Can Dark Matter Annihilation Dominate the Extragalactic Gamma-Ray Background?

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Annihilating dark matter (DM) has been discussed as a possible source of gamma rays from the galactic center and as a contribution to the extragalactic gamma-ray background. Assuming universality of the density profile of DM halos, we show that it is quite unlikely that DM annihilation is a main constituent of extragalactic gamma-ray background, without exceeding the observed gamma-ray flux from the galactic center. This argument becomes stronger when we include enhancement of the density profiles by supermassive black holes or baryon cooling. The presence of a substructure may loosen the constraint, but only if a very large cross section as well as the rather flat profile are realized.

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We have made great progress in our knowledge of what the Universe is composed of. Surprisingly, we already know that the main constituents of the universe are not baryonic, but are unknown dark matter (DM) and dark energy. Recent analyses using observational data of the cosmic microwave background anisotropy, type Ia supernovae, and large scale structure precisely give the relic density of these components, $\Omega_{\rm DM} = 0.22$ and $\Omega_\Lambda = 0.73$ [1]. In particular for DM, we have some candidates motivated by particle physics. The most viable candidate is the lightest supersymmetric particle, which is a neutralino in most models. This supersymmetric neutralino can annihilate into final states including photons via various channels, and these photons might be detectable or might have already been detected from several astrophysical objects (see Refs. [2] for reviews).

In the direction of the galactic center (GC), there are clear gamma-ray signals in the GeV and TeV energy regions, which have been detected, respectively, by the Energetic Gamma Ray Experimental Telescope (EGRET) [3], and atmospheric Čerenkov telescopes (ACTs) such as Whipple [4,5], CANGAROO-II [6], and HESS [7]. These gamma rays from the GC are potentially due to DM annihilation, and have been extensively studied [8,9]. These results show that if the density profile of the galactic central region is cuspy enough, as suggested by N-body simulations such as by Navarro, Frenk, and White [10] (NFW) and Moore *et al.* [11] (hereafter M99), then the gamma-ray fluxes can be explained by the neutralino annihilation with a cross section that gives the proper relic density $\Omega_{\rm DM}$.

On the other hand, analyses of the diffuse EGRET emission show the signature of an extragalactic gamma-ray background (EGB) in the GeV range [12,13]. Annihilating DM may also significantly contribute to this EGB flux. Using the hierarchical clustering formalism that is now widely accepted, several authors gave the flux predictions, investigating the effect of DM clustering or substructure [14–17], and suggested that the EGB data can be explained well by including the DM component. In particular, a bump around 3 GeV, discovered by the recent reanalysis [13], may be the signature [17].

In this Letter, we investigate the gamma-ray signature from the GC and EGB together, assuming that the halo profile is universal as suggested by recent N-body simulations [18]. With this self-contained treatment, we point out that the annihilating DM cannot be a main constituent of the observed EGB without exceeding observational bounds imposed by gamma-ray measurements of the GC. Since both the GC and EGB fluxes should be predicted using the same cross section and mass of the DM particle, they are connected if we specify these ingredients. We also show that the main conclusion of this Letter is quite robust, since it does not depend on uncertainties concerning both the particle physics models and other astrophysical inputs. The latter include the central spike of halos due to the presence of supermassive black holes (SMBHs) [19] or to the baryon cooling [20], and the significant enhancement of the EGB flux due to the inclusion of halo substructure.

Gamma rays from the galactic center.—The number flux of high-energy gamma rays due to DM annihilation can be calculated with the following formula:

$$\Phi_\gamma^{\rm GC}(E_\gamma)\Delta\Omega = 9.4\times 10^{-11}\ {\rm cm^{-2}\,s^{-1}} m_{\chi,2}^{-2}\langle\sigma v\rangle_{-26} \times \frac{dN_\gamma}{dE_\gamma}\overline{J(\Delta\Omega)}\Delta\Omega, \quad (1)$$

where $m_\chi = 100 m_{\chi,2}$ GeV is the mass of the DM particle, $\langle\sigma v\rangle = 10^{-26}\langle\sigma v\rangle_{-26}$ cm^3 s^{-1} is the average value of the annihilation cross section times the relative velocity (assumed to be independent of v), and dN_γ/dE_γ represents the gamma-ray spectrum per annihilation, for which we use a simple parameterization such as $dN_\gamma/dE_\gamma \simeq (0.73/m_\chi)e^{-7.76E_\gamma/m_\chi}/[(E_\gamma/m_\chi)^{1.5} + 0.00014]$ [14]. (Although this parameterization may be less precise, it is sufficient for our purpose.) $\overline{J(\Delta\Omega)}$ represents the average value of the following quantity:

$$J(\psi) = \frac{1}{8.5{\rm kpc}}\int_{\rm l.o.s.} dl(\psi)\left(\frac{\rho(r(\psi,l))}{0.3\ {\rm GeV/cm^{-3}}}\right)^2, \quad (2)$$

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over the detector angular resolution $\Delta\Omega$ [$\Delta\Omega \simeq 2 \times 10^{-3} (4 \times 10^{-5})$ for EGRET (ACTs)], and normalized to the local value. The integration is performed along the line of sight (l.o.s.) labeled by angle deviation ψ from the GC ($\psi = 0$ for the direction to the GC), and r is the direction to the integrated point from the GC.

For the density profile of the DM halos $\rho(r)$, we use the NFW and M99 models, which are characterized by the central slopes of $\gamma = 1$ and 1.5, respectively, where γ is defined by $\rho(r) \propto r^{-\gamma}$ for small radii. While the most recent N-body simulations suggest there is no asymptotic slope and do not give such a cuspy profile as M99 (NFW may still be marginally consistent) [18], we use these two profiles as our reference models, in order to investigate how our conclusion changes with the selected profile. Furthermore, considering some other physical processes, it would still be possible to obtain significant enhancement of the central density. The proposed mechanism giving such a "spike" that may be steeper than the M99 profile is the accretion of DM particles onto a central SMBH [19] or the effect of baryon cooling [20].

In Table I, we summarize the values of $\overline{J(\Delta\Omega)}$ evaluated with the NFW and M99 density profiles. Because of its steeper profile in the central region, the M99 profile gives much larger values of $\overline{J(\Delta\Omega)}$ than NFW. This difference becomes more prominent when we use detectors with better resolution, since a more concentrated region can be probed. In Table I, we used the cutoff scale 10^{-8} kpc, and the profile was assumed to be flat within that radius. This is because without this implementation, the l.o.s. integration would diverge mathematically at very small radius. The cutoff scale may be physically determined by the annihilation itself, scattering of DM particle off stars, contraction of baryons, or the presence of a central SMBH. Because even the most recent simulations do not reach the very inner region of the halo (but as large as $\sim$0.1–1 kpc), the choice of the cutoff scale is a nontrivial problem. However, the GC flux is rather weakly dependent on this parameter in the reasonable range [9], and the uncertainty does not strongly affect our conclusion.

Figure 1(a) shows the gamma-ray flux from the GC due to annihilating DM, with masses 50 GeV or 2 TeV. In deriving these expressions, we assumed $\langle\sigma v\rangle_{-26} = 3$ that is considered to be appropriate for leaving the observed relic density of DM [2]; larger values than this would imply a lower relic density, requiring an additional DM component. Data points in 0.03–10 GeV and 0.2–2 TeV are taken from the EGRET [3] and CANGAROO-II [6] papers. A solid line above 2 TeV represents the power-law fit to the HESS data [7] (the recent Whipple result is consistent with the HESS data [5]). Correspondingly, theoretical curves are evaluated using Eq. (1) with $\Delta\Omega = 2 \times 10^{-3}$ for 50 GeV, and with $\Delta\Omega = 4 \times 10^{-5}$ for 2 TeV DM particles. We can clearly see that, in the case of $m_\chi = 50$ GeV, the flux evaluated with the M99 profile can easily be quite consistent with the EGRET data points over the wide range of energy. With the NFW profile, on the other hand, we predict considerably less flux. TeV gamma rays may also be dominated by a DM component, although both the flux and spectral shape are still controversial.

Extragalactic gamma-ray background.—The EGB flux estimation involves somewhat more information, e.g., that on the cosmological clustering of DM halos. The intensity of EGB is calculated by

$$\Phi_\gamma^{\rm EGB}(E_\gamma) = \frac{c}{4\pi H_0} \frac{\langle\sigma v\rangle}{2} \frac{\Omega_\chi^2 \rho_{\rm crit}^2}{m_\chi^2} \int dz \frac{(1+z)^3}{h(z)} \times \frac{dN_\gamma(E'_\gamma)}{dE'_\gamma} f(z) e^{-\tau(z,E_\gamma)}, \quad (3)$$

where $E'_\gamma = (1+z)E_\gamma$, $h(z) = [(1+z)^3\Omega_m + \Omega_\Lambda]^{1/2}$, and $\rho_{\rm crit}$ is the critical density. We also include the effect

TABLE I. Angular acceptance $\overline{J(\Delta\Omega)}$ of the GC gamma rays, and local values of enhancement factor $f(0)$ for the EGB flux.

Model	$\overline{J(2 \times 10^{-3})}$	$\overline{J(4 \times 10^{-5})}$	$f(z=0)$
NFW	7×10^2	5×10^3	2×10^4
M99	6×10^4	4×10^6	2×10^5

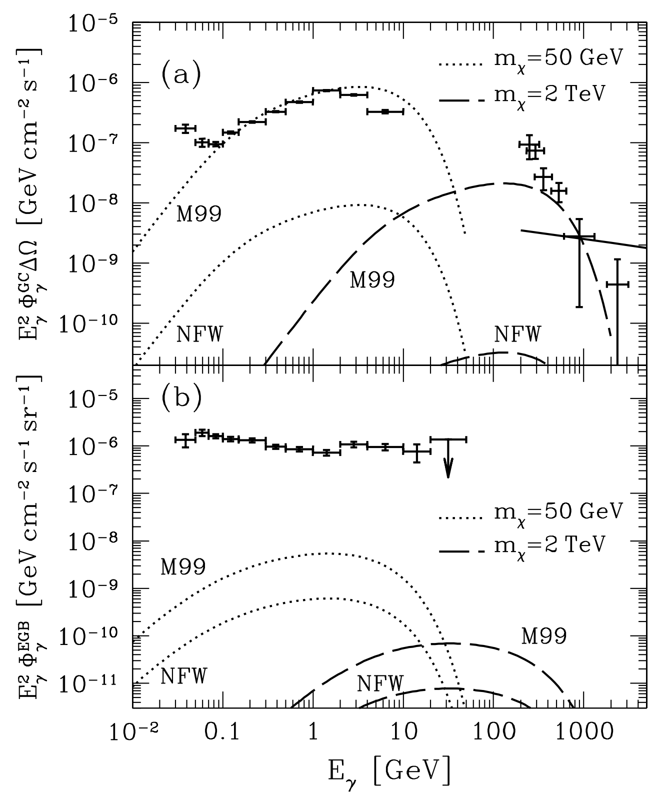

FIG. 1. (a) Gamma-ray flux from the GC from annihilating DM, with mass 50 GeV or 2 TeV, evaluated with the NFW and M99 profiles. Data from EGRET [3] and CANGAROO-II [6] are also plotted; the HESS result [7] is shown as a solid line. (b) EGB intensity from DM annihilation. EGRET data points [13] are also plotted.

of gamma-ray absorption by $e^{-\tau}$, which is caused by pair annihilation with the diffuse extragalactic background light in the infrared or optical wavebands [21]. This effect changes the EGB flux at TeV regions, but its extent is too small to affect the results. Hierarchical clustering of the DM halos is included in an intensity multiplier $f(z)$ [15,16]. For evaluating it we used the halo mass function based on the ellipsoidal collapse model [22] with a lower mass cutoff of $M_{\min} = 10^6 M_\odot$, which may be determined by the validity of hierarchical clustering formalism, self-limitation due to annihilation itself, or nuclear and star formation activities [16]. Varying it over a reasonable range (10^4–$10^8 M_\odot$) changes the EGB flux only by a factor of 2 or less [15,16]. To evaluate a concentration parameter that represents how the bulk of mass in each halo concentrates in the central region, we used a publicly available numerical code by Ref. [23]. The resulting values of $f(0)$ for each profile are summarized in the fourth column of Table I, and we note that our result is consistent with that of Refs. [15,16]. We should note that these values are significantly smaller than those adopted by previous studies such as Refs. [17]. This large discrepancy potentially comes from uncertainty concerning the concentration parameter, and the presence or absence of substructures. We also discuss these possibilities later.

We show in Fig. 1(b) the EGB intensity, with the same physical inputs as in the GC flux calculation. This shows that without any processes that give much larger $f(z)$, the expected DM contribution to the EGB flux is considerably smaller than the observed value. We also note that the dependence on the adopted profile is less prominent in the case of EGB, compared with strong dependence of gamma-ray flux from the GC. This is because the EGB flux is less sensitive to the very central region of the halo. The weaker dependence of $f(0)$ on the profile shown in Table I also reflects the same characteristic. With our canonical model, it is much more difficult to explain the observed EGB intensity mainly by annihilating DM component than gamma-ray flux from the GC; it requires an additional boost by more than 2 orders of magnitude.

Constraints on annihilating dark matter component.— The contribution of DM annihilation to the EGB flux is quite strongly constrained by the GC gamma-ray observations, and this result is rather robust, independent of uncertainties in the particle physics models. As a first step, we introduce a boost factor b for both the GC gamma rays and EGB, as a correction to the canonical predictions of each flux. All the corrections due to the other astrophysical and particle physical possibilities are included in b. In order for the DM annihilation to be a main constituent of the observed fluxes, the required values of b should be very close to the following quantity: $b^{\max} \equiv \min_i[\Phi_{\gamma,i}^{\rm obs}/\Phi_\gamma^{\rm th}(E_{\gamma,i})]$, where i represents bin-number of each observation, and $\Phi_{\gamma,i}^{\rm obs}$ and $\Phi_\gamma^{\rm th}$ are the observed intensity in ith bin and theoretical prediction given by Eqs. (1) and (3), respectively. By taking the minimum over all the bins, we renormalize the flux with keeping its shape, so as not to exceed the data points, which should be regarded as rigorous upper limits.

From Fig. 1, we can confirm that the value of b required for the GC gamma-ray data is much smaller than that for EGB, i.e., $b_{\rm GC}^{\max} \ll b_{\rm EGB}^{\max}$. These required values ($b_{\rm GC}^{\max}, b_{\rm EGB}^{\max}$) are plotted in Fig. 2, for both the NFW and M99 profiles and for several assumed DM particle masses. We used the CANGAROO-II data in the TeV region, since this would be more conservative for our purpose. If we add corrections that are related only to particle physics models (especially by renormalizing the cross section), we obtain the relation between two boost factors as $b_{\rm EGB} = b_{\rm GC}$, since the correction is common to the both cases. In this case, because of the relation $b_{\rm EGB}^{\max} \gg b_{\rm GC}^{\max}$ for all the models as shown in Fig. 2, we cannot explain the EGB data mainly by annihilating DM. Otherwise, it would overproduce gamma rays from the GC compared to the data. In addition, Fig. 2 also shows that this tendency is more prominent for the M99 profile than NFW. Although we restrict our argument within these two specific profiles, the conclusion derived here is general and applicable to other profile choices, as discussed below for more specific examples.

We note that the strong gamma-ray signal may not be coming from the GC; it has been suggested that the EGRET GeV source position is offset from the dynamical center of the galaxy, Sgr A*, at roughly 95% C.L. [24]. If this is true, it also strengthens our argument, because it suggests that the most of the gamma rays come from other

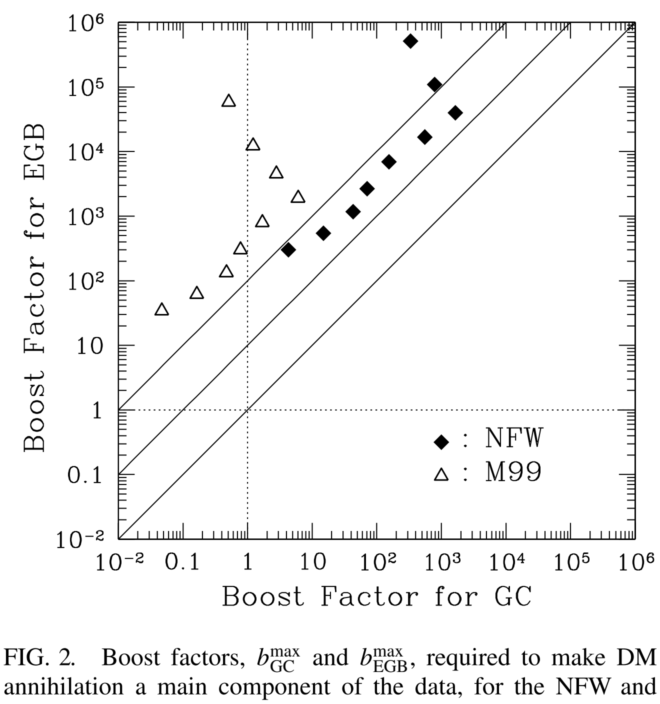

FIG. 2. Boost factors, $b_{\rm GC}^{\max}$ and $b_{\rm EGB}^{\max}$, required to make DM annihilation a main component of the data, for the NFW and M99 profiles. Assumed masses are 10, 20, 50, 100, 200, 500, 1000, 2000, and 5000 GeV (from bottom to top). The solid and dotted lines represent $b_{\rm EGB} = b_{\rm GC}$, $10b_{\rm GC}$, $100b_{\rm GC}$ and $b_{\rm GC} = 1$, $b_{\rm EGB} = 1$, plotted for comparison.

astrophysical sources, and DM component should be significantly smaller than the EGRET data.

Other astrophysical possibilities.—A SMBH, due to its deep potential well, could accrete a significant amount of DM particles, and this would make the density spike in the central region of halos [19]. It has also been pointed out that the infall of baryons due to radiative cooling could lead the DM compression in the GC [20]. Both these effects, potentially and significantly, enhance gamma-ray signals from DM halos. It should be noted that an enhancement of the central density profile by any possible processes strengthens our main conclusion. This is because the GC gamma-ray flux is much more sensitive to the slope of the central region, and the resulting relation of the boost factors, $b_{\rm GC} > b_{\rm EGB}$, prevents the DM component from becoming dominant in EGB, without violating the gamma-ray observations of the GC.

On the other hand, if the density profile in the central region of halos is less steep than the NFW (due to, e.g., rather large inner cutoff radius, as already mentioned), the required relation between the boost factors would become close to $b_{\rm EGB}^{\rm max} \sim b_{\rm GC}^{\rm max}$. In this case, however, we should note it becomes *absolutely* difficult for the DM component to be dominant both in the GC and EGB, while it is *relatively* easier to explain the EGB flux without overproducing the GC gamma rays; it requires, e.g., much larger cross section, which is unlikely. For example, the calculation using the profile with $\gamma = 0.5$ and $m_\chi = 100$ GeV gives $b_{\rm EGB}^{\rm max} \simeq 5b_{\rm GC}^{\rm max} = 3 \times 10^3$.

Recent N-body simulations suggest the presence of a DM substructure, although it is not observationally confirmed. According to the literature, this might boost the GC gamma-ray and EGB flux by at most a factor of a few [25] and about an order of magnitude [15,16], respectively. Therefore, we obtain the relation, $b_{\rm EGB} \lesssim 10b_{\rm GC}$ that is still below the required points shown in Fig. 2. It suggests that even the inclusion of substructure cannot provide a way that violates the main thrust in this Letter. In the previous studies of the EGB flux [17], the intensity multiplier as large as $f(0) \simeq 10^7$ (for the M99 profile) was used, which is about a factor of 50 larger than our value (see Table I). This discrepancy may come from the different choice of the concentration parameter, in addition to inclusion of a substructure. The former is extensively discussed in Ref. [15], and found to give an uncertainty of a factor $\sim$5. Even if we use this extreme boost factor for the EGB ($b_{\rm EGB} \sim 50b_{\rm GC}$), for the M99 profile it still requires some additional effects that enhances the EGB flux with changing the GC gamma rays by a significantly smaller amount. For the NFW or less steep profile, while it might provide a solution to the relative smallness of the predicted EGB flux, we still require considerable amount of corrections, which is physically unlikely.

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