A minimal model for neutral naturalness and pNGB dark matter

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Motivation

- Electroweak Hierarchy Problem and Dark Matter are two of the main motivations to go beyond the SM.
- the Higgs mass is sensitive to new physics scales
- A 125 GeV Higgs is unnatural, unless there is some mechanism that explains the hierarchy
- No collider discoveries so far, but the problem remains
- Maybe some symmetry makes the Higgs mass insensitive to higher scales
- In supersymmetric theories the masses of scalars are related to fermions, which can be protected by chiral symmetry

Motivation

- Beyond this theoretical puzzle, there is experimental evidence for DM
- If the DM has weak scale couplings to the SM and a weak scale mass then its thermal relic abundance matches observation
- It is suggestive that both Higgs naturalness and WIMP dark matter point to the weak scale
- This connection has been explored in many ways, perhaps most popularly through SUSY neutralinos, supersymmetric partners of the electroweak gauge fields

Motivation

- Another possibility to have naturally light scalar is if they are pNGBs, which are generated when global symmetry is sponteniously broken
- In Composite Higgs models, the Higgs doublet arises as a pseudo Nambu-Goldstone bosons (pNGBs) of a spontaneously broken global symmetry.
  Kaplan, Georgi: 84
- Minimal composite Higgs model: $SO(5) \to SO(4)$, the 4 Goldstone bosons make the Higgs doublet H.
  Agashe, Contino, Pomarol:hep-ph/0412089
- Non-minimal composite Higgs models involve extra pNGBs
- Extra pNGBs can be WIMP dark matter candidates if they are stable!
  Frigerio, Pomarol, Riva, Urbano:1204.2808; Balkin, Ruhdorfer, Salvioni,Weiler:1707.07685 +....
- pNGB dark matter is naturally light and weakly coupled. Its mass and interactions are determined by the global symmetry.

Example pNGB WIMP

- Consider a SO(7)/SO(6) model with pNGBs given by Balkin, Ruhdorfer, Salvioni, Weiler, 1707.07685, where $\Phi = f\sqrt{1-\frac{2|H|^2+2|\chi|^2}{f^2}}$, f is symmetry breaking VEV
- The complex scalar χ is stabilized by the residual global symmetry $SO(2) \approx U(1)_D$

$$\sqrt{2}\mathcal{H} = \begin{array}{c c} SO(4)_C & \\ U(1)_D & \end{array} \begin{pmatrix} -i\mathrm{Im}h^+ \\ \mathrm{Re}h^+ \\ i\mathrm{Im}h^0 \\ \mathrm{Re}h^0 \\ \hline \mathrm{Im}\chi \\ \mathrm{Re}\chi \\ \hline \sqrt{2}\Phi \end{pmatrix}$$

χ is neutral under all SM gauge groups, but develops couplings to the Higgs through explicit breaking of the $SO(7)$

For instance, elements of the top multiplet must be lifted to higher scales due to collider bounds
This is a soft breaking of the SO(7)

$$\sqrt{2}\mathcal{Q} = \begin{array}{c} \\ SO(4)_C \\ \\ \\ \\ U(1)_D \\ \\ \end{array} \begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ \hline 0 \\ 0 \\ \hline 0 \end{pmatrix}$$

And generates a potential at 1-loop
$V_S = \frac{1}{2}\mu_h^2 h^2 + \frac{\lambda_h}{4} h^4 + \mu_\chi^2 |\chi|^2 + \lambda_\chi |\chi|^4 + \lambda_{h\chi} h^2 |\chi|^2$

- Collider bounds on new colored states imply that the soft symmetry breaking is somewhat large, with new colored states above the TeV scale
- This increases the size of the potential terms, producing heavier dark matter and stronger coupling to the Higgs
$$V_S = \frac{1}{2}\mu_h^2 h^2 + \frac{\lambda_h}{4} h^4 + \mu_\chi^2 |\chi|^2 + \lambda_\chi |\chi|^4 + \lambda_{h\chi} h^2 |\chi|^2$$
- Thus, minimal realizations of this model are in tension with direct DM searches
- If we can lower the scale of the top partners, we not only make the model more natural, we explain why we have not yet seen the WIMPs!

Neutral Naturalness from SO(7)/SO(6)

- The global symmetry structure: $SO(7) \times U(6)$
- $U(6) \simeq SU(6) \times U(1)_X \supset SU(3)_c \times SU(3)_{\hat{c}} \times U(1)_X$
- At some scale f the global $SO(7)$ is broken to $SO(6) \supset SO(4) \times SO(2) \cong SU(2)_L \times SU(2)_R \times U(1)_D$
- We gauge the SM subgroup $\simeq SU(2)_L \times U(1)_Y$, where $Y = T_R^3 + X$

- Same scalar sector as before: $\Phi = f\sqrt{1 - \frac{2|H|^2+2|\chi|^2}{f^2}}$
  $H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$

$$\sqrt{2}\mathcal{H} = \begin{array}{c} SO(4)_C \\ \\ U(1)_D \\ \\ \end{array} \left(\begin{array}{c} -i\mathrm{Im}h^+ \\ \mathrm{Re}h^+ \\ i\mathrm{Im}h^0 \\ \mathrm{Re}h^0 \\ \hline \mathrm{Im}\chi \\ \mathrm{Re}\chi \\ \hline \sqrt{2}\Phi \end{array}\right)$$

- But, now the top multiplets are

$$\mathcal{T}_R = \begin{array}{cc} SU(3)_c & SU(3)_{\hat{c}} \end{array} \\ \left(\begin{array}{c|c} t_R & \widehat{T}_R \end{array}\right)$$

$$\sqrt{2}\mathcal{Q}_L = \begin{array}{c} \\ SO(4) \\ \\ U(1)_D \\ \\ \end{array} \begin{array}{c} \begin{array}{cc} SU(3)_c & SU(3)_{\hat{c}} \end{array} \\ \left(\begin{array}{c|c} ib_L & i\widehat{b}_L \\ b_L & \widehat{b}_L \\ it_L & i\widehat{t}_L \\ -t_L & -\widehat{t}_L \\ \hline 0 & i\widehat{X}_L - i\widehat{Y}_L \\ 0 & \widehat{X}_L + \widehat{Y}_L \\ \hline 0 & \sqrt{2}\widehat{T}_L \end{array}\right) \end{array}$$

The quark sector

- In order to get the correct hypercharge for t_L, t_R, b_L, both $\mathcal{Q}$ and $\mathcal{T}_R$ have a $U(1)_X$ charge of $\frac{2}{3}$
- This would introduce hypercharge for : $\widehat{T}, \widehat{t}, \widehat{b}, \widehat{X}, \widehat{Y}$
- This feature of top-partners give interesting collider signatures!
- LEP excludes such new EW charged fermions for $\lesssim 100\text{GeV}$
- Top sector Yukawa coupling: $\mathcal{L} \supset \lambda_t \overline{\mathcal{Q}}_L \mathcal{H} \mathcal{T}_\mathcal{R} + \text{H.c.}$
- These hidden quarks can be lifted through vector-like mass terms

$$\mathcal{L}_{\text{vec mass}} = -m_Q \overline{\widehat{q}}_L \widehat{q}_R - m_X \overline{\widehat{X}}_L \widehat{X}_R - m_Y \overline{\widehat{Y}}_L \widehat{Y}_R + \text{H.c.}$$

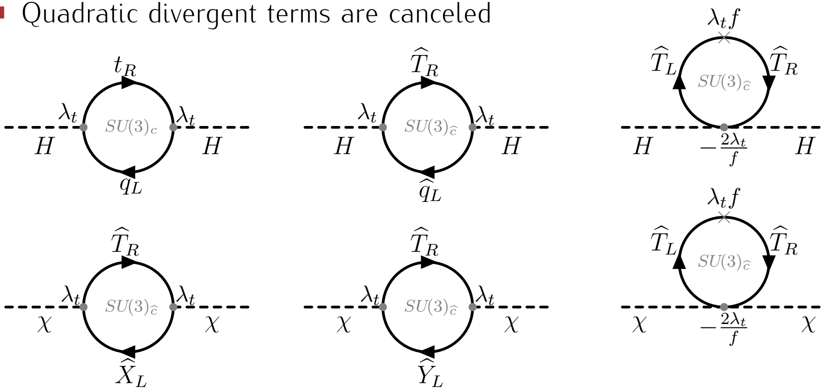
where $\widehat{q}_R = (\widehat{t}_R, \widehat{b}_R)^T$, an $SU(2)_L$

For simplicity: $m_X = m_Y \equiv m_V$

Top Partners

$$
\begin{aligned}
\mathcal{L} \supset & \lambda_t \overline{\mathcal{Q}}_L \Sigma \mathcal{T}_R + \text{H.c.} \\
= & \lambda_t \left[\left(\overline{q}_L t_R + \overline{\widehat{q}}_L \widehat{T}_R \right) \widetilde{H} + \overline{\widehat{X}}_L \widehat{T}_R \chi^* + \overline{\widehat{Y}}_L \widehat{T}_R \chi + f \left(1 - \frac{|H|^2 + |\chi|^2}{f^2} + \dots \right) \overline{\widehat{T}}_L \widehat{T}_R \right] + \text{H.c.}
\end{aligned}
$$

- These fermion interactions induce potential for for pNGBs.
- Quadratic divergent terms are canceled



- The Coleman-Weinburg potential at one loop leads to:

$$V_S = \frac{1}{2}\mu_h^2\overline{h}^2 + \frac{\lambda_h}{4}\overline{h}^4 + \mu_\chi^2|\chi|^2 + \lambda_\chi|\chi|^4 + \lambda_{h\chi}\overline{h}^2|\chi|^2$$

$$\mu_h^2 \approx \frac{3\lambda_t^2}{8\pi^2}\left(m_Q^2 - \lambda_t^2 f^2\right)\ln\frac{\Lambda_{\rm UV}^2}{m_Q^2}, \quad \lambda_h \approx \frac{3\lambda_t^4}{16\pi^2}\left[\frac{2}{3} + \ln\frac{\Lambda_{\rm UV}^4}{m_Q^2\frac{\lambda_t^2}{2}\overline{h}^2}\right]$$

$$\mu_\chi^2 \approx \frac{3\lambda_t^2 m_V^2}{4\pi^2}\ln\frac{\Lambda_{\rm UV}^2}{\lambda_t^2 f^2}, \quad \lambda_\chi \approx \frac{3\lambda_t^4 m_V^4}{4\pi^2(m_Q^2 - m_V^2)^2}, \quad \lambda_{h\chi} \approx \frac{3\lambda_t^4 m_V^2 m_Q^2}{8\pi^2(m_Q^2 - m_V^2)^2}$$

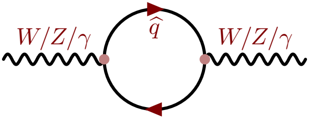
- For DM stability we require $U(1)_D$ to be unbroken theerfore, the vacuum is $\langle\chi\rangle = 0$, $h = v$

$$\mu_h^2 = -\lambda_h v^2, \quad m_h^2 = 2\lambda_h v^2 c_v, \quad m_\chi^2 = \mu_\chi^2 + \lambda_{h\chi}v^2$$

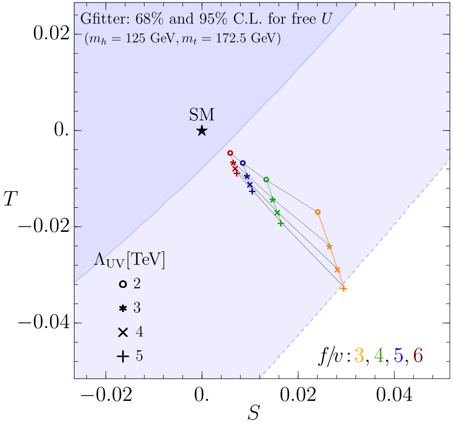
- Fixing $v = 246\text{GeV}$ and $m_h = 125\text{GeV}$ would require $f \gtrsim 750\text{GeV}$ and $m_Q \approx \lambda_t f$

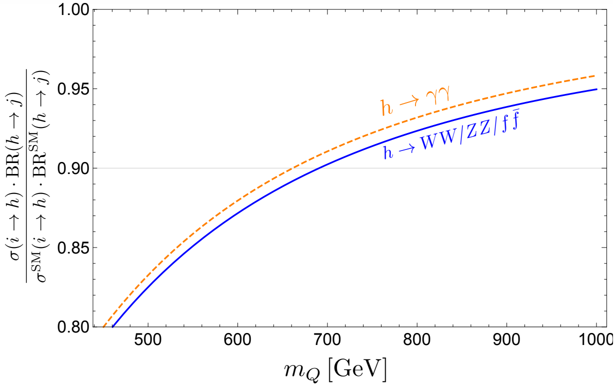
- Tuning of the Higgs mass parameter is $\Delta = \left| \frac{2\delta\mu^2}{m_h^2} \right|^{-1}$
- where $\delta\mu^2 = \frac{3}{8\pi^2}\lambda_t^2 \left(m_Q^2 - \lambda_t^2 f^2 \right) \ln \frac{\Lambda_{\rm UV}^2}{m_Q^2}$
- Minimizing the Higgs potential leads to $\frac{v^2}{f^2} = 1 - \frac{m_Q^2}{\lambda_t^2 f^2}$

The top-partners are electroweak charged, so they introduce corrections to the electroweak precision tests.

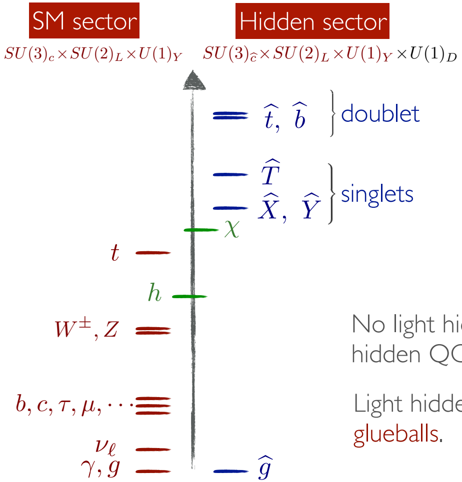


- $S \approx \frac{2N_{\hat{c}} m_t^2}{15\pi m_Q^2} + \frac{1}{12\pi}\frac{v^2}{f^2}\ln\left(\frac{\Lambda_{\rm UV}^2}{m_h^2}\right)$
- $T \approx \frac{13 N_{\hat{c}} m_t^4}{120\pi m_Z^2 m_Q^2 \sin^2 2\theta_W} - \frac{3}{16\pi}\frac{1}{\cos^2\theta_W}\frac{v^2}{f^2}\ln\left(\frac{\Lambda_{\rm UV}^2}{m_h^2}\right)$





- Higgs signal strength measurements of massive gauge bosons and fermions are reduced.
- The existence of new fermionic states with electric charge that couple to the Higgs amplifies its coupling to photons.



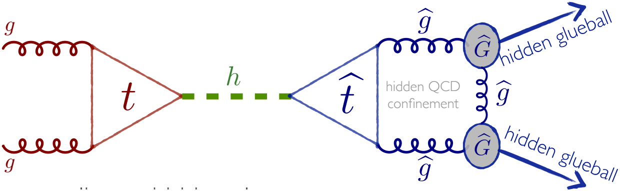
singlet-doublet mixing

$$\begin{pmatrix} \widehat{t} \\ \widehat{T} \end{pmatrix} \to \begin{pmatrix} \widehat{T}_+ \\ \widehat{T}_- \end{pmatrix}$$

No light hidden quarks, implies large hidden QCD confinement scale $\widehat{\Lambda}_{\rm QCD}$

Light hidden hadrons are the hidden glueballs.

HIDDEM GLUBALLS DECAYS



The Higgs coupling to hidden gluons: $c_g \frac{\widehat{\alpha}_s}{12\pi} \frac{h}{v} \widehat{G}^a_{\mu\nu} \widehat{G}^{a\mu\nu}$

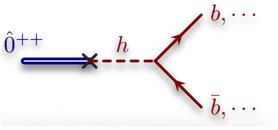
Higgs decay width to hidden gluons: $\Gamma(h \to \widehat{g}\widehat{g}) = \frac{\widehat{\alpha}_s m_h^5}{288\pi^3 v^2} |c_g|^2$

Ligthest hidden gluballs: $m_{\widehat{0}^{++}} \simeq 6.8\widehat{\Lambda}_{\mathrm{QCD}}$

$$\widehat{\Lambda}_{\mathrm{QCD}} \approx [4,7]\mathrm{GeV}$$

HIDDEM GLUBALLS DECAYS

Dark gluball mixes with the SM Higgs and decays to SM light fermions with displaced vertices.



$$\Gamma\left(0^{++} \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right) = |c_g|^2 \left[\frac{\widehat{\alpha}_s}{6\pi v} \frac{f_{0^{++}}}{m_h^2 - m_0^2}\right]^2 \Gamma_{\mathrm{SM}}\left(h\left(m_0\right) \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right)$$

$$f_{0^{++}} = \left\langle 0 \left| \mathrm{Tr}\, \widehat{G}_{\mu\nu} \widehat{G}^{\mu\nu} \right| 0^{++} \right\rangle \simeq \frac{3.1}{4\pi \widehat{\alpha}_s} m_0^3$$

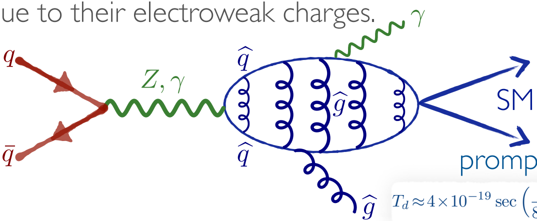
$m_0 \in [30 - 50]\mathrm{GeV}$

Glueballs decay length about [10 -100] meters which might be accessible at future MATHUSLA-like detectors.

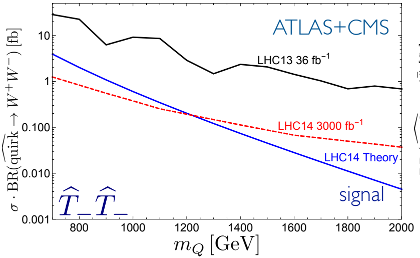
QUIRKY SIGNALS

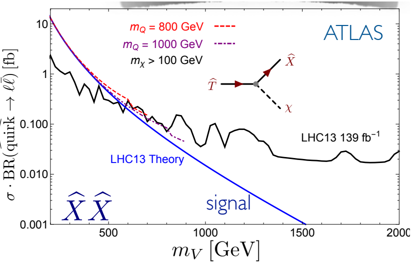
Hidden sector quarks ($\widehat{T}_\pm$, $\widehat{b}$, $\widehat{X}$, $\widehat{Y}$) can be produced through Drell-Yan due to their electroweak charges.

Kang, Luty:0805.4642



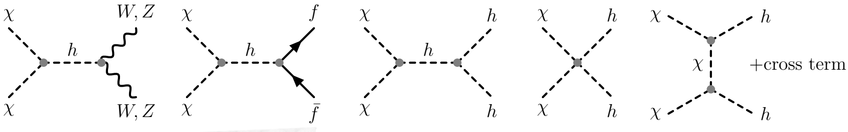
$$T_d \approx 4\times 10^{-19}\,\mathrm{sec}\left(\frac{m_{\widehat{f}}}{800\,\mathrm{GeV}}\right)^3\left(\frac{6\,\mathrm{GeV}}{\widehat{\Lambda}_{\mathrm{QCD}}}\right)^4$$



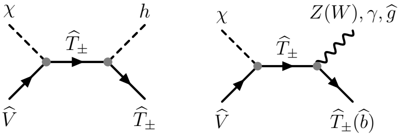


DM ANNIHILATION

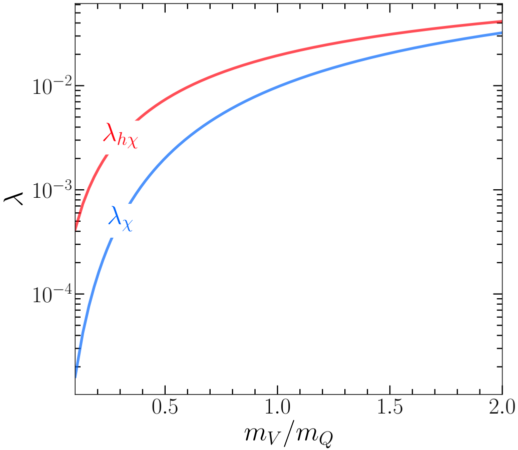
- The pNGB DM interacts with the SM via the Higgs portal: $\frac{1}{2f^2}\partial_\mu\left(h^2\right)\partial^\mu\left(\chi^*\chi\right)+\lambda_{h\chi}h^2\chi^*\chi$
- DM annihilation to the SM



- $\mathcal{M}\left(\chi\chi^*\to \mathrm{SM}\right)\propto\left(\frac{s}{f^2}-2\lambda_{h\chi}c_v\right)v$
- $U(1)_D$ symmetry implies semi-annihilation processes (relevant when: $m_V\approx m_\chi$), e.g.

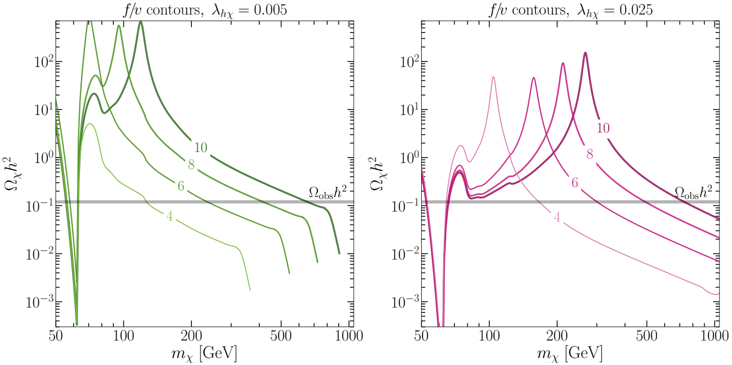


HIGGS PORTAL COUPLING



- Relatively small m_V leads to very small DM-Higgs portal coupling
- Significant implications for the DM direct detection.

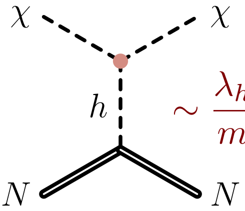
DARK MATTER: THERMAL FREEZE-OUT



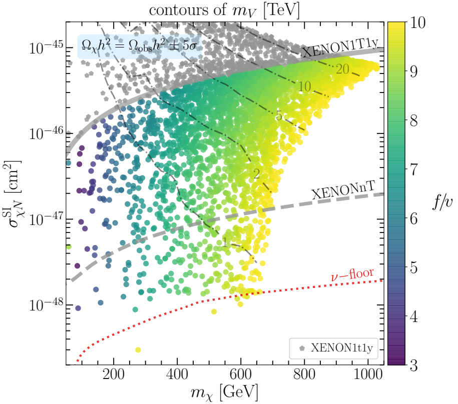
$$\Omega_\chi h^2 \approx 0.12 \left(\frac{2.2\times10^{-26}\ \text{cm}^3\ \text{s}^{-1}}{\langle \sigma(\chi\chi^* \to \text{SM}) v_{\text{Mol}} \rangle} \right)$$

$$\langle \sigma \left(\chi\chi^* \to \text{SM} \right) v_{\text{Mol}} \rangle \propto \frac{1}{m_\chi^2} \left(\frac{4m_\chi^2}{f^2} - 2\lambda_{h\chi} c_v^2 \right)^2$$

Direct detection experiments provide the most stringent constraints on WIMP DM.



$$\sim \frac{\lambda_{h\chi}}{m_h^2} m_q$$

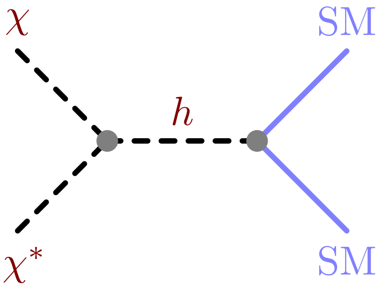


$$\sigma^{\rm SI}_{\chi N} \simeq \frac{f_N^2 m_N^4}{\pi m_h^4} \frac{\lambda_{h\chi}^2}{m_\chi^2} \approx$$

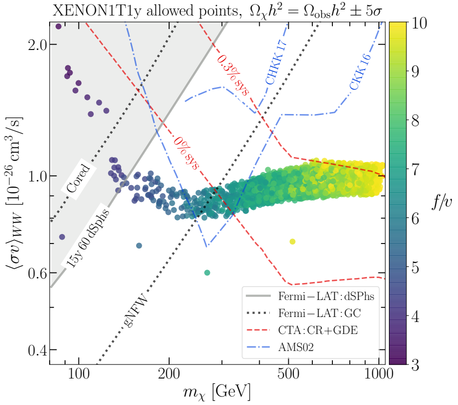
$$2 \times 10^{-46}\ \mathrm{cm}^2 \left(\frac{\lambda_{h\chi}}{0.025}\right)^2 \left(\frac{300\mathrm{GeV}}{m_\chi}\right)^2$$

Where $f_N \simeq 0.3$

Indirect signals of DM annihilation in galaxies



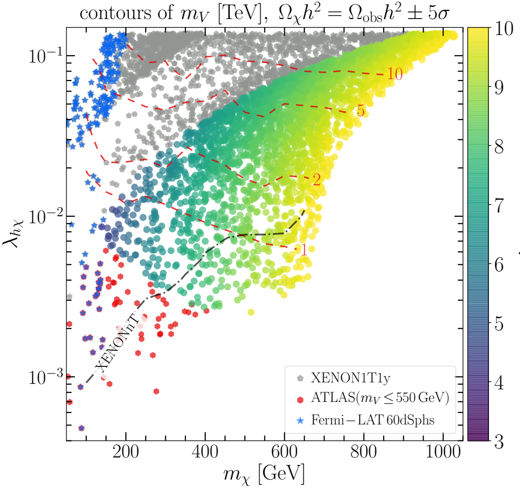
dominant channel: WW, hh, ZZ



Current gamma-ray and cosmic-ray results have large systematic uncertainties.

DARK MATTER: SUMMARY

Direct Detection: XENON1T
Indirect Detection: Fermi-LAT
LHC: quirky signals
Current and future direct/indirect detection experiments along with the collider searches of quirky dynamics would probe all the natural parameter space.



Conclusions

- A minimal model of neutral naturalness $SO(7)/SO(6)$ pNGBs: SM Higgs doublet + a complex scalar DM
- The top-partners are SM color-neutral and hence evade the LHC constraints (also reduce fine-tuning).
- The hidden glueballs and top-partner quirks lead to interesting signatures at the LHC.
- The pNGB DM is light, weakly coupled, and stable under the global $U(1)_D$ symmetry
- The natural parameter space of our model is within the reach of current and future experiments.