Constraints on the dark matter annihilation scenario of Fermi 130 GeV gamma-ray line emission by continuous gamma-rays, Milky Way halo, galaxy clusters and dwarf galaxies observations

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Abstract. It was recently reported that there may exist monochromatic $\gamma$-ray emission at $\sim 130\,\text{GeV}$ from the Galactic center in the Fermi Large Area Telescope data, which might be related with dark matter (DM) annihilation. In this work we carry out a comprehensive check of consistency of the results with the DM annihilation scenario, using the 3.7 yrs Fermi observation of the inner Galaxy, Galactic halo, clusters of galaxies and dwarf galaxies.

The results found are as follows. 1) Very strong constraints on the DM annihilation into continuous $\gamma$-rays from the Galactic center are set, which are as stringent as the “natural” scale assuming thermal freeze-out of DM. Such limit sets strong constraint on the DM models to explain the line emission. 2) No line emission from the Galactic halo is found in the Fermi data, and the constraints on line emission is marginally consistent with the DM annihilation interpretation of the $\sim 130\,\text{GeV}$ line emission from the inner Galaxy. 3) No line emission from galaxy clusters and dwarf galaxies is detected, although possible concentration of photons from clusters in 120–140 GeV is revealed. The constraints from clusters and dwarf galaxies are weak and consistent with the DM annihilation scenario to explain the $\sim 130\,\text{GeV}$ line emission.

Keywords: dark matter theory, gamma ray experiments

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1 Introduction

Through analyzing the public Fermi Large Area Telescope (Fermi-LAT) data, several groups reported the hints of monochromatic $\gamma$-ray emission with energy $E \approx 130$ GeV [1–5]. The morphology of the potential line emission is still in debate. In some works the results showed that there were various regions lying basically in the Galactic plane having excess in 120–140 GeV [3, 4], while in another work the excess concentrated in the inner 5$^\circ$ of the Milky Way center [5]. The results stimulated active discussions of the possible dark matter (DM) origin [6–22]. Alternatively the astrophysical explanations of the line-like $\gamma$-ray emission were also proposed [23, 24].

Due to the importance of the high energy line emission, many works were trying to test the line emission (and its DM interpretation) with Fermi-LAT observations of continuous $\gamma$-rays [25–28], the line emission from dwarf galaxies and clusters of galaxies [29, 30], the unassociated Fermi sources [31], and the future detection with high energy resolution telescope [32, 33]. The basic results show that the allowed cross section of the DM annihilation final states giving rise to the continuous emission can only be about $O(10^2)$ times larger than that of the line emission [25–28], which needs to be considered when constructing the DM models. The recent search for line emission in the Milky Way halo by Fermi collaboration with two-year PASS 6 data showed no indication of signals [34], and the upper limits seemed to be marginally in conflict with the results found in [2, 3]. Furthermore, no signal from dwarf galaxies was found and the constraints on DM annihilation into monochromatic $\gamma$-rays were consistent with the results found in the inner Galaxy [29]. For the galaxy clusters, however, it was claimed a $\sim 3\sigma$ signal of possible 130 GeV line emission by Hektor et al. [30].

In this work we try to make a comprehensive test of the DM scenario of the line emission, through analyzing the Fermi-LAT $\gamma$-ray data in the Galactic center, the Milky Way halo, dwarf galaxies and galaxy clusters. In our analysis the information of the spatial distribution of DM is taken into account. We further include the effects of substructures on the DM annihilation in the analysis, both the enhancement of annihilation luminosity and the change of surface brightness distribution [35, 36].

This paper is organized as follows. In section II we will discuss the constraints on the continuous $\gamma$-ray emission from the Galactic center region. In section III, IV and V we give the results of the line search from the Milky Way halo, galaxy clusters and dwarf galaxies respectively. Finally section VI is our conclusion and discussion.
As DM is a neutral particle it can not couple to photons directly. Therefore DM annihilate into to monochromatic photons through loop processes with charged virtual particles in the loop. If DM annihilate into the charged particles at the tree level, such as quarks, charged leptons or gauge bosons, these annihilation products may induce significant continuous $\gamma$-ray flux. Using the Fermi data we can set a strong constraint on the DM annihilation cross section into these final states.

The current most stringent limits on the DM annihilation cross section set by the Fermi collaboration were derived from the analysis of ten dwarf satellite galaxies with 24 months of Fermi data \[37\]. The Galactic center (GC) has been thought to be the best target for probing the DM annihilation signals. It may have larger DM annihilation rate than dwarf galaxies, and is a good target for searching for the continuous $\gamma$-rays induced by DM. In this section, we will use the Fermi data from the inner Galaxy to place limits on the DM annihilation cross section. This analysis is important for building the DM model to explain the monochromatic $\gamma$-ray emission as it has to satisfy the continuous $\gamma$-ray limit simultaneously.

In this analysis we use the 3.7 years Fermi-LAT data\(^1\) recorded from 4 August 2008 to 18 April 2012, with the Pass 7 photon selection. The “SOURCE” (evclass=2) event class is selected, and the recommended filter cut “(DATA\_QUAL==1) & (LAT\_CONFIG==1) & (ABS(ROCK\_ANGLE)< 52)” is applied. The energy range of events is restricted from 500 MeV to 300 GeV, and the region-of-interest (ROI) is adopted to be a $10^\circ \times 10^\circ$ box centered around the GC. We carry out the binned likelihood analysis with the LAT Scientific Tools v9r23p1. The instrument response function used is “P7SOURCE\_V6”. For the diffuse background, we use the Galactic diffuse model \texttt{gal\_2yearp7v6\_v0\_fits} and the isotropic diffuse spectrum \texttt{iso\_p7v6source\_txt} provided by the Fermi Science Support Center.\(^2\) The Galactic diffuse model is based on the interstellar gas distribution from spectral line surveys and the dust distribution from infrared observations. An inverse Compton scattering component based on GALPROP \[38\] was also included in the modelling. Together with the isotropic diffuse background, the model template was derived through fitting the LAT diffuse $\gamma$-ray data.

The data are binned with 30 energies bins logarithmically spaced and 100 $\times$ 100 spatial bins with size 0.1$^\circ$ each. For the likelihood analysis we include the point sources within 5$^\circ$ around the Galactic center based on the 2-year LAT source catalog (using the user-contributed software \texttt{make2FGLxml.py}) \[39\]. For other sources located in the ROI we fix their parameters to be the values of the LAT source catalog. Before taking the DM contribution into account, we first make a global fit to derive the spectral parameters of the point sources. All the spectral parameters of the sources within 5$^\circ$ of the Galactic center and the normalizations of the diffuse backgrounds are left free during the fit. Then we add the DM component as a diffuse source, and re-do the fit to get the upper limits of the DM contribution. The free parameters of the latter fit include the normalizations of the point sources within 5$^\circ$ of the Galactic center, the normalizations of the diffuse backgrounds and the DM component.

For the DM component we discuss $W^+W^-$, $b\bar{b}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. The photon production spectra are calculated with the PYTHIA simulation package (version 6.4, \[40\]). The spatial density distribution of DM is assumed to be either an Navarro-Frenk-White

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\(^1\)http://fermi.gsfc.nasa.gov/ssc/data.
\(^2\)http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html.
Figure 1. 95% confidence level constraints on the DM annihilation cross sections to $W^+W^-$ (solid), $bb$ (dashed), $\mu^+\mu^-$ (short-dashed) and $\tau^+\tau^-$ (dash-dotted), for $10^2 \times 10^6$ region around the Galactic center. Lines are for NFW profile, and lines with points are for Einasto profile.

(NFW, [41]) profile

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \quad (2.1)$$

with $r_s = 20$ kpc and $\rho_s = 0.35$ GeV cm$^{-3}$, or an Einasto profile [42]

$$\rho(r) = \rho_s \exp \left( \frac{-2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right), \quad (2.2)$$

where $\alpha = 0.17$, $r_s = 20$ kpc and $\rho_s = 0.08$ GeV cm$^{-3}$. The scale density of both the profiles is to give a local DM density $\simeq 0.4$ GeV cm$^{-3}$ [43].

In the analysis we also take the DM substructures into account. We employ the results from Aquarius simulations [44] and the fitted annihilation rate from the substructures in ref. [45]

$$\langle \rho_{\text{sub}} \rangle^2 = 9.3 \times 10^{-4} \times \frac{M_{\text{max}}^{-1.14} - M_{\text{min}}^{-1.14}}{M_{\text{res}}^{-1.14} - M_{\text{min}}^{-1.14}} \times \frac{1}{1 + (r/54 \text{ kpc})^{2.76}} \text{GeV}^2 \text{cm}^{-6}, \quad (2.3)$$

where $M_{\text{max}} \approx 10^{10} M_\odot$ is the maximum mass of subhaloes in the Milky Way halo, $M_{\text{res}} \approx 3 \times 10^5 M_\odot$ is the resolution mass of the simulation, and the minimum subhalo mass is assumed to be $M_{\text{min}} \approx 10^{-6} M_\odot$. For the inner Galaxy discussed in this section, the substructures play little role in the enhancement of the annihilation signal.

We project the density square into a 2-dimensional surface map to give the spatial template of the DM annihilation. With the spatial template and the energy spectrum, we use the above described likelihood analysis method to derive the upper limits of the DM component. The only parameter of the DM component is the normalization factor.

The results of the constraints are shown in figure 1. It can be seen that for DM particle with mass less than hundreds of GeV most of the constraints can reach the “natural” scale,
3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}, assuming DM is the thermal relic of the early universe. These constraints are so far the most stringent constraints on the DM annihilation with Fermi-LAT $\gamma$-ray data. Compared with [34], our constraints are more stringent because we use the likelihood fit involving the astrophysical background, instead of assuming the DM component not to exceed the observational data conservatively. Also in [46] the constraints were given directly by comparing the DM contribution with the observed excess in the Galactic center region with the known sources and diffuse emission subtracted.

For DM mass $\sim 130$ GeV and NFW (Einasto) profile, the constraints on the cross sections of $W^+W^-, b\bar{b}, \mu^+\mu^-$ and $\tau^+\tau^-$ are $7.4 \times 10^{-26}$ $(3.7 \times 10^{-26})$, $5.1 \times 10^{-26}$ $(2.6 \times 10^{-26})$, $4.8 \times 10^{-26}$ $(2.0 \times 10^{-26})$ and $3.6 \times 10^{-27}$ $(1.6 \times 10^{-27})$ cm$^3$ s$^{-1}$ respectively. Compared with the cross section to monochromatic $\gamma$-rays $\langle \sigma v \rangle_{\text{mono}} \approx 2.3 \times 10^{-27}$ $(1.3 \times 10^{-27})$ cm$^3$ s$^{-1}$ [2], the continuous cross section can only be larger by a factor of $1.2 - 30$. Our results are stronger than that derived in [26, 28], and are comparable with that in [27].

Before the discussion of the physical implication of such constraints, we need to be cautious about the possible systematic uncertainties of the constraints. The discussion of systematic uncertainties from the instrument response functions and calibration can be found in [47]. Here we discuss a little bit about the systematic effects from the choice made in this analysis. The adopted energy band may cause systematic uncertainties of the constraints. Since we discuss the DM particle with mass as low as 10 GeV, the lower limit of photon energies should not be too high in order to give effective constraints. On the other hand to avoid the influence of large resolution angle, and to save the computation time the low energy limit is better to be higher. Through varying the low energy limit of selected photons from 500 MeV to 2 GeV, we find the derived upper limits will change by tens of percents for $m_\chi \lesssim 300$ GeV. For higher masses of DM, the differences become larger and at most a factor of $\sim 3$. This is primarily due to the differences of the modeling of diffuse backgrounds for various energy bands. We further check that, through fixing or relaxing the point sources in the ROI, increasing or decreasing the ROI boxes, the derived constraints will change by a factor less than 2. Thus the overall systematic uncertainties of the current results should be a factor of several.

Such strong constraints on the DM annihilation cross section of the tree level processes are very important when constructing the DM models to explain the monochromatic emission. In the following we discuss the implications of the constraints briefly.

As we have mentioned, DM annihilate into monochromatic photons through higher order processes with charged particles running in the loop. These charged particles will induce large continues $\gamma$-ray flux. Here we define a criterium as the ratio of the tree level process into continuous $\gamma$-rays and the loop process into line $\gamma$-ray, $R \equiv \langle \sigma v \rangle_{\text{cont}}/\langle \sigma v \rangle_{\text{mono}} = \langle \sigma v \rangle_{XX}/\langle \sigma v \rangle_{\gamma\gamma}$ where $X$ denote a charged particle. To satisfy the Fermi constraints, $R$ should be smaller than $1.2 - 30$, depending on different annihilation modes.

The charged particle, $X$, in the loop can be a SM particle and/or an exotic particle in new physics. Since the loop processes are generally suppressed, the large DM annihilation cross section into monochromatic photons $\sim 10^{-27}$ cm$^3$ s$^{-1}$ often requires additional enhancement mechanism. If all the charged particles in the loop are SM particles, an additional narrow resonance mediator $A$ is useful to enhance DM annihilation cross section [22, 25]. Using the narrow width approximation, $R$ can be determined by the branching ratios of $A$ decay $BR(A \to XX)/BR(A \to \gamma\gamma)$. In general, $R$ is proportional to $1/\alpha^2$ due to the loop factor and two QED couplings. If $X$ are quarks or leptons, $R$ would be enhanced by an additional factor of $m_X^2/m_A^2$. In this case, the continuous $\gamma$-ray flux is much larger than monochromatic
Figure 2. Constrains on the DM annihilation cross section to monochromatic \( \gamma \)-rays. Left panel is for Reg. 1 and right panel is for Reg. 2. The DM density profile is assumed to be Einasto profile, and no substructures are included.

flux, for instance by a factor of \( > 10^6 \), and are certainly excluded by Fermi results. If \( X \) is \( W \) boson, \( R \) is \( \sim O(10^4) \) and can be excluded by continuous \( \gamma \)-ray observations too.

If the mediated charged particles in the loop include both SM particles and exotic particles in new physics, the estimation of \( R \) depends on the details of model, and is more complicated. A familiar example is supersymmetry in which the neutralinos can annihilate into photons through box loop including chargino-\( W \) boson and sfermion-fermion contributions [48–51]. If the main component of DM is Wino or Higgsino, the diagram including chargino-\( W \) boson contributions would be dominated. In such cases, the large Wino/Higgsino-chargino-\( W \) couplings are also helpful to obtain required annihilation cross section. However, \( R \) is still as large as \( O(10^2) - O(10^3) \) at least [28], and can be excluded by Fermi continuous \( \gamma \)-ray limits.

Therefore, these constraints suggest the charged particles in the loop have to be heavier than the DM particle so that the tree level process into the charged particles is forbidden. For example, a chargino triangle loop can be used to explain required DM annihilation cross section into monochromatic photons [21, 22]. In this case, the processes producing line and continuum \( \gamma \)-ray spectra are independent. Therefore, no excess continuous \( \gamma \)-ray flux would be induced by adjusting model parameters.

Finally, we give another comment on the importance of the continuous \( \gamma \)-ray constraints. Any successful DM model needs to explain the observed DM relic density \( \Omega h^2 \sim 0.11 \). If DM is thermally produced through velocity independent annihilation process in the early universe, the cross section is about the “natural” scale \( 3 \times 10^{-26} \) cm\(^3\) s\(^{-1}\). If the future upper-limits derived from continuous \( \gamma \)-ray observations on DM annihilation cross section are lower than the “natural” scale, it means the DM should be totally or partially produced through other mechanisms. For example, the corrected DM relic density can be obtained by co-annihilation, or velocity suppressed annihilation [25], or non-thermal production mechanism [45]. These results will be important for the DM model building and DM detections.

3 Line emission from the Galactic halo

The tentative \( \gamma \)-ray line emission was found mainly in the inner Galaxy, which is expected in the DM annihilation scenario. As a consistency check, the search for the line emission in the Galactic halo should be of great importance, especially in case that there might be
significant contribution from DM substructures as shown by the cold DM simulations. We use the same period and data version as in section II, but the whole sky region is adopted. Both the event classes “SOURCE” and “CLEAN” are analyzed. Since we focus on the high energy line emission, the energy range in this analysis is adopted to be \([20, 300]\) GeV. We choose two sky regions in the analysis. The first one (hereafter Reg. 1) is \(|b| > 10^\circ\), which can exclude most of the Galactic plane and keep most of the halo region. The second one (Reg. 2) is \(|b| > 10^\circ\) plus \(|l| \leq 10^\circ\), \(|b| \leq 10^\circ\), due to the fact that DM will concentrate in the central Galaxy and such an adoption of the sky region may keep more potential DM signal. The latter adoption is the same as that in ref. \([34]\). We also test the effect of point sources, through masking 1° radius of each point source based on the second Fermi-LAT source catalog \([39]\).

To search for the \(\gamma\)-ray line emission, we perform a likelihood fit to the photon counts using a continuous background together with a monochromatic \(\gamma\)-ray line. The Possion likelihood function is defined as

\[
\ln L = \sum_i n_i \ln \phi_i - \phi_i - \ln n_i!,
\]

where \(n_i\) is the observed photon counts in energy bin \(i\), and \(\phi_i\) is the expected counts (flux times exposure) in the energy bin. The continuous background spectrum in this energy range is approximated with a power-law or log-parabolic function. The energy resolution of Fermi-LAT detector (as given in \([34]\) with an average of the angular acceptance) has been taken into account when calculating \(\phi_i\). The data in the energy range adopted here are binned logarithmically into 400 energy bins, which makes the fit effectively “unbinned” \([2]\). The 95% confidence level upper limits on the line emission are derived with the profile likelihood method \([52]\), setting \(-2 \ln(L/L_{\text{best}}) = 2.71\), where \(L_{\text{best}}\) is the best fit likelihood with the line contribution. The photon upper limits can be translated into constraints on the DM annihilation cross section to monochromatic photons. To get the constraints on the cross
section, we first compute the dimensionless astrophysical $J$-factor, defined as

\[
J_{\Delta \Omega} = \frac{1}{\rho_\odot^2 R_\odot} \int d\Omega \int_{\text{l.o.s.}} \rho^2(l)dl,
\]

where $\rho_\odot = 0.4 \text{ GeV cm}^{-3}$ is the local density, $R_\odot = 8.5 \text{ kpc}$ is the distance from the Galactic center to the Earth, and l.o.s. means integral along the line of sight. The $J$-factors for NFW and Einasto profiles, with and without substructures are listed in table 1. The numbers in parenthesis are the results after masking $1^\circ$ radius around each point source of the 2-year LAT source catalog [39].

The 95% confidence level constraints on the DM annihilation cross section are shown in figures 2 and 3, for power-law and log-parabolic continuous background spectra respectively. The left panel of each figure is for Reg. 1 and the right panel is for Reg. 2. Here we adopt the Einasto density profile, and the possible effects from substructures are not considered. The cross section derived in Weniger (2012) [2] is also shown for comparison. The differences between figure 2 and figure 3 implies that the spectral shape for the continuous background is important for the search for line emission. For the “SOURCE” events, there is a residual cosmic ray component which makes the continuous background deviate from a single power-law. Therefore if assuming single power-law background, one may over-estimate (underestimate) the background at the low (high) energy part and accordingly the constraints are stronger (weaker). For the “CLEAN” events we can see that the differences between these two continuous backgrounds are smaller, which means the background of the “CLEAN” events can be more or less approximated by a single power-law function. We also test the broken power-law spectrum of the continuous background, which gives similar results with the log-parabolic one.

The results show that the constraints from the Galactic halo are well consistent with Weniger (2012) result from the Galactic center when we choose “SOURCE” data as done in [2]. For the “CLEAN” data the constraints are of the same level as the best-fit line-like “signal” [2]. If the DM substructures are taken into account, the constraints from the Milky Way halo will be stronger by a factor of $\sim 2$, which may then indicate a weak tension between the halo and the inner Galaxy. However, considering the uncertainties of the present constraints (from e.g., the adoption of continuous background), the errorbars of the fitting result of the “signal”, and the data sample used to derive the “signal” in [2], we can only conclude that the present constraints from the Milky Way halo observations of the line-like emission are marginally consistent with that from the inner Galaxy if explaining it with DM annihilation. The “CLEAN” results of Reg. 2 are also consistent with that derived by Fermi-LAT collaboration [34], in which two-year Pass 6 “ULTRACLEAN” data are used.

4 Line emission from galaxy clusters

Galaxy clusters (this section) and dwarf galaxies (next section) are also potential good targets for probing DM signals. In this section we analyze the Fermi-LAT data on a series of nearby clusters to search for the potential line emission. The data version and time window are the same as in the above discussions, but the energy range is set from 200 MeV to 300 GeV. The ROI is adopted to be $14^\circ \times 14^\circ$ box centered in the target galaxy cluster. Seven clusters, Fornax, AWM7, M49, NGC4636, Centaurus, Coma and Virgo are chosen as our targets. The mass of Virgo is adopted from [53], and for others the masses are adopted from the extended HIFLUGCS X-ray catalog [54, 55].
Figure 4 shows the individual photons with arrival directions within the virial radius of these clusters. The left panel is for “SOURCE” events, and the right panel is for “CLEAN” events. It is interesting to find that for the “CLEAN” events, photons with energies between 120 and 140 GeV are more abundant than nearby energy ranges. We checked for the “ULTRACLEAN” events and find identical results with the “CLEAN” events. From figure 4 it seems hard to claim the existence of line emission. Recently it was found a 3σ evidence for the existence of ∼ 130 GeV line emission from galaxy clusters in [30].

We then derive the constraints on the DM annihilation cross section to γ-ray line from the galaxy cluster observations. The DM signals from galaxy clusters are modeled as extended sources as in [56], with surface brightness

\[
S_{\text{sm}}(\theta) \propto \int \rho_{\text{sm}}^2(l, \theta) dl,
\]  

where \(\theta\) is the angle between l.o.s. and the cluster center, \(\rho_{\text{sm}}\) is the density profile of the smooth halo, which is assumed to be NFW profile. The mass-concentration relation is adopted to be [57]

\[
c(M_{200}) = 5.74 \left( \frac{M_{200}}{2 \times 10^{12} h^{-1} M_\odot} \right)^{-0.097}.
\]  

The DM substructures may play a significant role on the enhancement of annihilation signal from clusters [35, 58]. Following ref. [35] we adopt the boost factor of substructures as a function of cluster virial mass \(M_{200}\)

\[
b(M_{200}) = 1.6 \times 10^{-3} (M_{200}/M_\odot)^{0.39},
\]

and the surface brightness profile of subhalo emission

\[
S_{\text{sub}}(\theta) = \frac{16 b(M_{200}) S_{\text{NFW}}}{\pi \ln(17)} \frac{1}{\gamma_{200}^2 + 16(d_A \theta)^2} \times \max \left[ e^{-2.377(d_A \theta/r_{200} - 1)}, 1 \right],
\]

where \(S_{\text{NFW}}\) is the integral flux of the smooth NFW halo of the cluster, \(d_A\) is the angular diameter distance.
To study the $\gamma$-ray line, we need to take into account the energy resolution of the detector. We use an energy dependent resolution from [34], where the energy resolution was derived through Monte-Carlo simulations with an integral over the angular acceptance. Then we use the binned likelihood analysis tool as in section II to derive the upper limits of DM annihilation final state $\gamma\gamma$. The point sources of the second Fermi-LAT catalog [39] located in the ROI are modeled simultaneously, with the normalizations free. The normalizations of the diffuse backgrounds are also left free in the likelihood fit. Besides the constraint from individual galaxy clusters, we also do a combined likelihood analysis of all the seven galaxy clusters simultaneously to combine the statistical power of these different target regions [56]. Constraints on the DM annihilation cross section are shown in figure 5, for the cases without (left) and with (right) substructure. It can be seen that the constraints from galaxy clusters are quite weak and are still consistent with the DM interpretation of the inner Galaxy line emission, even for the case with significant substructure boost.

5 Line emission from dwarf galaxies

Same as the analysis of galaxy clusters, we perform the search for line emission with Fermi-LAT data of dwarf galaxies in this section. In ref. [29] the authors have done a similar analysis and found no signal of line emission from the dwarf galaxies. Here we redo the analysis with a slightly different way\(^3\) from that of ref. [29], for the seek of completeness and independent check. We use the same data selection conditions as above in the galaxy clusters analysis. The targets chosen are Bootes I, Draco, Fornax, Sculptor, Segue 1, Sextans and Ursa Minor, which are the same as in ref. [29]. For each dwarf galaxy, we model it as point source and the annihilation $J$-factor is adopted to be the best fit value given in [37]. Then we perform the binned likelihood analysis to search for the line emission and derive the constraints on monochromatic $\gamma$-ray line flux.

We have found no significant $\gamma$-ray line emission in the target regions. The constraints on $\langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma}$ are shown in figure 6. We can see that the upper limits are still far away from the best fit point from ref. [2]. This result is consistent with the upper limit derived in [29], though we use a different method to deal with background photons. At the present

\(^3\)Specifically, our method is the same as the analysis of galaxy clusters, with point sources in the ROI and diffuse backgrounds involved.
time the constraint from dwarf galaxies can neither confirm nor exclude the DM-induced line interpretation of the Galactic center data.

6 Conclusion and discussion

The recently reported tentative $\gamma$-ray line emission from the Fermi-LAT observations in the inner Galaxy [1–5] has invoked many discussions of the DM annihilation signals. In this paper we do a comprehensive analysis using the Fermi-LAT data in the Galactic center region, Galactic halo, galaxy clusters and dwarf galaxies, to test the DM annihilation interpretation of this line emission.

Using the Fermi-LAT data in the Galactic center region, we get strong constraints on the continuous $\gamma$-ray emission of DM annihilation to $W^+W^−$, $b\bar{b}$, $\mu^+\mu^−$ and $\tau^+\tau^−$ final states, which set useful constraints on DM models to explain the 130 GeV line emission.

We further perform the search for line emission with Fermi-LAT data in the Milky Way halo. The constraints on the line emission are generally consistent with the tentative “signal” found in the inner Galaxy [2]. Only when the enhancement effect due to DM substructures is taken into account, and the “CLEAN” events are studied, the constraints seem to have a weak tension with the DM annihilation interpretation of the 130 GeV line emission if the DM density profile follows Einasto or NFW profiles. However, considering the uncertainties of both the constraints and the fitting “signal”, we can not draw a firm conclusion on it at present. We just mention that if it is finally proven to be true, one may need to assume cuspier density profile of DM in the Galactic center (e.g., accreted by the central supermassive black hole [59]) to consistently understand the results in the inner Galaxy and the Galactic halo within DM annihilation scenario.

Galaxy clusters and dwarf galaxies are also studied to further test the DM interpretation of the 130 GeV line emission. It is interesting to find that there is a concentration of photons in 120–140 GeV from the six nearby clusters (figure 4) for the “CLEAN” and “ULTRACLEAN” classes of events. However, the result seems hard to indicate an excess of line emission. Therefore we set upper limits on the DM annihilation cross section to monochromatic $\gamma$-ray line, which are consistent with the claimed results in the inner Galaxy [2], even when the large
boost factor of substructures are taken into account. No signal of line emission from dwarf galaxies is found, and the constraints on DM annihilation cross section to monochromatic $\gamma$-ray line are derived. Compared with the galaxy clusters, the constraints are weaker for dwarf galaxies, and are consistent with the claimed results in the inner Galaxy [2].

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