Recent Results

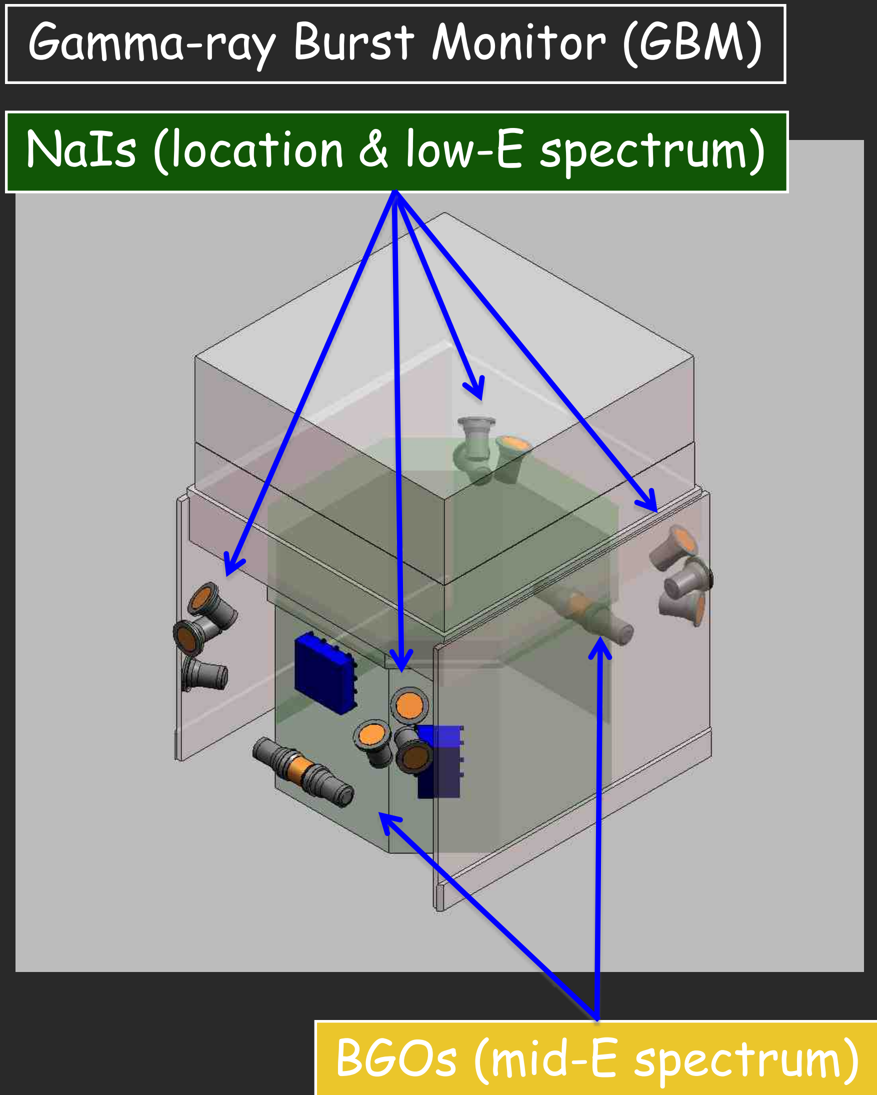
Fermi GBM

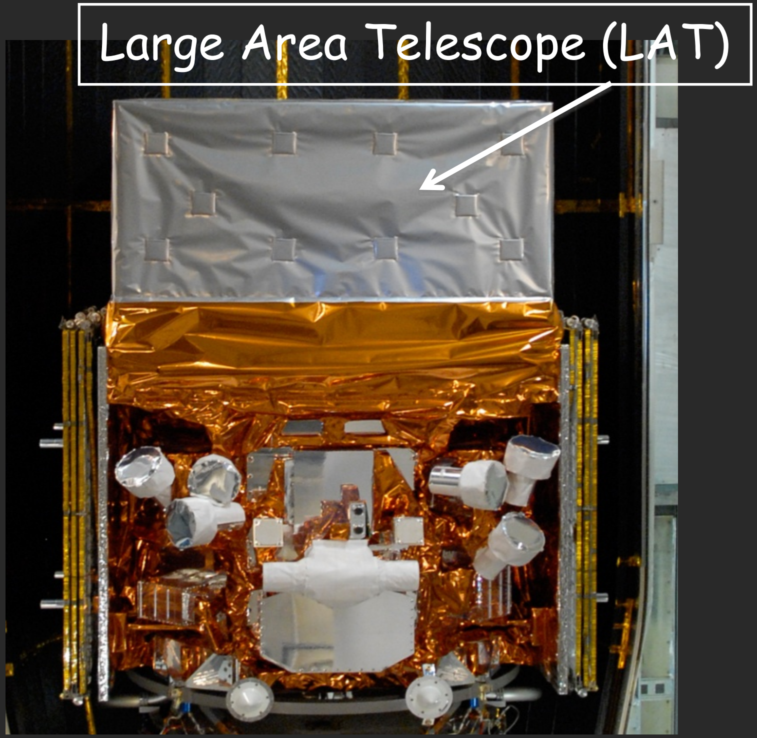
Andreas von Kienlin

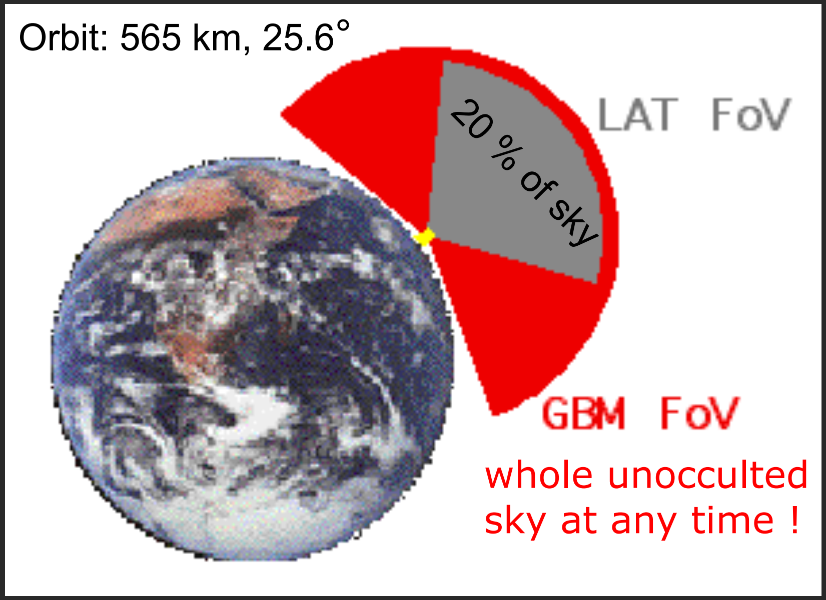
Max-Planck-Institut für extraterrestrische Physik (MPE), Garching

on behalf of the *Fermi* GBM Science Team

The *Fermi* Observatory



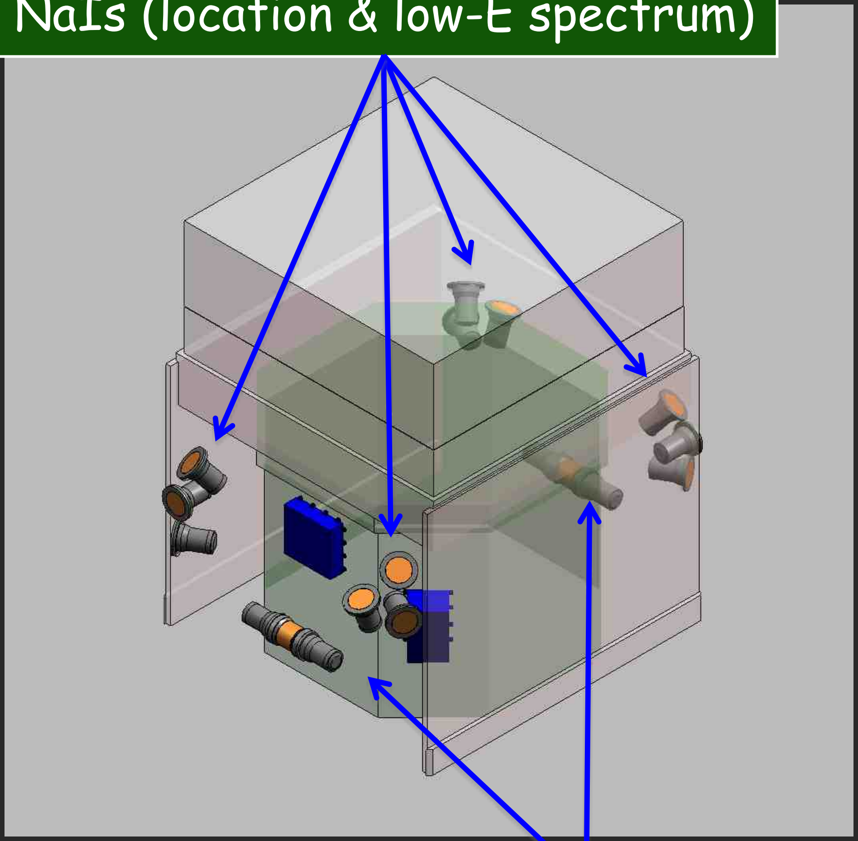


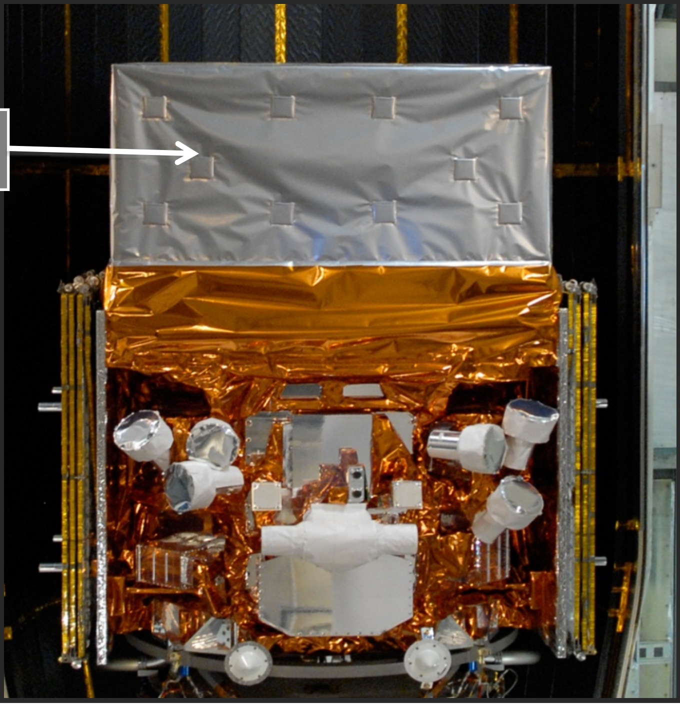


The *Fermi* Observatory

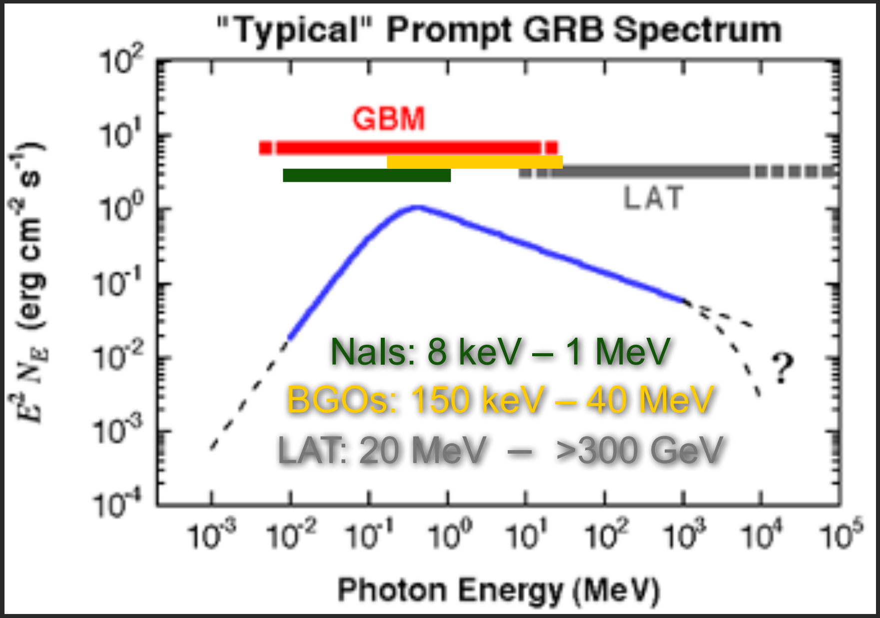
LAT (high-E spectrum)

NaIs (location & low-E spectrum)



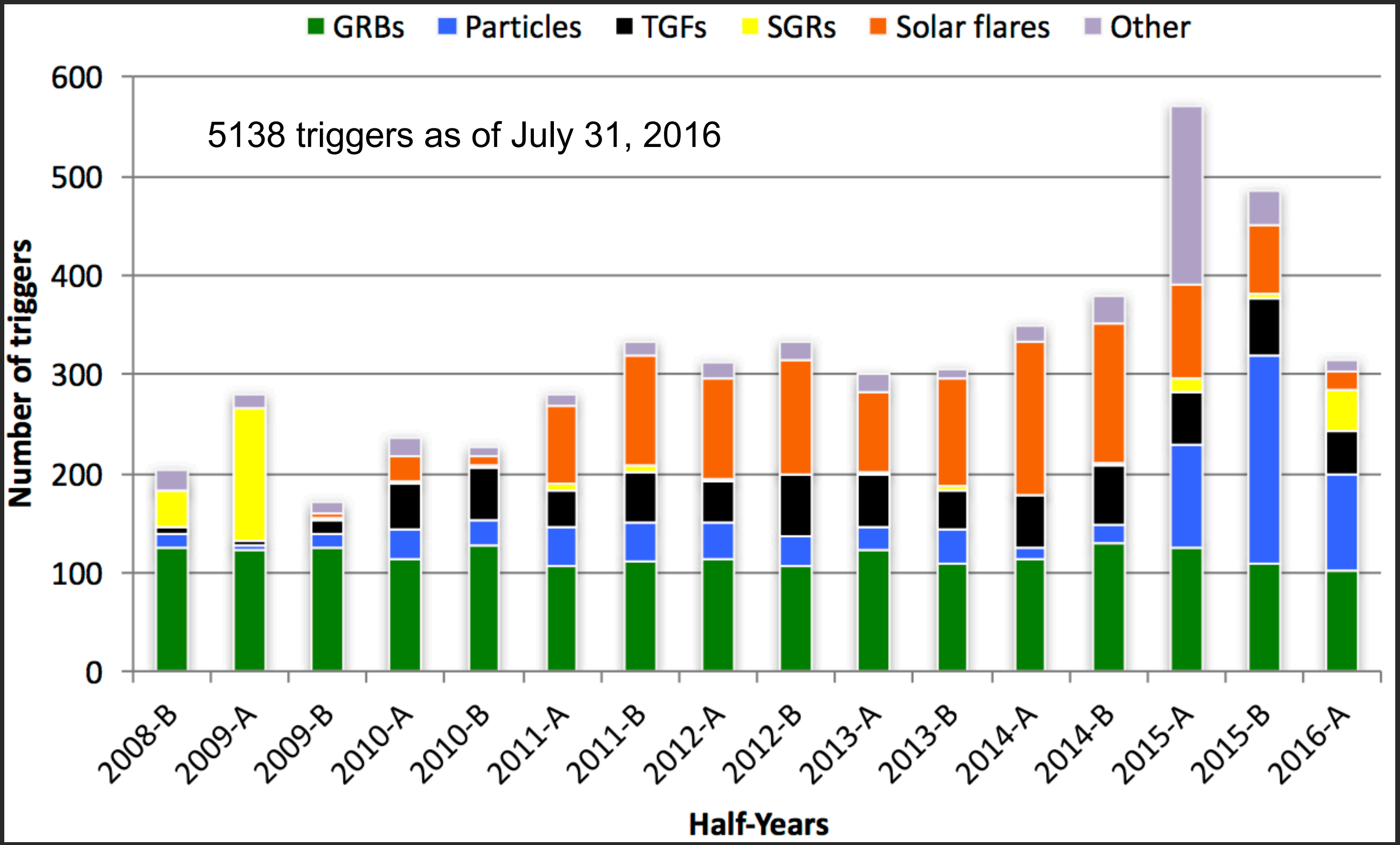


BGOs (mid-E spectrum)



What does GBM see?

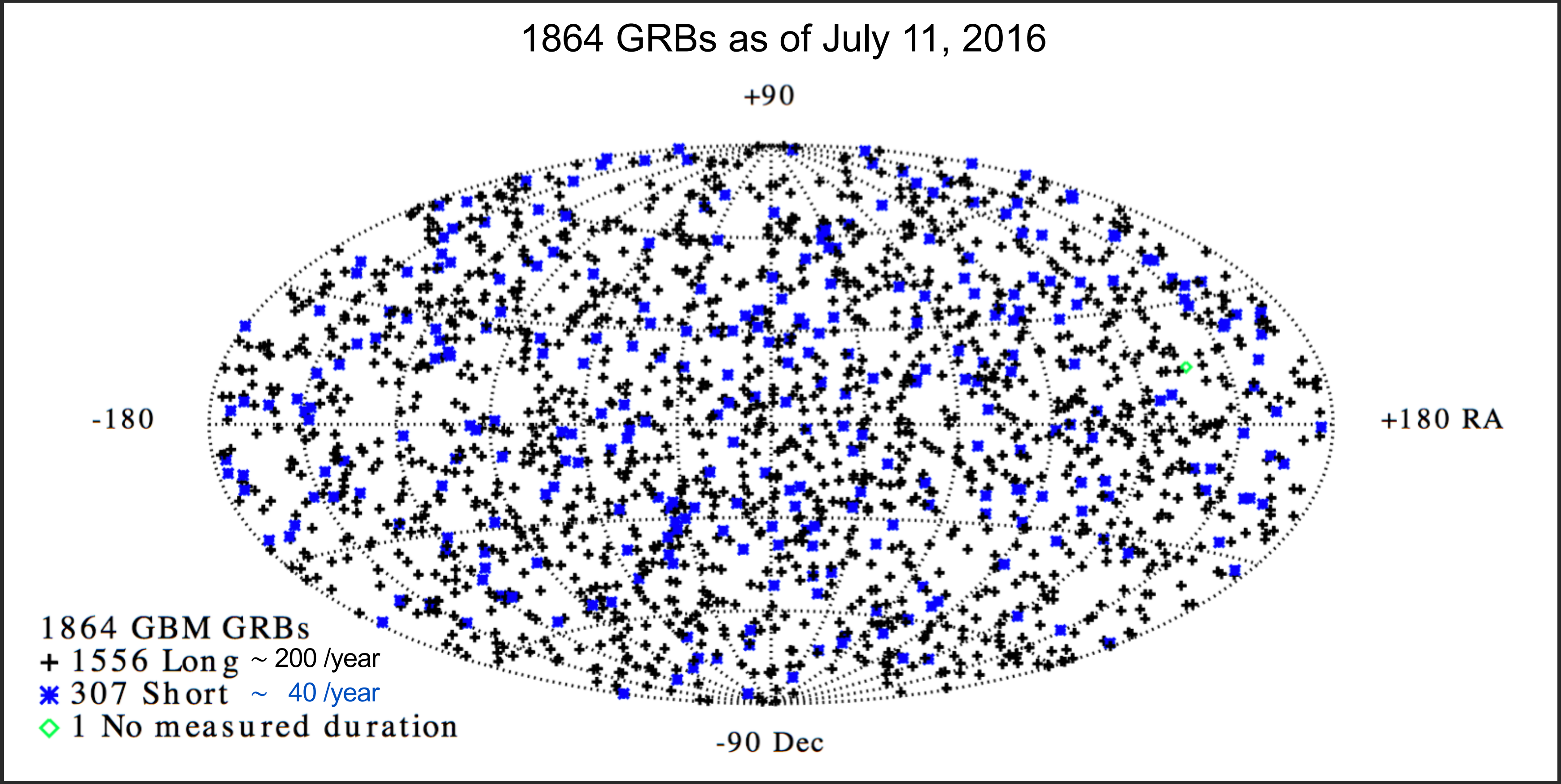
Lots of stuff



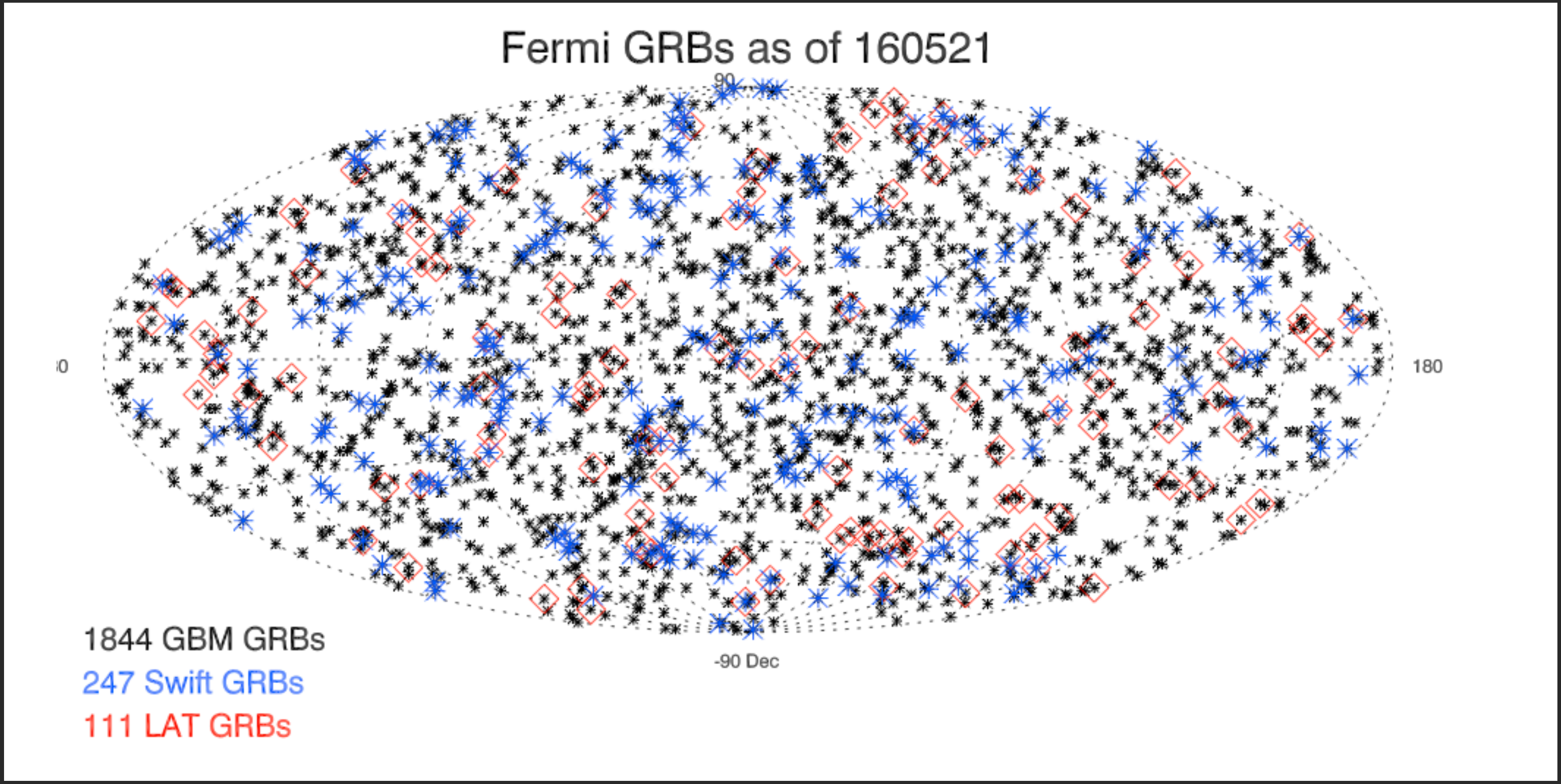
Gamma-ray bursts (GRBs): 1879 (triggered twice on each of four long GRBs)
Particles: 746
Terrestrial gamma flashes (TGFs): 686 triggered, ~5x more untriggered
Soft gamma repeaters (SGRs) aka magnetars: 267 (from >8 sources)
Solar Flares: 1121
Others (galactic XRBs, accidental, uncertain): 435 (169 from V404 Cygni)

168 positive ARRs: Autonomous Repoint Recommendations

Fermi GBM in first eight years of operation



Fermi GBM in first eight years of operation



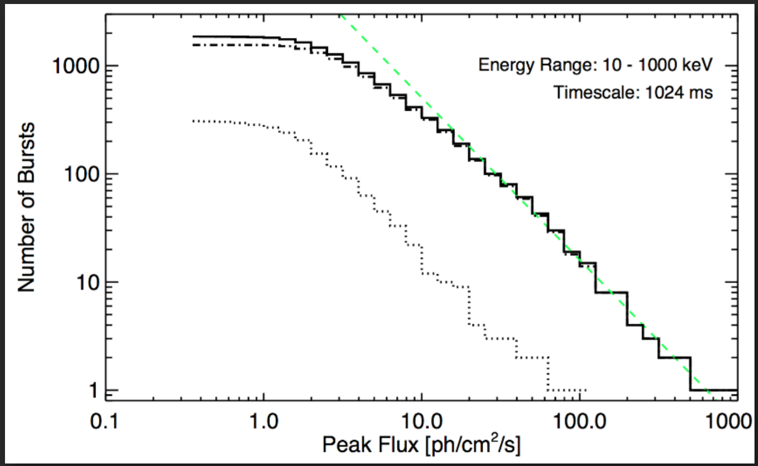
GBM GRB online catalog now updated within 1 hour, spectral information ~weekly

→ http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

Recent Results

- GBM catalogs
  - The 3rd Fermi GBM Gamma-ray Burst Catalog: The First Six Years
    - Bhat, P.N. et al., ApJSS, 223, 28 (2016)
  - GRB time-resolved spectral catalog: the brightest bursts in the first 4 years
    - Yu, H.-F. et al., A&A, 588, A135 (2016)
  - The Fermi-GBM Three-year X-ray Burst Catalog
    - Jenke, P.A. et al., ApJ, 826, 228 (2016)
  - First GBM TGF catalog: http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/
    - includes GBM and WWLLN data
  - The Five Year Fermi/GBM Magnetar Burst Catalog
    - Collazzi A.C. et al., ApJ, 218, 11 (2015)
- Other results: Earth occultation monitoring, Pulsar Monitoring, …
- GBM Observations of GW Events
  - Untriggered & Targeted Search
  - GW150914, LVT151012, GW151226

GBM GRB catalogs



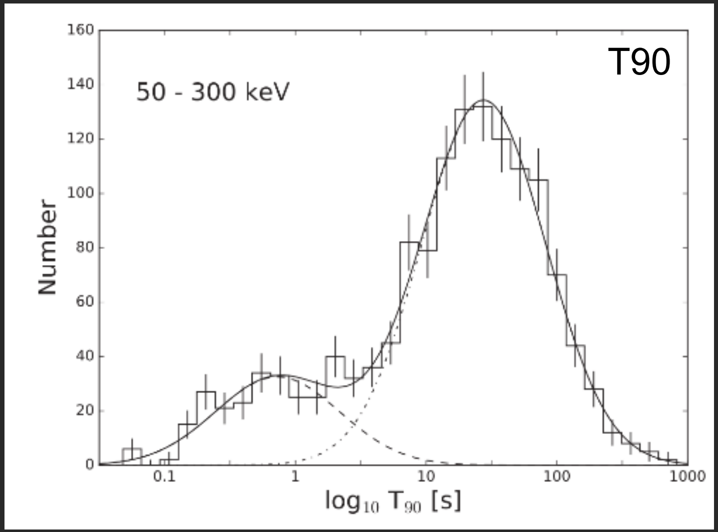
3rd GBM GRB Catalog / 6 year catalog

- Bhat P.N. et al., ApJSS, 223, 28 (2016)

Each GRB: location, duration, peak flux & fluence

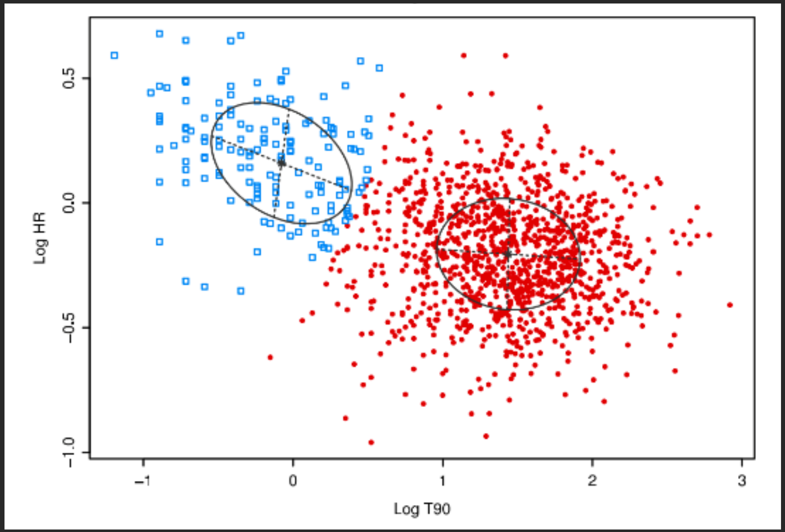
Distribution of GRB durations

- Consistent with bimodal distribution
- Median T90 durations:
  - 0.58 s (short)
  - 26.62 s (long)



Hardness-duration diagram

- Using statistical methods to assess clustering: Hardness and duration of GRBs are better fit by a two-component model with short-hard and long-soft bursts than by a model with three components.

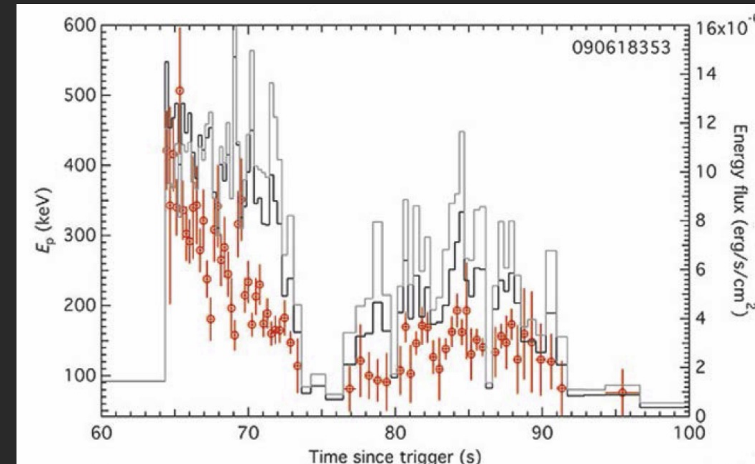


Ellipses show the best-fitting multivariate Gaussian models

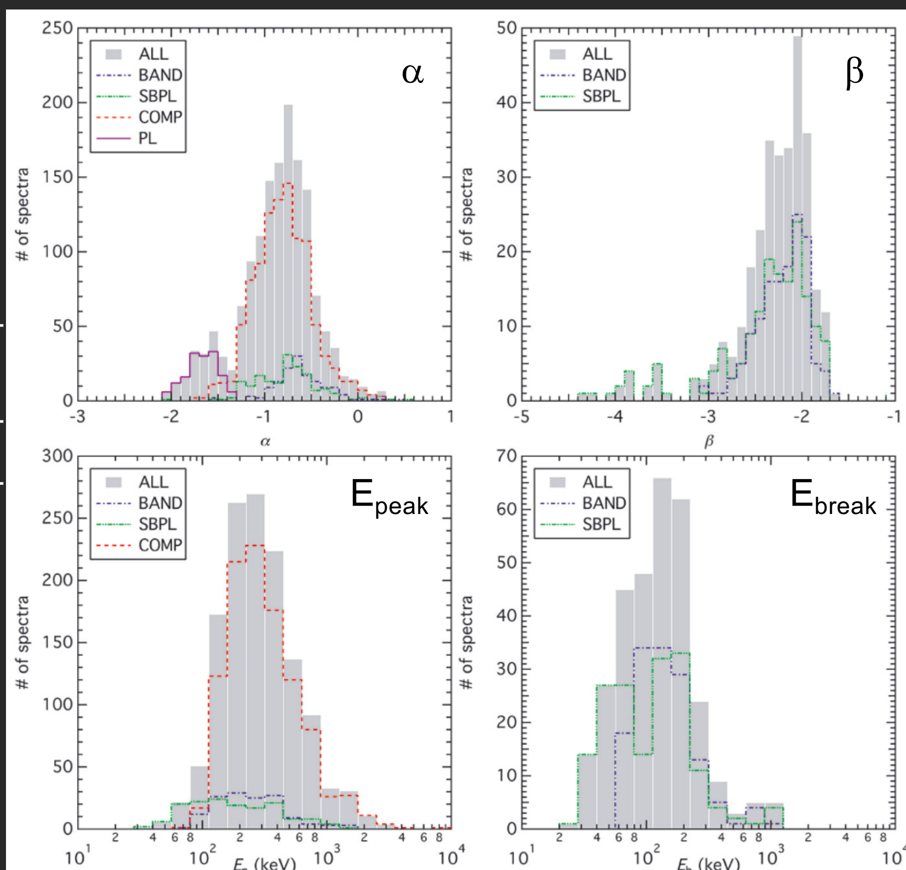
GBM GRB catalogs

1st Time-resolved spectral catalog

- ➢ H. Yu et al., A&A, 588, A135 (2016)

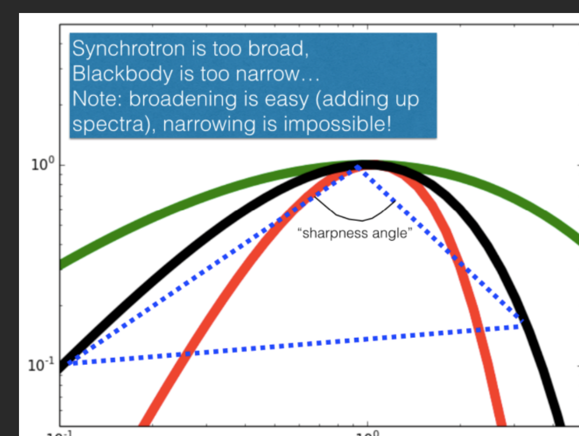


- Data from 4 year burst catalog (954 GRBs)
  - ➢ Bright subsample - selections on
    - energy fluence and/or peak photon flux
    - 81 GRBs / 1802 time resolved spectra



Distributions of the BEST sample spectral parameters

- Data analysis:
  - ➢ Band-, Compt-, SBPL-, PL- fit models
  - ➢ 1491 “BEST” model fits
  - ➢ Preferred model: COMP (69%)
- Sharpness of prompt GRB spectra
  - ➢ H. Yu et al., A&A, 588, A135 (2016)
  - ➢ **91%** of the spectra in the sample are inconsistent with any kind of standard synchrotron radiation function



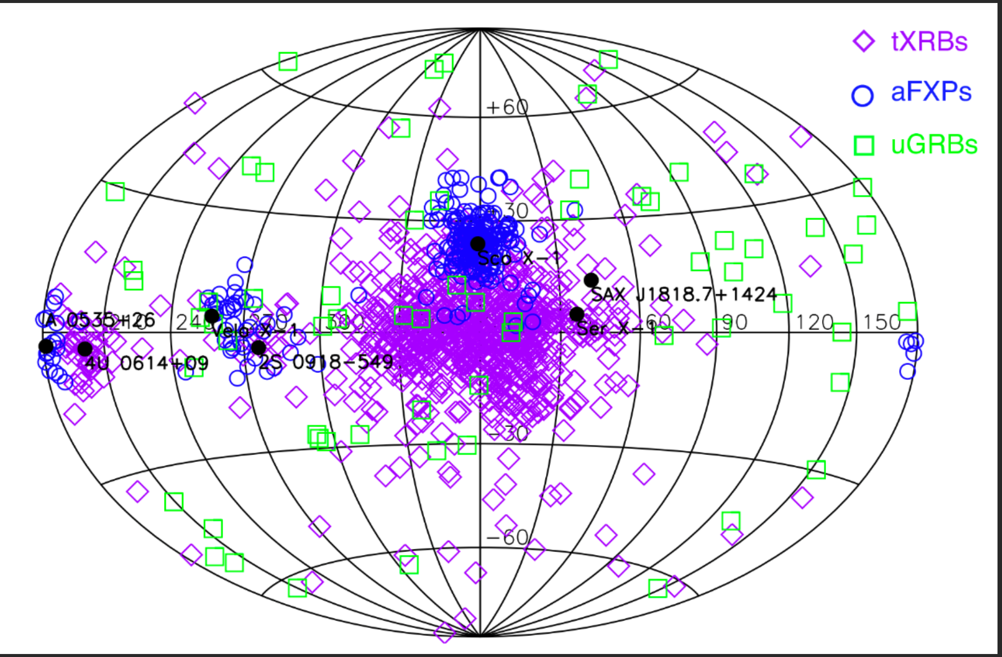
Catalogs from GBM

- The Fermi-GBM Three-year X-ray Burst Catalog,
  - P. Jenke et al. 2016, ApJ, 826, 22
  - Systematic search for transients in the 12–25 keV E-channel, with a time resolution of 8.2 s
  - 1084 events, classified using spectral analysis, location, and spatial distributions

752 thermonuclear X-ray bursts

267 accretion flare events
+ X-ray pulses

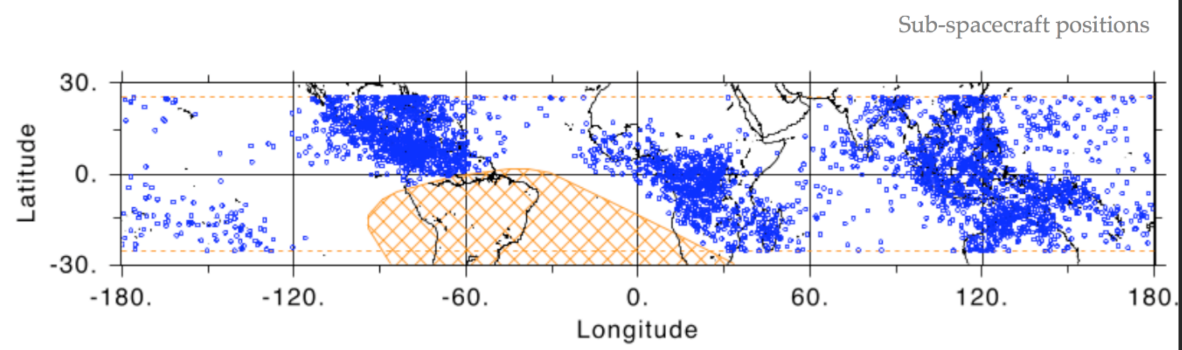
65 untriggered GRBs



- Thermonuclear bursts have peak blackbody temperatures broadly consistent with photospheric radius expansion (PRE) bursts

Catalogs from GBM

- 2nd GBM TGF catalog is now online including VLF locations
  - http://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/
  - Fitzpatrick, et al., in preparation
  - 3356 TGFs from 2008 Jul 11 – 2015 June 23; >80% untriggered



    - Offline search: 3348 TGFs
    - Triggered TGFs: 579 TGF, with 8 that are not the Offline Search Table
    - Terrestrial Electron Beams (TEBs): 16 reliable, 8 possible
  - Over 1000 GBM TGFs have VLF geo-locations good to ~10km

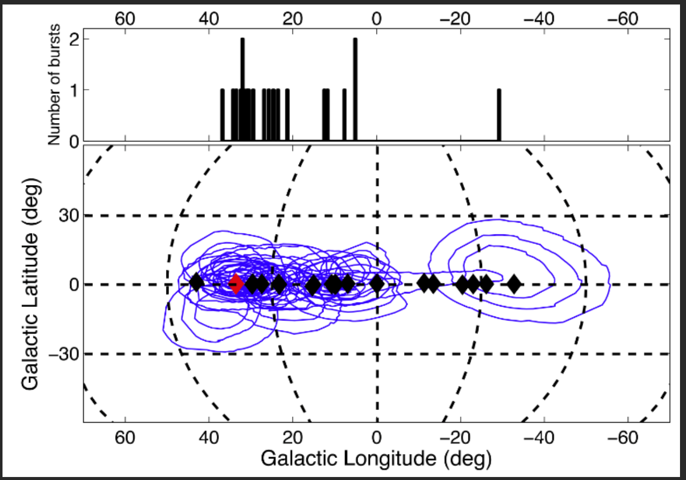
Catalogs from GBM

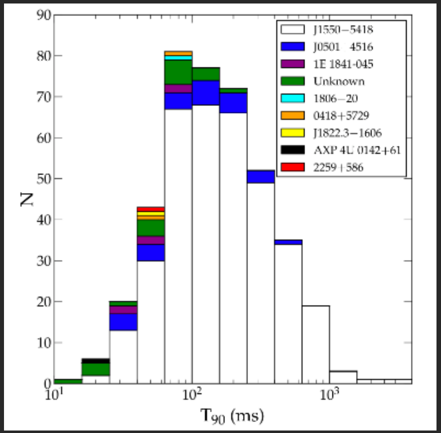
- The Five Year *Fermi*/GBM Magnetar Burst Catalog
  - Collazzi A.C. et al., ApJ, 218, 11 (2015)
  - July 2008 to June 2013
  - Temporal & spectral analysis of 446 magnetar bursts
    - providing durations, spectral parameters for various models, fluences, and peak fluxes
  - Small sample of magnetar-like bursts of unknown origin
  - Combined durations and spectral parameters

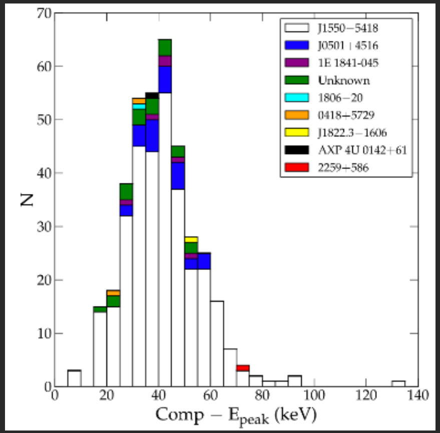
    Several similarities:
    - T90 ~100ms,
    - COMP E_{peak} ~40 keV
    - Temperatures of BB+BB center around ~4.5 and ~15 keV

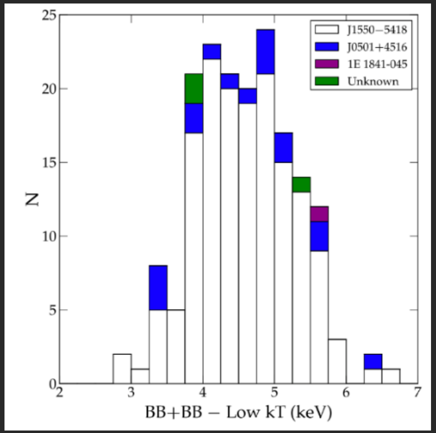
Summary of GBM Magnetar Bursts

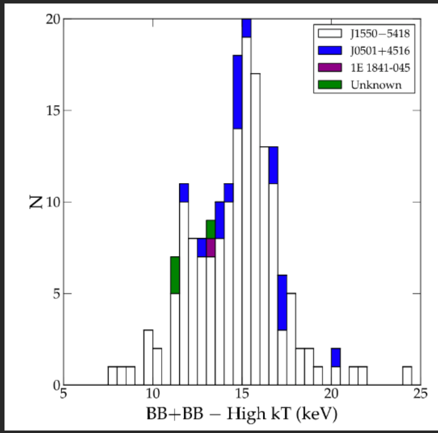
Source	Burst Active Periods	Number of Bursts with TTE data
SGR J1550–5418	2008 Oct–2009 Apr	386
SGR J0501+4516	2008 Aug/Sep	29
1E 1841–045	2011 Feb–Jul	6
SGR J0418+5729	2009 Jun	2
SGR 1806–20	2010 Mar	1
SGR J1822.3–1606	2011 Jul	1
AXP 4U 0142+61	2011 Jul	1
AXP 1E 2259+586	2011 Aug	1
Unknown	…	19









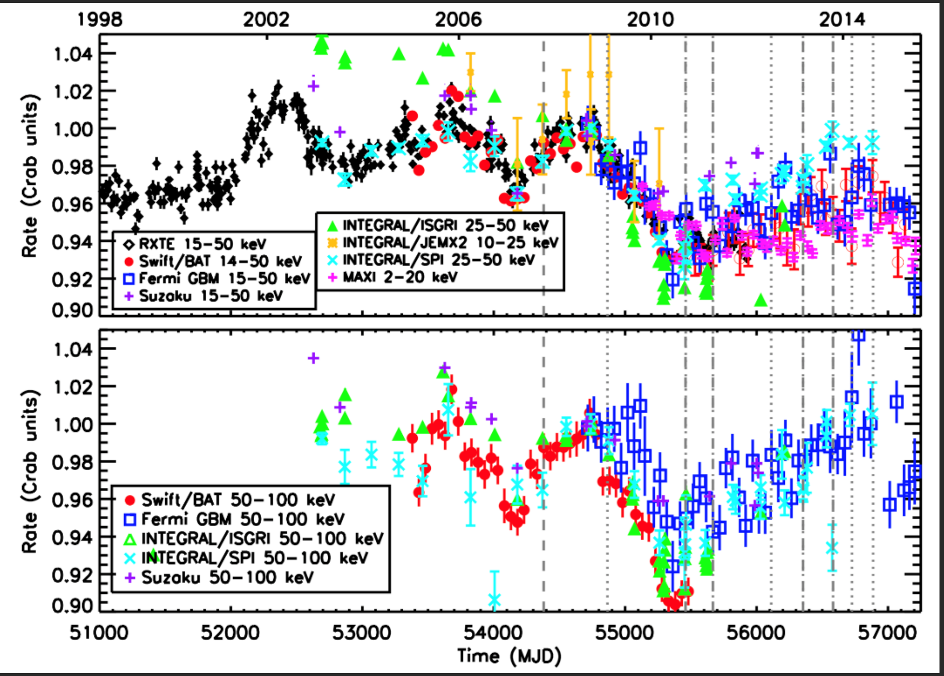


GBM earth occultation observations

- GBM Earth Occultation Project
  - PI Colleen Wilson-Hodge
- Crab Nebula Hard X-ray Variations
  - Wilson-Hodge et al 2011, ApJ, 727, L40

    "WHEN A STANDARD CANDLE FLICKERS"
- > 200 sources are monitored

  http://heastro.phys.lsu.edu/gbm/



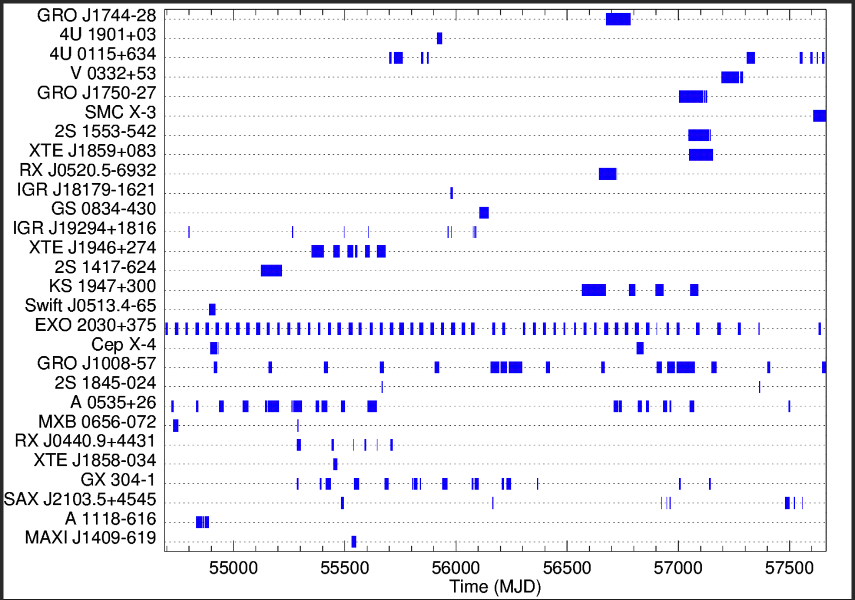
GBM Earth Occultation Monitored Sources

#	SOURCE NAME	RA (DEG)	DEC (DEG)	L (DEG)	B (DEG)	OBJECT TYPE	MISSION AVG FLUX (MCRAB)	5 DAY AVG FLUX (MCRAB)	2 DAY FLUX (MCRAB)
1	SUN	NA	NA	96.337	-60.189	Star	36.31 ± 0.83	29.59 ± 14.76	ND
2	IGR_J00234+6141	5.740	61.685	119.561	-1.000	CV	3.64 ± 0.91	193.15 ± 27.07	261.40 ± 36.16
3	V709_CAS	7.204	59.289	120.042	-3.456	CV/DQHer	5.98 ± 0.91	88.59 ± 24.16	86.87 ± 28.65
4	BD+6270	9.300	61.380	121.227	-1.445	Star	8.01 ± 0.90	ND	ND
5	FERMIJ0109+6134	17.445	61.558	125.115	-1.236	AGN	4.28 ± 0.80	ND	ND

GBM pulsar monitoring

- Monitoring Program
  - 37 sources monitored
  - 34 sources detected
  - 8 Persistent, 26 transients
  - PI Colleen Wilson-Hodge

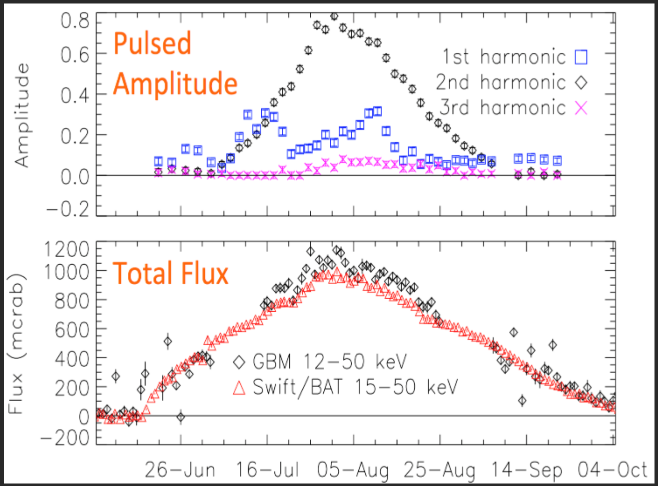
  http://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html



Times of Transient Outburst Detections

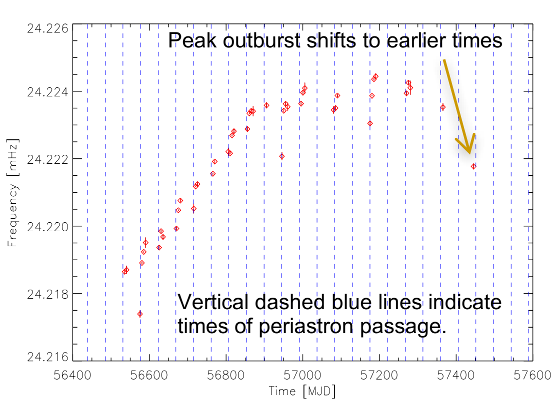
V0332+53

- 4.3 s X-ray pulsar orbiting an O8-9Ve star
- Major outbursts in 1983, 1989, 2004, **2015**
- 2015 outburst shows considerable pulse profile evolution
- New orbital analysis in progress



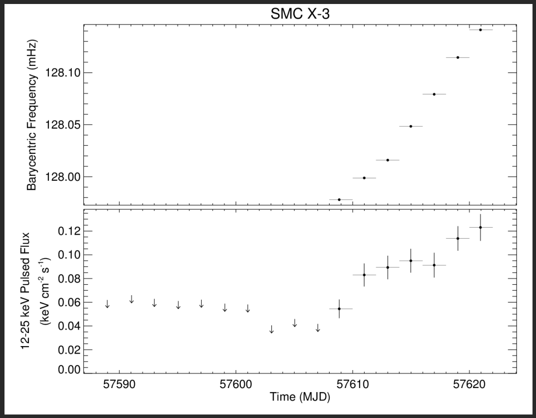
EXO 2030+375

- GBM discovers latest rare torque reversal in the Be X-ray binary
- Last seen in 1994 / Possible shift in orbital phase of the peak of the outburst



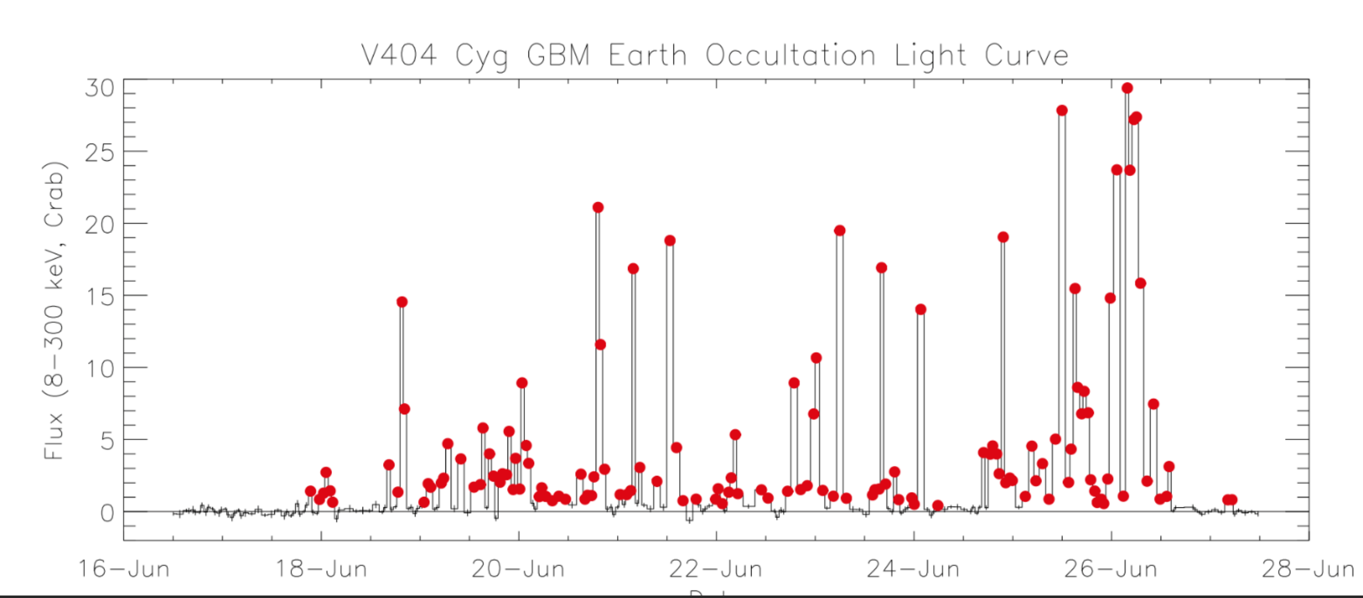
SMC X-3

- GBM monitors rare X-ray outburst of the Be binary last seen in 2003



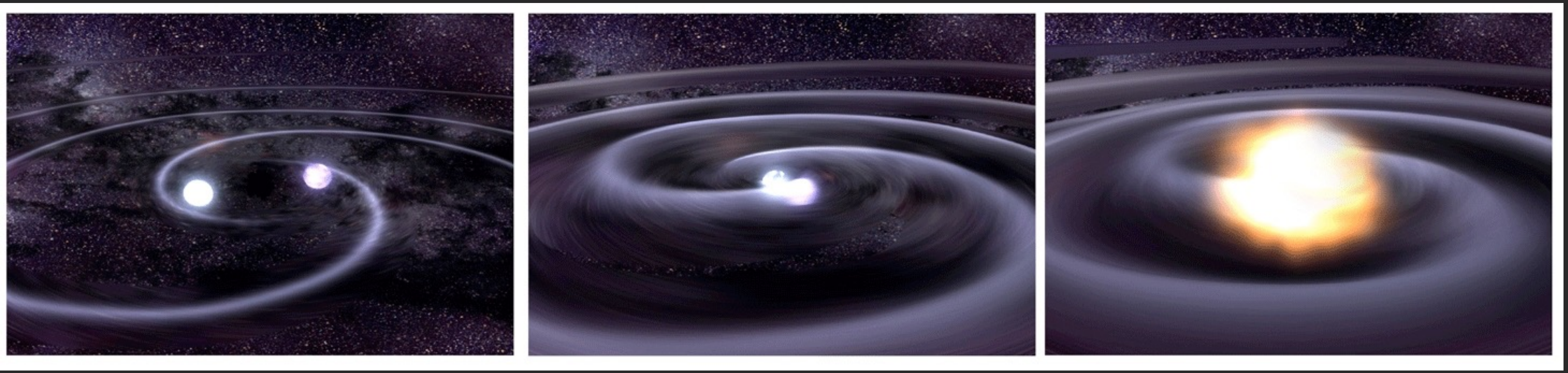
GBM Observations of V404 Cygni

- 10 $M_{\odot}$ Black hole only 2.4 kpc away
- Discovered by the Ginga X-ray satellite during its only previously observed X-ray outburst in 1989. Two other confirmed outbursts were seen in the optical band in 1938 and 1956.
- 169 GBM Triggers over 13 days starting June 15, 2015
- 73 Distinct flaring episodes
- Reached a brightness of 30 Crab with emission to 300 keV
- Jenke et al. , ApJ, 826, 37 (2016)



GBM detected Short GRBs

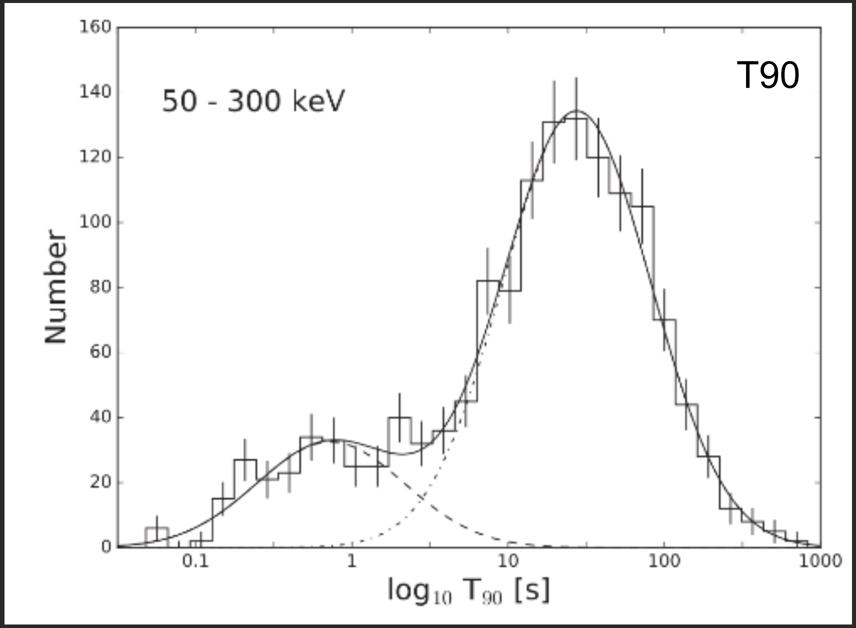
- GBM instrument best suited for EM counterpart search of GW events!



Short GRBs → NS-NS, NS-BH

GBM: ~ 40 triggered short GRBs/year

Swift: ~ 9 short GRBs/year



Untargeted GBM offline searches

- Search algorithm for un-triggered short GRBs (sGRBs)
  - Using CTTE data, 2μs time resolution,128 energy channels
  - 2 detectors: 2.5 σ and another 1.25 σ above background
    - On-Board, 2 detectors: 4.5 ≤ σ ≤ 7.5
  - 10 timescales: 0.1s to 2.8s
    - On-Board: 16 ms ≤ t ≤ 8.096 s
  - 5 energy ranges (optimized on GBM-triggered weak sGRBs)
  - 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

Untrigered GBM sGRB candidates

Short GRB Candidates

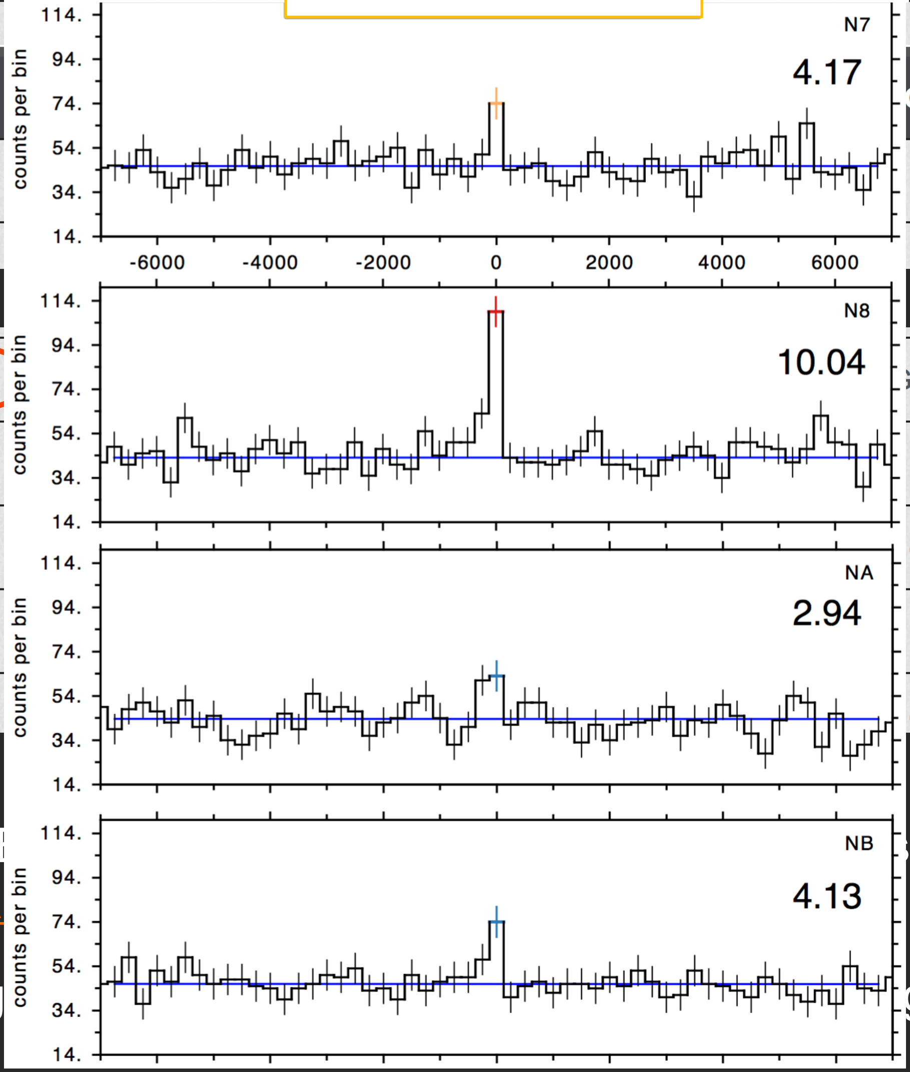
MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)	COMMENT
392494389.500	3.17E-0007	2013-06-09	18:13:6.500	323.24	+21.54	13.83	
392551943.650	2.55E-0007	2013-06-10	10:12:20.650	73.68	-19.40	11.76	
…							
423745096.625	1.91E-0016	2014-06-06	10:58:13.625	232.07	+37.47	18.86	Swift GRB, also ACS
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	ACS confirmation
424968038.500	2.80E-0007	2014-06-20	14:40:35.500	319.45	-17.40	17.05	
426588599.600	7.75E-0014	2014-07-09	08:49:56.600	12.77	-49.36	6.53	ACS confirmation

- 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

Untrigered GBM sGRB candidates

MET	RANK	DATE (UT)	OMMENT
392494389.500	3.17E-0007	2013-06-09	
392551943.650	2.55E-0007	2013-06-10	
423745096.625	1.91E-0016	2014-06-06	RB, also ACS
424708158.025	2.36E-0007	2014-06-17	
424757010.500	1.92E-0016	2014-06-18	confirmation
424968038.500	2.80E-0007	2014-06-20	
426588599.600	7.75E-0014	2014-07-09	confirmation

SWIFT GRB 140606A

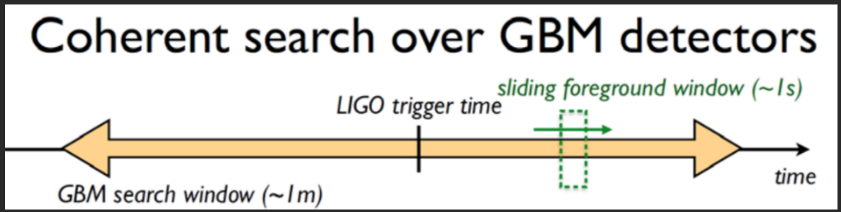


- A list of untriggered SGRB … ted at http://gammaray.nsstc.na…
- Working towards creating … gered events type

Targeted Search of GBM data to GW events

- ➢ Developed during LIGO S6 observing run (Blackburn et al. 2015)

- Coherent search over all GBM detectors (NaI and BGO)
  - ➢ seeded with time & (optionally) sky location of any LIGO/Virgo candidate event
  - ➢ over user-specified time window
  - ➢ estimate of background rate by polynomial to local data outside the foreground interval



- For each template spectrum (soft, medium & hard) and sky location
  - ➢ Detector counts for each energy channel are weighted according to the modeled rate
  - ➢ and inverse noise variance due to background
  - ➢ Weighted counts from all NaI and BGO detectors are summed to obtain a signal-to-noise optimized light curve for that model
  - ➢ Each model is assigned a likelihood by the targeted search based on the foreground counts
- Candidates are ranked by a Bayesian likelihood statistic
- Will reveal short-duration candidates between 0.256 s to 8.192 s (CTIME)

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

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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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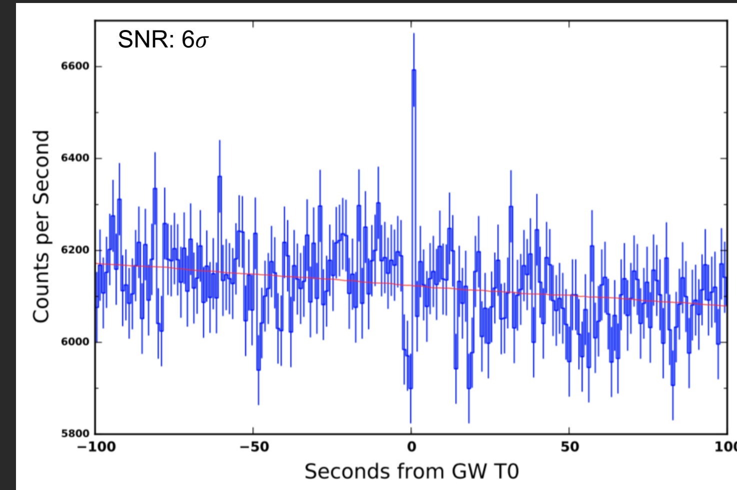
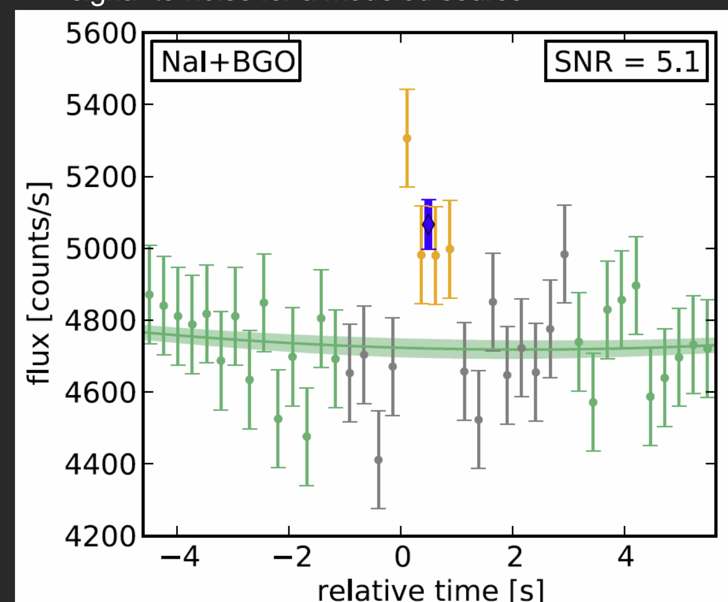
Raw count rates:

- Sum of all GBM detectors: 12 x NaI + 2 x BGO
- NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV



Model-dependent count rates:

- Raw count rates weighted & summed to max signal-to-noise for a modeled source



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)

False Alarm Probability Calculation:

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

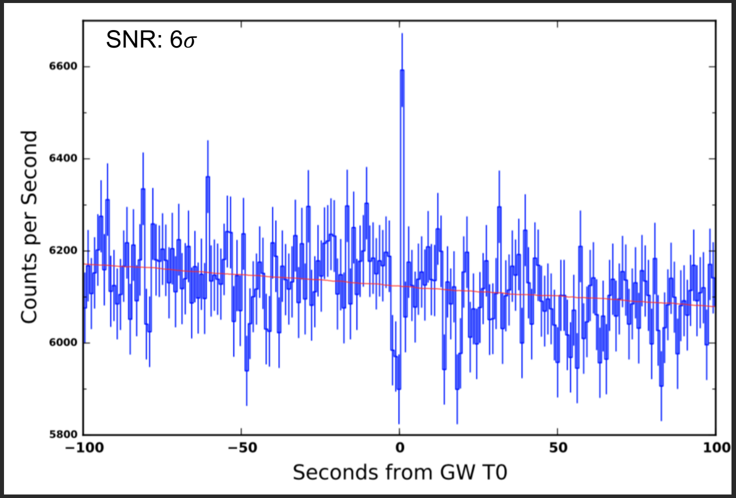
P = 2 x (4.79 x 10-4 Hz) x 0.4 s x (1 + ln(30 s / 0.256 s)) = 0.0022

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

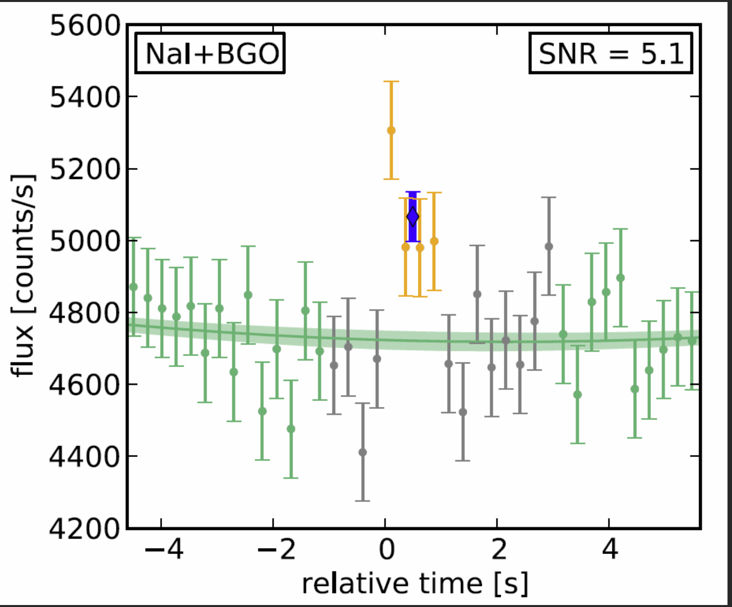
Offset between GW T0 and GBM event start

Effective trials factor for bins/durations Searched:
- 30 s: max offset (search window)
- 0.256 s: min CTIME bin

Raw count rates:
- Sum of all GBM detectors: 12 x NaI + 2 x BGO
- NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV

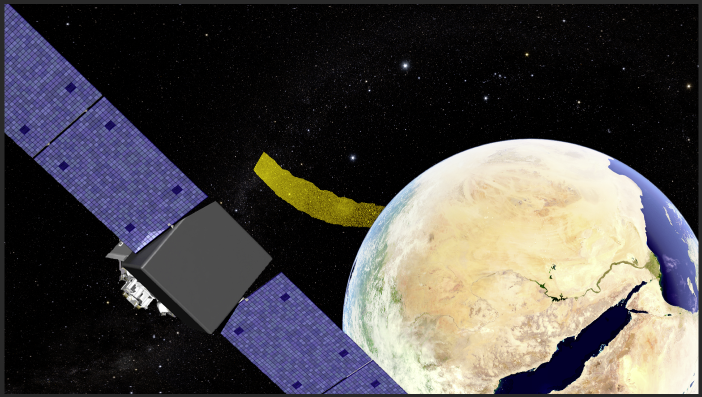


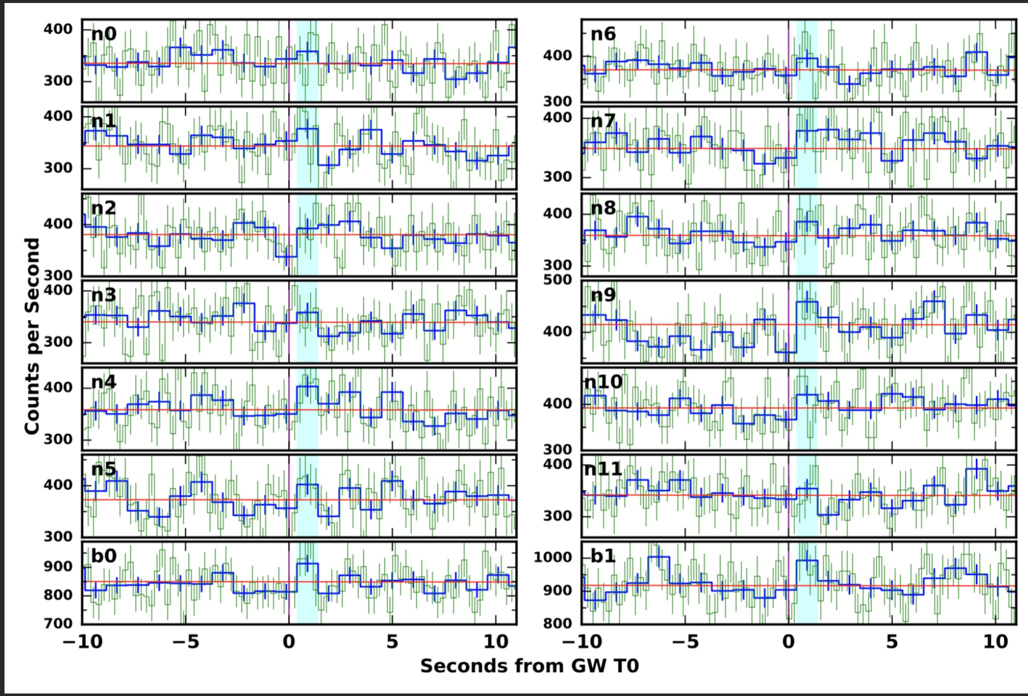
Model-dependent count rates:
- Raw count rates weighted & summed to max signal-to-noise for a modeled source



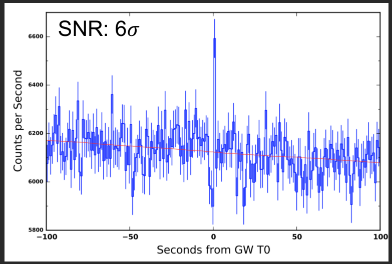
Characteristics of GW150914-GBM

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





NaIs:
50 – 980 keV
BGOs:
420 keV – 4.7 MeV



σ deviation from a background fit

NaI 0	NaI 1	NaI 2	NaI 3	NaI 4	NaI 5
1.31	1.81	0.64	1.05	2.42	1.68
NaI 6	NaI 7	NaI 8	NaI 9	NaI 10	NaI 11
1.31	1.64	1.45	2.20	1.61	0.66
BGO 0	BGO 1				
2.25	2.56				

Characteristics of GW150914-GBM

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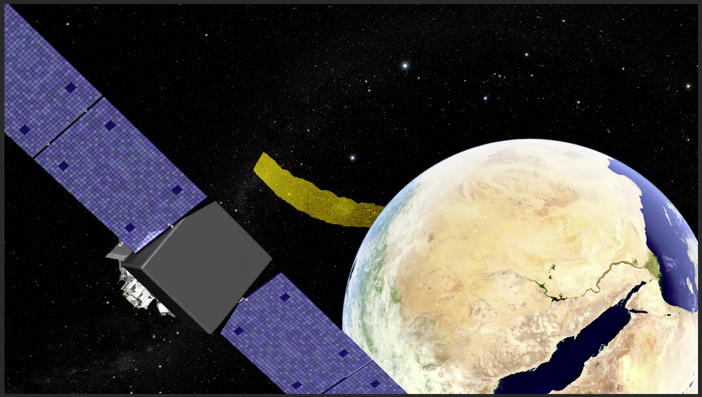
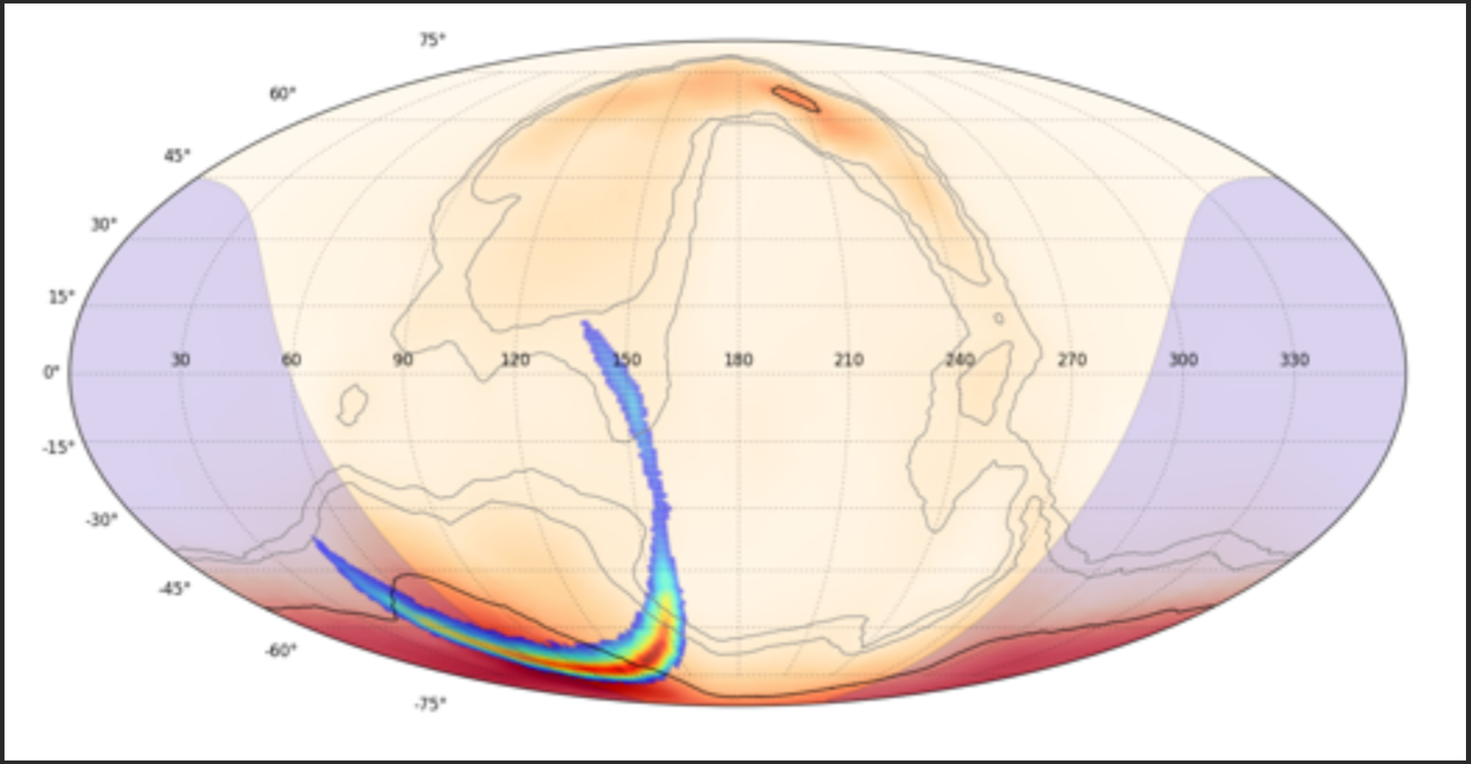
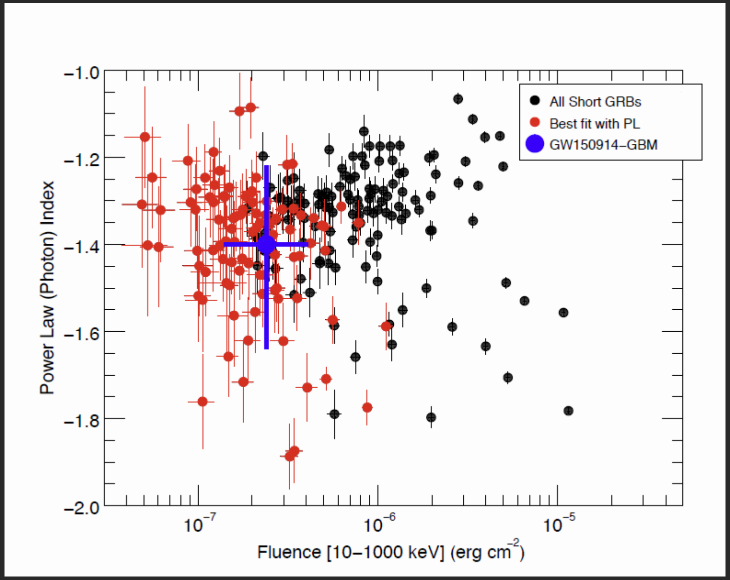
  - If association with GW150914 was true: shrink LIGO localization by 2/3

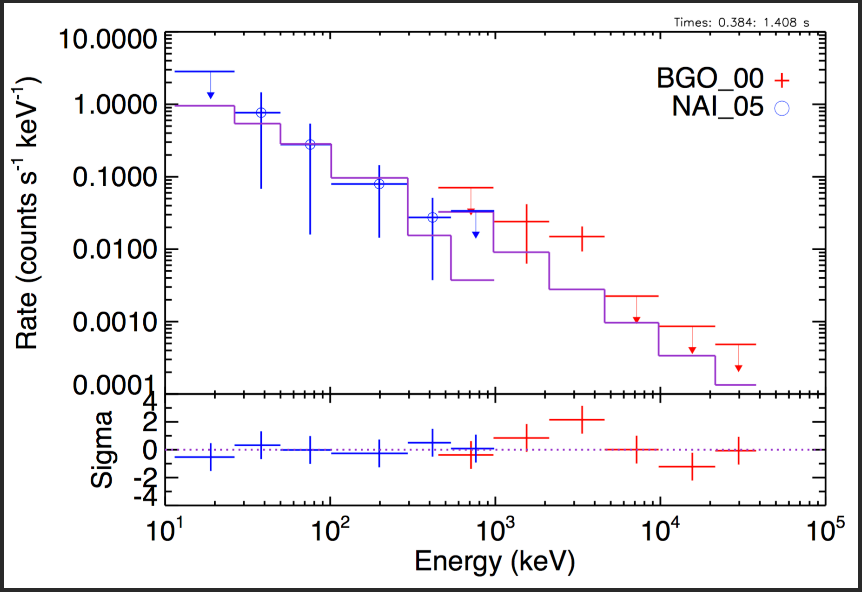




Characteristics of GW150914-GBM

- Unusual detector pattern:
  nearly equal count rates in all NaI detectors
  - Localization: source direction **underneath** the spacecraft, 163° to the spacecraft pointing direction
  - If association with GW150914 was true: shrink LIGO localization by 2/3
- 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)





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

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Magneto spheric	No	?	?	No	No	No
Solar Activity	?	No	No	No	N/A	No
Something New	?	?	?	?	?	Maybe? Unlikely
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

The most likely explanation is a short GRB …

GBM Observations of GW Events

GW 150914
(Abbot et al. 2016a)

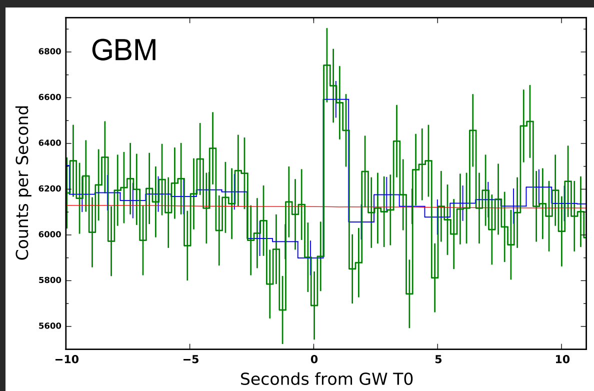
- BH+BH Merger
- 36 & 29 $M_{\odot}$
- 410 Mpc

LVT 151012
(Abbot et al. 2016a)

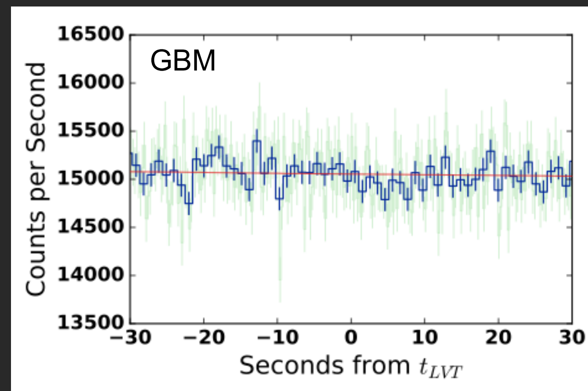
- Candidate BH+BH
- 23 & 13 $M_{\odot}$
- 1100 Mpc

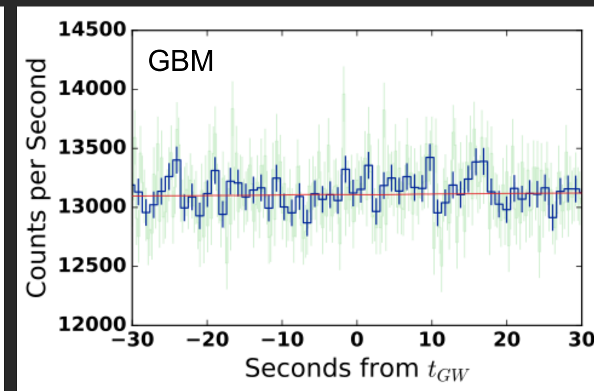
GW 151226
(Abbot et al. 2016b)

- BH+BH Merger
- 14 & 7.5 $M_{\odot}$
- 440 Mpc



(Connaughton et al 2016)





(Racusin et al 2016)

- GW150914-GBM, a 2.9σ event consistent with a short GRB
  - Not predicted by theoretical models
- 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!

Summary / Conclusions

- New GRB catalogues provide a wealth of data on individual burst characteristics
- Fermi/GBM has excellent capabilities for non GRB science:
  - Detecting & performing detailed spectral and temporal characterizations of Magnetar bursts
  - Detection of rare, short-lived Galactic transients - GBM acts as an all-sky monitor
  - TGFs
  - Monitoring of Galactic source with earth occultation
  - Pulsar monitoring
- GBM is an ideal partner instrument in the search for EM signals in coincidence with GW detections
  - GW150914-GBM: weak transient above 50 keV, 0.4 s after the GW event, with a false-alarm probability of 0.0022 (2.9σ)
  - 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
- LIGO's next observing run (O2) expected to begin in November!
  - Expect more BH-BH- candidates! Can we confirm association between BH-BH events and (sub-luminous?) short-GRB-like events?
  - Looking forward to weaker GW signals from NS-NS merger events