Searching for EM Counterparts to Gravitational Waves with the *Fermi* Gamma-ray Burst Monitor

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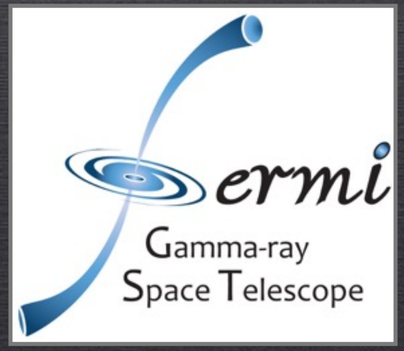
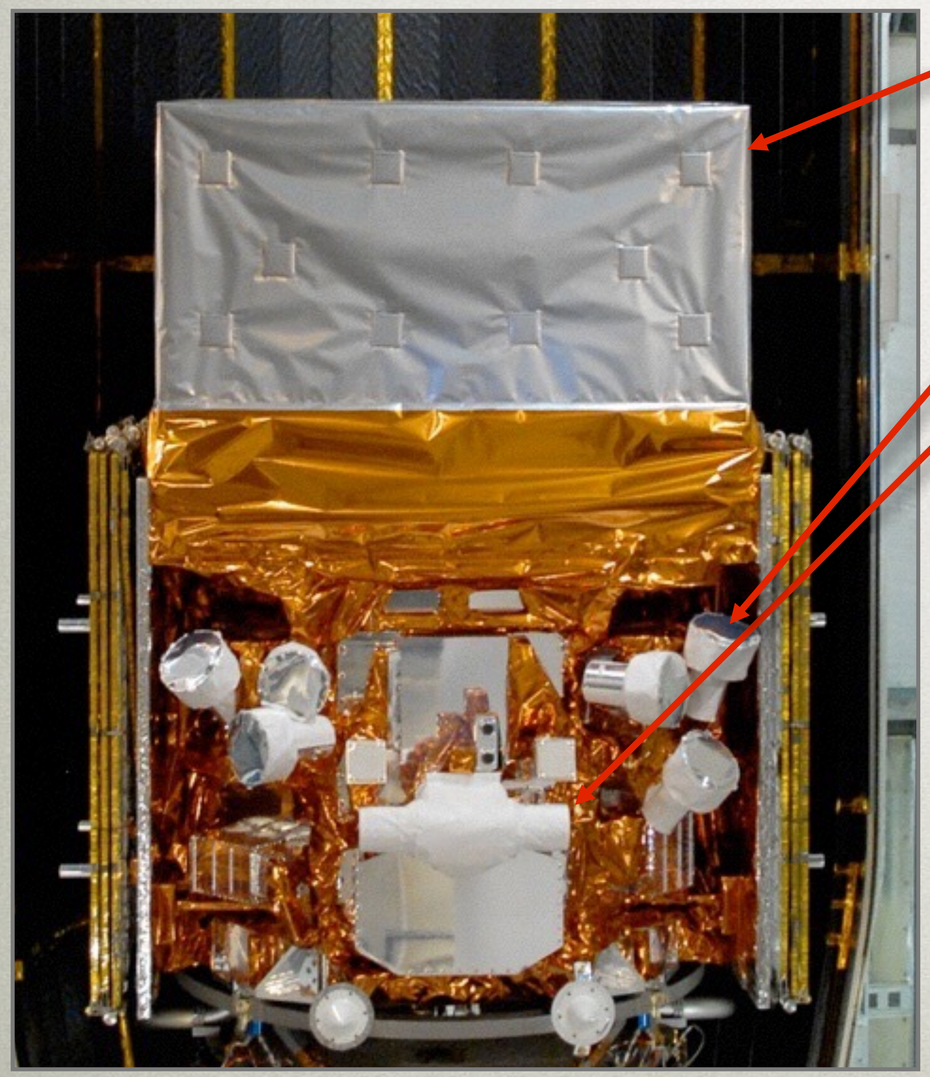
On behalf of the *Fermi* GBM Science Team



The Fermi Gamma-ray Burst Monitor

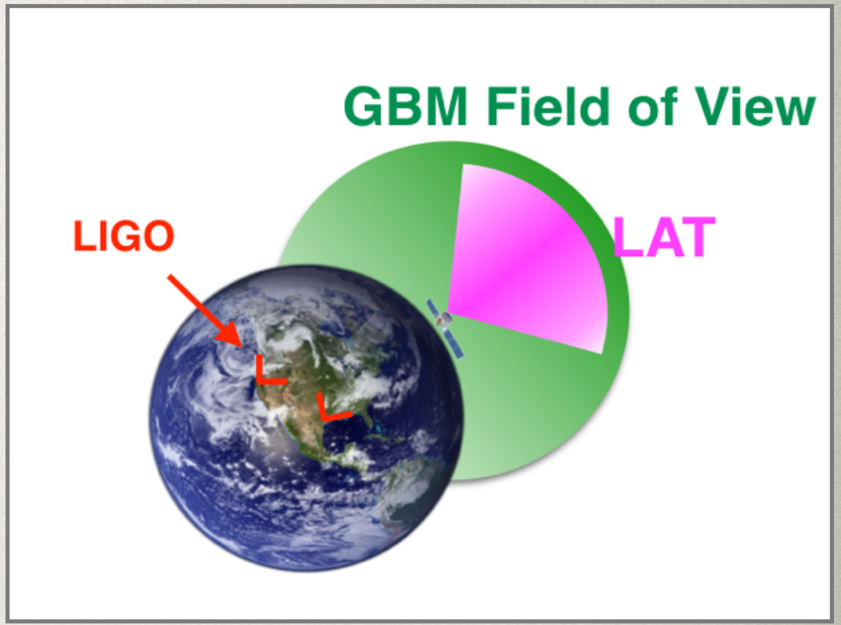


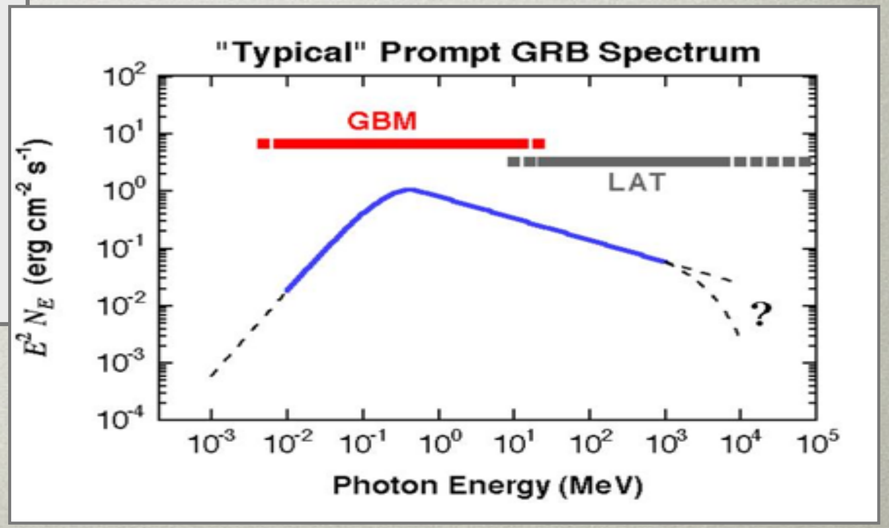
Large Area Telescope (LAT
30 MeV -> 300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV -> 40 MeV

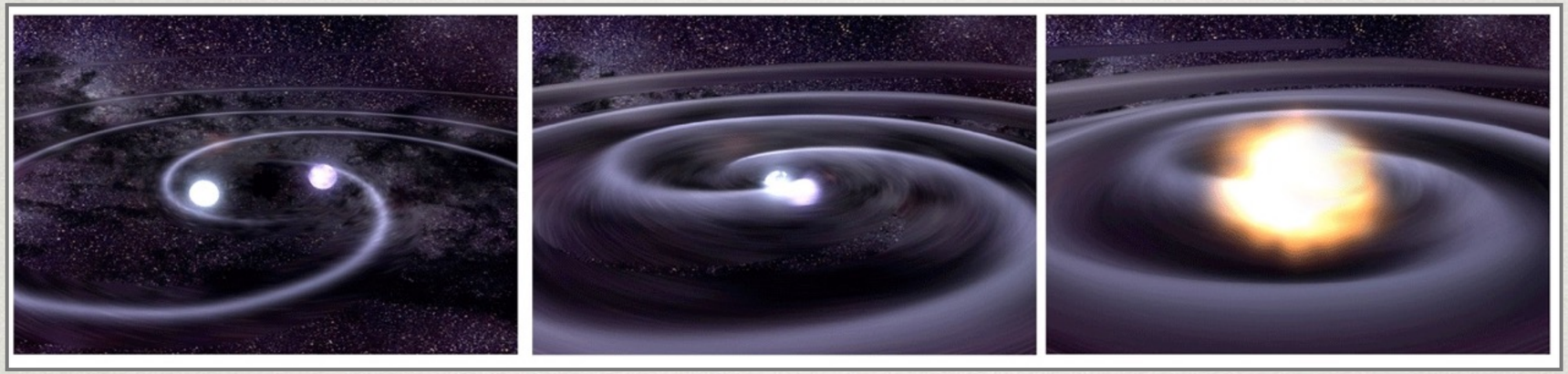
KEY FEATURES

- Huge field of view
  - –whole unocculted sky at any time (~70%)
- Operating nearly continuously (85%)
- Low detection dead time 2.6 μs
- GBM+LAT: Total of >7 energy decades!





Why GBM? Short GRBs, of course!



Short GRBs -> NS-NS, NS-BH

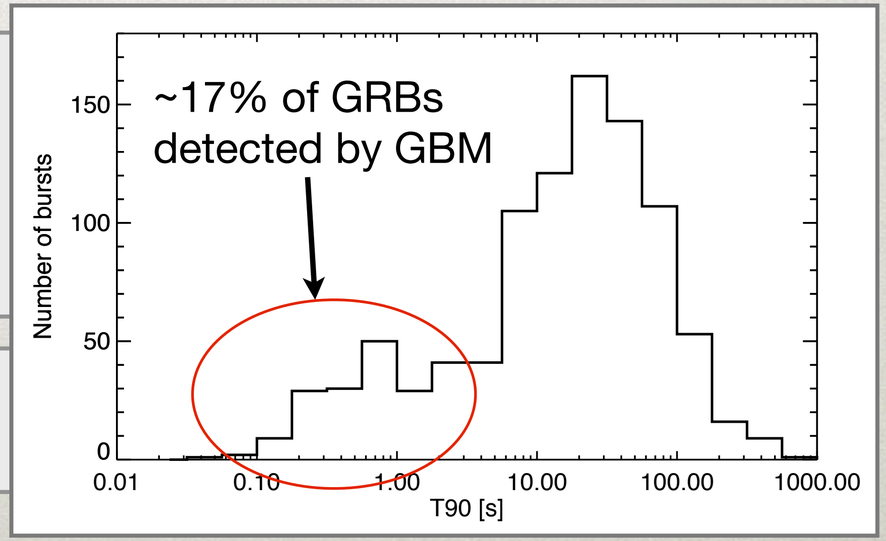
GBM: ~40 triggered short GRBs/year

potentially ~30-40 sub-threshold

(Swift: ~9 short GRBs/year)

~0.2-200 BNS/year within 200 Mpc

(unknown collimation)



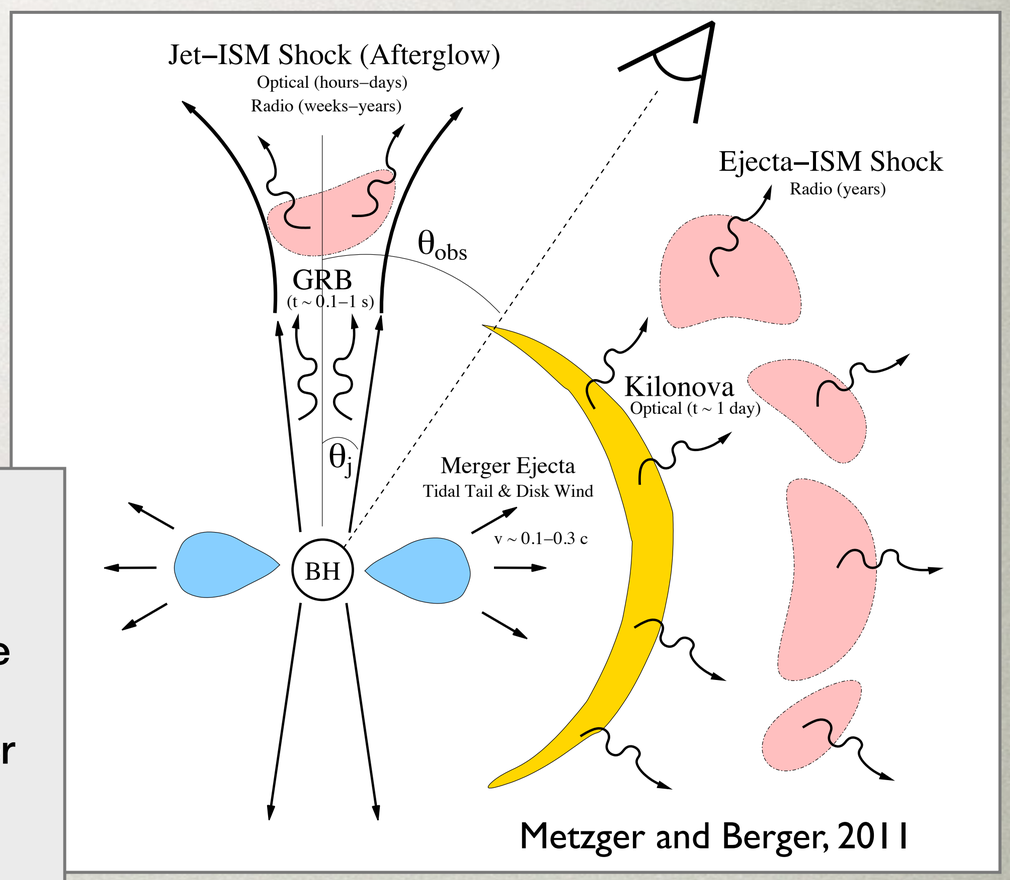
Short GRB/CBC Association

GW

- In-spiral confirms CBC progenitor model
- Information about binary system parameters
- precise merger time
- standard candle -> luminosity distance

EM

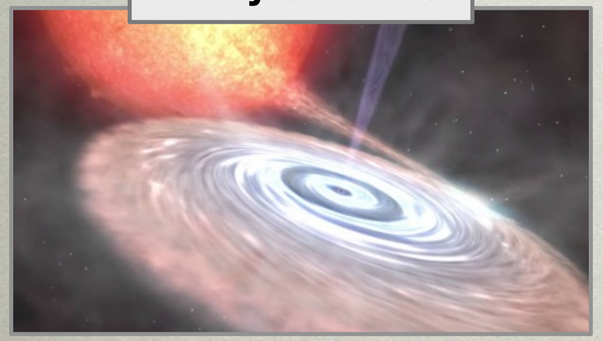
- Detection confidence
- EM energetics
- X-ray or optical afterglow gives precise location
- Breaks degeneracy in binary parameter estimation
- Host galaxy/redshift
- Local environment information



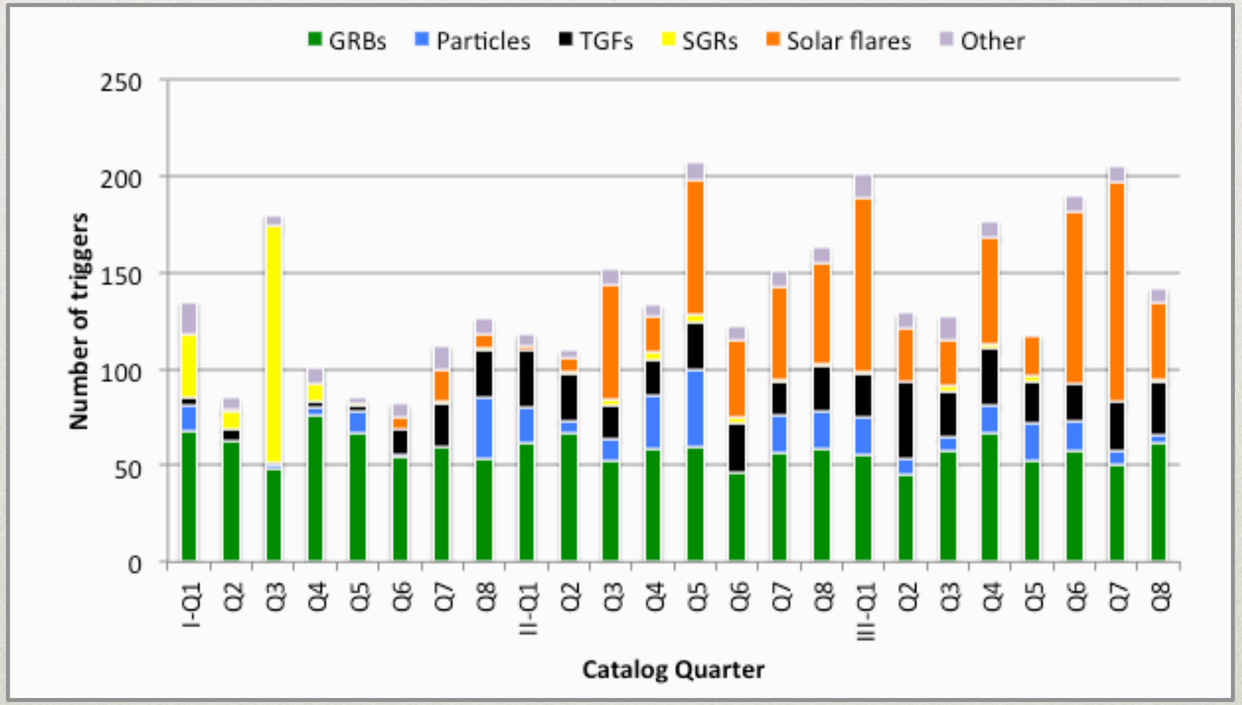
What Does GBM See?

Terrestrial Gamma-ray Flashes

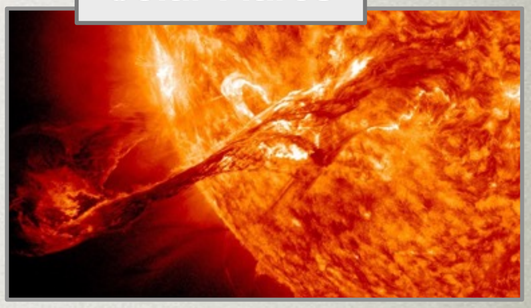
X-ray Binaries



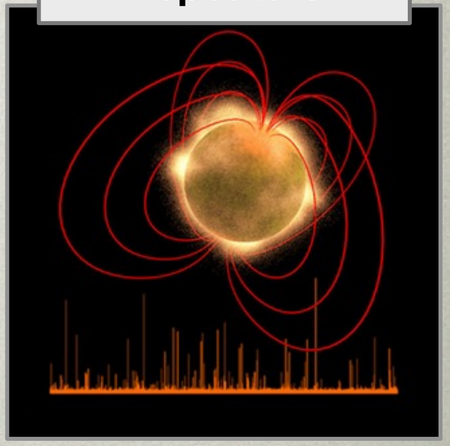
Lots of stuff (aside from GRBs)



Solar Flares

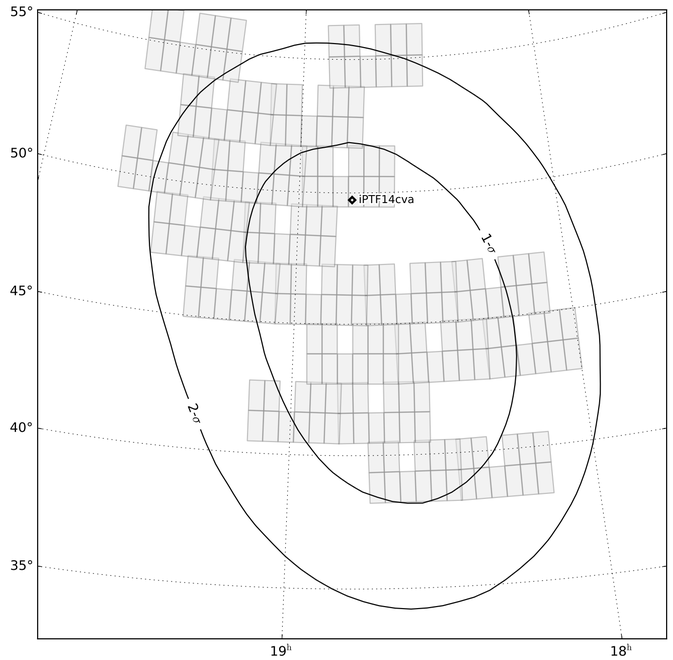


Soft Gamma Repeaters



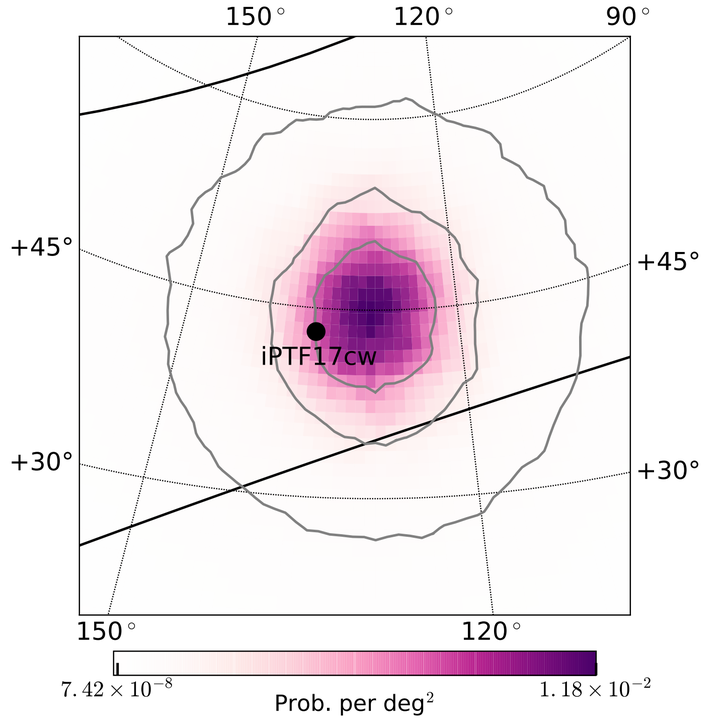
Follow-up of GBM GRBs

Example: GRB 140620A



Singer+ 2015, ApJL, 806, 52

GRB 161228B / iPTF17cw



Corsi+ 2017, arXiv:1706.00045

- **8** detections by iPTF from **35** follow-ups (campaign during 2013-2014)
- **2** confirmed **Master OT** counterparts found from the ground automated location
- **iPTF17cw** found searching for EM counterpart to **GW170104** — Core-Collapse SN likely to be associated with GRB 161228B (**a GBM trigger!**) with very interesting properties. FAR estimated to be ~1 per 2 years.

GBM Offline Searches

- **GBM Un-targeted Search (Michael S. Briggs)**
  - Developed to find un-triggered short GRBs (below triggering threshold)
  - Improved spline background can also find some un-triggered long GRBs
  - Uses all 12 NaI detectors and flags candidates that meet a pre-defined count rate threshold in "legal" detector pairs in 50-300 keV
  - Follow-up vetting using the standard GBM localization technique
  - Fast, efficient, runs over a complete hour of data as it is downlinked
  - Can trigger follow-up observations

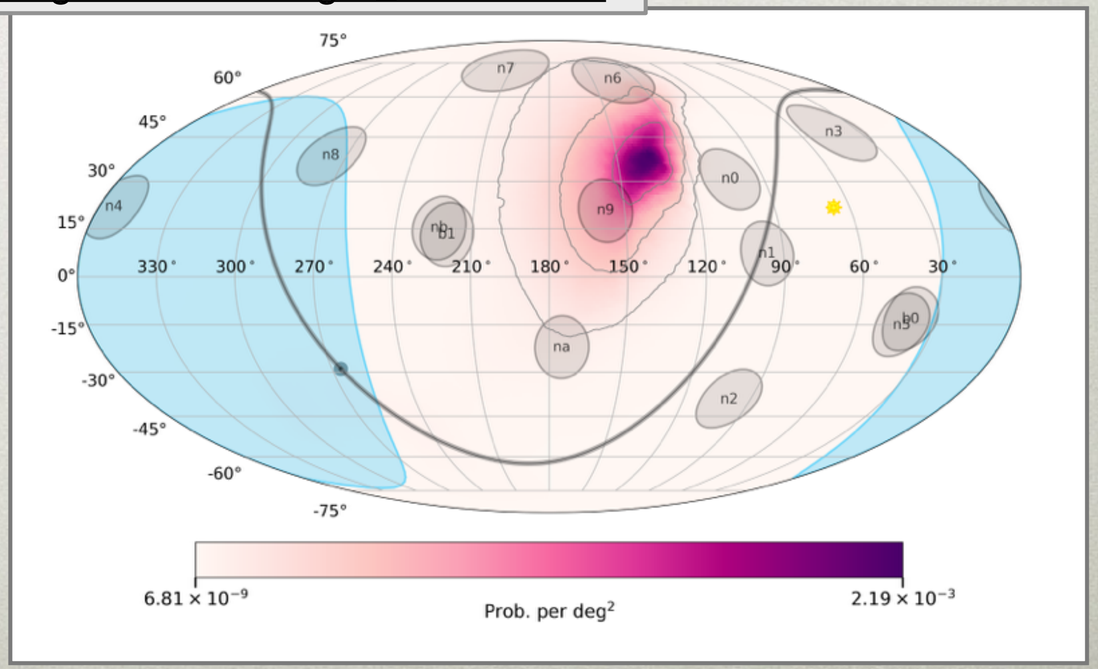
- **GBM Targeted Search (Blackburn+ 2015; Goldstein+ 2016)**
  - Seeded with a time of interest and optionally a sky map (prior)
  - Search employs detector-coherent search:
    - Assume spectral templates
    - Convolve assumed spectrum with detector responses, calculated over the entire sky
    - Expected signal in count rate compared to observed count rate
  - Very powerful but expensive
  - Intended to be follow-up search for multi-messenger events

GBM Un-targeted Search

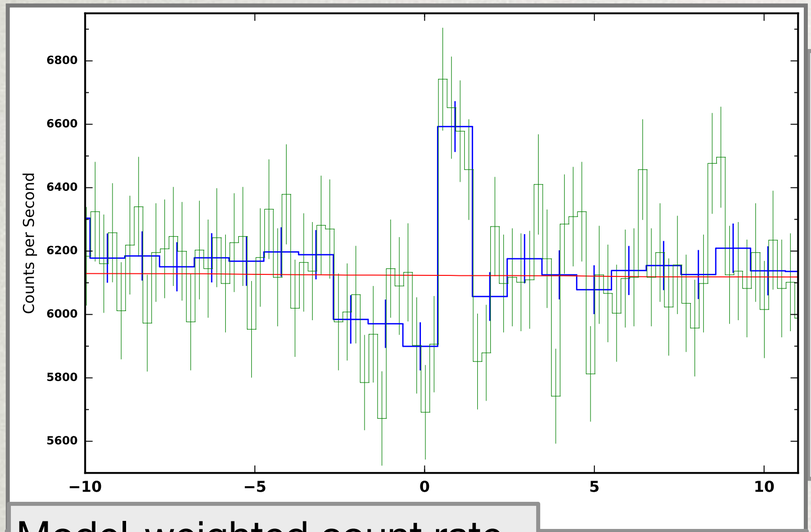
- Producing GCN notices with reliability scores (low, medium, high)
  - More info: https://gcn.gsfc.nasa.gov/fermi.html
- Expected rate is ~70/month total
- Notices contain links to a HealPix sky map, a quick-look localization plot (below), and the lightcurves for each detector
- Data must be downlinked — notice latency will be 0.5-6 hours
- Archival candidates dating back to January 2013
  - https://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

Short GRB Candida

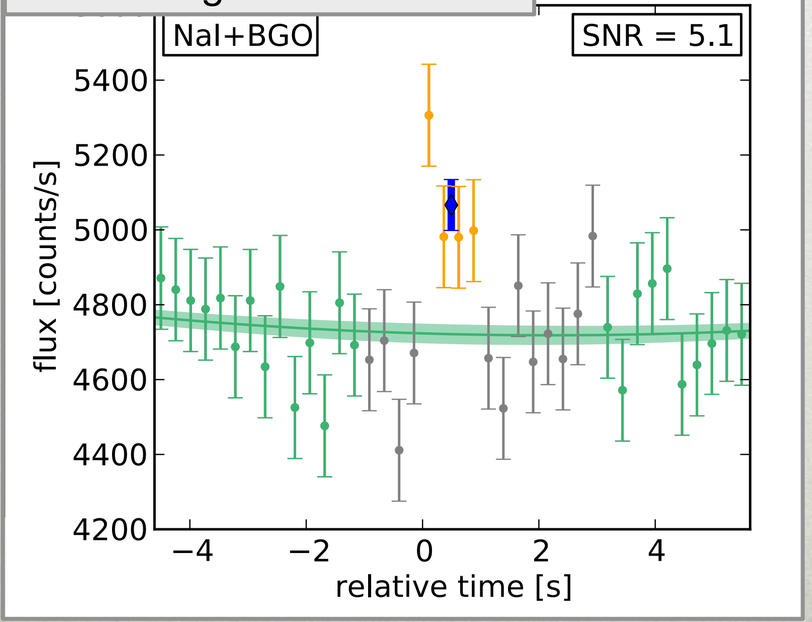
MET	RELIABILITY	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)
379031971.10	Medium	2013-01-04	22:39:28.10	9.62	-23.71	9.37
379272722.53	Medium	2013-01-07	17:31:59.53	295.41	+70.24	10.90
379728909.72	Medium	2013-01-13	00:15:06.72	161.90	+72.03	10.59
380281256.96	Medium	2013-01-19	09:40:53.96	263.02	-0.67	13.72
380891288.45	Medium	2013-01-26	11:08:05.45	353.25	+51.94	23.59
382070601.38	Medium	2013-02-09	02:43:18.38	338.74	-34.73	18.66
382475323.10	Medium	2013-02-13	19:08:40.10	84.71	+19.45	11.85
382651774.94	Medium	2013-02-15	20:09:31.94	198.90	+29.48	12.90
382973218.96	Medium	2013-02-19	13:26:55.96	286.18	+14.58	32.54
383922044.70	Medium	2013-03-02	13:00:41.70	219.93	+16.00	18.16
384187887.55	Medium	2013-03-05	14:51:24.55	68.31	-32.91	3.49
384772642.33	Medium	2013-03-12	09:17:19.33	190.48	-7.88	27.49
384839856.54	Medium	2013-03-13	03:57:33.54	321.07	+32.79	6.44
384867339.47	Medium	2013-03-13	11:35:36.47	254.74	-9.40	10.98
385052258.56	Medium	2013-03-15	14:57:35.56	228.31	-7.25	20.09



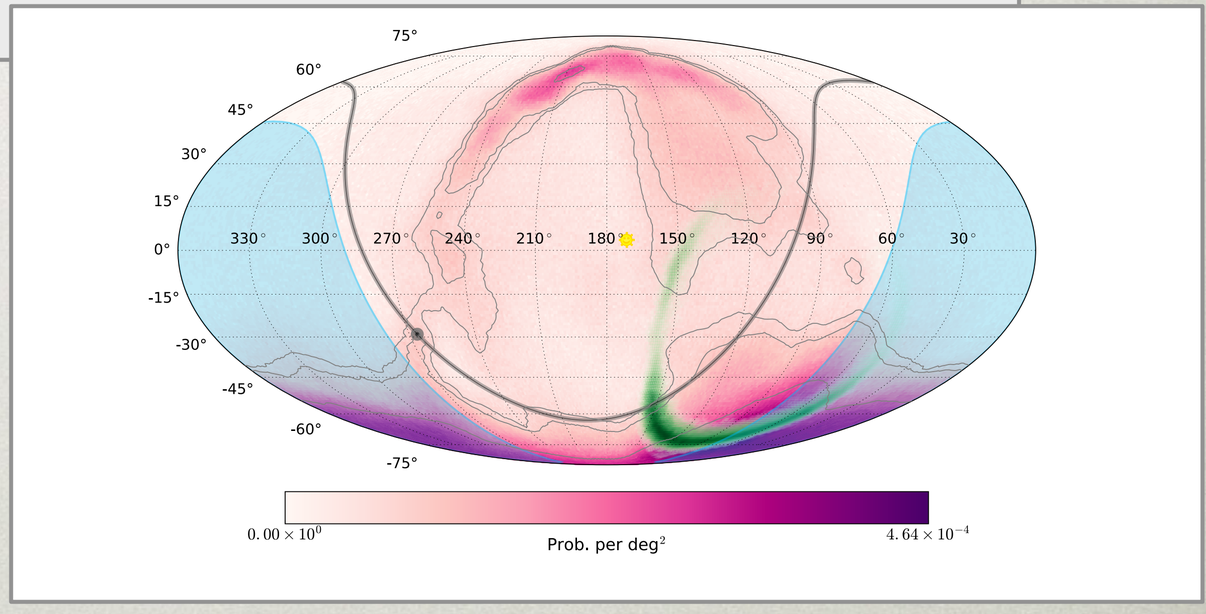
The Curious Case of GW150914-GBM



Model-weighted count rate



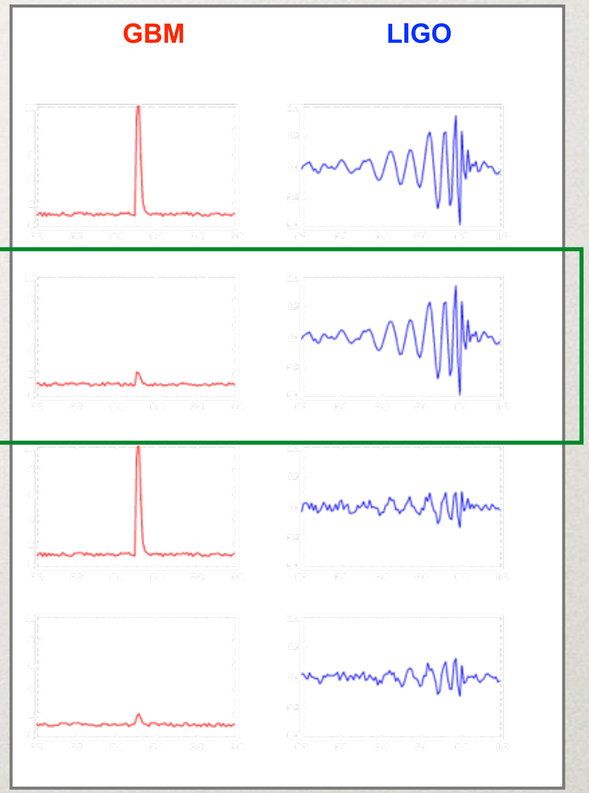
- ~0.4 s after the GW signal, ~1 s duration
- Did not trigger GBM
- Found with the targeted search
- Raw summed lightcurve SNR ~6 sigma above 50 keV
- 2.9 sigma FAP - inconclusive + no emission expected from a BBH merger.



Connaughton+ 2016, ApJL, 826, L6

Joint Sub-threshold Search

Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO



GBM has a special MOU with LIGO/Virgo — Access to all LIGO sub-threshold triggers.

In all cases, the presence of a signal in GBM or LIGO, can raise the significance of the signal being real in the other instrument.

A confident gamma-ray signal allowing a fainter gravitational wave signal, would push the LIGO detection distance limit further, in turn increasing the event rate by a factor of distance cubed

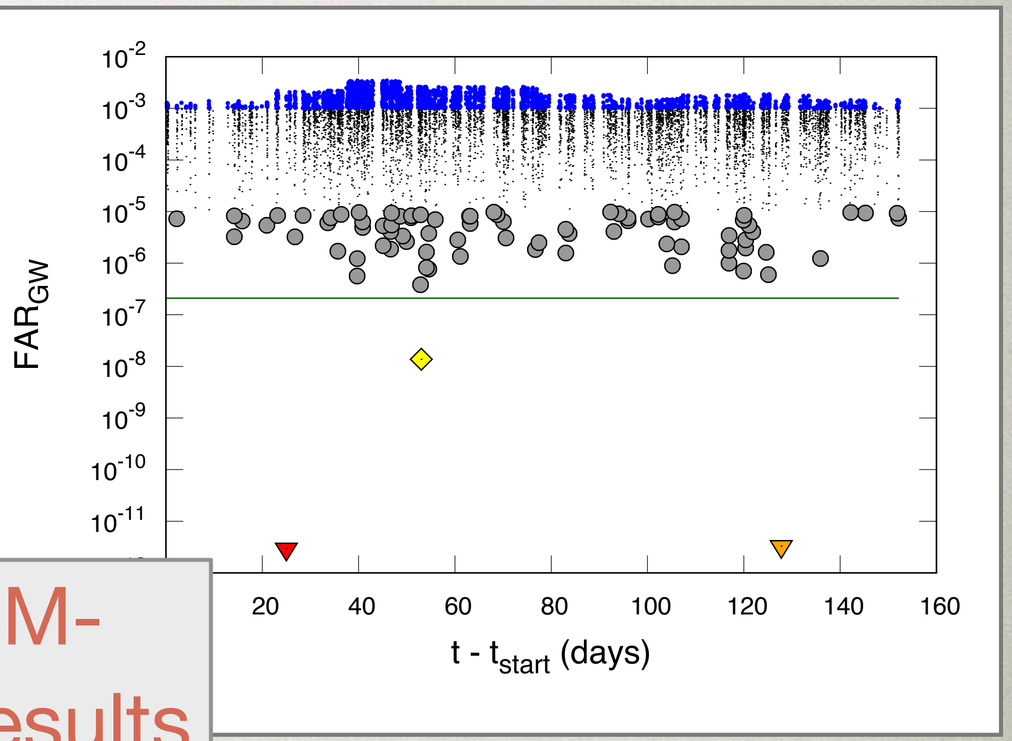
All-O1 Offline Follow-up Analysis

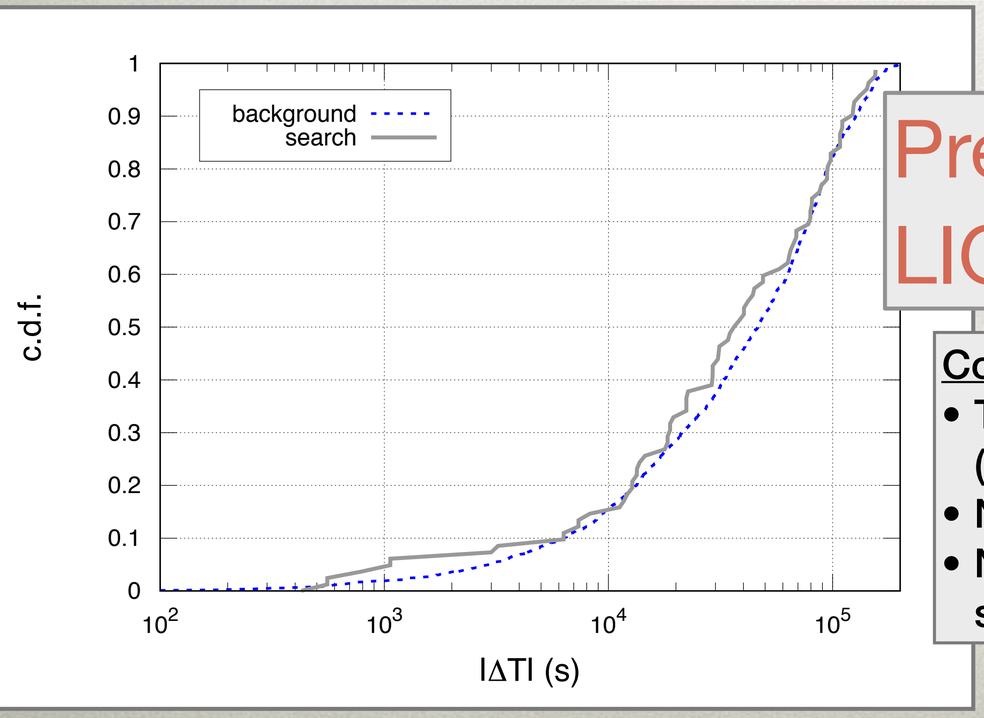
GBM-LVC Joint Result

GBM Analysis led by Eric Burns

LIGO triggers

- PyCBC & GstLAL offline triggers
- Search sample: FAR < ~1/day
- Background sample: FAR > 1/(15 min)
- Overlapping triggers with higher FAR discarded



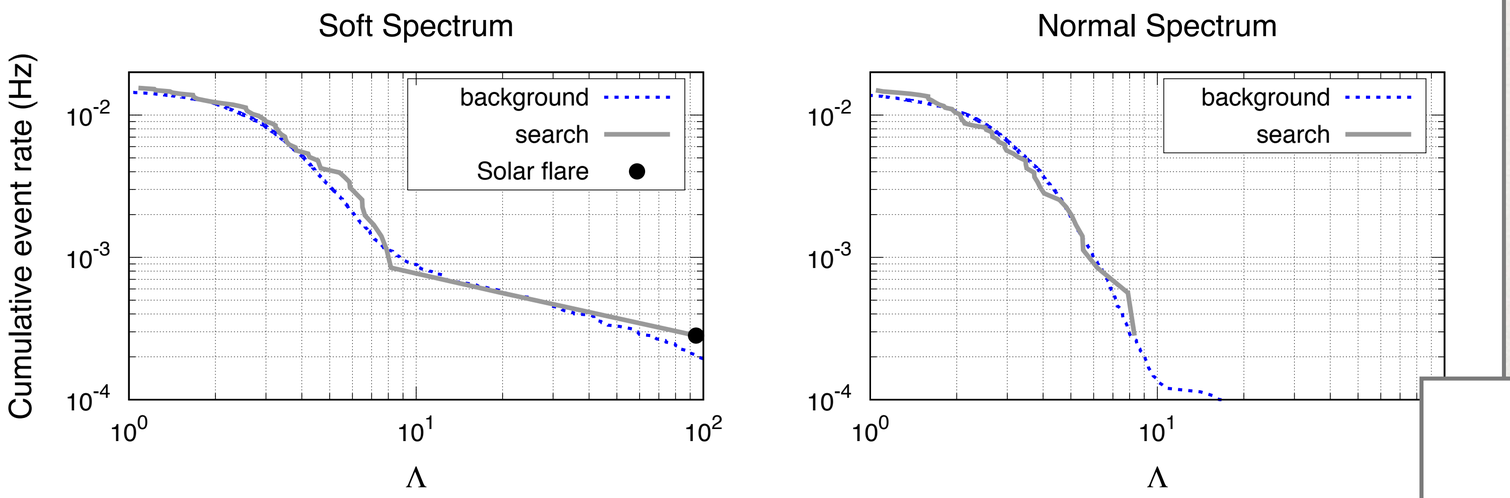


Preliminary GBM-LIGO-VIRGO results

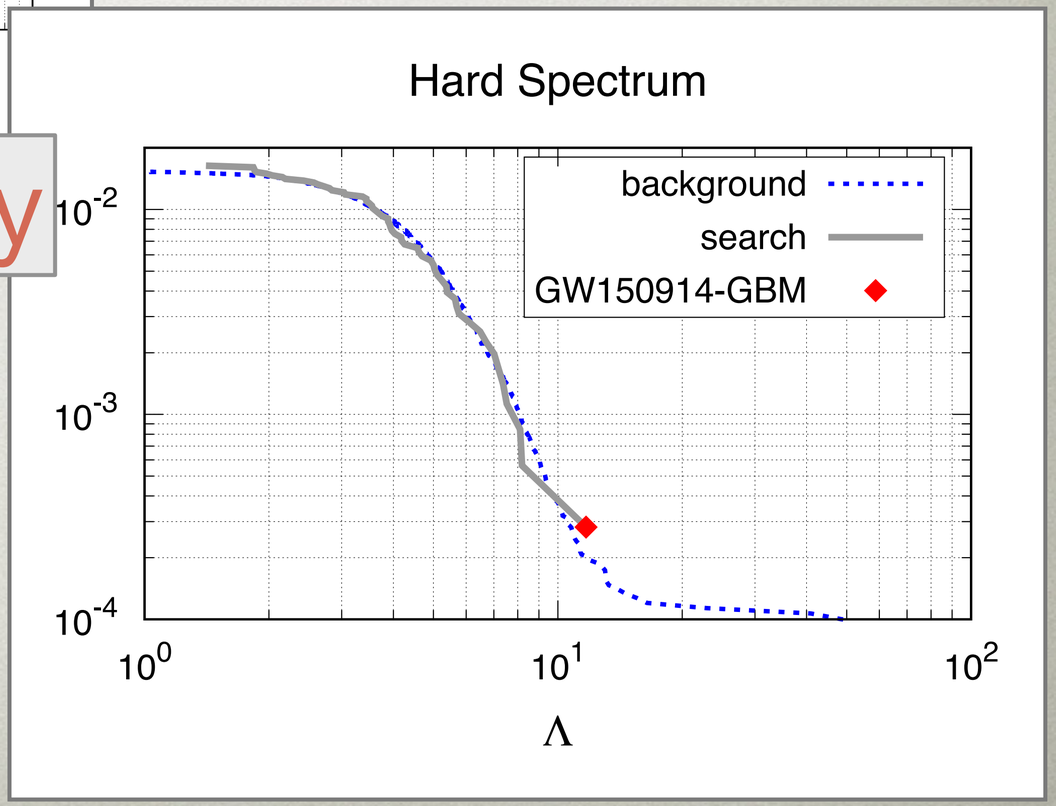
Comparison with GBM triggers

- Time offset between triggered and sub-threshold GRBs (untargeted) and nearest CBC trigger
- No discernible difference between background and search
- No candidates from search sample occurred within O(100) s of a triggered or sub-threshold GRB (untargeted)

Targeted Search Follow-up



Preliminary



GBM Targeted Search

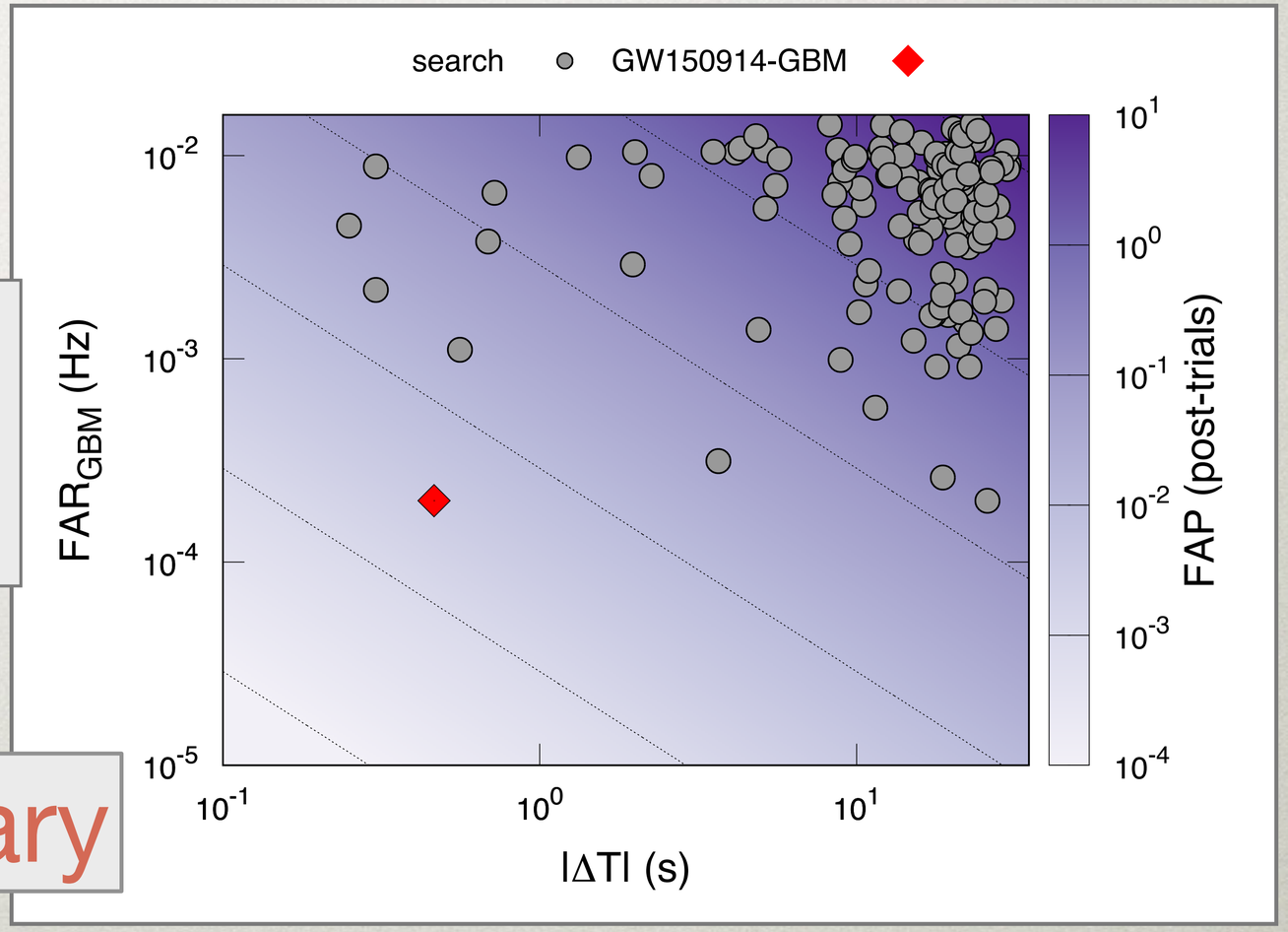
- Search performed over 3 template spectra
- GW150914-GBM candidate is most significant at FAR ~2×10^{-4} Hz
- Second lowest FAR is a chance coincidence with a solar flare (soft spectrum)

False Alarm Probability for All-O1

False Alarm Probability

- GW150914-GBM has lowest post-trials FAP at ~2×10^{-3}
- FAP is still too high to declare an unambiguous EM counterpart
- No other candidates had FAP < 0.01

Preliminary



Setting Upper Limits

Impulsive upper limits:

- GBM can set flux upper limits in the event no interesting counterpart was found.
- The upper limit is primarily dependent on the noise background in GBM and the geometry to the GBM detectors for each patch of sky that is inspected.
- Requires assumption of signal timescale and spectrum —currently 1s timescale and the average GBM-observed short GRB spectrum
- For O2, upper limits of LIGO 99% credible region have been produced

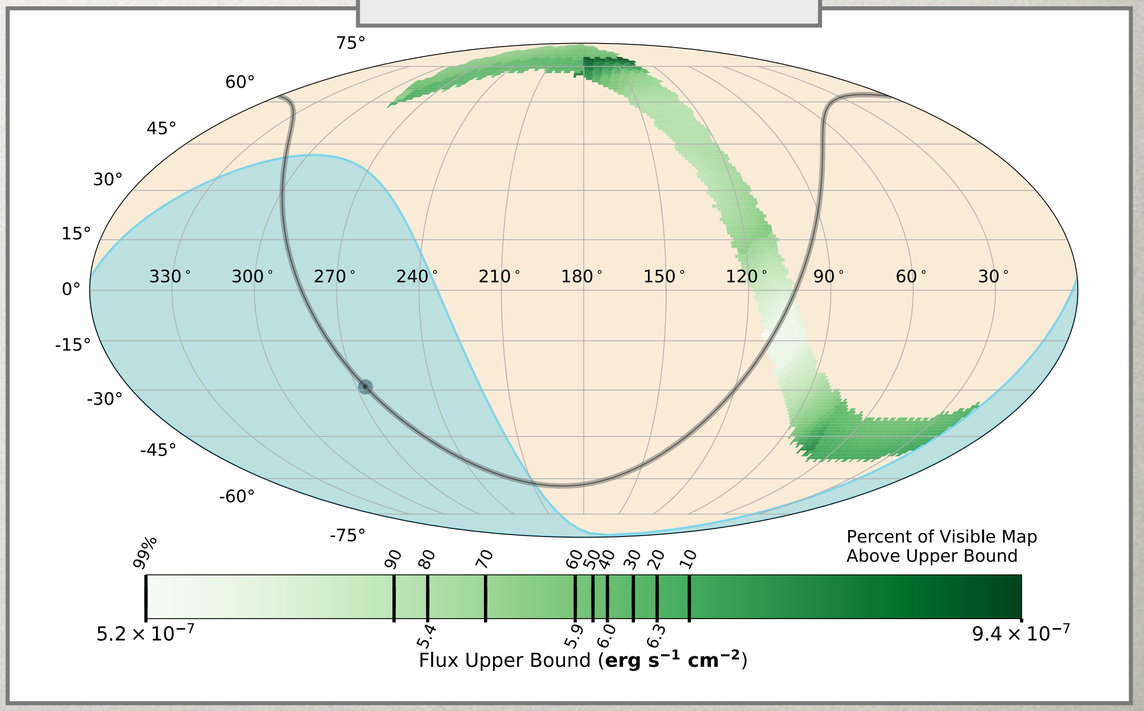
Other Upper Limits

Earth Occultation Technique (Wilson-Hodge + 2012) set upper limits on emission from flaring sources

Have also issued upper limits for IceCube and ANTARES neutrinos

Group at UMD using GBM data to set UL for some previous FRBs

GW170104



Fermi GBM+LAT 2017, arXiv:1706.00199

Wilson-Hodge+ 2012, ApJS, 201, 33

O2, O3, and Beyond

- Improvements made to the background estimation of the targeted search — **Done for O2**
- Updated ‘hard’ spectral template — **Done for O2**
- Characterization and determination of recovery efficiency for both searches — **Ongoing**
- Adapting the the GBM flight software trigger classifier to work for both searches — **Ready for O3?**
- Joint FAR estimation between GBM and LIGO candidates — **Ready for O3?**

Conclusions

- GBM provides a window into the **high-energy transient universe**
- **~85% time** coverage, **~70%** instantaneous **sky** coverage, over 3 decades of energy
- GBM teams have developed and are improving **low-latency offline searches** to study un-triggered events and for follow-up of interesting events
- **Have reported** on every LV-EM trigger in O1 and O2 and completed the **All-O1 analysis** of LIGO sub-threshold triggers.
- Our **search pipelines continue to process** incoming sub-threshold triggers in O2 and **automatically search** for candidates
- GBM team will be providing **new continuous data** in hour-long chunks, over the next 2 years will be releasing **new public tools** to enable analysis
- **GBM provides unmatched ability to follow-up and characterize high-energy transient counterparts to GW events**

Backup