CONSTRaining the distribution of dark matter in the inner galaxy with an indirect detection signal: The case of a tentative 130 GeV γ-ray line

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ABSTRACT

Dark matter distribution in the very inner region of our Galaxy is still debated. In N-body simulations, a cuspy dark matter halo density profile is favored. Several dissipative baryonic processes, however, are found to be able to significantly flatten dark matter distribution, and a cored dark matter halo density profile is possible. Baryons dominate the gravitational potential in the inner Galaxy, hence a direct constraint on the abundance of dark matter particles is rather challenging. Recently, a few groups have identified a tentative 130 GeV line signal in the Galactic center, which could be interpreted as the signal of dark matter annihilation. Using current 130 GeV line data and adopting the generalized Navarro–Frenk–White profile of the dark matter halo—local dark matter density \( \rho_0 = 0.4 \text{ GeV cm}^{-3} \) and \( r_s = 0.2 \text{ kpc} \)—we obtain a 95% confidence level lower (upper) limit on the inner slope of dark matter density distribution, \( \alpha = 1.06 \) (the cross section of DM particles annihilating into \( \gamma \)-rays \( (\sigma v)_{\chi \chi \rightarrow \gamma \gamma} = 1.3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \)). Such a slope is consistent with the results of some N-body simulations and, if the signal is due to dark matter, suggests that baryonic processes may be unimportant.

Key words: dark matter – galaxies: structure – gamma rays: general

Online-only material: color figures

1. INTRODUCTION

In the leading cold dark matter (CDM) model, structure forms hierarchically from the bottom-up, with dark matter (DM) collapsing first into small halos, which then accrete normal matter, merge, and eventually give rise to larger halos. Galaxies are thought to form out of gas that cools and collapses to the matter, merge, and eventually give rise to larger halos. Galaxies

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Weniger (2012) found possible evidence of a monochromatic $\gamma$-ray line with an energy of $\sim$130 GeV. Later independent analyses confirmed such an excess. The center of the most prominent signal region is around the Galactic center Sgr A*, with an offset $\geq1.2$ (Tempel et al. 2012; Su & Finkbeiner 2012), which has been thought to be at odds with the DM origin. However, within the DM annihilation scenario, such an offset can be interpreted by the limited statistics of the current $\gamma$-ray line signal consisting of only $\sim$14 photons (Yang et al. 2012). Furthermore, it is interesting to note that there is a small wiggle in the electron spectrum of PAMELA/Fermi-LAT at energies of $\sim$100 GeV, which may be interpreted as being consistent with the 130 GeV line signal (Feng et al. 2013).

With a typical cuspy DM density profile, such as NFW (Navarro et al. 1997) and Einasto (1965), the annihilation cross section $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma} \sim 2.5 \times 10^{-27}$ cm$^3$ s$^{-1}$ is needed to produce the signal data (Weniger 2012; Tempel et al. 2012), which, however, is larger than the upper limit ($\sim 10^{-27}$ cm$^3$ s$^{-1}$) set by the non-detection of the 130 GeV line in other regions by a factor of quite a few. This puzzle has been taken to be a piece of evidence against the DM origin of the 130 GeV line in the Milky Way center (e.g., Huang et al. 2012). As already mentioned in Section 1, in the Galactic center the DM density profile is rather uncertain; it is thus not confidential to refute the DM model just based on the tension between the values or upper limits of $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$ inferred in different regions.

In principle, one may be able to find an ideal region to reliably evaluate $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$. In such a region, the following conditions should be met, including (1) the DM density distribution is reasonably determined by astrophysical observations; (2) the signal-to-noise ratio is relatively high; and (3) the contribution of the DM substructure is not expected to be dominated. For the Milky Way, the dynamical data play a role in constraining the DM distribution for $r > 3$ kpc, where $r$ is the distance to the Galactic center (e.g., Sofue 2012). Observationally, there is still no strong evidence for the existence of abundant substructures in the Milky Way DM halo. In the N-body simulation Aquarius found that abundant substructures of the Galaxy might be present at $r > 20$ kpc (Springel et al. 2008). The contribution to the $J$-factor may be non-ignorable (i.e., the contribution is about the same as the smooth halo) any longer at $\psi \approx 30^\circ$. However, for the very cuspy DM halo, the signal-to-noise is also acceptable in the region $\psi \gtrsim 30^\circ$ (e.g., Bringmann et al. 2012). In view of these facts, the region $\psi \in (20^\circ, 40^\circ)$, excluding $b \leq 10^\circ$, may be a suitable region to constrain/measure $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$, where $b$ is the Galactic latitude and $\psi$ is the angle to the Galactic center. As an unbiased constraint on the DM density profile, the data in other regions should be taken into account, too. It should also be mentioned that the dwarf galaxies are also ideal candidates to constrain the annihilation cross section of DM. Geringer-Sameth & Kouhiappas (2012) performed a joint analysis of dwarf galaxy data and found that the upper limit on the annihilation cross section to a two-photon final state is $3.9_{-3.1}^{+2.9} \times 10^{-26}$ cm$^3$ s$^{-1}$ at 130 GeV (see also Huang et al. 2012), which is well above the limits that needed to account for the signal identified in the Galactic center (see below).

### 2.2. Fermi-LAT Data Analysis

In last subsection, we suggested that $\psi \in (20^\circ, 40^\circ)$, excluding $b \leq 10^\circ$, may be a suitable region to constrain/measure $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$. In reality, for a given DM density profile, the intrinsic $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$ should be smaller than the values or upper limits inferred from any other regions. Currently, the tentative $\gamma$-ray signal is present in a very compact region, hence we are only able to set an upper limit on $\langle \sigma v \rangle_{X\rightarrow\gamma\gamma}$ and impose a constrain on the slope of the DM density profile.

For such a purpose, we analyze the publicly available Fermi-LAT data in several regions, including (a) $\psi \leq 2^\circ$, which covers the most prominent signal region identified in Tempel et al. (2012); (b) $\psi \in (2^\circ, 6^\circ)$; (c) $\psi \in (6^\circ, 10^\circ)$; (d) $\psi \in (10^\circ, 20^\circ)$, excluding $b \leq 10^\circ$; (e) $\psi \in (20^\circ, 30^\circ)$, excluding $b \leq 10^\circ$; (f) $\psi \in (30^\circ, 45^\circ)$, excluding $b \leq 10^\circ$; and (g) $\psi \in (45^\circ, 180^\circ)$, excluding $b \leq 10^\circ$. We take into account the data in the time interval from 2008 August 4 to 2012 April 18 (MET 239557417–MET 356439845), with energies between 20 and 200 GeV, and use the standard LAT analysis software (v9r27p1). To reduce the effect of the Earth albedo background, time intervals when the Earth was appreciably in field of view (FoV), specifically when the center of the FoV was more than $52^\circ$ from zenith, as well as time intervals when parts of the region of interest (ROI) were observed at zenith angles $>100^\circ$, were also excluded from the analysis. The spectral analysis was performed based on the P7v6 version of post-launch instrument response functions (IRFs). The ULTRACLEAN data set was selected to avoid contamination from the charged particle. The spectra are shown in Figure 1.

To investigate the line signal at 130 GeV, we use the unbinned analysis method similar to the one described in Ackermann et al. (2012). It should be noted that in drawing Figure 1, we binned the counts to different energy bins, which may introduce a fake signal when the count number is small. However, in fitting the data to derive the possible line signal or upper limits, we use the unbinned analysis (e.g., the likelihood function was built by multiplying the probability distribution function of each photons in the assuming model. This method can minimize the fake

![Figure 1](http://fermi.gsfc.nasa.gov/ssc)
signal due to binning and take advantage of the full information of the observed data. The likelihood is described as

$$\mathcal{L} = \prod_i f S(E_i) + (1 - f) B(E_i),$$

where $S(E_i)$ and $B(E_i)$, both normalized to 1, represent the signal and background function, respectively, and $i$ runs over all the photons; $f$ is the signal fraction and has been set to be in the range $[-1, 1]$ for line signal search and $[0, 1]$ for getting upper limits; and $B(E_i)$ takes the form

$$B(E_i) \sim E_i^{-\gamma} \epsilon(E_i),$$

where $\epsilon(E_i)$ is the exposure generated by the gtexpcube2 routine. $S(E_i)$ is derived by convolving the energy dispersion function and exposure. Pyminuit\(^4\) is used to find the maximum of the likelihood and the MINOS asymmetric error at the level $\Delta \ln \mathcal{L} = 1.35$ is adopted to have the upper limit correspond to a coverage probability of 95%. To see the possible systematics due to the different choice of the background spectrum, we redo the analysis by using two different background spectral templates of $B(E_i)$: (1) adding an exponential cutoff to the pure power-law spectrum and leaving the cutoff energy to be free, as in,

$$B(E_i) \sim E_i^{-\gamma} \epsilon(E_i),$$

(2) a log-parabola spectrum,

$$B(E_i) \sim \left(\frac{E_i}{E_b}\right)^{-\left(\alpha + \beta \log E_i/E_b\right)} \epsilon(E_i).$$

We do not find significant improvement in the fitting, so for simplicity we use the pure power-law spectrum as our fiducial background spectral model.

The region we chose is larger than several degrees; meanwhile, the angular resolution above 20 GeV is within $0^\circ 2$, which is much smaller than the size of the region of interest. Thus,

\(^4\) http://code.google.com/p/pyminuit.

Figure 2. Energy dispersion used in our analysis, the form of which is described in the text and has already been normalized.

Table 1

| Region | Position | Signal/Upper Limit \((10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})\) |
|--------|----------|--------------------------------------------------|
| a      | $\psi \leq 2^\circ$ | $3.8 \pm 1.6$ |
| b      | $\psi \in (2^\circ, 6^\circ)$ | $0.55$ |
| c      | $\psi \in (6^\circ, 10^\circ)$ | $0.34$ |
| d      | $\psi \in (10^\circ, 20^\circ)$ | $0.133$ |
| e      | $\psi \in (20^\circ, 30^\circ)$ | $0.028$ |
| f      | $\psi \in (30^\circ, 45^\circ)$ | $0.0084$ |
| g      | $\psi \geq 45^\circ$ | $0.0015$ |

Note. Please note that $b \leq 10^\circ$ is excluded for the last four regions.

we neglect the point dispersion function in the analysis. On the other hand, energy dispersion is extremely important in the line searching process. In this work, we focus on the tentative 130 GeV line and adopt the energy dispersion at 130 GeV with the form described in the Web site.\(^5\) The P7ULTRACLEANv6 version of the IRFs is used and the final energy dispersion is averaged for different incidence angles. The derived energy dispersion used in the analysis is shown in Figure 2 and the signal fluxes (or upper limits) obtained in different regions are summarized in Table 1.

2.3. Constraints on $(\sigma v)_{\gamma \gamma}$ and the Dark Matter Density Profile

To constrain DM distribution in the inner Galaxy, we implement spherically symmetric generalized NFW profiles,

$$\rho_{\text{DM}}(r) = \rho_s (r/r_s)^{-\alpha}(1 + r/r_s)^{-3+\alpha},$$

where $r_s$, restricted in the range 10–35 kpc, is the scale radius (Iocco et al. 2011) and $\alpha$ is the inner slope for the NFW profile.

\(^5\) http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_E_dispersion.html
One main reason for adopting the generalized NFW profiles is that they can reproduce the three types of dark halo profiles presented in Maccio et al. (2012). The normalization of the DM profile is set by the local DM density, (i.e., $\rho_0 \equiv \rho_{\text{DM}}(R_\odot)$) and $r_s = \rho_0 v^2(r_\odot)/\Omega_\odot^2$, where $R_\odot \approx 8.5$ kpc is the distance from the Sun to the Galactic center. The fiducial interval $0.04 \pm 0.1$ GeV cm$^{-3}$ is adopted in line with recent astrophysical measurements (Salucci et al. 2010). The $\gamma$-ray flux produced by DM annihilation can be written as

$$\Phi(\Delta \Omega, E_\gamma) = \frac{1}{4\pi} \times \frac{\langle \sigma v \rangle_{\gamma\gamma}}{m_\chi^2} \times \frac{dN_{\gamma}}{dE_\gamma} \times \tilde{J}(\Delta \Omega,\Delta \psi).$$ \hspace{1cm} (6)$$

where $m_\chi$ is the mass of DM particles and $dN_{\gamma}/dE_\gamma = 2\delta(E_\gamma - m_\chi)$ is the differential energy spectrum of $\gamma$-rays. The astrophysical factor ($\tilde{J}$) is defined as

$$\tilde{J}(\Delta \Omega) = \frac{1}{\Delta \Omega} \int d \Omega \int_{\text{LOS}} dl \rho^2(l(l)).$$ \hspace{1cm} (7)$$

where $r(l)$ is the distance to the center of the object, which is a function of line-of-sight (LOS) distance $l$.

For region (a), there is a tentative $\gamma$-ray line signal. If interpreted as DM particles annihilating into a pair of photons, the cross section of DM annihilation ($\langle \sigma v \rangle_{\gamma\gamma}$) can be inferred with Equation (6). For regions (b), (c), (d), (e), (f), and (g), we have 95% confidence level upper limits of the line flux and then obtain constraints on the annihilation cross section. As long as

$$\langle \sigma v \rangle_{\gamma\gamma,\text{region}} \leq \min(\langle \sigma v \rangle_{XX-\gamma\gamma,a}, \langle \sigma v \rangle_{XX-\gamma\gamma,b}, \langle \sigma v \rangle_{XX-\gamma\gamma,c}, \langle \sigma v \rangle_{XX-\gamma\gamma,d},$$

$$\times (\langle \sigma v \rangle_{XX-\gamma\gamma,e}, \langle \sigma v \rangle_{XX-\gamma\gamma,f}, \langle \sigma v \rangle_{XX-\gamma\gamma,g}),$$

the DM profile is in agreement with the 130 GeV $\gamma$-ray line data. Such a fit to the current tentative 130 GeV $\gamma$-ray line data suggests that $\alpha \geq 1.71$ and $\langle \sigma v \rangle_{XX-\gamma\gamma} \leq 7.5 \times 10^{-28}$ cm$^3$ s$^{-1}$ for $r_s = 20$ kpc and $\rho_0 = 0.4$ GeV cm$^{-3}$ (see the dotted line in Figure 3).

To get more robust constraint, we adopt a combined likelihood analysis in all seven regions to constrain $\langle \sigma v \rangle_{XX-\gamma\gamma}$ and $\alpha$ for $r_s$ ranging from 10 to 35 kpc. The method is similar to that described in Tsai et al. (2013), and the combined likelihood is calculated as

$$L_c = \prod L_i,$$

where $L_i$ is the unbinned likelihood in the $i$th region. The definition of the unbinned likelihood is similar to that in the last section, but now the influence of $\langle \sigma v \rangle_{XX-\gamma\gamma}$ as well as $\alpha$ should be taken into account. Thus, we modify the signal ratio $f$ in Equation (1) to $f = \Phi((\sigma v)_{XX-\gamma\gamma}, \alpha)/\Phi_{\text{obs}}$, where $\Phi((\sigma v)_{XX-\gamma\gamma}, \alpha)$ is the flux predicted in the DM model (i.e., Equation (6)) with varying $\langle \sigma v \rangle_{XX-\gamma\gamma}$ and $\alpha$, and $\Phi_{\text{obs}}$ is the observed $\gamma$-ray flux (i.e., the integration of $J_{\gamma}$ in Figure 1 in the whole energy range). In our approach, the profile likelihood technique is adopted (Rolke et al. 2005). To constrain $\langle \sigma v \rangle_{XX-\gamma\gamma}$, we treat $\alpha$ as a nuisance parameter and vice versa. $\Delta \ln(L_c) = 1.35$ is adopted to obtain the upper (lower) limit corresponding to a coverage probability of 95%. In this work, we do not constrain $\rho_0$ (or alternatively $\rho_i$), since it couples with the annihilation cross section, i.e., $\langle \sigma v \rangle_{XX-\gamma\gamma} \propto 1/\rho_0^2$. Our general 95% confidence level lower (upper) limit on $\alpha$ ($\langle \sigma v \rangle_{XX-\gamma\gamma}$) as a function of $r_s$ is presented in Figure 4. For $r_s = 20$ kpc and $\rho_0 = 0.4$ GeV cm$^{-3}$, the 95% confidence level constraints are $\alpha \geq 1.06$ and $\langle \sigma v \rangle_{XX-\gamma\gamma} \leq 1.3 \times 10^{-27}$ cm$^3$ s$^{-1}$, respectively. The required $\langle \sigma v \rangle_{XX-\gamma\gamma}$ is consistent with the constraints set by the non-detection of a reliable signal in dwarf galaxies, a diffuse Galactic halo, and Galaxy clusters (Strigari 2012; Bringmann & Weniger 2012). Even for $r_s = 10$ kpc, the smallest value suggested in Iocco et al. (2011), $\alpha \geq 0.96$, is needed, and hence the HFR DM profile suggested in Maccio et al. (2012) is disfavored, implying that the baryonic processes that can considerably flatten the central DM distribution might not play an important role in the evolution of the Milky Way.

In Eris, a very recent high-resolution cosmological hydrodynamics simulation of a realistic Milky Way analog disk galaxy, the DM density profile within $\sim 1$ kpc is found to be very flat, and the peak of the DM density profile is $\sim$ a few 100 pc away from the Galactic center (Kuhlen et al. 2013). It is interesting to check whether or not the specific cored DM distribution found in Eris is consistent with the current line data. The data fits are

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**Figure 3.** Annihilation line flux expected in the theoretical models vs. the current 130 GeV line data. See the text for details.

(A color version of this figure is available in the online journal.)

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**Figure 4.** Ninety-five percent confidence level lower (upper) limit on the generalized NFW distribution parameter $\alpha$ ($\langle \sigma v \rangle_{XX-\gamma\gamma}$) set by current 130 GeV line data for $\rho_0 = 0.4$ GeV cm$^{-3}$. Following Iocco et al. (2011), $r_s$ is restricted within the range 10–35 kpc.

(A color version of this figure is available in the online journal.)
shown in Figure 3. The dashed line represents the best fit. In region (b), the model and the data diverge by a factor of >4. The dash-dotted line (i.e., the so-called Eris limit model) represents the case that the predicted flux of the Eris model in region (a) has been normalized to a flux $\approx 1.17 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (i.e., the 95% confidence level lower limit of the line signal). In such a fit, the model-predicted line flux in region (b) is still above the upper limit. We thus conclude that the Eris model has some tension with the line data.

3. SUMMARY

In the very inner region of the Galaxy, DM abundance is much less than that of normal matter, hence current microlensing and Galactic rotation curve data cannot directly constrain the DM density distribution. In principle, numerical simulations can solve such a problem. However, our current knowledge of the history of the Galaxy is very limited, and the complicated physical processes able to shape DM distribution are hard to fully address. That is why so far the distribution of DM in the very inner region of the Galaxy is still heavily debated (e.g., Gnedin et al. 2004; Maccio et al. 2012; Pontzen & Governato 2012; Kuhlen et al. 2013). Recently, several groups have identified a tentative 130 GeV $\gamma$-ray line that might exist due to the annihilation of DM particles in the inner Galaxy. In this work, we adopt the hypothesis that these signals are due to DM annihilation and use this hypothesis to examine which DM profile is consistent with the line. Our finding is that at the 95% confidence level, the DM density profile toward the center should be not shallower than $r^{-1.06}$ (for the generalized NFW profile with $r_s = 20$ kpc), and the DM annihilation cross section should be smaller than $\langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma} = 1.3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} (\rho_0/0.4 \text{ GeV cm}^{-3})^{-2}$ (see Figure 4). Such a density profile is in agreement with that found in some $N$-body simulations, and the baryon compression effect might play a role. The dissipative baryonic processes that are able to considerably flatten DM profiles seem not to play important roles in our Galaxy, implying that the formation and evolution of the Milky Way may not follow that of a prototypical spiral galaxy. Finally, we caution that the tentative 130 GeV $\gamma$-ray line has not yet been officially confirmed by the Fermi collaboration. Whether or not our constraints on the DM distribution in the very inner Galaxy and on the corresponding annihilation cross section are robust will be directly tested by the upcoming pass 8 data of Fermi-LAT, in which the amount of usual data at energies greater than 10 GeV are expected to be boosted by some 60% (Bloom et al. 2012).

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