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Recent results from the FERMI gamma-ray telescope

A. Morselli
INFN, Sezione di Roma Tor Vergata - Roma, Italy

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Summary. — 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 and positrons in the 7 GeV–1 TeV range. These impressive statistics allow one to perform a very sensitive indirect experimental search for dark matter.

PACS `96.50.sb` – Composition, energy spectra and interactions.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS `95.85.Ry` – Neutrino, muon, pion, and other elementary particles; cosmic rays.
PACS `98.70.Sa` – Cosmic rays (including sources, origin, acceleration, and interactions).

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 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. Here we will present the main results regarding the indirect Dark Matter searches

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 (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 and at accelerators, the indirect search for DM is one of the main items in the broad Fermi Science menu.

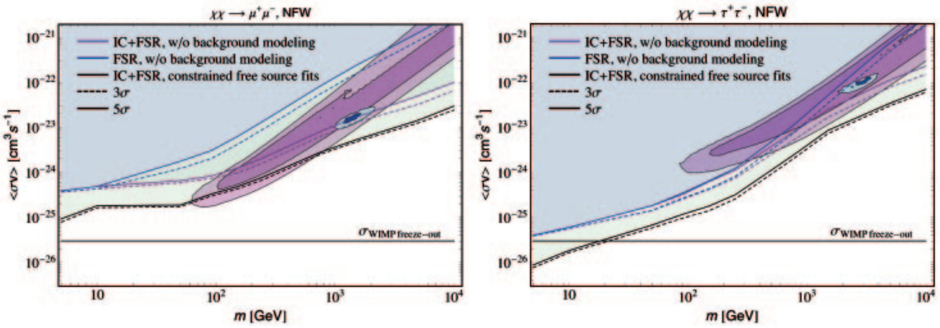

Fig. 1. – Derived 95% C.L. upper limits on WIMP annihilation cross sections in the Milky Way halo, for the muon (left) and tau (right) annihilation channels.

2˙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 [3-5]. A preliminary analysis of the data, taken during the first 11 months of the Fermi satellite operations is presented in [6, 7].

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 [6, 7]. 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 the uncertainties connected with the region of the Galactic center, analysis [8] considered a region of interest consisting of two off-plane rectangles ($5° \leq |b| \leq 15°$ and $|l| \leq 80°$) and searched for continuum emission from dark matter annihilation or decay in the smooth Galactic dark matter halo.

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 of the positron rise, observed by PAMELA [9] and Fermi LAT [10, 11] (see fig. 1).

2˙3. *Dwarf Spheroidals galaxies*. – Dwarf Spheroidals satellites (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 such 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 section for low DM masses (below a few tens of GeV), has been recently performed [13]. The derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels are shown in fig. 2 (left). The most generic cross section (about $3 \cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for a purely s-wave cross section) is plotted as a reference. These results are obtained for NFW profiles [14] but for 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 [13].

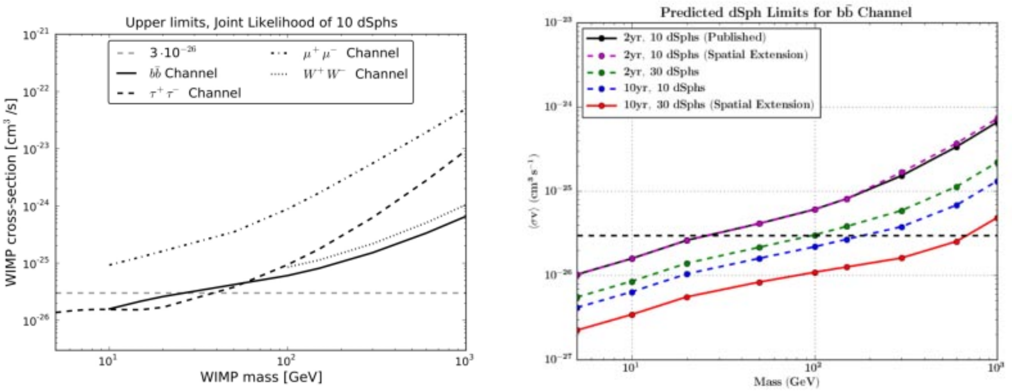

Fig. 2. – Left: Derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels. Right: Predicted 95% C.L. upper limits on WIMP annihilation cross sections in 10 years for $b\bar{b}$ channel.

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 (updated from [12]). Future improvements (apart from an 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 fig. 2 (right) 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 $E \geq 10\,\text{GeV}$, $M \geq 200\,\text{GeV}$) are shown. These results are comparable to the limits obtained at LHC (see for example fig. 3 from [15]).

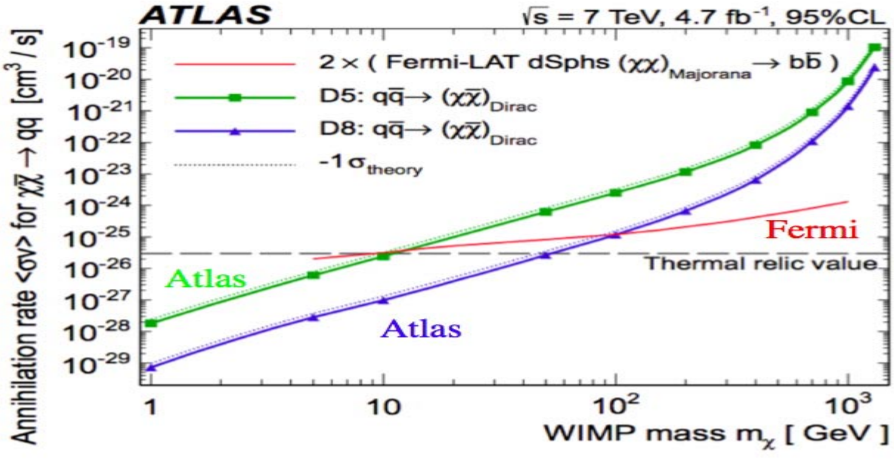

Fig. 3. – Inferred ATLAS limits on WIMP annihilation rates together with limits from observations of Galactic satellite galaxies with the Fermi-LAT experiment [15].

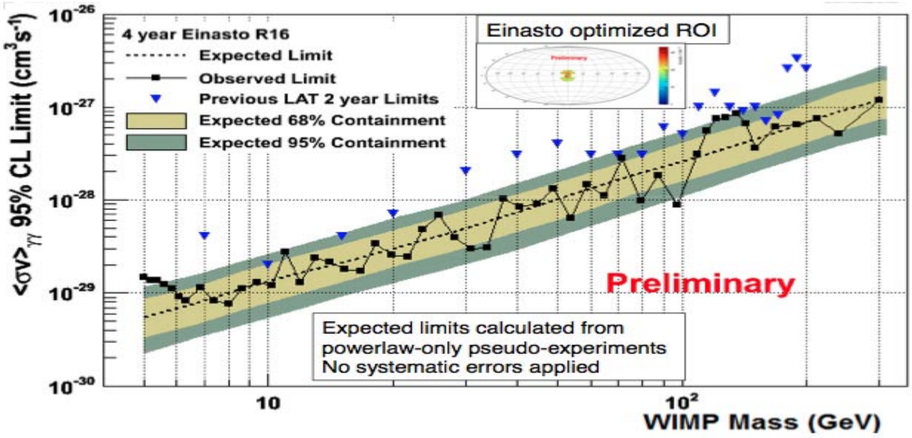

Fig. 4. – Dark matter annihilation 95% CL cross section upper limits into $\gamma\gamma$ for the Einasto profile for a circular region of interest (ROI) with a radius $R_{GC} = 16°$ centered on the GC with $|b| > 5°$ and $|l| > 6°$ masked.

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

2$\dot{}$4. *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 [5]. 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. No significant evidence of gamma-ray line(s) has been found in the first two years of data from 7 to 200 GeV [19] (see also [20]). 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 [20], but doubling the amount of data as well as 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 about 130 GeV that, if interpreted as a signal would amount to a cross-section of about $\langle \sigma v \rangle = 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$.

The signal is found to be 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 [19]. In the new analysis of the 4 year data the Fermi LAT team [24] no globally significant lines have been fond and new limits to this DM annihilation channel were set (see fig. 4). In a close inspection of the 130 GeV feature it was found that indeed there exists a 135 GeV signal at 4.01σ local significance, when a "1D" PSF and old data sets were used (consistently with what [21, 22] have found). However, the significance drops to 3.35σ (local, or $\leq 2\sigma$ global significance once trials factors are taken into account). 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.

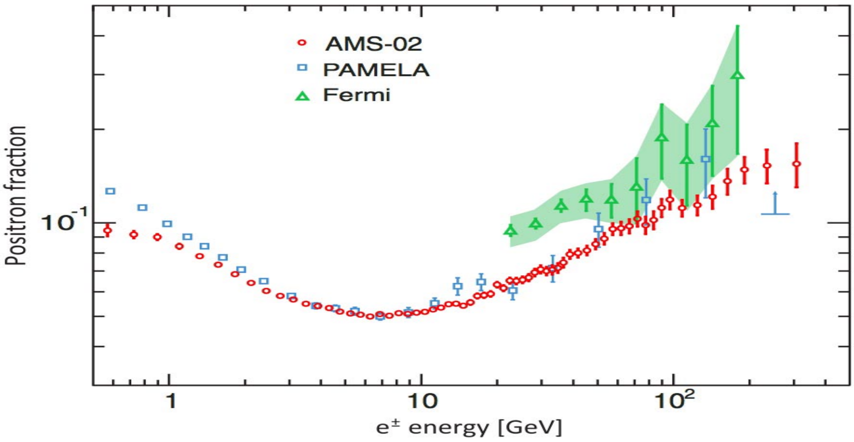

Fig. 5. – Positron fraction measured by the Fermi LAT, PAMELA and AMS-0 [11, 9, 29]. The Fermi statistical uncertainty is shown with error bars and the total (statistical plus systematic uncertainty) is shown as a shaded band.

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 [10, 11]. 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 [25]. 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 $\sim$ 100 GeV and determines for the first time that it continues to rise between 100 and 200 GeV (see fig. 5). These measurements show that a new component of e^+ and e^- is needed with a peak at about 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 [26] 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 Cosmic Ray Electron (CRE) anisotropy was reported by the Fermi-LAT collaboration, but some stringent upper limits were published [27] and the pulsar scenario is still compatible with these upper limits.

During the conference the AMS-02 collaboration presented the result on the positron fraction [28, 29] 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. – 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.

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