Fermi Gamma-ray Burst Monitor Observations of Gravitational Wave Counterparts

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on behalf of the GBM-LIGO/Virgo working gorup

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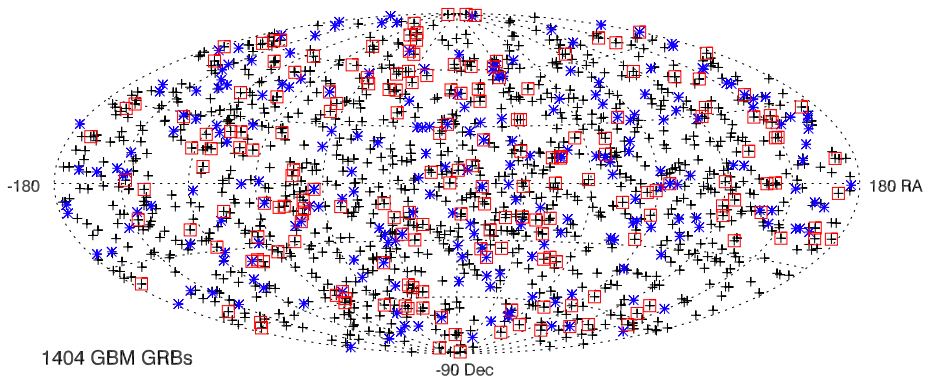
Gamma-ray Bursts - Overview

- Random directions on the sky ($\sim$ few per week)
- Short/long divide in duration
- Broad non-thermal spectrum: emerging complex picture
- Lightcurve/variability $\gtrsim$ 10 ms
- Afterglow visible for $\sim$ week(s)
- Prompt: keV to $\lesssim$ MeV
- Deduce: compact object, $\theta_{\rm jet} \approx$few $^\circ$, $E_{\rm iso} = 10^{50} - 10^{55}$ erg



3$^{\rm rd}$ GBM GRB catalog Bhat+16

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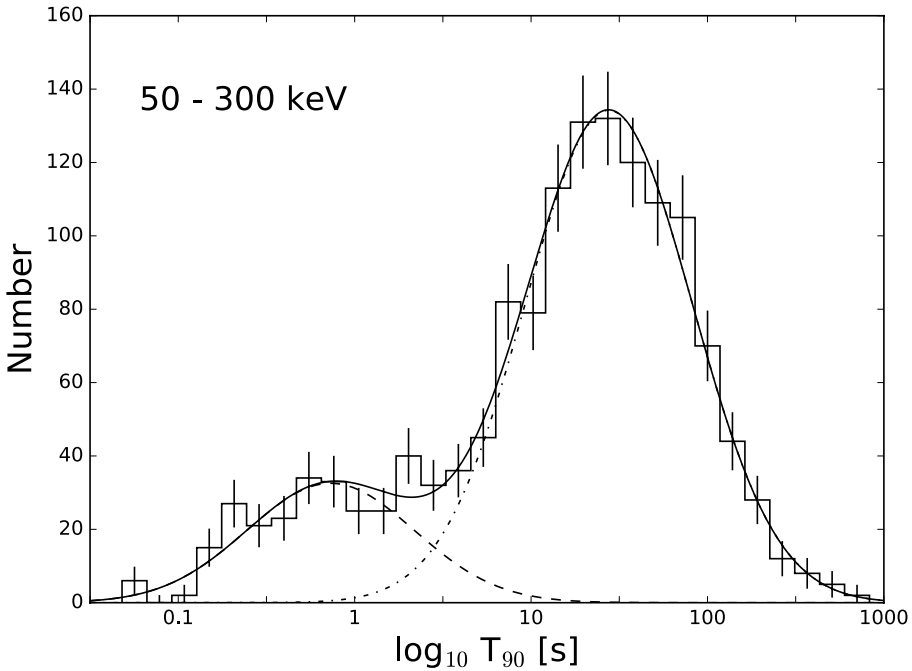

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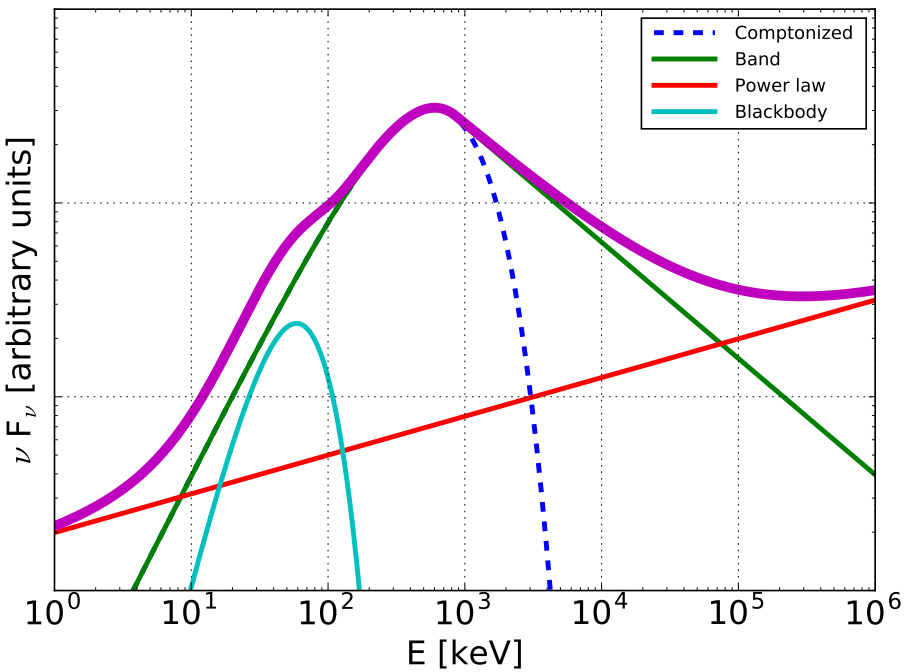

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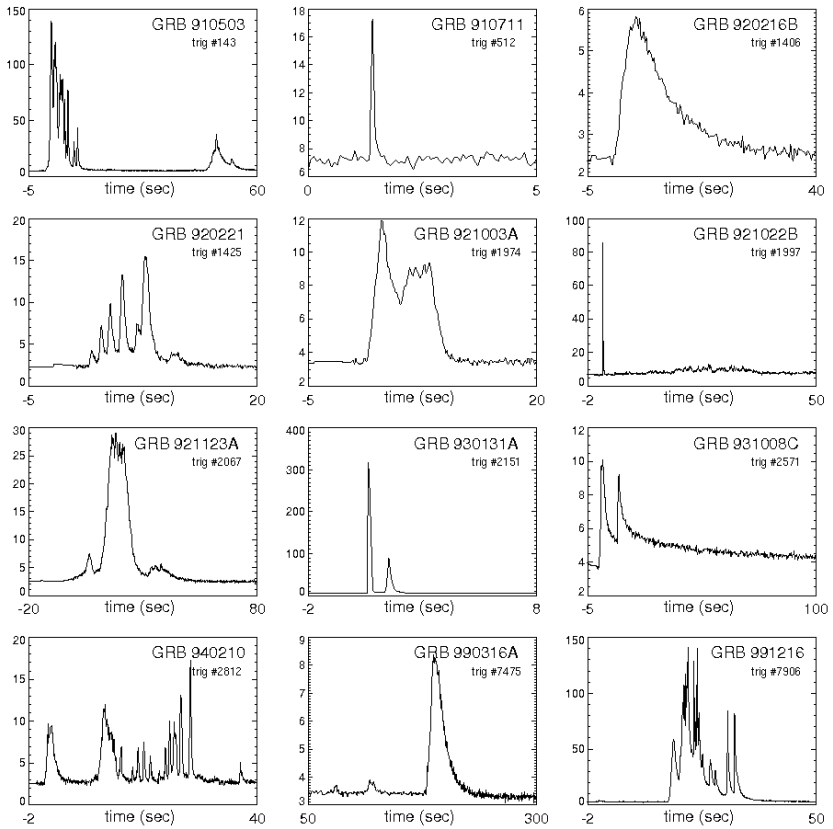

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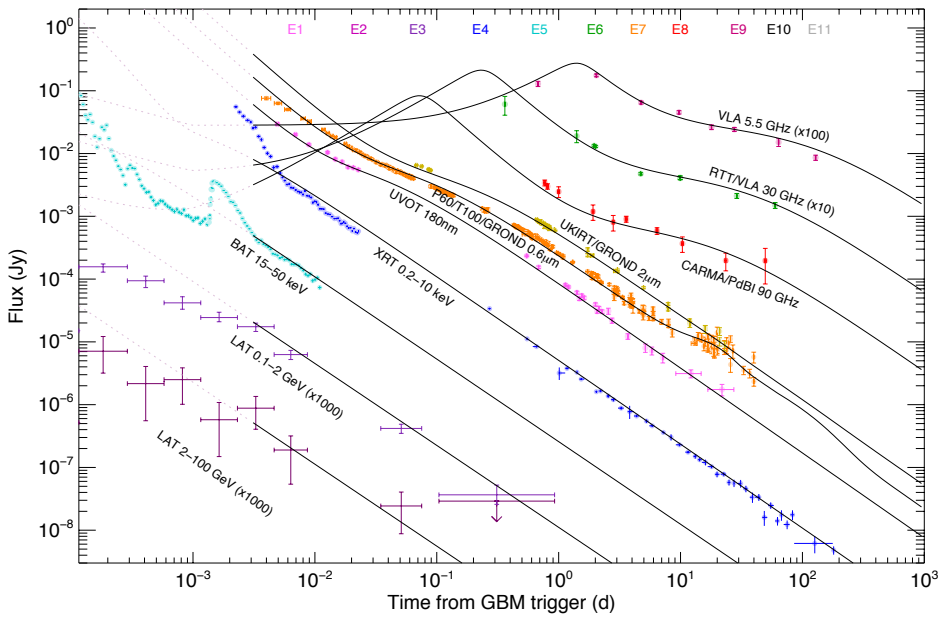

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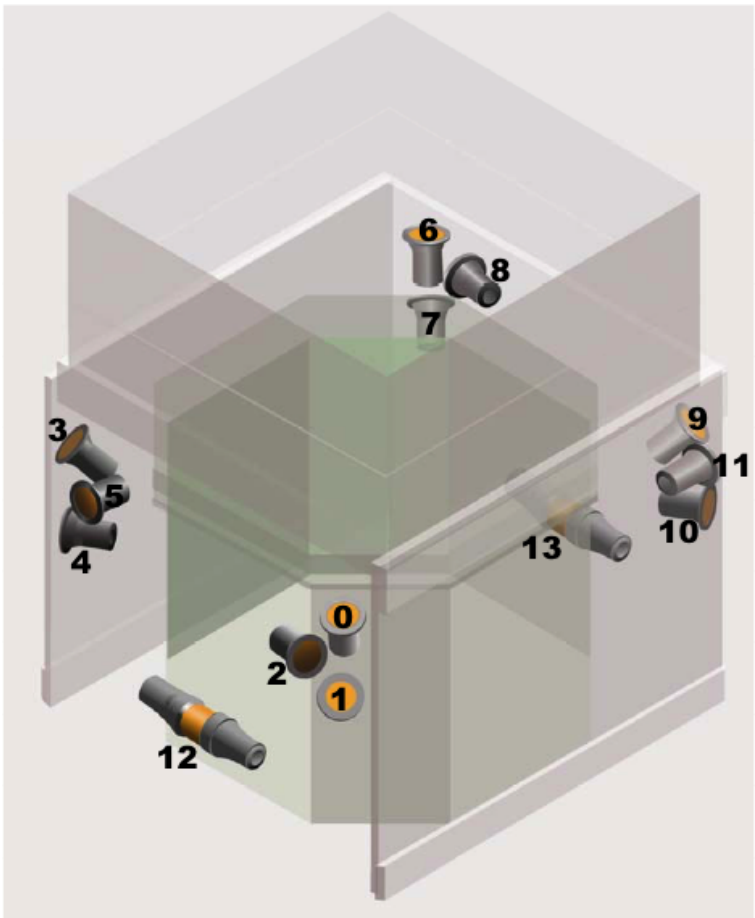
credit: NASA/Swift/deWilde

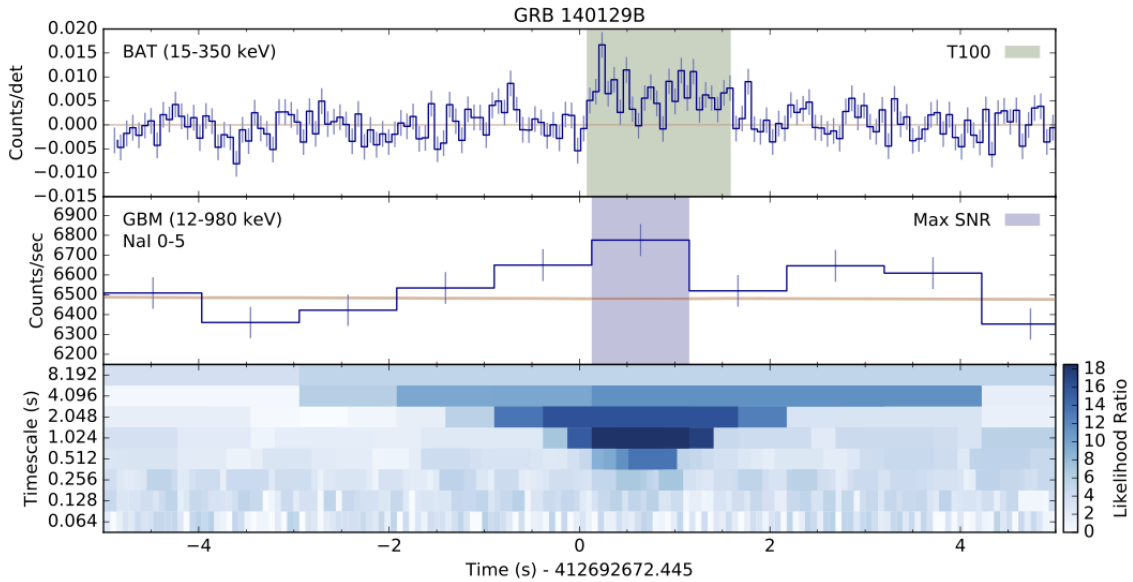
Fermi Gamma-ray burst Monitor (**GBM**)
An instrument for multi-messenger astronomy

- 12 NaI (8-1000 keV),
  2 BGO (0.2-40 MeV)
- 87% uptime (SAA), 67% of the sky,
  any location: $\sim$ 60% of time
- Real-time **triggers**:
  in orbit detection of rate increase
- **Localization**:
  compare relative counts in detectors
- Short GRB: $\sim$ 40 per year
- Off-line searches increase sensitivity:
  Targeted, Untargeted



Sub-threshold searches (1) - **Targeted** search

- Independent seed time (e.g. GW, ν, FRB etc.)
- 3 template spectra (soft, normal, hard)
- Assumes point source
- Scans the whole sky
- 64 ms to 8 s, $\pm$30 s (**1 run $\sim$30 minutes**)
- Significance based on false alarm probability from background runs

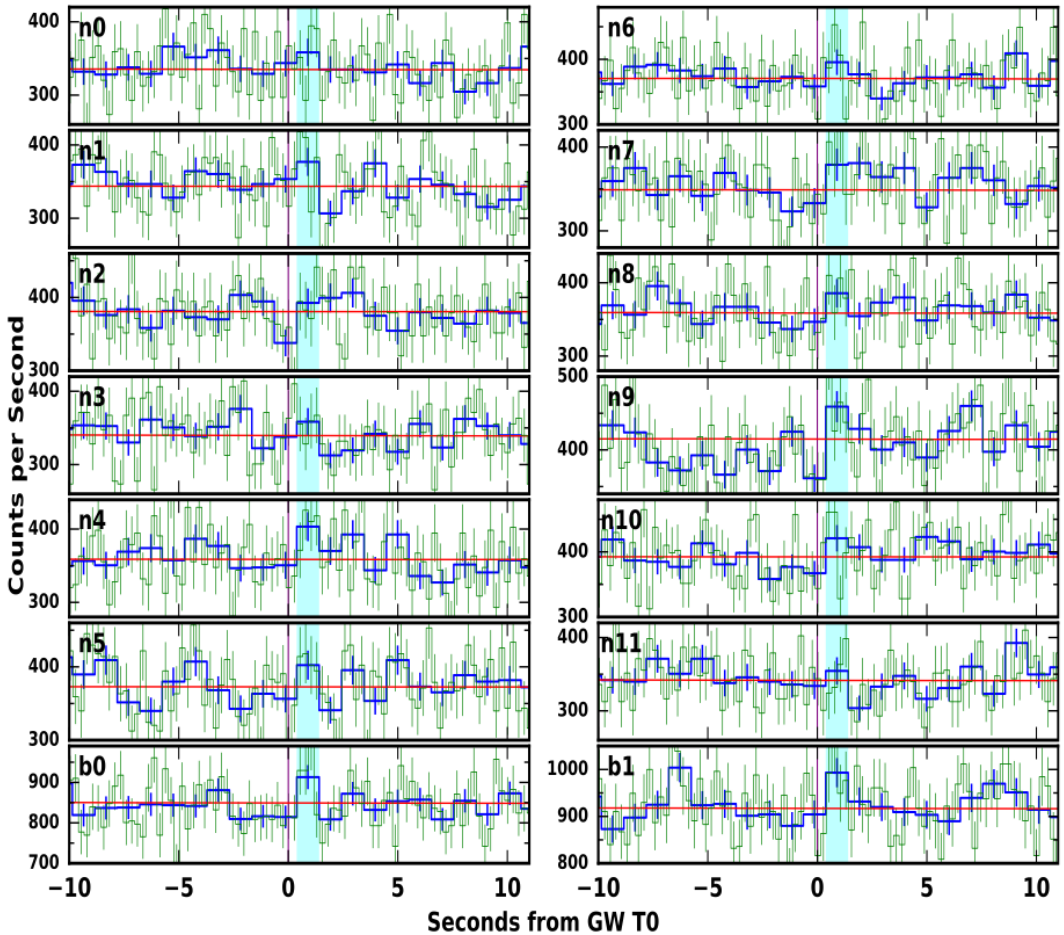


Example: recovery of a Swift GRB that didn't trigger GBM

Blackburn et al., ApJ, 2015; Goldstein et al., 2016, arXiv:1612.02395, Kocevski et al., ApJ, 2018

GW150914-GBM

- A weak gamma-ray transient 0.4 s after GW150914, duration $\sim$ 1 s,
- Positive fluctuation in all dets., E$>$ 50 keV.
- Location $\sim$163 dec to Fermi pointing (under S/C)
- Weak constraints on the spectrum
- Consistent with a short GRB.
- False Alarm Probability for association with GW150914: 0.0022



Connaughton et al. 2016 ApJL, Veres et al. 2017 ApJ

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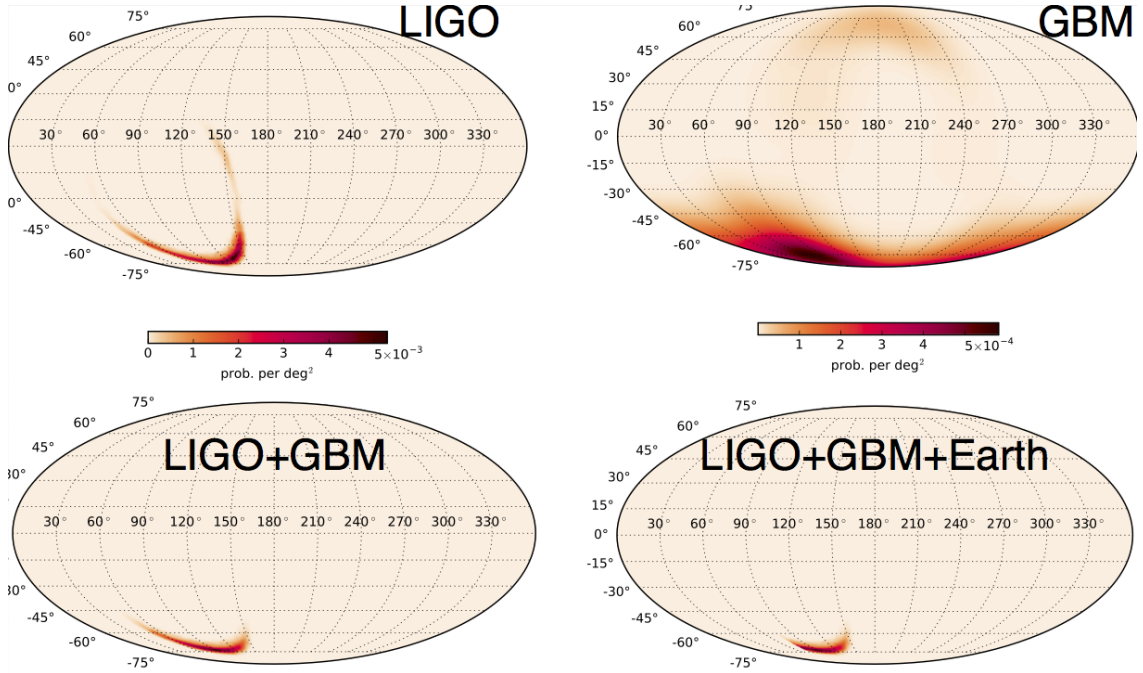

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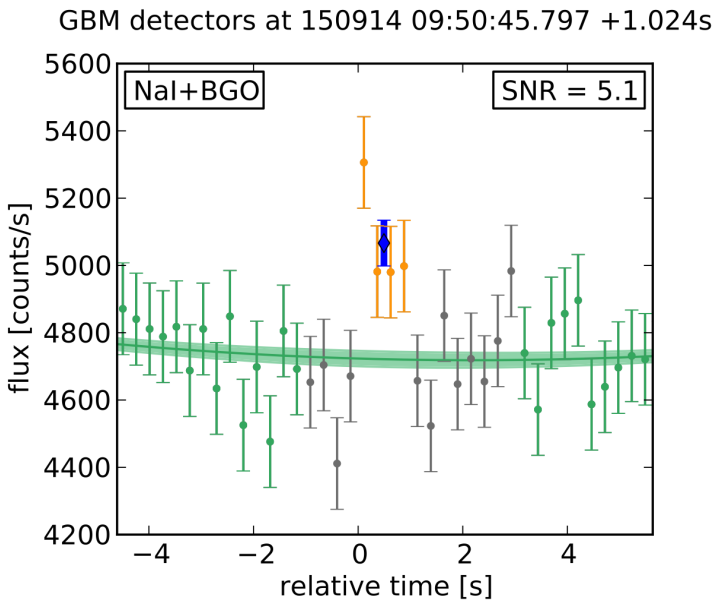
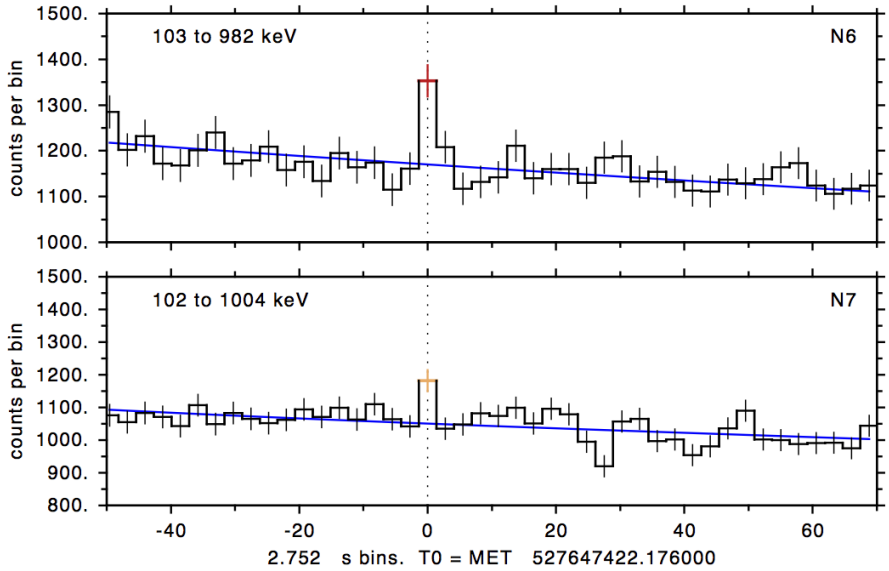
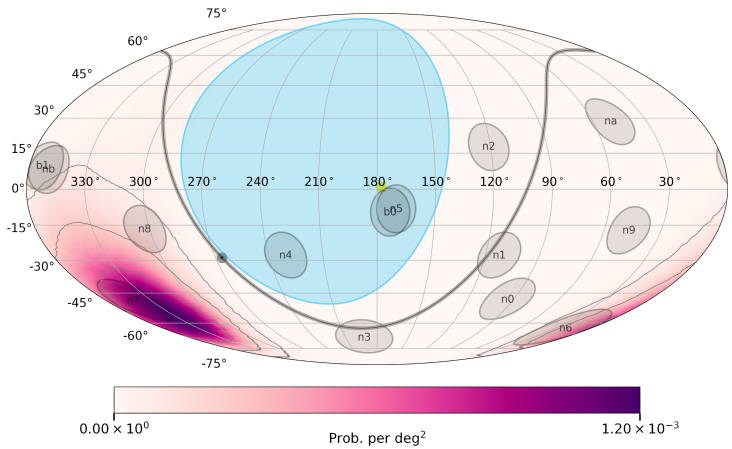


Connaughton et al. 2016 ApJL, Veres et al. 2017 ApJ

Sub-threshold searches (2) - **Untargeted** search

- Briggs et al. 2008 (in prep)
- Improved background
- Excess signal in 2+ dets, lower than for triggers (e.g. 1.25 & 2.5 σ)
- Few hours latency - public GCN
- Confirmation by other instruments
- **Increase # of short GRBs by $\sim$ 80 yr^{-1}** (from 40 triggered yr^{-1})





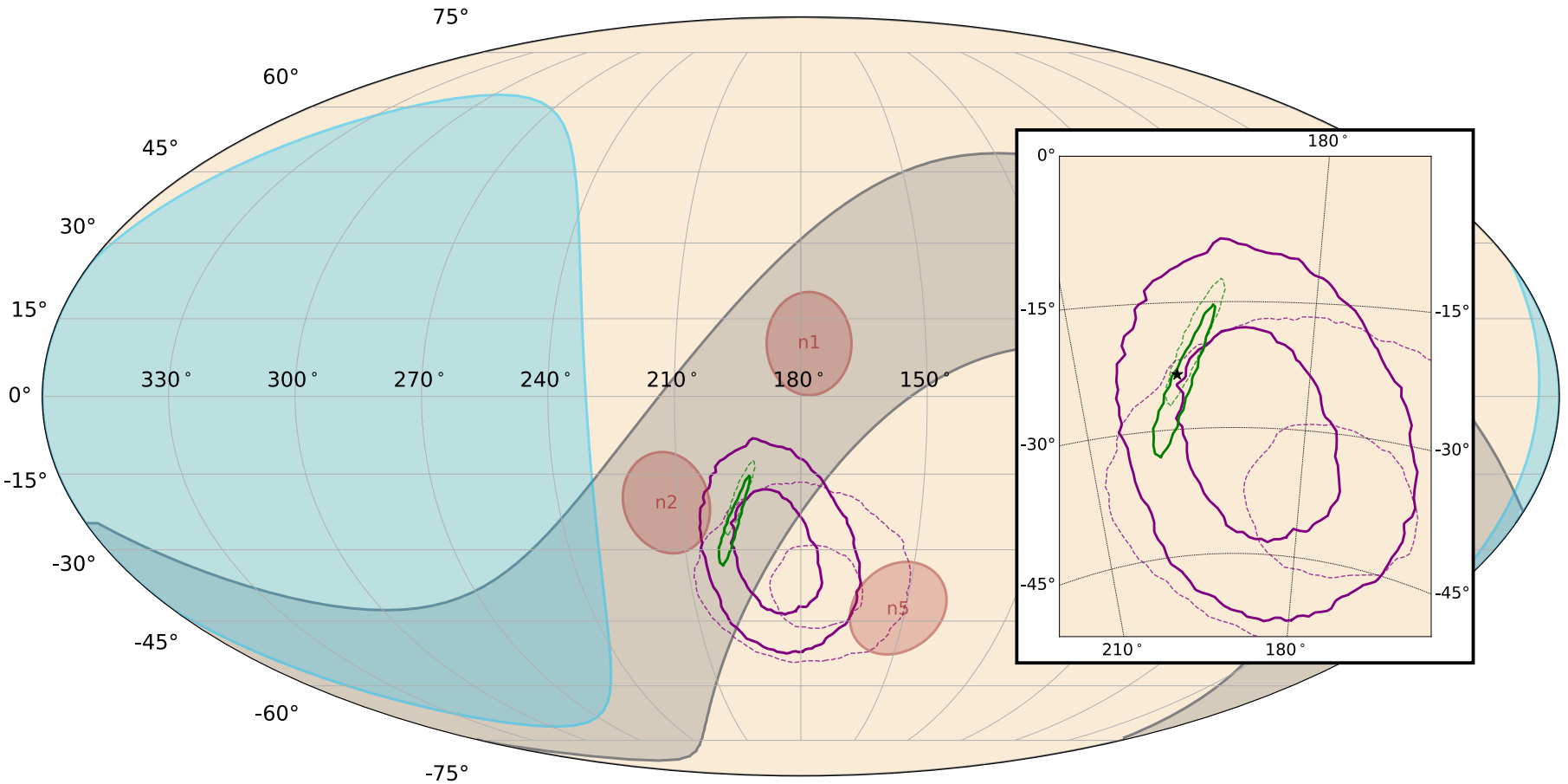
https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html

GRB 170817A / GW170817

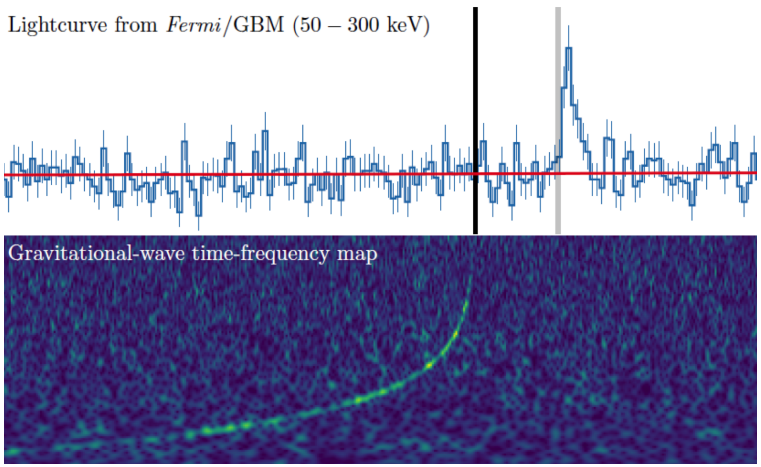
Goldstein et al. ApJL (2017), LVC-GBM-ACS ApJL (2017)

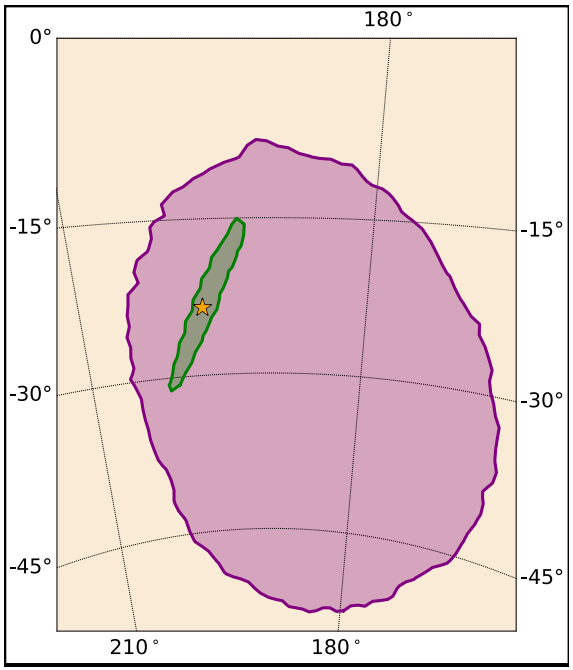
GRB 170817A - location - timeline

- $T_{GW} = T_{GRB}$ - 2.02 s
- T_{GW}+16 s: first **public** notice by flight software
- T_{GW}+27 s: on-board localization and classification
- T_{GW}+40 s: automatic on-ground localization
- T_{GW}+40 min: LVC reports GW trigger conc. w GRB
- T_{GW}+45 min: improved human-guided location
- Single IFO location consistent with GBM $\rightarrow$ good sign
- T_{GW}+67 min: report GRB properties
- T_{GW}+5 h: HLV map still consistent with GBM map (that was when we knew they are surely associated)



GRB 170817A - Significance of association



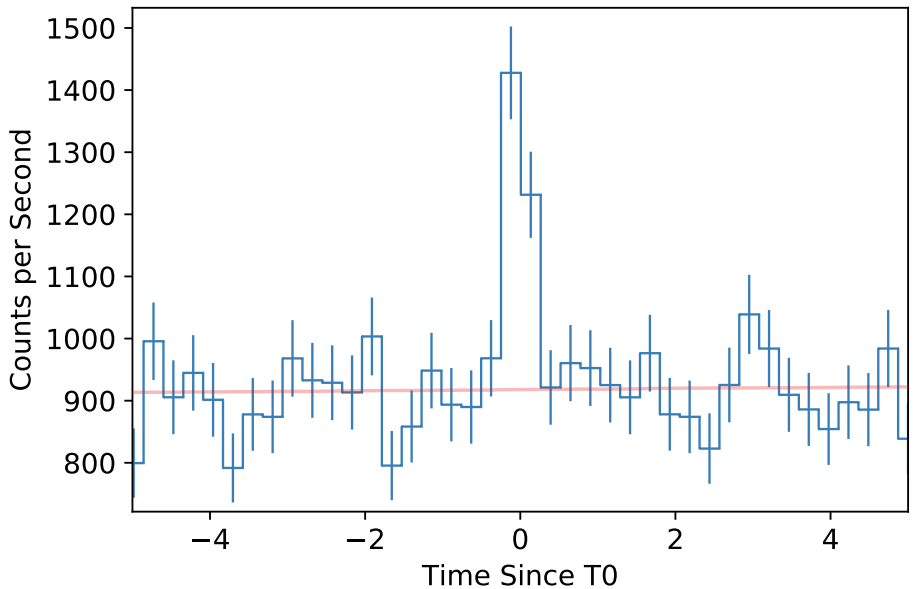


- $P_{\text{temporal}} = 5 \times 10^{-6}$
- $P_{\text{spatial}} = 10^{-2}$

$$P = 5 \times 10^{-8}\ (5.3\ \sigma)$$

GRB 170817A - Basic information

- GRBs brightest in 50-300 keV
- Triggered GBM: excess counts on 256 ms timescale
- Start: T_{GW}+1.7 s $\approx$ T_{GRB}-0.3 s
- Duration, T_{90}= 2.0$\pm$0.5 s
- "By eye" it's only 0.5 s long
- Main peak + soft component $\sim$ 1 to 2 s after trigger



50-300 keV lightcurve

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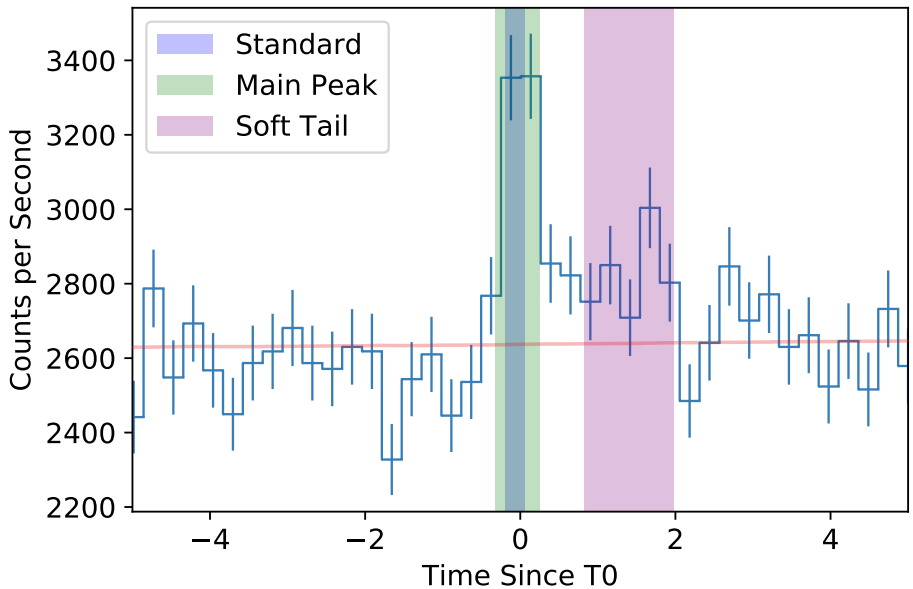
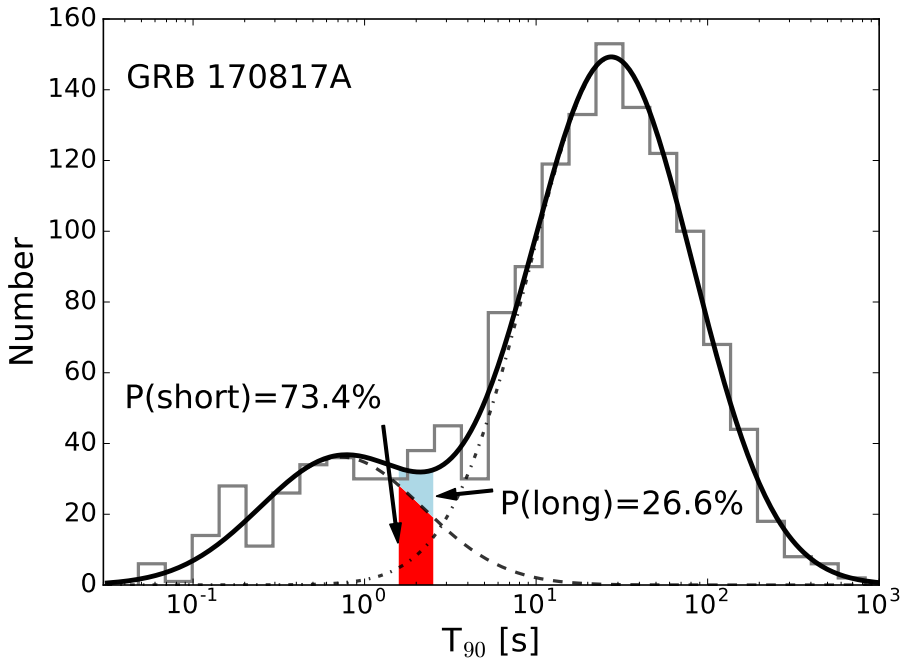


10-300 keV lightcurve

GRB 170817A - Is this a short GRB?

- Short - long divide (2 s ?)
- 3^{rd} GBM GRB catalog
- $T_{90} = 2.0 \pm 0.5$ s $\rightarrow$conservative (~ 0.5 s + soft episode)
- 2 log-normals describe the duration distribution
- Answer:
  YES, short more likely ($\sim$ 3:1)



GRB 170817A - astrophysics - detectability

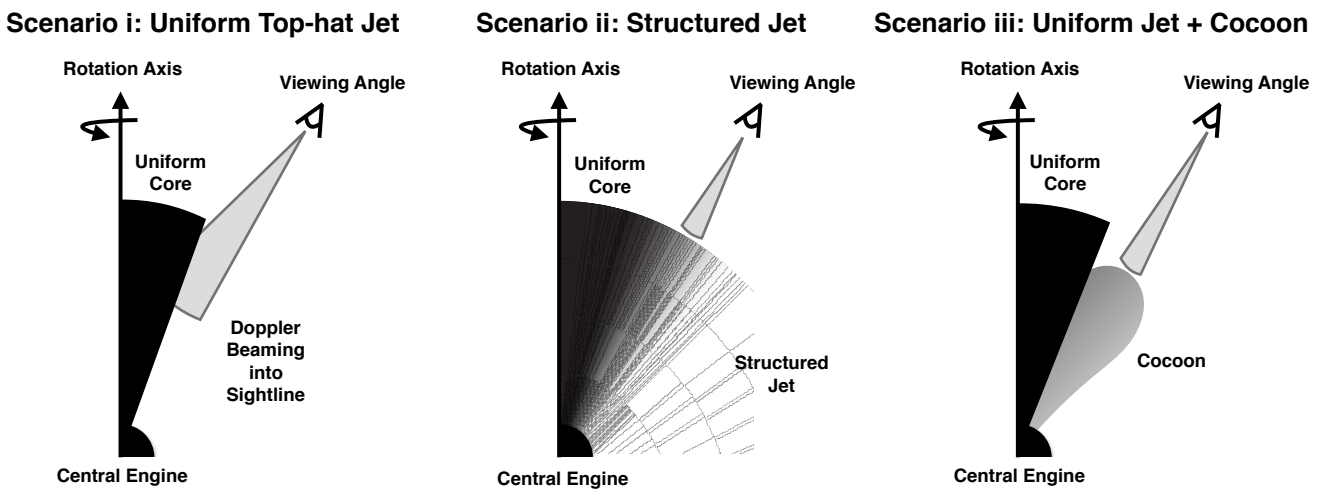
Observationally **ordinary** GRB. Redshift $\rightarrow$ subluminous by orders of magnitude.

- On axis: sublum: sel. effect (?)
- Cocoon shock breakout (?)
- Off-axis structured jet

- Speed of gravity $\Delta v = v_g - v_{EM}$: -10 s $\leq$ dt $\leq$ 1.7 s
- $-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\rm EM}} \leq 7 \times 10^{-16}$

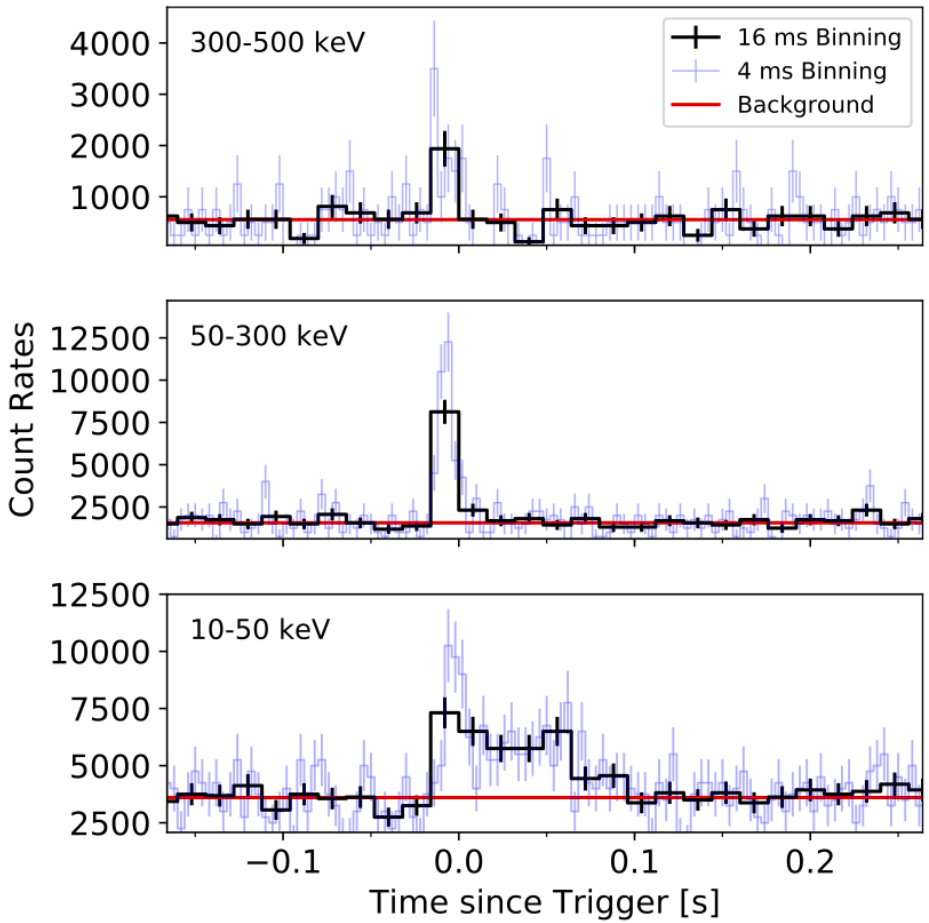
- O3: 1-50 BNS/year (0.1-1.4 joint)
- Design: 6-120 BNS/year (0.3-1.7 joint)

- 30 % dimmer : still triggered
- 50 % dimmer : untargeted search
- 60 % dimmer : targeted search



GRB 150101B another GRB like 170817A

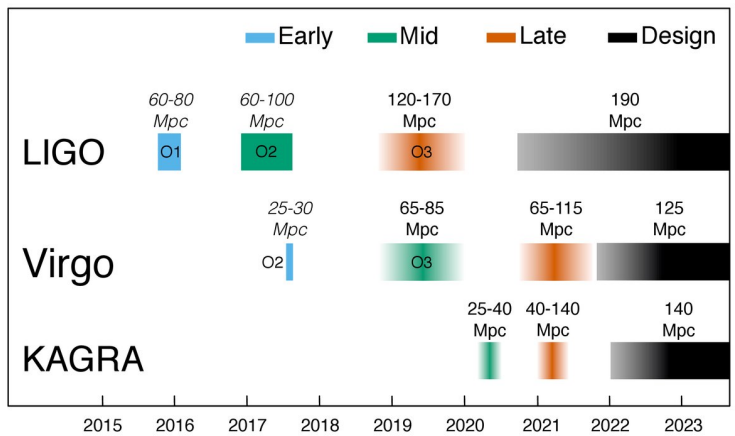
- Third closest sGRB /w z, z=0.134
- Hard pulse (E_{peak}=550 keV) / soft episode (kT = 6 keV)
- Much brighter / shorter than GRB 170817A
- Rules out (simple) cocoon model
- Possible kilonova and off-axis afterglow (Troja et al. 2018)



Burns et al. ApJL (2018)

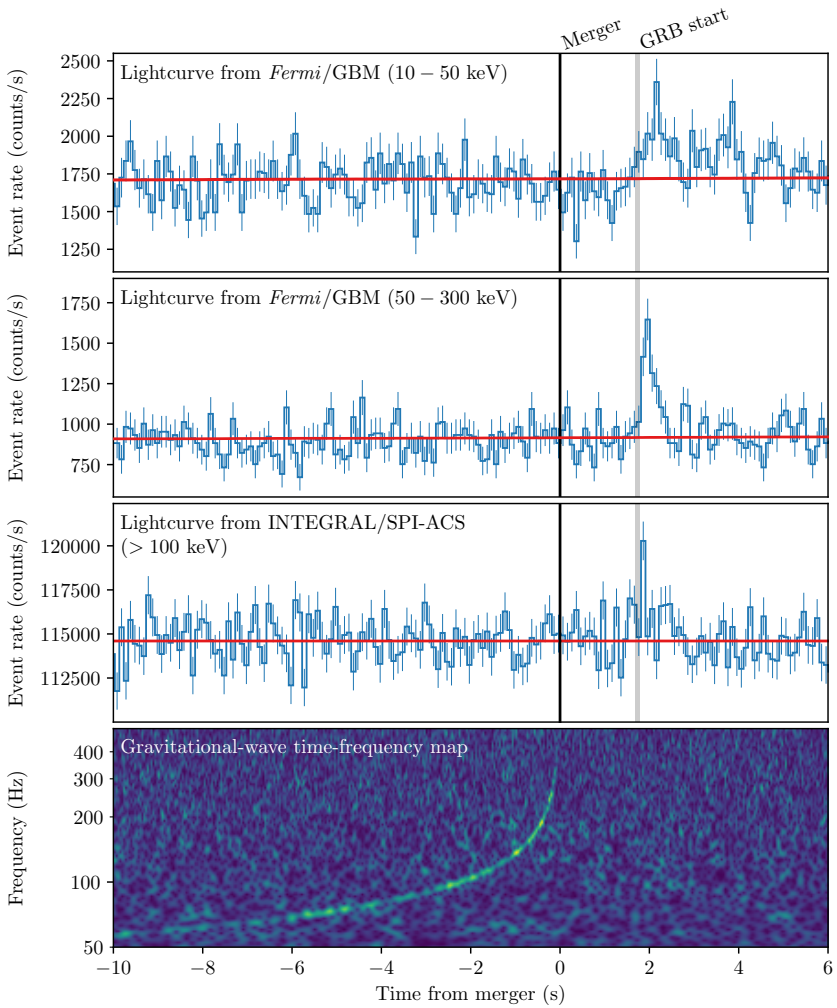
Plans of LIGO/Virgo 3rd observing run (O3)

- Starts ∼Feb 2019
- Improve targeted search
  - ∼10-15x improvement in runtime
  - Full atmospheric scattering in the response
  - Exclude poorly modeled energy channels
- Add very soft, bbody template spectrum - for source char. inspired by GRB 170817A
- GBM / LIGO-Virgo joint localization
- Fast (∼10 min.) GBM / ACS joint annulus



Conclusions

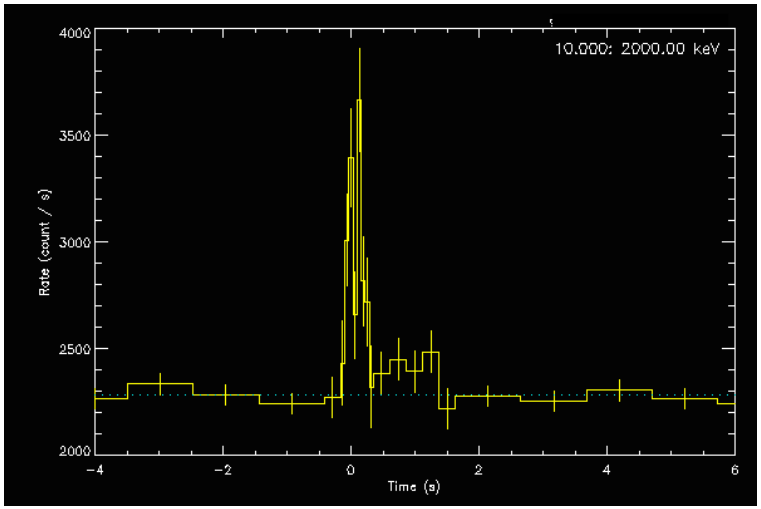
- **Fermi-GBM can detect GW counterparts!**
- **At least some short GRBs originate from binary neutron star mergers!**
- GRB 170817A: an ordinary GRB with extraordinary implications
- Emerging signature: hard peak+soft tail structure
- BBH counterparts?
- Optimistic for future multimessenger detections

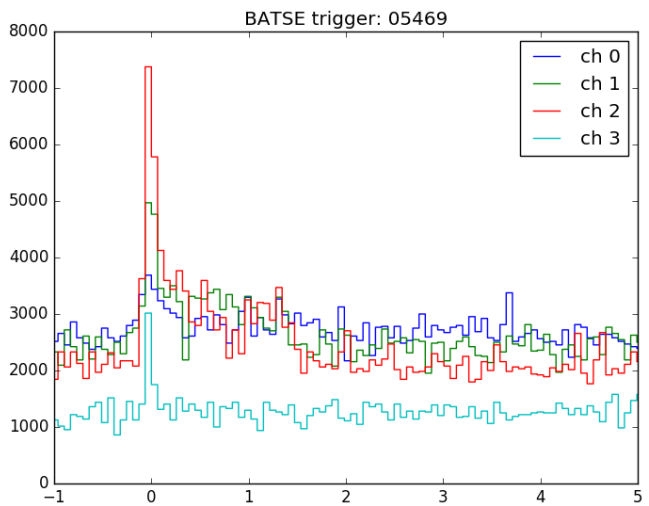


Backup slides

GRB 170817A - archival searches

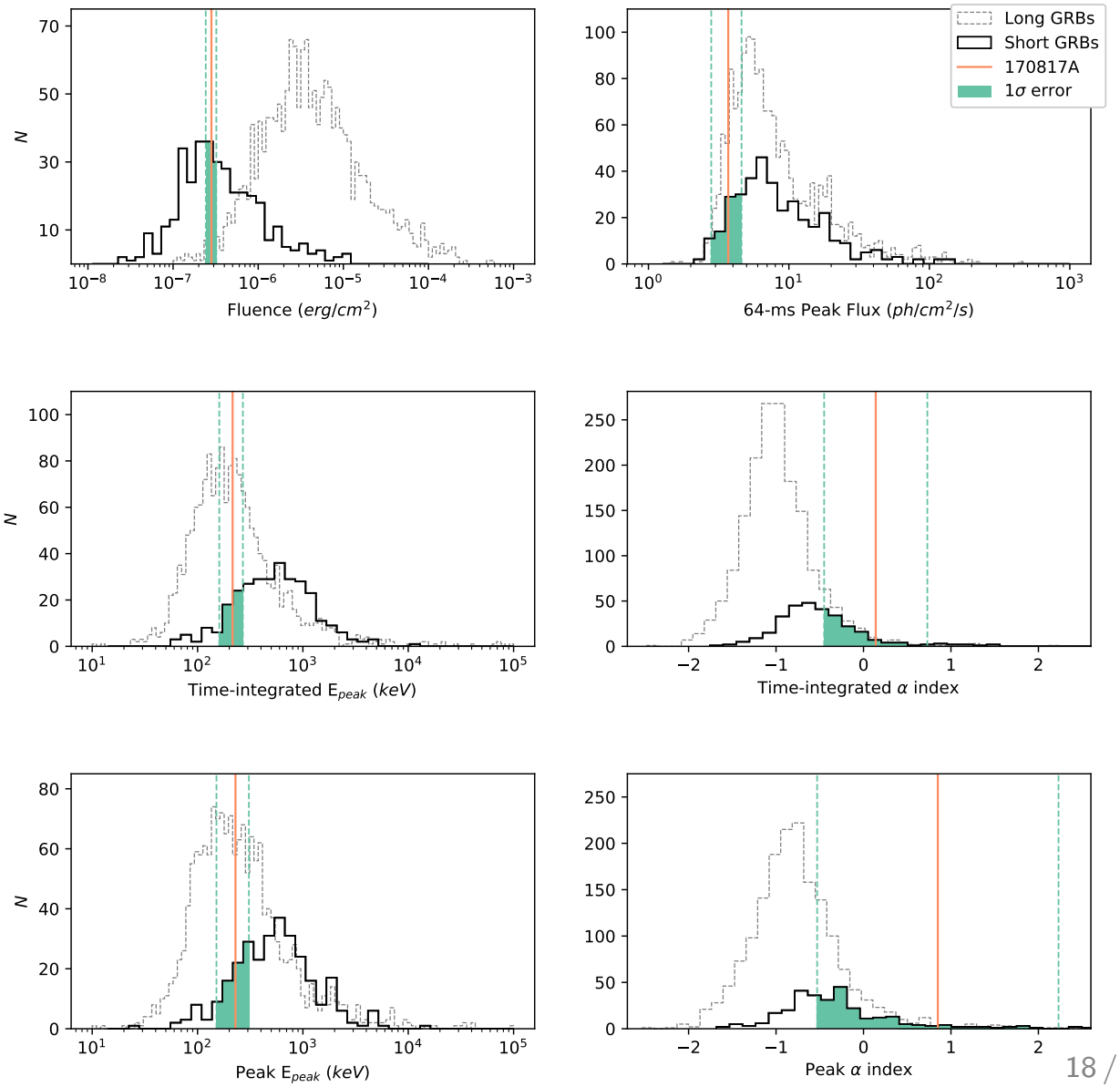
- $\lesssim$ 1 s peak followed by $\gtrsim$ 1 s soft tail
- Initial search (von Kienlin et al. in preparation) Preliminary
- GBM: 2228 GRBs. 460 sGRBs (21%), few ($\lesssim$ 10) similar
- BATSE: 2704 GRBs. 650 sGRB (24%), few similar



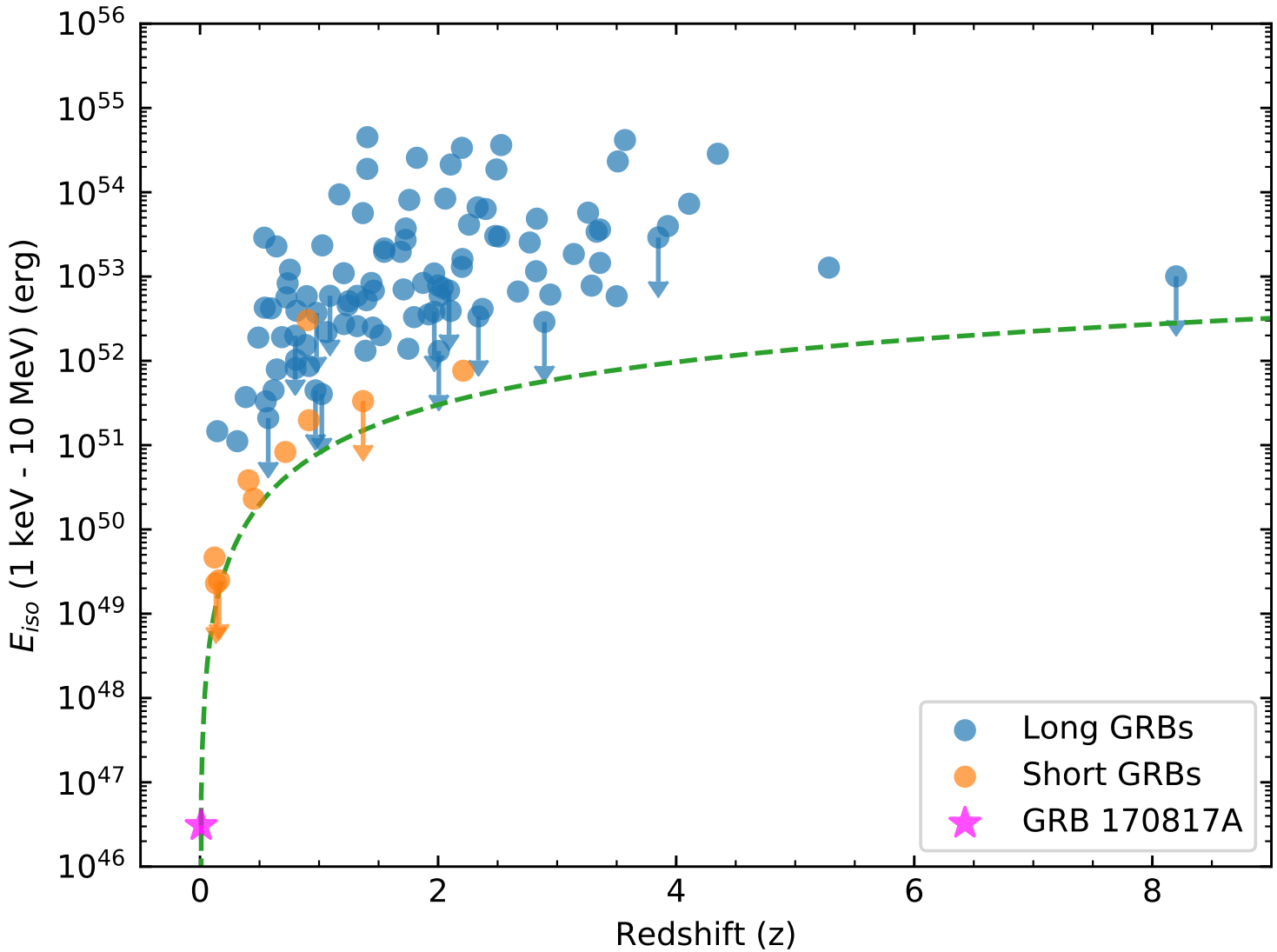


Where does it fit?

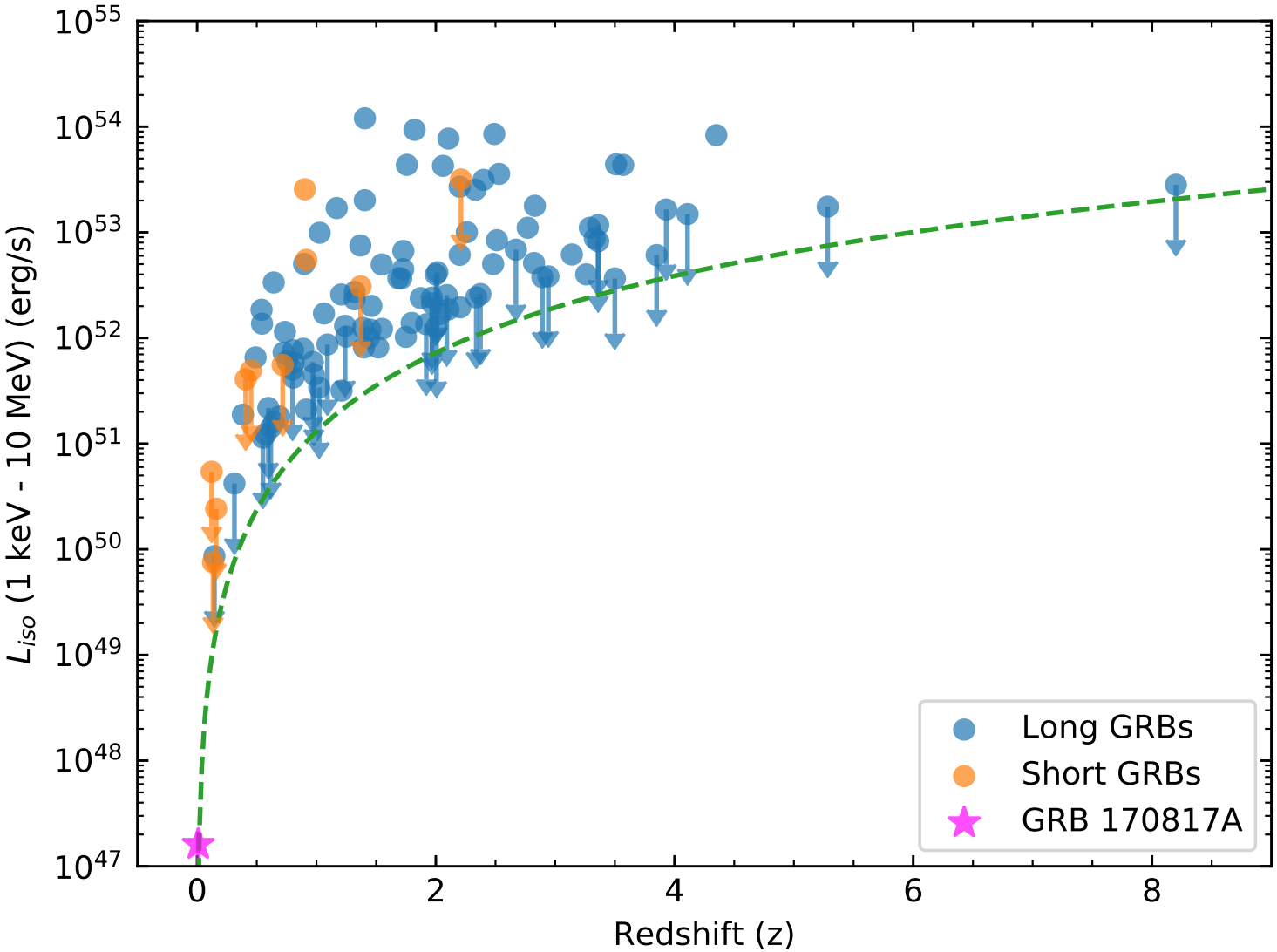
- All GBM GRBs analyzed consistently
- Generally: dimmer/softer than sGRBs but not unusually so
- Except soft episode, weak but **ordinary** short GRB



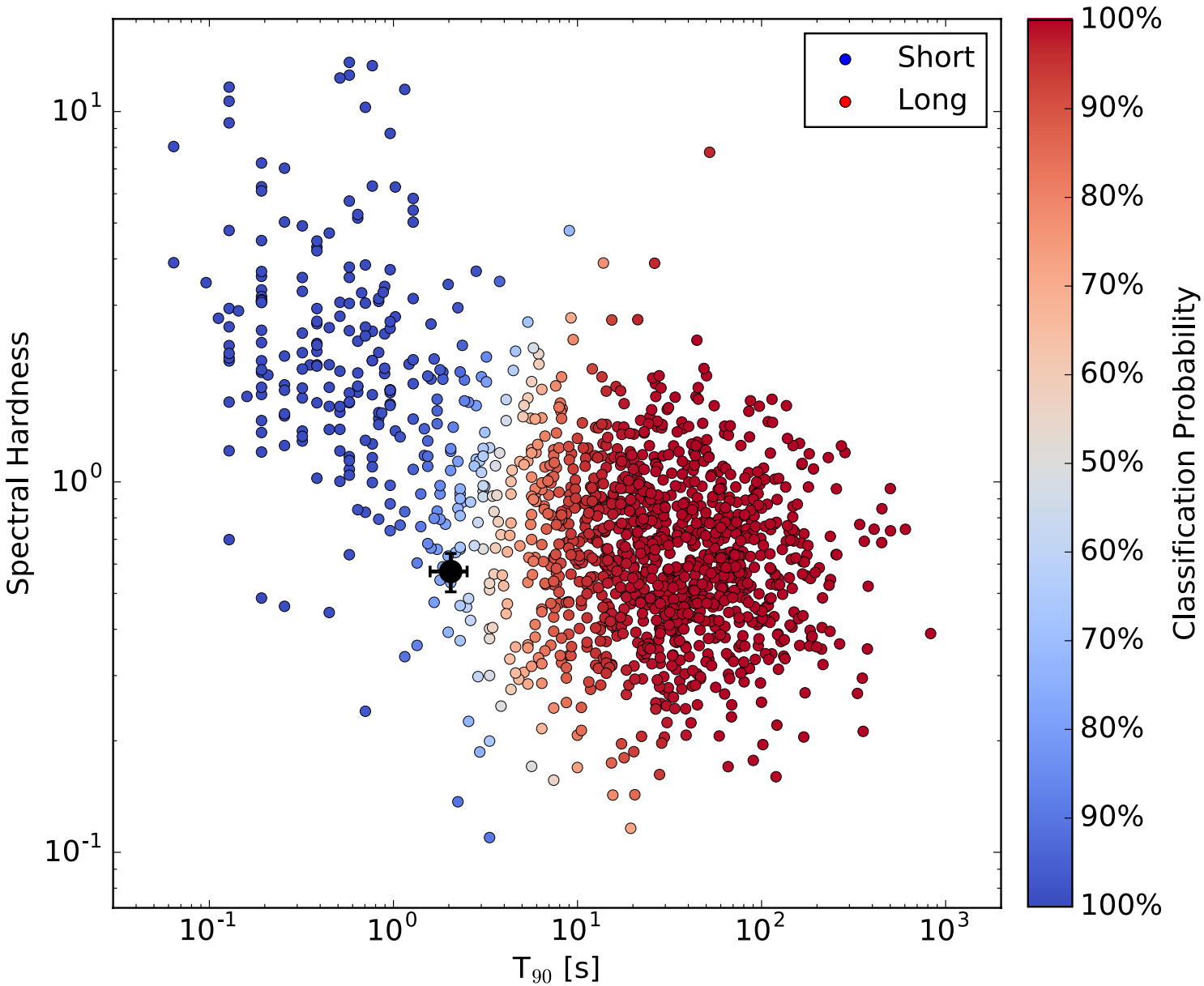
GRB 170817A - Energy distribution



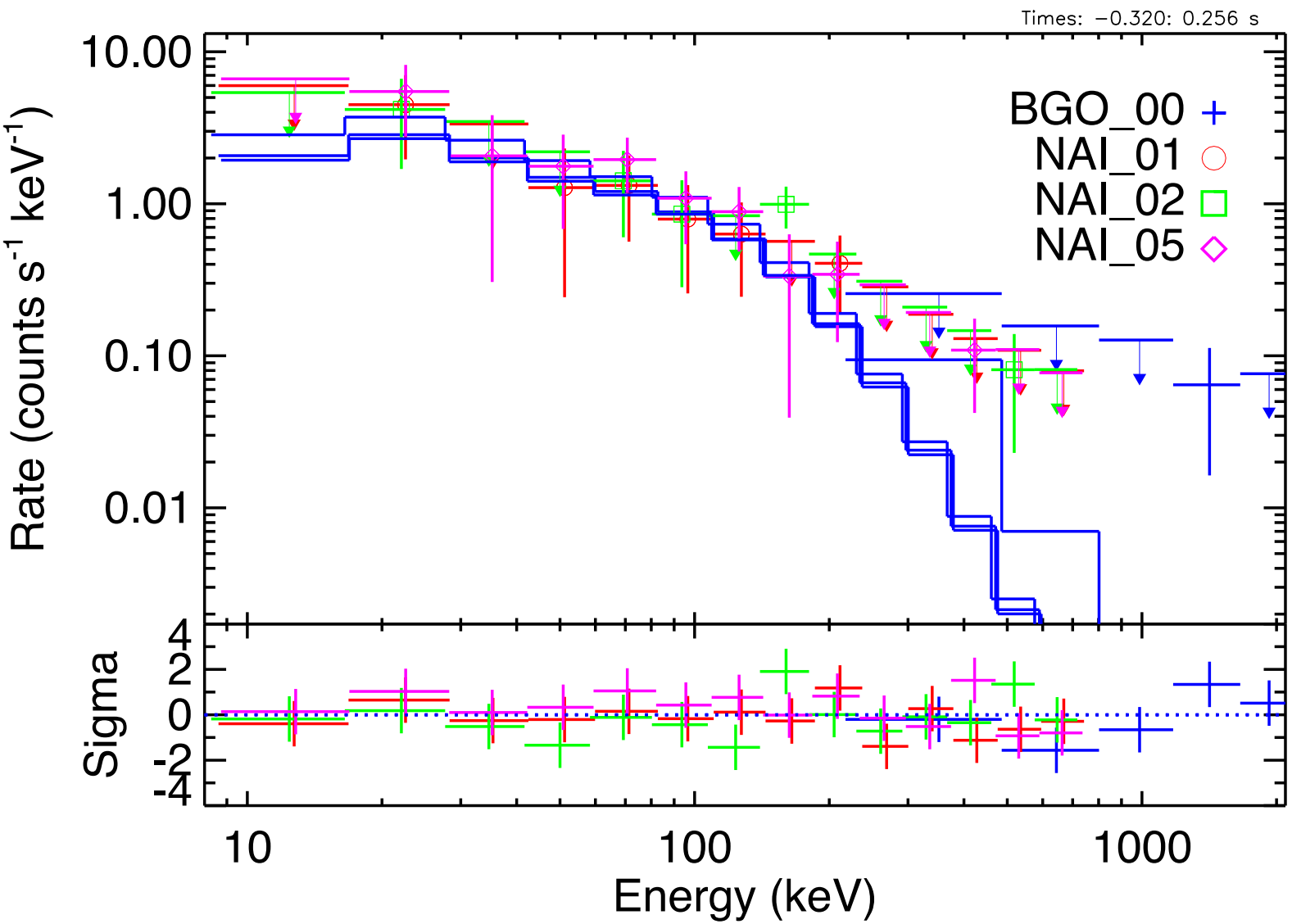
GRB 170817A - Luminosity distribution



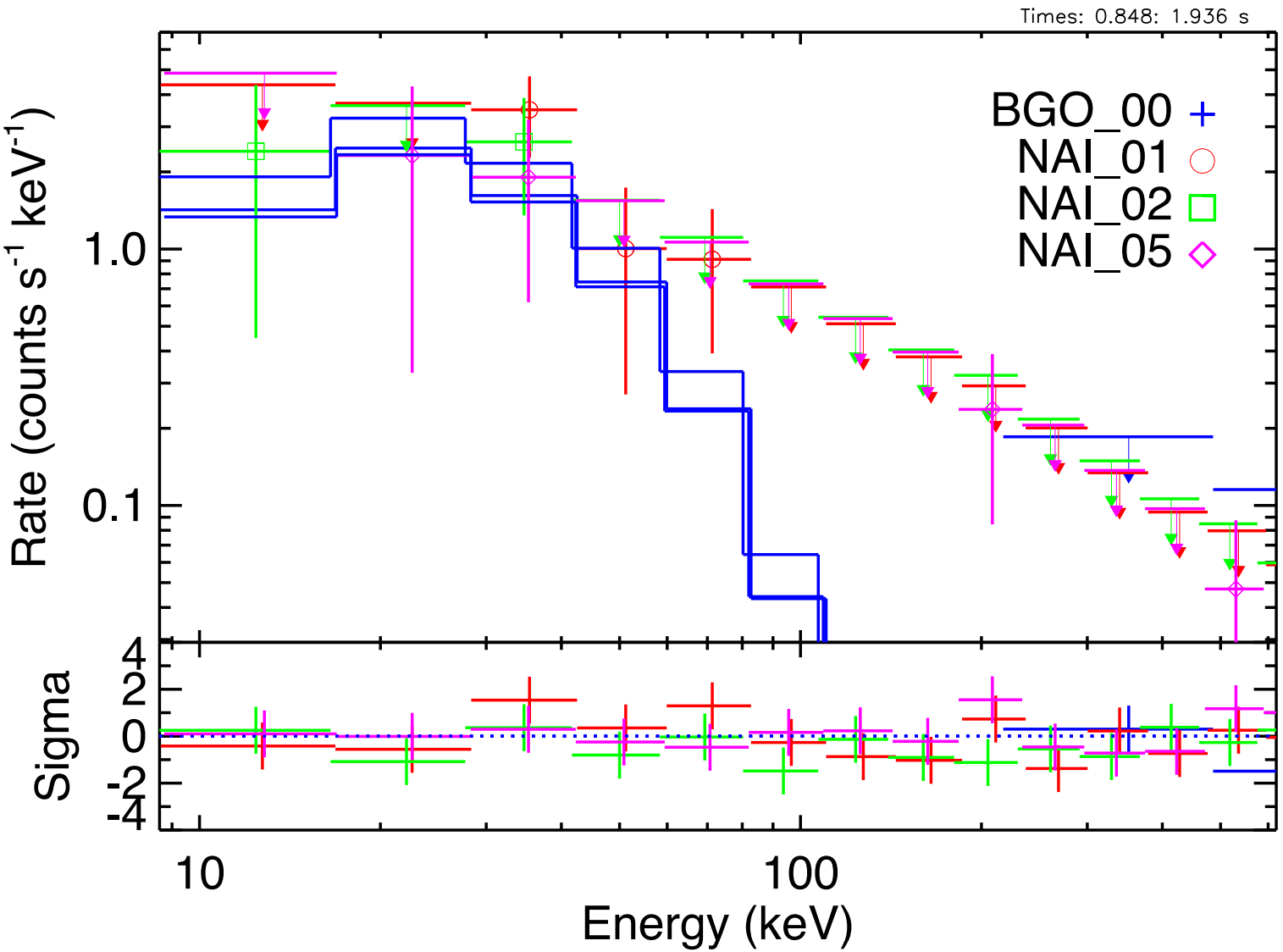
GRB 170817A - Hardness duration



GRB 170817A - spectrum - Main pulse

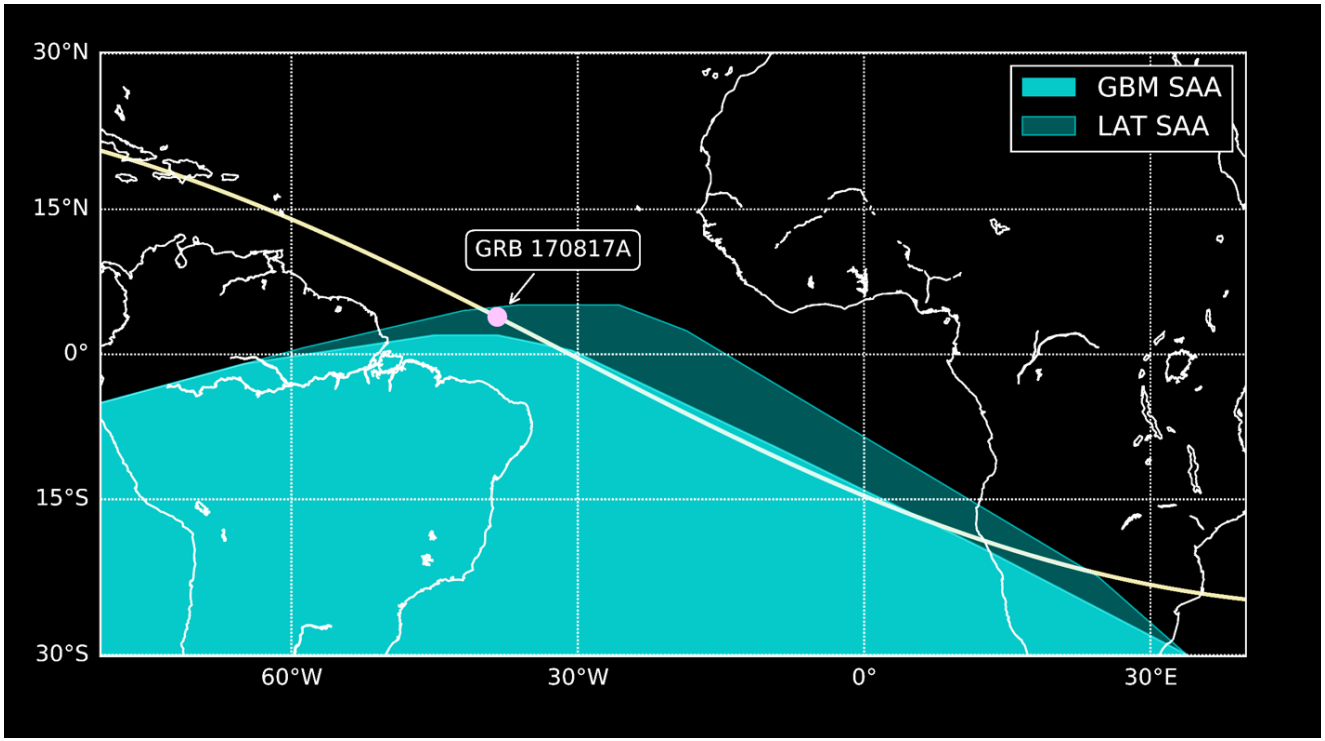


GRB 170817A - spectrum - soft emission



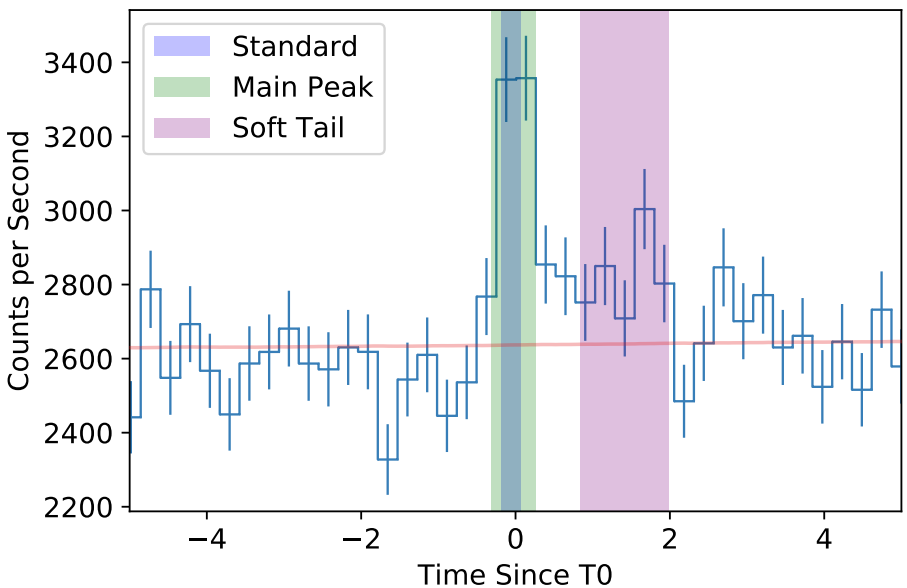
GRB 170817A - Fermi location at the time of discovery

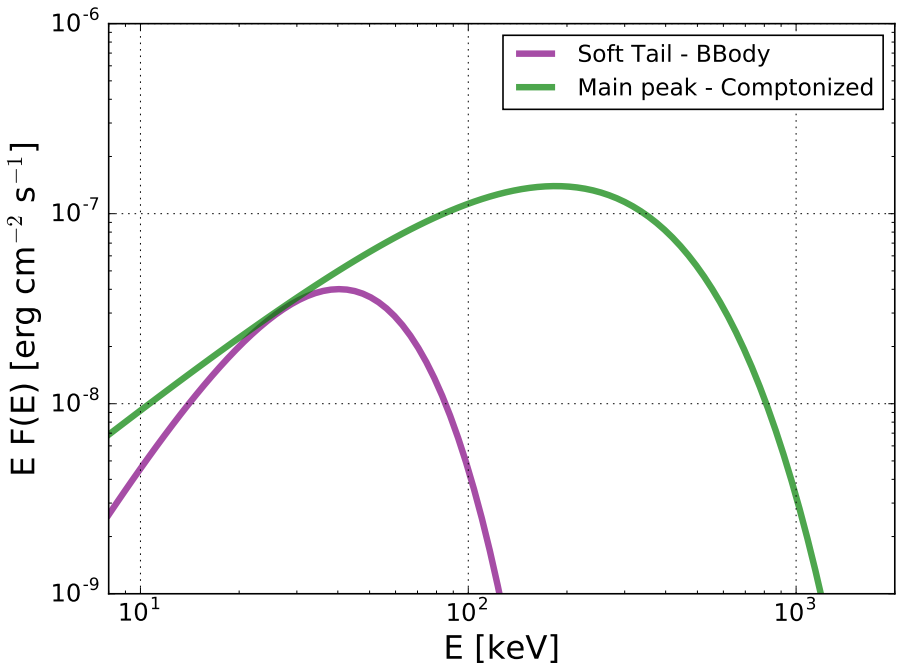
- SAA high levels of charged particles
- Slightly different shape for LAT



GRB 170817A - spectrum

Time Range (s)	Model	E_{peak} (keV)	Index	kT (keV)	Energy Flux (10^{-7} erg s^{-1} cm^{-2})
		Standard Analysis			
−0.192:0.064	Comp	215 ± 54	0.14 ± 0.59	-	5.5 ± 1.2
−0.128:-0.064	Comp	229 ± 78	0.85 ± 1.38	-	7.3 ± 2.5
		Detailed Analysis			
−0.320:0.256	Comp	**185 ± 62**	−0.62 ± 0.40	-	3.1 ± 0.7
0.832:1.984	BBody	-	-	**10.3±1.5**	0.53 ± 0.10





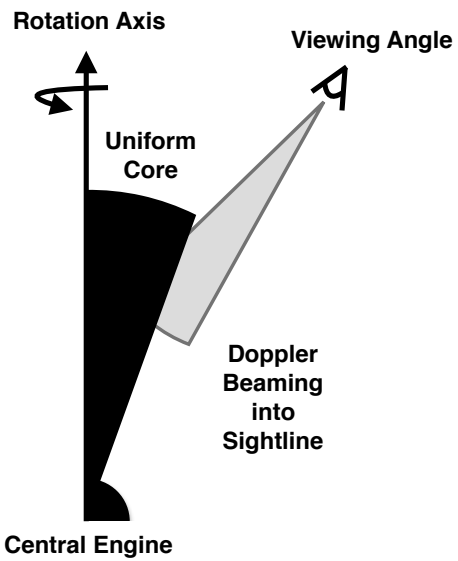
GRB 170817A - an off-axis GRB?

$$\frac{T_{90}(\mathrm{off})}{T_{90}(\mathrm{on})} = \frac{E_{\mathrm{p}}(\mathrm{on})}{E_{\mathrm{p}}(\mathrm{off})} = \frac{\delta_{\mathrm{D}}(0)}{\delta_{\mathrm{D}}(\theta_{\mathrm{j}} - \theta_v)} = \frac{1 - \beta\cos(\theta_{\mathrm{j}} - \theta_v)}{1 - \beta} \triangleq b \approx 1 + \Gamma^2(\theta_v - \theta_{\mathrm{j}})^2$$

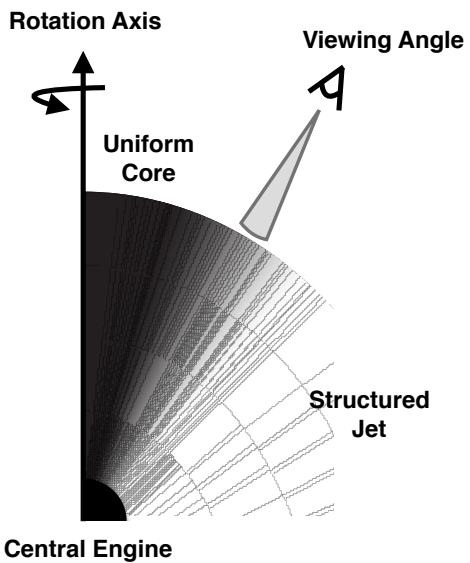
- θ_v <56° GW only
- θ_v <36° H_0 high+ NGC 4993
- θ_v <28° H_0 low

- $E_p \approx 200\,\mathrm{keV}$, $E_{\gamma,\mathrm{iso}} = 5.3 \times 10^{46}\,\mathrm{erg}$ $T_{90} \approx 2\,\mathrm{s}$,
- $E_p = 6(b/30)\,\mathrm{MeV}$, $E_{\gamma,\mathrm{iso}} = 5 \times 10^{49}(b/30)^2\,\mathrm{erg}$ $T_{90} = 7 \times 10^{-2}(b/30)^{-1}\,\mathrm{s}$.
- $\theta_v = 30°$ and $\Gamma = 300$: $\theta_v - \theta_{\mathrm{j}} \simeq 1$ deg unlikely
- $\Gamma = 30$: $\theta_v - \theta_{\mathrm{j}} \simeq 10 \pm 4$ deg

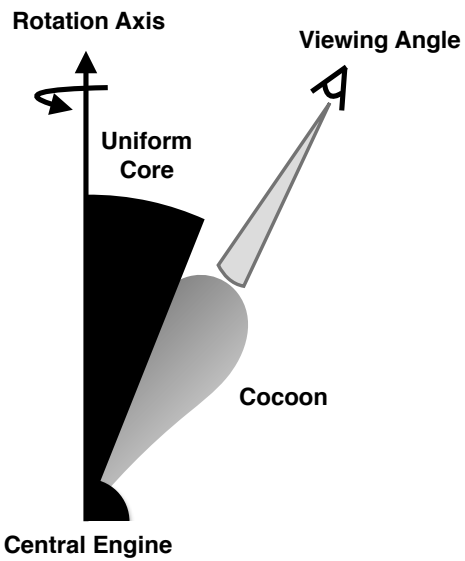
Scenario i: Uniform Top-hat Jet



Scenario ii: Structured Jet



Scenario iii: Uniform Jet + Cocoon



Sub-threshold searches (1)

- Ideal $\sim$ GRB170817A/ GW170817
- GW 150914-GBM
- Typical distance short GRB
- Both sources faint
  joint data may be significant