

The Fermi-GBM follow-up of GW150914

*On behalf of the Fermi-GBM Team and
the GBM-LIGO/Virgo electromagnetic follow-up group:*

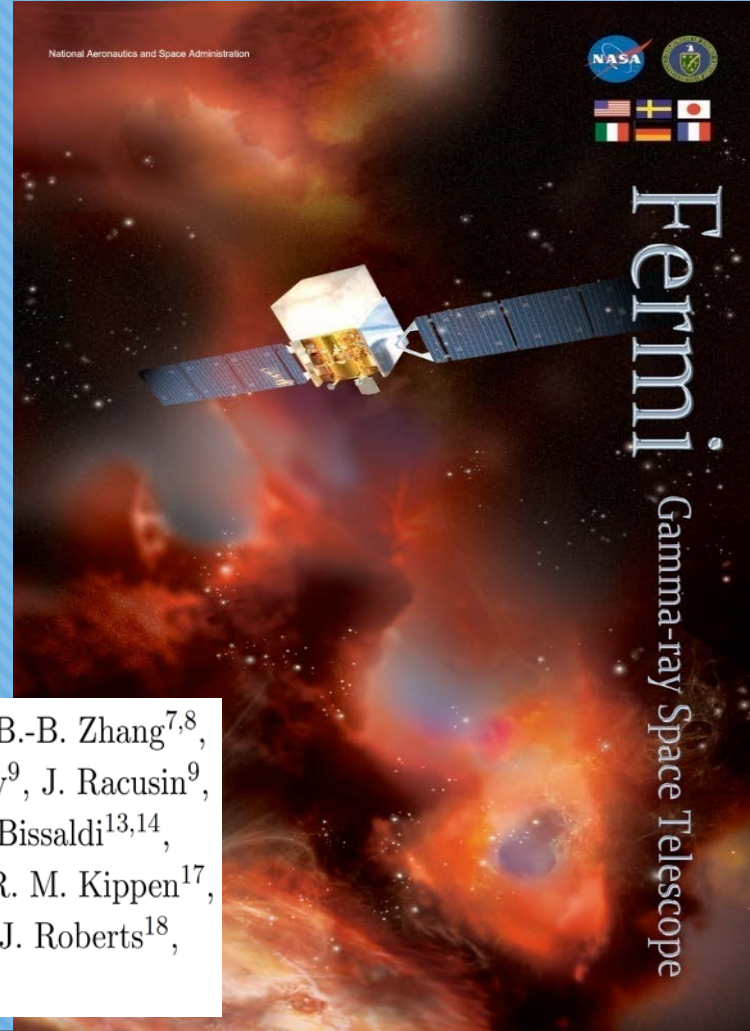
V. Connaughton^{*1}, E. Burns², A. Goldstein⁺³, L. Blackburn^{4,5}, M. S. Briggs^{6,7}, B.-B. Zhang^{7,8},
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L. Sparke¹⁹, M. Stanbro⁶, K. Toelge¹⁴, P. Veres⁷

Elisabetta Bissaldi
Elisabetta.Bissaldi@ba.infn.it

National Aeronautics and Space Administration



Fermi
Gamma-ray Space Telescope



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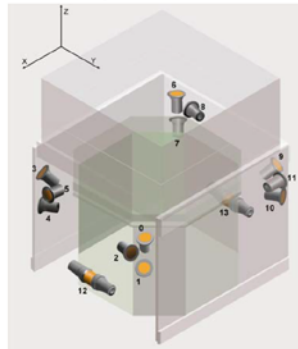
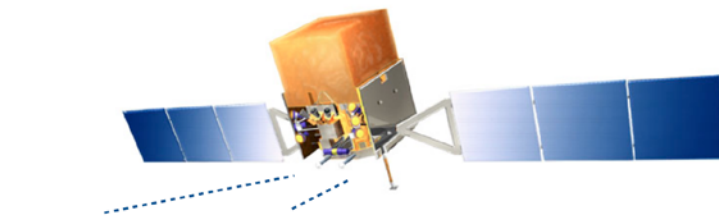


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The Gamma-Ray Burst Monitor (GBM)

Fermi Gamma-ray Burst Monitor¹⁰ (GBM)



GBM consists of an array of:

- 12 NaI scintillation detectors < 1 MeV
- 2 BGO detectors < 40 MeV

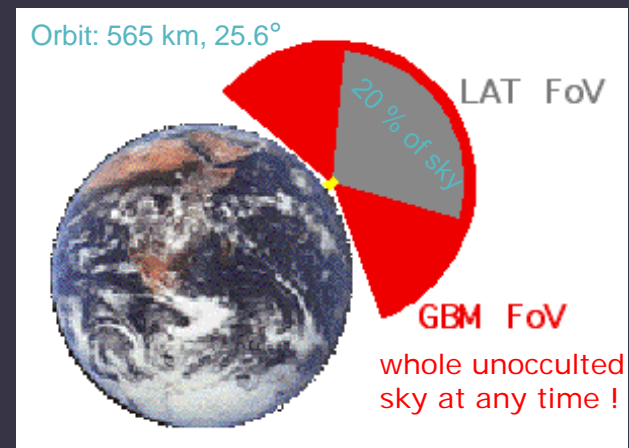
Bursts are seen as coincident excess over background in multiple detectors

- smooth background fit
- coincidence rejects noise
- relative rates determine source location

Continuous production of offline (daily) data products

- CTIME: (0.256s, 8 channels) for high time resolution
 - CSPEC: (4s, 128 channels) for high spectral resolution
 - TTE: (2 μ s, 128 channels) for detailed time and spectral resolution
- continuous archiving of TTE data starting end of 2012

- Energy range: 8 keV to 40 MeV
- Excellent FoV: ~70% of sky
- Full individual-photon archival data+ spectral information
- Localization through observation of relative observed rates in each detector



What does GBM see?

- o GBM triggers when 2 or more detectors exceed background by **n** sigma over **t** timescale in **e** energy band.
- o 70 algorithms operating simultaneously.
 - $4.5 \leq n \leq 7.5$
 - $16 \text{ ms} \leq t \leq 8.096 \text{ s}$
 - **e1** = 25–50 keV, **e2** = 50–300 keV, **e3** = 100–300 keV, **e4** ≥ 300 keV

The Fermi-GBM Gamma-Ray Burst Catalogs: The First Six Years

E. Bissaldi^(1,2) on behalf of the Fermi-GBM Team

⁽¹⁾ Politecnico di Bari, Italy ⁽²⁾ INFN Sezione di Bari, Italy
*E.Bissaldi@poliba.it, E.Bissaldi@na.infn.it

ABSTRACT Since its launch in 2008, the Fermi Gamma-ray Burst Monitor (GBM) has triggered and located on average approximately two gamma-ray bursts (GRBs) every three days. Here we present the main results from the latest two catalogs provided by the Fermi-GBM science team, namely the third GBM GRB catalog and the first GBM time-resolved spectral catalog. The intention of the GBM GRB catalog is to provide information to the community on the most important observables of the GBM detected bursts. It comprises 1426 triggers identified as GRBs. For each one, location and main characteristics of the prompt emission, the duration, peak flux and energy are derived. The GBM time-resolved spectral catalog presents high-quality time-resolved spectral analysis with high temporal and spectral resolution of the brightest bursts observed by Fermi GBM in a shorter period than the former catalog, namely four years. It comprises 1491 spectra from 81 bursts. Distributions of parameter, statistics of the parameter populations, parameter-parameter and parameter-uncertainty correlations, and their exact values are extracted.

Supported by: INFN

The 3rd GBM Trigger Catalog [1]

- From 2008 July 12 to 2014 July 11
- 3300 GBM triggers on transient events
- Country trigger fraction (see Fig. 1)
- GBM catalog: 1426 GRBs
- Six year coverage GBM rates
- 2442 ± 0.078 day⁻¹
- 242 at 3 year

GBM sky distribution in celestial coordinates [see Fig. 2]

- Area covered: 1176 long GRBs ($P_{90} = 1.3$)
- Area covered: 226 short GRBs ($P_{90} = 2.1$)
- Redshifts: 111 Sub-LAT co-triggers
- Lower fraction of GBM short GRBs (35.7%) compared to LAT (34%) due to the lack of long events detected by GBM's longer timescale trigger algorithms
- Isotropic distribution of long and short GRB sky directions

GBM Catalog ANALYSIS – Main steps

- Burst localization**
 - Accurate: derivation of systematic uncertainties is well represented (68% CL) by a Gaussian of standard deviation 3.37° with a non-Gaussian tail that contains about 10% of GBM-detected GRBs and extends to approximately 14° [2]
 - Probability maps produced through convolution of the statistical uncertainty with our best current model for the systematic error. The maps reflect the occasional non-circular shape of the statistical uncertainty region as well as its size
- Detector Response Matrix (DRM) production**
 - Generated using the General Response Simulation System [3]
 - Routinely delivered to the Fermi Science Support Center [4]
- GBM Duration, Peak Flux and Fluence computation**
 - Method: automatic batch fit routine implemented within the spectroscopy software package BART [5]
 - Durations: Tukey's interval: between the times where the burst has reached 25/0.5 and 75/0.5% of its maximum fluence (50–300 keV & 10–1000 keV)
 - Fluences: computed in energy ranges (50–300 keV & 10–1000 keV)
 - Peak fluxes: some energy range, 3 timescale [44, 256, and 1024 ms]

The 1st GBM Time-resolved Spectral Catalog [6]

Data selection

- From 2008 July 12 to 2012 July 11 (954 triggered GRBs)
- 23 bins (8–300 keV) × 1300 (250 keV–40 MeV) detector selected
- TTE data used
- Slight GBM subsample criteria (see also [7] and [10]):
 - 10 keV–1 MeV energy fluence $F > 4 \times 10^{10} \text{ erg cm}^{-2}$ and/or
 - 10 keV–1 MeV peak photon flux $F_p > 20 \text{ ph s}^{-1} \text{ cm}^{-2}$
 - Presence of at least five time bins in the light curve when binned with signal-to-noise ratio $\text{SN} > 3$
 - 81 bursts satisfy these criteria (only 1 short GRB (100329A))
 - 1000 time-resolved time bins and spectra obtained

Data analysis

- 4 different empirical fit models (analysis via RMFIT, Cauchy C-Statistics applied)
- Band function
- Cutoff power law ("Comptonized" model)
- Smoothly broken power law (SBL)
- Simple power law (PL)

Results

- BEST model sample criteria [9, 10]:
 - relative error $\sigma/Q \leq 0.4$ for each parameter Q of a model
 - $\sigma_Q \leq 0.4$ and $\sigma_p \leq 1.0$ for models that have two P_i indices
 - Extraction of 1491 BEST model fits (Tab. 1)
- Distributions of the BEST sample spectral parameters (Fig. 5 and Tab. 2)

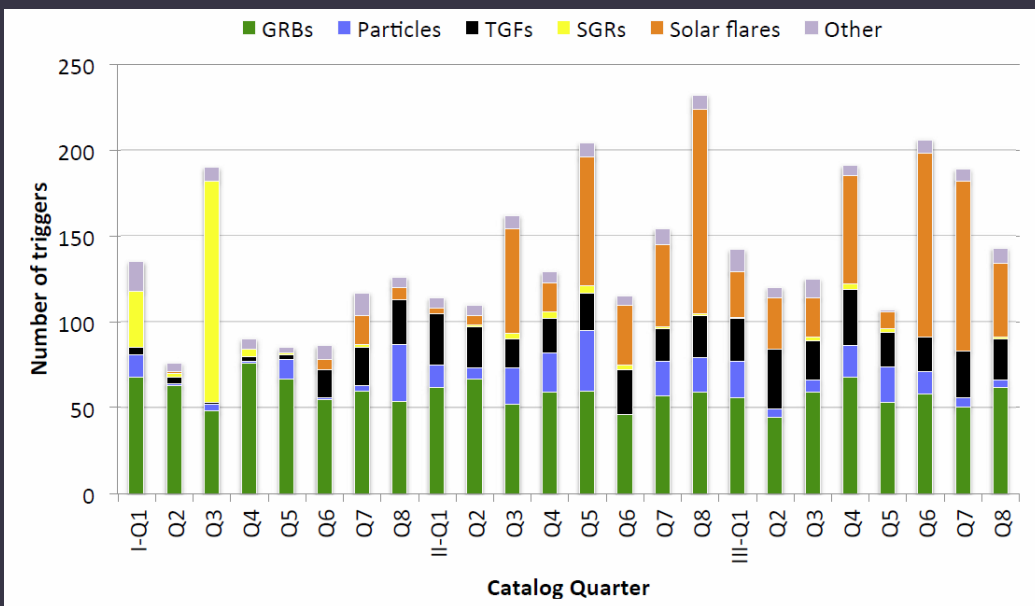
Considerations:

- Preferred model: COMP (6%)
 - Bias due to poor count statistics at high energies!
 - GRBs in the LAT FoV which remain untriggered show that upper limits are usually inconsistent with the GBM fit (uncertainties), as expected to the LAT energy range. Best model selection of GBM physical
- No significant deviations of the distributions of fit parameters from those observed in the Fermi-GBM GRB time-integrated spectral catalog [11]
 - comparison of merged time-resolved parameters to time-integrated parameters that averaged time-scale is and t_{90} are harder than time-integrated
- Widening of time-int spectra w/ time-res spectra (see also [1] and [7, 2])
 - effect caused by limited analysis
 - different best-fit models used
 - shift in peak position
 - Might lead to incorrect physical interpretation
- Spectral evolutionary trends (Fig. 4): establishment of a possible logical criteria for automated process of distinguishing between hard-to-soft and internally hardening
 - Only 3.5% of bursts would be misclassified to the opposite end
 - However, inspections with the human eyes are often necessary
- Search for plausible blackbody components in time-res spectra (inspiration on IceCube bursts)
 - Only 3 GRBs show extra blackbody components in multiple time bins

See Poster #256

What does GBM see?

- GBM triggers when 2 or more detectors exceed background by **n** sigma over **t** timescale in **e** energy band.
- 70 algorithms operating simultaneously.



The Fermi-GBM Gamma-Ray Burst Catalogs: The First Six Years

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^{*} E. Bissaldi, A. Barone, et al.

ABSTRACT Since its launch in 2008, the Fermi Gamma-ray Burst Monitor (GBM) has triggered and located on average approximately two Gamma-ray bursts (GRBs) every three days. Here we present the main results from the latest two catalogs provided by the Fermi-GBM science team: namely the third GBM GRB catalog and the first GBM time-resolved spectral catalog. The main goal of the GBM GRB catalog is to provide information to the community on the most important observables of the GBM detected bursts. It contains 1405 GRBs identified as GRBs. For each one, location and main characteristics of the prompt emission, the duration, peak flux and peak energy are derived. The GBM time-resolved spectral catalog presents high-quality time-resolved spectral analysis with high temporal and spectral resolution of the brightest bursts observed by Fermi GBM in a shorter period than the former catalog, namely four years. It comprises 1491 spectral GBM bursts. Distributions of parameters, statistics of the parameter populations, parameter-parameter and parameter-uncertainty correlations are presented, and their exact values are displayed.

The 3rd GBM Trigger Catalog

- From 2008 July 12 to 2014 July 11
- 3300 GBM triggers on transient events
- Country trigger statistics (see Fig. 1)
- GBM catalog: 1404 GRBs
- Six year coverage GBM rates
- 2422 ± 2074 day⁻¹
- 242 ± 7 year⁻¹

GBM sky distribution in celestial coordinates (see Fig. 2)

- Area covered: 1174 long GBMs, 74 ± 10 deg², 225 short GBMs, 7 ± 1 deg²
- Efficiency: 191 GBM-ACAT, 100% (100%)
- Lower fraction of GBM coverage in the Galactic plane
- Comparison to BATSE (see Fig. 3)
- Comparison to BATSE (see Fig. 3)
- Comparison of long events triggered by GBM's larger time resolution trigger algorithms
- Isotropic distributions of parameters and error GBM sky directions

GBM Catalog ANALYSIS - Main steps

- Burst localization
 - Accuracy: location of systematic uncertainties is well represented (68% CL) by a Gaussian standard deviation 3.7° with a non-Gaussian tail that contains about 10% of the detected GRBs and extends to approximately 14° [1]
 - Prediction maps produced through convolution of the statistical uncertainty with our best-fit model for the systematic error. The maps reflect the occasional non-linear shape of the statistical uncertainty region as well as its size.
- Detector Response Matrix (DRM) production
 - Implemented using the General Response Simulation System (GRSS) [2]
 - Routine delivered to the Fermi Science Support Center [3]
 - GRSS Questions: Peak Flux and Fluence computation
 - Method: automatic batch fit routine implemented within the spectroscopy software package BATSI [4]
 - Durations: Tukey's interval: between the times where the burst has reached 25.01% and 75.01% of its maximum fluence (20–200 ms energy range)
 - Fluence: computed in 1 energy range (20–200 keV & 10–1000 keV)
 - Peak flux: some energy ranges, 3.8 seconds (J4, 26, and 100 keV)

GBM Catalog RESULTS

- Distributions of GBM durations (Fig. 3)
 - Consistent with bimodal distribution
 - Verified by various independent analyses:
 - 1. model-based clustering method with logarithmic model components [5]
 - 2. Monte Carlo simulations
 - 3. Bayesian Dirichlet mixture model [6]
 - Median T₉₀ durations:
 - 0.38 s (short)
 - 23.42 s (long)
- Hopkins-Skellam diagram (Fig. 4)
 - Consistent with two clusters: the short/rapid group and the long/slow group
 - Also verified by independent analysis as in 1)
 - Based on coverage short/rapid
 - Flux on average long/slow
 - Ellipses: lie contour of the two-dimensional Gaussian model

The 1st GBM Time-resolved Spectral Catalog [8]

Data selection

- From 2008 July 12 to 2012 July 11 (954 triggered GRBs)
- 23 bursts (B–300 keV) + 1300 (250 keV–40 MeV) (detector selected)
- TTE data used
- Slight GBM subsample criteria (see also [7] and [10]):
 - 10 keV–1 MeV energy fluence $F > 4 \times 10^3$ erg cm² on-axis
 - 10 keV–1 MeV peak photon flux $\Phi > 20$ ph s⁻¹ cm⁻² on-axis
 - Presence of at least five time bins in the light curve when binned with signal-to-noise ratio $\text{SN} > 3$
 - All bursts satisfy these criteria (only 1 short GRB (200320A))
 - 1000 time-resolved time bins and spectra obtained

Data analysis

- 4 different empirical fit models (analysis via RMFIT, Cauchy C-Statistics applied)
- Band function
- Cutoff power law ("Comptonized" model)
- Smoothly broken power law (SBPL)
- Simple power law (PL)

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- relative error $\sigma/Q \leq 0.4$ for each parameter Q of a model
- $\sigma_Q \leq 0.4$ and $\sigma_Q \leq 1.0$ for models that have two PL indices
- Extraction of 1491 BEST model fits (Table 1)
- Distributions of the BEST sample spectral parameters (Fig. 5 and Tab. 2)

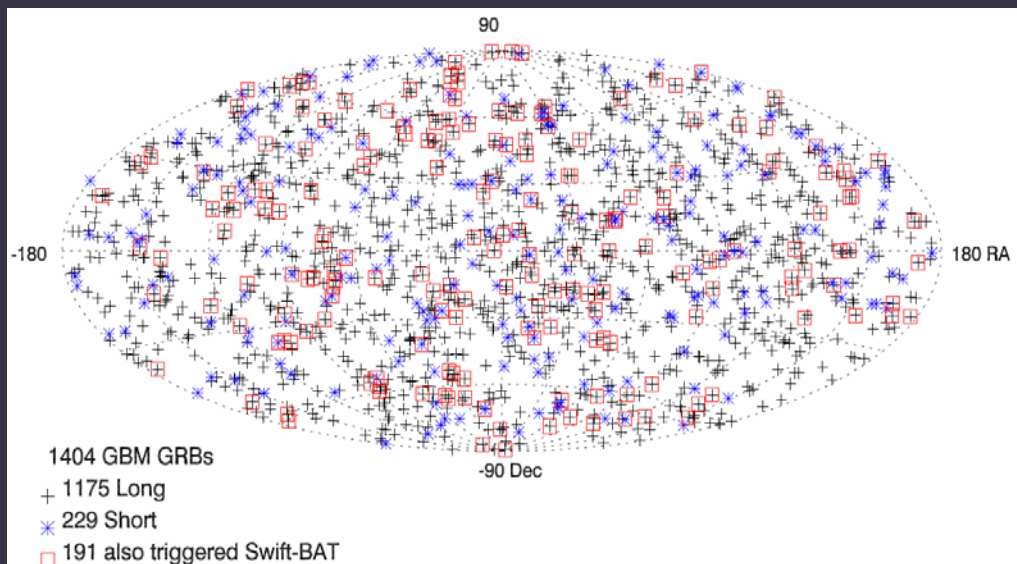
Considerations:

- Preferred model: COMP (95%)
 - Due to poor count statistics at high energies
 - GRBs in the LAT FOV which remain unclassified show that upper limits are usually inconsistent with the GBM fit bandfunction. It was applied to the LAT energy range. Best model definition of GBM physical
- No significant deviations of the distributions of fit parameters from those observed in the Fermi GBM GBM time-resolved spectral catalog [10]
 - comparison of measured time-resolved parameters to time-integrated parameters that averaged time-intervals t_{avg} are harder than time-integrated
- Widening of time-int spectra w/ time-res spectra (see also [11] and [7])
 - which caused by fit-mis-analysis
 - different best-fit models used
 - might lead to incorrect physical interpretation
- Spectral evolutionary trends (Fig. 4): establishment of a possible logical criteria for automated process of distinguishing between low-to-high and internally hopping
 - Only 3.5% of bursts would be misclassified to the opposite end
 - However, inspections with the human eye are often necessary
- Search for plausible blackbody components in time-res spectra (distributions on individual bursts)
 - only 3 GRBs show extra blackbody components in multiple time bins

See Poster #256

What does GBM see?

- o GBM triggers when 2 or more detectors exceed background by **n** sigma over **t** timescale in **e** energy band.
- o 70 algorithms operating simultaneously.



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The 3rd GBM Trigger Catalog [1]

- From 2008 July 12 to 2012 July 11
- 3305 GBM triggered events
- Quenchy trigger (see Fig.1)
- GBM catalog 1404 GRBs
- Six year coverage GBM rates
- 242 ± 3 day⁻¹
- 242 ± 3 year⁻¹

GBM sky distribution in celestial coordinates [see Fig.2]

- Area covered: 119 long GBMs, $P_{90} = 134^\circ$
- Area covered: 229 short GBMs, $P_{90} = 134^\circ$
- Area covered: 191 Swift-BAT trigger
- Lower fraction of GBM short GRBs (35.7%) compared to BATO (48%) due to the presence of long events detected by GBM's longer timescale trigger algorithm
- Isotropic distribution of long and short GRB directions

GBM Catalog ANALYSIS - Main steps

- Burst localization**
 - Accurate determination of burst uncertainties is well represented (68% CL) by a Gaussian of standard deviation 3.7" with a non-Gaussian tail that contains about 10% of GBM detected GRBs
 - Probability maps obtained through convolution of the statistical uncertainty with our best guess for the systematic error. The most likely the occasional non-circular tail of the statistical uncertainty region as well as its trace
- Detecting the Gamma-ray Burst Monitor (GBM) production**
 - Calibration of the Gamma-ray Burst Monitor (GBM) production
 - Calibration delivered to the Fermi Science Support Center (FSSC)
 - Method: automatic batch fit routine implemented within the spectroscopy software package BATFIT [3]
 - Durations T₉₀ intervals between the times where the burst has reached 25/50% and 75/75% of its maximum fluence (50-300 keV energy range)
 - Fluences: computed in energy ranges (50-300 keV & 10-1000 keV)
 - Peak fluence: some energy ranges, 3 timescale (44, 256, and 1024 ms)

GBM Catalog RESULTS

- Distributions of GBM durations [Fig. 3]**
 - Consistent with bimodal distribution
 - Verified by various independent analyses:
 - model-based clustering method with logarithmic model components [4]
 - Monte Carlo simulations
 - Bayesian Dirichlet mixture model [7]
 - Median T₉₀ durations:
 - 0.58 s (short)
 - 23.42 s (long)
- Histogram-duration diagram [Fig. 4]**
 - Consistent with two clusters: the short/short group and the long/long group
 - Also verified by independent analysis as in 1)
 - Based on average short/long
 - Flux on average long/short
 - Ellipses: the contour of the two-dimensional Gaussian models

The 1st GBM Time-resolved Spectral Catalog [8]

Data selection

- From 2008 July 12 to 2012 July 11 (554 triggered GRBs)
- 3 Nobs (8-100 keV) + 1 BOO (250 keV - 40 MeV) detector selected
- TTE data used
- Slight GRB sub-sample criteria (see also [7] and [10]):
 - 10 keV-1 MeV energy fluence $F > 4 \times 10^{10}$ erg cm² or larger
 - 10 keV-1 MeV peak photon flux $F_p > 20$ ph s⁻¹ cm⁻²
 - Presence of at least five time bins in the light curve when binned with signal-to-noise ratio (SN) > 3
 - All bursts satisfy these criteria only if short GRB (2023/24)
 - 1000 time-resolved time bins and spectra obtained

Data analysis

- 4 different empirical fit models (analysis via RMFIT, Cauchy Coefficients applied)
 - Band function
 - Cutoff power law ("Comptonized" model)
 - Smoothly broken power law (SBPL)
 - Simple power law (PL)

Results

- BEST model sample criteria [9, 10]:
 - relative error of $\chi^2 \leq 0.4$ for each parameter Q of a model
 - $\chi^2_{\text{red}} \leq 0.4$ and $\chi^2_{\text{red}} \leq 1.0$ for models that have two PL indices
 - Extraction of 1491 BEST model fits (Tab.1)
- Distributions of the BEST model spectral parameters (Fig. 5 and Tab. 2)

Considerations:

- Preferred model: COMP (69%)**
 - Size due to poor count statistics at high energies
 - GRBs in the LAT FOV which remain unclassified show that upper limits are usually inconsistent with the GBM fit (uncertainty δ is wide, compared to the LAT energy range. Best model definition of GBM physical
- No significant deviations of the distributions of fit parameters from those observed in the Fermi-GBM GRB time-integrated spectral catalog [11]**
 - comparison of measured time-resolved parameters to time-integrated parameters that averaged time-scale is and τ_{dec} are harder than time-off time
- Widening of time-int spectra w/ time-res spectra** (see also [1] and [7, 2])
 - which caused by fit-model analysis
 - different best-fit models used
 - shift peak position
 - Might lead to incorrect physical interpretation
- Spectral evolutionary trends [Fig. 4]:** establishment of a possible logical criteria for automated process of distinguishing between hard-to-soft and internally hardening
 - Only 3.5% of bursts would be misclassified to the opposite end
 - However, inspections with the human eye are often necessary
- Search for plausible blackbody components in time-res spectra** (inspiration on the GRB 080903)
 - Only 3 GRBs show extra blackbody components in multiple time bins

References:

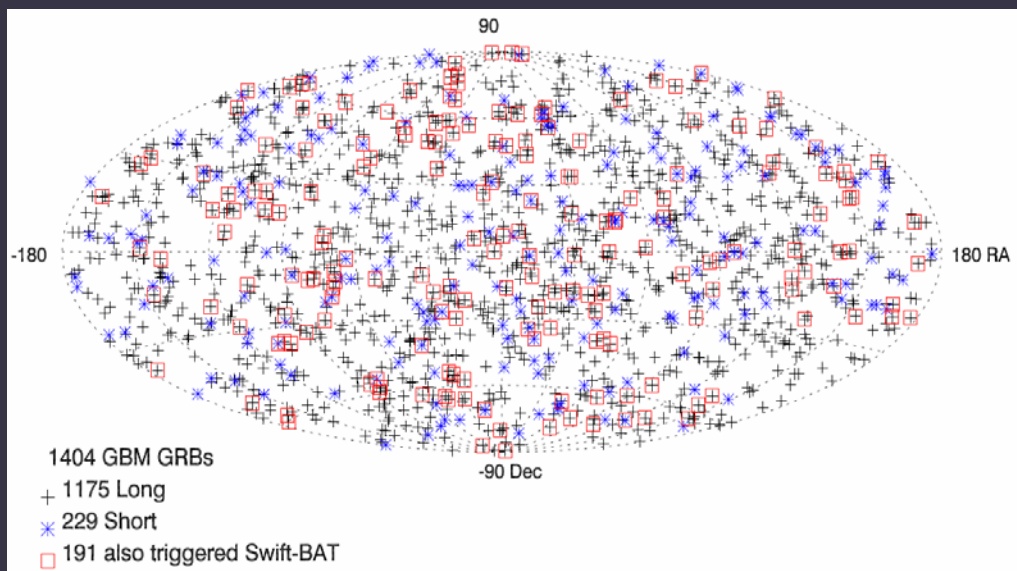
[1] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [2] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [3] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [4] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [5] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [6] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [7] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [8] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [9] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [10] Bissaldi, E. et al., *AAS 2012, 2012-07-11*
 [11] Bissaldi, E. et al., *AAS 2012, 2012-07-11*

<http://gamma.nas.nasa.gov/gbm/>

See Poster #256

What does GBM see?

- GBM triggers when 2 or more detectors exceed background by **n** sigma over **t** timescale in **e** energy band.
- 70 algorithms operating simultaneously.



Owing to all-sky coverage, Fermi GBM detects and localizes more short GRBs than other GRB detectors:

GBM: 40 short GRBs per year, coarse localization (tens square degrees)

Swift BAT: 9 short GRBs per year, arcminutes localization facilitating follow-ups

Untargeted GBM offline searches



- **Dedicated search algorithms** for untriggered transient sources
 - Magnetar burst (~200)
 - TGFs (> 1000)
 - Other Galactic sources (>100)
 - **Short GRBs (sGRBs)**
 - Initially developed for TGF search
 - Using CTTE data (10 timescales, 5 energy ranges)
 - 2 detectors: 2.5σ and another 1.25σ above background
 - Unfavorable geometry of the two above-threshold detectors are eliminated
 - Soft and long duration candidates are removed
- ➔ **Additional ~ 35 per year**, most of them undetected by other instruments (verification in progress)

Untriggered GBM sGRB candidates

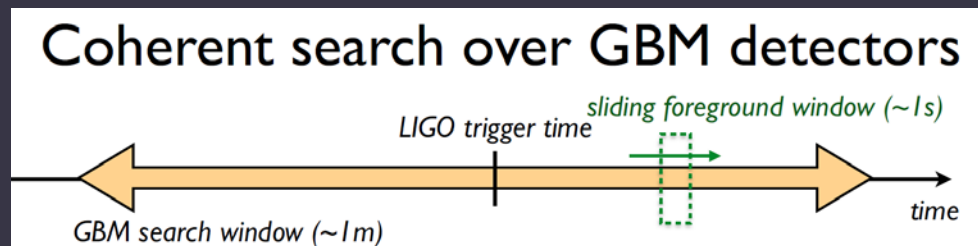
Short GRB Candidates

MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)
423745096.625	1.91E-0016	2014-06-06	10:58:13.625	232.07	+37.47	18.86
424708158.025	2.36E-0007	2014-06-17	14:29:15.025	359.06	-32.47	5.59
424757010.500	1.92E-0016	2014-06-18	04:03:27.500	278.84	+64.38	4.67
424968038.500	2.80E-0007	2014-06-20	14:40:35.500	319.45	-17.40	17.05
426319641.550	2.00E-0010	2014-07-06	06:07:18.550	64.10	+25.04	6.41
426588599.600	7.75E-0014	2014-07-09	08:49:56.600	12.77	-49.36	6.53

- A list of untriggered SGRB candidates (June 2014 to present) are listed at http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html
- Working towards creating automated GCNs, will be distinct from triggered events type

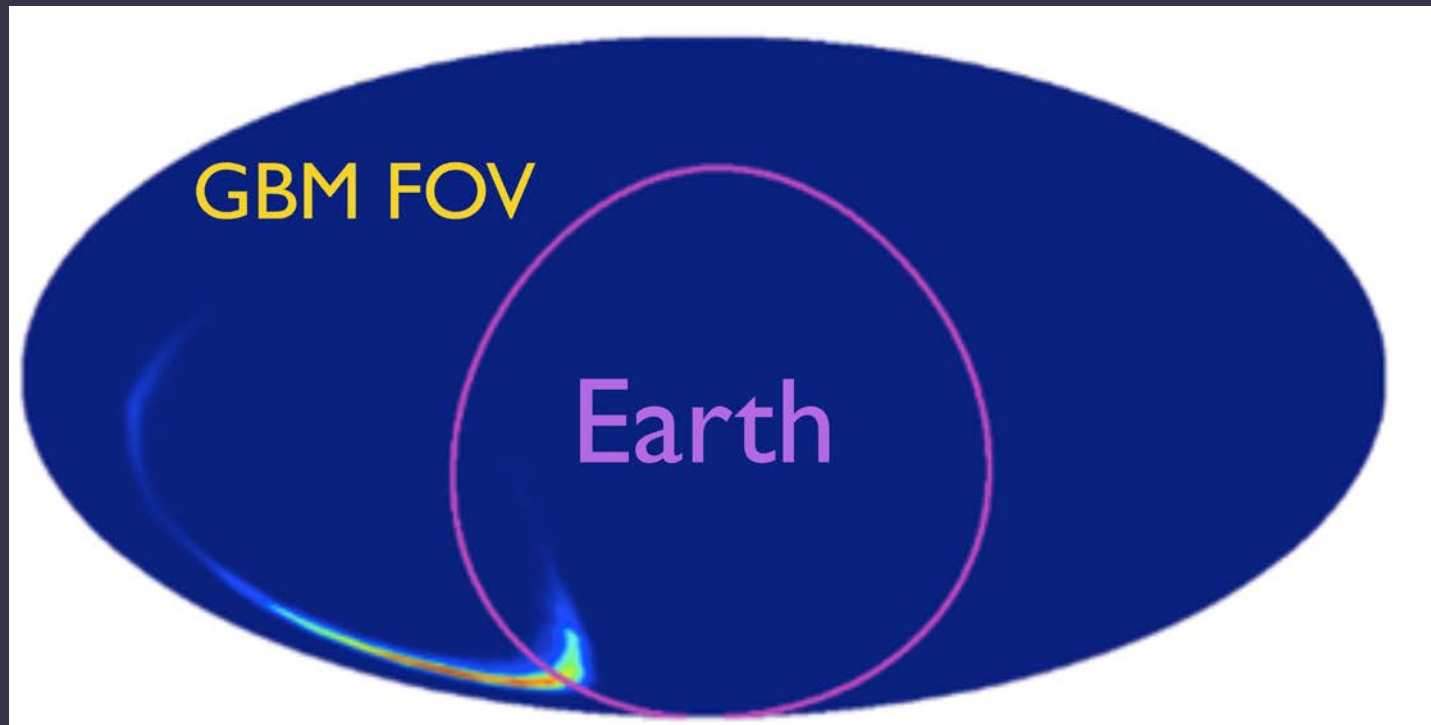
Targeted searches of GBM data to GW events

- Developed during LIGO S6 observing run
(Blackburn et al. ApJS 2015, 217, 8)
- Seeded with time & (optionally) sky location of a LIGO/Virgo event
- Using the full response for a point source at each sky position
- Search over user-specified time window
- estimate of background rate by polynomial fitting over 8 CTIME energy channels outside the foreground interval
- Time resolution of candidates between 0.256 s to 8.192 s (CTIME)
- Candidates are ranked by a Bayesian likelihood statistic
- Method tested on Swift GRBs: determination of an empirical False Alarm Rate (FAR)



The curious case of GW150914

- GBM ground-based GW follow-up
 - 75% of GW150914 skymap observed



The curious case of GW150914



TITLE: GCN CIRCULAR
NUMBER: 18339
SUBJECT: LIGO/Virgo G184098: Fermi-GBM ground-based follow-up
DATE: 15/09/20 01:46:08 GMT
FROM: Lindy Blackburn at CfA <lindy.blackburn@ligo.org>

Lindy Blackburn (CfA), Michael S. Briggs (UAH), Eric Burns (UAH), Jordan Camp (NASA/GSFC), Nelson Christensen (Carleton College), Valerie Connaughton (USRA), Adam Goldstein (NASA/MSFC), Tyson Littenberg (UAH), John Veitch (Birmingham), Judith Racusin (NASA/GSFC), Peter Shawhan (UMD), Leo Singer (NASA/GSFC), Binbin Zhang (UAH)

We report on a sub-threshold targeted followup of LIGO candidate event G184098 in Fermi-GBM survey data for bursts between 0.256s and 8s in duration, and covering a range of GRB spectral models. Although there was no on-board GBM trigger at the time of the event, Fermi-GBM was exposed to a large fraction of the LIGO sky position and thus we searched offline data for untriggered events. The GBM FOV is blocked by the Earth which occults 67 degrees from (RA, DEC) = (355.14, -21.23). Thus GBM observation is able to cover about 87.8% of the cWB sky posterior, and 91.5% of the LIB posterior. We scanned several minutes of GBM live-time centered on the GW event time using a pipeline developed specifically for following-up LIGO-Virgo events in GBM archival data during the LIGO-Virgo S6/VSR3 run [1].

The search identified a possible transient beginning at 150914 09:50:45.8, about 0.4s after the reported LIGO burst trigger time of 09:50:45.39, and it lasted for about 1 second. The intrinsic time resolution for this search was 0.256s. Of the three GRB model spectra tested in the search, the event was best matched to the one corresponding to the hardest spectrum. Using GBM

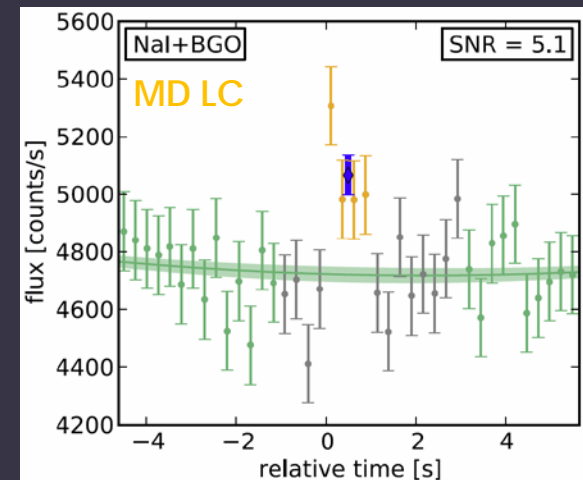
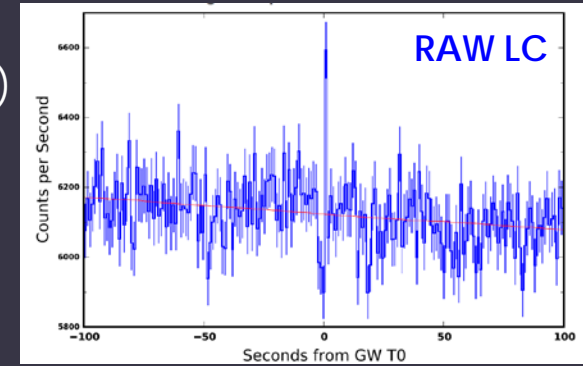
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(Private communication)



«GW150914-GBM»

- Targeted search around GW150914:
 - Initial 60s (± 30 s) search window (selected a priori)
 - 2 candidates
 - Soft transient, $T_{\text{GW}}+11$ s, 2s long: Gal.Cent. region
 - Hard transient, $T_{\text{GW}}+0.4$ s, 1s long: **GW150914-GBM**
- 0.2% probability of occurring by chance (**2.9σ**)



FAR = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

$$P = 2 \times (4.79 \times 10^{-4} \text{ Hz}) \times 0.4 \text{ s} \times (1 + \ln(30 \text{ s} / 0.256 \text{ s})) = 0.0022$$

Offset between GW T0 and GBM event start

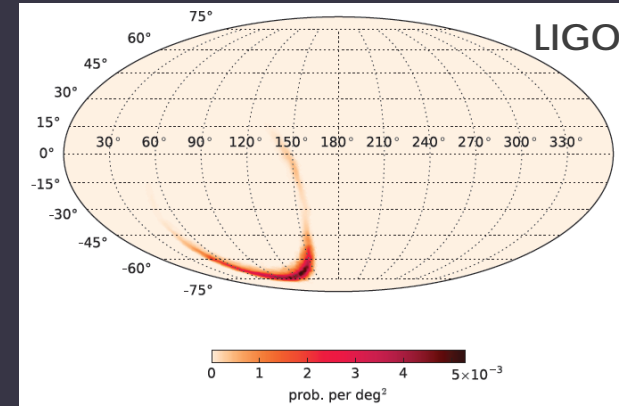
Effective trials factor for non-independent, variable time bins (30s is maximum offset set by the search window, 0.256 is the minimum set by native CTIME data)

Factor of 2 to account for offset in time in either direction

Characteristics of GW150914-GBM

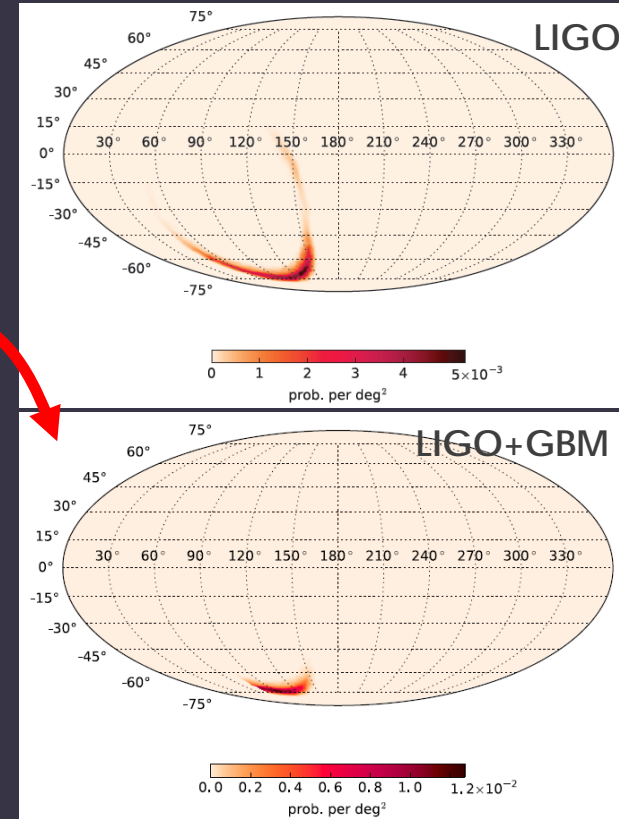


- Unusual detector pattern:
nearly equal count rates in all NaI detectors
 - Localization: source direction underneath the spacecraft, **163°** to the spacecraft pointing direction (similar to Swift-GRB130306A)



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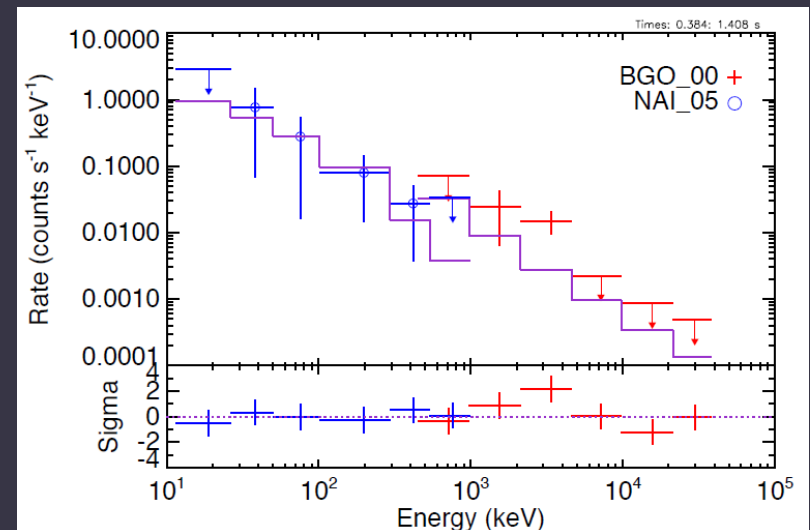
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- Energy spectrum:
 - Peaking in BGO energy range.
Best fit simple PL with index **-1.4** (average for sGRBs),
Fluence **2.4×10^{-7} erg cm⁻²** (weaker than average for sGRBs)

Possible origins for GW150914-GBM



	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	X	X			X	X
Galactic Sources		X	X			X
Magnetospheric Activity				X	X	X
Solar Activity		X	X	X		X
Something New	?	?	?	?	?	?
Short GRB	✓	✓	✓	✓		✓

- PLUS: No evidence for
 - steady emission from that direction
 - Contamination by known sources of hard X-ray emission
 - Non-impulsive emission related to the GW event in the days surrounding it

Association with GW150914?



○ Evidence for

- 3 sigma False Alarm Probability
- GBM signal localized to a region consistent with the LIGO sky map
- Cannot be attributed to other known astrophysical, solar, terrestrial or magnetospheric activity

○ Evidence against:

- Low significance
- Lack of corroboration by other experiments
- **Nature of the LIGO event is a BH-BH merger**

o Current analysis

- **IN PROGRESS:** Search of GBM data corresponding to all sub-threshold GW events from the O1 initial science operation period of LIGO
- **SUBMITTED:** Racusin et al. reported non-detections for GW151226 and LVT151012 (arxiv. 1606.04901v1)
 - The Fermi non-detections of gamma-ray counterparts to LVT151012 and GW151226 can **neither confirm nor refute** the potential association between GW150914 and the GBM candidate counterpart

○ Current analysis

- **IN PROGRESS:** GBM and Integral SPI-ACS teams working together on **joint sensitivities!**
 - Non-detection of a GRB in one of the two instruments is not surprising (many cases in the past!)
 - Non-detection can constrain location/spectrum
 - SPI-ACS non-detection puts constraints on the **hardness of the spectrum of the event**
 - Further GBM SPI-ACS cross-analysis including systematic effects may further constrain the spectrum and brightness of the event

○ Current analysis

- **IN PROGRESS:** Dealing with papers expressing doubts/criticisms
 - Greiner et al. finds problems with the spectral analysis software (overestimation of fluence)
 - However, this software is not used neither to discover nor to estimate the event's significance
 - The significance was determined using an empirically derived false alarm rate calculated before O1
 - If the fluence is actually lower, then all tension with the SPI-ACS non-detection is resolved!

○ Next steps in GBM GW follow-up

- Development of pipelines and data products, and improvement of algorithms to rapidly search GBM data for counterparts and eventually communicate localizations within hours

○ Future outlook

- In O2: expect more BH-BH candidates. Can we **confirm** association between BH-BH events and sub-luminous short-GRB-like events? Can we **rule out** GW150914-GBM with no further detections during O2?
- Looking forward to weaker GW signals from **neutron star binary systems!**

➔ **GBM is an ideal partner instrument** in the search for EM signals in coincidence with GW detections