Physics Letters B 718 (2013) 1425–1429

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

130 GeV Fermi gamma-ray line from dark matter decay

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ARTICLE INFO

Article history:
Received 25 May 2012
Received in revised form 12 December 2012
Accepted 17 December 2012
Available online 21 December 2012
Editor: G.F. Giudice

Keywords:
Fermi-LAT
Gamma-ray
Dark matter decay
Scalar dark matter
Dimension 6 operator

ABSTRACT

The 130 GeV gamma-ray line based on tentative analyses on the Fermi-LAT data is hard to be understood with dark matter annihilation in the conventional framework of the MSSM. We point out that it can be nicely explained with two body decay of a scalar dark matter ($\tilde{\phi}_{\rm DM} \to \gamma\gamma$) by the dimension 6 operator suppressed with the mass of the grand unification scale ($\sim 10^{16}$ GeV), $\mathcal{L} \supset |\tilde{\phi}_{\rm DM}|^2 F_{\mu\nu}F^{\mu\nu}/M_{\rm GUT}^2$, in which the scalar dark matter $\tilde{\phi}_{\rm DM}$ develops a TeV scale vacuum expectation value. We propose a viable model explaining the 130 GeV gamma-ray line.

A thermally produced weakly interacting massive particle (WIMP) would be the most promising dark matter (DM) candidate explaining 23 percent of the mass-energy density in the present universe [1]. It might be closely associated with a new physics at the electroweak (EW) energy scale beyond the standard model in particle physics. In this sense, the on-going indirect DM searches, which cover the EW energy scales, are expected to provide a hint toward the fundamental theory in particle physics as well as in cosmology.

Recent tentative analyses [2–4] based on the data from the Fermi Large Area Telescope (Fermi-LAT) [5,6] exhibited a sharp peak around 130 GeV in the gamma-ray spectrum coming from near the galactic center (GC). The authors pointed out the gamma-ray excess could be a result from DM annihilation to a photon pair.[1] Since DM should carry no electromagnetic charge,[2] the annihilation, $\chi\chi \to \gamma\gamma$ is possible only through radiative processes. If the sharp peak of the gamma-ray around 130 GeV really originates from DM annihilation, the annihilation cross section and the mass of DM would be $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}$ cm^3/s ($2.27 \pm 0.57^{+0.32}_{-0.51} \times 10^{-27}$ cm^3/s) and $m_{\rm DM} = 129.8 \pm 2.4^{+7}_{-13}$ GeV, respectively, when the Einasto (NFW) DM profile employed [3]. It is almost one order of magnitude smaller than the total cross section for the thermal production of DM needed for explaining the present DM density ($\sim 10^{-6}$ GeV/cm^3), which is about 3×10^{-26} cm^3/s [1]. Indeed, the cross section of order 10^{-27} cm/s is much larger than the expected estimation of one-loop suppressed processes, assuming a thermal relic DM [3].

On the other hand, at the tree level, DM may annihilate into other final states, e.g. W^+W^-, ZZ, $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, etc, which can produce secondary continuous γ-ray spectrum through hadronizations or final state radiations. Thus, one can derive the constraints on the DM annihilation cross sections for those channels from the Fermi-LAT γ-ray observation data. Current limits on those annihilation modes are at the level of $\mathcal{O}(10^{-26}\text{–}10^{-25})$ cm^3/s for $m_{\rm DM} \approx 130$ GeV. For more details, see Refs. [11–16]. Moreover, produced W and Z bosons can also lead to a sizable primary contribution to the antiproton flux measured by PAMELA [17], which provides another constraint of $\mathcal{O}(10^{-25})$ cm^3/s on the DM annihilation into W^+W^- and ZZ [18,19]. Consequently, any annihilating DM model to explain the 130 GeV γ-ray signal should also satisfy such limits.

Actually, the full one-loop calculations of the neutralino annihilation into two photons [20–22] show that the annihilation cross section of order 10^{-27} cm^3/s is impossible in the region of 20 GeV–4 TeV DM mass in the minimal supersymmetric standard model (MSSM). In fact, the neutralino in the MSSM can be annihilated also into one photon plus one Z boson through one-loop induced processes, and this gamma-ray can cause the excess of the

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[1] In Refs. [7,8], it is argued that the gamma-ray line can be still explained with an astrophysical origin, associated with hard photons in the "Fermi bubble" regions.

[2] The possibility that DM is a milli-charged particle has been studied in Refs. [9,10].

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2012.12.041

observed flux. Unlike the case of $\chi\chi \to \gamma\gamma$, the emitted photon energy is estimated as $E_\gamma = m_{\rm DM}(1 - m_Z^2/4m_{\rm DM}^2)$ for $\chi\chi \to \gamma Z$. From the 130 GeV photon energy, hence, the DM mass of 144 GeV is predicted. (If the Z boson is replaced by an unknown heavier gauge field X, the DM mass can be raised more.) Even in such a case, the cross section of $\chi\chi \to \gamma Z$ is just about 10^{-28} cm^3/s in the MSSM [22,23], which is still smaller than 10^{-27} cm^3/s.

Renouncing the possibility of thermal production of the neutralino DM required to explain the observed DM relic density, the annihilation cross sections $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ and $\langle\sigma v\rangle_{\chi\chi\to\gamma Z}$ can be of order 10^{-27} cm^3/s or even larger. In this case, however, the mass difference between the chargino and the neutralino should be of order 10 GeV or less [18,24]. Moreover, such large neutralino annihilation cross sections for the one-loop suppressed processes are necessarily accompanied by much larger annihilation cross section into W^+W^- of order 10^{-25} cm^3/s or even larger [18]. As discussed above, the large annihilation cross section, $\langle\sigma v\rangle_{\chi\chi\to W^+W^-}$, is constrained by the current Fermi-LAT limits on continuum photon spectrum [12–16].

If the neutralino is wino- or higgsino-like, one might think that the cross section of $\chi\chi \to \gamma\gamma$ could be enhanced by nonperturbative effects, called "Sommerfeld effect." It turns out, however, that the cross section $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ cannot reach 10^{-27} cm^3/s, unless the mass of the neutralino is of TeV or hundreds of GeV scales [25–27], which is exceedingly heavier than 130 GeV. In addition, the nonperturbative effects on heavy wino- or higgsino-like DM also enhance the annihilation cross sections into W^+W^- and ZZ, $\langle\sigma v\rangle_{\chi\chi\to W^+W^-/ZZ}$ [19,25–27], which are inevitably constrained by the Fermi-LAT continuum photon limits [12–16] and the PAMELA antiproton flux limits [18,19].

Thus, the 130 GeV gamma-ray is quite hard to explain with DM annihilation, if the framework is restricted within the MSSM: we need to consider a possibility of the presence of a new DM sector, introducing a new DM and its interactions with ordinary charged particles. The basic reason for the difficulty is the charged superparticles' masses circulating in the loop cannot be light enough to enhance the cross section, because they should be heavier than the neutralino DM. Hence, if a new interaction coupling between a new DM and charged particles is introduced, which is larger enough than the weak coupling, we may obtain the required cross section $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ with relatively heavy ($130 +$ a few $\times$ 10 GeV) charged particles in the loop. Of course, the out-going interaction of the photons should be still given by the electromagnetic interaction. In order to reconcile the difference between the demanded cross sections for 130 GeV gamma-ray by DM annihilation and for the thermal relic DM, one may introduce two quite different interactions such that a photon annihilation interaction with $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \sim 2\times 10^{-27}$ cm^3/s is separated from the interaction explaining the thermal relic with $\sum\langle\sigma v\rangle \sim 3\times 10^{-26}$ cm^3/s [28–30]. However, we will not pursue such an ambitious job in this Letter.

Instead, in this Letter we will discuss the possibility that the gamma-ray line at 130 GeV is explained by DM decay. By comparing the differential photon flux by DM decay ($\Phi_{\rm dec}$) with that by annihilation ($\Phi_{\rm ann}$) [31,32],

$$\frac{d\Phi_{\rm dec}}{dE_\gamma\, d\Omega} = \frac{\Gamma}{4\pi} r_\odot \left(\frac{\rho_\odot}{2m_{\rm DM}}\right) \int_{\rm l.o.s.} ds\, \frac{1}{r_\odot}\left(\frac{\rho_{\rm halo}(r)}{\rho_\odot}\right)\frac{dN_{\rm dec}}{dE_\gamma},$$
$$\frac{d\Phi_{\rm ann}}{dE_\gamma\, d\Omega} = \frac{\langle\sigma v\rangle}{8\pi} r_\odot \left(\frac{\rho_\odot}{m_{\rm DM}}\right)^2 \int_{\rm l.o.s.} ds\, \frac{1}{r_\odot}\left(\frac{\rho_{\rm halo}(r)}{\rho_\odot}\right)^2\frac{dN_{\rm ann}}{dE_\gamma}, \quad (1)$$

one can estimate the decay rate Γ, needed for explaining the gamma-ray excess, where $dN_{\rm dec(ann)}/dE_\gamma$ is the differential photon energy spectrum, $\rho_{\rm halo}(r)$ is the DM halo density profile, $\rho_\odot \approx 0.4$ GeV cm^{-3} is the local DM halo density, $r_\odot \approx 8.5$ kpc is the distance from the GC to the Sun and $\int_{\rm l.o.s.} ds$ is the integral along the line of sight (l.o.s.). The morphology of the signal from DM decay is linearly proportional to the DM density profile, while that from DM annihilation has the density square dependence. Consequently, the decay case tends to show a less steep increase of the signal towards the GC compared with the annihilation case, although the morphology of the signal still has uncertainty by the DM halo density profile itself. In addition, for decaying DM more γ-ray flux is generically expected from the galactic halo compared to annihilating DM. However, the Fermi collaboration has observed no γ-ray excess from the galactic halo: it just reported the lower limits on the partial DM lifetime $\tau_{\gamma\nu}$ [5]. Although the best-fit values for the lifetime are in tension with the limit from the Fermi collaboration, however, the required lifetime to explain the 130 GeV γ-ray signal marginally satisfies the experimental limit allowing 2σ level error bars [33]. Moreover, there still exist the large uncertainty of the DM distribution around the GC, and also large statistical and systematic uncertainties at the moment. To confirm which scenario explains the 130 GeV γ-ray line, more improvement in observation is therefore essential in the near future. In Ref. [34], it was shown that both of decaying and annihilating DM explanations similarly give good χ^2-fits for DM halo profiles more enhanced around the GC (with $\alpha > 1$), compared to the original form of NFW profile (with $\alpha = 1$).

In Eq. (1), we set the DM mass in the decay case as two times heavier than the annihilation case to obtain the same resulting gamma-ray fluxes around $E_\gamma = 130$ GeV. Thus, the decay rate leading to the same gamma-ray flux by the annihilation with $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \sim 2\times 10^{-27}$ cm^3/s is estimated as [5,6]

$$\Gamma_{\chi\to\gamma\gamma} \sim 10^{-29}\ {\rm s}^{-1}, \quad (2)$$

by which the life time of DM becomes sufficiently longer than the age of the universe ($\sim 10^{16}$ s). Note that the required annihilation cross section for $\chi\chi \to X\gamma$ is approximately twice of that for $\chi\chi \to \gamma\gamma$; the required decay rate for $\chi \to X\gamma$ is also approximately twice of that for $\chi \to \gamma\gamma$.

If the gamma-ray excess should be explained by DM decay, the sharp peak of the gamma-ray would imply two body decay of the DM, since the three body decay would make the spectrum broad and the intensity much weaker. In the case of $\chi \to \gamma X$, the emitted photon energy is estimated as $E_\gamma = (1 - m_X^2/m_{\rm DM}^2)m_{\rm DM}/2$. For $E_\gamma \approx 130$ GeV, thus, the required DM mass is around $m_{\rm DM} \approx 288$ (1138) GeV for $X = Z$ (1000 GeV), which is heavier than that in the annihilation case. Thus, in the decaying DM case the DM mass can be much heavier than 260 GeV, say upto $\mathcal{O}$(TeV).

In Ref. [35], radiative DM decays to gamma-ray were extensively studied. For fermionic DM decay, the author considered the following renormalizable interactions:

$$\begin{aligned} -\mathcal{L}_{\rm eff} = {}& \overline{\psi}_{\rm DM}\gamma^\mu\big[g_\psi^L P_L + g_\psi^R P_R\big] l V_\mu + \overline{N}\gamma^\mu\big[g_N^L P_L + g_N^R P_R\big] l V_\mu \\ & + \overline{\psi}_{\rm DM}\big[y_\psi^L P_L + y_\psi^R P_R\big] l\Sigma + \overline{N}\big[y_N^L P_L + y_N^R P_R\big] l\Sigma \\ & + {\rm h.c.}, \end{aligned} \quad (3)$$

where "g"s and "y"s denote the coupling constants, and $P_{L,R}$ the projection operators. V_μ and Σ are superheavy vector and scalar fields with the masses m_V and m_Σ, respectively, which radiatively mediate DM decay. N and l indicate neutral and charged fermions, respectively. We suppose $m_{\rm DM} < 2m_l$ to disallow the three body decays of DM kinematically at tree level. Note that for producing the photons radiatively, the vector field V_μ (and also Σ) should carry an electromagnetic charge like the "X" or "Y" gauge bosons in the SU(5) grand unified theory (GUT). The interactions of