Searching for GRB Counterparts to Neutrinos with *Fermi*-GBM

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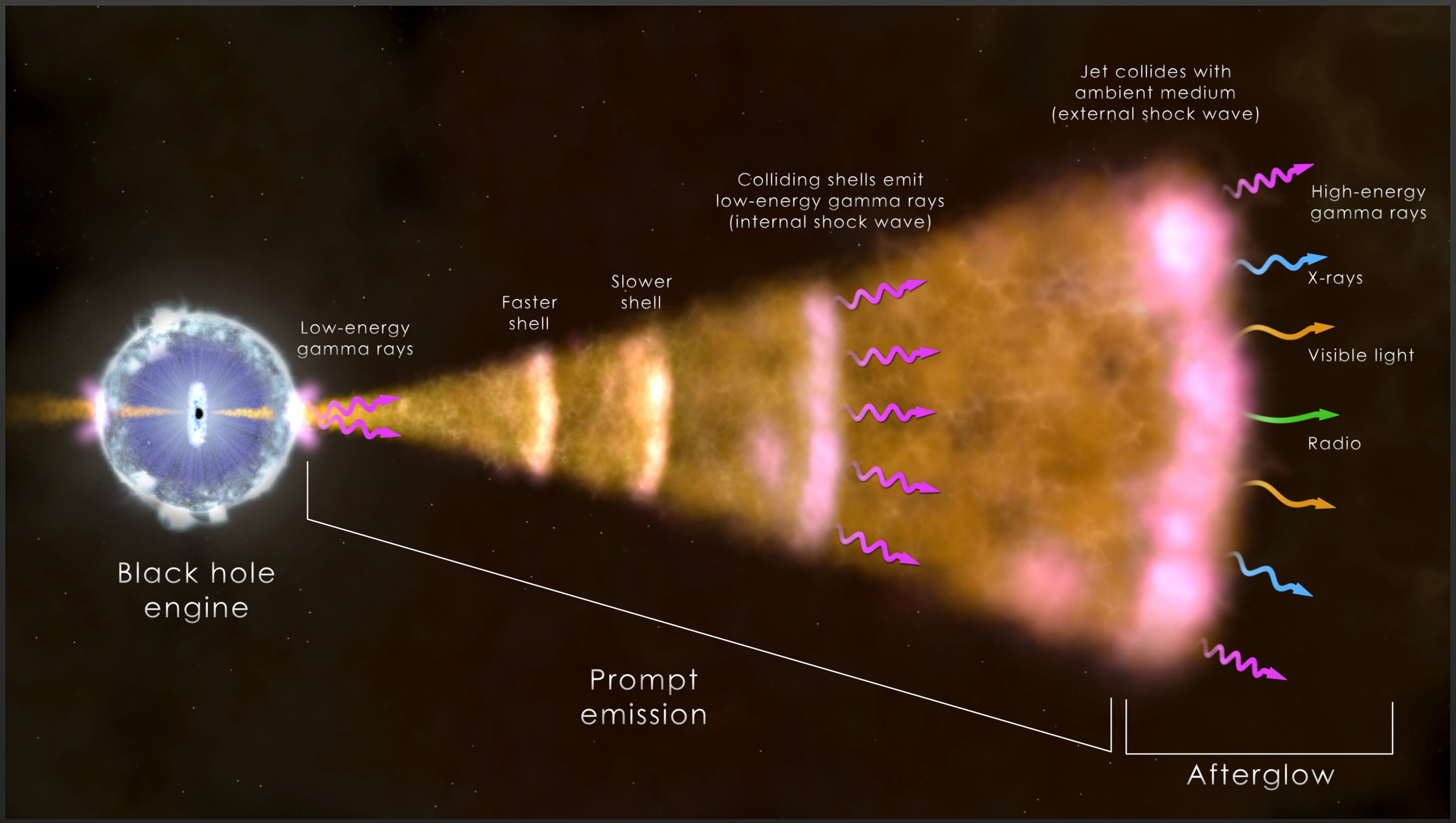
on behalf of the *Fermi*-GBM Team

Topics in Cosmic Neutrino Physics

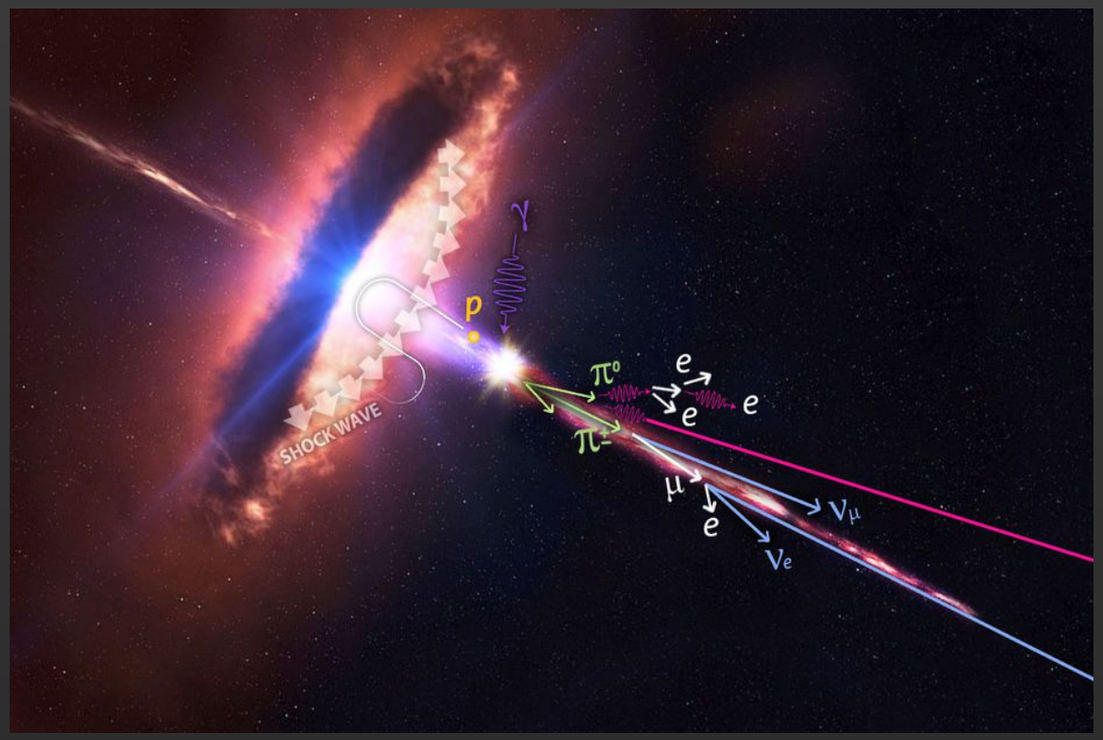
Oct 9-11, 2019

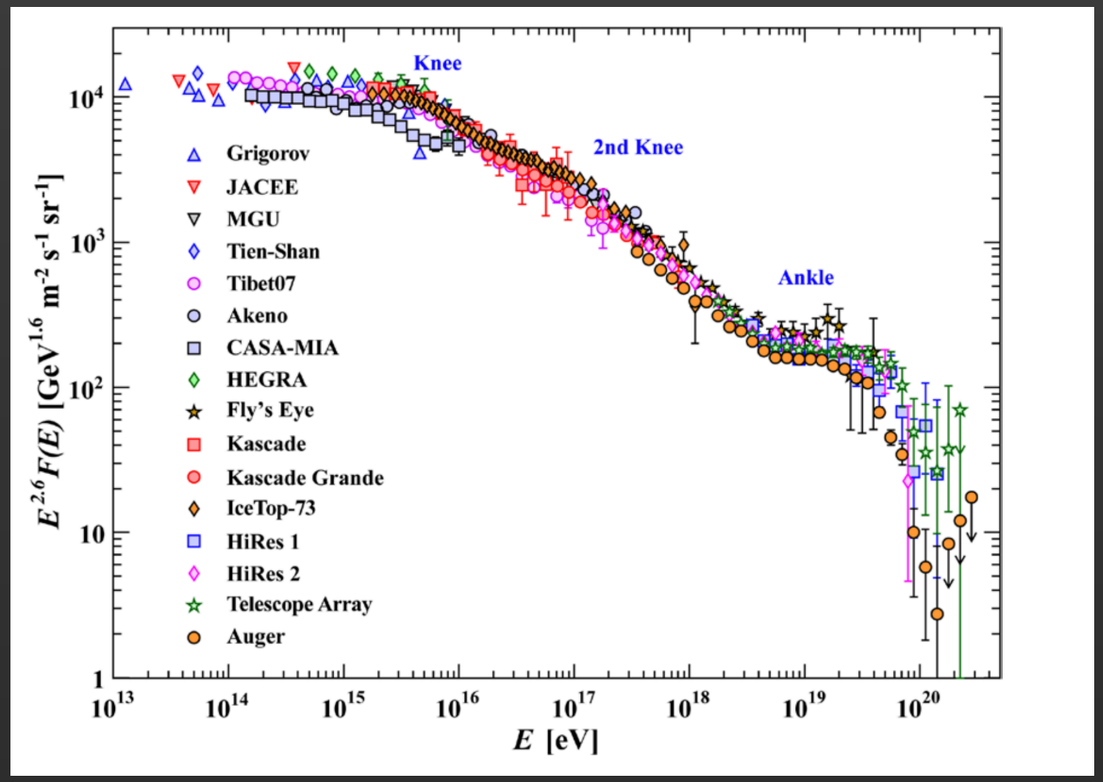
What is a gamma-ray burst?



What are the sources of astrophysical neutrinos?

- Cosmic ray acceleration sites produce both high energy neutrinos and gamma-rays



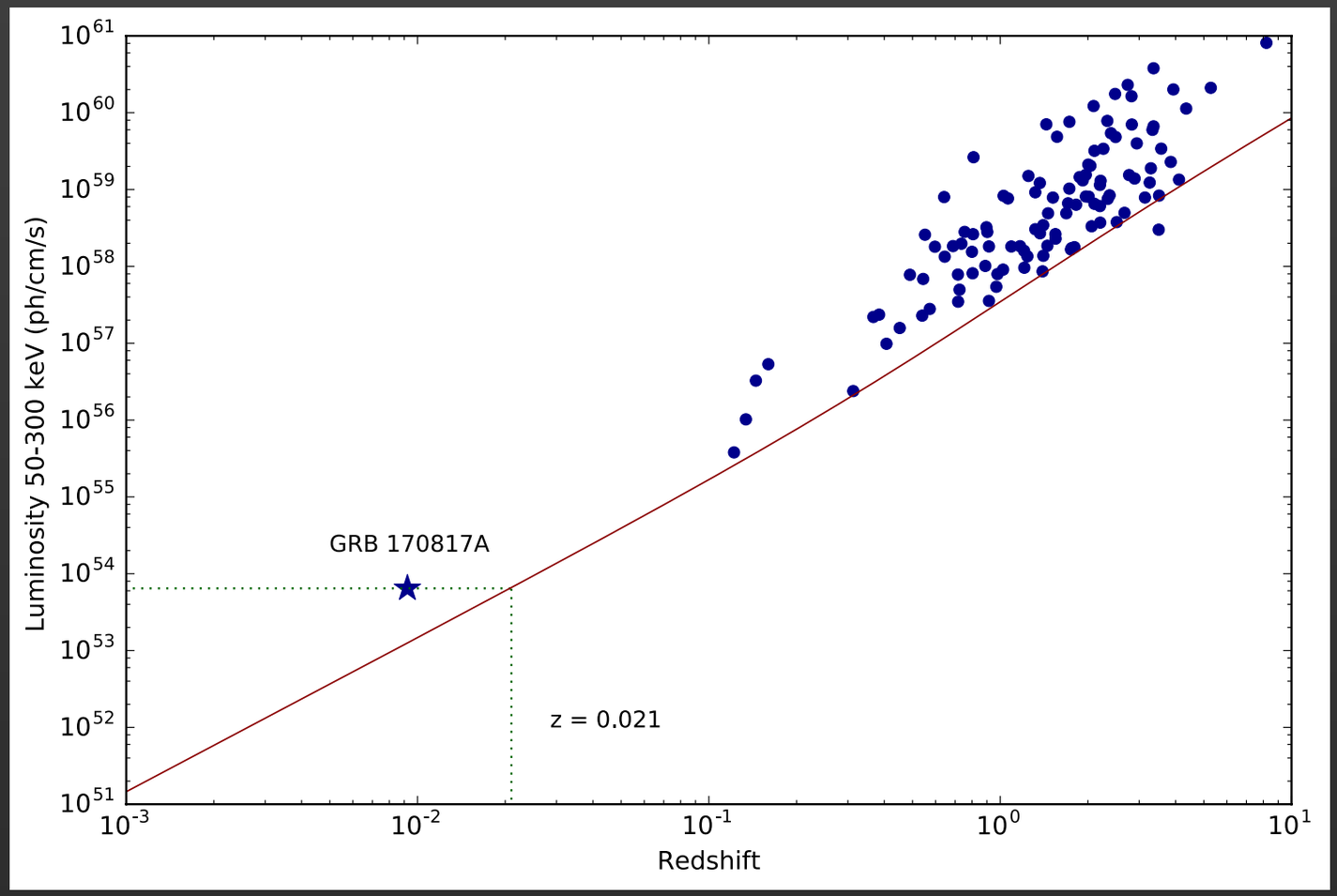


Markus Ahlers and Francis Halzen 2015 Rep. Prog. Phys. 78 126901

- Historically, GRBs have also been likely candidates based on energetics (i.e., the energy density of extragalactic cosmic rays and GRBs is comparable, given some assumptions)

- IceCube has constrained GRB contributions to <1% of the astrophysical neutrino flux (Aartsen et al 2015) but we're learning new things from GRB 170817A…

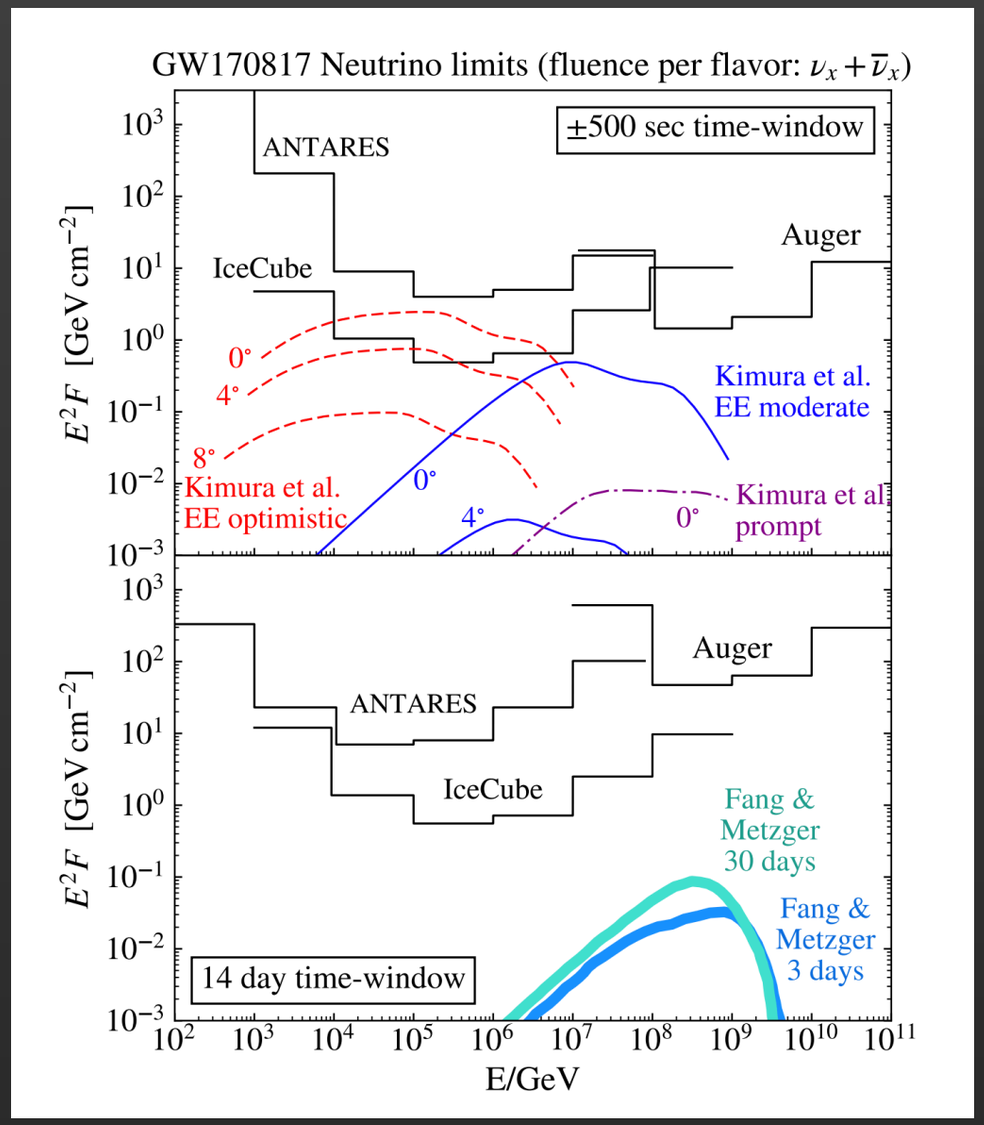
GRB 170817A

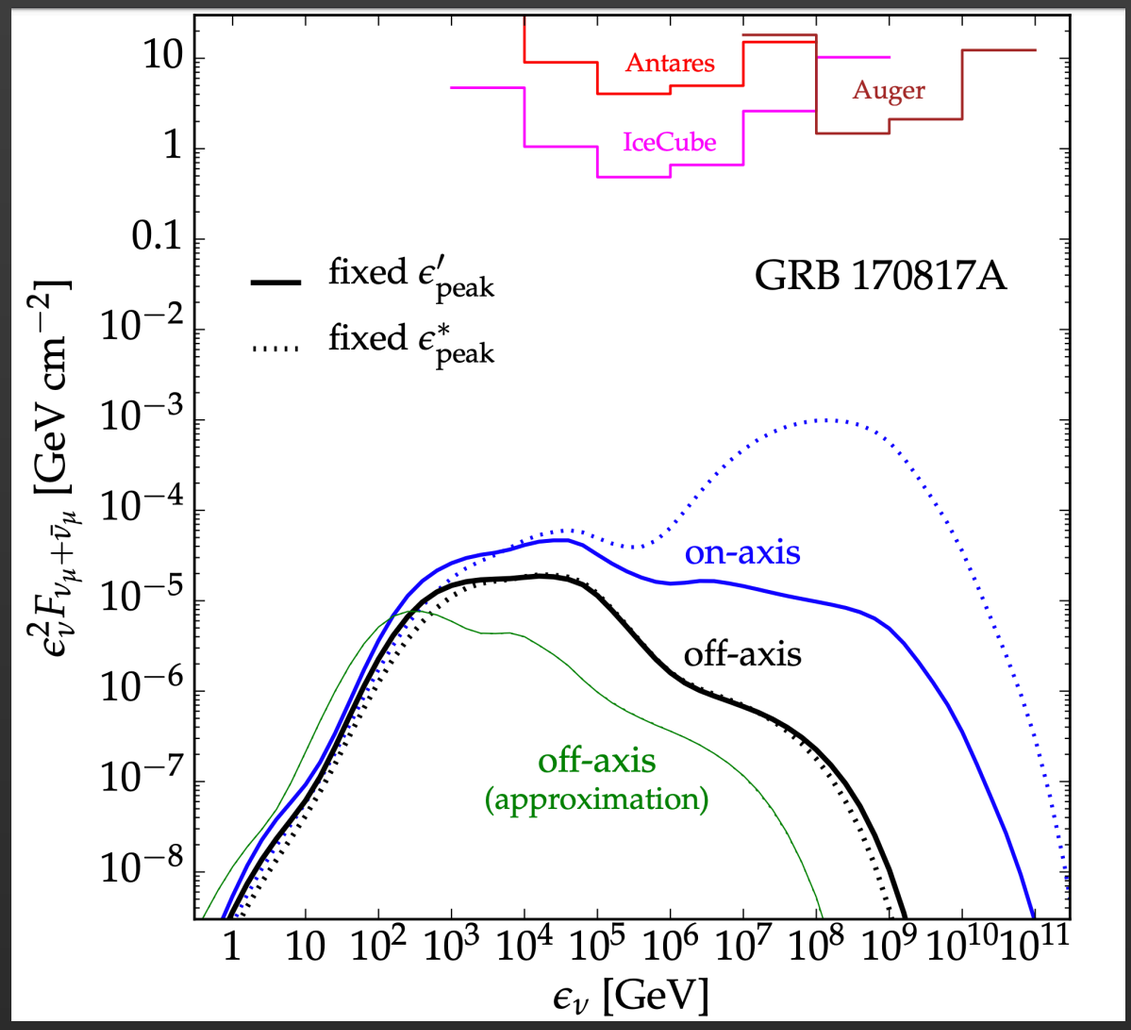


Adapted from Abbott et al. 2017, ApJL, 848, L13

- GRB 170817A was the closest and orders of magnitude less luminous than other GRBs with known redshift
- Off-axis interpretation supported by X-ray and radio observations (Alexander et al. 2018, Mooley et al. 2018)
- There may be a unique class of nearby, dim bursts and we must use subthreshold searches to get more joint detections

Neutrinos and Off-Axis Bursts





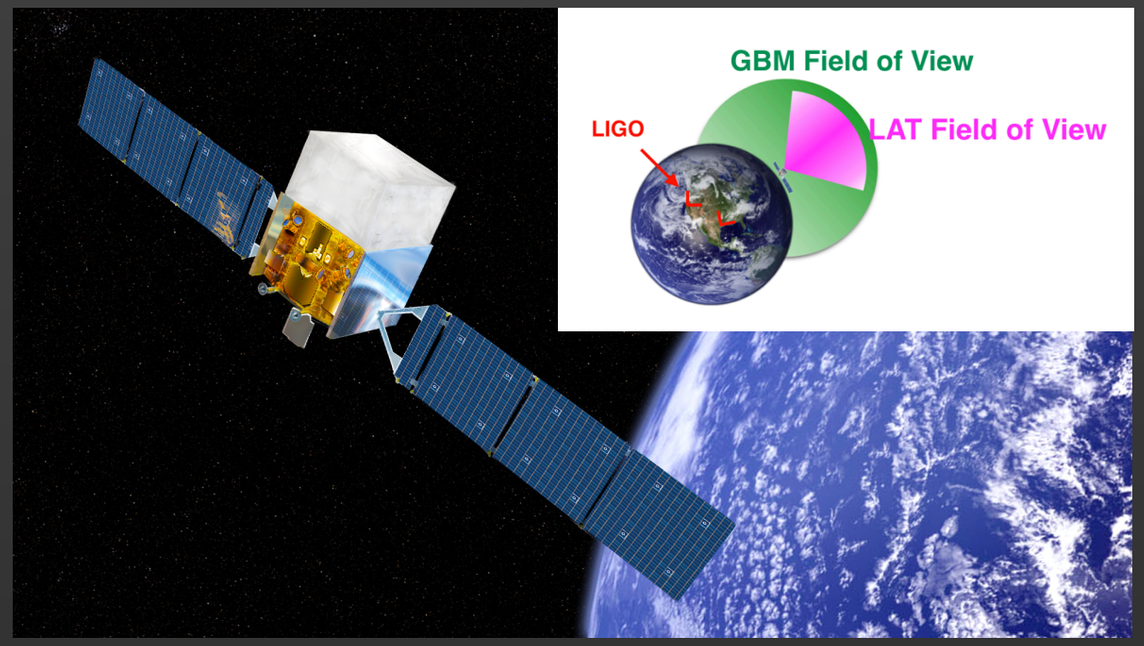
- Albert et al. 2017 - "non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle."

- Ahlers and Halser 2019 - "neutrino fluence from structured jets can exhibit a strong angular dependence relative to that of γ-rays and can be far more extended."

Fermi Gamma-ray Burst Monitor (GBM)

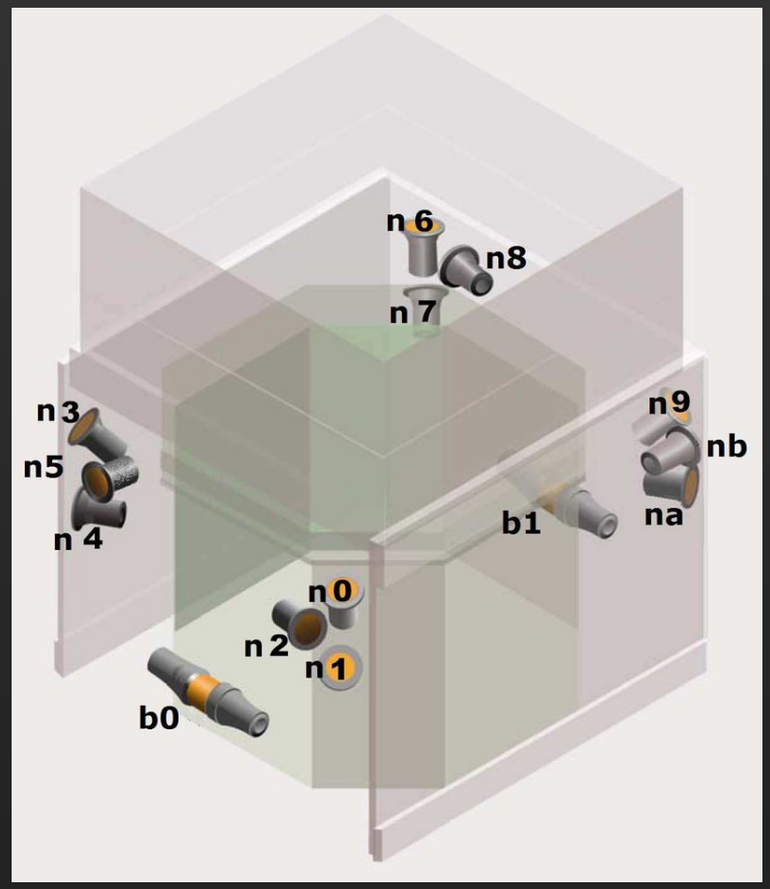
- Survey instrument
  - 8 keV — 40 MeV
  - 12 NaI(Tl) and 2 BGO scintillators
  - Large FOV (~70% sky)
  - 85% livetime

- Detects ~40 short GRBs per year, more through subthreshold searches



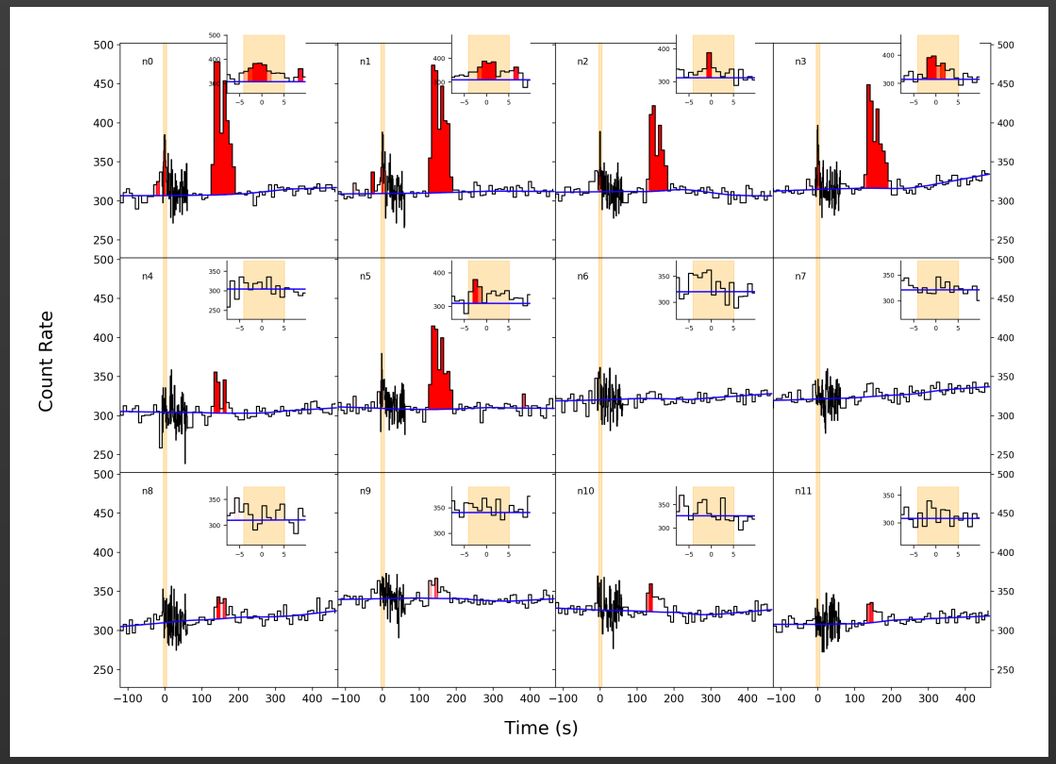
- Continuous time-tagged event (CTTE) data for offline analysis
  - 2.6 microsecond timing resolution
  - 128 energy channel resolution

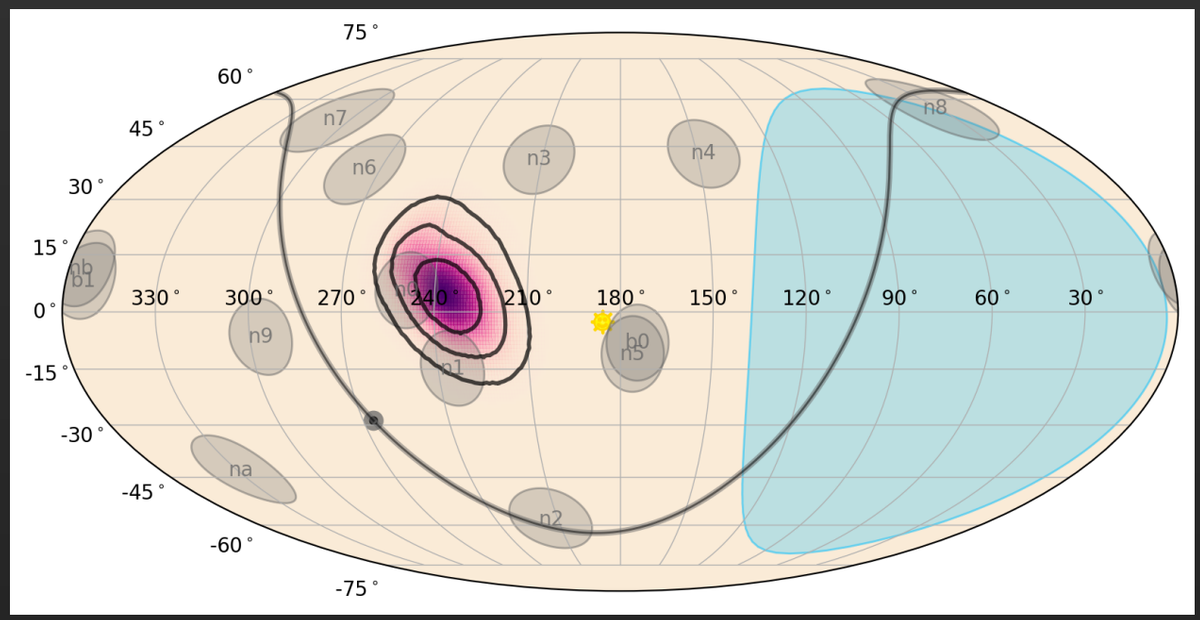
- During normal operations, GBM gets MMA counterparts for “free!”



GBM Localization

- Compares relative rates in the NaI detectors to estimate most likely arrival direction, given the angular and spectral response of the detectors
- Compare model rates to observed count rates
- 3 standard GRB templates are assumed for spectral response to “hard,” “normal,” and “soft” GRBs
- Localization accuracy on order ~ degs, limited by systematic. However…

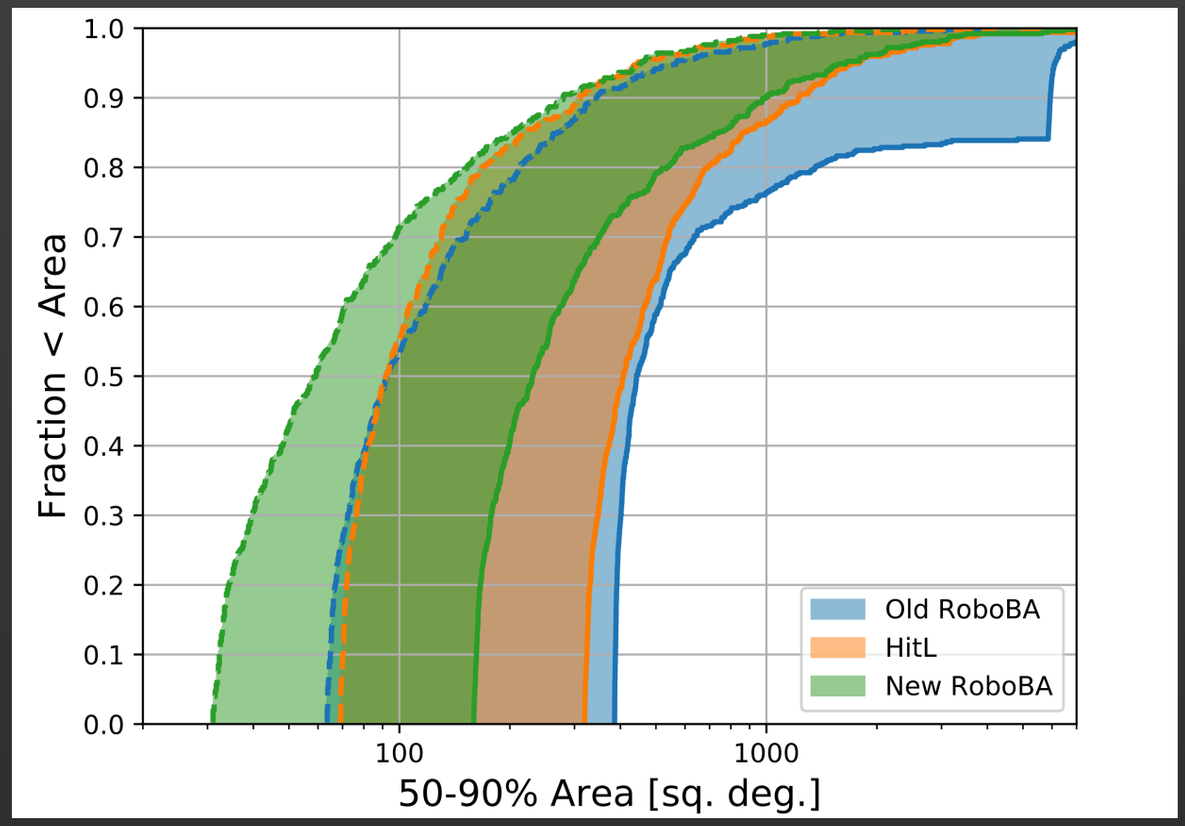




GRB 190930A

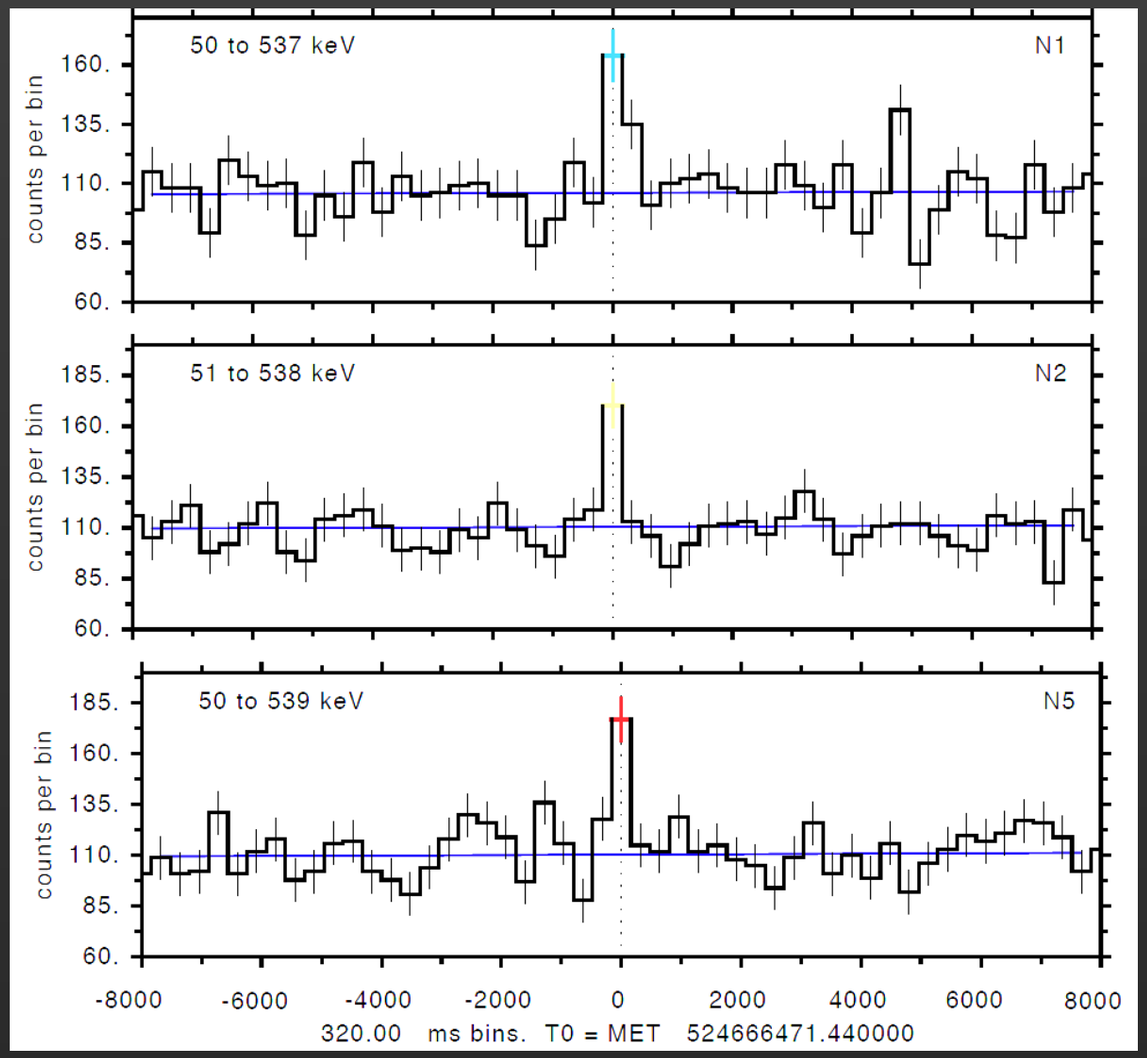
Localization Improvements

	Original RoboBA	Updated RoboBA
Systematic Model	long (short)	long (short)
Core (deg.)	2.6 (3.6)	1.86 (2.55)
Core Fraction (%)	65 (98)	57.9 (39.0)
Tail (deg.)	6.0 (29.6)	4.14 (4.43)
Angular Offset	all (bright)	all (bright)
Median	4.3° (3.7°)	4.1° (3.5°)
90% Range	1.3 – 15° (1.1 – 11°)	1.0 – 15° (0.9 – 10°)
50% Area (sq. deg.)	all (bright)	all (bright)
Median	83 (69)	49 (34)
90% Range	64–461 (64–140)	29–330 (29-78)
90% Area (sq. deg.)	all (bright)	all (bright)
Median	423 (395)	209 (175)
90% Range	386–5982 (386–5867)	166–1138 (165–299)
Failure Rate	$\lesssim 15\%$	$\lesssim 5\%$
CPU Time	$\lesssim 10$ s	$\lesssim 10$ s



- GBM localizations are now smaller!
- Median 90% localization area reduced from 400 to 200 sq. deg
- Accomplished by improving localization systematics through improved spectral template
- Changes summarized in Goldstein et al. 2019, https://arxiv.org/abs/1909.03006
- New final localization GCN reports location with Healpix maps and whether GRB is likely long or short (GCN #24408 and #25726)

Untargeted Search



SGRB candidate 52764742 confirmed as GRB170921C by Insight-HXMT

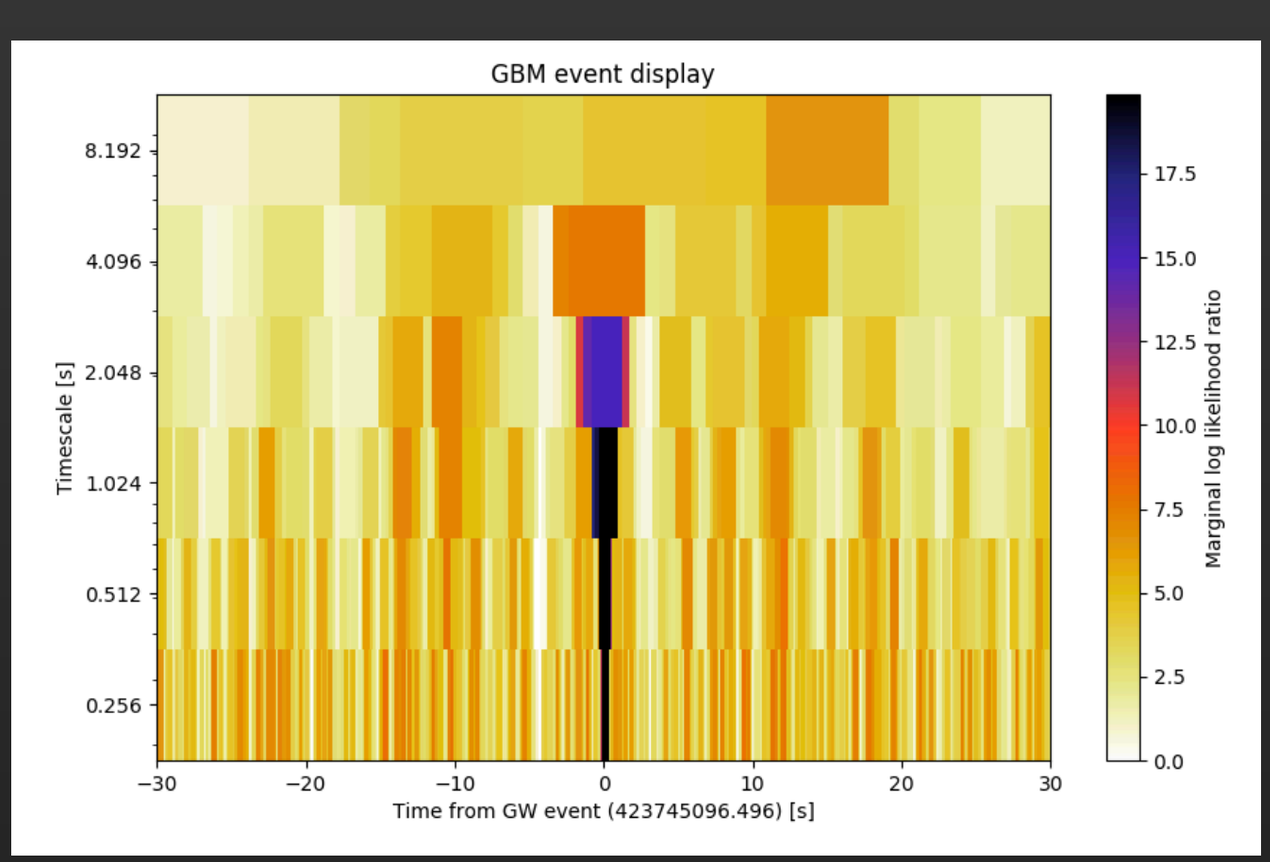
- Offline, agnostic search over all CTTE data using extension of flight software trigger
- Reports short GRB candidates with detector light curves and Healpix localization maps
- Now reports long GRBs up to 10 s
- Search results distributed via GCN: https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html

Targeted Search

- Coherent stacking of data from all 12 detectors
- Utilizes multiple timescales and spectral templates in combination with detector responses
- Input: GW detection time and (optionally) LIGO/Virgo skymap
- Reports short GRB candidates with detector light curves and Healpix localization maps

$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi\sigma_{d_i}}} \exp\left(-\frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

$$\mathcal{L} = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\widetilde{d}_i}{2\sigma_{n_i}^2} - \frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right]$$



GBM Follow-up of IceCube Events

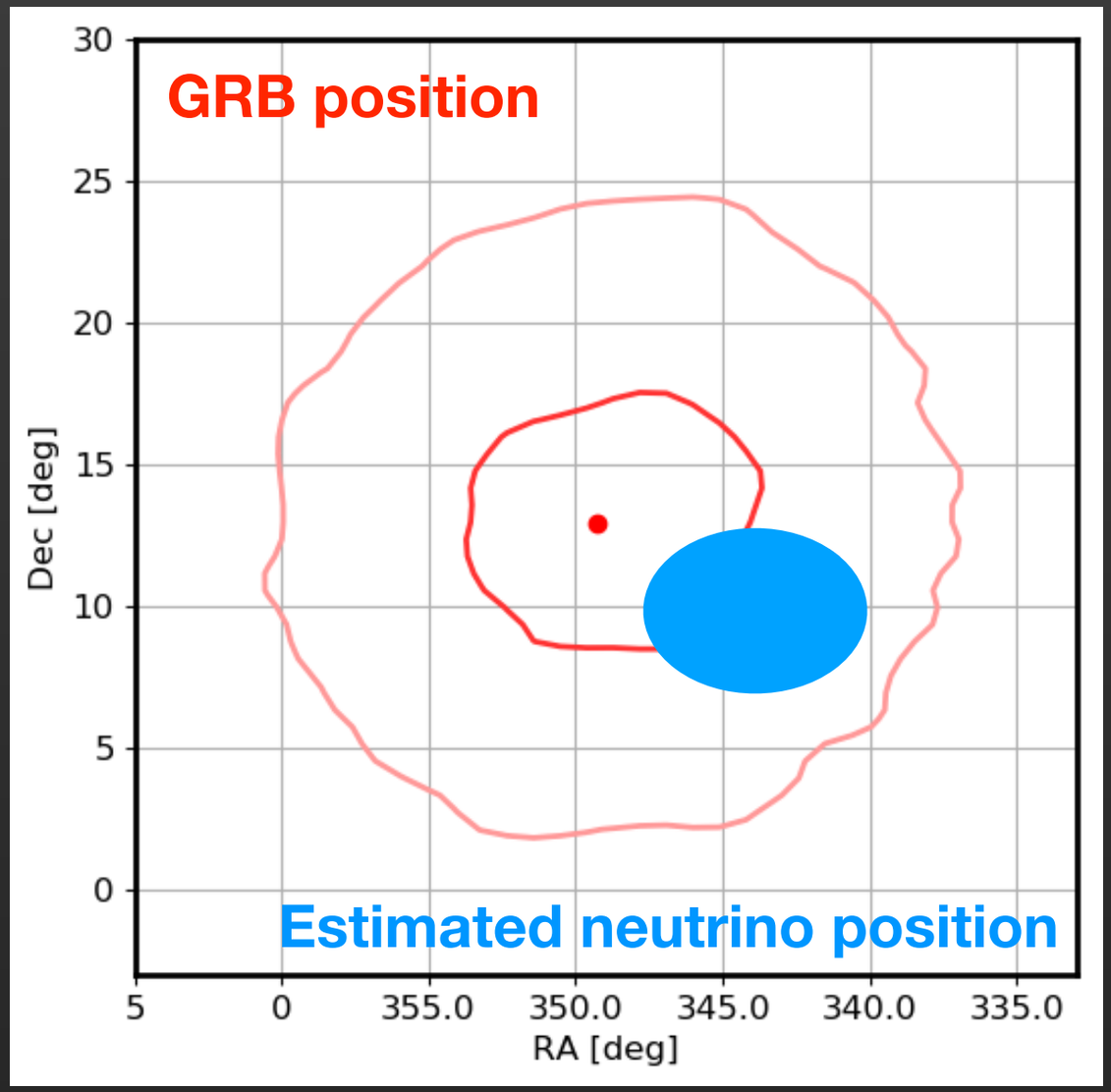
Neutrino Events

Neutrino Event (IceCube-YYMMDDx)	Follow-up Result (#XXXXXXXXX)	Follow-up GCN (GCN #XXXXX)	Astro Prob (Signalness) (XX.X%)	Comments (Text or blank)
IceCube-191001A	#591653363	GCN #25927	>50%	Gold, Earth-occulted
IceCube-190922B	#590886240	GCN #25808	50.5%	Gold
IceCube-190922A	#590838170	GCN #25807	20.0%	Gold with signalness < 50% because it's a corner clipping event
IceCube-190819A	#587928869	GCN #25404	29.2%	Bronze
IceCube-190730A	#586212646	GCN #25233	67.2%	Gold, Earth-occulted for Fermi-GBM
IceCube-190712A	#584586922	GCN #25062	30.3%	Bronze
IceCube-190704A	#583958937	GCN #24984	48.6%	Bronze, Fermi in SAA
IceCube-190629A	#583529060	GCN #24917	33.9%	Bronze
IceCube-190619A	#582642863	GCN #24856	54.6%	Gold, Fermi in SAA
IceCube transition to Gold/Bronze events on June 1, 2019				
IceCube-190504A	#578687123	No GCN sent	63.0%	HESE
IceCube-190503A	#578596993	GCN #24384	36.0%	EHE, Earth-occulted for Fermi-GBM
IceCube-190331A	#575708148	No GCN sent	57.0%	HESE
IceCube-190221A	#572430345	GCN #23923	37.0%	HESE, Earth-occulted for Fermi-GBM
IceCube-190124A	#569994239	GCN #23811	91.0%	HESE
IceCube-190104A	#568283683	GCN #23621	35.0%	HESE

- 15 Ice-Cube GCN detections since January 2019
  - 40% not observable to GBM due to SAA passage or Earth-occultation
- For each neutrino detection
  - Examine time offset of recent GRB triggers
  - Search public Untargeted Search results and check non-public candidates: https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html
  - Use the Targeted Search to seek subthreshold gamma-ray signals +/- 30 s with neutrino localization input
- Population-level analysis to come

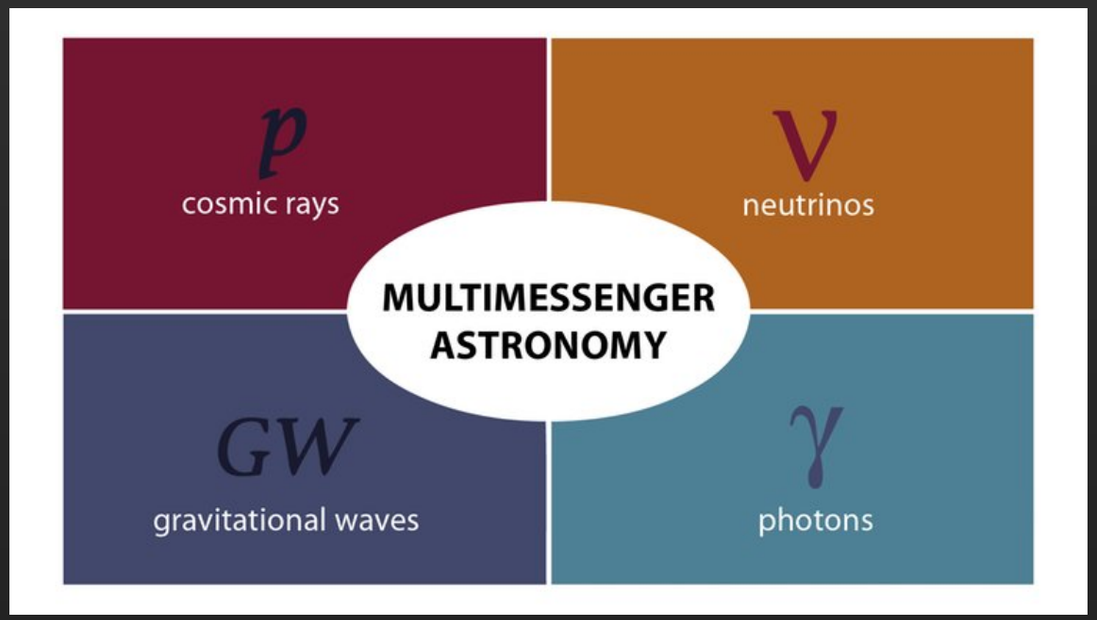
IceCube-190619A and GRB 190619A

- Long GRB detected by GBM 13 hours before neutrino
    - Time offset of 13 hours not unexpected given rate of GBM GRB triggers
- Transients spatially consistent with one another
    - 2.5% prob of the GRB localization contained in the neutrino 50% error box
    - Rough spatial p-value ~ 0.002
- No X-ray or optical counterparts reported
- What time offset should we expect for associated neutrinos and gamma-rays? Is it different for long and short GRBs?



Looking to the Future

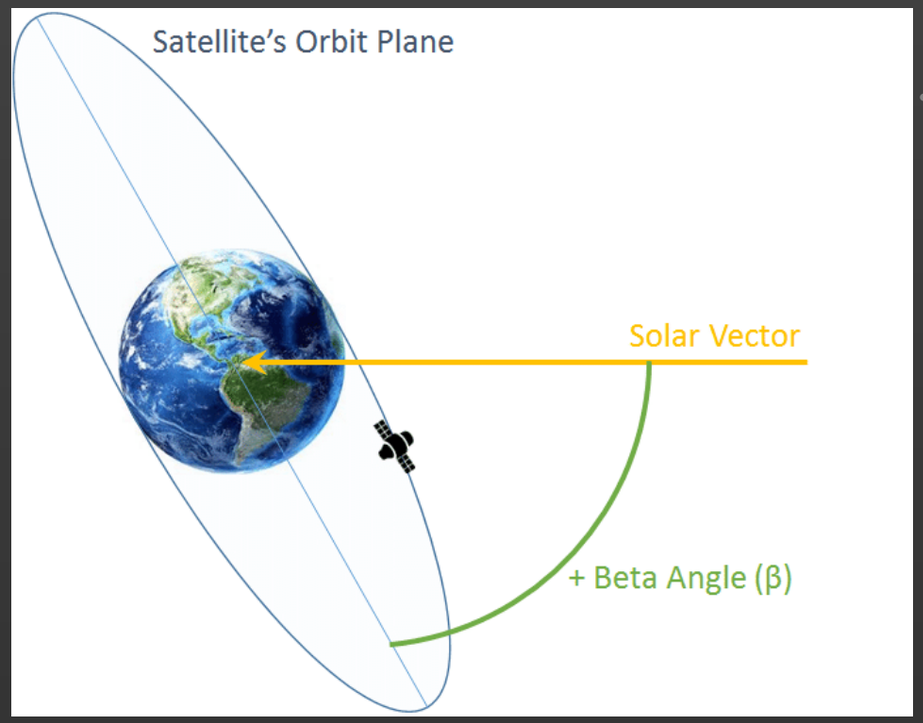
- GRBs are still likely candidates for multi-messenger detections with neutrinos.
- GBM is ideal for detecting gamma-ray counterparts and has been recently improving its localization capabilities!
- Subthreshold searches are crucial for increasing GBM sensitivity and the detection horizon to weak GRBs.
- Working towards a neutrino+GBM partnership!

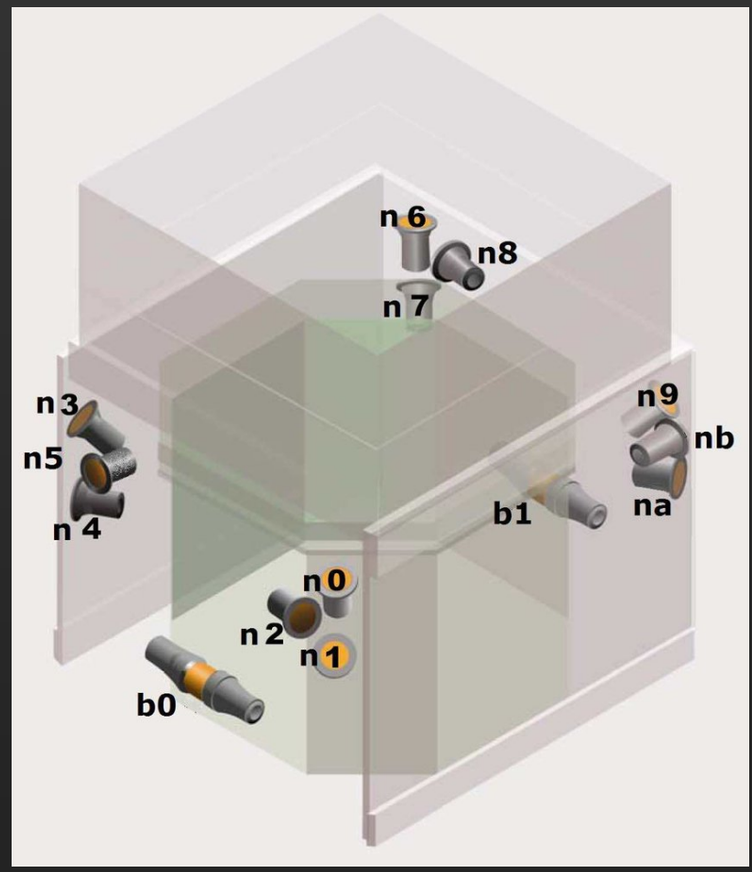


Backup

Instrument Status

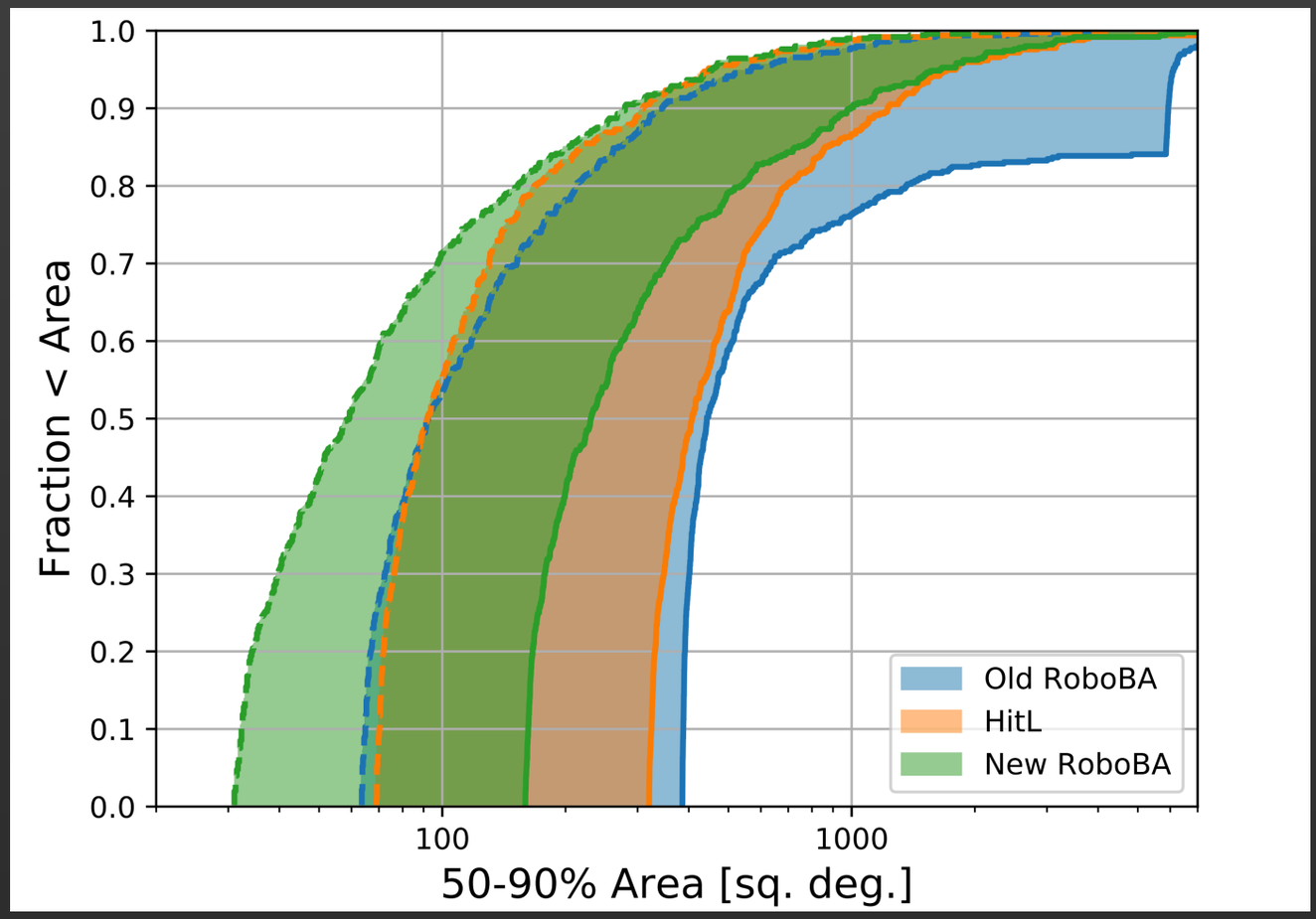
- N0 and N5 detectors are Sun facing and tend to run hot
- Were temporarily shut down due end of 2018 and early 2019
- Orbital conditions that caused previous shutdown occurred this summer
  - RoboBA and Targeted Search can now operate on a subset of detectors
  - Temperature variations were not as extreme as expected, so no detectors went offline
  - No indication of any permanent changes in performance (e.g. no loss in PMT gain)
- We are currently “cooking” a GBM detector in Huntsville to better quantify the threshold for the maximum operating temperature





Localization Improvements

- RoboBA provides automatic, rapid, on-the-ground localizations for GRBs
- Takes ~10 minutes vs. 1–2 hours manually
- New final localization GCN reports RoboBA localization with Healpix map and if GRB is likely long or short (GCN #24408 and #25726)



Goldstein et al. 2019

- Recent Improvements:
  - Replaced Band spectral templates with cut-off power law (“Comptonized”)
  - More robust (~5% failure rate)
  - Improved systematics, and smaller localization areas than Human-in-the-Loop
  - Summarized in Goldstein et al. 2019, https://arxiv.org/abs/1909.03006

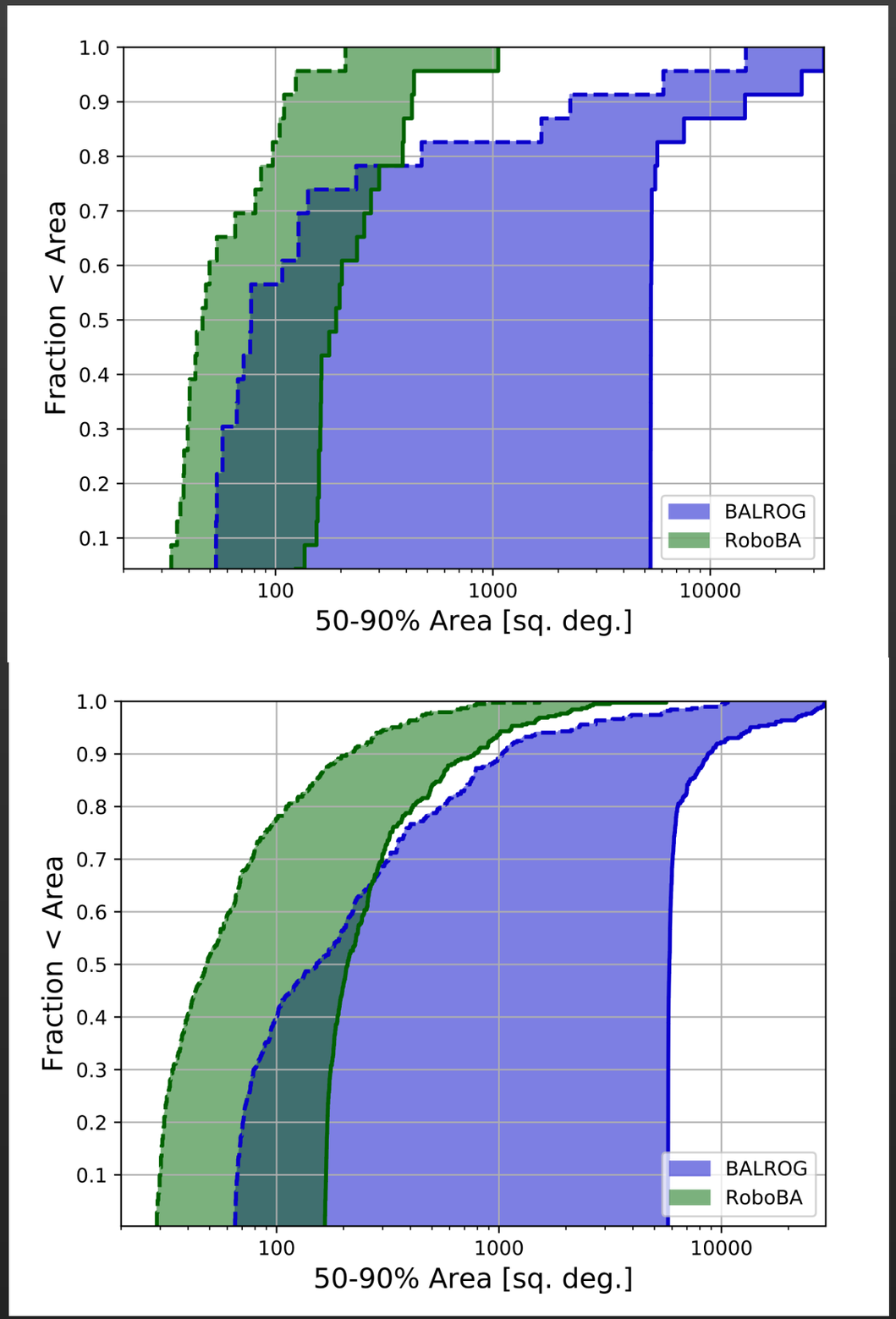
Comparing GBM and BALROG Localizations

- BALROG developed via MLE method to simultaneously fit GRB source location and spectral parameters (Burgess et al. 2018)

- Claim GBM spectral templates introduce large systematics which BALROG can reduce (GCN #23956)

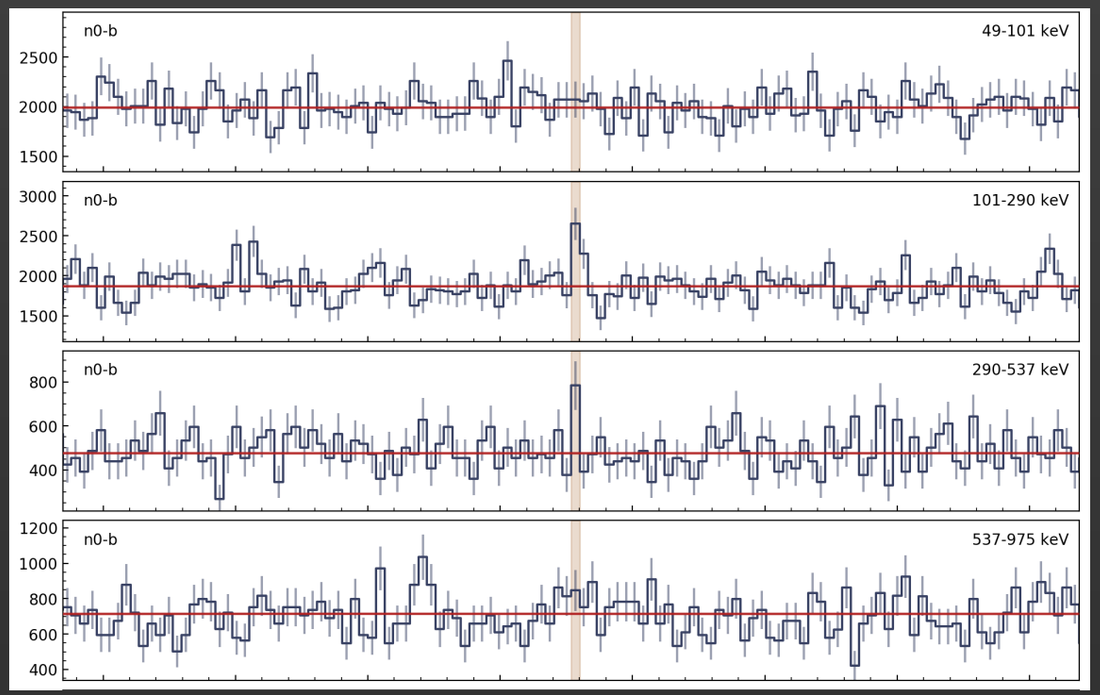
- Comparing BALROG GCN localizations to 23 GRBs with known location shows larger offset than pre-updated RoboBA

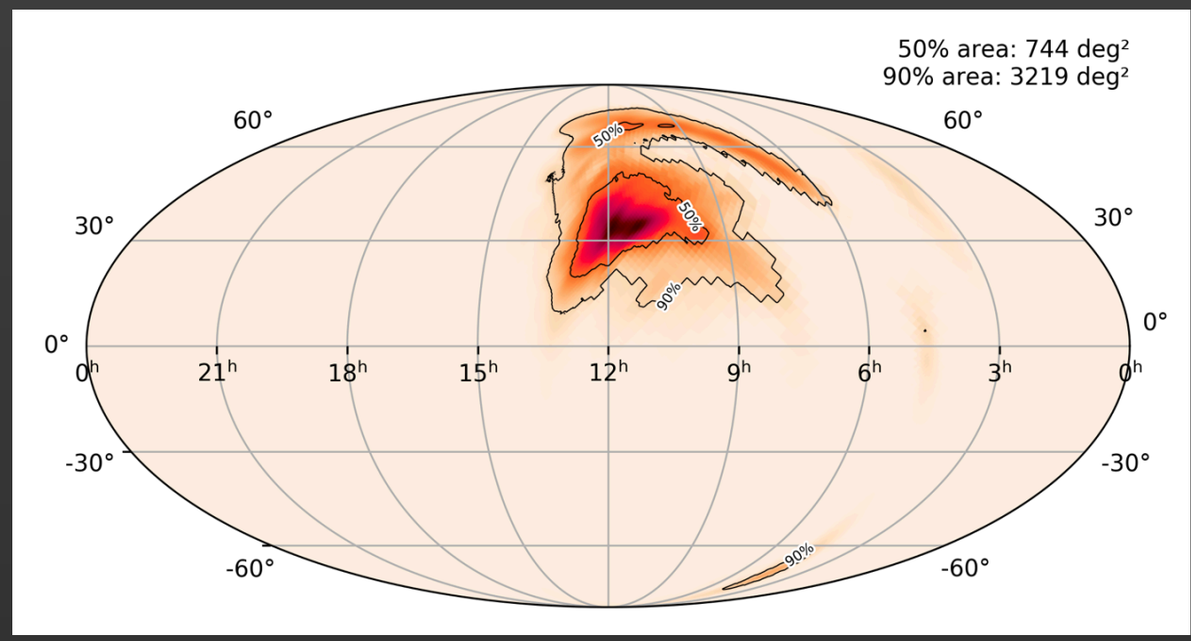
- Comparison of 500 GRBs with known localization via public BALROG tool shows ~3 deg systematic for 73% of GRBs and ~30 deg for the rest



Goldstein et al. 2019

Joint Subthreshold *Fermi* GBM-190816





- Livingston & Virgo observed CBC candidate at 2019-08-16 21:22:13.027 UTC
  - Did not exceed the public FAR limit
  - Lighter compact object with < 3 solar mass
- Targeted Search identified weak candidate at $T0_{GW}$ + 1.5 s w/ ~0.1 s duration
- Neither signal was significant on its own, but combined was a source of interest (GCN #25406)
- Resulted in a slew of followup observation but no kilonova or afterglow candidates