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Exploring the Extreme Universe in the *Fermi* Era

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Gamma rays, the most energetic form of light, reveal extreme conditions in the Universe. The *Fermi Gamma-ray Space Telescope* has been exploring the gamma-ray sky for over 14 years, enabling a search for powerful transients like gamma-ray bursts, novae, solar flares, and flaring active galactic nuclei, as well as long-term studies including pulsars, binary systems, supernova remnants, and searches for predicted sources of gamma rays such as dark matter annihilation. Some results include a stringent limit on Lorentz invariance derived from a gamma-ray burst, unexpected gamma-ray variability from the Crab Nebula, a huge gamma-ray structure associated with the center of our galaxy, surprising detections of gamma rays from novae, a gamma-ray burst from merging neutron stars, and a possible constraint on some Weakly Interacting Massive Particle (WIMP) models for dark matter. The *Fermi* instruments continue to monitor the gamma-ray sky and are expected to be important contributors to multiwavelength and multimessenger astrophysics in coming years.

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1. Introduction

The *Fermi Gamma-ray Space Telescope* illustrates a trend in observational astrophysics to have instruments with a wide field of view surveying large parts of the sky repeatedly. A primary incentive for this approach is the growing emphasis on multiwavelength and multimessenger research, particularly for transient or variable phenomena. With more than 14 years of observations, *Fermi* has shown three ways in which a wide-field survey instrument can contribute to understanding the universe:

1. Discovery and study of transients on various time scales;
2. Establishment of long-term trends and archival reference information;
3. Use of non-detections to characterize astrophysical phenomena.

Following a brief description of *Fermi* and its instruments, this short review will describe some examples of these three approaches to revealing aspects of the high-energy sky.

2. *Fermi Gamma-ray Space Telescope*

Launched into a low-Earth orbit in June, 2008, the *Fermi Gamma-ray Space Telescope* monitors the gamma-ray sky continuously. Compared to ground-based telescopes, its is fairly small, with an effective area less than 1 square meter. The two instruments carried on the satellite can be seen in the pre-launch photo (Fig. 1), and a recent overview of the project is given in [1].

The Large Area Telescope (LAT) detects gamma rays that interact interact with the instrument, initiating electron-positron pair production, using a silicon-strip tracking detector and a Cesium Iodide calorimeter to identify gamma rays and measure arrival direction, energy, and arrival time for individual photons [2]. LAT measurements cover an energy range from about 20 MeV to more than 500 GeV. Its field of view is 2.4 steradians, or about 20% of the sky at any instant.

The Gamma-ray Burst Monitor (GBM) uses a set of Cesium Iodide and Bismuth Germanate scintillators to detect gamma rays with energies between 8 keV and 40 MeV [3]. At any given time, the GBM views every part of the sky that is not occulted by the Earth.

Because there are no mirrors or lenses for high-energy photons, both the LAT and GBM have limited angular resolution. Source locations are determined by measurements of ensembles of detected photons, ranging as a function of photon energy from a few degrees down to a few arcminutes. The individual photons seen by the two instruments have arrival times that are measured with microsecond accuracy.

The *Fermi* satellite is operated almost entirely in a scanning mode, with the LAT pointed away from Earth. By alternating the pointing angle in successive orbits, both instruments can achieve exposure to the entire sky approximately every three hours. The result is continual monitoring of the sky covering over seven decades of photon energies.

One important aspect of the *Fermi* mission is that all the gamma-ray data become public immediately. The *Fermi* Science Support Center located at Goddard Space Flight Center, makes

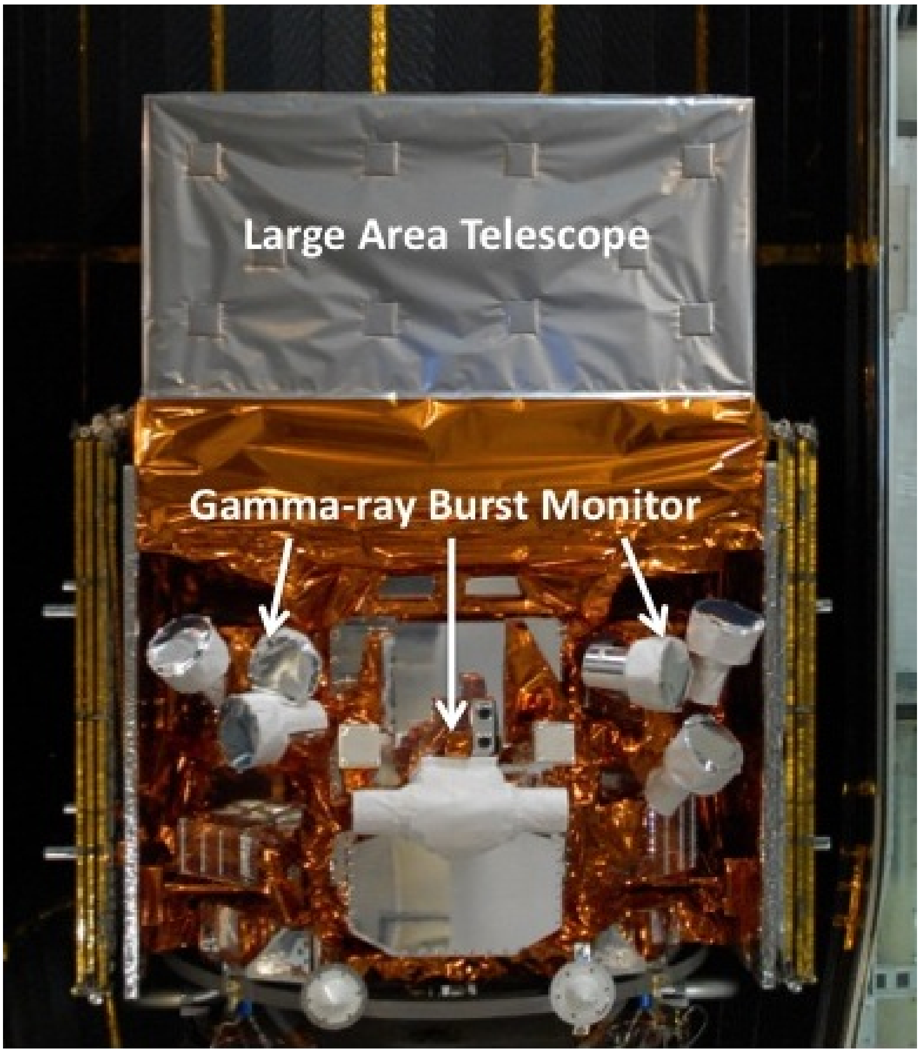

Figure 1: Photo of *Fermi Gamma-ray Space Telescope* atop the rocket before launch. The solar panels on the sides of the satellite unfolded after launch (Credit: NASA).

the data available along with software and detailed documentation about how to do analysis of the data [1].

3. Transients

The high-energy sky is highly dynamic. Transients are seen with durations of fractions of a second, seconds, minutes, hours, days, weeks, and even longer, to the point it would be more accurately described as variability rather than transient. Especially for the shorter transients, wide-field survey missions like *Fermi* maximize the chance of detecting such phenomena, measuring their properties, and alerting other observatories of such activity.

The best-known transient discovery is the likely the gamma-ray burst/gravitational wave event GRB 170817A/GW170817 that signaled the inspiral of two neutron stars [4, 5]. The first an-

[1] https://fermi.gsfc.nasa.gov/ssc/

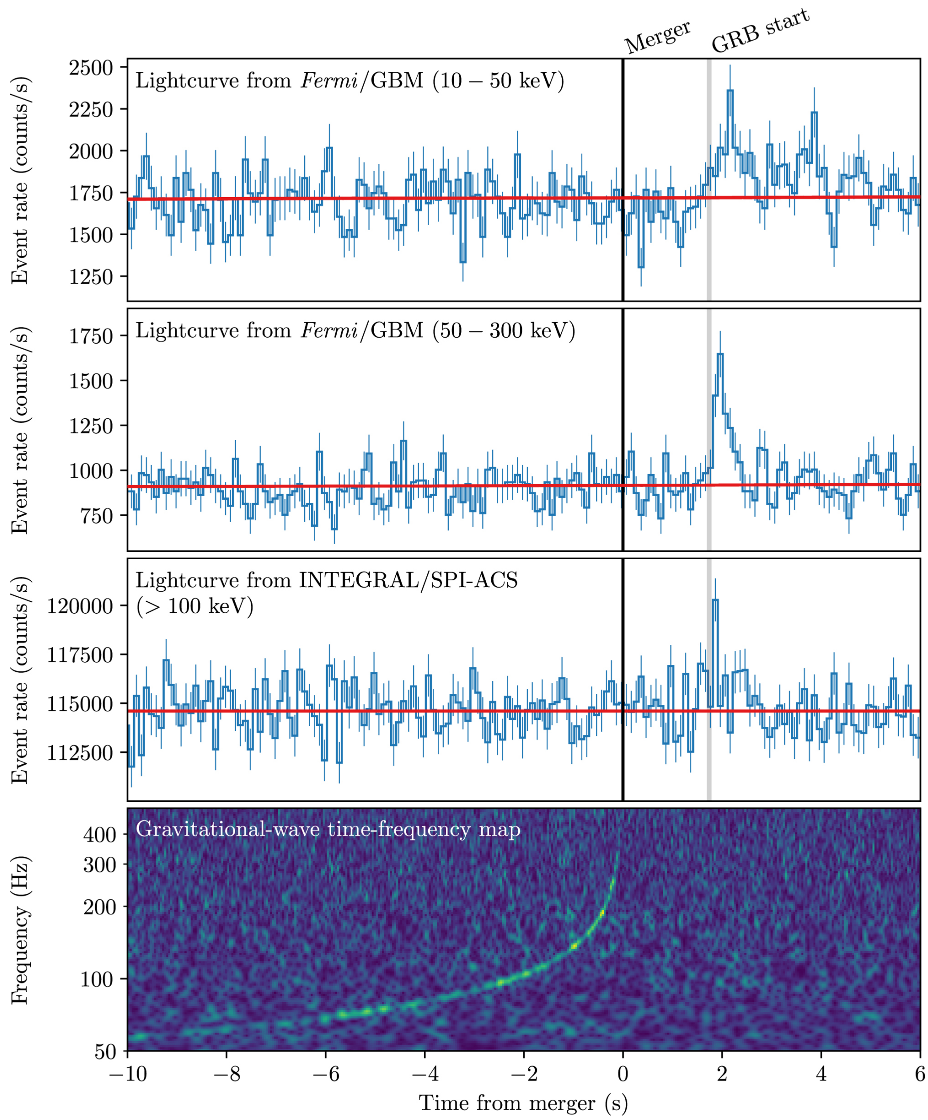

Figure 2: Multimessenger detection of GW170817 and GRB 170817A [5]). Top two panels: *Fermi* GBM light curves in the 10-50 keV and 50-300 keV energy bands. Next panel: *INTEGRAL* SPI-ACS lightcurve for the energy range > 100 keV. Bottom panel: the time-frequency map of GW170817 from LIGO-Hanford and LIGO-Livingston. Reproduced with permission.

nouncement of this event was the Gamma-ray Coordinates Network (GCN) notice from the *Fermi* GBM, generated autmatically on board and sent out just 14 seconds after the burst [6]. The timeline of the initial observations is shown in Fig. 2. This discovery stimulated a huge multiwavelength/multimessenger campaign that produced an array of scientific results. One immediate result from the measurements is the first direct determination that the speed of gravity is essentially the same as the speed of light.

Another *Fermi* gamma-ray burst result that involves fundamental physics was the measurement of GRB 090510. What this burst tested was the concept of Lorentz invariance, the idea that the speed of light is the same for all photon energies. Some models of quantum gravity predict that

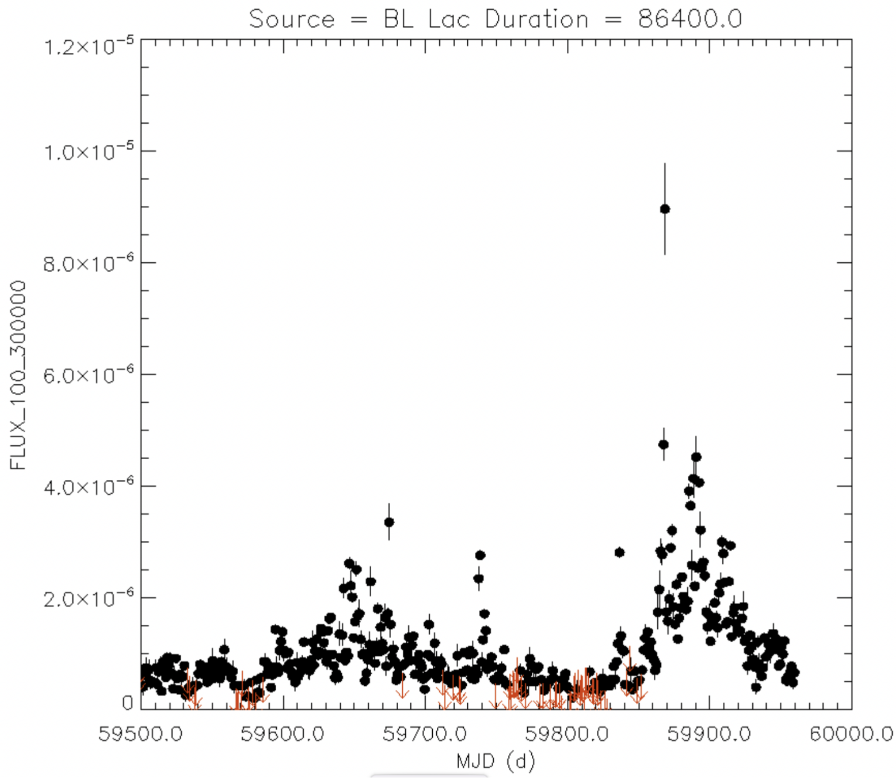

Figure 3: One year, shown in Modified Julian Days, of *Fermi*-LAT daily E>100 MeV flux values from BL Lac, from the public automated data release at the *Fermi* Science Support Center (`https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/`).

Lorentz invariance could be violated. This distant burst (redshift 0.9, representing a light travel time of about 7 billion years) produced gamma rays in both the GBM and the LAT, allowing simultaneous measurements over a broad range of energies. The lack of time offsets in the *Fermi* data put strong constraints on any variation of the speed of light and some quantum gravity models [7].

Transients with time scales of days were an unexpected gamma-ray discovery by the Italian *AGILE* gamma-ray telescope and the *Fermi* LAT of bright, rapid flares from the Crab Nebula [8, 9]. Long considered a completely steady source at high energies (except for the pulsar that powers it), the nebula must have physical processes that can accelerate electrons to PeV energies in order to produce the observed flares. A review of the new views of the Crab can be found in [10].

On a transient scale of weeks, another surprise discovery was gamma-ray novae [11]. Novae are produced when accretion onto a white dwarf in a binary system produces runaway fusion, but this process seems unlikely to accelerate particles to high enough energies to produce gamma rays. Instead, the particle acceleration/gamma-ray production seems to come from shocks in the surroundings of the binary. In at least one case, the optical light curve matches the *Fermi*-LAT gamma-ray light curve, implying that the optical emission itself comes from these shocks [12].

Blazars, active galactic nuclei with jets pointed close to the line of sight, are the most numerous high-energy gamma-ray sources. As illustrated in Fig. 3 for BL Lacertae, these blazars show flaring activity on time scales ranging from days to months. The monitoring by *Fermi* LAT allows

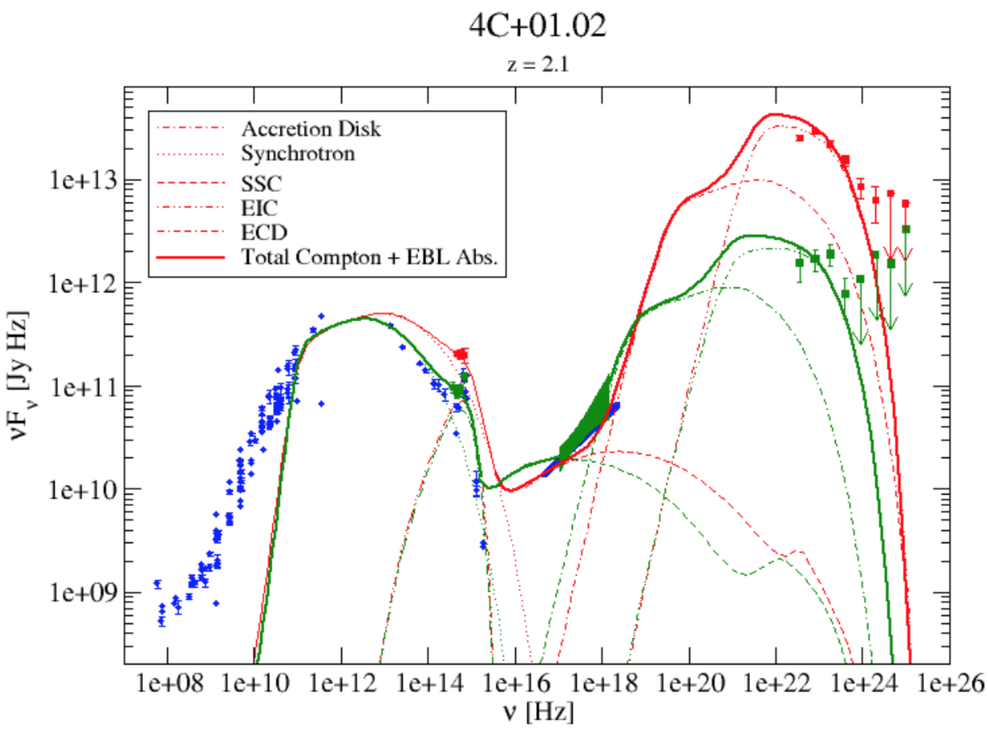

Figure 4: Broadband spectral energy distributions of blazar 4C+01.02 under quiescent (green lines) and flaring (red lines) states [13]. ©AAS. Reproduced with permission.

simultaneous observations whenever multiwavelength observations could be taken. A comparison, shown in Fig. 4, of spectral energy distributions for blazar 4C+01.02 under different conditions [13] illustrates how different these spectra can be, not only in magnitude but in shape. Simultaneous observations are essential in order to have models with any hope of extracting physical parameters from these blazar jets.

4. Long-duration Studies

Repeated surveys of the sky not only flag transients, they also accumulate an archival monitor that can be referenced for a variety of purposes. The story of the association of a high-energy IceCube neutrino with blazar TXS 0506+056 is an example of how the process can work. The IceCube team put out an alert for a track-like neutrino event (`https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3`), and a number of telescopes did follow-up, but the error region for the neutrino was too large to identify a good candidate. That changed when the LAT team recognized that one of the gamma-ray blazars in the region was flaring, announcing the result in an Astronomer's Telegram [14]. This ATel then provided the community with a specific target, enabling dedicated observations. Even with this candidate, the challenge was to determine whether this association was just a chance coincidence. Both IceCube and *Fermi* had archives that allowed an empirical determination of the chance probability [15]. IceCube data also revealed a previous cluster of neutrinos from the direction of this source [16].

Table 1: Numbers of Sources in *Fermi* Large Area Telescope catalogs

Catalog name	Number of Sources
1FGL	1451
21FGL	1873
3FGL	3033
4FGL	5064
4FGL-DR2	5788
4FGL-DR3	6658

The neutrino analysis was one example of the value of having an all-sky archive, but there are other aspects to archival studies. The *Fermi*-LAT observations are largely statistics-limited rather than being background-limited, so as the archive builds up, more sources can be found in the data. Table 1 shows the effect of accumulation of data. Each of these is an all-sky catalog. All can be found at the *Fermi* Science Support Center (`https://fermi.gsfc.nasa.gov/ssc/data/access/`.)

Pulsar timing is another example of the value of archival data. This synergy between radio and gamma-ray pulsar analysis has produced numerous discoveries. One example is the discovery of PSR J1555−2908. The radio pulsar was found in 2017 during a search of unidentified *Fermi*-LAT source regions. Once the radio timing model had been established, the gamma-ray archive allowed the gamma-ray pulsations to be traced all the way back to the beginning of the *Fermi* mission in 2008 [17], as shown in Fig. 5. The many new pulsars being found with MeerKat include some found using this same approach (e.g. `http://www.trapum.org/`). In fact, there are now enough well-timed gamma-ray pulsars that it is possible to do the same sort of pulsar timing array searches for gravitational radiation that are being done in the radio [18].

Long-term monitoring from surveys allows for searches for periodic or quasi-periodic behavior. One of the best examples in the *Fermi*-LAT data is the strong indication of a ~ 2.2 year period in blazar PG 1553+113, Fig. 6 [19, 20]. Having the continuous monitoring from *Fermi* helps avoid artifacts that come from having gaps in the data. This periodicity suggests the possibility that this system contains two supermassive black holes.

Having all-sky survey data is important not only for time-domain studies but also for large-scale spatial analysis. A primary example is the discovery of the *Fermi* Bubbles, giant gamma-ray structures that span about 100 degrees on the sky, centered on the direction of the Galactic Center [21]. These features, which suggest some form of activity from the center of the Milky Way, are far too large to be seen with narrow-field instruments.

5. Non-detections

Although not obvious, wide-field survey missions also benefit studies that involve non-detections of sources. The key idea is that having all-sky exposure allows analysis of many objects in a class, so that failure to detect one or a few targets cannot be dismissed as having chosen the wrong sample.

Before the launch of *Fermi*, there were predictions, made with some confidence, that *Fermi* LAT would see clusters of galaxies as gamma-ray sources. Galaxy clusters are known to have non-

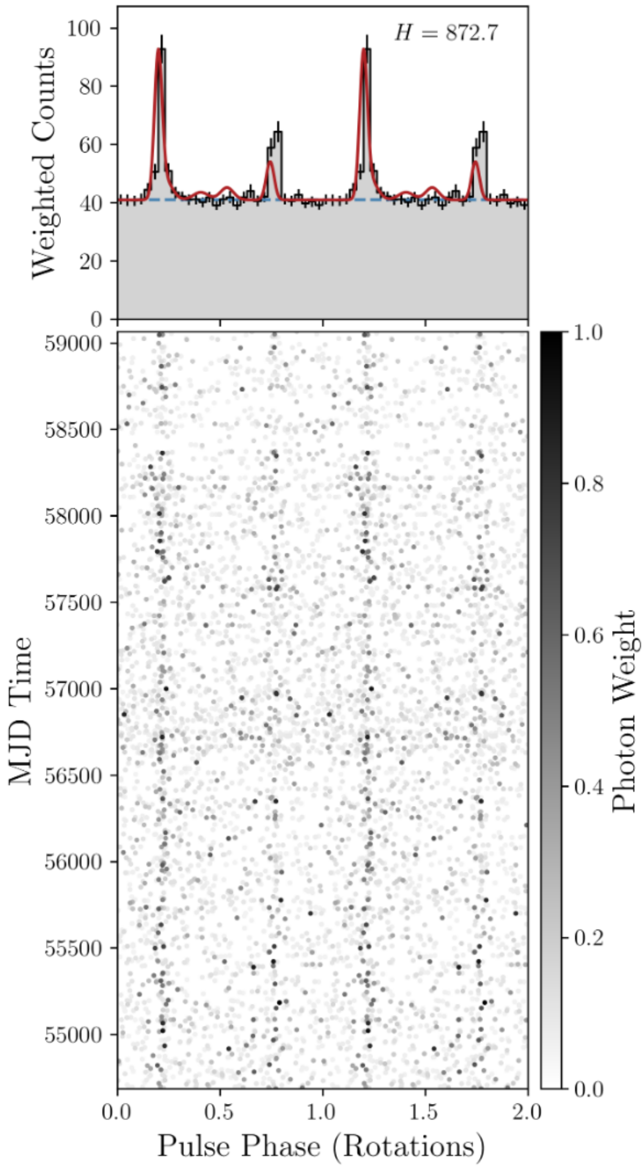

Figure 5: Top: pulse profile of PSR J1555−2908, showing two identical rotations for clarity. The gray is the gamma-ray signal, while the red is from the radio. Bottom: phase-folded gamma rays as a function of time[17]. ©AAS. Reproduced with permission.

thermal emission that implies particle acceleration, so it seemed quite plausible that these accelerated particles would produce gamma rays. There are, however, no high-confidence detections of clusters of galaxies in the LAT catalogs, and explicit searches for such sources have produced only upper limits [22]. These non-detections imply that clusters of galaxies, either individually or collectively, are not accelerating as many particles or particles with high enough energies to match the model predictions.

Another example is dwarf spheroidal galaxies. These satellite galaxies of the Milky Way are thought to be mostly made of dark matter and do not contain any of the familiar classes of gamma-

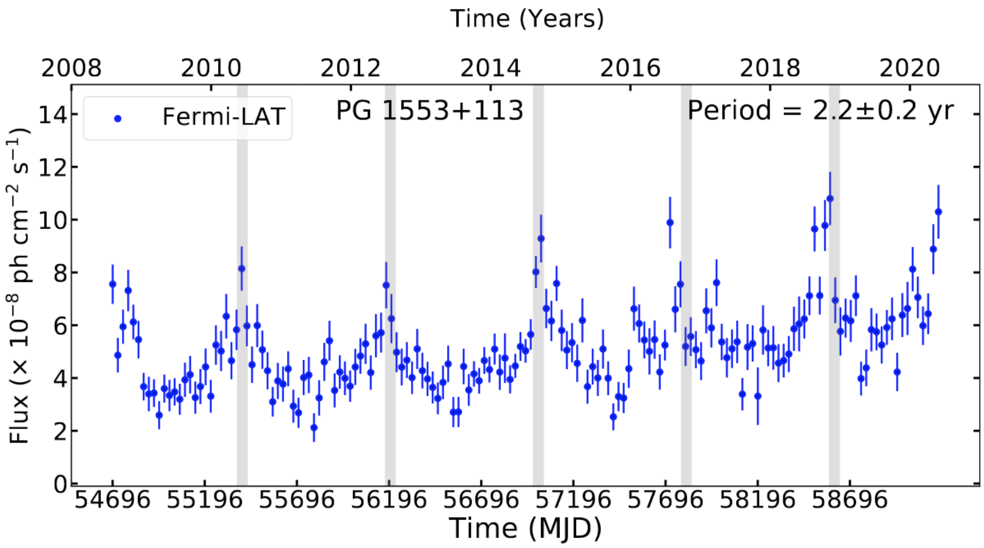

Figure 6: Multi-year gamma-ray fluxes above 100 MeV from blazar PG 1553+113 [20]. Reproduced with permission.

ray sources. If dark matter interactions produces gamma rays, as some Weakly Interacting Massive Particle (WIMP) models suggest, then dwarf spheroidals could be gamma-ray sources. Numerous studies have looked, and no dwarf spheroidal has been found in the LAT data with high confidence. Being able to look at all the known dwarf spheroidals eliminates the possibility that we just looked in the wrong direction. An example is shown in Fig. 7 [23], which shows upper limits on the WIMP interaction cross section derived from the non-detections. This interaction cross section determines the abundance of such particles in the universe. Although there is some tension with the LAT results from the Galactic Center region interpreted as coming from WIMP interactions (the little ovals near the middle [24]), the limits can rule out the possibility that lower-mass WIMPs can account for all the known dark matter.

6. Conclusion

The more than 14 years of observations by the two instruments on the *Fermi Gamma-ray Space Telescope* have demonstrated the scientific value of wide-field instruments surveying the full sky repeatedly. Transients, long-term variability, large spatial features and even non-detections of sources by *Fermi* have added to our understanding of the high-energy universe, particularly through multiwavelength and multimessenger studies. Because the *Fermi* detectors have no consumables and the satellite orbit is stable, the mission may continue for many years.

7. Acknowledgments

A major observatory like *Fermi* involves the work of hundreds of scientists, engineers, technicians, software developers, and others. I am grateful to all those who have contributed to the success of *Fermi*.

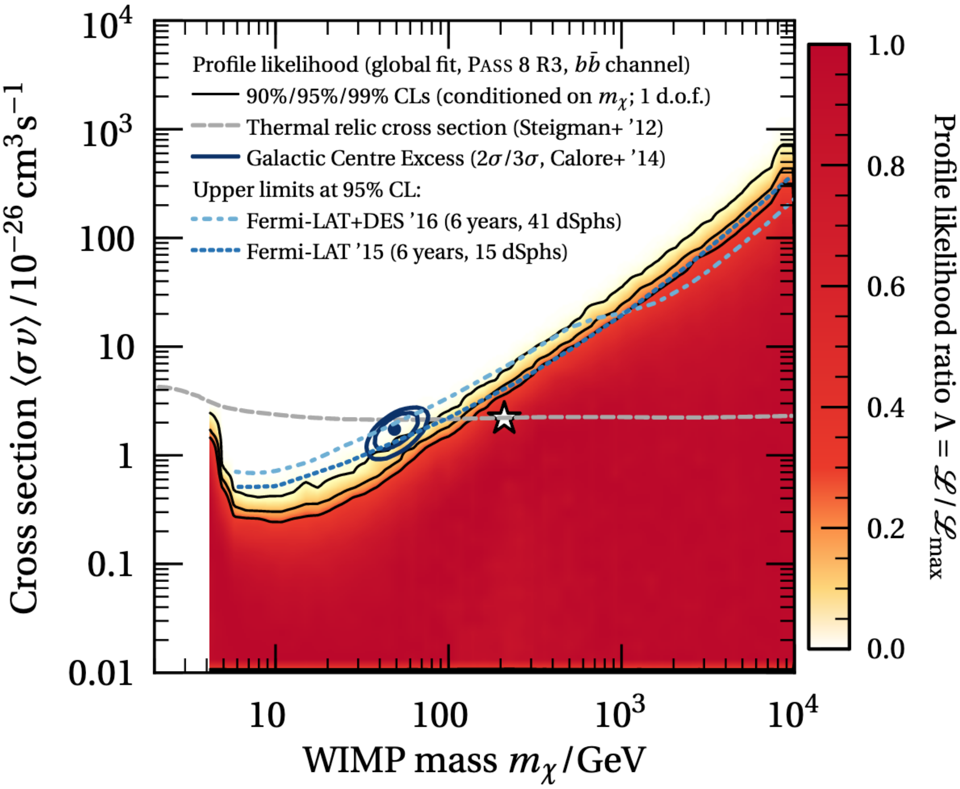

Figure 7: Example of upper limits on WIMP interaction cross sections as a function of WIMP mass, shown as solid or colored lines and derived from non-detections of dwarf spheroidal galaxies [23]. The dashed gray line shows the cross section that would be needed to explain the known dark matter in the universe. The small ovals are possible cross sections from a dark matter interpretation of the gamma-ray excess in the Galactic Center region [24]. Reproduced with permission.

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