Fermi Large Area Telescope as a dark matter search tool

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Abstract
Since its launch five years ago, the Large Area Telescope, onboard of the Fermi Gamma-ray Space Telescope, has detected the largest amount of gamma rays in the 20 MeV - $\geq$ 300 GeV energy range (nicely covering electro weak scale) with good angular resolution and good rejection power of more numerous charged cosmic rays. These impressive performance allows to attempt to learn about New Physics with astronomical and astro-particle data. We will present the latest results on these searches.

1 Introduction

The Large Area Telescope (LAT), one of two instruments onboard the Fermi Observatory, [1], 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 sr and the LAT observes the entire sky every $\sim$ 3 hours (2 orbits). The operation of the instrument through the first five years of the mission was smooth: the LAT has been collecting science data for more than 99% of the time spent outside the South Atlantic Anomaly.

Its data are made public and distributed to the Community through the Fermi Science Support Center (FSSC) [1] and have been used widely.

In what follows we will present some of the most important results of the Fermi LAT mission, focusing on those related to searches for signatures of Dark Matter (DM) annihilations in our and neighboring Galaxies.

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 interactions of the Galactic cosmic rays with interstellar medium and radiation fields. As a consequence the disk of our Milky Way Galaxy shines brightly in the Fermi sky. An additional diffuse component with an almost-isotropic distribution presents another significant fraction of the LAT photons. Due to its isotropic distribution it is thought to be of extragalactic in origin. The rest consists of various different types of point-like or extended sources: extragalactic ones as Active Galactic Nuclei (AGN) and normal star forming galaxies, as well as Galactic sources as 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) [2] is the deepest catalog ever produced in the energy band between 100 MeV and 100 GeV, containing more than 1800 sources. Most of the sources are of extragalactic origin, blazars being the most numerous kind, with more than 800 detected ones. Among Galactic sources, LAT identified 117 gamma ray pulsars [3] and discovered millisecond gamma ray pulsars, being therefore dubbed the 'pulsar machine'. In addition to firmly identified sources, based either on periodic variability or on spatial morphology or on correlated variability, 576 (i.e. 31% of

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

the total number of entries in the catalog) are still unassociated with known astrophysical objects. In addition, the first catalog of high energy sources has recently been published [4] and the first catalog of Super Nova Remnants (SNRs) is in preparation [5].

3 Indirect Dark Matter searches

One of the major open issues in our understanding of the Universe is the nature of an extremely-weakly interacting form of matter, the dark matter. The evidence for its existence is supported by a wide range of observations including large scale structures, the cosmic microwave background and the isotopic abundances resulting from the primordial nucleosynthesis, all of them being sensitive to its gravitational interaction. Due to the universal nature of gravity a different kind of probe is needed to pinpoint its particle physics properties. Complementary to direct searches being carried out in underground facilities and at accelerators, the indirect search for DM is one of the main of goals of Fermi Science. The indirect searches look for signatures of Weakly Interactive Massive Particle (WIMP) annihilation or decay in the surplus of its final products: stable standard model particles as gamma-rays, electrons and positrons, antiprotons. 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, Cosmic Ray (CR) electrons and positrons.

3.1 Galactic center

The center of our Galaxy 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 [6], [7], [8].

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 in a preliminary analysis of the data, taken during the first 11 months of the Fermi satellite, a residual emission not accounted for by the above models was found [9], [10]. Improved modeling of the Galactic diffuse emission (for example, by taking advantage of advanced statistical analysis tools to scan over many parameters of the diffuse emission, along the lines of work presented in [11, 13]), as well as the potential contribution from other astrophysical sources (for instance unresolved point sources) should provide a more robust description of the data. Analyses are underway to investigate these possibilities. At the same time the community has responded actively to this issue, with many papers discussing properties and nature of such residual emission, e.g. [14, 15]. It should be noted that based only on gamma ray signatures in the Galactic Center it might be impossible to distinguish between dark matter signal and that of the unresolved population of pulsars. In such case DM detection can be claimed only if its signatures are confirmed by some other probe and/or in a different target.

3.2 Galactic halo

In order to minimize uncertainties connected with the region of the Galactic Center, analysis in [11] considered a region of interest consisting of two off-plane rectangles ($5^0 \le |b| \le 15^0$ and $|l| \le 80^0$) 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, arguably more realistic approach, dark matter source and astrophysical emission were fit simultaneously to the data, marginalizing over several relevant parameters of the astrophysical emission. As no robust signal of DM emission is found, further conservative choices were made in a process of setting the DM limits.

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

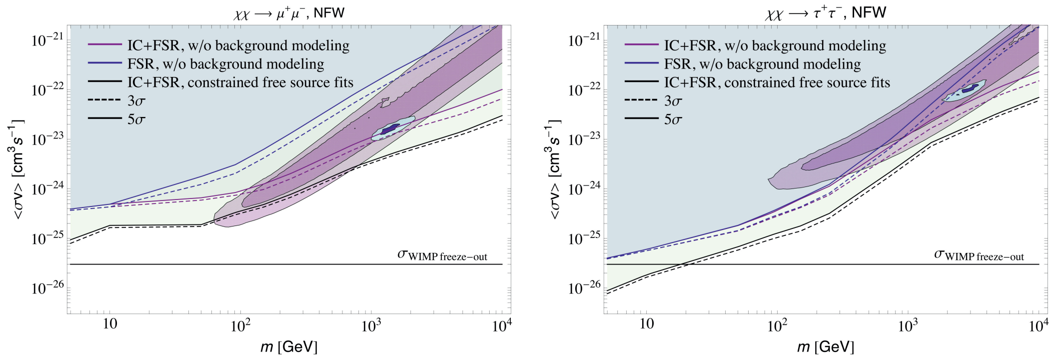

Fig. 1: Upper limits on WIMP annihilation cross sections in the Milky Way halo, for the muon (*left*) and tau (*right*) annihilation channels, as derived in [11].

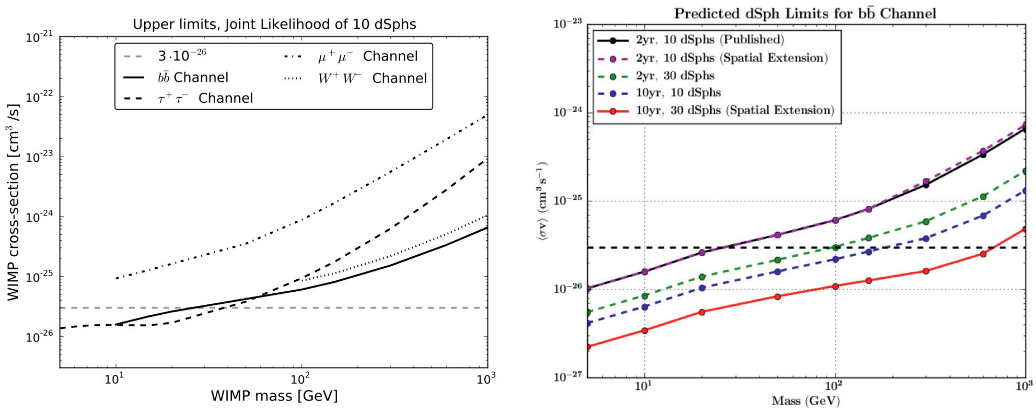

Fig. 2: *Left:* 95% C.L. upper limits on WIMP annihilation cross sections for different channels, from [21]. *Right:* Predicted 95% C.L. upper limits on WIMP annihilation cross sections in 10 years for $bbar$ channel, from [22].

challenges DM interpretation [12] of the positron rise, observed by PAMELA [16], Fermi LAT [17, 18] and most recently AMS-02 [19] (see figure 1).

3.3 Dwarf galaxies

Dwarf spheroidal (dSphs) satellites of the Milky Way are old system with small amount of interstellar gas and with a very large mass-to-luminosity ratio (i.e. systems which are largely DM dominated). Detection of gamma rays from dwarf Galaxies is therefore considered to be one of the "smoking guns" of dark matter detection. The LAT so far detected no significant emission from these objects and the upper limits on the γ-ray flux were used to put stringent constraints on the parameter space of well motivated WIMP models [21].

A combined likelihood analysis of the 10 most promising dwarf galaxies, based on 24 months of data was presented in [21]. The main advantages of the combined likelihood are that the background analysis can be individually optimized for location of each dwarf galaxy, while the combined limits are more robust under individual background fluctuations and under uncertainties related to the estimated dark matter content, when compared to the limits from each individual dwarf galaxy. The derived 95% C.L. upper limits on WIMP annihilation cross sections for different channels are shown in figure 2 (left). 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 [20] but for cored dark matter profile 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, in particular thermally produced WIMPS with mass of few tens of GeV.

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 (right) 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, such as Dark Energy Survey (DES) and PanSTARSS will find new dSph due to their larger coverage of the sky) and due to the inclusion of the spatial extension of dSphs in the analysis (source extension increases the signal region at high energy $E \geq 10\ GeV, M \geq 200\ GeV$) as calculated in [22].

Other complementary limits derived with the Fermi LAT collaboration include the search for DM signatures in Galaxy clusters [23], possible anisotropies generated by the DM halo substructures [24], the search for Dark Matter Satellites [25] and a search for high-energy cosmic-ray electrons from the Sun [26].

3.4 Gamma-ray lines

A gamma-ray spectral line at the WIMP mass could be produced in annihilations or decays of DM particles to two photons (via loop processes, as direct coupling to photons is usually considered forbidden for standard *dark* matter candidates[2]). It could be observed as a particular feature in the astrophysical source spectrum [8]. Such an observation would be another "smoking gun" for WIMP DM as it is difficult to explain such feature by usual astrophysical processes, specially if it is observed over several directions in the sky. A 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 [27] (see also [28]).

In early 2012, the claim of an indication of line emission in Fermi-LAT data [29, 30] has drawn considerable attention. Using an analysis technique similar to [28], but doubling the amount of data as well as optimizing the region of interest for signal over square-root of background, [29] found a (trial corrected) 3.2 σ significant excess at a mass of ~ 130 GeV that, if interpreted as a signal would amount to a cross-section of about $< \sigma v > \sim 10^{-27} cm^3 s^{-1}$.

The signal is found to be concentrated on the Galactic Centre with a spatial distribution consistent with an Einasto profile [31]. This is marginally compatible with the upper limit presented in [27].

The follow up analysis of the Fermi LAT team uses 4 year data and 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, [32]) 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) point spread function (PDF) was improved by adding a second dimension to the previously used triple Gaussian PDF model (such procedure is shown to increase the sensitivity to a line detection by 15%). In that analysis [33, 34] 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 133 GeV signal at 4.5σ local significance, when a '1D' PSF and old data sets were used (consistently with what [29, 30] have found). However, the significance drops to 3.3σ (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 effect present 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.

[2]However, there are several models which can generate the γ-ray line from tree level. For instance, some composite Dark Matter models or magnetic dipole interaction have the photon production directly.

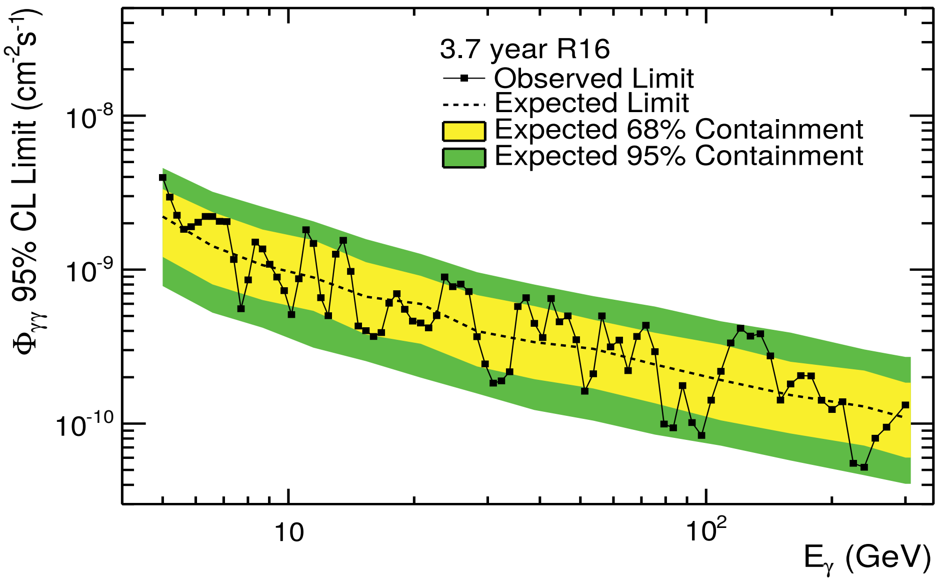

Fig. 3: Dark matter annihilation 95% CL cross section upper limits into $\gamma\gamma$ for the Einasto profile for a circular region of interest (ROI) with a radius $R_{GC} = 16°$ centered on the GC with $|b| < 5°$ and $|l| > 6°$ masked, [34].

A new version of the event-level reconstruction and analysis framework (called Pass 8 , [35]) is being prepared for release within 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. Also, a new observational strategy exposing favorably the region of the Galactic Center has recently been recommended[3] and could start already towards the end of this year.

4 Conclusions

The Fermi LAT turned five years in orbit on June, 2013, and it is living up to its expectations in terms of richness of scientific results delivered to the community. The mission is planned to continue at least four more years with many remaining opportunities for discoveries, both astrophysics-related and some hopefully in the fundamental sector.

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