IL NUOVO CIMENTO Vol. 34 C, N. 3 Maggio-Giugno 2011
DOI 10.1393/ncc/i2011-10896-7

Colloquia: Scineghe2010

The indirect search for Dark Matter from the centre of the Galaxy with the Fermi LAT

A. Morselli, B. Cañadas and V. Vitale
on behalf of the Fermi-LAT Collaboration

INFN, Sezione Tor Vergata - Rome, Italy

(ricevuto il 25 Febbraio 2011; pubblicato online l'1 Giugno 2011)

Summary. — Dark Matter (DM) constitutes around a 25% of the Universe, while baryons only a 4%. DM can be reasonably assumed to be made of particles, and many theories (Super-symmetry, Universal Extra Dimensions, etc.) predict Weakly Interacting Massive Particles (WIMPs) as natural DM candidates at the weak scale. Self-annihilation (or decay) of WIMPs might produce secondary γ-rays, via hadronization or as final state radiation. Since its launch in the 2008, the Large Area Telescope on-board of the *Fermi* γ-ray Space Telescope has detected the largest amount of γ-rays to date, in the 20 MeV 300 GeV energy range, allowing to perform a very sensitive indirect experimental search for DM (by means of high-energy γ-rays). DM forms large gravitationally bounded structures, the halos, which can host entire galaxies, such as the Milky Way. The DM distribution in the central part of the halos is not experimentally known, despite a very large density enhancement might be present. As secondary γ-rays production is very sensitive to WIMP density, a very effective search can be performed from the regions where the largest density is expected. Therefore the information provided by the DM halo N-body simulations is crucial. The largest γ-ray signal from DM annihilation is expected from the centre of the Galaxy. In the same region a large γ-ray background is produced by bright discrete sources and the cosmic rays interacting with the interstellar gas and the photons fields. Here we report an update of the indirect search for DM from the Galactic Center (GC).

PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS 95.30.Cq – Elementary particle processes.
PACS 95.55.Ka – X- and γ-ray telescopes and instrumentation.

1. – The Large Area Telescope on-board of *Fermi*

The *Fermi* γ-ray Space Telescope (*Fermi*) was launched on June 11, 2008 and began operations on August 11, 2008. The observatory carries two instruments for the study of γ-ray emission from astrophysical sources: the Large Area Telescope (LAT) and the γ-ray Burst Monitor (GBM). LAT is the primary instrument and is a pair-conversion telescope. It is composed of a 4×4 array of equal modules (towers) and surrounded by a segmented anti-coincidence detector (ACD). Each tower is made of a precision silicon-strip tracker (36 layers arranged in 18 X-Y pairs alternating with W converter layers) and a calorimeter. The calorimeter is a hodoscopic configuration of 8.6 radiation lengths (X_0) of CsI crystals that allows imaging of the shower development in the calorimeter and thereby corrections of the energy estimate for the shower leakage fluctuations out of the calorimeter. The total thickness of the tracker and calorimeter is approximately 10 X_0 (1.5 X_0 for the tracker and $8.6 X_0$ for the calorimeter) at normal incidence. The ACD covers the tracker array, and a programmable trigger and data acquisition system uses prompt signals available from the tracker, calorimeter and ACD to form a trigger that initiates readout of these three subsystems. The on-board trigger is optimized for rejecting events triggered by cosmic-ray background particles while maximizing the number of events triggered by γ-rays, which are transmitted to the ground for further processing. The second instrument is the γ-ray Burst Monitor (GBM), which is a detector covering the 8 keV–40 MeV energy range, devoted to the study of the γ-ray Bursts. GBM complements the LAT for observations of high-energy transients. The GBM consists of two sets of six low-energy (8 keV to 1 MeV) NaI(Tl) detectors and a high-energy (0.2 to 40 MeV) BGO detector. Detailed descriptions of the *Fermi* observatory can be found in [1] and the LAT on-orbit calibration is reported in [2].

During the first two years, *Fermi* operations have been mainly performed in the so-called "scanning" mode, with which the sky exposure is almost uniform. For autonomous repoints or for other targets of opportunity, the observatory can be inertially pointed.

The Large Area Telescope has an effective area five times larger, a much better angular resolution, and a sensitivity more than 10 times better than its predecessor EGRET. The *Fermi*-LAT Collaboration has already detected thousands of high energy γ-ray sources [3] and has carried out the study of several scientific objectives during the first two years of operations. These studies span many topics of astrophysics and fundamental physics. Among the galactic sources Globular Clusters, Supernova Remnants, Binary Sources as well as a large number of pulsars have been detected and studied. The Galactic diffuse emission has also been investigated. Regarding the extragalactic sources, hundreds of Blazars and Active Galaxies, some Radio Galaxies, the Large Magellanic Cloud and a couple of Starburst Galaxies have been detected. The nature of the extragalactic γ-ray background has been studied. High energy γ-ray emission associated with γ-ray bursts has also been detected as well as local γ-ray sources (Earth, Sun and the Moon).

One of the major scientific objectives of the LAT is the indirect search for DM, by means of the production of secondary γ-rays after the annihilation (or decay) of the DM particle candidates. The search strategy, which was assessed with a detailed study [4], comprises the study of targets with an expected relatively large γ-ray signal (such as the Galactic Center, which was previously studied with EGRET data [5]), or with a very low foreseen conventional γ-ray emission [6], the search for annihilation lines [7] and also the search of possible anisotropies generated by the DM halo substructures [8]. The indirect DM searches with γ-rays are complemented with those performed with the detection of cosmic-ray electrons by the LAT [9, 10]. In the next sections we provide an introduction on the indirect search for DM signal form the GC and an update of the results obtained so far by the *Fermi*-LAT Collaboration on this target.

2. – The indirect search for DM with high energy γ-rays

In models in which DM is characterized by weak-scale interaction cross-sections (WIMP DM), DM particles can produce a gamma-ray signal by pair annihilation. As

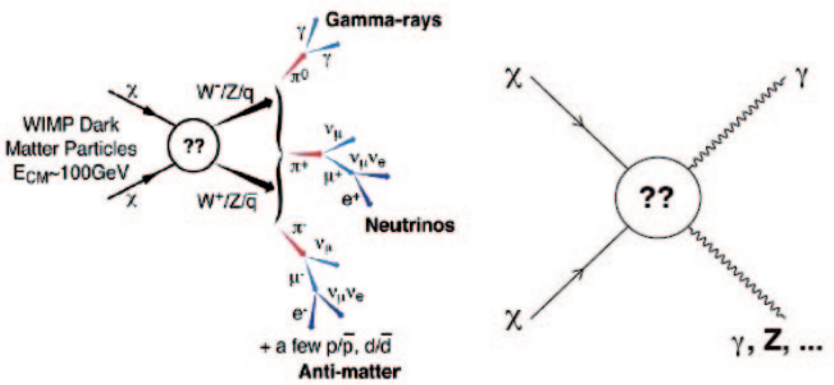

Fig. 1. – Schematic view from ref. [4] of how gamma rays and other secondary particles can be produced by WIMP annihilation. On the left figure the production of a continuum spectrum is illustrated, whereas on the right the production of monochromatic lines is shown.

shown in fig. 1, this signal can be either a monochromatic line if WIMPS annihilate directly into photons, or a continuum spectrum if they annihilate into a pair of intermediate particles ($q\bar{q}, W^+W^-, l^+l^-$) which would subsequently produce gamma rays. The former process is in general suppressed by around two orders of magnitude with respect to the latter. The differential gamma-ray flux from WIMP annihilation coming from a given direction in the sky (θ, ϕ) and from a given solid angle $\Delta\Omega$ is

$$(1)\qquad \frac{\mathrm{d}\Phi}{\mathrm{d}E} = \sum_i \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m^2_{\mathrm{WIMP}}} br_i \frac{\mathrm{d}N_i}{\mathrm{d}E} \int_{los,\Delta\Omega} \rho^2(l, \theta, \phi) \mathrm{d}l \mathrm{d}\Omega,$$

which can be factorized in two parts:

a) Particle-physics–related terms: the thermally averaged annihilation cross-section $\langle \sigma v \rangle$, the mass of the WIMP m_{WIMP} and the branching ratio br_i for annihilation through the particular channel i depend on the theory by which the WIMP is predicted. The photon yield per WIMP annihilation $\mathrm{d}N_i/\mathrm{d}E$, depends on the annihilation channel we are considering, and on the mass of the WIMP. Figure 2 shows the differential yields for different WIMP masses and for two annihilation channels, namely the $b\bar{b}$ and $\tau^+\tau^-$ channels, which are strongly motivated by supersymmetry.

b) Astrophysics-related term: the integral of the squared DM density along the line of sight depends uniquely on the DM distribution. Usually it is expressed in terms of the factor $J(\theta, \phi, \Delta\Omega)$, which is defined as

$$(2)\qquad J(\theta, \phi, \Delta\Omega) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV\,cm^{-3}}} \right)^2 \int_{los,\Delta\Omega} \rho^2(l, \theta\phi) \mathrm{d}l \mathrm{d}\Omega.$$

The strategies and design of instruments for direct and indirect DM searches must lie on some theoretical assumptions. These assumptions are related to both the intrinsic nature of DM, and the interactions it is subjected to (particle-physics–related terms in eq. (1)), and also to how it is distributed in the Universe (astrophysics-related term). Regarding the latter issue, numerical cosmological simulations have proven to be

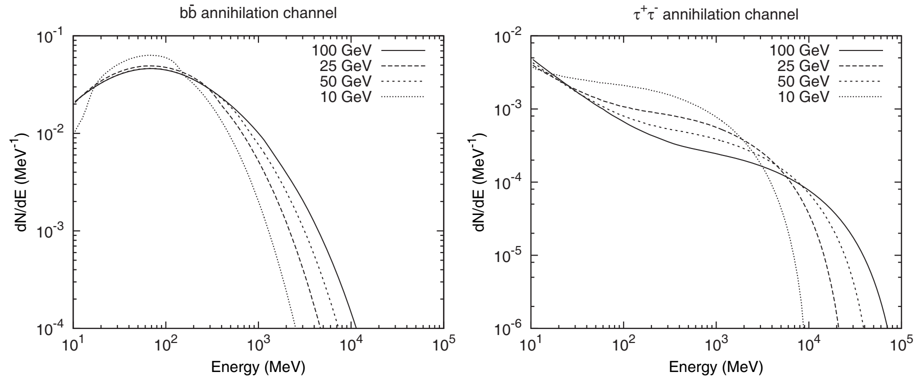

Fig. 2. – Differential photon yield per DM annihilation. In the left panel, we represent annihilation into $b\bar{b}$, and in the right panel annihilation into $\tau^+\tau^-$. These yields have been calculated using the DarkSUSY code [11].

a fundamental tool in the study of DM. Being weakly interacting, DM can be very well approximated by a collisionless fluid, its dynamics being driven only by the gravitational interaction. However, high non-linearity makes it impossible to study analytically its dynamics and the evolution of its distribution, and numerical simulations become essential. These have shown that large amounts of DM accumulate in the center of galactic halos. The center of our galaxy is therefore the closest and brightest source of gamma rays coming from annihilating DM and a very promising target for DM searches. Over the last years, the development of new numerical algorithms and simulation codes together with the rapid progress in computer technology have permitted to increase the resolution of cosmological simulations by several orders of magnitude and to produce some of the current state-of-the-art cosmological simulations, such as Via Lactea [12], GHALO [13] or Aquarius [14]. These confirm that the inner density profiles of halos are well fitted by functions which are steeper and cuspier than the traditionally used Navarro Frenk and White profile [15]. However, moving yet further towards the center of the halos, predictions on the dark matter and total mass distribution require a realistic treatment of the baryons and their dynamical interactions with the DM. Indeed, the presence of baryons and the physical processes in which they are involved, dramatically affect the distribution of DM in galaxies. In particular, the DM density profiles can steepen through the adiabatic contraction due to dissipating baryons. This adiabatic contraction can be implemented analytically within halo models obtained in collisionless DM simulations, or one can attempt to include baryons in numerical simulations, as done, *e.g.*, within the CLUES project [16]. However, there is still a large uncertainty on how baryons affect the distribution of DM in the center of our galaxy, which needs to be taken into account when trying to disentangle a DM signal from the galactic center.

3. – Results on indirect search from the Galactic Center

A preliminary analysis of first 11 months of *Fermi*-LAT observations (August 2008-July 2009) is reported. A binned likelihood analysis was performed with the analysis software developed by the *Fermi*-LAT Collaboration (gtlike, from the *Fermi* analysis tools [17]). The P6_v3 version of the Instrument Response Functions and event classification was used. For this analysis a region of interest (RoI) of $7^\circ \times 7^\circ$ was considered in

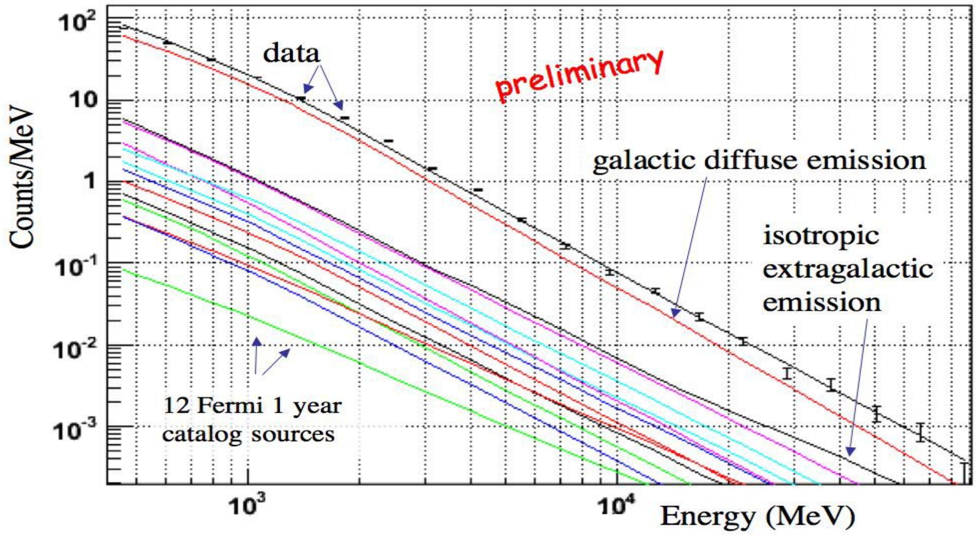

Fig. 3. – Spectra from the likelihood analysis of the *Fermi*-LAT data (number of counts *vs.* reconstructed energy) in a $7^\circ \times 7^\circ$ region around the Galactic Center (number of counts *vs.* reconstructed energy).

order to minimize the diffuse backgrounds contributions. The RoI was centered at the Galactic Center position at RA $= 266.46^\circ$, Dec $= -28.97^\circ$. The events were selected to have an energy between 400 MeV and 100 GeV, to be of the "diffuse" class (high-purity sample) and to have converted in the *front* part of the tracker. The selection conditions provided us with events with very well reconstructed incoming direction. Data have been binned into a 100×100 bins map for the subsequent likelihood analysis. In order to perform maximum-likelihood analysis of the data, a model of the already known sources and the diffuse background should be built. The used model is made of 11 sources from the *Fermi* 1 year catalog [3] which are located within or very close to the considered region being analyzed. These sources have a point-like spatial model and a power-law spectrum in the form of a power law. The model also contains the diffuse γ-ray background which is made of two components: 1) the *Galactic Diffuse γ-ray background* was modeled by means of the GALPROP code (model number 87XexphS) [18] and [19]; 2) the *Isotropic*

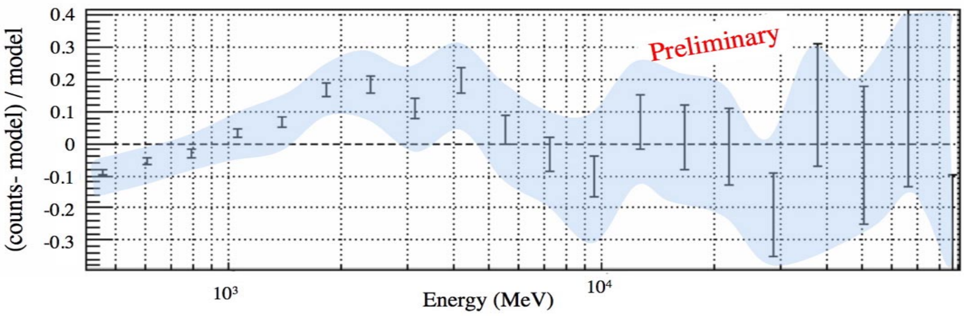

Fig. 4. – (Colour on-line) Residuals ((exp.data - model)/model) of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

Background was modeled as an isotropic emission with a template spectrum and should account for both the extragalactic γ-ray emission and residual charged particles in the data sample. The results of the likelihood analysis are shown in figs. 3 and 4, for further details see [20]. The diffuse γ-ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected γ-ray emission from the Galactic Center. Nevertheless a residual 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.

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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 Foundation, 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.

REFERENCES

[1] Atwood W. B. *et al.* (*Fermi* Collaboration), *Astrophys. J.*, **697** (2009) 1071 [arXiv:0902.1089].
[2] Abdo A. A. *et al.* (*Fermi* Collaboration), *Astropart. Phys.*, **32** (2009) 193 [arXiv:0904.2226].
[3] Abdo A. A. *et al.* (*Fermi* Collaboration), *Astrophys. J. Suppl. Ser.*, **188** (2010) 405 [arXiv:1002.2280].
[4] Baltz E. *et al.*, *J. Cosmol. Astropart. Phys.*, **07** (2008) 013.
[5] Cesarini A., Fucito F., Lionetto A., Morselli A. and Ullio P., *Astropart. Phys.*, **21** (2004) 267 [astro-ph/0305075].
[6] Abdo A. A. *et al.* (*Fermi* Collaboration), *Astrophys. J.*, **712** (2010) 147 [arXiv:1001.4531].
[7] Abdo A. A. *et al.* (*Fermi* Collaboration), *Phys. Rev. Lett.*, **104** (2010) 091302 [arXiv:1001.4836].
[8] Siegal-Gaskins J. M., *J. Cosmol. Astropart. Phys.*, **10** (2008) 040.
[9] Abdo A. A. *et al.* (*Fermi* Collaboration), *Phys. Rev. Lett.*, **102** (2009) 181101 [arXiv:0905.0025].
[10] Ackermann M. *et al.* (*Fermi* Collaboration), *Phys. Rev. D*, **82** (2010) 092004 [arXiv:1008.3999].
[11] Gondolo P., Edsjo J., Ullio P., Bergstrom L., Schelke M. and Baltz E. A., *J. Cosmol. Astropart. Phys.*, **07** (2004) 008.
[12] Diemand J. *et al.*, *Nature*, **454** (2008) 735 [arXiv:0805.1244].
[13] Stadel J. *et al.*, *Mon. Not. R. Astron. Soc. Lett.*, **398** (2008) L21 [arXiv:0808.2981].
[14] Springel V. *et al.*, *Mon. Not. R. Astron. Soc.*, **391** (2008) 1685 [arXiv:0809.0898].
[15] Navarro J. F., Frenk C. S. and White S. D. M., *Astrophys. J.*, **462** (1996) 563 [arXiv:astro-ph/9508025].
[16] `http://www.clues-project.org`.
[17] `http://Fermi.gsfc.nasa.gov/ssc/data/analysis/software/`.
[18] Strong A. *et al.*, *Astrophys. J.*, **613** (2004) 962S.
[19] Strong A. *et al.*, *Annu. Rev. Nucl. Part. Sci.*, **57** (2007) 285.
[20] Vitale V. and Morselli A. (for the *Fermi*-LAT Collaboration), *2009 Fermi Symposium* [arXiv:0912.3828].