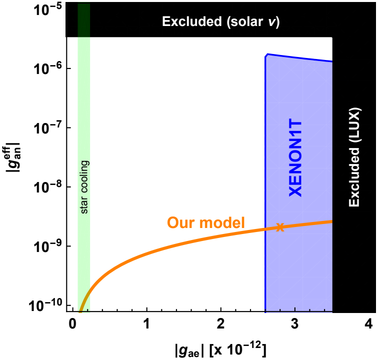
A light scalar boson, η, is always predicted. It can probably explain the XENON1T data. Interactions:

$$\mathcal{L}_{\text{WZW}} = \frac{d_\psi \cos\theta}{64\sqrt{2}\pi^2 f}\eta\left(g^2 W^a_{\mu\nu}\tilde{W}^{a,\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right) \quad (14)$$

η is photophobic. Its coupling to the fermions are generated in loop levels.

- The data implies $36 < \frac{f}{\text{TeV}} < 55$
- Prediction: Z boson decay $6 < \frac{Br(Z\to\gamma+\eta)}{10^{-12}} < 14$
- Prediction: K-meson decay $1.17 < \frac{Br(K_L\to\pi+inv)}{Br(K_L\to\pi+inv)|_{SM}} < 1.4$

[C. Cai et al., PRD.102, 075018]



Conclusion

- SU(6)/Sp(6) CHM can (partially) solve the Hierarchy problem and provide a DM candidate.
- In SU(6)/Sp(6) model B, DM can be asymmetrically produced.
- The Higgs boson becomes a part of the dark sector, protected by a $U(1)_X$ in HL vacuum.
- The vacuum departure from the HL phase in low T, $U(1)_X$ is broken and the Higgs boson emerges.
- A light boson η is always predicted, and it can explain the XENON1T result.
- The model can be tested in future Z boson factory.

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Thank you for listening!