Scalar Singlet Dark Matter and Gamma Lines

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We point out the possibility to test the simplest scalar dark matter model at gamma-ray telescopes. We discuss the relevant constraints and show the predictions for direct detection, gamma line searches and LHC searches. Since the final state radiation processes are suppressed by small Yukawa couplings one could observe the gamma lines from dark matter annihilation.

INTRODUCTION

The possibility to describe the properties of the dark matter (DM) in the Universe using a particle in models for physics beyond the Standard Model (SM) of particle physics has called the full attention of the high-energy physics community. Currently, we know basically nothing about the dark matter in the Universe apart from that the DM relic density should be \( \Omega_{\text{DM}} h^2 = 0.12 \). We have, however, a series of important constraints coming from many types of experiments. Direct detection experiments constrain the interactions with the Standard Model fermions. One important “smoking gun” for any dark matter model would be the existence of at least one gamma line from dark matter annihilation which can be used to predict the dark matter mass.

The testability of a dark matter model is a complex task. In this Letter we revisit the simplest scalar dark matter model [1] where the Standard Model is extended by a real scalar field. In this dark matter model, one can relate the predictions for direct and indirect experiments once we use the relic density constraints. Therefore, one can hope to test this model at different experiments. See Refs. [2–18] for previous studies of this model.

In this Letter we investigate the annihilation into gamma rays in the scalar singlet model, and our main aim is to investigate the visibility of the gamma lines. In this model one can have only two gamma lines coming from the annihilation into two photons and into \( Z \gamma \). In this context the dark matter annihilation into two Standard Model fermions and a photon is suppressed by the small bottom Yukawa coupling. This is the so-called final state radiation channel which typically spoils the visibility of the gamma line. Since these processes are suppressed one can hope to observe clearly the gamma lines at gamma ray telescopes such as Fermi-LAT.

Our main result is that in the simplest scalar dark matter model one can observe the gamma lines when one has a good energy resolution. This is a striking result which has been overlooked in past studies and is crucial to test this model at gamma ray experiments.

SCALAR SINGLET DARK MATTER

In the simplest scalar dark matter model [1] the Standard Model is extended by one real scalar singlet \( S \), and the relevant part of the Lagrangian reads as

\[
-\mathcal{L} \supset \frac{1}{2} m_S^2 S^2 + \lambda_S S^4 + \lambda_p H^\dagger H S^2,
\]

where \( H \) is the SM Higgs. After electroweak symmetry breaking the mass of the scalar dark matter is given by \( M_S^2 = m_S^2 + \lambda_p \nu_0^2 \), where \( \nu_0 = 246 \text{ GeV} \) is the SM Higgs vacuum expectation value. In order to guarantee the dark matter stability a discrete \( Z_2 \) symmetry is imposed under which only \( S \) is odd, i.e., \( S \rightarrow -S \).

This model has only one extra degree of freedom and only two parameters, the portal coupling \( \lambda_p \) and the physical dark matter mass \( M_S \). The quartic coupling \( \lambda_S \) does not play any role in DM phenomenology. Therefore, using the bounds from relic density, direct detection and indirect detection one can show in a simple way the allowed parameter space in agreement with all experiments. See Refs. [2–18] for the study of phenomenological and cosmological aspects of this model.

To discuss the testability of this model, we focus on the low mass region \( M_S < M_h/2 \) where one could hope to test the model at the LHC or at future colliders through the invisible SM Higgs decay. For \( M_S > M_h/2 \), it is very challenging to test this model at colliders; see Ref. [19] for a recent discussion.

In this low mass region, the main annihilation channels of \( S \) are into two SM fermions \( f \), for which the cross section is given by

\[
\sigma(SS \rightarrow ff) = \frac{\lambda_p^2 M_f^2 (s - 4M_f^2)^{3/2}}{2\pi \sqrt{s - 4M_f^2} ((s - M_S^2)^2 + M_S^4)}.
\]

Below threshold, the total decay width of the SM Higgs includes the invisible decay to \( S \),

\[
\Gamma_h = \Gamma_h^{\text{SM}} + \Gamma(h \rightarrow SS),
\]

where

\[
\Gamma(h \rightarrow SS) = \frac{\lambda_p^2 \nu_0^2}{8\pi M_h^2} (M_h^2 - 4M_S^2)^{1/2}.
\]
The predicted values for the spin-independent nucleon–DM cross section as a function of the dark matter mass $M_S$ assuming that $S$ makes up the full DM relic density. The LUX [22] (blue dashed) and projected XENON1T [23] (green dotted) bounds cut into the parameter space.

Knowing the results from the relic density and the constraints from direct detection experiments we are ready to study the predictions for indirect detection. In Fig. 3 we show the predictions for the annihilation into $bb$ (blue solid curve) as well as the current corresponding bound from Fermi-LAT [24] (green dotted curve). Notice that the Fermi-LAT $bb$-limit rules out the

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1 Notice that the bound on the direct detection cross section assumes that the DM candidate under consideration makes up the full DM relic density.
region for $M_S > 62.8$ GeV. Therefore, only the range $53$ GeV $\leq M_S \leq 62.8$ GeV is allowed by the relic density, direct detection and $b\bar{b}$ constraints. This information is crucial to understand the predictions for the annihilation into gamma rays in this model, which we study in detail in the next section.

**GAMMA LINES**

In this model one can have two possible gamma lines from dark matter annihilation,

$$SS \rightarrow \gamma\gamma, Z\gamma.$$  

In order to investigate the visibility of these gamma lines one has to understand the correlation between the predictions for final state radiation and the annihilation into gamma lines. The final state radiation in the low mass window is suppressed by the small Yukawa coupling of the bottom quark, which is the dominant contribution. To the annihilation into gamma lines, however, all charged SM fields contribute. Therefore, one can observe easily the $\gamma\gamma$ line in this scenario.

In Fig. 3 we show the velocity-averaged cross section times velocity for the dark matter annihilation into two gammas, and corresponding limit from Fermi-LAT [26]. The $Z\gamma$ line is at $E_\gamma \approx 29.2$ GeV when $M_S = 62.5$ GeV (the benchmark scenario we use later), and is therefore more difficult to observe due to secondary photons from pion decays. However, the visibility of the $\gamma\gamma$ line is unobstructed. As in the case of the annihilation into $b\bar{b}$, the region above 62.8 GeV is ruled out. Notice that the region around the resonance cannot be tested in direct searches but can be tested in indirect detection experiments. This means that the complementarity of these experiments is crucial to test or rule out this model.

In Fig. 4 we show the predictions for the final state radiation and the gamma line assuming a Gaussian distribution for the detector resolution, for 1% (green solid), 5% (red dashed), and 10% (blue dotted) energy resolution. We use $M_S = 62.5$ GeV and $\lambda_p = 9.1 \times 10^{-5}$, in agreement with today’s relic density. For these values of the parameters, the $Z\gamma$ line is at $x_\gamma = 0.47$. For the plot, the $J$-factor for the R3 region-of-interest is used, given by the Fermi-LAT collaboration to be $J_{\text{ann}} = 13.9 \times 10^{27}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ [27].

![Figure 4. Spectrum of the gamma line from $SS \rightarrow \gamma\gamma$ for 1% (green solid), 5% (red dashed), and 10% (blue dotted) energy resolution. We use $M_S = 62.5$ GeV and $\lambda_p = 9.1 \times 10^{-5}$, in agreement with today’s relic density. For these values of the parameters, the $Z\gamma$ line is at $x_\gamma = 0.47$. For the plot, the $J$-factor for the R3 region-of-interest is used, given by the Fermi-LAT collaboration to be $J_{\text{ann}} = 13.9 \times 10^{27}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ [27].](image)

In Fig. 5 we show the invisible branching ratio, $BR(h \rightarrow SS)$, as a function of $M_S$. The blue dashed line corresponds to the CMS upper limit [21]. The blue solid part of the curve is excluded by the LUX experiment [22]. The red line shows the exclusion potential of XENON1T [23]. The limit on $b\bar{b}$ from Fermi-LAT [24] (green dot) constrains the region around the resonance and sets a lower limit in the invisible branching ratio.

![Figure 5. Invisible branching ratio, $BR(h \rightarrow SS)$, as a function of $M_S$. The blue dashed line corresponds to the CMS upper limit [21]. The blue solid part of the curve is excluded by the LUX experiment [22]. The red line shows the exclusion potential of XENON1T [23]. The limit on $b\bar{b}$ from Fermi-LAT [24] (green dot) constrains the region around the resonance and sets a lower limit in the invisible branching ratio.](image)
rect detection and indirect detection we show in Fig. 5 the predicted branching ratio for the invisible decay of the Standard Model Higgs. In blue we show the current LHC bound from CMS [21]. Notice that the direct detection bound from LUX rules out the region where BR(\(h \rightarrow SS\)) > 10^{-1}. This means that if the invisible decay width of the Higgs is large this model can be ruled out. Notice that there is a chance to test this model at LHC or future colliders if the invisible decay is not too small.

SUMMARY

We have revisited the simplest model for scalar dark matter discussing all constraints coming from relic density, direct and indirect detection experiments, and the LHC. We have showed the allowed parameter space and discussed the possibilities to test this simple model, emphasizing the complementarity of all dark matter experiments. Additionally, we discussed the predictions for the annihilation into gamma rays in agreement with all constraints.

For the first time we demonstrated that the gamma line can actually be observed in this model. This is due to the fact that the final state radiation cross section is suppressed by the small bottom Yukawa coupling. Therefore, if the low mass version of this model is realized in nature one can clearly observe a gamma line in near future at gamma ray telescopes such as Fermi-LAT [26] and the GAMMA-400 [28] experiments.

Acknowledgments: The work of P.F.P. is partially funded by the Gordon and Betty Moore Foundation through Grant 776 to the Caltech Moore Center for Theoretical Cosmology and Physics and Walter Burke Institute for Theoretical Physics, Caltech, Pasadena CA. P.F.P. thanks the theory group at Caltech for hospitality at the end of this project.

[1] V. Silveira and A. Zee, “Scalar Phantoms,” Phys. Lett. B 161 (1985) 136.
[2] J. McDonald, “Gauge singlet scalars as cold dark matter,” Phys. Rev. D 50 (1994) 3637 [arXiv:hep-ph/9702143].
[3] C. P. Burgess, M. Pospelov and T. ter Veldhuis, “The minimal model of nonbaryonic dark matter: a singlet scalar,” Nucl. Phys. B 619 (2001) 709 [arXiv:hep-ph/0011335].
[4] D. O’Connell, M. J. Ramsey-Musolf and M. B. Wise, “Minimal Extension of the Standard Model Scalar Sector,” Phys. Rev. D 75 (2007) 037701 [arXiv:hep-ph/0611014].
[5] V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf and G. Shaughnessy, “LHC Phenomenology of an Extended Standard Model with a Real Scalar Singlet,” Phys. Rev. D 77 (2008) 035005 [arXiv:0706.4311 [hep-ph]].
[6] X. G. He, T. Li, X. Q. Li, J. Tandean and H. C. Tsai, “Constraints on Scalar Dark Matter from Direct Experimental Searches,” Phys. Rev. D 79 (2009) 023521 [arXiv:0811.0658 [hep-ph]].
[7] M. Farina, D. Pappadopulo and A. Strumia, “CDMS stands for Constrained Dark Matter Singlet,” Phys. Lett. B 688 (2010) 329 [arXiv:0912.5038 [hep-ph]].
[8] W. L. Guo and Y. L. Wu, “The Real singlet scalar dark matter model,” JHEP 1010 (2010) 083 [arXiv:1006.2518 [hep-ph]].
[9] S. Profumo, L. Usaldi and C. Wainwright, “Singlet Scalar Dark Matter: monochromatic gamma rays and metastable vacua,” Phys. Rev. D 82 (2010) 123514 [arXiv:1009.5377 [hep-ph]].
[10] A. Djouadi, A. Falkowski, Y. Mambrini and J. Quevillon, “Direct Detection of Higgs-Portal Dark Matter at the LHC,” Eur. Phys. J. C 73 (2013) 2455 [arXiv:1205.3169 [hep-ph]].
[11] K. Cheung, Y. L. S. Tsai, P. Y. Tseng, C. T. Yuan and A. Zee, “Global Study of the Simplest Scalar Phantom Dark Matter Model,” JCAP 1210 (2012) 042 [arXiv:1207.4930 [hep-ph]].
[12] J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, “Update on scalar singlet dark matter,” Phys. Rev. D 88 (2013) 055025 [arXiv:1306.4710 [hep-ph]].
[13] L. Feng, S. Profumo and L. Usaldi, “Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines,” JHEP 1503 (2015) 045 [arXiv:1412.1105 [hep-ph]].
[14] H. Han and S. Zheng, “New Constraints on Standard Model with Scalar Dark Matter,” arXiv:1509.01765 [hep-ph].
[15] M. Kadastik, K. Kannike, A. Racioppi and M. Raidal, “Implications of the 125 GeV Higgs boson for scalar dark matter and for the CMSSM phenomenology,” JHEP 1205 (2012) 061 [arXiv:1112.3647 [hep-ph]].
[16] N. Khan and S. Rakshit, “Study of electroweak vacuum metastability with a singlet scalar dark matter,” Phys. Rev. D 90 (2014) 113008 [arXiv:1407.6015 [hep-ph]].
[17] E. Yaguna, “Gamma-rays from the annihilation of singlet scalar dark matter,” JCAP 0903 (2009) 003 [arXiv:0810.4267 [hep-ph]].
[18] F. Kahlhoefer and J. McDonald, “WIMP Dark Matter and Unitarity-Conserving Inflation via a Gauge Singlet Scalar,” arXiv:1507.03600 [astro-ph.CO].
[19] N. Craig, H. K. Lou, M. McCullough and A. Thalapillil, “The Higgs Portal Above Threshold,” arXiv:1412.0258 [hep-ph].
[20] P. A. R. Ade et al. [Planck Collaboration], “Planck 2013 results. XVI. Cosmological parameters,” Astron. Astrophys. 571 (2014) A16 [arXiv:1303.5076 [astro-ph.CO]].
[21] S. Chatrchyan et al. [CMS Collaboration], “Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes,” Eur. Phys. J. C 74 (2014) 2980 [arXiv:1404.1344 [hep-ex]].
[22] D. S. Akerib et al. [LUX Collaboration], “First results from the LUX dark matter experiment at the Sanford Underground Research Facility,” Phys. Rev. Lett. 112 (2014) 091303 [arXiv:1310.8214 [astro-ph.CO]].
[23] E. Aprile [XENON1T Collaboration], “The XENON1T Dark Matter Search Experiment,” Springer Proc. Phys. 148 (2013) 93 [arXiv:1206.6288 [astro-ph.IM]].
[24] M. Ackermann et al. [Fermi-LAT Collaboration], “Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data,” arXiv:1503.02641 [astro-ph.HE].

[25] J. Billard, L. Strigari and E. Figueroa-Feliciano, “Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments,” Phys. Rev. D 89 (2014) 023524 [arXiv:1307.5458 [hep-ph]].

[26] M. Ackermann et al. [Fermi-LAT Collaboration], “Updated search for spectral lines from Galactic dark matter interactions with pass 8 data from the Fermi Large Area Telescope,” Phys. Rev. D 91 (2015) 122002 [arXiv:1506.00013 [astro-ph.HE]].

[27] M. Ackermann et al. [Fermi-LAT Collaboration], “Search for gamma-ray spectral lines with the Fermi large area telescope and dark matter implications,” Phys. Rev. D 88 (2013) 082002 [arXiv:1305.5597 [astro-ph.HE]].

[28] N. P. Topchiev et al., “GAMMA-400 gamma-ray observatory,” [arXiv:1507.06246 [astro-ph.IM]].