Search for Galactic dark matter from γ-ray spectral lines with *Fermi*-LAT data

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Abstract. Most of the matter in the universe is invisible and is known as dark matter (DM). Weakly Interacting Massive Particles (WIMPs) are possible theoretical candidates for DM. Hypothetically, WIMPs can be detected indirectly by their annihilation or decay products. A possible product is a γ ray. Many DM profile models predict a higher density of WIMPs near the Galactic center. Here we search for monochromatic γ-ray emission from the Galactic center region in data from the Large Area Telescope (LAT), the main instrument onboard the *Fermi* Gamma-ray Space Telescope. We present the preliminary results of the analysis of γ-ray spectral lines to search for DM annihilation and decay signals using the latest version of the LAT data.

1. Introduction

Many studies in cosmology and astrophysics provide evidence of the existence of dark matter (DM) (see, e.g., [1, 2]). Observations of the dynamics of galaxies in a cluster and the rotational velocities of a galaxy imply that there is more mass in the cluster or the galaxy than what can be detected electromagnetically [3–5]. Observation of the Bullet Cluster by weak lensing indicates that DM can be described as particles with low interaction cross section with ordinary matter [6, 7]. Moreover, the cosmic microwave background measurement constrains the DM density in the Universe [8]. Many possible hypothetical candidates for DM exist, including Weakly Interacting Massive Particles (WIMPs) thermally produced in the early universe [1, 2, 9]. Theoretically WIMPs could be observed via WIMP-nucleon scattering in underground experiments, could be produced by a collision of particles in the collider, or could also contribute to cosmic ray (CR) fluxes by their annihilation or decay [10]. Among various candidate particles produced by WIMP annihilation or decay, γ rays are interesting because their propagation is unperturbed by the interstellar magnetic field and preserves spatial information about their sources.

Typical astrophysical sources emit a broad spectral shape in ∼GeV range γ rays, which can usually be well approximated as a power law with a high-energy cutoff. Sharp spectral features in this energy range are not expected from any known sources, but could originate from the annihilation or decay of nonrelativistic particles in the ∼GeV–TeV mass range. Therefore, the search for γ-ray spectral lines has been employed as one possible tool for DM detection [11, 12].

Since June 2008, the *Fermi* Large Area Telescope (LAT), which is the main instrument on the *Fermi* Gamma Ray Space Telescope (*Fermi*), has been continuously observing the γ-ray sky in the energy range from about 20 MeV to more than 300 GeV. The LAT may be sensitive to γ rays produced from WIMP annihilation or decay. We use 8 years of public data with the most recent event selection version of the LAT data (Pass 8 Clean) to search for spectral lines between 50–290 GeV in many regions of interest.

2. Method

2.1. Regions of interest

The regions of interest (ROIs) are defined as circular regions of the sky with different angular radii centered at the Galactic center (GC). Each region is optimized for different profiles of the DM distribution in the Galaxy (i.e., Navarro-Frenk-White profile (NFW), contracted NFW profile (NFWc), Einasto profile, and the core isothermal profile). The details of the optimization procedure are described in [14] in appendix B. The names of five ROIs used in this analysis come from the values of the radius that they subtend, e.g., R3 for $r = 3°$. R3 (optimized for NFWc), R16 (optimized for Einasto), R41 (optimized for NFW), and R90 (optimized for core isothermal) are more sensitive to WIMP annihilation, while R180 is more sensitive to the WIMP decay [15]. In addition, we mask out the Galactic plane (GP) ($\mid b \mid < 5°$ and $\mid l \mid > 6°$) where γ-ray emission from astrophysical sources is very bright and can obscure the faint DM signals. Although both R3 and R16 also contain high-concentration of astrophysical sources similar to the GP, DM particles which only interact gravitationally are predicted to clump together more densely near the GC. Therefore, the fraction of DM signals to the astrophysical background in R3 and R16 may be higher in than that in the GP.

We use the Earth limb (EL) and the GP (excluding the GC), which we call the inverse ROI, as control regions. The γ-ray emission from the EL is produced by CRs interacting with the Earth's upper atmosphere, resulting in an extremely bright γ-ray ring as viewed by *Fermi* due to its proximity [16]. The inverse ROI contains various types of γ-ray sources, so it provides good statistics of the astrophysical background. The γ-ray emission in the inverse ROI is also dominated by astrophysical sources and the diffuse emission due to CRs interacting with interstellar medium. Thus, we do not expect to detect any DM signals in these control regions.

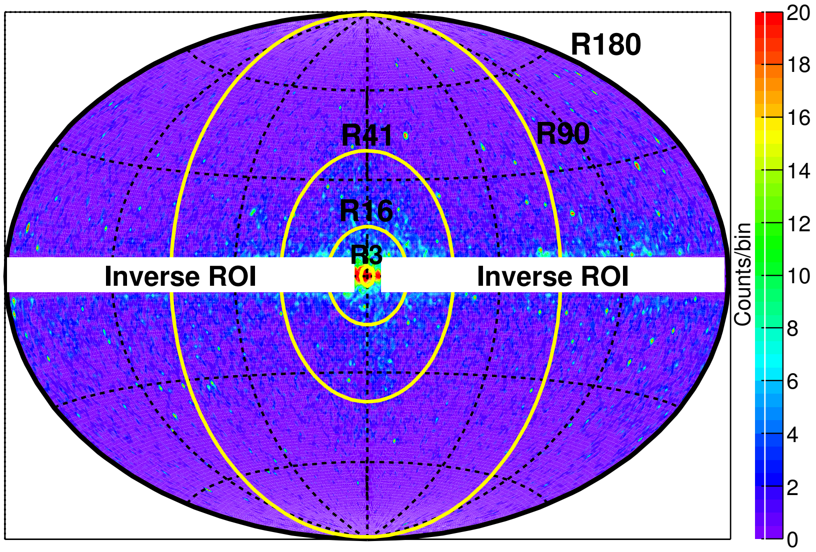

Figure 1: Counts map of 40–300 GeV photons in the Galactic coordinates plotted in the Aitoff projection. The ROIs (R3, R16, R41, R90, and R180) are shown. The inverse ROI (white area) has been masked out here.

2.2. Data selection

We use the latest version of data (Pass 8) [13] developed by the LAT Collaboration. We use 8 years *Fermi*-LAT data (August 2008 – August 2016) with the "Clean" event selection between 40–300 GeV to search for spectral lines between 50 and 290 GeV. In addition, In addition, we avoid contaminations from the bright EL emission by selecting photons with zenith angle smaller than 100°, where the zenith angle is the angle between the originated location of a photon and the zenith direction from the LAT's point of view. It is important to note that the LAT energy resolution between 40–300 GeV is about 5–8%.

2.3. Fitting procedure

To search for γ-ray lines, we perform a maximum likelihood fit in the selected energy range for each of the 5 ROIs. We use 130 energy bins with equal width across the fit energy range, so the bin width is comparable to or smaller than the LAT energy resolution. We define the functional form for the background photon count spectrum as

$$F_{\mathrm{Bg}}(E) = N_{\mathrm{Bg}} E^{-\Gamma_{\mathrm{Bg}}}$$

We define the functional form for the DM signal as a narrow Gaussian shape:

$$F_{\mathrm{DM}}(E) = N_{\mathrm{DM}} \exp\left(- \frac{(E - E_\gamma)^2}{2w^2} \right)$$

where E_γ is the line energy which is varied between 50–290 GeV, and N_{DM} and w are free model parameters. From the instrument's energy resolution, w is constrained to be between 5–8% of E_γ. The best-fit parameters are obtained by performing a maximum likelihood analysis of the measurement data and the $F_{\mathrm{Bg}} + F_{\mathrm{DM}}$ model. The likelihood function is $\mathcal{L} \equiv \prod_{\mathrm{i}}^{\mathrm{N}} P(o_{\mathrm{i}} \mid m_{\mathrm{i}})$, where $P(o_{\mathrm{i}} \mid m_{\mathrm{i}})$ is the Poisson probability of observing o_{i} counts given that the model predicts m_{i} counts in each energy bin i. We vary the fitting parameters of the power law (background) and the Gaussian (DM signal) to determine the maximum likelihood. The significance (s) of the line signal at E_γ is derived from the square-root of the test statistic $(TS):\ s = \sqrt{TS} = (2 \ln \frac{\mathcal{L}^{\mathrm{Bg+DM}}}{\mathcal{L}^{\mathrm{Bg}}})^{\frac{1}{2}}$ where $\mathcal{L}^{\mathrm{Bg+DM}}$ is the maximum likelihood from the background+DM signal hypothesis, and $\mathcal{L}^{\mathrm{Bg}}$ is that for only the background hypothesis (without DM signal).

3. Results & Discussion

We perform a search for γ-ray lines in the energy range 50–290 GeV in the five ROIs and two control regions. The signal significance values from fitting spectral lines at various energies in all regions are shown in Figure 2. The calculated statistical significances for all the ROIs and the line energies are below 3.0σ. In high-energy particle physics, a statistical significance less than 3.0σ is considered consistent with background fluctuation. Thus, we find no evidence of significant lines between 50–290 GeV. Figure 2 shows the count spectrum and fit results for R180 with the line energy at 90 GeV, where we observe the largest significance ($s = 1.8\sigma$). We check the influence of the arbitrarily chosen energy bin width of 2.0 GeV used in our analysis by varying the energy bin width among these values: 0.5, 1.0, 1.5, 2.0, 4.0, and 8.0 GeV. All fit results give significances less than 2.0σ.

We examine two control regions which are expected to contain no DM signal and find no lines with $s > 3.0\sigma$ in this energy range. Figure 2 shows the count spectrum fit at 90 GeV using EL and the inverse ROI data, which indicate 0.0σ and 0.0σ. The γ-ray spectra from the control regions can therefore be concluded as featureless. This excludes the possibility that the instrumental effect is responsible for any spectral line in the ROIs.

We have performed a search for γ-ray lines from 50–290 GeV in the five ROIs which are

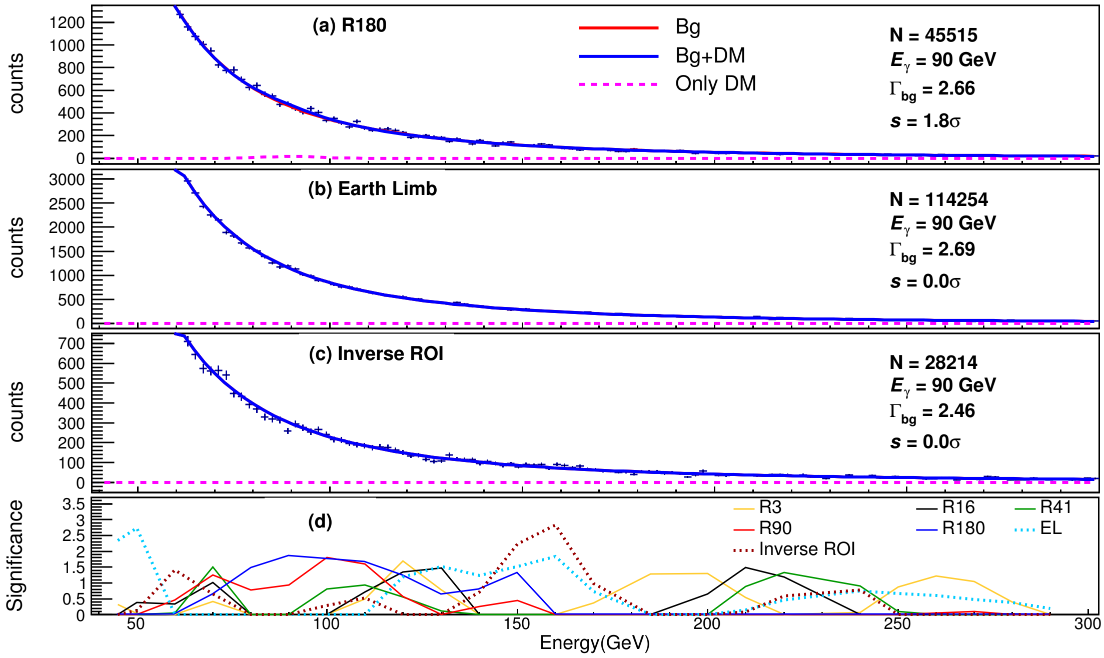

Figure 2: Fit results at 90 GeV line energy in R180 (a), the Earth limb (b), and the inverse ROI (c) are shown. The significance value as a function of line energy from the analyses of count spectra from five ROIs and two control regions are summarized in (d).

optimized for various DM density profiles, using 8 years of *Fermi*-LAT Pass 8 data. We find no significant spectral lines in all ROIs. Our analyses in the control regions, the EL and the inverse ROI, show no significant sharp spectral feature. We will expand the search to a wider energy range in the future study.

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