Scalar singlet dark matter and gamma lines

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ABSTRACT

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.

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1. 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 $\Omega_{\mathrm{DM}} h^2 = 0.12$. 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. [2–12] 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.

2. 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

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

where H is the SM Higgs. After electroweak symmetry breaking the mass of the scalar dark matter is given by $M_S^2 = m_S^2 + \lambda_p v_0^2$, where $v_0 = 246$ GeV is the SM Higgs vacuum expectation value. In order to guarantee the dark matter stability a discrete $\mathbb{Z}_2$ symmetry is imposed under which only S is odd, i.e., $S \to -S$.

This model has only one extra degree of freedom and only two parameters, the portal coupling λ_p and the physical dark matter mass M_S. The quartic coupling λ_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. [2–12] 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. [13] for a recent discussion.

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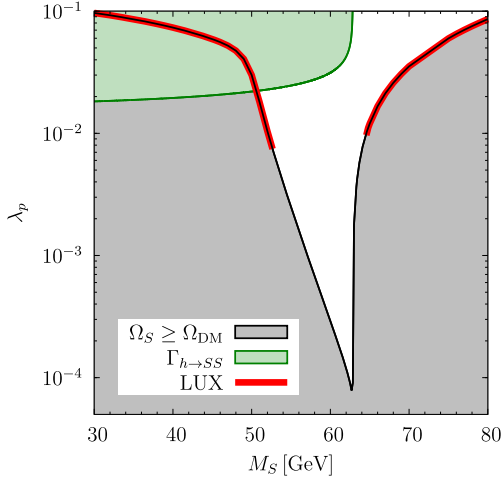*E-mail address:* fileviez@mpi-hd.mpg.de (P. Fileviez Pérez).

Fig. 1. Allowed parameter space in the M_S–λ_p plane. The black line corresponds to values in agreement with the full relic density today, $\Omega_{DM}h^2 = 0.1199 \pm 0.0027$ [14], and the gray area is robustly excluded by a too large DM relic density. The green area is ruled out by the invisible decay of the SM Higgs, BR($h \to SS$) < 58% [15]. The lines in red correspond to the values in disagreement with the LUX results [16]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

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

$$\sigma(SS \to \bar{f}f) = \frac{\lambda_p^2 M_f^2 (s - 4M_f^2)^{3/2}}{2\pi s \sqrt{s - 4M_S^2} \left[(s - M_h^2)^2 + M_h^2 \Gamma_h^2\right]}. \qquad (2)$$

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

$$\Gamma_h = \Gamma_h^{SM} + \Gamma(h \to SS), \qquad (3)$$

where

$$\Gamma(h \to SS) = \frac{\lambda_p^2 v_0^2}{8\pi M_h^2} (M_h^2 - 4M_S^2)^{1/2}. \qquad (4)$$

Fig. 1 shows the parameter space allowed by all relevant constraints. The black line corresponds to the values in agreement with the full relic density, $\Omega_{DM}h^2 = 0.1199 \pm 0.0027$ [14]. The gray area is ruled out since in this part of the parameter space one overcloses the Universe. The green area is ruled out by the invisible decay of the SM Higgs imposing that $\Gamma(h \to SS) < 58\%$ [15]. The lines in red correspond to the values in disagreement with the LUX direct detection experiment, see below for more details.[1] Therefore, the only allowed values for the mass M_S and the coupling λ_P are defined by the black line except for the red parts. These results are in agreement with the results presented in Ref. [11].

Using the allowed values for M_S and λ_P by relic density, we show in Fig. 2 the predicted values for the spin-independent nucleon–DM cross section which is given by

$$\sigma_{SI} = \frac{\lambda_p^2 f_N^2 \mu^2 m_N^2}{\pi M_h^4 M_S^2}, \qquad (5)$$

where $\mu = m_N M_S / (m_N + M_S)$. Here m_N is the nucleon mass and $f_N = 0.3$ is the matrix element [11]. The blue dashed line corresponds to the current LUX upper bound on the cross section [16],
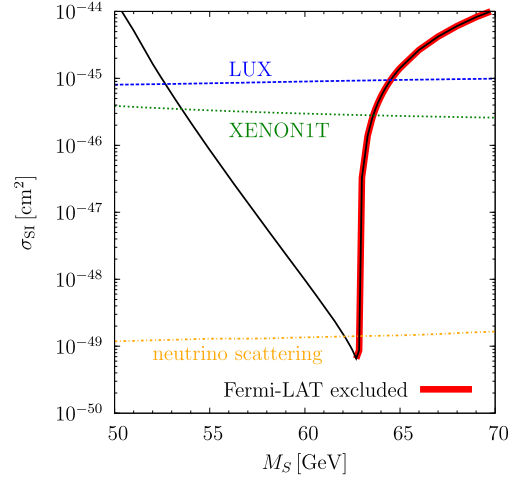
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[1] Notice that the bound on the direct detection cross section assumes that the DM candidate under consideration makes up the full DM relic density.

Fig. 2. 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 [16] (blue dashed) and projected XENON1T [17] (green dotted) bounds cut into the parameter space. The red part of the curve is excluded by $b\bar{b}$ limits from Fermi-LAT [18], see also Fig. 3. We show the neutrino coherent scattering background (orange dash-dotted) [19]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
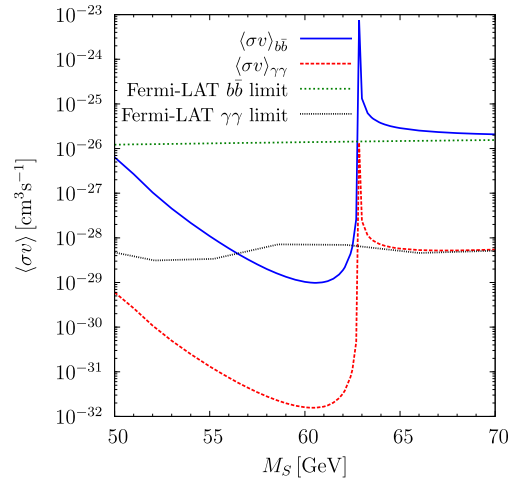

Fig. 3. Velocity-averaged cross sections times velocity for the annihilation into $b\bar{b}$ (blue solid) and $\gamma\gamma$ (red dashed), and the corresponding upper bounds from Fermi-LAT [18,20] (green and black dotted). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

and the projected XENON1T bound [17] is represented by the green dotted line.

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 $b\bar{b}$ (blue solid curve) as well as the current corresponding bound from Fermi-LAT [18] (green dotted curve). Notice that the Fermi-LAT $b\bar{b}$-limit rules out the 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.

3. Gamma lines

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