

An interpretation of a simple portal dark matter model on Fermi-LAT gamma-ray excess

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Abstract. Dark matter is one of the main components of the universe. Due to its weak interaction with other particles, dark matter cannot be identified as a particle that we know of. We are interested in a simple particle physics scenario where dark matter is identified with the fermion in the dark sector and the standard model sector is connected to dark matter via the portal scalar field. One of the promising signals from these models are gamma-rays from dark matter annihilation processes. In 2016, the Fermi-LAT collaboration detected a gamma-ray excess signal coming from Milky Way's galactic center which was immediately regarded as a possible candidate for the first detection of dark matter. In this project, we study an interpretation of the signal from Fermi-LAT as a dark matter annihilation from portal dark matter model. First, we calculated gamma-ray fluxes from dark matter annihilations as subsequent decays of portal scalars where the astrophysical factor is calculated from the Navarro-Frenk-White (NFW) dark matter density profile. We found that the simplest model does not fit adequately with chi-squared per degree of freedom, $\chi^2_\nu \sim 19.9$. We proposed that a part of the Fermi-LAT excess might come from another source of gamma-ray. The dark matter model combined with an unknown astrophysical source is then studied. The combined model is able to provide a reasonable fit ($\chi^2_\nu \sim 10$) indicating that scalar mass is 130 GeV, where dark matter mass is in the range of 150 – 350 GeV and $\langle\sigma v\rangle$ is around $7 \times 10^{-26} \text{ cm}^3/\text{s}$.

1. Introduction

There are many astronomical observations that can indicate the existence of dark matter (DM), the most confirmed evidence is Cosmic Microwave Background (CMB) from the space telescope called Wilkinson Microwave Anisotropy Probes (WMAP) launched in 2001, which surveyed the map of the residual radiation from the Big Bang. The results strongly indicate that DM is an important part of the universe. Although we only have indirect evidence of DM from its gravitational effect, we still do not know about their properties. In order to study its properties and identity, it is then important to make an effort to detect the signal of dark matter by using different methods other than gravity [1–3]. The Fermi Gamma-ray Large Area Space Telescope (Fermi-LAT) [4] barring issues of background gamma ray coming from the galactic center, this signal is often considered a potential detection of DM. Therefore, in this work, we are interested to compare the signal with the Portal Dark Matter model in which DM behaves like a fermion in the dark region and the standard model (SM) is linked through the scalar field.



2. The galactic center excess from Fermi-LAT

The Fermi Gamma-ray Large Area Space Telescope or Fermi-LAT has measured gamma-ray from hot gas in the center of the Milky Way which is called Fermi bubbles. The Fermi bubbles are two large structures that extend to 55° above and below the Galactic center [5]. There are many models of an origin and creation of bubble shape, whether the release of a jet from the black hole, the spherical outflow from black holes, or a wind caused by supernova explosions. M. Ackermann and his team [4] analysed Fermi-LAT data for 6.5 years recorded between 2008 August 4 and 2015 January 31 in the range of energy between 100 MeV to 1 TeV in order to find the spectrum and morphology of the Fermi bubbles. In the analysis the gamma-ray background caused by collision cosmic-ray with interstellar gas, the product from Inverse Compton Scattering from gamma-rays, gamma-ray radiation from extragalactic and the contamination of cosmic rays have been removed. It is found that there are still gamma-ray flux remaining, which can be interpreted in any other ways, but the most interesting one would be a dense DM in the center of the galaxy.

3. Portal dark matter model

One of the interesting DM models is the Portal Dark Matter model [6]. Generally the Lagrangian of the model in this class is given by

$$\begin{aligned} \mathcal{L} = & (D_\mu H)^\dagger (D^\mu H) + \frac{1}{2} (\partial_\mu \Phi) (\partial^\mu \Phi) + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 + \frac{\mu_\phi^2}{2} \Phi^2 \\ & - \frac{\lambda_\phi}{2} \Phi^4 - \frac{\lambda_{\phi H}}{2} \Phi^2 H^\dagger H + \lambda_\chi \phi \bar{\chi} \chi. \end{aligned} \quad (1)$$

The underlying assumption of the model we will use is that the scalar mediator ϕ is mixed with Higgs so that all couplings of the scalar mediator with the SM particles is equal to the Higgs couplings multiply by $\sin^2(\theta_{\text{mix}})$, where θ_{mix} is the mixing angle in the Higgs-scalar sector. The implication is that the scalar decays similarly to the Higgs. We will use a model independent approach such that many parameters in the model are reduced to simply 3 parameters, i.e., the cross section of dark matter annihilation into standard model particles, the mass of the dark matter, and the mass of the scalar mediator. Since DM cannot be a particle in the SM, it is natural to propose that the DM is a new particle. This Portal DM model, we use fermions as DM and allow DM to interact with regular matter through a scalar particle and this interaction is in the form of Yukawa interaction. (It is the same interaction that the Higgs particles have with the fermions in the SM.) In this type of models, the 2-2 DM annihilation process such as $\chi\bar{\chi} \rightarrow j\bar{j}$, where χ is DM and j is a SM particle, is mainly controlled by the mixing with Higgs particle. Since the scalar mixing alters the Higgs coupling to SM particles and the best fit of Higgs data shows no sign of significant deviation from the SM, we consider the mixing parameters to be small and hence the 2-2 channel is suppressed. Instead, the annihilation process $\chi\bar{\chi} \rightarrow \phi_1\phi_2 \rightarrow j\bar{j} + j'\bar{j}'$, dominates the gamma-ray production where ϕ is the scalar portal. The discussion of the gamma-ray production is of non-trivial matter since the energy of the final states is not fixed. In order to calculate gamma-ray flux from this process, we start from the rest frame of the scalar ϕ . Boost back to the DM center of mass frame, the energy of the final states can be written as

$$E_j = \frac{m_\chi}{2} (1 + \lambda_\phi \lambda_j \cos \theta), \quad (2)$$

where $\lambda_\phi = \sqrt{1 - (m_\phi/m_\chi)^2}$ and $\lambda_j = \sqrt{1 - (2m_j/m_\phi)^2}$. The energy range from equation (2) corresponds to $\theta \in [0, \pi]$. The maximum and minimum energy are

$$E_{min}^\phi = \frac{m_\chi}{2} (1 - \lambda_\phi \lambda_j) \quad , \quad E_{max}^\phi = \frac{m_\chi}{2} (1 + \lambda_\phi \lambda_j). \quad (3)$$

Next we find the probability of finding a particle j with energy E_j . From the solid angle ($d\Omega = \sin\theta d\theta d\phi$) we can find the probability of finding particles j at the azimuthal angle θ as $dP \propto \int_{\phi=0}^{2\pi} d\Omega \propto 2\pi \sin\theta d\theta$. We obtain

$$\frac{dP}{d\theta} = \frac{\sin\theta}{2}. \quad (4)$$

From equation (2) we find that $\sin\theta = \frac{1}{\lambda_\phi \lambda_j} \sqrt{\lambda_\phi^2 \lambda_j^2 - \left(\frac{2E_j}{m_\chi} - 1\right)^2}$. Since a particle j with angle θ is equivalent to a particle with energy E_j , the probability to find SM particles j at E_j are

$$\frac{dP}{dE} \propto \frac{dP}{d\theta} = \frac{1}{2\lambda_\phi \lambda_j} \sqrt{\lambda_\phi^2 \lambda_j^2 - \left(\frac{2E_j}{m_\chi} - 1\right)^2}. \quad (5)$$

Integrate equation (5) using the energy range from equation (3), we have the normalization factor $N = 8/(m_\chi \pi \lambda_j \lambda_\phi)$ and the equation (5) becomes

$$\left(\frac{dP}{dE}\right)_\phi = \frac{4}{\pi m_\chi} \frac{\sqrt{\left(1 - \frac{m_\phi^2}{m_\chi^2}\right) \left(1 - \frac{4m_j^2}{m_\phi^2}\right) - \left(1 - \frac{2E_j}{m_\chi}\right)^2}}{\left(1 - \frac{m_\phi^2}{m_\chi^2}\right) \left(1 - \frac{4m_j^2}{m_\phi^2}\right)}. \quad (6)$$

Therefore the gamma-ray spectrum from the subsequent decay of $j\bar{j}j'\bar{j}'$ is given by the convolution of the spectrum and the probability of finding particle j with energy E_j

$$\left(\frac{dN}{dE}\right)_{\phi_1\phi_2} = \int_{E_{min}}^{E_{max}} dE_j \left(\frac{dP}{dE_\gamma}\right)_{j\bar{j}} \left(\frac{dP}{dE_j}\right)_{\phi_1} + \int_{E_{min}}^{E_{max}} dE'_j \left(\frac{dP}{dE_\gamma}\right)_{j'\bar{j}'} \left(\frac{dP}{dE'_j}\right)_{\phi_2}, \quad (7)$$

where $\left(\frac{dP}{dE_\gamma}\right)_{j\bar{j}}$ is the spectrum E_γ coming from particle j . We use the gamma-ray spectrum from [7] where they simulated the signals of DM annihilations into charged particles. We will focus only the channel that DM annihilation into $b\bar{b}$ particles as an example. Another reason being that $b\bar{b}$ is the main channel of the scalar decay the branching ratio of Higgs decay and hence the main channel for the scalar decay. Including the astrophysical factor, the gamma-ray flux produced from DM annihilation process is given by

$$\frac{d\Phi}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi} \frac{R_{sc}\rho_{sc}^2}{m_\chi^2} J \frac{dN}{dE}, \quad (8)$$

where $\langle\sigma v\rangle$ is annihilation cross section, R_{sc} is the distance between the Sun and Milky Ways center ($R_{sc} = 8.5$ kpc), ρ_{sc} is the DM density at the position of the Sun. The J -factor which is an astronomical factor that depend on the DM profile density $\rho(r)$,

$$J = \frac{1}{R_{sc}^2 \rho_{sc}^2} \int_0^{4\pi} d\Omega \int_0^{l_{max}} \rho(r) dr. \quad (9)$$

The integral over the line of sight gives the value of $J = 3.34$ for the Navarro-Frenk-White (NFW) profile [8] and $J = 1.61$ for the Burkert profile [9]. These values agree with reference [10]. In our analysis, we use the NFW profile. However, the flux from dark matter annihilation alone might not be sufficient to explain the excess observed by Fermi-LAT since the nature of the excess

flux coming from the center of galaxies is still largely unknown [5]. For example, the studies of millisecond pulsars as a possible explanation of galactic center excess have been extensive yet inconclusive, [11–13]. We therefore assume a semi-realistic approach such that there are two difference sources responsible for the galactic center excess. First is an unknown astrophysical gamma-ray source, responsible for the high energy tail of the gamma-ray spectrum. Second is coming from DM annihilation,

$$\Phi = \Phi_{astro} + \Phi_{DM}. \quad (10)$$

For astronomical source, in references [5, 14, 15] they have assume that the contribution of astronomical component scale as a simple power law with an exponential cut off as

$$\Phi_{astro} = NE^{-\alpha}e^{E/E_{cut}}, \quad (11)$$

where N, α and E_{cut} are free parameters. As a result we use 7 parameters fit, $\langle\sigma v\rangle$, m_χ , m_ϕ and m_j for DM flux and N, α and E_{cut} for astronomical component. The quality of the fit is evaluated by χ_ν^2

$$\chi^2 = \sum_i \frac{(\Phi_{obs}^i - \Phi_m^i)^2}{\sigma^2}, \quad (12)$$

where Φ_{obs}^i is the flux from sample model [4], Φ_m^i is the predicted flux from portal DM model and σ is error bars from data. We can find χ_ν^2 by taking χ^2 divided by degree of freedom ν .

4. Result

In figure 1, we use the scalar mass $m_\phi = 130$ GeV in $b\bar{b}$ channel. It can be seen that the lowest region of χ^2 occurs where DM mass is in the range of 150 – 350 GeV and $\langle\sigma v\rangle \sim 10^{-26} - 10^{-25}$ cm³/s. The minimum χ^2 is 183.2 where the flux compared to Fermi-LAT data is shown in figure 2. The best fit corresponds to the following parameters, $m_\chi = 150$ GeV, $\langle\sigma v\rangle = 6.5 \times 10^{-26}$ cm³/s, where parameters of an unknown astronomical flux are $E_{cut} = 83.700$ GeV, $\alpha = -1.002$ and $N = 8.130 \times 10^{-9}$ GeV^(1+ α)/(cm²/s). It shows that flux from the Portal DM model is insufficient to describe all the data from Fermi-LAT especially at high energy, $E_\gamma > 20$ GeV. Due to the uncertainty of flux origin, we model the high energy tail of the Galactic excess as an astrophysical component with power law with a physical cutoff scale. After including an unknown astronomical flux, we obtain the best fit with $\chi_\nu^2 = 10.1$.

5. Conclusions

In this analysis, we generate the Portal DM model flux to compare with gamma-ray excess from Fermi-LAT. We found that flux from Portal DM model alone cannot be used to explain the excess gamma-ray data of Fermi-LAT since gamma-ray events from Fermi-LAT at high energy range is much higher than fluxes generated from the model. We then assumed that there might be other unknown gamma-ray sources such as blackhole/neutron star related events which can produce gamma-rays in the high energy range. After adding unknown astronomical flux, it was found that the combination can give the best fit with the minimum $\chi_\nu^2 \sim 10.1$. The best fit corresponds to the scalar mass $m_\phi = 130$ GeV, DM mass m_χ in the range of 150 – 350 GeV and $\langle\sigma v\rangle$ around 7.0×10^{-26} cm³/s.

The light dark matter and mediator with mass around ~ 100 GeV is within the collider search limit. However, the cross section of quarks and gluons to dark matter can be strongly suppressed by the mixing parameters and the smallness of Yukawa couplings [16]. An exploration of the parameter space from collider experiments of the scalar portal model is left for the future research.

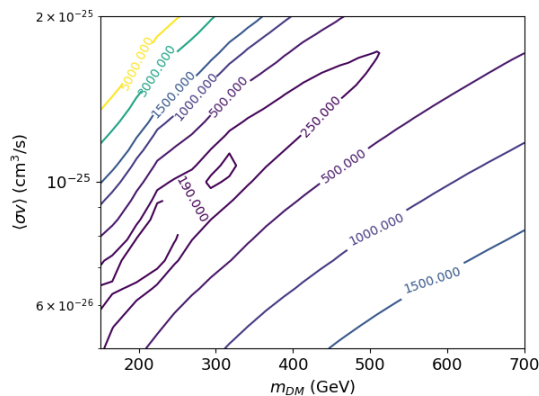


Figure 1. Contour plot of χ^2 between total DM flux and flux from Fermi-LAT.

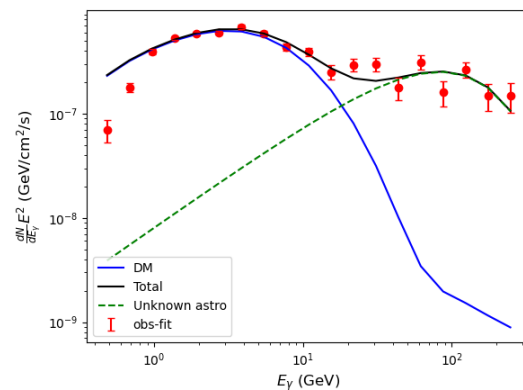


Figure 2. Fit of Fermi-LAT excess (red dots) to the combination unknown astrophysical sources (green dash), plus DM annihilation from Portal DM model (blue line).

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