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New results from Fermi

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Summary. — With more than one billion photons from the whole sky, accumulated in the 100 MeV–100 GeV band since 2008, the Fermi Large Area Telescope offers the most precious vault for high-energy gamma-ray astrophysics. This unique database was used to study thousands of gamma-ray sources of very different nature, from our own Galaxy to distant and active galactic nuclei. Leveraging the excellent stability of the Large Area Telescope detectors, which operate with no performance degradation since launch, and on improved event analyses that extend the LAT sensitivity below 100 MeV and up to the TeV regime with improved resolution, the Fermi Observatory can operate for many more years to respond to fundamental questions of modern particle astrophysics.

1. – Gamma-ray astrophysics and the Fermi observatory

1˙1. *Instruments for gamma-ray observations.* – The relevance of gamma rays for answering fundamental questions about Cosmic Rays (CR) origin and particle acceleration mechanisms was realized already by Enrico Fermi in the 1940s. But the first observation of cosmic gamma-rays appeared much later, after pioneering satellite instruments overcame the problem of the opacity of the Earth's atmosphere to photons above a few MeV, which produces pairs of electrons and positrons.

This same physical interaction is the basis of the pair-conversion telescope concept, that starting with the SAS-2 [1] and COS-B [2] missions allowed direction reconstruction of the incoming gamma rays, therefore directly imaging sources and opening the way to the study of CR production sites.

A pair-conversion telescope detects gamma-rays in a tracker-converter subsystem (TKR), where the pair is produced and tracked. A calorimeter (CAL) subsystem measures the event energy to complete the kinematical event reconstruction, while an anti-coincidence detector (ACD) surrounding the telescope suppresses the background of charged cosmic rays.

EGRET on board CGRO [3] was the first large scale gamma-ray observatory to perform a full sky survey.

The Fermi Large Area Telescope (LAT) develops the pair-conversion design to full maturity, thanks to technological advances that make the LAT unique and allow a performance improvement of more than an order of magnitude with respect to any previous mission:

- *Solid state sensors* offer fast, high resolution, high efficiency detections of point-space coordinates and energy deposits of particles crossing the telescope, with no consumable and very compact design, well suited for the limited space available on satellites. The LAT TKR subsystem, for example, is a densely packed vertical stack of 36 planes of silicon strip sensors, with $73\,\mathrm{m}^2$ of active surface and 900 k channels, and features a very low aspect ratio which results into an impressive 2.4 sr Field of View (FOV), enabling the LAT to cover $\sim 20\%$ of the sky at any time and observe any sky position for ~ 30 minutes every ~ 3 hours in sky-survey operation mode.

- *Segmented detectors*, thanks to a large number of channels, can finely image the complex development of particle interactions inside the telescope. The LAT CAL subsystem, for example, is a hodoscope of 16 units of 12 by 8 CsI crystals which copes with the mass limitations imposed by the rocket by having a maximum vertical depth of 8.6 total radiation lengths, but features an energy resolution better than 30% up to 3 TeV thanks to its capability of a full 3D reconstruction of EM showers.

- High performance, low-power on-board *computers* and *electronics* allow the implementation of flexible, redundant, multiple software trigger levels on the satellite. For example, all the LAT detectors are self-triggering, up to rates $\sim 10\,\mathrm{KHz}$, and the onboard processor can dynamically match the downlink rate to the available bandwidth by selecting either charged particles or gamma rays, typically by tagging signals in the outer ACD tiles pointed to by the tracks reconstructed with the on-board software.

The LAT is sensitive to gamma rays above $\sim 20\,\mathrm{MeV}$, with unparalleled high efficiency and resolution provided by the combination of the telescope design and the ground event reconstruction [4]. Its effective area is $\sim 9000\,\mathrm{cm}^2$, roughly flat above 1 GeV and up to $\sim 1\,\mathrm{TeV}$, rapidly decreasing by a factor of 3 at 100 MeV. The LAT angular resolution is a strong function of the energy of the incoming photon, as a consequence of the Multiple Scattering (MS) determined by the stack of converters interleaved with the silicon planes in the tracker. It follows the typical MS $1/E$ behavior starting from $\sim 0.6°$ at 100 MeV and getting down to a flat value of 0.1° at $\sim 10\,\mathrm{GeV}$, determined by the TKR geometry (strip pitch over lever arm). The energy resolution of the LAT is also a strong function of the energy, with a best performance at the level of 7%–10% between 1 GeV and 800 GeV and values of the 68% containment of the reconstucted energy always below 30% up to 3 TeV. Below 1 GeV, energy losses in the TKR are important and their estimate is poor because of the digital readout of the TKR. Around 1 TeV, the peak of the shower development is out of the telescope, and 3D shower reconstruction becomes harder, particularly since the fraction of crystals saturating in the CAL rapidly increases above 1 TeV.

The large energy range sampled by the LAT is home to extraordinarily violent phenomena in the Universe, happening at the core of a vast class of different sources in extreme conditions, like magnetic fields and density of matter. Gamma rays from such sources can track the morphology of the parent source and the surrounding material, therefore revealing regions and mechanisms of CR acceleration. GeV gamma rays travel cosmological distances, providing a deep view of the Universe and probing the intervening medium between the source and the observers through their interactions.

1˙2. *Operations context.* – The LAT is the main instrument onboard the Fermi Gamma-ray Space Telescope, an observatory flying on a dedicated NASA satellite since 2008. Fermi data are made publicly available in real time, within hours from the onboard trigger needed to downlink and process the data.

Fermi entered the phase of *extended operations* in 2013, after the first five years of design operations, and is now subjected to bi-yearly competitive NASA Senior Reviews to continue operating [5].

Both the LAT and the all-sky detector Gamma-ray Burst Monitor (GBM), that catches transient emissions of photons with energies between 8 KeV and 40 MeV, perform very stably and have no consumable, and can therefore sustain extended operations for many more years. Furthermore, the LAT collaboration has recently released an improved event analysis package, called Pass 8, that greatly boosts the sensitivity of the telescope, as well as offering opportunities for selections of statistically significant subsamples of events with optimal angular and energy resolution. All archival data have been reprocessed with Pass 8 and new data are routinely processed and served with the new software since June 2015.

Recently, opportunities for *multi-wavelength* and *multi-messenger* observations concurrent with Fermi have flourished, making the scientific case for long term operations of Fermi beyond 2018 even more compelling. Synergies are expected from the continuing and upcoming operations of many diverse and complementary observatories:

- *Cosmic ray* observatories covering many orders of magnitudes in energy, from space instruments like AMS-02, CALET and DAMPE, reaching $\sim 10^{14}$ eV, to ground arrays for extended showers reaching Ultra High Energies of $\sim 10^{20}$ eV with Auger.

- *Neutrino* detectors for high energy astrophyisical events, like the running IceCube installation at the South Pole and upcoming Km3Net under the Mediterranean Sea, that together will cover both hemispheres.

- *Gravitational wave* interferometers, like LIGO and Virgo, which recently opened the ground to gravitational wave astronomy and the search for associated electromagnetic emissions.

- *Electro-magnetic* telescopes at other frequencies, like large, high sensitive arrays of radio detectors like SKA, high resolution optical surveys like DES and LSST, TeV telescopes like HAWC, LHAASO and the Imaging Cerenkov telescopes (MAGIC, VERITAS, HESS and the future CTA).

The scientific impact of combined observations from these many observatories would have far reaching consequences both in the astrophysics of time-domain, with detection of short transients like AGN flares or gamma ray bursts, and in the field of astroparticle physics, with identification of CR production sites, constraints on the particle nature of Dark Matter, and studies of the properties of gravity around black holes.

2. – Fermi highlights today and tomorrow

2˙1. *The gamma-ray sky*. – The ultimate goal of the Fermi observatory is to explain the physics behind the high energy Universe through its gamma-ray map. Our observations provide the energy and the coordinates of each photon, but cannot measure the distance of the parent source. The Fermi skymap is therefore a projection of all sources of gamma rays along the line of sight. Based on our knowledge of the astrophysics of the source and of the interactions of photons, we model the gamma-ray sky as the overlap of four components:

- *Point sources*: these are clustered photons that reach a significance of 5σ against the background; due to the poor angular resolution below ~ 1 GeV and its complex dependence on the energy, assigning each photon to a given source requires a convolution of the LAT Instrument Response Functions (IRFs) with of a model of the sky. The background is also the result of a complex modeling, as it includes the three components described below.

- *Diffuse Galactic Emission (DGE)*: the galactic plane shines in gamma rays from the interactions of CRs with the interstellar medium and fields, which produce high energy photons via *p*-*p* collisions (and subsequent production of π^0 decaying into $\gamma\gamma$), *bremmstrahlung* and synchrotron emissions from high energy electrons, Inverse Compton scattering of high-energy electrons onto lower-energy photons of the Cosmic Microwave Background (CMB) or starlight. The first two components map the distribution of gas and clouds in the Galaxy, the latter two probe the shape and intensity of magnetic fields and the distribution of dim fossil light from early stages of the formation of the Universe [6].

- *Isotropic emission*: this is by definition a signal component with no spatial information, and it results from the combination of residual hadronic backgrounds crossing the LAT as well as an isotropic glow of gamma rays. This results from the combination of the collective emission of sources below detection threshold, and unmodelled contributions.

- *Unknown contributions*: any residual isotropic emission not included above, typically of unknown nature like Cosmological Dark Matter (DM) or relic gamma rays from the early Universe.

Some of the most exciting Fermi results fit naturally in this breakout of the gamma-ray sky, and the science highlights reviewed below are indeed examples of these four components.

2˙2. *Catalogs*. – The list of steady sources detected by the LAT is an important outcome of the Fermi Collaboration activity. It is the starting point for modeling the gamma-ray emissions of different types of sources, for computing fluxes of known sources when analyzing specific areas and times of interest in the sky, and for estimating contributions to the gamma-ray sky from unresolved populations of sources.

The LAT catalogs are periodically updated with the most recent statistics and incorporate our best knowledge of the telescope performance and of the contributions from diffuse emission.

The most comprehensive search for sources in the Fermi LAT data between 100 MeV and 300 GeV is the Third Fermi source Catalog (3FGL [7]), which detected more than

3000 sources of different nature in four years of data. About a third of these sources are still unidentified and not associated to known counterparts at other wavelengths. Despite the limited angular resolution of the LAT, most of these could be associated using new observations to be taken at other wavelengths. Since we do expect to find unknown gamma-ray source types, as for the newly discovered class of Galactic Novae [8], continuous efforts for reducing the population of Unidentified sources are indeed important, although challenging.

The large photon statistics now available allows development of specific source population catalogs. Particularly important are catalogs of:

- *Pulsars* [9]: this is the most numerous population of galactic sources, now surpassing 200 in number; an important class is that of pulsars with period in the millisecond range, often found after followup radio observations of unidentified LAT sources, that are important for searching low frequency gravitational waves in the $\sim$ ns to $\sim$ microsec frequency range through Pulsar Timing Arrays (PTA).

- *Supernova remnants* [10]: SNR detection requires a systematic study of effects of modeling diffuse emission, given their location on the galactic plane, and their extension; this study now provides the first statistically significant sample of SNR of different size, extension and age based on three years of data. Prospects for resolving complex morphologies and perform spatially resolved spectral studies of some SNR are becoming a real opportunity with the advent of Pass 8.

- *Hard sources above 50 GeV (2FHL* [11]*)*: based on a full 80 months dataset and the enhanced acceptance of Pass 8, this effort is currently the most sensitive investigation of high-energy gamma-ray sources, and complements other Fermi catalogs at lower energies and surveys by Cerenkov telescopes at higher energy. With 360 detections, we can now for the first time characterize gamma-ray emissions in the 100 GeV domain for a large number of sources, measure the high energy spectra of both galactic and extra-galactic sources, spectrally resolve extended galactic sources like the SNR IC443, perform joint spectral measurements of H.E.S.S. sources and provide a list of candidate sources for observations with current and future IACTs (see fig. 1).

2˙3. *Galactic Center excess.* – We understand very well the physical processes behind the production of celestial gamma rays. By folding them with our knowledge of the relevant astrophysical properties of the Galaxy (*e.g.* CR source spectra and distribution, galactic halo size, gas and field maps), we can build models that fit the whole-sky diffuse emission with good accuracy [6]. On the other hand, gamma-ray data leave a considerable degeneracy in the model parameters describing CR interactions and propagations, and fractional residuals from the best all-sky fits are found in several regions at the level of a few and up to $\sim 30\%$ [13].

A particularly important residual is the so called Galactic Center (GC) excess. Several authors have independently measured a significant emission of GeV gamma rays with an azimuthally symmetric morphology peaked at $\sim 2^\circ$ from the center of the Galaxy (see fig. 2). While it is difficult to absorb this emission into all-sky diffuse models, it is fairly straightforward to fit such excess with a standard distribution of WIMPs of ~ 8 GeV mass at the GC, annihilating into $b\bar{b}$ quarks with a thermal relic cross section (see [14, 15] and references therein).

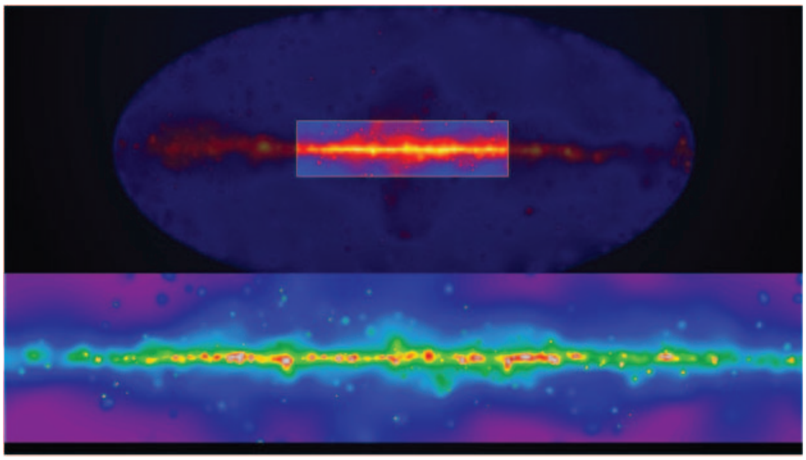

Fig. 1. – Fermi gamma-ray sky map above 50 GeV. The inset shows the sources in the highlighted region along the Galactic plane [11]. Many of these sources are in common with those detected during the multi-year H.E.S.S. program Galactic Plane Survey [12], which detects sources above 100 GeV, but many of them are different, pointing to a large variety of sources with different spectra to be investigated with joint GeV–TeV observations.

However, the existence of similar fractional residuals in other areas of the sky, our incomplete knowledge of the sources and fields along the line of sight to the GC, and the existence of viable astrophysical models fitting well the excess, like a population of unresolved millisecond pulsars in the Galaxy, or unconventional assumptions on the CR distribution, raise the question of how robust a DM interpretation of the GC excess is.

The availability of other targets in the sky where Fermi can cross-check the same DM hypothesis with different analysis methods is therefore extremely convenient.

2˙4. *Isotropic emissions*. – Modeling the contribution of unresolved sources to the isotropic flux of gamma-rays (IGRB) is an iterative effort that benefits from advances on source population studies [16, 17]. The recent catalog of high energy sources [11] allows

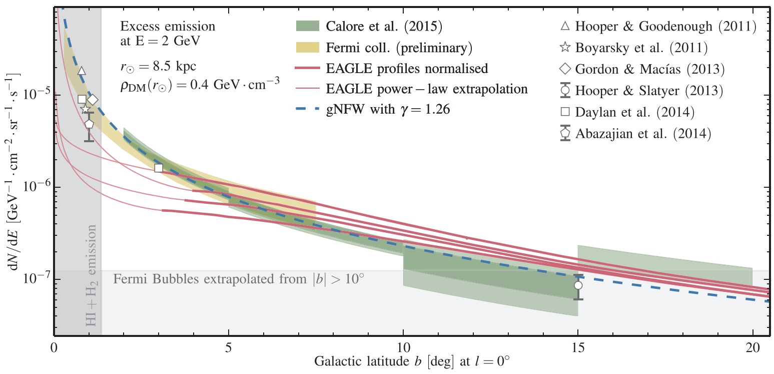

Fig. 2. – Radial intensity of the excess gamma-ray emission from the Galactic center as measured in Fermi data by various authors [15].

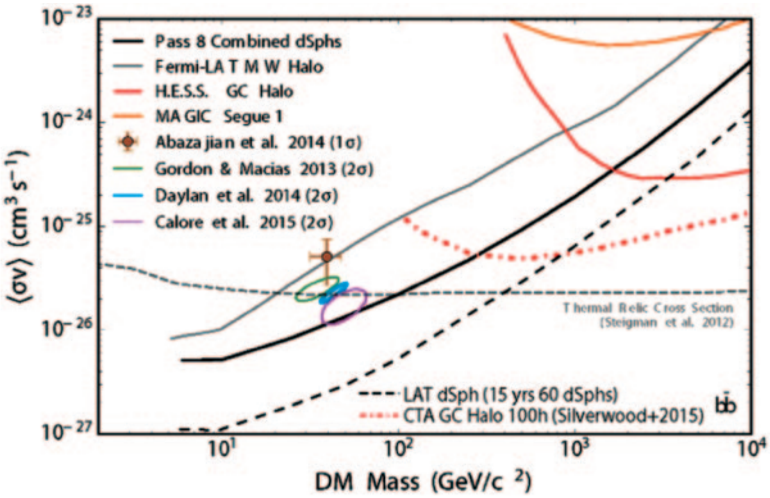

Fig. 3. – Exclusion plot for WIMP DM candidates from search of gamma-rays from dwarfs (lines) and the Galactic centre (circled colored areas)—see [15] for details.

a further improvement in the estimate of the contribution of hard sources to the IGRB, which we now constrain to be $85^{+16}_{-14}\%$ of the total IGRB, further reducing the phase space for DM contributions [18].

An interesting example of isotropic emission not related to photons, with potential implications for searches of DM, is the inclusive spectrum of Cosmic Ray Electrons (CRE). The LAT does in fact detect electron-initiated showers, with an acceptance higher than that for photons above $\sim 20\,\text{GeV}$. Previous LAT measurements of the CRE spectrum indicated a single power law spectral component between 7 GeV and 1 TeV [19], with a harder than expected index that can be interpreted as the signature of a local component of either astrophysical or DM origin [20]. Upcoming results with Pass 8 will extend the spectral measurement up to 2 TeV, challenging direct measurements from CR observatories and for the first time closing the gap with TeV measurements from ground Čerenkov telescopes.

2·5. *Dark Matter searches in dwarf spheroidals.* – These DM dominated systems represent an optimal target for searches of gamma-ray DM signatures. They are in fact point sources mostly located away from the Galactic Plane, where contributions from the diffuse emission is small, and no astrophysical emission is known to exist. Upper limits to their gamma-ray flux are computed with small systematic uncertainties, and are directly converted into a limit into the mass *vs.* cross-section phase space for candidate WIMPs.

Figure 3 shows the current best limits from an ensemble of 25 dwarfs, and prospects for updates in the next years based on the assumptions of a 15 years dataset and reasonable expectations on the additional number of new dwarfs expected from upcoming surveys. Based on these assumptions, Fermi will be able to either exclude WIMPs up to $\sim 400\,\text{GeV}$, or find evidence of DM below that energy, and reject / confirm the hypothesis that the GC excess is due to DM annihilation. Synergies with Cerenkov telescopes, sensitive to energies above several hundreds of GeV, will become a reality.

3. – Conclusions

Fermi continues to be a reference observatory for particle astrophysics. Prospects for further advances in our knowledge of the high energy sky are boosted by the extremely stable operations of the LAT, the improved performance of the new Pass 8 event recontruction package and the enriched sinergies with other observatories available in a multi-messenger and multi-wavelength operational context.

Time-domain astrophysics, not covered in this contribution, is a major output of the Fermi science, thanks to the LAT sensitivity and large field of view, which enable efficient coverage of transients of different timescales and nature, and continous stable operations, which allow long-term observations of periodic emissions.

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REFERENCES

[1] `https://heasarc.gsfc.nasa.gov/docs/sas2/sas2.html`
[2] `http://sci.esa.int/cos-b/`
[3] `https://heasarc.gsfc.nasa.gov/docs/cgro/cgro.html`
[4] `http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.html`
[5] `http://science.nasa.gov/astrophysics/documents/`
[6] Acero F. *et al.*, *ApJ Suppl.*, **223** (2016) 26.
[7] Acero F. *et al.*, *ApJ Suppl.*, **218** (2015) 23.
[8] Ackerman M. *et al.*, *Science*, **345** (2014) 554.
[9] Ackerman M. *et al.*, *ApJ Suppl.*, **208** (2013) 17.
[10] Acero F. *et al.*, *ApJ Suppl.*, **224** (2016) 8.
[11] Ackerman M. *et al.*, *ApJ Suppl.*, **222** (2016) 5.
[12] Carrigan S. *et al.*, *33rd ICRC Proceedings*, 2013 (arXiv:1307.4690).
[13] Ackerman M. *et al.*, *ApJ*, **750** (2012) 3.
[14] Ajello M. *et al.*, *ApJ*, **819** (2016) 44.
[15] Charles E. *et al.*, *Phys. Rep.*, 2016 (arXiv:1605.02016).
[16] Ajello M. *et al.*, *ApJ*, **751** (2012) 108.
[17] Ajello M. *et al.*, *ApJL*, **850** (2015) L27.
[18] Ackermann M. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 151105, arXiv:1511.00693.
[19] Ackermann M. *et al.*, *Phys. Rev. D*, **82** (2010) 092004.
[20] Grasso D. *et al.*, *AstroPart. Phys.*, **140** (2009) 32.