Pseudo-Goldstone dark matter

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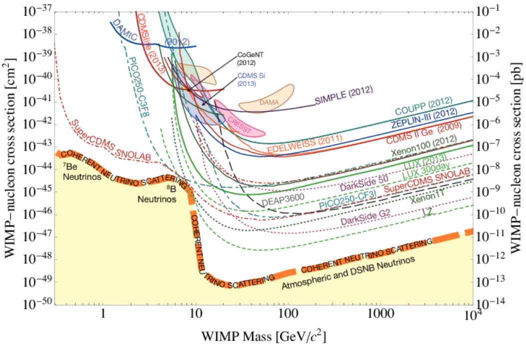
Contents

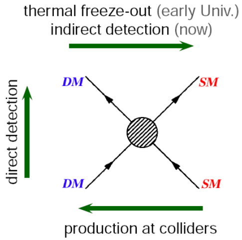
Pseudo-Goldstone DM

- There is plenty of evidence for DM.
- But the allowed parameter space for WIMPs is getting smaller, due to ever tighter limits from direct detection.
- There are many options in the market for producing DM in a way that does not imply a detectable direct detection signal (FIMPs, ultralight DM/ALPs, spectator DM...)



Pseudo-Goldstone DM

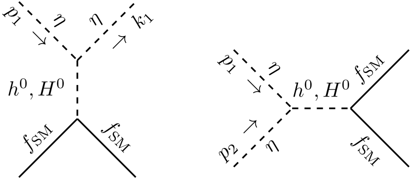
- However, the thermal freeze-out scenario is very simple and predictive, as it relates the DM abundance via the annihilation cross section to the indirect detection signal.
- Is there a way to suppress the direct detection signal within the thermal freeze-out scenario?
- If there is a mediator particle with $m \approx 2m_D$, the s-channel annihilation cross section is enhanced with respect to the non-resonant t-channel direct detection cross section.
- This can be arranged (e.g. Higgs-portal DM with $m_D \approx 62.5$ GeV), but requires some finetuning.



Pseudo-Goldstone DM

- Pseudo-Goldstone DM offers a general framework where the direct detection cross section is naturally suppressed, with no finetuning.
- In the non-linear representation, the Goldstone bosons have derivative interactions, implying a vanishing cross section in the limit of zero momentum transfer (i.e. non-relativistic DM-nucleus elastic scattering).
- In the linear representation the vanishing of the cross section is due to a cancellation between two diagrams.

$$\frac{\mathrm{d}\sigma_{\mathrm{SI}}}{\mathrm{d}\cos\theta} \sim \frac{\lambda_{HS}^2 f_N^2 m_N^2}{(m_{h^0}^2 - t)^2 (m_{H^0}^2 - t)^2} t^2$$



Explicit symmetry breaking

- The DM particle must be massive, thus it can not be an exact Goldstone boson.
- The global symmetry protecting the zero mass of the GB must be explicitly broken.
- But the vanishing of the direct detection cross section was due to the same global symmetry!
- Some care required in accounting for the effects of symmetry breaking from possible tree-level operators and loop corrections.

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O(N)/O(N − 1) Global symmetry

- Consider a global symmetry O(N), spontaneously broken to O($N-1$) by a vev of a SM-singlet scalar field

$$\Sigma = (\eta_1, \eta_2, \ldots, \eta_{N-1}, \sigma)$$

where σ is the field direction along which the vev of Σ develops.

- Effective Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial\eta_a\partial\eta_a - V(\Sigma, H)$$

$$V(\Sigma, H) = \mu_H^2 H^\dagger H + \frac{1}{2}\mu_\Sigma^2 \Sigma^\dagger\Sigma + \lambda_H (H^\dagger H)^2 + \frac{\lambda_{H\Sigma}}{2}(H^\dagger H)\Sigma^\dagger\Sigma + \frac{\lambda_\Sigma}{4}(\Sigma^\dagger\Sigma)^2 + V_{\rm sb}$$

$$V_{\rm sb} = -\frac{1}{2}\mu_X^2(\sigma^2 - \eta_a\eta_a) - \frac{\lambda_X}{2}(H^\dagger H)(\sigma^2 - \eta_a\eta_a)$$

Mass eigenstates

- The η-multiplet is stable (and degenerate in mass) $\rightarrow$ DM candidate.
- The CP-even component of H mixes with σ. The scalar potential is minimized for

$$\mu_H^2 = -\frac{1}{2}(2\lambda_H v^2 + (\lambda_{H\Sigma} - \lambda_X) w^2),$$

$$\mu_\Sigma^2 = -\frac{1}{2}(2\lambda_\Sigma w^2 + (\lambda_{H\Sigma} - \lambda_X) v^2 - 2\mu_X^2),$$

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \sigma \end{pmatrix},$$

$$\tan(2\alpha) = -\frac{(\lambda_{H\Sigma} - \lambda_X) v w}{\lambda_H v^2 - \lambda_\Sigma w^2}.$$

- Identify the lightest eigenstate with the SM Higgs, $m_{h^0} = 125$ GeV.
- Free parameters: $\lambda_{H\Sigma}, m_{H^0}, m_\eta$, α, and λ_X

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Direct detection

The following constraints are for the simplest case of O(2)∼U(1) global symmetry.

- Direct detection cross section at tree-level

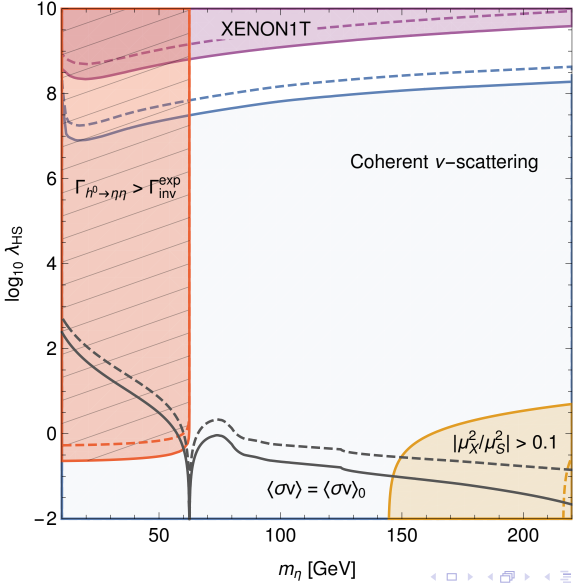
$$\frac{\mathrm{d}\sigma_{\mathrm{SI}}}{\mathrm{d}\cos\theta} = \frac{\lambda_{\mathrm{eff}}^2 f_N^2 m_N^2 \mu_R^2}{8\pi m_\eta^2},$$

$$\lambda_{\mathrm{eff}} = \frac{\lambda_{HS}\, t}{(m_{h^0}^2 - t)(m_{H^0}^2 - t)} - \frac{2\lambda_X \left[s_\alpha^2 (m_{h^0}^2 - t/2) + c_\alpha^2 (m_{H^0}^2 - t/2)\right]}{(m_{h^0}^2 - t)(m_{H^0}^2 - t)}.$$

- The only non-zero contribution in the limit $t \to 0$ is from the explicit symmetry breaking coupling λ_X.
- Setting $\lambda_X = 0$, the direct detection limits do not constrain the parameter space of the model at all.

Direct detection

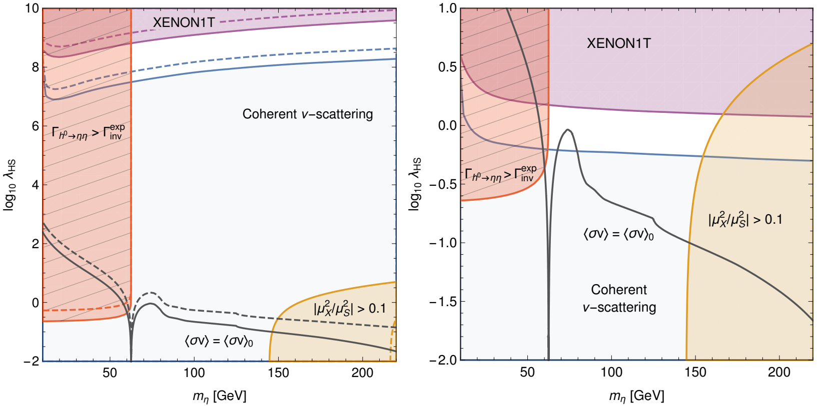
$s_\alpha = 0.3$; Solid lines: $m_{H^0} = 500$ GeV, dashed lines: $m_{H^0} = 750$ GeV.



Direct detection

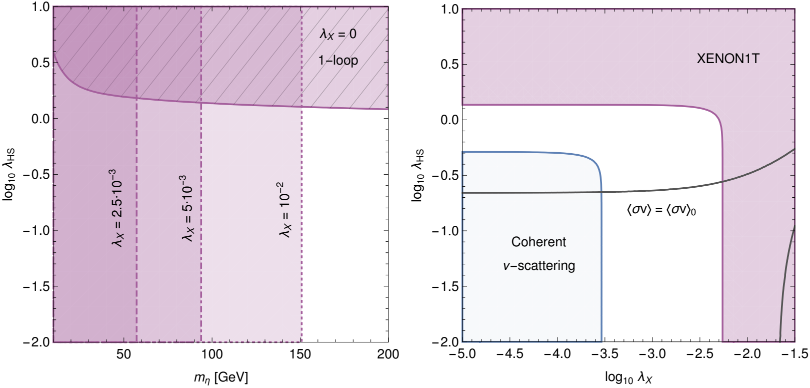
At one-loop level the explicit breaking of the global symmetry by the mass term m_η manifests in a non-vanishing term in the $t \to 0$ limit, estimated in [C. Gross, O. Lebedev and T. Toma, arXiv:1708.02253] as:

$$\sigma_{\rm SI}^{1-\rm loop} \approx \frac{\sin^2\alpha}{64\pi^5} \frac{m_N^4 f_N^2}{m_{h^0}^4 v^2} \frac{m_{H^0}^2 m_\eta^2}{w^6}$$



Direct detection

The explicit symmetry breaking coupling λ_X becomes relevant at $\lambda_X \gtrsim 10^{-3} - 10^{-2}$



Indirect detection

- Contrary to the direct detection cross section, the annihilation cross section $\eta\eta \to$SM does not vanish in the limit of zero incoming three-momentum, $\sqrt{s} \to 2m_\eta$:

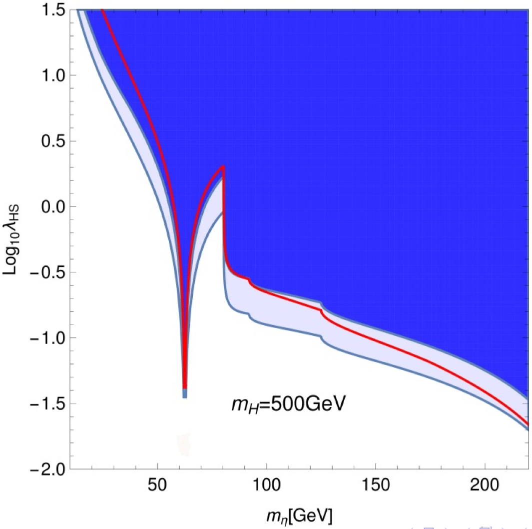
$$v_{\rm rel} \cdot \sigma_{\eta\eta\to\bar{b}b} = \frac{N_c \lambda_{HS}^2 \sqrt{s}\; m_b^2 (s - 4m_b^2)^{3/2}}{4\pi (s - m_{h^0}^2)^2 (s - m_{H^0}^2)^2}.$$

- The strongest constraints for the pseudo-Goldstone DM model arise from indirect detection
- For N degenerate DM species ($O(N+1)/O(N)$ symmetry breaking), $\Omega_i h^2 \sim \langle \sigma v \rangle^{-1}$, thus the annihilation cross section must scale as $\langle \sigma v \rangle \sim N$.
- The indirect detection signal strength for a single species scales as $n_i^2 \langle \sigma v \rangle \sim N^{-2} \times N \sim N^{-1}$.
- Hence the total rate scales as N times the rate for a single species: $N \times N^{-1}$, *i.e.* the indirect detection signal rate is independent of the multiplicity of the GB-multiplet.

Indirect detection

Fermi-LAT exclusion limit (dark blue) from observation of dwarf spheroidal satellite galaxies, arXiv:1611.03184, and 10-year projection (light blue) 1605.02016.

Red line = correct DM abundance.



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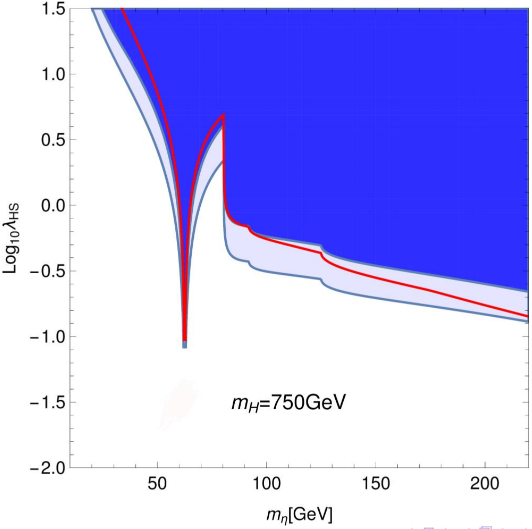

Conclusions

- Pseudo-Goldstone bosons of a spontaneously broken global symmetry are an attractive candidate for a thermal relic (WIMP) dark matter particle.
- The direct detection cross section vanishes in the non-relativistic limit at tree-level.
- Additional explicit symmetry breaking couplings and/or one-loop corrections will induce a non-vanishing cross section in the $t \to 0$ limit, but the cross section remains suppressed in comparison to a vanilla WIMP.
- Indirect detection signal is not suppressed, and the model is testable with future data up to a few hundred GeV (m_D).

Backup: Higgs invisible decay width

$$\Gamma_{h^0\to\eta\eta} = \frac{\lambda^2_{h^0\eta\eta}}{32\pi m_{h^0}}\sqrt{1-\frac{4m_\eta^2}{m_{h^0}^2}},$$

$$\lambda_{h^0\eta\eta} = \frac{(\lambda_{HS}-\lambda_X)m^2_{h^0}v}{\cos\alpha(m^2_{h^0}-m^2_{H^0})} + 2\lambda_X v\cos\alpha.$$

Backup: Annihilation cross sections

$$\sigma_{\eta\eta\to\bar{f}f} = \frac{N_c m_f^2 \beta_f^3}{8\pi\beta_\eta (s - m_{h^0}^2)^2 (s - m_{H^0}^2)^2} \times \left[(\lambda_{HS} + \lambda_X)s - 2\lambda_X \left(s_\alpha^2 m_{h^0}^2 + c_\alpha^2 m_{H^0}^2\right)\right]^2,$$

$$\beta_x \equiv \sqrt{1 - \frac{4m_x^2}{s}}.$$

$$\sigma_{\eta\eta\to VV} = \frac{\delta_V \beta_V \left(12 m_V^4 - 4 m_V^2 s + s^2\right)}{16\pi s \beta_\eta (s - m_{h^0}^2)^2 (s - m_{H^0}^2)^2} \times \left[(\lambda_{HS} + \lambda_X)s - 2\lambda_X \left(s_\alpha^2 m_{h^0}^2 + c_\alpha^2 m_{H^0}^2\right)\right]^2,$$

where $\delta_V = 1,\ 1/2$ for $W^\pm$ and Z.

Backup: Annihilation cross sections

$$\sigma_{\eta\eta\to h^0 h^0} = \frac{\beta_{h^0}}{32\pi s \beta_\eta}\left[\frac{16\lambda^4_{\eta\eta h^0}}{(s-2m^2_{h^0})^2}\right.$$
$$+\left(\lambda_{\eta\eta h^0 h^0} + \frac{\lambda_{h^0 h^0 h^0}\lambda_{\eta\eta h^0}}{s-m^2_{h^0}} + \frac{\lambda_{h^0 h^0 H^0}\lambda_{\eta\eta H^0}}{s-m^2_{H^0}}\right)^2$$
$$\left.-\frac{8\lambda^2_{\eta\eta h^0}}{s-2m^2_{h^0}}\left(\lambda_{\eta\eta h^0 h^0} + \frac{\lambda_{h^0 h^0 h^0}\lambda_{\eta\eta h^0}}{s-m^2_{h^0}} + \frac{\lambda_{h^0 h^0 H^0}\lambda_{\eta\eta H^0}}{s-m^2_{H^0}}\right)\right].$$

Backup: Direct detection recoil spectrum

Left: Pseudo-GB, $m_\eta = 100$ GeV, right: vanilla Higgs portal WIMP, $m_D = 100$ GeV.