FERMI GAMMA-RAY HAZE VIA DARK MATTER AND MILLISECOND PULSARS

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ABSTRACT

We study possible astrophysical and dark matter (DM) explanations for the FERMI gamma-ray haze in the Milky Way halo. As representatives of various DM models, we consider DM particles annihilating into \( W^+W^-, bb, \) and \( e^+e^- \). In the first two cases, the prompt gamma-ray emission from DM annihilations is significant or even dominant at \( E > 10 \) GeV, while inverse Compton scattering (ICS) from annihilating DM products is insignificant. For the \( e^+e^- \) annihilation mode, we require a boost factor of order 100 to get significant contribution to the gamma-ray haze from ICS photons. Possible astrophysical sources of high-energy particles at high latitudes include type Ia supernovae (SNe) and millisecond pulsars (MSPs). Based on our current understanding of Ia SNe rates, they do not contribute significantly to gamma-ray flux in the halo of the Milky Way. As the MSP population in the stellar halo of the Milky Way is not well constrained, MSPs may be a viable source of gamma-rays at high latitudes provided that there are \( \sim (2-6) \times 10^4 \) of MSPs in the Milky Way stellar halo. In this case, pulsed gamma-ray emission from MSPs can contribute to gamma rays around few GeV, while the ICS photons from MSP electrons and positrons may be significant at all energies in the gamma-ray haze. The plausibility of such a population of MSPs is discussed. Consistency with the Wilkinson Microwave Anisotropy Probe (WMAP) microwave haze requires that either a significant fraction of MSP spin-down energy is converted into \( e^+e^- \) flux or the DM annihilates predominantly into leptons with a boost factor of order 100.

Key words: cosmic rays – dark matter – Galaxy: halo – gamma rays: diffuse background – pulsars: general

Recently, Dobler et al. (2009) have found evidence for a gamma-ray haze in the halo around the Milky Way Galactic center (GC). This signal can be a signature of dark matter (DM) annihilation (e.g., Zeldovich et al. 1980; Springel et al. 2008; Kuhlen et al. 2009). The primary purpose of this paper is to look for possible astrophysical sources of the haze and compare them with DM. Annihilating DM particles that produce many prompt gamma’s (via channels such as \( \chi \chi \to W^+W^-, ZZ, bb, \tau^+\tau^- \)) may significantly contribute or even dominate at photon energies above 10 GeV. The DM particles that predominantly annihilate into leptons contribute significantly to the gamma-ray haze only if their annihilation cross section is enhanced by a boost factor of order 100. This boost factor can be attributed to Sommerfeld enhancement (Hisano et al. 2005; Arkani-Hamed et al. 2009) in, e.g., eXciting Dark Matter (XDM) models with annihilation channel \( \chi \chi \to \varphi\varphi \to 2e^+2e^- \) (Finkbeiner & Weiner 2007; Cholis et al. 2009b; Arkani-Hamed et al. 2009).

A useful discrimination of various sources is their total power in the Milky Way halo. In order to estimate the power of the gamma-ray haze, let us first calculate it in the gamma-ray haze “window” used by Dobler et al. (2009) to find the spectrum of gamma-rays in the haze. This region is \( -15^\circ < l < 15^\circ \) and \( -30^\circ < b < 10^\circ \). The corresponding solid angle is \( \Omega_{\text{haze}} = (l_2 - l_1)\sin b_2 - \sin b_1 \approx 0.17 \). Integrating the gamma-ray spectrum in Figure 11 of Dobler et al. (2009), we find

\[
W_{\gamma-\text{haze}} = \Omega_{\text{haze}} \frac{4 \pi R^2}{d^2} \int E \frac{dN}{dE} dE \sim 10^{37} \text{ erg s}^{-1},
\]

where \( R_\odot = 8.5 \) kpc is the distance from the GC to the Sun. The haze is observed within approximately \( \theta = 45^\circ \) from the GC. The corresponding solid angle \( \Omega_{\text{tot}} = 2\pi (1 - \cos \theta) \approx 1.8 \). Therefore, the total luminosity of this gamma-ray emission is

\[
W_{\gamma-\text{tot}} = \frac{\Omega_{\text{tot}}}{\Omega_{\text{haze}}} W_{\gamma-\text{haze}} \sim 10^{38} \text{ erg s}^{-1}.
\]

At first, we will discuss possible astrophysical sources of the gamma-ray haze. The current star formation rate in the halo of the Milky Way is very small. Thus, the sources of the high-energy particles should have a long lifetime. The two possibilities are type Ia supernovae (SNe) and millisecond pulsars (MSPs).

Let us estimate the output in the high-energy electrons from the type Ia SNe. On average, SNe must produce \( \sim 10^{38} \) erg in relativistic electrons to account for the observed flux of cosmic-ray electrons (Kobayashi et al. 2004). The calculations for observed SNe predict similar or smaller power in electrons (Berezhko & Volk 2008; Zirakashvili & Aharonian 2010). The birth rate of Ia SNe per unit stellar mass in the Galactic halo can be estimated as \( (5.3 \pm 1.1) \times 10^{-14} \text{ yr}^{-1} M_\odot^{-1} \) (Sullivan et al. 2006). In order to estimate the mass of the Milky Way stellar halo, we use the distribution of matter in the disk and in the halo given by Juric et al. (2008) and, for the overall normalization, we use the local stellar density of the thin disk, 35 \( M_\odot \) pc\(^{-2} \) (Kuijken & Gilmore 1989). Therefore, the inferred mass of the Milky Way stellar halo within 20 kpc of the GC is

\[
M_{\text{halo}} \sim 10^9 M_\odot,
\]

with an uncertainty of at most a factor of 2. This gives a Ia SNe rate in the halo of about \( 5 \times 10^{-5} \) yr\(^{-1} \) or \( 2 \times 10^{-12} \) s\(^{-1} \). Consequently, the electron output of the halo Ia SNe is

\[
W_{e^+ e^-} < 10^{37} \text{ erg s}^{-1}.
\]

This is insufficient to account for the gamma-ray haze already based on the total output energy (we need at least \( 10^{38} \) erg s\(^{-1} \)).
with a cutoff in the spin-down energy of an MSP goes into electrons and positrons (Abdo et al. 2009a, 2009b). Observations of X-ray nebulae from MSPs is similar to the electron emission from young radio pulsars, such as the Crab pulsar (Atoyan & Aharonian 1996). In particular, we assume that a large fraction of the spin-down energy of an MSP goes into electrons and positrons (Stappers et al. 2003; Kargaltsev et al. 2006), GeV (Abdo et al. 2009a, 2009b). Observations of X-ray nebulae (Stappers et al. 2003). The average properties of pulsed γ-ray emission from MSPs for a sample of eight pulsars detected by Fermi (Abdo et al. 2009a) are presented in Table 1.

| Index | Cutoff $E_{\text{cut}}$ (GeV) | $\log_{10} L$ (erg s$^{-1}$) |
|-------|-------------------------------|-------------------------------|
| 1.5 ± 0.4 | 2.8 ± 1.9 | 33.9 ± 0.6 |

Notes. Here, we assume that the γ-ray spectrum is a power law with an exponential cutoff, $F \sim E^{-\Gamma} e^{-E/E_{\text{cut}}}$. The total power in γ-rays equals the total spin-down luminosity times the conversion efficiency $L_{\gamma} = \eta_{\gamma} L$. Assuming the log-normal distribution of $L$, the mean luminosity is $\langle L \rangle \sim 2 \times 10^{34}$ erg s$^{-1}$. Assuming $\eta_{\gamma} \sim 10\%$, we get the mean luminosity in pulsed γ-rays to be $\langle L_{\gamma} \rangle \sim 2 \times 10^{33}$ erg s$^{-1}$.

Provided that the above estimations are good within an order of magnitude, we conclude that Ia SNe will not contribute a significant number of electrons and γ-rays in the haze region and we will not consider them in the following.

MSPs are known to emit pulsed γ-rays with a cutoff at a few GeV (Abdo et al. 2009a, 2009b). Observations of X-ray nebulae around some MSPs show a production of high-energy electrons and positrons (Stappers et al. 2003; Kargaltsev et al. 2006), but the uncertainties in the particle spectrum are rather large. We will consider two possibilities for the total energy output in $e^+e^-$ pairs in their magnetosphere is on the order of $10^{42}$ erg. In the first case, we assume that the electron emission from MSPs is similar to the electron emission from young radio pulsars, such as the Crab pulsar (Atoyan & Aharonian 1996). In particular, we assume that a large fraction of the spin-down energy of an MSP goes into electrons and positrons with a cutoff in the $e^+e^-$ injection spectrum, $E_{\text{cut}} \gtrsim 100$ GeV. In this case, we demonstrate that the MSPs may be sufficient to explain γ-ray haze at all energies (although prompt γ-ray emission from DM annihilation may contribute significantly at $E \gtrsim 100$ GeV). In the second case, we assume that $e^+e^-$ emission from MSPs is small, then the spectrum above 10 GeV requires an additional source, such as annihilating DM. At the moment, both possibilities for $e^+e^-$ emission are consistent with observations of MSP nebulae (Stappers et al. 2003). The average properties of pulsed γ-ray emission from MSPs for a sample of eight pulsars detected by Fermi (Abdo et al. 2009a) are presented in Table 1.

Let us estimate the number of active MSPs in the Milky Way halo. One of the standard models for the formation of the Galaxy assumes that the halo is formed before the disk (Binney & Tremaine 2008). The star formation in the halo happens predominantly during the early stages of the evolution. Based on the location of observed MSPs on the $P-P$ diagram (Lorimer & Kramer 2005; Chen & Ruderman 1993), the length of time they can produce $e^+e^-$ pairs in their magnetosphere is on the order of the Hubble time. Therefore, we expect that any MSPs produced during this period are still active today. This conclusion is also consistent with the observed characteristic age of the MSPs (Manchester et al. 2004; Ferrario & Wickramasinghe 2007).

Since the direct detection of MSPs in the Milky Way halo is difficult, we need an indirect way to estimate their number. An important observation is that the number density of MSPs depends sensitively on the stellar density. For instance, globular clusters have much higher stellar density than the galaxies. The 47 Tucanae cluster is expected to have about 30 MSPs (Abdo et al. 2009b) and a mass of $10^9 M_\odot$, which gives the MSP number to stellar mass ratio of $5 \times 10^{-3} M_\odot^{-1}$. For the Milky Way disk, the local column density of MSPs is estimated to be $50$ kpc$^{-2}$ (Cordes & Chernoff 1997). For a local total mass density of $50 M_\odot$ pc$^{-2}$ (Kuijken & Gilmore 1989), this gives the MSP number to mass ratio of $10^{-6} M_\odot^{-1}$, which is 50 times smaller than the corresponding ratio for the 47 Tuc.

The halo of the Milky Way is formed from both the initial spherical stellar population and via mergers with nearby dwarf galaxies and stellar clusters (Bullock & Johnston 2005; Font et al. 2006; Zolotov et al. 2009). Galaxies at high redshift have significantly higher stellar density than the low-redshift galaxies, for instance, at $z = 2$ the density may be up to 100 times higher (Bezanson et al. 2009). For comparison, the Milky Way stellar density is of order $10^4$ times smaller than the stellar density of 47 Tuc within half-mass radius (Harris 1996). We expect the MSP number to mass ratio to be determined by the stellar density at the time of star formation. Thus, the MSP number to stellar mass ratio for the Milky Way halo should be higher than that for the Milky Way disk but lower than that in the globular clusters. For a Milky Way stellar halo mass of $M_{\text{halo}} \sim 10^9 M_\odot$, the expected number of MSPs is

$$N_{\text{halo, MSPs}} \sim 1 \times 10^{33} - 5 \times 10^4,$$

where the lower bound comes from the MSP number to stellar mass ratio for the Milky Way disk and the upper bound comes from the MSP number to stellar mass ratio for the 47 Tuc. Using the parameters from Table 1, we find that the total power emitted by the halo MSPs can be as high as

$$W_{\text{halo, MSPs}} \sim 10^{39} \text{ erg s}^{-1}$$

and the power in pulsed γ-rays can be $10^{38}$ erg s$^{-1}$. This estimation can vary significantly due to uncertainty in the total number of MSPs in the stellar halo. It may also depend on the distribution of pulsar properties, e.g., the index, the cutoff, and the luminosity in pulsed γ-rays. With only eight observed γ-ray MSPs, this distribution cannot be well measured, but it should be possible in the future with a better observational statistic. Thus, at the moment, we cannot robustly estimate the contribution of MSPs to high-latitude γ-rays. The main purpose of this work is to point out the possibility of a significant population of MSPs in the stellar halo of the Milky Way which are a viable source of the γ-ray haze. In this paper, we will take the γ-ray luminosity of MSPs in Table 1 as a reference value. Then, for some particular DM models, we will be able to estimate the number of MSPs in the stellar halo from the γ-ray haze data.

MSPs are also continuously created in the Galactic disk. Every pulsar acquires a kick velocity at the birth. For regular pulsars, the mean kick velocity is about $400$ km s$^{-1}$ (Faucher-Giguère & Kaspi 2006). MSPs are usually found in binaries. The center-of-mass velocities of the binary systems have typical values $\sim 80$ km s$^{-1}$ (Cordes & Chernoff 1997). Lyne et al. (1998) obtained the average velocity $\sim 130$ km s$^{-1}$ for their sample of MSPs. These velocities are not sufficient for the majority of MSPs to overcome the gravitational potential of the disk (Cordes & Chernoff 1997; Story et al. 2007). Although the disk MSPs contribute significantly to the diffuse γ-ray background (Story et al. 2007; Faucher-Giguère & Loeb 2010), the corresponding flux of γ-rays has a disk-like morphology which is different from an egg-like shape of the γ-ray haze (Dobler et al. 2009). Consequently, we need an additional population of MSPs that stretches to higher latitudes.

The distribution of the stellar mass in the halo falls approximately as $r^{-3}$ (Jurić et al. 2008; Bell et al. 2008). In order to get a smooth distribution in the GC, we introduce a cutoff radius $R_c$.
and take the following profile of MSPs

$$\rho_{\text{MSPs}} \sim \frac{1}{(r + R_c)^3}.$$  

(7)

where we will take $R_c = 2$ kpc as our reference value. Physically, at $R_c$ the power-law distribution of the matter in the halo breaks down and merges to a Gaussian or exponential distribution near the GC (Dwek et al. 1995). Since we are interested in high-latitude fluxes, the precise shape of the matter distribution near the GC is not important and the approximation in Equation (7) is sufficient.

In our calculations, we will use the following source function for $e^\pm$ and $\gamma$ emission from the MSPs (the parametric form of the source functions for $e^\pm$ and for $\gamma$ are the same, but the index and the cutoff are different)

$$Q_{\text{MSPs}}(r, E) = Q_0 \frac{1}{(r + R_c)^3} \left( \frac{E}{E_{\text{cut}}} \right)^{-\alpha} \exp \left( - \frac{E}{E_{\text{cut}}} \right).$$  

(8)

where for the $\gamma$-ray spectrum we will use the parameters from Table 1, $n = 1.5 \pm 0.4$ and $E_{\text{cut}} = 2.8 \pm 1.9$. Motivated by possible similarities between the electron spectrum from MSPs and younger radio pulsars, we use the following parameters to describe the spectrum of electrons: $n = 1.5 \pm 0.5$ and $E_{\text{cut}}$ equal to a few hundred GeV (see, e.g., Atoyan & Aharonian 1996) for the $e^+e^-$ spectrum in the Crab Nebula). The total energy output is proportional to the total stellar mass of the halo in Equation (3) times the MSP number to stellar mass ratio in Equation (5).

Annihilating DM provides a source for prompt $\gamma$-rays and $e^+e^-$ of the form

$$Q_{\text{DM}}(r, E) = \frac{\rho_{\text{DM}}^2}{2 M_{\text{DM}}^2} \langle \sigma v \rangle_0 \frac{dN}{dE},$$  

(9)

where $\rho_{\text{DM}}^2/M_{\text{DM}}^2$ is the DM number density, $\langle \sigma v \rangle_0 = 3.0 \times 10^{-26}$ cm$^3$ s$^{-1}$ is the thermally averaged annihilation cross section at freeze out, and $dN/dE$ is the differential energy spectrum of either $e^\pm$ or $\gamma$ produced in a single annihilation event. In general, the annihilation rate can be enhanced by a boost factor which we denote as BF. For the calculations, we use the Einasto profile of DM (Merritt et al. 2005):

$$\rho_{\text{DM}}(r) = \rho_{\text{DM},0} \exp \left( - \frac{2 r^\alpha - R_\odot^\alpha}{\sigma R_\odot^\alpha} \right),$$  

(10)

where $R_\odot = 25$ kpc, $\alpha = 0.17$, and $R_\odot = 8.5$ kpc. For the local DM density, we take $\rho_{\text{DM},0} = 0.4$ GeV cm$^{-3}$ (Catena & Ullio 2009). Merritt et al. (2005) motivated the use of this profile by the DM N-body simulations. The rotation curves in the inner part of the Galaxy are dominated by the luminous matter and do not constrain significantly the DM distribution (e.g., Dehnen & Binney 1998); see also Salucci et al. (2007) for a recent fit with a less cuspy profile). In any case, the spectrum of photons in the $\gamma$-ray haze window is not sensitive to the choice of DM profile.

The total power released by annihilating DM is

$$W_{\text{DM}} = \frac{1}{2} \int \rho_{\text{DM}}^2 \langle \sigma v \rangle_0 2 M_{\text{DM}} 4\pi r^2 dr.$$  

(11)

For a DM particle with the mass $M_{\text{DM}} = 300$ GeV and the rest of the parameters described above, the total power from annihilating DM within 20 kpc from GC is

$$W_{\text{DM}} \sim 2 \times 10^{37} \text{ erg s}^{-1},$$  

(12)

which is about five times smaller than the total power in the $\gamma$-ray haze. Based on this crude estimate, we already expect that without boost factors this DM model will not explain the $\gamma$-ray haze at all energies, but it can be significant at some energies provided that the production of high-energy photons is efficient.

For the propagation of $e^\pm$ in the interstellar medium, we use GALPROP (Strong et al. 2007; Moskalenko & Strong 1999),
with the interstellar radiation field model of Porter & Strong (2005). We assume the following magnetic field model:

\[ B(R, z) = B_0 \exp \left( \frac{R_\odot - R}{R_c} \right) \exp \left( -\frac{z}{z_c} \right), \]

(13)

where \( B_0 = 5 \, \mu G \) is the value for the total (combined random and large-scale “ordered”) local magnetic field. \( R_c = 4.5 \) kpc and \( z_c = 2.0 \) kpc are the characteristic scales along \( R \) and \( z \) directions, respectively, and \( R_\odot = 8.5 \) kpc.

Our main result is shown in Figure 1. In order to explain the \( \gamma \)-ray haze, we add the direct emission of pulsed \( \gamma \)-rays from MSPs, the ICS photons from MSP and DM electrons, and prompt \( \gamma \)-ray emission from annihilating DM. The prompt \( \gamma \)-ray emission from annihilating DM becomes comparable to ICS photons from MSP electrons around 100 GeV. The bump in the \( \gamma \)-ray haze spectrum around 4 GeV is naturally explained with the pulsed \( \gamma \)-ray emission from MSPs. We also compare the synchrotron radiation with the microwave haze data (Finkbeiner 2004). We add the synchrotron from MSP and DM electrons together with a constant a priori unknown offset. Our model seems to give synchrotron radiation that is less cuspy than the microwave haze data. The deviation happens below \( 10^4 \) which corresponds to a distance of about 1.5 kpc from the GC where our mass distribution in Equation (7) may be invalid. We also expect some contribution from sources in the bulge which may provide cusplier latitudinal profile of synchrotron radiation than the one presented in Figure 1.

In this example, we need about \( 3 \times 10^4 \) MSPs in the Milky Way halo which corresponds to (1–2) \( \times 10^3 \) MSPs in the \( \gamma \)-ray haze “window.” The question is whether it is possible to distinguish between the \( \gamma \)-ray flux from MSPs and the diffuse ICS photons. The flux from an average MSP with pulsed \( \gamma \)-ray luminosity \( L_\gamma \sim 10^{33} \) erg s\(^{-1}\) at a distance of 8.5 kpc from the Earth is \( < 10^{-12} \) erg s\(^{-1}\) cm\(^{-2}\), which is less than the \textit{Fermi} sensitivity for a detection of a point source with 8σ significance even after a year of observation.\(^5\) One can also use more sophisticated methods to distinguish between the point sources and the diffuse background without point source identification (Slater & Finkbeiner 2009). The problem is that the expected typical separation between MSPs in the \( \gamma \)-ray haze “window” is comparable to the \textit{Fermi}-LAT point-spread function at energies \(< 10 \) GeV (Rando 2009). Consequently, it seems implausible that one will be able to distinguish between the \( \gamma \)-ray emission from MSPs and the diffuse ICS photons using available \( \gamma \)-ray observations.

Let us argue now that a population of \( 3 \times 10^4 \) MSPs in the Milky Way halo is not inconsistent with the properties of currently known MSPs. Since the luminosity of MSPs is generally very low, most of the observed MSPs are within \( \sim 1–2 \) kpc from the Earth. Thus, we cannot directly observe the halo MSPs at large heights above the disk and the only parameter that can effectively distinguish a halo MSP from a disk MSP is the velocity relative to the Sun. Based on the force in the vertical direction at \( R = R_\odot, z = 1.1 \) kpc (Kuijken & Gilmore 1991), \( v = 23 \) km s\(^{-1}\), we can estimate the escape velocity \( v_{\text{esc}} \sim 100 \) km s\(^{-1}\). Pulsars with the transverse velocity \( v_t \gg v_{\text{esc}} \) can be attributed to the halo population.

According to the ATNF catalog (Manchester et al. 2004), there are about three MSPs with \( v_t \gtrsim 200 \) km s\(^{-1}\) at a distance \( r \sim 1 \) kpc from the Earth (e.g., B1957+20, J1909–3744, and B1257+12). This is consistent with the local number density that follows from the distribution in Equation (7) \( n_{\text{halo}} \sim 3 \) kpc\(^{-3}\). One should also take into account that not all local MSPs can be observed due to beaming of the radio emission. The local MSP number density that we need is significantly larger than the one estimated by Cordes & Chernoff (1997), \( n_h < 0.4 \) kpc\(^{-3}\) at 90% confidence. We believe that this discrepancy may be due to the small velocity dispersion \( \sigma_v = 53 \) km s\(^{-1}\) in the sample of MSPs used by Cordes & Chernoff (1997). This velocity dispersion implies that the probability to have \( v_t > 200 \) km s\(^{-1}\) is less than 10\(^{-3}\) which is inconsistent with a few MSPs out of about 100 in the ATNF catalog that have \( v_t > 200 \). The analysis of Lyne et al. (1998) gives \( \sigma_v = (80 \pm 20) \) km s\(^{-1}\) which corresponds to the probability \( P(v_t > 200 \) km s\(^{-1}\)\) ≈ 4%. This probability is consistent with both the currently observed MSPs and the local halo MSP number density \( n_{\text{halo}} \sim 3 \) kpc\(^{-3}\) relative to the disk MSP number density \( n_{\text{disk}} \sim 40 \) kpc\(^{-3}\) (Cordes & Chernoff 1997).

In Figure 2, we consider the case that MSPs do not emit enough electrons and fit the \( \gamma \)-ray haze data with the pulsed

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\(^5\) Fermi-LAT performance: http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm
mass reference injection parameters are and DM and the contribution of the component whose properties we vary in each case. The reference model is as shown in Figure 1. DM has a mass of 300 GeV and annihilates via $\chi\chi\rightarrow W^+W^-$ and $\chi\chi\rightarrow b\bar{b}$, with $M_{\chi}=300$ GeV. The pulsed $\gamma$-ray emission parameters are $n_{\gamma}=1.3$ and $E_{cut}=300$ GeV. The pulsar $\gamma$-ray emission parameters are $n_{\gamma}=1.3$ and $E_{cut}=4$ GeV. Upper left: varying DM mass $M_{DM}=200, 300, 500$ GeV for $\chi\chi\rightarrow W^+W^-$ and $M_{\chi}=300$ GeV for $\chi\chi\rightarrow b\bar{b}$. Upper right: varying scaling radius $R_{c}$ of MSPs distribution profile. Lower left: varying MSPs electron injection (and $\gamma$-ray) index ($n_{e}=n_{\gamma}$). Lower right: varying MSPs electron injection cutoff $E_{cut}$. On each plot, there are two lines of the same type: two solid lines, two dashed lines, two dotted lines, etc. The lower one only has MSPs or only DM contribution, while the upper one has MSPs plus DM contributions.

Figure 3. Pulsed $\gamma$-ray emission from MSPs and DM with $e^+e^-$ annihilation mode. This DM model was used by Cholis et al. (2009a) to fit the local $e^+e^-$ cosmic-ray experiments. The spectrum of ICS photons is too flat to reproduce the bump around 4 GeV. As a result, a contribution of $\gamma$-rays from a population of about $2 \times 10^3$ MSPs in the Milky Way halo is necessary.
emission from MSPs and with DM annihilation products. In this case, we need a rather mild boost factor $BF = 3$. For the microwave haze data, we need a significantly larger constant offset than in Figure 1, and the shape of the microwave haze is not fit nicely due to the small production rate of $e^+e^-$ by annihilating DM in this case.

In both of the cases considered above, the $e^+e^-$ emission from MSPs and DM is too small to significantly contribute to local $e^+e^-$ fluxes. In particular, we need to assume that the rising positron fraction in the PAMELA experiment (Adriani et al. 2009) is due to a different astrophysical source, such as young radio pulsars (Hooper et al. 2009; Yüksel et al. 2009; Profumo 2008; Malyshev et al. 2009).

In the case when $e^+e^-$ emission from MSPs is small, one can also consider DM particles that predominantly annihilate into leptons with large boost factors. As an example, we study a DM model (Arkani-Hamed et al. 2009) used to explain the local $e^+e^-$ fluxes (Cholis et al. 2009a). The corresponding $\gamma$-rays signal is shown in Figure 3. The ICS photons have a flat spectrum and cannot explain the bump around 4 GeV which can be produced by pulsed $\gamma$-ray emission from about 20,000 MSPs in the Milky Way halo. Another possibility is to consider a model with more than one species of DM particles (e.g., Cholis & Weiner 2009).

In Figures 4 and 5, we address the question whether the observationally unknown parameters used in Figure 1 were fine tuned. In particular, we study the dependence on the index and cutoff of $e^+e^-$ injection spectrum from MSPs, on the scaling radius of the MSP distribution $R_c$, on the DM mass, and on the DM annihilation channel. We show that rather large changes of these parameters do not change our conclusions.

In this paper, we have studied possible contributions to the $\gamma$-ray Fermi haze. We have shown that two major contributions may come from the MSPs and annihilating DM. The electron and positron emission from MSPs is uncertain, and we considered two cases. In the first case, we assume that a large part by pulsed $\gamma$-ray emission from about 20,000 MSPs in the Milky Way halo. Another possibility is to consider a model with more than one species of DM particles (e.g., Cholis & Weiner 2009).

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In this paper, we have studied possible contributions to the $\gamma$-ray Fermi haze. We have shown that two major contributions may come from the MSPs and annihilating DM. The electron and positron emission from MSPs is uncertain, and we considered two cases. In the first case, we assume that a large part
of MSP spin-down luminosity is transformed in the $e^+e^-$ flux. In this case, a population of $3 \times 10^6$ MSPs in the Milky Way halo can explain the $\gamma$-ray haze if about 50% of the MSPs spin-down is transformed into $e^+e^-$ and about 10% is transformed in pulsed $\gamma$-rays. The synchrotron emission from MSP electrons is consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) microwave haze data as well. Prompt $\gamma$-ray emission from a DM particle annihilating into $W^+W^-$ contributes significantly around 100 GeV. In the second case, we assumed that practically no MSP spin-down energy goes into $e^+e^-$. The $\gamma$-ray haze can be explained by the pulsed $\gamma$-rays from MSPs and a DM particle annihilating into $W^+W^-$ with a boost factor 3. However, the synchrotron emission (of $e^+e^-$ from our assumed DM model) is insufficient to explain the microwave haze data. Another alternative to explain the $\gamma$-haze in the case of small $e^+e^-$ emission from MSPs is DM particles with leptonic annihilation modes and boost factors of order 100 together with pulsed $\gamma$-rays from MSPs. The last scenario is also consistent with the WMAP microwave haze data.

In general, the $\gamma$-ray haze, if confirmed, provides a strong evidence for new sources of $\gamma$-rays additional to the standard ones, such as the $\pi^0$ production by cosmic rays and the ICS photons from the electrons accelerated by SNe in the Galactic plane. Possible new sources of $\gamma$-rays include DM annihilation and a large population of MSPs in the stellar halo of the Milky Way. The $\gamma$-ray haze may also suggest a recent active galactic nucleus activity or an existence of a bipolar Galactic wind (Su et al. 2010).

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