Phase Transitions & Gravitational Waves in the $\mathbb{Z}_3$ Pseudo-Goldstone Dark Matter

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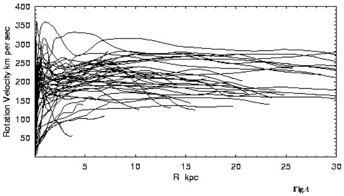
Euroopa Liit
Euroopa
Regionaalarengu Fond

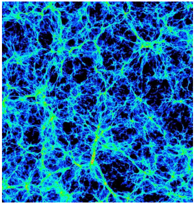
Eesti tuleviku heaks

2 Dark Matter Exists…

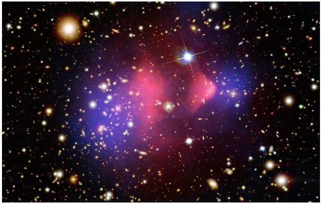
- Dark matter constitutes 27% of the energy content of the Universe
- Plenty of evidence: rotation curves of galaxies, the CMB, cosmological large scale structure, Bullet Cluster



Sofue et al. (1999)

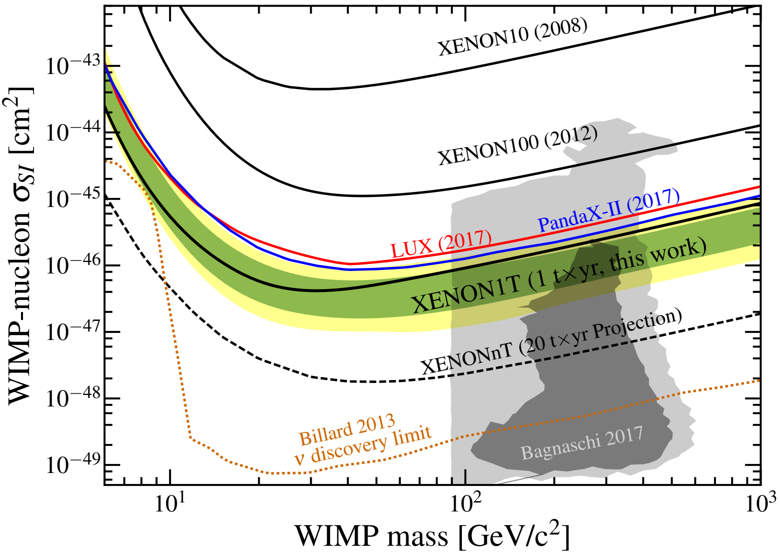


CFA



MPA

…But Has Not Been Detected



Xenon1T Collaboration, arXiv:1805.12562

Motivation

- Direct detection puts strong bounds on usual WIMP dark matter
- Is there something else or does the WIMP still work?
- Pseudo-Goldstone dark matter produces a negligible direct detection signal

  Gross, Lebedev, Toma, arXiv:1708.02253
- Can it produce gravitational wave signals via first-order cosmic phase transitions?

5 Pseudo-Goldstone Dark Matter

- Higgs boson H and complex singlet S
- V is invariant under $U(1)$ symmetry $S \to e^{i\alpha} S$, broken only softly (e.g. into $\mathbb{Z}_2$)
- Breaking $U(1)$ by a vacuum expectation value for s produces a pseudo-Goldstone particle

  Chiang, Ramsey-Musolf, Senaha, arXiv:1707.09960;

  Gross, Lebedev, Toma, arXiv:1708.02253
- Lots of phenomenological interest

  Alanne, Heikinheimo, Keus, Koivunen, Tuominen, arXiv:1812.05996;

  Huitu, Koivunen, Lebedev, Mondal, Toma, arXiv:1812.05952

6 Pseudo-Goldstone Dark Matter

$$V = V_0 + V_{\text{soft}}$$

with

$$V_0 = \frac{1}{2}\mu_H^2|H|^2 + \frac{1}{2}\mu_S^2|S|^2 + \frac{1}{2}\lambda_H|H|^4 + \frac{1}{2}\lambda_{HS}|H|^2|S|^2 + \frac{1}{2}\lambda_S|S|^4$$

- For explicit $U(1) \to \mathbb{Z}_2$ breaking,

$$V_{\text{soft}} = \frac{1}{4}\mu_S'^2(S^2 + S^{*2})$$

- This $\mathbb{Z}_2$ is $S \to -S$
- *Another* $\mathbb{Z}_2$ symmetry: $S \to S^\dagger$

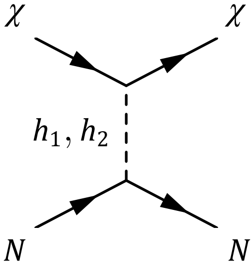
7 Pseudo-Goldstone Dark Matter

In our vacuum, we decompose the fields as

$$S = \frac{v_s + s + i\chi}{\sqrt{2}}, \qquad H = \begin{pmatrix} 0 \\ \frac{v_h + h}{\sqrt{2}} \end{pmatrix}$$

- $\mathbb{Z}_2$ symmetry $S \to S^\dagger$ the same as $\chi \to -\chi$
- Pseudo-Goldstone χ is dark matter
- h and s mix into $h_1 \equiv h_{\mathrm{SM}}$ and h_2
- $v_h = v = 246.22$ GeV, $m_1 = m_h = 125.09$ GeV

8 Direct Detection



$$\propto \sin\theta\cos\theta\left(\frac{m_2^2}{t-m_2^2}-\frac{m_1^2}{t-m_1^2}\right)\simeq 0$$

- Dark matter χ interacts with SM particles *only* via h_1 and h_2
- Amplitude suppressed by small transfer momentum t

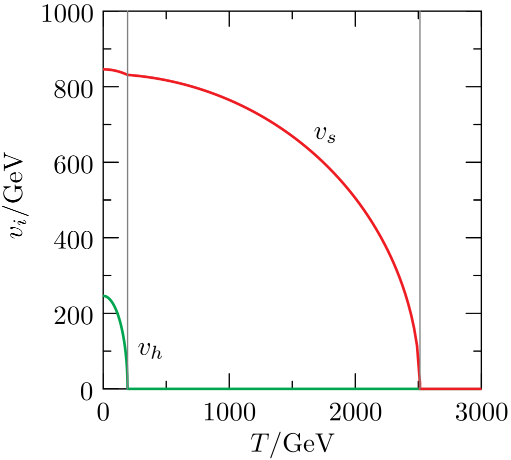
9 Direct Detection

- Amplitude suppressed by small transfer momentum t
- Small contribution at one-loop level
  Ishiwata & Toma, arXiv:1810.08139;

  Azevedo, Duch, Grzadkowski, Huang, Iglicki, Santos, arXiv:1810.06105

10 Pseudo-Goldstone Dark Matter

- In the original pseudo-Goldstone dark matter model, all phase transitions are *second*-order



K.K. & Raidal, arXiv:1901.03333

$\mathbb{Z}_3$ Complex Scalar Singlet Model

The scalar potential

$$V = \mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{SH}|S|^2|H|^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3})$$

is invariant under the $\mathbb{Z}_3$ transformation

- The Higgs doublet $H \to H$
- $S \to e^{i2\pi/3}S$

and also under $S \to S^\dagger$

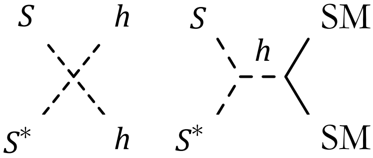
- Explicit breaking $U(1) \to \mathbb{Z}_3$

Ma, arXiv:0708.3371; Bélangèr, K.K., Pukhov, Raidal, arXiv:1211.1014; Arcadi, Queiroz & Siqueira, arXiv:1706.02336; Cai & Spray, arXiv:1807.00832; Hektor, Hryczyk, K.K., arXiv:1901.08074

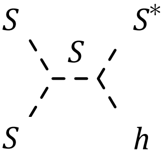
12 $\mathbb{Z}_3$ Complex Scalar Singlet Model

- Two phases that produce a dark matter candidate
- $\mathbb{Z}_3$ symmetry stabilises S as a dark matter candidate
- If $\mathbb{Z}_3$ is broken, the $S \to S^\dagger$ symmetry still stabilises the imaginary part χ of S

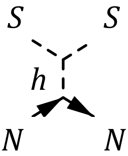
13 Phenomenology with *Unbroken* $\mathbb{Z}_3$



annihilation

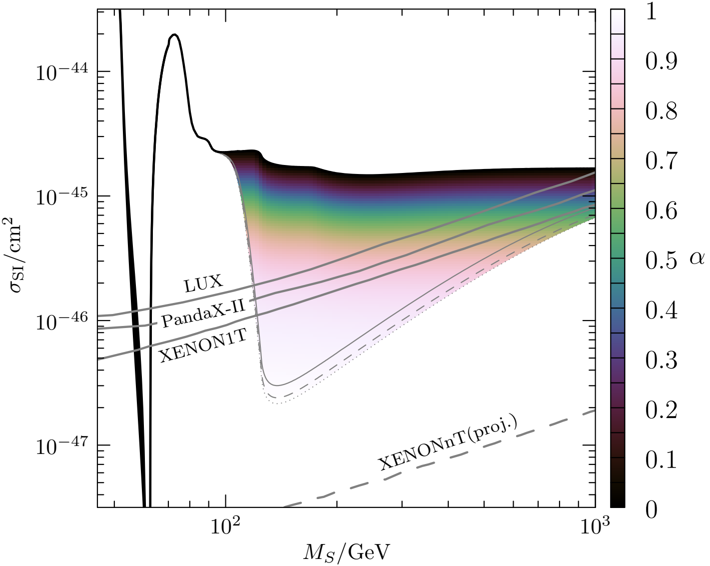


semi-annihilation



direct detection

Direct Detection with *Unbroken* $\mathbb{Z}_3$



Hektor, Hryczyk, K.K., arXiv:1901.08074

15 Minima & Masses

The stationary point conditions are

$$h\left(2\lambda_H h^2 + 2\mu_H^2 + \lambda_{SH} s^2\right) = 0,$$
$$s\left(4\lambda_S s^2 + 3\sqrt{2}\mu_3 s + 4\mu_S^2 + 2\lambda_{SH} h^2\right) = 0$$

- Fully symmetric $(0, 0)$
- EW-symmetry-breaking $(v_h, 0)$
- $U(1)$-breaking $(0, v_s)$
- Mixed (v_h, v_s)

16 Minimum & Masses

- h and s mix into $h_1 \equiv h_{\mathrm{SM}}$ and h_2
- $v_h \equiv v = 246.22$ GeV, $m_1 = m_h = 125.09$ GeV
- The mass of the pseudoscalar χ is

$$m_\chi^2 = -\frac{9}{2\sqrt{2}}\mu_3 v_s$$

Constraints

- Unitarity & perturbativity
- Vacuum stability
- Globality of the (v_h, v_s) vacuum
- Dark matter relic density
  $\Omega_{\rm DM} = 0.120 \pm 0.001$

  Planck Collaboration, arXiv:1807.06209

- Higgs invisible $BR_{\rm inv} < 0.17$ from
  $h_1 \to \chi\chi$ and $h_1 \to h_2 h_2$
- Mixing angle of h and s
  $|\sin\theta| < 0.5$ for $m_2 < m_1$ and
  $|\sin\theta| < 0.36$ for $m_2 > m_1$

  Robens & Stefaniak, arXiv:1601.07880

18 Higgs Invisible Width

If $m_x \leqslant m_h/2$, then Higgs invisible width

$$\Gamma_{h_1 \to xx} = \frac{g_{hxx}^2}{32\pi\, m_h}\sqrt{1 - 4\frac{m_x^2}{m_h^2}}$$

and

$$\mathrm{BR}_{\mathrm{inv}} = \frac{\Gamma_{h_1 \to \chi\chi} + \Gamma_{h_1 \to h_2 h_2}}{\Gamma_{h_1 \to \mathrm{SM}} + \Gamma_{h_1 \to \chi\chi} + \Gamma_{h_1 \to h_2 h_2}}$$

with

$$g_{h1\chi\chi} = \frac{m_h^2 + m_\chi^2}{v_S}, \qquad g_{h1h_2h_2} = \frac{1}{vv_S}\Big[\Big(\frac{1}{2}m_h^2 + m_2^2\Big) \times \big(v\cos\theta + v_S\sin\theta\big) + \frac{1}{6}vm_\chi^2\cos\theta\Big]\sin 2\theta$$

19 Globality of the (v_h, v_s) Vacuum

Globality of the (v_h, v_s) vacuum implies that

$$m_\chi^2 < \frac{9m_1^2 m_2^2}{m_1^2 \cos^2\theta + m_2^2 \sin^2\theta}$$

- For $\sin\theta \approx 0$, $m_\chi \lesssim 3m_2$

20 Thermal Corrections

In the high temperature approximation, the mass terms acquire thermal corrections:

$$\mu_H^2(T) = \mu_H^2 + c_H T^2, \quad \mu_S^2(T) = \mu_H^2 + c_S T^2$$

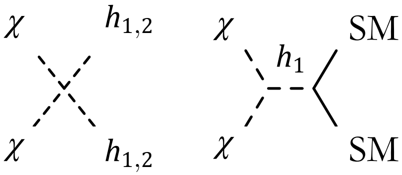
with the coefficients

$$c_H = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_H + 4\lambda_{SH}\right),$$
$$c_S = \frac{1}{6}\left(2\lambda_S + \lambda_{SH}\right)$$

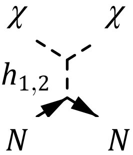
Parameter Space Scan

- Free parameters m_χ, m_2, $\sin\theta$ and v_s
- Fix v_s by relic density
- $m_\chi \in [25, 1000]$ GeV
- $m_2 \in [25, 4000]$ GeV
- $\sin\theta \in [-0.5, 0.5]$ GeV
- We use micrOMEGAs for relic density and CosmoTransitions for phase transitions

22 Phenomenology with *Broken* $\mathbb{Z}_3$

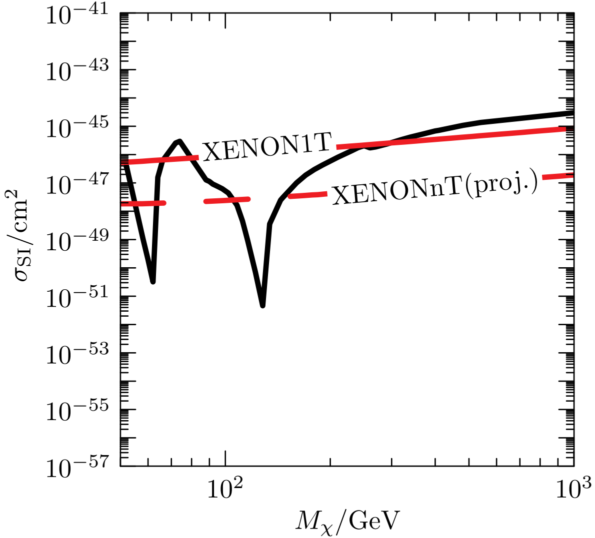


annihilation



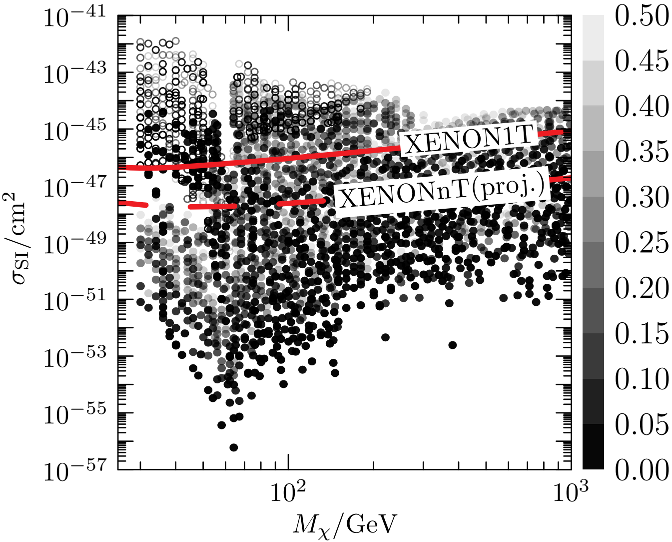
direct detection

Direct Detection



- $m_2 = 250$ GeV, $\sin\theta = 0.2$
- Resonances at $m_h/2$ and $m_2/2$

Direct Detection



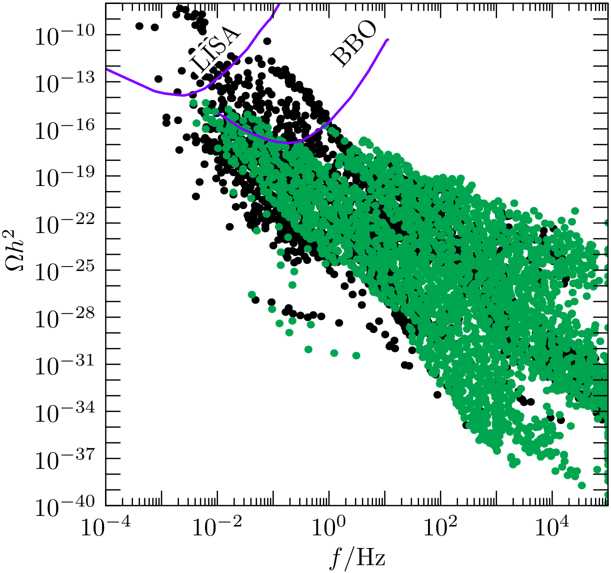
- σ_{SI} roughly proportional to μ_3

Gravitational Wave Signals

- First-order phase transitions produce a gravitational wave signal

  E.g. Weir, arXiv:1705.01783

- Largest signals due to the $(0, 0) \to (0, v_s)$ transition because of the cubic barrier


LISA
BBO
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-34}
10^{-37}
10^{-40}
Ωh^2
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
f/Hz

Conclusions

- Direct detection puts strong bounds on WIMP dark matter
- Pseudo-Goldstone dark matter has a suppressed direct detection cross section
- $\mathbb{Z}_3$ pseudo-Goldstone model has first-order phase transitions and can produce a potentially measurable stochastic gravitational wave background