



Swift によるガンマ線バースト 観測の最前線

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Swift Gamma-ray Burst Explorer Mission

■ NASA's Medium-Class Explorers (MIDEX)

- Jan 1999: Selected for Phase A study
- Oct 1999: Selected for flight
- Nov 2004: Launch

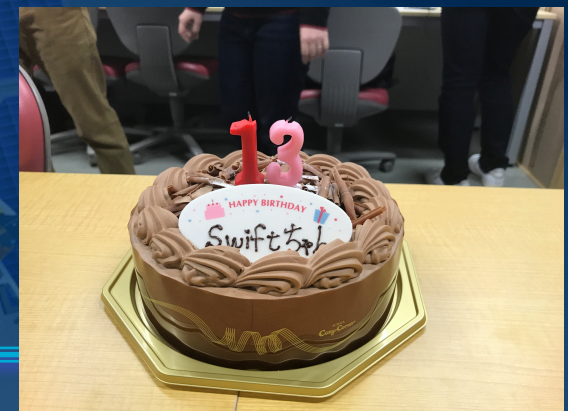
■ International collaboration (mainly US, UK and Italy)

- Burst Alert Telescope (BAT): New development at NASA/GSFC and LANL
- X-ray Telescope (XRT): Mirror (JET-X FM unit), CCD (XMM-Newton EPIC MOS); PSU, INAF and UL
- Ultra-Violet/Optical Telescope (UVOT): Copy of XMM-Newton OM; PSU and MSSL

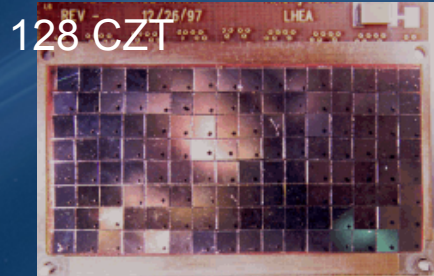
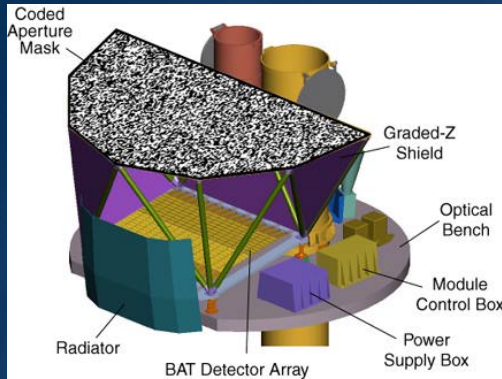
■ Successful mission extension

- 2016 NASA Astrophysics Senior Review **ranked #1!**

13 years on orbit!!



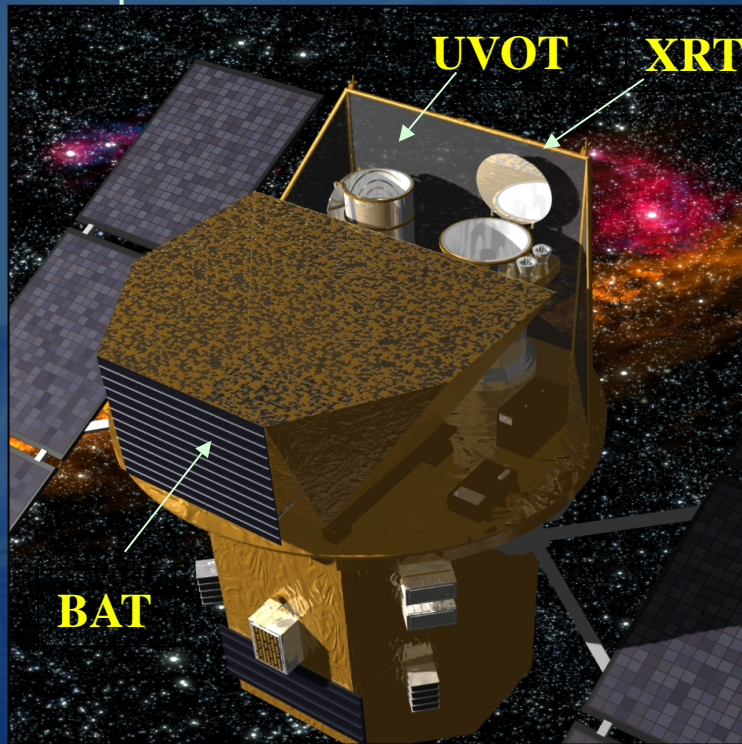
Burst Alert Telescope (BAT)



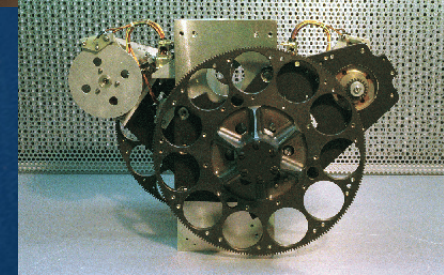
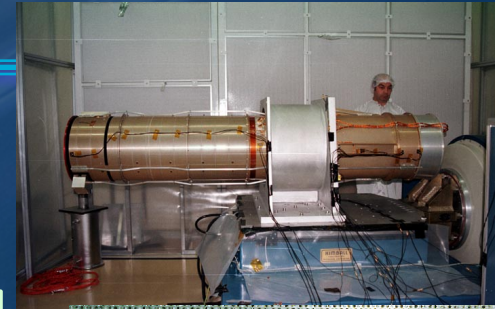
E_range: 15-150 keV (15-350 keV)
 Det: CdZnTe ($4 \times 4 \times 2 \text{ mm}^3$)
 # of detectors: 32,768 (256×128)
 FOV: 120 deg x 90 deg
 Pos: $1' - 3'$

UV/Optical Telescope (UVOT)

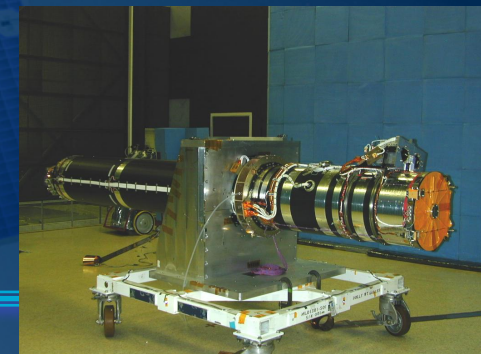
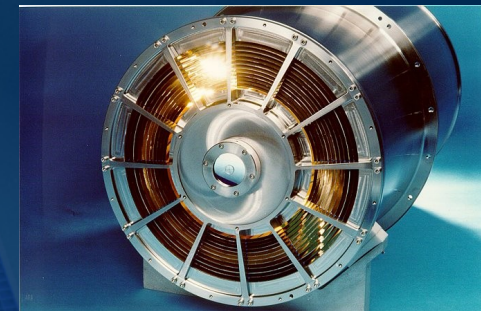
Aperture: 30 cm (XMM OM)
 Det: MCP+CCD (XMM OM)
 FOV: $17' \times 17'$
 7 filters (UV - Opt)+2 grism



E_range: 0.3-10 keV
 Focal Length: 3.5m
 Det: X-ray CCD (XMM MOS)
 FOV: $23' \times 23'$



X-Ray Telescope (XRT)

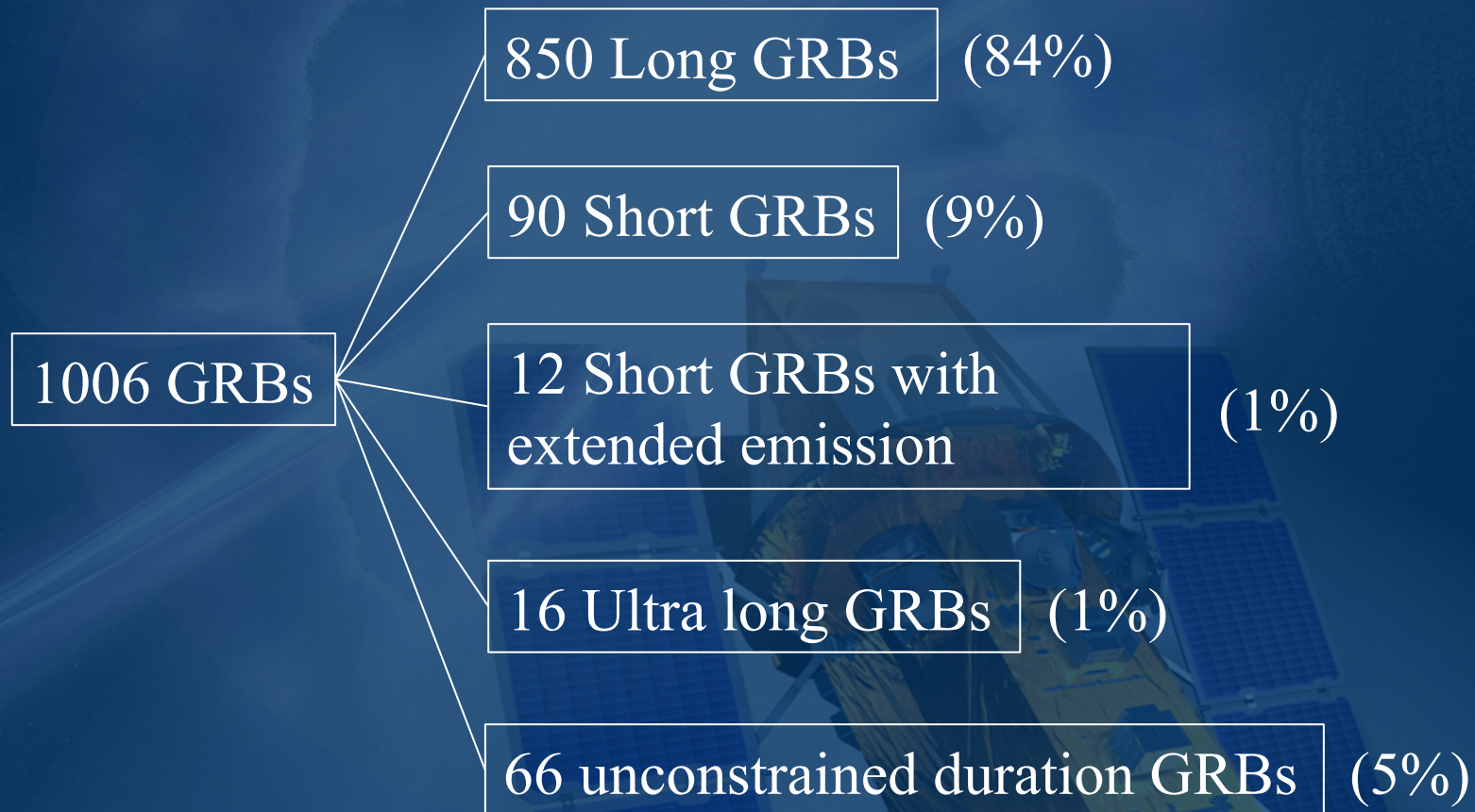


BAT Operation

- HV is on for all time
- BAT flight software does not process the data when the total count rate $> \sim 16,000$ c/s
- BAT on-board trigger is off during a high count-rate ($> \sim 16,000$ c/s) and a slew
- BAT fraction of observing time
 - $\sim 78\%$ (Off time of 2015: 14% slew + 8% high count-rate)
- Number of enabled detectors: $\sim 20,000$ (60%)

BAT GRB Demographics (Lien et al. 2016)

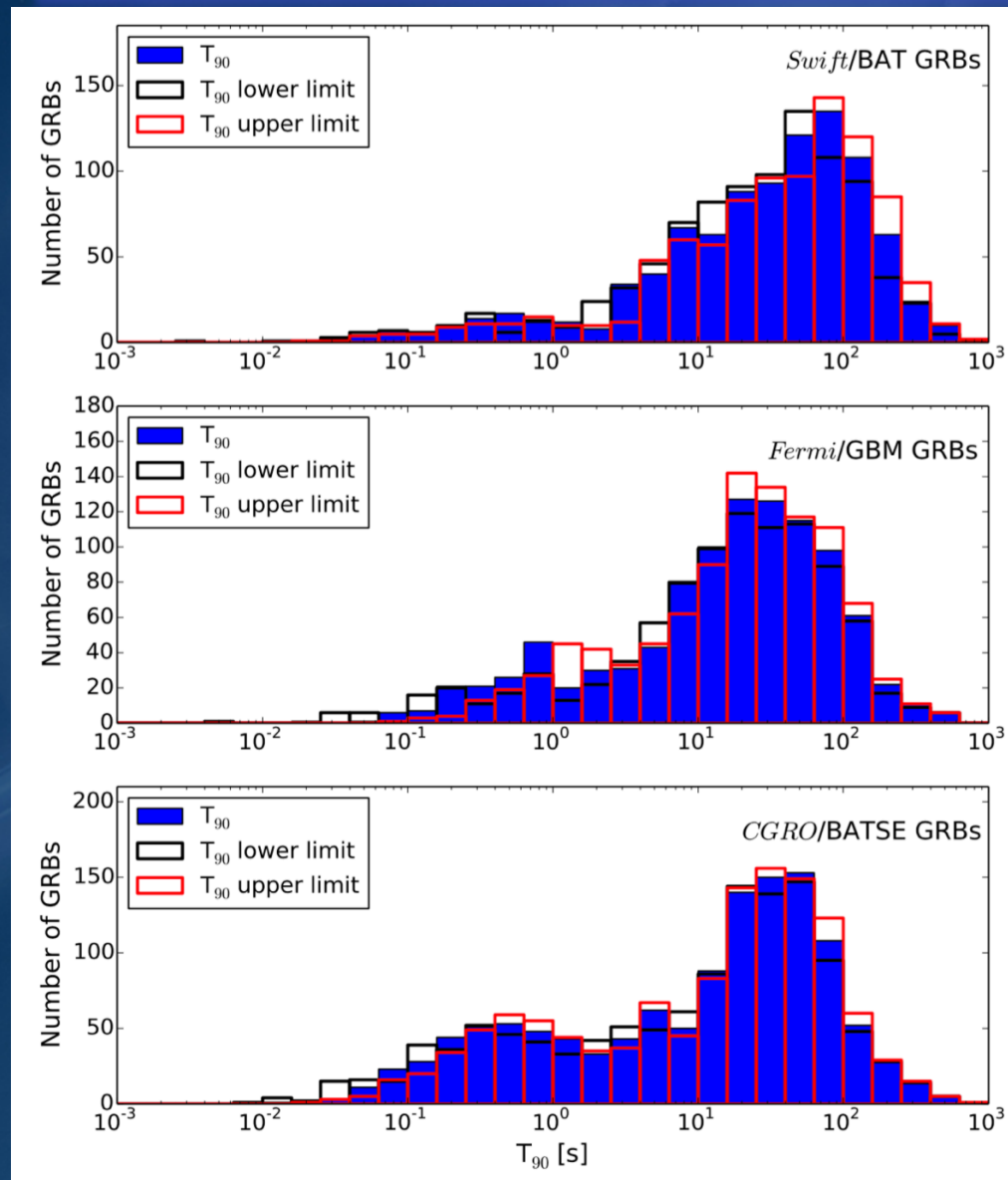
- **1006** GRBs (from GRB 041217 to GRB 151027B)
(e.g., BAT 2nd catalog: 476 GRBs)



(Long GRB: $T_{90} \geq 2$ s Short GRB: $T_{90} < 2$ s)

Duration Distribution

(Lien et al. 2016)



- 940 BAT GRBs
(Constrained T_{90} with error)

- Averaged T_{90} of Long GRB

- **BAT: ~80 s**

- Fermi-GBM: 30 s

- BATSE: 30 s

BAT energy band is lower than the Fermi GBM and the BATSE

- Fraction of Short GRB

- **BAT: 9%**

- Fermi-GBM: 17%

- BATSE: 26%

‘GRB detection’ of BAT requires the localization of a GRB

Short on short GRBs in BAT

(Sakamoto et al. 2010 @ Annapolis)

BAT: 10% S-GRBs (90% L-GRBs)

BATSE: 25% S-GRBs (75% L-GRBs)

Factor of 2.5 small # on S-GRBs in BAT

BATSE

- Rate trigger

vs.

BAT

- Rate trigger

- Imaging

BATSE complete spectral catalog
(Goldstein, Preece & Mallozzi)

BATSE short GRBs Band spectral parameters



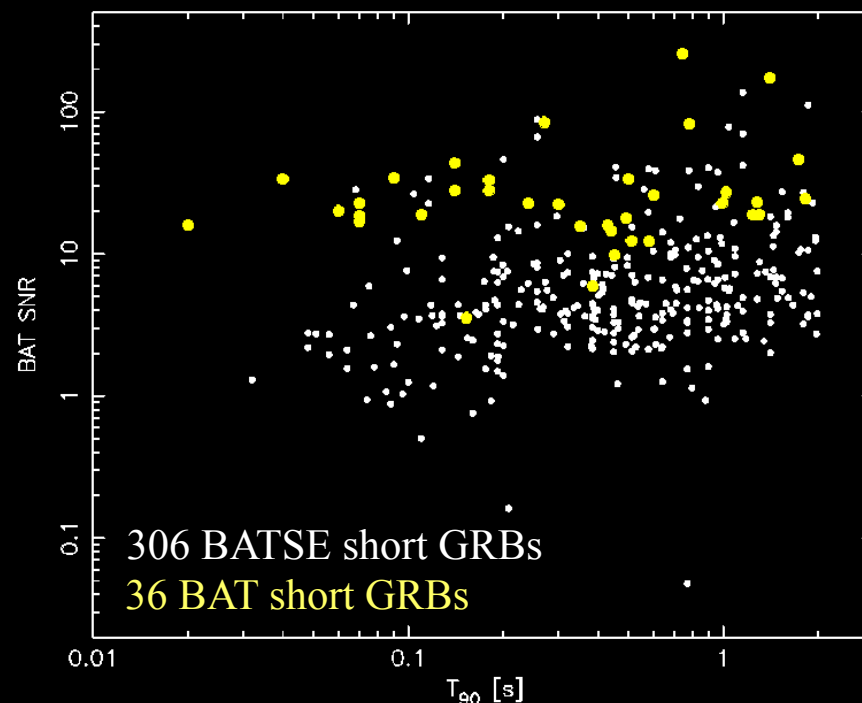
BAT energy response (30^d) + background



Simulate BAT fg/bg spectrum

→ SNR

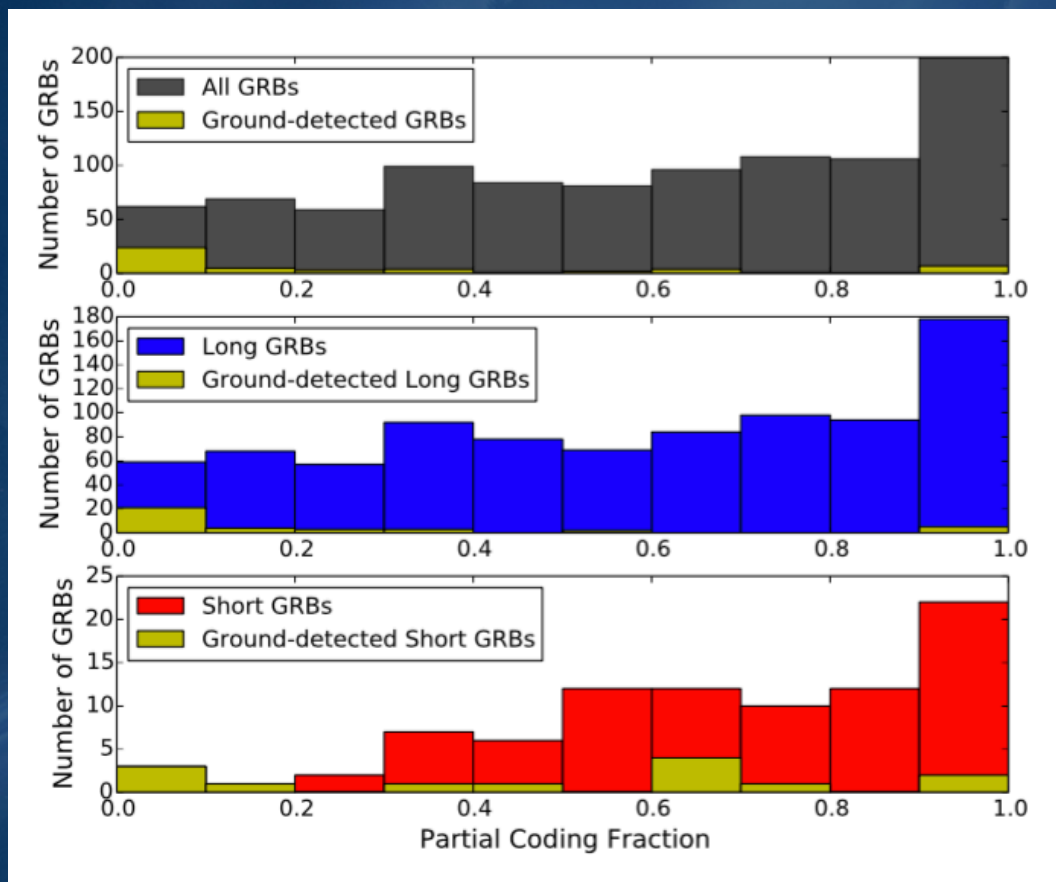
Preliminary



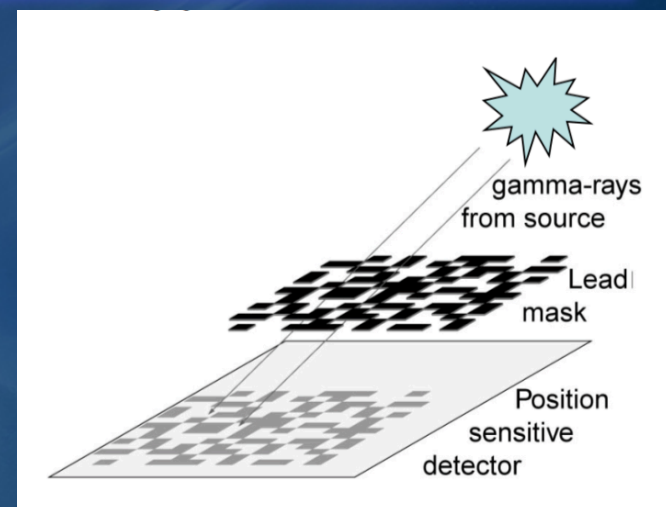
Majority of the BATSE short GRBs
is too faint in BAT

Small number of short GRBs in BAT samples

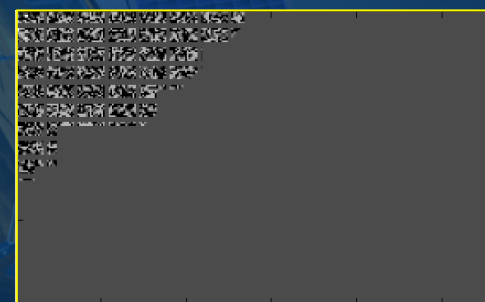
Number of BAT GRBs vs. Partial coding fraction



Short GRBs are difficult to localize below partial coding fraction of 0.3
Smaller effective FoV for s-GRBs



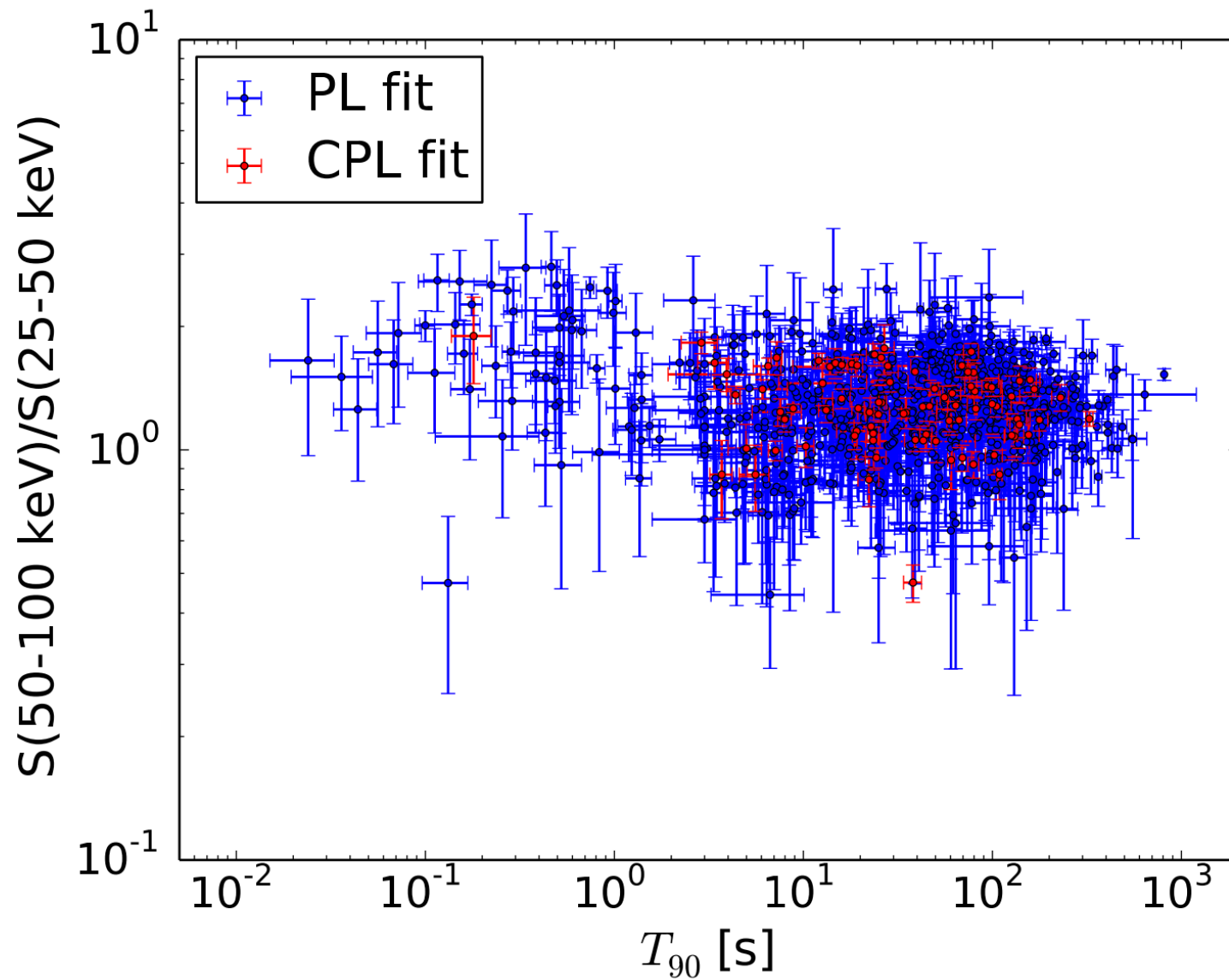
Partial
Coding
Fraction: 1.0



Partial
Coding
Fraction: 0.1

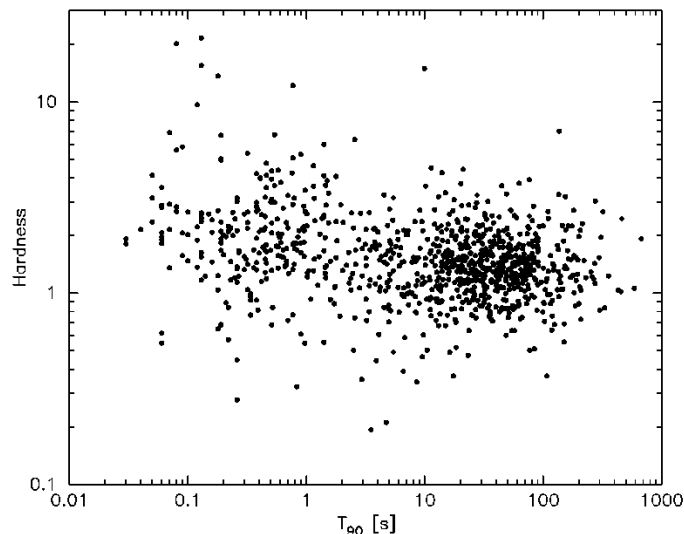
Hardness vs. T_{90}

(Lien et al. 2016)

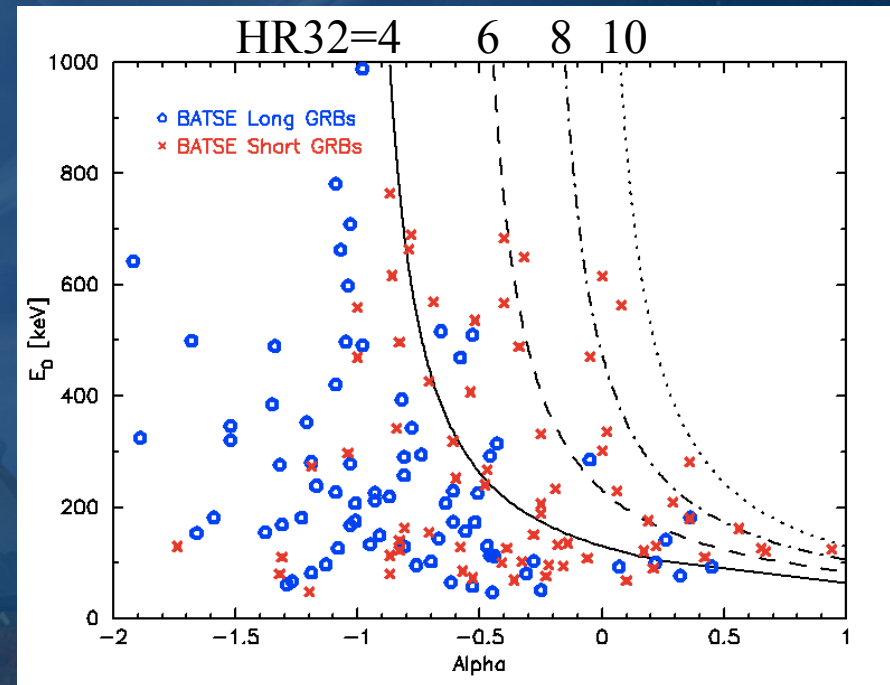
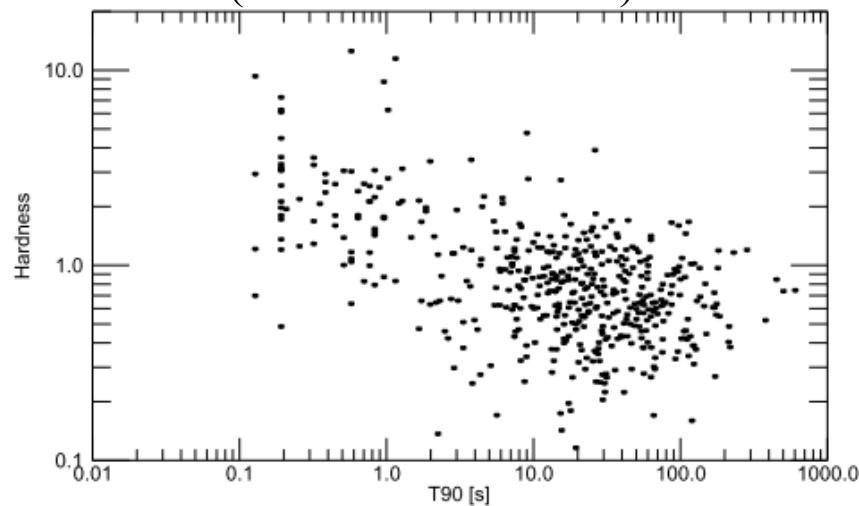


Hardness of S-GRBs?

BATSE



Fermi GBM (Paciesas et al. 2012)



(Sakamoto et al. 2006)

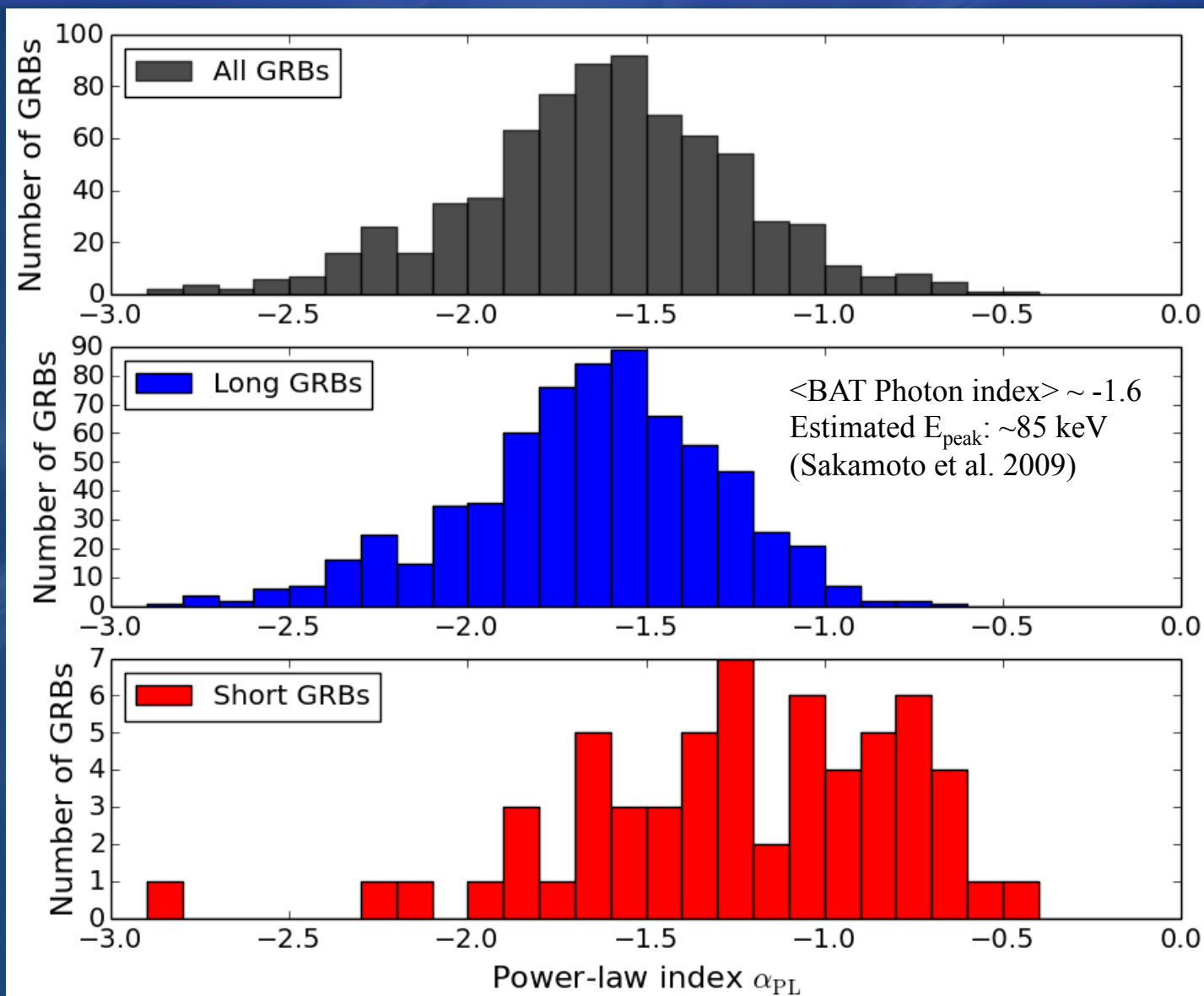
$$(*) E_{\text{peak}} = (2 + \alpha) E_0$$

HR > 4 requires low-energy photon index to be extremely flat or positive

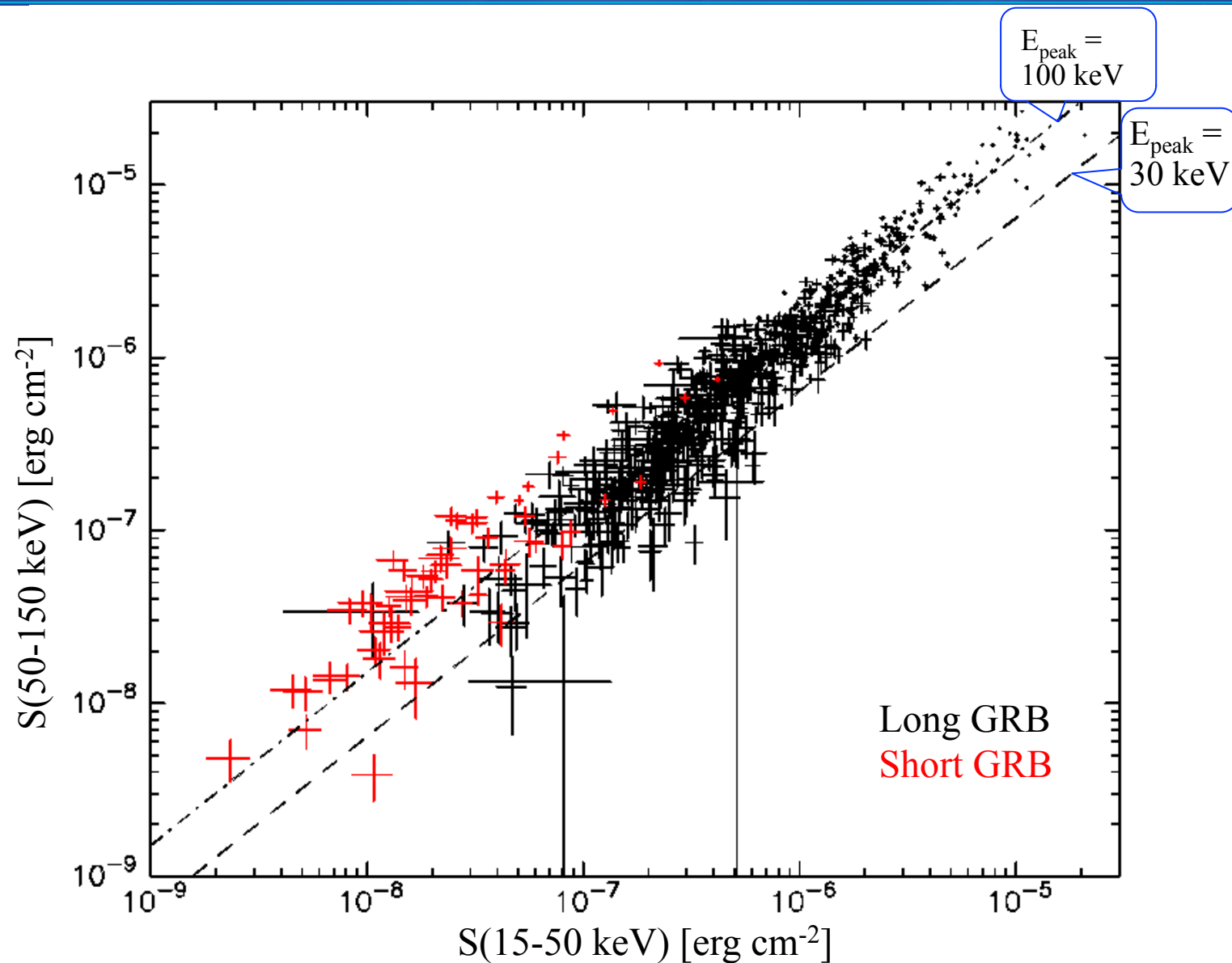
“Clear anti-correlation between hardness and T_{90} ”

PL: Photon index distribution

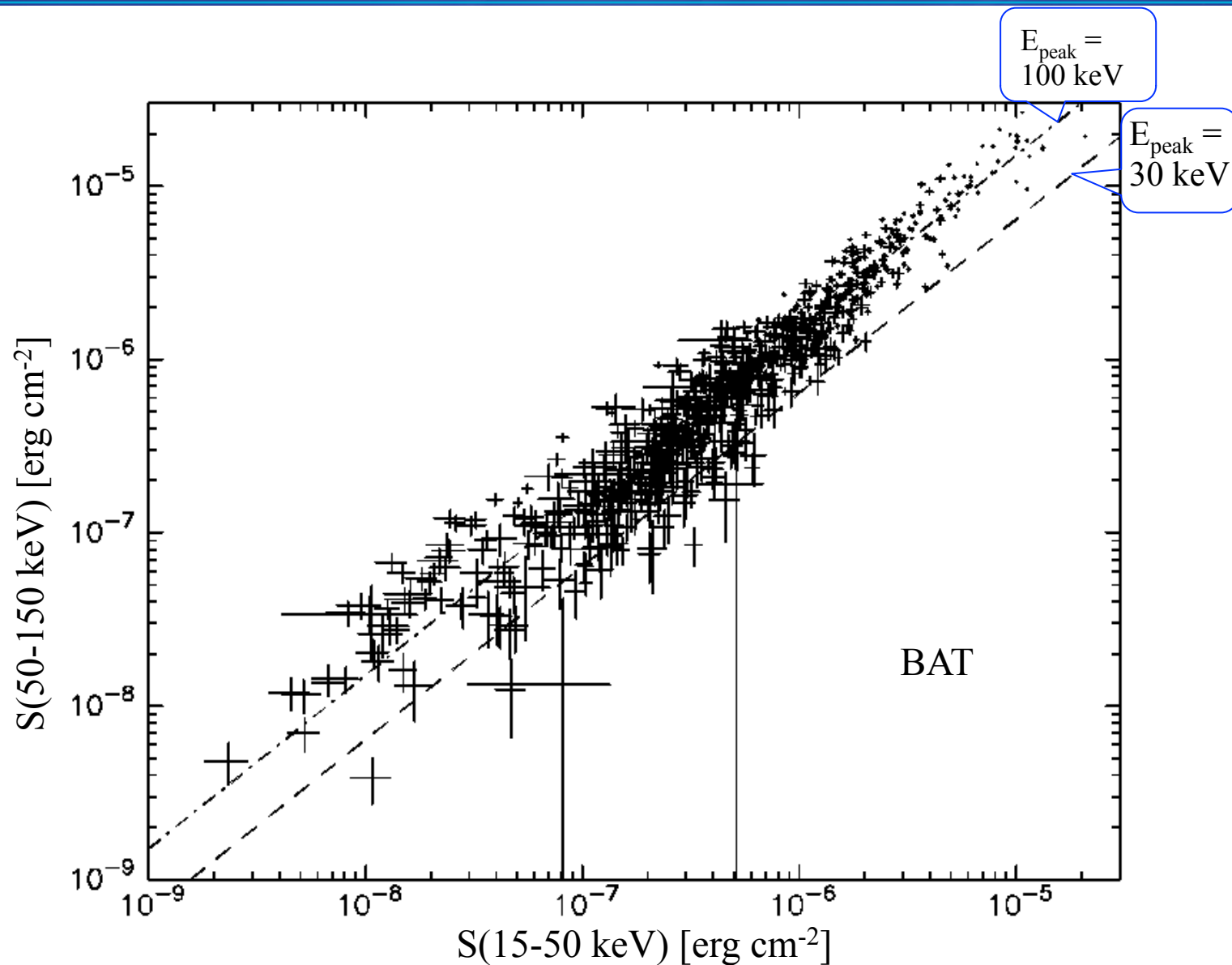
(Lien et al. 2016)



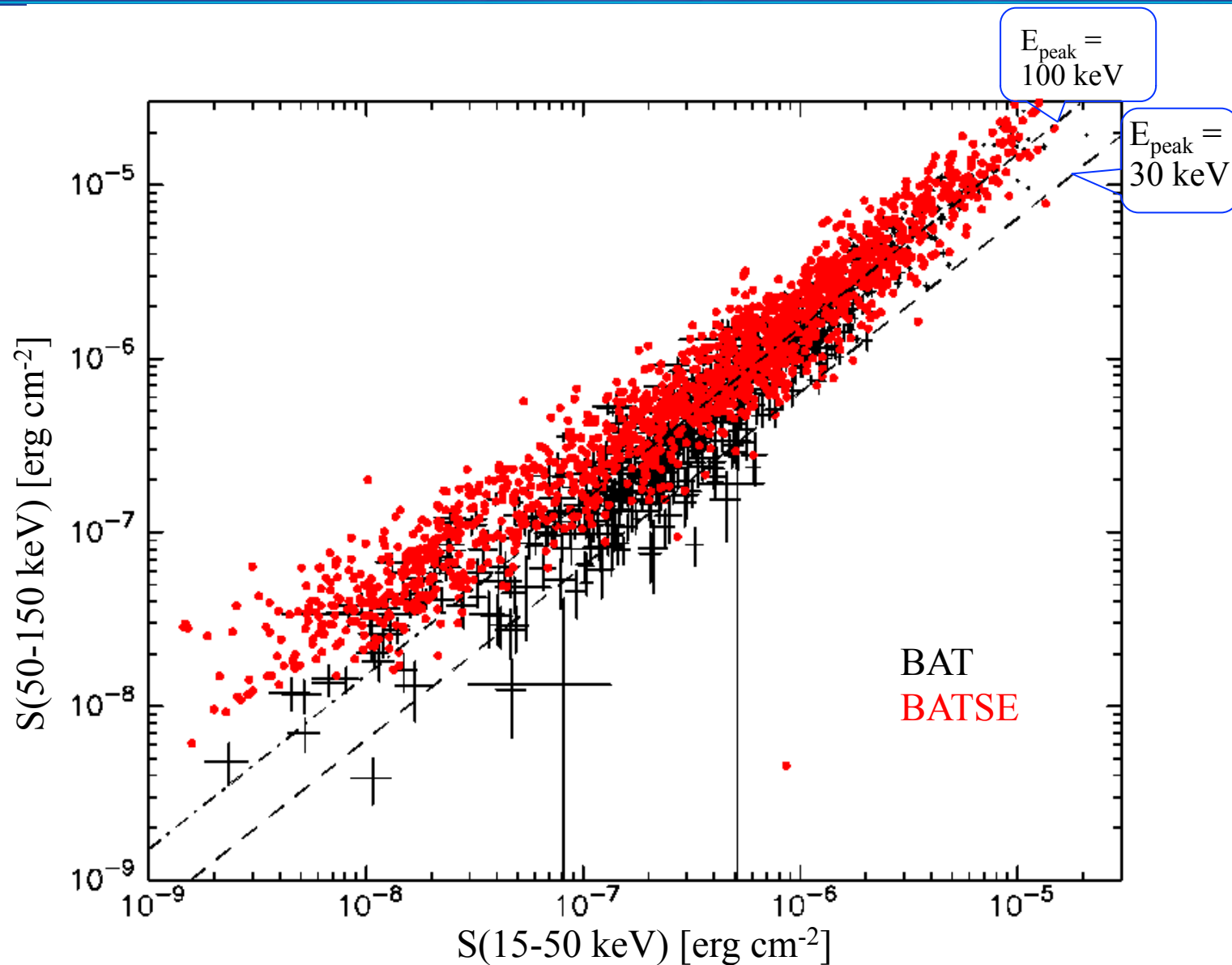
S(50-150 keV) vs. S(15-50 keV)



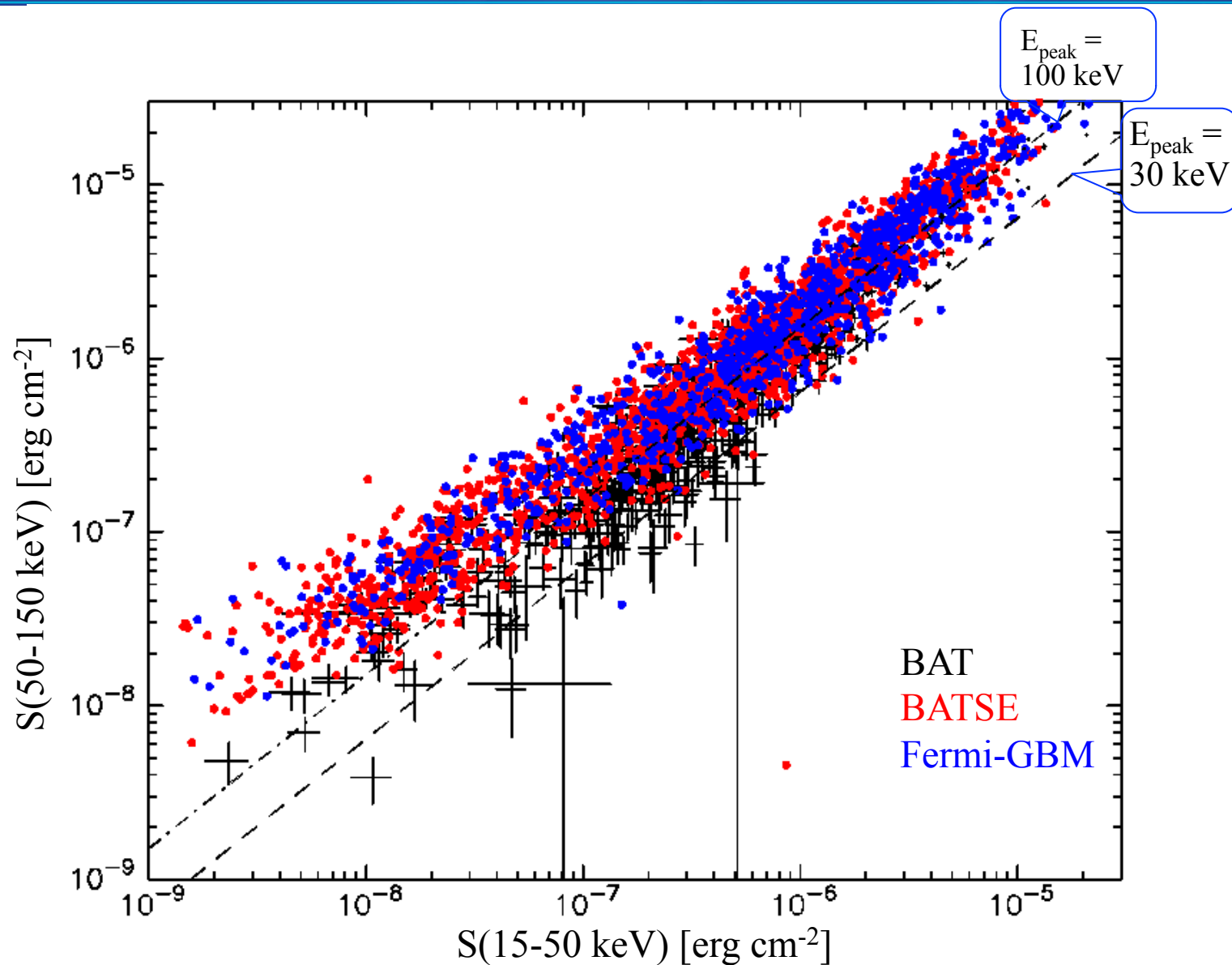
S(50-150 keV) vs. S(15-50 keV)



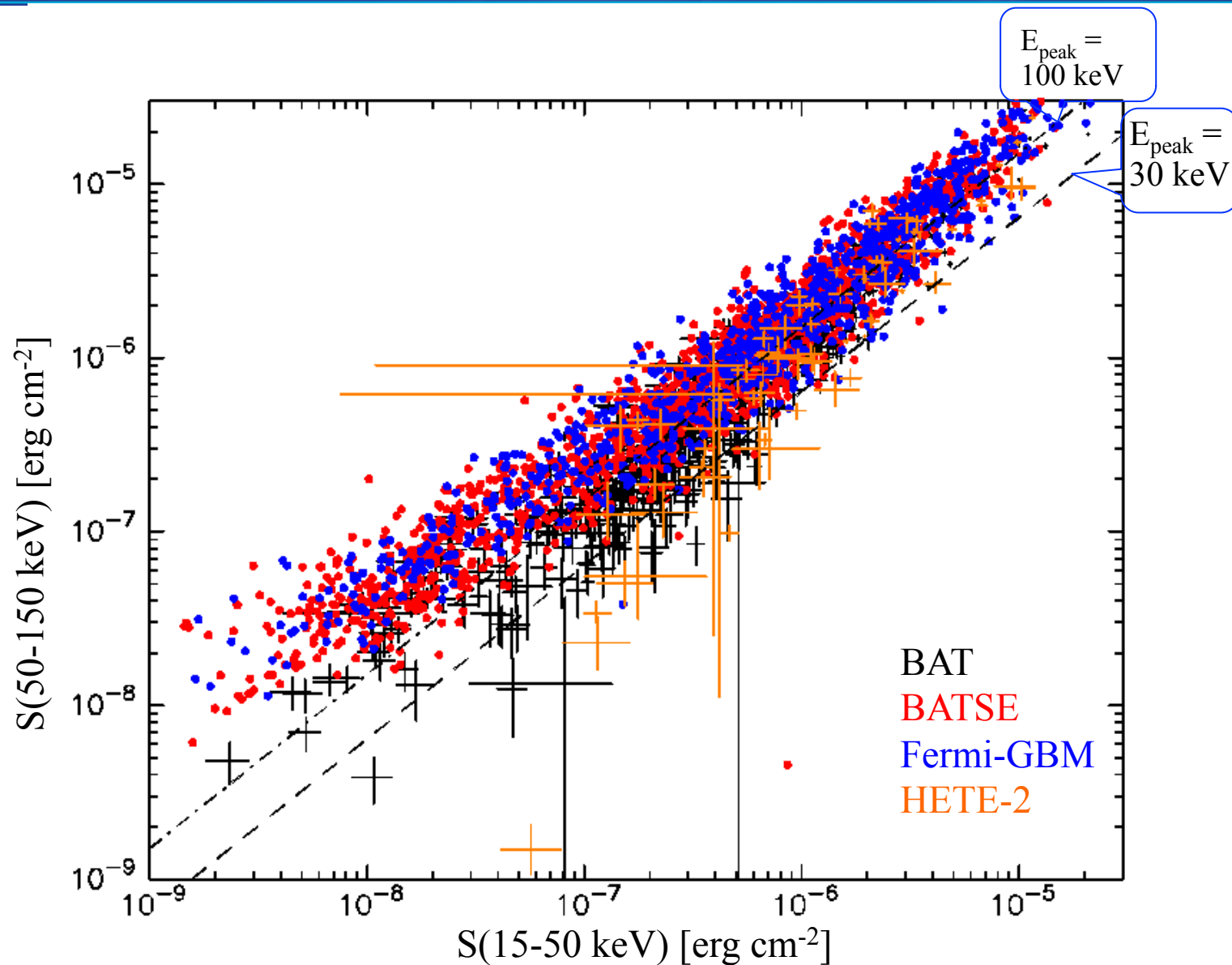
S(50-150 keV) vs. S(15-50 keV)



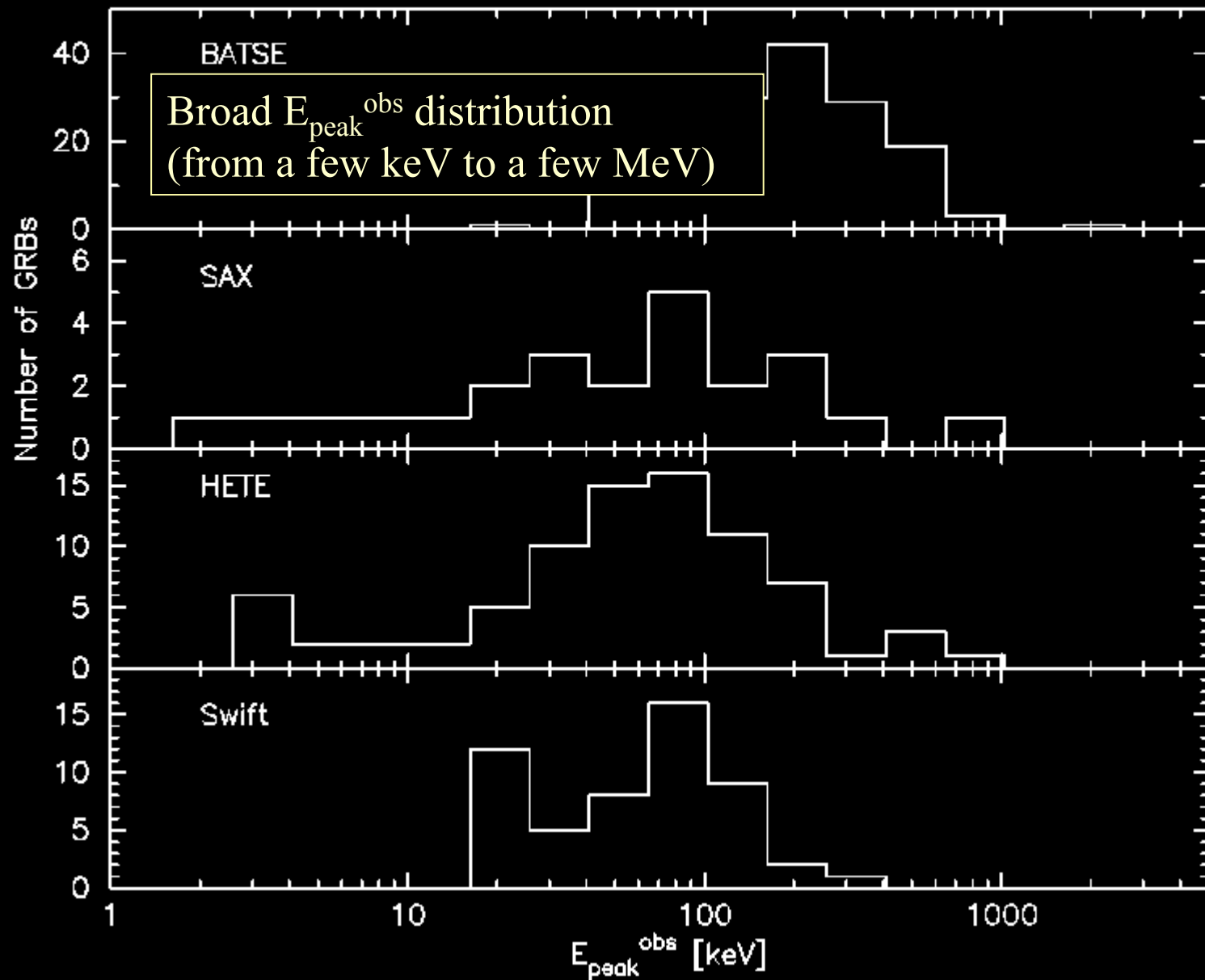
S(50-150 keV) vs. S(15-50 keV)



S(50-150 keV) vs. S(15-50 keV)

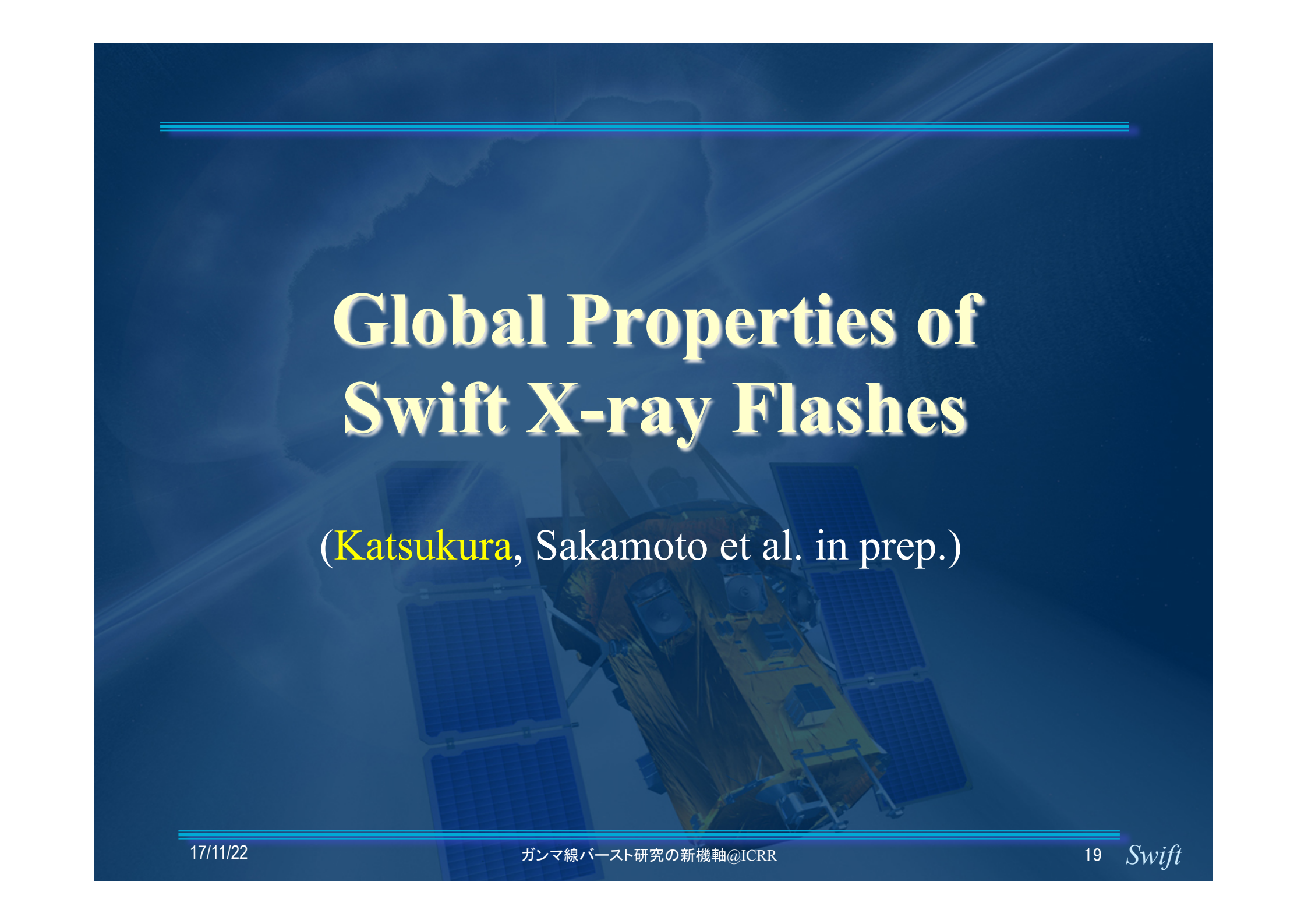


$E_{\text{peak}}^{\text{obs}}$ Distribution



Summary

- BAT is fine. Swift is in very good shape after 13 years on-orbit.
- Short on short GRBs in BAT. Require many photons to localize GRBs. The effective FoV for short GRBs is narrower.
- “Short GRBs are hard” needs to be careful about the actual meaning.
- BAT detects relatively soft GRBs comparing to that of BATSE

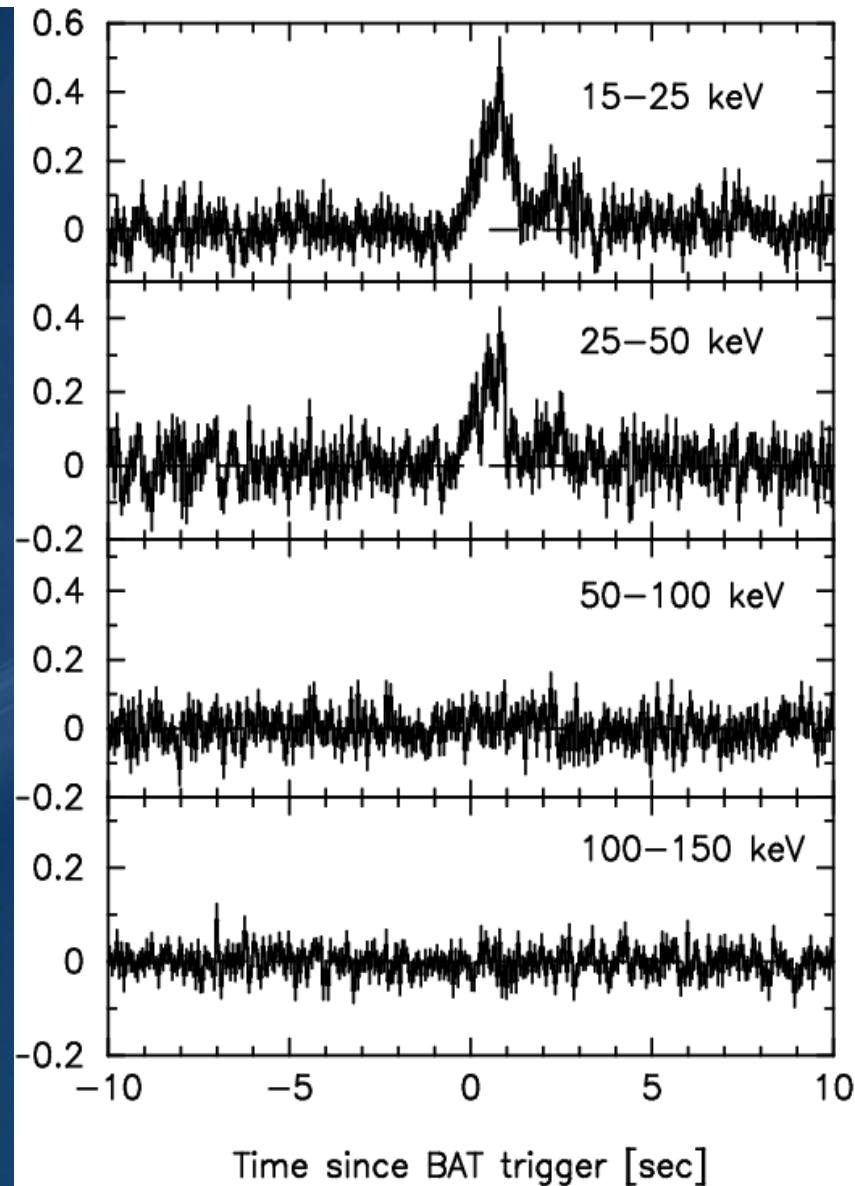


Global Properties of Swift X-ray Flashes

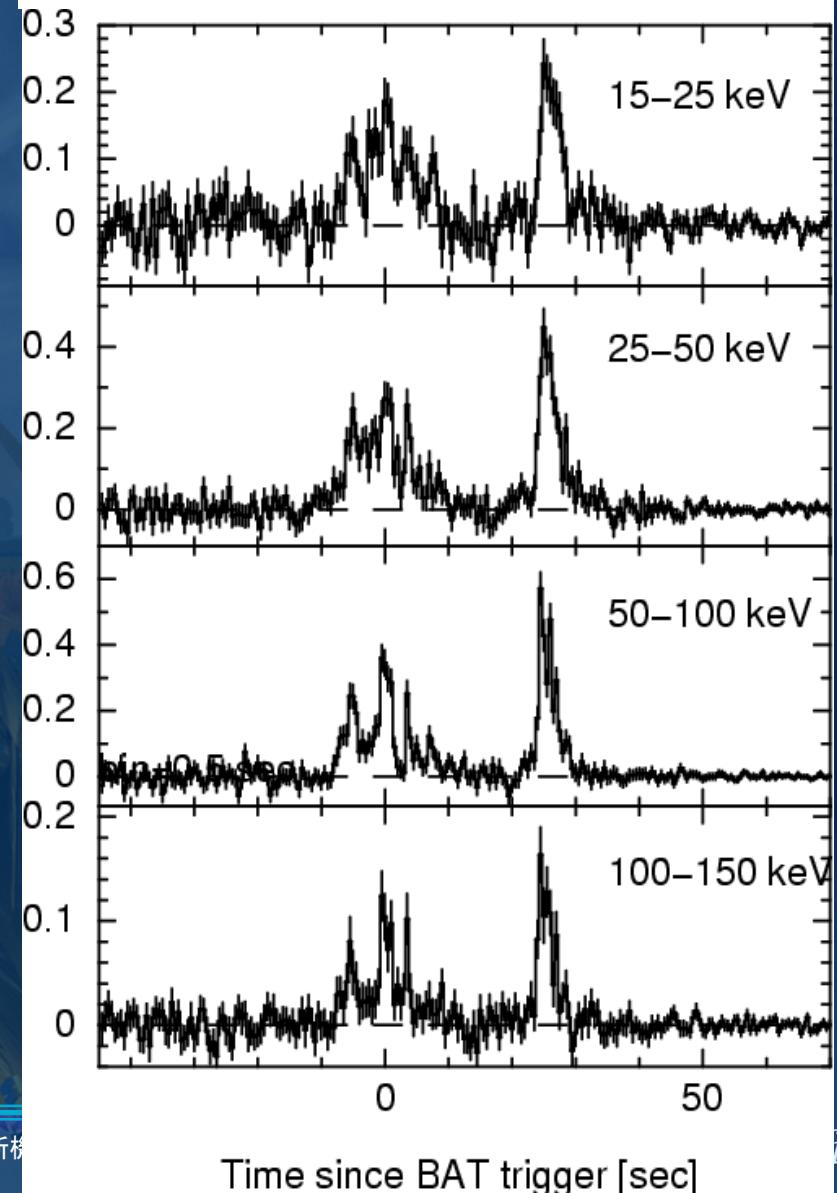
(Katsukura, Sakamoto et al. in prep.)

X-ray Flashes and Classical GRBs

XRF 050416A



GRB 050401



Classification of GRBs

BeppoSAX “XRFs: Detected by Wide Field Camera (WFC), but not by Gamma-ray burst monitor (GRBM)”

HETE-2

(Sakamoto et al. 2005)

$\log (S_x / S_\gamma) > 0$	XRF
$-0.5 < \log (S_x / S_\gamma) \leq 0$	XRR
$\log (S_x / S_\gamma) \leq -0.5$	C-GRB

(Fluence in 2-30 keV : S_x , Fluence in 30-400 keV : S_γ)

Swift/BAT

(Sakamoto et al. 2008)

$\alpha = -1, \beta = -2.5, E_p = 100 \text{ keV}$

$S(25 - 50 \text{ keV}) / S(50 - 100 \text{ keV}) \leq 0.72$	C-GRB	
$0.72 < S(25 - 50 \text{ keV}) / S(50 - 100 \text{ keV}) \leq 1.32$	XRR	(1)
$S(25 - 50 \text{ keV}) / S(50 - 100 \text{ keV}) > 1.32$	XRF	

$\alpha = -1, \beta = -2.5, E_p = 30 \text{ keV}$

Sample

■ Classified sample

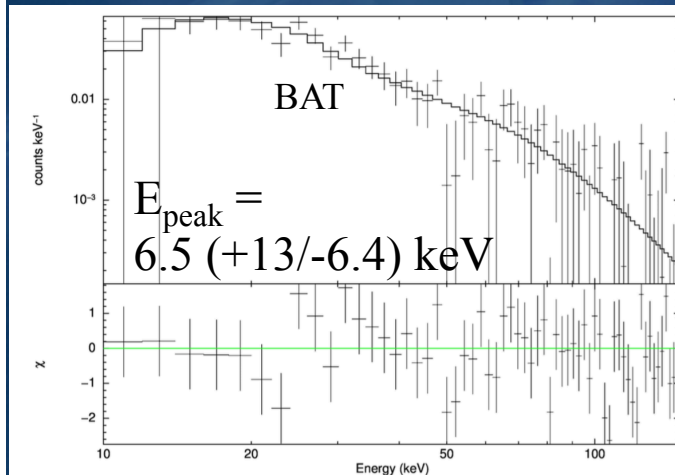
- 745 Swift detected GRBs (April 2005 – January 2014) (cf., Sakamoto et al. 2008; total 158 GRBs)

■ Spectral analysis sample

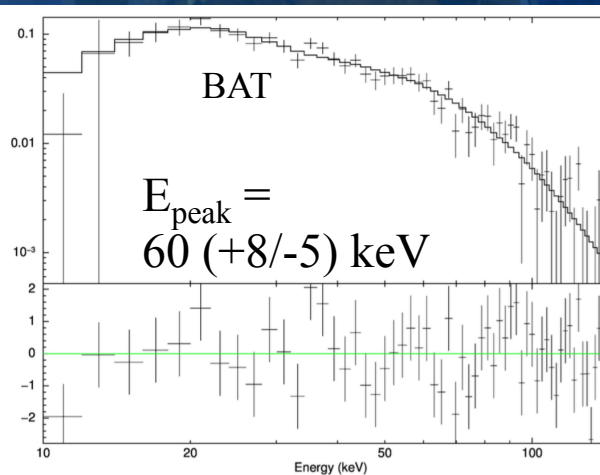
- 26 XRFs, 50 XRRs, 18 C-GRBs (35 known-z)

(cf. Sakamoto et al. 2008; 10 XRFs, 17 XRRs, 14 C-GRBs)

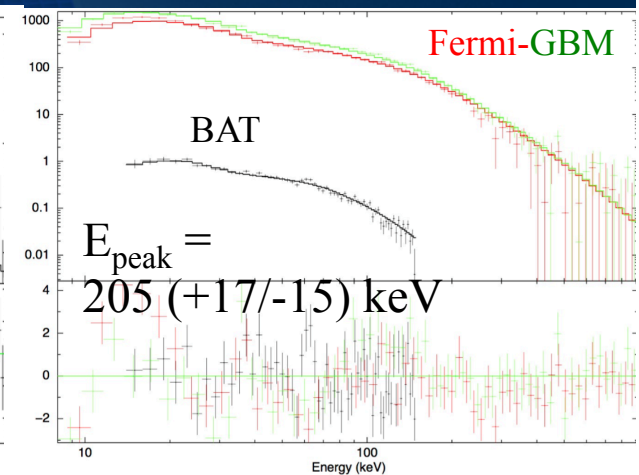
XRF 081007



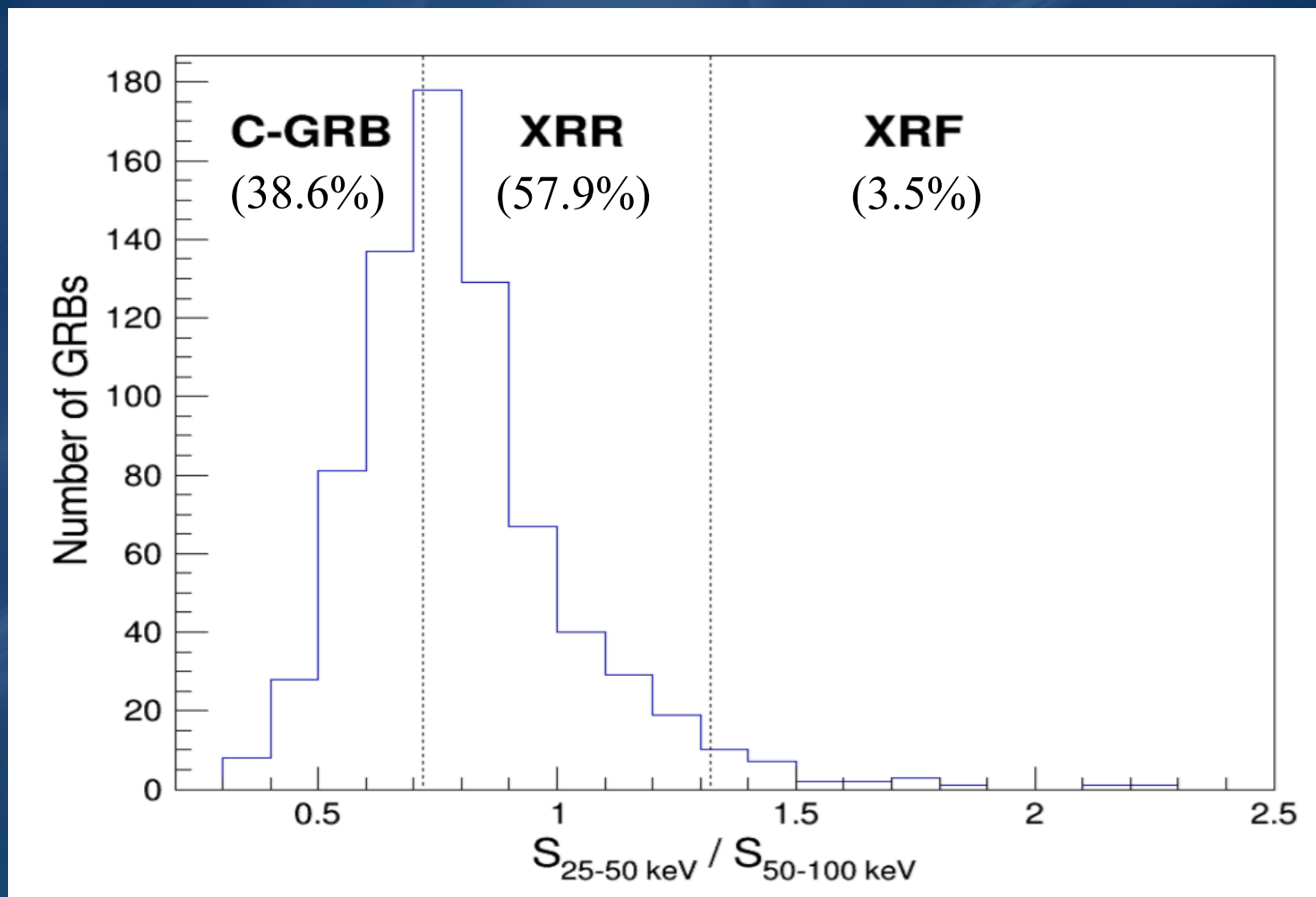
XRR 120927A



GRB 110625A

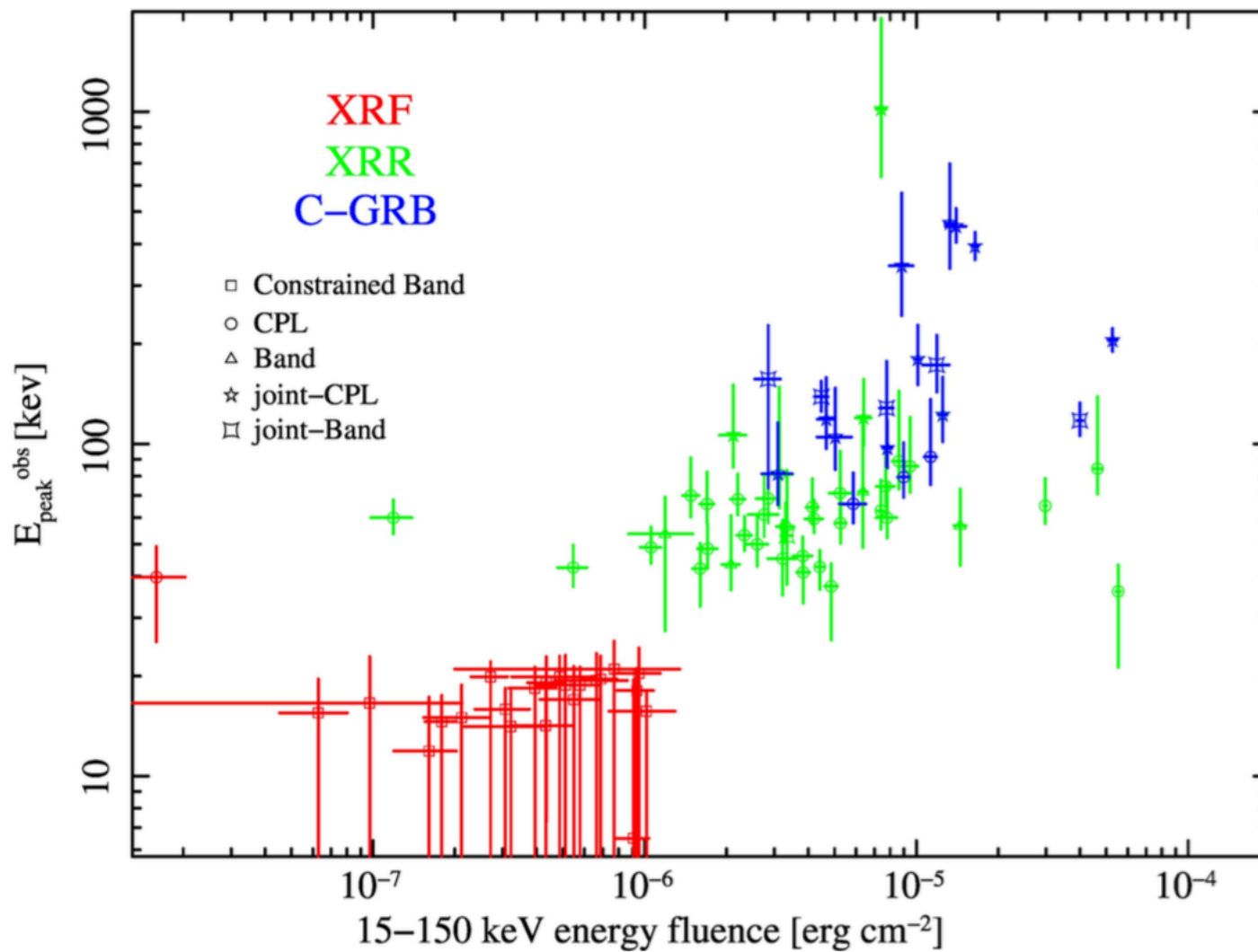


Fluence ratio Distribution

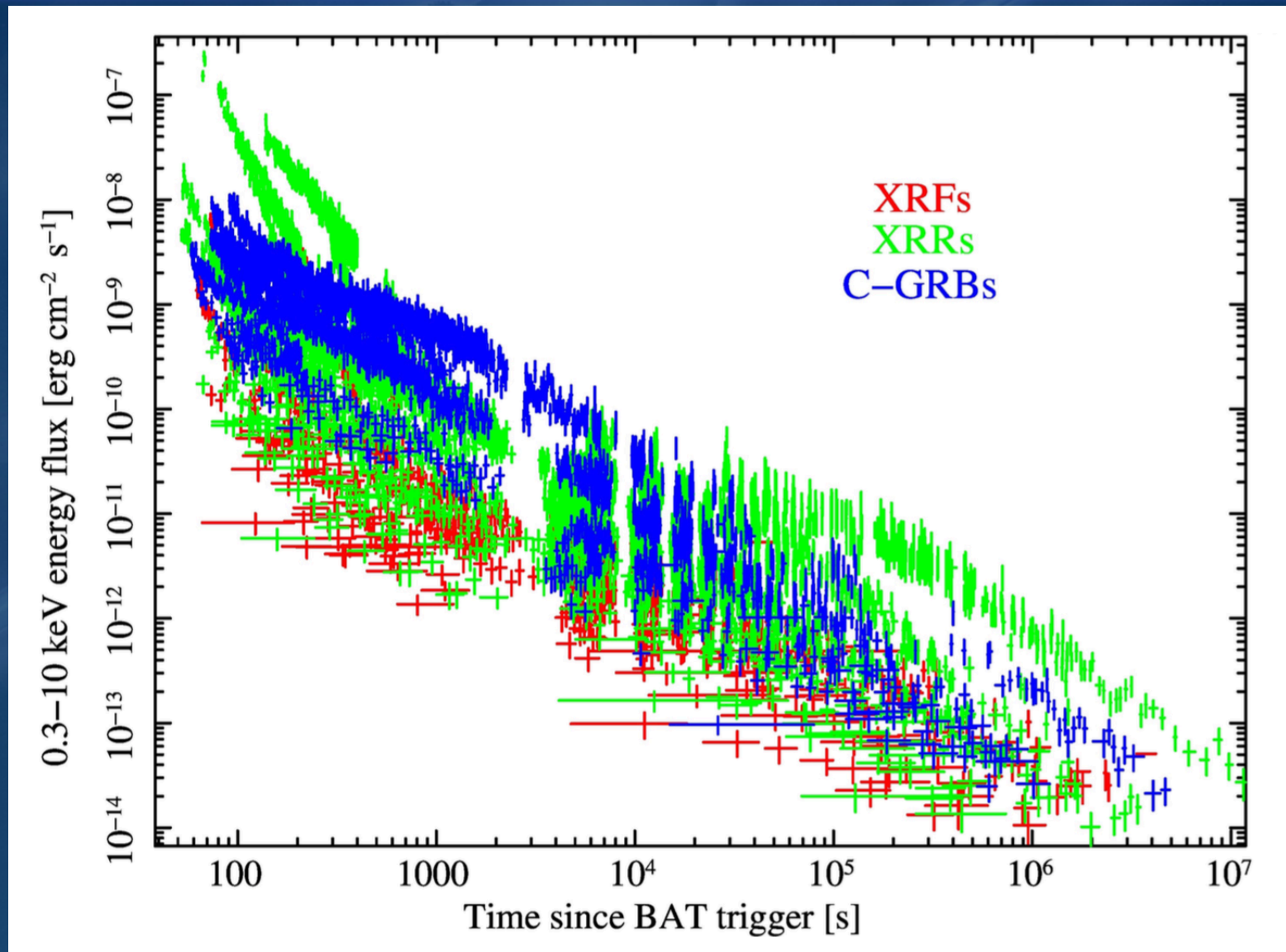


Single distribution among XRF, XRR and C-GRB

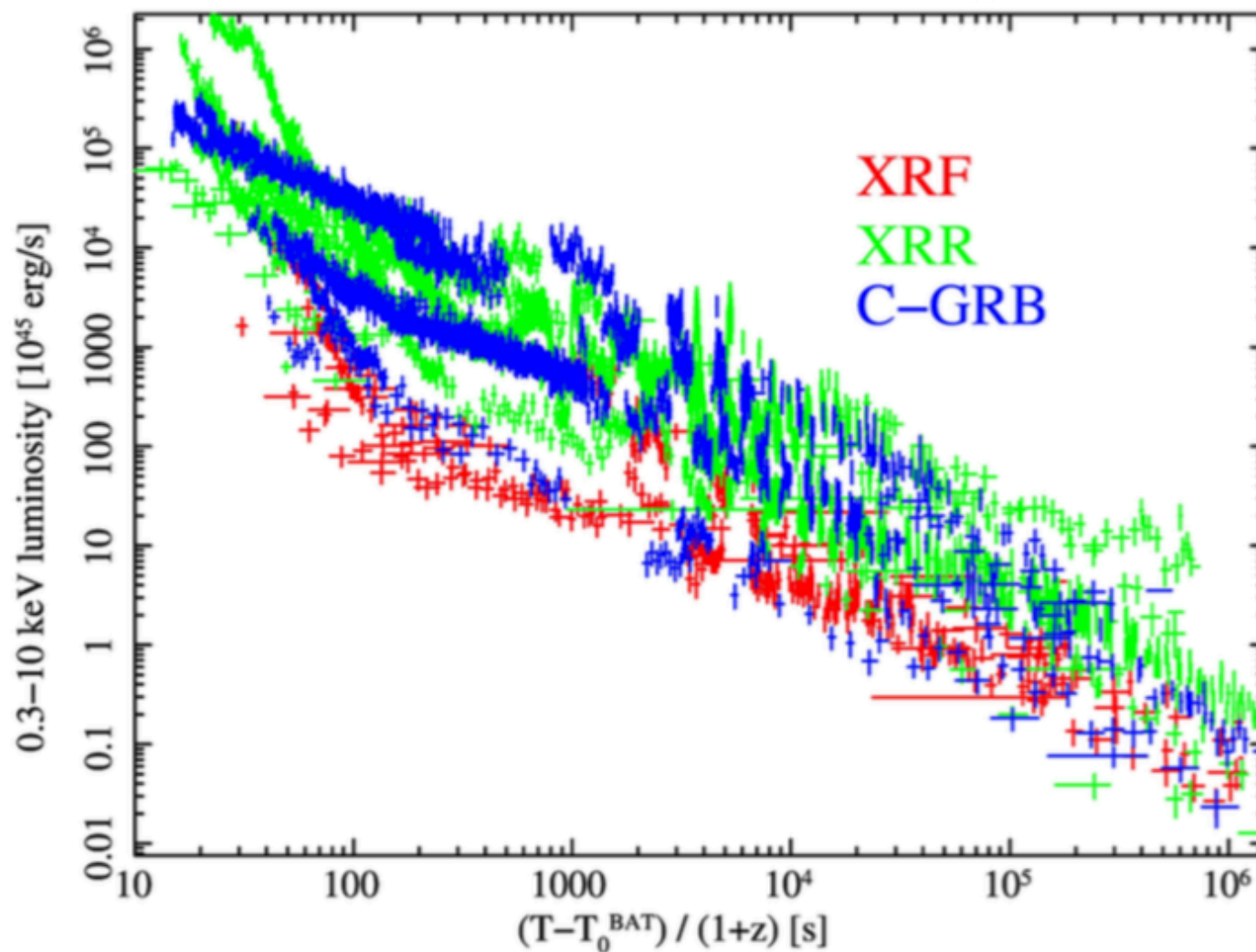
$E_{\text{peak}}^{\text{obs}}$ vs. $S(15-150 \text{ keV})$



X-ray Afterglows at Observer's Frame

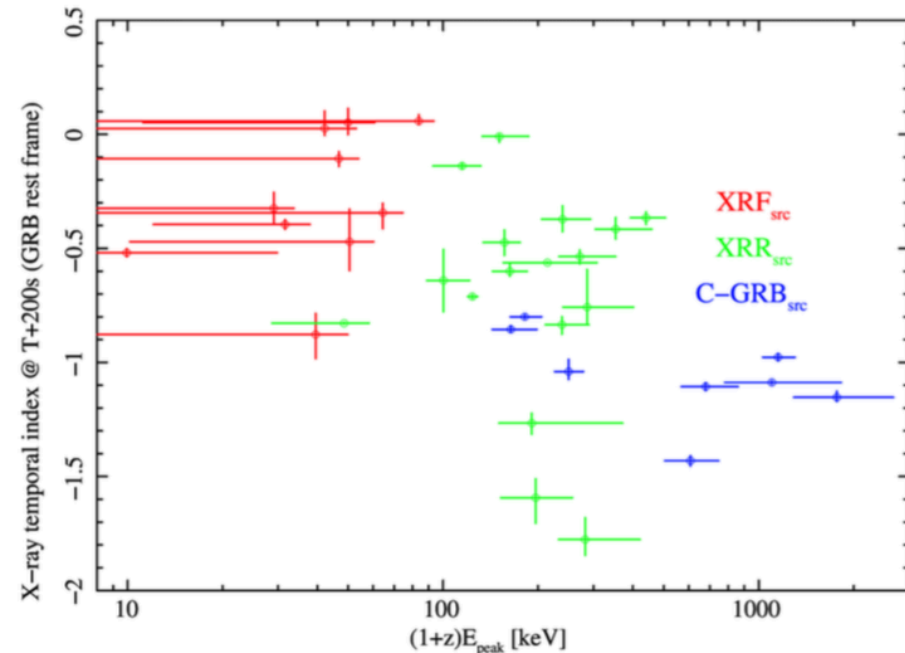
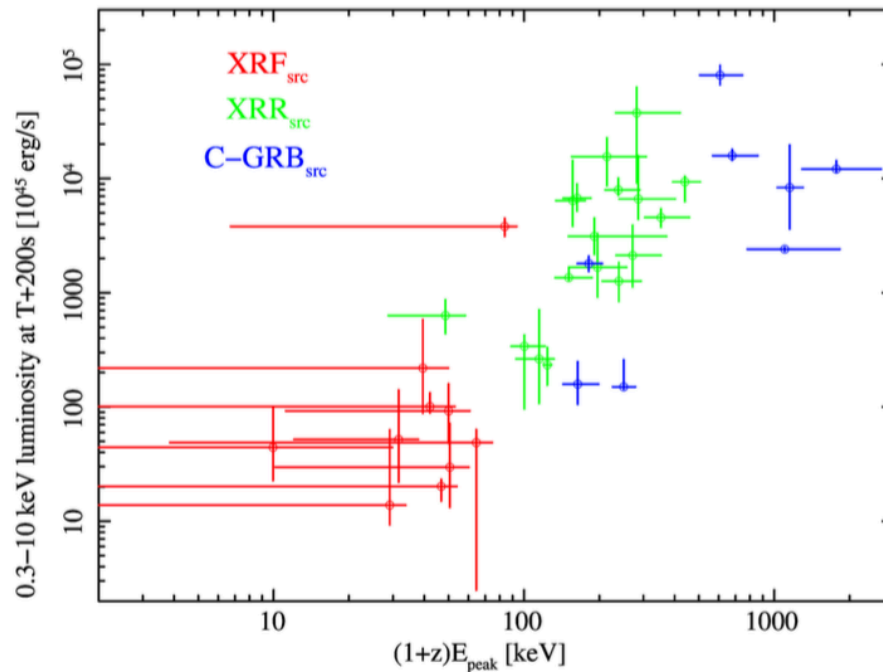


X-ray Afterglows at Source frame



Prompt vs. X-ray Afterglow

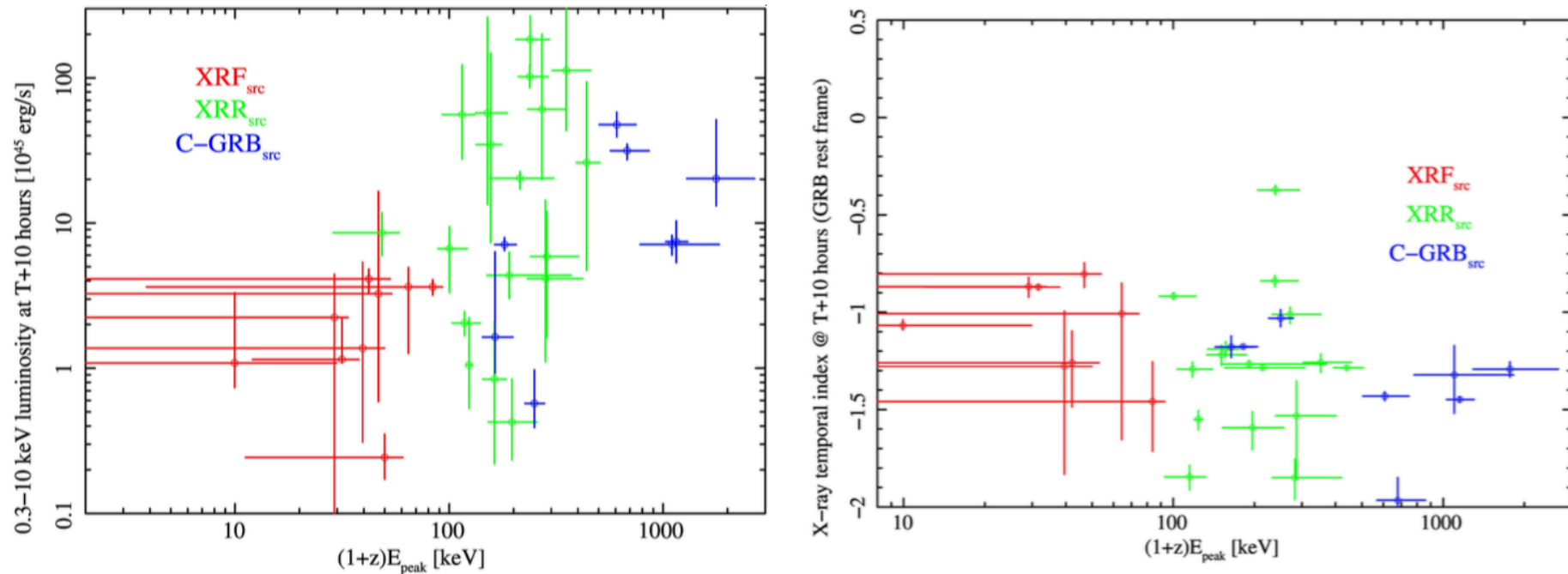
T+200 seconds



- Lower X-ray luminosity for XRFs comparing to that of C-GRBs
- Shallower decay index for XRFs comparing to that of C-GRBs

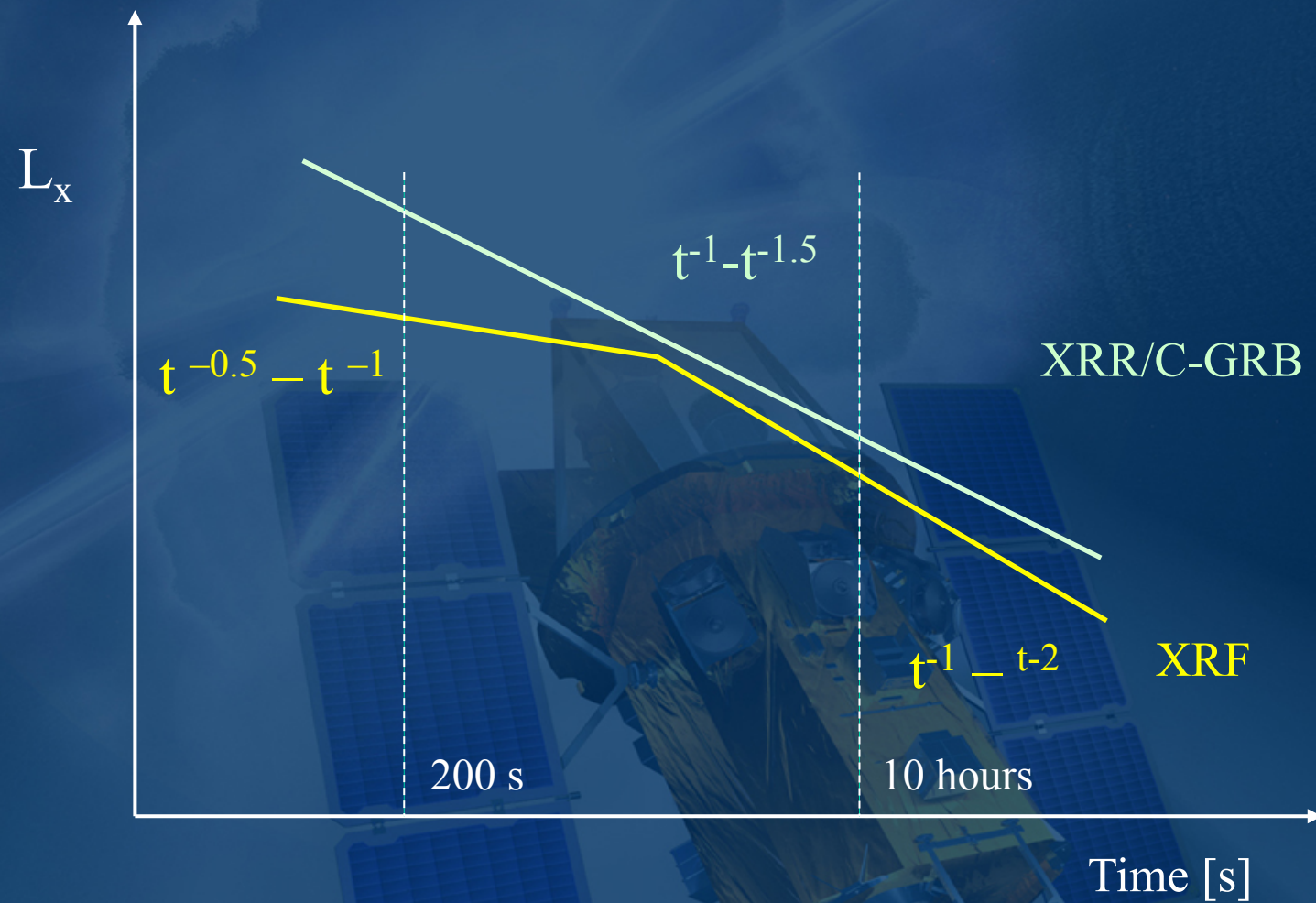
Prompt vs. X-ray Afterglow

T+10 hours



- Similar X-ray luminosity between XRFs and C-GRBs
- No difference in decay index between XRFs and C-GRBs

X-ray Light Curve Properties



Discussion (1)

Variable Opening Angle Jet model (Lamb et al. 2003)

- $L_\gamma \sim (\Delta\theta)^2 L_{\text{iso}}$
- $L_{\text{iso}} \sim E_{\text{peak}}^2$ (Yonetoku relation)

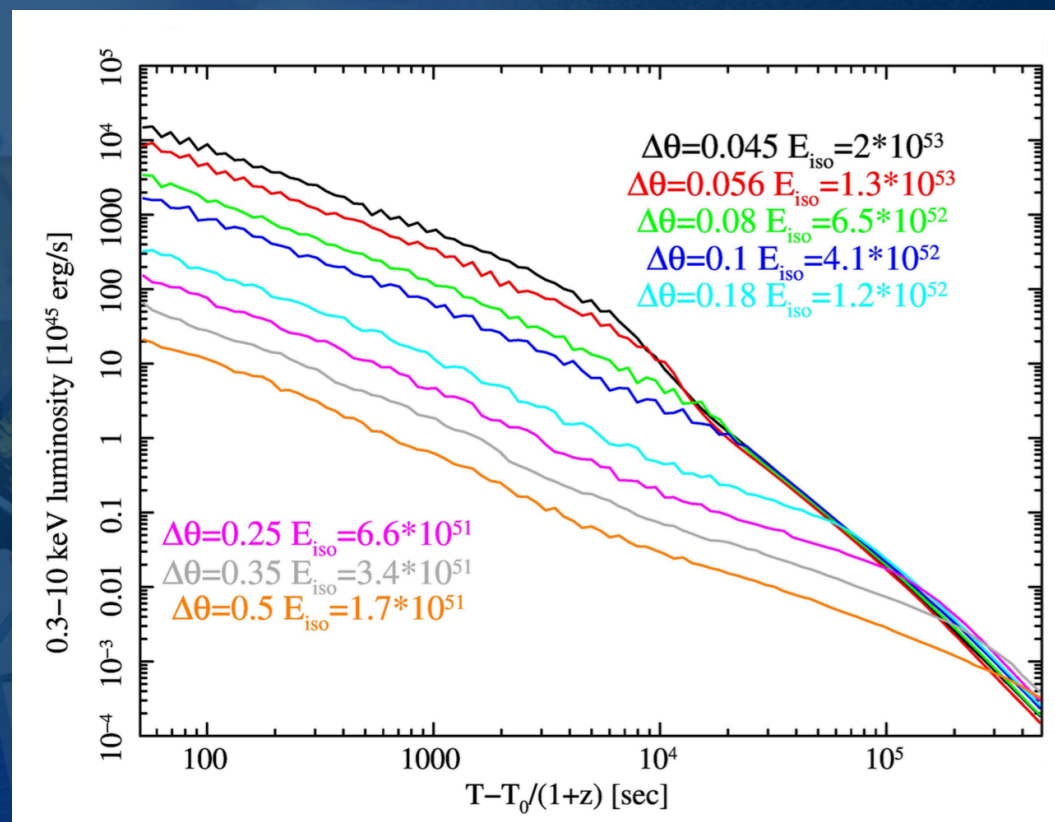
$$E_{\text{peak}} \sim L_\gamma^{0.5} \Delta\theta^{-1} \sim \Delta\theta^{-1}$$

- Large jet opening angle jet (low E_{peak})
→ low Luminosity

Okey

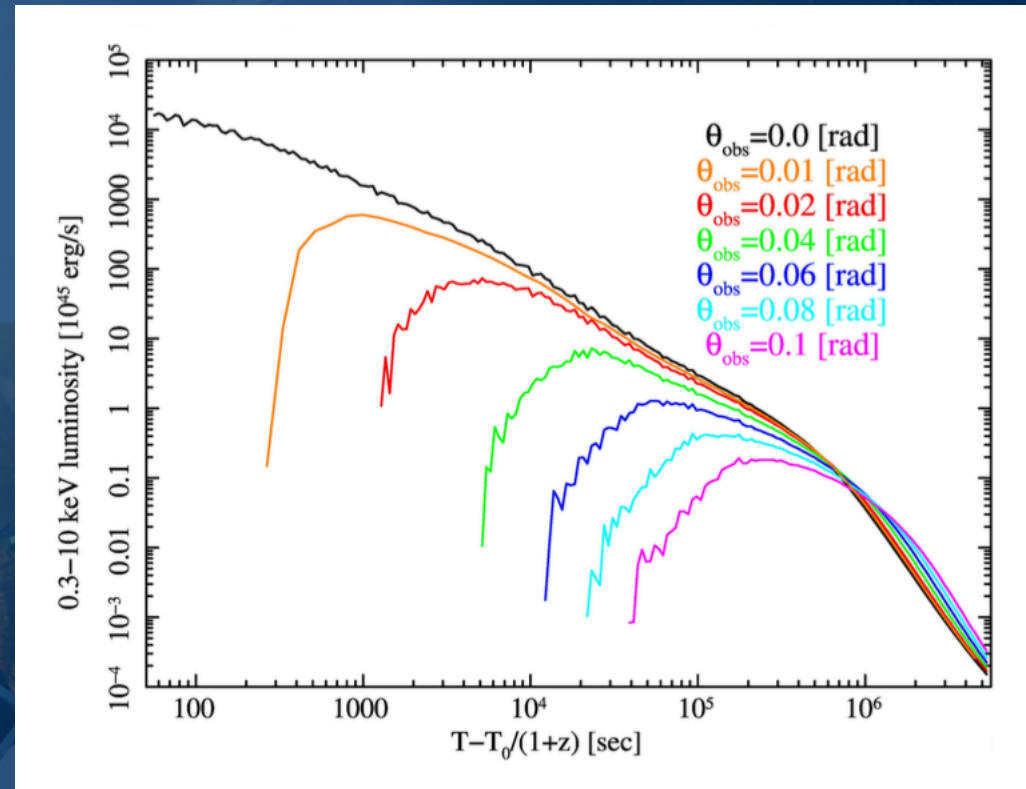
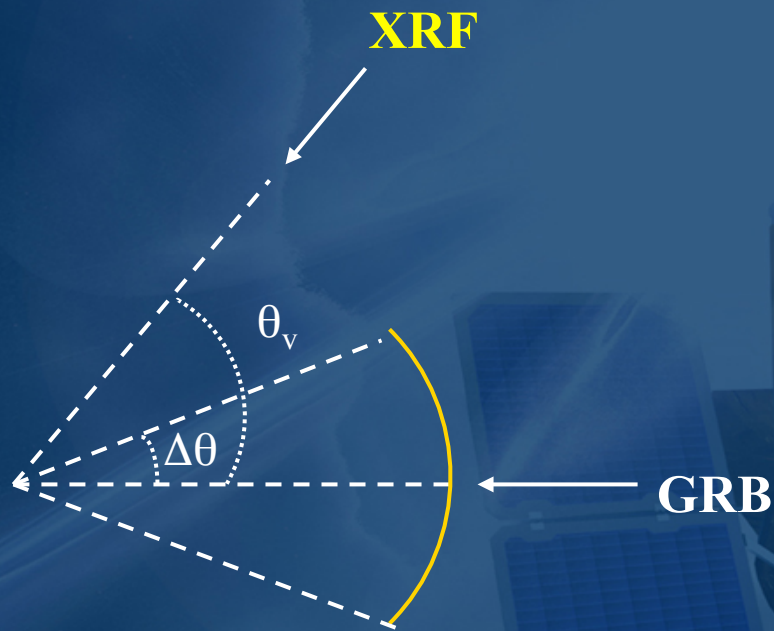
- No difference in decay index

Probably not okay



Discussion (2)

Off-axis jet model (Yamazaki et al. 2002, 2003)



No rise and peak light curve seen in XRFs

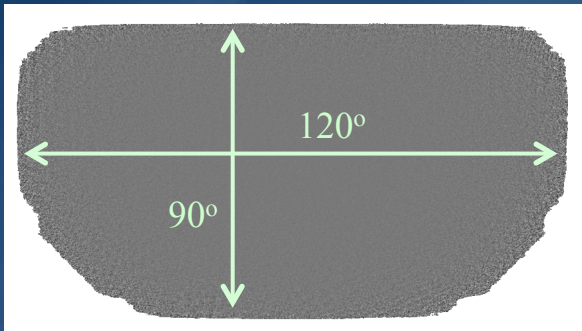
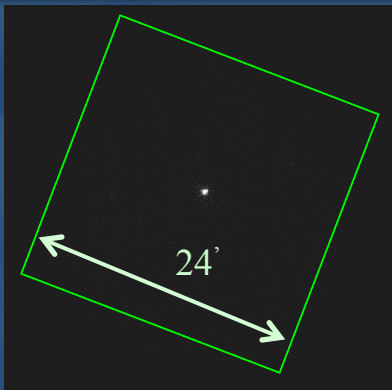
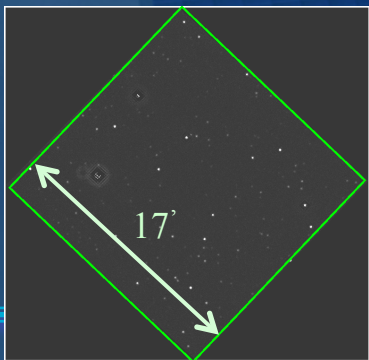
Summary

- BAT XRFs are $\sim 3.5\%$ of the entire GRB samples.
- BAT XRFs: A lower X-ray luminosity and a shallower decay index at T+200 s; a similar X-ray luminosity and a decay index at T+10 hours comparing to those of C-GRBs.



Electromagnetic Counterpart Search of Gravitational-wave Events

Characteristics of Instruments

	Field of view	Typical Sensitivity	
BAT		$\sim 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (15-150 keV)	Prompt data around T_0
XRT		$5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3-10 keV; 1 ksec)	Follow-up
UVOT		$\sim 20 \text{ mag (v; 200 s)}$	Follow-up

Available Data for EM Search

■ BAT on-board trigger

- Automatic XRT/UVOT Observations ($T_0 + \sim 100\text{s}$)
- BAT event data ($T_0 - 250\text{ s} - T_0 + 1000\text{ s}$)

■ Target of Opportunity (ToO) observation

- Fast ToO is possible (within an hour)
- New X-ray (XRT) and UV/optical (UVOT) data of the field
- Possible tiling observation

■ Regular operation

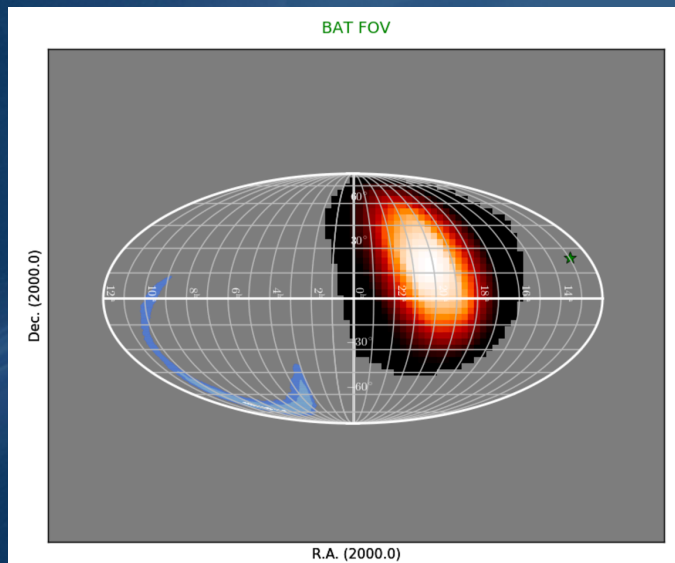
- BAT: raw light curve data (64 ms, 1.6 s), scaled map data and survey data

BAT EM Counterpart Search

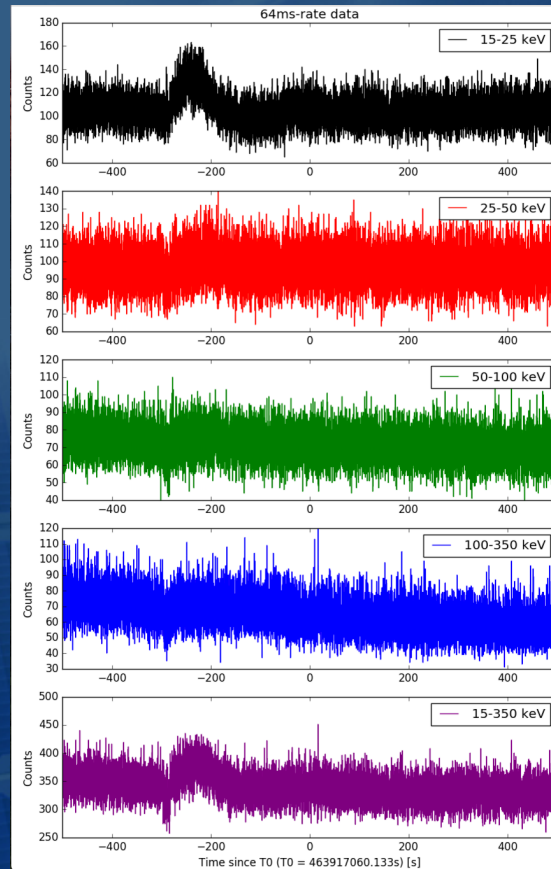
Semi-automatic analysis pipeline (internal web site)

Example of GW 150914

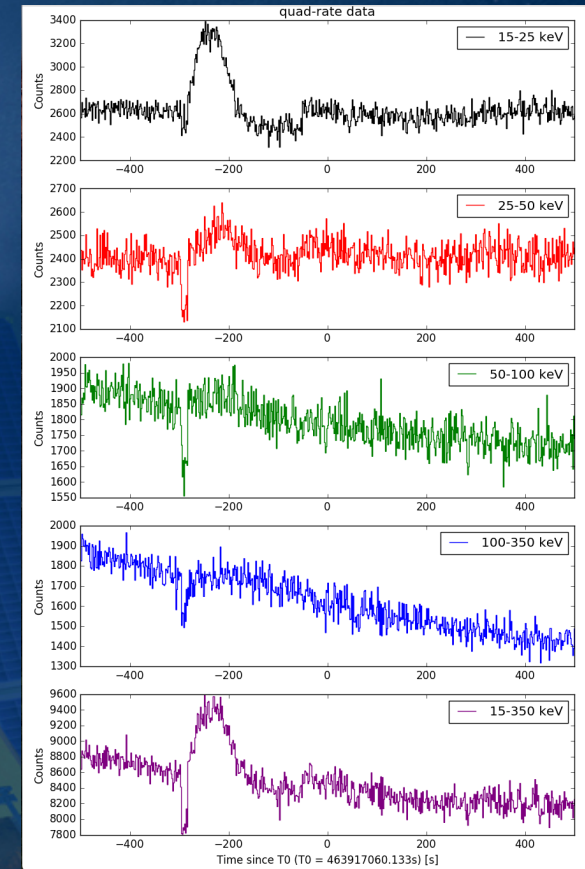
BAT FoV and
LIGO error region



Raw light curve (64 ms)



Raw light curve (1.6 s)



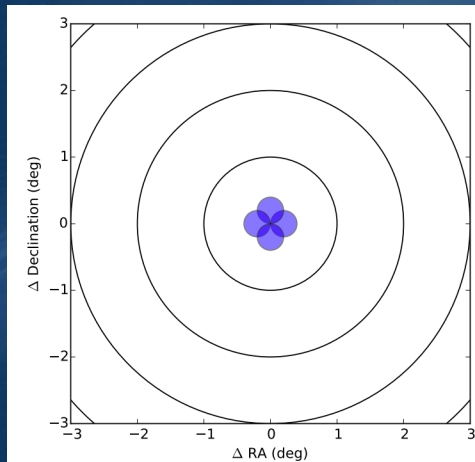
Automatic Tiling Observation

Automatic tiling observation capability (Part of the BAT on-board software)

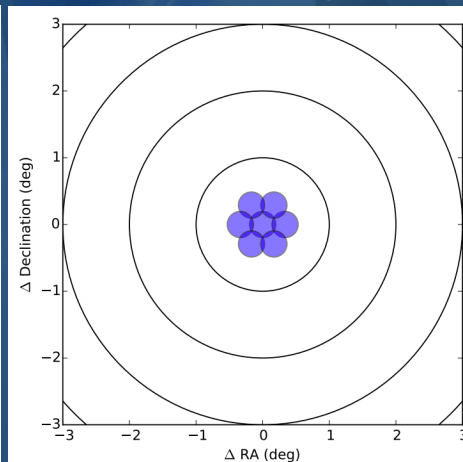
- Try to observe all N tiles in the first orbit
- Continue observing until the requested observing time (min exp/tile = 60 s)

Tiling patterns (figures from J. Kennea)

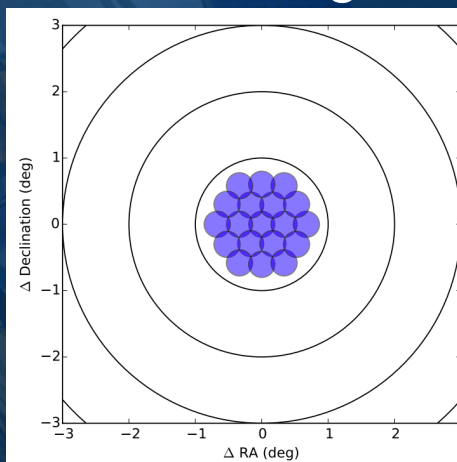
4-tiling



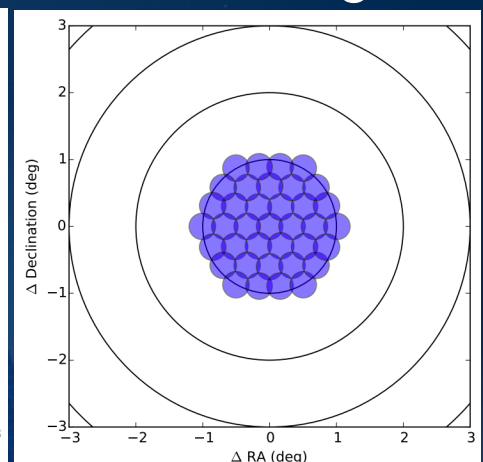
7-tiling



19-tiling



37-tiling



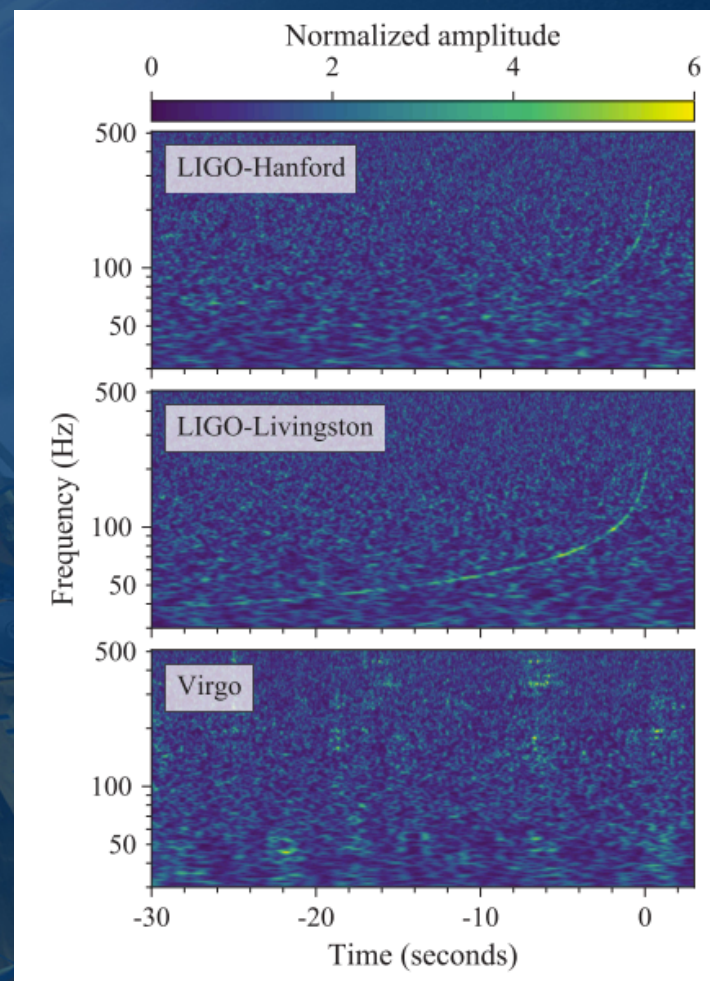
Required tiling pattern
to cover 1° diameter

Required tiling pattern
to cover 2° diameter

GW 170817

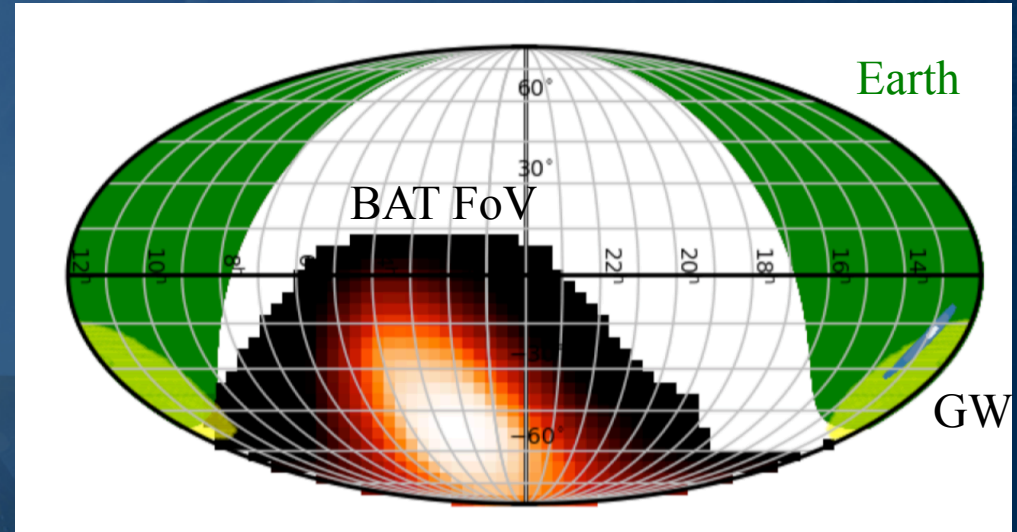
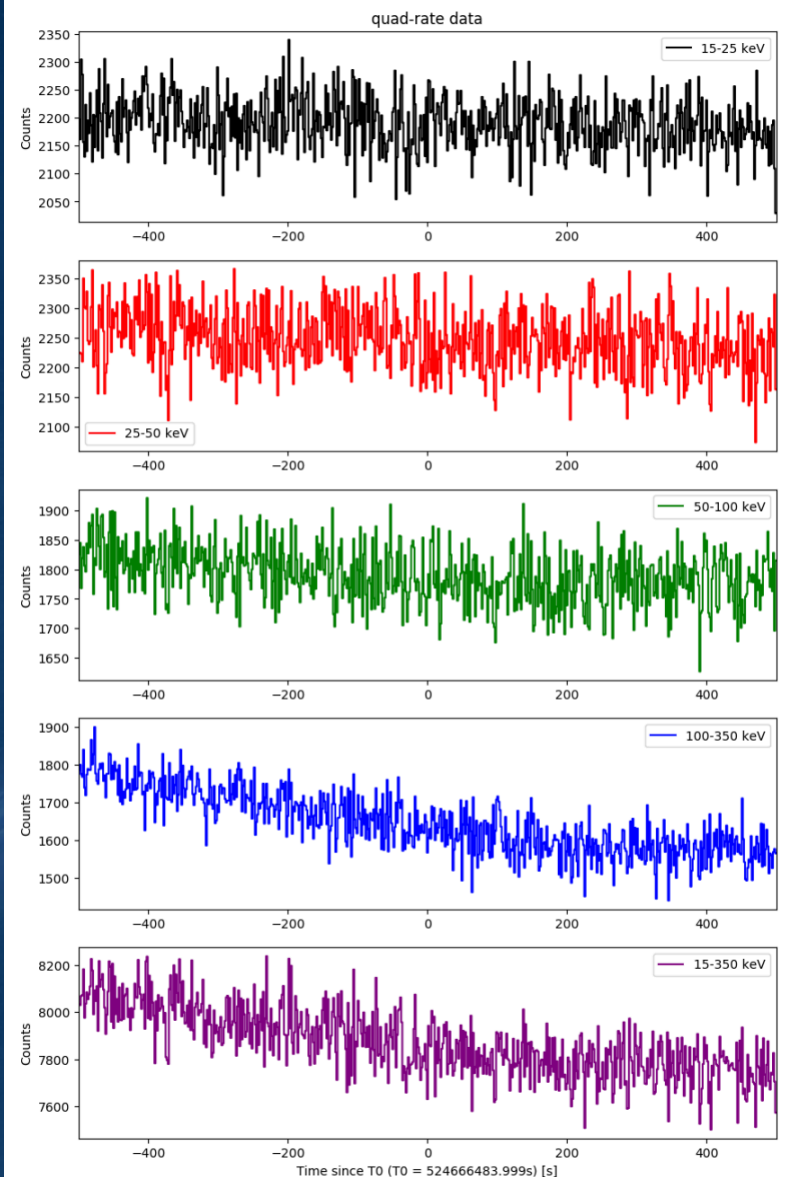
Gravitational-wave event
from BNS merger!

Abbott et al. 2017



GW 170817: BAT Observation

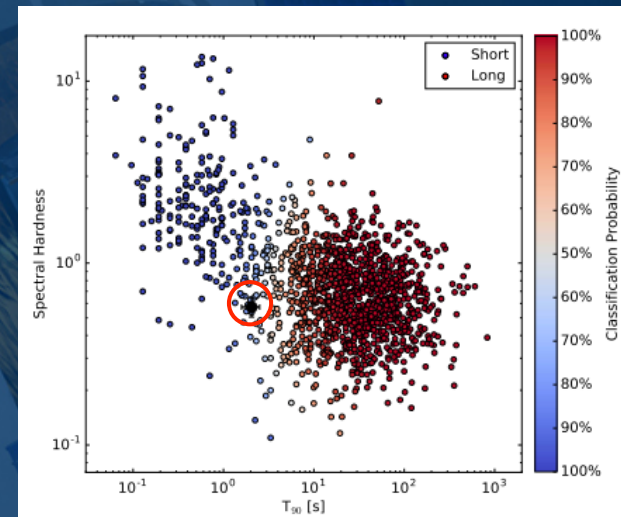
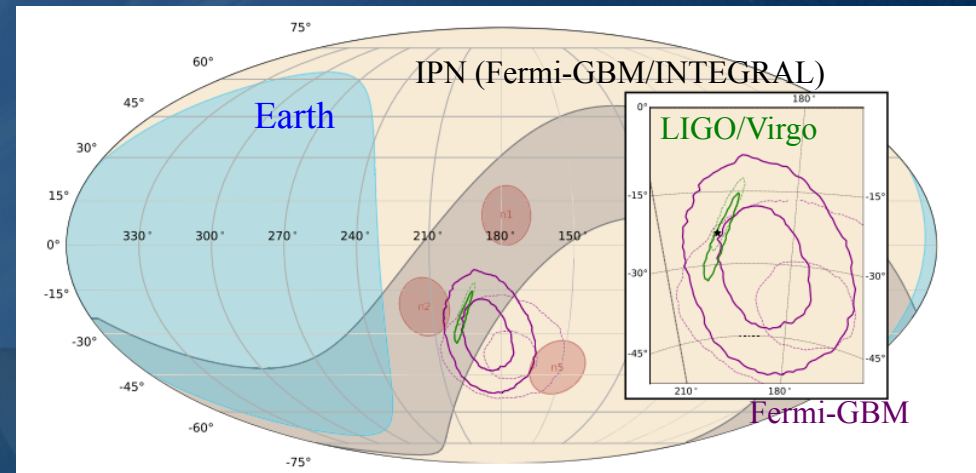
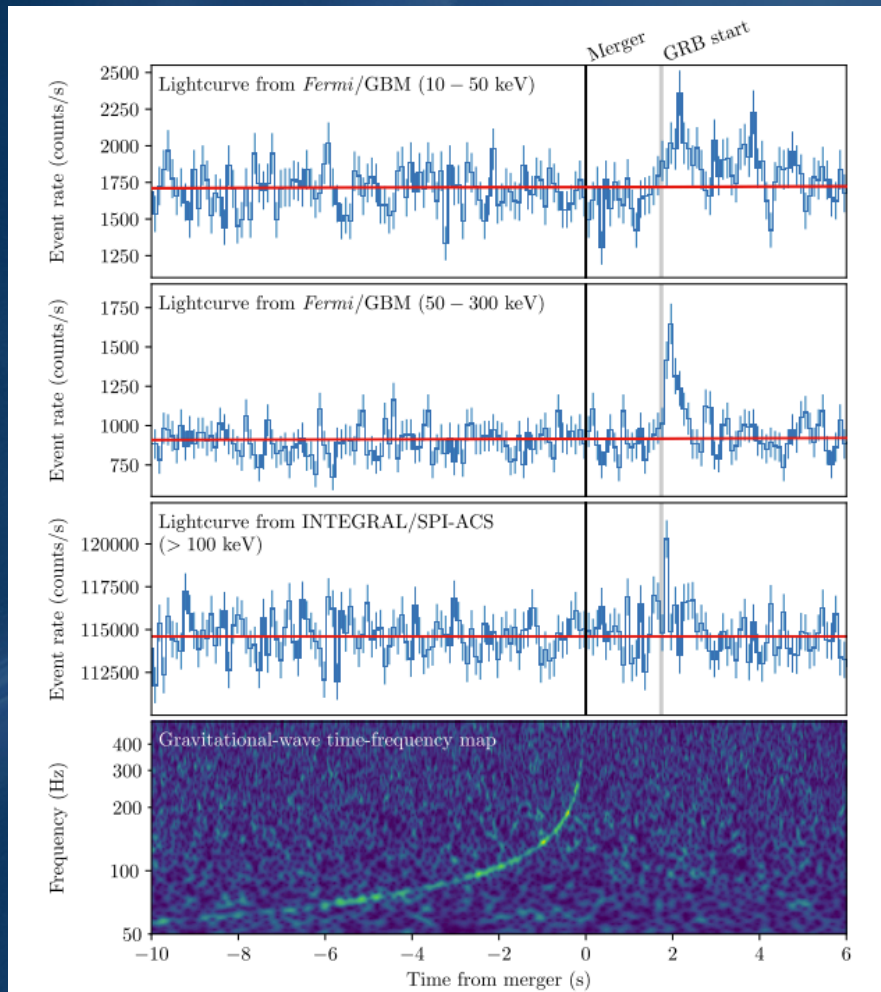
(Evans et al. 2017)



- Nothing in the BAT light curve at $T_0(\text{GW})$
- GW 170817 error region was covered by the Earth

Association of GW 170817 and GRB 170817A?

GW 170817/GRB 170817A (Abbott et al. 2017) GRB 170817A (Goldstein et al. 2017)



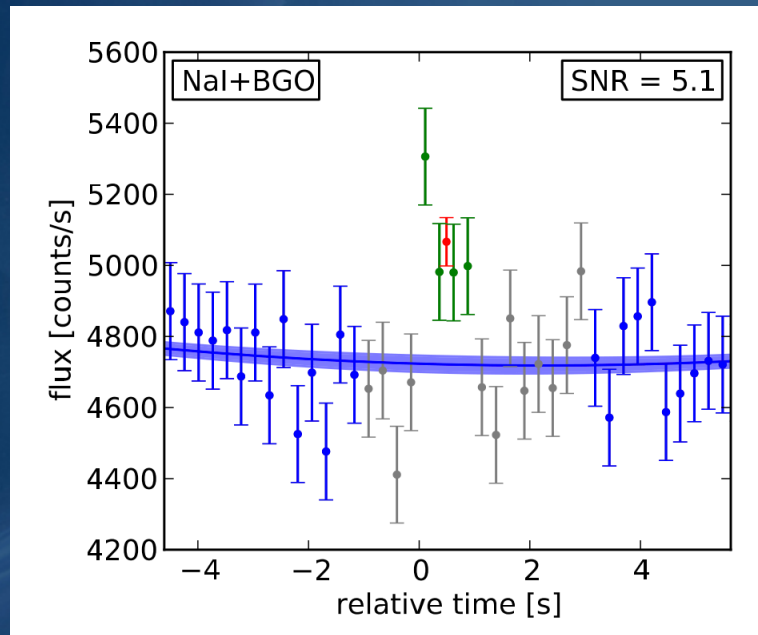
$$T_{90} = 2.0 \pm 0.5 \text{ s}$$

Probability of
S-GRB class:
72%

Real Signal?

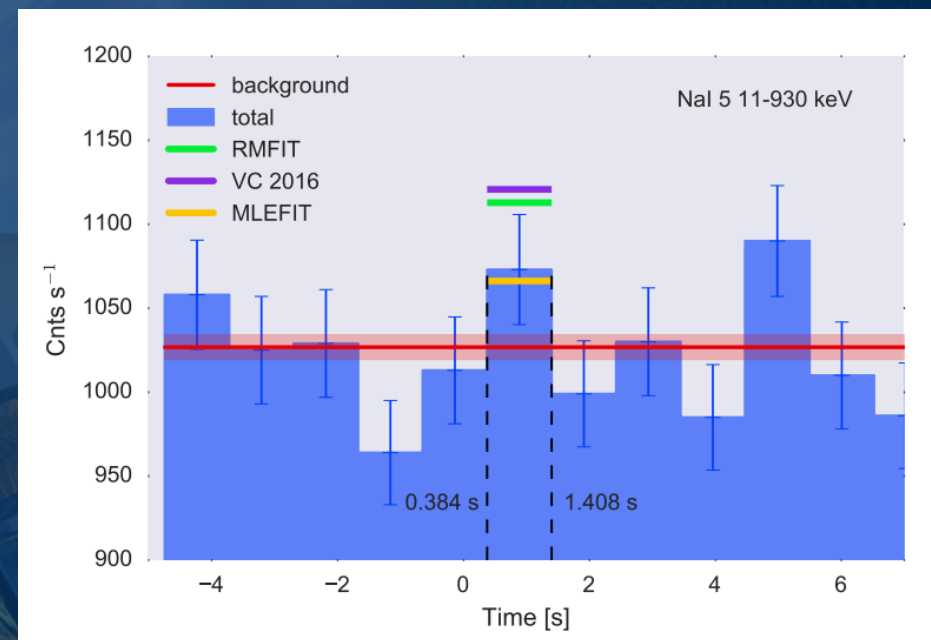
GW 150914: Fermi-GBM confused the entire community

Connaughton et al. 2016



Detection

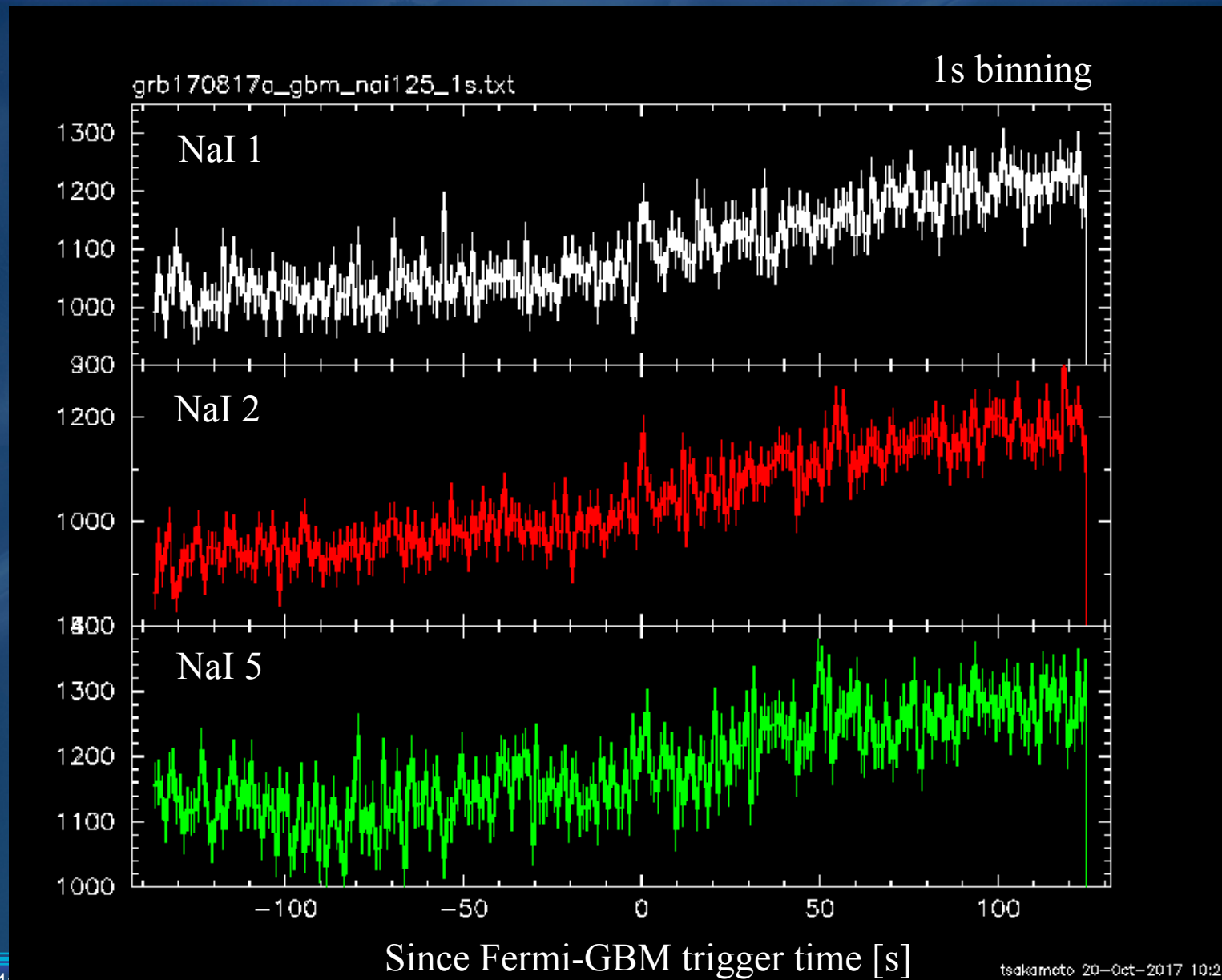
Greiner et al. 2016



Non-detection

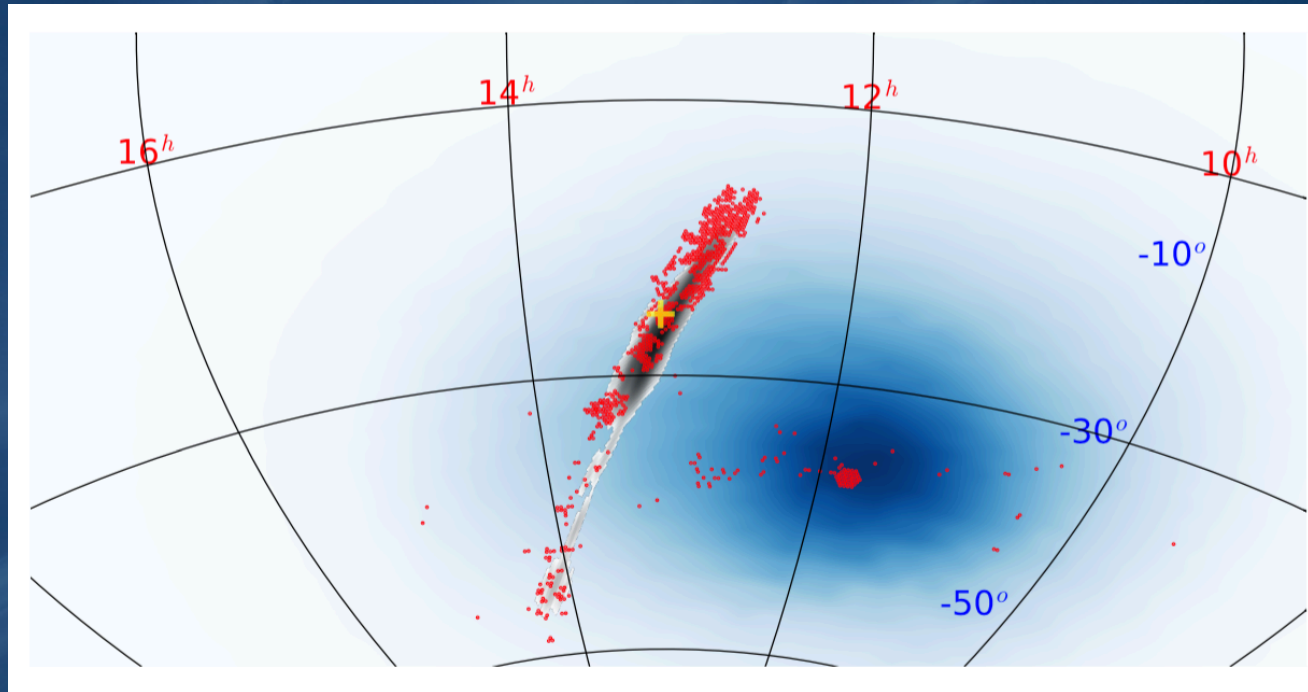
Fermi-GBM (Scintillator) detects both photons and particles.

My personal view of Fermi-GBM data



Swift Follow-up Observations

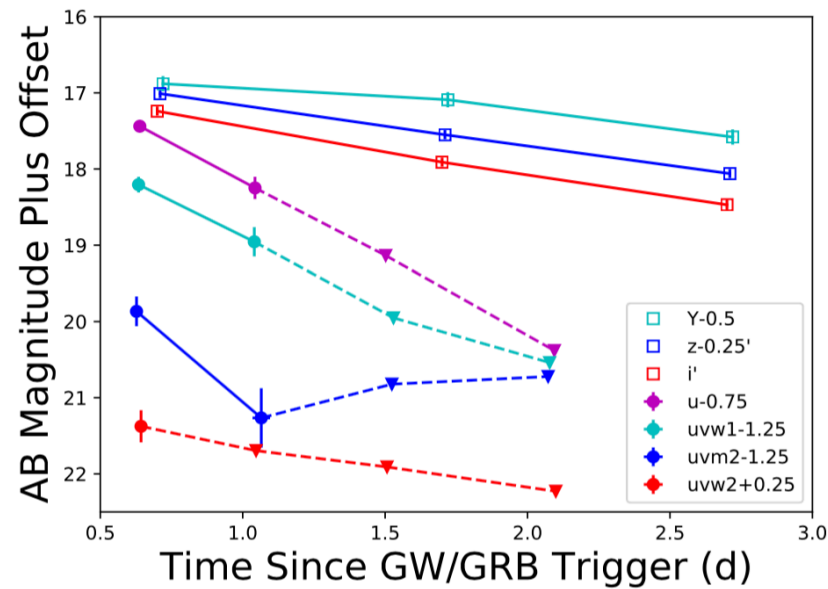
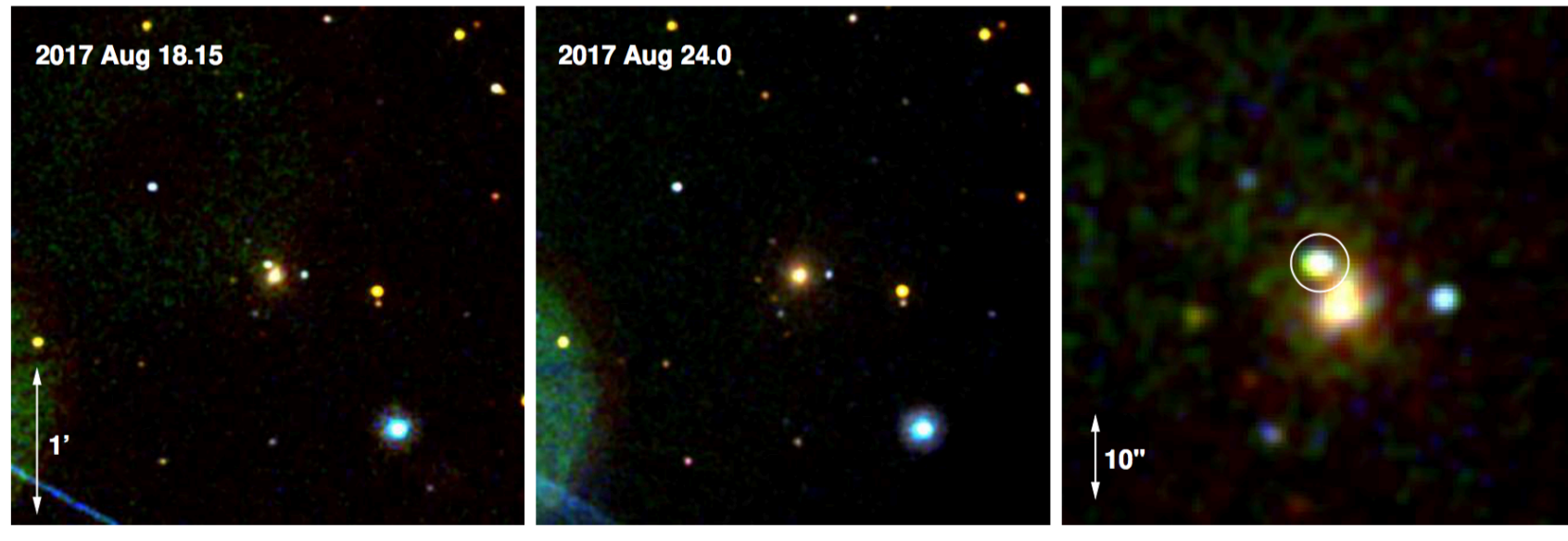
(Evans et al. 2017)



1. T_0+1 hr: 37 tiling at the center of the Fermi-GBM position
2. $T_0+4.6$ hr: (LIGO single sky map + GWGC) & Fermi-GBM location
3. $T_0+7.4$ hr: LIGO three detector sky map + GWGC
4. $T_0+14.4$ hr: Follow-up on EM 170817
 - UVOT detections in all filters, but no XRT detection

UVOT works!

(Evans et al. 2017)



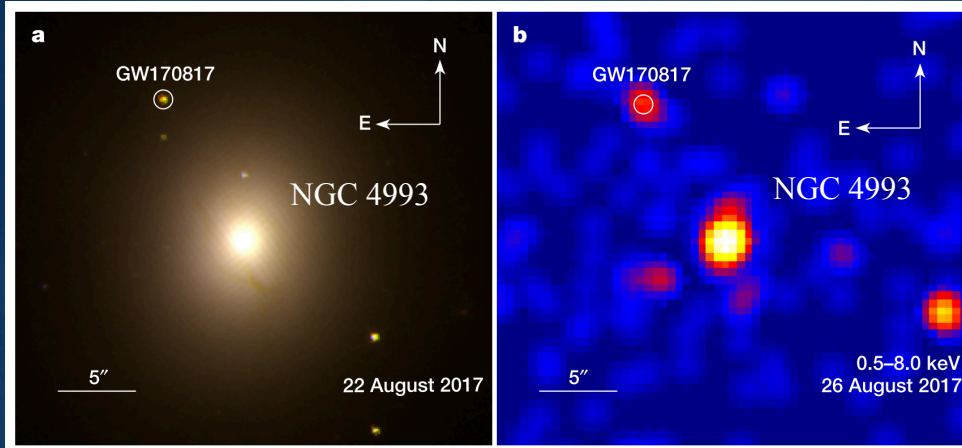
Rapidly fading UV emissions
were detected by UVOT

Chandra detection of X-rays from EM 170817

(Troja et al. 2017)

Hubble (T_0+1 day)

Chandra (T_0+9 days)



$T_0+2.2$ d: Non detection

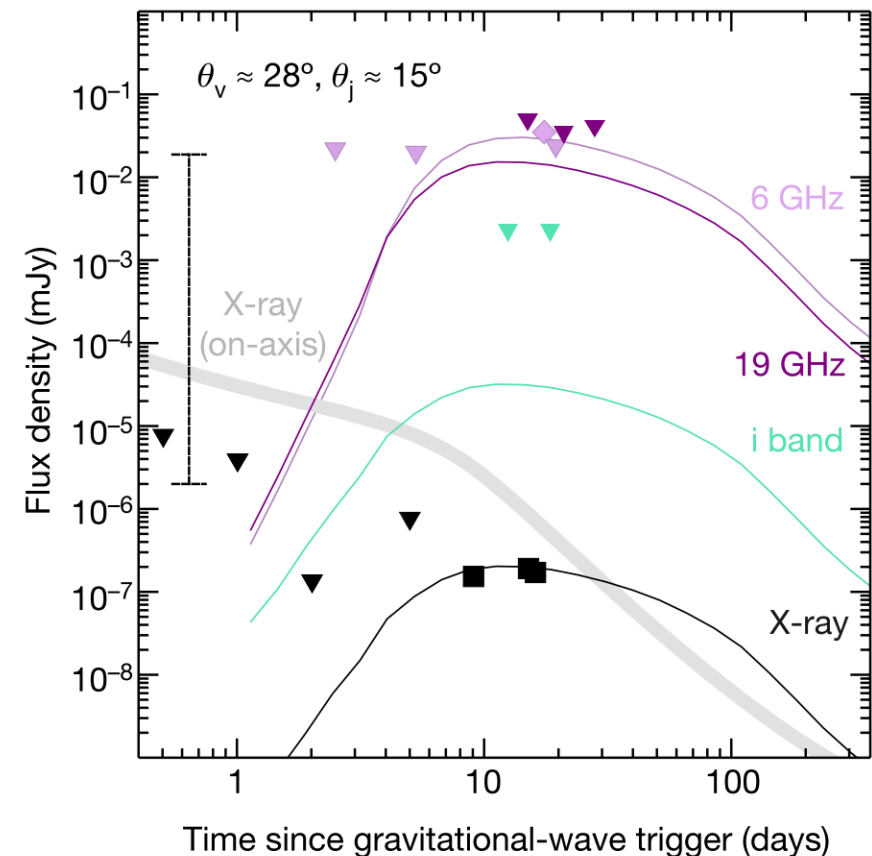
T_0+9 d : 12 photons

: $(4.0 \pm 1.1) \times 10^{-15}$ erg/cm²/s

T_0+15 d: 17 photons

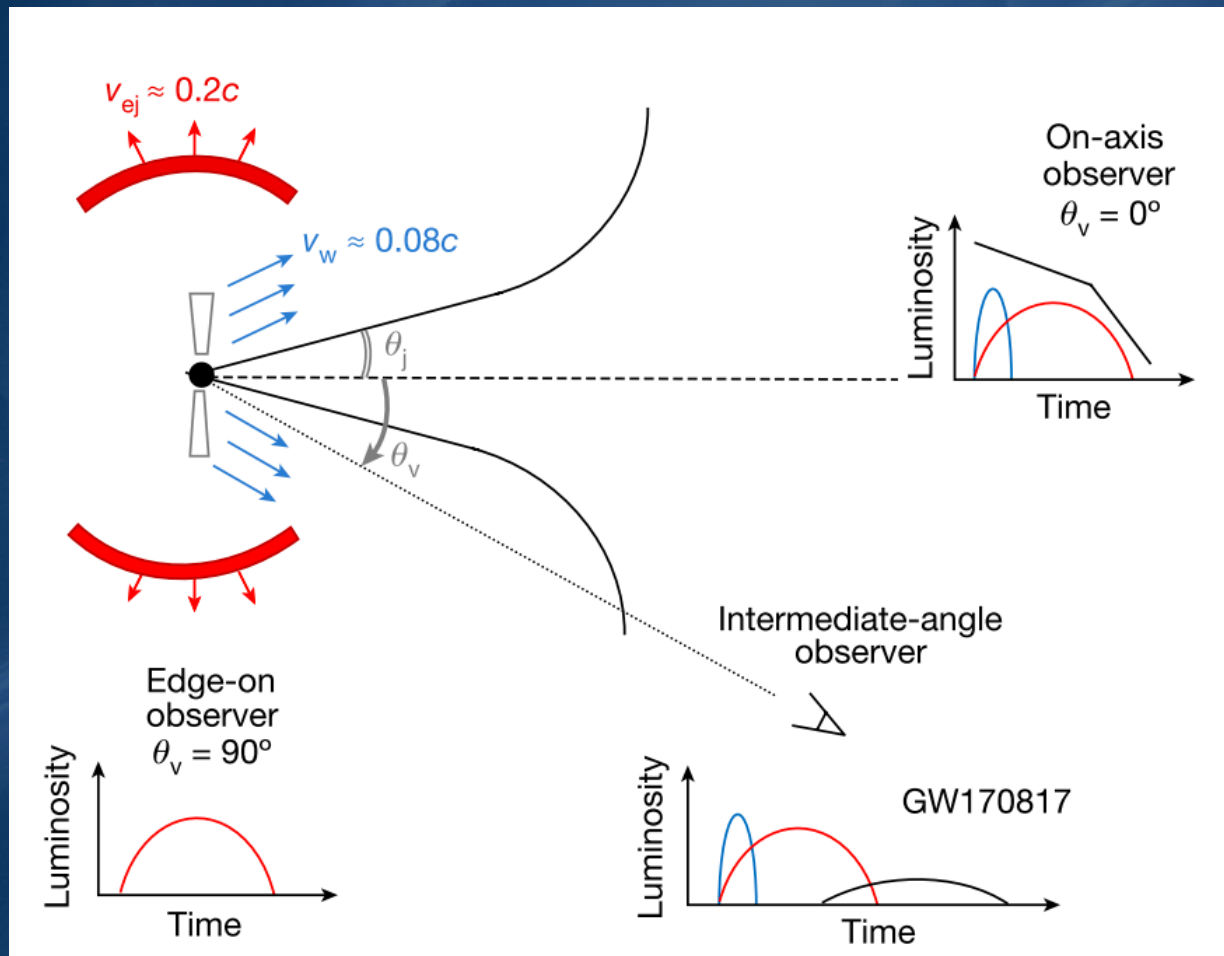
: $(5.0 \pm 1.0) \times 10^{-15}$ erg/cm²/s

Slowly rising: $t^{0.5}$



Off-axis GRB Afterglow?

(Troja et al. 2017)



Jet opening angle:

$\theta_j = 15^\circ$

Viewing angle:

$\theta_v = 28^\circ$

Consistent with late-time
rise in both X-ray and radio

Standard uniform jet:

Prompt GRB emission
should be fainter than GRB
170817A

Gaussian jet:

Consistent with the data

Future Prospect

High-sensitive Wide FoV X-ray Survey

- 16 GRBs (Vela) —————→ 2700 GRBs (BATSE)
- A few degree (BATSE) —————→ A few arcmin (BeppoSAX)
- A few hours (BeppoSAX) —————→ A few minutes (HETE-2)
- A few arcsec in a few minutes (Swift)

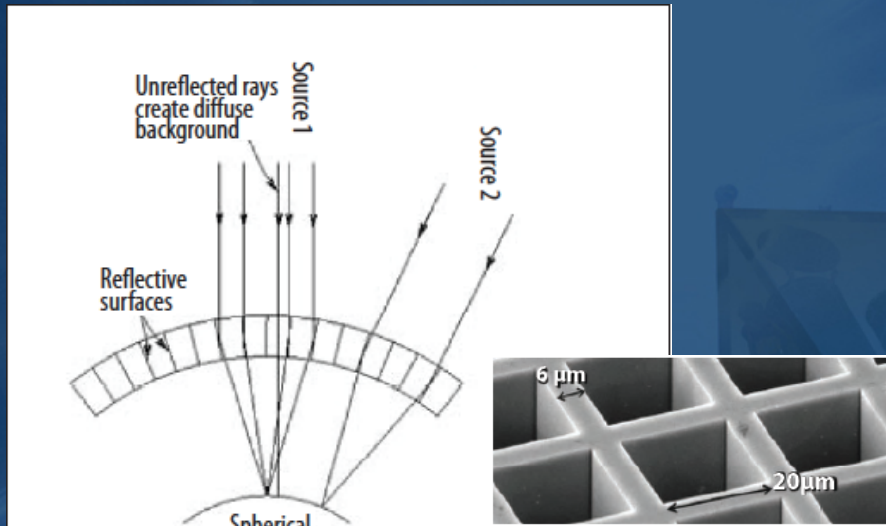
1.5 – 2 order of magnitude deep survey with wide FoV

Soft X-ray: Lobster eye optics + X-ray Imaging sensor

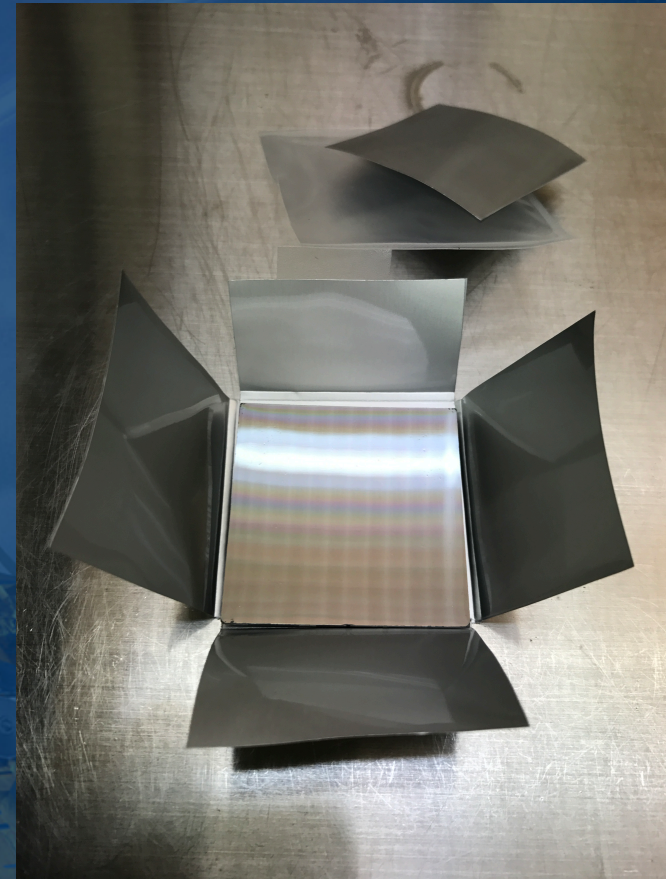
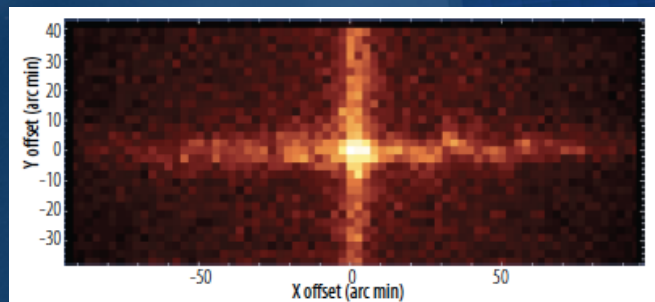
Lobster eye Telescope: optics

Micro-Channel Optics (MCO)

- Photonis Inc.
- 40 x 40 x 1 mm MCO tiles
- 8 x 8 arrays of tiles (Lobster mission)



PSF (measured @ GSFC)



40 x 40 x 1.2 mm (R 600 mm)
MCO purchased from Photonis (12K Euro)
@ AGU

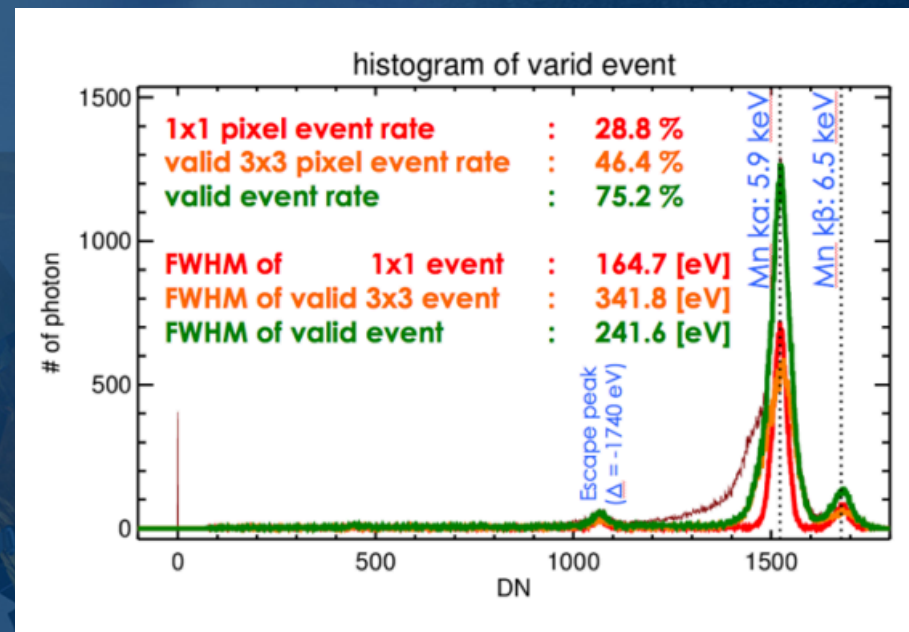
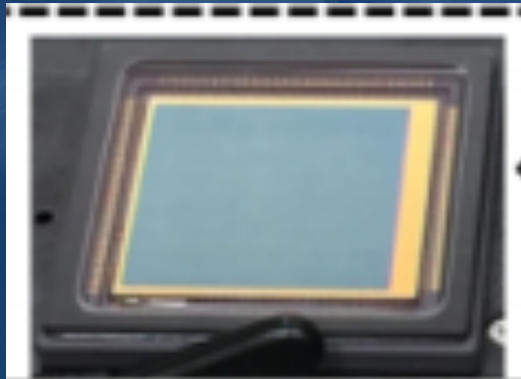
Lobster eye Telescope: sensor

Large format CMOS camera

- Operate at room temperature (unlike CCD)
- Very fast readout: ~ 1 ms (unlike CCD)

Narukage et al. (2017)

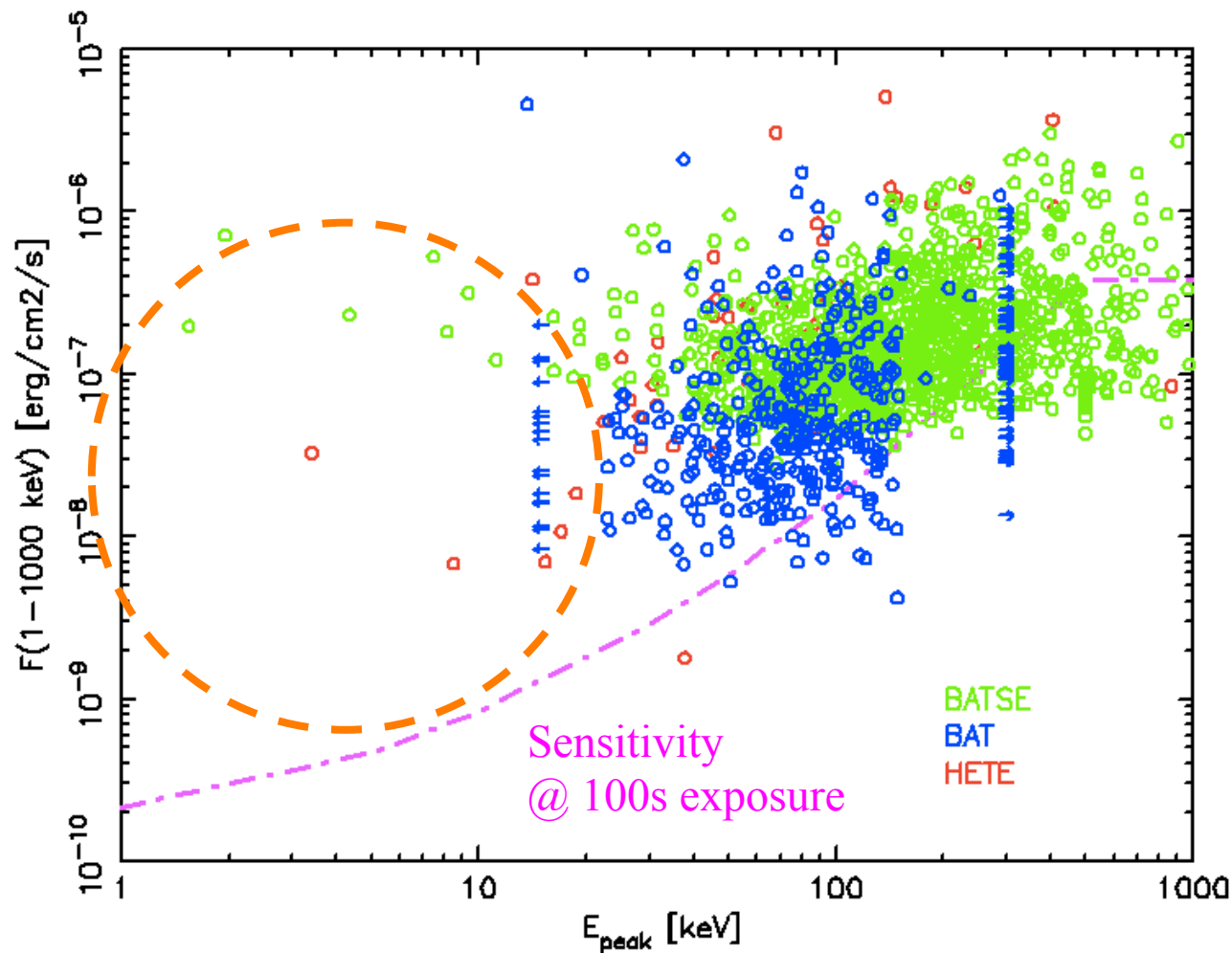
Backside illuminated CMOS;
2K x 2K



Excellent energy resolution

Sensitivity of Lobster eye Telescope

Focal length of 30 cm



TAO-ISS

PI: Jordan Camp (NASA/GSFC)

Instruments

- Wide-field Imager (WFI)

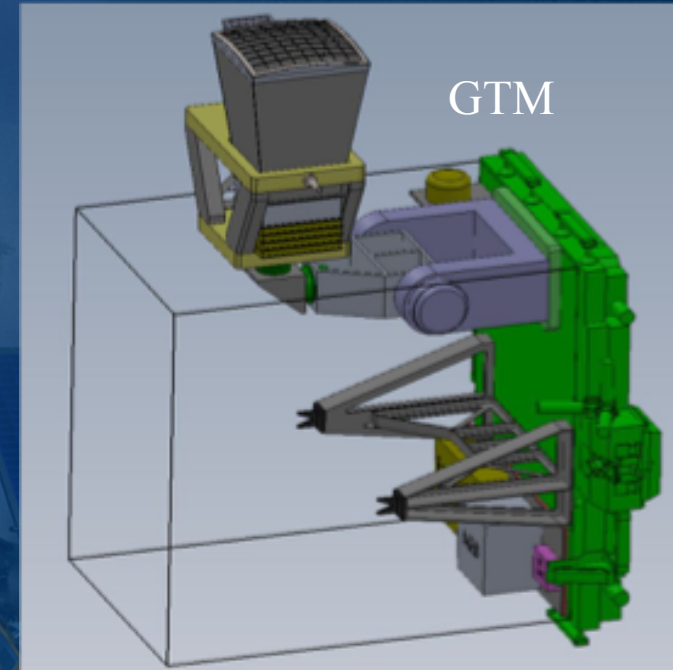
- Micro-Channel Pole (MPO) optics with CCD focal plane (Angel 1979)
- 45 cm focal length (30 cm)
- FoV: $20^\circ \times 20^\circ$ ($28.5^\circ \times 28.5^\circ$)
- Sensitivity: $10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (20 s),
 $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (10 ks)
- Energy range: 0.3-5 keV
- Localization accuracy: $\sim 1'$

- Gamma-ray Transient Monitor (GTM)

- 2 x Fermi-GBM NaI detectors
- FoV: $\sim 2\pi$
- Energy range 10 keV – 1 MeV

WFI

GTM



Selected for 2016 NASA Explorer MoO phase A study!

Gamma-ray Bursts in the Gravitational Wave Era 2019

Targeting date: November 2019

Candidate place: Yokohama, Kanagawa

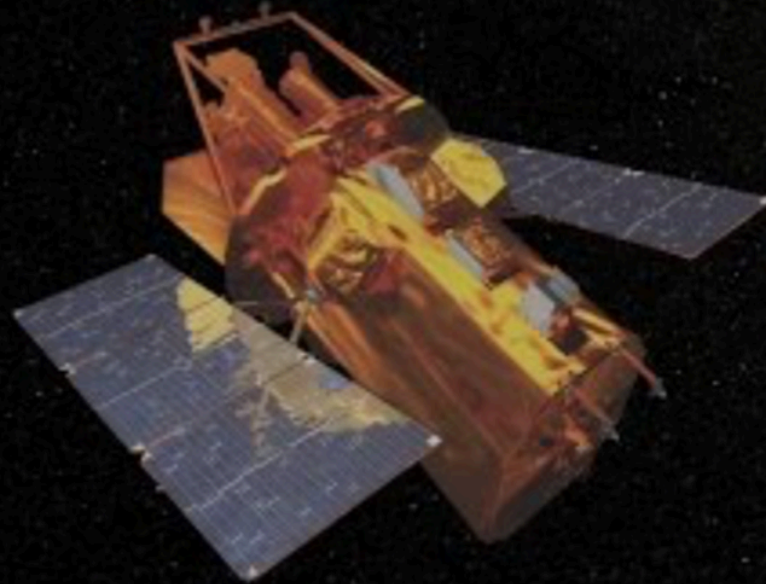
Funding support by Yamada Science Foundation

L. Amati, J.-L. Atteia, B. Cenko, V. Connaughton, J. Greiner, P. Meszaros, P. O'Brien, T. Piran, J. Racusin, L. Singer, N. Tanvir, E. Troja, W. Xiang-Yu, B. Zhang, K. Asano, K. Ioka, N. Kanda, N. Kawai, K. Toma, Y. Fukazawa, K. Murase, R. Yamazaki, M. Yoshida, D. Yonetoku

LOC: T. Sakamoto, M. Serino, S. Kisaka



Neil Gehrels (1952-2017)



Neil's memorial scientific conference: May 21-22@ D.C.