Search for Line-like and Box-shaped Spectral Features from Nearby Galaxy Clusters with 11.4 Years of Fermi Large Area Telescope Data

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Received 2021 May 5; revised 2021 July 23; accepted 2021 July 31; published 2021 October 6

Abstract

Sharp spectral structures in the γ-ray band are an important dark matter (DM) signature. Previously, a tentative line feature at ~43 GeV was reported in 16 nearby galaxy clusters (GCls) with 7.1 yr of Fermi Large Area Telescope (LAT) data, whose test statistic (TS) value is ~16.7. In this work, we search for line signals and box-shaped structures using the stacked data from those 16 GCls with 11.4 yr of Fermi-LAT P8R3 data. There is still a hint at ~42 GeV, dominated by the radiation of the Virgo and Ophiuchus clusters. Though the TS value was high up to 21.2 in 2016 October, currently it has dropped to 13.1. Moreover, the TS value at ~42 GeV decreases to 2.4 when the EDisp2 data are excluded from the analysis. Consequently, we do not find any statistically significant line-like signal and then set up the 95% confidence level upper limits on the thermally averaged cross section of DM annihilating into double photons. The same line search has been carried out for an alternative GCl sample from the Two Micron All-Sky Survey, but no evidence has been found. We also search for box-shaped features in those 16 baseline GCls. No signal is found, and the corresponding upper limits on the annihilation cross section are given.

1. Introduction

Observations require dark matter (DM) to explain various gravitational phenomena of different scales (Bertone et al. 2005; Bertone & Hooper 2018). According to the latest cosmic microwave background power spectrum measurement (Aghanim et al. 2020), around 84.4% of the matter density is contributed by DM. Lots of DM candidates are proposed in the literature (see Feng (2010) for a review), and weakly interacting massive particles (WIMPs) are the leading ones since they can naturally explain today’s relic density of DM. If WIMPs annihilate or decay into standard model particles, the stable products may be observed by the γ-ray or cosmic ray detectors; thereby, the particle nature can be inferred. In many cases, the energy spectra of the products are smooth (Cirelli et al. 2011), so it is often hard to distinguish them from astrophysical backgrounds (see Charles et al. (2016) for a review). However, if the products have a sharp feature, it will have a much better signal-to-noise ratio and therefore is more likely to be identified.

One of the sharp structures is a line-like signal, which can be produced by the annihilation or decay of WIMPs χ into a two-body final state γX (Bergström & Snellman 1988). The γ-ray line is located at $E_\gamma = m_\chi (1 - m^2_\chi / 4m^2_\chi)$ for DM annihilation. Such a process is proposed in some extensions of standard particle physics models, e.g., the annihilation of the lightest neutralinos through $\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow Z^0$ (Bergström & Snellman 1988; Rudaz 1989; Rudaz & Stecker 1991; Ullio & Bergström 1998), or the decay of the gravitinos through $\chi \rightarrow \gamma\nu$ (Ibarra & Tran 2008).

Great efforts have been paid to search for lines with the Fermi Large Area Telescope (LAT; Atwood et al. 2009), but no significant signal has been found up to now (Abdo et al. 2010; Vertongen & Weniger 2011; Ackermann et al. 2012b; Bringmann et al. 2012; Weniger 2012; Tempel et al. 2012a; Su & Finkbeiner 2012a, 2012b; Tempel et al. 2012b; Huang et al. 2012b; Ackermann et al. 2013; Hektor et al. 2013; Albert et al. 2014; Ackermann et al. 2015; Anderson et al. 2016; Liang et al. 2016a, 2016b; Quincy Adams et al. 2016; Liang et al. 2017; Li et al. 2019). Interestingly, some tentative lines have been reported above 3σ. One is the ~130 GeV line first suggested in the Galactic halo using 3.6 yr of Fermi-LAT P7V6 data. After considering the look-elsewhere effect, it still has a significance of 3.1σ (Bringmann et al. 2012; Weniger 2012). This line candidate was later confirmed by other groups (Tempel et al. 2012a; Su & Finkbeiner 2012a; Ackermann et al. 2013) and also observed in unassociated sources (Su & Finkbeiner 2012b) and some Galaxy clusters (GCls; Hektor et al. 2013). A weak excess at ~110 GeV was also reported in Su & Finkbeiner (2012b) and Tempel et al. (2012b). However, this candidate reduced to ~0.7σ in the Fermi-LAT P8 data and is consistent with the Earth Limb control region, which suggested a small systematic effect at this energy (Ackermann et al. 2015). Another tentative line was found at ~43 GeV in a GCl sample with a global significance of 3.0σ using 7.1 yr of Fermi-LAT P8R2 data (Liang et al. 2016a). However, it does not appear in the Galactic center (Ackermann et al. 2015), Milky Way satellites (Liang et al. 2016b), and subhalos (Liang et al. 2017; Li et al. 2019). γ-ray line searches have also been performed with other telescopes, such as DAMPE (Shen et al. 2019), CALET (Mori 2021), H.E.S.S. (Cirelli et al. 2018; Abdallah et al. 2018), and HAWC (Albert et al. 2020), but only null results have been reported.

The box-shaped spectrum is also a prominent structure, which can be produced by the decay into double γ-rays of a pair of intermediate particles $\varphi$ from DM annihilation. The intermediate particles can be standard model particles (Ibarra et al. 2012) or exotic particles, such as axions (Ibarra et al. 2013). Box-shaped structures have been searched in the Galactic center (Ibarra et al. 2012, 2013), dwarf spheroidal galaxies (dSphs) (Li et al. 2018), and the Sun (Mazziotta et al. 2020) with Fermi-LAT, but no signal is found.

GCls are promising targets for DM indirect search, because they are the most massive gravitational bound systems in the
universe and contain a large number of substructures. A continuum search was performed with Fermi-LAT (Ackermann et al. 2010; Dugger et al. 2010; Huang et al. 2012a; Lisanti et al. 2018), and null results were obtained. As previously mentioned, a tentative line was found in a GCl sample but not detected in other types of sources. This may be possible considering the large uncertainty in the boost factor (Gao et al. 2012). In order to improve our understanding of this potential feature, we use 11.4 yr of Fermi-LAT data to revisit the analysis. We also investigate the temporal behavior of the line candidate. Furthermore, we use another GCl sample from the Two Micron All-Sky Survey (2MASS; Tully 2015; Kourkchi & Tully 2017; Lisanti et al. 2018) to check whether the line-like structure also exists. The box-shaped structure is another interesting sharp structure, so we search for it in this work as well.

This paper is arranged as follows. In Section 2, the baseline GCl sample, the Fermi-LAT data, and the likelihood method are introduced. We then focus on the search of line-like and box-shaped structures in Sections 3 and 4, respectively. Finally, a summary is presented in Section 5.

2. Data Analysis

2.1. Galaxy Clusters

Our baseline sample of GCls is the same as that used in Anderson et al. (2016) and Liang et al. (2016a). This sample consists of 16 GCls with large J-factors, as listed in Table 1. 15 of these sources were selected from the extended HIFLUGCS catalog (Reiprich & Böhringer 2002; Chen et al. 2007) and have masses that can be easily measured with X-ray observations, and the other one is the Virgo cluster. The positions (α, δ), redshifts z, virial radii R200, and masses M200 of these sources are directly taken from Anderson et al. (2016), where the M200 and R200 of HIFLUGCS GCls are derived from the M500 and R500 reported in Reiprich & Böhringer (2002) and Chen et al. (2007), while the information of Virgo is taken from Fouqué et al. (2001). The region of interest (ROI) θROI is defined with the angular radius θ200 ≡ arctan(R200/dA) for the sources, except for Virgo and M49, where dA is the angular diameter distance. 2°.6 and 1°.7 are chosen as the sizes of the ROIs for Virgo and M49, respectively, to avoid overlapping (Liang et al. 2016a).

We assume that the smooth DM halo of a GCl follows the Navarro–Frenk–White (NFW) profile (Navarro et al. 1997), i.e., ρsm(r) = ρ0/[r/r_s(1 + r/r_s)^2]. With the help of the concentration relation in Sánchez-Conde & Prada (2014), we can derive the concentration parameter c200 = R200/r_s for M200. We then obtain the scale radius r_s using R200, and the normalization ρ0 using M200. Cosmological parameters (Aghanim et al. 2020) are adopted in the calculations. The J-factor of a smooth halo within a given ROI can be calculated with

$$J_{ROI} = \int_{ROI} d\Omega \int_0^{\infty} dl \rho_{sm}^2(r(l)),$$

(1)

where l is the line-of-sight distance from the Earth.

The substructures will enhance the annihilation of DM particles. However, because of the uncertainties in the concentration relation and the mass function for the low-mass subhalos, the boost factor can vary from ~3 to 1000 (Gao et al. 2012; Sánchez-Conde & Prada 2014; Bartels & Ando 2015; Ando et al. 2019; Wang et al. 2020). We adopt the relation given in Sánchez-Conde & Prada (2014) since it gives an intermediate value. For Virgo and M49, whose ROIs are smaller than their angular radii, the surface profile of subhalos in Gao et al. (2012) is used to calculate the boost factors within the ROIs. The average boost factor of our sample is $b_{sh,ROI} = \sum_i J_i b_{sh,ROI,i}/\sum_i J_i = 24.7$.

2.2. γ-Ray Data

Fermi-LAT P8R3 data are based on the most recent event-level analysis, which alleviates the background cosmic rays leaked from the ribbons of the anticoincidence detector (Bruel et al. 2018). To further reduce the cosmic-ray contamination in the data, we only use the events satisfying the ULTRACLEAN

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Table 1

| GCI       | α (°) | δ (°) | z    | M200 (10^4M_⊙) | R200 (Mpc) | θROI (°) | lg(JROI) (GeV^2 cm^{-5} sr) | b_{sh,ROI} |
|-----------|-------|-------|------|----------------|------------|---------|---------------------------|------------|
| Virgo     | 187.70| 12.34 | 0.004| 5.60           | 1.70       | 2.60    | 18.44                     | 18.6       |
| M49       | 187.40| 8.00  | 0.003| 0.72           | 0.88       | 1.70    | 17.88                     | 14.5       |
| Ophiuchus | 258.10| −23.38| 0.028| 42.44          | 3.43       | 1.63    | 17.73                     | 36.2       |
| Fomax     | 54.63 | −35.45| 0.005| 1.39           | 1.10       | 2.84    | 17.72                     | 30.1       |
| A3526     | 192.20| −41.31| 0.011| 3.72           | 1.52       | 1.80    | 17.44                     | 33.0       |
| NGC 4636  | 190.70| 2.69  | 0.003| 0.19           | 0.56       | 2.43    | 17.36                     | 23.4       |
| S636      | 157.50| −35.32| 0.009| 1.69           | 1.17       | 1.69    | 17.29                     | 30.8       |
| Coma      | 195.00| 27.98 | 0.023| 10.92          | 2.18       | 1.25    | 17.28                     | 35.3       |
| A3627     | 243.90| −60.91| 0.016| 5.38           | 1.72       | 1.41    | 17.28                     | 34.0       |
| Perseus   | 49.65 | 41.52 | 0.018| 6.66           | 1.85       | 1.35    | 17.27                     | 34.4       |
| AWM7      | 43.63 | 41.59 | 0.017| 5.38           | 1.72       | 1.33    | 17.23                     | 34.0       |
| A1367     | 176.10| 27.98 | 0.023| 10.92          | 2.18       | 1.25    | 17.28                     | 35.3       |
| NGC 5813  | 225.30| 1.70  | 0.007| 0.46           | 0.76       | 1.40    | 16.99                     | 26.4       |

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Note. The R.A. α, Decl. δ, redshift z, virial radius R200, and mass M200 of each GCl is taken from Anderson et al. (2016). θROI is the size of the ROI from which we select the events. JROI and b_{sh,ROI} are the J-factor and subhalo boost factor inside the ROI, respectively.
selection (Ackermann et al. 2012a). According to the reconstruction quality of energy, Fermi-LAT P8 data are further classified into four disjoint subsets. They are denoted by EDISP0–3, each accounting for a quarter of the data, according to the energy reconstruction quality estimator (Atwood et al. 2013). Since the energy resolution of the EDISP0 data is significantly worse than that of the remaining events, we remove them to improve the sensitivity. Unless otherwise noted, the analysis is based on the combined data set of EDISP1+EDISP2+EDISP3.

The data collected between 2008 October 27 and 2020 March 19 (Fermi Mission Elapsing Time between 246823875 and 606273279) are selected.4 To reduce the emission from the Earth Limb, we only use the events with zenith angles less than 90°. In addition, we apply the quality filter cut (DATA_QUAL = = 1)&&(LAT\_CONFIG == 1), which removes the time intervals and the corresponding events when Fermi-LAT is not in the science mode or when strong solar flares or particle events happen.

We use events within the ROIs to perform the analysis. The stacked spectrum energy distribution (SED) shown in Figure 1 is derived with

\[
\frac{dN/dE_i}{d\Omega_i} = \frac{\sum n_{ij}}{\Delta E_j \sum \Omega_i \epsilon_{ij}},
\]

where for the i-th GCl, \( n_{ij} \) is the number of photons in the energy bin centering at \( E_j \), while \( \Omega_i \) and \( \epsilon_{ij} \) are the solid angle and the average exposure, respectively. We utilize Fermi-tools v1.0.105 to select the events and make the live time cube.

An excess at \( \sim 43 \text{ GeV} \) is still distinct compared to the best-fit power law with exponential cutoff (PLE) model. To derive the significance and constraints of this structure, we adopt the unbinned likelihood method in the following sections, which alleviates the uncertainty caused by the energy binning.

2.3. Unbinned Likelihood

The unbinned likelihood method is used to derive the significance of this suspected line and the constraints of the annihilation cross section. The events of all the target sources within their ROIs are put together in the stacking data cube. The background in the stacking data is contributed by various point sources, the Galactic diffuse emission, and the isotropic background. To reduce the influence of an inaccurate background spectral shape on the signal, we adopt the sliding windows technique: fittings are only performed using the data within a given small energy bin \([E_{\text{min}}, E_{\text{max}}]\) containing the signal. In such an energy window, it is safer to choose a power-law model as an approximation of the background spectrum.

We set \( E_{\text{min}} = E_\chi - 0.5E_\chi \) and \( E_{\text{max}} = E_\chi + 0.5E_\chi \), where \( E_\chi \) are the bounds of the sharp structure \((E_\chi = E_\chi \text{ for a line})\), and \( E_\chi = (E_\chi + E_\chi) / 2 \). The energy difference between two adjacent windows is 0.5σ(\( E_\chi \)), where σ(\( E \)) is the half-width of 68% energy dispersion containment at energy \( E \).

The unbinned likelihood function \( L_k \) in the \( k \)-th energy window is defined as (Mattox et al. 1996; Ackermann et al. 2013; Liang et al. 2016a)

\[
\ln L_k(\Theta) = -\int_{E_{\text{min}}^k}^{E_{\text{max}}^k} \lambda(E; \Theta) dE + \frac{N_{\text{ph}}^k}{\sum_i \ln \lambda(E_i)}. \tag{3}
\]

\( N_{\text{ph}}^k \) is number of photons in the window. \( \lambda(E; \Theta) \) is the expected counts of the target sources per energy range with parameter \( \Theta \). Hypothesis tests are performed to evaluate the pretrial significance of lines. For the null hypothesis, photons are only contributed by the power-law background. Therefore, we have

\[
\lambda_{\text{null}}(E; N_\gamma, \Gamma) = N_\gamma E^{-\Gamma} \sum_i \epsilon_i(E) \Omega_i, \tag{4}
\]

where \( i \) is the index of a GCl. For the alternative hypothesis, the \( \gamma \)-ray model is made of a power-law background and a sharp structure and is given by

\[
\lambda_{\text{alt}} = \sum_i \Omega_i \int dE' d\theta \phi(E'; N_i) D_i(E; E', \theta) \epsilon_i(E', \theta) + \lambda_{\text{null}}(E; N_\gamma, \Gamma). \tag{5}
\]

\( D(E; E', \theta) \) is the energy dispersion function,6 which is related to the incident angle \( \theta \) and energy \( E' \). \( \phi(E) \) is the spectrum of the line-like or box-like structure.

For a line signal caused by the direct annihilation of DM particles into photon pairs, we have \( \phi(E) = N_\gamma \delta(E - E_{\text{line}}) \), where \( E_{\text{line}} \) is the line energy and also the DM mass \( m_\chi \). \( \delta(\chi) \) is the delta function. \( N_\gamma \) is the normalization factor. In this case, the first part of Equation (5) can be reduced to \( N_\gamma \sum_i \Omega_i \int d\theta D_i(E; E_{\text{line}}, \theta) \epsilon_i(E_{\text{line}}, \theta) \).

For a box-shaped signal caused by the process \( \chi \chi \to \varphi \varphi \) and \( \varphi \to \gamma \gamma \), we define the spectrum as \( \phi(E) = N_\gamma H(E - E_{\text{line}}) H(E_{\text{line}} - E) / \Delta E \) (Ibarra et al. 2012). \( H(x) \) is the Heaviside step function. \( E_{\pm} = (m_\chi / 2)(1 \pm \sqrt{1 - m_\chi^2 / m_\chi^2}) \) are the lower and upper bounds of the spectrum. \( \Delta E = E_{+} - E_{-} \) is its width, which is related to the degeneracy parameter \( \delta m / m_\chi \equiv (m_\chi - m_\pm) / m_\chi \) (Ibarra et al. 2012).

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5 https://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/photon/
6 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone\_LAT\_IRFs/IRF\_E\_dispersion.html
We optimize the likelihood function with the MINUIT algorithm (James & Roos 1975). The likelihood ratio test is performed to find the goodness of the alternative model. We use the likelihood ratio test statistic $T^2 = -2 \ln \Lambda$, where $\Lambda \equiv L_{\text{null}}/L_{\text{sig}}$ is the likelihood ratio of the best-fit null and alternative models. According to Chernoff’s theorem (Chernoff 1954), the TS value distributes according to $\frac{1}{2}\left(\delta + \chi^2_{\text{dof}=1}\right)$. If no significant signal is detected, the 95% confidence level upper limit can be derived by increasing $N_\chi$ until $\ln L_{\text{sig}}$ decreases by 1.35 (2.71/2) with respect to the maximum value.

3. Search for Line-like Structures

The $\sim$43-GeV line candidate was first reported with a global significance of $3.0\sigma$ using 7.1 yr of Fermi-LAT P8R2 data (Liang et al. 2016a). Since $\sim$4 more yr of observations have been made by Fermi-LAT and updated Fermi-LAT P8R3 data are released, we revisit the line search at 5–300 GeV. In each window, we fix the line energy and fit the normalization of the line and spectral parameters of the background. The TS values of lines at different energies are shown in the left panel of Figure 2. Clearly, no significant line signal is detected. The largest TS value is 13.1 at an energy of $\sim$42.2 GeV. Since the pretrial/local significance of a line is $s_{\text{local}} = \sqrt{TS}$ (Ackermann et al. 2013), the TS value corresponds to a local significance of $3.6\sigma$. Considering that 40.9 independent trials are made when performing the sliding windows technique (Liang et al. 2016a), the global significance is $2.5\sigma$.

To look into this issue, we split the data according to the event types and repeat the unbinned analyses. As shown in the right panel of Figure 2, the $\sim$42 GeV spike only displays in the EDISP2 data with a TS value of 16.9, but is absent in both the EDISP1 and EDISP3 data, which might indicate an instrumental origin. In any case, both the results with and without EDISP2 data are presented in the paper, and the constraints are derived with the EDISP2 data included in order to be conservative.

In addition, as shown in Figure 3, we calculate the individual TS value for each cluster and the cumulative TS value for the gradually increasing GC1 samples. If the EDISP2 data are included in the data, the GCs with large $J$-factors appear to have large TS values. In particular, the TS values of the line are 9.3 and 6.9 for Virgo and Ophiuchus, respectively. If we stack the data from the top five GCs, the TS value is 19.4, which means a global significance of $2.7\sigma$ with a trial factor of 654.4. The tentative line at $\sim$42 GeV happens to appear in all the top seven GCs with the largest unboosted $J$-factors except for M49. The stacked TS value of these seven GCs is 24.6, corresponding to a $3.5\sigma$ global significance. When the EDISP2 data are dropped, the TS value decreases to 8.7 for the top five GCs, but is still around 5.0 for the Virgo cluster.

Analyses are also done in “test regions” around the GCs. First, since the Virgo cluster has the largest TS value, we define a test region around it with a ring-shaped region, whose inner and outer angular radii are $6^{\circ}28$ (Anderson et al. 2016) and $7^{\circ}5$, respectively, so as to remove the events associated with Virgo and keep the similar photon counts as the source region in the energy window. A zero TS value is achieved in the test region when we carry out the same unbinned likelihood analysis. To extend the analysis to the stacked GCs, we define the test ROIs whose centers are shifted by twice the angular radii from the original positions of GCs to avoid overlapping. Lines are also searched within these regions, and the TS values are drawn in Figure 2. Similarly, no lines with TS values larger than five are found in the test regions.
The signal-to-background ratio is expected to grow as the square root of the observing time for a signal limited by the background emission. However, the latest TS value is smaller than the previous value of 16.7 reported in Liang et al. (2016a). To further investigate the change in the TS value with the observation time, we split the observation equally into 23 parts with each one containing approximately half a year of data. We gradually add each part to the fitting and perform the line search. In this way, the TS values of the 42.2 GeV line using accumulating data are achieved and are shown in Figure 4. The result of Liang et al. (2016a) is also marked in the figure with an orange star. The TS value of the line has a growing trend before 2016 October when more data are included. A TS peak of 21.2 is reached in 2016 October (7.9 yr data), and thereafter the significance begins to decrease. The drop in the TS value is caused by both the slight increase of the background emission and the decrease of the line signal. The expected photon number of the line is $36.5 \pm 9.5$ in the 7.9 yr data but drops to $34.2 \pm 9.8$ in the 11.4 yr data according to the best-fit models. If the count of the line signal increases proportionally to the observing time, this result may imply a $\sim 2\sigma$ tension.

If the annihilation of DM really happens and is strongly boosted in the GCIs, the tentative line may also be found in an independent GCI sample. The GCI catalog constructed from the 2MASS Redshift Survey (Tully 2015; Kourkchi & Tully 2017; Lisanti et al. 2018) is adopted to create a different GCI sample. We first sort these GCIs according to their $J$-factors, delete the Andromeda following Lisanti et al. (2018), and then remove those overlapping with the regions (defined with $\theta_{200}$) of other sources. The GCIs within $|b| < 20^\circ$ are also excluded to reduce the events from the Galactic plane (Lisanti et al. 2018). We select the top 16 GCIs whose ROIs do not overlap with the baseline sample or significant sources ($>1000\sigma$) in Fermi-LAT 4FGL-DR2 (Ballet et al. 2020), where the ROIs are defined as $\theta_{200}/2$ of the GCIs. The boost factors within the ROIs are calculated with Sánchez-Conde & Prada (2014) and Gao et al. (2012). The same unbinned likelihood method with the sliding windows technique is applied to the stacked photon events, and the resulting TS value is shown in Figure 2. No lines including the 42.2 GeV line candidate are detected in this GCI sample.

The line flux induced by the annihilation of DM into photons is

$$\phi(E) = \frac{\langle \sigma v \rangle_{\chi \chi 
rightarrow \gamma \gamma}}{8\pi m_{\chi}^2}2\delta(E - E_{\text{line}}) \times J_{\text{tot}},$$

where $\langle \sigma v \rangle_{\chi \chi 
rightarrow \gamma \gamma}$ is the thermally averaged cross section for $\chi \chi \rightarrow \gamma \gamma$ and $E_{\text{line}} = m_{\chi}$. $J_{\text{tot}}$ is the sum of boosted $J$-factors of the GCIs, which can be calculated with

$$J_{\text{tot}} = \sum_{i=1}^{16} J_{\text{ROI},i} \times (1 + b_{\text{ROI},i}).$$

Since no signal is found, the 95% confidence level upper limit on $\langle \sigma v \rangle$ can be evaluated based on the upper limit of the normalization $N_\chi$. In Figure 5, we present our constraints using the baseline GCI sample (blue solid line) and 2MASS sample (orange dashed line). Also shown are the expected 68% and 95% containment of upper limits obtained with 1000 no-DM Monte Carlo simulations. For the baseline sample, the fluctuation in the constraint is mostly within the 95% containment region except that around 42 GeV. This is reasonable since only the $\sim 42$ GeV candidate has a global significance larger than 2$\sigma$. On the other hand, the constraint from the 2MASS GCI sample restricts the parameter space of the line candidate since no tentative signal is found in that data set. Yet, we are aware that the $J$-factors of 2MASS GCIs have an uncertainty of $\sim 0.35$ dex (Lisanti et al. 2018). We also plot the results from GCIs (Liang et al. 2016a; Quincy Adams et al. 2016), the Galaxy center (Ackermann et al. 2015), dwarf galaxies (Liang et al. 2016b), and Milky Way subhalos (Liang et al. 2017). Our result from the baseline sample is stronger than the previous GCIs results, but is much weaker than the constraints from the Galactic center, dwarf galaxies, and the subhalo population.

### 4. Search for Box-shaped Structures

The box-shaped structures have been explored in the data of the Galactic center (Ibarr et al. 2012, 2013) and dSphs (Li et al. 2018). In this section, we also search the GCIs for possible box-like excess. We are mainly interested in the box-shaped structure, which has a similar width as the energy dispersion, where the width is $\Delta E = E_+ - E_- = \sqrt{m_{\chi}^2 - m^2}$. Considering that the energy resolution $\Delta E/E$ is $\gtrsim 6\%$ for the Fermi-LAT P8R3 data, we take into account the box-shaped structures with the degeneracy parameter $\Delta m/m_{\chi}$ of 0.001, 0.01, and 0.05, which are approximately 1, 2, and 5 times as wide as the best energy resolution, respectively. Unlike in the previous works of Ibarr et al. (2012, 2013) and Li et al. (2018), we convolve the narrow boxes with the energy dispersion functions provided by Fermi tools instead of Gaussian functions. In addition, the unbinned likelihood method with the sliding windows technique is applied rather than performing a broadband fit, which shares the same method as the line search above. For a broad box-shaped feature, the constraint mainly comes from its high-energy edge and therefore can be converted between boxes with different

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Figure 4. The change in the TS values of the 42.2 GeV line with time using accumulating data. Each TS value is derived using the data from 27 October 2008 to the date given by the x-axis value. The orange star is the TS value presented in Liang et al. (2016a).

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[9] The ROI size $\theta_{200}/2$ reduces the probability of overlapping but has a small impact on the $J$-factor.
widths, so we only analyze the broad box with $\Delta m/m_\gamma = 0.4$ as a representative. Unlike in the search of narrow box-like spectra, we perform a broadband fit of the events above 2.5 GeV, where the background emission is assumed to be a PLE model.

In Figure 6, we show the TS values of the box-shaped excess with respect to the DM mass. Similar to the line search results above, we do not find any significant box-shaped structure. A tentative excess is found at $m_\gamma = 84.3$ GeV (80.3 GeV, 71.2 GeV) with the maximum TS value being 12.9 (13.8, 10.6) for the boxes with $\Delta m/m_\gamma = 0.001$ (0.01, 0.05). They are all caused by the sharp structure at $\sim 40$ GeV in the stacked SED. The box with $\Delta m/m_\gamma = 0.01$ has a slightly larger TS value, which shows that the sharp component is wider than the energy resolution. Moreover, no broad box-like candidate ($\Delta m/m_\gamma = 0.4$) is found with a TS value larger than 9. If we just analyze the EDISP1 and EDISP3 data, the TS values of the above signal decrease to 2.6, 4.2, and 3.1 for $\Delta m/m_\gamma = 0.001$, 0.01, and 0.05, respectively.

Because no significant box-shaped structures are found, the constraints are set. We focus on the case when the branching ratio of $\phi \rightarrow \gamma \gamma$ is 1. The expected flux is given by (Ibarra et al. 2012)

$$\phi(E) = \frac{\langle \sigma v \rangle_{\phi \rightarrow \gamma \gamma}}{8 \pi m_\phi^2} \frac{4}{\Delta E} H(E - E_\gamma) H(E_\gamma - E) \times J_{\text{tot}},$$

where $\langle \sigma v \rangle_{\phi \rightarrow \gamma \gamma}$ is the thermally averaged annihilation cross section into intermediate particle $\phi$ pairs. The left panel of Figure 7 shows the constraints for several degeneracy parameters. The upper limit of the narrowest box has a similar shape to that of the line except that the former is slightly smoother than the latter. The boxes with larger $\Delta m/m_\gamma$ have broader shapes, hence have weaker and smoother constraints. Comparing with the constraints from the Galactic center (orange lines; Ibarra et al. 2012) and dSphs (blue lines; Li et al. 2018) for $\Delta m/m_\gamma = 0.001$ and 0.4 in the right panel of Figure 7, our results are weaker if the average boost factor of $\sim 25$ is adopted. However, better constraints could be achieved if the boost factors of GCs are larger than those adopted in this work.

5. Summary

Sharp structures in the $\gamma$-ray spectra can be related to the annihilation or decay of DM particles. In this work, we used 11.4 yr of Fermi-LAT P8R3 data of GCs to search for line-like or box-shaped structures. The GCs adopted in this work are those with the largest $J$-factors inside the HIFLUGCS catalog (Reiprich & Böhringer 2002; Chen et al. 2007; Anderson et al. 2016). We used the unbinned likelihood with the sliding windows technique to search for signals and set constraints.

We searched for lines and did not find any significant (TS > 25) excess, as shown in Figure 2. The 42.2 GeV line candidate persists in the new Fermi-LAT P8R3 data set, even though the TS value decreases to 13.1, corresponding to a local (global) significance of 3.6$\sigma$ (2.5$\sigma$). We split the data into different event types and found that the line candidate mostly comes from the EDISP2 data. The TS value decreases to 2.3 if only the EDISP2 data are dropped. To find which GC contributes to the weak structure, unbinned analysis was performed in each GC and mild excesses were found in several...
Figure 7. The 95% confidence level upper limit on the cross section of DM cascade annihilation using the baseline GC sample when the intermediate particle $\varphi$ decays into two photons with a branching ratio of 1. The left panel shows the constraints for several degeneracy parameter $\Delta m_{\chi}$ values. The right panel compares our results with the previous constraints based on data of the Galactic center (intermediate approach; Ibara et al. 2012) and dSphs (H16 sample; Li et al. 2018) for $\Delta m_{\chi} = 0.001$ and 0.4.

GCIs (Figure 3). In particular, Virgo and Ophiuchus, the two galaxies with the largest boosted $J$-factors, have the highest TS values. If the events from the first five GCIs with the biggest boosted $J$-factors are stacked, the local (global) significance is 4.4$\sigma$ (2.7$\sigma$). However, if the EDISP2 data are excluded, the local significance decreases to merely 2.9$\sigma$. We further derived the change in the TS value with time (Figure 4), which increased to the TS value of 21.2 in 2016 October but has been decreasing since then. There is a $\sim 2\sigma$ tension between the photon counts from the line observed in 2016 October and in 2020 March. We also searched for lines in an alternative GC sample built from the 2MASS Redshift Survey, but no line including the tentative $\sim$42 GeV signal was detected. We calculated the 95% confidence level upper limit on the DM annihilation cross section in Figure 5. Only the cross section around the DM mass of 42 GeV exceeds the 95% containment regions; however, it is restricted by the observations of 2MASS GCs. Generally speaking, since the significance of the $\sim$42 GeV line does not increase with the observing time in recent years and the parameter space is constrained by the 2MASS GCs observation, it is unlikely to have an astrophysical origin. The statistical fluctuation, unusual astrophysical processes (e.g., Aharonian et al. 2012), or incomplete understanding of the energy reconstruction method of Fermi-LAT might be responsible for it.

We also searched for box-like structures in the baseline GC sample. No significant box-shaped feature was found either (Figure 6). A tentative excess was found at $m_\chi = 84.3$ GeV (80.3 GeV, 71.2 GeV) with the maximum TS value being 12.9 (13.8, 10.6) for the boxes with degeneracy parameter $\Delta m_{\chi} = 0.001$ (0.01, 0.05), which are all contributed by the sharp structure at $\sim$42 GeV shown in the stacked SED. However, when the EDISP2 data are excluded, the TS value decreases to $\leq 4$. We calculated the 95% confidence level upper limit on the cross section of DM cascade annihilation, as shown in Figure 7. The upper limit we obtained with the averaged boost factor of $\sim$25 is weaker than those of the Galactic center (Ibara et al. 2012, 2013) or dSphs (Li et al. 2018). However, suppose the boost factor follows the relation in Gao et al. (2012), GCIs can be the optimal targets.

Some clues, including the low significance in the EDISP1 and EDISP3 data, the decrease in the TS value with time since 2016, and the null results in the alternative GC samples, may point toward the nonastrophysical origin of the weak line/box-like structure at $\sim$42 GeV. However, it is still puzzling that the GCIs in the HIFLUGCS catalog with large $J$-factors tend to have high TS values. A better understanding of Fermi-LAT data can be helpful, but, more importantly, verifications with independent telescopes are also necessary because of the systematic uncertainties involved (see, e.g., Ackermann et al. 2013). The next generation $\gamma$-ray missions, such as the High Energy Cosmic-Radiation Detection facility (HERD; Dong et al. 2019) and Very Large Area $\gamma$-ray Space Telescope (VLAST), will be powerful instruments to settle the problem.

We would like to thank Kai-Kai Duan, Shang Li, and Xiang Li for helpful discussions. In the data analysis, we make use of the NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007), Astropy (Price-Whelan et al. 2018), and iminuit (Dembinski et al. 2020) packages. This work is supported by the National Natural Science Foundation of China (Nos. U1738210, 12030574, and 12030369), the National Key Program for Research and Development (No. 2016YFA0400200), and the Entrepreneurship and Innovation Program of Jiangsu Province.

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