Two remarkable features of Composite Dark Matter

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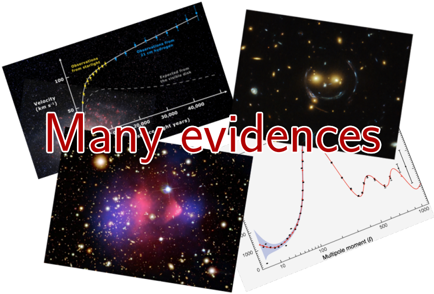
Based on *1905.13244*
with A. Davoli, A. De Simone, D. Marzocca

Dark matter problem



Many evidences

But **what** is it? Not yet known

Many possible candidates →
→ **W**eakly **I**nteracting **M**assive **P**article (WIMP)

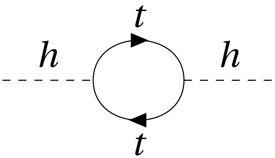
Naturalness/Hierarchy

Naturalness principle

A guide on the size of couplings: $[g] = \alpha \rightarrow g \approx \Lambda^{\alpha}$

$[\lambda] = 0 \rightarrow |\lambda| \approx 1, \quad [m_h^2] = 2 \rightarrow m_h^2 \approx m_{Pl}^2$

Hierarchy problem



Loop gives contribution δm_h^2:
$\delta m_h^2 \propto \Lambda_{NP}^2 \gg m_h^2$

Open issues

Dark Matter

$\Omega_{\mathsf{DM}} h^2 \approx 0.1198$

Naturalness

$m_h \ll m_{\mathsf{Pl}}$

↘ ↙

Composite Higgs

New particles → DM candidate?

New scale f: $m_h \lesssim f \ll m_{\mathsf{Pl}}$

CH paradigm (see e.g. 1105.5403)

There is a strong sector at $m_* = g_* f$

Spontaneous:

$\mathscr{G} \xrightarrow{\text{condensate}} \mathscr{H}$ $\Longrightarrow$ Particles generated

Explicit:

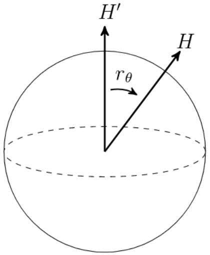
$\mathscr{G} \xrightarrow{\text{Yukawa, gauge}} \mathscr{H}$ $\Longrightarrow$ Masses generated

Where is the SM?

$\mathrm{SM} \subset \mathrm{SO}(4)_c \subset \mathscr{H}' \neq \mathscr{H}$

The two groups are misaligned!

CH paradigm (see e.g. 1105.5403)



Two different vacua

↓

Two different field expansions

Related by r_θ: $\sin\theta = v/f$

Gauge basis T related to $\mathscr{H}'$: $\langle h\rangle = v$

Physical basis T_θ related to $\mathscr{H}$: $\langle h\rangle = 0$

$$T_\theta = r_\theta T r_\theta^{-1}$$

Generators

$$\mathscr{G} = \mathrm{SO}(7), \ \mathscr{H} = \mathrm{SO}(5) \times \mathrm{SO}(2)$$

$$T_{L,R} \sim \mathrm{SO}(4)_c, \ T_5 \sim \frac{\mathrm{SO}(5)}{\mathrm{SO}(4)_c}, \ T_2 \sim \mathrm{SO}(2), \ \hat{T} \sim \frac{\mathrm{SO}(7)}{\mathrm{SO}(5) \times \mathrm{SO}(2)}$$

$$(T, \hat{T}) = \left(\begin{array}{c:c|cc} T_{L,R} & T_5 & \hat{T}_1 & \hat{T}_2 \\ \hdashline T_5 & 0 & & \\ \hline \hat{T}_1 & & & \\ \hat{T}_2 & & T_2 & \end{array} \right).$$

$\mathrm{SO}(7) \to \mathrm{SO}(5)\mathrm{x}\mathrm{SO}(2) \implies$ 10 NGBs generated in a $(5, 2)$

Our coset and pNGBs

	Field	SO(4)′	C_2	P_7
2HDM {	ϕ_1	$\mathbf{4}$	$+$	$+$
	ϕ_2	$\mathbf{4}$	$-$	$+$
singlets {	η	$\mathbf{1}$	$+$	$-$
	κ	$\mathbf{1}$	$-$	$-$

Symmetries

C_2: no sizable vacuum for ϕ_2 → safe custodial breaking

P_7: no $\eta \bar{q} q$ coupling → stability of DM

Particle identification

$$\phi_1 = \begin{pmatrix} G_1 \\ G_2 \\ G_3 \\ h \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} \frac{-i}{\sqrt{2}}(H_+ - H_-) \\ \frac{1}{\sqrt{2}}(H_+ + H_-) \\ H_0 \\ A_0 \end{pmatrix}$$

Why that H_0 and A_0 identification? (spoilers ahead)

$$\mathcal{L} \supset -\frac{m_q}{v}\bar{q}q(k_q h + k_{H_0 q} H_0) - i\frac{m_q}{v^2}\bar{q}\gamma^5 q(g_{\eta\kappa q}\eta\kappa + \tilde{g} h A_0)$$

CCWZ construction

First part of the model: **CCWZ Lagrangian**

$\vec{\Phi} = U(\Pi)\,\vec{F}$, where $U \to g \cdot U \cdot h^{-1}$

We define a symbol: $d_\mu \equiv i \sum_I \mathrm{Tr}[U^{-1} D_\mu U \hat{T}_I] \hat{T}_I$

D_μ contains the SM gauge bosons!

Simplest invariant object: $\mathscr{L}_\Pi^{(2)} = \frac{f^2}{4} d_\mu d^\mu$

CCWZ construction

We work in the physical basis!

$$U_\theta = \exp\left(i\frac{\sqrt{2}}{f}\Pi_I \hat{T}_I^\theta\right)$$

d_μ contains SM particles (W_μ, Z_μ, h) and new particles

- ⇒ m_Z, m_W generated
- ⇒ SM Higgs interactions modified
- ⇒ totally new interactions with the new pNGBs

VEV structure

$$\sin\theta_1 = \sqrt{\xi}\cos\beta, \quad \sin\theta_2 = \sqrt{\xi}\sin\beta$$

$$\Downarrow$$

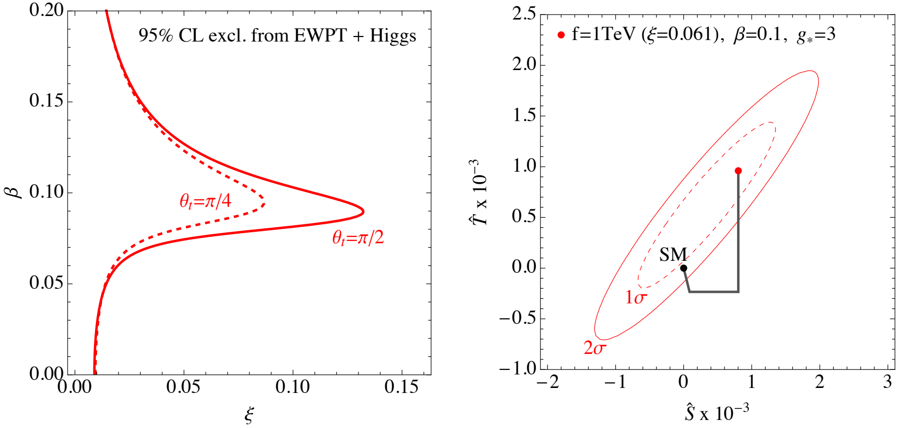
$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{v^2(g^2+g'^2)}{4}\left[1-\xi\left(1-\cos(4\beta)\right)\right]$$

$$\Downarrow$$

$$(\Delta\hat{T})_{2HDM} = \frac{\xi}{4}(1-\cos 4\beta) \approx 2\xi\beta^2$$

What is the limit from EWPT?

EWPT



95% CL excl. from EWPT + Higgs
$\theta_t=\pi/4$
$\theta_t=\pi/2$
β
ξ
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
f=1TeV (ξ=0.061), β=0.1, g_*=3
$\hat{T}$ x 10^{-3}
$\hat{S}$ x 10^{-3}
SM
1σ
2σ
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−2
−1
0
1
2
3

Partial compositeness

Linear coupling to strong sector:

$$\mathcal{L}_{\text{int}}^{f} = \bar{q}_L^{\alpha} \mathcal{Y}_L^{\alpha\,T} \mathcal{O}_L + \bar{t}_R \mathcal{Y}_R^{T} \mathcal{O}_R + \text{h.c.}$$

We want $\mathcal{H}$ invariants:

$$\bar{\mathcal{Y}}_L^{\alpha} \equiv \left(r_\theta^{-1} U_\theta^{\dagger} \mathcal{Y}_L \right)^{\alpha}, \quad \bar{\mathcal{Y}}_R \equiv r_\theta^{-1} U_\theta^{\dagger} \mathcal{Y}_R$$

Now we can give mass:

$$\mathcal{L}_t = c_t \frac{m_*}{g_*^2} \bar{q}_L^{\alpha} \left(\bar{\mathcal{Y}}_L^{\alpha} \right)^{I} \left(\bar{\mathcal{Y}}_R \right)_I^{\dagger} t_R$$

Partial compositeness

Next choice, fermion embedding:

$$\mathbf{7}_{\frac{2}{3}} = \mathbf{2}_{\frac{7}{6}} \oplus \mathbf{2}_{\frac{1}{6}} \oplus \mathbf{1}_{\frac{2}{3}} \oplus \mathbf{1}_{\frac{2}{3}} \oplus \mathbf{1}_{\frac{2}{3}}$$

Do you remember P_7? It forbids a 5th component

$$\mathscr{Y}_L = \frac{y_L}{\sqrt{2}} \begin{pmatrix} 0 & 0 & i & 1 & 0 & 0 & 0 \\ i & -1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\mathscr{Y}_R = y_R \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & \cos\theta_t & i\sin\theta_t \end{pmatrix}$$

$$Y_t \approx c_t \frac{y_L y_R}{g_*} (\sqrt{1-\xi}\cos\theta_t + \beta \sin\theta_t)$$

Potential construction

Without getting into the details of the invariant construction...

Fermions

Chirality → New objects $\bar{\Delta}_L = \bar{\mathscr{Y}}^*_L \bar{\mathscr{Y}}_L$, $\bar{\Delta}_R = \bar{\mathscr{Y}}^*_R \bar{\mathscr{Y}}_R$

$\mathscr{I}_1 = \bar{\Delta}^{ii}_L$, $\mathscr{I}_3 = \bar{\Delta}^{ij}_L \bar{\Delta}^{ji}_L$ and so on

Gauge

$$\mathscr{G}^\alpha = g T^\alpha_L, \mathscr{G}'^\alpha = g' T^3_R \quad \rightarrow \quad \bar{\mathscr{G}} \equiv r_\theta^{-1} U_\theta^\dagger \mathscr{G} U_\theta r_\theta .$$

Make invariants with $\mathbf{21} = (\mathbf{10}, \mathbf{1}) \oplus (\mathbf{5}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1})$

Embedding + symmetries → $V = \sum_i c_i \mathscr{I}_i$, $c_i \approx \mathscr{O}(1)$

Potential

$\mathscr{I}_4$ breaks $C_2 \implies h$, H_0 can both acquire a VEV!

We want $\xi \approx 0.05$, $\beta \approx 0.1$, $m_h = 125\,\text{GeV}$

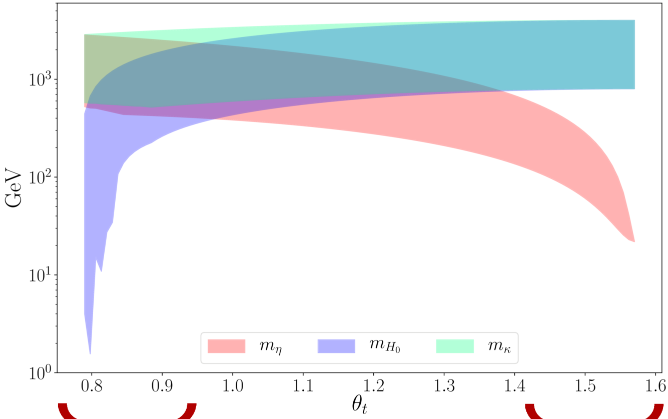
Where is the fine tuning?

$$\xi \approx c_3 + \frac{g_*^2}{y_L^2} c_1$$

$$\tan\beta \approx \frac{2 y_L^2}{g_*^2} \frac{c_4}{c_2} \tan(2\theta_t)$$

$$m_h^2 \approx \frac{N_c g_*^2}{8\pi^2} m_t^2 \left(2 \frac{y_L^2}{y_R^2} c_3 + \frac{y_R^2}{y_L^2} c_5 (3 + 4\cos(2\theta_t) + \cos(4\theta_t)) \right)$$

Spectrum



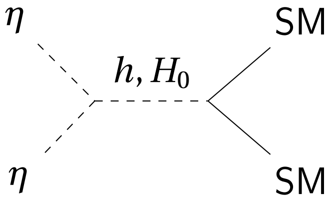
$\theta_t \approx \pi/4$

Non-thermal relic

$\theta_t \approx \pi/2$

Standard freeze-out

Relic density



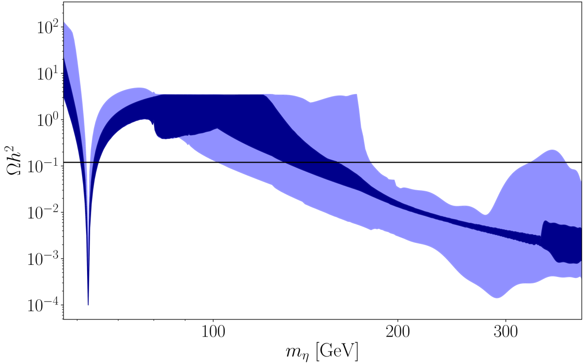
SM$= b, W, Z, h, t$

⚠ W^*, Z^* off-shell decays can be relevant!

$$\Omega h^2 = \frac{0.03}{\int_{x_F}^{\infty} dx \frac{\sqrt{g_*}}{x^2} \frac{\langle \sigma v \rangle_{\text{eff}}}{1\,\text{pb}}}, \quad \text{with } x_F \sim 25$$

Relic density $\theta_t \lesssim \pi/2$

All processes included, no experimental limits (for now)

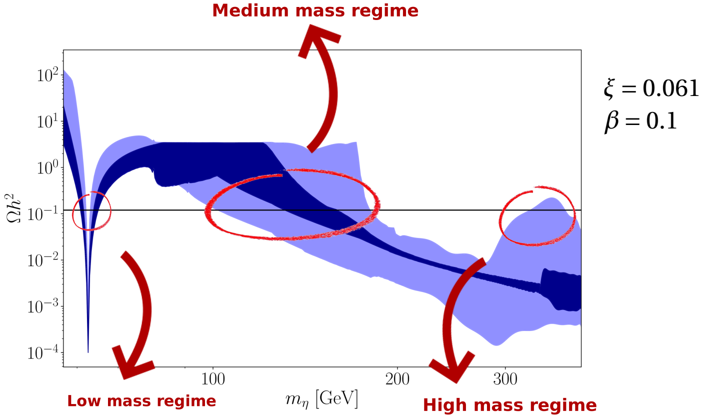


$\xi = 0.061$
$\beta = 0.1$

Naturalness ✓ Perturbativity ✓

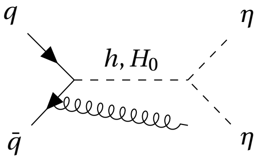
Relic density $\theta_t \lesssim \pi/2$

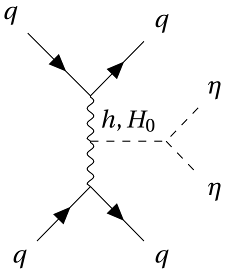
All processes included, no experimental limits (for now)

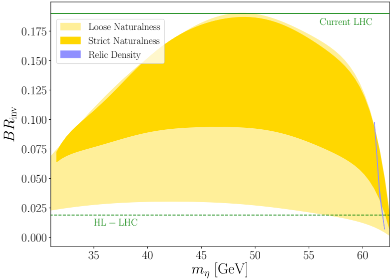


Naturalness ✓ Perturbativity ✓

LHC



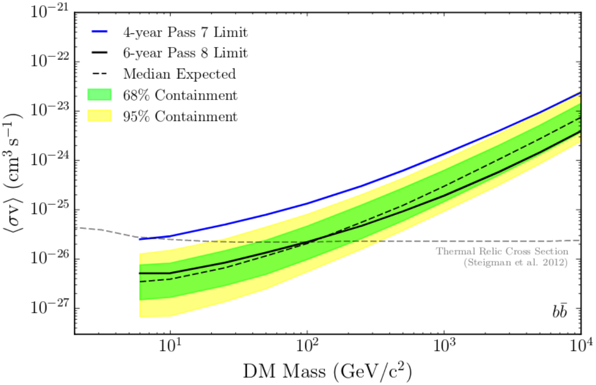




$$\Gamma_{h\to\eta\eta} = \frac{g_{\eta h}^2}{32\pi m_h} v^2 \sqrt{1 - \frac{4m_\eta^2}{m_h^2}}$$

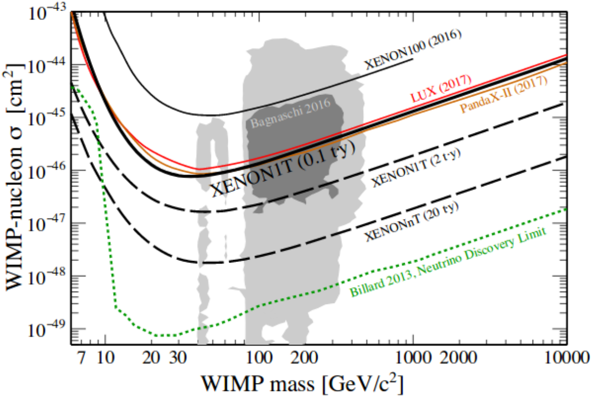
Indirect detection

- ⇒ We use γ-ray data
- ⇒ Overestimate $\sigma_{b\bar{b}} = \sigma_{\text{tot}}$
- ⇒ Processes are not p-wave suppressed



Direct detection

⇒ We use XENON result
⇒ Energy exchanged of order keV
⇒ Processes are not p-wave suppressed



Experimental constraints

- LHC: (CMS, 1809.05937)
  MJ, VBF weaker than BR_{inv} and not relevant at higher masses
  BR_{inv} constraining in the HL projection

- ID: (FERMI-LAT, 1503.02641)
  dSPh data: we are safe

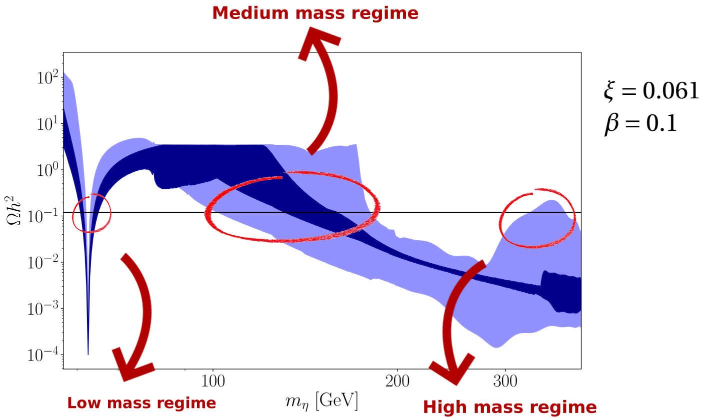
- DD: (XENON1T, 1705.06655)

$$a_q = \frac{1}{2}\left[\frac{g_q}{v^2} - \left(k_q \frac{g_{\eta h}}{m_h^2} - k_{H_0 q}\frac{g_{\eta H_0}}{m_{H_0}^2}\right)\right]$$

cancellation possible, increasing coefficient tuning to evade

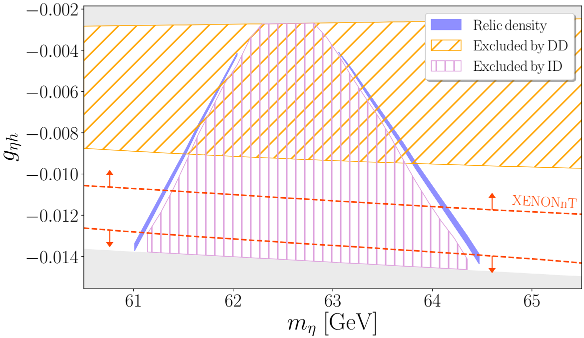
Relic density $\theta_t \lesssim \pi/2$ (again)

All processes included, no experimental limits (for now)



Naturalness ✓ Perturbativity ✓

Low mass regime (benchmark)

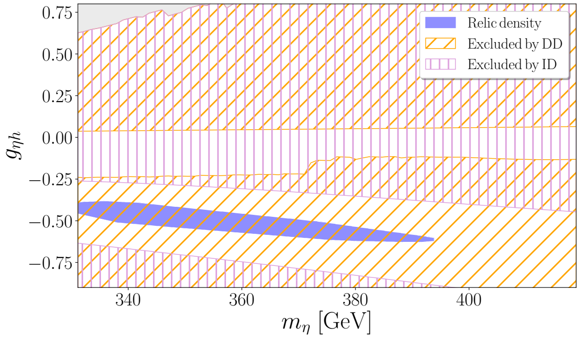


$\xi = 0.061$
$\beta = 0.1$

Limited by DD, ID safe by a factor $1.1 \div 1.2$

Available mass range $\lesssim 1\,\text{GeV}$ wide

High mass regime (benchmark)

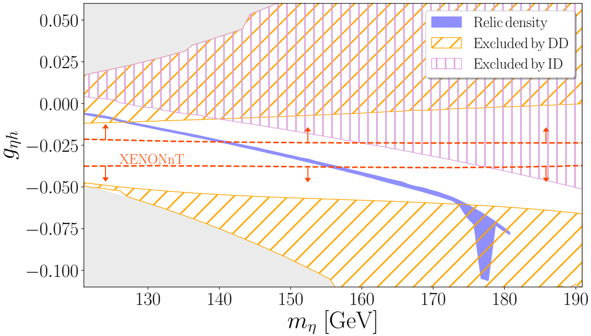


$\xi = 0.061$
$\beta = 0.1$

Excluded by DD up to $\xi \approx 0.01$

Mass range defined by $H_0 - h$ cancellation

Medium mass regime (benchmark)

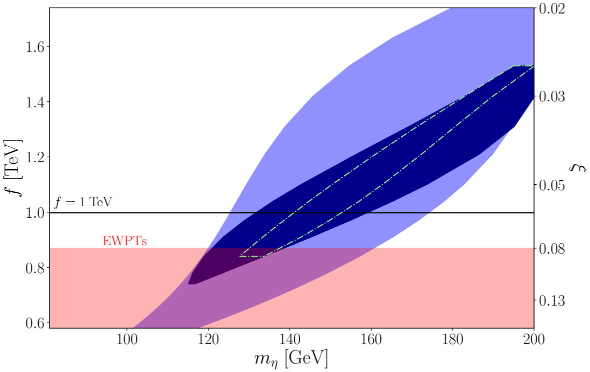


$\xi = 0.061$
$\beta = 0.1$

Limited by DD, insensitive to other searches

Available mass range $130\,\text{GeV} \div 175\,\text{GeV}$

Medium mass regime (scan)



Relic density ✓ Direct detection ✓

Lowest fine tuning set by EWPTs

XENONnT will reduce, but not exclude, the model parameter space

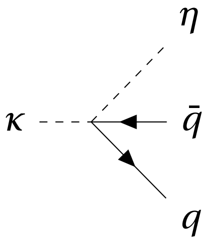
Relic density $\theta_t \gtrsim \pi/4$

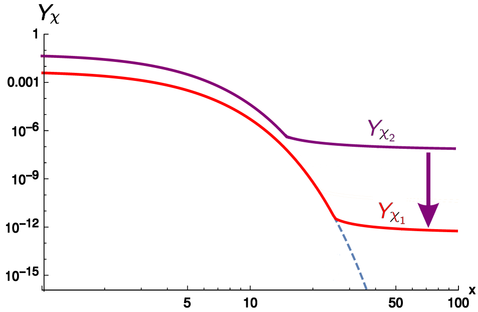
Let's go to the other θ_t regime

$\theta_t \gtrsim \frac{\pi}{4}$ has many consequences!

- $\Rightarrow$ η becomes heavy ($\sim$ TeV)
  $m_\kappa > m_\eta > m_{H_0}$, but η still stable
- $\Rightarrow$ Particles become close in mass,
  so coannihilations and long-lived particles
- $\Rightarrow$ many natural suppressions become unnatural,
  because $\sin(2\theta_t) \sim 1$

Relic density $\theta_t \gtrsim \pi/4$



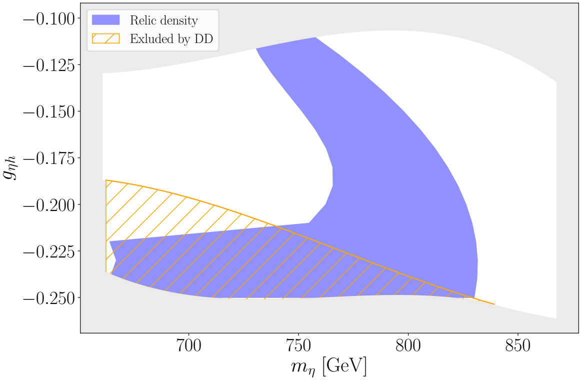


Two contributions: $\Omega_{\rm DM} h^2 = \Omega_\eta h^2 + \frac{m_\eta}{m_\kappa} \Omega_\kappa h^2$

Late time decay: $t_{\rm FO} < \tau_\kappa < t_{\rm BBN}$

$\Gamma_\kappa \propto \frac{\Delta m^5 m_q^2}{m_k^2 v^4} \rightarrow 20\,\text{GeV} \lesssim \Delta m \lesssim 50\,\text{GeV}$

Non thermal



$\xi = 0.01$
$\beta = 0.2$

Evade DD → $\xi \approx 0.01$ needed

$\Omega_\kappa \approx \Omega_\eta$: same order contribution

LHC and ID are not relevant

Conclusions

- CH model based on SO(7)/SO(5)xSO(2) delivers a viable DM candidate consistent with all exp. results;
- the level of fine tuning required is $f \gtrsim 0.8\,\text{TeV}$ (set by EWPT);
- DM can be produced non-thermally via decays of an heavier pNGB (but with higher fine tuning).

Thank you!

BACKUP

$$\xi \approx \frac{2N_c y_L^4 c_{(2,0)}^{(1)} + g_*^2 \left(N_c y_L^2 c_{(1,0)}^{(1)} - 3g^2 c_g^{(1)} - g'^2 c_{g'}^{(1)} \right)}{N_c y_L^4 c_{(2,0)}^{(1)}}$$

$$\tan\beta \approx \frac{N_c\, c_{(1,1)}^{(1)} y_L^2 y_R^2 \sin 2\theta_t}{2g_*^2 (g'^2 c_{g'}^{(1)} + 2N_c\, y_R^2 c_{(0,1)}^{(1)} \cos 2\theta_t)}$$

$$a_q = \frac{1}{2}\left[\frac{g_q}{v^2} - \left(k_q \frac{g_{\eta h}}{m_h^2} - k_{H_0 q}\frac{g_{\eta H_0}}{m_{H_0}^2}\right)\right]$$

$g_q \approx -2\xi \frac{\cos\beta\cos\theta_q}{\cos(\beta-\alpha_q\theta_q)}$

$k_q = 1 + \mathcal{O}(\xi)$

$g_{\eta h} \approx -\frac{g_*^2}{8\pi^2}\cos^2\theta_t\left[2\tilde{c}_y^{(5)} - \tilde{c}_y^{(7)} + 2\tilde{c}_y^{(8)} + 2\cos(2\theta_t)(\tilde{c}_y^{(5)} + \tilde{c}_y^{(8)})\right]$

Fixing coefficients $\neq$ Tuning coefficients

Fixing coefficient (with tuning)

$\xi = c_1 + c_2 = 0.01 \rightarrow c_1 = 1.01, c_2 = -1$

Change c_2: $\delta c_2 = +5\% \rightarrow \delta\xi = +500\%$

Fixing coefficient (without tuning)

$m_h = c_1 + c_2 = 2 \rightarrow c_1 = 1, c_2 = 1$

Change c_2: $\delta c_2 = +5\% \rightarrow \delta m_h = +2.5\%$