

REVIEW ARTICLE

Some highlights of the first four years of the Fermi
Gamma-ray Space Telescope

Steven Ritz

Department of Physics and the SCIPP, University of California Santa Cruz, Santa Cruz, CA 95064, USA
E-mail: sritz@ucsc.edu

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The Fermi Gamma-ray Space Telescope, formerly called GLAST, measures the cosmic gamma-ray flux in the energy range 8 keV to > 300 GeV. In addition to breakthrough capabilities in energy coverage and localization, the very large field of view enables observations of 20% of the sky at any instant, and the entire sky on a timescale of a few hours. With its launch in 2008, Fermi opens a new and important window on a wide variety of phenomena, including pulsars, black holes and active galactic nuclei, gamma-ray bursts, supernova remnants and the origins of cosmic rays, and searches for hypothetical new phenomena such as particle dark matter annihilations. A brief overview and selected science highlights from the first four years are provided.

Keywords high-energy gamma-ray astrophysics, dark matter, fundamental physics tests, space-based astrophysics, space-based particle astrophysics, gamma-ray bursts, blazars, pulsars

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		1	Introduction
			The Fermi Gamma-ray Space Telescope (originally the Gamma-ray Large Area Space Telescope, GLAST) is a gamma-ray observatory with breakthrough capabilities,

made possible by a closely knit multicultural, multinational, and multiagency collaboration. In the U.S., the primary government agency is NASA, with key contributions made possible by the Department of Energy, and this close partnering of particle physicists and astrophysicists is similarly reflected in several of the other countries that made Fermi possible: Italy, Japan, France, Germany, and Sweden. There are two instruments on the Fermi observatory, the Large Area Telescope (LAT), which covers the energy range 20 MeV to > 300 GeV (with good acceptance to well above 1 TeV), and the Gamma-ray Burst Monitor (GBM), which covers the energy range 8 keV to 40 MeV. Details about the LAT and GBM and their science performance can be found in Refs. [1–4]. The observatory was launched into low earth orbit (circular orbit 565 km altitude, $\sim 25.6^\circ$ inclination) on 11 June 2008, with science operations starting on 4 August 2008. The mission has a five-year lifetime requirement, with a ten-year goal.

High-energy gamma-ray science with Fermi stands on the foundation provided by previous facilities, including SAS-II [5], COS-B [6], and EGRET [7] on the Compton Gamma-Ray Observatory. EGRET has provided much of the initial context for Fermi observations. An excellent review is given in Ref. [8]. Fermi satellite observations up to more than 300 GeV connect with ground-based observations, typically above ~ 100 GeV, with air-Cherenkov telescopes (e.g., H.E.S.S. [9], VERITAS [10], MAGIC [11], and Cangaroo [12]) and air-shower arrays such as Milagro [13] and HAWC [14]. For an overview of ground-based, very high-energy gamma-ray detectors and results see, e.g., [15, 16]. At the lower end of the LAT energy range, Fermi is joined by AGILE [17].

There have already been a number of Fermi review articles, including [18]. With more than 220 LAT team papers [20] and 44 GBM team papers [21] already published, plus many hundreds more using public data [22], it is impossible even just to list here the papers produced by Fermi. Instead, we provide selected highlights, and refer the interested reader to Ref. [19], where comprehensive links to current papers and results can be found.

1.1 Leap in capabilities and implications

One of the transformative features of the Fermi Observatory is the huge field of view (FOV), since it has a direct impact on many aspects of the mission. The LAT sees approximately 20% of the sky (~ 2.4 sr) at any instant, and the GBM sees the full sky (~ 9 sr) unocculted by the earth. Because the LAT FOV is so large, it is possible to cover the full sky with good uniformity, exposing all parts of the sky for ~ 30 minutes, every two orbits

(~ 3 hours). This *sky survey* is a great advance, enabling many science studies simultaneously, with minimal observing bias, and it has therefore been the primary observing mode for the mission so far, as described in the Operating Modes section below.

Several features immediately stand out in the LAT all-sky image, based on the first four years of data, shown in Fig. 1. At high latitudes, there is an isotropic diffuse flux of approximately 10^{-5} photons/(cm²·s·sr) above 100 MeV. The origin of this flux is not yet completely determined, though a sizable fraction can be accounted as due to unresolved, faint extragalactic sources, based on extrapolations of large source populations we can resolve with LAT data. Approximately two orders of magnitude more intense is the Galactic diffuse emission, which is primarily due to high energy hadronic cosmic rays colliding with gas, and to high energy electrons inverse Compton scattering ambient photons. Thus, the Galactic diffuse emission is a beautiful convolution of the distribution of matter and the distribution of cosmic rays. In amongst the Galactic diffuse emission reside many important types of gamma-ray sources, including pulsars, supernova remnants, novae, and possibly massive dark matter particles interacting or decaying to produce additional gamma-ray emission. The challenge is to untangle these contributions to understand each source type in detail. In other words, most Fermi science topics are deeply connected to each other. The higher latitude region (away from the Galactic plane) is dominated by extragalactic sources, including gamma-ray bursts and also a large number of active galaxies, which are thought to harbor supermassive black holes at their cores and which somehow produce very high energy charged particles in narrow jets producing gamma rays. Finally, closer to home, the sun, moon, and earth are all visible in gamma rays, primarily due to local cosmic-ray interactions. During intense solar flares, the sun manages to become a GeV-class accelerator, which is another topic for Fermi, particularly as we enter the more active portion of the solar cycle.

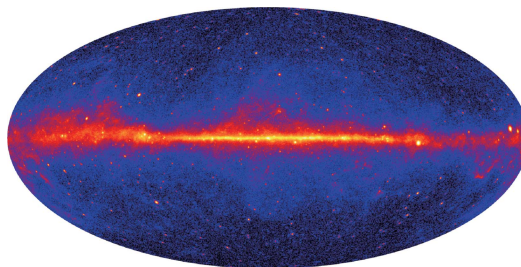


Fig. 1 The Fermi LAT sky map in Galactic coordinates showing gamma rays with energies > 1 GeV detected during the first 4 years of the mission. (From the LAT Collaboration.)

Most of these classes of objects are discussed in detail in the other papers of this Volume, so we focus here on Fermi: what we have learned, as well as anticipated progress.

Fermi covers a huge energy range – together, the GBM and LAT cover more than seven decades – and the LAT also provides excellent coverage into the largely unexplored band between 10 GeV and 100 GeV. Because the gamma-ray sky is so variable, Fermi also offers important capabilities in the time domain: the whole dynamic sky may be studied from hard-X-ray through > 300 GeV.

One of the other important characteristics of Fermi is that it draws together scientists from different fields. In particular, the cooperation between high-energy particle physicists and high-energy astrophysicists, and their respective funding agencies, has resulted in a mission with far greater capabilities than would otherwise have been possible, to the benefit of all [34]. These diverse groups have braided themselves together over time, making a very strong team. The mission has also benefitted from the activities of the Fermi Users Group [26], which provides critical links with the broad scientific community and advises the mission on all aspects affecting users.

Combined, the new capabilities of Fermi have a major impact on a broad range of science topics. Overall, Fermi science expectations [36] have been met and exceeded. Many of these topics rely heavily on multi-wavelength and/or multi-messenger observations, an area of considerable effort [35]. A pre-launch mission overview [37] categorized topics by significantly improved capability, and it is interesting to compare expectation with results:

- **Dynamic range and variability.** Fermi opens a high-energy, whole-sky aperture for transients and variable sources. The sky survey provides long-term, evenly sampled light curves of variable sources such as active galactic nuclei (AGN). The advance provided by LAT is illustrated plainly by

comparing observations by EGRET (Fig. 2) and just the early operations data from the LAT (Fig. 3, and over longer timescales in Fig. 11) of blazar 3C 454.3, a well-known radio source at $z = 0.859$. This is an illustration using a single source; the LAT sees more than 1000 AGN across the whole sky. We know that gamma-ray emission is associated with AGN jets, but where is the emission originating and what are the jet formation, composition, and propagation characteristics? Note that the sky survey sampling intervals are generally well matched to the LAT integration times of hours or longer. Also, because of the much greater sensitivity, the dynamic range of the fluxes of variable sources has been greatly expanded and made accessible over the whole sky. As of January 2013, LAT issued [30] 225 ATel alerts and 47 gamma-ray burst (GCN) alerts. Light curves are automatically produced and released [31] (Figure 11 was made this way) for approximately 100 sources, and new flaring sources are added automatically. Although this has been quite successful already, there is much more to do with this great data set, as discussed below.

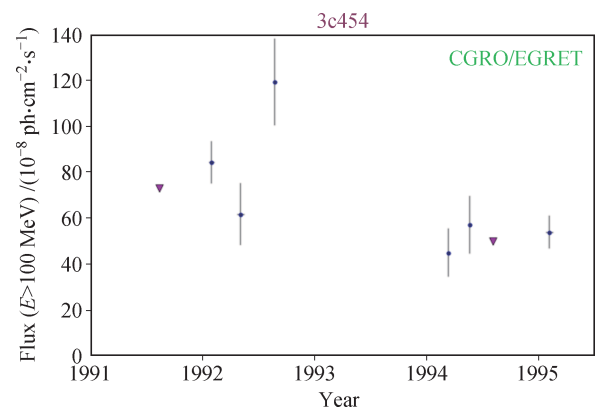


Fig. 2 Light curve of blazar 3C 454.3 over the full EGRET mission lifetime.

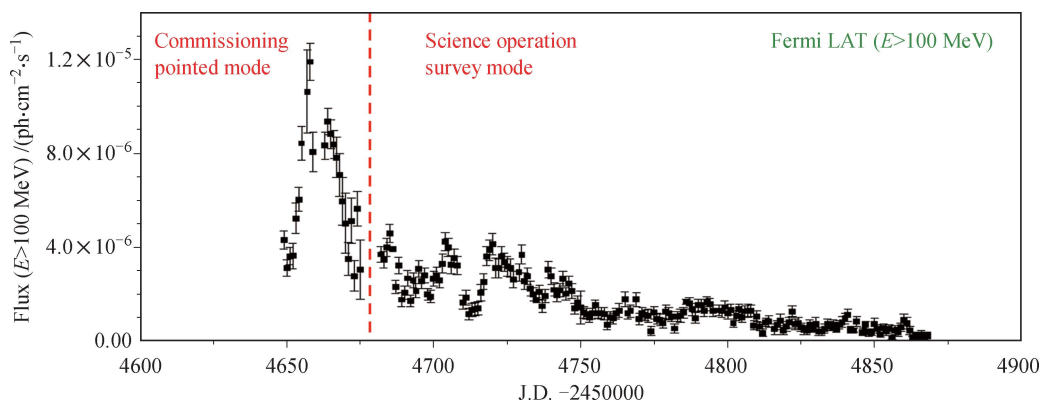


Fig. 3 Light curve of blazar 3C 454.3 during LAT commissioning and very early operations phases.

- **Depth.** Fermi takes data continuously (except for time spent in the South Atlantic Anomaly (SAA), which is about 13% on average), including during slews, deepening the exposure on the whole sky over time.
- **Energy range.** The ground-based gamma-ray instruments have spectacular effective area above ~ 100 GeV, while the energy range from a few GeV to ~ 100 GeV is important territory for Fermi to fill in. Measurements in this energy band enable us to discover the energy budgets and characteristics of a wide variety of cosmic accelerator systems on different scales. The spectral connections between space-based and ground-based gamma-ray facilities are being made in the Fermi era, but the symbiosis is even more significant. While Fermi covers the variability timescales of $>$ hours for sources like AGN for the whole sky, the ground-based Cherenkov telescopes follow the variability of select sources, many of which are suggested by Fermi observations, down to timescales of *minutes*. Finally, over cosmological distances, the Universe starts to become opaque to gamma-rays with energy significantly above 10 GeV, due to pair-attenuation with the optical-UV-IR extragalactic background light. While TeV observations are typically limited to more modest redshifts ($z < \sim 0.6$), Fermi is able to see sources at much larger distances at low energy and has now detected the onset of the opacity effects at higher energy, as described below.
- **Spatial.** Thanks to the improved point spread function (PSF), effective area, and wide field of view, source localizations have been greatly improved, in some cases to the sub-arcmin realm (depending on source characteristics), allowing counterpart identification. In addition, space-based gamma-ray astrophysics has moved beyond the study of point sources and large-scale diffuse emissions: extended sources with features larger than $\sim \frac{1}{2}$ degree are resolved spatially as well as spectrally and temporally. This has opened the door to studies of sources such as supernova remnants (SNR) and galaxy clusters, as well as resolving lobes of radio galaxies in gamma rays. Long-standing questions such as the origin of the cosmic rays are being addressed in unique ways with Fermi data. There is much more to do: untangling the sources in the Galactic Center, searches for AGN haloes, and further SNR studies are all ongoing topics of investigation.
- **Temporal.** With a very low deadtime per event and relatively large effective area, the LAT can

study the evolution of GRB lightcurve characteristics with energy. In a very different domain, because of the frequent full-sky coverage and good precision event timestamps [32], blind searches for periodic emission (e.g., radio-quiet pulsars) have been made possible. This has been particularly fruitful.

- **Measurement detail.** With greatly expanded statistics, and a large amount of information about every photon event, there is a very rich data set to mine for both the sources we know and, most important, those still awaiting discovery. For the more exotic (and therefore potentially even more exciting) possibilities, such as particle dark matter annihilations, large extra dimensions, or Lorentz invariance violations, the challenge is to show first that all the known astrophysical effects are excluded as the causes of any apparently anomalous signals. The LAT is also an excellent e^+e^- detector, enabling a very high precision measurement of the flux to 1 TeV and possibly higher. Even more is now being done with the detailed information from the instrument and the experience gained from science operations: the reconstruction and event analysis software is being completely rewritten (called Pass 8), holding the promise of improved science performance across the entire energy range but especially at the lowest and highest energies.

1.2 A quick tour of the observatory and processes

The aspects of operations [23] that most directly bear on science are summarized in this section. It is worth noting that it is the *lack of problems* that most elegantly demonstrates the excellent work of the international instrument teams and Flight Operations Team, which work seamlessly together.

1.2.1 Operating modes, operations phases, data

As noted above, the intrinsic instrument capabilities have a large impact on the observing plans and data policies. Because of the large LAT FOV, the primary observing mode has thus far been sky survey, which is implemented as a modified zenith-pointed mode, with the observatory tilted $\sim 50^\circ$ relative to the orbit plane. (This was originally 35° , but was later modified to assist in the thermal management of the battery.) After one orbit tilted north of the plane, a slew maneuver tilts the observatory south of the plane by the same amount. Thus, after two orbits (approximately three hours), the entire sky is covered, and the pattern is repeated. This cadence of exposing all regions of the sky for ~ 30 minutes every three hours is well matched to the natural

LAT integration times for most (non-GRB or other impulsive) sources. The resulting exposure non-uniformity is relatively small. The orbit plane precession period is about 54 days, which tends to reduce the non-uniformity further. The sky survey optimally serves the vast majority of anticipated Fermi science, and it simplifies multi-wavelength observation planning. Although the primary science mode is sky survey, the observatory is capable of pointed observations when warranted (see the following section). In addition to scheduled pointed observations, target of opportunity (TOO) observations are also supported by the Fermi system. There have been 8 approved TOOs [24] to date.

Both GBM and LAT can send GRB alerts to the ground in near-real time (in most cases, alerts reach the GCN in less than about 15 seconds), followed by updates. Alert messages include both position and spectral information. Either instrument can also initiate an autonomous repoint request to the spacecraft, which will then slew to keep the GRB candidate location within the LAT FOV for a selectable dwell time (initially five hours). The trigger and repoint request thresholds are adjustable.

The GBM is the most prolific detector of GRBs and Terrestrial Gamma-ray Flashes (TGFs). The history of GBM triggers is summarized in Fig. 4.

1.2.2 The photon data are public

As of September 2012, there were more than 275 billion LAT onboard data system triggers, with > 99% uptime for science (excluding SAA, which approximately 13% of the time). More than 50 billion events have been down-linked for processing. Of these, 1.5 billion events have been classified as photons in Level 1 processing (of which > 225 million are of the higher quality *source* class) and

delivered to the Fermi Science Support Center (FSSC) for public release. This is not a trivial task: more than 500 CPU-years of Level 1 processing have been used at SLAC, which hosts the LAT data Instrument Science Operations Center (ISOC). In addition to application of calibrations, pattern recognition, and event classification, the processing includes automated searches for flaring sources, flux and spectral monitoring, searches for prompt/afterglow emission from all GRB triggers within LAT FOV, transients searches, and more. LAT team members monitor some 120 000 quantities, and serve on shifts to evaluate transient triggers found in the data processing. Typically, within 10 hours after a photon hits the LAT the information is available publicly on the FSSC site. Similarly, data processing for the GBM is performed by the instrument team in Huntsville and is then transferred to the FSSC for distribution.

Data analysis tools are developed jointly by the FSSC and the instrument teams. Driven by the science and characteristics of the gamma-ray sky, there is a huge dynamic range of needed source sensitivity and background rejection, so there are several different event classes for LAT photons [3].

The instrument teams are constantly developing new data classes, which are then added to the public data archive. The LAT Low Energy data (LLE) [27], useful for gamma-ray bursts and solar flares, as well as the GBM continuous time-tagged events (TTE) [28] are the latest additions.

1.3 Scientific productivity

A recent bibliographic search [29] finds 1425 Fermi-related publications, with 32231 citations, and the pace of discovery is not slowing. There have been four dedicated, international Fermi symposia, the most recent [38]

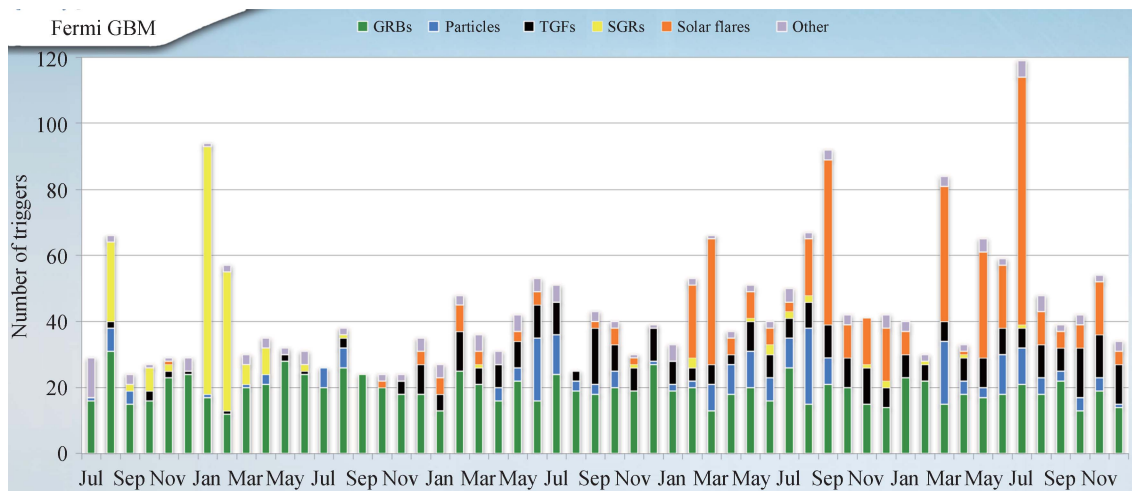


Fig. 4 Summary of GBM Triggers. (From the GBM Team.)

in Monterey, CA, in October 2012. Over the past year alone, there were many remarkable results, including discovery of a new black widow pulsar that appears to be the most massive neutron star ever found; additional millisecond pulsars, which can also be used to search for gravitational radiation; a measurement of the gamma-ray horizon that is due to the optical-UV extragalactic background light; and features in high-energy spectra, particularly from the Galactic center region, that may be a hint of particle dark matter annihilation. These, and many other topics, will be highlighted below.

2 The Fermi LAT second catalog

The stage is set by the LAT second catalog [39], which is the top-cited paper [40] in all of Astronomy in 2012. Constructing the catalog was an enormous effort, involving many complex and iterative steps, and the process depended critically on a detailed model of the Galactic diffuse emission (see Section 5). First, an iterative pattern recognition was performed to detect and localize the sources (the second catalog includes both point sources and some spatially extended sources). Then, the spectra and variability were characterized with defined metrics. The fluxes were reported in 5 energy bands, from 100 MeV to 100 GeV. Finally, an attempt was made to identify or associate each source with known sources from other wavebands.

The result was 1873 sources, of which 108 were associated with pulsars, 71 with supernova remnants and pulsar wind nebulae, 11 with globular clusters, 4 with high-mass binaries, 1 with a Nova, 1091 with active galactic nuclei (AGN) [435 with BL LAC blazars, 370 with flat spectrum radio quasars (FSRQ), 11 with non-blazar AGN, 12 with radio galaxies, 6 with Seyfert galaxies, and 257 with AGN of uncertain type], and 10 with normal or starburst galaxies. Thus, 577 of the 1873 sources were formally unassociated. Although subsequent identifications have been made, this represents important additional discovery space.

The second catalog was based on the first 24 months of LAT data. Another catalog will be based on 5 years of data, and it will benefit from a number of improvements in instrument capability, as outlined in Section 8.1.1.

3 Galactic sources

Fermi has uncovered a rich variety of sources, including transients such as Nova V407 Cyg [42] (since the time of the second catalog, two more novae have been detected by LAT, one of which was seen first in gamma rays, raising the interesting possibility of using the LAT as

a nova finder [43]). The GBM has seen several magnetar bursts (SGR J1550–5418 [44, 45], SGR J0501+4516 [46], SGR J0418+5279 [47]), as well as several hard X-ray/soft gamma-ray sources using the occultation technique [48]. However, pulsars are, by far, the most prominent Galactic source class, as Fermi has demonstrated.

3.1 Pulsars

Pulsar pulsation may be detected in radio (“radio-selected”) or in gamma rays (“gamma-ray selected”) or both, depending on the source characteristics. A good overview of source characteristics is provided by the First LAT Pulsar Catalog [50] and forthcoming LAT Second Pulsar Catalog [51]. Of the 125 LAT-detected pulsars thus far [52], 78 are young or middle-aged pulsars and 47 are millisecond (MS) pulsars. Of the young or middle-aged pulsars, 39 are radio selected and 36 are gamma-ray selected. Prior to Fermi launch, 7 gamma-ray pulsars were known [8], of which one (Geminga [54–56]) was radio quiet.

The two peaks frequently seen in the gamma-ray light curves suggest emission from wide fanlike regions, distinct from the radio emission regions, as displayed in the schematic of Fig. 5.

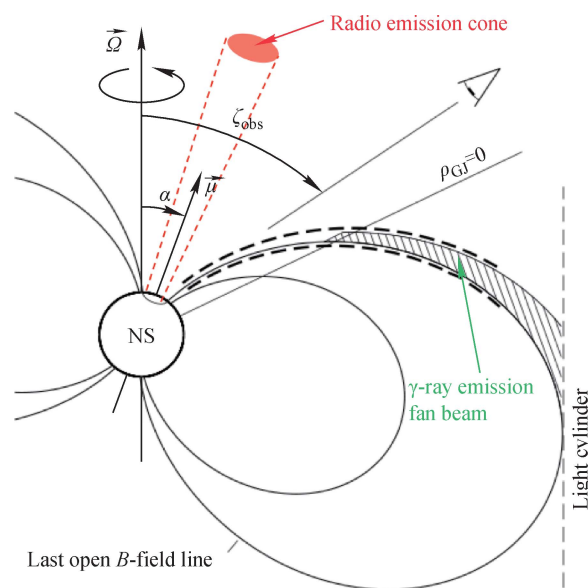


Fig. 5 An illustration [57] of pulsar geometry (co-rotating frame) displaying key features of radio and gamma-ray emission. Understanding the three-dimensional field configurations and gamma-ray emission regions is a key topic for Fermi.

Even a bright source detected with high significance has a relatively low count rate (one photon per hour is not too low) compared with the pulsar period (less than one second). This safely fits the definition of sparse data! Because the individual photons are time tagged and barycenter corrected to good precision (small frac-

tion of a period), separately knowing the pulsar timing characteristics enables phase folding of the events to yield a good light curve. This was the most common technique prior to Fermi, using timing information from radio observations, and a large effort was mounted to provide radio ephemerides for Fermi [58].

Due to sparseness, looking for pulsation with just the gamma-ray data (“blind searches”) requires use of Fourier transforms. For most pulsars, however, the period derivative is sufficiently large that the period changes significantly over the integration times required for sufficient statistics, obscuring the signal. Scans over period derivative ranges are needed, which quickly become costly in computing time. Furthermore, pulsars are known to glitch and exhibit timing noise. A clever new algorithm was developed [59] for Fermi pulsar analysis, based on application of Fourier transforms to photon time *differences*, that is robust against these effects and is therefore extremely efficient. The algorithm was applied [61] during the first few weeks of LAT operations to a gamma-ray and X-ray source associated with the remnant CTA 1, discovered in radio observations [62] in the early 1960’s. See Fig. 6, which shows the vast improvement in localization provided by the LAT. The high-energy source was suspected to be a pulsar, but pulsation had never been detected in radio. The LAT light curve (Fig. 7) using the new algorithm showed clear pulsation.

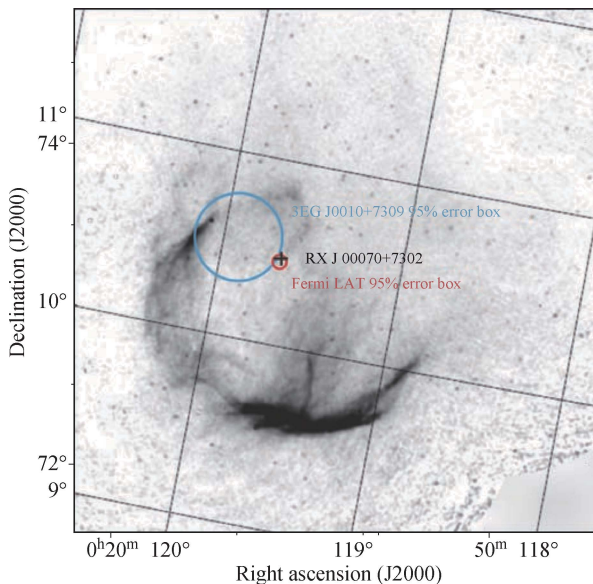


Fig. 6 On a radio map of CTA 1, the LAT source and its 95% error region (small red circle) is displayed, together with the central PWN source RX J 00070+7302 (black cross) and the position and error of the corresponding EGRET source 3EG J0010+7309 (large blue circle). The great improvement in gamma-ray localization from the LAT, with just a small amount of data, is apparent. Reproduced from Ref. [62].

This early success was quickly repeated on dozens of

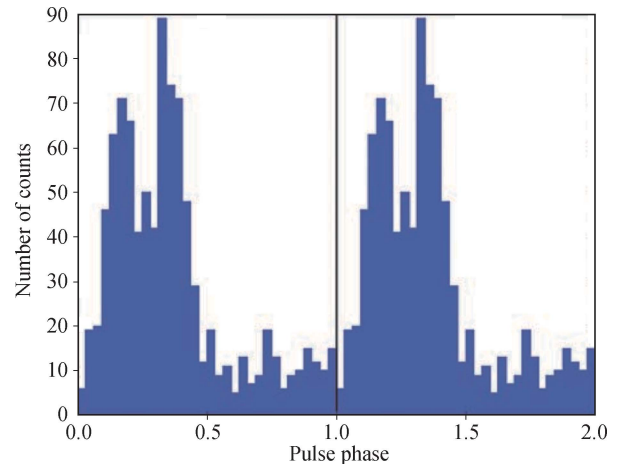


Fig. 7 Discovery light curve of the gamma-ray pulsar in the CTA-1 supernova remnant. Reproduced from Ref. [62].

other sources, enabling studies of 3-D magnetic field modeling and a variety of tests of gamma-ray emission models. This is very much a work in progress using both radio-selected and gamma-ray selected pulsars. Another beautiful example from early in the mission is shown in Fig. 8, the Vela light curves [63] for different energy

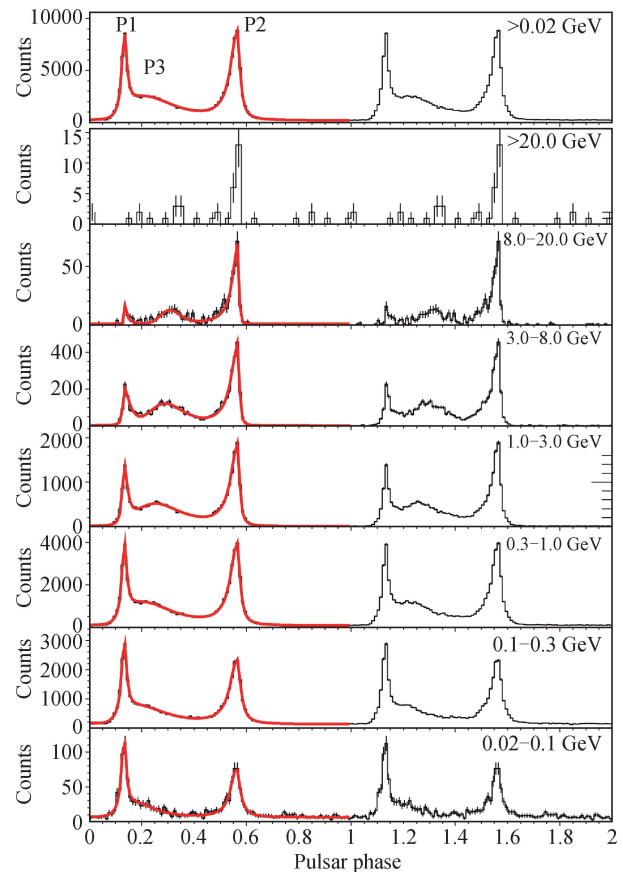


Fig. 8 Vela. Light curves for different energy bands over two pulse periods. Joint fits of the three emission peak regions P1, P2 and P3 in each energy band (as described in Ref. [63]) are superimposed on the light curves in the first cycle.

bands. The light curve presumably comprises emission from different regions that produce photons intercepting our line of sight, and the energy selection probes the geometry and dynamics.

The question of where the emission occurs may also be addressed with Fermi LAT data. Particle acceleration can only occur in regions where the acceleration voltage is not shorted out by the plasma surrounding the neutron star. Referring again to Fig. 5, models suggest this can happen in the outer region near the light cylinder or near the poles. In addition to the geometric differences, which may be accessed through population statistics, there is an important environmental difference between these regions: the magnetic field near the pole is so large, $O(10^{12}\text{G})$, that the vacuum is opaque to high-energy photons, due to the reaction $\gamma\gamma \rightarrow e^+e^-$, where one γ represents a virtual photon of the magnetic field and the other is a gamma ray with sufficient energy to produce the e^+e^- pair. The attenuation due to this opacity would therefore produce a super-exponential cutoff in the gamma-ray energy spectrum. This was excluded [63] to very high significance in the early Vela analysis, suggesting that the emission we see is produced at higher altitudes.

The pulsars Fermi sees in this way are energetic, young pulsars, with large magnetic fields and remarkably high efficiency to convert spin-down power to gamma rays, apparently [50] on the scale of 10% or more. There are many exciting questions to answer about these objects. Still missing is the detection of a young pulsar in a massive binary system, but this may come in time. However, the existing Fermi pulsar yield is even greater, involving another type of pulsar in binary systems: millisecond pulsars.

3.1.1 Millisecond pulsars

Pulsars with millisecond-scale periods, a.k.a. millisecond pulsars (MSPs), are believed to be much older pulsars that have been spun up by accretion from a companion. The number of known MSPs has increased dramatically thanks to Fermi data, providing new insights into the MSP population and opening new opportunities, as discussed below. As radio observatory beams are relatively narrow, discovery of new pulsars is significantly enhanced by a list of high-likelihood targets. As mentioned in the previous subsection, prior to Fermi, the gamma-ray community relied heavily on radio ephemerides to detect gamma-ray pulsation in young, energetic pulsars; with Fermi, the gamma-ray community is now giving back: with suitable selections, the Fermi LAT all-sky catalog provides the high-likelihood target list. This has worked remarkably well. More than 40 new MSPs have

been discovered by radio observations thanks to the LAT data [53], and more are likely on the way. It is gratifying that gamma-ray analyses are now returning the favor of decades of pulsar ephemerides to our radio astronomer colleagues.

Remarkably [64], radio searches guided by Fermi data have increased by an order of magnitude the number of known Galactic MSPs in binaries with pulsar-driven winds from the companions, colorfully referred to as “black widows” and “red backs”. The gamma rays allow us to see through the wind material, which obscures the radio emission and makes the radio signal intermittent and otherwise challenging to detect. Another big recent breakthrough was the first discovery of a millisecond pulsar, PSR J1311–3430, in a blind search [60] of LAT data, enabled by optical constraints [65–67], and soon thereafter detected in radio [53]. This tour-de-force result was due to analysis advances and application of large-scale computing, even with the new, efficient algorithms. The J1311 system is understood to be a black widow binary, and the pulsar orbital period is only about 93 minutes, the shortest of any spin-powered pulsar binary ever found. Furthermore, modeling of the emission suggests [49] an enormous neutron star mass, at least $2.1M_\odot$.

3.1.2 Neutron star environments

Neutron stars illuminate and alter their environments. Because neutron stars are formed in supernovae, young pulsars have particularly important effects on supernova remnant (SNR) nebulae. Shocks from the supernova itself can account for galactic cosmic ray acceleration, and this hypothesis is being tested and refined with LAT data (see, e.g., [69] and references therein). Gamma rays are emitted in a variety of processes, especially when protons interact hadronically with gas swept up in the shock or in nearby molecular clouds, or when electrons inverse Compton scatter ambient photons.

In addition, pulsar winds drive particle acceleration processes in pulsar wind nebulae (PWN), so these objects are also prime targets for LAT data analysis. See Ref. [68] for a summary. A particularly interesting and well-known PWN is the Crab Nebula.

3.1.3 Crab surprises

For decades, the Crab Nebula had been considered a calibration standard in high-energy astrophysics, so it caused quite a stir when both AGILE and Fermi LAT reported [70] flares from the Crab. Although the Crab had been observed many times, across many wave bands, it had not been monitored continuously. With the careful and continuous observing enabled by Fermi, several

surprises were found. First, in the high-energy (LAT) band, there are numerous, isolated flares, as displayed in Fig. 9. These very short, intense flares [71, 72, 74] pose significant challenges to models of particle acceleration. Furthermore, thanks to GBM and other observations [73], we now know that the overall hard X-ray flux changes steadily with time, as shown in Fig. 10. During the first two years of the Fermi mission, the flux declined by about 7%. In addition, VERITAS has reported [75, 76] Crab pulsar pulsation to energies beyond 100 GeV! None of this is easily explained. A forthcoming review can be found in Ref. [77].

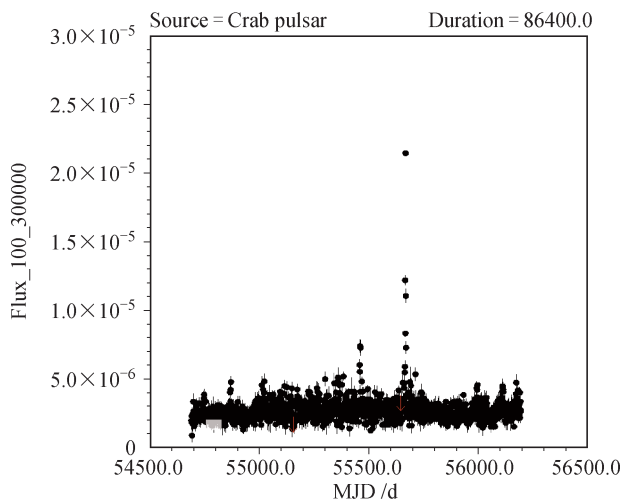


Fig. 9 LAT monitored source light curve [31] of the Crab, ca. Sept. 2012.

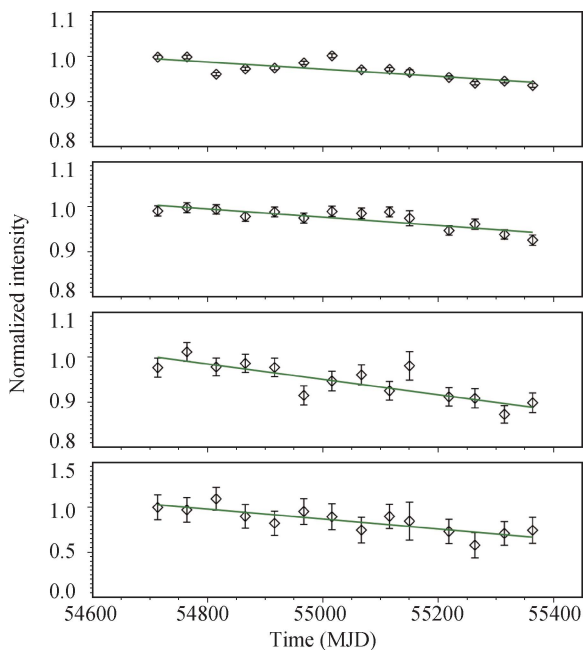


Fig. 10 GBM Crab flux measurements [73] in the bands 12–50 keV, 50–100 keV, 100–300 keV, and 300–500 keV (top to bottom, respectively) in fifty-day bins. The solid lines are fits used to compute the flux rate of change.

3.2 Using galactic sources

3.2.1 Nanohertz gravitational radiation searches

The Nobel-prize-winning radio measurement of the orbital decay of the binary pulsar PSR B1913+16 by Hulse and Taylor [78] heralded the use of precision pulsar timing to detect the effects of gravitational radiation. Their measurement was indirect, inferring the existence of gravitational radiation from the energy loss of the binary. However, a more direct measurement using pulsars is possible: a gravitational wave passing near the earth will leave a characteristic imprint on the timing residuals of a constellation of well-timed MSPs. Given the observing cadence and other factors, the method is sensitive to gravitational wave frequencies in the *nanohertz* band. Fortunately, detectable sources are expected in this range [79]. To be successful, at least several dozen MSPs are needed. Fermi is playing an important role in this endeavor: as noted above, more than 40 new MSPs have been discovered by radio observations thanks to the LAT data [53], and more are likely on the way. It is interesting to note that a gamma-ray facility with breakthrough capabilities is likely enabling a much earlier detection of gravitational radiation using radio pulsars! Such connections, spurred by new capabilities, are difficult to anticipate, but they frequently occur.

4 Extragalactic sources

Numerous extragalactic sources have been detected and studied by Fermi. These sources are of great interest as individuals and as source classes, and their cosmological distances also enable tests of fundamental physics, as discussed below.

4.1 Active galactic nuclei

At the core of most, if not all, galaxies is a supermassive black hole ($O(10^6\text{--}10^{10}M_\odot)$). These remarkable objects have a profound impact on their environments and *vice versa*, and they are understood to be the engines of active galactic nuclei (AGN), i.e., compact regions producing extremely powerful electromagnetic emission. These systems typically include sizable accretion disks and remarkably columnated jets of very high energy particles. How the jets form and maintain their organized configuration over vast distances are important open questions. Extraction of black hole spin energy has been suggested [90] as the underlying cause of jet formation, and detailed simulations are providing beautiful results [91]. Blazars are the most extreme class of AGN, thought to be due to

a jet pointed close to the earth line of sight. Gamma-ray emission is due, in most models, to some combination of inverse Compton scattering by electrons and hadronic interactions of protons. Thus, gamma rays offer a unique probe of jet energetics, dynamics, and composition. The power output is apparently highly variable, as can be seen in Fig. 11, and enormous: a bright flare can produce an isotropized flux in gamma rays alone [88] of more than 10^{50} ergs/s, generated from a very compact region. The true power generated is of course a few orders magnitude smaller, as beaming factors are thought to be of $O(10^{-3})$. As luminous AGN are known [80, 81] to exist at redshifts $z > 6$, the fast formation and growth of super-massive black holes in the early Universe is a challenge to explain [82–84]. Major mergers may help significantly [85–87].

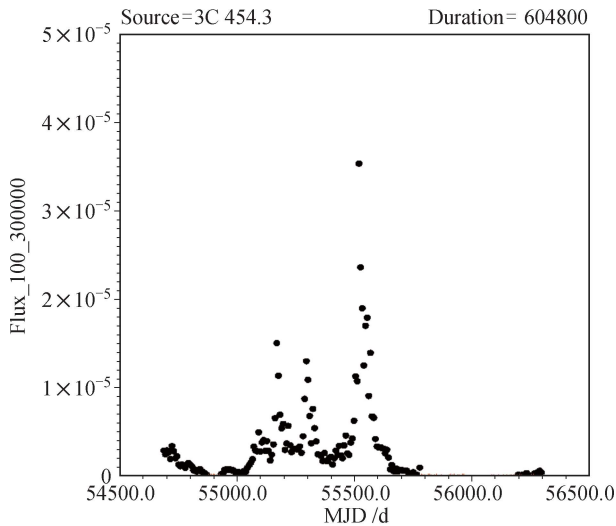


Fig. 11 Light curve of blazar 3C 454.3 from the public monitored source list [31], as of 2012 December.

The great advances in observational capabilities offered by Fermi enable both detailed studies of individual objects and population studies over cosmic time, both of which should be important for improving our understanding of jet formation, jet activity, and major merger history. The capability to study individual sources is illustrated well in Fig. 12, the gamma-ray spectral energy distribution (SED) of blazar 3C 454.3 in different flaring states. Now that data are sufficiently precise, it is not too surprising that simple, single power law fits do not describe the data. Whether the spectral break is a common feature remains to be seen. Another example is Markarian 421, whose broadband SED is shown in Fig. 13. The two-bump structure is a feature commonly seen in blazars, and the energies of the peak values are shifted left and right for different blazars. The low-energy bump is understood to be due to electron synchrotron radi-

ation, but the mechanism for the high-energy emission is still under investigation. Fermi LAT data provide important constraints on models, particularly for those blazars – like Markarian 421 – whose SED high-energy bump peaks above the high-energy gamma-ray regime. Prior to Fermi, most of the GeV band information for these blazars was in the form of upper limits; now, there are spectra [94] that can be compared in detail with models.

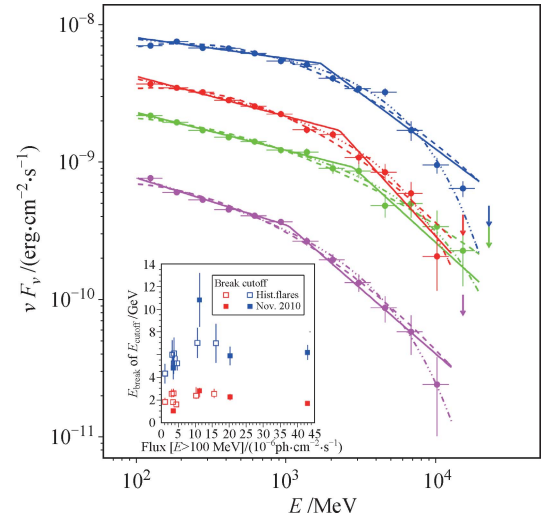


Fig. 12 3C 454.3 Spectral energy (νF_ν) distributions [88] for four different time periods, pre-flare (magenta), plateau (green), during flare (blue), and post-flare (red), along with the fitted BPL (solid), log-parabola (dashed) and PLEC (dashed-dotted) functions. The inset displays E_{break} (red) and E_{cutoff} (blue) as a function of flux (filled symbols) and for historical flares (open symbols).

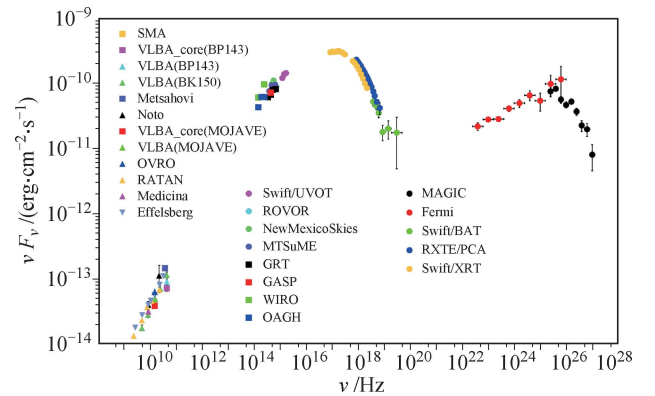


Fig. 13 Spectral energy distribution of Mrk421 averaged over all the observations taken during the multifrequency campaign from 2009 January 19 to 2009 June. Reproduced from Ref. [94].

Population studies with minimal selection biases are also enabled by Fermi LAT data. For example, using hundreds of blazars [92] detected by Fermi over a sizable redshift range, the number of blazars per comoving volume element per luminosity range, called the luminosity function (LF), can be determined [93]. The LF provides a method to study blazar evolution, which is connected

to the history of jet activity and major merger events. In addition, the LF can be extrapolated to infer the blazar contribution to the diffuse background [112]. Populations of blazars also enable us to probe the density of extragalactic background light (EBL), using pair attenuation effects over large distances at high energy [89], as outlined in Section 4.3.1.

Distributions of the parameters that characterize blazar emission, such as spectral index, have been analyzed in detail and compiled in the Second LAT AGN Catalog (2LAC) [92]. Other classes of AGN, whose jets are further off the axis of the line of sight, can now also be studied with LAT data. For example, the lobes of nearby radio galaxy Centaurus A [95] have been resolved for the first time in gamma rays.

The LAT AGN light curves are a goldmine still waiting to be exploited. For example, a recent paper [101] suggests possible correlations between the shortest variability timescales and central black hole masses. Many other studies are possible probing a range of timescales.

4.2 Gamma-ray bursts

As the most powerful explosions, by far, gamma-ray

bursts (GRB) continue to fascinate and frustrate, and Fermi measurements have contributed additional surprises. The GBM sees approximately 250 GRBs per year, as expected, and on 21 September 2012 the GBM detected its 1000th GRB [108]. Approximately 20% of the GBM bursts are short GRBs. The GBM Burst catalog [41] presents the first 491 GRBs from its first two years of operations, describing the criteria used for triggering and quantifying the general characteristics of the triggered GRBs, including their locations, durations, peak flux, and fluence. The online version [102] also contains all subsequent bursts.

The anticipated LAT burst trigger rate was much less certain for several reasons, not the least of which is that GRB emission in the LAT energy range is not well understood. The LAT GRB detections are continuously updated and summarized online [103]. To date, there have been 35 detected, or about 9 per year. Only a fraction ($\sim 10\%$ or less) of the GBM bursts that occurred in the LAT FOV were detected by the LAT. GRB photons up to ~ 30 GeV (observer frame) have been detected, and 9 of the 35 LAT bursts have measured redshifts from 0.74 (GRB 090328) to 4.35 (GRB 080916C, which, remarkably, is also the brightest, with an isotropized energy of

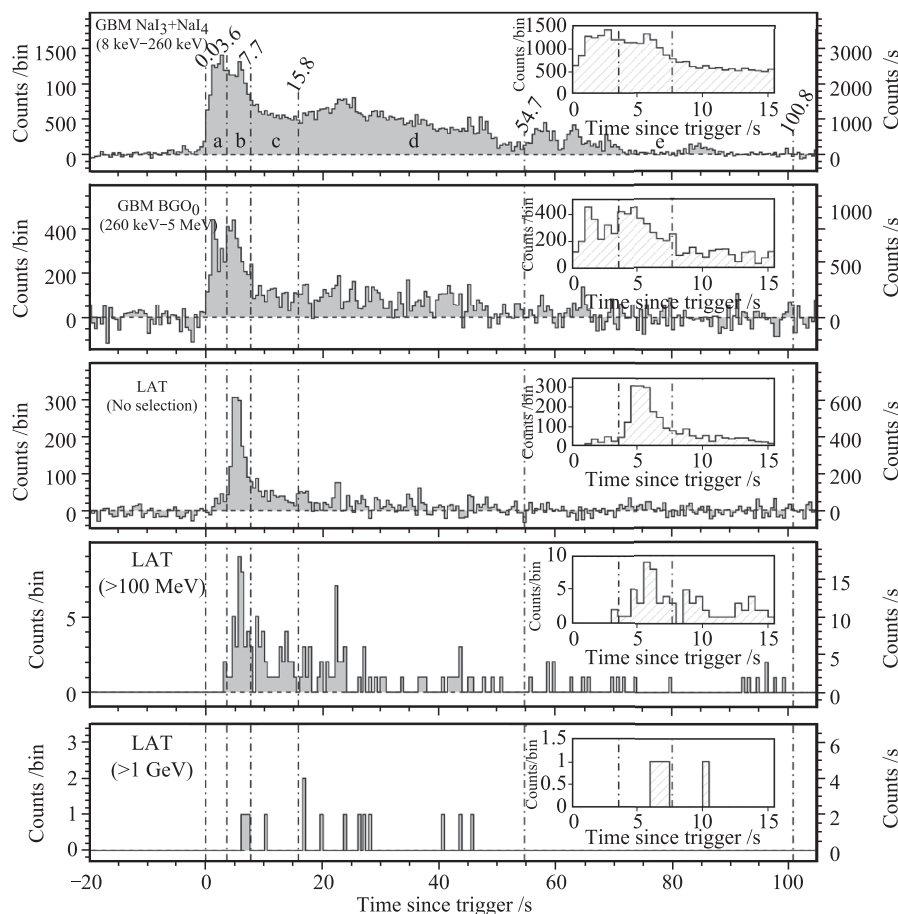


Fig. 14 The light curve for GRB 080916C. The top two curves are from the GBM, and the bottom three are from LAT [105].

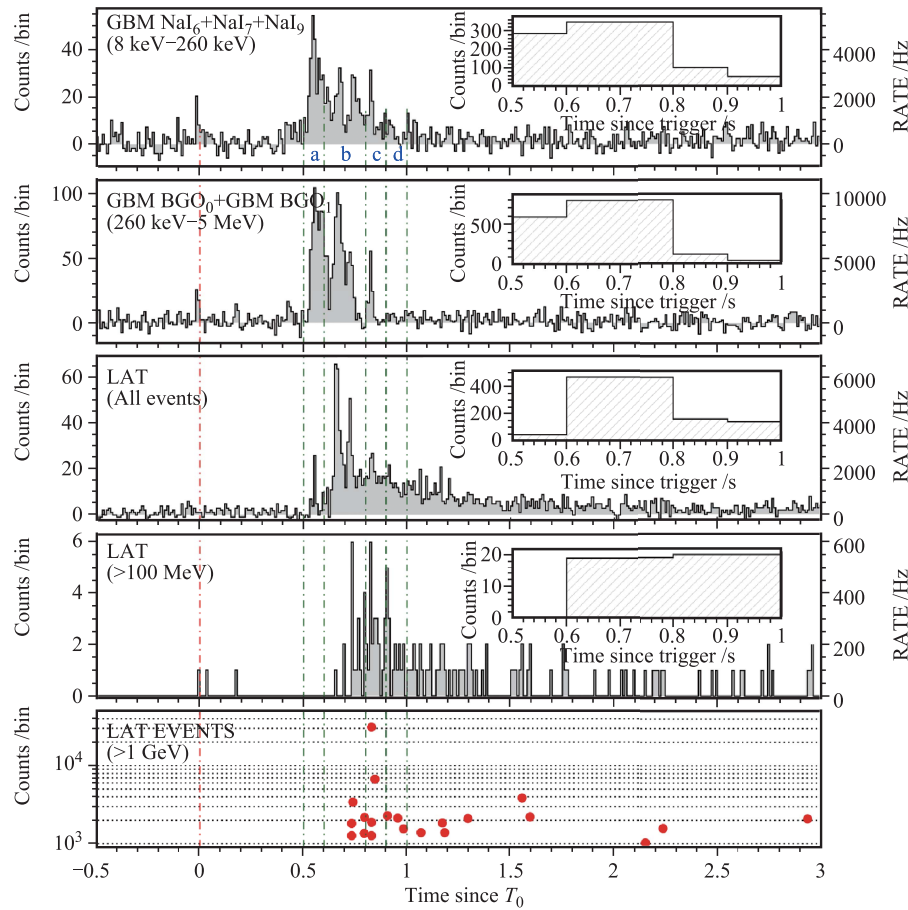


Fig. 15 The light curve for GRB 090510. The top two curves are from the GBM, and the bottom two are from LAT [104].

$\sim 9 \times 10^{54}$ ergs, the largest ever detected from any burst). The brightest LAT bursts (GRB 080916C [105], GRB 090510 [104], GRB 090902B [106], and GRB 090926A [107]) each have hundreds of photons detected with energy > 100 MeV, so GBM+LAT measurements provide fantastic broadband spectra.

One surprise is that the GeV emission is, in at least several cases, delayed relative to the MeV emission. For long bursts, the delay is about 4–5 seconds, and for short bursts the delay is about 0.1–0.2 seconds. The light curve for GRB 080916C is shown in Fig. 14. The GeV emission starts in a second pulse that is delayed by about 4 seconds. The light curve for short GRB 090510 is shown in Fig. 15, in which the delay of the high-energy emission is a fraction of a second. The spectral evolution (soft to hard) is a common feature of all the bright bursts. The emission above 100 MeV also typically lasts longer than the emission below 1 MeV.

Some GBM+LAT spectra require additional components beyond the standard Band parameterization, e.g., GRB 090510 and GRB 090902B, which exhibit a strong second component extending above 10 GeV without an obvious break. This extra, flat component dominates

both at high energy and at low energy (below 50 keV).

The fact that LAT detected high energy emission from short bursts was itself surprising, as none had been detected by EGRET. Interestingly, for short GRBs the LAT fluence is larger than the GBM fluence, whereas for long bursts the LAT fluence is only 5%–60% that of the GBM fluence.

The interpretations of these surprising characteristics uncovered by Fermi are not clear, and the goal is to move beyond phenomenological parameterizations to physically motivated models. There are still many open questions, including the nature of the progenitor(s), dynamics and composition of GRB jets, details of the gamma-ray emission mechanisms (where and how is energy dissipated and why are fewer than 10% of GBM bursts detected by LAT?), and explanations of the observed broad-band spectrum (including the origin of the extra component).

The coming years of Fermi data will provide additional clues. Furthermore, the hadronic component of bursts may be probed using IceCube data, and any detections by gravitational wave facilities such as Advanced LIGO and ground-based TeV gamma-ray detectors such

as CTA [111] would help tremendously. Another intriguing possibility is the detection of Pop. III GRBs [110], which may occur when the core of such a massive, metal-poor star collapses to a $O(100)$ solar-mass black hole.

4.3 Using extragalactic sources

4.3.1 Extragalactic background light

Two photons with sufficient energy in the center-of-momentum frame can produce an electron and a positron (e^+e^- , sometimes called a pair). For gamma rays in the LAT energy range, the threshold partner photon energy is in the optical-UV range, i.e., starlight. The density of the extragalactic background light (EBL) can therefore be probed by looking for pair-attenuation effects (only $e^- \tau_{\gamma\gamma}$ reaches us, where $\tau_{\gamma\gamma}$ is the opacity) on the high-energy spectra of gamma-ray sources at cosmological distances. The opacity should increase with both gamma-ray energy and source distance. Binning those sources in redshift enables [97] a probe of the EBL over cosmic time. As the EBL density is governed by the star formation rate history of the Universe, this is a very interesting measurement that has been pursued for decades. Of the > 1000 LAT blazars, a subset (150) are of the BL Lacertae (BL Lac) type and have significant fluxes measured above 3 GeV. These sources, which are at redshifts between 0.03 and 1.6, were recently used to measure [89] the gamma-ray attenuation due to the EBL, as shown in Fig. 16 at $z = 1$.

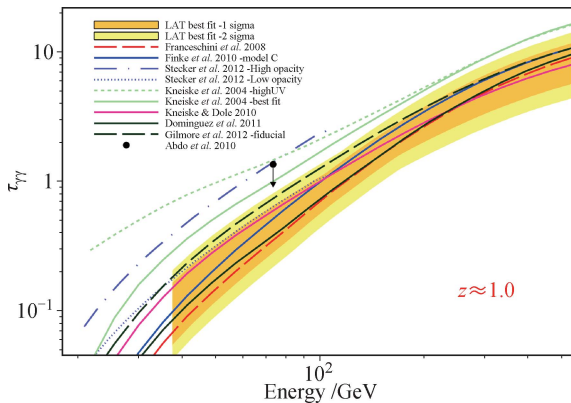


Fig. 16 Measurement of the opacity $\tau_{\gamma\gamma}$ at $z = 1$ (average in the redshift interval $0.5 \leq z < 1.6$) compared to predictions of EBL models. See Ref. [89].

Similarly, the gamma-ray horizon (the gamma-ray energy at which $\tau_{\gamma\gamma} = 1$ as a function of redshift) can be calculated for different EBL models and compared [96] with blazar spectra, as shown in Fig. 17.

As the EBL column density depends on the cosmic expansion, gamma-ray opacity measurements may even

provide [99] an independent measurement of the Hubble constant. Finally, we note that the energy of the attenuated flux does not disappear, but is converted to an e^+e^- pair that propagate through the intergalactic magnetic field (IGMF) and subsequently inverse Compton scatter CMB photons to produce additional gamma rays.

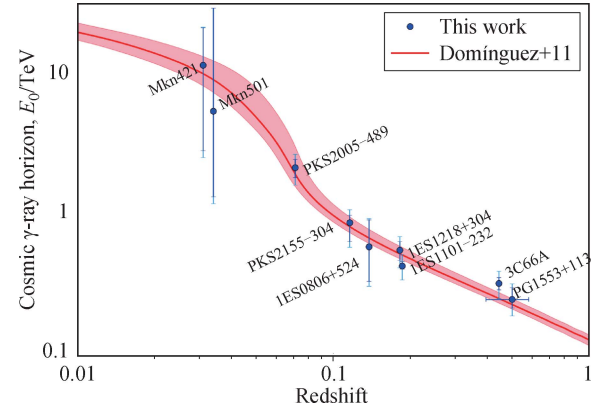


Fig. 17 Estimate of the cosmic gamma-ray horizon using individual blazars (blue circles), compared with an EBL model [98] (red thick line). The shaded regions show the uncertainties from the EBL modeling. Reproduced from Ref. [96].

Depending on the IGMF strength and inhomogeneities, the reprocessed gamma rays can appear as a gamma-ray halo [100] around AGN, presumably not tracking the core's temporal variability due to the significant differences in flight paths. This is an area that will likely receive additional attention in the near future.

4.3.2 A test of Lorentz invariance

Do photons with different energies all travel at the same speed? Of course, that is the expectation from Special Relativity, but ultimately this is an experimental question. Velocity dispersion in vacuum, which would be a violation of Lorentz Invariance (LIV), could be due to quantum gravity effects [116]. The physical picture is that smaller wavelength photons would be more sensitive to tiny vacuum fluctuations of space-time – a microscopic black hole analog to QED vacuum fluctuations – effectively encountering different distances than those with longer wavelength. Laboratory tests for tiny speed differences are impossible, but a race over cosmological distances could reveal velocity dispersion, if the measurement is done with sufficient timing resolution for photons of very different energy. Combined GBM and LAT observations of GRB are a perfect match for this test, and GRB090510, mentioned previously, provided an excellent opportunity [117], as shown in Fig. 18. The dispersion can be parameterized by

$$\frac{v}{c} \sim 1 \pm \left(\frac{E_\gamma}{M_{\text{QG}} c^2} \right)^n \quad (1)$$

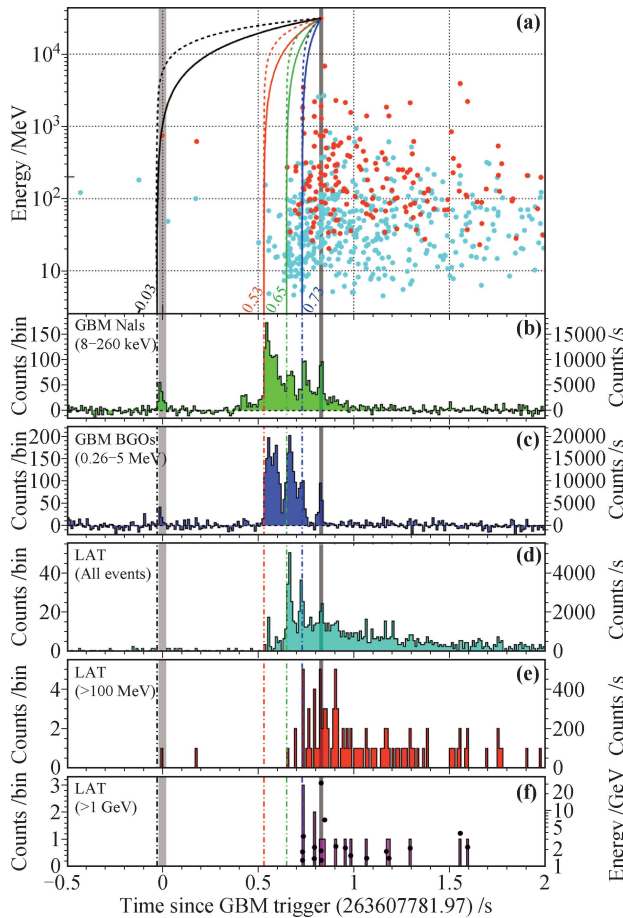


Fig. 18 Reproduced from Ref. [117]. Panel (a): Energy vs. arrival time relative to the GBM trigger time for the 160 LAT photons (red) that passed the ground-based analysis and the 161 photons that passed the onboard gamma-ray filter (cyan), coming from the direction of GRB 090510. The solid and dashed curves are normalized to pass through the highest energy (31 GeV) photon and represent the relation between a photon's energy and arrival time for linear ($n = 1$) and quadratic ($n = 2$) LIV, respectively, assuming it is emitted at $t_{\text{start}} - T_0 = -30$ ms (black; first small GBM pulse onset), 530 ms (red; main <MeV emission onset), 648 ms (green; >100 MeV emission onset), 730 ms (blue; >GeV emission onset). Photons emitted at t_{start} would be located along such a line due to (a positive) LIV induced time delay. Panels (b), (f): GBM and LAT lightcurves, from lowest to highest energies. For more details, see Ref. [117].

where M_{QG} is the hypothetical quantum gravity scale and n is typically 1 or 2. With a large number of photons over a huge energy range, several different methods can be used to check for time delays that depend on photon energy. Fig. 18 shows traces of the hypothesized effect back from the highest energy photon detected, which was 31 GeV, to different lower energy features in the light curve. For linear, $n = 1$, dispersion, the resulting M_{QG} is found to be significantly larger than the Planck mass. In other words, if this new physics is there, it is doing a good job of hiding itself! Using additional bursts over a range of redshifts, more sensitive checks will be possible.

5 Diffuse emissions

Any observed flux not associated with a discrete source is considered to be diffuse emission. Diffuse emission may come from truly distributed processes, such as interactions of propagating cosmic rays, or from portions of populations of discrete sources that are too dim to resolve. Understanding diffuse emission is of great interest in its own right, and it is also a critical ingredient in many other science topics in gamma-ray astrophysics.

5.1 Galactic diffuse

Galactic diffuse emission is such a prominent feature, as seen in Fig. 1, that it must be taken into account in almost any analysis. A diffuse model [118], provided by the LAT team, is therefore supplied along with science tools [119]. A particularly challenging aspect of the Galactic diffuse emission is the large spatial variation. Sometimes this can be accommodated by leaving the diffuse emission normalization as a free parameter in a specific point source analysis, but a deeper understanding requires a different approach [112]. Radio maps of tracer material distributions are convoluted with physical models [120] of cosmic-ray injection and propagation to produce a gamma-ray brightness distribution. Ranges of physical parameters are then extracted using fits to the data, and the resulting residuals are particularly illuminating in some cases, particularly toward the Galactic center, as can be seen in Fig. 19.

5.1.1 The Fermi bubbles

The residuals in the data compared with the LAT diffuse model contained a big surprise [121]: bubble-like features, with apparently well-defined boundaries, extending symmetrically above and below to the plane to 50° , centered near the direction of the Galactic Center, as can be seen in Fig. 19. Are these the remnant of some earlier activity of the central black hole, or are they due to some other dynamics? A recent update [122] asks whether there may be in addition a cocoon-like structure containing a jet. This is naturally a topic of multi-wavelength investigation, and there are currently more questions than answers.

5.2 Extragalactic diffuse

Much of the isotropic, apparently extragalactic gamma-ray emission is believed to originate from unresolved active galaxies, starburst galaxies, and other discrete

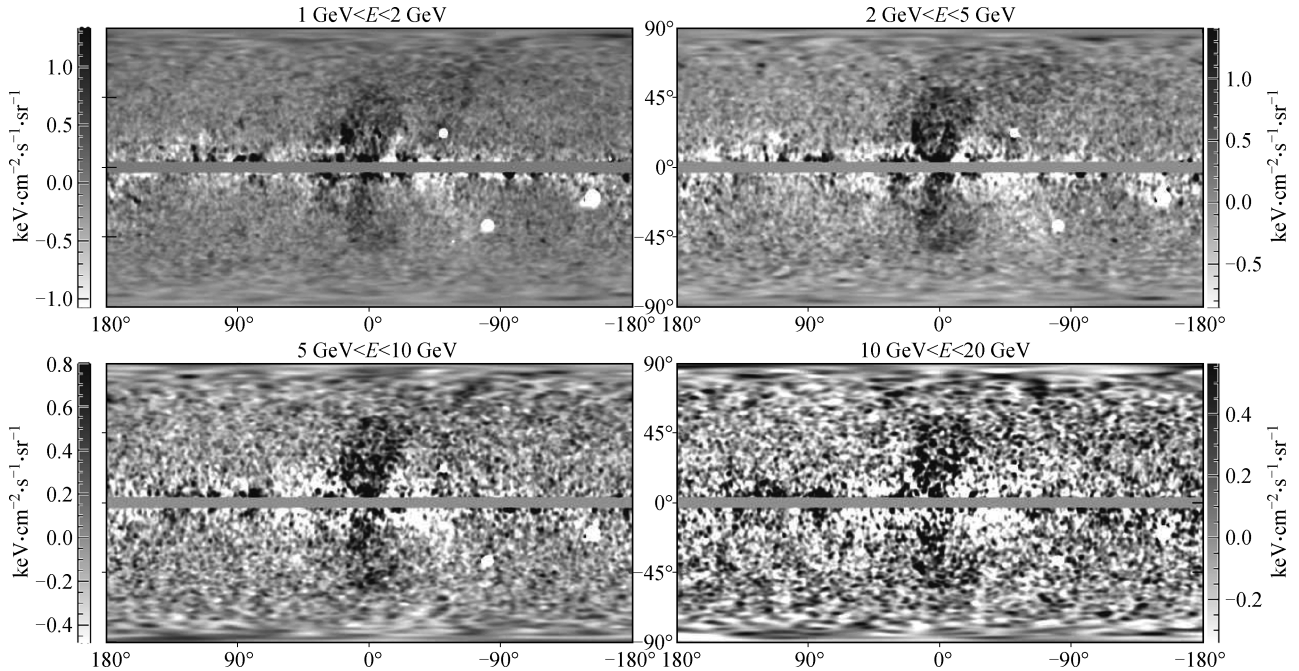


Fig. 19 All-sky residual maps [121] in four energy bins. Two symmetric bubble structures extending to $b = \pm 50^\circ$ are apparent.

sources of gamma rays. Indeed the LAT has resolved a large fraction of what was isotropic emission for EGRET [8], and extended the measurements to > 500 GeV. The LAT-detected populations of extragalactic sources can be extrapolated to account [113] for much of the remaining isotropic component but particularly below about 500 MeV a potentially truly diffuse component remains [112]. This is of interest for a number of reasons, including its potential as a dark matter annihilation feature integrated (redshifted) over cosmological distances.

5.2.1 Anisotropy studies

Determinations of the contributions of extragalactic source populations to the isotropic gamma-ray background and more precisely constrain the contributions of dark matter annihilation at cosmological distances to the residual diffuse component. With increasing statistics, anisotropies in the distribution of cosmic-ray electron arrival directions (see Section 7.1) should become apparent if a nearby pulsar is in fact the source of the ~ 300 GeV feature in the electron spectrum measured by the LAT.

6 Dark matter and new physics searches

The large discovery space opened by Fermi has enabled searches for signals of new physics, including dark matter particle interactions, axions [114], large extra dimen-

sions [115], and Lorentz Invariance Violation (see Section 4.3.2). Most new physics searches using Fermi data have centered on dark matter, so it will be covered in more detail here; however, it is important to remember this is just one exciting example of what we may yet find.

6.1 Dark matter interactions

One of the primary science drivers for the Fermi LAT is the search for signals of particle dark matter. A recent review of the opportunities and challenges is given in reference [126]. As almost nothing is known about what composes the dark matter, much of the work is highly speculative and any experimental or observational guidance is extremely valuable. Weakly interacting massive particles (WIMPs) are popular candidates for particle dark matter, for many reasons, and in broad classes of models the WIMPs can annihilate when they interact with each other (or, in some models, decay), producing Standard Model particles, including photons, in the final state [123–125]. As galactic WIMPs are non-relativistic, the rest mass sets the energy scale for the final-state particles, and the branching fractions determine the distribution of the signal. The signal, therefore, would be an anomalous flux of particles above the more conventional astrophysical backgrounds. These so-called indirect searches are complementary to direct searches (kinetic energy transfer to sensitive detectors placed in low-background environments deep underground or in ice) and to accelerator searches, and they are essential for

characterizing the dark matter.

Gamma rays are especially useful for dark matter signal searches, as they suffer essentially none of the propagation uncertainties due to magnetic fields and interactions with the interstellar medium that are inherent in charged particle cosmic ray flux calculations, and the measured gamma-ray directions point directly back to the sources. For annihilations, the gamma-ray intensity is proportional to the square of the dark matter density (probability of two dark matter particles being in the same place), so the preservation of gamma-ray directional information could provide a sensitive and direct probe of the dark matter spatial distribution, while the spectrum – if detectable – can tell us about the mass and branching fractions. The signal flux is given the product of astrophysical and particle physics model factors:

$$\Phi_{WIMP}(E, \Psi) = J(\Psi) \times \Phi^{PP}(E) \quad (2)$$

where the astrophysical J factor for annihilations is given by the line-of-sight integral over the density squared, $\rho^2(l)$

$$J(\Psi) = \int_{\text{l.o.s.}} \rho^2(l) dl \quad (3)$$

and the particle physics factor for annihilations is given by

$$\Phi^{PP}(E) = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_\chi^2} \sum_f \frac{dN_f}{dE} B_f \quad (4)$$

where m_χ is the WIMP mass, $\langle \sigma v \rangle$ is the velocity-averaged annihilation cross-section, and for each final state, f , B_f is the branching fraction and $\frac{dN_f}{dE}$ is the differential photon flux. In the most straightforward models, $\langle \sigma v \rangle$ also sets the relic abundance due to thermal production in the early Universe, and a value of about $3 \times 10^{-26} \text{ cm}^3/\text{s}$ would produce the amount of dark matter suggested by Cosmic Microwave Background and other observations, so this is a benchmark for indirect searches.

The gamma-ray fluxes from WIMP interactions are generally broad spectra (a.k.a. “continuum”) from final-state particle decays (typically $q\bar{q}$ final states hadronizing into jets that include π^0 s) and/or final-state radiation, or two-body final states (typically $\gamma\gamma$ and/or γZ producing mono-energetic “lines”). The two-body final states would provide a narrow spectral bump – a clear and compelling signature – if sufficiently bright; however, the branching fractions are expected to be small (usually $O(10^{-3})$ or less due to the higher-order processes required in most models). The integrated LAT exposure

is now great enough to begin to allow searches for detecting DM signals in mass ranges expected from widely used models with annihilation cross-sections around the benchmark value. When no signal is apparent, limits are often set by using specific dark matter density models (usually suggested by results of large N -body simulations) and observations to calculate J factors, and then for each final state (i.e., assuming 100% branching fraction to each final state separately) the limit on $\langle \sigma v \rangle$ is calculated as a function of m_χ .

The challenge is to understand the backgrounds sufficiently well to prove that any signal is due to dark matter interactions or to set useful limits. Astrophysical settings that have larger J factors and smaller expected backgrounds are understood to be the most promising. Searches have been performed for the Galactic halo [127], dwarf spheroidal (dSph) satellites of the Milky Way [132, 133], galaxy clusters [128], unassociated LAT sources [129], and in the isotropic background (from studies of the angular power spectrum) [130, 131]. Currently, the most constraining limits are from dSph satellites. Joint analyses of LAT observations of ten dSphs has provided velocity-averaged cross-section limits [132] for the $b\bar{b}$ channel and WIMP masses below 30 GeV that are better than the benchmark value. See Fig. 20.

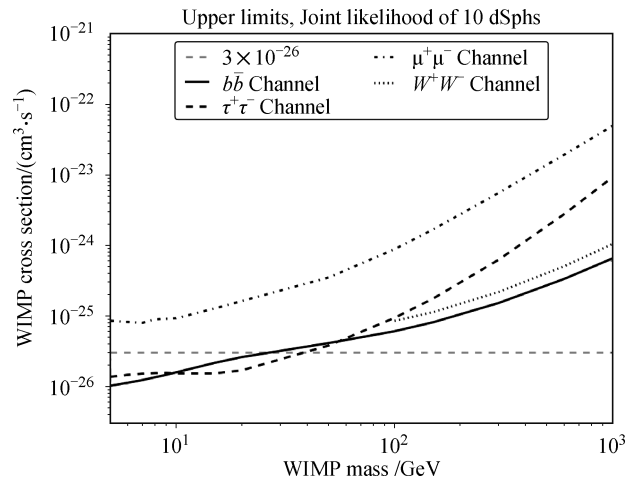


Fig. 20 Limits on WIMP velocity-averaged annihilation cross-section for different final states as a function of WIMP mass from a joint likelihood analysis of dwarf spheroidal (dSph) galaxies from Ref. [132].

Our Galactic center is expected to be the brightest dark matter signal region, but it is also produces the most complex backgrounds, so line searches are most often performed on that region. Limits on the fluxes of gamma-ray annihilation lines from the Milky Way have been obtained using two years of LAT data [134]. Recently, users of the the public data (e.g., [135]) have re-

ported a low-significance line-like spectral feature near 135 GeV in the region of the Galactic center. This work, and related searches for possible pairs of lines or the continuum associated with an annihilation line have stimulated many papers on interpretation of the LAT data in 2012. Similar features have now been reported in a selectively stacked galaxy cluster analysis, in some of the unidentified LAT sources published in the LAT two-year source catalog, and from the earth's atmosphere, which is very bright in gamma rays due to showers from high-energy cosmic rays. Given the last result, a natural question is whether there is some unanticipated instrumental and/or analysis effect; however, these features have not been seen in other bright sources, and other checks we have done have found little evidence for this kind of problem. None of these results is statistically definitive, but they all demand careful attention, as detection of a DM annihilation line would be a major discovery. Because any claims of new physics require a very high standard of proof, it is important to check for all possible systematic effects, and to increase statistics as quickly as possible. Within the LAT Collaboration, the potential systematic effects are being intensively studied, and alternative observing plans are under discussion. In addition, the LAT Collaboration is pushing forward on the reconstruction/analysis software re-write, called "Pass 8" (described in Section 8.1.1), which is expected to increase the acceptance for events in the 100 GeV energy range by a factor ~ 1.5 –2. There are good reasons to be confident that these studies will explain the origin of the 135 GeV feature or similar features. In addition, H.E.S.S. II is expected to begin Galactic center observations in March 2013, which may soon provide additional information [136].

All efforts to date have led to the same conclusion: more data are needed. Higher statistics will, of course, help to determine if this is just a statistical fluctuation, but more data will also enable more effective systematics studies. Modifications to the observing profile to provide increased exposure of the Galactic center, particularly at large off-axis angles where the energy resolution is best, will be considered. See Section 8.1.2.

Dark matter particle annihilations and decays could also produce anomalous charged-particle cosmic-ray fluxes, and the LAT is an excellent electron and positron detector (see Section 7.1). There is valuable information in both the energy spectrum and the arrival direction. For example, limits on the anisotropy of the electron distribution with respect to the direction of the Sun have been used to set limits on dark matter interactions in the Sun, providing severe constraints [138, 139] on some models.

7 Additional topics

7.1 Electron and positron fluxes

As mentioned above, the LAT also detects electrons and positrons with large acceptance over a broad energy range. Prior to Fermi, features were reported in the spectrum that could be due to dark matter particle annihilations. Although those features were not confirmed in the high-precision LAT measurement [137], as shown in Fig. 21, there is more work to do to nail down the origin of the flux.

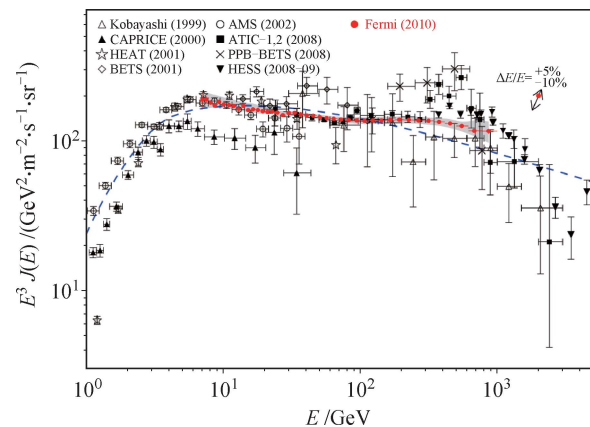


Fig. 21 Cosmic-ray electron+positron spectrum as measured by Fermi LAT for one year of observations (filled circles), along with other recent high-energy results. Systematic errors are shown by the gray band. The range of the spectrum rigid shift implied by a shift of the absolute energy is shown by the arrow in the upper right corner. See Ref. [137] for details.

7.2 Gamma-ray sources in our neighborhood

7.2.1 Solar flares

The Sun is now in active phase of its apparent eleven-year cycle. On 7 March 2012, a high-energy flare [140] lasting approximately 20 hours was detected. This is the longest duration gamma-ray emission from the Sun to date, and the characteristics were particularly impressive, exceeding 1000 times the flux of the steady-state Sun, 100 times the flux of Vela, 50 times the brightest Crab flare, and with high-energy emission up to 4 GeV. The GBM separately detected quasi-periodic pulsations in solar flares [141].

7.2.2 Terrestrial gamma-ray flashes

As lightning involves megavolt or higher potential differences, it perhaps is not too surprising that charged

particles can be accelerated to high energy, resulting in gamma-ray emission. Terrestrial Gamma-ray Flashes (TGFs), associated with lightning strikes are under study using both GBM [142] and LAT. Remarkably, the GBM even detected [143] positron and electron beams associated with terrestrial lightning.

8 A look forward

The LAT, GBM and the spacecraft are all functioning extremely well. The Fermi science mission has a five-year primary phase plus an extended phase that is conditionally an additional five years, with reviews throughout the extended phase to evaluate that the mission continues to have excellent productivity and promise. NASA, which directly operates the observatory, just completed a Senior Review that included Fermi for the first time. (All of NASAs extended-phase astrophysics missions are included in the Senior Review, which occurs every two years.) Fermi is now approved to operate through at least 2016 [33]. The LATs international partners, agencies funding particle physics and astrophysics, are also planning continued support of the experiment.

8.1 What's next

8.1.1 *Pass8*

Motivated by effects observed in flight data, as well new ideas for improvements, the LAT Collaboration has been hard at work [144] on a complete rewrite of the ground-based event reconstruction and analysis. This rewrite, called Pass 8, is expected to improve many aspects of the performance, including the point spread function, effective area, and energy resolution, and it will also further expand the energy range of the LAT at both the low-energy and high-energy ends. At this time, Pass 8 is essentially complete and is entering an extended verification phase, which will culminate in the production of the 5-year LAT source catalog and rerelease of the photon data since mission start, reprocessed with the new algorithms.

8.1.2 *Modified observing*

As discussed in the dark matter section above, greater statistics are needed in the Galactic center region. This will happen automatically in sky survey, but options to improve statistics further with time are under consideration. The exposure accumulation rate could be increased by as much as a factor ~ 3 . As five or more years of sky

survey data are already in hand, to be effective the modified profile would presumably be used for more than one year, and it would be designed to minimize negative impacts on other science. Several topics, including searches for pulsars, intermediate timescale transients, and shorter timescale AGN variability [101] might also benefit significantly from the modified profile. The all-sky survey has been extremely productive, but an assessment of alternatives several years into the mission was part of the baseline plan well before launch. Prompted by what has been learned, the Fermi mission is now proceeding with a call [145] for white papers to support the assessment. Good ideas are always welcome!

8.1.3 *GBM continuous TTE*

Much of the GBM trigger and data analysis relies on differential rates in the different detectors. Triggers are based on changes in rates that meet preset criteria. Individual events (time-tagged events, or TTE data) are nominally sent to the ground only around the time of a trigger. In November 2012, the GBM flight software was updated to allow continuous recording and downlink of TTE data with 2 μ s precision, allowing further studies of TGFs and other transients.

8.1.4 *The highest energy Fermi sky*

Fermi has transformed our view of the gamma-ray universe, and the pace of new results and surprises has not slowed after four years. One of the breakthrough areas expected at this stage of the experiment involves events at the highest energies. Because of the characteristics of astrophysical sources, the photon number flux falls steeply with increasing energy, so only now is the LAT beginning to accumulate sufficient statistics for systematic studies and searches for new phenomena well above 100 GeV: of the $\sim 2 \times 10^8$ gamma-ray events from the LAT, there are now ~ 5000 events above 200 GeV (selection dependent), with the highest-energy gamma-ray candidate event recorded at approximately 4 TeV. In some exciting ways, analyses of LAT data above a few hundred GeV are like the early days of a completely new experiment, and there is still much to understand. With its unique all-sky capabilities, the LAT is now opening discovery space for new high-energy phenomena that may even exceed the imaginations of theorists.

The reader is invited to join the fun!

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