THE SEARCH FOR DARK MATTER WITH GAMMA-RAYS: A REVIEW

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Abstract. Successfully launched in June 2008, the Fermi Gamma-ray Space Telescope, formerly named GLAST, has been observing the high-energy gamma-ray sky with unprecedented sensitivity in the $20\,\mathrm{MeV} \div 300\,\mathrm{GeV}$ energy range and electrons + positrons in the $7\,\mathrm{GeV} \div 1\,\mathrm{TeV}$ range, opening a new observational window on a wide variety of astrophysical objects.

Keywords: gamma ray, gamma ray detectors, dark matter.

1. Introduction

The Fermi Observatory carries two instruments on-board: the Gamma-ray Burst Monitor (GBM) [1] and the Large Area Telescope (LAT) [2]. The GBM, sensitive in the energy range between 8 keV and 40 MeV, is designed to observe the full unocculted sky with rough directional capabilities (at the level of one to a few degrees) for the study of transient sources, particularly Gamma-Ray Bursts (GRBs). The LAT is a pair conversion telescope for photons above 20 MeV up to a few hundreds of GeV. The field of view is $\sim 2.4\,\mathrm{sr}$ and LAT observes the entire sky every ~ 3 hours (2 orbits). These features make the LAT a great instrument for dark matter (DM) searches. The operation of the instrument through the first three years of the mission was smooth at a level which is probably beyond the more optimistic pre-launch expectations. The LAT has been collecting science data for more than 99 % of the time spent outside the South Atlantic Anomaly (SAA). The remaining tiny fractional down-time accounts for both hardware issues and detector calibrations [3, 4].

More than 650 million gamma-ray candidates (i.e. events passing the background rejection selection) have been made public and distributed to the Community through the Fermi Science Support Center (FSSC) [1]. Over the first three years of the mission, the LAT collaboration has put considerable effort into achieving a better understanding of the instrument and of the environment in which it operates. In addition, a continuous effort has been made to publish the advances as soon as possible. In August 2011, the first new event classification (Pass 7) since launch was released, along with the corresponding Instrument Response Functions. Compared with the pre-launch (Pass 6) classification, it features a greater and more uniform exposure, with a significance enhancement in acceptance below 100 MeV.

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[1]The FSSC is available at
`http://fermi.gsfc.nasa.gov/ssc`

2. The Second Fermi-LAT catalog

The high-energy gamma-ray sky is dominated by diffuse emission: more than 70 % of the photons detected by the LAT are produced in the interstellar space of our Galaxy by interactions of high-energy cosmic rays with matter and low-energy radiation fields. An additional diffuse component with an almost-isotropic distribution (and therefore thought to be extragalactic in origin) accounts for another significant fraction of the LAT photon sample. The rest consists of various types of point-like or extended sources: Active Galactic Nuclei (AGN) and normal galaxies, pulsars and their relativistic wind nebulae, globular clusters, binary systems, shock-waves remaining from supernova explosions and nearby solar-system bodies like the Sun and the Moon.

The Second Fermi-LAT catalog (2FGL) [5] is the deepest catalog ever produced in the energy band between 100 MeV and 100 GeV. Compared to the First Fermi-LAT (1FGL) [6], it features several significant improvements: it is based on data from 24 (vs. 11) months of observations and makes use of the new Pass 7 event selection. The energy flux map is shown in Fig. 1, and the sky-distribution of the 1873 sources is shown in Fig. 2. It is interesting to note that 127 sources are firmly identified, based either on periodic variability (e.g. pulsars) or on spatial morphology or on correlated variability. In addition, 1170 sources are reliably associated with sources known at other wavelengths, while 576 (i.e. 31 % of the total number of entries in the catalog) are still unassociated.

3. Indirect Dark Matter searches

One of the major open issues in our understanding of the Universe is the existence of an extremely-weakly interacting form of matter, Dark Matter (DM), supported by a wide range of observations including large-scale structures, the cosmic microwave background and the isotopic abundances resulting from the primordial nucleosynthesis. Complementary to direct searches being carried out in underground facilities
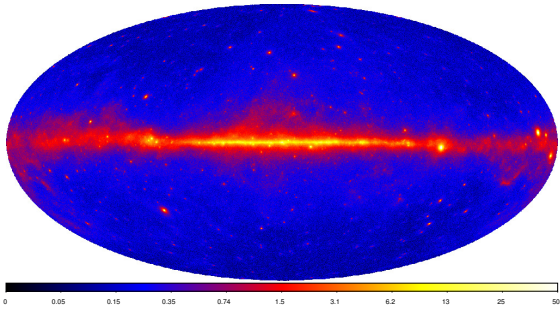
Figure 1. Sky map of the energy flux derived from 24 months of observations. The image shows the γ-ray energy flux for energies between 100 MeV and 10 GeV, in units of $10^{-7} \, \mathrm{erg \, cm^{-2} \, s^{-1} \, sr^{-1}}$.
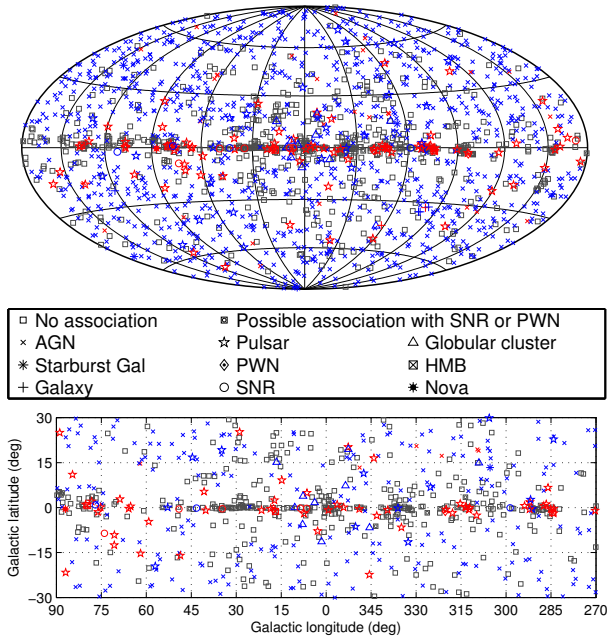

□ No association	⊠ Possible association with SNR or PWN
× AGN	☆ Pulsar	△ Globular cluster
✳ Starburst Gal	◇ PWN	⊠ HMB
+ Galaxy	○ SNR	✳ Nova

Figure 2. Full sky map (top) and blow-up of the inner Galactic region (bottom) showing sources by source class. Identified sources are shown with a red symbol, associated sources in blue.

and at accelerators, the indirect search for DM is one of the main items in the broad Fermi Science menu. The word indirect denotes here the search for signatures of Weakly Interactive Massive Particle (WIMP) annihilation or decay processes through the final products (gamma-rays, electrons and positrons, antiprotons) of such processes. Among many other ground-based and space-borne instruments, the LAT plays a prominent role in this search through a variety of distinct search targets: gamma-ray lines, Galactic and isotropic diffuse gamma-ray emission, dwarf satellites, CR electrons and positrons.

3.1. Galactic center

The Galactic center (GC) is expected to be the strongest source of γ-rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile [7–9].
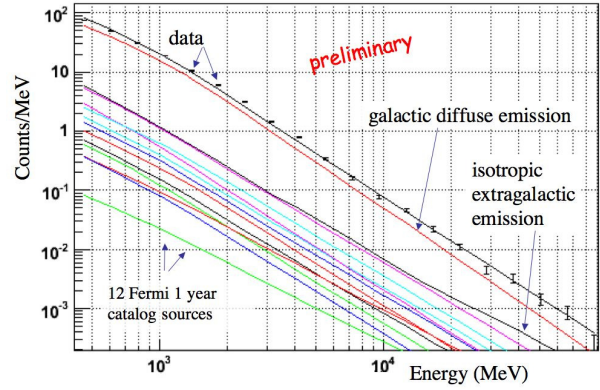
Figure 3. Spectra from likelihood analysis of the Fermi-LAT data (number of counts vs reconstructed energy) in a 7° × 7° region around the Galactic Center (number of counts vs reconstructed energy).

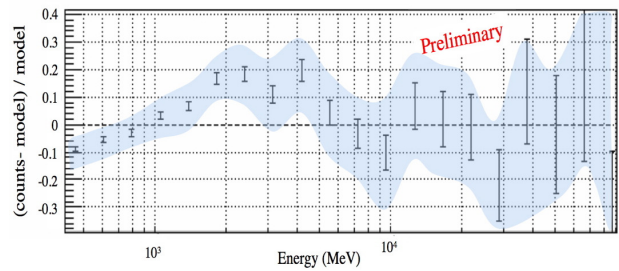Figure 4. Residuals ((exp. data − model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

A preliminary analysis of the data taken during the first 11 months of the Fermi satellite operations is presented in [10, 11] and is shown in Figs. 3 and 4.

The diffuse gamma-ray backgrounds and discrete sources, as we know them today, can account for a large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless, a residual emission is left, not accounted for by the above models [10, 11].

Improved modeling of the Galactic diffuse model as well as the potential contribution from other astrophysical sources (e.g. unresolved point sources) could provide a better description of the data. Analyses are underway to investigate these possibilities.

3.2. Dwarf galaxies

Dwarf spheroidal galaxies (dSphs) of the Milky Way are among the cleanest targets for indirect dark matter searches in gamma-rays. They are systems with a very large mass/luminosity ratio (i.e. systems which are largely DM dominated). The LAT detected no significant emission from any of these systems, and the upper limits on the γ-ray flux allowed us to put very stringent constraints on the parameter space of well motivated WIMP models [12].

A combined likelihood analysis of the 10 most promising dwarf galaxies, based on 24 months of data and pushing the limits below the thermal WIMP cross
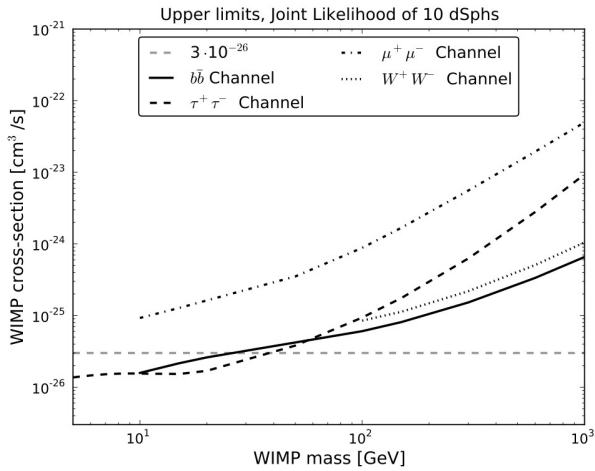
FIGURE 5. Derived 95 % C.L. upper limits on WIMP annihilation cross sections for different channels.
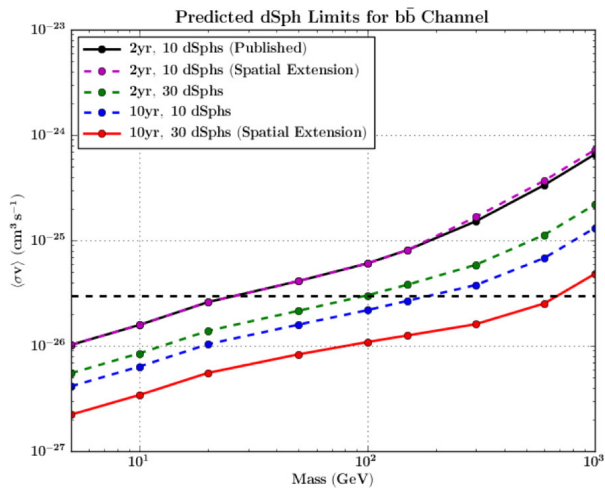

FIGURE 6. Predicted 95 % C.L. upper limits on WIMP annihilation cross sections in 10 years for the $b\bar{b}$ channel.

FIGURE 7. MSSM models in the (m_{wimp}, $\langle \sigma v \rangle$) plane. The models are consistent with all accelerator constraints, and red points have a neutralino thermal relic abundance corresponding to the inferred cosmological dark matter density (blue points have a lower thermal relic density, and we assume that neutralinos still comprise all of the dark matter in virtue of additional non-thermal production processes).

section for low DM masses (below a few tens of GeV), has been recently performed [14].

The derived 95 % C.L. upper limits on WIMP annihilation cross sections for different channels are shown in Fig. 5. The most generic cross section ($\sim 3 \times 10^{-26}$ cm^3 s^{-1} for a purely s-wave cross section) is plotted as a reference. These results are obtained for NFW profiles [13], but for a cored dark matter profile the J-factors for most of the dSphs would either increase or not change much, so these results include J-factor uncertainties [14].

With the present data, we are able to rule out large parts of the parameter space where the thermal relic density is below the observed cosmological dark matter density and WIMPs are dominantly produced non-thermally, e.g. in models where supersymmetry breaking occurs via anomaly mediation (see Fig. 7 for the MSSM model, updated from [12]).

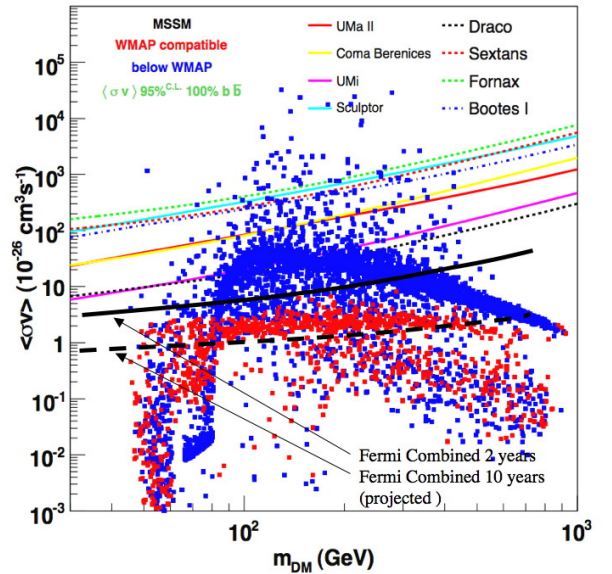These γ-ray limits also constrain some WIMP models proposed to explain the Fermi-LAT and PAMELA e$^+$e$^-$ data, including low-mass wino-like neutralinos and models with TeV masses pair-annihilating into muon–antimuon pairs.

Future improvements (apart from increased amounts of data) will include improved event selection with a larger effective area and photon energy range, and the inclusion of more satellite galaxies. Figures 6 and 7 show the predicted upper limits in the hypothesis of ten years of data instead of two; thirty dSphs instead of ten (supposing that the new optical surveys will find new dSph); spatial extension analysis (source extension increases the signal region at high energy $E \geq 10$ GeV, $M \geq 200$ GeV).

Other complementary limits were obtained with the search for possible anisotropies generated by the DM halo substructures [15], the search for Dark Matter Satellites [16] or in the Galactic Halo [17] and a search for high-energy cosmic-ray electrons from the Sun [18].

3.3. GAMMA-RAY LINES

A line at the WIMP mass, due to the 2γ production channel, could be observed as a feature in the astrophysical source spectrum [9].

Such an observation would be a "smoking gun" for WIMP DM, as it is difficult to explain by a process other than WIMP annihilation or decay, and the presence of a feature due to annihilation into γZ in addition would be even more convincing. Up to now, however, no significant evidence of gamma-ray line(s) has been found in the first 11 months of data, between 30 and 200 GeV [19] and in the first two years of from
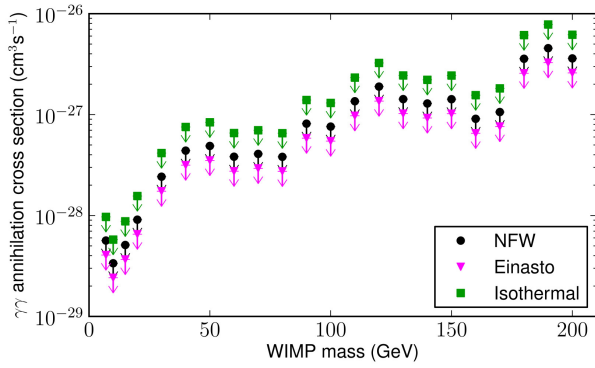
FIGURE 8. Dark matter annihilation 95 % C.L. cross section upper limits into γγ for the NFW, Einasto, and isothermal profiles for the region $|b| > 10°$ plus a $20° \times 20°$ square at the GC.

7 to 200 GeV [20] (see Fig. 8). Work is ongoing to extend the energy range of the analysis and include more data.

Recently, the claim of an indication of line emission in Fermi-LAT data [21, 22] has drawn considerable attention. Using an analysis technique similar to [19], but doubling the amount of data and also optimizing the region of interest for signal over square-root of background, [21] found a (trial corrected) 3.2σ significant excess at a mass of ~ 130 GeV which, if interpreted as a signal, would amount to a cross section of about $\langle \sigma v \rangle \sim 10^{-27}$ cm^3 s^{-1}.

The signal is concentrated on the Galactic Centre with a spatial distribution consistent with an Einasto profile [23]. This is marginally compatible with the upper limit presented in [20]. The main problems are the limited statistics in the GC sample and the check for any systematic effect that can mimic the line. A new version of the Instrument Response Function (IRF) (called Pass 8) is foreseen soon from the Fermi-LAT collaboration. With this new analysis software we should increase the efficiency of the instrument at high energy and have better control of the systematic effects.

3.4. THE COSMIC RAY ELECTRON SPECTRUM

Recently, the experimental information available on the Cosmic Ray Electron (CRE) spectrum has been dramatically expanded with a high precision measurement of the electron spectrum from 7 GeV to 1 TeV [24, 25]. The spectrum shows no prominent spectral features and it is significantly harder than that inferred from several previous experiments (see Fig. 9).

More recently, we provided further, and stronger, evidence of the positron anomaly by providing a direct measurement of the absolute e$^+$ and e$^-$ spectra, and of their fraction, between 20 and ~ 200 GeV, using the Earth magnetic field (see Fig. 9). A steady rise of the positron fraction was observed up to that energy, in agreement with that found by PAMELA. In the
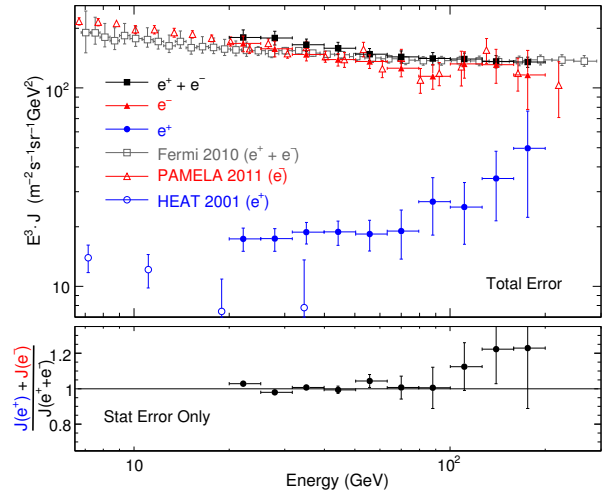

FIGURE 9. Energy spectra for e$^+$, e$^-$, and e$^+$ + e$^-$ (control region). In the control region where both species are allowed, this analysis reproduces the Fermi-LAT results reported previously for the total electron plus positron spectrum [24, 25] (gray). Previous results from HEAT [27] and PAMELA [26] are shown for reference. The bottom panel shows that the ratio between the sum and the control flux is consistent with 1, as expected.
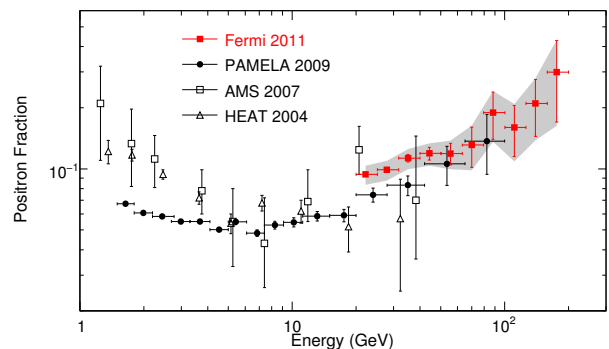

FIGURE 10. Positron fraction measured by the Fermi-LAT and by other experiments [26–28]. The Fermi statistical uncertainty is shown with error bars, and the total (statistical plus systematic) uncertainty is shown as a shaded band.

same energy range, the e$^-$ spectrum was fitted with a power-law with index $\gamma(\mathrm{e}^-) = -3.19 \pm 0.07$. This is in agreement with what was recently measured by PAMELA between 1 and 625 GeV [26]. Most importantly, Fermi-LAT for the first time measured the e$^+$ spectrum in the $20 \div 200$ GeV energy interval (see Fig. 10). The e$^+$ spectrum is fitted by a power-law with index $\gamma(\mathrm{e}^+) = -2.77 \pm 0.14$.

These measurements seems to rule out the standard scenario, in which the bulk of electrons reaching the Earth in the GeV$\div$TeV energy range are originated by Supernova Remnants (SNRs) and only a small fraction of secondary positrons and electrons come from the interaction of CR nuclei with the interstellar medium (ISM). An additional electron + positron component

peaked at $\sim 1\,\mathrm{TeV}$ seems necessary for a consistent description of all the available data sets. The temptation to claim the discovery of dark matter from the detection of electrons from the annihilation of dark matter particles is strong, but there are competing astrophysical sources, such as pulsars, that can give a strong flux of primary positrons and electrons (see [29] and references therein). At energies between $100\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$, the electron flux reaching the Earth may be the sum of an almost homogeneous and isotropic component produced by Galactic supernova remnants and the local contribution of a few pulsars, with the latter expected to contribute more and more significantly as the energy increases. If a single pulsar makes the dominant contribution to the extra component, large anisotropy and small bumpiness should be expected; if several pulsars contribute, the opposite scenario is expected.

So far, no positive detection of CRE anisotropy has been reported by the Fermi-LAT collaboration, but some stringent upper limits have been published [30], and the pulsar scenario is still compatible with these upper limits.

Forthcoming experiments like AMS-02 and CALET are expected to reduce drastically the uncertainties on the propagation parameters by providing more accurate measurements of the spectra of the nuclear components of CR. Fermi-LAT, and these experiments are also expected to provide more accurate measurements of the CRE spectrum and anisotropy, looking for features which may give a clue to the nature of the extra component.

4. Conclusions

Fermi reached four years in orbit in June 2012, and it is definitely living up to expectations in terms of scientific results delivered to the community. The mission is planned to continue at least four more years (likely more), with many remaining opportunities for discoveries.

Acknowledgements

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