Fermi and *INTEGRAL* observations of GW170817 / GRB 170817A

Frédéric Piron

Laboratoire Univers et Particules de Montpellier (CNRS / IN2P3)

Third SVOM Scientific Workshop
Les Houches, May 13-18, 2018

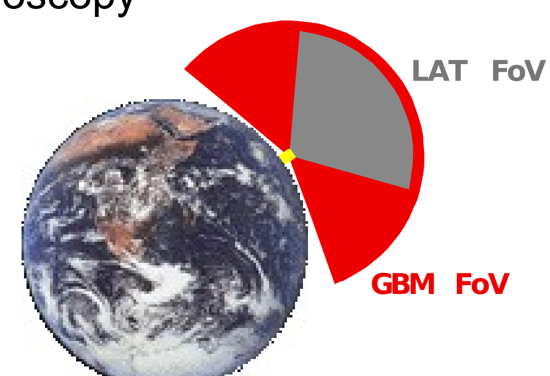
Outline

- ***Fermi*/GBM: onboard detection; localization; spectral analysis**
- ***Fermi*/LAT follow-up observations**
- ***INTEGRAL*/SPI-ACS detection and follow-up observations**
- **Constraints from GW and gamma-ray observations**
  - Possible GRB physical scenarios
  - Revised estimate of joint detection rates

The *Fermi* observatory

- **Large Area Telescope (LAT)**
  - Large field of view (2.4 sr @ 1 GeV)
  - Sees the entire sky every 3 hours
  - 20 MeV to >300 GeV
  - Onboard and ground burst triggers
  - Localization, spectroscopy

- **Gamma-ray Burst Monitor (GBM)**
  - Sees the entire unocculted sky (>9.5 sr)
  - 8 keV to 40 MeV
  - 12 NaI detectors (8 keV to 1 MeV)
    - Onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - Spectroscopy



GBM timeline (1/2)

12:41:06.474598	0	GBM Trigger Time T0: End of 0.256 s data interval with GBM rate increase
12:41:06.477006	2.4 ms	GBM Triggered: Autonomously detected in-orbit by the Fermi GBM flight software
12:41:20	14 s	Public Fermi GBM GCN Notice sent
12:41:31	25 s	Public Fermi GBM GCN Notice: Automatic location from GBM flight software. 97% probability GRB.
12:41:44	38 s	Public Fermi GBM GCN Notice: More accurate automatic location by ground software
13:21:42	40.5 min	First LIGO GCN Circular. GW candidate near time of Fermi GBM trigger (Essick et al. 2017)
13:26:36	44.9 min	Public Fermi GBM GCN Notice: More accurate human-guided localization

GBM timeline (2/2)

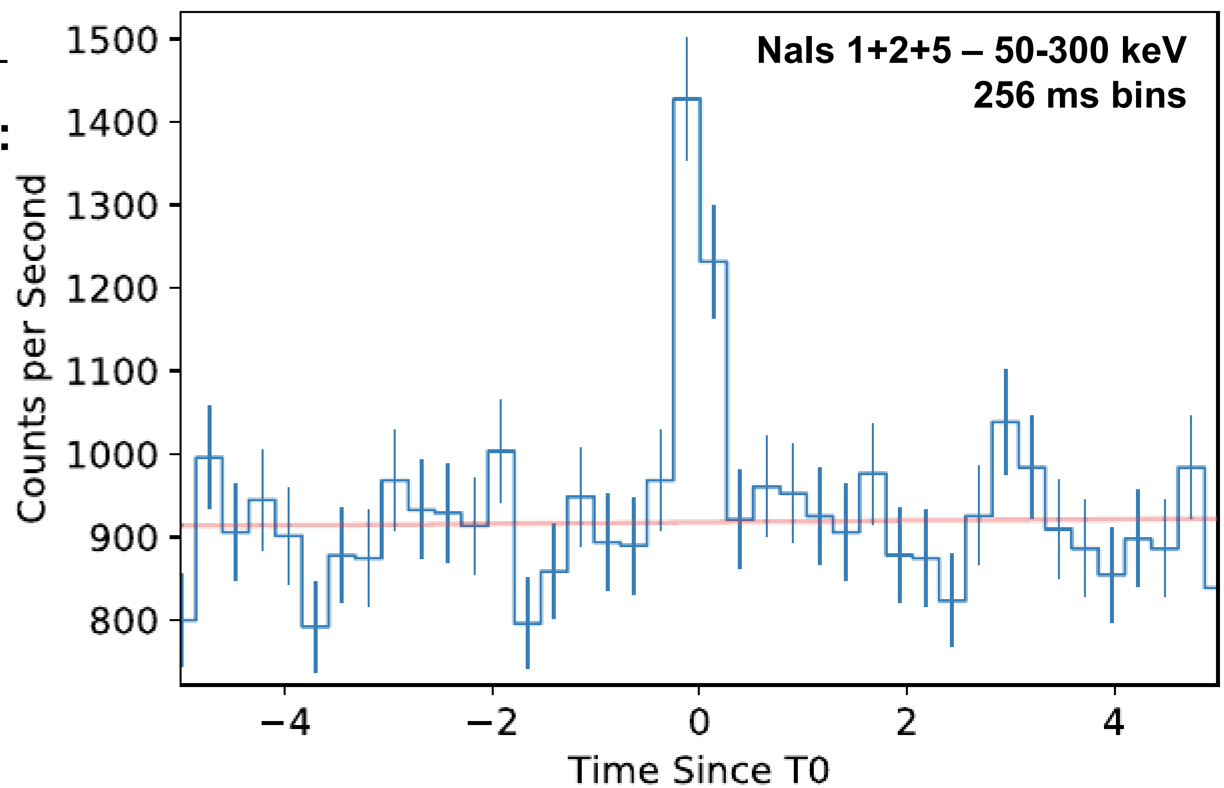
13:47:37	1.1 hr	LVC GCN Circular reporting localization and consistency of GBM signal with a weak short GRB (Connaughton et al. 2017)
13:57:47	1.3 hr	LVC GCN Circular. INTEGRAL/SPI-ACS routine follow-up search detects transient coincident with the GBM trigger. (V. Savchenko et al. 2017)
20:00:07	7.3 hr	Public Fermi GBM Circular establishing GRB name, with standard GBM analysis (von Kienlin et al. 2017)
17/08/18 01:05:23	12 hr	LVC GCN Circular. optical transient detected. (Coulter et al. 2017)

GBM detection

Detector	Angle (°)	Comment
NaI 0	63	
NaI 1	39	Good geometry
NaI 2	15	Good geometry
NaI 3	86	
NaI 4	101	
NaI 5	42	Good geometry
NaI 6	104	blocked by spacecraft
NaI 7	130	blocked by spacecraft
NaI 8	167	blocked by spacecraft
NaI 9	86	blocked by LAT radiator
NaI 10	78	blocked by LAT radiator
NaI 11	138	blocked by LAT radiator
BGO 0	44	Good geometry
BGO 1	136	blocked

- **The GBM flight software autonomously detected the GRB**
  - Scans 28 combinations of timescales and energy ranges
  - Requires two or more NaI detectors above 4.5σ: here NaI 1, 2, 5
- **Detection: 256 ms, 50-300 keV, 4.82σ in the second brightest detector (NaI 2)**

- **In 320 ms, 5 (3) NaIs above 3σ (5σ): 3.41σ, 3.57σ, 5.63σ, 5.67σ, 6.34σ**
- **Three other trigger algs above threshold (all in 50-300 keV)**
  - 256 ms (other phasing, 5.16σ)
  - 512 ms (6.25σ)
  - 1024 ms (4.52σ)
- **If 30% less bright, the GRB would have been still detected**



GBM localization

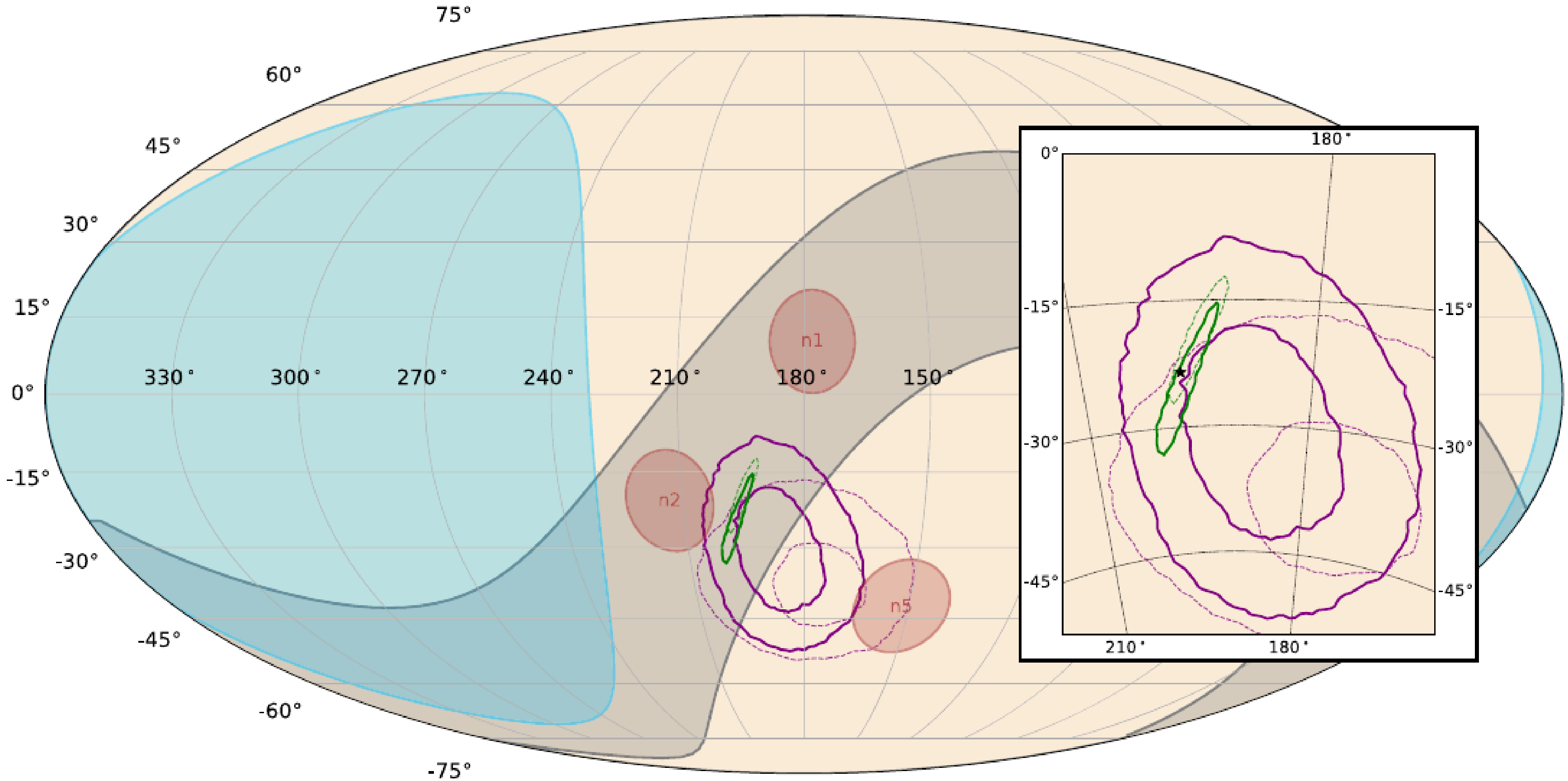
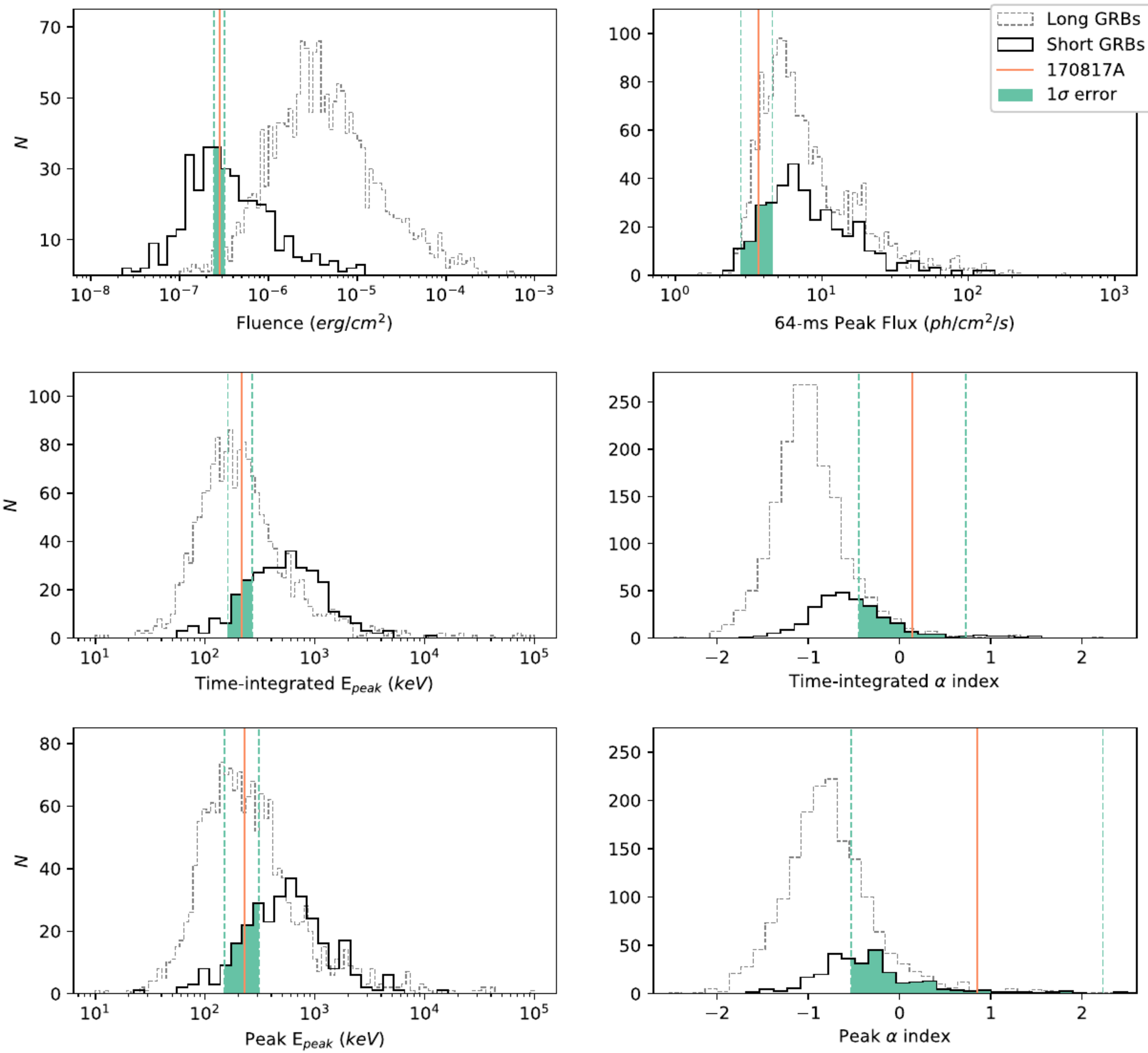


Figure 3. GBM and HLV initial and final localizations. The original GBM human-in-the-loop localization (50% and 90% regions) is shown with purple dashed contours, and the original BAYESTAR skymap (90% region) is shown with a green dashed contour. The targeted search localization and the LALInference HLV skymap are the corresponding solid contours. The inset shows a close-up of the GBM localization and the position of the the optical transient candidate (black star).

- **HLV initial map: 50% (90%) credible region spanning 9 (31) square deg**
- **Final GBM map: 50% (90%) credible region spanning ~350 (~1100) square deg**
- ***Fermi-INTEGRAL* IPN annulus consistent with GBM localization and HLV map**

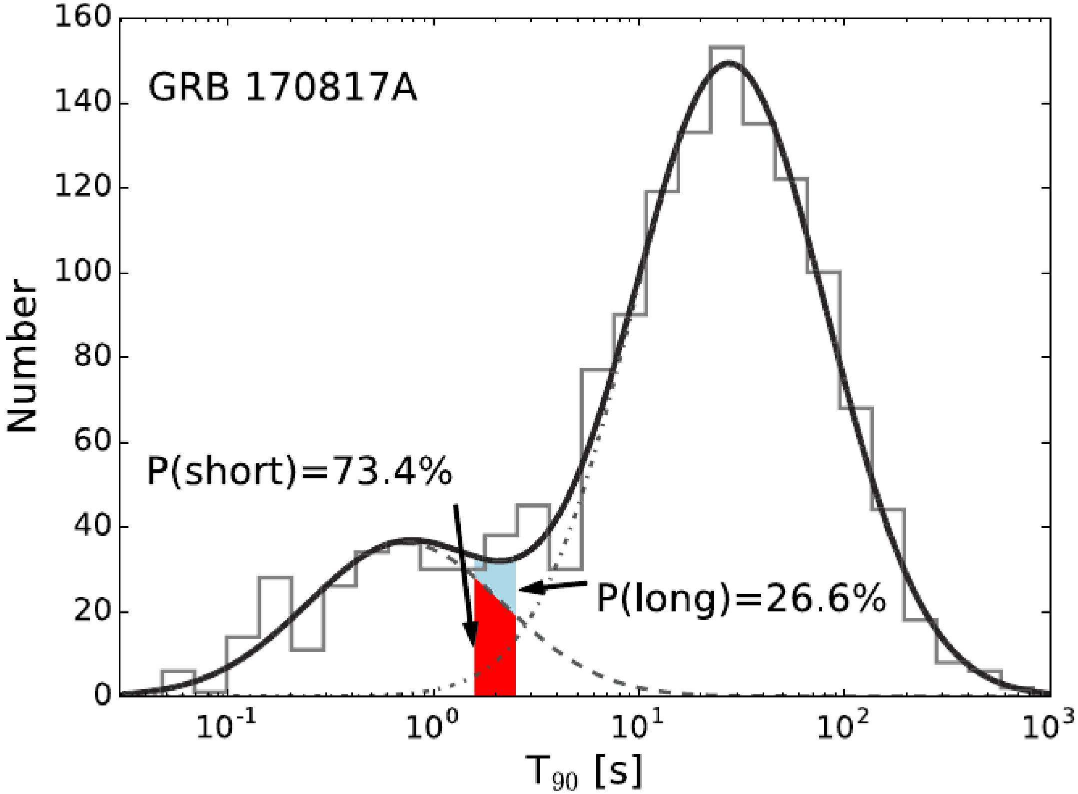
- **Unambiguous GW170817 / GRB 170817A association: $P_{temporal} \times P_{spatial} = 5 \times 10^{-8}$ (5.3σ)**

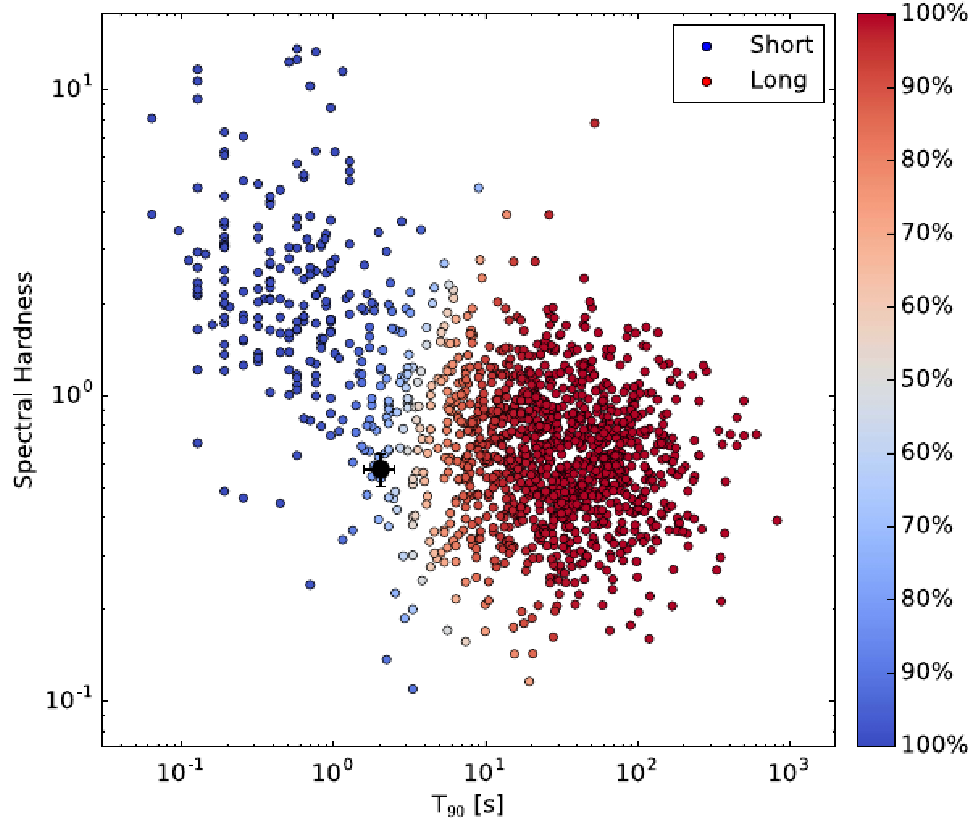
GBM standard analysis (1/2)



- **GBM has triggered on >2000 GRBs, including ~40 short GRBs per year**
- **GRB 170817A is an ordinary short GRB**
- **At the ~40% fluence percentile for GBM short GRBs**

GBM standard analysis (2/2)

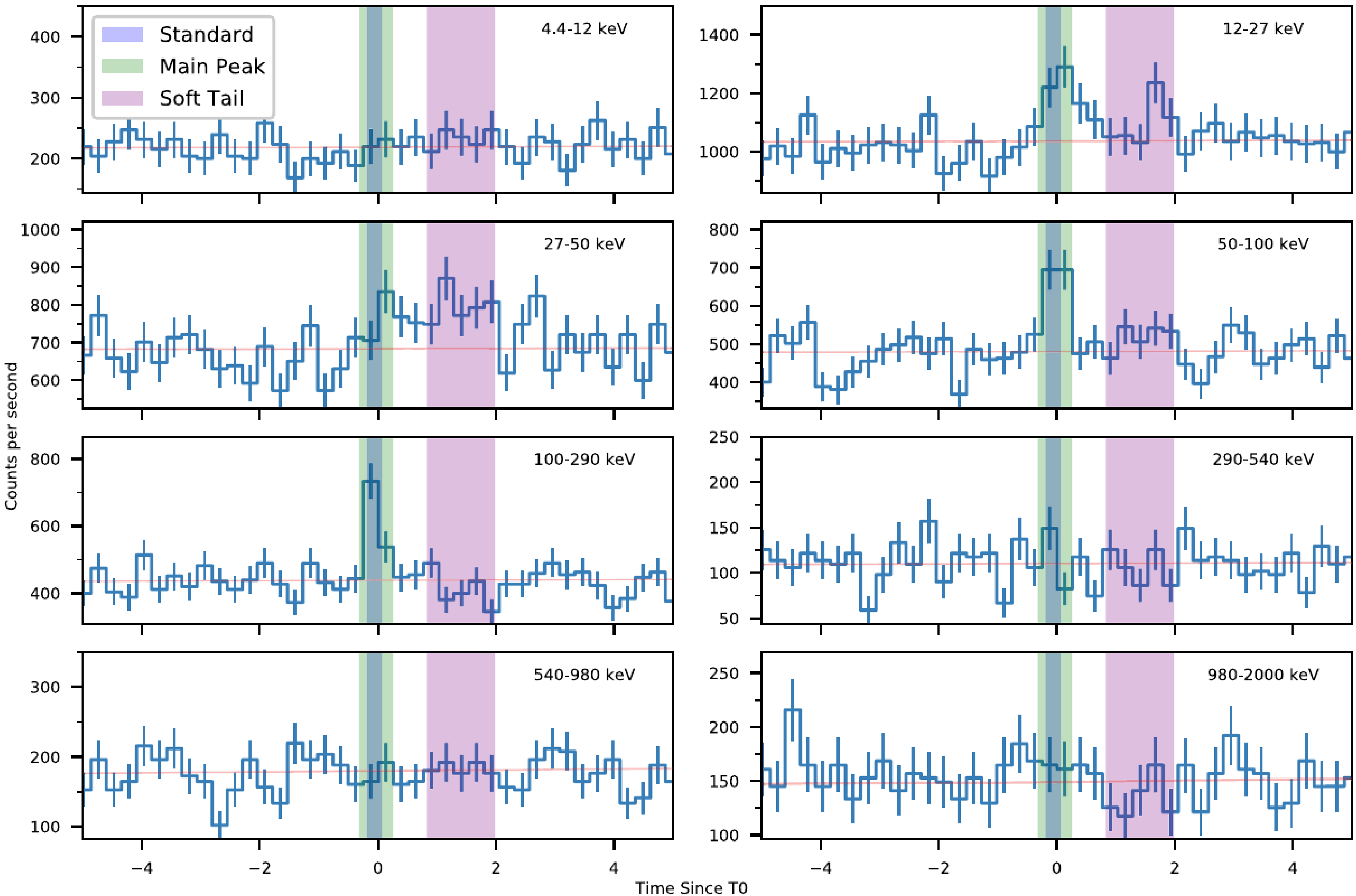




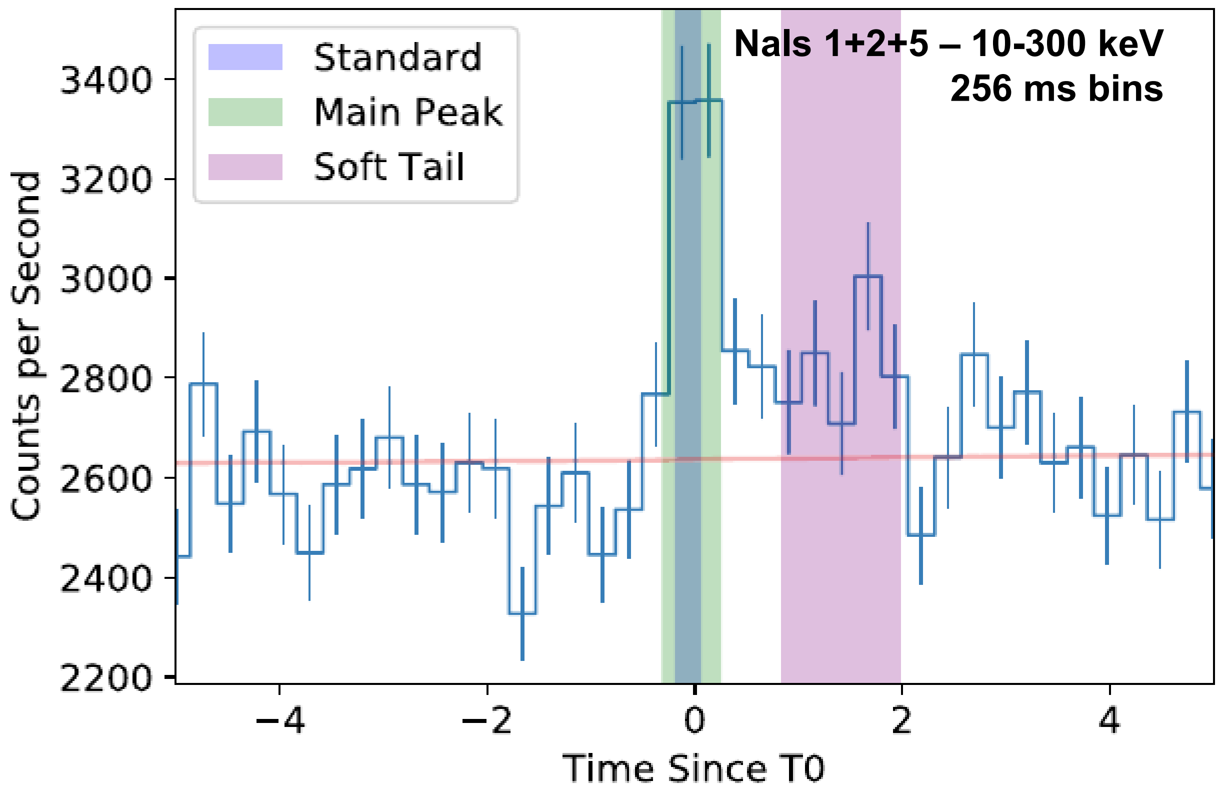
- **T90 = 2.0 ± 0.5 s**
  - defined as the time interval over which 90% of the burst fluence between 50–300 keV is accumulated
  - duration extends beyond the main emission pulse due to the soft component

- **73% probability that the GRB belongs to the short class**

GBM light curves



GBM detailed analysis (1/2)



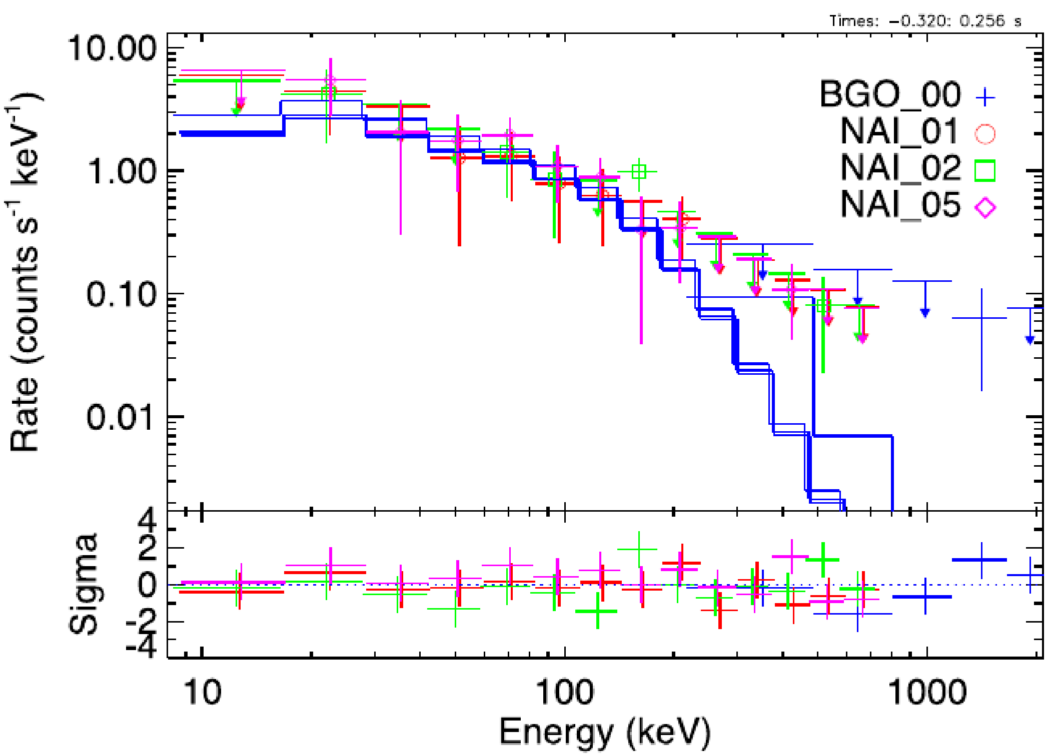
- **Main pulse**
  - ~0.5 s duration, from T0−0.320 s to T0+0.256 s
  - Best fit with cutoff power law, aka “Comptonized”: Epeak = 185 ± 62 keV, α = −0.62 ± 0.40

- **Soft tail**
  - ~1.1 s duration, from T0+0.832 s to T0+1.984 s
  - Well fit with Black Body spectrum: 10.3 ± 1.5 keV

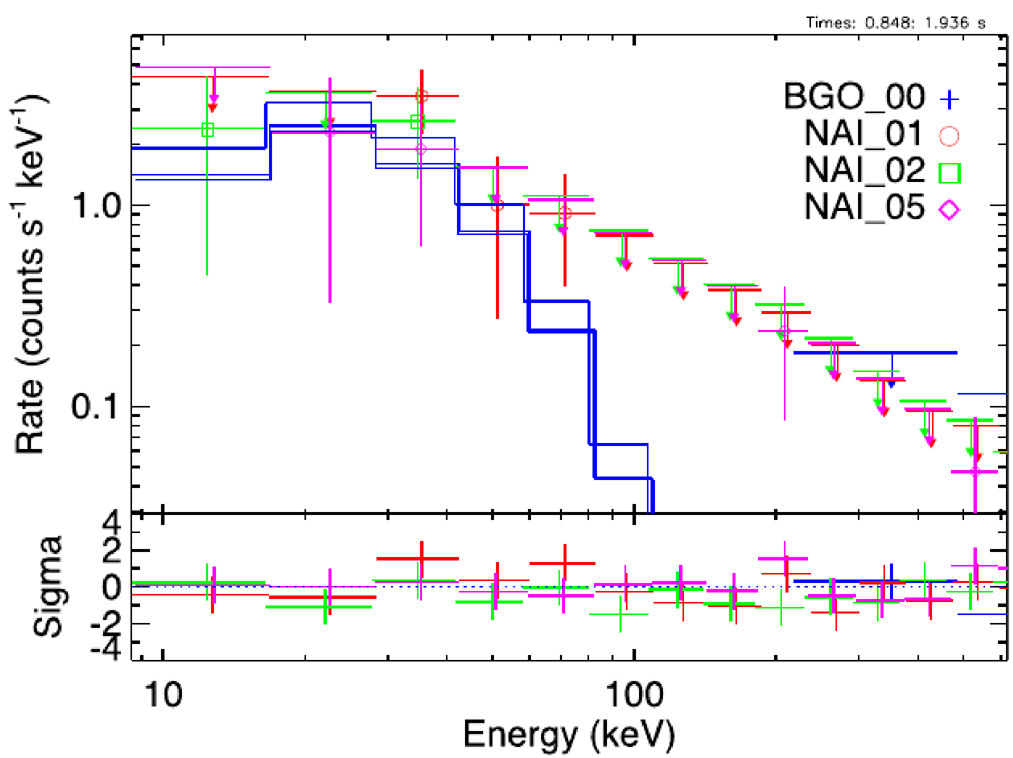
GBM detailed analysis (2/2)

Time Range (s)	Model	E_{peak} (keV)	Index	kT (keV)	Energy Flux (10^{-7} erg s^{-1} cm^{-2})	Energy Fluence (10^{-7} erg cm^{-2})
Standard Analysis						
−0.192:0.064	Comptonized	215 ± 54	0.14 ± 0.59	⋯	5.5 ± 1.2	1.4 ± 0.3
−0.128:-0.064	Comptonized	229 ± 78	0.85 ± 1.38	⋯	7.3 ± 2.5	0.5 ± 0.2
Detailed Analysis						
−0.320:0.256	Comptonized	185 ± 62	−0.62 ± 0.40	⋯	3.1 ± 0.7	1.8 ± 0.4
0.832:1.984	Blackbody	⋯	⋯	10.3 ± 1.5	0.53 ± 0.10	0.61 ± 0.12

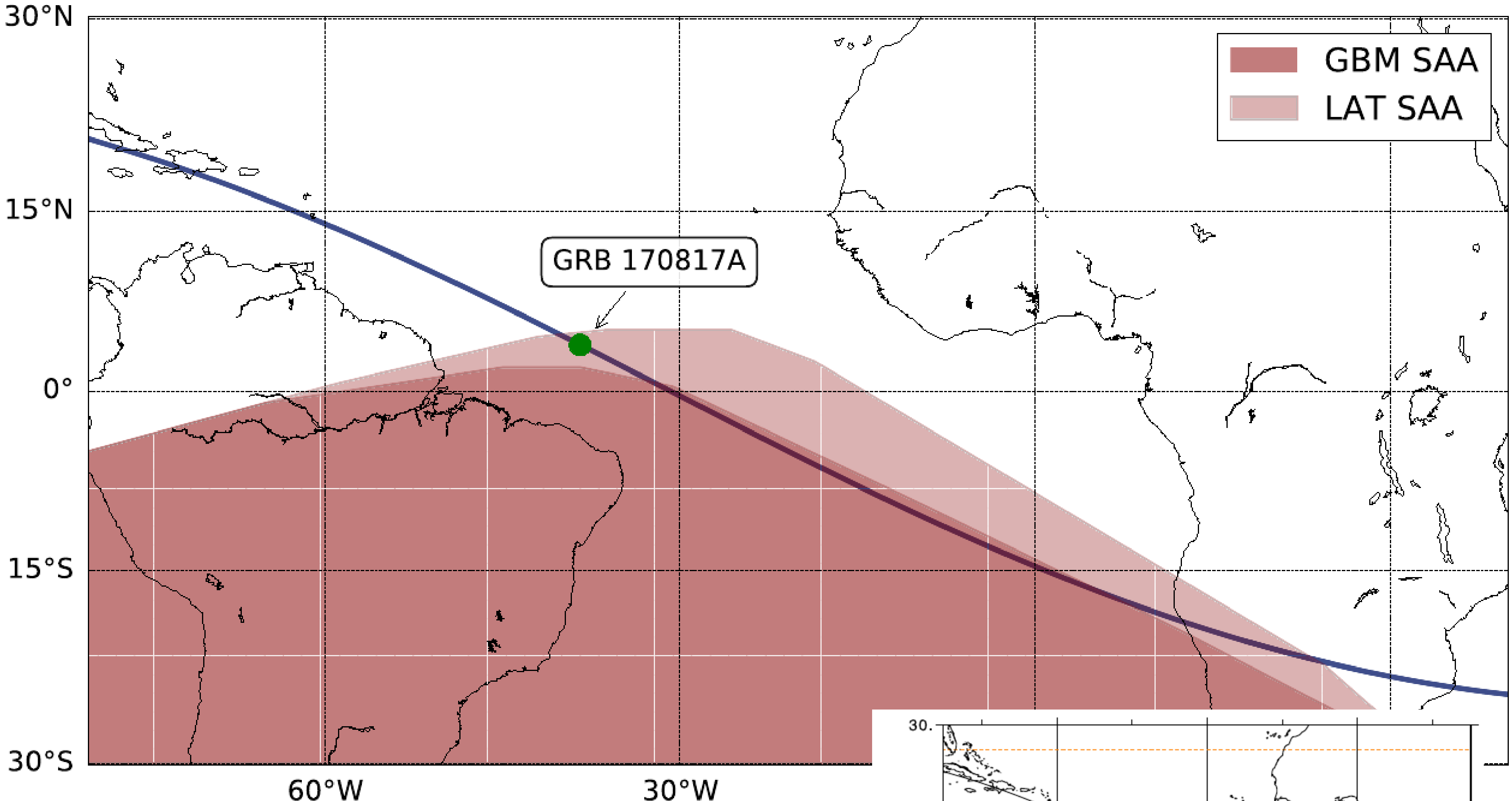
Main pulse (cutoff PL)

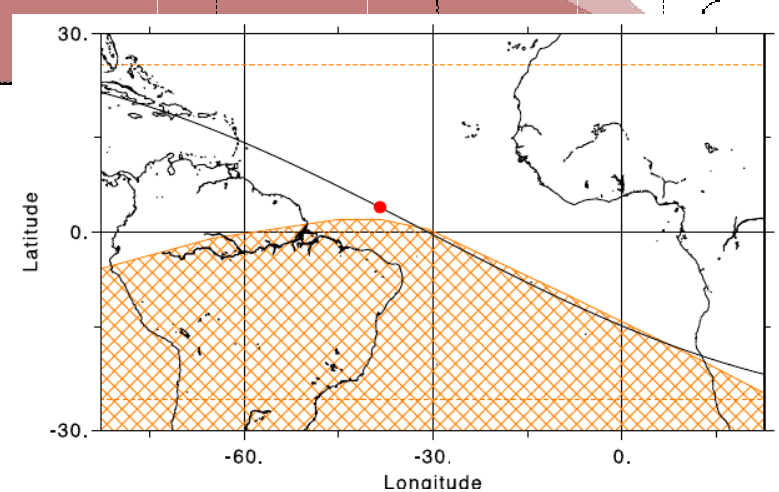


Soft tail (BB)



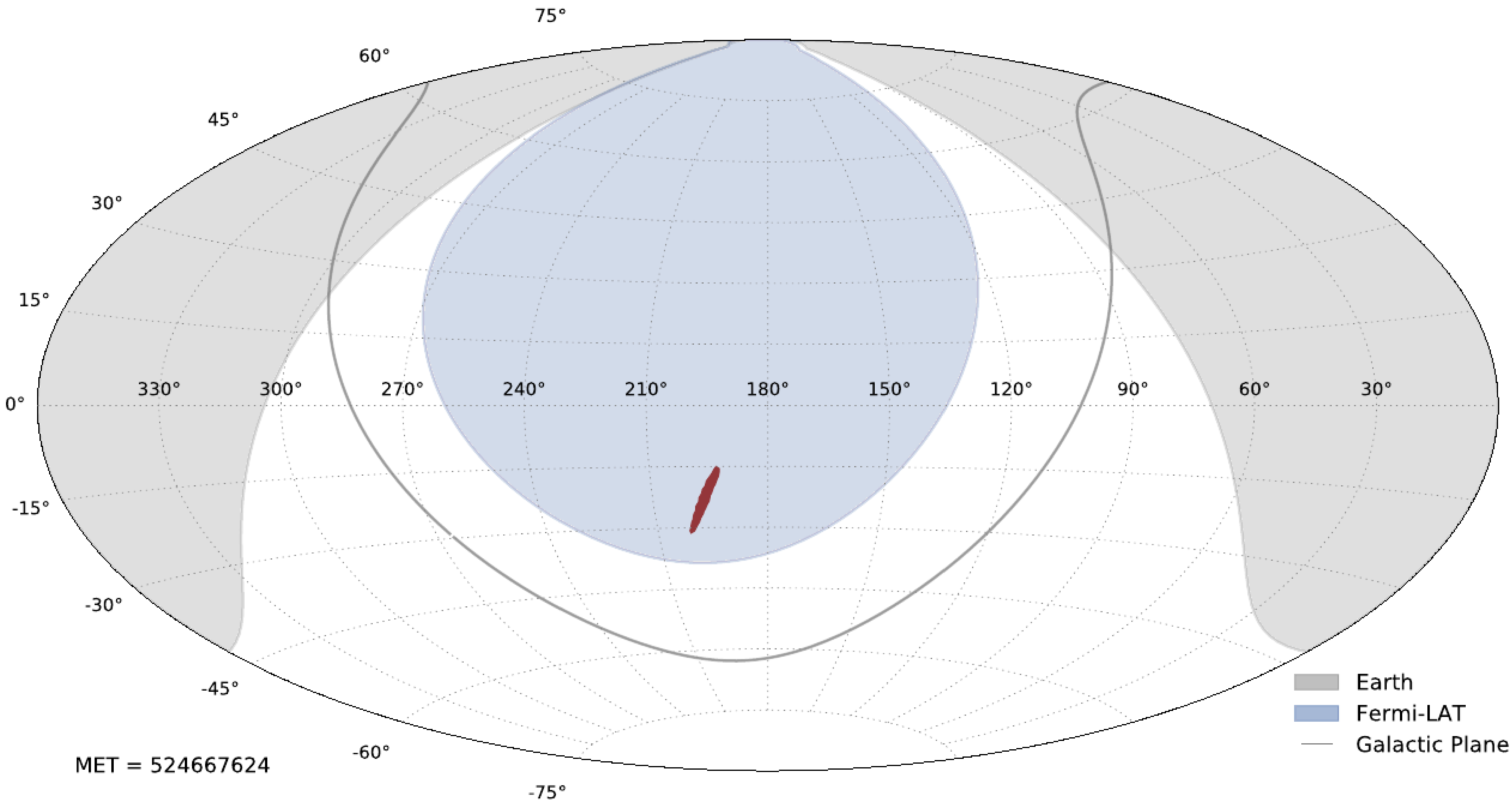
Orbital path and South Atlantic Anomaly boundaries





- **At T0, LAT was entering the SAA and not collecting data**
- **GBM data taking ended at T0+2 min**
- **LAT resumes observations at T0+1153 s**

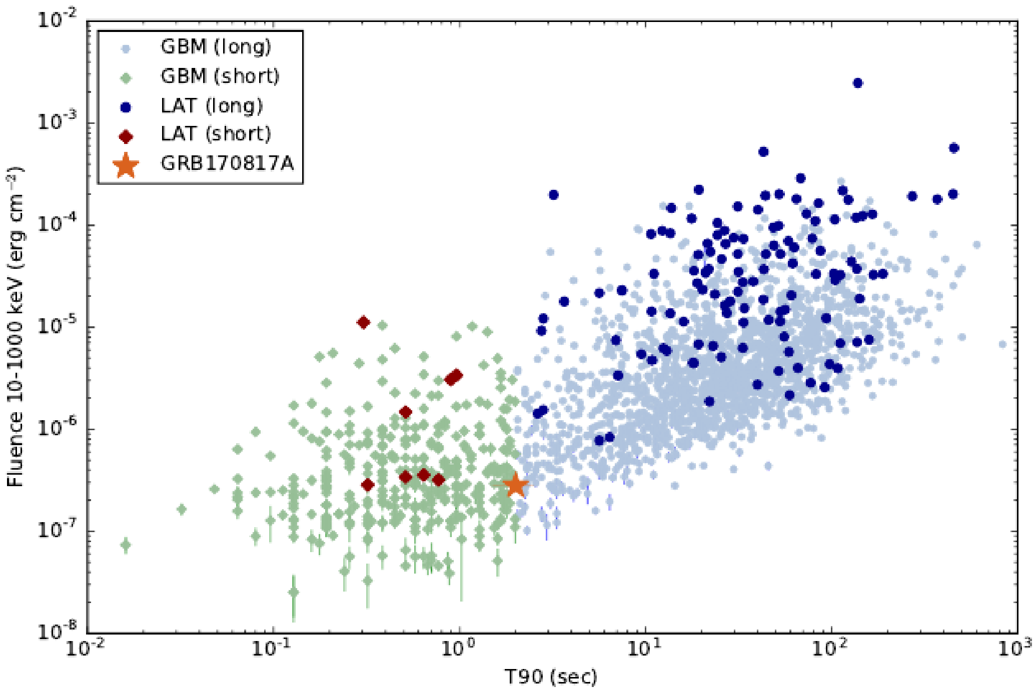
LAT observation of GRB 170817A



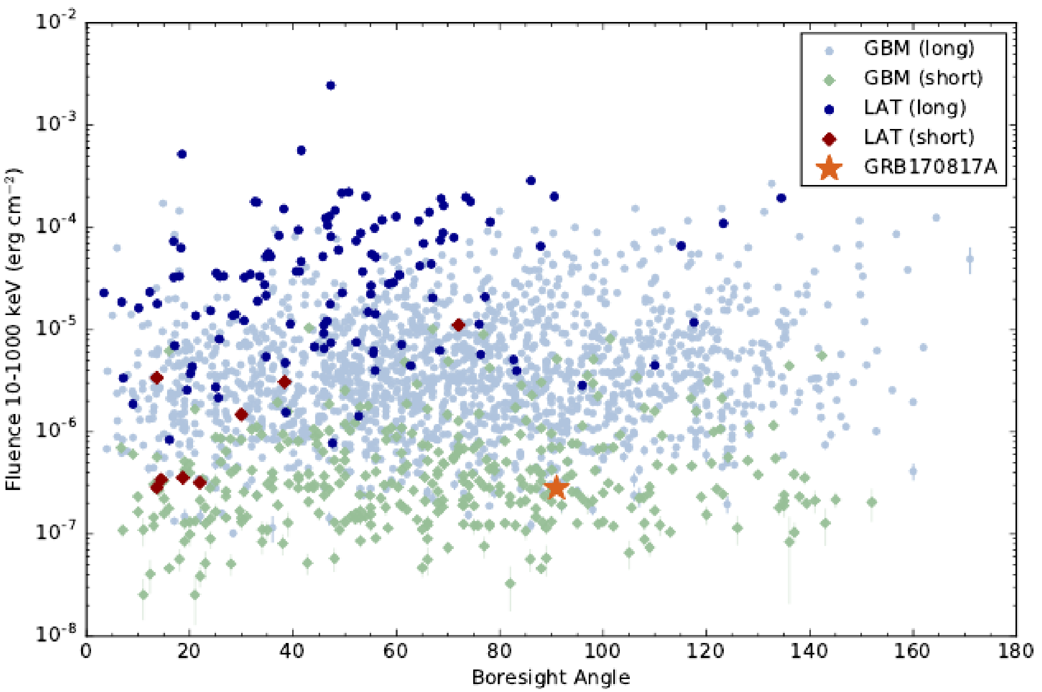
- **LAT pointing after exiting SAA (T0+1153 s)**

GRB 170817A and other *Fermi* GRBs

GBM fluence (10-1000 keV) vs. GBM duration



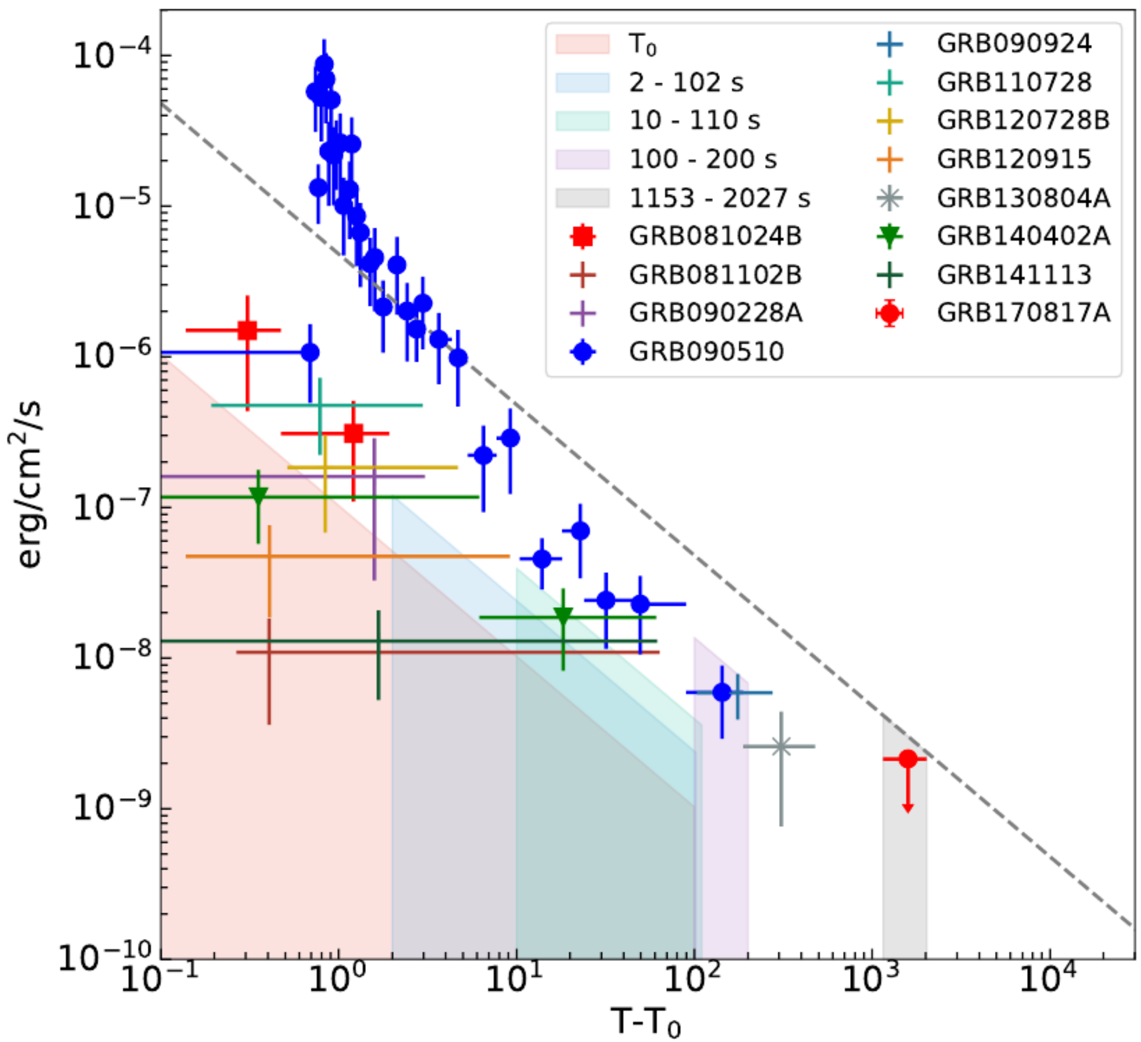
GBM fluence vs. angle to the LAT boresight



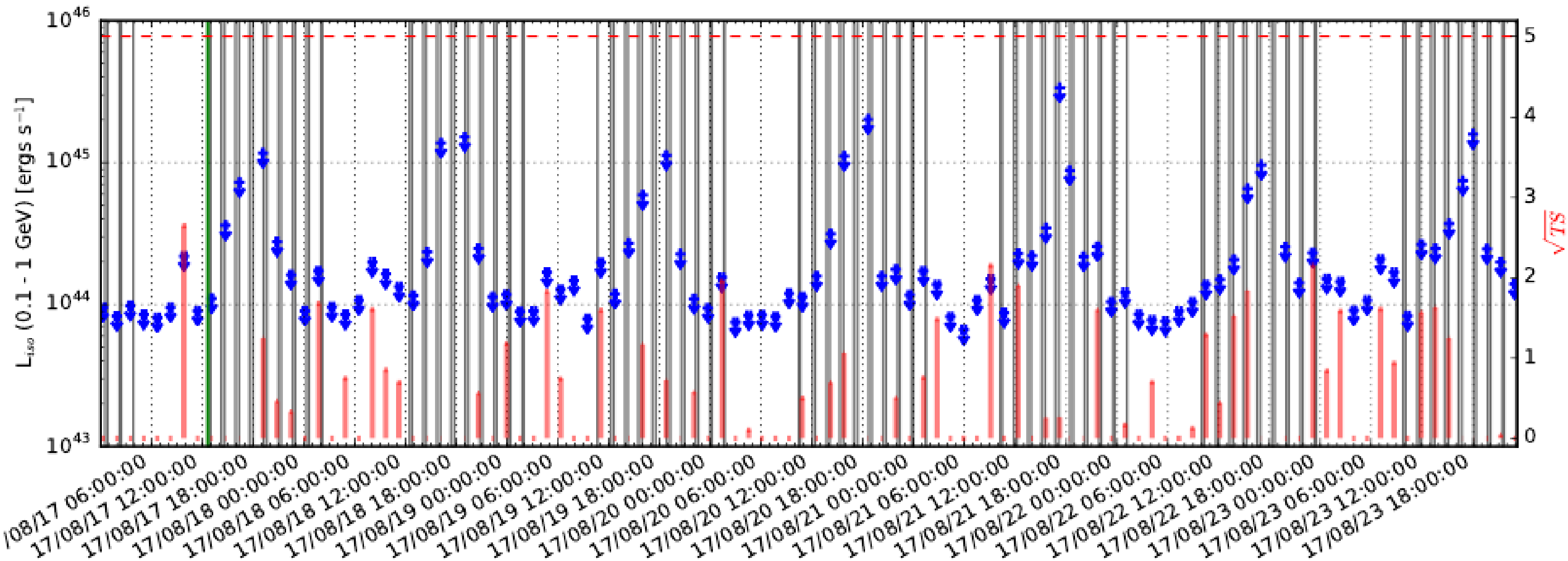
- **LAT detects 1–2 SGRBs / yr (~5% of all GBM-detected SGRBs)**
- **LAT sensitivity decreases significantly wih increasing boresight angle**
- **Lowest fluence bursts are only detected by the LAT when they occur close to the instrument boresight**
- **Initial position of GRB 170817A was outside the LAT field of view**

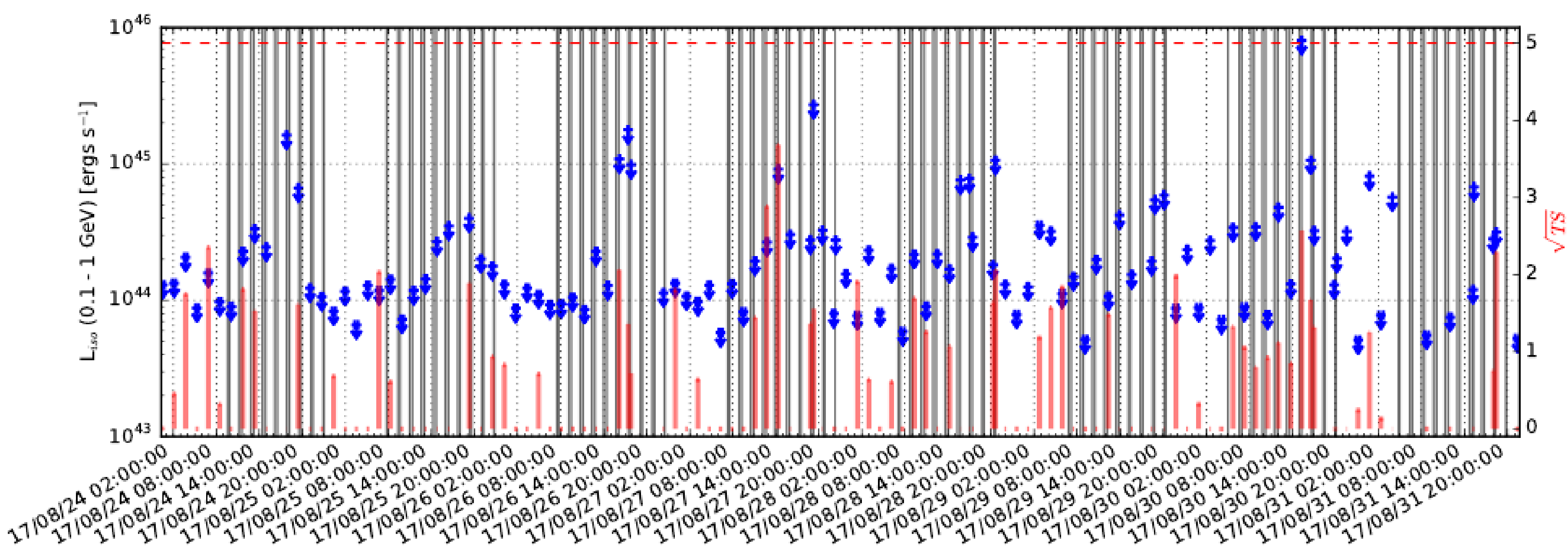
GRB 170817A and LAT short GRBs

- **Flux UL from T0+1153 s to T0+2027 s**
- **Flux UL above the expected temporally-extended emission from LAT-detected short GRBs**
- **Luminosity UL (above 100 MeV) ~10^{44} erg/s**
- **To be compared with the brightest LAT short GRB 090510 at T0+1153 s: 4×10^{49} erg/s**
- **Observations at earlier time of a more typical short GRB will be crucial**

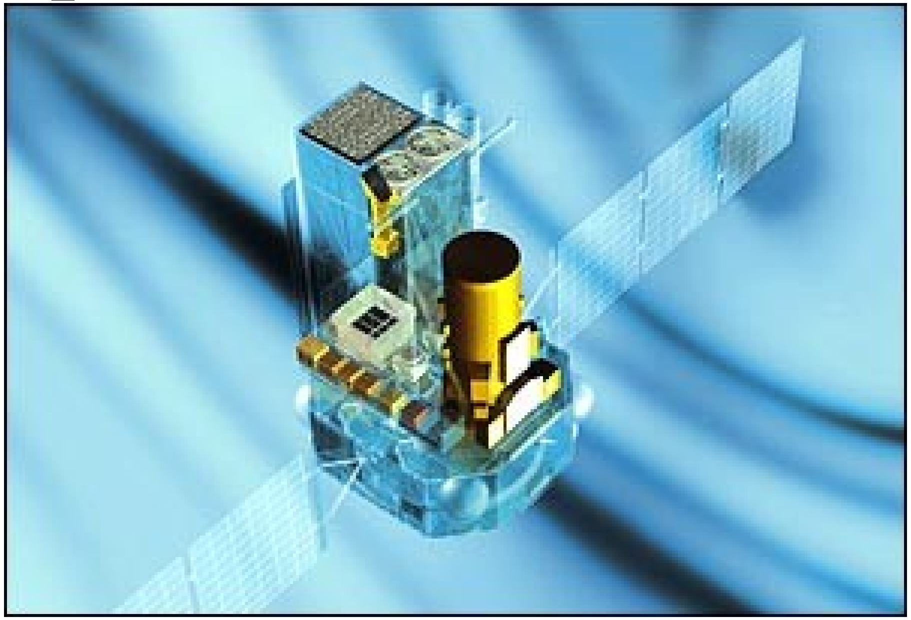


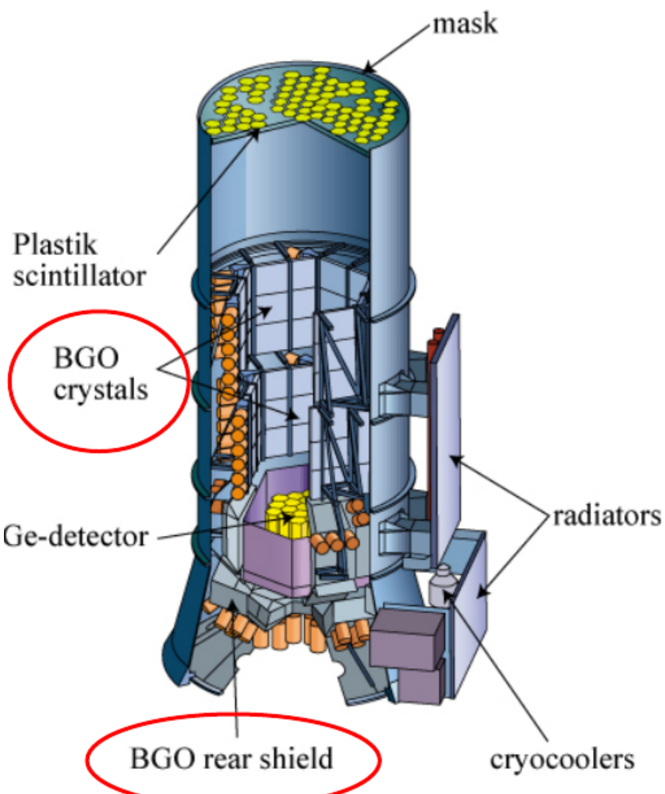
LAT observations within two weeks





The *INTEGRAL* observatory

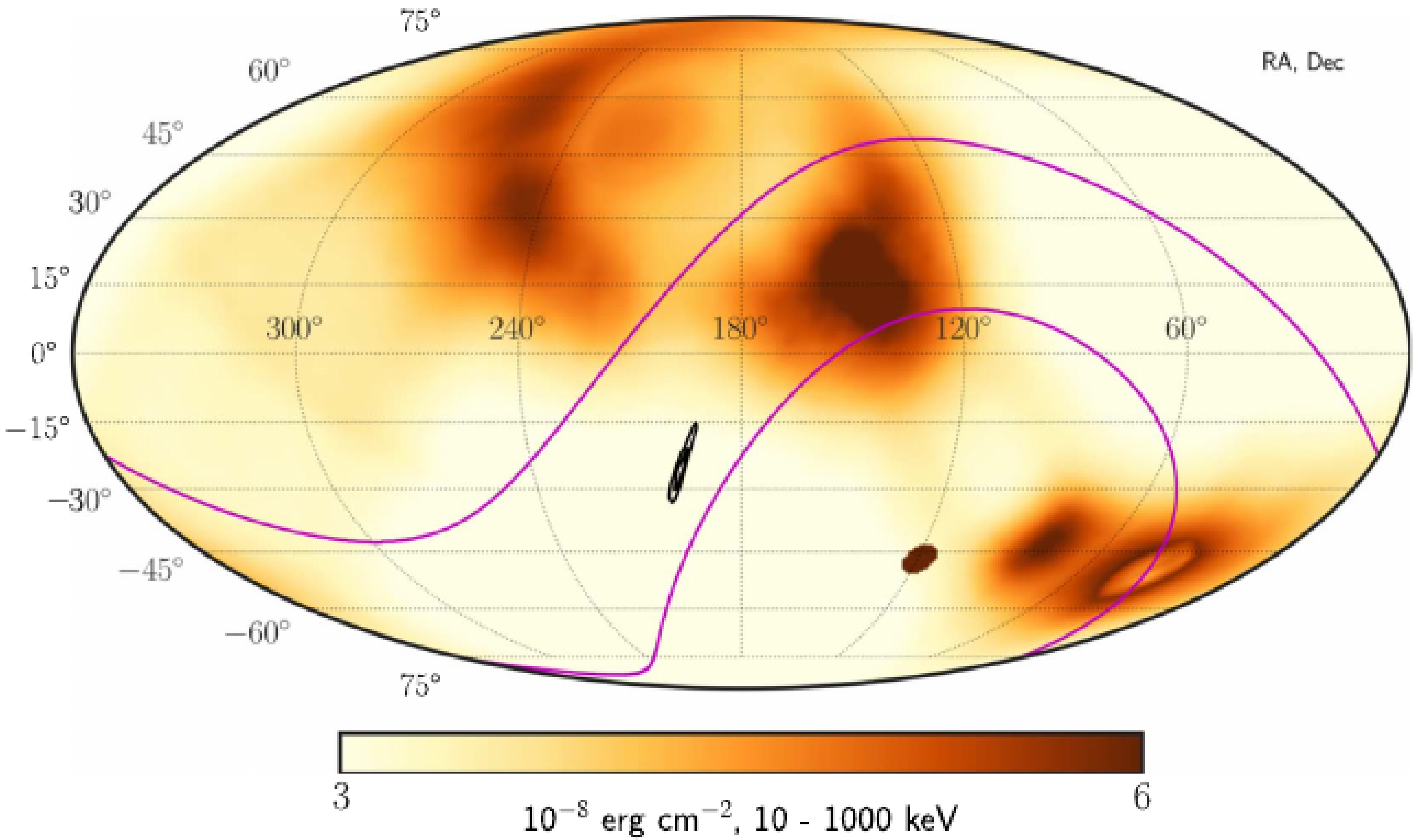




- **INTErnational Gamma-Ray Astrophysics Laboratory**
  - Launched in Oct. 2002 (ESA M2 mission)
  - Combines imaging and spectroscopy
- **SPI spectrometer:** emphasis on spectroscopy, 16° FoV
  - Coded mask + 19 high-purity Ge detectors (85 K)
- **IBIS imager:** emphasis on imaging, 9°x9° FoV
  - Coded mask + 2 layers of pixel detectors: ISGRI (CdTe) and PICsIT (CsI)
- **X-ray monitor JEM-X**
  - 3-35 keV, 4.8° FoV, localization <20″
- **Optical monitor OMC**
  - 5° FoV, localization <8″
- **SPI-Anti-Coincidence Shield (SPI-ACS)**
  - 512 kg of BGO scintillator
  - Viewed by 81 photomultipliers
  - Low threshold of ~80 keV
  - Effective area ~ 1m² for some directions and energies

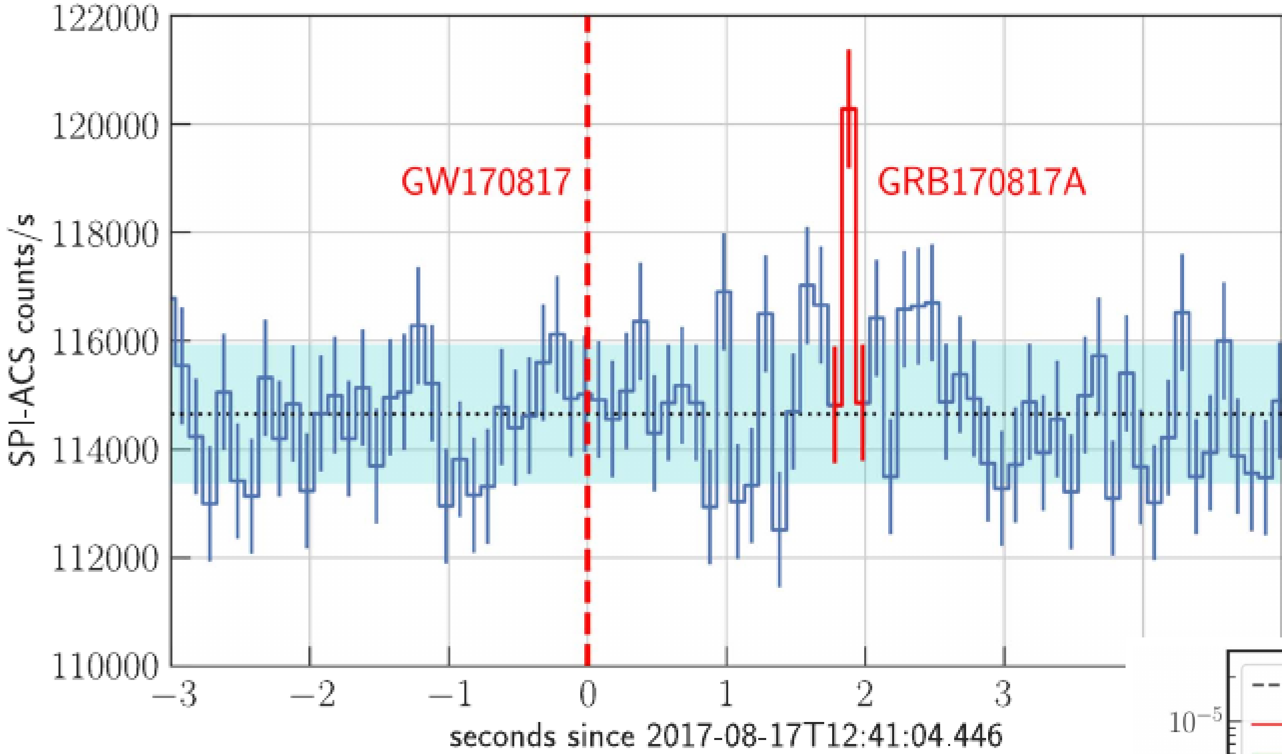
INTEGRAL sensitivity during GW170817

3σ sensitivity to a 100 ms burst (α = −0.65 and Epeak = 185 keV)

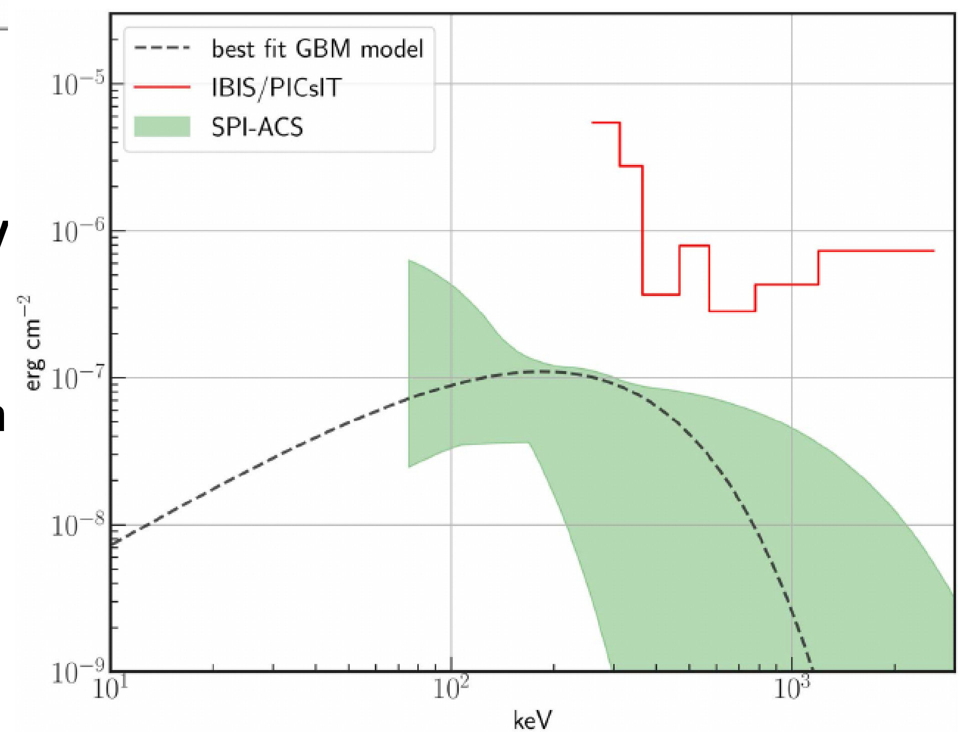


- **With this orientation, IBIS sensitivity much lower than that of SPI-ACS**
- **Orientation favorable to detect a signal from GRB 170817A, although not optimal**

SPI-ACS detection



- **Despite soft GRB spectrum and moderately favorable orientation, *INTEGRAL* achieved confident detection**
- **Triggered search → SNR=4.6 (100 ms timescale)**
  - 3.2σ association with GW170817
  - 4.2σ association with GBM



- **Average spectrum assuming a specific family of models**
- **Representative of SGRB spectra, not far from the GBM best-fit model of GRB 170817A**
- **Fluence of (1.4 ± 0.4) × 10^{-7} erg/cm^2 (75–2000 keV), consistent with GBM**

Final localizations

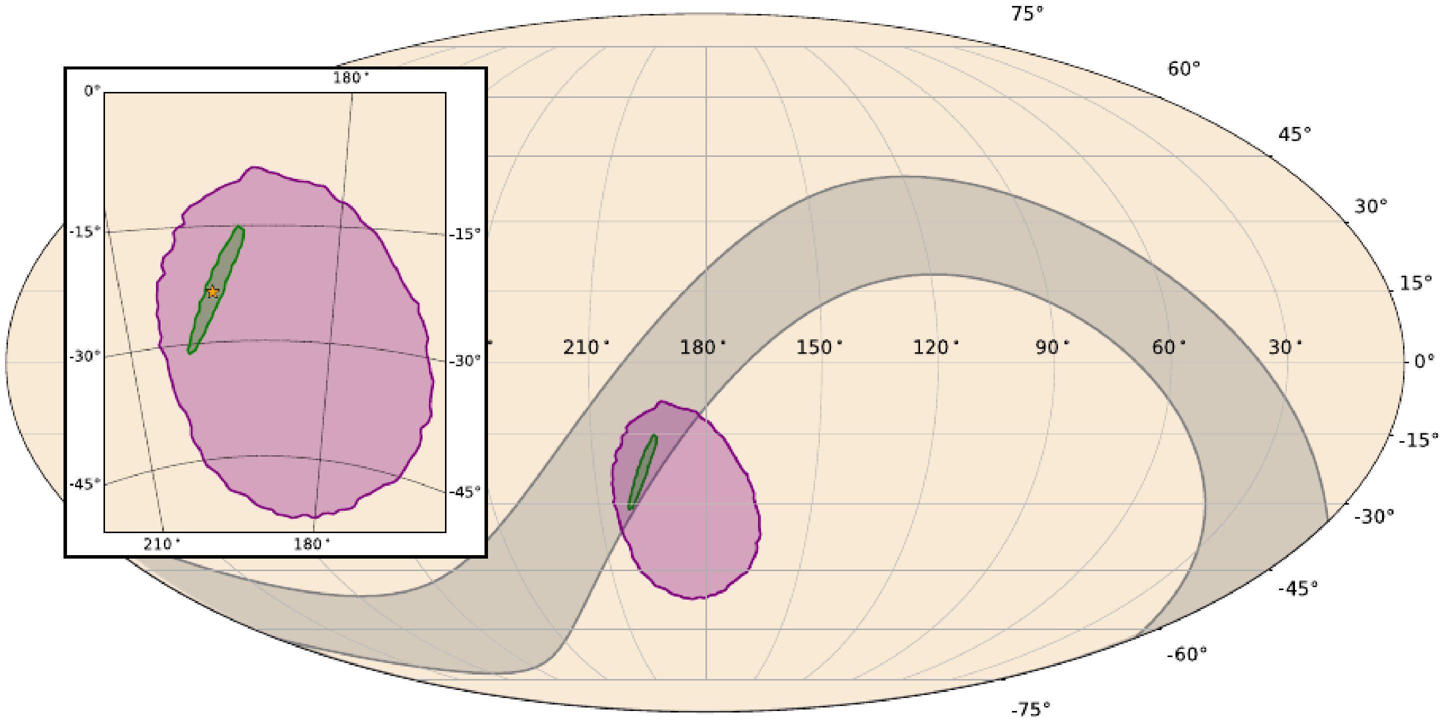
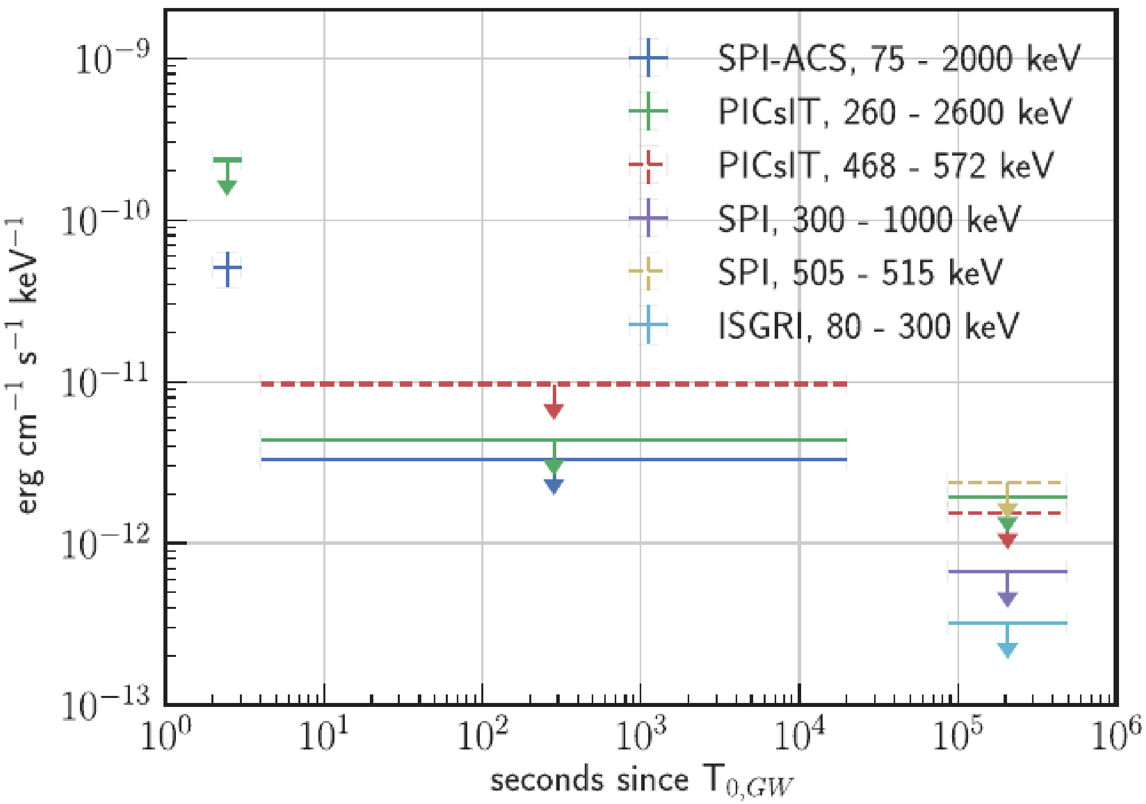


Figure 1. Final localizations. The 90% contour for the final sky-localization map from LIGO–Virgo is shown in green (LIGO Scientific Collaboration & Virgo Collaboration 2017a, 2017b, 2017c). The 90% GBM targeted search localization is overlaid in purple (Goldstein et al. 2017). The 90% annulus determined with *Fermi* and *INTEGRAL* timing information is shaded in gray (Svinkin et al. 2017). The zoomed inset also shows the position of the optical transient marked as a yellow star (Abbott et al. 2017f; Coulter et al. 2017a, 2017b). The axes are R.A. and decl. in the Equatorial coordinate system.

- **The addition of the *INTEGRAL* observation reduces the final 90% GBM localization area**

INTEGRAL follow-up pointed observations



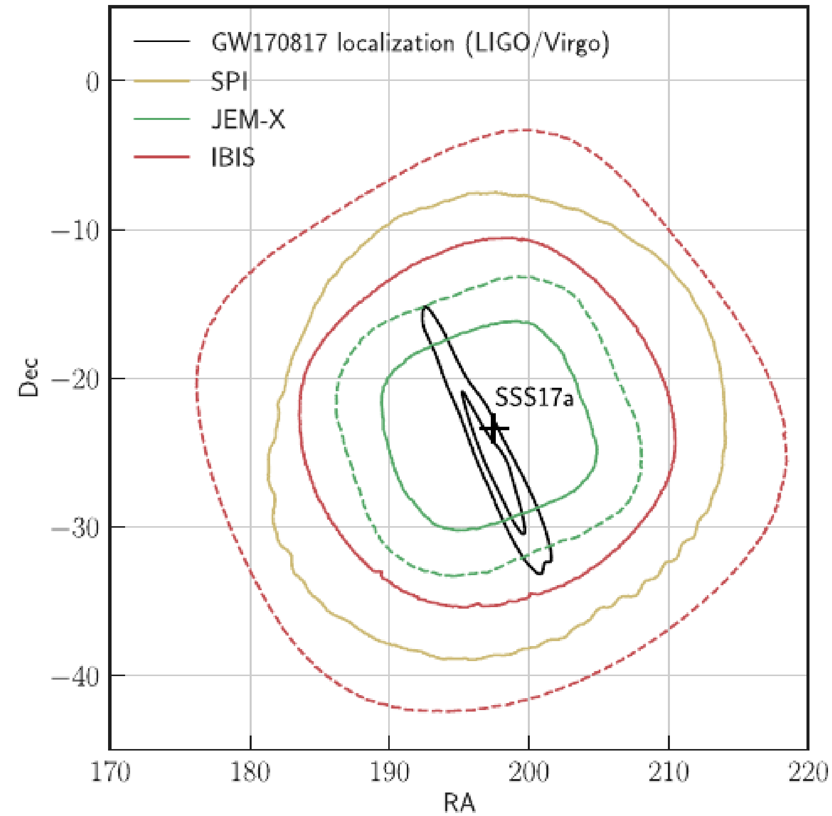
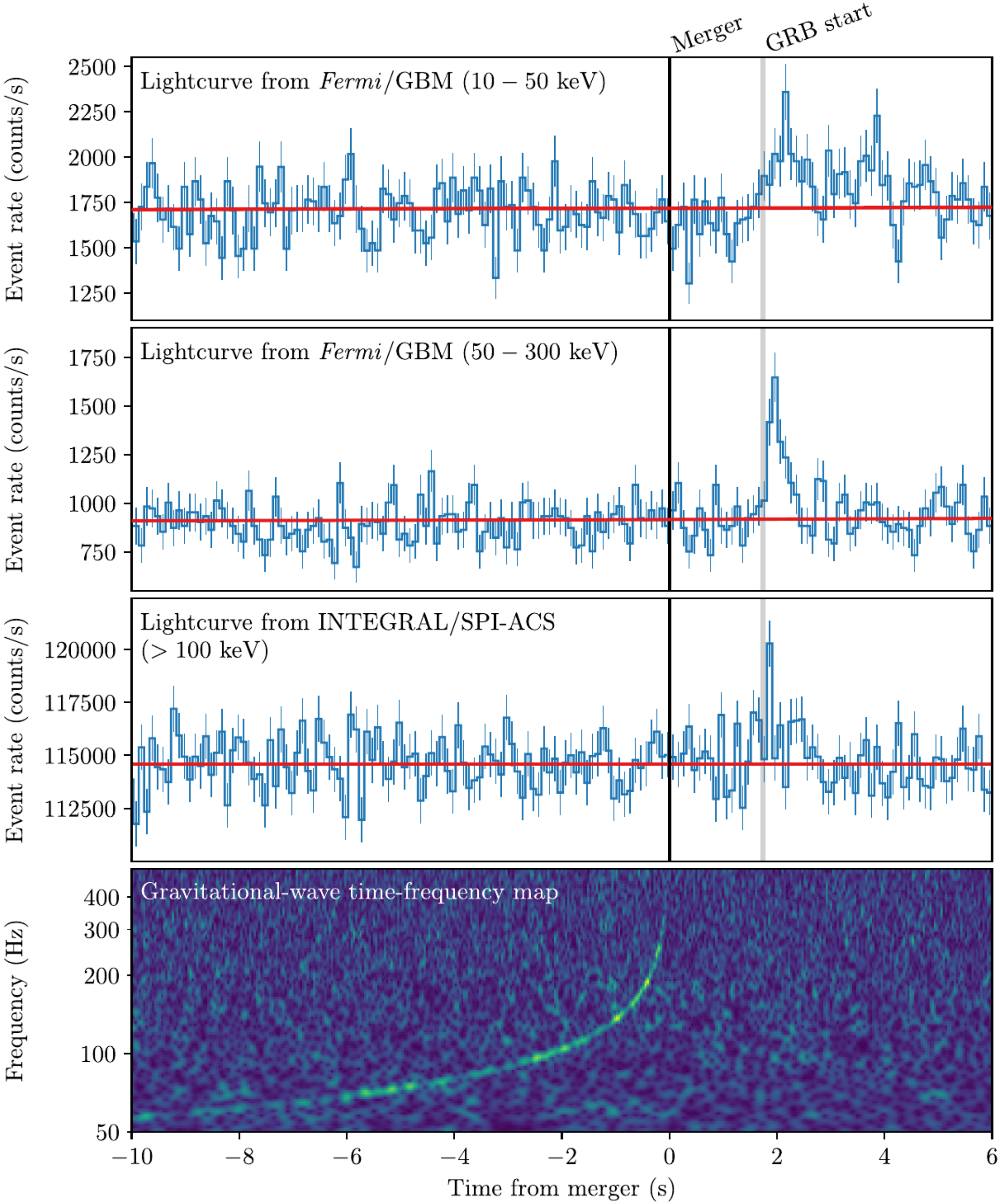


Figure 7. Sensitivity levels (50%—solid line and 10%—dashed line, of the optimal sensitivity achieved for AT 2017gfo/SSS17a) of the complete IBIS, JEM-X, and SPI mosaics of the targeted *INTEGRAL* follow-up observation,

- **A GRB at 40 Mpc could have produced bright hard X-ray afterglow**
- ***INTEGRAL* constrained new flux at least up to T0+20 ks**

Time delays

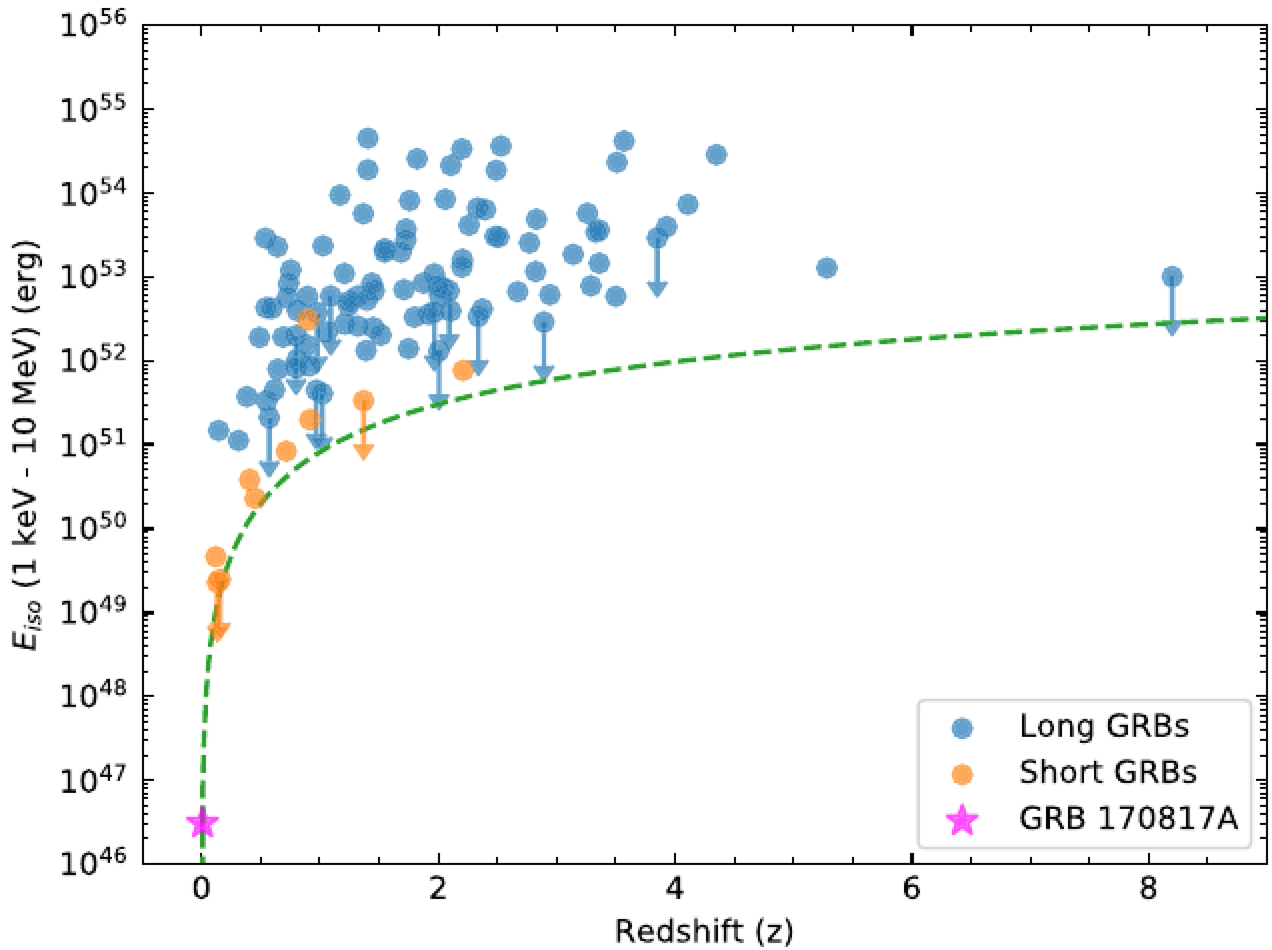


- **Delay of the start of GBM gamma-rays relative to the BNS merger (GW): 1.74 ± 0.05 s**
  - From fitting the first GBM pulse
- **Implications for GRB physics**
  - IS & jet propagation time
  - ES & deceleration radius
  - Soft tail: photospheric emission?
- **Implications for fundamental physics**
  - Speed of gravity

$-3\times10^{-15} \leq \Delta v / v_{EM} \leq +7\times10^{-16}$

  - Improved constraints on LIV
  - Test of the equivalence principle (propagation time of massless particles through gravitational field – i.e., of Milky Way)
  - Probe of the neutron star equation of state

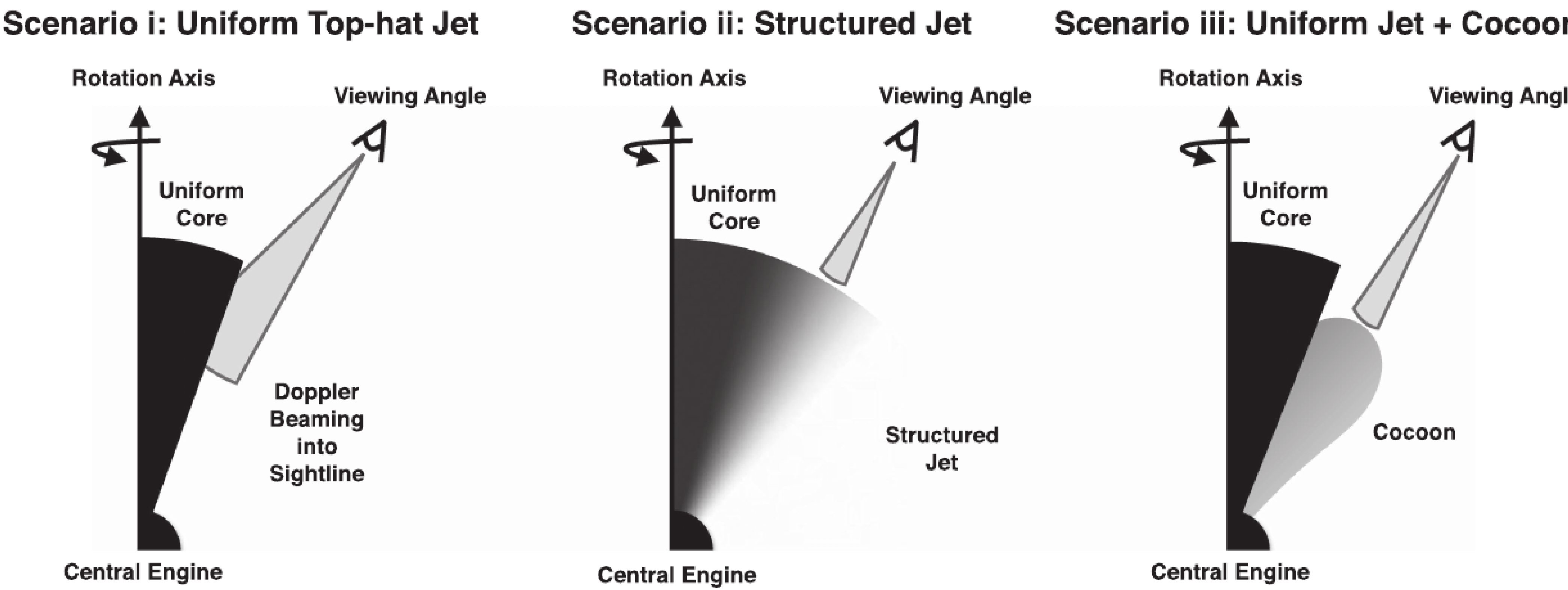
Energetics



- **Eiso = (5.3 ± 1.0) × 10^{46} erg**

- **Two orders of magnitude closer and 2 to 6 orders of magnitude less energetic than other SGRBs detected by the GBM**

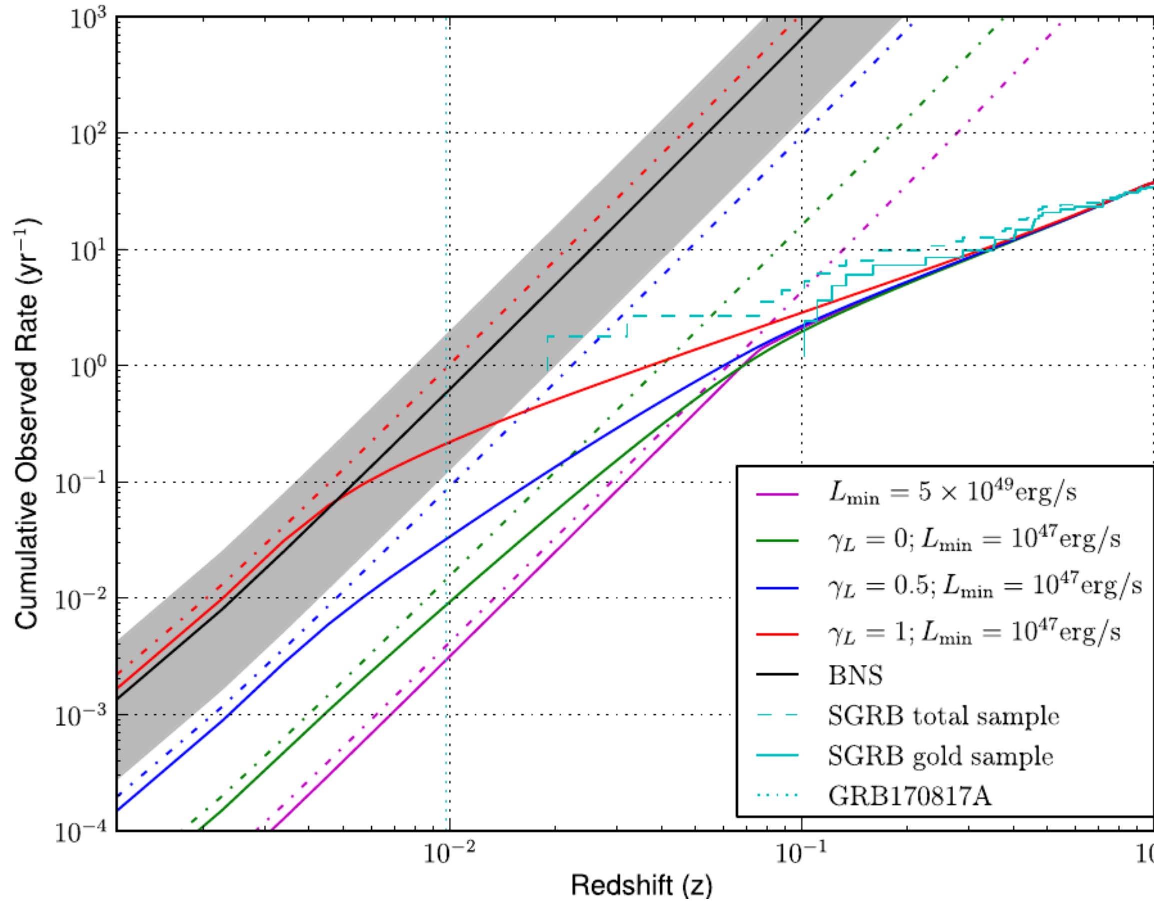
Possible observing scenarios



- **Intrinsic brightness vs geometric effects (jet viewing angle)?**
- **Several possible explanations, including:**
  - Simple jet with uniform Lorentz factor and sharp edges
  - Structured jet with non uniform Lorentz factor, observed off-axis
    - could explain dimness & marginally softness of the main pulse
  - A cocoon of surrounding material may explain the low-energy emission after initial spike

Detection rate

- **Evidence for a population of sub-luminous SGRBs → higher SGRB rate and higher joint GBM / LIGO-Virgo detection rate**
- **2018–19 observing run: expect 0.1 – 1.4 joint detections / yr (TBC) (GW & triggered GBM SGRBs)**
- **At design sensitivity of LIGO-Virgo: 0.3 – 1.7 joint detections / yr**
- **The LIGO-Virgo horizon can be larger than the horizon of current GRB instruments**
  - GBM could have seen GRB 170817A up to ~80 Mpc
- **Importance of the GBM sub-threshold searches!**



Conclusions

- **BNS mergers are progenitors of (at least some) SGRBs**
- **GRB 170817A is nearby and slightly softer than typical GBM-triggered SGRBs**
- **Softer (BB) emission (during and?) after the initial emission peak**
  - Near the detection limits of GBM
- **Possible full model for GRB 170817A?**
  - Off-axis emission from a top-hat jet providing the main emission episode
  - “Cocoon” emission arising from the jet’s interaction with the surrounding torus that powers the jet
    - May be a common property that is missed for SGRBs at greater distances
- **There likely exists a population of nearby weak events**
  - Importance of sub-threshold searches with current gamma-ray space monitors
- **Consequences for future missions like SVOM?**

More?

The Astrophysical Journal Letters, 848:L14 (14pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa8f41

An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: *Fermi*-GBM Detection of GRB 170817A

A. Goldstein[1], P. Veres[2], E. Burns[3,17], M. S. Briggs[2,4], R. Hamburg[2,4], D. Kocevski[5], C. A. Wilson-Hodge[5], R. D. Preece[2,4], S. Poolakkil[2,4], O. J. Roberts[1], C. M. Hui[5], V. Connaughton[1], J. Racusin[6], A. von Kienlin[7], T. Dal Canton[3,17], N. Christensen[8,9], T. Littenberg[5], K. Siellez[10], L. Blackburn[11], J. Broida[8], E. Bissaldi[12,13], W. H. Cleveland[1], M. H. Gibby[14], M. M. Giles[14], R. M. Kippen[15], S. McBreen[16], J. McEnery[6], C. A. Meegan[2], W. S. Paciesas[1], and M. Stanbro[4]

The Astrophysical Journal Letters, 848:L15 (8pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa8f94

INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817

V. Savchenko[1], C. Ferrigno[1], E. Kuulkers[2], A. Bazzano[3], E. Bozzo[1], S. Brandt[4], J. Chenevez[4], T. J.-L. Courvoisier[1], R. Diehl[5], A. Domingo[6], L. Hanlon[7], E. Jourdain[8], A. von Kienlin[5], P. Laurent[9,10], F. Lebrun[9], A. Lutovinov[11,12], A. Martin-Carrillo[7], S. Mereghetti[13], L. Natalucci[3], J. Rodi[3], J.-P. Roques[8], R. Sunyaev[11,14], and P. Ubertini[3]

The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa920c

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

LIGO Scientific Collaboration and Virgo Collaboration, *Fermi* Gamma-ray Burst Monitor, and INTEGRAL

Backup

GBM observation sequence

Time (UTC)	Relative	Comment
12:41:06.474598	0	Trigger Time: End of 0.256 s interval containing statistically significant rate increase
12:41:06.477006	+2.4 ms	Triggered: Autonomously detected in-orbit by the *Fermi*-GBM flight software
12:41:20	+14 s	*Fermi*-GBM Alert Notice sent by the GCN system at NASA/GSFC
12:41:31	+25 s	Automatic location from GBM flight software sent by the GCN: R.A. = 172.0, Decl. = −34.8, err = 32.6 deg
12:41:44	+38 s	More accurate automatic location by ground software sent by GCN: R.A. = 186.6, Decl. = −48.8, err = 17.4 deg
13:26:36	+44.9 min	More accurate human-guided localization sent by GCN: R.A. = 176.8, Decl. = −39.8, err = 11.6 deg
13:47:37	+66.5 min	LVC GCN Circular reporting localization and consistency of signal with a weak short GRB (Connaughton et al. 2017)
20:00:07	+7.3 hr	Public GCN Circular establishing GRB name and standard GBM analysis (von Kienlin et al. 2017)
00:36:12 (next day)	+11.9 hr	LVC GCN Circular reporting updated spectral analysis, energetics, and association significance (Goldstein 2017)

Minimum variability timescale