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Light dark matter for Fermi-LAT and CDMS observations

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ABSTRACT

Light fermionic/scalar dark matter (DM) ($m_{\mathrm{DM}} \approx 8$ GeV) neutral under the standard model can be responsible for the CDMS and CoGeNT signals, and the Fermi-LAT gamma-ray excesses. In order to explain them in a relatively simple framework, we have explored various DM annihilation and scattering processes, discussing important phenomenological constraints coming from particle physics. Assuming that the two independent observations have a common DM origin and the processes arise through a common mediator, DM should annihilate into tau/anti-tau lepton pairs through an s-channel, and scatter with nuclei through a t-channel process. To avoid the p-wave suppression, a new Higgs-like scalar field with a mass of $\mathcal{O}(1)$ TeV is necessary as a common mediator of both the processes. We propose a supersymmetric model realizing the scenario.

1. Introduction

Dark matter (DM) is one of the most important building blocks constituting the universe [1]. According to the recent precise observation from the Planck satellite experiment, it is believed that DM occupies 27 percent of the present energy density of the universe [2]. In particular, weakly interacting massive particle (WIMP), which is the most promising DM candidate, is essential for understanding the physics law at the electroweak (EW) scale as well as the structure formation in the universe. Thus, various experiments to explore DM are being carried out on the earth and also outside the atmosphere.

Recently, DM direct detection experiments such as CoGeNT [3], CDMS-Ge [4] and CDMS-Si [5] have reported the observations of some WIMP-candidate events at (2–3)σ confidence level. They are claimed to be interpreted as DM signals with a relatively light mass of $m_{\mathrm{DM}} \approx 7$–$10$ GeV and a spin-independent (SI) elastic scattering cross section per nucleon of $\sigma_{\mathrm{SI}} \approx 10^{-41}$–$10^{-40}$ cm^2. The best fit point for these three measurements is around $m_{\mathrm{DM}} \approx 8$ GeV and $\sigma_{\mathrm{SI}} \approx 3 \times 10^{-41}$ cm^2. DAMA/LIBRA [6] and CRESST-II [7] results also support similar parameter regions. However, all such signals are not exactly compatible with the constraints from XENON10 [8] and XENON100 [9]. Recently, the authors of Ref. [10] have pointed out that XENON10's constraint should be weakened, and the XENON10 Collaboration has corrected the old result in the erratum to Ref. [8]. In addition, the author of Ref. [11] has studied various uncertainties and assumptions, which could affect XENON100's constraint on light DM. Very recently, CoGeNT released the updated data, confirming their previous light DM signals [12]. Under such a tension among the observations, we will particularly focus on the positive results of CDMS and CoGeNT in this paper.[1]

If DM annihilates into the standard model (SM) chiral fermions, it should also emit gamma-rays. Fermi Large Area Telescope (Fermi-LAT) [17] is a satellite based experiment measuring cosmic gamma-rays. The recent analyses [18] based on the data from Fermi-LAT show peaks at energies around 1–10 GeV in the gamma-ray spectrum coming from around the galactic center. It could be interpreted as an evidence of DM annihilation into the leptons $l\bar{l}$ with $m_{\mathrm{DM}} \approx 7$–$12$ GeV or the bottom quarks $b\bar{b}$ with $m_{\mathrm{DM}} \approx 25$–$45$ GeV. In this case, the required annihilation cross section is $\sigma v \sim 10^{-26}$ cm^3/s.[2]

[1] Right after completion of this work, LUX [13] reported more stringent limit, constraining all the positive signal regions. In light of LUX, light DM possibilities have been examined in various ways in Refs. [14–16].

[2] The current limits on the annihilation of light DM into leptons coming from the cosmic microwave background (CMB) are $\langle\sigma v\rangle_{e\bar{e}} \approx 0.5$–$1 \times 10^{-26}$ cm^3/s, $\langle\sigma v\rangle_{\mu\bar{\mu}} \approx 1$–$2 \times 10^{-26}$ cm^3/s, and $\langle\sigma v\rangle_{\tau\bar{\tau}} \approx 2$–$3 \times 10^{-26}$ cm^3/s [19]. Thus, the case of DM annihilations into e^-e^+, $\mu^-\mu^+$, $\tau^-\tau^+$ with the same ratio is slightly constrained by the CMB bound. However, if DM mainly annihilates only into $\tau^-\tau^+$, the CMB constraint could be easily avoidable.

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We note that the DM direct detections and the cosmic gamma-ray observation require the similar mass of DM ($m_{\mathrm{DM}} \approx 8$ GeV) if they all indeed originate from DM. In this paper, we will discuss the required DM properties and attempt to construct a DM model reflecting them, assuming that the results of Fermi-LAT and CDMS have a common DM origin. In order to accommodate the two independent classes of experimental results *within a single framework*, we will show that

- 8 GeV fermionic/scalar DM, which is assumed to be a SM singlet field, should annihilate into SM leptons *via an s-channel* and scatter with nuclei via a t-channel process, and
- both the DM annihilation and scattering processes should be dominantly mediated by a *new Higgs-like scalar* field with an $\mathcal{O}(1)$ TeV mass.

This paper is organized as follows. In Section 2, we will discuss the required DM properties, assuming that the Fermi-LAT gamma-ray observation and CDMS DM direct detection have a common DM origin. In Section 3, we will propose a model to satisfy the required conditions discussed in Section 2. Section 4 is a conclusion.

2. Dark matter annihilation and scattering

As mentioned in Introduction, the annihilation process for the Fermi-LAT observation requires a relatively large cross section ($\sigma v \sim 10^{-26}$ cm^3/s). First, we will discuss the DM annihilation via s-channels. We will assume that the scattering process to explain the DM direct detection, which is relatively easier to explain, originates from the similar process to that of DM annihilation for the Fermi-LAT observation for simplicity.

2.1. Annihilation via s-channel process

Let us suppose that DM, X and X^c annihilate into SM chiral fermions, f and f^c,

$$X + X^c \longrightarrow f + f^c. \qquad (1)$$

The masses of $\{X, X^c\}$ are required to be around 8 GeV as mentioned above. Because of phenomenological and cosmological difficulties, we suppose that 8 GeV DM is not a member of the minimal supersymmetric standard model (MSSM) fields. In order to pass the EW precision test, we regard them as SM singlets. Since f and f^c are all fermions, a particle mediating the process between $\{X, X^c\}$ and $\{f, f^c\}$ should be a vector or a scalar. If the chiralities of the final *states*, f and f^c, are opposite in Eq. (1), namely, $\{f_L, (f^c)_R\}$ or $\{f_R, (f^c)_L\}$, only a vector particle or a gauge boson can attach to them as the mediator of DM annihilation. It is because the relevant vertex in the Lagrangian takes the form of $g'(\overline{f}_{L,R}\gamma^\mu f_{L,R})Z'_\mu$. See Fig. 1(a).[3] In this case, the gauge boson should be an extra gauge boson absent in the SM, because 8 GeV DM $\{X, X^c\}$ cannot carry any SM quantum numbers.[4] SM chiral fermions $\{f, f^c\}$ should also be charged under a new gauge symmetry accompanied with the extra gauge boson. However, the mass of the new gauge boson should be quite heavy ($M_{Z'} \gtrsim 2$–3 TeV) to evade the Z' mass constraints by the ATLAS [22] and CMS [23] Collaborations at the LHC. If the extra gauge field exclusively couples only to $\tau^\pm$ among the leptons, of course, the Z' constraint could be a bit weaker [24].

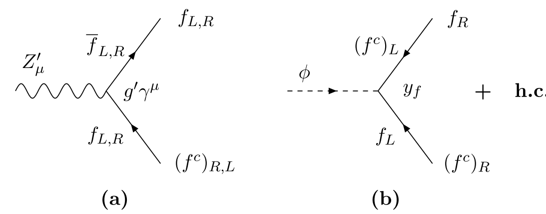

Fig. 1. Vector (a) and scalar mediators (b) coupled to SM chiral fermions. The subscripts L and R indicate the chiralities. Z'_μ is a new gauge boson. The newly introduced Higgs-like scalar ϕ together with the sizable Yukawa coupling y_f is needed for a desired cross section.

On the other hand, if the chiralities of the final states, f and f^c, are same, i.e. $\{f_L, (f^c)_L\}$ or $\{f_R, (f^c)_R\}$, the coupling between the SM matter and the mediator should be a type of Yukawa interaction. In this case, the relevant vertex in the Lagrangian reads $(f_L f_L^c)\phi + \mathrm{h.c.}$ in the Weyl notation [or $(\overline{f} P_L f)\phi + \mathrm{h.c.}$ in the Dirac notation, where P_L denotes the projection operator]. See Fig. 1(b). Since f_L [$(f^c)_L$] would be an SU(2)$_L$ doublet (singlet) of the SM, the mediator ϕ should be a scalar particle carrying the same gauge quantum numbers with the SM Higgs boson. If the mediator is just the SM Higgs [25], the coupling y_f must be very small for the SM leptons. Because of this reason, we need to introduce a new Higgs-like scalar $\widetilde{L}$ with sizable Yukawa couplings in this case. Unlike the SM Higgs, the new SU(2) doublet $\widetilde{L}$ does not have to get a vacuum expectation value (VEV).

2.1.1. Fermionic dark matter

Now let us discuss the spin of $\{X, X^c\}$. If the DM $\{X, X^c\}$ in Eq. (1) are fermions ($\equiv \{X_F, X_F^c\}$), the mediator linking $\{X_F, X_F^c\}$ and $\{f, f^c\}$ should be a pseudo-scalar or a vector: the annihilation cross section through a real scalar mediator of Eq. (1) would be p-wave suppressed, unless a fine-tuning effect such as enhancement by a resonance overcomes the suppression. It is because the initial state, $(X_L X_L^c)$ or $(X_R X_R^c)$, is CP-odd, while the $(X_L X_R^c)$ state is CP-even. As a result, an initial state $(X_L X_L^c)$ or $(X_R X_R^c)$ [$(X_L X_R^c)$] pair in an s-wave state can couple to a pseudo-scalar [vector] mediator. The needed vertices in the Lagrangian can be provided from $(\overline{X}\gamma^5 X)\,\mathrm{Im}\,\phi$ in the Dirac notation, which is a part of $(\overline{X} P_L X)\phi + \mathrm{h.c.}$ (or $X_L X_L^c \phi + \mathrm{h.c.}$ in the Weyl notation), and $(\overline{X}\gamma^\mu P_{L,R} X)Z'_\mu$, respectively. By replacing $\{f, f^c\}$ by $\{X, X^c\}$, the relevant vertices can also be displayed via Fig. 1.

For the Majorana DM case ($X_F = X_F^c$), however, the annihilation cross section would be proportional to the mass squared of the final particles, m_f^2, if the mediator is a vector field: since the total spin of the initial states, $X_F + X_F$, is zero by the Pauli's exclusion principle in an s-wave state, the helicity flipping should arise in Fig. 1(a) such that the chiralities (helicities) of $\{f, f^c\}$ are same (opposite) for the angular momentum conservation. It is possible by adding a mass insertion on an external leg of f or f^c. Although $\{X_F, X_F^c\}$ exclusively annihilate into $\tau^\pm$, $X_F + X_F \to \tau^+ + \tau^-$, the Z' mass bound is still 1–2 TeV [24]. Thus, the suppression factor $(m_\tau/m_{Z'})^2$ is too small to yield the needed annihilation cross section, $\sigma v \sim 10^{-26}$ cm^3/s.

For the Dirac DM case ($X_F \neq X_F^c$) with a vector field mediation, it is still hard to get the desired annihilation (and also scattering) cross section with a gauge boson heavier than ~ 2–3 TeV, which is required to avoid the Z' constraints [22,23] as mentioned

[3] In fact, a scalar mediator also can attach to them, if chirality flipping arises by adding a mass insertion on an external leg in Fig. 1(b). However, $\{f, f^c\}$ are regarded as being quite light in our case, and so such a diagram is suppressed. In this paper, thus, we do not consider such a possibility.

[4] If our discussion was confined only in DM scattering with nuclei without considering DM annihilation into leptons, an extra gauge boson could also be a possible mediator [20]. At one-loop level, the SM gauge fields could also couple to a SM singlet DM [21]. However, this case turns out to yield too small annihilation cross sections to account for the Fermi-LAT gamma-ray excesses. Throughout this paper, we consider only tree level processes for DM annihilation.