16 years of Gamma Ray Discoveries with Fermi

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Abstract. In the year 2024, the Fermi Gamma-ray Space Telescope is celebrating its 16th year of operation. The Large Area Telescope (LAT) is the main instrument onboard the Fermi satellite and is designed to be sensitive to gamma rays in the energy range from about 20 MeV up to the TeV regime. From its launch, the LAT has collected more than 4.53 billion photon events, providing crucial information to improve our understanding of particle acceleration and gamma-ray production phenomena in astrophysical sources. The Gamma-ray Burst Monitor (GBM), the secondary instrument onboard Fermi, has a field of view (FoV) several times larger than the LAT and provides spectral coverage of gamma-ray bursts (GRBs) and other transients phenomena that extends from the lower limit of the LAT down to 10 keV. GBM has detected more than 3800 bursts to date, including the famous short GRB 170817A jointly detected in gravitational waves (GWs), thus providing the first direct evidence that colliding neutron stars can produce GRBs. In this talk, some of the main results obtained by the Fermi LAT and GBM collaborations will be reviewed, with a particular focus on GRB science.

1 Introduction

The Fermi Gamma-ray Space Telescope, commonly known as Fermi, is a mission designed to observe gamma rays, the highest-energy form of light, originated from sources throughout the Universe. Launched on June 11th, 2008, it recently celebrated 16 years of successful operations in space. Fermi is equipped with two main instruments: the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT is the primary instrument onboard the Fermi satellite. It scans the entire sky every three hours, detecting gamma rays by means of the pair production mechanism in the energy range from about 20 MeV to over 300 GeV. The LAT has a wide FoV and high sensitivity, enabling it to detect and map gamma-ray sources with high precision. Fermi's secondary instrument, the GBM, is designed to detect transient gamma-ray events such as gamma-ray bursts (GRBs). With its 14 scintillator detectors, GBM covers a lower energy range than the LAT, from about 8 keV to 40 MeV, complementing the LAT's observations.

Over the past 16 years, GBM and LAT contributed to an incredible amount of observations and discoveries of the most extreme galactic and extragalactic objects, such as pulsars, Active Galactic Nuclei (AGN) and Gamma-Ray Bursts (GRBs). Fermi has created detailed maps of gamma-ray sources both within our Galaxy and beyond, cataloging thousands of objects over different gamma-ray energy ranges, thus providing a comprehensive view of the high-energy Universe. Moreover, while definitive evidence of dark matter has not been found yet, Fermi LAT data has placed constraints on theoretical models and has guided future searches.

The Fermi Gamma-ray Space Telescope is an international collaboration involving several institutions and agencies from around the world, including NASA, the primary agency responsible for the Fermi

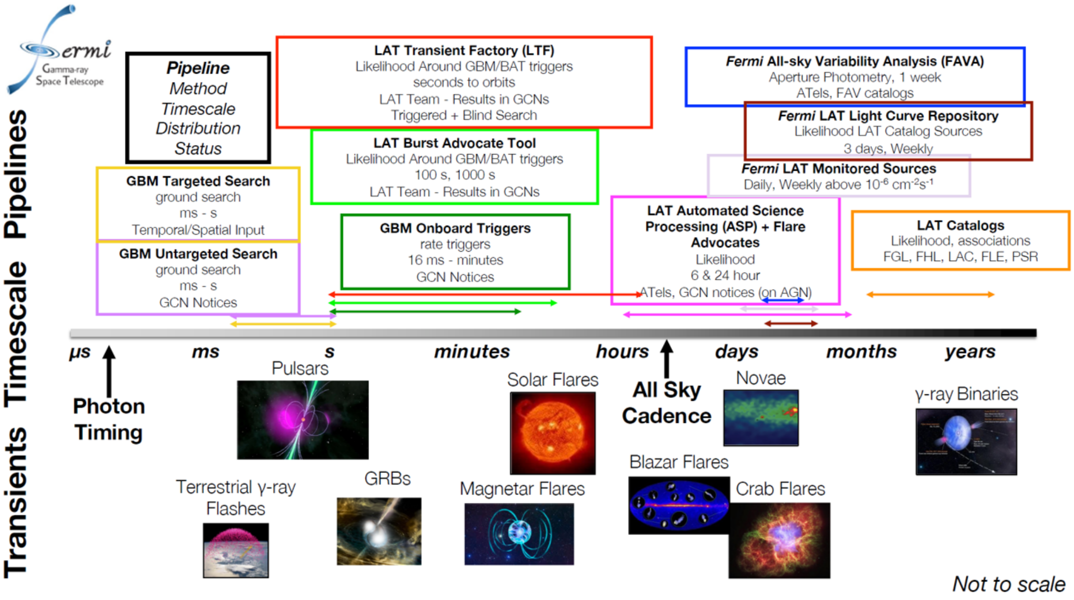

Figure 1: Fermi GBM and LAT Pipeline searches on various timescale. Credit: Fermi LAT and GBM Collaborations 2017.

mission, which manages the overall mission operations, the U.S. Department of Energy (DOE), the French Atomic Energy Commission (CEA) and the National Institute for Nuclear and Particle Physics (IN2P3) of the National Center for Scientific Research (CNRS) in France, the Italian Space Agency (ASI), the Italian National Institut for Nuclear Phyisc (INFN) and the Italian National Institut for Astrophyiscs (INAF) in Italy and numerous universities and research institutions from countries such as Japan, Germany, Sweden, and the United Kingdom. Scientists from these institutions participate in data analysis, theoretical modeling, and interpretation of the results, in an effort that establishes the profound collaborative nature of the Fermi mission.

2 Fermi Mission status and news

As of July 2024, the Fermi satellite is operational and the spacecraft and instrument performance are excellent, with no consumables or expected rapid degradation of the spacecraft or instruments' components. Since the only hardware issue on March 16, 2018, when a mechanism driving one of its solar panels had a failure, the Fermi mission has implemented new survey strategies to continue its observations effectively. This modified survey strategy maintains comfortable power margin, while avoiding loss of observational efficiency due to the solar panel position at fixed angle. Furthermore, over the whole mission period, the Fermi Team conducted two maneuvers to prevent close encounters with other satellites by fireing Fermi's decommissioning thrusters to move it to safety. The first maneuver took place on April 3rd, 2012, when Fermi avoided a potential collision with Cosmos 1805, a defunct Soviet Cold War spy satellite; and the second one on January 31st, 2024, in order to mitigate a close approach to the free-flying CubeSat deployer and technology demonstrator IONSCV-004.

Since the beginning of the mission, the Fermi Science Support Center (FSSC)[1] has been continuously providing comprehensive documentation, tutorials, and user support for both LAT and GBM software tools. These tools and resources are supplied to the scientific community allowing to effectively analyze Fermi data as soon as they are available for download at the data access portal. The Fermi mission offers a comprehensive suite of tools known as Fermitools[2] for analyzing data from both the LAT and GBM instruments. This suite, developed by FSSC and the instrument teams, was originally named ScienceTools and later changed to Fermitools when the software hosting and distribution were moved to GitHub and Conda. Additionally, the GBM team has created specialized tools specifically designed for

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

[2] `https://github.com/fermi-lat/Fermitools-conda`

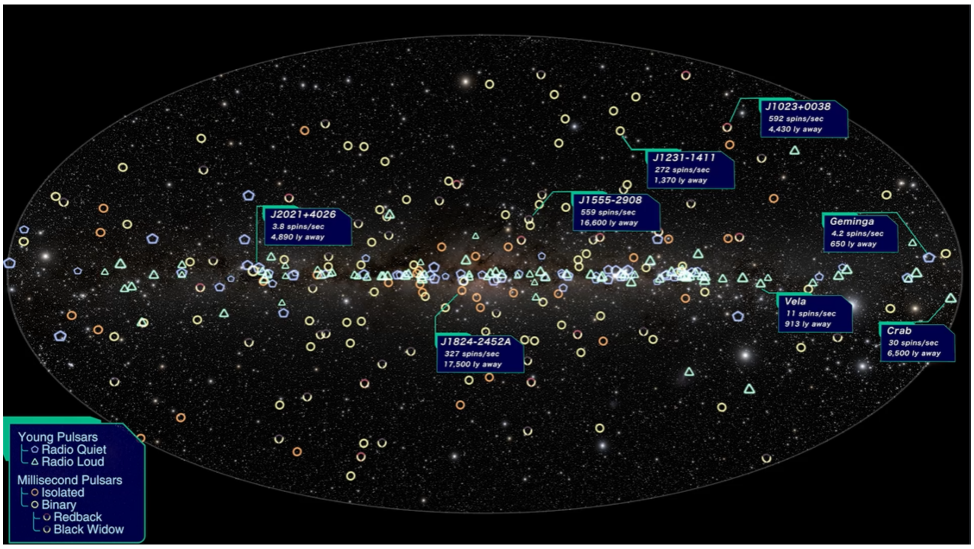

Figure 2: 294 gamma-ray pulsars seen by LAT, in galactic coordinates. Symbols mark different types of pulsars as given in the box in the bottom left corner. A few notable objects are highlighted, including the Crab, Vela, and Geminga pulsars, which were among the 11 gamma-ray pulsars known before Fermi launched. Image Credit: NASA's Goddard Space Flight Center, full video available at `https://svs.gsfc.nasa.gov/14434`.

GBM data analysis, the Gamma-ray Data Tools (GDT), released on June 6th, 2024[3]. The FSSC also maintains a library of contributed software, developed by the Fermi user community, such as Fermipy, which can be beneficial for various analyses.

Together, Fermi LAT and GBM monitor a wide range of transient and steady high-energy phenomena from microseconds to years. Figure 1 effectively summarizes the different analysis pipelines set up and maintained by both collaborations over the years according to the various timescales of the potential transient phenomena to detect, ranging from milliseconds for terrestrial gamma-ray flashes or pulsars to years for gamma-ray binaries.

At the shortest timescales, we find the GBM Targeted and Untargeted Searches, which represt ground searches operating from milliseconds to seconds, specifically designed to follow up various multimessenger signals such as gravitational wave events and neutrino alerts. While the first need a specific temporal and spectral input, the latter can be triggerd by external GCN notices. The GBM instrument has a trigger system designed to detect transient gamma-ray events on several temporal and energy scales to maximize its detection capabilities, with triggering timescales ranging from 16 milliseconds up to a few seconds (see [1] for more details about current Fermi GBM trigger settings).

The Fermi LAT Transient Factory (LTF) and LAT Burst Advocate Tool use likelihood analysis methods around GBM or external triggers (e.g. provided by the Swift-BAT instrument) to detect high-energy emission from astrophysical transients above 100 MeV, both operating on a timescale of hundreds to thousands of seconds. On longer timescales, the LAT Automated Science Processing (ASP) analyses data over 6 and 24-hour periods, particularly focusing on active galactic nuclei (AGN). The automatic pipeline is closely monitored by Team members acting as Flare Advocates.

On even longer timescales, pipelines like the Fermi All-sky Variability Analysis (FAVA) performs aperture photometry on a weekly basis. Results are then distributed either through ATels in case of important results, or later on in catalogs. Also the Fermi LAT Light Curve Repository analyzes LAT catalog sources over three days to a week. Known Fermi-LAT sources are monitored daily or weekly (for sources above 10^{-6} cm^{-2}s^{-1}). All the long-term analysis results are then regularly published in LAT Catalogs.

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[3] `https://astro-gdt.readthedocs.io/en/latest/`

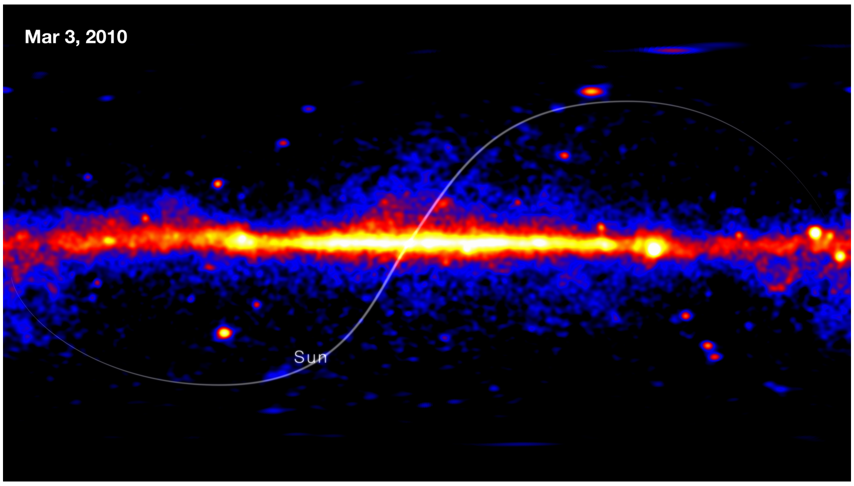

Figure 3: From solar flares to black hole jets: a unique time-lapse tour of the dynamic high-energy sky, compressing 14 years of gamma-ray observations (from August 10, 2008, to August 2, 2022.) into 6 minutes. The entire gamma-ray sky is unwrapped into a rectangular map, with the center of the Milky Way galaxy located in the middle. A moving source, the Sun, can be seen following its annual curving path through the sky. Full video available at `https://svs.gsfc.nasa.gov/14399`.

3 Fermi LAT highlights

Over the past 16 years, Fermi LAT has made numerous groundbreaking discoveries that have significantly advanced our understanding of the high-energy Universe. As of June 2024, LAT has registered more than 939 billion triggers, ofr a total of more than 4.5 billion LAT events available for analysis at the FSSC. The LAT has conducted a comprehensive survey of the gamma-ray sky, revealing thousands of new gamma-ray sources. As a result, four major source catalogs have been published over its mission, starting from 1FGL (First Fermi-LAT Catalog, [2]), released in 2010 and covering the first 11 months of the mission, up to 4FGL [3], the latest major catalog, initially released in 2019, including sources detected in the first eight years of the mission. Updated versions of the 4FGL catalog have been released to include more recent data, the latest one being 4FGL-DR4[4], based on 12 years of data and covering a broad energy range from 50 MeV to 1 TeV. The extended observation period allowed for the detection of fainter and more distant sources compared to earlier catalogs, for a total of 7194 gamma-ray sources, out of which more than a thousand were totally new ones. Each source is analyzed using different spectral models to determine the best fit, with localization and variability indices provided to enhance follow-up observations. The catalog includes extended sources that are spatially resolved in gamma-rays, such as certain SNRs and PWNe, with detailed morphological information. Associations with sources detected in other wavelengths (radio, optical, X-ray) are included, providing a comprehensive view of each source's multi-wavelength properties. The majority of identified sources are AGN ($\sim$57%), particularly blazars ($\sim$23%), while $\sim$34% of sources still remains unassociated.

Regarding blazar science, the biggest breakthrough was the detection of a 290 TeV neutrino, IC-170922A, by the IceCube experiment in 2017, coinciding with the flaring blazar TXS 0506+056 observed by Fermi-LAT [4]. This event, followed by several other multiwavelength observations, including optical, X-ray, radio, and very-high energy (VHE) gamma-ray, which confirmed the heightened activity, provided strong evidence that blazars can be sources of high-energy cosmic neutrinos and marked an incredibly significant milestone in multimessenger astrophysics.

The third most numerous type of sources detected by Fermi LAT are pulsars ($\sim$5%). The latest published catalog is the Third Pulsar Catalog (3PC [5]), which includes 294 known and 34 candidate pulsars detected at GeV energies by Fermi LAT (see Figure 2). The catalog highlights the methods used to detect and analyze gamma-ray pulsars, including information on their timing, spectral properties, and spatial distribution, providing insights into their origins and behaviors. Almost half of the objects in the catalog are old, fast-spinning millisecond pulsars. The catalog also includes about a dozen candidate "spider" binary systems, in which the emissions and particle outflows of a spinning pulsar become so

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[4] `https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/`

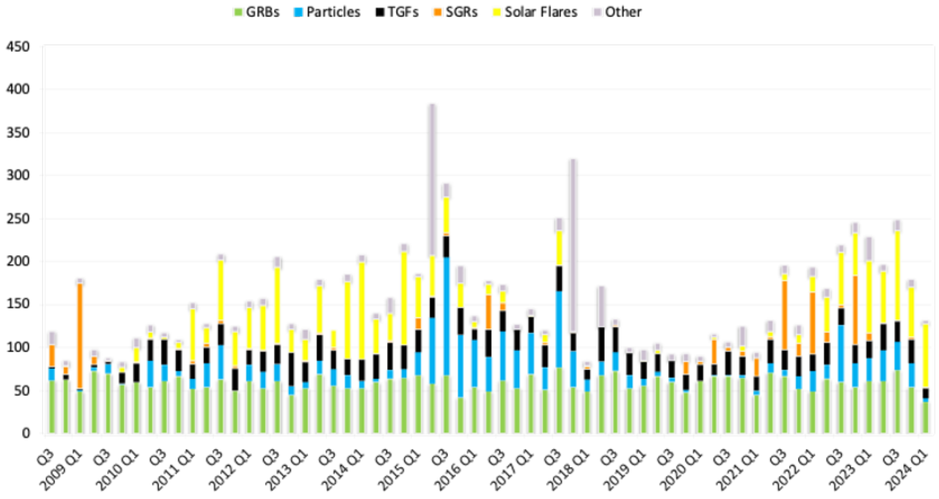

Figure 4: Fermi GBM triggers as of April 2024. Credit: Fermi GBM Collaboration 2024.

energetic that they heat up and slowly vaporize their companions.

In December 2023, the Fermi-LAT Collaboration released an all-sky time-lapse movie made from 14 years of data, showing spatially and temporally smoothed maps of gamma-ray intensity above 200 MeV observed between August 2008 and August 2022 (see Figure 3). Fermi completes 16 orbits every day, thus normally observing the entire sky several times every day. The maps are based on Pass 8 source class gamma rays with arrival directions within 100 degrees of the zenith, in order to exclude contamination by the Earth's limb. Daily maps were smoothed spatially with a 2-dimensional Gaussian of FWHM 2 degrees and temporally (via a 1-dimensional gaussian weighting of FWHM = 4.7 days) to suppress statistical fluctuations. The temporal smoothing suppressed variations on time scales shorter than about 5 days.

In the movie, the central plane of the Milky Way glows in gamma rays produced from cosmic rays striking interstellar gas and starlight, and it is flecked with many other sources, including neutron stars and supernova remnants. Above and below the Galactic plane, rapidly changing sources, like flaring blazars and other extragalactic sources, provide striking snapshots of black hole activity throughout cosmic time. Not seen in the time-lapse are many short-duration events like GRBs, as a result of processing data across several days to sharpen the images. The Sun, occasionally flaring into prominence, traces a path through the sky against the backdrop of high-energy sources within our Galaxy. Not shown in the video are the Fermi Bubbles, enormous, bubble-like structures emanating from the center of the Milky Way, discovered in LAT data in 2010 [6]. These structures, extending about 25,000 light-years above and below the Galactic plane, emit gamma rays and are thought to be the remnant of past energetic events, such as outflows from the supermassive black hole at the galaxy's center or intense star formation activities. Their discovery remains one of the most important over the whole Fermi mission time.

4 Fermi GBM highlights

During Fermi's mission lifetime, GBM has primarily provided extensive data on the spectral and temporal properties of GRBs. It has also played a crucial role in multimessenger astronomy, as it has been the key instrument to confirm the association of short GRBs with GW events, providing crucial timing and location information. As of June 2024, GBM registered over 9300 onboard triggers, resulting in more than 3800 confirmed GRBs. The GBM Collaboration produced four trigger and four spectral GRB catalogs over the years, with the most recent ones covering 10 years of GRB observations [1, 7].

Besides GRBs, GBM regularly detectes many other high-energy gamma-ray transient phenomena, such as Solar Flares, Soft Gamma-Ray Repeaters (SGRs), or Terrestrial Gamma-ray Flashes (TGFs). Figure 4 shows the number of GBM triggers over the whole mission period, divided into quarterly bins. Different colors indicate different sources, as indicated on the top. Particularly interesting is the fact that solar triggers follow the solar cycle, which had a maximum around 2014 (Solar Cycle n.24) and is reaching the next one in 2025 (Solar Cycle n.25). Other interesting sources showing an extreme number of triggers over very short period are V404 Cygni (first gray peak in 2015) and Swift J0243.6+6124 (second gray

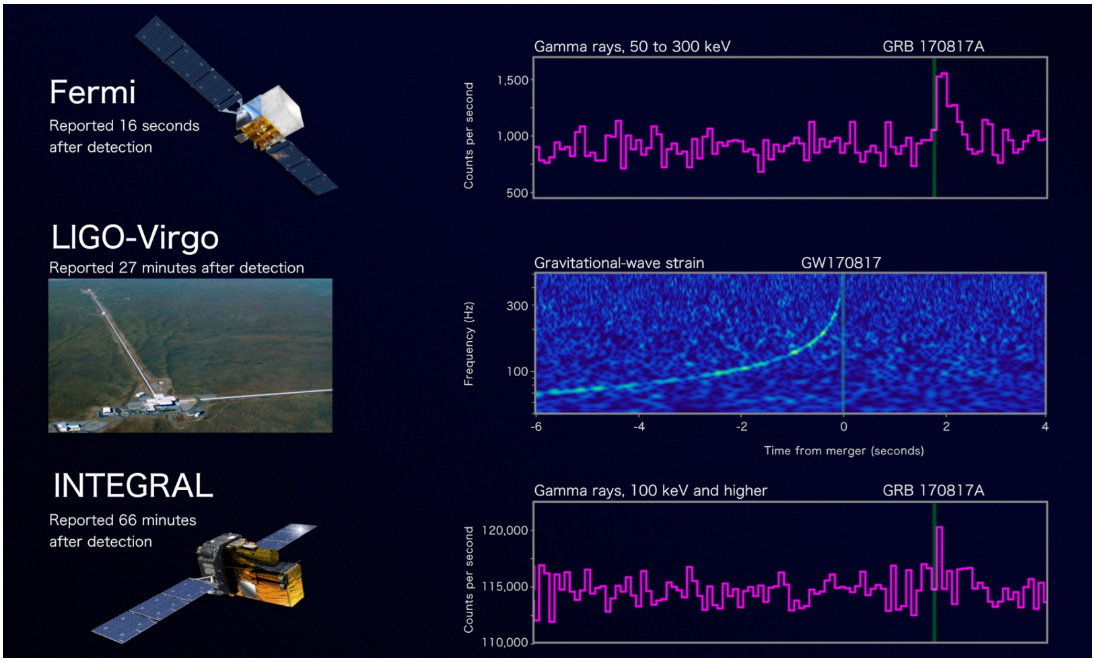

Figure 5: Joint, multi-messenger detection of GW170817 and GRB 170817A. Top panel: GBM lightcurve between 50 and 300 keV. Middel panel: Time-frequency map of GW170817 obtained by coherently combining LIGO-Hanford, LIGO-Livingston and Virgo data. Bottom panel: INTEGRAL SPI-ACS lightcurve starting at 100 keV (high energy limit ∼80 MeV). Time is referenced to the GW170817 trigger time. Adapted from [17].

peak in 2017). V404 Cygni is a binary star system consistsing of a black hole and a companion star, which experienced a notable outburst event in June 2015, exhibiting intense and variable emissions across multiple wavelengths [8], while Swift J0243.6+6124 is a neutron star X-ray binary system discovered by the Swift satellite and is known for being the first ultraluminous X-ray pulsar in our Galaxy. This source flared dramatically in October 2017, exhibiting extremely high X-ray luminosity and pulsations, providing valuable insights into the behavior of neutron stars and the mechanisms of accretion [9].

Another milestone for GBM was the early study of the Crab Nebula, traditionally considered to be a reliable standard candle in hard X-ray and gamma-ray astronomy. A notable ∼7% decline in the overall Crab Nebula flux in the 15-50 keV band was observed since August 2008 by GBM using the Earth occultation technique, which was independently confirmed by other instruments across similar and broader energy ranges [10]. A list of ∼250 sources, both Galactic and Extragalactic, monitored by GBM through the Earth Occultation technique, is available at the National Space, Science, and Technology Center (NSSTC)[5].

5 The role of Fermi in GRB Science and the Multimessenger era

The first 16 year of the Fermi mission proved that GBM and LAT successfully complement each other to provide a comprehensive understanding of GRB phenomena across a broad range of energies and timescales. GBM was designed to detect GRBs and other transient phenomena across a wide FoV, i.e. the entire sky not obscured by the Earth. Its wide energy range extending from 8 keV to 40 MeV, enabled the detection of both the lower and higher energy emissions of GRBs. Also GBM's high temporal resolution proved to be crucial for studying the rapid variability of GRBs. While the GBM provides relatively coarse burst localization, it can quickly alert other telescopes, both ground-based and space-based, to follow up with more precise measurements. This rapid dissemination of GRB coordinates is vital for multimessenger and multiwavelength observations.

The detection of high-energy emissions by the LAT, whose energy range reaches down to 20 MeV, thanks to the LAT Low-Energy technique (LLE), and extends to hundreds of GeVs, provided insights

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[5] `https://gammaray.nsstc.nasa.gov/gbm/science/earth_occ.html`

into the most energetic processes occurring in GRBs. LAT's excellent spatial resolution often enabled precise localization of GRBs, especially in the first 10 years of the mission, when the autonomous repoint capability was still operational, and the burst could be kept in the LAT FoV and followed-up for almost six hours. This precision has been crucial in identifying GRB counterparts in other wavelengths, such as optical and radio, and in determining their host galaxies.

Many dedicated single GRB paper have been published, highlighting the uniqueness of each event. One of the first and most important bursts of the Fermi mission was GRB 080916C, detected by both GBM and LAT just three months after launch. The detection of extremely high-energy photons (up to 13.2 GeV), the presence of a distinct high-energy component extending beyond the duration of the prompt emission, the hard power-law spectral component extending to high energies, and the inferred high Lorentz factors (~ 1000): all these characteristics, combined with the extreme high redshift of 4.3, making it the farthest high-energy GRB ever detected to date, deserved a publication in Science [11].

Other remarkable events comprise GRB 090510, which provided a crucial test of Einstein's theory, showing that gamma rays of different energies travel at the same speed through space, probing that there was no evidence for the violation of Lorentz invariance [12]; and GRB 130427A, which had the largest fluence, the highest-energy photon (95 GeV), longest gamma-ray duration (20 hours), and one of the largest isotropic energy releases ever observed from a GRB, challenging the widely accepted model that nonthermal high-energy emission in the afterglow phase of GRBs is synchrotron emission radiated by electrons accelerated at an external shock. [13]. This event was so bright that it caused saturation effects in the GBM instruments during its main emission episode. Therefore the GBM analysis focused on the initial pulse up to 2.5 s, which represented the brightest well-isolated pulse observed at the time, showing how difficult it was for any of the existing models to account for all of the observed spectral and temporal behaviors simultaneously [14]. The Fermi GBM and LAT papers were published in the same issue of the Science journal, which dedicated the cover in January 2014 to their remarkable findings. More results on joint GBM and LAT GRB studies are summarized in the Second Fermi LAT GRB catalog [15], covering a decade of burst observations.

A truly groundbreaking discovery in multi-messenger astronomy was marked by the association of GRB 170817A with the gravitational wave event GW170817. On August 17, 2017, the LIGO and Virgo collaborations detected GW170817, a GW signal from the merger of two neutron stars. Almost simultaneously, Fermi-GBM and the INTEGRAL satellite detected a short gamma-ray burst (GRB 170817A) from the same region of the sky (see Figure 5). This association provided the first direct evidence that short gamma-ray bursts can result from the merger of neutron stars. The detection of both gravitational waves and gamma rays from the same event allowed scientists to study the astrophysical processes in unprecedented detail [16].

GRB 170817A was relatively weak compared to other gamma-ray bursts, suggesting that it was observed off-axis, not directly along the jet's axis. This provided new insights into the geometry and orientation of the jets produced by neutron star mergers. Subsequent observations across the electromagnetic spectrum, including X-rays, optical, and radio waves, revealed the afterglow of the merger and the formation of heavy elements, like gold and platinum, through the r-process nucleosynthesis.

The coordinated observation of GW170817 and GRB 170817A also improved the measurement of the Hubble constant, which describes the rate of expansion of the universe. This event demonstrated the power of multimessenger astronomy, combining gravitational wave and electromagnetic observations, to enhance our understanding of cosmic phenomena and the fundamental physics governing them. Moreover, the "cosmic convergece" also gained the honor to be elected as Breakthrough of the Year for 2017 by Science[6].

As of now, the LIGO and Virgo collaborations have completed three main observational runs, and a fourth one is currently underway. O1 (Observing Run 1) between 2015 and 2016, which marked the first direct detection of gravitational waves, including the famous GW150914 event; O2, between 2016 and 2017, when GW170817 was detected; O3, which was divided into two segments, O3a in 2019 and O3b between 2019 and 2020, resulting in numerous detections of black hole mergers and other GW events, unfortunately with no further association with electromagnetic signals. The current run O4 began on May 24, 2023, and is ongoing. Fermi-GBM plays a crucial role in this time, providing constant monitoring of the entire sky for possible gamma-ray counterparts to GW events. In case of GW detections by LIGO and Virgo, Fermi's pipelines (see Figure 1) swiftly searches on various timescales for coincident gamma-ray signals, providing valuable data to pinpoint the source location and understand the physical processes involved in the merger events. This collaboration enhances the multi-messenger astronomy approach, offering deeper insights into the violent processes in the universe.

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[6] `https://vis.sciencemag.org/breakthrough2017/`

The plan for the LIGO-Virgo Observational Run O5 involves several key improvements and goals. Scheduled to begin after the completion of O4, O5 aims to enhance the sensitivity and detection capabilities of the LIGO and Virgo detectors. This will likely include upgrades to the hardware and software systems to improve the range and precision of GW detections. The collaboration may also involve the KAGRA detector in Japan, furthering the global network of gravitational wave observatories. Future observational runs, such as O5, are planned, with expectations of improved detector sensitivities and more frequent detections, In the multimessenger era, the Fermi Gamma-ray Space Telescope continues to play a critical role by providing gamma-ray observations that complement GW and neutrino detections. By correlating gamma-ray data with signals from LIGO, Virgo, and neutrino observatories, Fermi helps pinpoint sources of cosmic events, enhances our understanding of the Universe, and facilitates breakthroughs in astrophysics by combining different types of observational data.

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