Search for dark matter signals with Fermi-LAT observation of globular clusters NGC 6388 and M 15

Lei Feng\textsuperscript{a,b,c}, Qiang Yuan\textsuperscript{a}, Peng-Fei Yin\textsuperscript{a}, Xiao-Jun Bi\textsuperscript{a} and Mingzhe Li\textsuperscript{b,c}

\textsuperscript{a}Key laboratory of particle astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{b}Department of Physics, Nanjing University, Nanjing 210093, China
\textsuperscript{c}Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing University – Purple Mountain Observatory, Nanjing 210093, China

fenglei@chenwang.nju.edu.cn, yuanq@ihep.ac.cn, yinpf@ihep.ac.cn, bixj@ihep.ac.cn, limz@nju.edu.cn

ABSTRACT: The globular clusters are probably good targets for dark matter (DM) searches in $\gamma$-rays due to the possible adiabatic contraction of DM by baryons. In this work we analyse the three-year data collected by Fermi Large Area Telescope of globular clusters NGC 6388 and M 15 to search for possible DM signals. For NGC 6388 the detection of $\gamma$-ray emission was reported by Fermi collaboration, which is consistent with the emission of a population of millisecond pulsars. The spectral shape of NGC 6388 is also shown to be consistent with a DM contribution if assuming the annihilation final state is $b\bar{b}$. No significant $\gamma$-ray emission from M 15 is observed. We give the upper limits of DM contribution to $\gamma$-ray emission in both NGC 6388 and M 15, for annihilation final states $b\bar{b}$, $W^+W^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and monochromatic line. The constraints are stronger than that derived from observation of dwarf galaxies by Fermi.

KEYWORDS: dark matter, globular cluster, gamma-ray
1. Introduction

A standard model of cosmology is developed, in which the universe consists of 4% ordinary baryonic matter, \( \sim 23\% \) dark matter (DM), \( \sim 73\% \) dark energy, and a tiny abundance of relic neutrinos [1]. The nature of DM particle remains a mystery. One of the leading candidates is the weakly interacting massive particle (WIMP), which is predicted in several models, such as neutralino in supersymmetry model (see the reviews [2, 3, 4]). In this kind of models, the mass and interaction strength of DM particles can produce the correct relic density of DM if the WIMPs are thermally “freeze-out”, which is called “WIMP miracle”.

If DM particles annihilate or decay into standard model particles, they can be detected indirectly from the cosmic ray (CR) radiation. Among many kinds of CR particles, \( \gamma \)-rays are the best probe due to their simple propagation. Fermi gamma-ray telescope, which was launched in 2008, has surveyed the \( \gamma \)-ray sky with very high resolution and sensitivity for more than three years. Nearly 2000 sources as well as the diffuse \( \gamma \)-ray emission were detected by Fermi Large Area Telescope (Fermi-LAT) [5, 6, 7, 8]. The analysis of the Fermi-LAT data in the Galactic center region did see some excesses with respect to the background model [5, 6], however, there is no strong indication of signals from DM annihilation or decay\(^1\). The constraints on DM model parameters can be derived according to the non-detection of DM signals from e.g., dwarf galaxies [12, 13, 14, 15, 16], galaxy clusters [17, 18, 19, 20, 21, 22], and the diffuse \( \gamma \)-rays [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33].

Due to the very weak interactions of DM particles, it is important to investigate the sites with high DM density when searching for DM annihilation signals. The proposed

\(^1\)See also the argument of possible DM explanation of the \( \gamma \)-ray haze/bubble [1].
good candidates include the Galactic center, dwarf galaxies, Galactic subhalos and cluster of galaxies. The Milky Way globular clusters (GCs), defined as spherical ensemble of stars that orbits the Galaxy as satellites, are also potentially good targets for indirect detection of DM. The formation of GCs remains a poorly understood problem. There are generally two scenarios to describe the formation of GCs. The primordial formation scenario suggests that GCs were formed in cosmological DM minihalos before the formation of galaxies [34]. The other way to form GCs might be the star-forming events such as the merger of galaxies. There was evidence to show that metal-poor GCs might have a cosmological origin and metal-rich GCs might form in the galaxies [35]. If the GCs were formed in cosmological DM minihalos, they would experience the adiabatic contraction (AC) due to the infall of baryons during the evolution of GCs and leave a high density spike of DM. GCs are not usually discussed for DM detection due to the poor knowledge about their origin and the observational fact that there is in general no significant amount of DM in vicinity of GCs [36, 37, 38]. However, there is possibility that the high density spike of DM due to the AC process may still play an important role for the annihilation signals. The previous works to search for or constrain DM models with $\gamma$-rays from GCs include [39, 40].

Recently the atmospheric Cherenkov telescope array High Energy Stereoscopic System (H.E.S.S.) had investigated two GCs NGC 6388 and M 15 to search for possible DM signals [41]. No $\gamma$-ray signal was detected by H.E.S.S. and strong constraints on the DM model parameters were given. In this work, we use the three-year data of Fermi-LAT to study the $\gamma$-ray emission from DM annihilation in these two GCs. Detections of $\gamma$-ray emission from some GCs with Fermi-LAT were reported [42, 43, 44, 45], including NGC 6388 studied here. For M 15 there is no detection yet. In this work we will focus on the possible DM component of the $\gamma$-ray emission, if any, from the GCs. The upper limits of DM contribution will be derived and the constraints on DM model parameters will be presented.

2. Gamma-rays from DM annihilation in globular clusters

M 15 is a metal-poor GC which favors a cosmological origin of it [46]. For NGC 6388, there is strong evidence to show the existence of an intermediate mass black hole (IMBH) with mass $\sim 6 \times 10^3$ M$_\odot$ [47], which also suggests a cosmological origin even though the metallicity is relatively high [48]. Therefore we have good motivation to search for the possible DM annihilation signal from these two GCs. The estimated stellar masses of NGC 6388 and M 15 are $10^6$ and $5 \times 10^5$ M$_\odot$, with distances 11.5 and 10.0 kpc respectively [47, 48]. Other parameters of them can be found in Table 2 of Ref. [41].

2.1 DM density distribution

For the purpose of this work, these two GCs are assumed to form in the cosmological context, which were DM dominated in the primordial stage, before reionization and the galaxy formation [44]. The AC process of baryons to form the GC is expected to pull DM into the center and results in a high density core of DM [15]. After the AC process the heating effect of DM due to scattering with baryons will tend to sweep out the high density
DM core, leaving a constant density \([49]\). The IMBH, if exists, may further modify the density profile through adiabatic accretion \([50]\).

The modelling of the GC DM halo can be divided into three steps. The first step is the AC process of the dark halo during the collapse of the core of GC. Supposing that the DM particles travel on circular orbits, the enclose mass distribution of DM \(M(r)\) can be calculated with the follow equation \([48]\)

\[
[M_{DM,i}(r_i) + M_{b,i}(r_i)]r_i = [M_{DM,f}(r_f) + M_{b,f}(r_f)]r_f, \tag{2.1}
\]

where the subscript \(i(f)\) denotes the initial (final) mass distribution of baryon or DM. The initial mass of the minihalo is assumed to be \(10^7 \, M_\odot\), with Navarro-Frenk-White (NFW, \([51]\)) density profile for both the DM and baryon distributions\(^2\). The mass fraction of baryons is adopted to be 20%. For the convenience of comparison, these adoptions are the same as that in Ref. \([41]\). We should keep in mind that these parameters may have large uncertainties and the quantitative results of this work may also suffer from uncertainties.

Given the final baryon distribution, which can be derived according to the observed surface density distribution of the GC\(^3\), one can get the DM density profile after AC \([48]\). The final baryon density for NGC 6388 is taken from \([41]\), which was computed using the surface density profile given in \([47]\). For M 15 the final baryon density is taken from \([55]\).

The second step is to take into account the smoothing effect due to baryon heating after AC process. For the convenience of discussion, we employ the relaxation time \(T_r\) defined as \([56]\)

\[
T_r = 3.4 \times 10^9 \left( \frac{v_{\text{rms}}}{\text{km s}^{-1}} \right)^3 \left( \frac{m}{M_\odot} \right)^{-2} \left( \frac{n}{\text{pc}^{-3}} \right)^{-1} \text{yr}, \tag{2.2}
\]

where \(v_{\text{rms}}\) is the velocity dispersion of stars, \(m\) is the typical stellar mass in the GC, \(n\) is the stellar number density, and \(\ln \Lambda\) is the Coulomb logarithm. \(T_r\) is estimated to be \(\sim 7 \times 10^4 \text{ yr}\) in the central region of M 15, and \(\sim 8 \times 10^6 \text{ yr}\) for central NGC 6388 \([41]\). The relaxation time is an increasing function of the distance to the center. The DM will be heated up due to the scattering with the stars, which will lead to the dissipation of the DM core \([57]\). The scattering time scale is comparable to \(T_r\). The heating radius, \(r_{\text{heat}}\), is then defined with \(T_r(r_{\text{heat}}) = t_{\text{age}}\), where \(t_{\text{age}}\) is the age of the Universe. Therefore at small radius \(r < r_{\text{heat}}\), the relaxation time is shorter than the age of the Universe and the heating effect on DM is important. At large radius \(r > r_{\text{heat}}\) the DM distribution is unaffected by heating. The heating radii are estimated to be about 5 pc and 4 pc for M 15 and NGC 6388 respectively. Roughly speaking we have the DM density distribution with baryonic heating

\[
\rho(r) = \begin{cases} 
\rho_0, & r < r_{\text{heat}}, \\
\rho_0 \times \frac{\rho_{\text{AC}}(r)}{\rho_{\text{AC}}(r_{\text{heat}})}, & r > r_{\text{heat}},
\end{cases} \tag{2.3}
\]

where \(\rho_{\text{AC}}(r)\) is the DM density profile after AC, which can be solved with Eq. (2.1), and \(\rho_0\) is the density at \(r = r_{\text{heat}}\).

\(^2\)Note that for such minihalos the density profile might be smoother \([52, 53]\), however, as shown in \([54]\) the initial density profile does not affect significantly the final DM profile after AC process.

\(^3\)See, e.g., http://www.physics.mcmaster.ca/ harris/mwgc.dat
The third step is to consider the effect of the IMBH, if exists. The AC profile of DM will not be significantly affected by the IMBH due to its small mass compared with the total baryon mass. However, the following adiabatic accretion of IMBH will modify the DM density profile after dynamic heating. The radius within which the IMBH is gravitational dominant is defined by 

$$M(< r_h) = \int_0^{r_h} \rho(r) d^3r = 2M_{\text{IMBH}}.$$ 

Then the DM distribution can be expressed in three regions

$$\rho(r) = \begin{cases} 
\rho_0 (r/r_h)^{-3/2}, & r < r_h, \\
\rho_0, & r_h < r < r_{\text{heat}}, \\
\rho_0 \times \frac{\rho_{\text{AC}}(r)}{\rho_{\text{AC}}(r_{\text{heat}})}, & r > r_{\text{heat}}.
\end{cases} \tag{2.4}$$

The innermost density profile ($\propto r^{-3/2}$) corresponds to the collisionally regenerated structures (“crest”) of DM due to the joint evolution of baryons and DM in the environment of a central black hole [58]. For NGC 6388, $M_{\text{IMBH}} \sim 6 \times 10^3 M_\odot$, $r_h \sim 0.4$ pc is found with the observational baryon density. For M 15 there is no consensus of the existence of IMBH [59, 60], and we employ Eq. (2.3) to describe the DM density profile of M 15 without considering the possible IMBH.

### 2.2 Astrophysical $J$-factor

For Majorana fermion DM particles, the $\gamma$-ray flux from DM annihilation can be written as

$$\Phi(\Delta \Omega, E_\gamma) = \frac{1}{4\pi} \times \frac{\langle \sigma v \rangle}{2m_\chi} \frac{dN_\gamma}{dE_\gamma} \times \bar{J}(\Delta \Omega) \Delta \Omega,$$  

where $m_\chi$ and $\langle \sigma v \rangle$ are the mass and velocity weighted thermal average annihilation cross section of DM particles, $dN_\gamma/dE_\gamma$ is the $\gamma$-ray spectrum for one annihilation. The astrophysical factor ($\bar{J}$) is the integral of the density square along the line of sight (LOS) averaged over the solid angle $\Delta \Omega$

$$\bar{J}(\Delta \Omega) = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega \int_{\text{LOS}} dl \rho^2(r(l)). \tag{2.6}$$

For H.E.S.S. observations, the integral solid angle is $\Delta \Omega = 5 \times 10^{-6}$ sr, which corresponds to a cone with half angle 0.07° [11]. Since the resolution angle of Fermi-LAT in GeV range is much larger (> 0.5°, [61]), we need to enlarge the integral solid angle. The tidal radii of both GCs are about 30 pc, and the distances are about 10 kpc [11]. The opening angles of these two GCs are $\sim 0.17\degree$. Therefore they can be regarded as point sources for Fermi-LAT and we integrate all the DM contribution to the tidal radius to calculate the $J$-factor. It is found that the final $J \times \Delta \Omega$ is about $7.8 \times 10^{19}$ (3.4 × 10$^{20}$) GeV$^2$ cm$^{-3}$ for M 15 (NGC 6388), which is larger by $\sim 10\%$ (0.1\%) compared with that within 0.07° cone as adopted by H.E.S.S.. The $J$-factor of NGC 6388 is larger than M 15 is mainly due to the difference of the density profiles after AC which depends on the final baryon density profiles of the GCs, and the heating effect. Compared with the dwarf galaxies as given in [13], the $J$-factors of GCs are generally larger, which is also due to the AC process.
3. *Fermi*-LAT data analysis

The *Fermi*-LAT data\(^4\) used in this analysis are the new “Pass 7” data recorded between 4 August 2008 and 2 September 2011. Photons with Event Class “Source” (evclass=2) and zenith angle within 100° are selected. The energy range of events is cut from 200 MeV to 300 GeV, and the radius of region-of-interest (ROI) is adopted to be 6°. We use the LAT Scientific Tools v9r23p1 to do this analysis. The unbinned likelihood analysis method is adopted. The instrument response function used is “P7SOURCE\_V6”. For the diffuse background, we use the Galactic diffuse model `gal_2yearp7v6_v0.fits` and the isotropic background spectrum `iso\_p7v6source.txt` provided by the *Fermi* Science Support Center\(^5\).

3.1 NGC 6338

The detection of γ-ray emission from NGC 6388 was reported in [43], with Test Statistic \([62]\) value TS= 86.6. The spectral energy distribution can be fitted using power-law function with an exponential cutoff \(E^{-\Gamma}\exp(-E/E_c)\), which is expected for the emission from a population of millisecond pulsars (MSP). The best-fitting parameters are \(\Gamma = 1.1^{+0.7}_{-0.5}\) and \(E_c = 1.8^{+1.2}_{-0.7}\) GeV \([43]\). Using the likelihood tool `gtlike` we re-do the spectral analysis with more data. The source model XML file is generated using the user contributed tool `make2FGLxml.py`\(^6\) based on the 2FGL source catalog \([5]\). The spectrum of NGC 6388 is also modelled with \(E^{-\Gamma}\exp(-E/E_c)\). By setting all the source parameters within the ROI free, the best-fitting parameters for NGC 6388 are \(\Gamma = 1.21 \pm 0.17\) and \(E_c = 1.82 \pm 0.35\) GeV, with a TS value 596. The fitting parameters are consistent with that given in [43].

To derive the spectral energy distribution (SED) of NGC 6388, we divide the data into different energy bins, and use `gtlike` tool to fit the parameters for each bin. Two methods are adopted in the fit. We first fix the parameters of all other sources and the normalizations of diffuse backgrounds derived above in the global fit, leaving only the normalization parameters of NGC 6388 and the very bright pulsar PSR J1709-4429 free. The spectral parameters of NGC 6388 and PSR J1709-4429 are also fixed to be the best fitting values. Because the energy bin is relatively narrow the precise values of the spectral parameters have little effect on the final results \([43]\). The results are shown by the filled circles in Figure \([\text{I}]\). The solid line shows the fitting curve with spectrum \(E^{-\Gamma}\exp(-E/E_c)\), as a represent of MSP-type emission. It shows good agreement between the global fit and the individual fit for different energy bins. Then we relax the normalization parameters of all the sources and the diffuse backgrounds, and re-do the fit. The results are shown by the empty circles in Figure \([\text{I}]\). We can see that there are some differences between the results of these two methods, which might be originated from the complexity of the diffuse background models.

We then add a DM component at the position of NGC 6388 to search for possible DM contribution to the emission. Different annihilation final states are investigated, including

\(^4\)http://fermi.gsfc.nasa.gov/ssc/data

\(^5\)http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

\(^6\)http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/
Figure 1: SED of NGC 6388.

$b\bar{b}$, $W^+W^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and $\gamma$-ray line. We use PYTHIA simulation tool to calculate the $\gamma$-ray yield spectrum for each final state \[63\]. A series values of DM mass from 10 GeV to 10 TeV are considered. For monochromatic $\gamma$-ray line we use Gaussian function to model its spectral shape. The energies of photons from 300 MeV to 200 GeV are searched. The width of Gaussian function as a function of photon energy is adopted to be the energy resolution of Fermi-LAT, which is about $8\% \pm 13\% (\Delta E/E)$ in this energy range \[61\].

Given the spectrum shape of DM contribution, we use the python likelihood tool \[7\] to fit the normalization parameter and derive the flux upper limits.

It is found that the detected $\gamma$-ray spectrum of NGC 6388 can also be fitted with a DM component, with mass $\sim 25$ GeV and annihilation final state $b\bar{b}$, as shown by the dashed line in Figure 1. Note that the recent analysis of the Fermi-LAT data in the Galactic center region also showed possible additional emission compatible with DM contribution with $m_\chi \sim 30$ GeV for $b\bar{b}$ annihilation final state \[64\].

It is well motivated that the $\gamma$-ray emission from GCs may come from the MSPs, therefore we do not claim the DM origin of the $\gamma$-rays of NGC 6388. In any case we can instead set an upper limit of the contribution from DM annihilation. Here the upper limits are derived for different final states and different mass of DM particle individually. We use two ways to fit the data. The first one (Fit 1) is to fix all the parameters of sources derived in the above global fit. The free parameters are the normalizations of the diffuse backgrounds and the DM component. The other way (Fit 2) is to leave the normalizations of sources in the ROI and the diffuse backgrounds as well as the normalization of the DM component free. The spectral parameters of the sources are fixed to be the best fitting values in the global fit. Fit 1 corresponds to a more stringent constraint, based on the assumption that the observed $\gamma$-rays come from astrophysical sources. Fit 2 gives a weaker but more conservative constraint. The 95\% confidence level (C.L.) upper limits of the $> 100$ MeV fluxes from DM annihilation for NGC 6388 are shown in the left panel of

\[\text{http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/python_tutorial.html}\]
Figure 2. The thick and thin lines correspond to Fit 1 and 2 respectively. The same way is applied to the line analysis. The upper limits of line emission are shown in Figure 3.

**Figure 2:** Derived 95% C.L. upper limits of the WIMP annihilation contribution to the > 100 MeV γ-ray fluxes as functions of WIMP mass $m_\chi$, for GCs NGC 6388 (left) and M 15 (right).

**Figure 3:** 95% C.L. upper limits of the monochromatic γ-ray emission as functions of γ-ray energy.

### 3.2 M 15

There was no firm detection of emission from M 15 in the previous analysis. In [43] M 15 was reported to have a very weak signal with TS= 5.4. In our analysis with more data, we find a relatively higher TS value $\sim 12$, for both power-law and power-law + exponential cutoff models. We can derive the upper limits on DM annihilation to γ-rays, similar as the analysis of NGC 6388. Because there is no detection of γ-rays, only the method Fit 2 is adopted for M 15. There are three other sources in the ROI of M 15, 2FGL J2115.4+1213, 2FGL J2112.5+0818 and 2FGL J2147.3+0930. The free parameters include the spectral parameters of M 15 (power-law model for a possible MSP contribution) and these three sources, the normalizations of the diffuse backgrounds and the DM component of M 15. The results are shown in Figures 2 and 3.
4. Constraints on DM models

Integrating Eq. (2.3) above 100 MeV we can easily get the upper limits of the DM annihilation cross section using the flux upper limits. The results are presented in Figures 4 - 6 respectively.

Figure 4 shows the constraints on $m_\chi - \langle \sigma v \rangle$ for $b\bar{b}$ (left) and $W^+W^-$ (right) final states. For comparison we also show the results from the combined analysis of Fermi observations of 10 dwarf galaxies [15] and that given by H.E.S.S. observation of these two GCs ($W^+W^-$, [41]). It is shown that the constraints given in this work are generally stronger than that for dwarf galaxies, at least for DM mass $\gtrsim 50$ GeV. Because of the high density spike from the AC process, the distribution of DM is more concentrated than the initial NFW profile. Although the heating effect from stars will smooth out the central density spike, the $J$-factors of GCs are still higher than that of dwarf galaxies (e.g., estimated with NFW profiles), and the constraints on DM models are stronger accordingly. For $b\bar{b}$ final state, the DM annihilation induced $\gamma$-ray spectrum is similar with the observed data of NGC 6388, therefore the constraint is a bit weaker when $m_\chi < 50$ GeV. However, for the method Fit 1 the constraint is always stronger than that for dwarf galaxies. H.E.S.S. constraints are more effective for massive DM ($m_\chi \gtrsim 2$ TeV).

Also shown in Figure 4 are the theoretically expected neutralino annihilation cross sections (multiplied with the branching ratios to $b\bar{b}$ and $WW + ZZ$) in the Minimum Supersymmetric Standard Model (MSSM). In the right panel we sum the model predicted cross sections to $W^+W^-$ and $ZZ$ channels together due to the similarity of $\gamma$-ray spectra from these two channels. We utilize numerical code micrOMEGAs [13, 66] to perform a random scan in the 7-dimensional parameter space at the electroweak scale. These parameters include the CP-odd Higgs mass $m_A$, the Higgs mixing mass parameter $\mu$, the wino mass parameter $M_2$, the sfermion mass parameter $m_{\tilde{f}}$, the ratio of two Higgs vacuum expectation values $\tan \beta$, the trilinear parameters of the third family squark $A_t$ and $A_{\tilde{t}}$. The other trilinear parameters are set to zero. We also impose the assumptions that the gaugino mass parameters are related by $M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$ for grand unification, where the $\alpha_i$ are the coupling constants of three standard model gauge groups, and $M_1 : M_2 = \frac{5}{3}\tan^2 \theta_W$. The ranges of the parameters are taken as follows: 50 GeV < $|\mu|$, $M_2 < 10$ TeV, 100 GeV < $m_A$, $m_{\tilde{f}} < 1$ TeV, $1 < \tan \beta < 60$, $-5m_{\tilde{f}} < A_t, A_{\tilde{t}} < 5m_{\tilde{f}}$ and $\text{sign}(\mu) = \pm 1$. Several constraints from accelerator experiments and DM detection are implemented in our numerical scan. We set the limit for $\rho$ parameter as $\rho - 1 < 2.2 \times 10^{-3}$ [67]. Some important flavor physics constraints include: $\text{Br}(B \rightarrow X_s\gamma) = (3.55 \pm 0.24) \times 10^{-4}$ [38], $\text{Br}(B_s \rightarrow \mu^+\mu^-) = (0 \pm 1.4) \times 10^{-8}$ [35, 74], $\text{Br}(B_u \rightarrow \tau\nu)/\text{Br}(B_u \rightarrow \tau\nu)_{\text{SM}} = 1.28 \pm 0.38$ [68]. Here we only require the supersymmetric contributions to satisfy these constraints at 3$\sigma$ level, and adopt a very conservative bound for muon anomalous magnetic moment [71] as $-11.4 \times 10^{-10} < \delta a_\mu < 9.4 \times 10^{-9}$ [67]. The mass bound of standard model like Higgs $m_h > 114$ GeV, limits on the masses of light charge sparticle from LEP (for details, see [13, 66]), and DM direct detection constrains from XENON100 [72] are also taken into account.

In Figure 4 the squares are for DM models which can give the right relic density [4]
if DM is thermally produced in the early Universe (labelled as “MSSM-thermal”). The triangles are the cases with thermal relic density not higher than the measured value, the correct DM abundance in these models could be produced via some non-thermal mechanisms. We can see that for $b\bar{b}$ final state the current constraint can reach the natural scale for thermally produced DM with mass of $O(10)$ GeV. In the MSSM model, large neutralino annihilation cross section to $b\bar{b}$ final states could arise from the resonance effect with $m_A \sim 2m_{DM}$. Some non-thermal models with this feature have been excluded by our constraints. For $W^+W^-$ channel the constraint is a bit weaker but also close to the natural scale. In the MSSM scenario, large higgsino or wino component (depending on the relations between the three parameters $M_1$, $M_2$ and $\mu$) in the neutralino would enhance DM annihilation cross section to gauge bosons significantly. If the neutralino mass lies in the range $(80, 300)$ GeV, many non-thermal models would be also stringently constrained by our results.

**Figure 4:** Constraints on DM mass vs. annihilation cross section, for $b\bar{b}$ (left) and $W^+W^-$ (right) final states. Points are a random scan of the MSSM parameter space taking into account the current constraints from accelerator data. Magenta dotted lines in the right panel are the constraints got by H.E.S.S. observations of NGC 6388 (lower) and M 15 (upper).

**Figure 5:** Same as Fig. 4 but for leptonic final states $\mu^+\mu^-$ (left) and $\tau^+\tau^-$ (right) respectively.

Motivated by the recent observations of the CR positron/electron excesses at PAMELA, ATIC and Fermi-LAT [73, 74, 75, 76, 77], and the non-excess of antiprotons [78, 79], the leptonic DM models are proposed to explain the data (e.g., [80, 81, 82, 83, 84, 85]). We
Figure 6: Same as Fig. 4 but for DM annihilation into $\gamma\gamma$ (left) and $\gamma Z^0$ (right) final states.

also study the constraints on the leptonic final states $\mu^+\mu^-$ and $\tau^+\tau^-$ by DM annihilation which might be responsible for the $e^\pm$ excesses. Here the inverse Compton scattering $\gamma$-rays generated by the decaying products $e^\pm$ from muons or tauons are not taken into account.

As illustrated in [12], considering the inverse Compton $\gamma$-rays the constraints on DM model parameters will be stronger, however, depending on the uncertainties of the diffusion process of $e^\pm$. Thus the results given here should be conservative. Constraints on $m_\chi - \langle \sigma v \rangle$ parameter space are shown in Figure 3. The contours show the favored parameter region to fit the CR $e^\pm$ data [83]. It is shown that the models to explain the $e^\pm$ excesses should be excluded by the Fermi-LAT data about GCs.

Finally we study the constraints on possible monochromatic $\gamma$-ray line emission from, e.g., $\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow \gamma Z$ of DM annihilation. No significant line emission is found in the data. The upper limits of line emission are derived. The constraints on cross sections to $\gamma\gamma$ and $\gamma Z$ are given in Figure 3. Note we have $E_\gamma = m_\chi$ for $\chi\chi \rightarrow \gamma\gamma$, and $E_\gamma = m_\chi(1 - m_Z^2/4m_\chi^2)$ for $\chi\chi \rightarrow \gamma Z$. The results derived with Fermi-LAT data including the Galactic center region by Fermi collaboration (NFW profile, [80]) and Vertonger & Weniger [87] are also shown for comparison. Our constraints are a bit weaker than the results in these two works. We think it is reasonable because their analysis regions are much larger and include the Galactic center region, which will give a higher $J$-factor of DM annihilation.

5. Conclusions and Discussions

The GCs are thought to form in the cosmological context with AC process at the beginning which pulls DM into the halo center and results in a very high annihilation luminosity. Thus search for $\gamma$-rays from GCs may be effective to probe the particle nature of DM. In this work we analyze the Fermi-LAT three-year data (Pass 7) of GCs NGC 6638 and M 15 and constrain the DM annihilation models. A clear detection of $\gamma$-ray emission from NGC 6388 is found, with TS value $\sim 600$. The spectrum of NGC 6388 can be well fitted with a power-law + exponential cutoff function, which is expected for the emission of a population of MSPs. We find that a DM scenario with $m_\chi \sim 25$ GeV and $b\bar{b}$ final state can also fit the
SED. For M 15 no significant $\gamma$-ray emission if found (the spectral fit indicates a potential source with TS $\approx 12$).

Assuming there is an additional spectral component from DM annihilation of these two GCs, we derive the upper limits of the DM component for different DM masses ($10\,\text{GeV} - 10\,\text{TeV}$) and annihilation final states ($b\bar{b}, W^+W^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma, \gamma Z$) (Figures 2 and 3). The constraints on the DM annihilation cross section are given (Figures 4–6). Except for the line emissions, the constraints are stronger than that derived according to the Fermi-LAT observations of dwarf galaxies. For DM mass smaller than TeV our constraints are also stronger than that given by H.E.S.S. observations of the same GCs. For $b\bar{b}$ and $W^+W^-$ final states which are generally expected from supersymmetric DM model, the constraints can reach the natural scale with which DM is thermally produced. Especially the leptonic annihilation models to explain the CR $e^\pm$ excesses can be excluded by the current analysis.

However, the uncertainties of the present analysis, for example the properties of the hypothetical DM halo and the origin and evolution of the GCs, are far from clear. The GCs were assumed to be formed in the cosmological context, and the DM density profiles in the GCs are modelled taking into account the most probable astrophysical processes, e.g., the AC by baryons, adiabatic growth of an IMBH and the scattering by stars. Future studies on the observations and modelings of the DM distribution in the GCs are necessary to improve the current work.

Acknowledgments

We thank Yi-Zhong Fan, Rui-Zhi Yang and Xiao-Yuan Huang for discussion. This work is supported by the Natural Science Foundation of China under the grant Nos. 11075169, 11075074, 11065004, 11105155, 11105157 and 11175251, the 973 project under grant No. 2010CB833000 and the Chinese Academy of Science under Grant No. KJCX2-EW-W01. L. Feng is supported by the Research Fund for the Doctoral Program of Higher Education under grant No. 200802840009.

References

[1] E. Komatsu, K. M. Smith, J. Dunkley, et al., *Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation*, Astophys. J. Suppl. 192 (2011) 18 [arXiv:1001.4538].

[2] J. R. Primack, D. Seckel, and B. Sadoulet, *Detection of cosmic dark matter*, Annual Review of Nuclear and Particle Science 38 (1988) 751–807.

[3] G. Jungman, M. Kamionkowski, and K. Griest, *Supersymmetric dark matter*, Phys. Rept. 267 (1996) 195–373 [arXiv:hep-ph/9506380].

[4] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: evidence, candidates and constraints*, Phys. Rept. 405 (2005) 279–390 [arXiv:hep-ph/0404175].

[5] The Fermi-LAT Collaboration, *Fermi Large Area Telescope Second Source Catalog*, ArXiv e-prints (2011) [arXiv:1108.1439].
[6] A. A. Abdo, M. Ackermann, M. Ajello, et al., *Fermi LAT Observation of Diffuse Gamma Rays Produced Through Interactions Between Local Interstellar Matter and High-energy Cosmic Rays*, Astrophys. J. **703** (2009) 1249–1256 [arXiv:0908.1171](https://arxiv.org/abs/0908.1171).

[7] A. A. Abdo, M. Ackermann, M. Ajello, et al., *Fermi Large Area Telescope Measurements of the Diffuse Gamma-Ray Emission at Intermediate Galactic Latitudes*, Phys. Rev. Lett. **103** (2009) 251101 [arXiv:0912.0973](https://arxiv.org/abs/0912.0973).

[8] A. A. Abdo, M. Ackermann, M. Ajello, et al., *Spectrum of the Isotropic Diffuse Gamma-Ray Emission Derived from First-Year Fermi Large Area Telescope Data*, Phys. Rev. Lett. **104** (2010) 101101.

[9] G. Dobler, D. P. Finkbeiner, I. Cholis, T. Slatyer, and N. Weiner, *The Fermi Haze: A Gamma-ray Counterpart to the Microwave Haze*, Astrophys. J. **717** (2010) 825–842 [arXiv:1010.4583](https://arxiv.org/abs/1010.4583).

[10] M. Su, T. R. Slatyer, and D. P. Finkbeiner, *Giant Gamma-ray Bubbles from Fermi-LAT: Active Galactic Nucleus Activity or Bipolar Galactic Wind?*, Astrophys. J. **724** (2010) 1044–1082 [arXiv:1005.5480](https://arxiv.org/abs/1005.5480).

[11] G. Dobler, I. Cholis, and N. Weiner, *The Fermi Gamma-Ray Haze from Dark Matter Annihilations and Anisotropic Diffusion*, Astrophys. J. **741** (2011) 25 [arXiv:1102.5095](https://arxiv.org/abs/1102.5095).

[12] A. A. Abdo, M. Ackermann, M. Ajello, et al., *Observations of Milky Way Dwarf Spheroidal Galaxies with the Fermi-Large Area Telescope Detector and Constraints on Dark Matter Models*, Astrophys. J. **712** (2010) 147–158 [arXiv:1001.4531](https://arxiv.org/abs/1001.4531).

[13] R. Essig, N. Sehgal, L. E. Strigari, M. Geha, and J. D. Simon, *Indirect dark matter detection limits from the ultrafaint Milky Way satellite Segue 1*, Phys. Rev. D **82** (2010) 123503 [arXiv:1007.4199](https://arxiv.org/abs/1007.4199).

[14] A. Geringer-Sameth and S. M. Koushiappas, *Exclusion of Canonical Weakly Interacting Massive Particles by Joint Analysis of Milky Way Dwarf Spheroidal Galaxies with the Fermi-Large Area Telescope and Constraints on Dark Matter Models*, Astrophys. J. **712** (2010) 147–158 [arXiv:1001.4531](https://arxiv.org/abs/1001.4531).

[15] M. Ackermann, M. Ajello, A. Albert, et al., *Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope*, Physical Review Letters **107** (2011) 241302 [arXiv:1108.3544](https://arxiv.org/abs/1108.3544).

[16] R. C. Cotta, A. Drlica-Wagner, S. Murgia, et al., *Constraints on the pMSSM from LAT Observations of Dwarf Spheroidal Galaxies*, ArXiv e-prints (2011) [arXiv:1111.2604](https://arxiv.org/abs/1111.2604).

[17] M. Ackermann, M. Ajello, A. Allaforest, et al., *Constraints on dark matter annihilation in clusters of galaxies with the Fermi large area telescope*, JCAP **5** (2010) 25 [arXiv:1002.2235](https://arxiv.org/abs/1002.2235).

[18] Q. Yuan, P.-F. Yin, X.-J. Bi, X.-M. Zhang, and S.-H. Zhu, *Gamma rays and neutrinos from dark matter annihilation in galaxy clusters*, Phys. Rev. D **82** (2010) 023506 [arXiv:1002.0197](https://arxiv.org/abs/1002.0197).

[19] L. Dugger, T. E. Jeltema, and S. Profumo, *Constraints on decaying dark matter from Fermi observations of nearby galaxies and clusters*, JCAP **12** (2010) 15 [arXiv:1009.5988](https://arxiv.org/abs/1009.5988).

[20] J. Ke, M. Luo, L. Wang, and G. Zhu, *Gamma-rays from nearby clusters: Constraints on selected decaying dark matter models*, Physics Letters B **698** (2011) 44–51 [arXiv:1110.5878](https://arxiv.org/abs/1110.5878).
[21] A. Pinzke, C. Pfrommer, and L. Bergstrom, Prospects of detecting gamma-ray emission from galaxy clusters: cosmic rays and dark matter annihilations, ArXiv e-prints (2011) arXiv:1105.3240.

[22] X. Huang, G. Vertongen, and C. Weniger, Probing Dark Matter Decay and Annihilation with Fermi LAT Observations of Nearby Galaxy Clusters, ArXiv e-prints (2011) arXiv:1110.1529.

[23] A. A. Abdo, M. Ackermann, M. Ajello, et al., Constraints on cosmological dark matter annihilation from the Fermi-LAT isotropic diffuse gamma-ray measurement, JCAP 4 (2010) 14.

[24] M. Cirelli, P. Panci, and P. D. Serpico, Diffuse gamma ray constraints on annihilating or decaying Dark Matter after Fermi, Nuclear Physics B 840 (2010) 284–303 arXiv:0912.0663.

[25] M. Papucci and A. Strumia, Robust implications on dark matter from the first FERMI sky $\gamma$ map, JCAP 3 (2010) 14 arXiv:0912.0742.

[26] L. Zhang, C. Weniger, L. Maccione, J. Redondo, and G. Sigl, Constraining decaying dark matter with Fermi LAT gamma-rays, JCAP 6 (2010) 27 arXiv:0912.4504.

[27] G. Hüütsi, A. Hektor, and M. Raidal, Implications of the Fermi-LAT diffuse gamma-ray measurements on annihilating or decaying dark matter, JCAP 7 (2010) 8 arXiv:1004.2038.

[28] Q. Yuan, B. Yue, X. Bi, X. Chen, and X. Zhang, Leptonic dark matter annihilation in the evolving universe: constraints and implications, JCAP 10 (2010) 23 arXiv:0912.2504.

[29] K. N. Abazajian, P. Agrawal, Z. Chacko, and C. Kilic, Conservative constraints on dark matter from the Fermi-LAT isotropic diffuse gamma-ray background spectrum, JCAP 11 (2010) 41 arXiv:1002.3820.

[30] K. N. Abazajian, S. Blanchet, and J. P. Harding, Current and Future Constraints on Dark Matter from Prompt and Inverse-Compton Photon Emission in the Isotropic Diffuse Gamma-ray Background, ArXiv e-prints (2010) arXiv:1011.5090.

[31] F. Calore, V. De Romeri, and F. Donato, Conservative upper limits on WIMP annihilation cross section from Fermi-LAT $\gamma$-rays, ArXiv e-prints (2011) arXiv:1105.4230.

[32] J. Zavala, M. Vogelsberger, T. R. Slatyer, A. Loeb, and V. Springel, Cosmic X-ray and gamma-ray background from dark matter annihilation, Phys. Rev. D 83 (2011) 123513 arXiv:1103.0778.

[33] Q. Yuan, B. Yue, B. Zhang, and X. Chen, Constraint on dark matter annihilation with dark star formation using Fermi extragalactic diffuse gamma-ray background data, JCAP 4 (2011) 20 arXiv:1104.1233.

[34] P. J. E. Peebles, Dark matter and the origin of galaxies and globular star clusters, Astrophys. J. 277 (1984) 470–477.

[35] J. P. Brodie and J. Strader, Extragalactic Globular Clusters and Galaxy Formation, Ann. Rev. Astron. Astrophys. 44 (2006) 193–267 arXiv:astro-ph/0602601.

[36] H. Baumgardt, P. Côté, M. Hilker, et al., The velocity dispersion and mass-to-light ratio of the remote halo globular cluster NGC2419, Mon. Not. Roy. Astron. Soc. 396 (2009) 2051–2060 arXiv:0904.3323.
[37] R. R. Lane, L. L. Kiss, G. F. Lewis, et al., Halo globular clusters observed with AAOmega: dark matter content, metallicity and tidal heating, Mon. Not. Roy. Astron. Soc. 406 (2010) 2732–2742 [arXiv:1004.4693].

[38] C. Conroy, A. Loeb, and D. Spergel, Evidence Against Dark Matter Halos Surrounding the Globular Clusters MGC1 and NGC 2419, ArXiv e-prints (2010) [arXiv:1010.5783].

[39] G. Zaharijˇs, Implications of the intermediate mass black hole in globular cluster G1 on dark matter detection, Phys. Rev. D 78 (2008) 027301 [arXiv:0712.4181].

[40] M. Wood, G. Blaylock, S. M. Bradbury, et al., A Search for Dark Matter Annihilation with the Whipple 10 m Telescope, Astrophys. J. 678 (2008) 594–605 [arXiv:0801.1703].

[41] A. Abramowski, F. Acero, F. Aharonian, et al., H.E.S.S. Observations of the Globular Clusters NGC 6388 and M15 and Search for a Dark Matter Signal, Astrophys. J. 735 (2011) 12 [arXiv:1104.2548].

[42] A. A. Abdo, M. Ackermann, M. Ajello, et al., Detection of High-Energy Gamma-Ray Emission from the Globular Cluster 47 Tucanae with Fermi, Science 325 (2009) 845–.

[43] A. A. Abdo, M. Ackermann, M. Ajello, et al., A population of gamma-ray emitting globular clusters seen with the Fermi Large Area Telescope, Astron. Astrophys. 524 (2010) A75.

[44] A. K. H. Kong, C. Y. Hui, and K. S. Cheng, Fermi Discovery of Gamma-ray Emission from the Globular Cluster Terzan 5, Astrophys. J. Lett. 712 (2010) L36–L39 [arXiv:1002.2431].

[45] P. H. T. Tam, A. K. H. Kong, C. Y. Hui, et al., Gamma-ray Emission from the Globular Clusters Liller 1, M80, NGC 6139, NGC 6541, NGC 6624, and NGC 6752, Astrophys. J. 729 (2011) 90 [arXiv:1101.4106].

[46] W. E. Harris, A Catalog of Parameters for Globular Clusters in the Milky Way, Astron. J. 112 (1996) 1487.

[47] B. Lanzoni, E. Dalessandro, F. R. Ferraro, et al., The Surface Density Profile of NGC 6388: A Good Candidate for Harboring an Intermediate-Mass Black Hole, Astrophys. J. Lett. 668 (2007) L139–L142 [arXiv:0709.0119].

[48] G. R. Blumenthal, S. M. Faber, R. Flores, and J. R. Primack, Contraction of dark matter galactic halos due to baryonic infall, Astrophys. J. 301 (1986) 27–34.

[49] G. Bertone and M. Fairbairn, Compact stars as dark matter probes, Phys. Rev. D 77 (2008) 043515 [arXiv:0709.1485].

[50] H. Zhao and J. Silk, Dark Minihalos with Intermediate Mass Black Holes, Phys. Rev. Lett. 95 (2005) 011301 [arXiv:astro-ph/0501625].

[51] J. F. Navarro, C. S. Frenk, and S. D. M. White, A Universal Density Profile from Hierarchical Clustering, Astrophys. J. 490 (1997) 493 [arXiv:astro-ph/9611107].

[52] F. Donato, G. Gentile, P. Salucci, et al., A constant dark matter halo surface density in galaxies, Mon. Not. Roy. Astron. Soc. 397 (2009) 1169–1176 [arXiv:0904.4054].

[53] P. Salucci, M. I. Wilkinson, M. G. Walker, et al., Dwarf spheroidal galaxy kinematics and spiral galaxy scaling laws, ArXiv e-prints (2011) [arXiv:1111.1165].

[54] D. Spolyar, K. Freese, and P. Gondolo, Dark Matter and the First Stars: A New Phase of Stellar Evolution, Phys. Rev. Lett. 100 (2008) 051101 [arXiv:0705.0521].
[55] K. Gebhardt, C. Pryor, T. B. Williams, J. E. Hesser, and P. B. Stetson, *Fabry-Perot Observations of Globular Clusters. III. M15*, Astron. J. **113** (1997) 1026–1038 [arXiv:astro-ph/9612116].

[56] L. Spitzer, *Dynamical evolution of globular clusters*. Princeton, NJ, Princeton University Press, 1987, 191 p., 1987.

[57] D. Merritt, *Evolution of the Dark Matter Distribution at the Galactic Center*, Phys. Rev. Lett. **92** (2004) 201304 [arXiv:astro-ph/0311594].

[58] D. Merritt, S. Harfst, and G. Bertone, *Collisionally regenerated dark matter structures in galactic nuclei*, Phys. Rev. D **75** (2007) 043517 [arXiv:astro-ph/0610425].

[59] F. de Paolis, V. G. Gurzadyan, and G. Ingrosso, *Pulsars tracing black holes in globular clusters*, Astron. Astrophys. **315** (1996) 396–399 [arXiv:astro-ph/9610106].

[60] J. Gerssen, R. P. van der Marel, K. Gebhardt, et al., *Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in the Globular Cluster M15. II. Kinematic Analysis and Dynamical Modeling*, Astron. J. **124** (2002) 3270–3288 [arXiv:astro-ph/0209315].

[61] W. B. Atwood, A. A. Abdo, M. Ackermann, et al., *The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission*, Astrophys. J. **697** (2009) 1071–1102 [arXiv:0902.1089].

[62] J. R. Mattox, D. L. Bertsch, J. Chiang, et al., *The Likelihood Analysis of EGRET Data*, Astrophys. J. **461** (1996) 396.

[63] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, Journal of High Energy Physics **5** (2006) 26 [arXiv:hep-ph/0603175].

[64] D. Hooper and T. Linden, *On The Origin Of The Gamma Rays From The Galactic Center*, ArXiv e-prints (2011) [arXiv:1110.0006].

[65] G. Bélanger, F. Boujema, A. Pukhov, and A. Semenov, *micrOMEGAs 2.0: A program to calculate the relic density of dark matter in a generic model*, Computer Physics Communications **176** (2007) 367–382 [arXiv:hep-ph/0607059].

[66] G. Bélanger, F. Boujema, A. Pukhov, and A. Semenov, *Dark matter direct detection rate in a generic model with micrOMEGAs 2.2*, Computer Physics Communications **180** (2009) 747–767 [arXiv:0803.2360].

[67] A. Djouadi, M. Drees, and J.-L. Kneur, *Updated constraints on the minimal supergravity model*, Journal of High Energy Physics **33** (2006) 0603 [arXiv:hep-ph/0602001].

[68] Heavy Flavor Averaging Group, D. Asner, S. Banerjee, et al., *Averages of b-hadron, c-hadron, and τ-lepton Properties*, ArXiv e-prints (2010) [arXiv:1010.1584].

[69] D0 Collaboration, V. M. Abazov, B. Abbott, et al., *Search for the rare decay Bs0 → μ⁺μ⁻*, Physics Letters B **693** (2010) 539–544 [arXiv:1006.3469].

[70] LHCb Collaboration, R. Aaij, B. Adeva, et al., *Search for the rare decays Bs0 → μ⁺μ⁻ and B⁰ → μ⁺μ⁻*, Physics Letters B **699** (2011) 330–340.

[71] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, *Reevaluation of the hadronic contributions to the muon g − 2 and to α(M²_Z)*, European Physical Journal C **71** (2011) 1515 [arXiv:1010.4180].
[72] E. Aprile, K. Arisaka, F. Arneodo, et al., Dark Matter Results from 100 Live Days of XENON100 Data, Phys. Rev. Lett. 107 (2011) 131302.

[73] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, et al., An anomalous positron abundance in cosmic rays with energies 1.5-100GeV, Nature 458 (2009) 607–609 [arXiv:0810.4995].

[74] J. Chang, J. H. Adams, H. S. Ahn, et al., An excess of cosmic ray electrons at energies of 300-800GeV, Nature 456 (2008) 362–365.

[75] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, et al., Energy Spectrum of Cosmic-Ray Electrons at TeV Energies, Phys. Rev. Lett. 101 (2008) 261104 [arXiv:0811.3894].

[76] F. Aharonian, A. G. Akhperjanian, G. Anton, et al., Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S., Astron. Astrophys. 508 (2009) 561–564.

[77] A. A. Abdo, M. Ackermann, M. Ajello, et al., Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20GeV to 1TeV with the Fermi Large Area Telescope, Phys. Rev. Lett. 102 (2009) 181101 [arXiv:0905.0025].

[78] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, et al., New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation, Phys. Rev. Lett. 102 (2009) 051101 [arXiv:0810.4994].

[79] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, et al., PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy, Phys. Rev. Lett. 105 (2010) 121101 [arXiv:1007.0821].

[80] M. Cirelli, M. Kadastik, M. Raidal, and A. Strumia, Model-independent implications of the $e^\pm$, $\bar{p}$ cosmic ray spectra on properties of Dark Matter, Nuclear Physics B 813 (2009) 1–21 [arXiv:0809.2409].

[81] P. F. Yin, Q. Yuan, J. Liu, et al., PAMELA data and leptonically decaying dark matter, Phys. Rev. D 79 (2009) 023512 [arXiv:0811.0176].

[82] L. Bergström, J. Edsjö, and G. Zaharijas, Dark Matter Interpretation of Recent Electron and Positron Data, Phys. Rev. Lett. 103 (2009) 031103 [arXiv:0905.0333].

[83] P. Meade, M. Papucci, A. Strumia, and T. Volansky, Dark Matter interpretations of the $e^\pm$ excesses after FERMI, Nuclear Physics B 831 (2010) 178–203 [arXiv:0905.0480].

[84] J. Liu, Q. Yuan, X. J. Bi, H. Li, and X. M. Zhang, Markov chain Monte Carlo study on dark matter property related to the cosmic $e^\pm$ excesses, Phys. Rev. D 81 (2010) 023516 [arXiv:0906.3858].

[85] J. Liu, Q. Yuan, X.-J. Bi, H. Li, and X. Zhang, Cosmic ray Monte Carlo: A global fitting method in studying the properties of the new sources of cosmic $e^\pm$ excesses, Phys. Rev. D 85 (2012) 043507 [arXiv:1106.3882].

[86] A. A. Abdo, M. Ackermann, M. Ajello, et al., Fermi Large Area Telescope Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications, Phys. Rev. Lett. 104 (2010) 091302 [arXiv:1001.4836].

[87] G. Vertongen and C. Weniger, Hunting dark matter gamma-ray lines with the Fermi LAT, JCAP 5 (2011) 27 [arXiv:1101.2610].