The Fermi-GBM follow-up of GW150914

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

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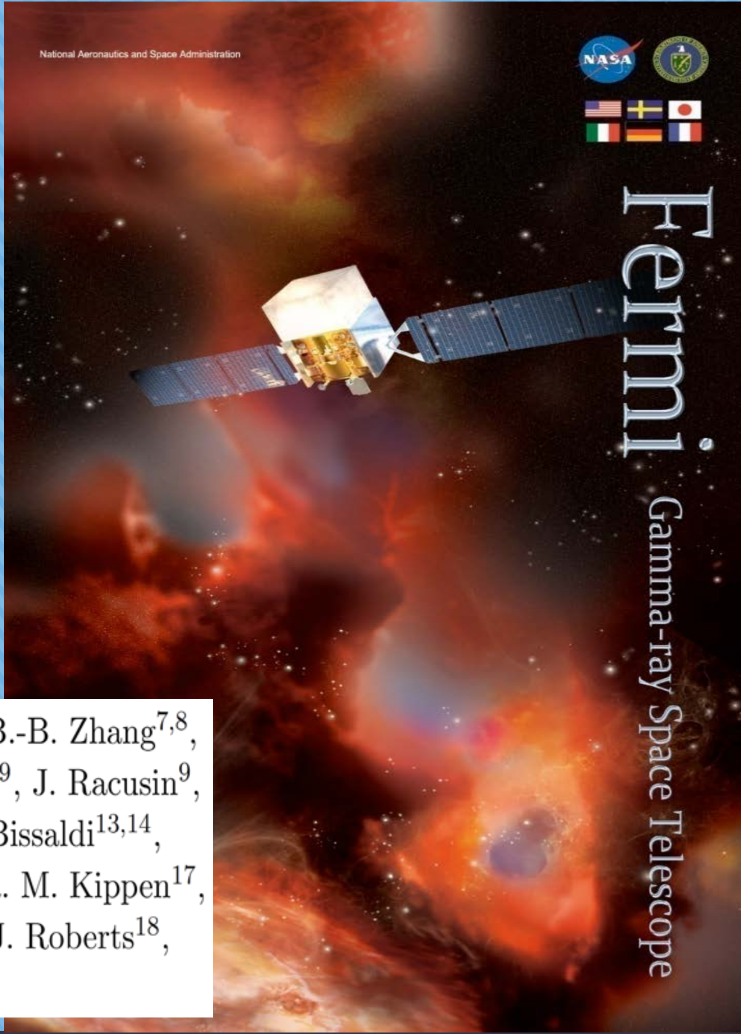

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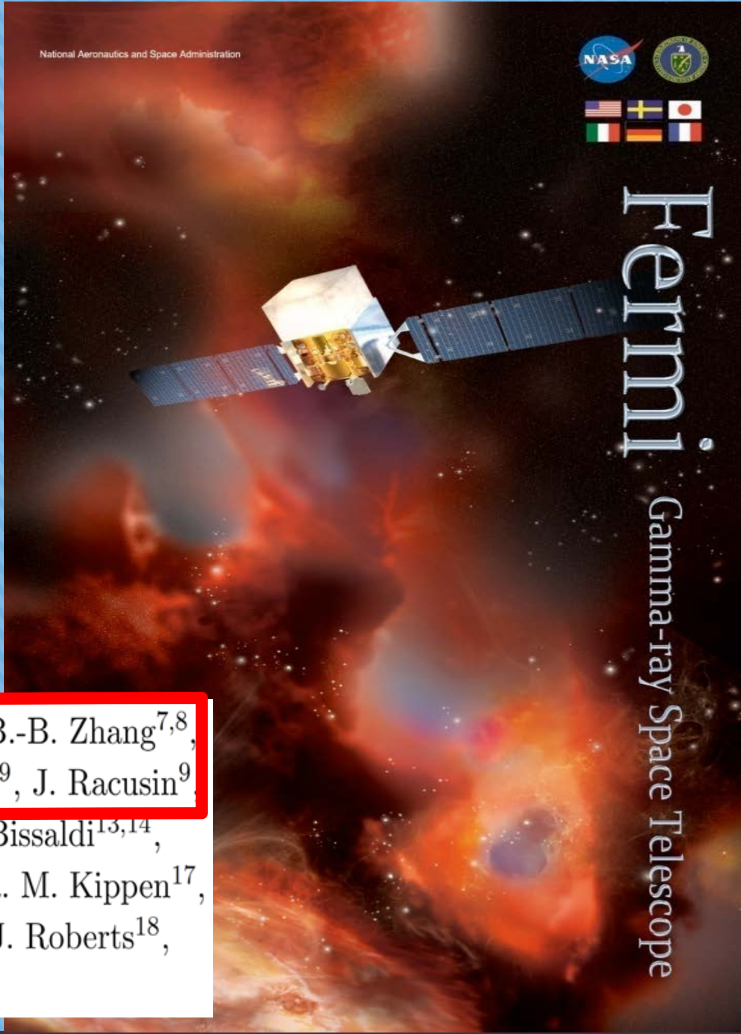

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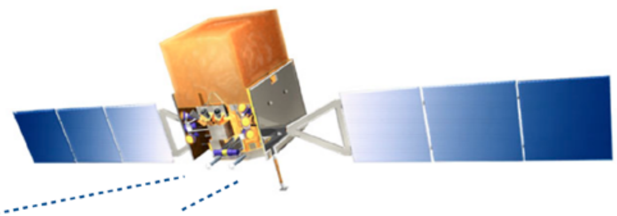
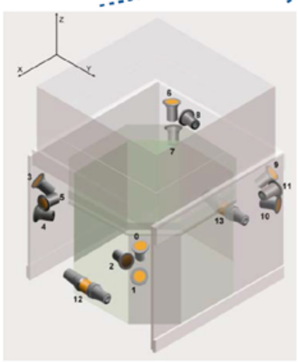
The Gamma-Ray Burst Monitor (GBM)

Fermi Gamma-ray Burst Monitor [10] (GBM)



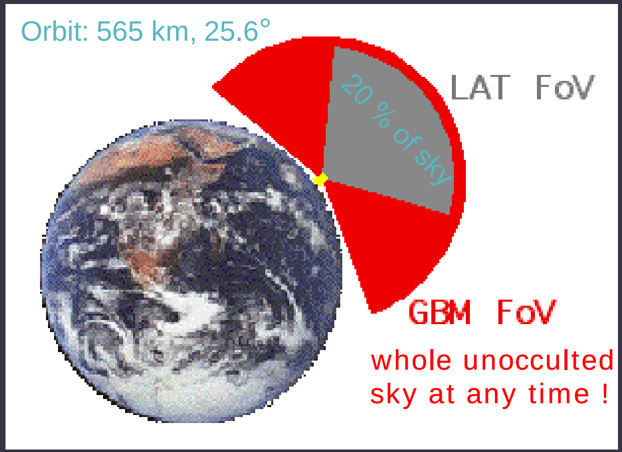


GBM consists of an array of:
- *12 NaI scintillation detectors < 1 MeV*
- *2 BGO detectors < 40 MeV*

Bursts are seen as coincident excess over background in multiple detectors
- *smooth background fit*
- *coincidence rejects noise*
- *relative rates determine source location*

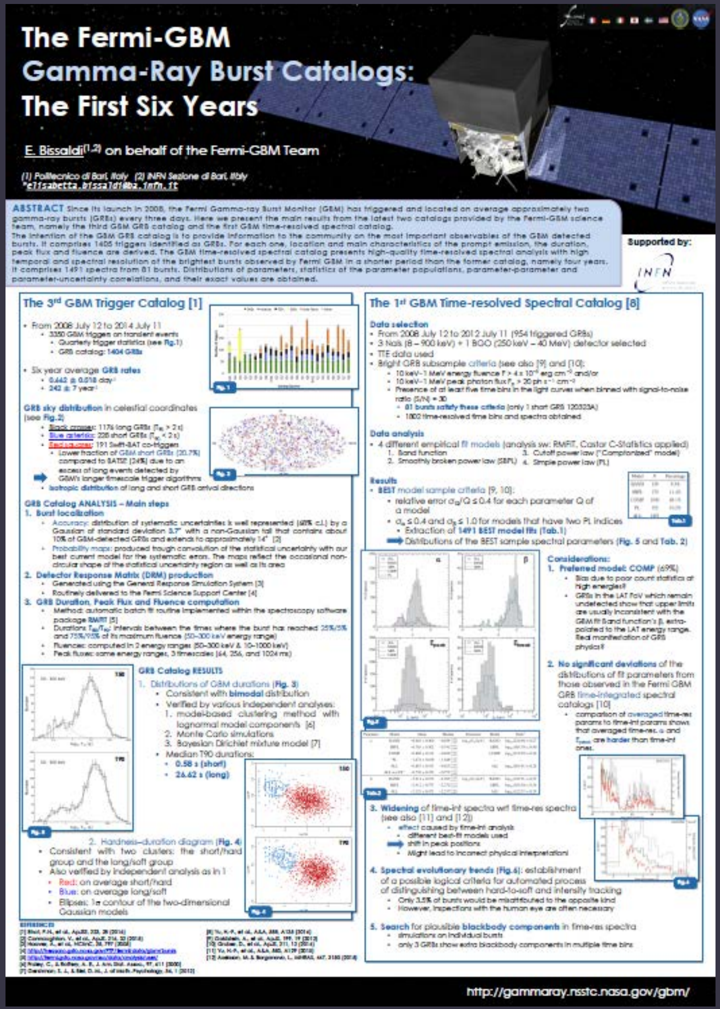
Continuous production of offline (daily) data products
- *CTIME: (0.256s, 8 channels) for high time resolution*
- *CSPEC: (4s, 128 channels) for high spectral resolution*
- *TTE: (2µs, 128 channels) for detailed time and spectral resolution*
  continuous archiving of TTE data starting end of 2012

- 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?

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



See Poster #256

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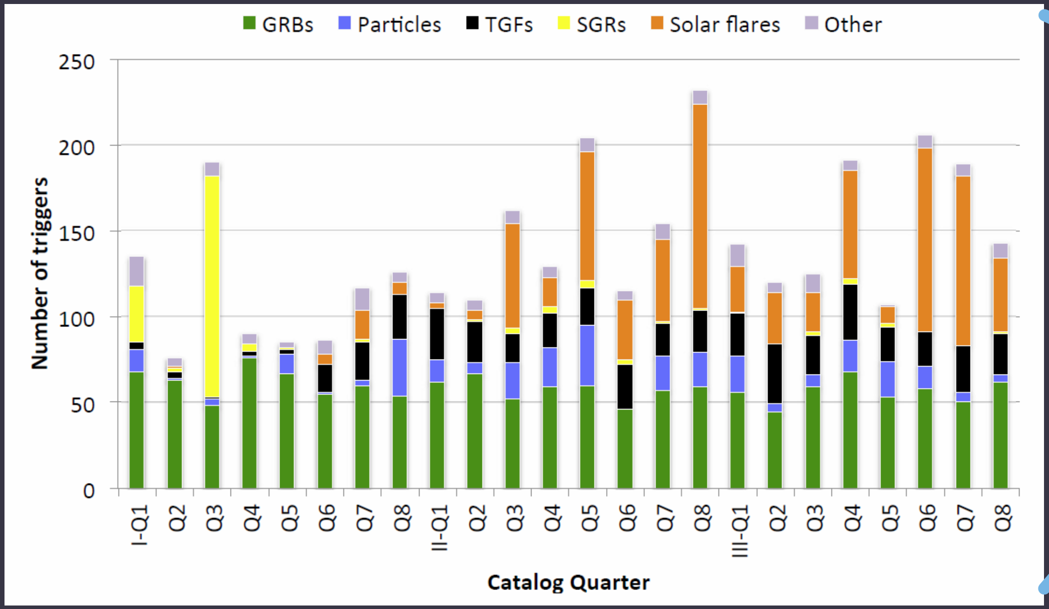

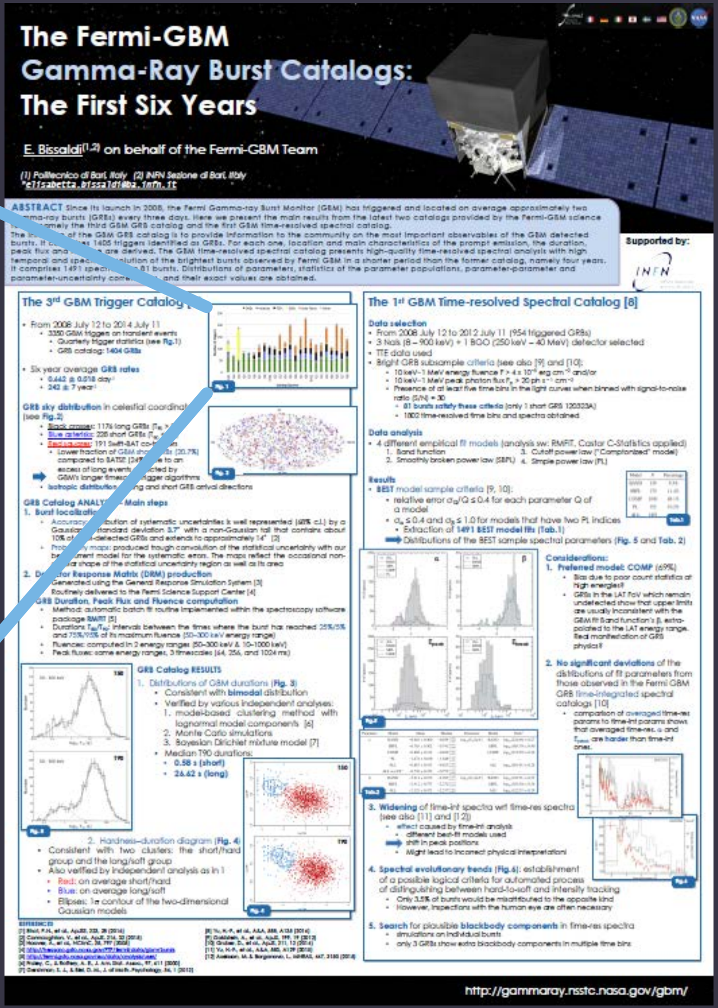

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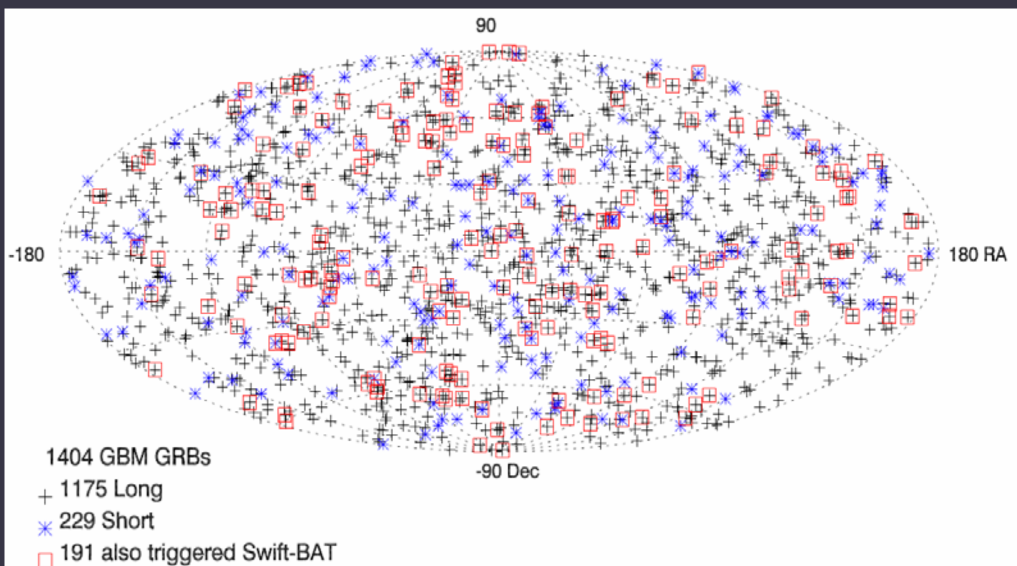

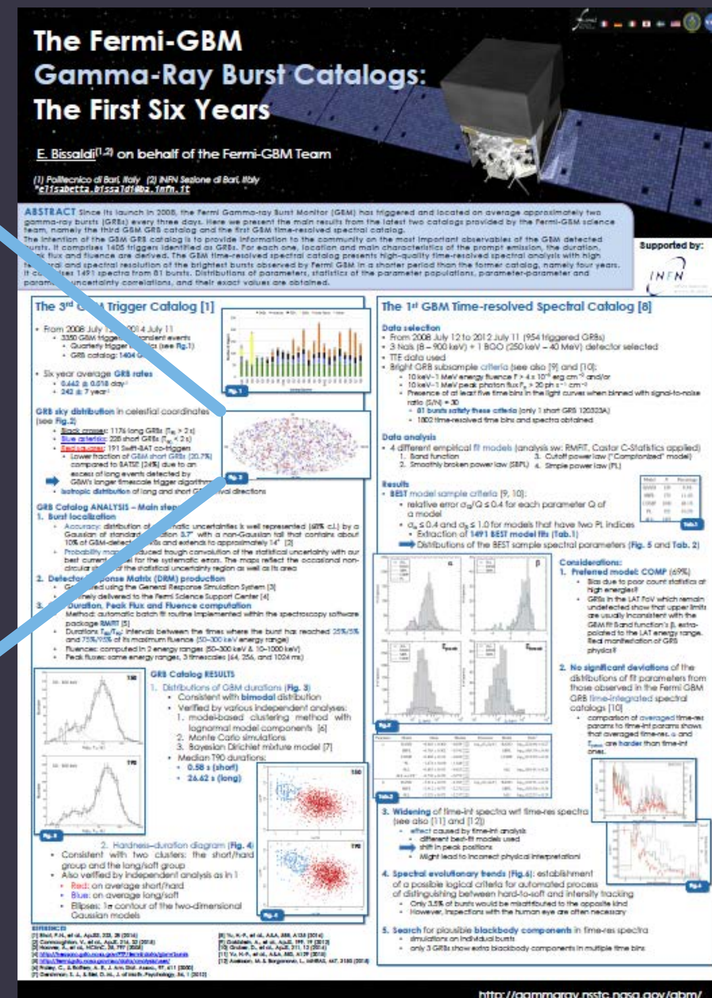

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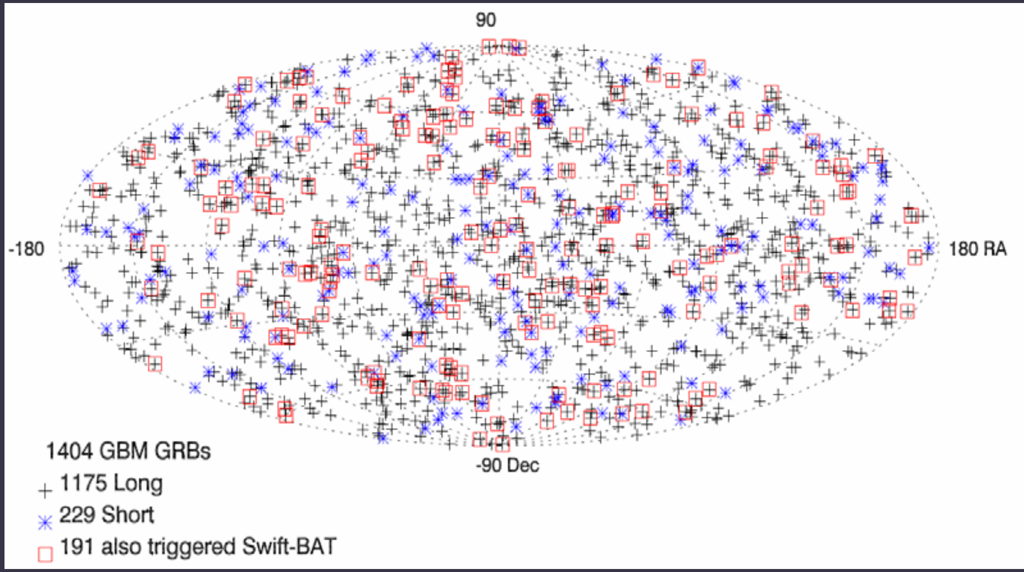


Owing to all-sky coverage, Fermi GBM detects and localizes more short GRBs than other GRB detectors:

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: 2.5 σ and another 1.25 σ 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

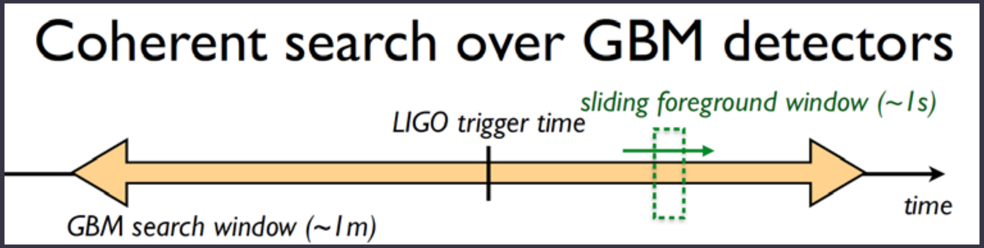
Short GRB Candidates

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

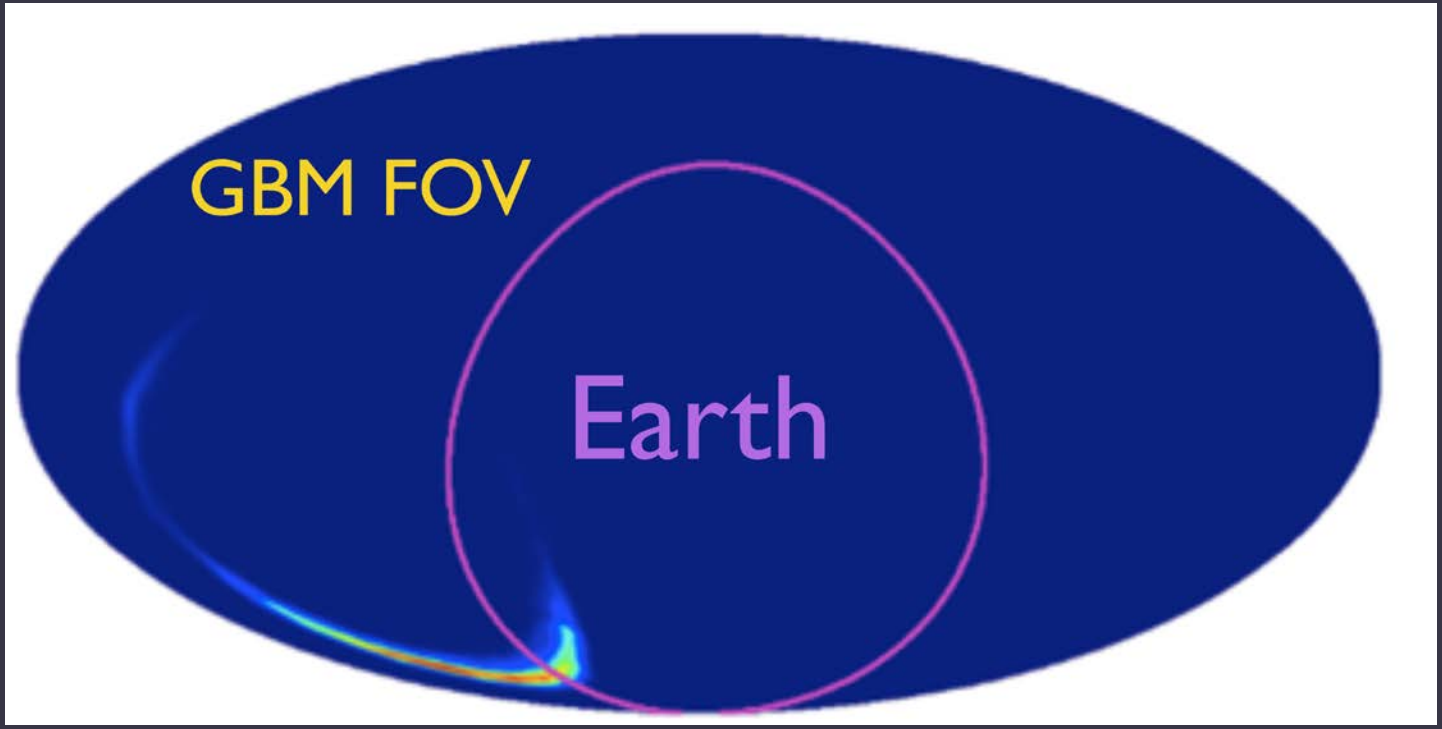
- Developed during LIGO S6 observing run **(Blackburn et al. ApJS 2015, 217, 8)**
- Seeded with time & (optionally) sky location of a LIGO/Virgo event
- Using the **full response** for a point source at each sky position
- Search over user-specified **time window**



- 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
...
```

(Private communication)

«GW150914-GBM»

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

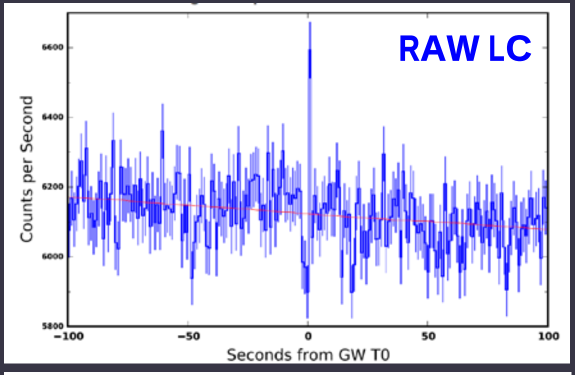
FAR = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

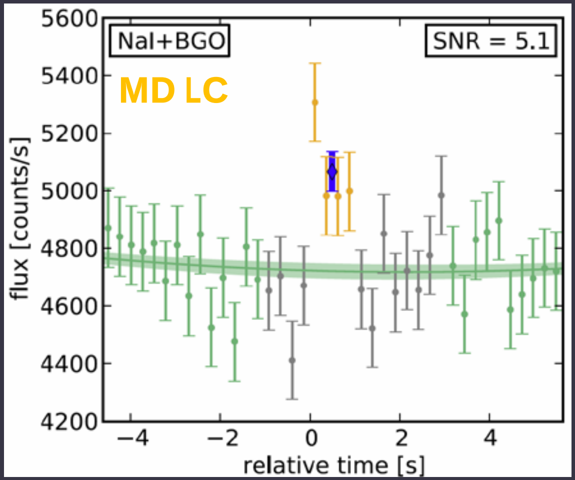
P = 2 x (4.79 × 10−4 Hz) × 0.4 s × (1 + ln(30 s / 0.256 s)) = 0.0022

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

Offset between GW T0 and GBM event start

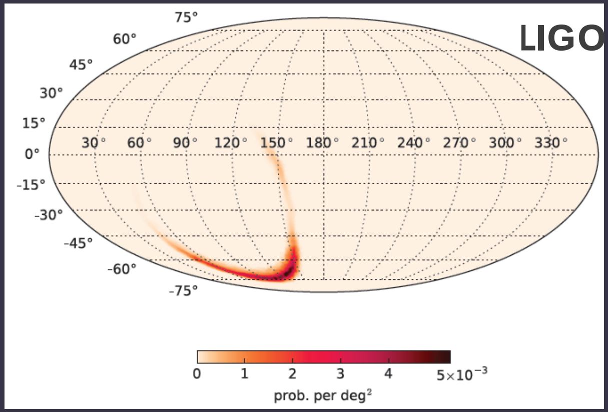
Effective trials factor for non-independent, variable time bins (30s is maximum offset set by the search window, 0.256 is the minimum set by native CTIME data)





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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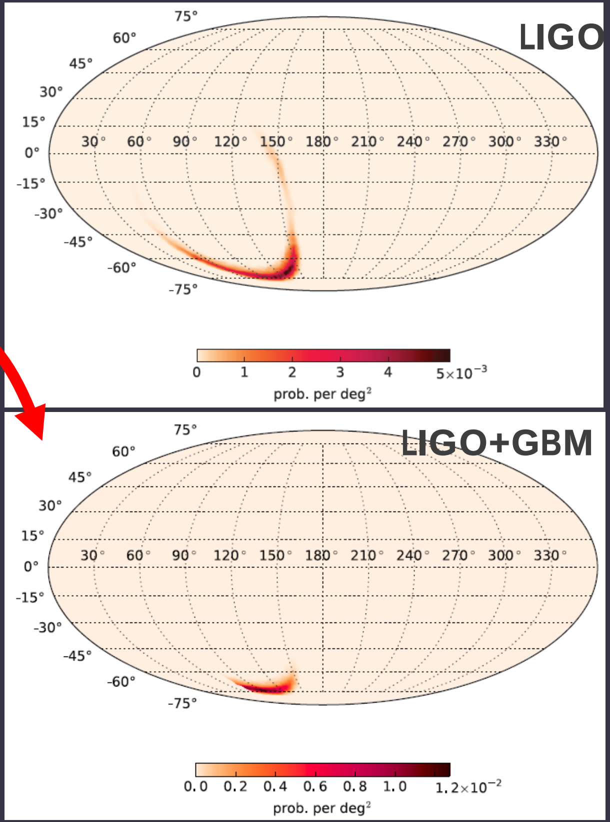
  - If association with GW150914 was true:
    shrink LIGO localization by 2/3



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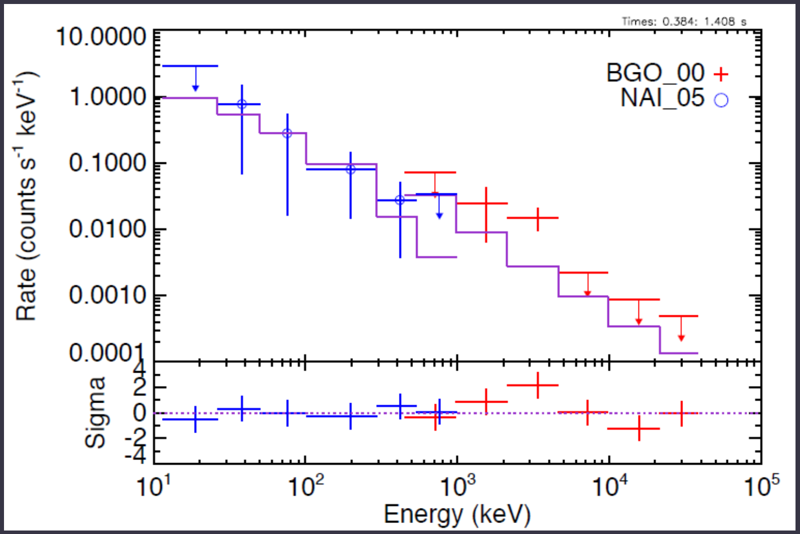

- Energy spectrum:
  - Peaking in BGO energy range.
    Best fit **simple PL** with index **–1.4** (average for sGRBs),
    Fluence **2.4 x 10^{-7} erg cm^{-2}** (weaker than average for sGRBs)

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 magnetospehric activity
- Evidence against:
  - Low significance
  - Lack of corroboration by other experiments
  - **Nature of the LIGO event is a BH-BH merger**

Conclusions

- 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

Conclusions

- 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

Conclusions

- 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!

Conclusions

- 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