EVIDENCE FOR INDIRECT DETECTION OF DARK MATTER FROM GALAXY CLUSTERS IN FERMI $\gamma$-RAY DATA

A. Hektor, M. Raidal, and E. Tempel

National Institute of Chemical Physics and Biophysics, Ravala 10, 10143 Tallinn, Estonia; andi.hekto@cern.ch, martti.raidal@cern.ch, elmo@aai.ee

Received 2012 November 13; accepted 2012 November 19; published 2012 December 17

ABSTRACT

Using the Fermi Large Area Telescope (LAT) we search for spectral features in $\gamma$-rays coming from regions corresponding to the 18 brightest nearby galaxy clusters determined by the magnitude of their signal line-of-sight integrals. We observe a double-peak-like excess over the diffuse power-law background at photon energies of 110 GeV and 130 GeV with a global statistical significance of up to 3.6$\sigma$, independently confirming earlier claims of the same excess from the Galactic center. Interpreting this result as a signal of dark matter annihilations to two monochromatic photon channels in galaxy cluster halos, and fixing the annihilation cross-section from the Galactic center data, we determine the annihilation boost factor due to dark matter subhalos from the data. Our results contribute to a discrimination of the dark matter annihilations from astrophysical processes and from systematic detector effects, offering them as possible explanations for the Fermi-LAT excess.

Key words: astroparticle physics – dark matter – galaxies: clusters: general – gamma rays: galaxies: clusters – methods: data analysis

Online-only material: color figures

1. INTRODUCTION

It is a prediction of the concordance cold dark matter cosmological model that galaxies and galaxy clusters are surrounded by massive dark matter (DM) halos. Firm evidence for DM existence comes from various gravitational effects in astrophysics and cosmology (Bertone et al. 2005). If the existing cosmological DM (Komatsu et al. 2011) is a thermal relic consisting of weakly interacting massive particles, then DM annihilations into the standard model particles should provide indirect evidence of DM in cosmic-ray experiments (Cirelli et al. 2011). Unfortunately, direct (XENON100 Collaboration et al. 2012) and indirect (Cirelli et al. 2011) searches for DM particles have all given either negative or contradictory results. A notable exception to this result is the recent evidence for $\gamma$-ray excess with an energy of 130 GeV (Bringmann et al. 2012; Weniger 2012; Tempel et al. 2012; Su & Finkbeiner 2012) in the Fermi Large Area Telescope (LAT; Atwood et al. 2009) data. This excess predominately originates from a small region in the Galactic center (Tempel et al. 2012; Su & Finkbeiner 2012) and may have a double-peak structure (Su & Finkbeiner 2012). Its global statistical significance is between 4.5$\sigma$ and 6.5$\sigma$ (Su & Finkbeiner 2012), depending on whether one or two peaks are fitted, and it is consistent with the Fermi-LAT bound on monochromatic photon lines from diffuse $\gamma$-ray data (Ackermann et al. 2012b). Although Galactic background effects make statistical fluctuation in the $\gamma$-ray spectrum more likely than naively expected (Boyarsky et al. 2012), the presence of a double peak in the background is very unlikely. Although the possibility that the 130 GeV $\gamma$-ray excess is a false detector effect is not entirely excluded, recent studies disfavor this possibility (Hektor et al. 2012; Finkbeiner et al. 2012). It is likely that Fermi-LAT has either observed an astrophysical process that unexpectedly creates photon peak(s) or has detected the DM annihilations into monochromatic photons.

To verify that the DM has been indirectly discovered, the $\gamma$-ray excess must either be confirmed by other experiments such as the planned high-resolution experiments CALET or TANSUO, or we must observe the same excess with Fermi-LAT from other known DM-dominated objects. The expected signal from nearby dwarf galaxies turned out to be too weak to compare with the 130 GeV $\gamma$-ray excess from Fermi-LAT (Geringer-Sameth & Kousshiappas 2012). However, galaxy clusters, the biggest nearby cosmological structures dominated by DM, are expected to be much better objects for that purpose (Huang et al. 2012) because the DM annihilation signal from there should be amplified by a boost factor due to the existence of many DM subhalos (Springel et al. 2008a, 2008b; Pinzke et al. 2009; Anderson et al. 2010; Pinzke et al. 2011; Gao et al. 2012). There are large uncertainties in the theoretical predictions of the boost factors (Pieri et al. 2008; Kuhlen et al. 2008; Kamionkowski et al. 2010); numerical estimates vary from 10 to 10,000. Experimental measurements are needed to discriminate between the different subhalo models.

Here, we report on searches for spectral features in Fermi-LAT $\gamma$-rays from regions corresponding to nearby galaxy clusters determined by the magnitude of their signal line-of-sight integrals ($J$-factors). We observe a double-peak-like excess at photon energies of 110 GeV and 130 GeV over the diffuse power-law background with a statistical significance up to 3.6$\sigma$, independently confirming the earlier claims of excess from the Galactic center. Interpreting this result as a signal of DM annihilations into two channels with monochromatic final-state photons, and fixing the annihilation cross-section from Galactic center data, we determine the annihilation boost factor due to galaxy cluster subhalos.

1 Also at Helsinki Institute of Physics, P.O. Box 64, FI-00014 Helsinki, Finland.
2 Also at CERN, Theory Division, CH-1211 Geneva 23, Switzerland.
3 Also at Institute of Physics, University of Tartu, 51014 Tartu, Estonia.
4 Also at Tartu Observatory, Observatooriumi 1, Tõravere 21602, Estonia.
In this work we search for spectral features in the $\gamma$-ray spectrum originating from known galaxy clusters in the Fermi-LAT data. To do this, we work with a set of galaxy clusters whose parameters are reliably known in the literature. We compute their $J$-factors according to Pinzke et al. (2011), which allows us to select clusters according to their expected contribution to the DM annihilation signal. Coordinates, masses, distances, and radii for the 18 galaxy clusters with the largest $J$-factors are presented in Table 1. Because of limited statistics, we cannot study the signal from each cluster individually. Instead, we sum up all the photons coming from the directions of these clusters and study the spectrum of stacked flux. Current determinations of the galaxy cluster DM halo parameters suffer from large uncertainties. Despite that, we do observe a correlation between the $J$-factors of the galaxy clusters and the number of signal photons from them (see Figure 1), supporting our claim that the signal originates from galaxy clusters. We reanalyze the Galactic center excess with the new LAT resolution and find the double peak in the same position, supporting our claim that both spectra signal DM annihilations. Assuming this, we determine the DM annihilation boost factor in galaxy clusters from Fermi-LAT data.

In the present analysis, we consider the public Fermi-LAT photon event data of 218 weeks within the energy region from 20 to 300 GeV. We apply the quality-filter cuts, as recommended by the Fermi-LAT team, as we did in our previous study (Tempel et al. 2012). We make use of the ULTRACLEAN event selection (Pass 7, Version 6) in order to minimize potential systematic errors. The selection of events as well as the calculation of exposure maps is performed using the Fermi ScienceTools. The most important improvement compared to our previous work (Tempel et al. 2012) is the usage of the newly improved Fermi-LAT energy resolution (Ackermann et al. 2012a).

To avoid effects from point sources, we exclude photons that are within an energy-independent cut radius of each source. We used all 1873 sources from the LAT two-year point source catalog (Nolan et al. 2012). The cut radius is chosen to be 0.2\degree (Ackermann et al. 2012b). We also tested the radii 0.0\degree, 0.15\degree, 0.25, and 0.5 and found no effect on the final result.

### Table 1

The Most Relevant Galaxy Clusters According to Their $J$-factors

| Cluster   | \(l\) (deg) | \(b\) (deg) | \(M_{200}\) \(
\times 10^{14} M_\odot\) | \(D\) (Mpc) | \(\rho_{200}\) (deg) | \(J\) (Mpc \(\rho_{200}^2\)) |
|-----------|-------------|-------------|--------------------------|-----------|----------------|-----------------|
| Virgo     | -76.2       | 74.5        | 6.9                      | 17.2      | 5.6            | 1465            |
| Fornax    | -123.3      | -53.6       | 2.4                      | 19.77     | 3.7            | 793             |
| M49       | -73.1       | 70.2        | 1.4                      | 18.91     | 3.24           | 549             |
| NGC 4636  | -62.3       | 65.5        | 0.5                      | 15.89     | 2.74           | 325             |
| A3526 (Centaurus) | -57.6 | 21.6        | 5.3                      | 44.46     | 2.15           | 315             |
| Ophiuchus | 0.6         | 9.3         | 40.5                     | 122.51    | 1.53           | 242             |
| A1060 (Hydra) | -90.4 | 26.5        | 4.1                      | 49.25     | 1.78           | 205             |
| NGC 5813  | -0.8        | 49.8        | 1.                        | 27.55     | 1.97           | 191             |
| A3627 (Norma) | -34.7 | -7.3        | 7.2                      | 70.69     | 1.49           | 160             |
| Perseus   | 150.4       | -13.4       | 8.6                      | 79.48     | 1.41           | 147             |
| AWM7      | 146.3       | -15.6       | 7.2                      | 74.64     | 1.41           | 144             |
| ANTLIA    | -87.1       | 19.1        | 2.8                      | 50.13     | 1.54           | 143             |
| Coma      | 58.1        | 88.          | 12.9                     | 101.14    | 1.27           | 131             |
| A1367     | -125.2      | 73.          | 10.1                     | 94.05     | 1.25           | 121             |
| NGC 5846  | 0.4         | 48.8        | 0.5                      | 26.25     | 1.66           | 120             |
| NGC 5044  | -48.8       | 46.1        | 1.1                      | 38.81     | 1.46           | 108             |
| A2877     | -66.9       | -70.9       | 9.5                      | 105.13    | 1.1            | 92              |
| 3C129     | 160.4       | 0.1         | 7.8                      | 97.15     | 1.11           | 91              |

**Notes.** The Galactic coordinates \((l, b)\) are taken from the NASA/IPAC Extragalactic Database (http://nedwww.ipac.caltech.edu/) and other data are collected from Chen et al. (2007), Han et al. (2012), Reiprich & Böhringer (2002), and Pinzke et al. (2011). The 2\sigma errors for $J$-factors are estimated to be \(+60\%\)/\(-40\%\).

![Figure 1](image_url)  
**Figure 1.** Correlation between the estimated number of signal photons and the $J$-factors of galaxy clusters. (A color version of this figure is available in the online journal.)

### 2. DATA

In this work we search for spectral features in the $\gamma$-ray spectrum originating from known galaxy clusters in the Fermi-LAT data. To do this, we work with a set of galaxy clusters whose parameters are reliably known in the literature. We compute their $J$-factors according to Pinzke et al. (2011), which allows us to select clusters according to their expected contribution to the DM annihilation signal. Coordinates, masses, distances, and radii for the 18 galaxy clusters with the largest $J$-factors are presented in Table 1. Because of limited statistics, we cannot study the signal from each cluster individually. Instead, we sum up all the photons coming from the directions of these clusters and study the spectrum of stacked flux. Current determinations of the galaxy cluster DM halo parameters suffer from large uncertainties. Despite that, we do observe a correlation between the $J$-factors of the galaxy clusters and the number of signal photons from them (see Figure 1), supporting our claim that the signal originates from galaxy clusters. We reanalyze the Galactic center excess with the new LAT resolution and find the double peak in the same position, supporting our claim that both spectra signal DM annihilations. Assuming this, we determine the DM annihilation boost factor in galaxy clusters from Fermi-LAT data.

In the present analysis, we consider the public Fermi-LAT photon event data of 218 weeks within the energy region from 20 to 300 GeV. We apply the quality-filter cuts, as recommended by the Fermi-LAT team, as we did in our previous study (Tempel et al. 2012). We make use of the ULTRACLEAN event selection (Pass 7, Version 6) in order to minimize potential systematic errors. The selection of events as well as the calculation of exposure maps is performed using the Fermi ScienceTools. The most important improvement compared to our previous work (Tempel et al. 2012) is the usage of the newly improved Fermi-LAT energy resolution (Ackermann et al. 2012a).

To avoid effects from point sources, we exclude photons that are within an energy-independent cut radius of each source. We used all 1873 sources from the LAT two-year point source catalog (Nolan et al. 2012). The cut radius is chosen to be 0.2\degree (Ackermann et al. 2012b). We also tested the radii 0.0\degree, 0.15\degree, 0.25, and 0.5 and found no effect on the final result.

### 3. METHODS

To estimate the photon spectrum related to the clusters, we select photons that are within an energy-independent radius around the center of each cluster. We will refer to this as the region of interest (ROI) below. The annihilation signal should arise predominantly within \(r_{200} \approx r_{\text{vir}}\) in each cluster. The boosting effect due to halo substructures should make the signal spatially flat (Pinzke et al. 2009). The morphology of an expected signal from a single main halo without substructure should be very different: it should arise from a small central region and must have a very cuspy nature (Ackermann et al. 2010). However, in order to determine the stability signal significance over the background, we need to consider larger and different regions than \(r_{200}\) around clusters.
We studied the radii $r_{200}$ in both dependent and independent ROIs around the clusters. We found that the result is independent of how the background photons are included—signal peaks are not affected while the background fluctuates within estimated errors. Thus, the simplest choice of ROI is the equal radii for all clusters. We considered radii $R = 3^\circ, 4^\circ, 5^\circ, 6^\circ$, and $8^\circ$ for ROI and found that starting from smaller values of $R$, at $5^\circ$ the significance reached a maximal value and remained stable for larger radii. We also found that galaxy clusters with small $J$-factors mostly contribute to the background reducing the signal background ratio. Starting from a smaller number of clusters, the significance reached the maximum at 5–7 clusters and remained stable beyond that. For numerical results, we therefore consider only the 18 most relevant galaxy clusters presented in Table 1.

To compute the $\gamma$-spectrum, we sum up all the photons from the selected cluster regions. The spectrum is calculated via a kernel smoothing as described in detail by Tempel et al. (2012). The characteristic kernel size is chosen based on the Fermi-LAT energy response function. We calculated the spectrum in logarithmic and linear energy scales and used different kernel functions and sizes. The results are rather insensitive to the exact kernel function and size, showing that this kernel smoothing method is rather robust.

To estimate the signal significance, we select $N$ random cluster-size regions in the sky and find the $\gamma$-spectrum for them. To avoid the crowded region at the Galactic plane and $\gamma$-cluster-size regions in the sky and find the significance of the double-peak signal with 30–300 GeV implies the global consistency with a generic prediction of gauge theories. Looking for the double-peak excess with at least the same strength as the observed lines (110 GeV and 130 GeV) corresponding to the two peaks in Figure 2. For larger values of considered radii the significance reached a maximal value and remained stable beyond that. For numerical results, we therefore consider only the 18 most relevant galaxy clusters presented in Table 1.

To compute the $\gamma$-spectrum, we sum up all the photons from the selected cluster regions. The spectrum is calculated via a kernel smoothing as described in detail by Tempel et al. (2012). The characteristic kernel size is chosen based on the Fermi-LAT energy response function. We calculated the spectrum in logarithmic and linear energy scales and used different kernel functions and sizes. The results are rather insensitive to the exact kernel function and size, showing that this kernel smoothing method is rather robust.

To estimate the signal significance, we select $N$ random cluster-size regions in the sky and find the $\gamma$-spectrum for them. To avoid the crowded region at the Galactic plane and $\gamma$-cluster-size regions in the sky and find the significance of the double-peak signal with 30–300 GeV implies the global consistency with a generic prediction of gauge theories. Looking for the double-peak excess with at least the same strength as the observed lines (110 GeV and 130 GeV) corresponding to the two peaks in Figure 2. For larger values of considered radii the significance reached a maximal value and remained stable beyond that. For numerical results, we therefore consider only the 18 most relevant galaxy clusters presented in Table 1.
The galaxy clusters, as well as the Galactic center, are fixed objects dominated by DM, thus our result does not suffer from statistical fluctuations related to scanning and choosing arbitrary regions of the sky or from possible astrophysical effects from the Galactic disk. The fact that the two signals from unrelated regions of sky, from the Galactic center and from the locations of galaxy clusters, give a double-peak-like excess that precisely coincides (see Figure 2) suggests that this is not a statistical fluctuation. This result disfavors an astrophysical explanation for the excess since astrophysical processes should not be exactly the same in galaxy clusters and in the Galactic center. Our result implies that, most plausibly, the DM of the universe has been discovered via indirect detection by Fermi-LAT.

5. CONCLUSIONS

We have found that Fermi-LAT data show a double-peak-like excess of $\gamma$-rays with energies of 110 GeV and 130 GeV from the nearby galaxy clusters. The maximal global significance of the excess is 3.6$\sigma$. Our result provides an independent confirmation of the previously claimed $\gamma$-ray excess from the Galactic center and supports the interpretation that the excess is due to DM annihilations into two monochromatic photon channels. Making this assumption, and fixing the DM annihilation cross-section from the Galactic center data, we found that the boost factor for DM annihilations is due to DM substructures in the galaxy cluster from the Fermi-LAT data. This is the first measurement of the DM boost factor from real data and has potentially important implications for understanding DM substructures in halos. Unfortunately, the related uncertainties are, at present, quite large. More data are needed to discriminate between the different theoretical models of DM substructure as well as to properly interpret the DM given excess the possible astrophysical origin and systematic detector effects.

The 130 GeV DM is kinematically accessible in the Large Hadron Collider experiments and should be searched for.

We thank L. Bergstrom, J. Conrad, D. Finkbeiner, and C. Weniger for numerous communications. This work was supported by the ESA grants 8090, 8499, 8943, MTT8, MTT59, MTT60, MJD52, and MJD272, by the recurrent financing projects SF0690030s09 and SF0060067s08, and by the European Union through the European Regional Development Fund.

REFERENCES

Ackermann, M., Ajello, M., Albert, A., et al. 2012a, ApJS, 203, 4
Ackermann, M., Ajello, M., Albert, A., et al. 2012b, PhRvD, 86, 022002
Ackermann, M., Ajello, M., Allafort, A., et al. 2010, JCAP, 05, 025
Anderson, B., Kuhlen, M., Diemand, J., Johnson, R. P., & Madau, P. 2010, ApJ, 718, 899
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Bertone, G., Hooper, D., & Silk, J. 2005, PhR, 405, 279
Boyarsky, A., Malyshev, D., & Ruchayskiy, O. 2012, arXiv:1205.4700
Bringmann, T., Huang, X., Ibarra, A., Vogl, S., & Weniger, C. 2012, JCAP, 07, 054
Chen, Y., Reiprich, T. H., Böhringer, H., Ikebe, Y., & Zhang, Y.-Y. 2007, A&A, 466, 805
Cirelli, M., Corcella, G., Hektor, A., et al. 2011, JCAP, 03, 051
Finkbeiner, D. P., Su, M., & Weniger, C. 2012, arXiv:1209.4562
Gao, L., Frenk, C. S., Jenkins, A., Springel, V., & White, S.D.M. 2012, MNRAS, 419, 1721
Geringer-Sameth, A., & Koushiappas, S. M. 2012, PhRvD, 86, 021302
Han, J., Frenk, C. S., Eke, V. R., et al. 2012, MNRAS, 427, 1651
Hektor, A., Raidal, M., & Tempel, E. 2012, arXiv:1209.4548
Huang, X., Vertongen, G., & Weniger, C. 2012, JCAP, 01, 042
Kamionkowski, M., Koushiappas, S. M., & Kuhlen, M. 2010, PhRvD, 81, 043532
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Kuhlen, M., Diemand, J., & Madau, P. 2008, ApJ, 686, 262
Nolan, P. L., Abd, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Pieri, L., Bertone, G., & Branchini, E. 2008, MNRAS, 384, 1627
Pinzke, A., Pfommer, C., & Bergström, L. 2009, PhRvL, 103, 181302
Pinzke, A., Pfommer, C., & Bergström, L. 2011, PhRvD, 84, 123509
Reiprich, T. H., & Böhringer, H. 2002, ApJ, 567, 716
Springel, V., Wang, J., Vogelsberger, M., et al. 2008a, MNRAS, 391, 1685
Springel, V., White, S. D. M., Frenk, C. S., et al. 2008b, Nat, 456, 73
Su, M., & Finkbeiner, D. P. 2012, arXiv:1206.1616
Tempel, E., Hektor, A., & Raidal, M. 2012, JCAP, 09, 032
Weniger, C. 2012, JCAP, 08, 007
WENiger100 Collaboration, Aprile, E., Alfonsi, M., et al. 2012, PhRvL, 109, 181301