Multi-messenger studies with the Fermi Satellite

Elisabetta Bissaldi*
Politecnico & INFN Bari – elisabetta.bissaldi@ba.infn.it

*on behalf of the Fermi-GBM
the Fermi-LAT Team
Large Area Telescope (LAT)
- 20 MeV to more than 300 GeV
- observes 20% of the sky at any instant
- entire sky every 3 hrs absolute timing to ~300 ns

Gamma-ray Burst Monitor (GBM)
- 8 keV to 40 MeV
- observes entire unocculted sky
- absolute timing ~2 μs

International and interagency collaboration between NASA and DOE in the US and agencies in France, Germany, Italy, Japan and Sweden
The Fermi Gamma-Ray Burst Monitor

Designed to study Gamma-Ray Bursts (GRBs)

- GBM primary objectives:
  1. **Extend** the energy range downward from the Fermi-LAT one (100 MeV – 300 GeV)
  2. Compute burst **locations** to allow re-orienting the spacecraft

**Key features**
- huge **FoV**
- huge **energy range**

![Diagram showing energy range and FoV comparison between GBM and LAT](image-url)
Fermi-GBM: 1) Triggering Operations

A total of 120 different triggers can be specified, each with a distinct threshold.

- GBM triggers when 2 or more detectors exceed a preset but adjustable threshold specified in units of the standard deviation of the background rate.
  - Background rate: average rate accumulated over the previous 17 s, excluding the most recent 4 s.

- Four energy ranges
  - 25 – 50 keV
  - 50 – 300 keV
  - 100 – 300 keV
  - >300 keV

- Ten timescales
  - from 16 ms to 8.192 s in steps of a factor of 2.
Fermi-GBM: 2) Trigger Statistics

Quarterly trigger statistics over 9.5 years of the mission

- GRBs
- Particles
- TGFs
- SGRs
- Solar flares
- Other

Trigger rate: twice per day!

Soft Gamma Repeaters
Galactic sources
Solar Flares
Terrestrial Gamma-ray Flashes
Fermi-GBM: 3) Skymaps

As of today: 2425 GBM GRBs

The GBM GRB online catalog is updated within 1 hour:

Fermi-GBM: 3) Skymaps

Fermi-GBM 9.5-year GRB map © Connaughton/Fermi GBM Collaboration

As of today: 146 LAT GRBs!

- Swift GRBs (13%, ~30/yr)
- LAT GRBs (6%, ~14/yr)
  [52% within LAT FoV]

Swift BAT: **only 9 sGRBs/yr** (arcmin localization!)
Fermi-LAT: **only 2-3 sGRBs/yr** (~0.1°-0.5 deg localization)

Facilitating follow-up!
Fermi-GBM: 4) Untriggered Sources

1. Earth Occultation Monitoring
   - Measure of the **change in the count rate** observed in the GBM detectors when the source **enters** or **exits** Earth occultation
   - Counts in each energy channel converted to **fluxes** using an assumed spectrum for each source
     - **~250 sources are monitored** (X-ray binaries, AGNs, etc., for a full list see https://gammaray.nsstc.nasa.gov/gbm/science/earth_occ.html)

2. Accreting Pulsars Monitoring
   - Using **epoch folded searches**
     - **36 sources detected** (8 persistent, 28 transient pulsars, for a full list see http://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html)

---

**Crab Nebula Hard X-ray Variations** Wilson-Hodge+2011

**Vela X-1 Full History**
Fermi-GBM: 5) Untargeted Searches

- **Since 2013:** Development of **automated search algorithms** for **untriggered** transient sources *(POC: M.S. Briggs)*
  - Magnetar burst (~200), TGFs (> 1000), other Galactic sources (>100), Short GRBs (sGRBs)

- Data search over **4 energy ranges and 10 timescales** (0.064 – 2.8 s)
- Uses all **12 NaI detectors** and flags candidates that meet a pre-defined count rate threshold in “legal” detector pairs in 50-300 keV
- Improved spline background can also find some **long GRBs**
- Standard GBM **localization** technique (uncertainties 10–40 deg, (68%))
- **Fast, efficient**, runs over a complete hour of data as it is downlinked

- **Since 2017:** **automated GCNs** can trigger **follow-up** observations
  - [https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold_archive.html](https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold_archive.html)

**Online sGRB catalog 2013–2017**
- [http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html](http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html)
Fermi-GBM: 6) LIGO/Virgo Partnership

- **Special MoU**: Small team of members from both collaborations that have worked together for years
  - Recognition that GBM is the *most prolific sGRB detector*, providing energy discrimination and localization capabilities
  - LVC has access to *sub-threshold GBM triggers*
    - **Untargeted blind search** for weak GBM sGRBs
  - GBM has access to *sub-threshold GW triggers*
    - Development and constant refinement of a GBM sub-threshold **targeted search**

→ The **joint sub-threshold work** may eventually be able to push GW detection horizon further by associating weak signals in both detectors

→ **All-O1 analysis of sub-threshold GW triggers** is currently under review by the LVC
→ **All-O2 sub-threshold analysis is just now beginning**, obviously very important now!
Fermi-GBM: 7) Targeted searches

- Search for **coherent signals in all detectors** given an input time and optional skymap (Blackburn+2015, Goldstein+2016)
  - Sliding timescales from 0.064 s to 8 s with a factor of 4 phase shift
  - 3 source spectral templates using Band function: soft, normal, and hard
  - Many improvements during O1 and O2: Various bug fixes, better background estimation, more realistic hard spectral template

<table>
<thead>
<tr>
<th>Ideal Scenario</th>
<th>Bright GBM</th>
<th>Bright LIGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914 Scenario</td>
<td>Sub-threshold GBM</td>
<td>Bright LIGO</td>
</tr>
<tr>
<td>Typical more distant short GRB</td>
<td>Bright GBM</td>
<td>Sub-threshold LIGO</td>
</tr>
<tr>
<td>Both Sources Faint</td>
<td>Sub-threshold GBM</td>
<td>Sub-threshold LIGO</td>
</tr>
</tbody>
</table>
Fermi-GBM: 8) Observations of GW Events

- **GW150914-GBM**, a 2.9 σ event consistent with a short GRB
  - Not predicted by theoretical models, poorly localized but consistent
- **No gamma-ray detections** for LVT151012 or GW151226 – not constraining
  - 32% and 17% of LIGO localization region blocked by Earth for GBM
  - Backgrounds were 18% and 3% higher in GBM
  - Distance for LVT151012 was 3x larger
  - If gamma-ray emission is in a jet, only 15-30% would be pointed toward Earth

➤ Need more events before we can say more!
Fermi-GBM: 8) Observations of GW Events

The transient “GW150914-GBM”

- Discovered through a targeted search around GW150914:
  - Hard transient at $t_{GW} + 0.4$ s, 1 s long
  - Association significance: 2.9 $\sigma$

- Localization: source direction underneath the spacecraft ($\theta = 163^\circ$)

- Energy spectrum peaking in BGO energy range
  - Best fit simple PL index $-1.4$ (average for sGRBs)
  - Fluence $2.4 \times 10^{-7}$ erg cm$^{-2}$ (weaker than average for sGRBs)

- Not detected by other gamma-ray instruments
Fermi-GBM: 9) GRB 170817A and GW170817

Credit: LIGO; Virgo; Fermi; NASA/DOE; NSF; EGO; ESA
GRB170817A also detected by the Anti-Coincidence Shield for the SPectrometer for Integral (SPI-ACS)

- Conclusive evidence for the Binary Neutron Star – short GRB connection
- GW–GRB association significance: 5.3 \( \sigma \)

Delayed onset of gamma-ray emission from a BNS merger progenitor is predicted to be within a few seconds after the merger

- Central engine is expected to form within a few seconds
- Jet propagation delays are at most of the order of the sGRB duration

Measured time delay between GW and light: \( \Delta t = 1.74 +/- 0.05 \text{ s} \)

Fermi-GBM: 9) GRB 170817A and GW170817

Standard GBM spectral analysis

- **Main peak**: typical non-thermal spectrum (peak at ~200 keV)
- **Soft tail**: 10 keV blackbody

→ Estimated peak luminosity and isotropic-equivalent energy is \textbf{~2-3 orders of magnitude lower} than previous observations

Goldstein+2017 ApJ 848, 14

Emerging scenario ii/iii: Structured jet + cocoon

- Unlikely to be observing on-axis (down the center of the jet)
- Could be a structured jet with “wings” of shocked material (e.g. Lazzati+ 2018)
- Could be a shock breakout from a “choked” trans-relativistic jet (e.g. Gottleib+ 2018)
Fermi-GBM: 9) Future prospects

Short GRBs at <40 Mpc are rare!

Expectations for O3:

- 1 – 50 BNS/yr (uncertainty on detector sensitivities during that run)
  ⇒ 0.1 – 1.4 joint BNS-sGRB/yr
- At design sensitivity:
  - 6 – 120 BNS/yr ⇒ 0.3 – 1.7 BNS-sGRB/yr

Current GBM preparation for O3:

- All-O1 Offline Follow-up Analysis
- Optimization of the targeted search
  ⇒ GBM-LVC Joint Result (Littenberg+2018 in prep)
Fermi-GBM: 10) Follow-up of IceCube neutrino events

- Utilizes all search methods:
  - On-board triggers
  - Untargeted search within the hour
  - Targeted search using event time
  - Earth occultation technique

- Good follow-up observation for IceCube-161103, upper limit published in GCN #20127

- Other follow-up with limited GBM coverage:
  - IceCube-170321A (GCN 20932)

- Also can use these techniques to search for counterparts to Fast Radio Bursts
Fermi-LAT: 1) GW follow-up

**Fermi Transient Searches**

**LAT Transient Factory (LTF)**
- Likelihood Around GBM/BAT triggers
- seconds to orbits
- LAT Team - Results in GCNs
- Triggered Operating + Blind Search Coming Soon

**Fermi All-sky Variability Analysis (FAVA)**
- Counts Map Aperture Photometry
- 3 day (coming soon), 1 week
- ATEls
- http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

**LAT Burst Advocate Tool**
- Likelihood Around GBM/BAT triggers
- 100 s, 1000 s
- LAT Team - Results in GCNs
- Operating

**LAT Automated Science Processing (ASP) + Flare Advocates**
- Likelihood
- 6 & 24 hour
- ATEls, GCN notices (on AGN)
- Operating

**LAT Catalogs**
- Likelihood, associations
- 3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
- http://fermi.gsfc.nasa.gov/ssc/data/access/4FGL_in_progress

**GBM Untriggered Search**
- ground search
- ms - s
- GCN Notices
- http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

**GBM Onboard Triggers**
- rate triggers
- 16 ms - minutes
- GCN Notices
- Operating

**Transients Timescale**
- μs
- ms
- s
- minutes
- hours
- days
- months
- years

**Photon Timing**
- Pulsars
- Solar Flares
- All Sky Cadence
- Novae
- y-ray Binaries
- Terrestrial γ-ray Flashes
- GRBs
- Magnetar Flares
- Blazar Flares
- Crab Flares

*Not to scale*
Fermi-LAT: 1) GW follow-up

- Fermi-LAT Automated Searches:
  - ASP, LAT BA, LAT Transient Factory, and FAVA
  - Long baseline search
    - ASP: integration time of 6 hours, 1 day
    - FAVA: integration time of 1 week

- Recent development of specific searches in the LIGO contours
  - See Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein et al. 2017 (GW170114), Vianello et al. 2017 (Methods)

1. **GW150914**: very bad coverage, search in the time interval from T0+4400-4500s
   - Fixed window of 10ks
   - "Adaptive" time window (entry-exit for each pixel in the interval of 10 days (before and after the trigger).

2. **LVT151012 & GW151226**: Much better sky coverage
   - Fixed (short) time windows of T0-10s, T0+10s
   - Fixed (long) time windows (8ks for GW151012 and 1.2 ks and 10ks for GW151226)
   - "Adaptive" time windows, as defined above

No significant excess detected → Upper Limits calculations
Fermi-LAT: 2) The unlucky case of GW170817

- **Sky coverage:** LAT was off, due to SAA
  - LAT SAA slightly larger than GBM (14%)
  - LAT observations of the entire region $t_{GW}$\([1153-2017]. Flux upper bound (0.1–1 GeV)\)
    $$F < 4.5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$$
    - Five orders of magnitude less luminous than GRB090510 (only LAT sGRB with redshift)

⇒ **BUT:** LAT has detected **14 sGRBs** with durations **shorter** than GRB 170817A, eight with comparably low fluence!
  - LAT can detect fainter sGRBs **the earlier the observation starts!**
Fermi-LAT: 3) Observation of IC170922A

The IceCube-170922A neutrino

- Arrived in a period of **flaring activity** (high-emission state) in high-energy gamma-rays of the very luminous blazar TXS 0506+056 detected by **Fermi-LAT** and **MAGIC**
  - Most probable neutrino energy: 290 TeV (>183 TeV)
  - Signalness (probability of astrophysical origin) reported to be 56.5 %

- **Correlation** of the neutrino with the flare of TXS 0506+056 is statistically significant at the 3 sigma level
Fermi-LAT: 3) Observation of IC170922A

The 3-months neutrino “flare” in 2014/2015

- IceCube archival search finds a compelling evidence for a 3.5 sigma excess (13 ± 5 events) positionally consistent with the same blazar

- No Fermi-LAT flare observed in coincidence with this excess
  - Gamma-ray lightcurve consistent with a quiescent state, with an average flux lower than in 3FGL. No significant evidence of hardening
  - Neutrino luminosity is 5 times larger than the gamma-ray luminosity.

Open questions:

- Which models can explain the MW data?
- How does the IC170922A fit together with the 2014/15 neutrino excess without coincident EM activity?

⇒ Further observations needed!
Conclusions

With the combined studies of gamma-ray transients / variable sources / gravitational wave events / neutrino events we are definitely entering the Multi-Messenger astronomy Era

Fermi-GBM and Fermi-LAT celebrated their 10th anniversary in space, and have proven to be FUNDAMENTAL instruments in unveiling the high-energy sky

- **GBM** is an **efficient** detector of counterparts to GWs
  - No pointed observations required, continuously observing large fraction (~67%) of the sky (~15% downtime)

The GBM and LAT Teams are looking forward to make many more key discoveries in the coming years!

Thank you!