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The spatial distribution of dark matter annihilation originating from a gamma-ray line signal [*]

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Abstract The $GeV-TeV$ γ-ray line signal is the smoking gun signature of dark matter annihilation or decay. The detection of such a signal is one of the main targets of some space-based telescopes, including Fermi-LAT and the upcoming missions CALET, DAMPE and Gamma-400. An important feature of γ-ray line photons that originate from dark-matter-annihilation is that they are concentrated at the center of the Galaxy. So far, no reliable γ-ray line has been detected by Fermi-LAT, and the upper limits on the cross section of annihilation into γ-rays have been reported. We use these upper limits to estimate the "maximal" number of γ-ray line photons detectable for Fermi-LAT, DAMPE and Gamma-400, and then investigate the spatial distribution of these photons. We show that the center of the distribution will usually be offset from the Galactic center (Sgr A*) due to the limited statistics. Such a result is almost independent of models of the dark matter distribution, and will render the reconstruction of the dark matter distribution with the γ-ray line signal very challenging for foreseeable space-based detectors.

Key words: cosmology: observations — cosmology: dark matter — Galaxy: center — instrumentation: detectors

1 INTRODUCTION

Dark matter (DM) is a type of special matter necessary to interpret gravitational effects observed on very large scale structures that cannot be accounted for by the amount of observed/normal matter (Jungman et al. 1996; Bertone et al. 2005; Hooper & Profumo 2007). Among various candidates, the leading ones are the so-called weakly interacting massive particles (WIMPs), which may annihilate each other or decay and then produce particle pairs such as photons, electrons and positrons (Jungman et al. 1996; Bertone et al. 2005; Hooper & Profumo 2007). The $GeV-TeV$ γ-ray line is extremely interesting in the search for the signal of DM annihilation or decay, as no other known physical processes can give rise to a similar signal. That is why the detection of such a signal is one of the main targets of certain space-based telescopes, including Fermi-LAT and the upcoming CALorimetric Electron Telescope[1] (CALET), DArk Matter Particle Explorer (DAMPE) and

[1] *http://calet.phys.lsu.edu*

Gamma-400[2]. After analyzing the publicly available Fermi-LAT γ-ray data, Bringmann et al. (2012) and Weniger (2012) found possible evidence for a monochromatic γ-ray line with an energy of ~ 130 GeV (see also Tempel et al. 2012 and Su & Finkbeiner 2012). Such a signal can be interpreted by ~ 130 GeV DM annihilation, which is why it has attracted wide attention (Bringmann & Weniger 2012; Feng et al. 2013; Yang et al. 2013). The offset of ~ 220 pc ($1.5°$) from the center of the most prominent region showing a signal from the Galactic center Sgr A* identified by Tempel et al. (2012) and Su & Finkbeiner (2012) has been widely regarded as a puzzle. This is because the DM distribution is usually assumed to be centered at Sgr A*, as is the expected DM annihilation signal. Since such a 130 GeV γ-ray line signal consists of only ~ 14 photons, the imperfect consistency of these photons with the expected DM distribution can just be due to the limited statistics (Yang et al. 2012). However, no firm evidence for the 130 GeV γ-ray line emission has been found by the Fermi-LAT collaboration (Ackermann et al. 2013). Such a negative result is slightly disappointing. Nevertheless, researchers are still keen on detecting the γ-ray line signal, the smoking gun signature of DM annihilation/decay. For example, CALET, DAMPE and Gamma-400, three upcoming spaced-based telescopes with an energy resolution $\sim 1\% - 2\%$ above 100 GeV, may significantly contribute to the γ-ray line search (Li & Yuan 2012; Bergström et al. 2012). In this work, we estimate the morphology of the potential line signal that is detectable with current and upcoming space-based γ-ray detectors. Following Yang et al. (2012), we carry out a Monte Carlo simulation of the direction of arrival for the photons produced by the annihilation of DM particles. The dependence of the expected "imperfect morphology" on the DM distribution models is also examined.

2 NUMERICAL RESULTS

For such purposes, we analyze public data from Fermi-LAT to estimate an upper limit on the number of γ-ray line photons. Standard LAT analysis software (v9r27p1)[3] is adopted. The data set was acquired during the time interval from 2008 August 4 to 2012 April 18, with energies between 20 and 200 GeV. We take the ULTRACLEAN dataset to avoid contamination from charged particles. In order to reduce the effect of background from the Earth albedo, time intervals when the Earth was appreciably in the field-of-view (FoV), in particular when parts of the region of interest (ROI) were observed at zenith angles $> 100°$, were excluded. Our spectral analysis was carried out based on the P7v6 version of the post-launch instrument response functions.

We use the un-binned analysis method, which is similar to the one described in Ackermann et al. (2013), to search for the line signal at different energies. The likelihood is described as

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

where $S(E_i)$ and $B(E_i)$, both normalized to 1, represent the signal and background function, respectively; the signal fraction f has been set to be in the range $[-1, 1]$ ($[0, 1]$) for a search of the line signal (getting upper limits), and i runs over all the photons (Ackermann et al. 2013). $B(E_i)$ takes the form

$$B(E_i) \sim E_i^{-\Gamma}\epsilon(E_i), \tag{2}$$

where $\epsilon(E_i)$ is the exposure generated by the *gtexpcube2* routine. Note that $S(E_i)$ is derived by convolving the energy dispersion function[4] with the exposure. We use Pyminuit[5] to obtain the maximum likelihood estimate and adopt the MINOS asymmetric error at the level $\Delta \ln \mathcal{L} = 1.35$ to get the upper limit corresponding to a coverage probability of 95% (see also Yang et al. 2013).

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[2] *http://gamma400.lebedev.ru/indexeng.html*

[3] *http://fermi.gsfc.nasa.gov/ssc*

[4] *http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_E_dispersion.html*
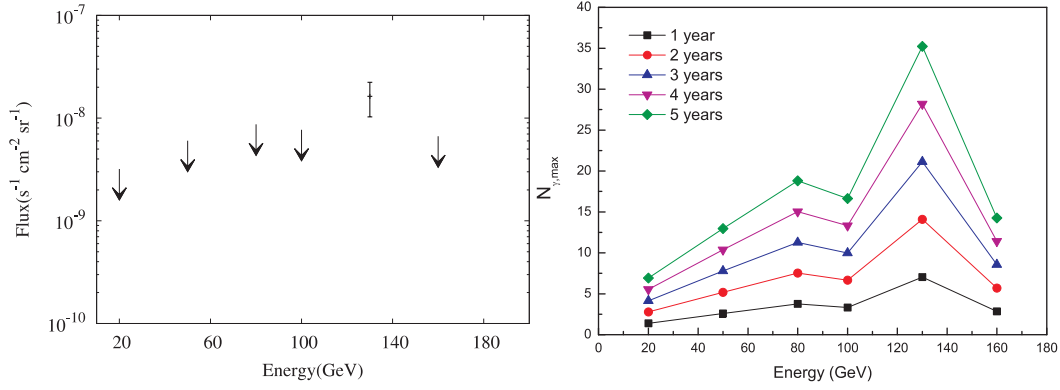
[5] *http://code.google.com/p/pyminuit*

Fig. 1 *Left*: the upper limits of photon fluxes with energy $E_\gamma = 20, 50, 80, 100$ and 160 GeV. The photon flux with $E_\gamma = 130$ GeV is also shown with a local significance of $\sim 3\sigma$. *Right*: The maximal number of γ-ray line photons with different energies detectable with a Fermi-LAT-like detector under different observation durations.

We chose $E_\gamma = 20, 50, 80, 100, 130$ and 160 GeV, and the ROI is the inner $3°$ from the galactic center. For 130 GeV, we obtained a signal with a flux of $1.63 \pm 0.6 \times 10^{-8}$ cm^{-2} s^{-1} sr^{-1} with a local significance of $\approx 3\sigma$, consistent with Yang et al. (2013). At other energies, we derived the upper limits, and the results are shown in Figure 1 (left). In Figure 1 (right) we show the detectable number of photons for a Fermi-LAT-like detector as a function of the observation time and photon energy. One can see that the potential numbers of γ-ray line photons are very limited.

In this work we consider several DM density profiles that have been widely adopted in the literature, including the so-called generalized Navarro-Frenk-White profile (NFW, Navarro et al. 1997), Einasto profile (Einasto 1965) and the isothermal profile (Bahcall & Soneira 1980). The generalized NFW DM density profile (Navarro et al. 1997) reads

$$\rho(r) = \frac{\rho_\mathrm{s}}{\left(\frac{r}{r_\mathrm{s}}\right)^\alpha \left(1 + \frac{r}{r_\mathrm{s}}\right)^{3-\alpha}}, \tag{3}$$

where $r_\mathrm{s} \approx 20$ kpc and $\rho_s \approx 0.11$ GeV cm^{-3}. $\alpha \sim 1$ is found in many numerical simulations. However, in the presence of baryonic compression, α can be as high as ~ 1.7. In this work, we take $\alpha \sim 1.7$, since such an extremely cuspy distribution can "narrow" the region where signal photons are concentrated.

The Einasto DM density profile (Einasto 1965) reads

$$\rho(r) = \rho_\mathrm{s,ein} \exp\left\{-\frac{2}{a}\left[\left(\frac{r}{r_\mathrm{s,ein}}\right)^a - 1\right]\right\}, \tag{4}$$

where $a = 0.17$, $r_\mathrm{s,ein} \approx 20$ kpc and $\rho_\mathrm{s,ein} \approx 0.06$ GeV cm^{-3}.

The isothermal DM density profile (Bahcall & Soneira 1980) reads

$$\rho(r) = \frac{\rho_\mathrm{s,iso}}{1 + \left(\frac{r}{r_\mathrm{s,iso}}\right)^2}, \tag{5}$$

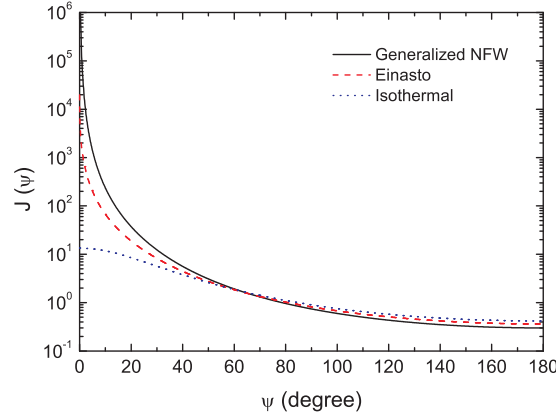where $r_\mathrm{s,iso} \approx 5.0$ kpc and $\rho_\mathrm{s,iso} \approx 1.16$ GeV cm^{-3}.

Fig. 2 The J-factor corresponding to the generalized NFW ($\alpha = 1.7$), Einasto and isothermal DM density distributions, as shown by the different line styles.

The possibility of detecting one γ-ray in a given direction (ℓ, b) is proportional to the J-factor

$$J = \frac{1}{\rho_\odot^2 R_\odot} \int \mathrm{d}s \rho^2[r(s)], \tag{6}$$

where $\rho_\odot = 0.3$ GeV cm^{-3} is the DM density in the local area, s is the line-of-sight distance, $r_\odot \simeq 8.5$ kpc is the distance from the Sun to the Galactic center, $r = (s^2 + r_\odot^2 - 2sr_\odot \cos \ell \cos b)^{1/2}$ is the Galactocentric distance, and (l, b) represent the Galactic longitude and latitude, respectively.

Figure 2 shows how the J-factor for different DM density distributions changes over the observed direction (the angle between the line-of-sight and the direction of the galactic center). If the number of signal photons is not sufficient, their distribution as a function of ψ will follow the $J-$factor and will be centered at the Galactic center, where $\cos \psi = \cos l \cos b$. However, current Fermi-LAT observations suggest that the number of signal photons is very limited ($N < 35$ for the current "most optimistic" signal, and usually $N < 20$). In such a case, due to the limited statistics, the spatial distribution of the signal photons can be very different from the ideal morphology, as shown below.

In the Monte Carlo simulations, following Yang et al. (2012), we assume that the photons are from an angle $\psi \leq 5°$ around the Galactic center. We simulate $100\,000$ observations with $N = 15, 40$ and 100 photons each. The average center of the photons is given by

$$\ell_0 = \sum_{i=1}^{N} \ell_i/N \quad \text{and} \quad b_0 = \sum_{i=1}^{N} b_i/N,$$

and the offset of the center from the Galactic center, in terms of morphology, is $r_0 = \sqrt{\ell_0^2 + b_0^2}$. Following Yang et al. (2012) we also define the elongation rate

$$\sigma_\ell/\sigma_b = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\ell_i - \ell_0)^2} \Big/ \sqrt{\frac{1}{N}\sum_{i=1}^{N}(b_i - b_0)^2} \tag{7}$$

to describe the asymmetric property of the photon map. In Figure 3 we show the distribution of photons about the elongation rate (σ_ℓ/σ_b) and the offset angle from the Galactic center (r_0). The
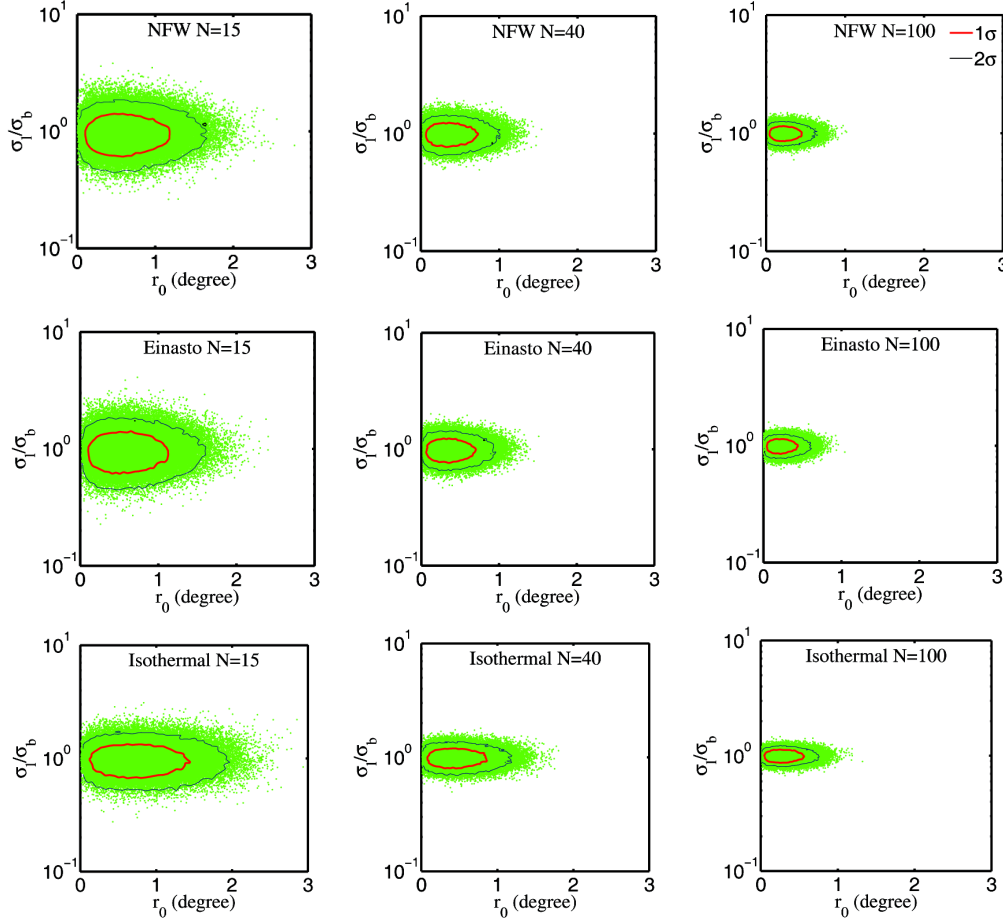
Fig. 3 The distribution of photons about the elongation rate (σ_ℓ/σ_b) and the offset angle from the Galactic center for the combinations of three DM distributions (NFW, Einasto and isothermal) with three numbers of detected photons ($N = 15$, 40 and 100).

lines in this figure present the 1σ and 2σ contours. The probability of $r_0 > 1.5°$ is about 1.95%, 1.38% and 6.29% for the generalized NFW, Einasto and isothermal DM density profiles in the case of $N = 15$, respectively. Such a fact strongly suggests that a sizable offset will be observed. Our prediction will be directly tested by the ongoing and upcoming high energy observations. With the increase in photon statistics, the deviation of the center as defined by morphology from the real center decreases, as expected. Then the chance of observing a large offset is accordingly much smaller. For example, in the case of $N = 40$, we have $P(r_0 > 1.5°) = 10^{-5}, 9.9 \times 10^{-6}$ and 6×10^{-4} for the generalized NFW, Einasto and isothermal DM density profile, respectively. That is to say, the morphology will be more symmetric if more photons are detected.

So far, we have assumed that the distribution of DM particles in the center of the Galaxy is centered at $(\ell, b) = (0°, 0°)$. If this is not the case, larger offsets are expected. For example, if we assume that the DM distribution is still spherically symmetric but centered at $(\ell_c, b_c) = (1.0°, 0°)$, it is straightforward to show that the simulated distribution of photons from the line signal would be centered at $(\ell, b) = (1.0°, 0°)$ and an offset from the center would be very likely. One possible
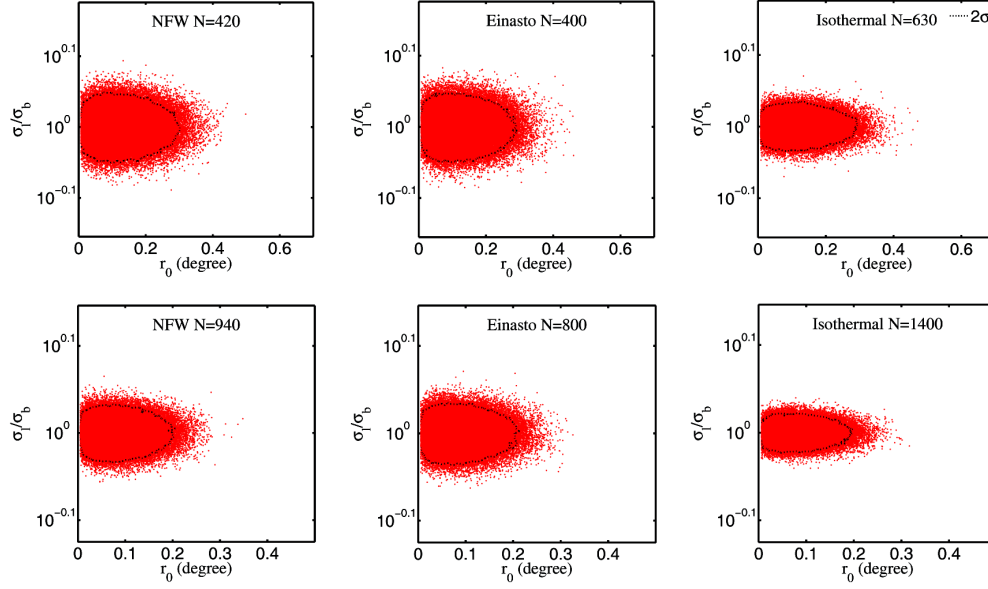
Fig. 4 The number of photons from the γ-ray line that are needed to reliably constrain whether an offset is due to the limited statistics or the non-standard spatial distribution of DM particles with $r_c \sim 0.3°$ and $\sim 0.2°$ (*top and bottom*, respectively) at a confidence level of 2σ.

example of a non-standard DM distribution can be found in Kuhlen et al. (2013). Therefore, so far at least, two effects can give rise to the offset of photons from the line signal. One is mainly due to the limited statistics, and the other is due to the non-standard spatial distribution of the DM particles (i.e., $\ell_c \neq 0$ or $b_c \neq 0$, or both). In principle, in the future we will be able to distinguish between these two possibilities. However, the number of signal photons needed is expected to be a few hundred.

In Figure 4, we have presented the number of photons needed to reliably constrain whether an offset is due to the limited statistics or alternatively due to the non-standard spatial distribution of DM particles. For example, to exclude the non-standard Einasto spatial distribution model with $r_c = \sqrt{\ell_c^2 + b_c^2} = 0.3°$ at a confidence level of $\sim 2\sigma$, we need $N \sim 400$. However, it is not easy to collect so many photons (see Fig. 1). The upcoming high-energy resolution detectors such as DAMPE and CALET have a much higher energy resolution than Fermi-LAT and are thus ideal instruments to identify line-like γ-ray signals (e.g., Li & Yuan 2012). However, these two detectors have an "acceptance" (i.e., the effective area times the FoV) that is smaller than Fermi-LAT (see Table 1), and this limits the detectable number of γ-ray line signals. We thus do not expect to get a perfect coincidence of the region defined by the signals with the expected DM distribution, even in

Table 1 Comparison of the performance of Fermi-LAT (Atwood et al. 2009), CALET (Mori & The CALET COLLABORATION 2013) and DAMPE (Chang 2013, private communication).

Parameter	Fermi	CALET	DAMPE
Energy Range	20 MeV–300 GeV	4 GeV–10 TeV	2 GeV–10 TeV
Effective Area	7600 cm^2	600 cm^2	3600 cm^2
Field of View	2.5 sr	2.0 sr	1.0 sr
Energy Resolution	10% (100 GeV)	2.5% (100 GeV)	1.5% (100 GeV)
Angular Resolution	0.25° (10 GeV)	0.35° (10 GeV)	0.25° (10 GeV)

future space-based observations. However, this situation may change in future ground-based observations. For example, with the Cherenkov Telescope Array[6], the goal of reliable identification of the DM distribution in the very inner Galaxy may be achieved.

3 SUMMARY

In summary, we have investigated the spatial distribution of the line signal originating from DM annihilation. Three representative DM distribution models were adopted and we discover that the center of the signal region will usually be different from the center of the DM distribution, unless the number of photons is huge. Even in future space-based observations, the expected photon number of the line signal will still be too small to reliably constrain the center of the DM distribution.

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[6] *http://www.cta-observatory.org/*