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Search for Dark Matter with Fermi Large Area Telescope: The Galactic Center

Vincenzo Vitale *, Aldo Morselli

INFN, Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy

For the Fermi/LAT Collaboration

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ABSTRACT

Dark Matter (DM) as a weakly interacting massive particle could annihilate or decay and give rise to high energy gamma-rays. Then an indirect search for Dark Matter is possible by means of the Large Area Telescope on board the Fermi satellite. A relatively large signal is expected from the regions where the Dark Matter is expected to have the greatest density, such as the central region of the Milky Way. This region also hosts many high-energy gamma ray sources, of many different classes. Furthermore diffuse gamma-ray emission due to cosmic-ray interactions with interstellar gas and radiation is detected from the same direction. A greatly improved understanding of the gamma ray emission from the Galactic Center region is going to be obtained with the Fermi LAT first-year data. The data along with refined modelling of the diffuse emission and a careful evaluation of the discrete sources will improve our ability to disentangle a potential dark matter signal from the astrophysical background and to place new limits on the mass and annihilation rate (or lifetime) of Dark Matter particles

1. Fermi

The Fermi Gamma-ray Space Telescope is a space observatory for the study of gamma-ray emission from astrophysical sources. It is equipped with two powerful instruments:

1. the Large Area Telescope (LAT), a pair-conversion telescope, composed of a precision silicon-tracker (18 double-sided layers) and a calorimeter (8.6 radiation lengths vertical depth), each of which consisting of a 4×4 array of 16 modules and surrounded by a segmented anti-coincidence detector (ACD). LAT is operated as a gamma-ray imager in the energy range between 20 MeV and 300 GeV;
2. the Gamma Ray Burst Monitor (GBM), a detector covering the 8 keV–40 MeV energy range, devoted to the study of the Gamma Ray Bursts.

Detailed descriptions of the Fermi observatory can be found in Refs. [1,2] and a report of the LAT detector is in Ref. [4]. The LAT on-orbit calibration is reported in Ref. [5].

Studies of the gamma-ray sources in the energy range between hundreds of MeV and tens of GeV were performed by means of the SAS 2 and COS B satellites in the years 1972–1982 and with the Energetic Gamma Ray Experiment Telescope (EGRET) onboard of the Compton Gamma Ray Observatory between 1991 and 2000. EGRET detected 271 sources [3]. About an half of the EGRET sources are unidentified, mainly because of the relatively large errors associated with the source locations. The sources detected with EGRET are mainly members of two classes: Active Galactic Nuclei (AGNs) of FSRQ (Flat Spectrum Radio Quasars) and Bl Lac types, with powerful relativistic jets of plasma, or pulsars (spinning neutron stars, with powerful magnetic fields, capable of accelerating particles up to the high energy regime). EGRET was able to detect both discrete sources and diffuse gamma ray emissions such as the extra-galactic gamma-ray background and the very intense Galactic component.

The Large Area Telescope has an effective area five times larger, a much better angular resolution, and a sensitivity 10 times better than its predecessor EGRET. The Fermi observatory has several scientific objectives, which span many topics of astrophysics and fundamental physics: (1) the detailed study of pulsar, AGNs, diffuse emissions and gamma-ray emission from nearby bodies; (2) the study of Gamma Ray Bursts, up to GeV energies with the LAT and in the better studied keV–MeV range by means of the GBM; (3) the search for new classes of gamma-ray emitters; (4) the possible signals of new physics. The indirect search for Dark Matter particles and the investigation of their nature are major research topics for Fermi. Here we report an update of the indirect search for Dark Matter from the Galactic Center (GC).

2. Indirect search for Dark Matter with Fermi

Accurate measurements of the cosmic microwave background provide us with an estimate of the energy content of the universe

* Corresponding author.
E-mail address: vincenzo.vitale@roma2.infn.it (V. Vitale).

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[6]. The *ordinary* baryonic matter accounts for 4% the total matter density, while another 23% is estimated to be Cold Dark Matter and 73% is considered to be in the form of Dark Energy. The evidences for the existence of Dark Matter are several: galaxies rotation velocities [8], galaxies orbital velocities within clusters [7], gravitational lensing [9], the cosmic microwave background [10], the abundances of light elements [11], and the large scale structures [12]. Dark Matter is gravitationally coupled with the ordinary matter. Non-gravitational DM couplings are studied with:

- the direct search for Dark Matter scattering on ordinary matter;
- the indirect study of Dark Matter annihilation via the secondary products, both charged and neutral (e^+, $\overline{p}$, $\overline{d}$, ν , γ rays and lower frequency electro-magnetic radiation).

Dark Matter particles might produce gamma rays:

1. if the DM particles self-annihilates in pairs, possibly following the scheme in Fig. 1. This yields a continuum gamma-ray emission, which is produced by hadronization (or final state radiation) of the annihilation products and has a cut-off at the DM particle mass. The direct production of two gamma-rays as annihilation products is suppressed in many models (10^{-3}–10^{-4} of the continuum);
2. if pseudo-stable DM particles decay in gammas. In this case the gamma ray flux is proportional to the DM particle density. The DM decay constant is bound to be larger than 10^{26} s and is model dependent [13].

The gamma ray flux from DM particle annihilation can be decomposed into a Particle physics factor and an Astrophysical one. The gamma-ray flux from annihilation can be written as

$$\Phi_{WIMP}(E,\psi) = \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi}\frac{1}{m_{WIMP}^2}\sum B_f \frac{dN_{\gamma,f}}{dE_\gamma}\int_{los}\rho(l)^2\, dl(\psi)$$

where σ is the annihilation cross-section, v is the Dark Matter particle speed, $dN_{\gamma,f}/dE_\gamma$ is the number of gamma rays emitted per annihilation for each annihilation channel f, B_f is the branching ratio of the annihilation channel f and M_{WIMP} is the mass of the Dark Matter particle candidate. $\rho($ l) is the Dark Matter density profile, i.e. the density of Dark Matter as a function of the distance from the halo center. $\rho(\mathrm{l})^2$ is integrated along the observer's line-of-sight (*los*). The gamma-ray flux from decay can be written as

$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{\Gamma}{4\pi m_{DM}}\frac{dN_\gamma}{dE_\gamma}\int_{los}\rho(l)\, dl(\psi)$$

where Γ is the decay constant, dN_γ/dE_γ is the number of gamma rays emitted for each decay and M_{DM} is the mass of the Dark Matter particle candidate. ρ_{DM} is the Dark Matter density profile. In the decay scenario ρ, not its square, is integrated along the observer's line-of-sight (*los*), then gamma-ray observations can be used for the indirect study of the Dark Matter. Many possible observation strategies are currently carried out by the Fermi/LAT collaboration. One of these is the targeting of regions where high Dark Matter density is foreseen. High Dark Matter density is believed to be in the Galactic Center, also this region hosts many ordinary gamma-ray emitters. A better ratio between the Dark and baryonic matter, and then a weaker gamma-ray background, is foreseen for the Dwarf Spheroidal Galaxies, or in Dark Matter sub-structures in the halo.

As a matter of fact N-body simulations predict that Dark Matter is arranged in large structures called *halos*. DM halos have clumps and a main central density enhancement, from which a larger gamma ray emission is expected (visualized in Fig. 3). Our Galaxy could be embedded in a DM halo with the central density enhancement co-located with the Galactic Center. Then the Galactic Center might be the brightest source of gamma rays coming from DM annihilation and it might be possible to detect such an emission [16,17]. The DM gamma ray emission is expected to be a function of the DM density profile (see Fig. 2 and also Ref. [14]), which is not experimentally known, in the center of the Galaxy. As mentioned previously, another challenge is the bright gamma-ray emission from astrophysical processes, which is generated both by discrete sources and diffuse emissions in the Galactic Center.

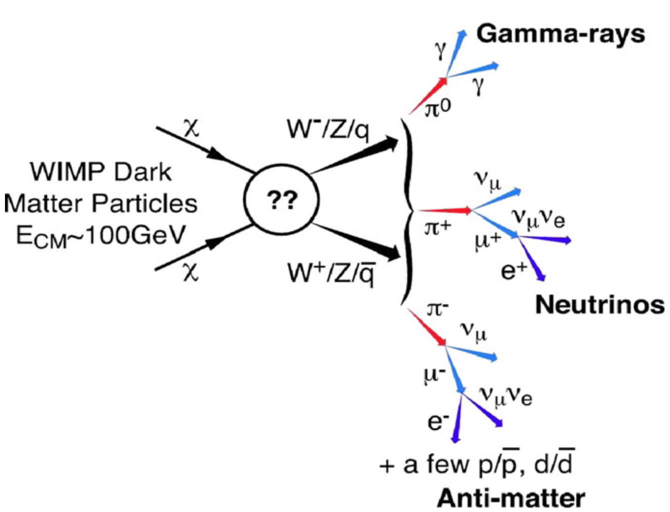

Fig. 1. Gamma ray production scheme for DM annihilation. Reproduced from Ref. [18]. If the DM particle self-annihilate and produce quarks, leptons and gauge bosons, then an indirect search is possible by searching for the secondary products. For weakly interacting massive particles (WIMPs) of Maiorana type the heavy fermions pairs, such as $b\overline{b}$,$t\overline{t}$, $\tau^+\tau^-$, are favoured as annihilation products. The annihilation into two gamma rays, for some models, is loop-suppressed, with a branching ratio of 10^{-3}–10^{-4}. Gamma-ray emission is expected after the heavy fermions hadronization. The gamma-ray emission energy spectrum is a continuum with curved shape (in log–log scale) and a sharp cut-off at the DM particle mass.

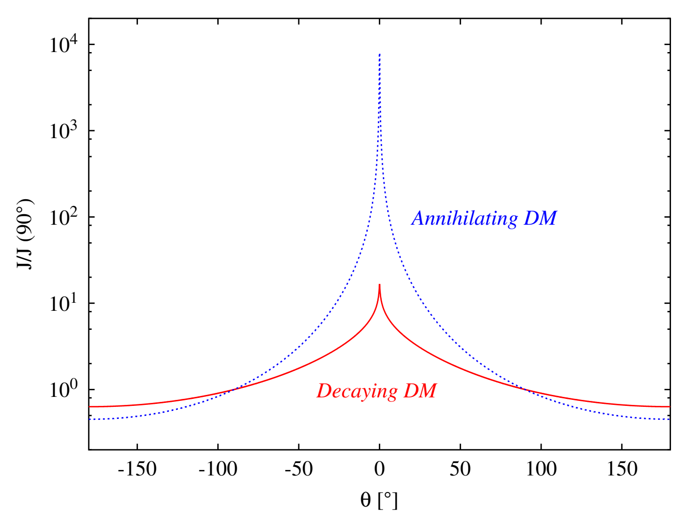

Fig. 2. Comparison of expected gamma ray emission profile in the case of annihilating (proportional to the square of the density) and decaying (proportional to the density) Dark. The angular profile of the gamma-ray signal is shown, as function of the angle θ to the centre of the galaxy for a NFW halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line. Both signals have been normalised to their values at the galactic poles, $\theta = \pm 90^\circ$. Reproduced from Ref. [13]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Pre-launch expectations and early Fermi results on the Galactic Center

In a pre-launch publication [18] the foreseen constraints on the $\langle\sigma v\rangle$ parameter, which can be obtained with observations of the Galactic Center, with the LAT, are reported. The plot in Fig. 4 shows the constraints in $\langle\sigma v\rangle$ vs. WIMP mass for an assumed pure $b\overline{b}$ annihilation channel. Further expectations based on simulations were reported in Ref. [19].

First results on the Galactic Center region are in the *Fermi Bright Source List* publication ([20], see Table 1), where all the sources detected with the LAT above 10σ in 3 months are reported. The 0FGL J1746.0-29.00 is the source closest to the dynamical center of the Galaxy.

A previous preliminary analysis was performed on data taken during the first 8 months of the science phase of the mission. A $1^\circ \times 1^\circ$ region was considered. Events with energies between 200 MeV and 40 GeV and the diffuse class have been selected. A conservative analysis, based on the spectral information only was performed. It was possible to put an upper limit of $2.43 \pm 0.02 \times 10^{-7}\,\mathrm{cm^{-2}\,s^{-1}}$ (95% confidence level, above 100 MeV) to the integral gamma ray flux from a DM annihilation source, which was assumed to have a Navarro–Frenk–White density profile. If a DM particle mass of 50 GeV is considered then an upper limit of $39.8 \times 10^{-26}\,\mathrm{cm^3\,s^{-1}}$ to the $\langle\sigma v\rangle$ parameter is obtained.

4. Preliminary analysis of first 11 months data

Any attempt to disentangle a potential dark matter signal from the galactic center region requires deep understanding of the conventional astrophysics background. The reported analysis is performed with data collected during the first 11 months of operation. A $7^\circ \times 7^\circ$ region centered on the Galactic Center was analyzed with binned likelihood analysis (gtlike, from the Fermi analysis tools [21]). The data were selected to have energy above 400 MeV, to be of diffuse class (high quality data), to have converted in the front part of the tracker, and to satisfy other quality requirements. The P6_v3 Instrument Response Function was used. In order to model the observed data a Galactic Diffuse emission model (gll_iem_54_87Xexph7S.fit), based on the GALPROP code [22,23] and Isotropic Diffuse emission (Extragalactic + residual charged particles) model have been used to fit the data plus the model of 11 sources in the Fermi 1 year catalog (to be published) contained in the region of interest. Only the normalization of the GALPROP model is varied, not the components. The results are illustrated in Figs. 5 and 6. The bulk of the gamma ray emission from this region is explained by means of the above described components, but a residual emission is left. The systematic uncertainty of the effective area of the LAT is 10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV. This uncertainty propagates to the model predictions and

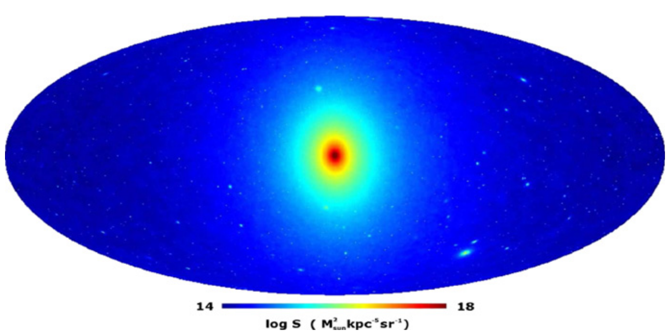

Fig. 3. Simulated gamma emission from an annihilating DM halo. The total surface brightness from all components together (the main halo + all resolved subhalos + all unresolved subhalos down to the free streaming limit) is shown. The surface brightness is in color code. Reproduced from Ref. [15]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

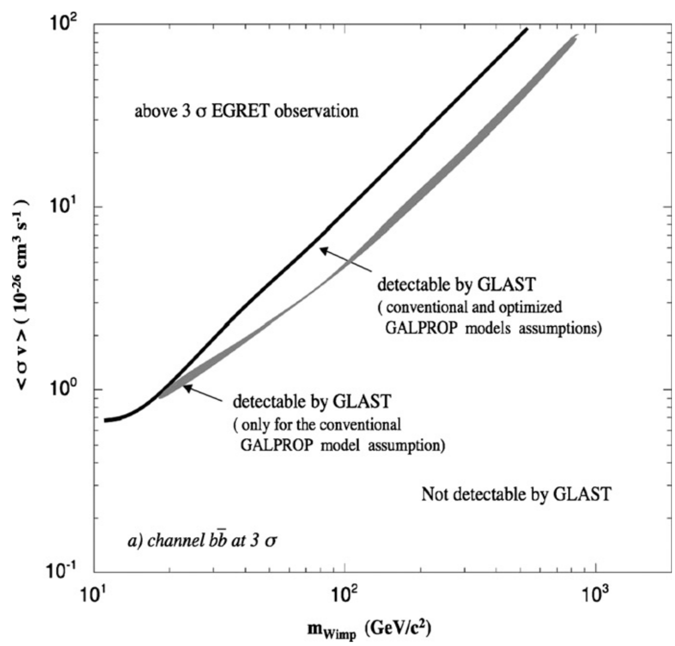

Fig. 4. The Fermi Gamma Ray Satellite sensitivity for DM indirect searches was investigated in Ref. [18]. For the GC the DM mass was considered between 10 and 1000 GeV, while the $\langle\sigma v\rangle$ parameter between 0.5 and $100 \times 10^{26}\,\mathrm{cm^3\,s^1}$. The Galactic diffuse emission (both conventional and optimized GALPROP models) was assumed as background, while the sources were not included as background, and a χ^2 analysis was applied. In Fig. 3 is reported the region of the $\langle\sigma v\rangle$ vs. DM mass plane which can be sampled with Fermi/LAT in 5 years, with the observations of the Galactic Center. For this plot a pure $b\overline{b}$ annihilation channel and a NFW spatial distribution are assumed.

Table 1
Sources of the Fermi Bright Sources List, with $-5^\circ < l < 5^\circ$ and $-5^\circ < b < 5^\circ$.

Source 0FGL id	l (deg)	b (deg)	Θ_{95} (deg)	Int.Flux ($1 < E < 100$ GeV) ($10^{-8}\,\mathrm{cm^{-2}\,s^{-1}}$)
J1732.8-3135	356.287	0.920	0.087	3.89 ± 0.33
J1741.4-3046	357.959	−0.189	0.197	2.00 ± 0.31
J1746.0-2900	359.988	−0.111	0.068	7.92 ± 0.47

The source identifier, the galactic longitude and latitude, the radius of the 95% source location confidence region and the integral flux between 1 and 100 GeV are reported. The Bright Sources were detected with a statistical significance above 10σ in 3 months. 0FGL J1746.0-2900 is likely associated to 3EG J1746-2851, an unidentified EGRET source, close to SgrA*, with a flux $F(E > 100\,\mathrm{MeV}) = (118.6 \pm 73) \times 10^8\,\mathrm{cm^2\,s^1}$. 0FGL J1746.0-2900 was reported to be marginally variable in Ref. [20], but this result was not confirmed with a larger statistics. The TeV source in the Galactic Center (HESS J1745-290), a bright source above 100 GeV, is notably located near 0FGL J1746.0-2900. The identification of the TeV gamma ray source is still pending. Furthermore the H.E.S.S. collaboration reported also *diffuse* very high energy gamma ray emission from the central part of the Galactic Ridge.

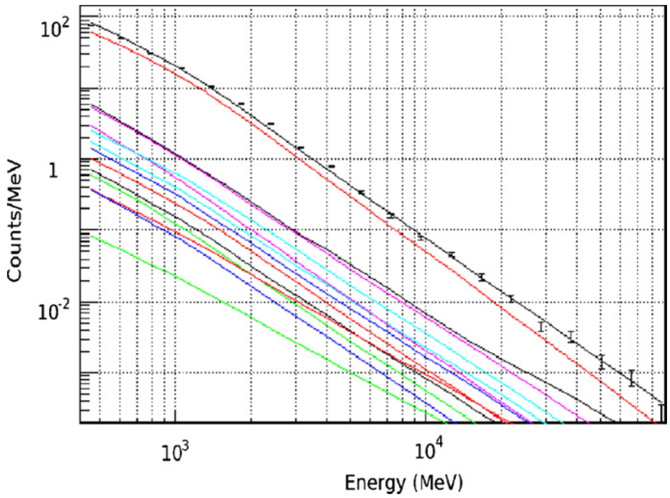

Fig. 5. Spectra from the likelihood analysis of the Fermi/LAT data (number of counts vs. reconstructed energy). The likelihood analysis is the standard one used with the LAT data. The main analysis steps are: (1) to select data of high quality (selection cuts on events energy, zenith angle, reconstruction and classification quality); (2) to build a emission model of the region, based on the previous knowledge and experimental evidence of new excesses with enough statistical significance; (3) to apply the likelihood analysis to the data and the considered model. For each model component a fit of the free parameters and the computation the statistical significance is obtained. Here in the plot, from above to below: the black point are the observed data; the black line is the sum of all the components; the red line is the Galactic diffuse emission; the lower black line is the isotropic extragalactic; other components are the sources detected. These results are preliminary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

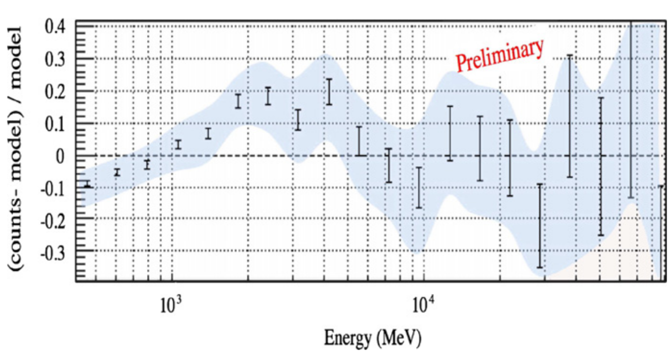

Fig. 6. Residuals ((exp.data – model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area. These results are preliminary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

should be considered in interpreting the residual spectrum in Fig. 6.

5. Conclusions

We have reported a preliminary analysis of the Fermi/LAT observations of the Galactic Center. This analysis was focused on the indirect search for Dark Matter. From this preliminary analysis the following conclusion are obtained:

- Any attempt to disentangle a potential dark matter signal from the galactic center region requires deep understanding of the conventional astrophysics background.
- The bulk of the gamma ray emission from the GC region is explained with the detected sources and the Galactic Diffuse emission model, but ……
- a residual gamma ray emission is left, not accounted for by the above models.

Improved modelling 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.

Acknowledgments

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