# Latest Results from the Fermi Gamma-Ray Telescope

Aldo Morselli[1]

[1] *INFN Roma Tor Vergata*

Corresponding author: aldo.morselli@roma2.infn.it

**Abstract**

Can we learn about New Physics with astronomical and astro-particle data? Since its launch in 2008, the Large Area Telescope, onboard of the Fermi Gamma-ray Space Telescope, has detected the largest amount of gamma rays in the 20 MeV - 300 GeV energy range and electrons + positrons in the 7 GeV- 1 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 onboard: the Gamma-ray Burst Monitor (GBM) [1] and the Large Area Telescope (LAT) [2]. The LAT is a pair conversion telescope for photons above 20 MeV up to a few hundreds of GeV. The field of view is ∼2.4 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 [4], [5].

More than 650 million gamma-ray candidates (i.e. events passing the background rejection selection) were made public and distributed to the Community through the Fermi Science Support Center (FSSC) [1].

Over the first three years of mission the LAT collaboration has put a considerable effort toward a better understanding of the instrument and of the environment in which it operates. In addition to that, a continuous effort was made to in order to make the advances public 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 (and a release of a new event class 'Pass 7 reprocessed' is planned for the near future). Compared with the prelaunch (Pass 6) classification, it features a greater and more uniform exposure, with a significance enhancement in acceptance below 100 MeV. The Fermi LAT results on the extragalactic sky will be covered by Benoit Lott [3]. Here we will present the main results regarding the Indirect Dark Matter searches and the Origin of Cosmic Rays.

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

## 2 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, the Dark Matter, 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 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.

### 2.1 Galactic center

The Galactic center (GC) is expected to be the strongest source of $\gamma$-rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile [10], [11], [12]. A preliminary analysis of the data, taken during the first 11 months of the Fermi satellite operations is presented in [13], [14].

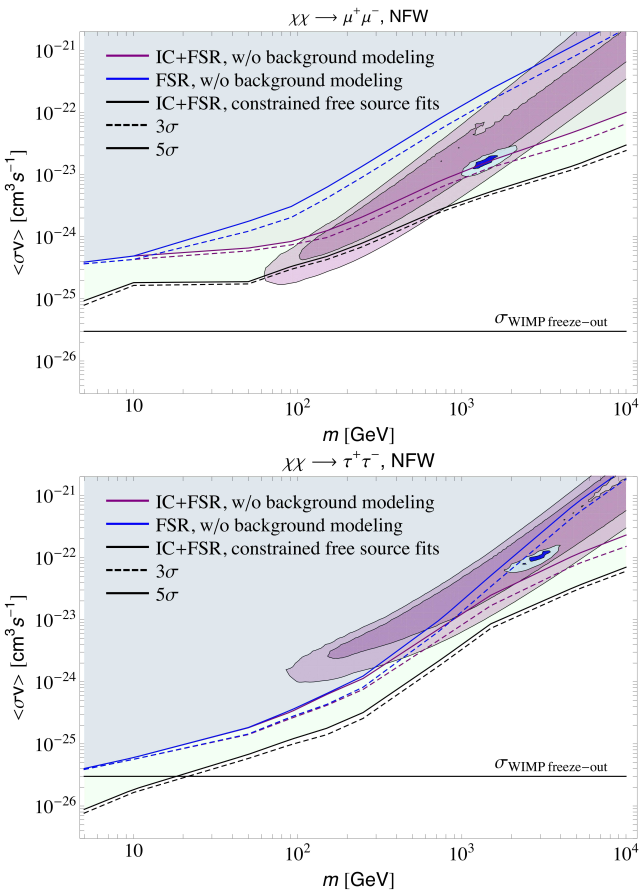


**Figure 1:** Derived 95% C.L. upper limits on WIMP annihilation cross sections in the Milky Way halo, for the muon (*left*) and tau (*right*) annihilation channels. The purple and blue contours show PAMELA and Fermi positron excess DM interpretation constraint regions.

The diffuse gamma-ray backgrounds and discrete sources, as we know them today, can account for the 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 [13], [14]. Improved modeling of the Galactic diffuse model as well as the potential contribution from other astrophysical sources (for instance unresolved point sources) could provide a better description of the data. Analyses are underway to investigate these possibilities.

## 2.2 Galactic halo

In order to minimize uncertainties connected with the region of the Galactic Center, analysis [15] considered a region of interest consisting of two off-plane rectangles ($5^\circ \leq |b| \leq 15^\circ$ and $|l| \leq 80^\circ$) and searched for continuum emission from dark matter annihilation or decay in the smooth Galactic dark matter halo. They considered two approaches: a more conservative one in which limits were set on DM models assuming that all gamma ray emission in that region might come from dark matter (i.e. no astrophysical signal is modeled and subtracted). In a second approach, dark matter source and astrophysical emission was fit simultaneously to the data, marginalizing over several relevant parameters of the astrophysical emission. As no robust signal of DM emission is found, DM limits are set.

These limits are particularly strong on leptonic DM channels, which are hard to constrain in most other probes (notably in the analysis of the dwarf Galaxies, described below). This analysis strongly challenges DM interpretation [16] of the positron rise, observed by PAMELA [17] and Fermi LAT [18, 19] (see figure 1).

## 2.3 Dwarf galaxies

Dwarf satellites 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 such systems and the upper limits on the $\gamma$-ray flux allowed us to put very stringent constraints on the parameter space of well motivated WIMP models [20]. 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 section for low DM masses (below a few tens of GeV), has been recently performed [21]. The main advantages of the combined likelihood are that the analysis can be individually optimized and that combined limits are more robust under individual background fluctuations and under individual astrophysical modelling uncertainties than individual limits. The derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels are shown in figure 2 (top). The most generic cross section ($\sim 3 \cdot 10^{-26} cm^3 s^{-1}$ for a purely s-wave cross section) is plotted as a reference. These results are obtained for NFW profiles [22] but for cored dark matter profiles the J-factors for most of the dSphs would either increase or not change much so these results includes J-factor uncertainties [21]. 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 for the MSSM model [20].

Future improvements (apart from increased amount of data) will include an improved event selection with a larger effective area and photon energy range, and the inclusion of more satellite galaxies. In figure 2 (bottom) are shown the predicted upper limits in the hypothesis of 10 years of data instead of 2; 30 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).

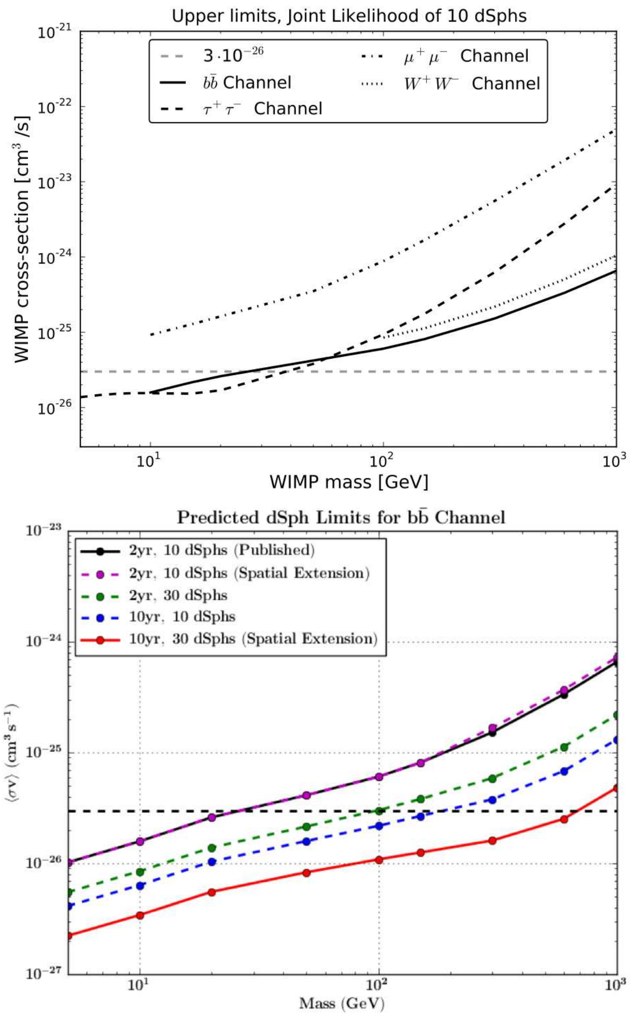


**Figure 2:** Derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels. *down:* Predicted 95% C.L. upper limits on WIMP annihilation cross sections in 10 years for *bbar* channel.

Other complementary limits were obtained with the search of possible anisotropies generated by the DM halo substructures [23], the search for Dark Matter Satellites [24] and a search for high-energy cosmic-ray electrons from the Sun [25].

## 2.4 Gamma-ray lines

A line at the WIMP mass, due to the $2\gamma$ production channel, could be observed as a feature in the astrophysical source spectrum [12]. 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 $\gamma Z$ in addition would be even more convincing. No significant evidence of gamma-ray line(s) has been found in the first two years of data from 7 to 200 GeV [26] (see also [27]).

Recently, the claim of an indication of line emission in Fermi-LAT data [28, 29] has drawn considerable attention. Using an analysis technique similar to [27], but doubling the amount of data as well as optimizing the region of interest for signal over square-root of background, [28] found a (trial corrected) 3.2 $\sigma$ significant excess at a mass of $\sim 130$ GeV that, if interpreted as a signal would amount to a cross-section of about $< \sigma v > \sim 10^{-27} cm^3 s^{-1}$.

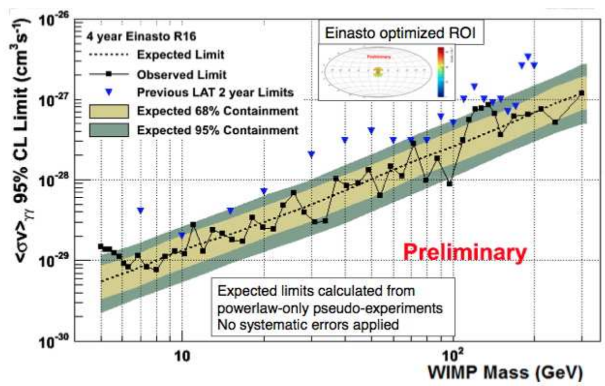


**Figure 3:** Dark matter annihilation 95% CL cross section upper limits into $\gamma\gamma$ for the Einasto profile for a circular region of interest (ROI) with a radius $R_{GC} = 16°$ centered on the GC with $|b| < 5°$ and $|l| > 6°$ masked.

The signal is found to be concentrated on the Galactic Centre with a spatial distribution consistent with an Einasto profile [30]. This is marginally compatible with the upper limit presented in [26]. In the analysis of the 4 year data the Fermi LAT team has improved over the two year paper in three important aspects: i) the search was performed in five regions of interest optimized for DM search under five different assumptions on the morphology of the DM signal, ii) new improved data set (pass 7 reprocessed) was used, as it corrects for loss in calorimeter light yield due to radiation damage during the four years of the Fermi mission and iii) the energy dispersion was improved by adding a 2nd dimension to the previously used triple Gaussian probability distribution function (PDF) model, leading to a so called '2D' PDF (such procedure is shown to increase the sensitivity to a line detection by 15%).. In that analysis [31] no globally significant lines have been fond and new limits to this DM annihilation channel were set (see figure 3). In a close inspection of the 130 GeV feature it was found that indeed there exist a 135 GeV signal at 4.01$\sigma$ local significance, when a '1D' Point Spread

Function (PSF) and old data sets were used (consistently with what [28, 29] have found). However, the significance drops to $3.35\sigma$ (local, or $\leq 2\sigma$ global significance once trials factors are taken into account). In addition, a weaker signal is found at the same energy in the control sample (in the Earth limb), which might point to a systematics effectpresent in this data set. In order to examine this possibility weekly observations of the Limb are scheduled, and a better understanding of a nature of the excess in the control sample should be available soon.

A new version of the event-level reconstruction and analysis framework (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 a data set based on independent event analysis thus gaining a better control of the systematic effects.

## 2.5 The Cosmic Ray Electron spectrum

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 by the Fermi LAT [18], [19]. The spectrum shows no prominent spectral features and it is significantly harder than that inferred from several previous experiments.

Recently the Fermi-LAT collaboration performed a direct measurement of the absolute $e^+$ and $e^-$ spectra, and of their fraction [35]. As the Fermi-LAT does not carry a magnet, analysis took advantage of the fact that due to its magnetic field, the Earth casts a shadow in electron or positron fluxes in precisely determined regions. As a result, this measurement confirmed a rise of the positron fraction observed by PAMELA, between 20 and 100 GeV and determined for the first time that it continues to rise between 100 and 200 GeV (see figure 4). These measurements show that a new component of $e^+$ and $e^-$ are needed with a peak at $\sim 1$ TeV. The temptation to claim the discovery of dark matter from detection of electrons and positrons from 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 [16] and references therein). At energies between 100 GeV and 1 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 nearby pulsar gives the dominant contribution to the extra component a large anisotropy and a small bumpiness should be expected; if several pulsars contribute the opposite scenario is expected. So far no positive detection of CRE anisotropy was reported by the Fermi-LAT collaboration, but some stringent upper limits were published [34] and the pulsar scenario is still compatible with these upper limits.

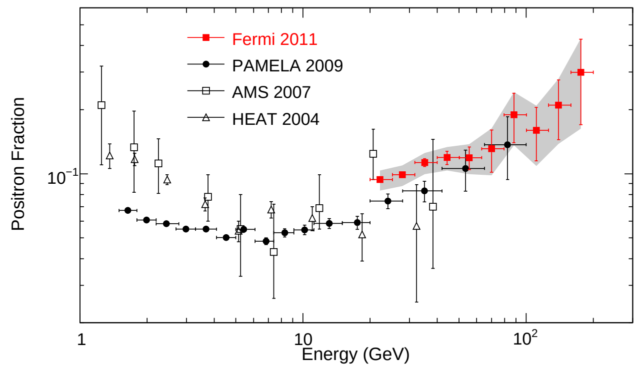


**Figure 4:** Positron fraction measured by the Fermi LAT and by other experiments [32, 33, 17]. The Fermi statistical uncertainty is shown with error bars and the total (statistical plus systematic uncertainty) is shown as a shaded band.

After the conference the AMS-02 collaboration presented the result on the positron fraction [36] that confim the positron ratio rise observed by PAMELA and Fermi and extend it up to 350 GeV.

Forthcoming measurements from 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 those experiments are also expected to provide more accurate measurements of the CRE spectrum and anisotropy looking for features which may give a clue of the nature of the extra component.

# 3 Origin of Cosmic Rays

Cosmic rays are particles (mostly protons) accelerated to relativistic speeds. Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking. When accelerated protons encounter interstellar material they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons. The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering. We detected the characteristic pion-decay feature in the gamma-ray spectra of two SNRs, IC 443 and W44, with the Fermi Large Area

Telescope. This detection provides direct evidence that cosmic-ray protons are accelerated in SNRs.

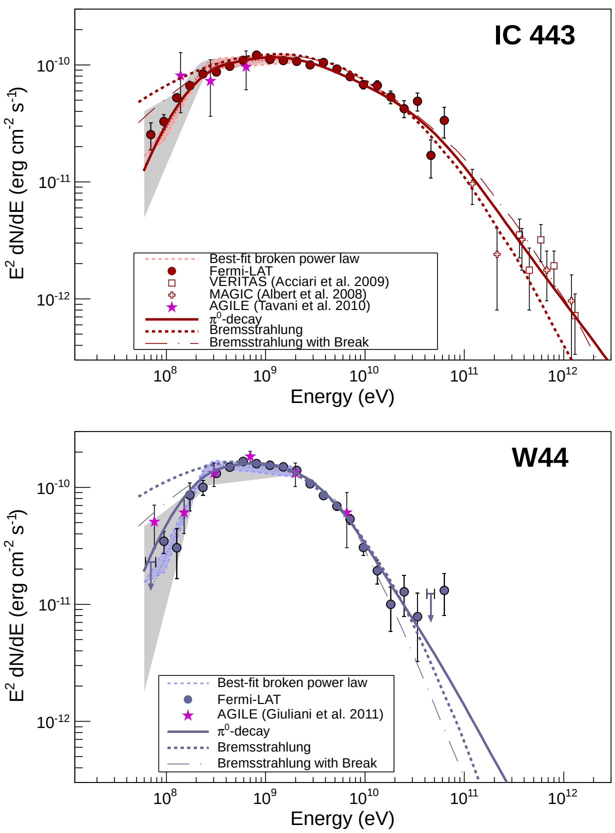


**Figure 5:** (A and B) Gamma-ray spectra of IC 443 (A) and W44 (B) as measured with the *Fermi*-LAT [37] . Color-shaded areas bound by dashed lines denote the best-fit broadband smooth broken power law (60 MeV to 2 GeV), gray-shaded bands show systematic errors below 2 GeV due mainly to imperfect modeling of the galactic diffuse emission. At the high-energy end, TeV spectral data points for IC 443 from MAGIC [38] and VERITAS [39] are shown. Solid lines denote the best-fit pion-decay gamma-ray spectra, dashed lines denote the best-fit bremsstrahlung spectra, and dash-dotted lines denote the best-fit bremsstrahlung spectra when including an ad hoc low-energy break at 300 MeV $c^{-1}$ in the electron spectrum. These fits were done to the *Fermi* LAT data alone (not taking the TeV data points into account). Magenta stars denote measurements from the AGILE satellite for these two SNRs, taken from [40] and [41], respectively.

Figure 5 shows the spectral energy distribution obtained for IC 443 and W44 through maximum likelihood estimation. The normalizations of the fluxes of IC 443 and W44 and those of neighboring sources and of the galactic diffuse model, were left free in the fit for each bin.

To determine whether the spectral shape could indeed be modeled with accelerated protons, we fit the LAT spectral points with a $\pi^0$-decay spectral model, which was numerically calculated from a parameterized energy distribution of relativistic protons.

The measured gamma-ray spectra, in particular the low-energy parts, matched the $\pi^0$-decay model (Fig.5) [37].

The $\pi^0$-decay gamma rays are likely emitted through interactions between "crushed cloud" gas and relativistic protons, both of which are highly compressed by radiative shocks driven into molecular clouds that are overtaken by the blast wave of the SNR

Unless we introduce in an *ad hoc* way an additional abrupt break in the electron spectrum at 300 MeV $c^{-1}$ (Fig.5 dash-dotted lines), the bremsstrahlung models do not fit the observed gamma-ray spectra. If we assume that the same electrons are responsible for the observed synchrotron radiation in the radio band, a low-energy break is not expected to be very strong in the radio spectrum and thus the existing data do not rule out this scenario. The introduction of the low-energy break introduces additional complexity and therefore a bremsstrahlung origin is not preferred.

Finding evidence for the acceleration of protons has long been a key issue in attempts to elucidate the origin of cosmic rays. Our spectral measurements down to 60 MeV enable the identification of the $\pi^0$-decay feature, thus providing direct evidence for the acceleration of protons in SNRs. The proton momentum distributions, well-constrained by the observed gamma-ray spectra, are yet to be understood in terms of acceleration and escape processes of high-energy particles.

## 4 Conclusions

Fermi turned four years in orbit on June, 2012, and it is definitely living up to its 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.

## Acknowledgement

The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foun- dation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

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