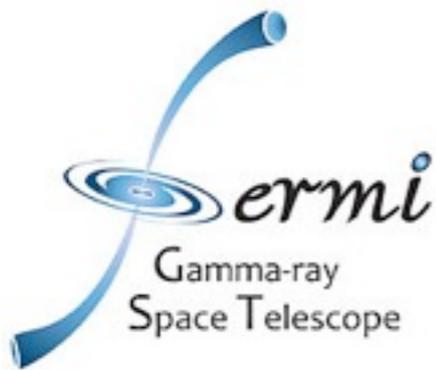


Fermi GBM observations of GW150914



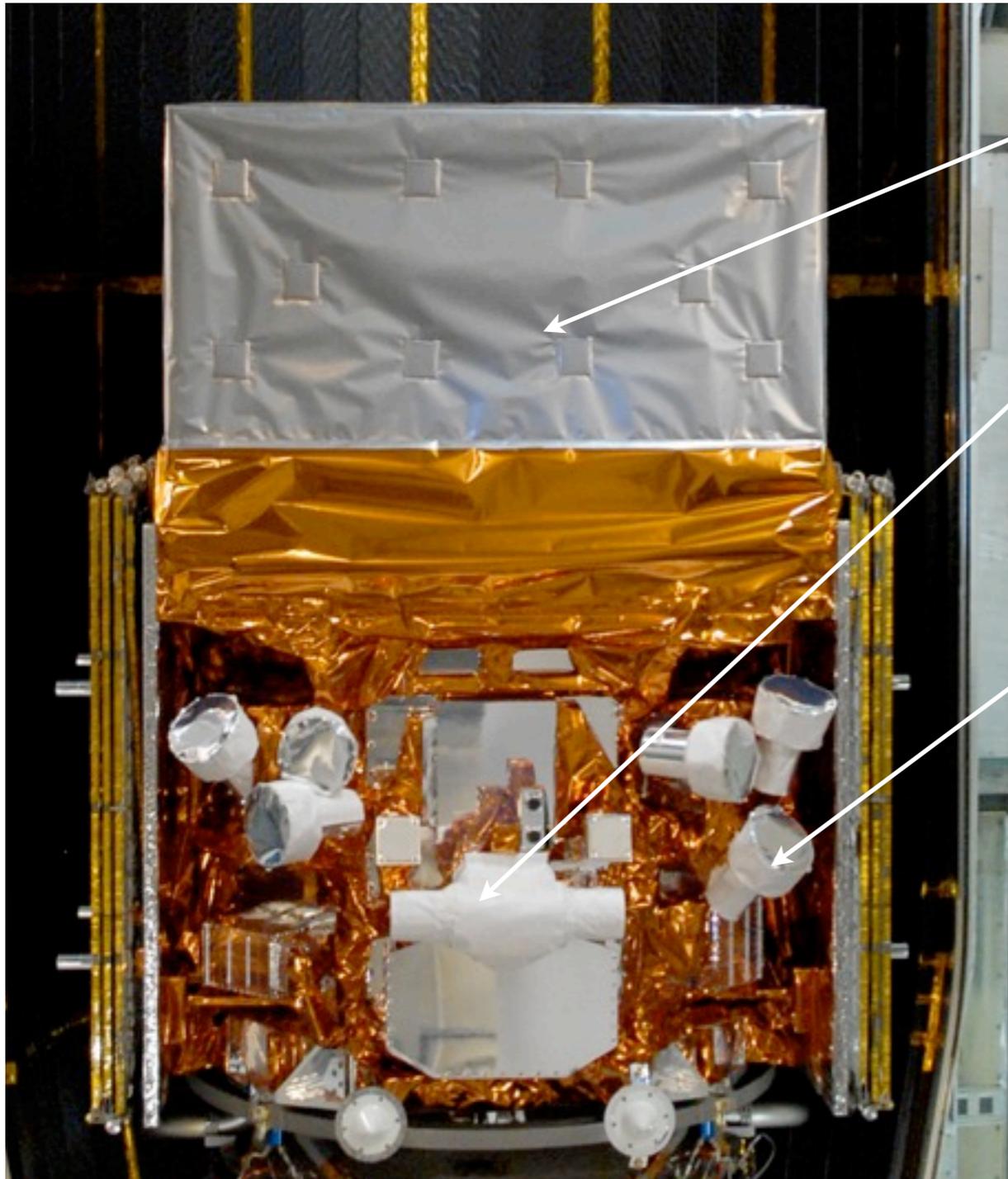
Valerie Connaughton
(USRA)



for the GBM-LIGO follow-up group:

Lindy Blackburn, Michael S. Briggs, Jacob Broida, Eric Burns, Jordan Camp, Nelson Christensen, Valerie Connaughton, Tito del Canto, Adam Goldstein, Rachel Hamburg, Michelle Hui, Peter Jenke, Tyson Littenberg, Rob Preece, Judith Racusin, Peter Shawhan, Leo Singer, John Veitch, Peter Veres, Colleen Wilson-Hodge

Fermi acts as a surveyor of the high-energy sky, with both instruments detecting Gamma-Ray Bursts over a broad energy baseline



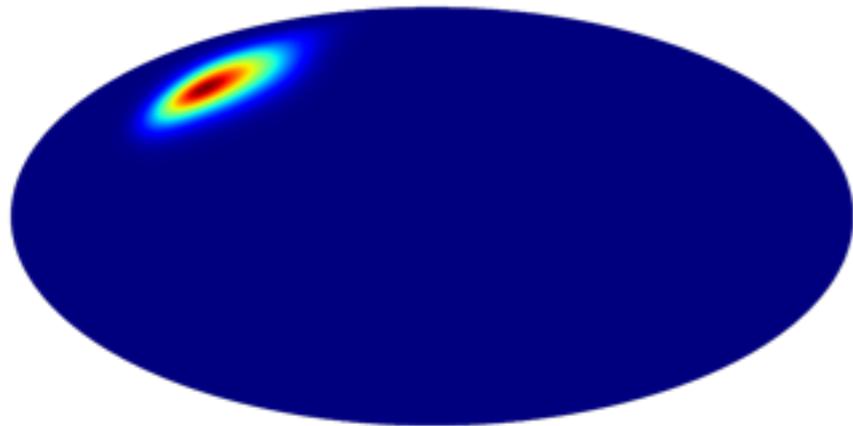
Fermi Large Area Telescope (LAT)
> 20 MeV, > 100 MeV

GBM BGO detector.
200 keV -- 40 MeV
126 cm², 12.7 cm

GBM NaI detector.
8 keV -- 1000 keV
126 cm², 1.27 cm

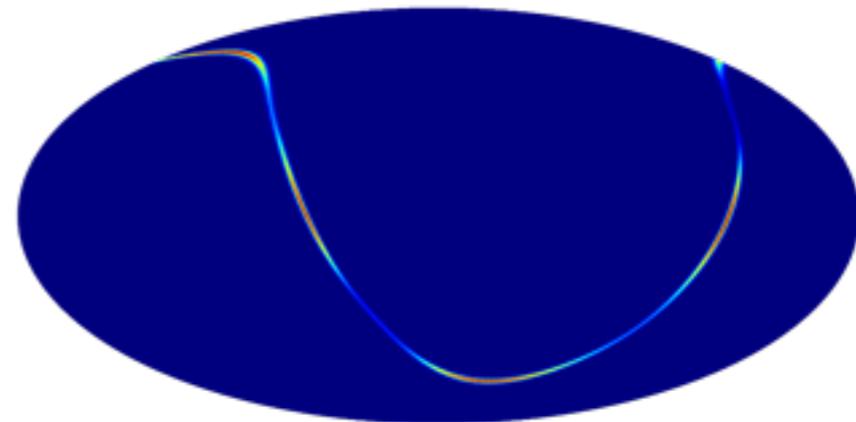
Even a large banana and a large orange can help: using joint GBM-LIGO/Virgo detections to guide follow-up observers

Typical GBM GRB localization region for weak GRB



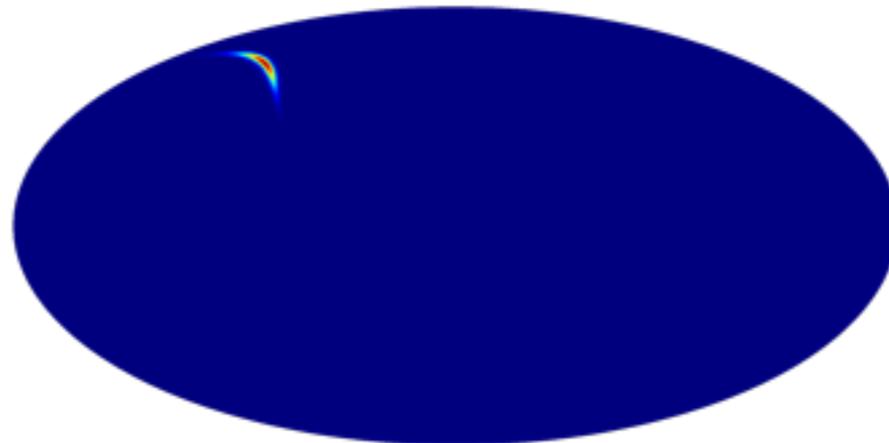
+

Typical LIGO localization region from <http://www.ligo.org/scientists/first2years/>: changes in 2016 with addition of Virgo



18 +/- 5 nearby galaxies (N. Gehrels et al. 2015, arXiv:1508.03608)

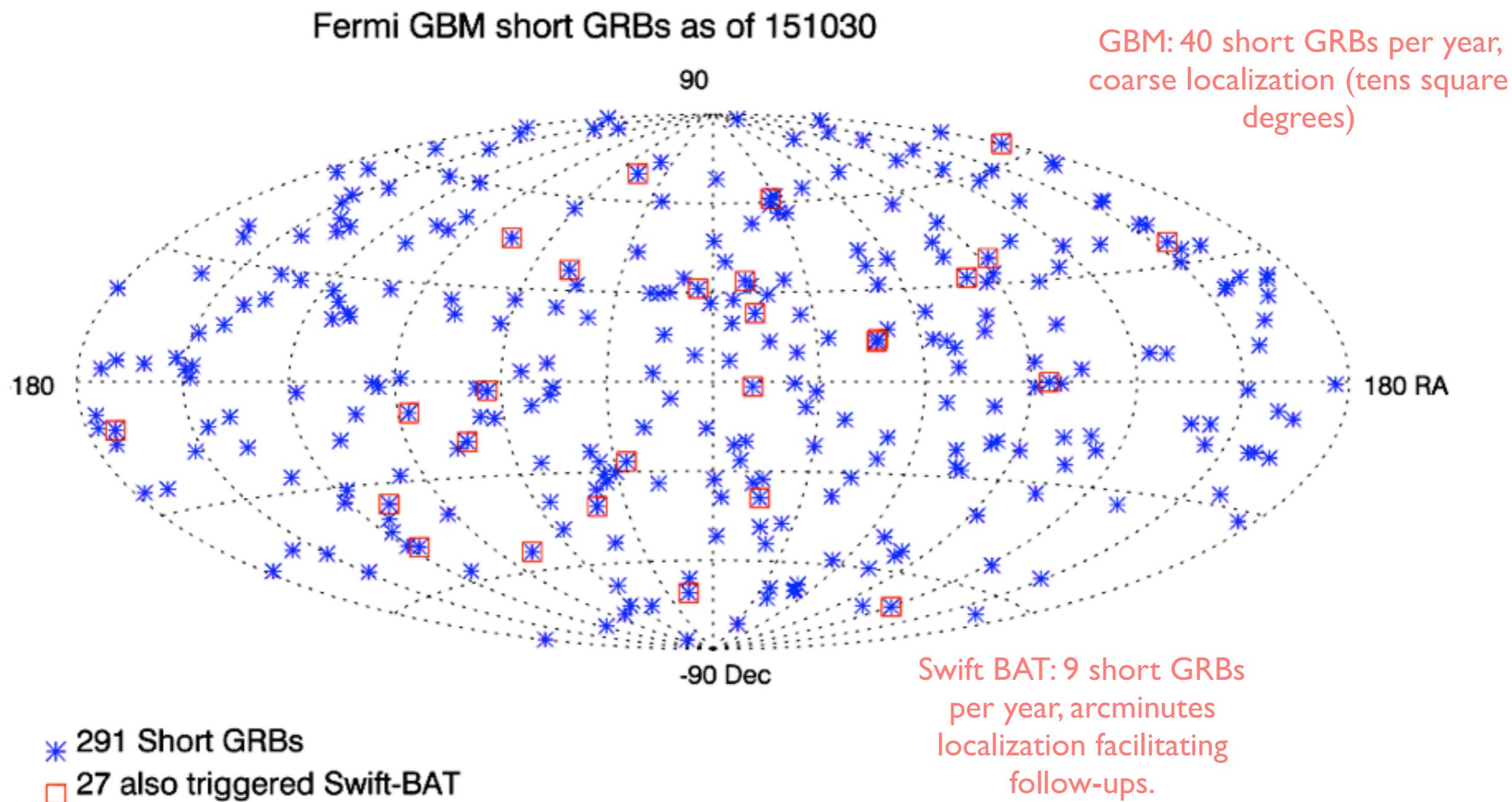
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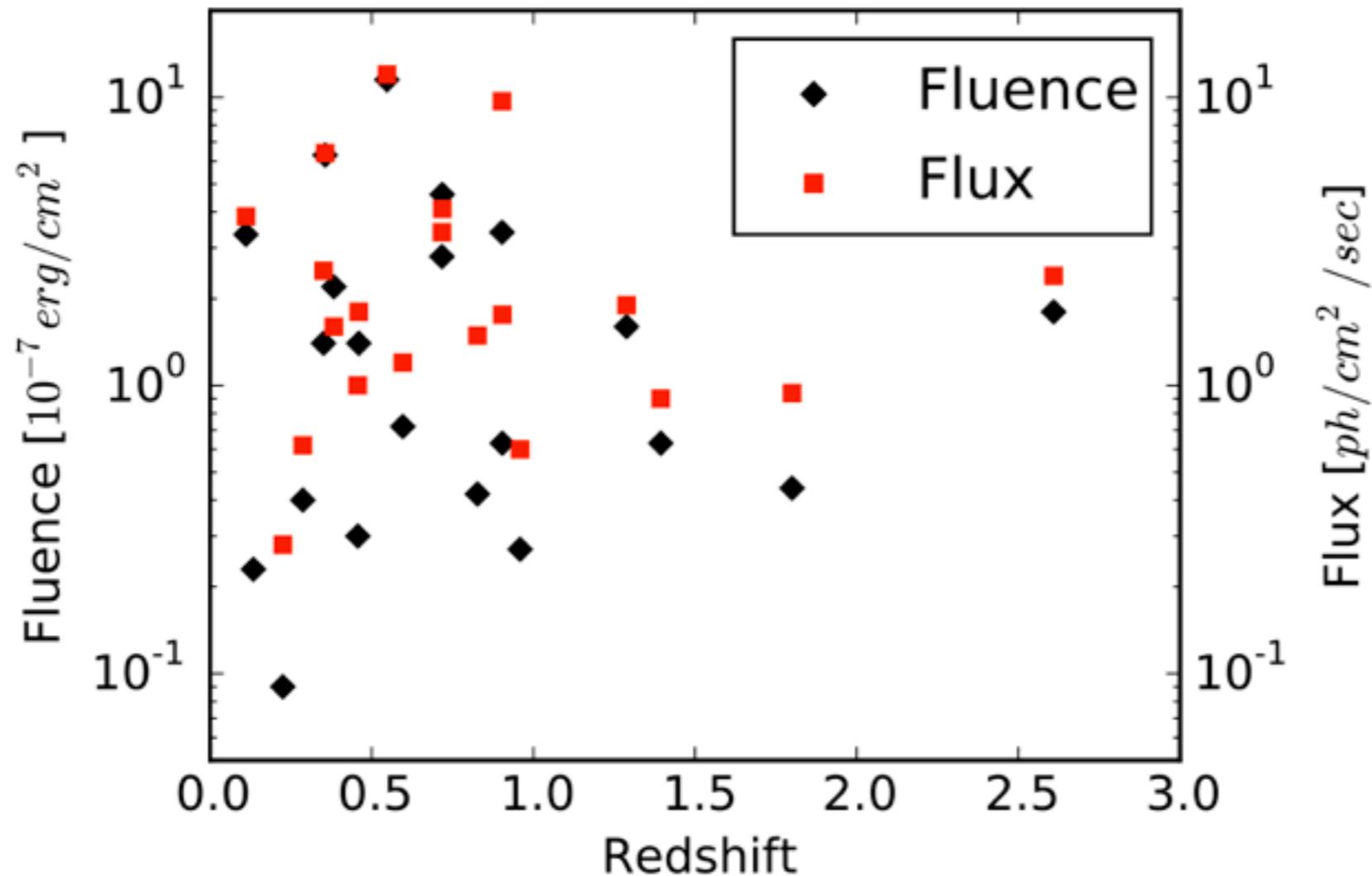
Typical reduction of 80% in sky region:

4 nearby galaxies: easier to follow up with XRT or optical telescopes.

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



Weak short GRBs are not necessarily more distant than bright short GRBs and may lie within the detection horizon of LIGO/Virgo: GBM team developed search for short GRBs too weak to trigger on-board Fermi



- ▶ Extrapolating from sGRBs with known redshift gives $<0.5 - 5$ per year sGRB for GBM within LIGO/Virgo horizon (nearby z uncertain).
- ▶ This number is doubled with unseeded search for GRBs that do not trigger on-board.

Untriggered GBM Short GRB Candidates

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

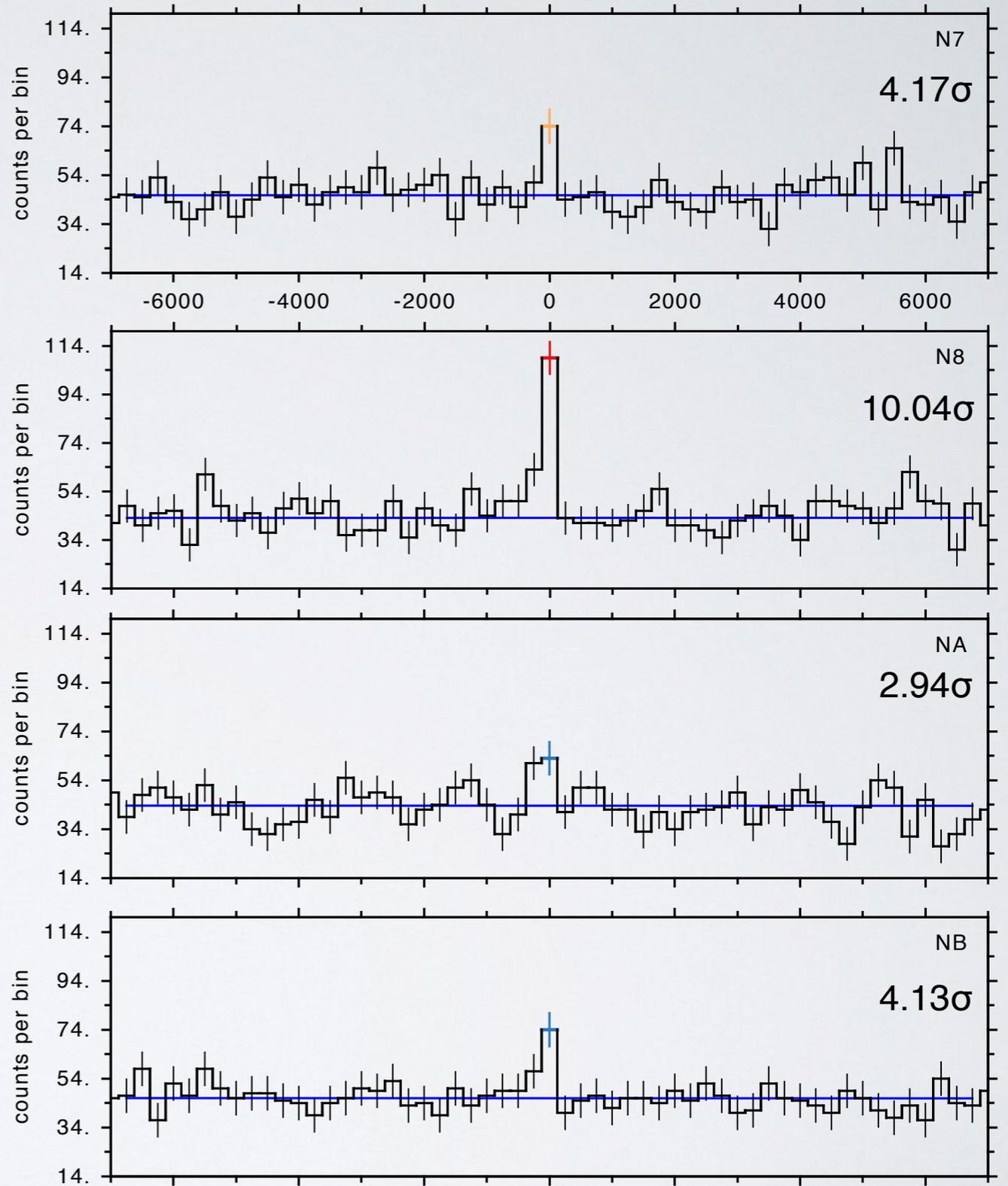
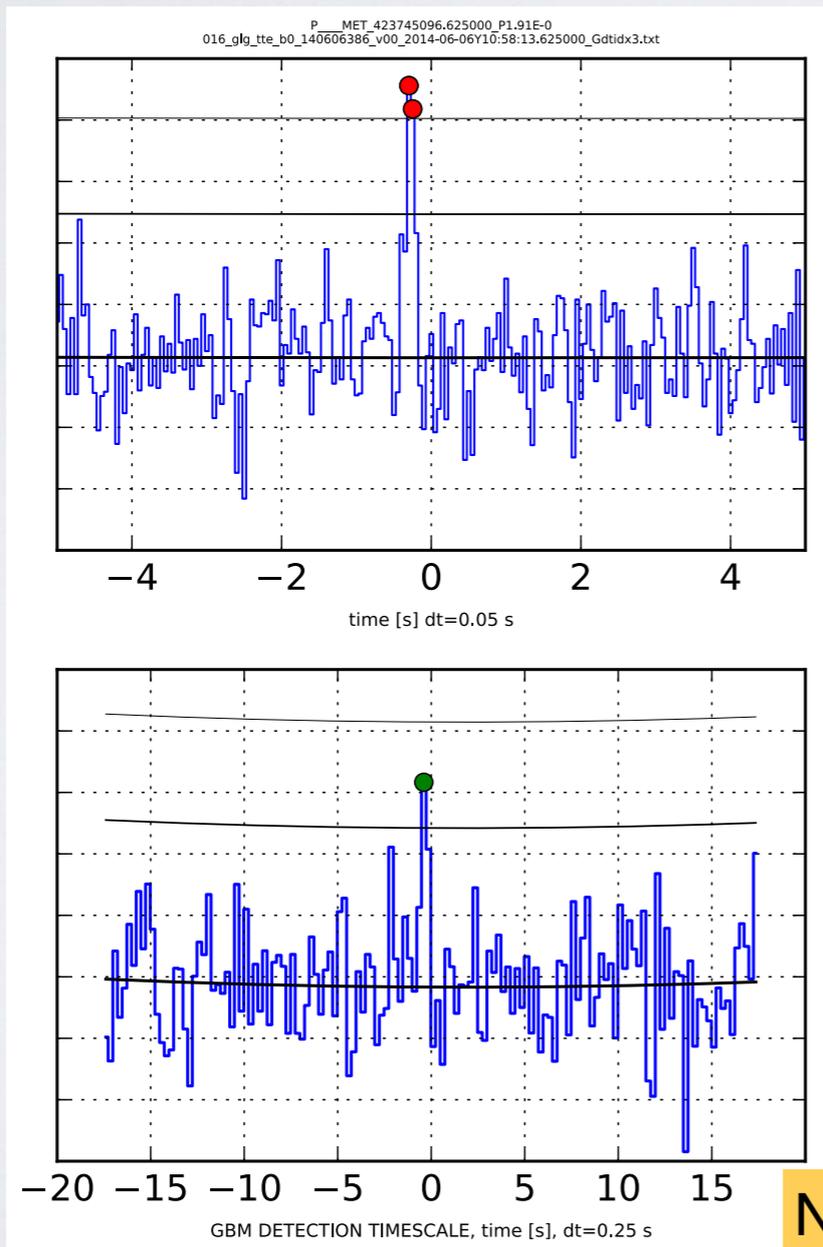
- A list of the untriggered candidates (June 2014 to present) are listed in website above.
- Working towards creating automated GCNs, will be distinct from triggered events type.

Short GRB Candidates							
MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)	COMMENT
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	
426950830.700	4.21E-0007	2014-07-13	13:27:7.700	264.57	-87.36	13.49	
427440502.000	2.65E-0007	2014-07-19	05:28:19.000	34.37	+45.94	15.21	
431283951.000	3.82E-0008	2014-09-01	17:05:48.000	80.94	+69.19	16.02	
431291510.000	3.03E-0007	2014-09-01	19:11:47.000	81.08	-17.32	15.88	
432797599.000	3.30E-0007	2014-09-19	05:33:16.000	177.15	-37.38	20.86	
433789586.000	1.95E-0007	2014-09-30	17:06:23.000	283.03	-9.27	11.33	
436073076.650	2.18E-0007	2014-10-27	03:24:33.650	62.59	-52.26	11.90	
437185383.600	3.72E-0014	2014-11-09	00:23:0.600	289.76	-28.56	14.73	
437703742.200	1.71E-0007	2014-11-15	00:22:19.200	107.66	-19.52	13.08	

GBM Candidate Event

- 2014-06-06 10:58:13.625
- **Swift GRB 140606A**
- Found in 0.25s time binning
- 93 - 494 keV energy range
- $P=1.91e-16$

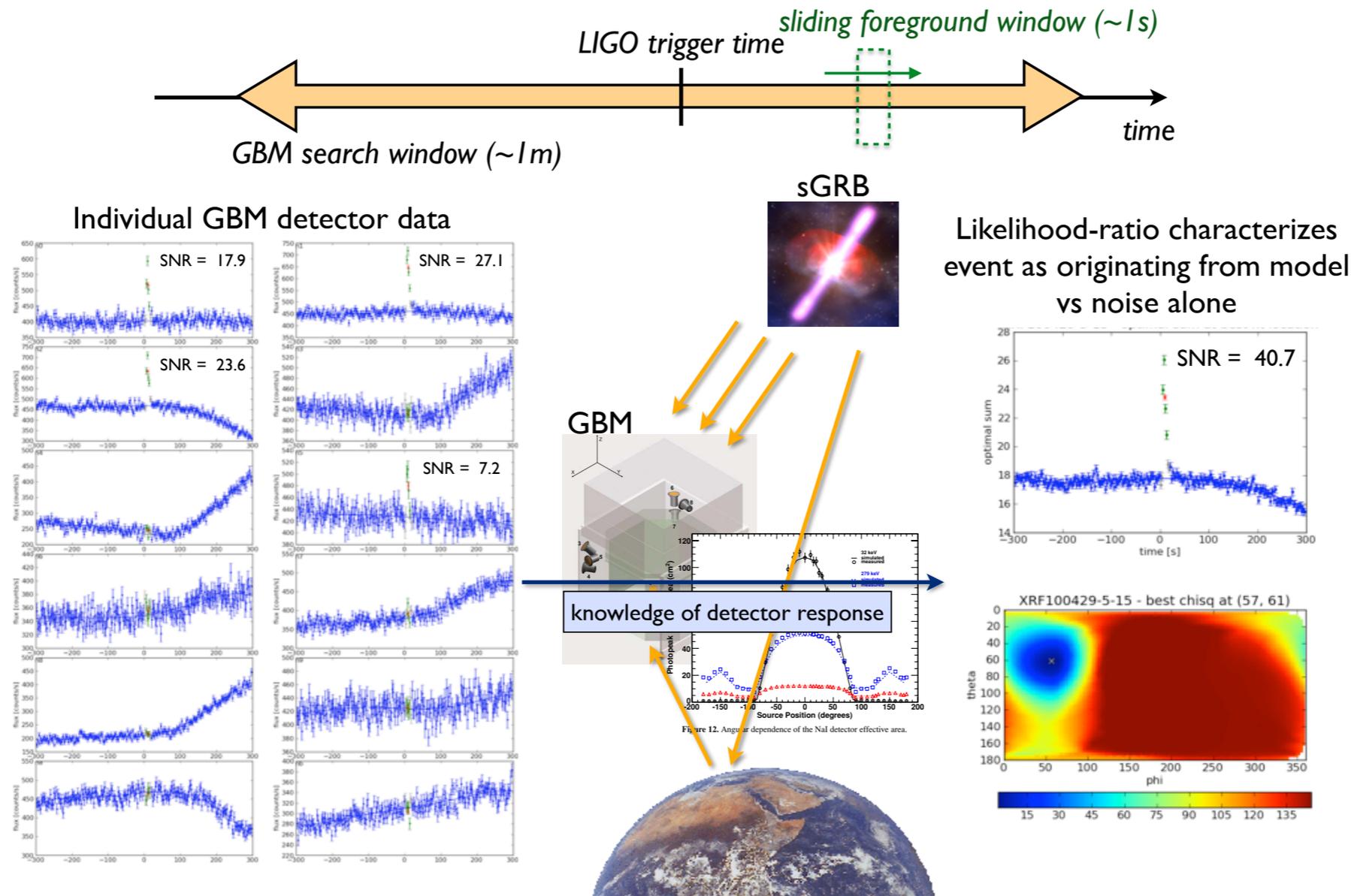
INTEGRAL ACS lightcurve



Not all GBM triggered short GRB are detected by ACS.

In addition to untargeted offline search, we developed a search seeded with LIGO time and (optionally) position. Sensitivity of LIGO/Virgo search can be improved by $\sim 15 - 20\%$ relative to LIGO/Virgo alone (Kelley+ 2013)

Coherent search over GBM detectors

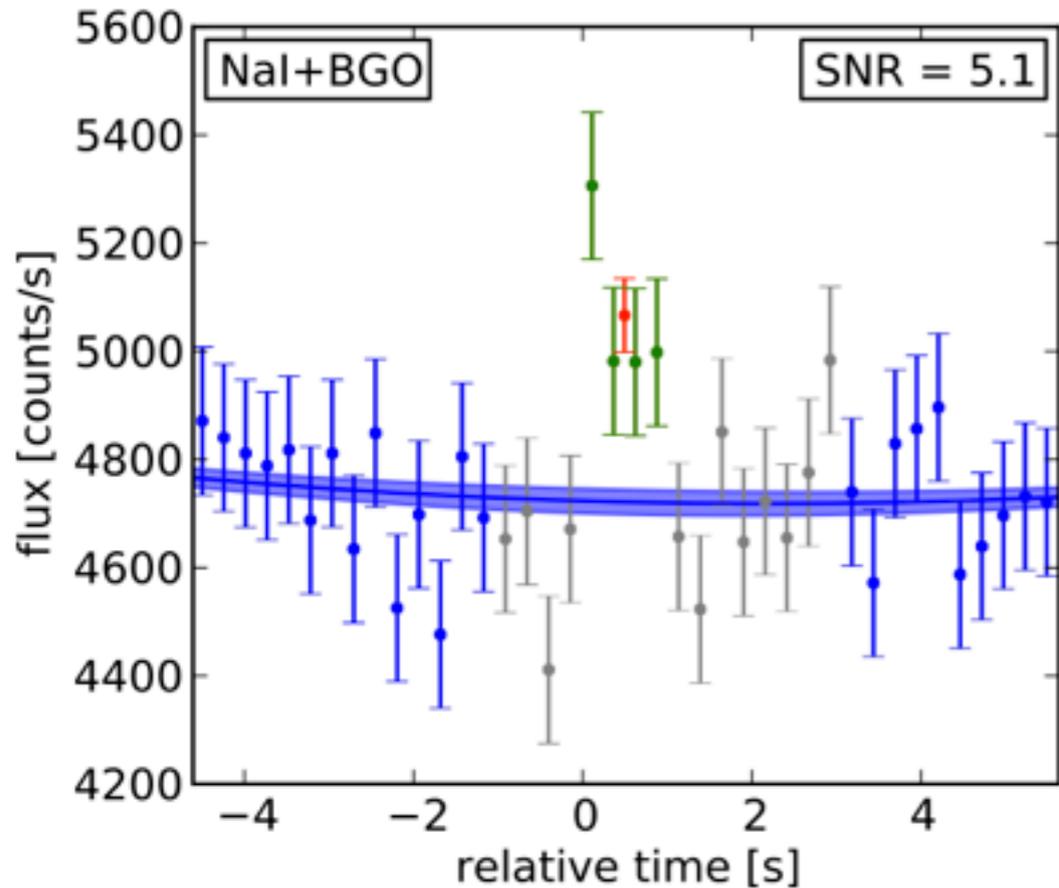


Method was developed during last science run of LIGO and tested on Swift GRBs: a false alarm rate (FAR) for a given likelihood is calculated from a test on 2 months of GBM data: this is an empirical FAR.

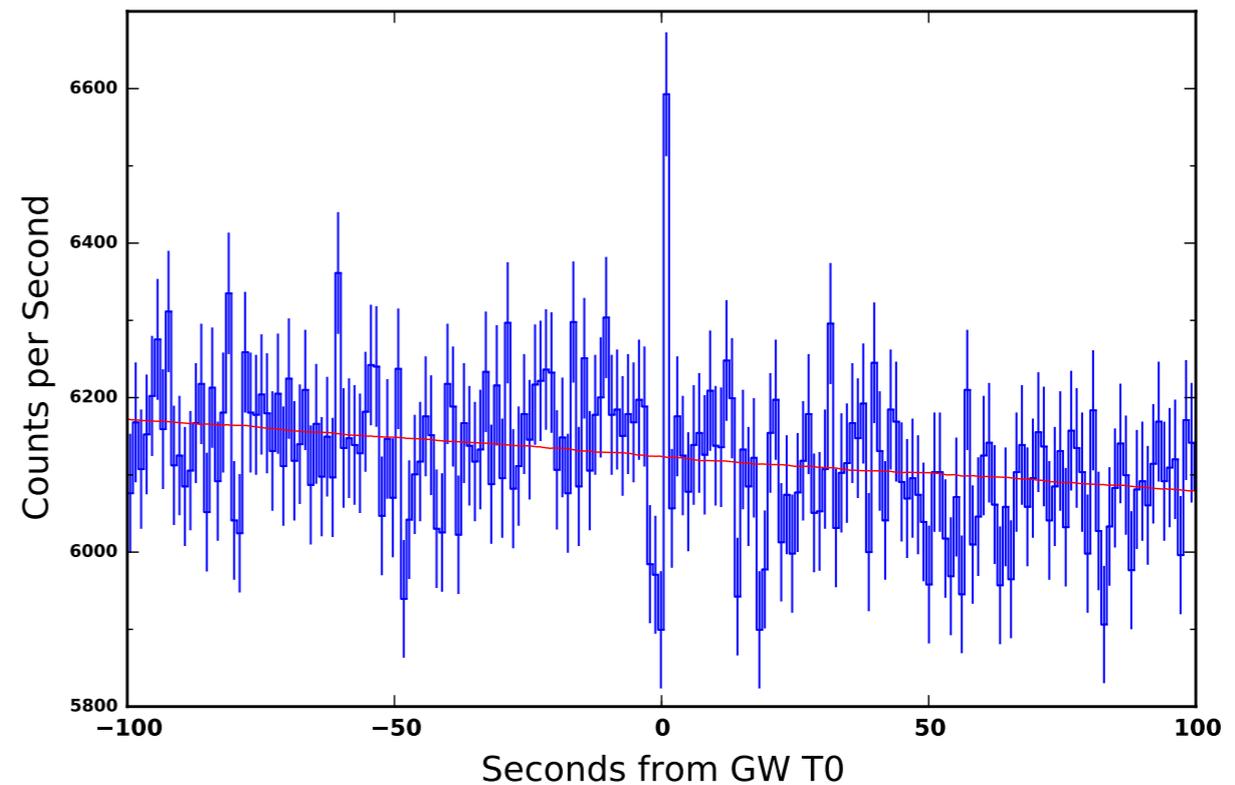
L. Blackburn et al. ApJS 2015, 217, 8

GBM detected a weak event 0.4 s after GW150914, with a 0.2% probability of occurring by chance. The search window was 30 s either side of the GW event.

Model-dependent “discovery” lightcurve
 GBM detectors at 150914 09:50:45.797 +1.024s



Raw lightcurve: not picked up in untargeted search. Why? BGO detectors not included in blind search. NaI signal equal in most detectors.



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

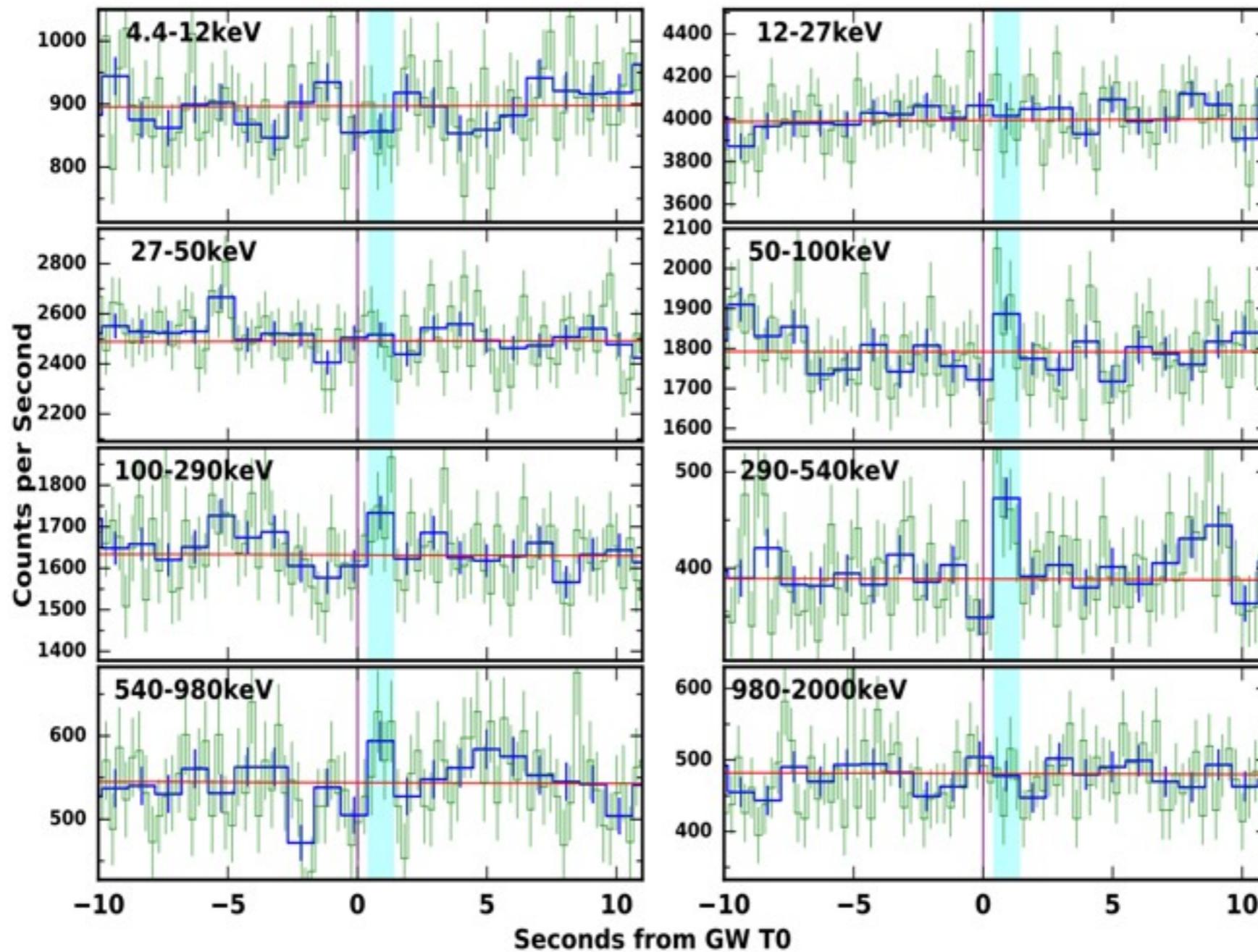
$$P = 2 \times (4.79 \times 10^{-4} \text{ Hz}) \times 0.4 \text{ s} \times (1 + \ln(30 \text{ s} / 0.256 \text{ s})) = 0.0022$$

Offset between GW T0 and GBM event start

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

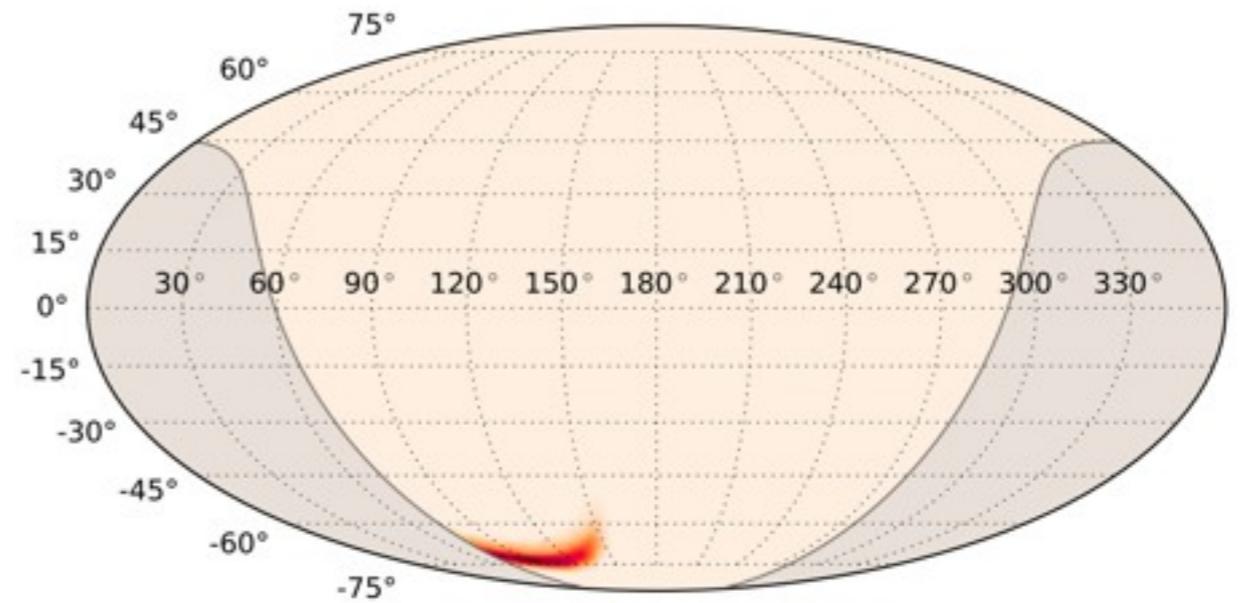
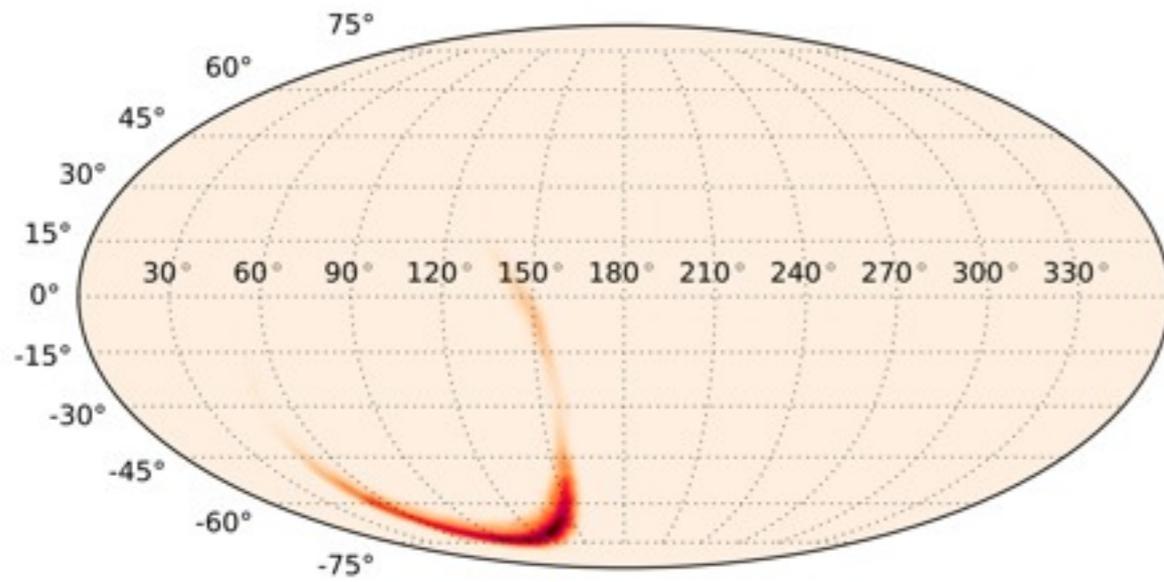
Effective trials factor for non-independent, variable time bins (30s is maximum offset set by the search window, 0.256 is the minimum set by native CTIME data)

The count energy spectrum appears reasonable

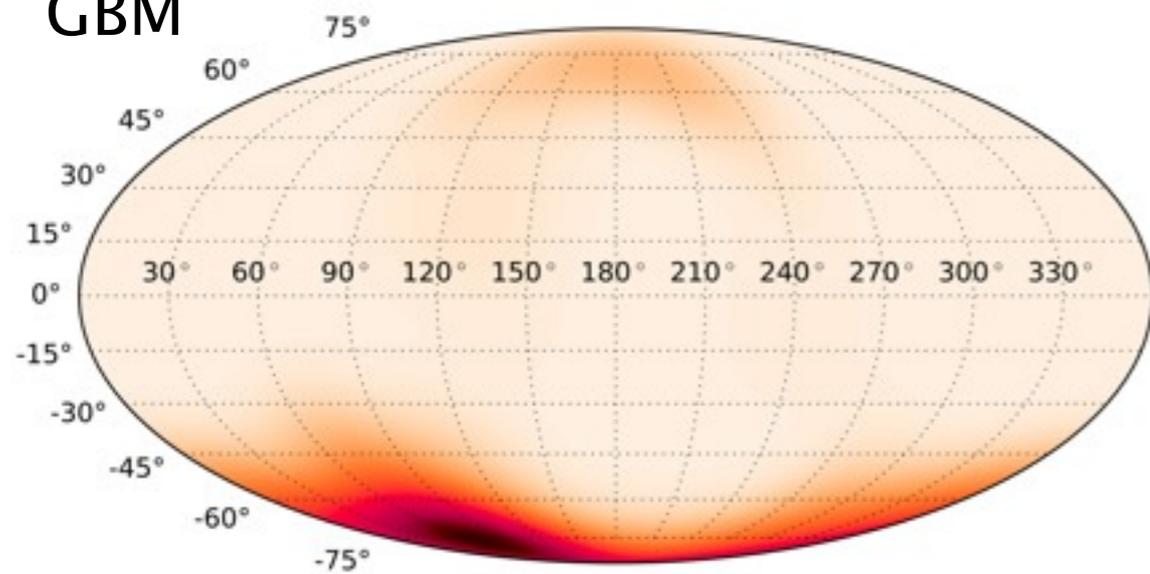


The localization is crude but consistent with the arrival direction of GW150914

LIGO



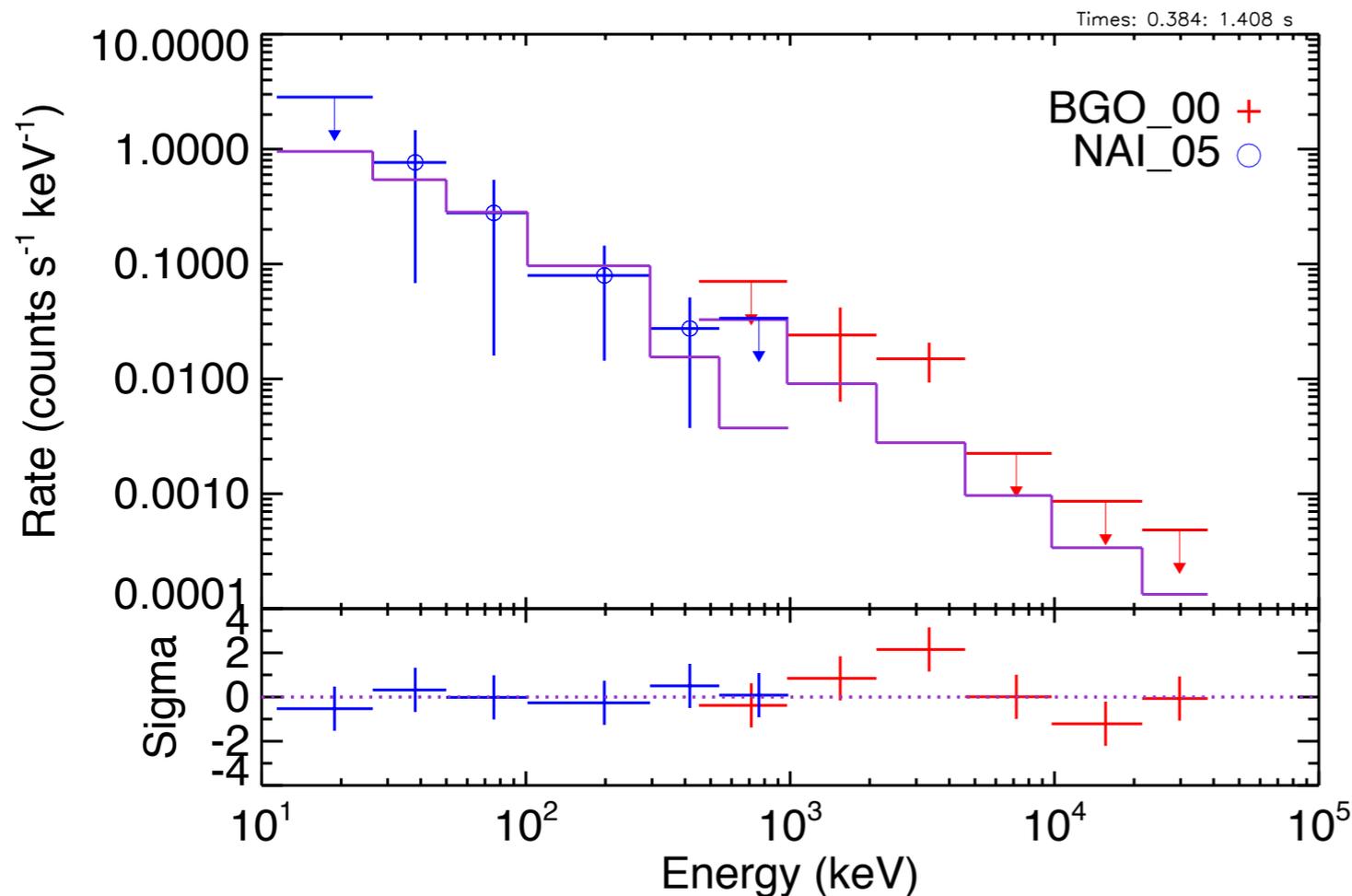
GBM



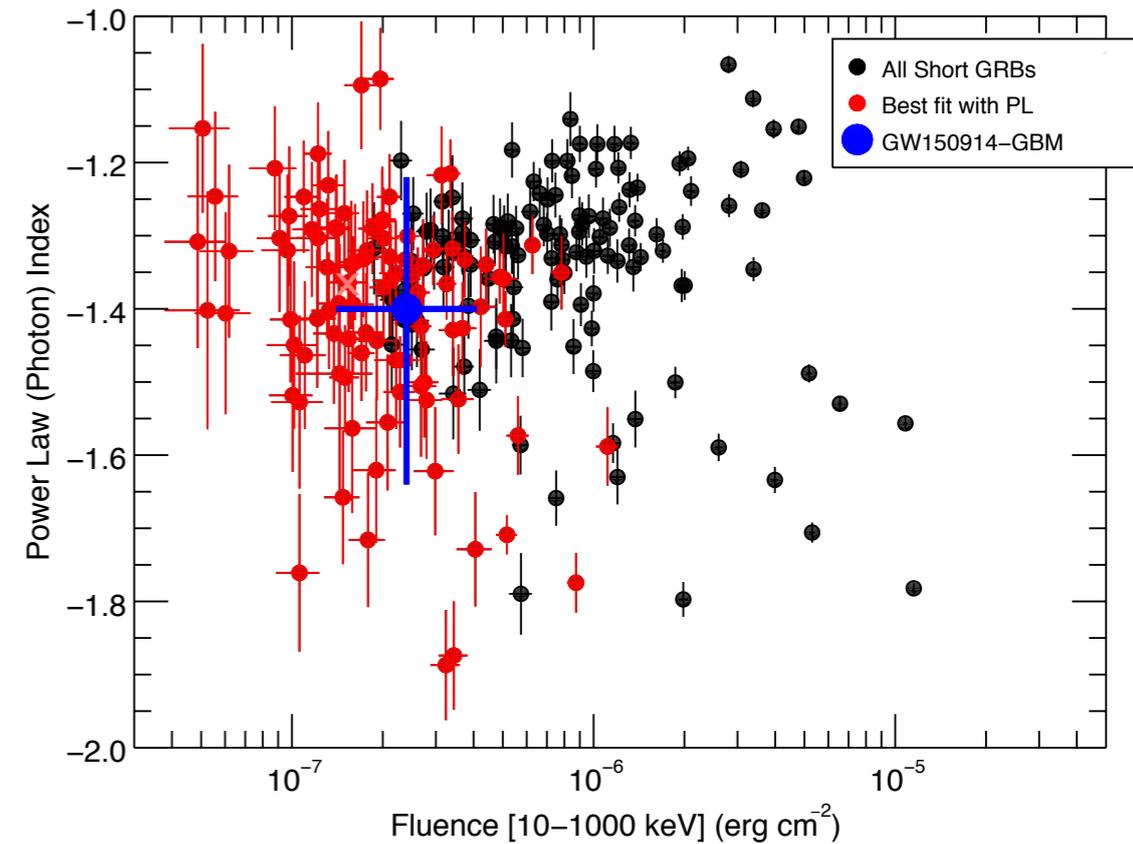
LIGO-GBM-Earth
Constraint

The spectrum is consistent with a short GRB that is sub-luminous in the source frame.

Fit to GW150914-GBM

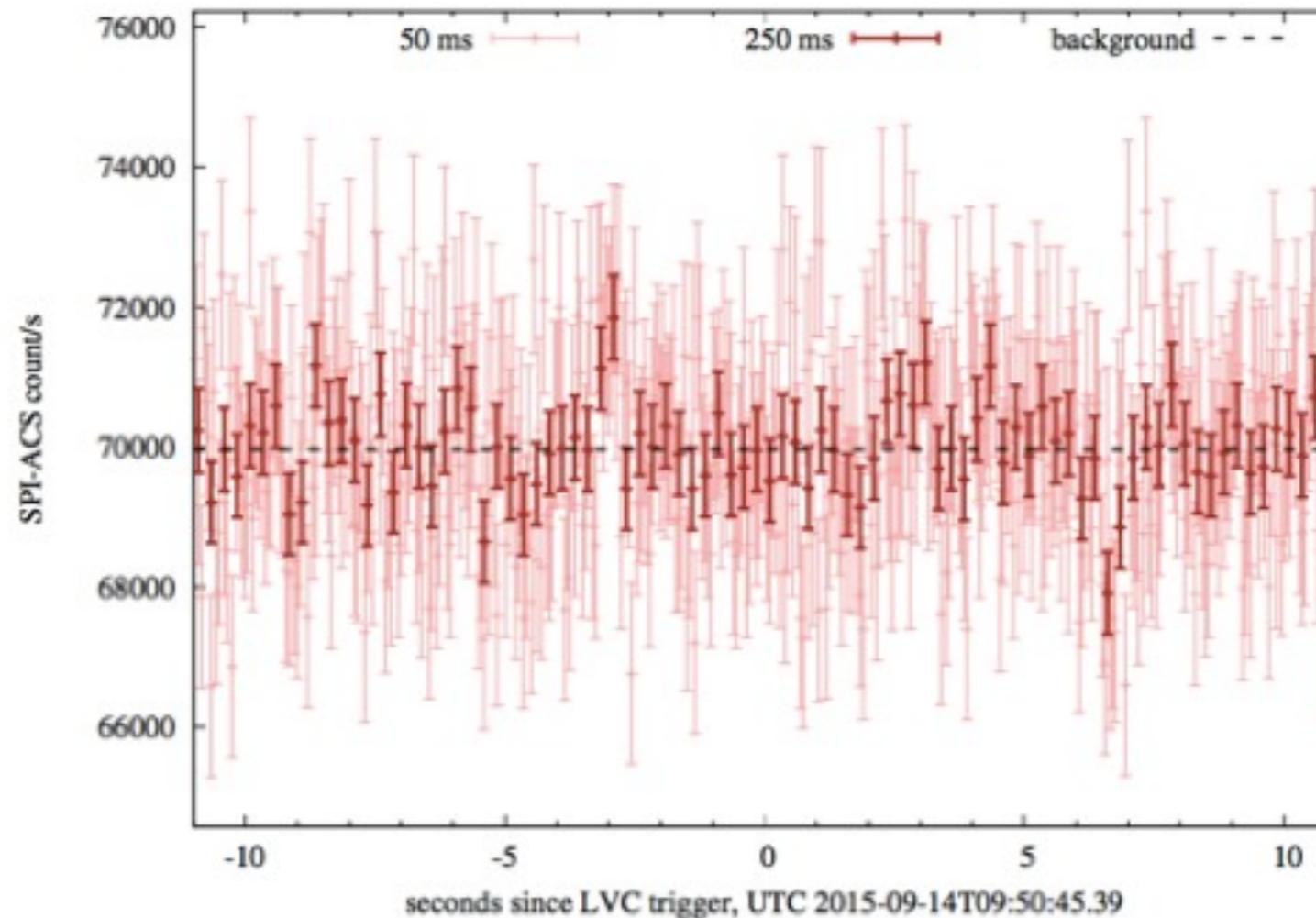


Power-law fits to short GRBs from GBM data



- ▶ At a distance of 410 Mpc (from GW data), this is a gamma-ray bolometric luminosity (1 keV - 10 MeV) of $\sim 2 \times 10^{49}$ erg/s
- ▶ Sub-luminous compared to short GRBs with known redshift

No count-rate increase was seen in the anticoincidence shield of the INTEGRAL spectrometer (SPI-ACS) or in the hard X-ray instrument on-board AGILE

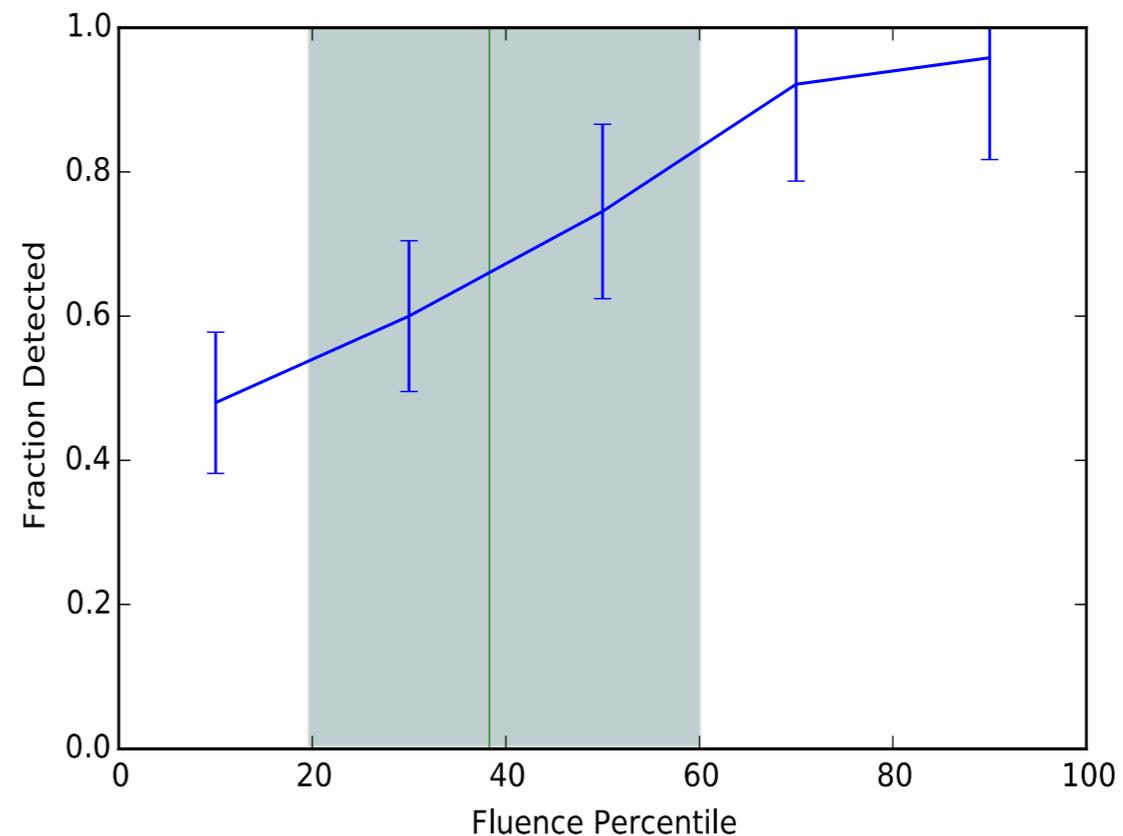


- ▶ The SPI-ACS non-detection constrains the spectrum to be softer than the template spectrum in our pipeline (which was not a fit to the data) and/or to a position on the LIGO arc to which SPI-ACS did not have a good view (Savchenko et al. 2016) (these positions are excluded by the GBM localization).
- ▶ More generally: non-detection in one instrument can constrain location/spectrum in another -> useful for the future. GBM and SPI-ACS teams working on joint sensitivities.

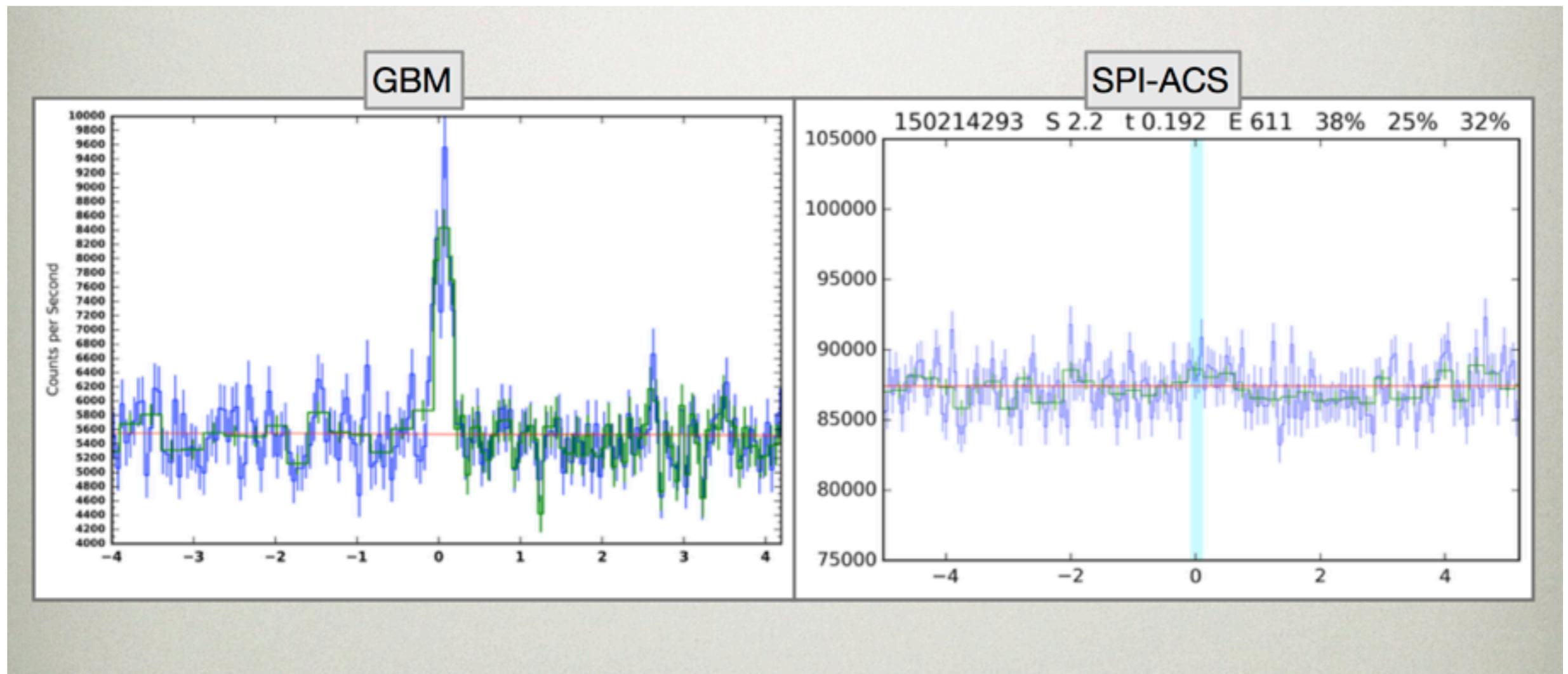
Detection rate of GBM triggered short GRBs in the Integral SPI-ACS

The SPI-ACS data was tested for excesses ≥ 4.5 sigma in intervals of the duration of each GBM SGRB. The plot shows the dependence of detection rate on fluence.

The shaded region indicates the GBM fluence (± 1 sigma) for GW-150914-GBM



GRB 150214293 has a hard spectrum and was bright enough to trigger GBM - but not seen in SPI-ACS.



Comparable in fluence and power-law spectrum to GW150914-GBM

The nature of GW150914-GBM

	Duration	Localization	Spectral Hardness	Lightcurve Morphology	Fermi Lat./ Long.	Believable ?
TGFs/TEBs	x	x			x	x
Galactic Sources		x	x			x
Solar Activity		x	x	x		x
Magnetospheric Origin				x	x	x
New or Unidentified Origin	?	?	?	?	?	x
SGRB	✓	✓	✓	✓		✓

▸ Adapted from Eric Burns (presentation at HEAD 2016).

• Fermi GBM Observations of LIGO Gravitational Wave event GW150914 – VC+

- ▶ Using a targeted search seeded with the LIGO time and a search window of 30 s either side of the GW event, we uncovered a weak transient associated with a false alarm rate of about 10^{-4} Hz.
- ▶ After accounting for trials and weighting the probability of uncovering an event by chance linearly with temporal offset from the GW event, the event has a false alarm probability of 0.2%.
- ▶ The transient is consistent in arrival direction with GW150914. If it is associated with the GW event, the GBM data reduce the LIGO localization region by 2/3.
- ▶ A spectral fit to the data from two GBM detectors, a fluence calculation using the fit parameters, and a luminosity estimate using the distance calculated from the GW data imply consistency with a sub-luminous short GRB.
- ▶ Other explanations for the nature of GW150914-GBM are not satisfactory.
- ▶ The non-detection of GW150914-GBM by SPI-ACS 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.
- ▶ If GW150914-GBM is associated with GW150914 we will detect more counterparts to BH-BH mergers. A full evaluation of the nature of GW150914-GBM will probably await further GW observations.

- Analyses of the GBM data:
 - [Fermi GBM Observations of LIGO Gravitational Wave event GW150914](#) – Valerie Connaughton, et al.
 - [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner, et al.
 - [Is the GW150914-GBM really associated with the GW150914?](#) – Shaolin Xiong
 - [Searching for electromagnetic counterpart of LIGO gravitational waves in the Fermi GBM data with ADWO](#) – Z. Bagoly, et al.
- Theory papers:
 - [Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts](#) – Bing Zhang
 - [Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO](#) – Abraham Loeb
 - [The Progenitor of GW 150914](#) – S. E. Woosley
 - [Fermi GBM signal contemporaneous with GW150914 – an unlikely association](#) – Maxim Lyutikov
 - [Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914](#) – Ryo Yamazaki, et al.
 - [Possible role of magnetic reconnection in the electromagnetic counterpart of binary black hole merger](#) – F. Fraschetti
 - [Electromagnetic counterparts to gravitational waves from black hole mergers and naked singularities](#) – Daniele Malafarina, Pankaj S. Joshi
 - [On the gamma-ray burst -- gravitational wave association in GW150914](#) – Agnieszka Janiuk, et al.
- Investigations with other Instruments:
 - [INTEGRAL upper limits on gamma-ray emission associated with the gravitational wave event GW150914](#) – V. Savchenko, et al.
 - [AGILE Observations of the Gravitational Wave Event GW150914](#) – M. Tavani, et al.
 - [Fermi LAT Observations of the LIGO Event GW150914](#) – M. Ackermann, et al.
 - (Upper limits, not detection) [High Energy Neutrinos from the Gravitational Wave event GW150914 possibly associated with a short Gamma-Ray Burst](#) – Reetanjali Moharana, et al.
- Implications and predictions assuming the association is true:
 - [Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914](#) – Xiang Li, et al.
 - [Modeling the Afterglow of GW150914-GBM](#) – Brian J. Morsony, et al.
 - [Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914](#) – R. Yamazaki, et al.

- [Is the GW150914-GBM really associated with the GW150914?](#) – Shaolin Xiong

- ▶ Compares relative count rates in GW150914-GBM with 3 sGRBs at 130 deg angle to spacecraft axis: In VC+ we show off-axis angle is likely >160 deg and show consistency with GRB130306A at 164 deg.
- ▶ Detectors are “Good” and “Bad” based on source angle to detector normal: no consideration of detector response or spacecraft mass model (response through back, blockage). Angle to normal irrelevant for BGOs.

- Searching for electromagnetic counterpart of LIGO gravitational waves in the Fermi GBM data with ADWO - Zoltan Bagoly et al.

- ▶ Finds GW150914-GBM and a counterpart to LVT151012 (which we do not find using our method). **Combination of energy channels and detector counts without considering physical source spectrum or valid weighting for consistency of relative rates with a sky location - it magnifies the largest SNR channels and detectors. Will find sources but will amplify fluctuations.**

- [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.

- ▶ Critique of rmlfit spectral analysis package vs alternative spectral analysis MLEfit using data from 1-2 detectors. Authors find lower fluence than VC+ and state GW150914-GBM is likely a background fluctuation. **rmlfit is not used in discovery or significance calculation of GW150914-GBM, just in fluence calculation.**
- ▶ Discovery of GW150914-GBM uses data from 14 detectors to evaluate likelihood of background vs source + background - finds source at FAR of 10^{-4} Hz. **Not clear how criticism of rmlfit is relevant to discovery and FAR.**

- [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.

- ▶ Greiner+ compare rmfit and MLEfit analysis of 128-channel TTE data. rmfit analysis in VC+ 2016 uses 8-channel CTIME data i.e., accounts for low-count regime.
- ▶ Incorrect single source position used in Greiner+ vs. sampling of LIGO annulus in VC+ (Fig 5). Error may be carried to further analysis - unclear in paper.
- ▶ Lower fluence with MLEfit implies consistency of GW150914-GBM with non-detection by SPI-ACS - a more natural conclusion?

• On the GBM event seen 0.4 sec after GW 150914 – Jochen Greiner et al.

rmfit fit with 128 channel data convolved with response for same source position used to produce fit.

Fluence in VC+ is calculated along LIGO arc. Purple point assumes single source position excluded by GBM and joint GBM/LIGO localization, with 27 deg angle to NaI 5 vs ~70 deg for favored source position.

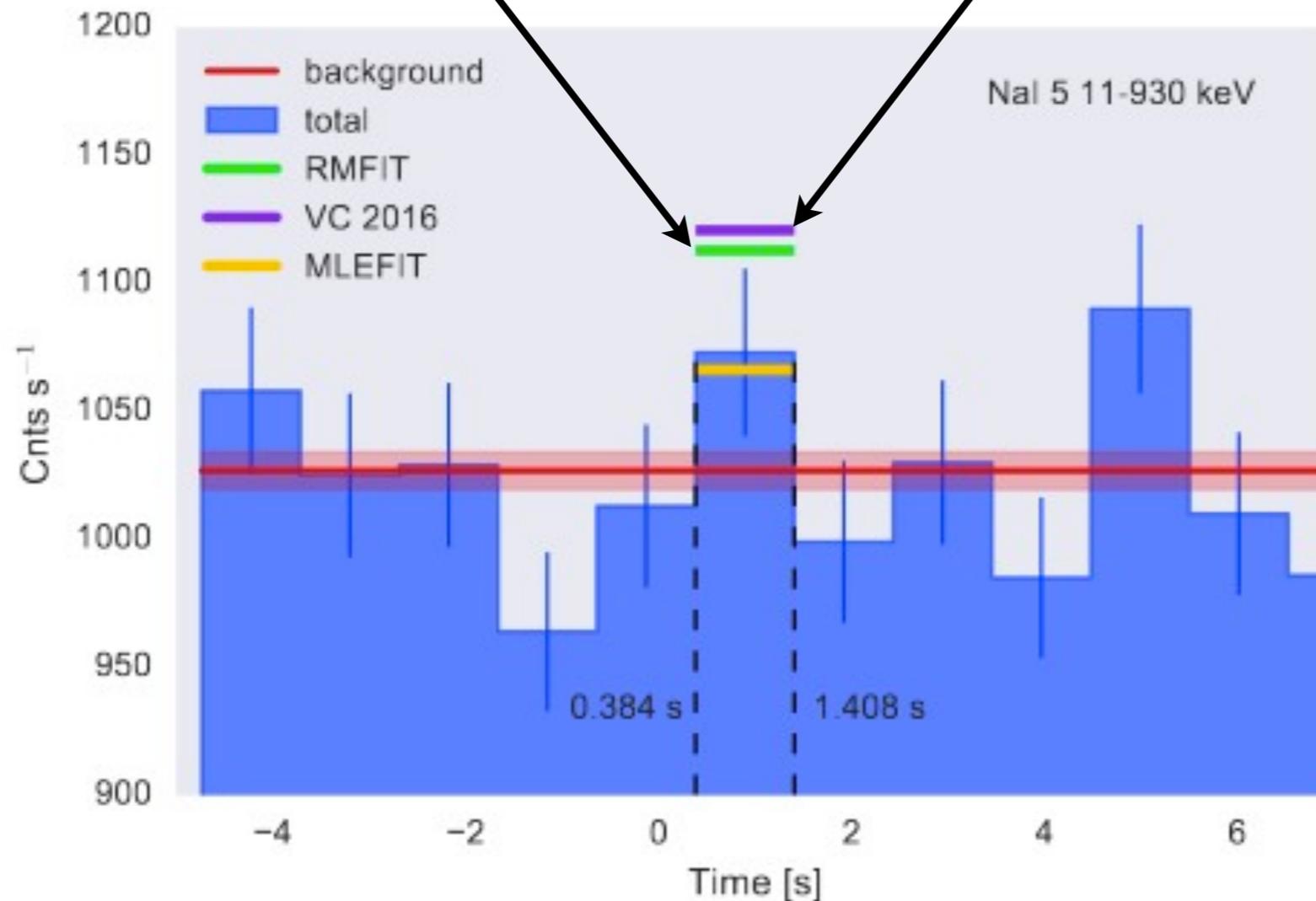


Fig 5 of Greiner et al.

This error appears to be propagated throughout the rest of the analysis - using the amplitude from VC+ but for a source at the wrong location.

• [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.

rmfit fit to 128-channel data in tension with non-detection of GW150914-GBM by INTEGRAL SPI-ACS (red crosses)

(Values not those in Table I of JG+ as stated in caption???)

MLEfit consistent with non-detection of GW150914-GBM by INTEGRAL SPI-ACS (green crosses)

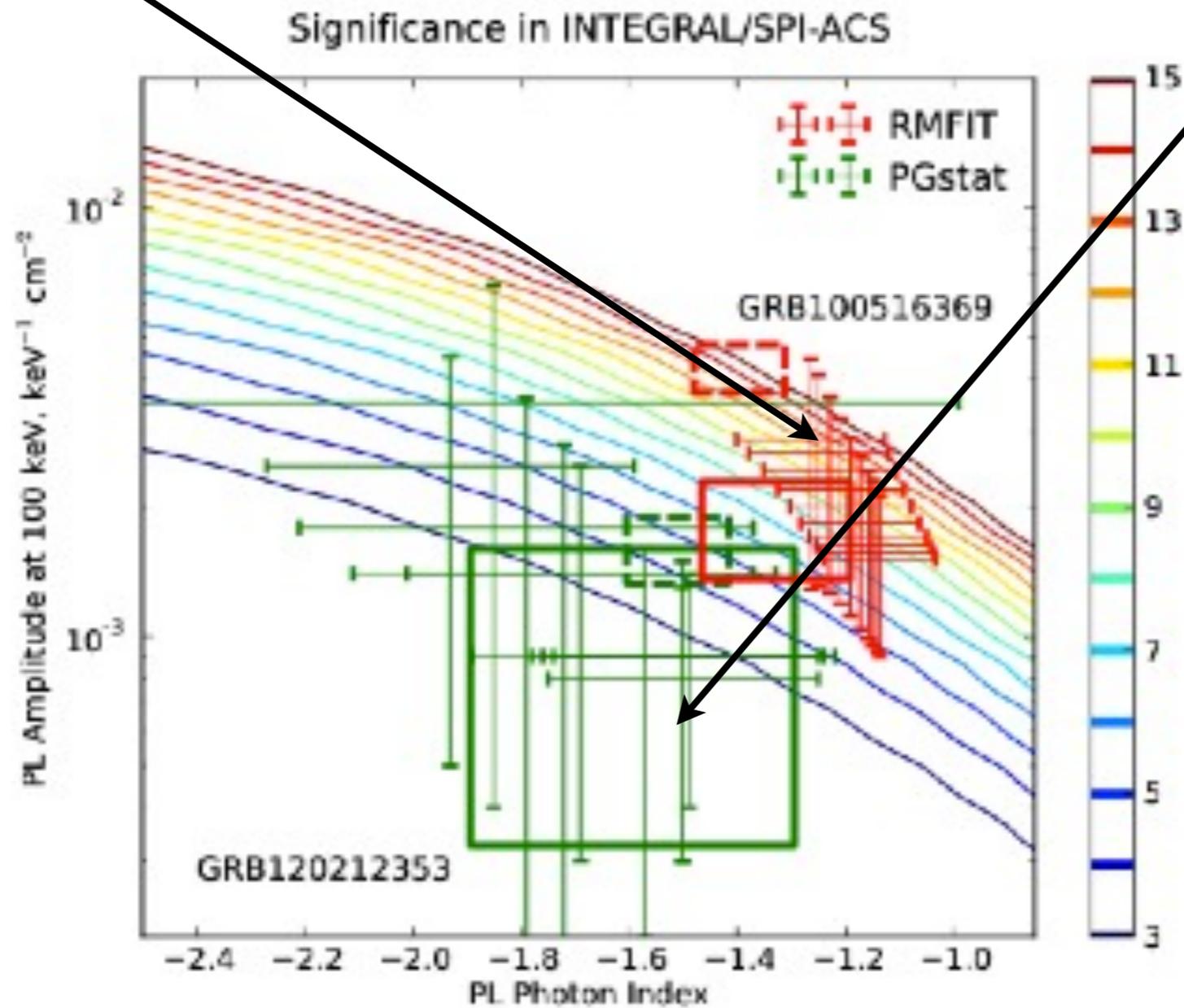
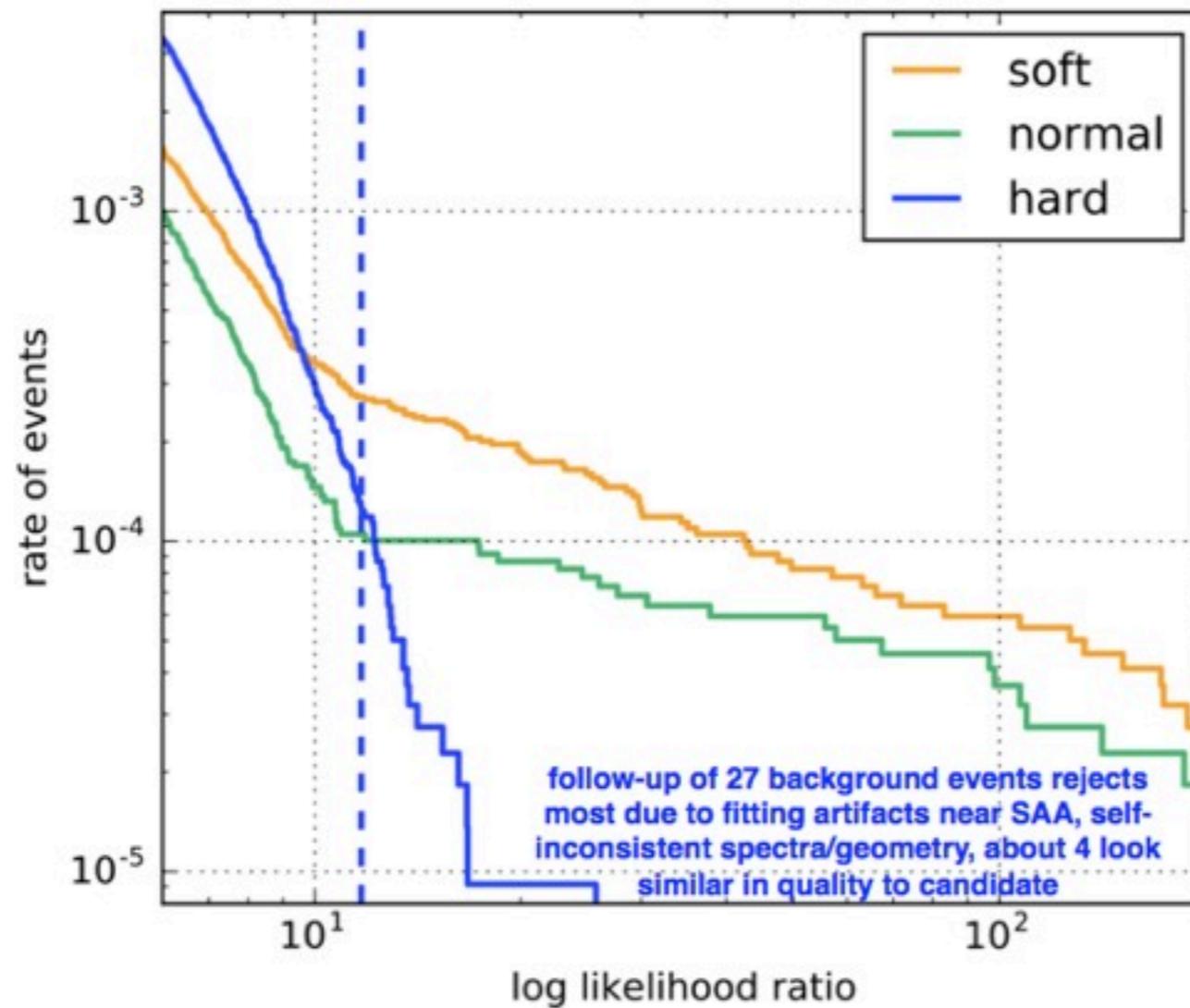


Fig 12 of Greiner et al.

- [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.
- ▶ Even if there were no problems with the analysis in the paper, it would not be a challenge to the statistical significance of the event reported in VC+ 2016, found using the data from 14 detectors, with a significance based on the empirically-derived FAR. The results in JG+ could be used to calculate an upper limit to the event fluence based on the alternative spectral analysis.

What next for our search?



Search algorithm could be improved: many of the candidates would fail our manual inspections: can we automate this?

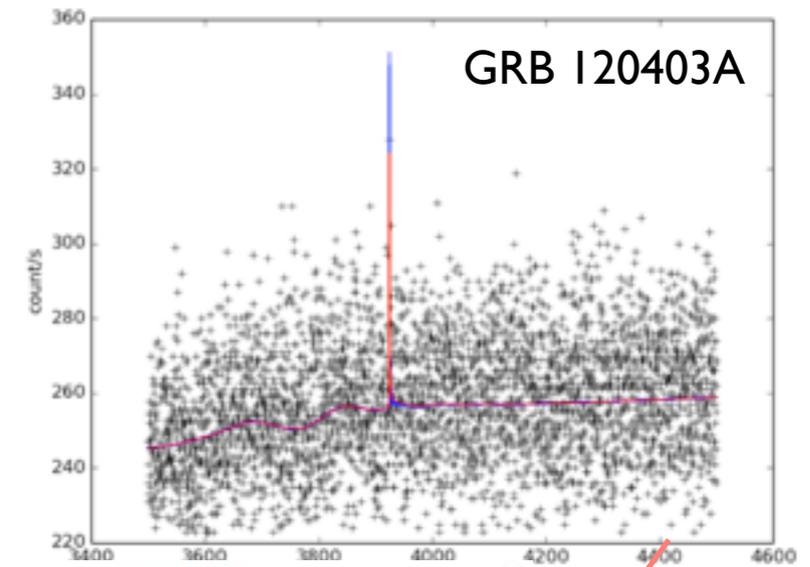
- ▶ Finish O1 analysis: for GW150914, the GW detection was bright but the GBM detection was sub-threshold.
- ▶ Get ready for O2!
- ▶ In O2: expect more BH-BH candidates. Can we confirm association between BH-BH events and sub-luminous short-GRB-like events? Can we rule out GW150914-GBM with no further detections during O2? Can we set more suitable priors for BH-BH candidates?

▶ Backup

Most of the Swift BAT short GRBs that did not trigger GBM are found in a ground search of the Continuous Time-Tagged Event (CTTE) data for untriggered bursts.

Missed GRBs are either weak (detected close to BAT's boresight) or at large offset to Fermi boresight.

Missed GRBs are not systematically long i.e. collapsars masquerading as mergers



GRB (Name)	BAT					GBM		
	T_{90} (sec)	Fluence (%ile)	Peak Flux (%ile)	PL Index	Partial Coding	LAT offset (degrees)	# of NaI detectors	Ground (signal)
140606A	0.34	34.1	6.7	0.53	86	91	3 (18, 49)	Strong
120403A	1.25	61.0	40.0	1.64	50	71	3 (32, 33)	Strong
140516A	0.19	8.5	6.7	1.87	75	31	3 (18, 31)	Weak
090305A	0.40	52.4	64.0	0.86	50	97	1 (39, 69)	Weak
140129B	1.36	47.6	28.0	2.23	100	14	3 (33, 53)	None
110112A	0.50	14.6	6.7	2.14	87	135	1 (45, 66)	None
090815C	0.60	28.0	16.0	0.90	76	116	1 (43, 86)	None

Recovered in untriggered search

Pre-date availability of CTTE

Oddbod - can be found in <50 keV data, v. soft, not like GRB

- ▶ GBM GRBs Swift BAT misses can also generally be found in ground search.
- ▶ Finding weaker short GRBs when search seeded by other instrument motivate blind search
- ▶ We expect 2x more short GRBs through this untriggered search: quality control in progress.

- [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.

- ▶ There are problems with the analysis in the paper. If the authors continue to use this assumed source position that is incompatible with both the GBM/LIGO localization and with the GBM-data alone, then the responses they use in their Bayesian analysis are incorrect given the most likely source position, or indeed all allowed source positions.

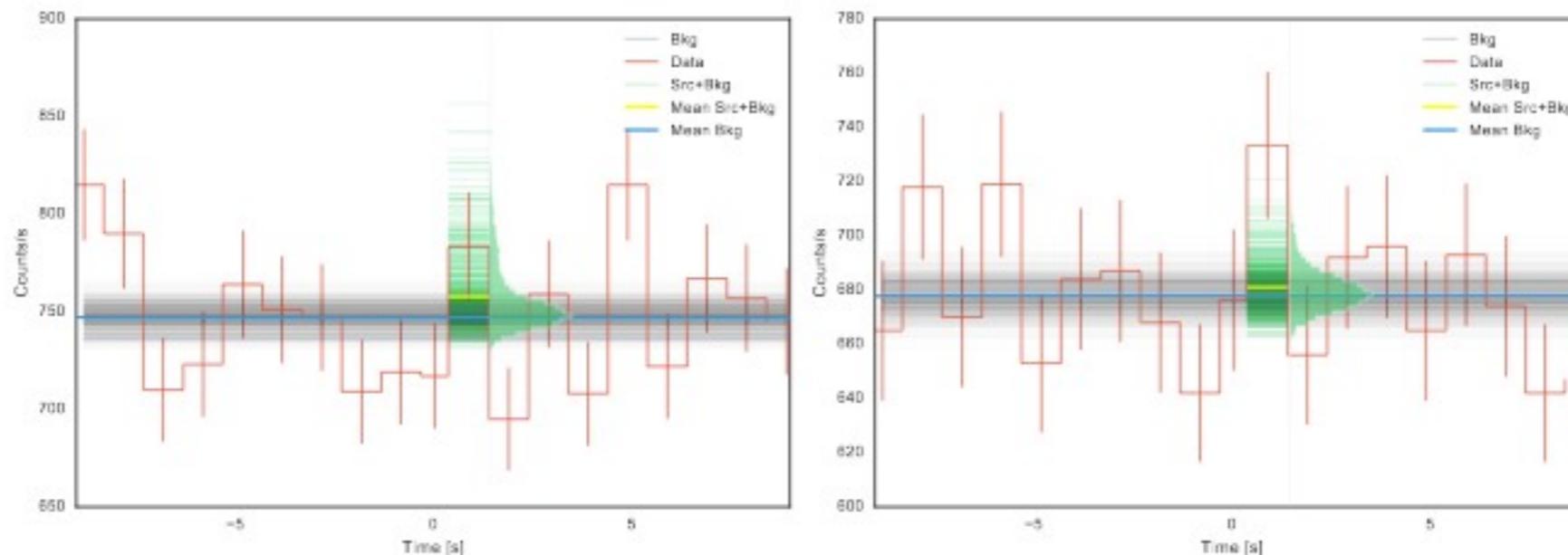


Fig 7 of JG+ The green bands indicate the source + background levels obtained in this analysis for NaI 5 (left) and BGO 0 (right). The yellow bar is the mean level of source + background.

Given that the relative rates observed in NaI 5 and BGO 0 are incompatible with the assumed source position, it is not surprising that this analysis finds the data consistent with the absence of a source at this position.

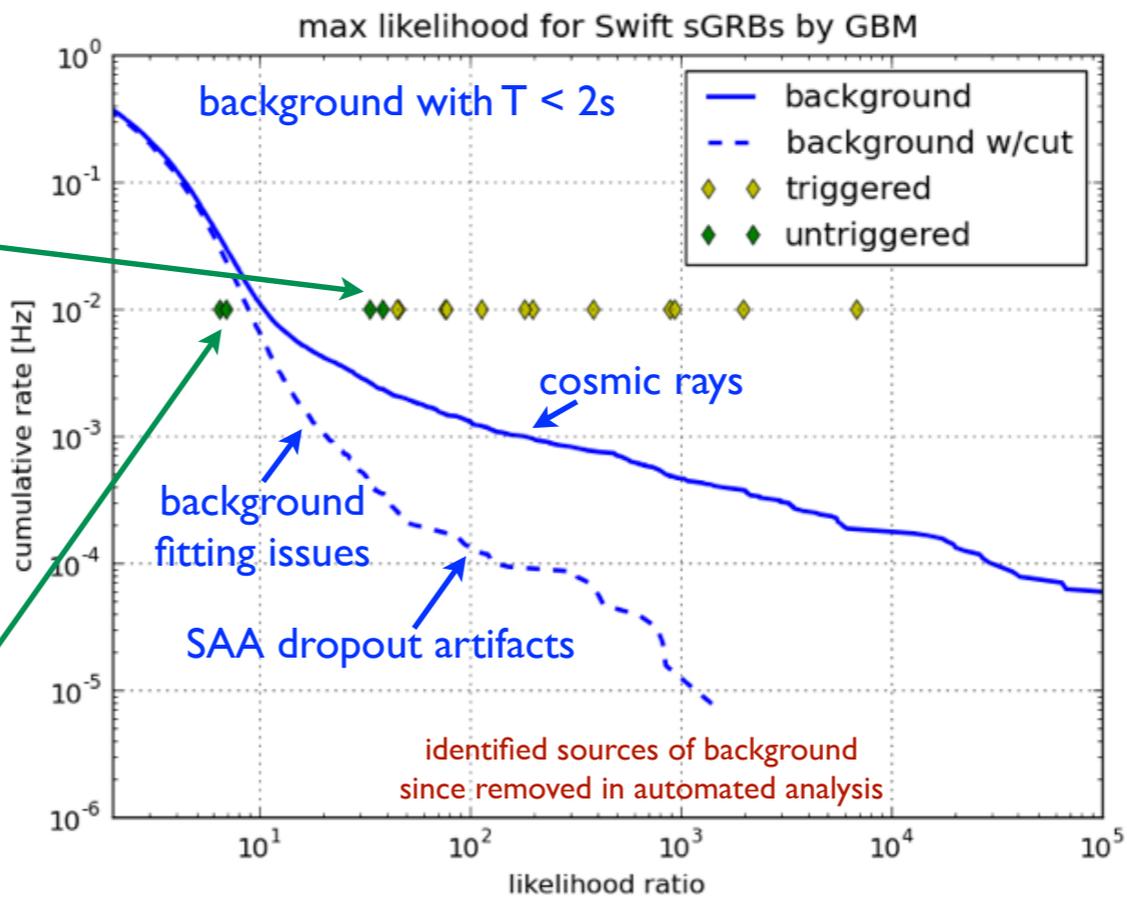
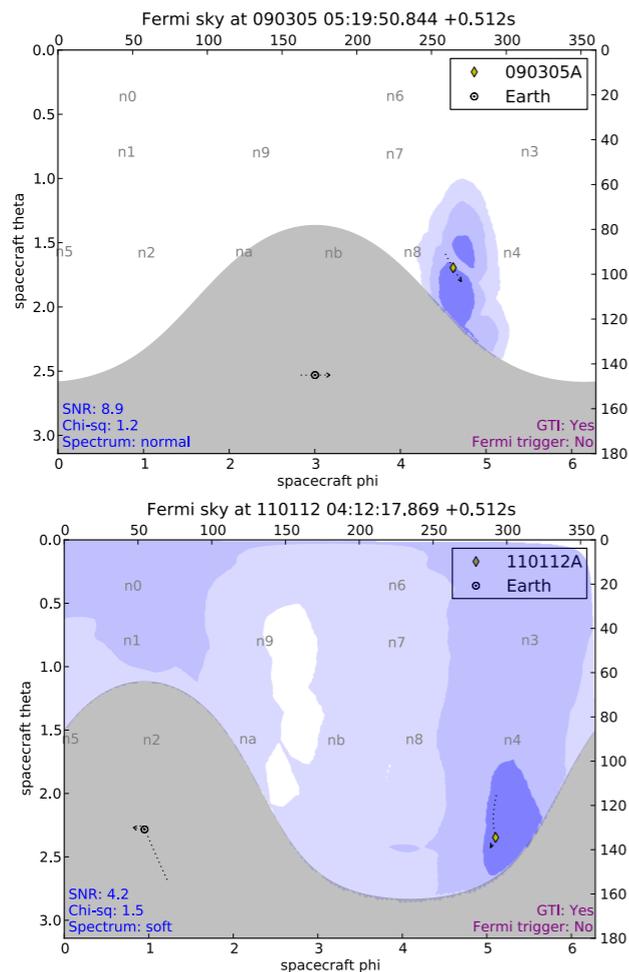
This will go in backup

Method was developed during last science run of LIGO and tested on Swift GRBs: a false alarm rate (FAR) for a given likelihood was subsequently calculated using 2 months of GBM data: this is an empirical FAR.

Test over Swift sGRB's

Swift-detected sGRB's are a good "hardware injection" test for the GBM followup

- ▶ 16 events within GBM FOV, 14 offline detections, 12 loudest trigger on-board
- ▶ large sample of nearby background times also searched, in total ~1 day of live-time
- ▶ not using sky-location information (marginalization over entire sky)



Blackburn et al, 2013 [arXiv:1303.2174]

Joint GBM-subthreshold search developed for LIGO/Virgo S6 science runs in 2009-2010 (L. Blackburn et al, ApJS 2015, 217, 8) - GBM background characterized and likelihood-based search finds known short GRBs in GBM data.

- [On the GBM event seen 0.4 sec after GW 150914](#) – Jochen Greiner et al.

- ▶ There are problems with the analysis in the paper. If the authors continue to use this assumed source position that is incompatible with both the GBM/LIGO localization and with the GBM-data alone, then the responses they use in their Bayesian analysis are incorrect given the most likely source position, or indeed all allowed source positions.

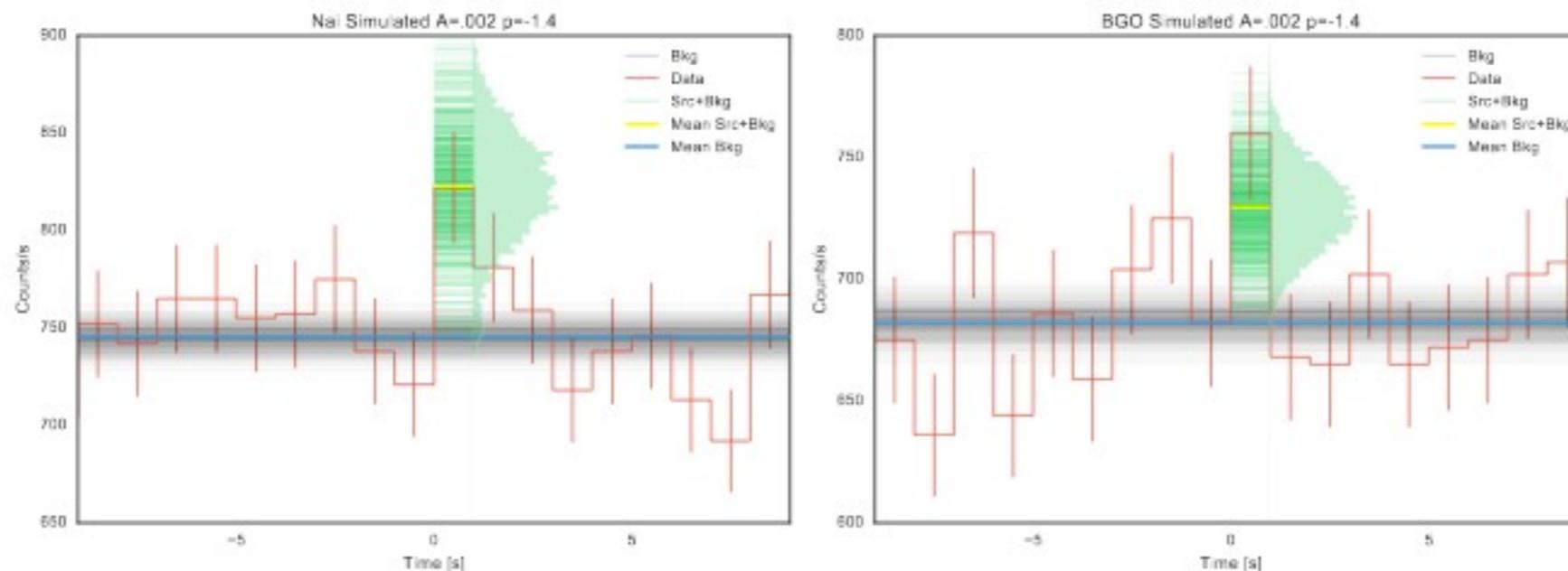


Fig 9 of JG+ The green bands indicate the source + background levels obtained for a simulation of a source at the incorrect source position assuming the amplitude of the fit in VC+ for NaI 5 (left) and BGO 0 (right). The yellow band indicates the mean source + background level. Given that the simulated rates in NaI from the source at this position are 2.7 x the rates expected from a source at the most likely position, and the rates are injected in the BGO data with the same source position (i.e., compatible relative rates), it is not surprising that this analysis uncovers a source.

This will go in backup