Direct and indirect probes of Goldstone dark matter

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Harmonia meeting 2018

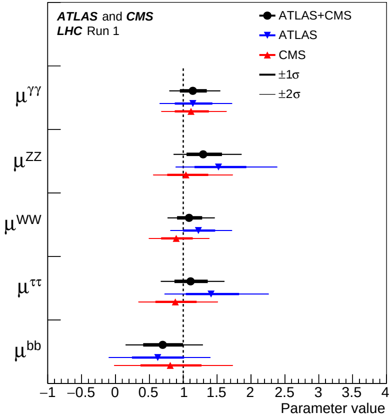
In praise of the Standard Model

Current formulation finalised in the 70's predicted:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

What's up at the LHC?

- Higgs looks SM-like
- No significant deviation from the SM
- No signs of new physics
- Is that all there is?



JHEP 08 (2016) 045

In criticism of the Standard Model

What is missing:

- An explanation for the Femion mass hierarchy
- EW vacuum stability
- Baryon asymmetry in the universe
  - Strongly first order phase transition
  - Sufficient amount of CP-Violation
- No suitable candidate for Dark Matter

Dark Matter

How we know it exists:

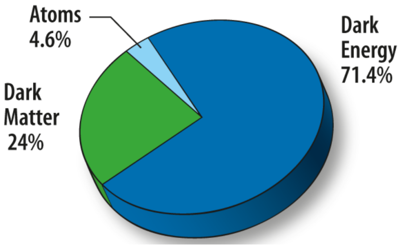
- Galaxy Clusters
- Galactic Rotation Curves
- The CMB
- The Bullet Cluster
- Large-Scale Structure Formation

Fritz Zwicky in 1933 using the Virial theorem

WIMP Dark Matter

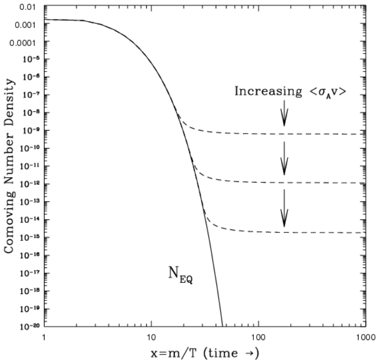
Characteristics:

- Cold (non-relativistic at the onset of galaxy formation)
- Non-baryonic
- Neutral & weakly interacting
- Stable due to a discrete symmetry



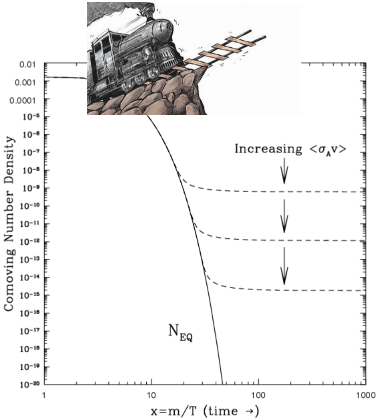
$$\underbrace{\mathrm{DM\ DM} \to \mathrm{SM\ SM},}_{\text{pair annihilation}} \quad \underbrace{\mathrm{DM} \not\to \mathrm{SM}, \ldots}_{\text{stable}}$$

WIMP Dark Matter freeze-out



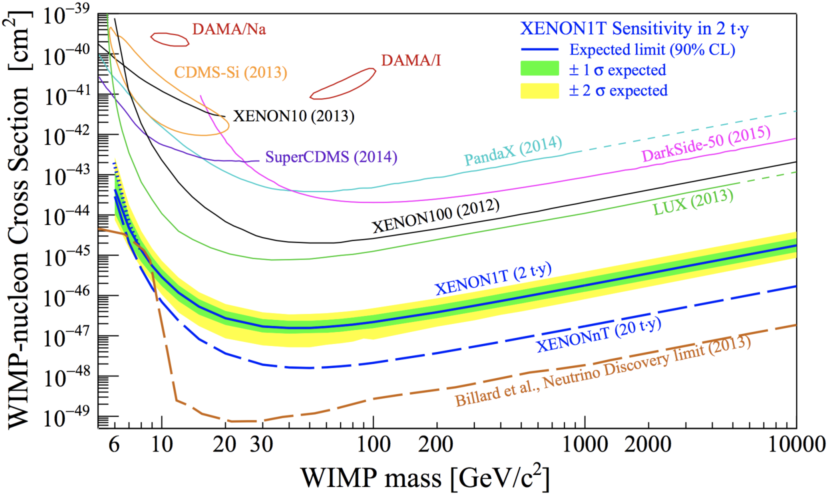
Observed relic density: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

WIMP Dark Matter freeze-out



Observed relic density: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

XENON1T suffocating WIMP



Goldstone Dark Matter

WIMPs escaping direct detection

A Goldstone Dark Matter example

The SM Higgs doublet and a scalar singlet:

$$H = \begin{pmatrix} \pi^+ \\ \frac{1}{\sqrt{2}}(v + \phi + i\pi^0) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(w + \sigma + i\eta),$$

The U(1)-symmetric potential:

$$\begin{aligned} V(H,S) &= \mu_H^2 H^\dagger H + \mu_S^2 |S|^2 + \lambda_H (H^\dagger H)^2 + \lambda_{HS}(H^\dagger H)|S|^2 + \lambda_S |S|^4 \\ &\quad - \frac{1}{2}\mu_X^2 (S^2 + S^{*2}) - \frac{\lambda_X}{2}(H^\dagger H)(S^2 + S^{*2}), \end{aligned}$$

Possible underlying dynamics

$$\mathcal{L} = \partial_\mu S \partial^\mu S^* - V(S) + \bar{\psi}(i\gamma^\mu \partial_\mu - m_\psi)\psi + \left(g_P \bar{\psi} i\gamma_5 \psi S + \mathrm{h.c}\right)$$

where

$$V(S) = \mu^2 |S|^2 - \lambda |S|^4$$

Integrating out the heavy fermion ψ:

$$V_{\rm eff}(S) = \mu_S^2 |S|^2 + \lambda_S |S|^4 + \widetilde{\mu}_X^2 \eta^2 + \widetilde{\lambda}_X \eta^4,$$

The induced symmetry-breaking couplings:

$$\widetilde{\lambda}_X \sim g_P^4, \qquad \widetilde{\mu}_X^2 \sim g_P^2,$$

The physical particles

$$V(H,S) = \mu_H^2 H^\dagger H + \mu_S^2|S|^2 + \lambda_H(H^\dagger H)^2 + \lambda_{HS}(H^\dagger H)|S|^2 + \lambda_S|S|^4 -\frac{1}{2}\mu_X^2(S^2+S^{*2}) - \frac{\lambda_X}{2}(H^\dagger H)(S^2+S^{*2}),$$

The mass eigenstates

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \sigma \end{pmatrix} \quad \text{with} \quad \tan(2\alpha) = -\frac{(\lambda_{HS}-\lambda_X)vw}{\lambda_H v^2 - \lambda_S w^2}$$

with eigenvalues

$$\begin{aligned} m_\eta^2 &= 2\mu_X^2 + v^2\lambda_X \\ m_h^2 &= (\lambda_H v^2 + \lambda_S w^2) - (\lambda_S w^2 - \lambda_H v^2)/\cos(2\alpha), \\ m_H^2 &= (\lambda_H v^2 + \lambda_S w^2) + (\lambda_S w^2 - \lambda_H v^2)/\cos(2\alpha). \end{aligned}$$

Relic density

Possible annihilation channels: $\eta\eta \to h^0 h^0, VV, \bar{f}f$

Assuming $m_\eta < m_{H^0}$: $\eta\eta \nrightarrow h^0 H^0, H^0 H^0$

Total annihilation x-section: $\sigma(\eta\eta \to SM) \leq \langle \sigma v_{\rm rel} \rangle_0 \simeq 3 \cdot 10^{-26}\,{\rm cm}^3/s$

Invisible Higgs decays

If $m_\eta < m_h/2$:

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

where

$$\lambda_{h\eta\eta} = \frac{(\lambda_{HS} - \lambda_X) m_h^2 v}{\cos\alpha (m_h^2 - m_H^2)} + 2\lambda_X v \cos\alpha$$

Invisible Higgs decays bound:

$$\mathrm{Br}(h^0 \to \mathrm{inv}) \leq 0.23$$

Direct detection bounds

At tree level:

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

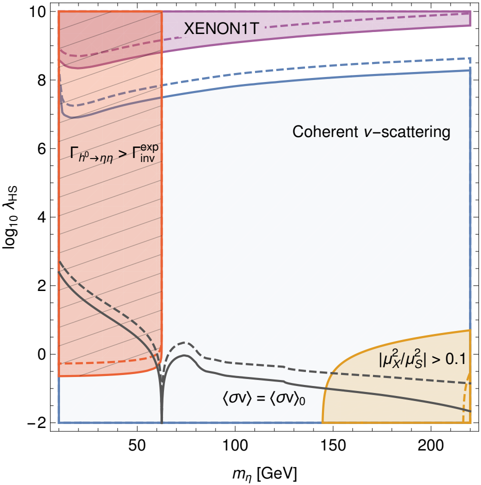
Reduced mass of η-nucleon system :

$$\mu_R = m_N m_\eta / (m_N + m_\eta)$$

At zero momentum transfer

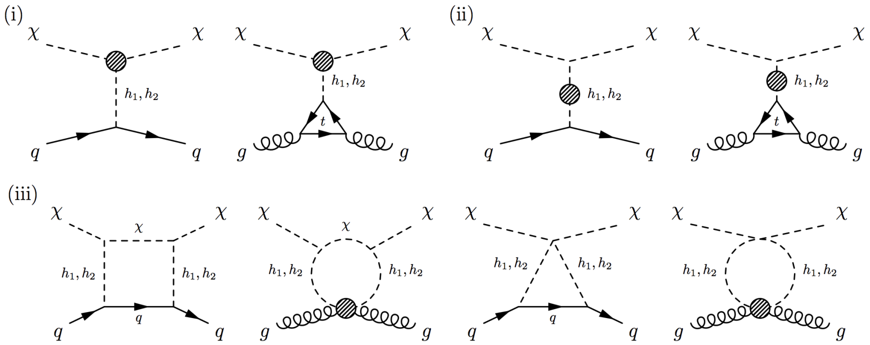
$$\lambda_{\mathrm{eff}} = \underbrace{\frac{\lambda_{HS}\, t}{(m_h^2 - t)(m_H^2 - t)}}_{\text{vanishes when } t\to 0} - \underbrace{\frac{2\lambda_X \left[\sin^2\alpha(m_h^2 - t/2) + \cos^2\alpha(m_H^2 - t/2)\right]}{(m_h^2 - t)(m_H^2 - t)}}_{\text{vanishes when } \lambda_X\to 0}$$

At tree-level ($\lambda_X = 0$)



$$m_H = 500,\ 750\ \text{GeV}$$

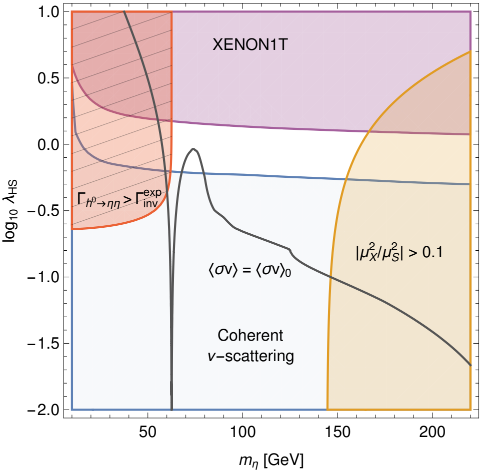
The 1-loop effect



$$\sigma_{\mathrm{SI}}^{1-\mathrm{loop}} \approx \frac{\sin^2\alpha}{64\pi^5}\frac{m_N^4 f_N^2}{m_h^4 v^2}\frac{m_H^2 m_\eta^2}{w^6}$$

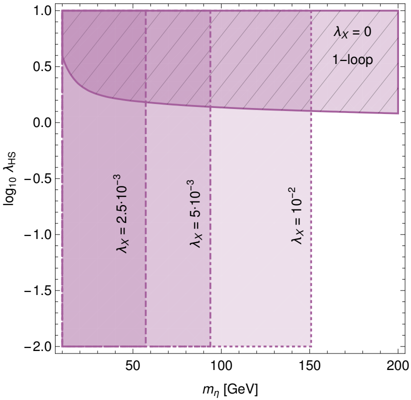
arXiv:1810.08139 [hep-ph]

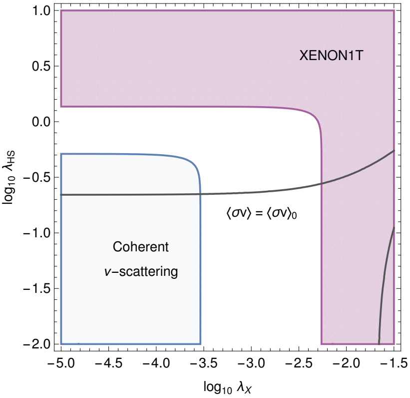
At 1-loop level ($\lambda_X = 0$)



$$m_H = 500 \text{ GeV}$$

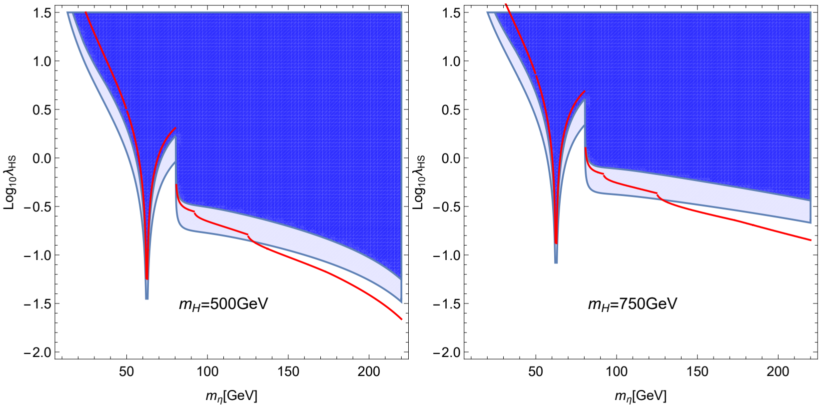
Non-zero values of λ_X





$m_\eta = 100$ GeV

Indirect detection ($\lambda_X = 0$)



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

$v\sigma(\eta\eta \to WW) \approx 2 v\sigma(\eta\eta \to b\bar{b})$

Summary

- GDM: a complex singlet scalar with U(1) global symmetry
- With momentum-dependent interactions
- Obtains the correct DM relic density
- Remains out of the reach of current direct-search experiments
- Indirect detections can already provide relevant constraints
- Through EWSB dynamics, tie together the origin of both visible and dark matter