Multi-Messenger Astronomy with Swift

T. Sakamoto (AGU)

(Special thanks for Phil Evans)

Contents

- Introduction of Swift
- Gravitational-wave (GW) electromagnetic (EM) counterpart search
  - Short GRBs
  - Swift GW EM counterpart search strategy during O2
  - GW170817
- High-energy neutrino EM counterpart search during 2017

Swift

2004-

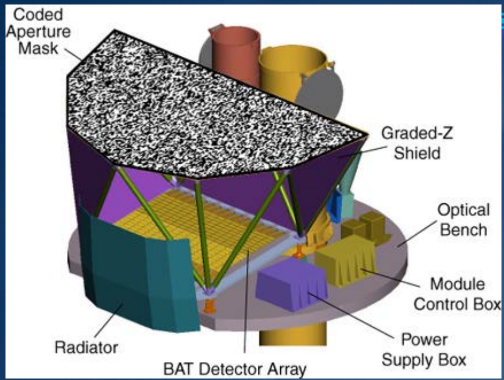
The Neil Gehrels Swift Observatory

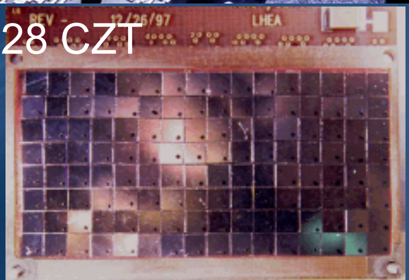
The Swift Gamma-Ray Burst Explorer has officially been renamed the Neil Gehrels Swift Observatory

Neil Gehrels (1952-2017)

Brad Cenko: Swift PI

Burst Alert Telescope (BAT)

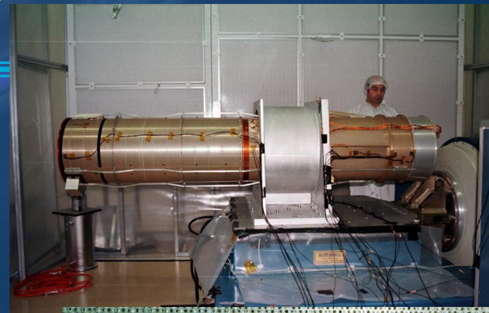


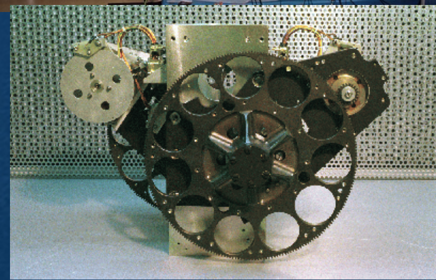


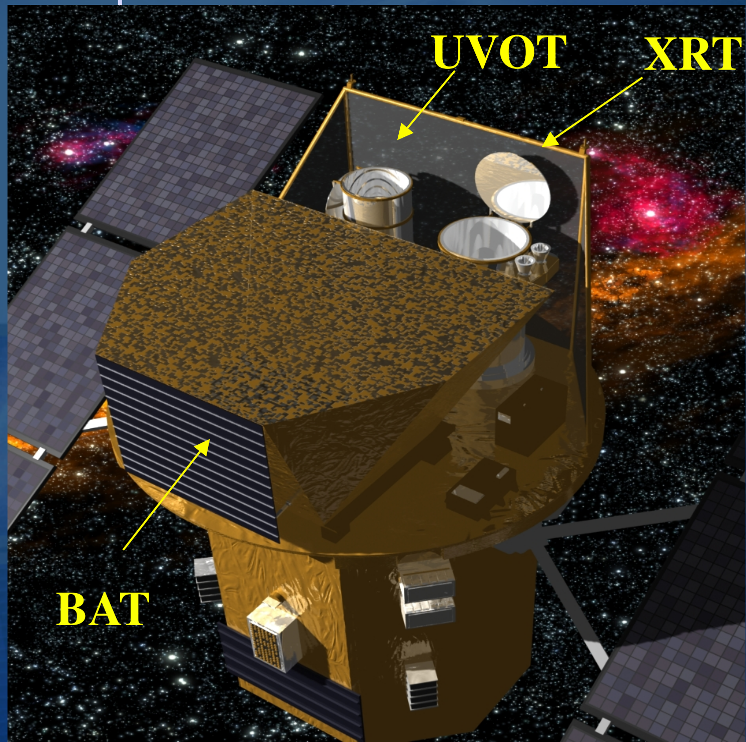
E_range: 15-150 keV (15-350 keV)
Det: CdZnTe (4 x 4 x 2 mm^3)
# of detectors: 32,768 (256 x 128)
FOV: 120 deg x 90 deg
Pos: 1’-3’

UV/Optical Telescope (UVOT)

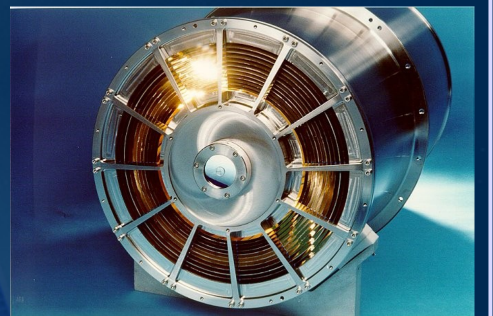
Aperture: 30 cm (XMM OM)
Det: MCP+CCD (XMM OM)
FOV: 17’ x 17’
7 filters (UV - Opt)+2 grism

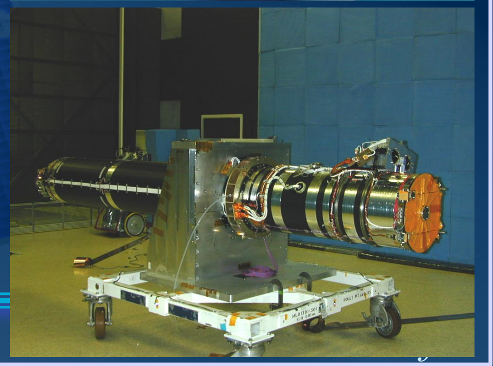






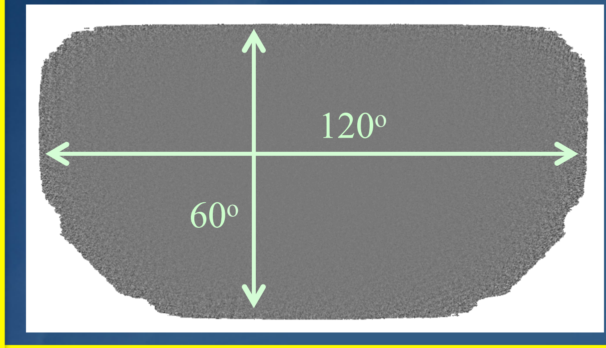
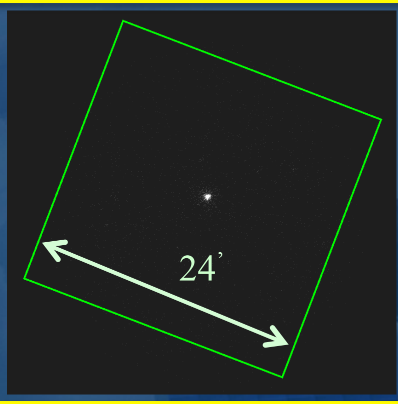
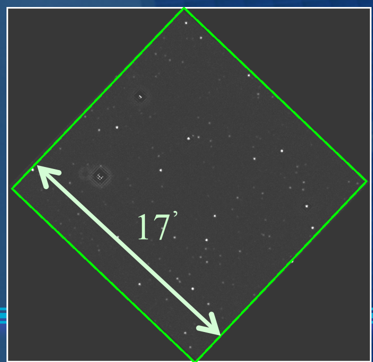
X-Ray Telescope (XRT)





E_range: 0.3-10 keV
Focal Length: 3.5m
Det: X-ray CCD (XMM MOS)
FOV: 23’ x 23’

Characteristics of Instruments

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

Why Swift for ToO Observations?

Chandra call for proposals handbook (page 37)

6.1 Transient Science (DDT Targets of Opportunity)

DDT proposals may be submitted at any time for transient phenomena such as supernovae, gamma ray bursts or accreting binaries. Proposers must demonstrate why the science return from the proposed observation is important and cannot be submitted to the peer review during the next cycle. Proposers should also note that TOO programs approved by the peer review take priority over DDT requests if the object in question fulfills the trigger criteria of a pre-approved TOO (Section 4.3) The long orbit and broad sky coverage of *Chandra* offer considerable flexibility in the treatment of TOOs. The minimum expected response time for a TOO is approximately 24 hours. The total number of TOOs performed is limited by operational and manpower constraints.

Given the limited availability and high operational impact of TOOs, proposers are asked to carefully consider whether *Chandra* is the optimal observatory for their particular target(s) and to justify this choice in their proposal. Other X-ray missions, e.g., SWIFT, are more flexible for performing TOO observations on medium/bright targets. SWIFT TOO application information either pre-approved (by peer review) or unanticipated, can be found on the SWIFT website at: http://www.swift.psu.edu/too.html.

Always Fast ToO

Automatic Tiling Observation

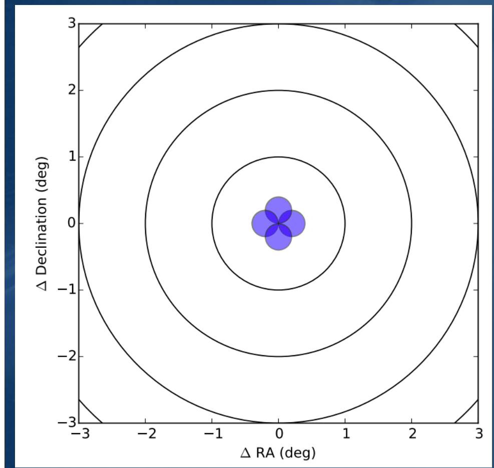
Automatic tiling observation capability
(Part of the BAT on-board software)

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

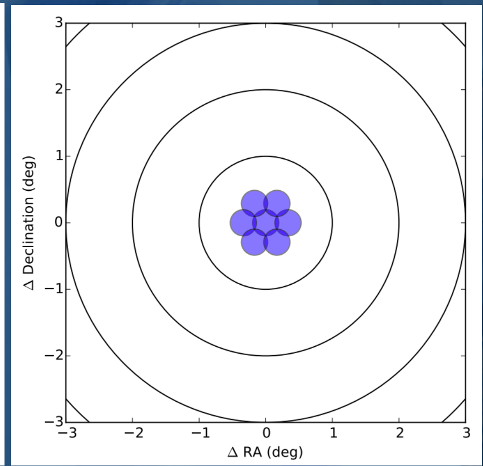
Tiling patterns

(figures from J. Kennea)

4-tiling

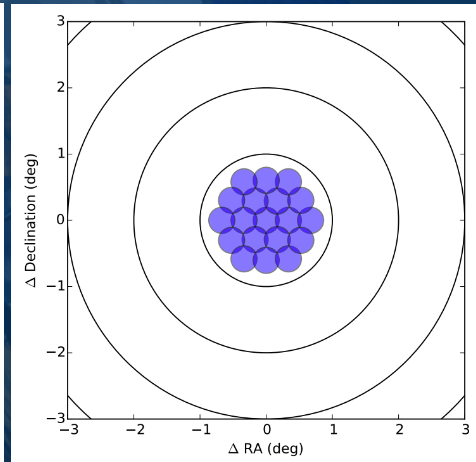


7-tiling

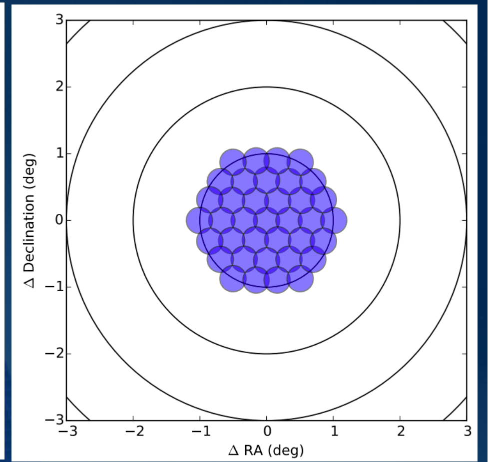


Required tiling pattern to cover 1° diameter

19-tiling



37-tiling



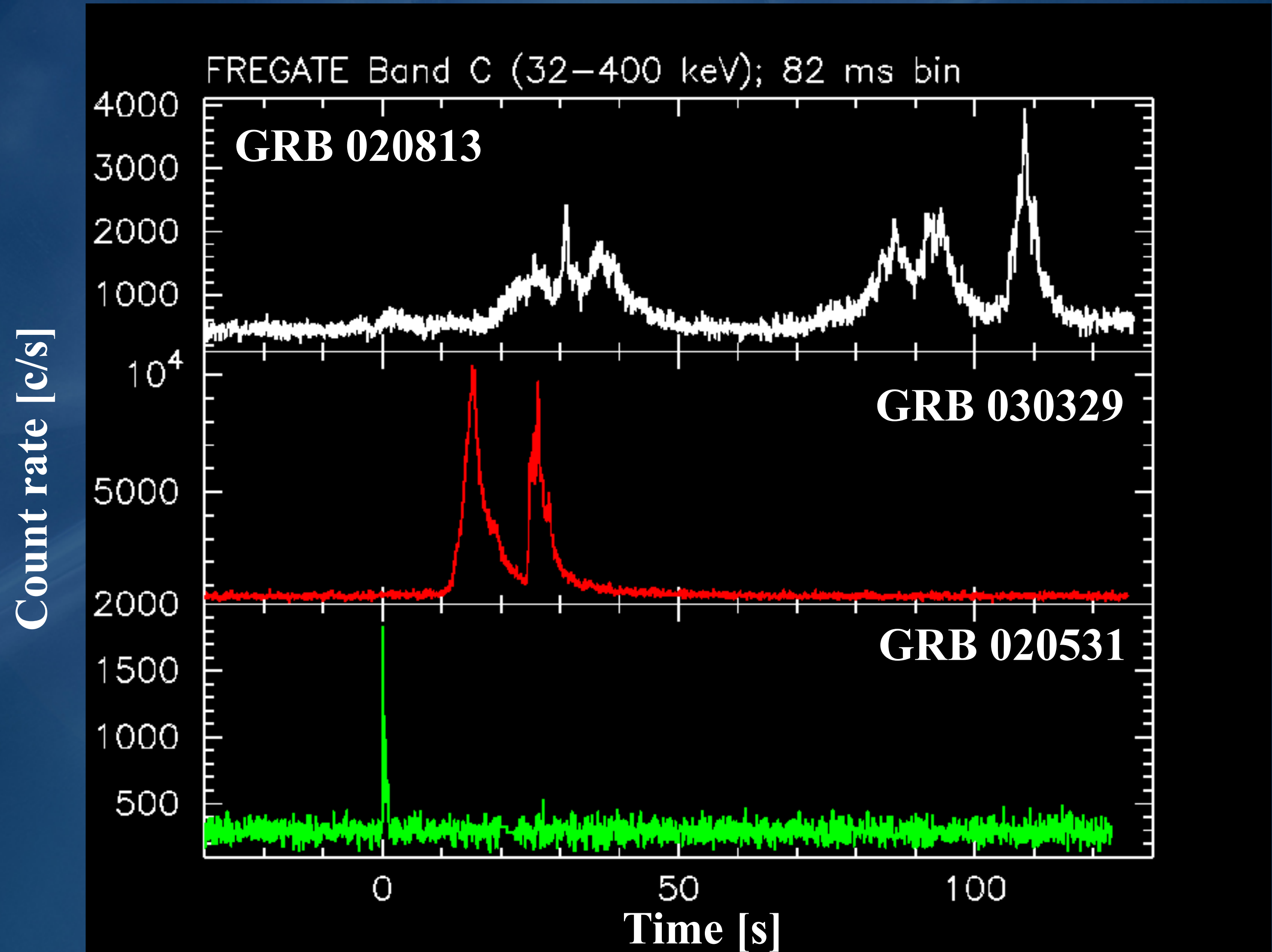
Required tiling pattern to cover 2° diameter

Gravitational-wave (GW) Electromagnetic (EM) Counterpart Search

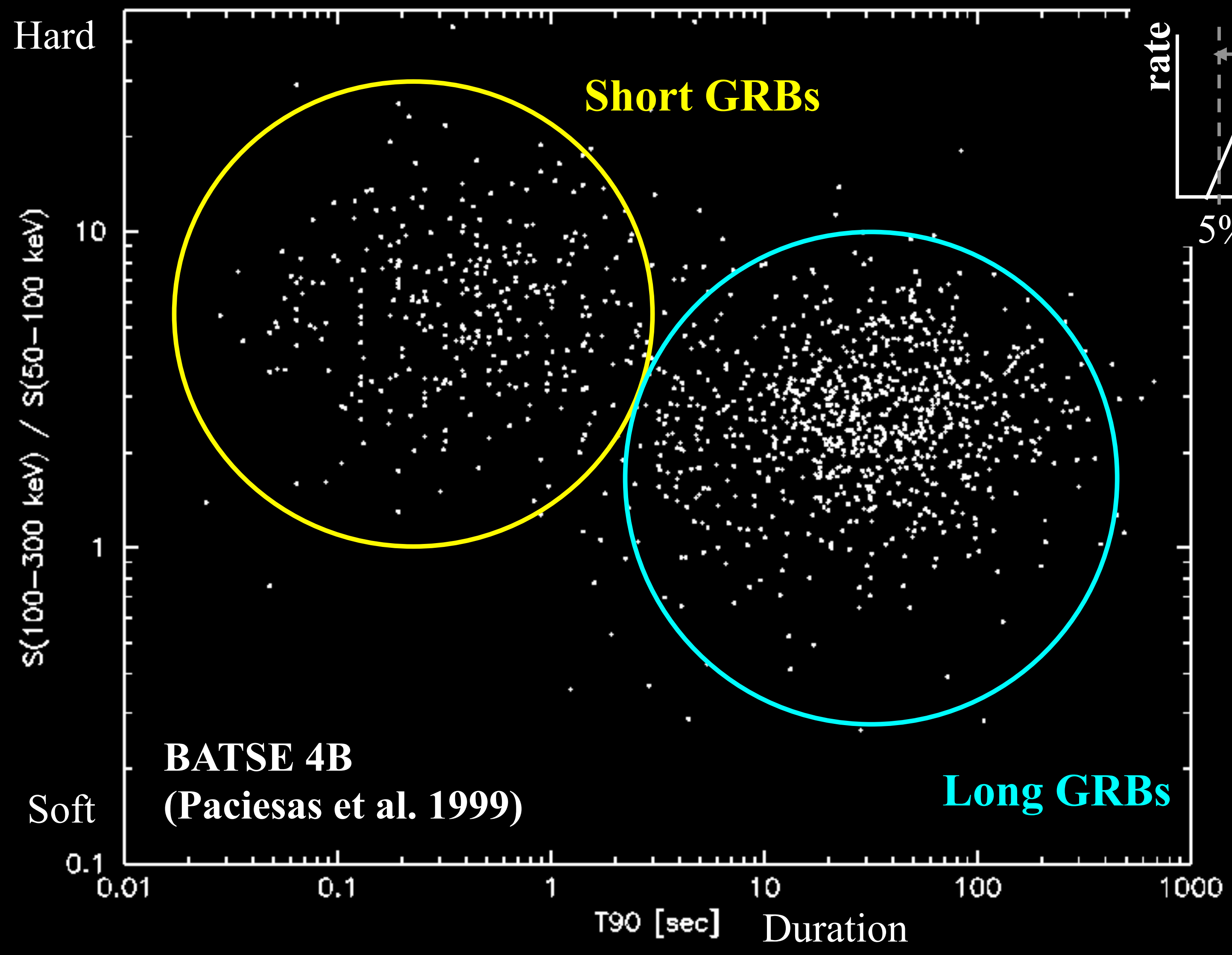
Short GRBs

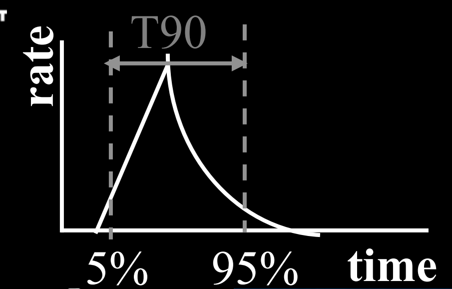
Light curves of GRBs

HETE-2/FREGATE



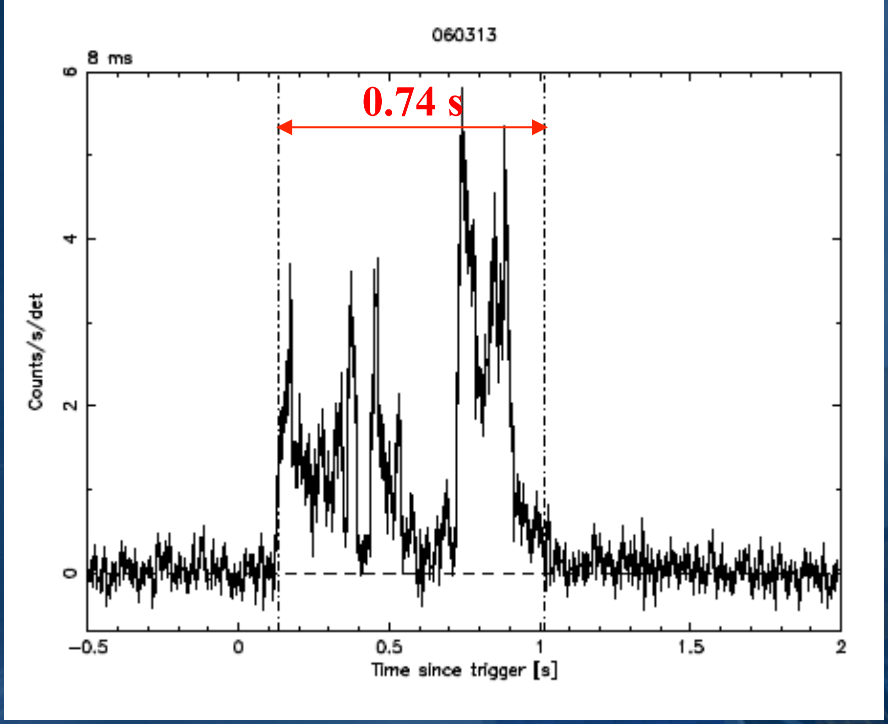
Two populations in GRBs



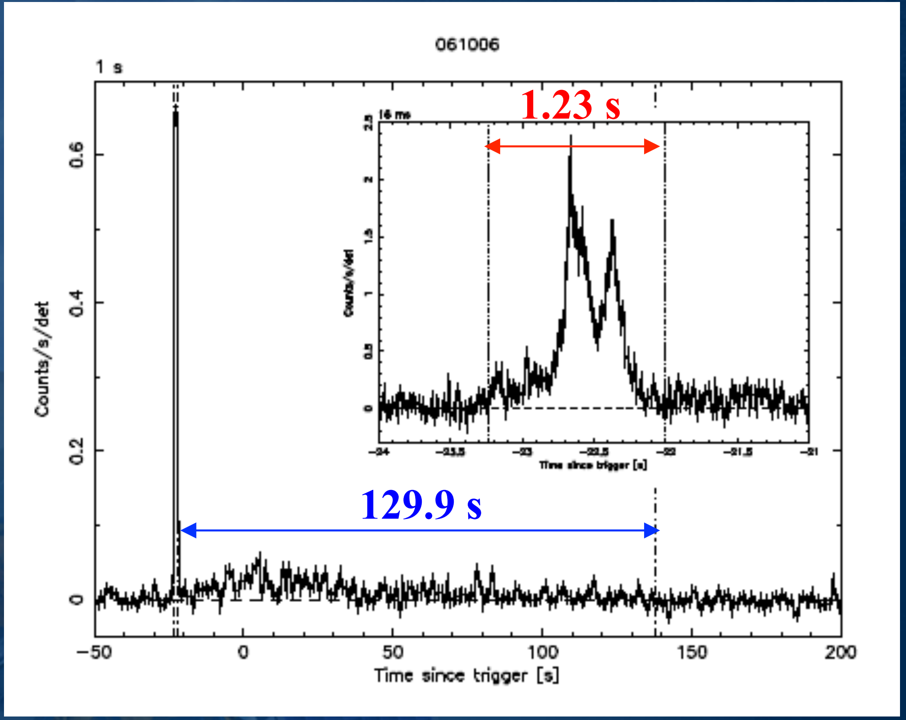


Prompt emission properties of Short GRBs

GRB 060313 (typical short GRB)

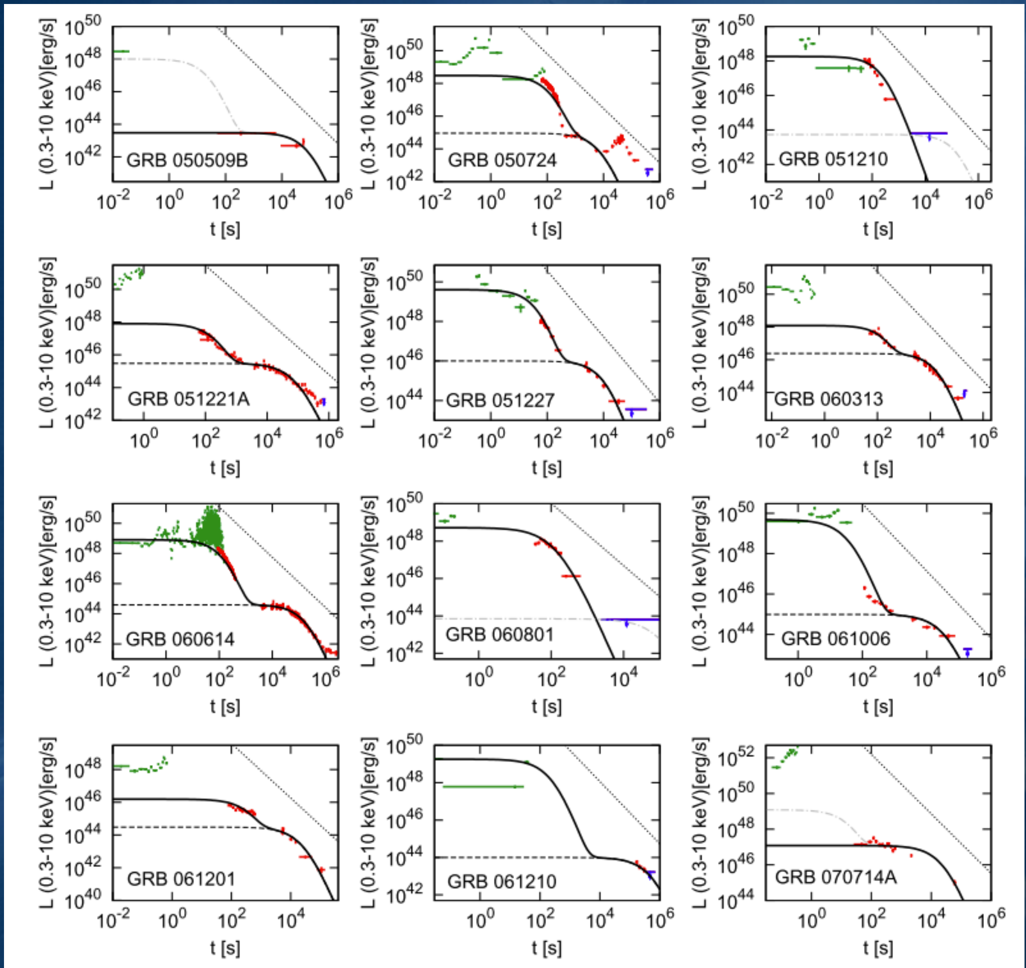


GRB 061006 (short GRB with E.E.)



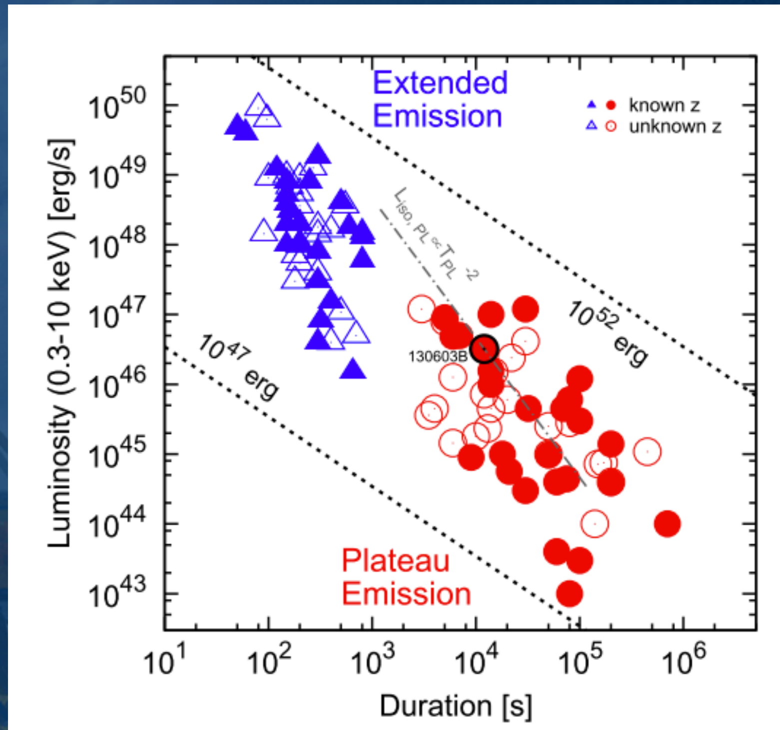
- With/without extended emission (E.E.) (Norris & Bonnell 2006)
- No spectral lag (Norris et al. 2001)
- Low fluence and high E_{peak} (Outlier of E_{peak}-E_{iso} relation) (Amati 2006)
- No soft short GRBs (Kouveliotou 1993, Sakamoto 2006)

Long-lasting X-ray Emission in s-GRBs



Two distinct components in X-ray light curves

(Kisaka, Ioka, Sakamoto 2017)

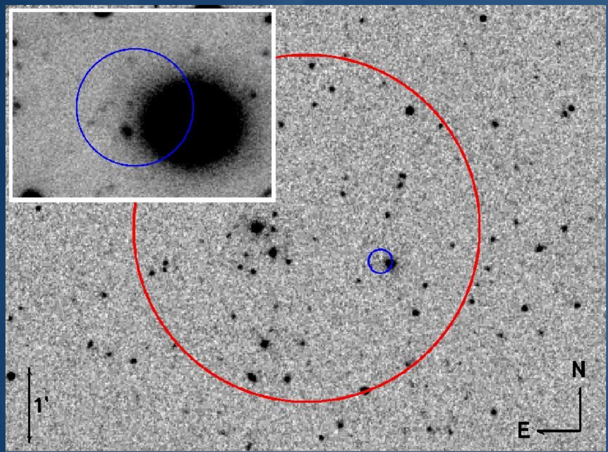


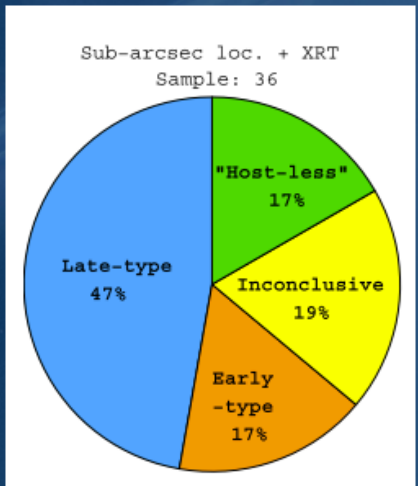
- About a half of s-GRBs has both EE and PE components
- Universal X-ray emission characteristics of s-GRBs?

S-GRB hosts and “kilonova” emission?

- Mixed (early-type/late-type) host galaxies

GRB 050509B (Gehrels et al. 2005)



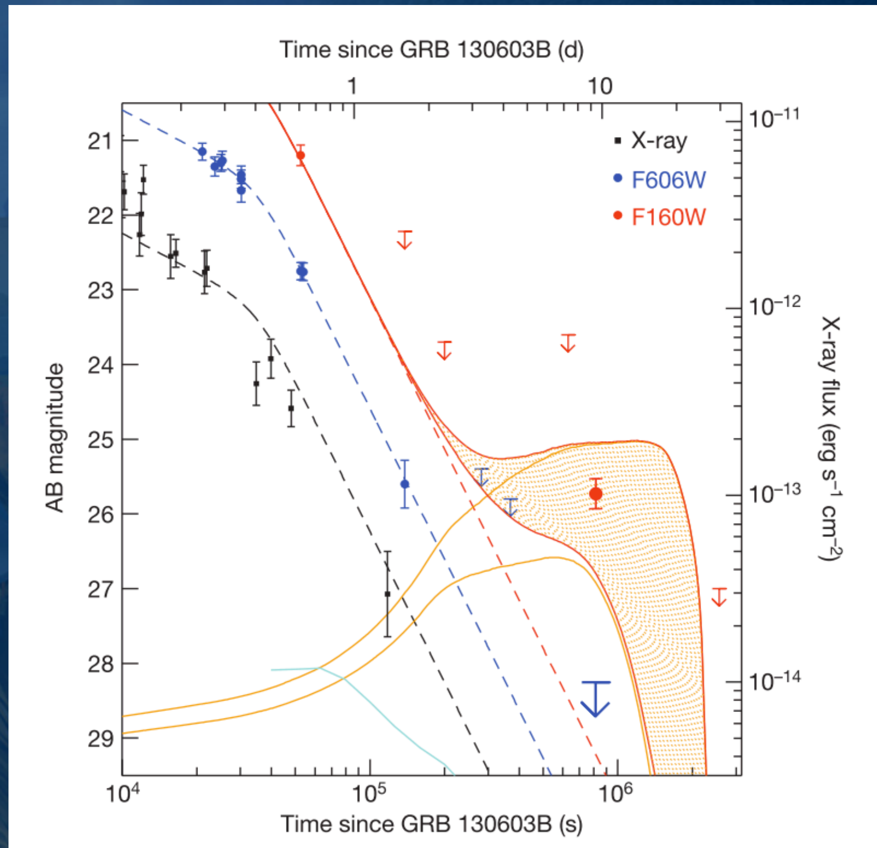


S-GRB host galaxy population (Berger 2014)

GRB 130603B (Tanvir et al. 2013)

‘kilonova’ association:

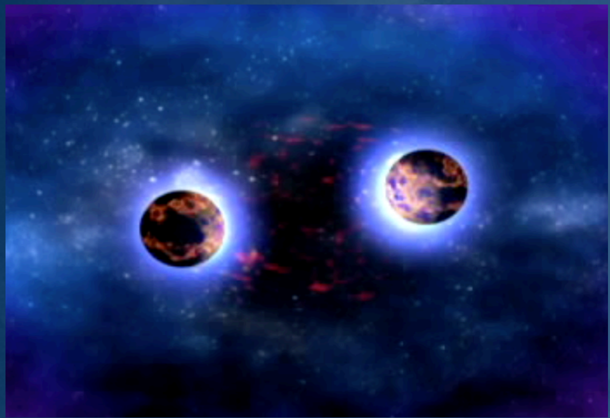
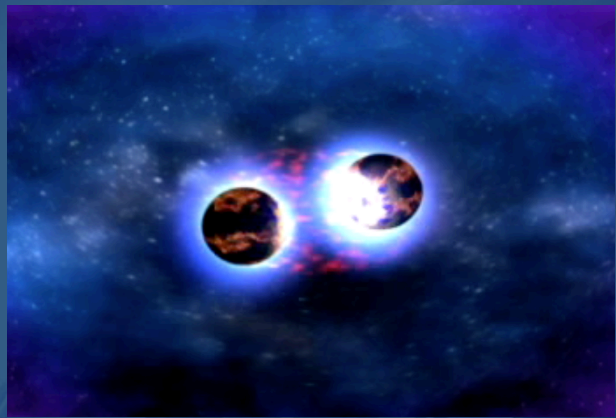
Indication of NS-NS/NS-BH merger



S-GRBs: NS-NS/NS-BH Merger Model

Eichler et al. 1989; Narayan, Paczynski & Piran 1992

(http://swift.sonoma.edu/resources/multimedia/animations/)


1. NS binary system

2. Getting close due to the energy loss by gravitational-wave



4. Merged

5. Remnant is BH with a disk

6. Lunch a GRB jet

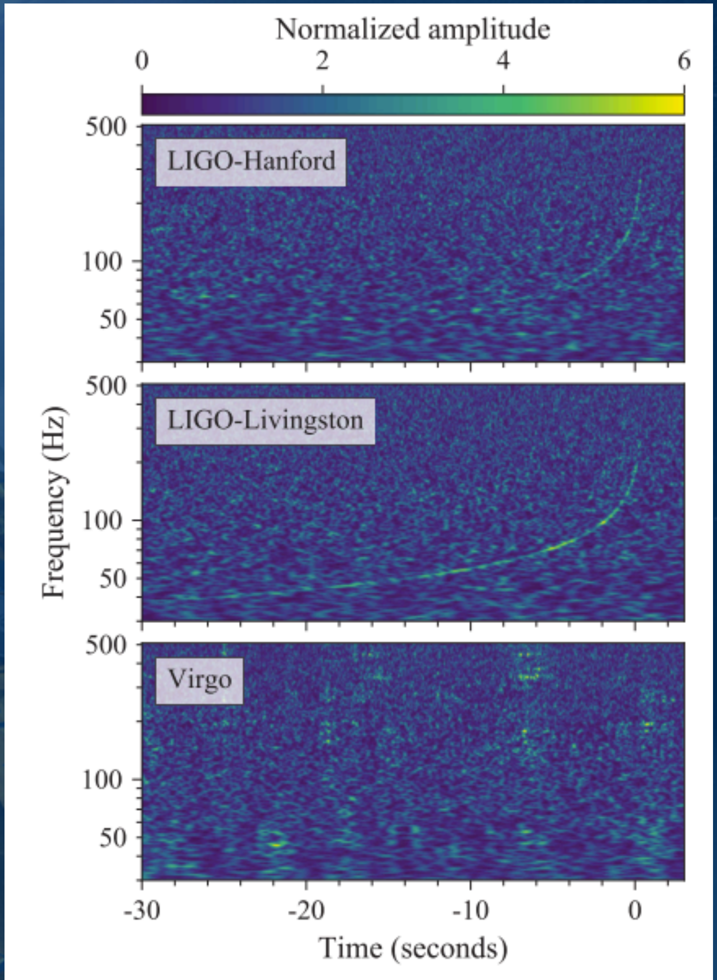
Swift O2-run Observing Strategy

- Co-detection of a short GRB with BAT and the GW signal from LIGO-Virgo (best case!)
  - 0.02-0.14 events per year (Wanderman & Piran 2015)
- Swift NFIs follow-up criteria
  - Unmodelled triggers: FAR < 1/6 months and P400 > 0.2 (P400: the amount of convolved probability covered by the top 400 Swift pointings)
  - CBC triggers: 1) "ContainsNS" > 0.25 or 2) "ContainNS" < 0.25 and P400 > 0.5
- If EM counterpart detected by other facilities, Swift will do follow-up

GW 170817

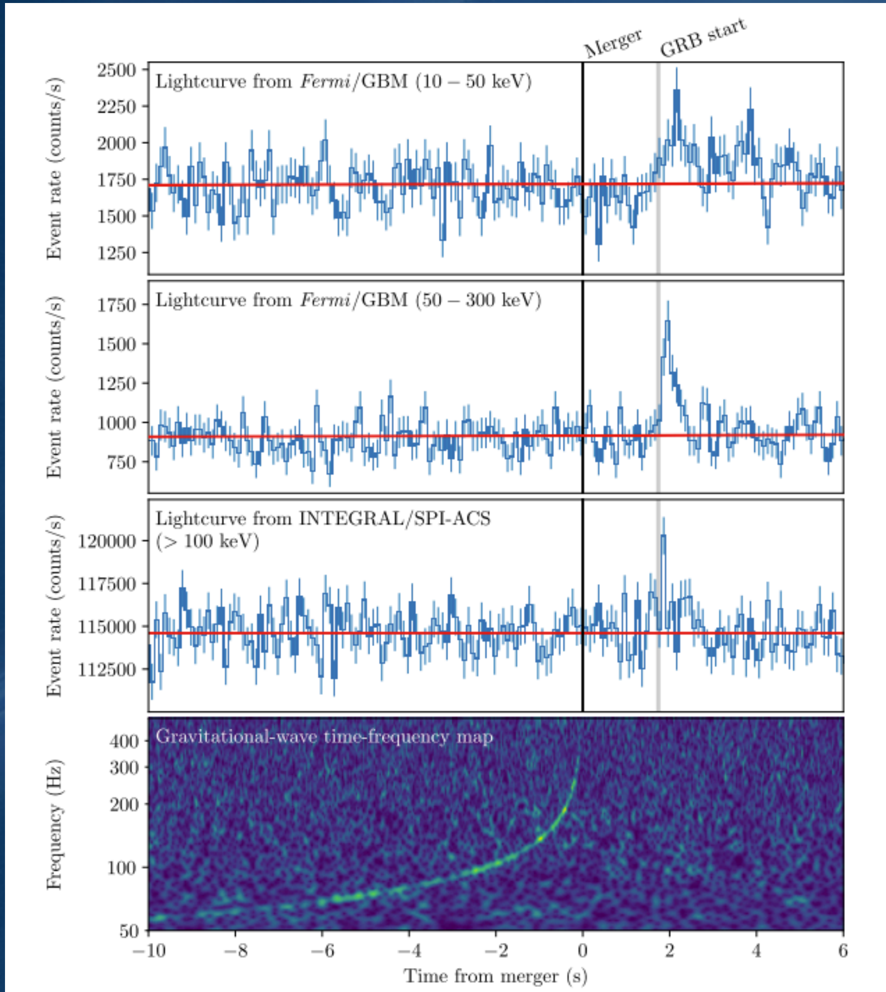
Gravitational-wave event from BNS merger!

Abbott et al. 2017

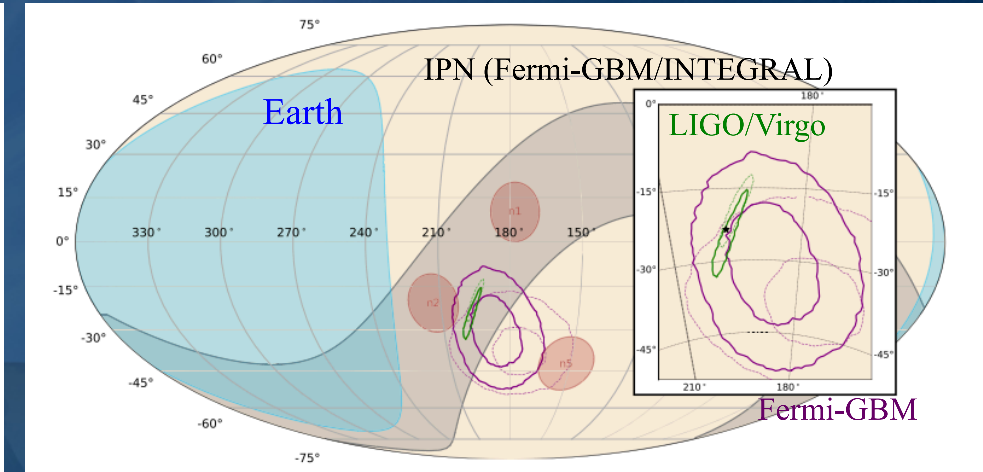


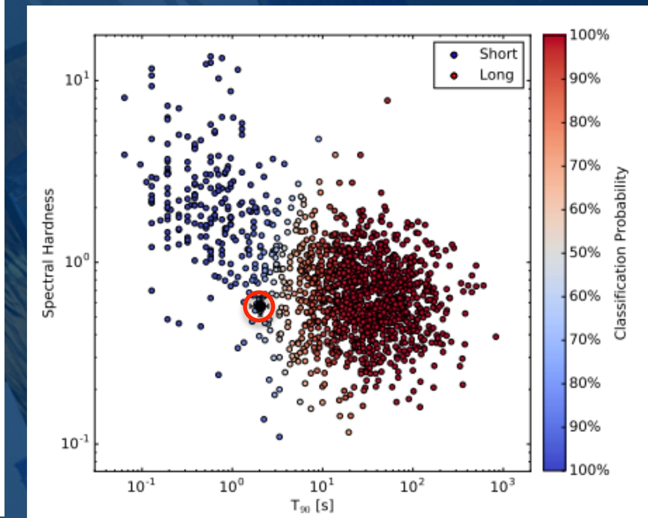
Association of GW 170817 and GRB 170817A

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



GRB 170817A (Goldstein et al. 2017)



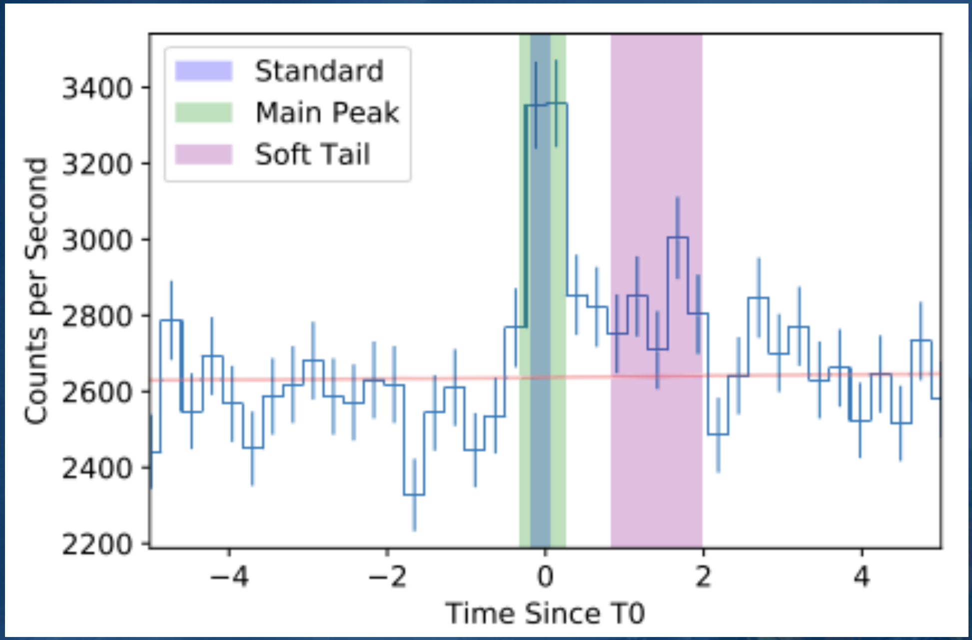


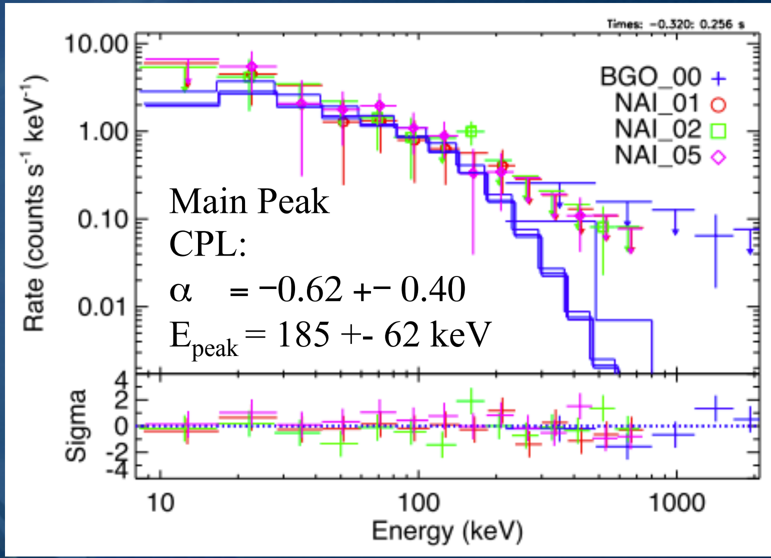
T_{90} = 2.0 +- 0.5 s

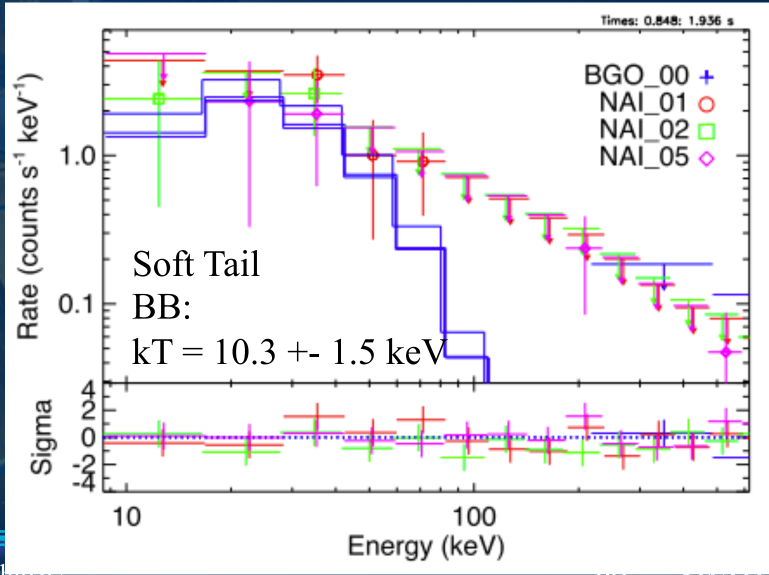
Probability of S-GRB class: 72%

Fermi-GBM spectrum of GRB 170817A

(Goldstein et al. 2017)

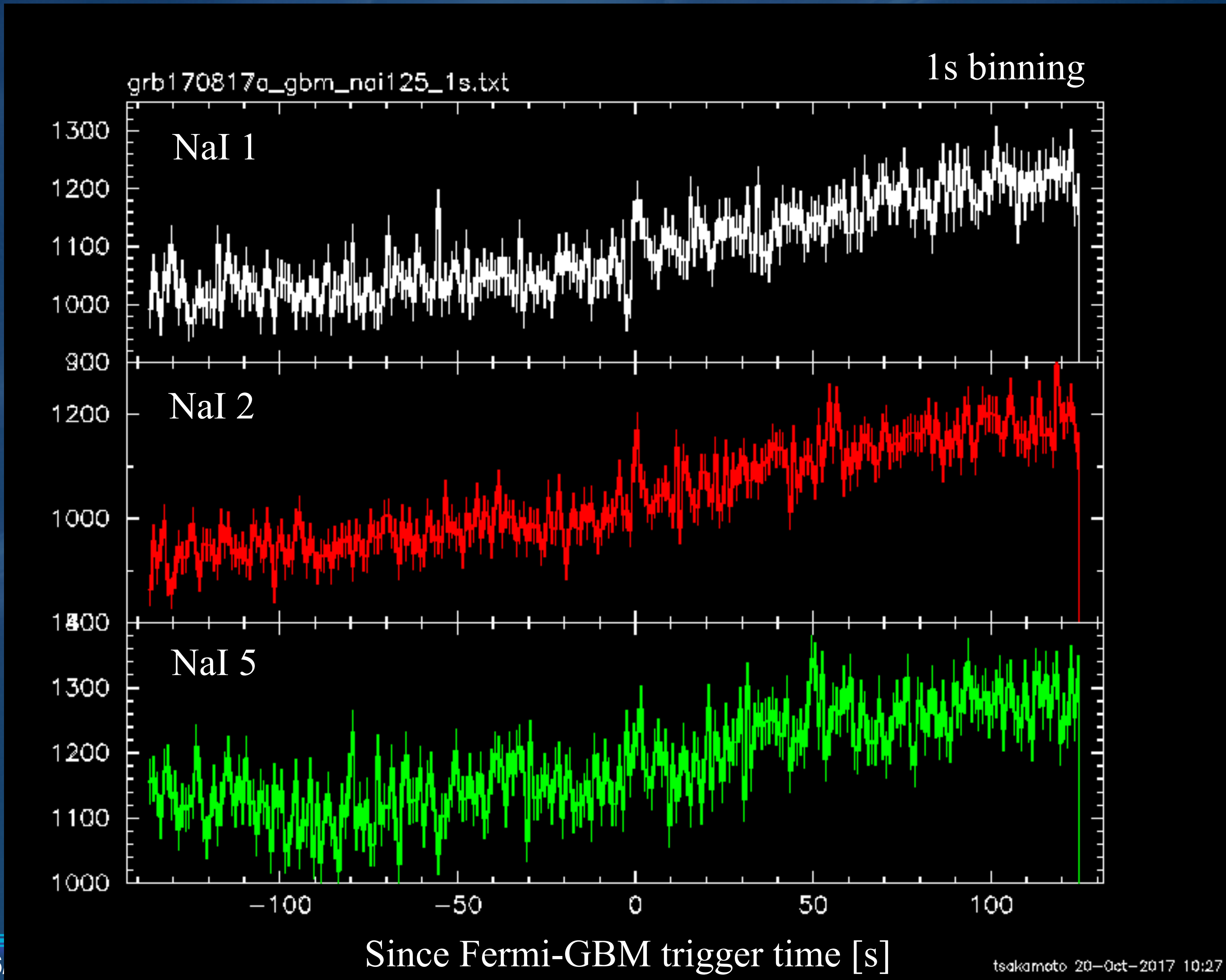






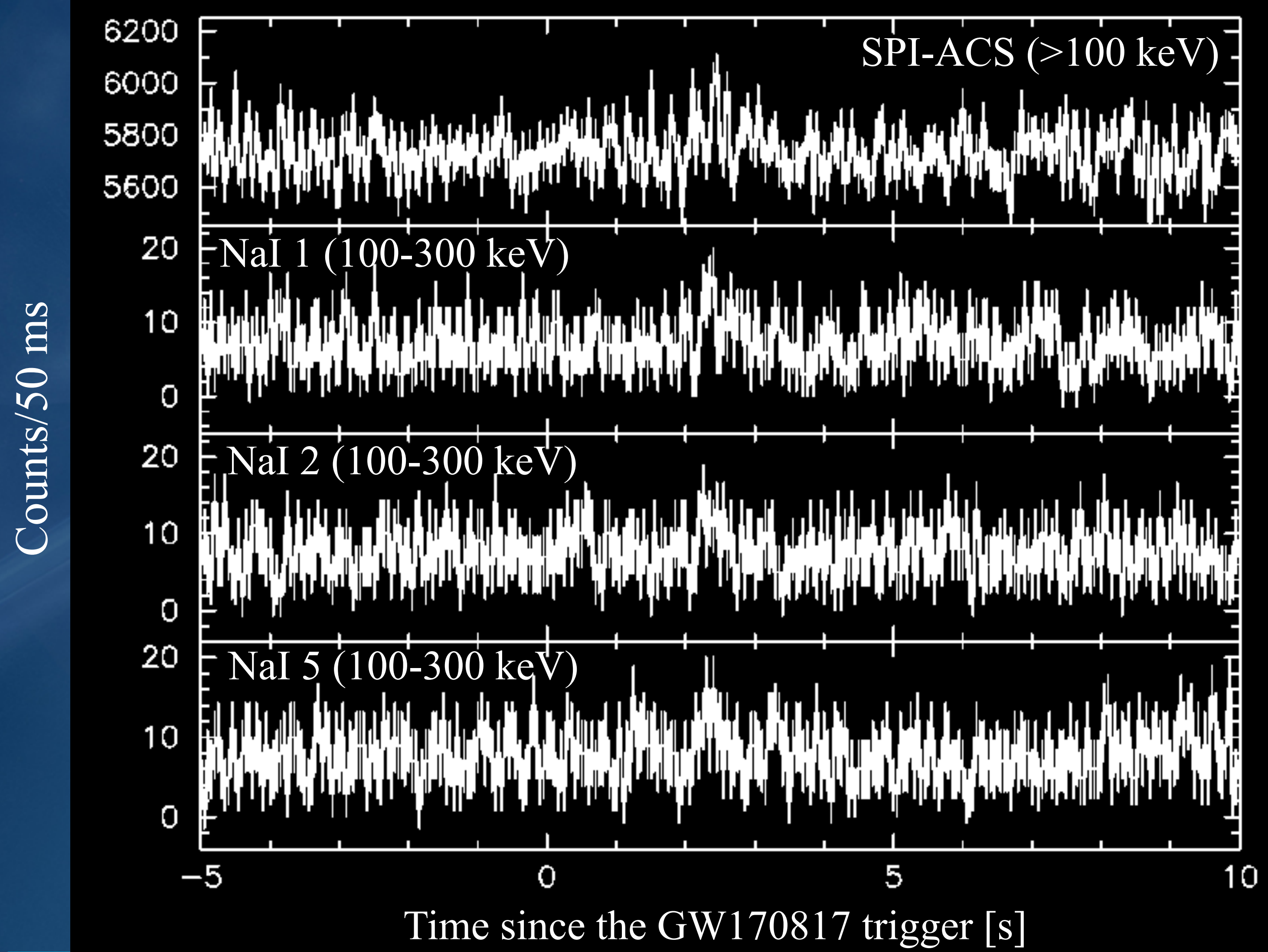
Main pulse:
time-averaged flux: (3.1 +- 0.7) x 10^{-7} erg/cm^2/s

GRB 170817: Fermi-GBM light curve



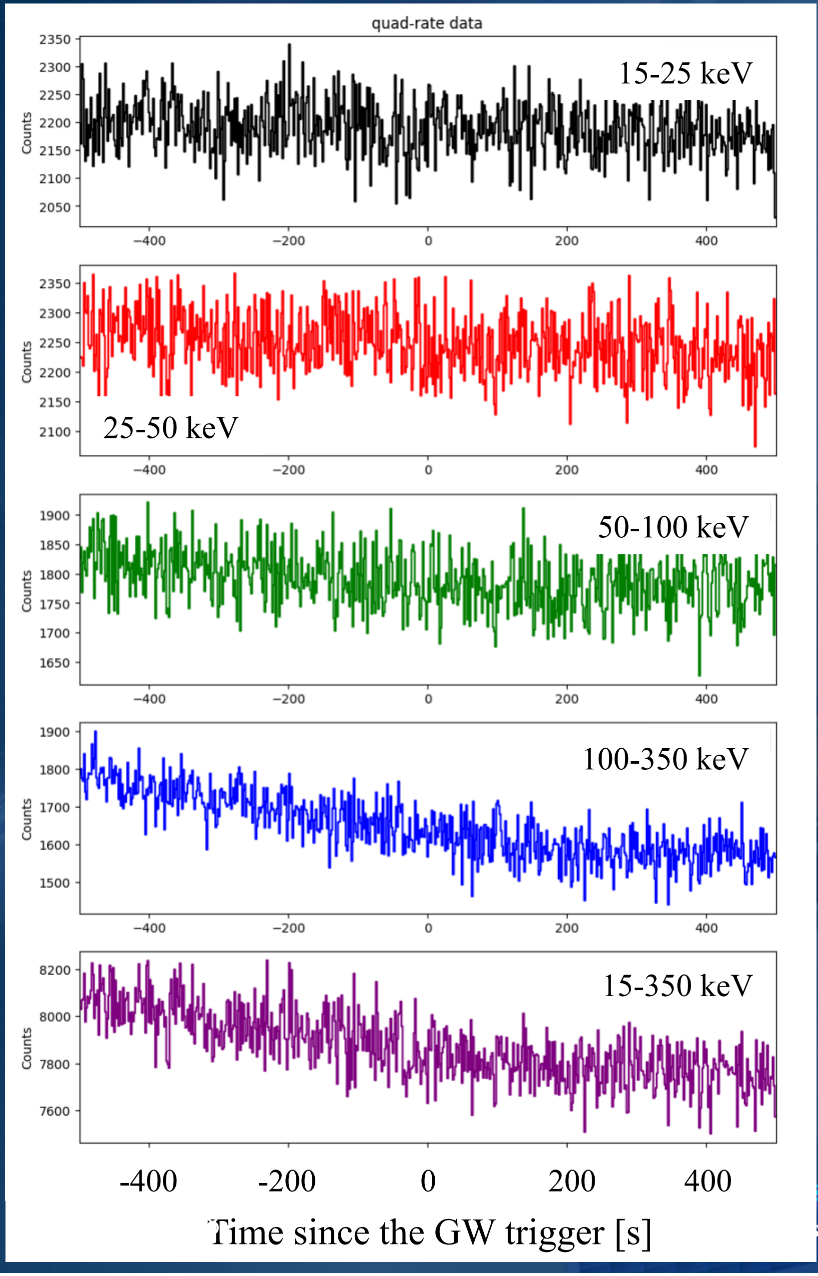
Swift

GRB 170817 50 ms Light curve of INTEGRAL/SPI-ACS and Fermi/GBM

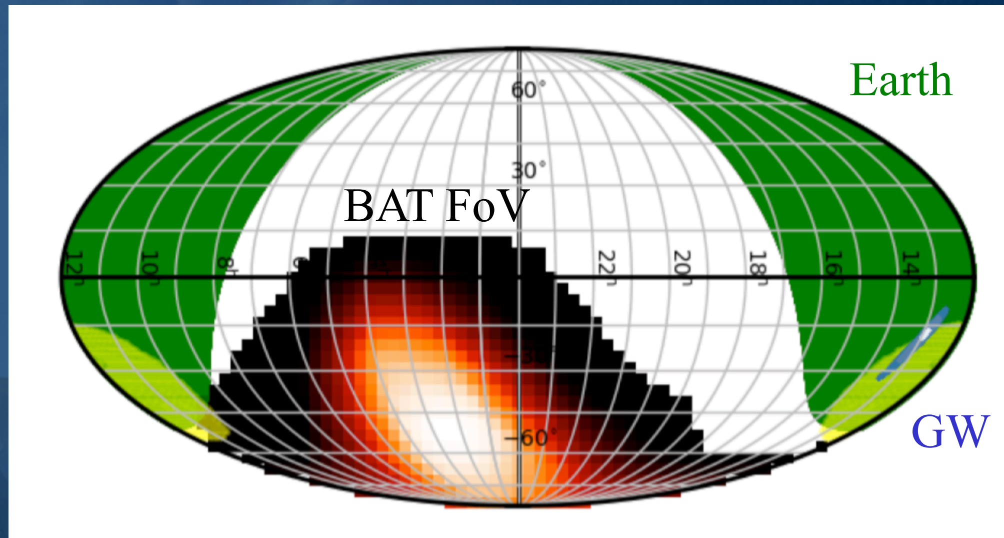


GW 170817: BAT Observation

1.6 s light curves



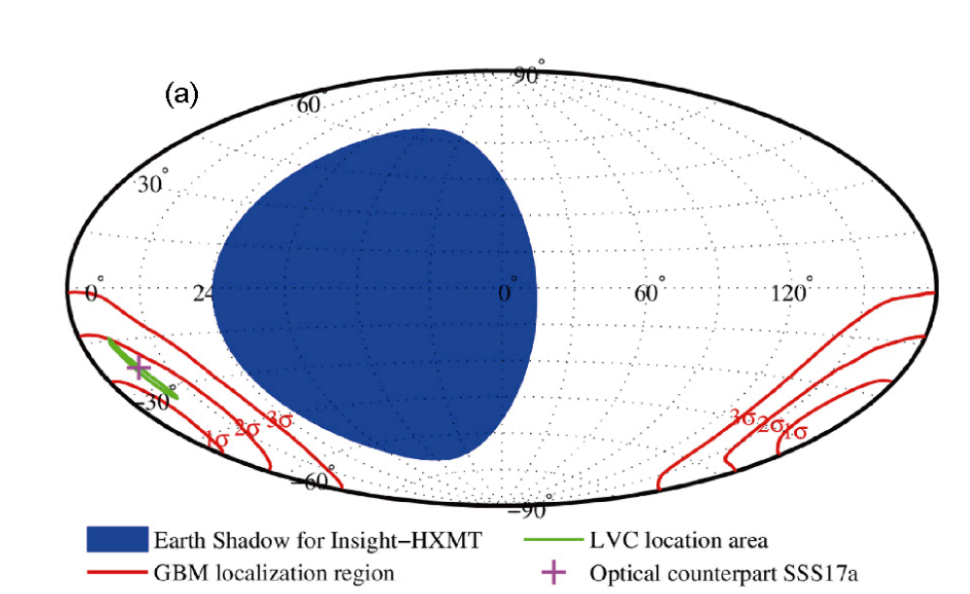
(Evans et al. 2017)

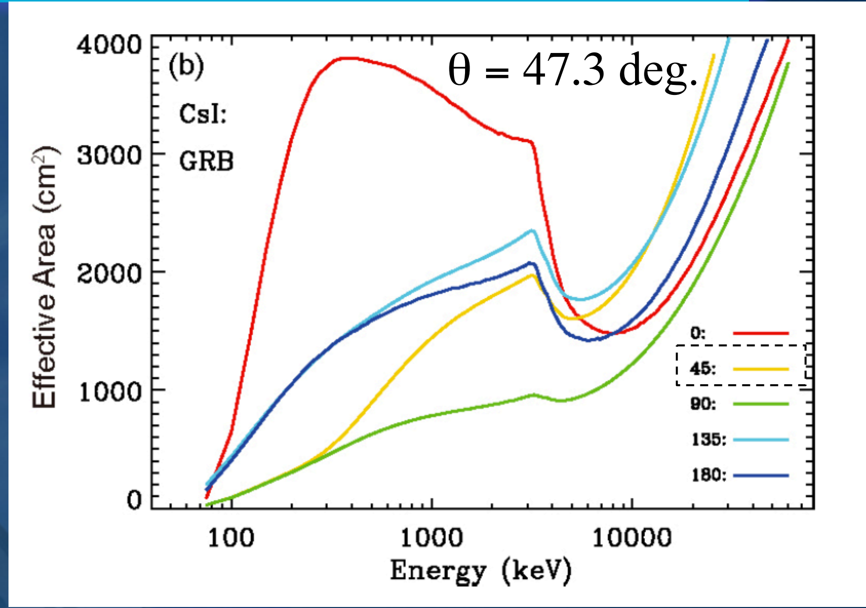


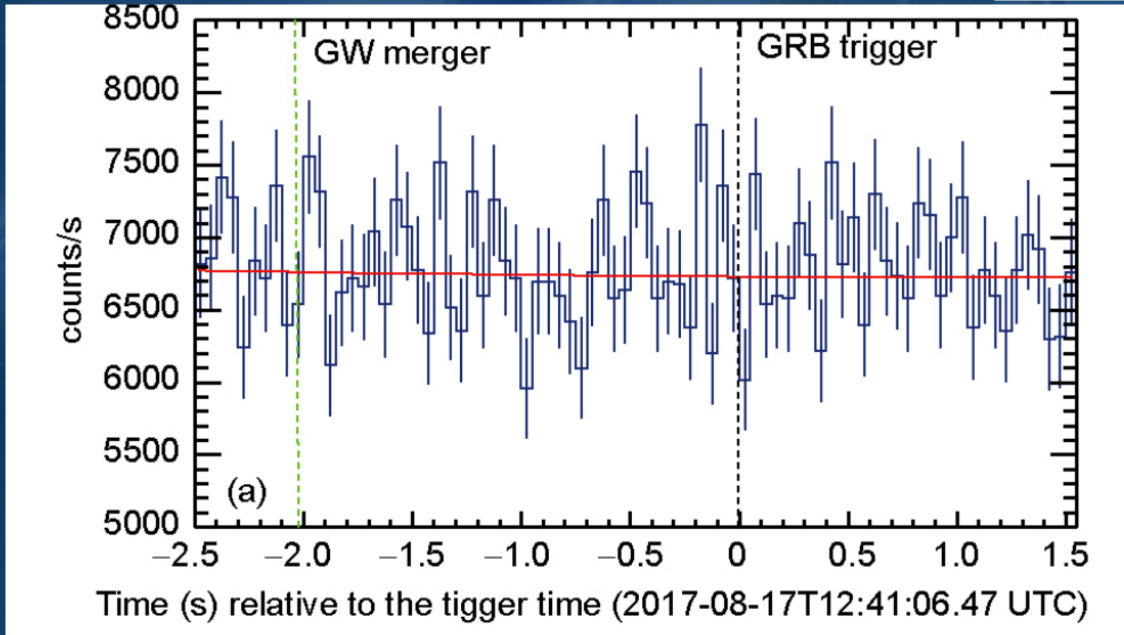
- Nothing in the BAT light curve at T_0(GW)
- GW 170817 error region was occulted by the Earth

Insight-HXMT: GRB 170817 Observation

(Li et al. 2017)







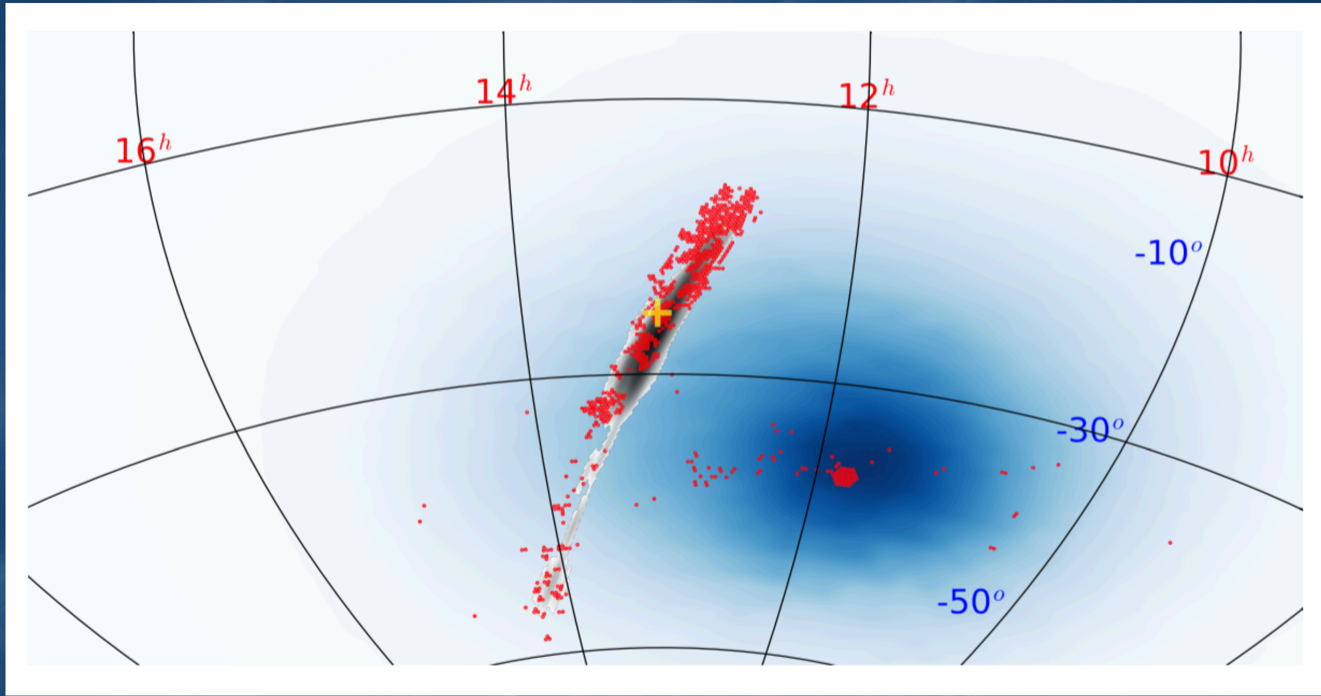
No detection

- Consistent that GRB 170817 is very weak and soft (3-sigma UL 10-1000 keV : 2 x 10^{-6} erg/cm^2/s)

Konus-Wind: No detection
90% UL: 3 x 10-7 erg/cm^2/s (~3 s)
(Svinkin et al. GCN circ. 21746)

Swift Follow-up Observations

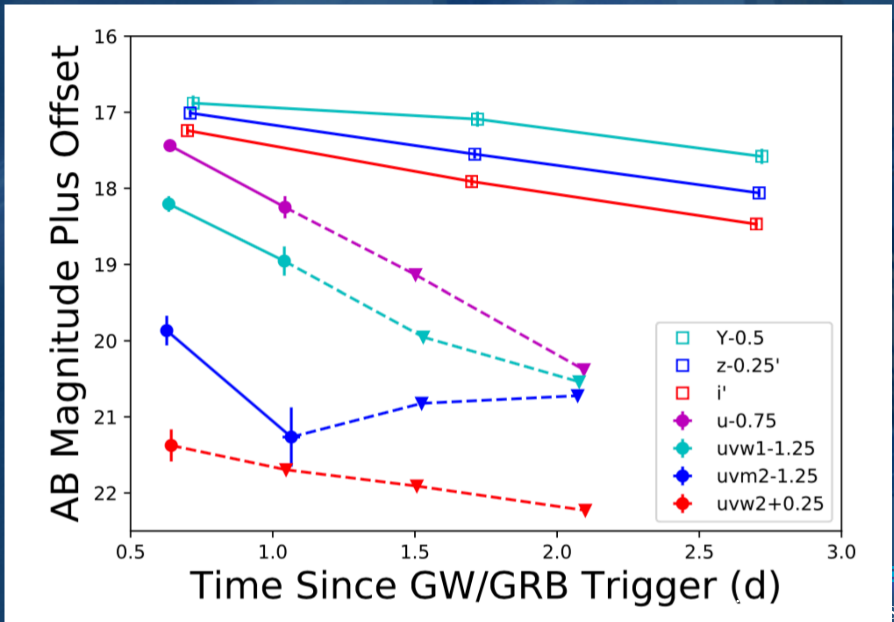
(Evans et al. 2017)



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/Virgo 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)



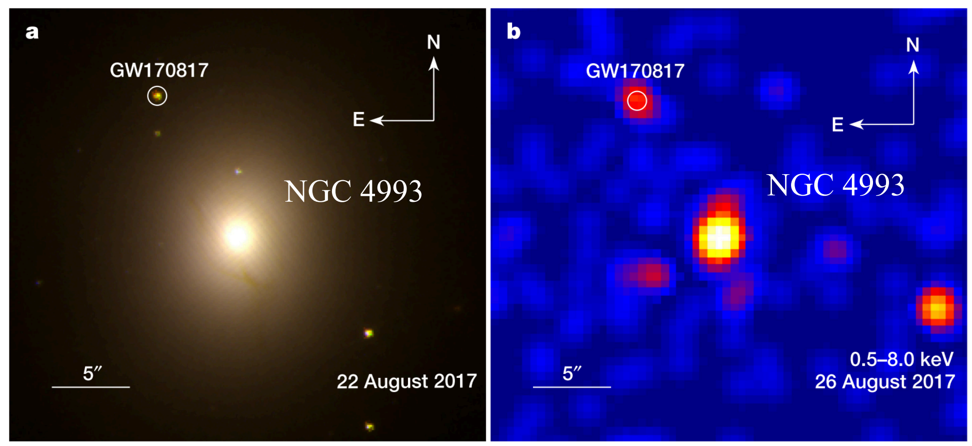
Rapidly fading UV emissions were detected by UVOT

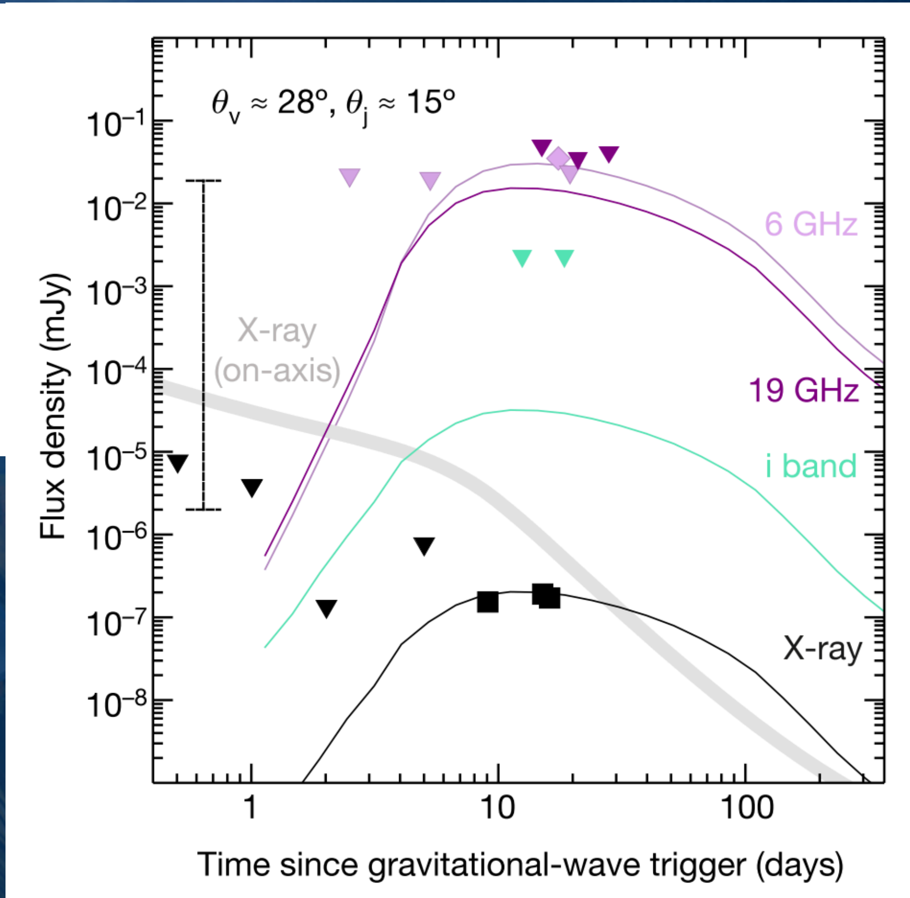
Clear detection of kilonova in UV

Chandra detection of X-rays from SSS17a

(Troja et al. 2017)

Hubble (T_0+1 day) Chandra (T_0+9 days)



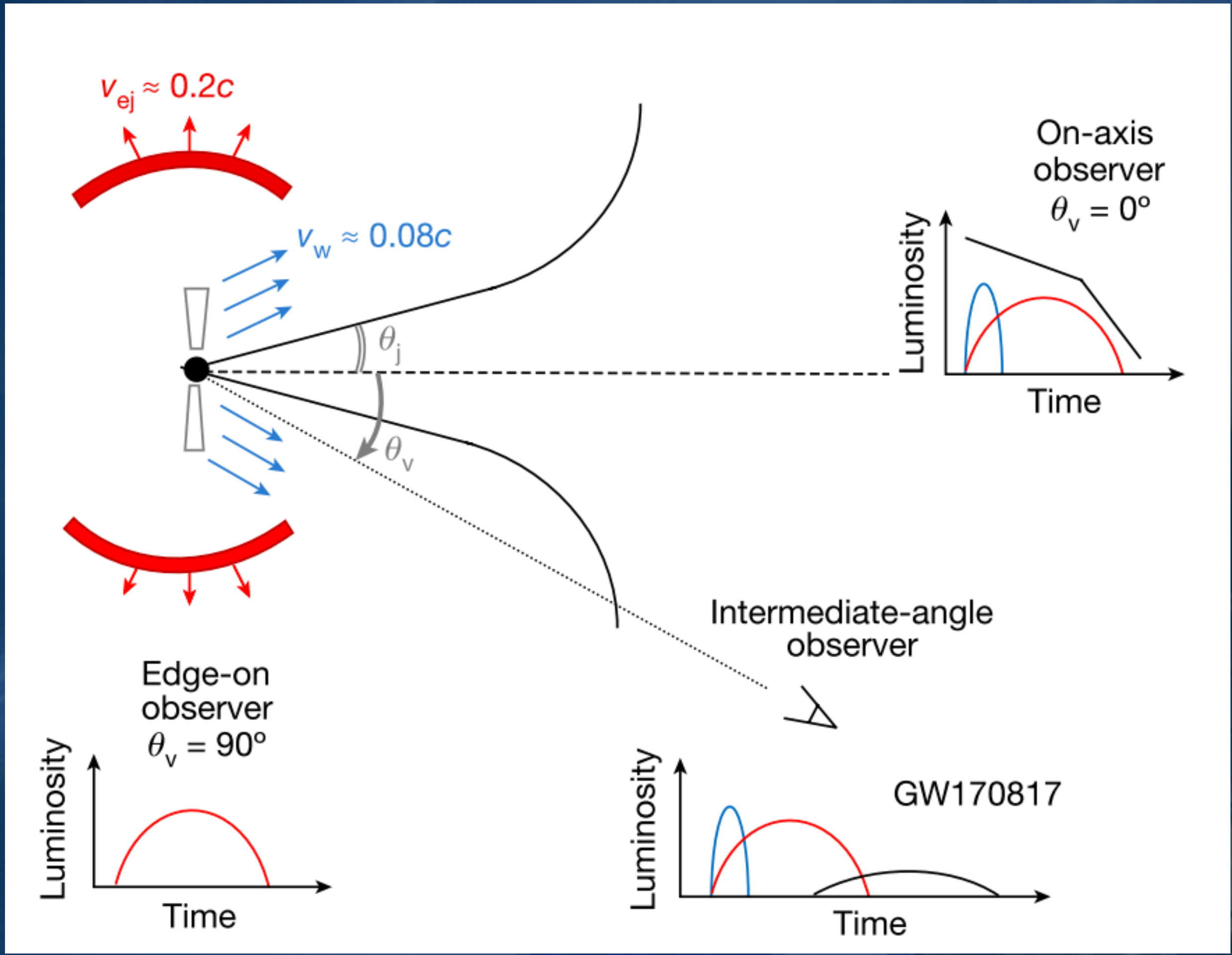


T_0:2.2 d: Non detection
T_0+9 d : 12 photons
: (4.0 +- 1.1) x 10^{-15} erg/cm2/s
T_0+15 d: 17 photons
: (5.0 +- 1.0) x 10^{-15} erg/cm2/s

Slowly rising: $t^{0.5}$

Off-axis GRB Afterglow?

(Troja et al. 2017)



Jet opening angle:
$\theta_j = 15$ deg
Viewing angle:
$\theta_v = 28$ deg

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

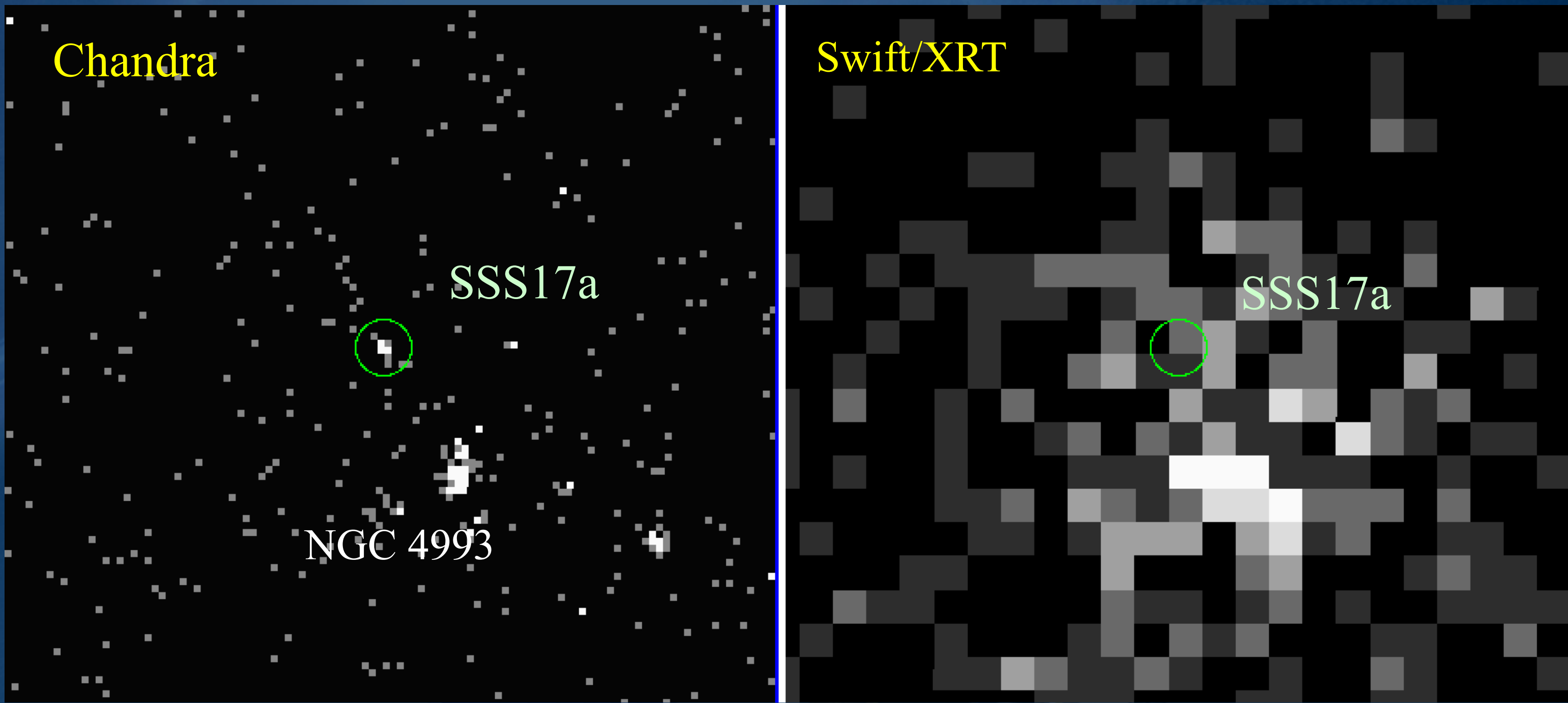
Standard uniform jet:
Prompt GRB emission should be fainter than GRB 170817A

Gaussian jet:
Consistent with the data

Swift/XRT Follow-up Observations of SSS17a

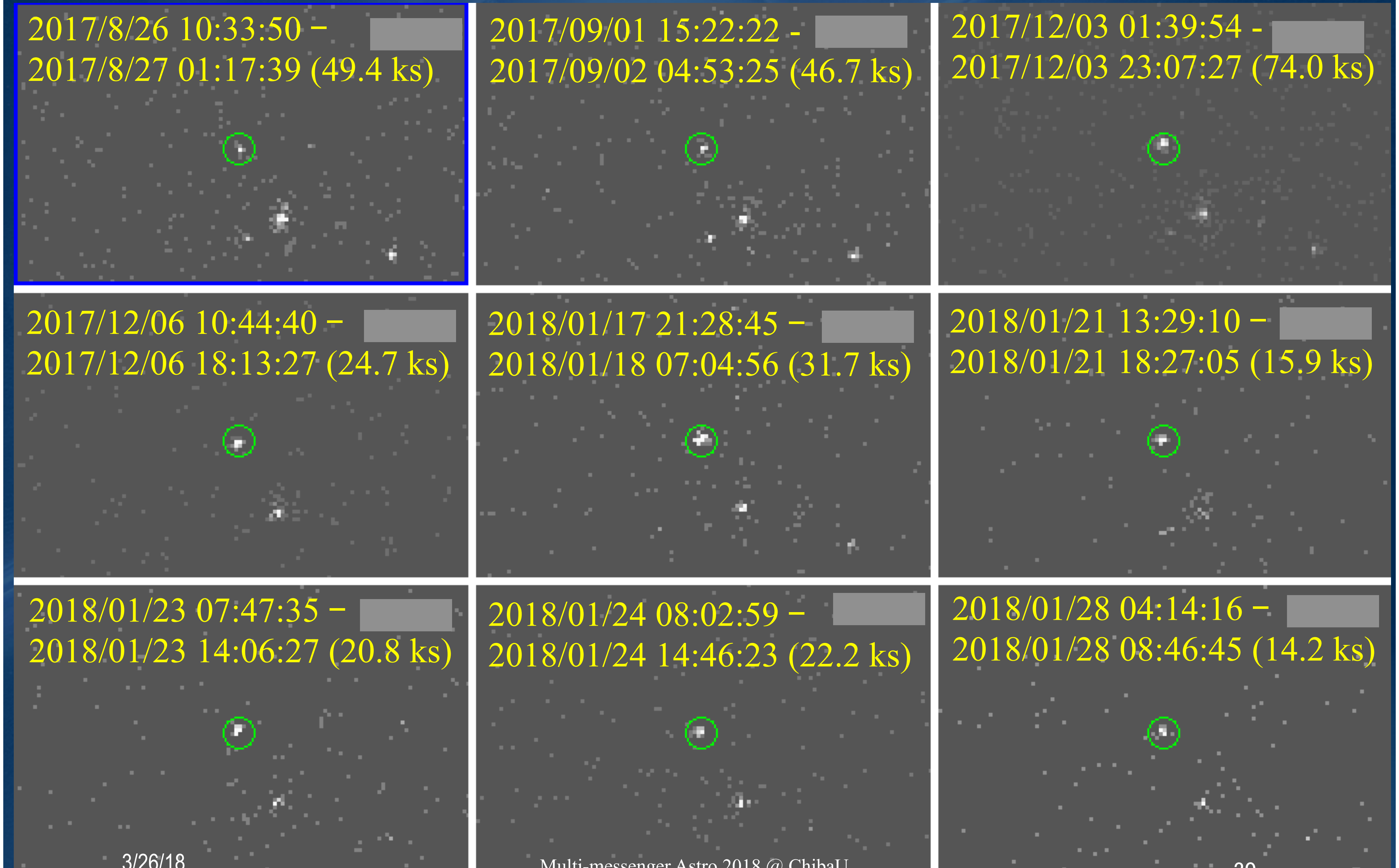
- 2017/8/18 – 2017/9/1
- 2017/9/12
- 2017/12/1 – 2018/1/4

Total exposure: 305 ks

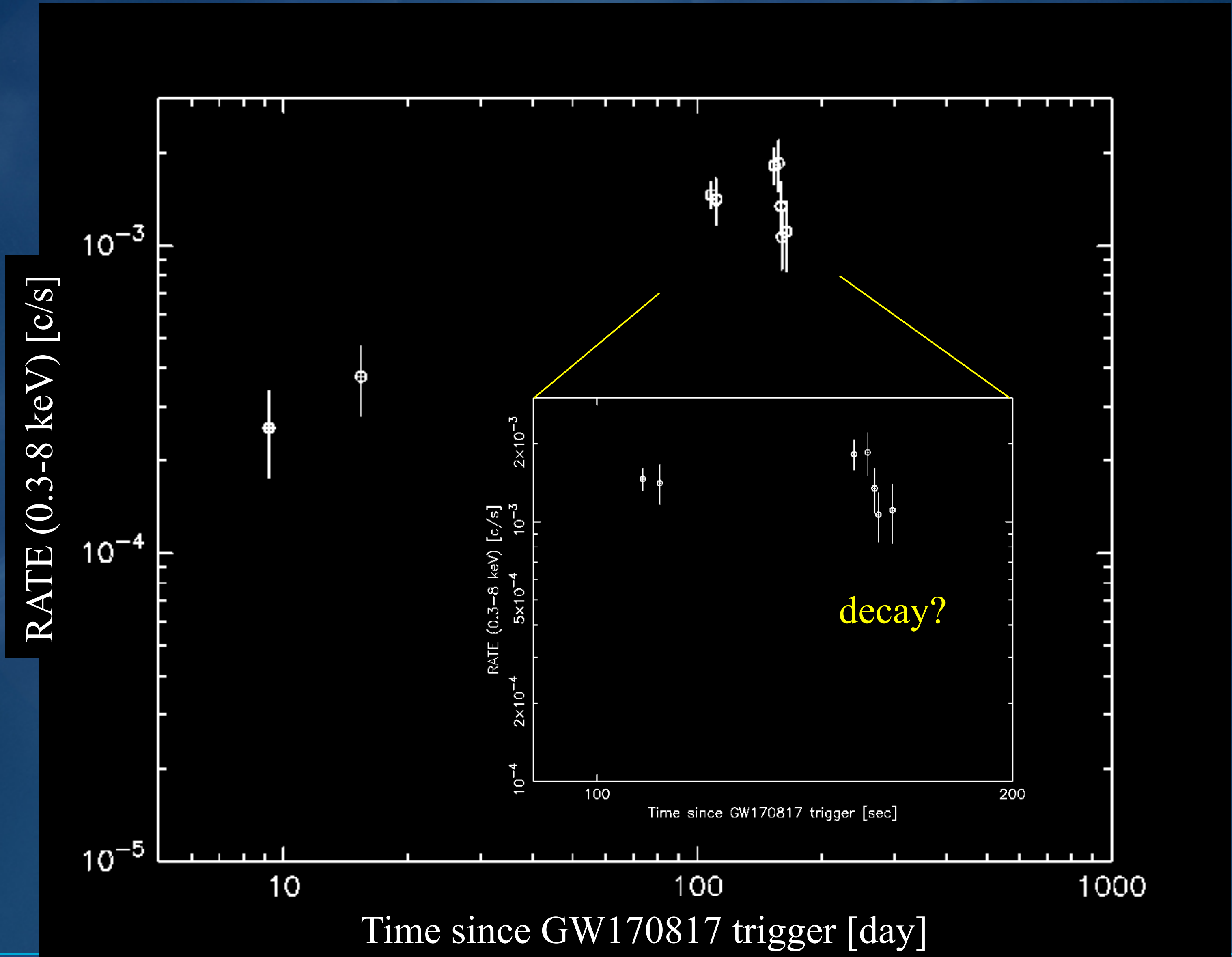


Chandra Further Observations

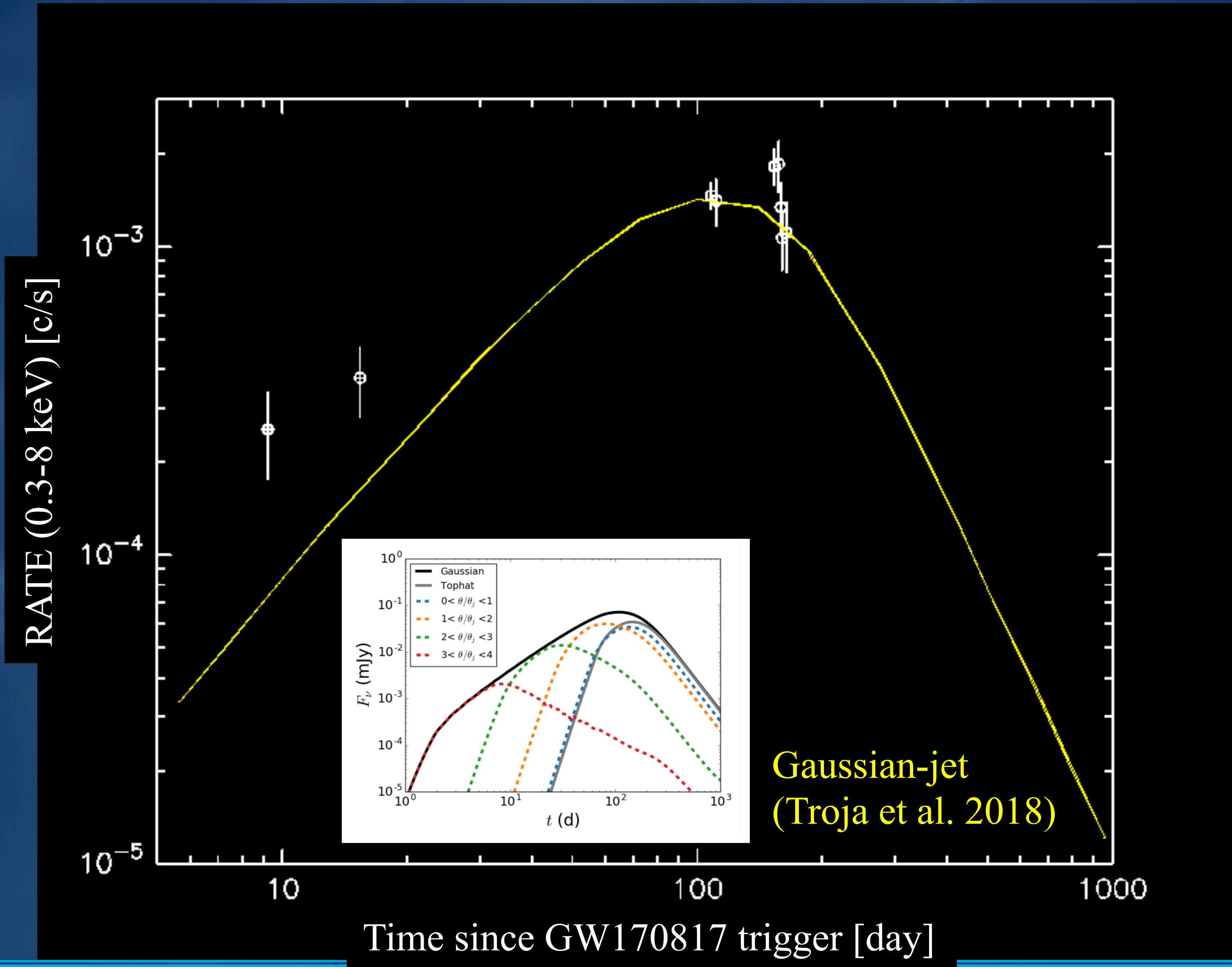
(Only archived data)



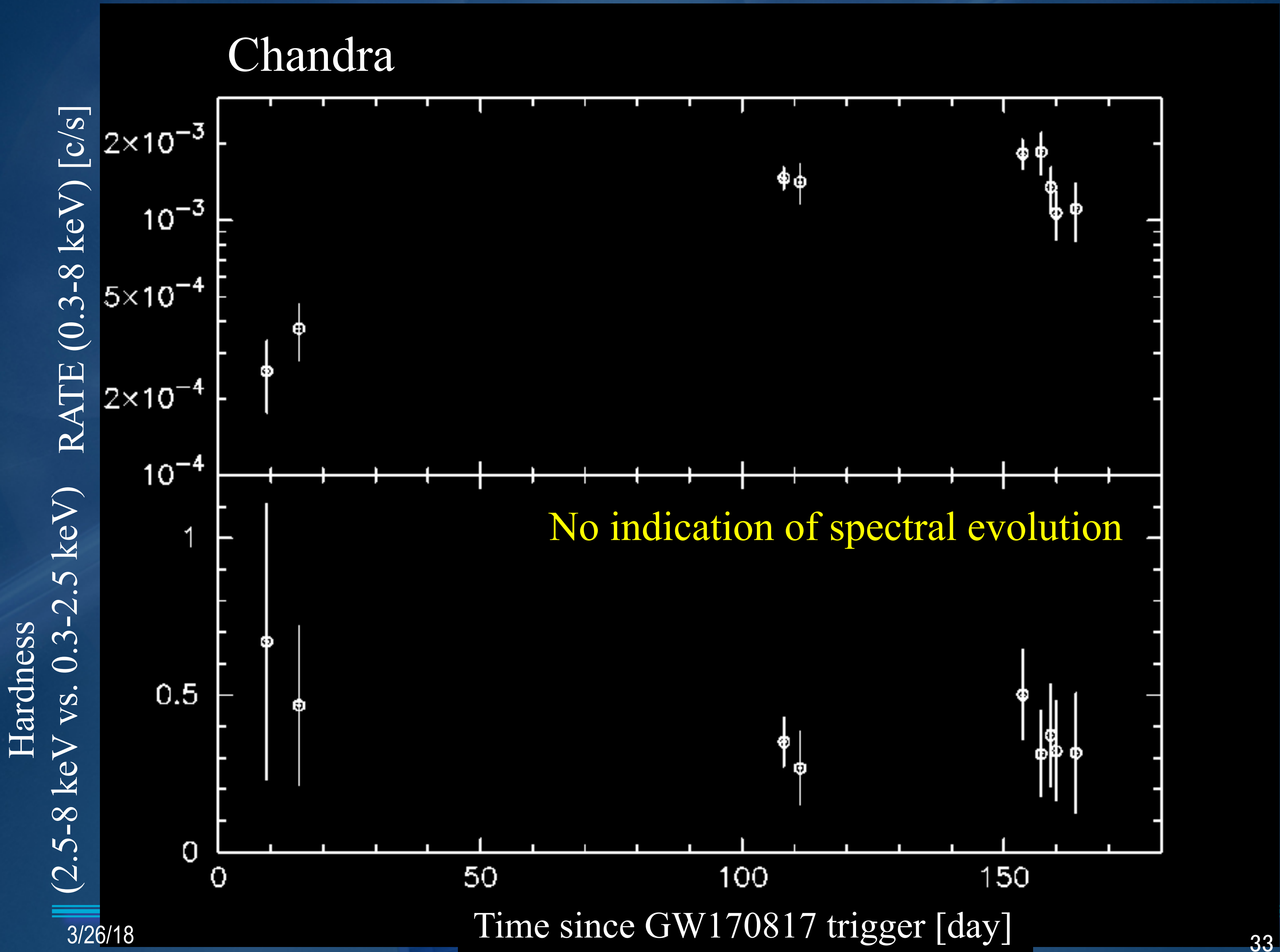
SSS17a: Chandra X-ray Light curve



SSS17a: Chandra X-ray Light curve



Hardness of SSS17a



Summary

- GW 170817
  - Swift observation
    - BAT: Occulted by the earth at T_0(GW)
    - UVOT: Detection of kilonova emission
    - XRT: None detection of X-ray emission (Hint of an off-axis GRB)
  - Chandra observation
    - Late time rise (T_0+9 days) in X-rays
    - Further Chandra observation is needed to see a decay in X-ray flux

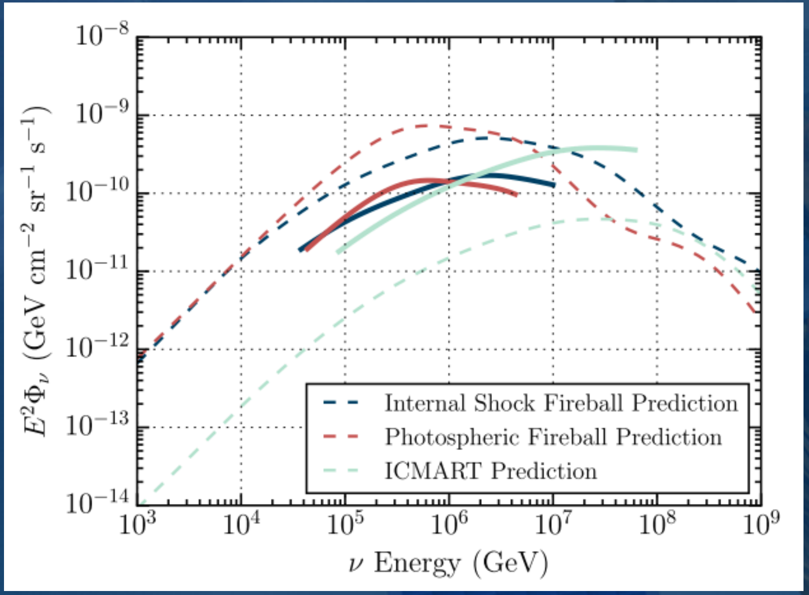
High Energy Neutrino EM Counterpart Search

GRBs as the sources for UHECR?

(Aartsen+ 2017, astro-ph/1702.06868)

$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \rightarrow n + e^{+} + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

IceCube:
508 GRBs (Northern Hemisphere), 664 GRBs (Southern Hemisphere)



$\gamma \rightleftarrows \nu$

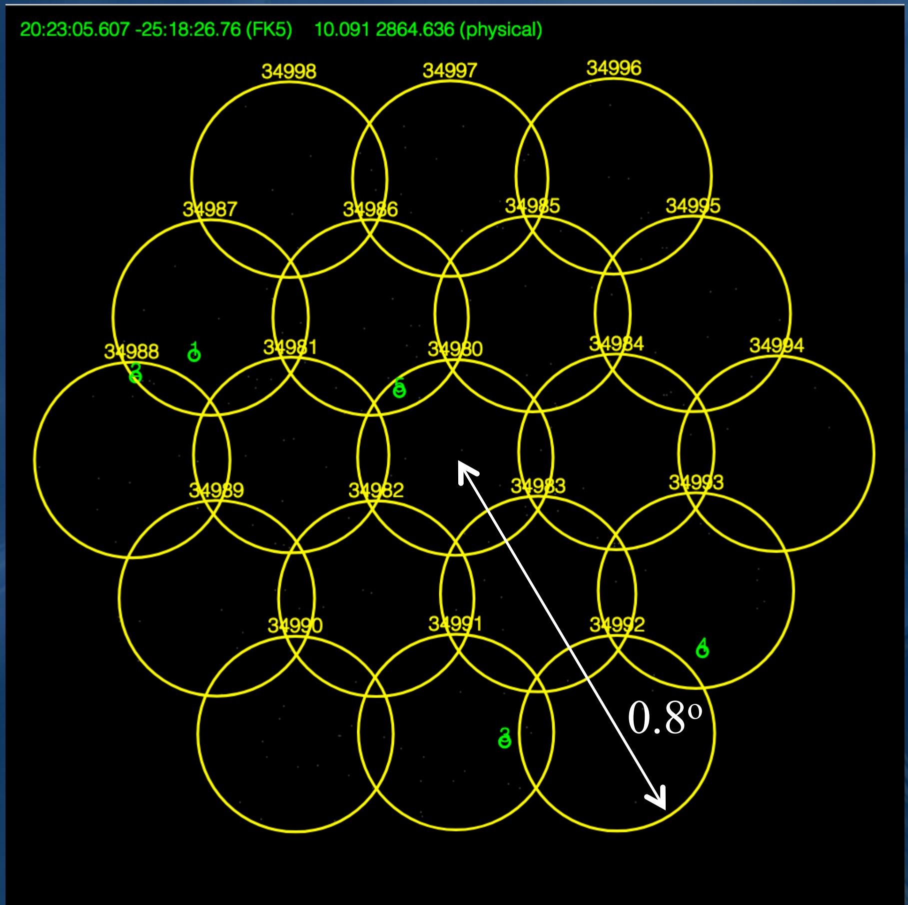
Real time IceCube Alerts on 2017

Trigger Time	Type	Position	Error (50% radius)	XRT follow-up	BAT FOV?
2017-03-12 13:49:39.83	HESE	(304.730, -26.238)	25.19’	T_0+ 2.0 hr (T_0+15.2 hr)	T_0+ 0.7 hr
2017-03-21 07:32:20.67	EHE	(98.326, -14.486)	19.48’	T_0+ 6.6 hr (T_0+7.2 hr)	T_0+ 6.6 min
2017-05-06 12:36:55.80	HESE	(221.675, -26.036)	25.19’	No	T_0
2017-09-22 20:54:30.43	EHE	(77.285, +5.752)	14.99’	T_0+ 3.3 hr (T_0+1.1 day)	T_0+ 25.6 s
2017-10-15 01:34:30.06	HESE	(162.579, -15.861)	25.19’	No	T_0+ 2.9 hr
2017-10-28 08:28:14.81	HESE	(275.076, +34.501)	96.00’	No	T_0+ 2.1 hr
2017-11-06 18:39:39.21	EHE	(340.250, +7.314)	14.99’	T_0+ 3.2 hr (T_0+17.2 hr)	T_0- 9.7 min

IceCube-170312A

(Keivani et al. 2017, GCN circ. 20890)

XRT
(T_0+7.3 ks − T_0+54.9 ks; 19 tiling)

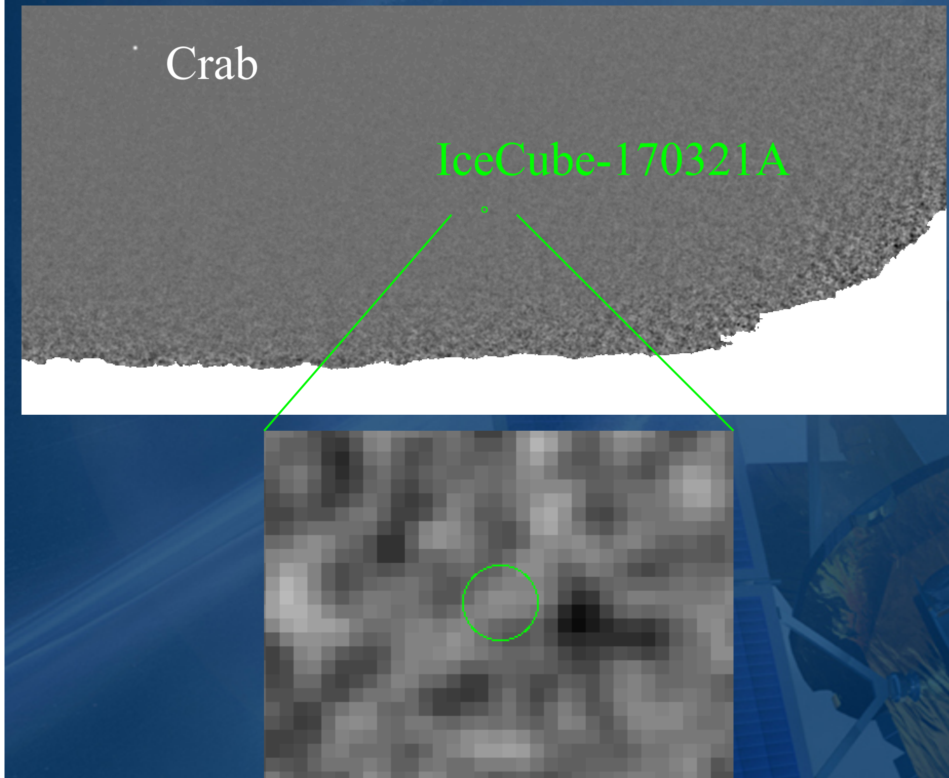


Five X-ray sources are detected including one known X-ray source. Four un-cataloged sources are well below the ROSAT All Sky Survey limit.

No new X-ray source (>3 sigma):
2.9×10^{-13} erg/cm^2/s (0.3-10 keV)
($N_H = 3 \times 10^{20}$ cm^{-2}; Γ=1.7)

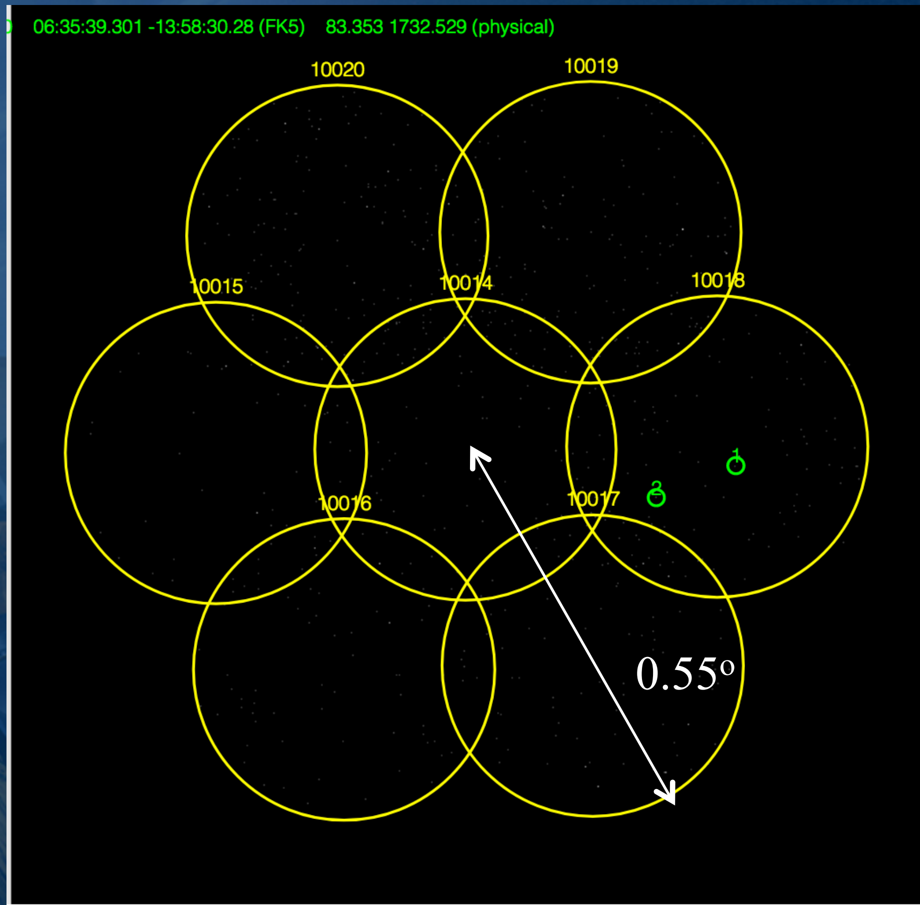
IceCube-170321A

BAT 14-195 keV sky image
(T_0+578 s - T_0+1643 s)



5-sigma UL (14-195 keV; Γ=2) :
6.1 x 10^{-9} erg/cm^2/s (@1065 s)

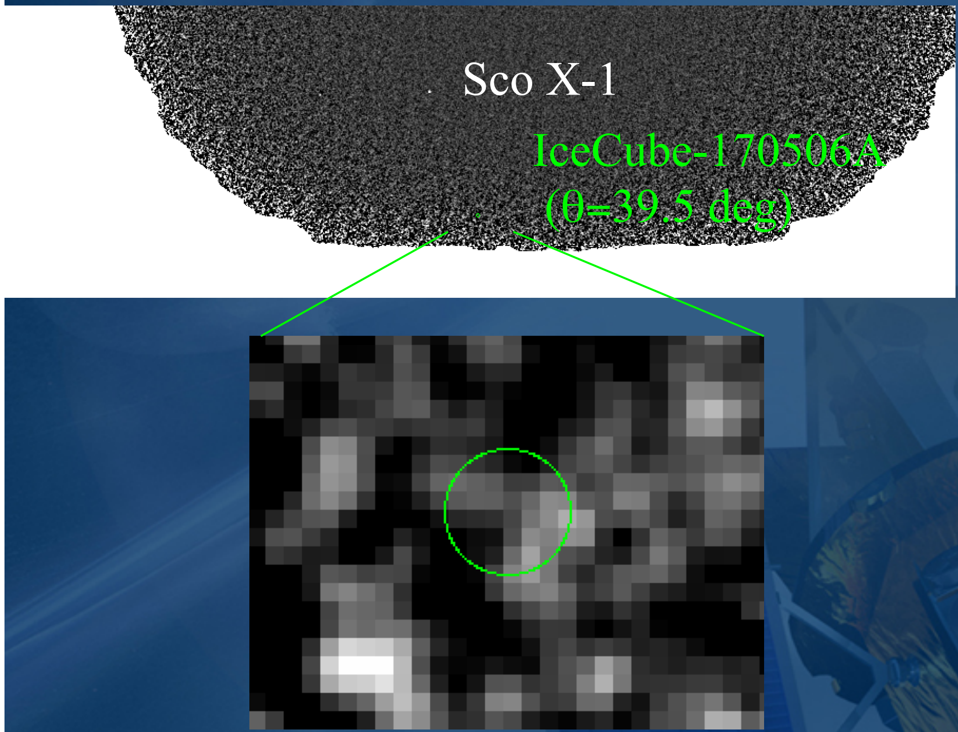
XRT (Keivani et al. GCN circ. 20964)
(T_0+23.7 ks – T_0+37.8 ks; 7 tiling)



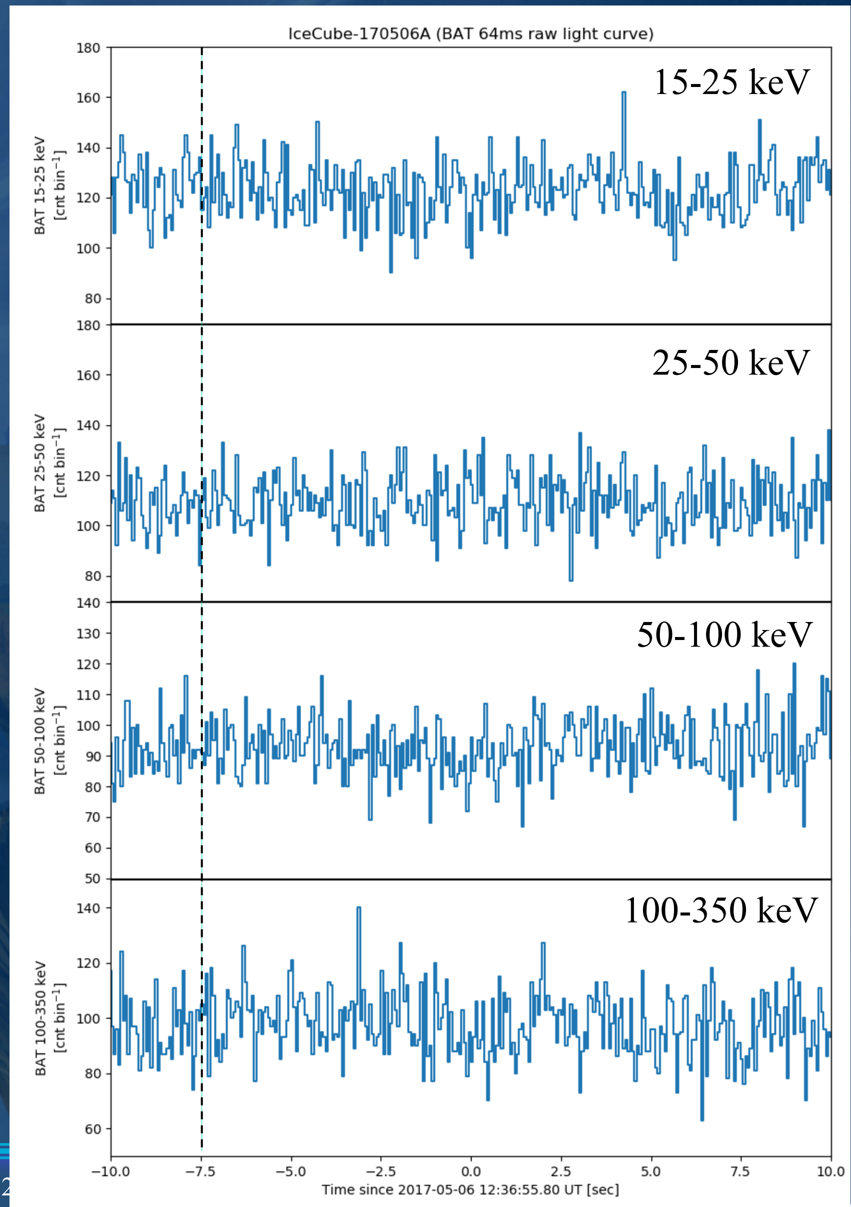
No new X-ray source (>3 sigma):
1.48 x 10^{-13} erg/cm^2/s (0.3-10 keV)
(N_H = 3 x 10^{20} cm^{-2}; Γ=1.7)

IceCube-170506A

BAT 14-195 keV sky image
(T_0+5 s - T_0+228 s)



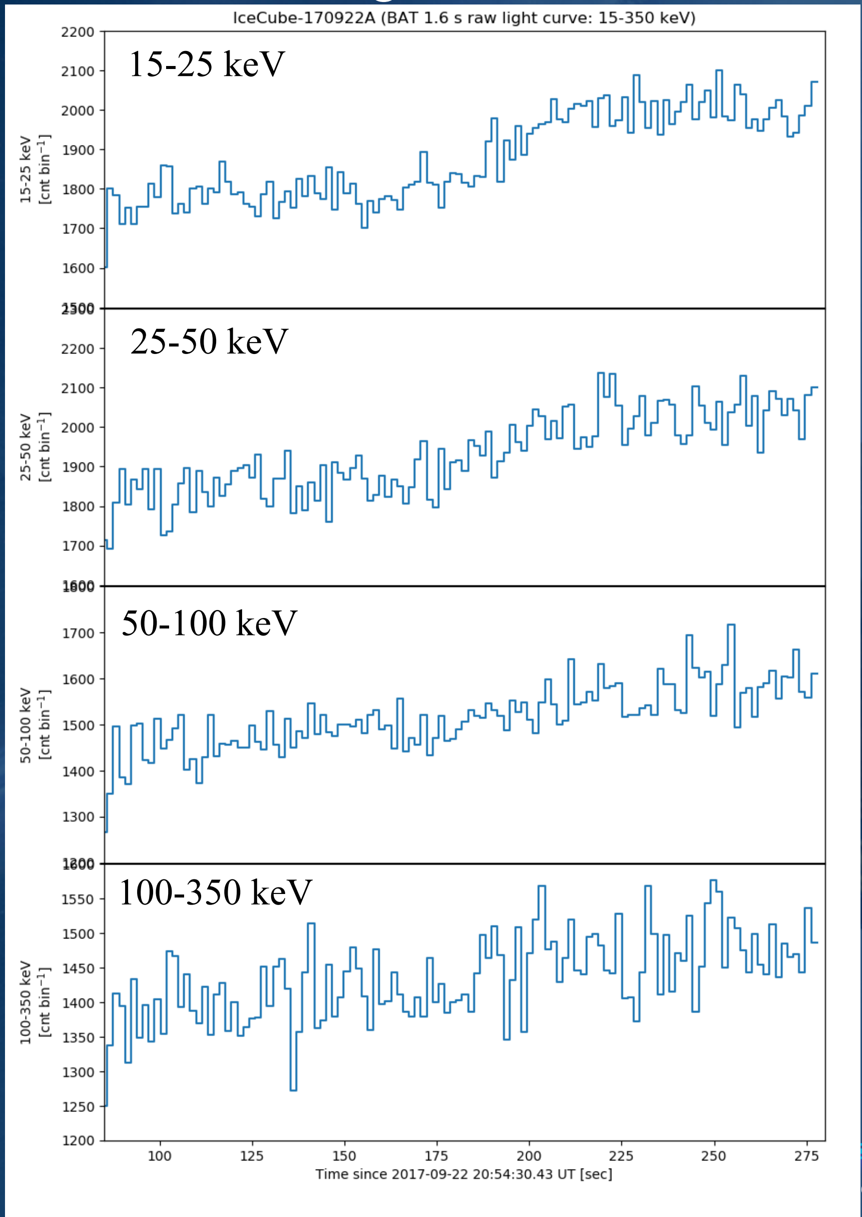
BAT 64 ms raw light curve



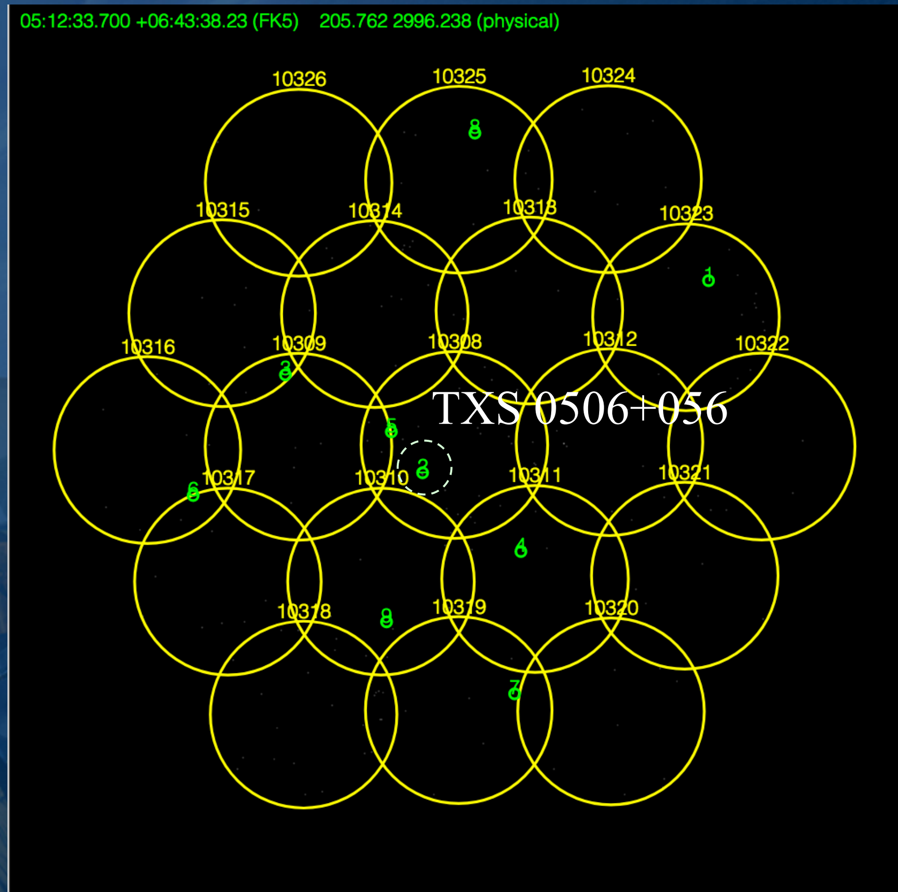
5-sigma UL (14-195 keV; Γ=2) :
3.7 x 10^{-8} erg/cm^2/s (@ 223 s)

IceCube-170922A

BAT raw 1.6 s light curve



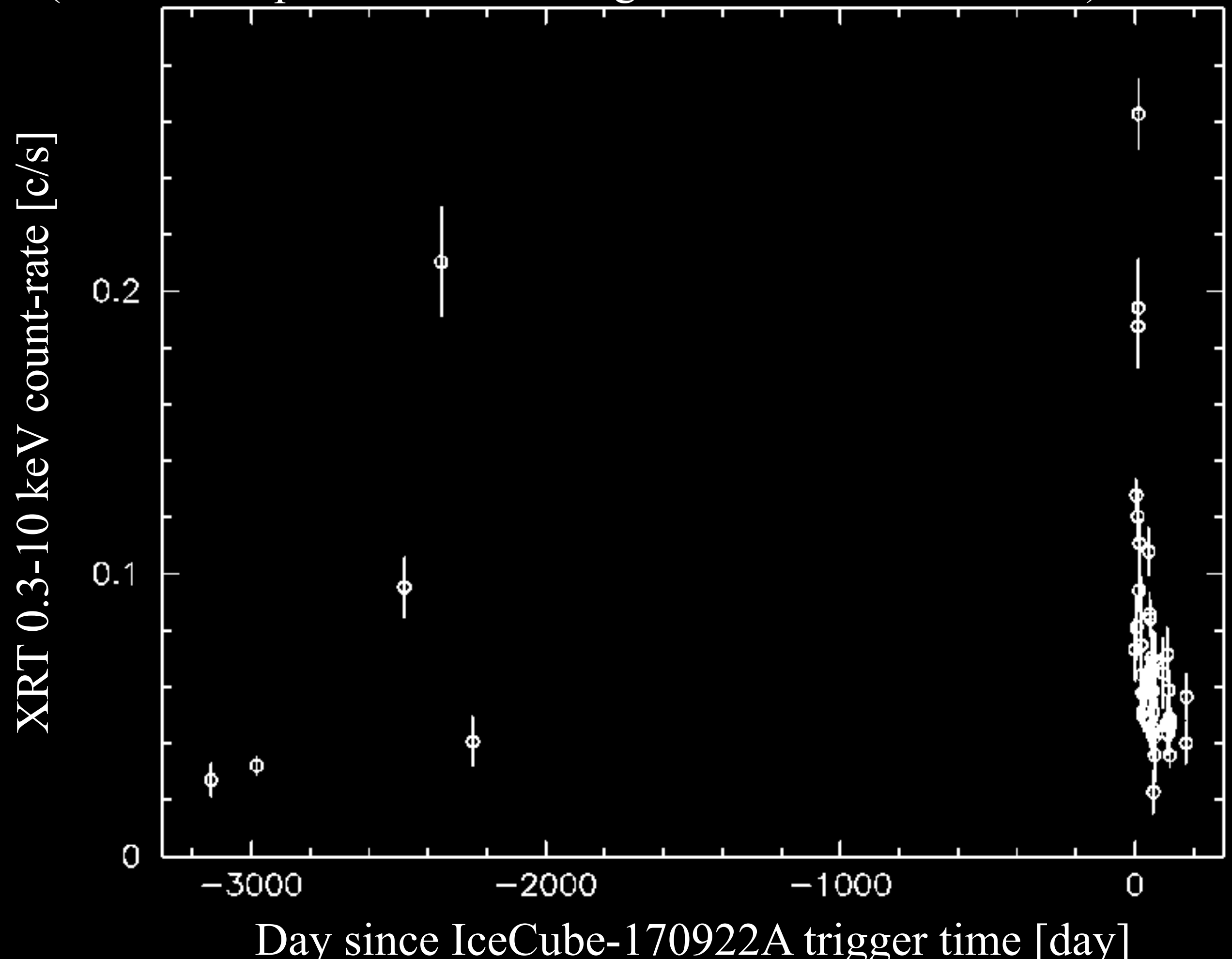
XRT (Keivani et al., GCN circ. 21930, 21941)
(T_0+11.7 ks – T_0+92.9 ks)



Nine X-ray sources are detected including the candidate blazar TXS 0506+056.

IceCube-170922A: Association of blazar TXS 0506+056?

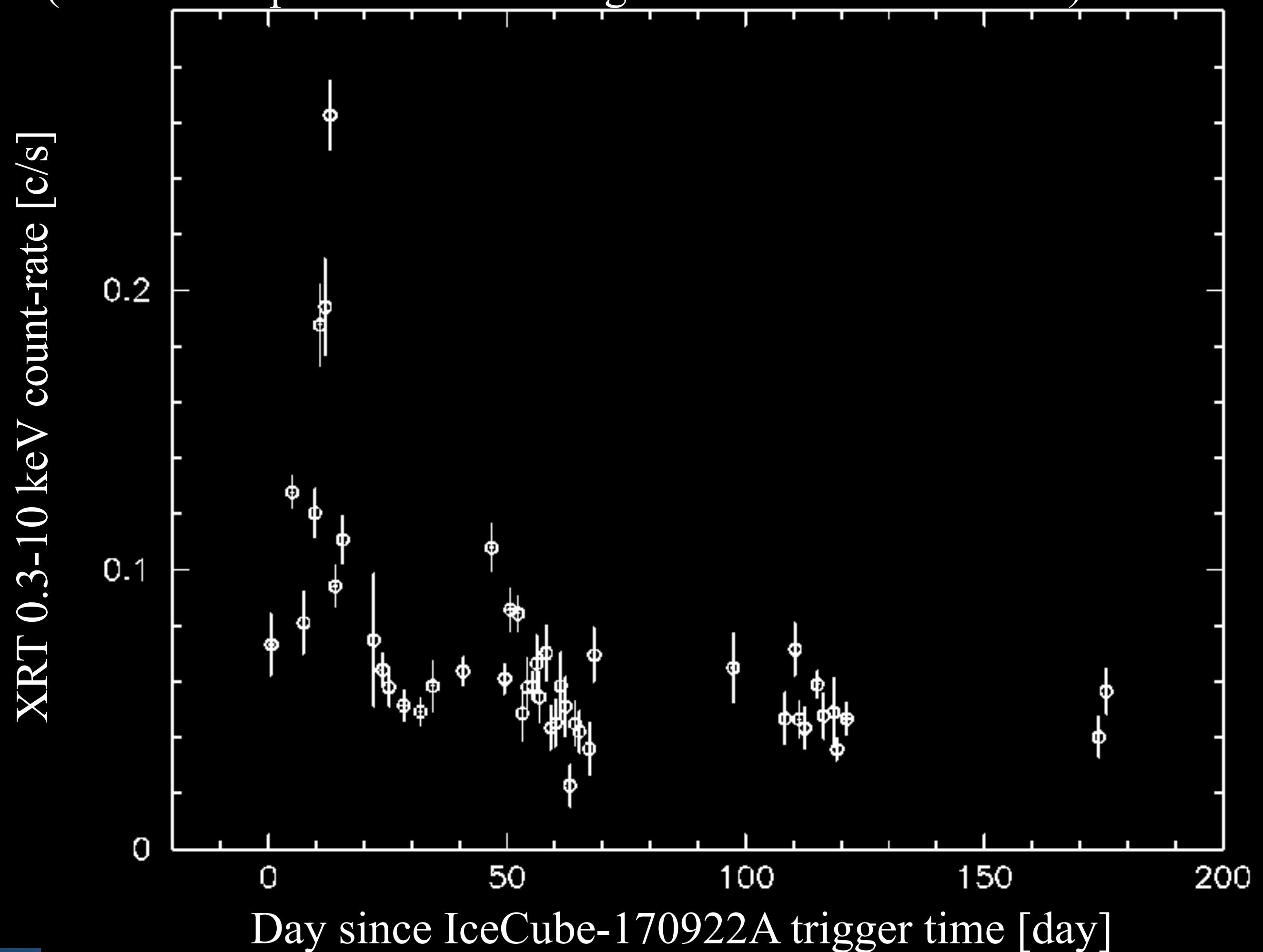
Data from Swift/XRT Monitoring of Fermi-LAT Sources of Interest
(www.swift.psu.edu/monitoring/ Stroh & Falcone 2013)



Swift

IceCube-170922A: Association of blazar TXS 0506+056?

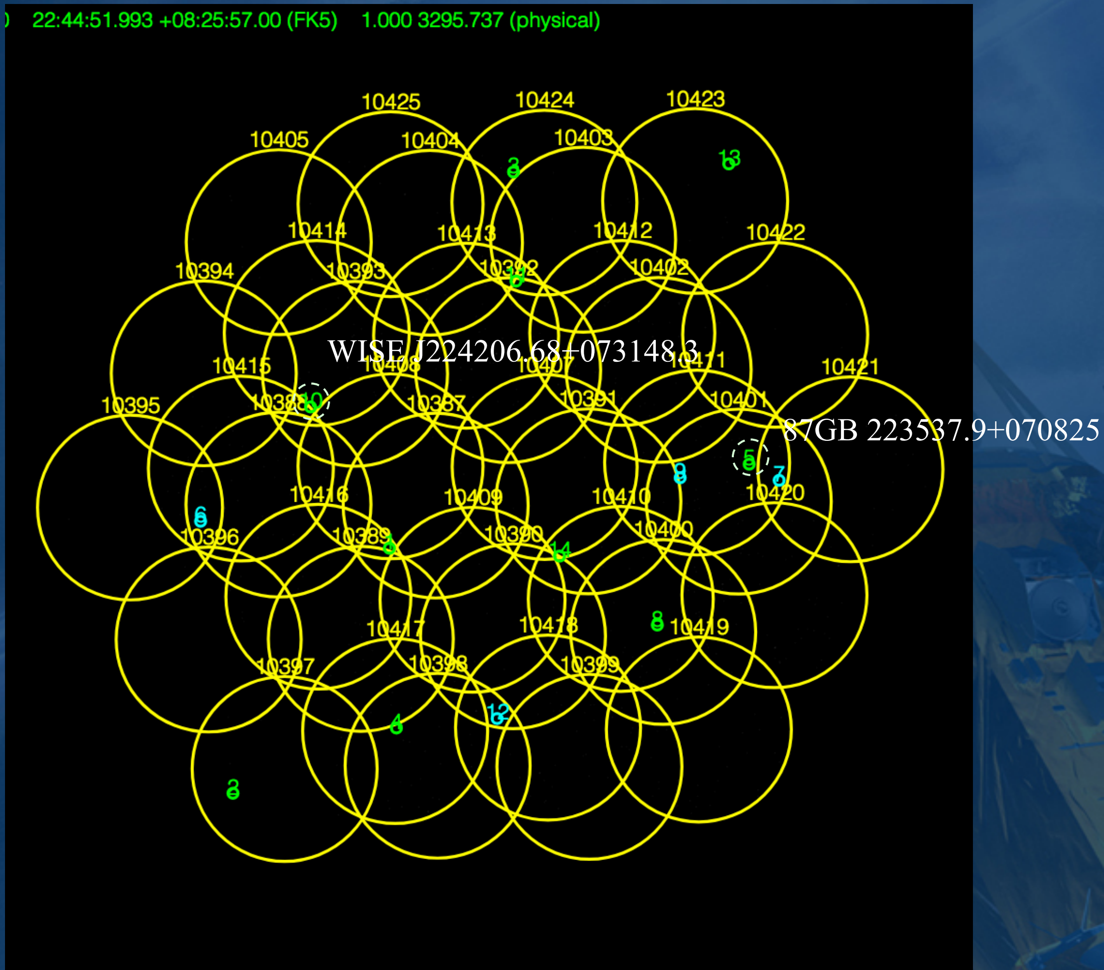
Data from Swift/XRT Monitoring of Fermi-LAT Sources of Interest
(www.swift.psu.edu/monitoring/ Stroh & Falcone 2013)



IceCube-171106A

XRT
(T_0+11.5 ks − T_0+62.0 ks; 19 tiling)

Keivani et al., GCN circ. 22115



- 14 X-ray sources are detected.
- 5 sources are within the IceCube error region.
- Two known blazars: 87GB 223537.9+070825 and WISE J224206.68+073148.3 are located inside the error region.

Summary

- IceCube Events
  - Swift observations of five IceCube events
  - IceCube-170922A
    - X-ray flare from blazar TXS 0506+056 after the IceCube alert
  - IceCube-171106A
    - Two known blazars are inside the IceCube error region.

Swift will keep revolutionize MMA.

Gamma-ray Bursts in the Gravitational Wave Era 2019

Targeting date: October - November 2019
Candidate place: Yokohama, Kanagawa
Funding support by Yamada Science Foundation

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