
Multi-Messenger Astronomy with Swift

T. Sakamoto (AGU)

Contents

- Swift
- Review: GW 170817
- GW 170817-like event in the BAT triggered samples?
- O3 run: Swift observation status

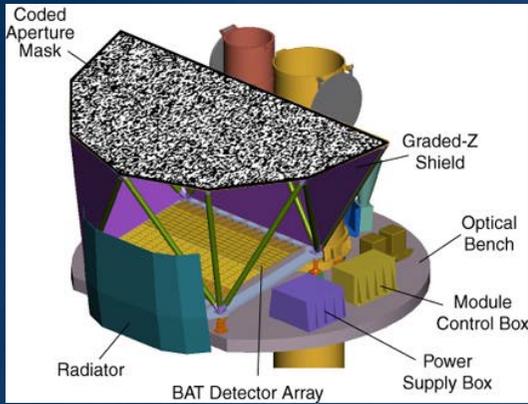
Swift neutrino search: Azadeh talk this afternoon

Swift



2004-

Burst Alert Telescope (BAT)



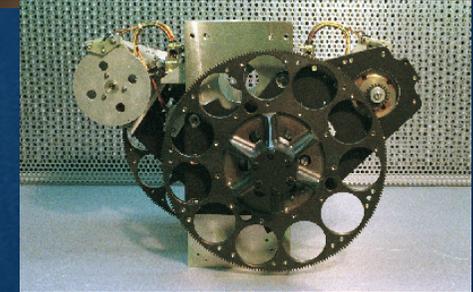
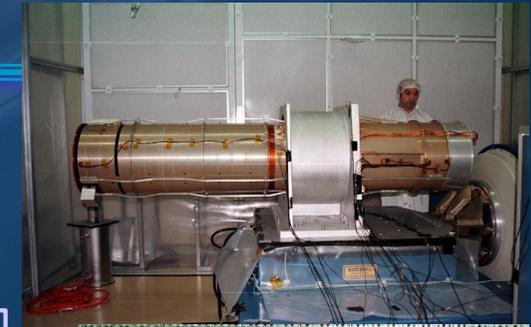
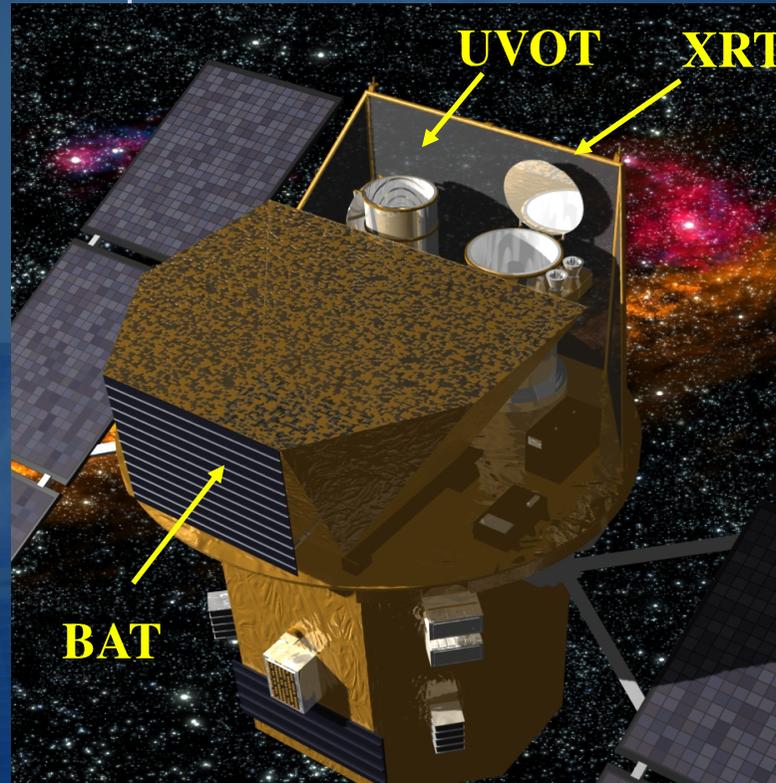
128 CZT



E_range: 15-150 keV (15-350 keV)
 Det: CdZnTe (4 x 4 x 2 mm³)
 # 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

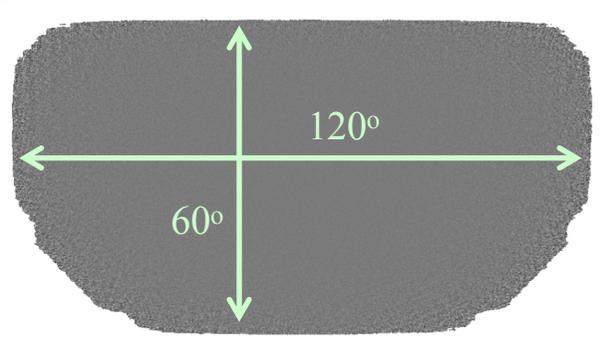
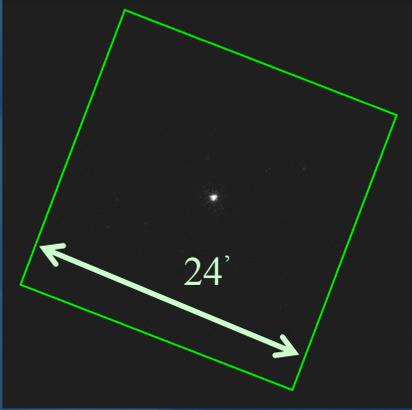
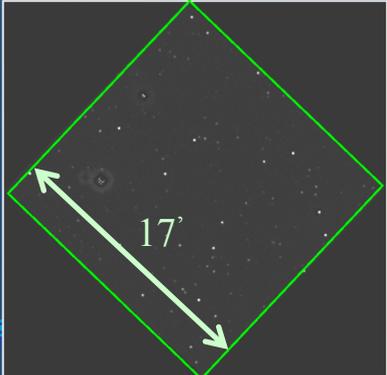


X-Ray Telescope (XRT)



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

Characteristics of Instruments

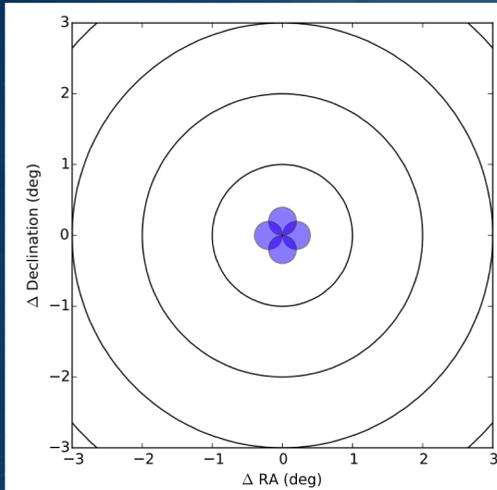
	Field of view	Typical Sensitivity	
BAT	 A dark, irregularly shaped field of view for the BAT instrument. It is bounded by a horizontal double-headed arrow labeled 120° and a vertical double-headed arrow labeled 60°.	$\sim 10^{-9}$ erg cm ⁻² s ⁻¹ (15-150 keV)	Prompt data around T ₀
XRT	 A dark field of view for the XRT instrument, showing a single bright star. A green diamond-shaped field is outlined, with a white double-headed arrow labeled 24'.	5×10^{-13} erg cm ⁻² s ⁻¹ (0.3-10 keV; 1 ksec)	Follow-up
UVOT	 A dark field of view for the UVOT instrument, showing several stars. A green diamond-shaped field is outlined, with a white double-headed arrow labeled 17'.	~ 20 mag (v; 200 s)	Follow-up

Automatic Tiling Observation

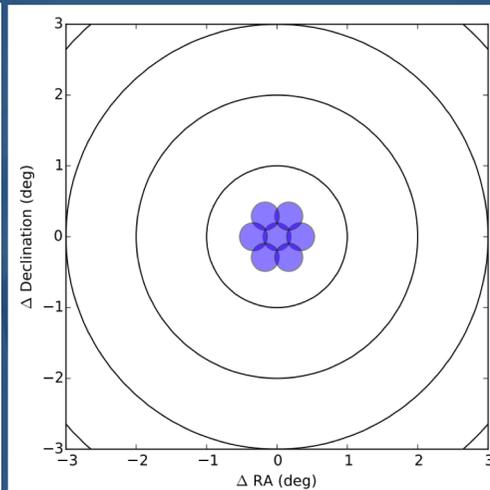
- Automatic tiling observation capability

Tiling patterns (figures from J. Kennea)

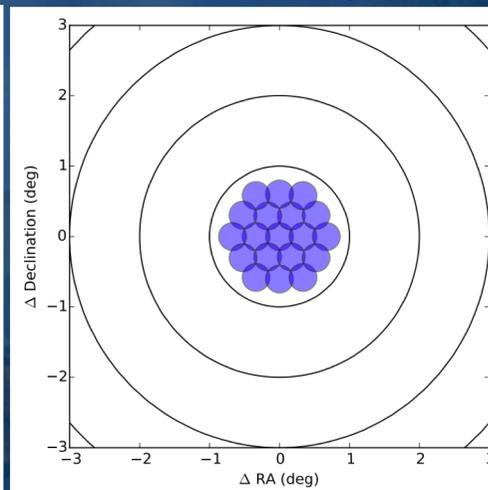
4-tiling



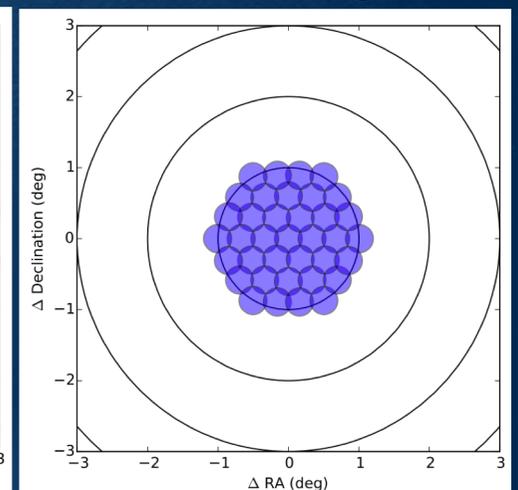
7-tiling



19-tiling



37-tiling



Required tiling pattern to cover 1° diameter

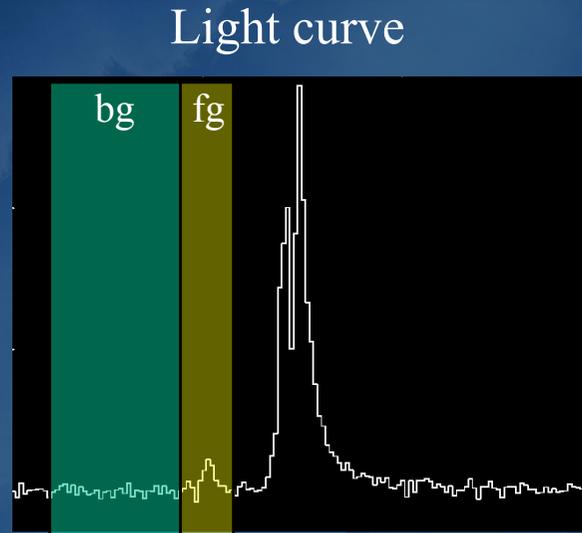
Required tiling pattern to cover 2° diameter

- Multiple pointing in one ToO upload (PPTOO)

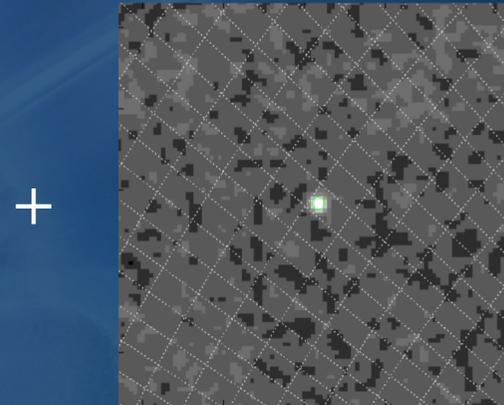
BAT On-board Trigger

Rate trigger

- 674 trigger criteria
- Each trigger criterion has a different trigger threshold
- ~80 triggers per day



Sky image



→ Trigger!

Image significance ≥ 6.5

- Event data (~10 s) capture (low priority)
- Subthreshold triggers (available through GCN; require regular data downlink)

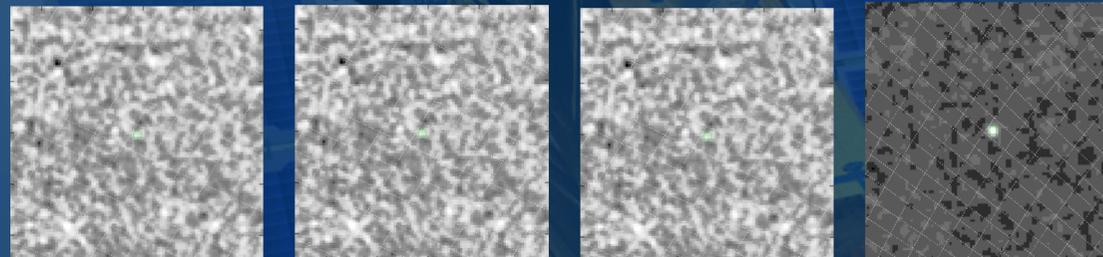
Successful triggers:

- Real time alert
- Autonomous SC slew
- Event data capture: T_0-250s – $T_0+1000s$ (high priority)

Image trigger

- Every 64 s
- 15-50 keV band only
- All the images are downloaded (high priority)
- Used in the BAT transient monitor (Krimm et al.)

Sky image



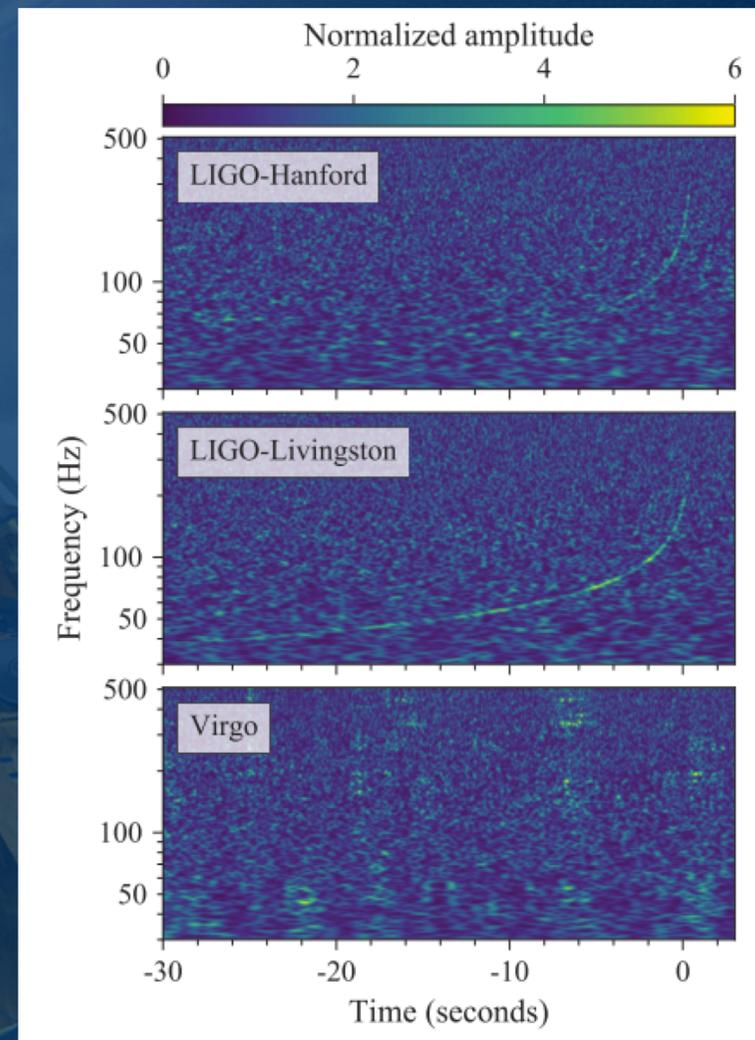
→ Trigger!

Image significance ≥ 7.0

GW 170817

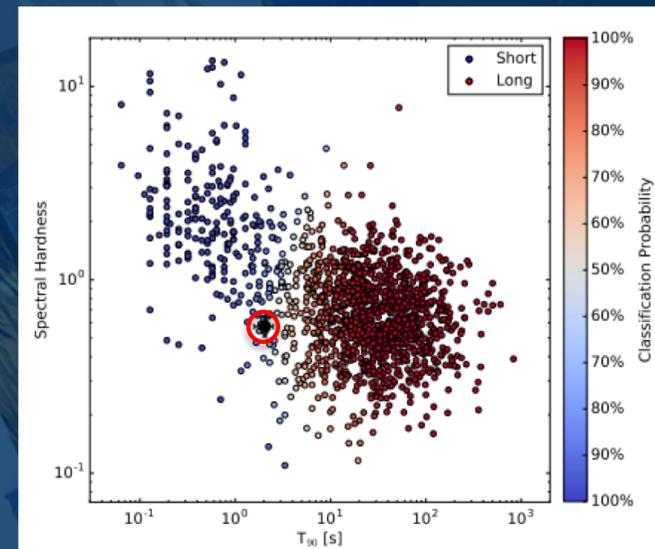
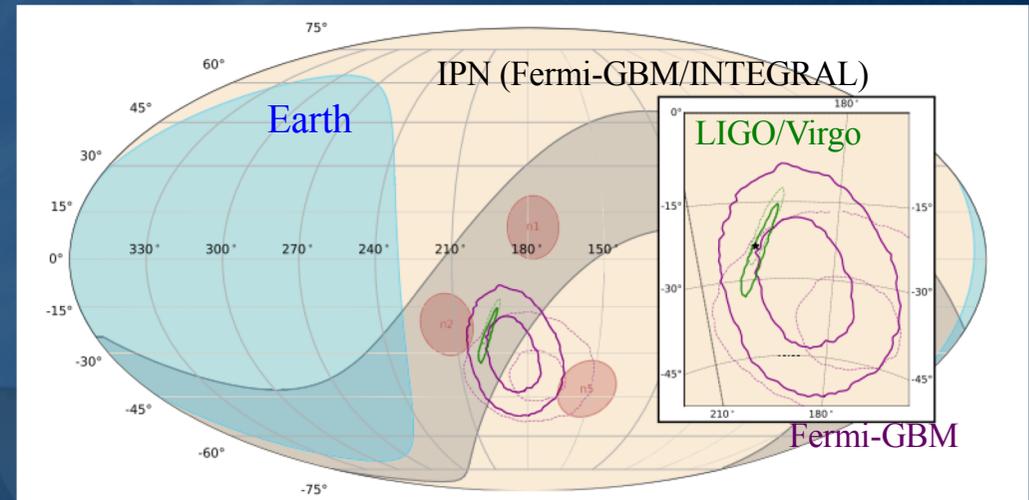
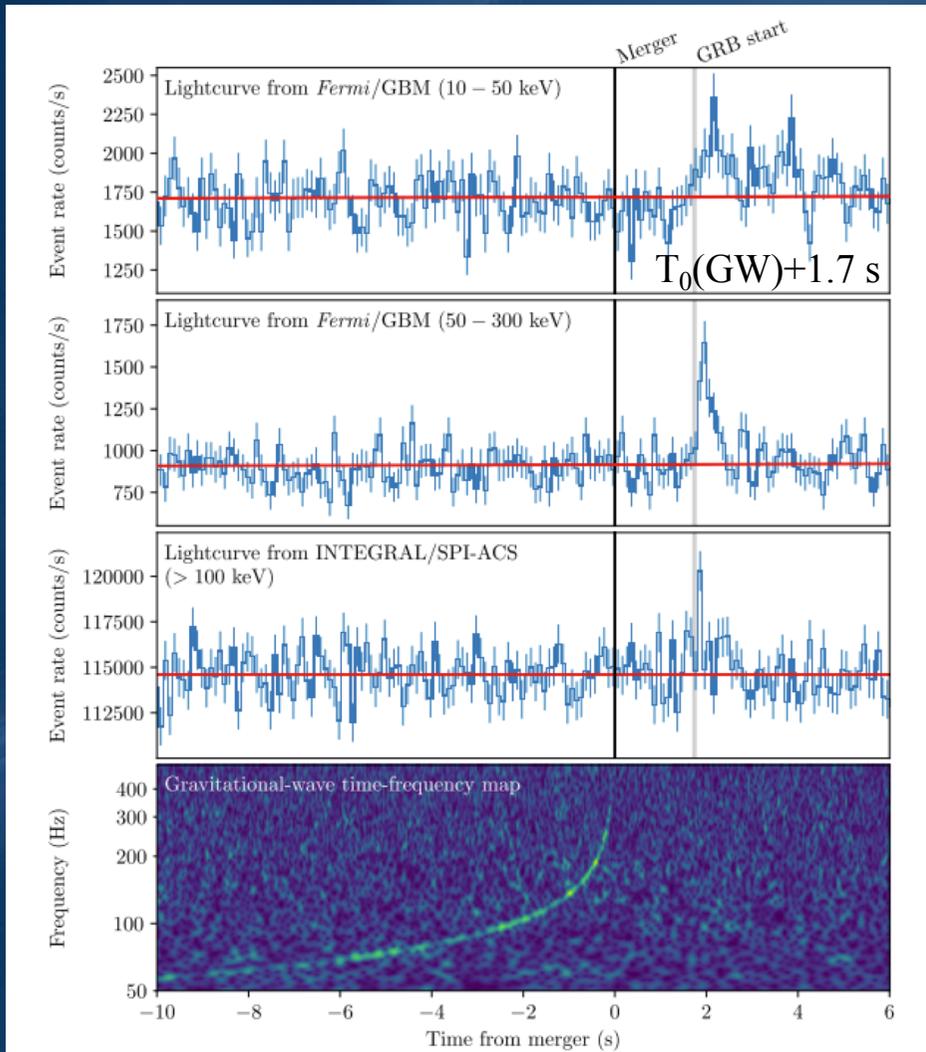
Gravitational-wave
event from BNS
merger!

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)

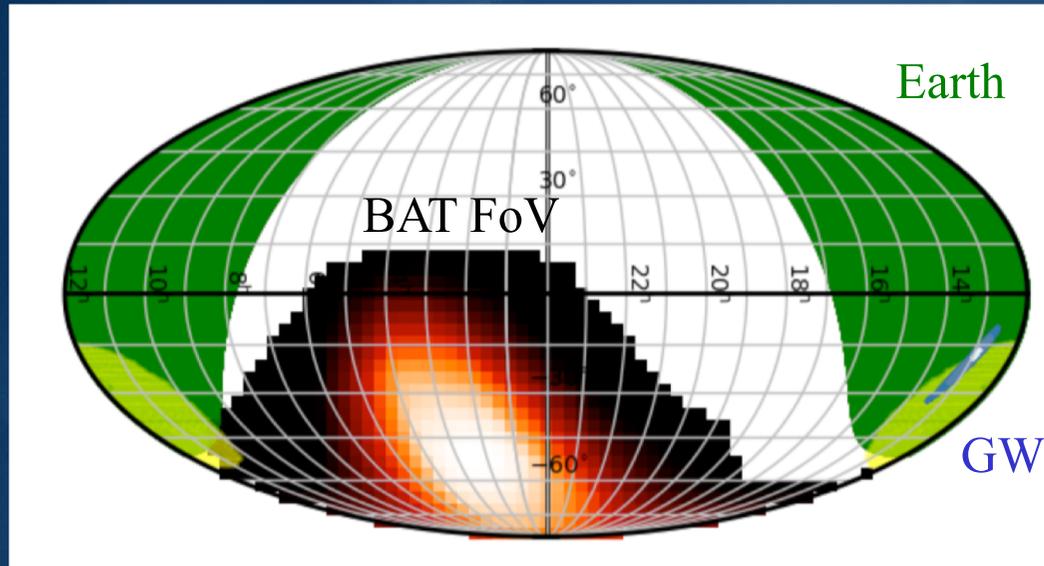


$T_{90} = 2.0 \pm 0.5$ s

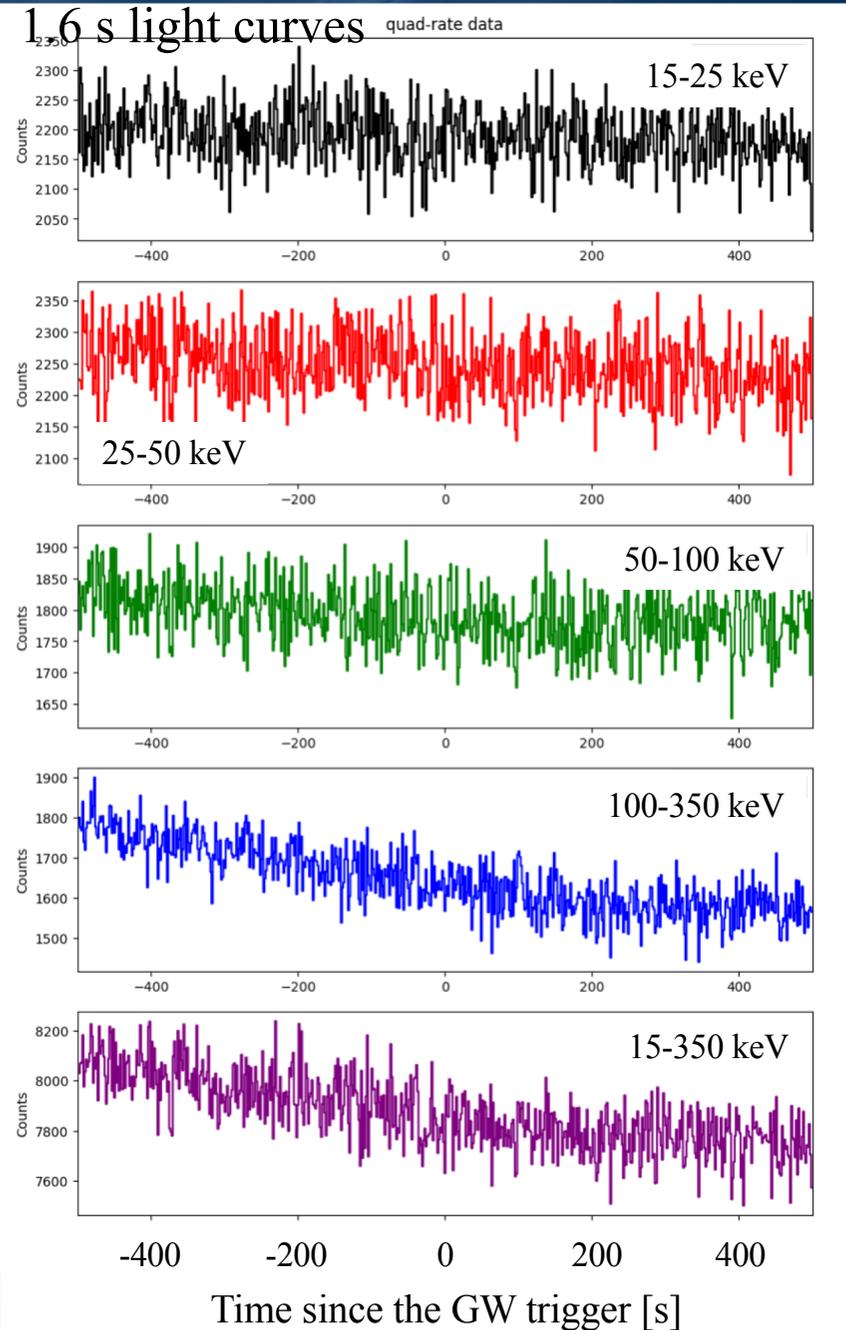
Probability of S-GRB class: 72%

GW 170817: BAT Observation

(Evans et al. 2017)

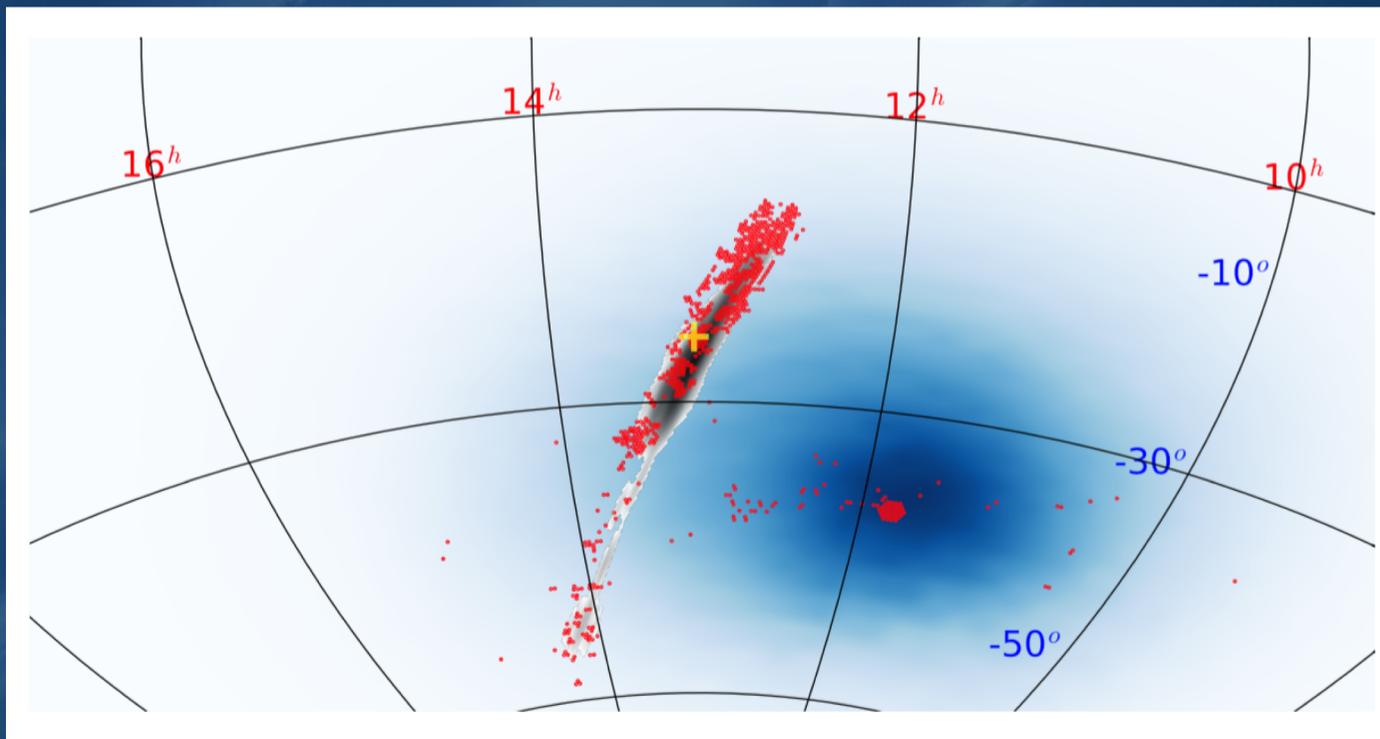


- GW 170817 error region was occulted by the Earth
- Nothing in the BAT light curve at $T_0(\text{GW})$



Swift Follow-up Observations

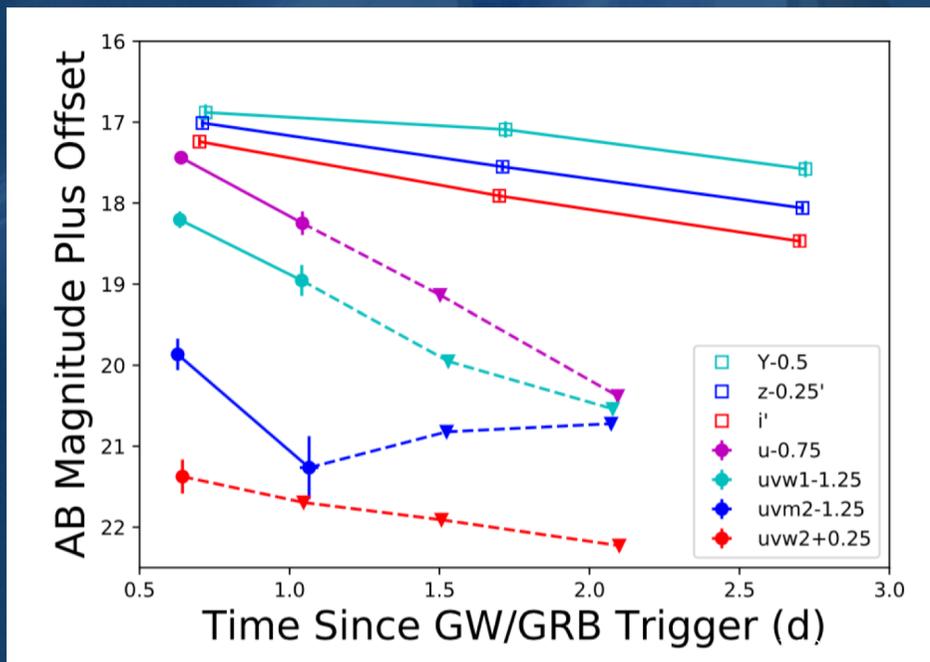
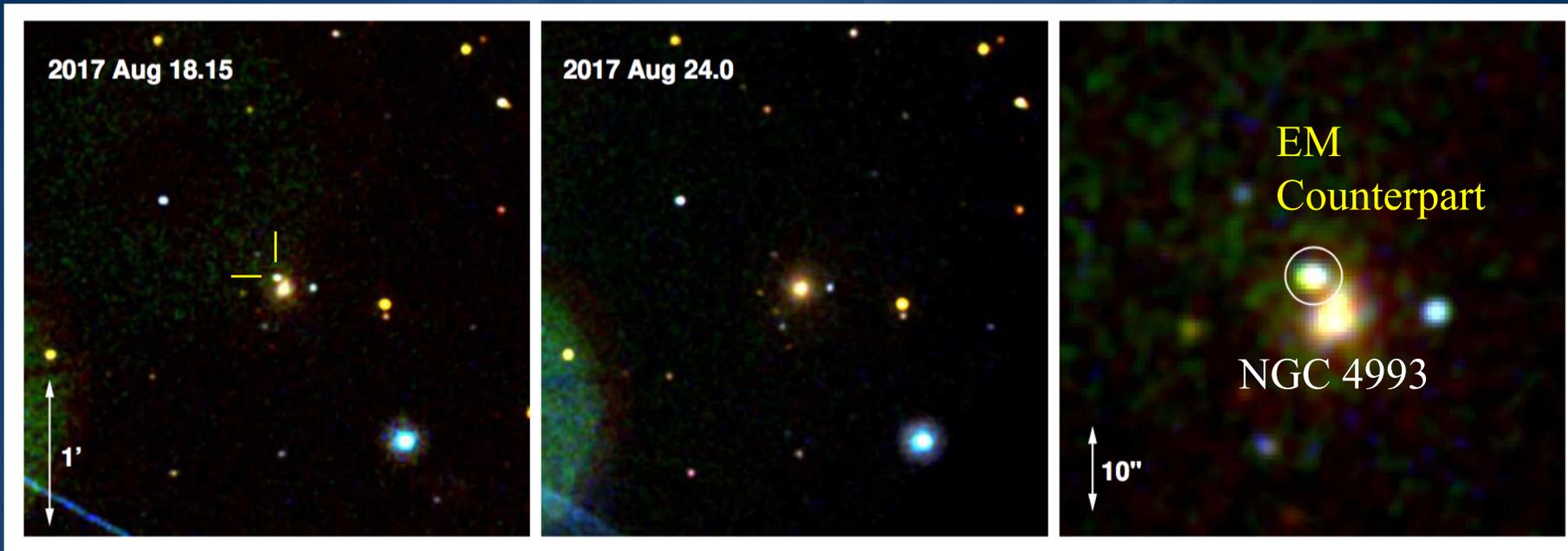
(Evans et al. 2017)



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 Detection of the Counterpart!

(Evans et al. 2017)



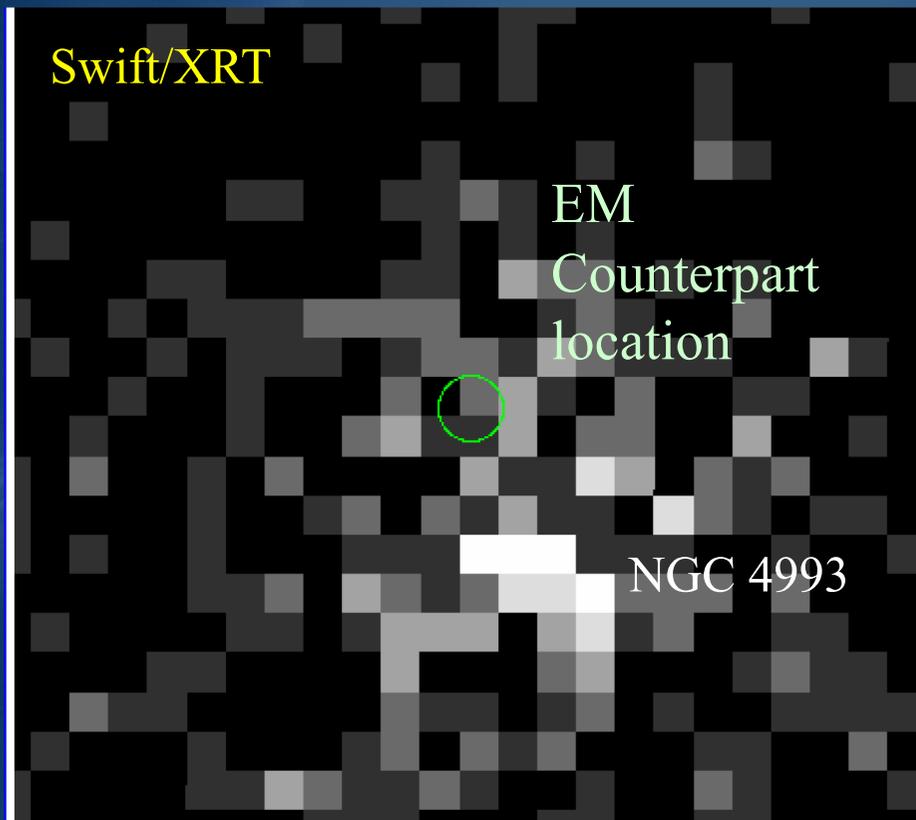
Rapidly fading UV emissions
were detected by UVOT

Clear detection of kilonova in UV

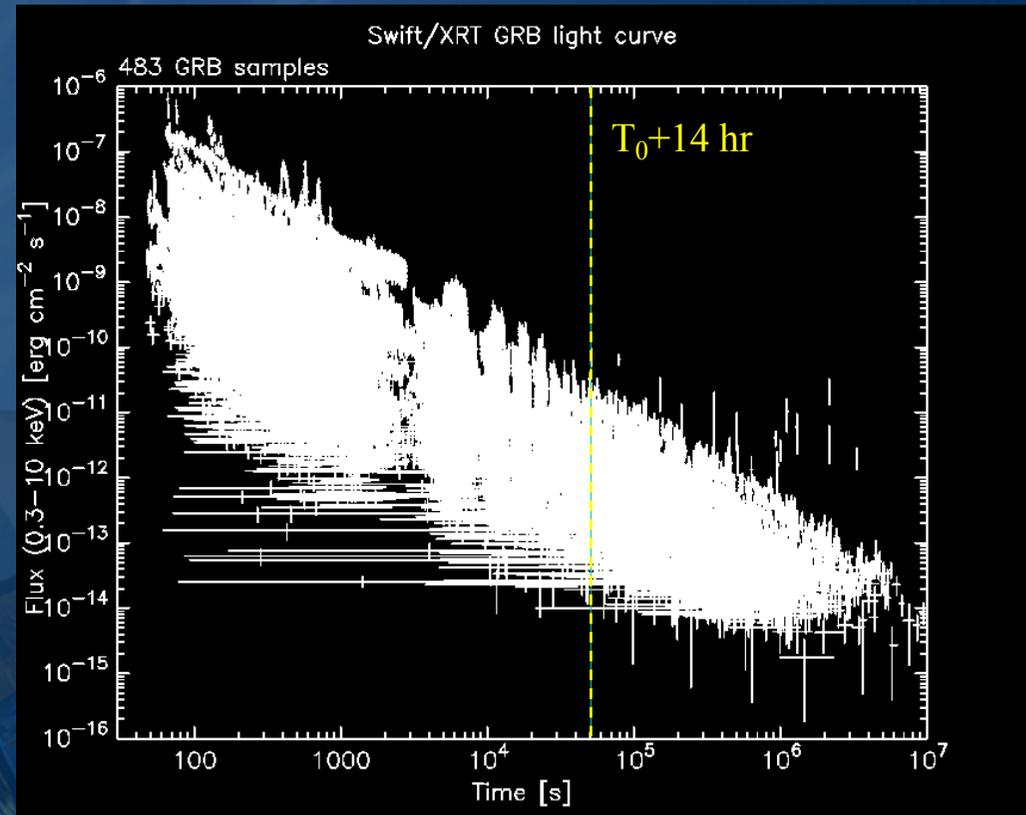
No XRT Detection at Early Phase

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

Total exposure: 305 ks



Swift GRB X-ray afterglow light curves



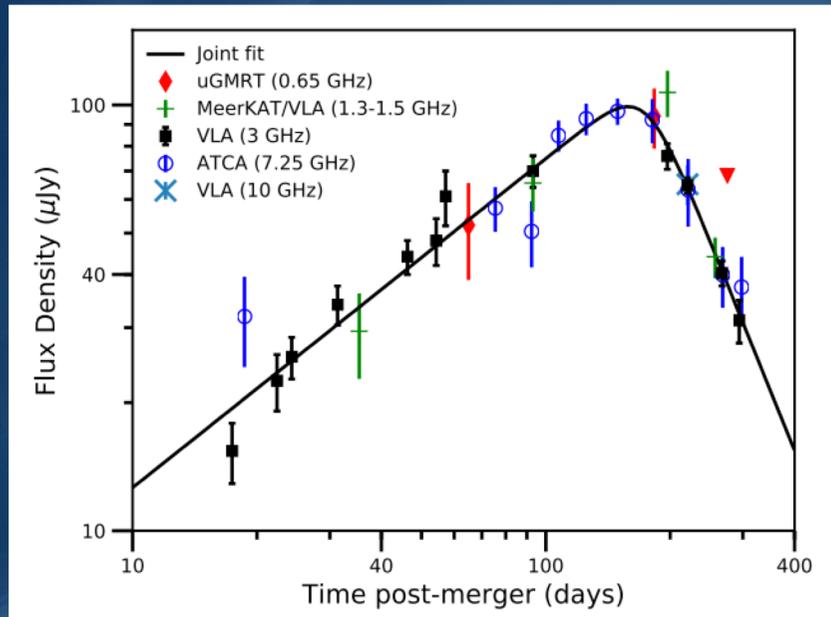
- Typical X-ray afterglow flux @ T₀+14 hr:
10⁻¹¹ – 10⁻¹³ erg/cm²/s
- XRT should be able to detect X-rays in a few ks exposure

Off-axis Relativistic Jet Emission

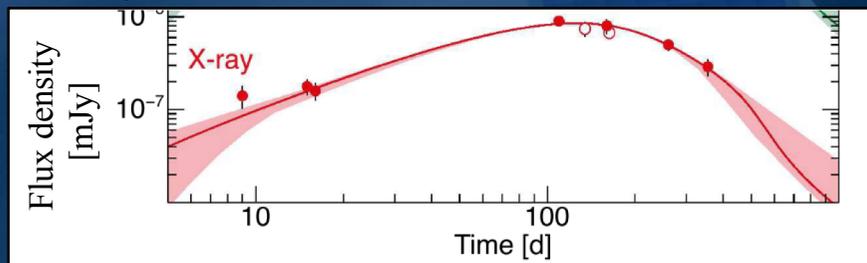
Rise and fall radio/X-ray light curve

(e.g., Mooley et al. 2018, Troja et al. 2018)

Radio

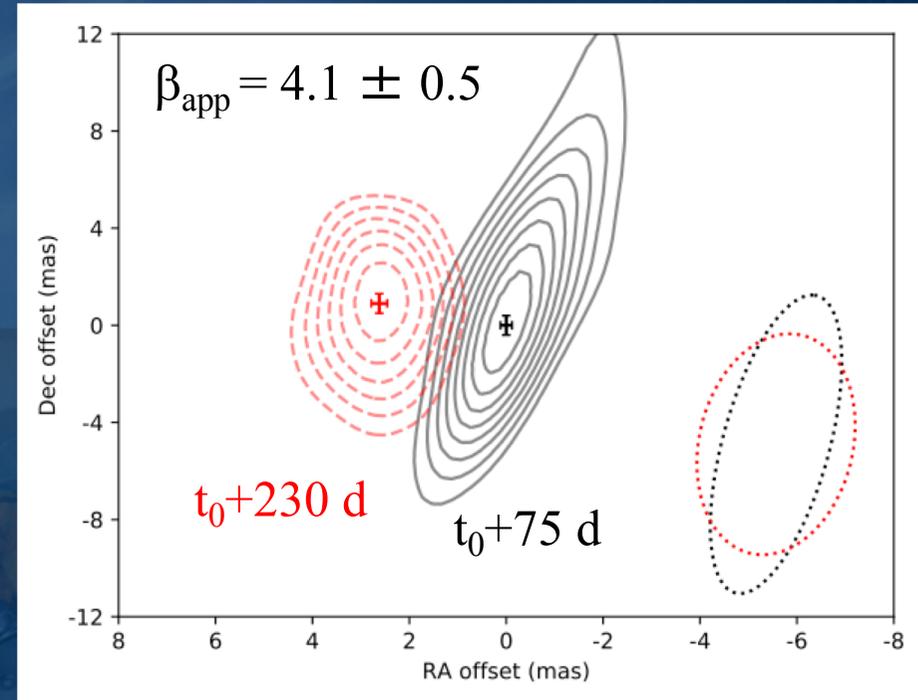


X-ray



VLBI Superluminal Motion

(Mooley et al. 2018)



Relativistic jet (GRB) is playing a major role on late time radio and X-ray emission.

EM counterpart of GW 170817

- S-GRB like prompt gamma-ray emission ($T_{90} + 2s$) at $T_0(\text{GW}) + 1.7 s$
- Bright UV/optical emission (kilonova)
- No X-ray emission at the early phase
- Rise and fall radio and X-ray emission (off-axis GRB jet emission)

GW 170817-like event in the BAT triggered samples?

A. Sudo, T. Sakamoto, M. Serino (AGU)

EM Counterpart of GW 170817

- Weak prompt gamma-ray emission
- No X-ray emission detectable by XRT
- UV emission detection by UVOT

Swift GRB observations

- Detection of a prompt gamma-ray emission by BAT
- X-ray detection by XRT: $\sim 80\%$ (including no immediate slew)
- Detection of UV/IR emission by UVOT: $\sim 30\%$

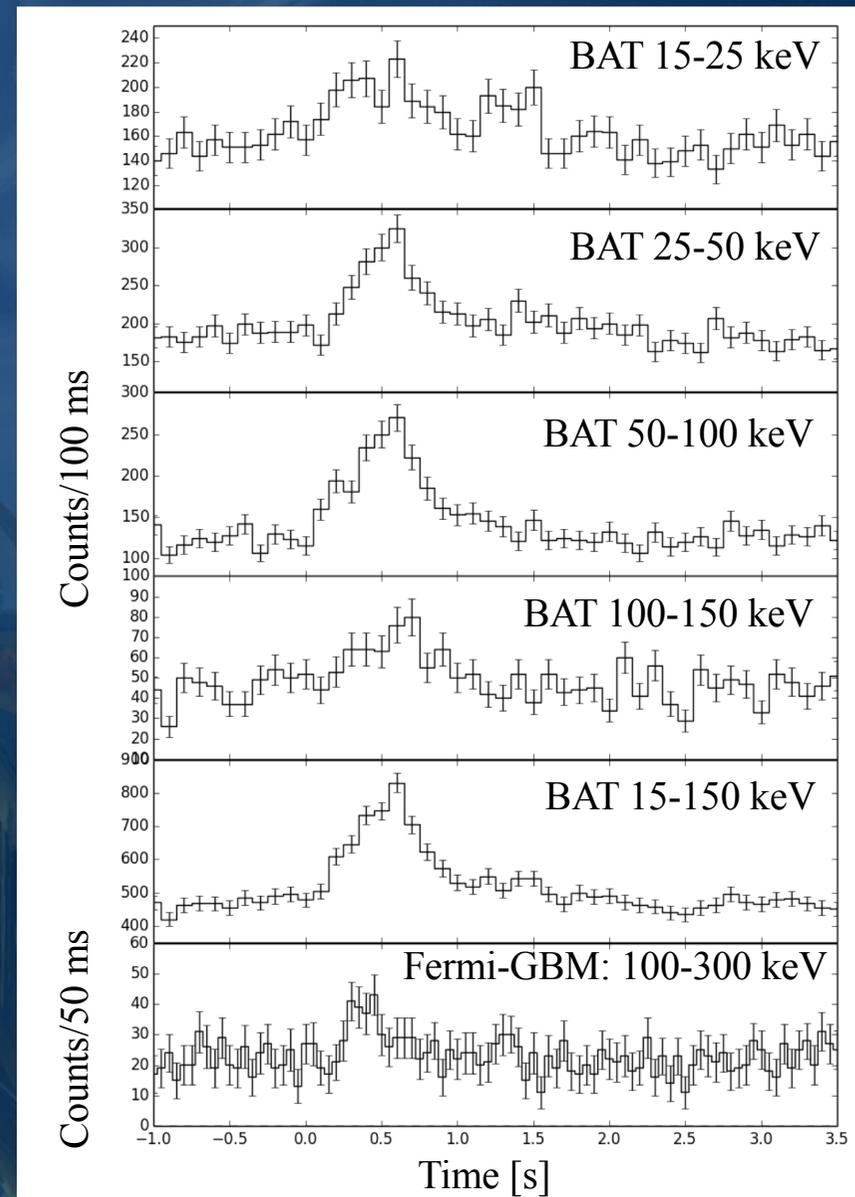
Will BAT trigger?

- Simulation setup
 - Light curve shape of GRB 170817A is modeled by fitting.
 - Best fit spectral models (Goldstein et al. 2018) are used for the 1st peak and the 2nd peak.
 - Using the background data of GRB 170516A.
 - 30 degree off-axis energy response is used.
 - Simulated the counts in the BAT standard 80 channels every 100 ms.

BAT will detect GRB 170817A
in **23 sigma** (15-150 keV)

BAT will trigger GRB 170817A
if it happens in the FoV

Simulated light curves of GRB 170817A



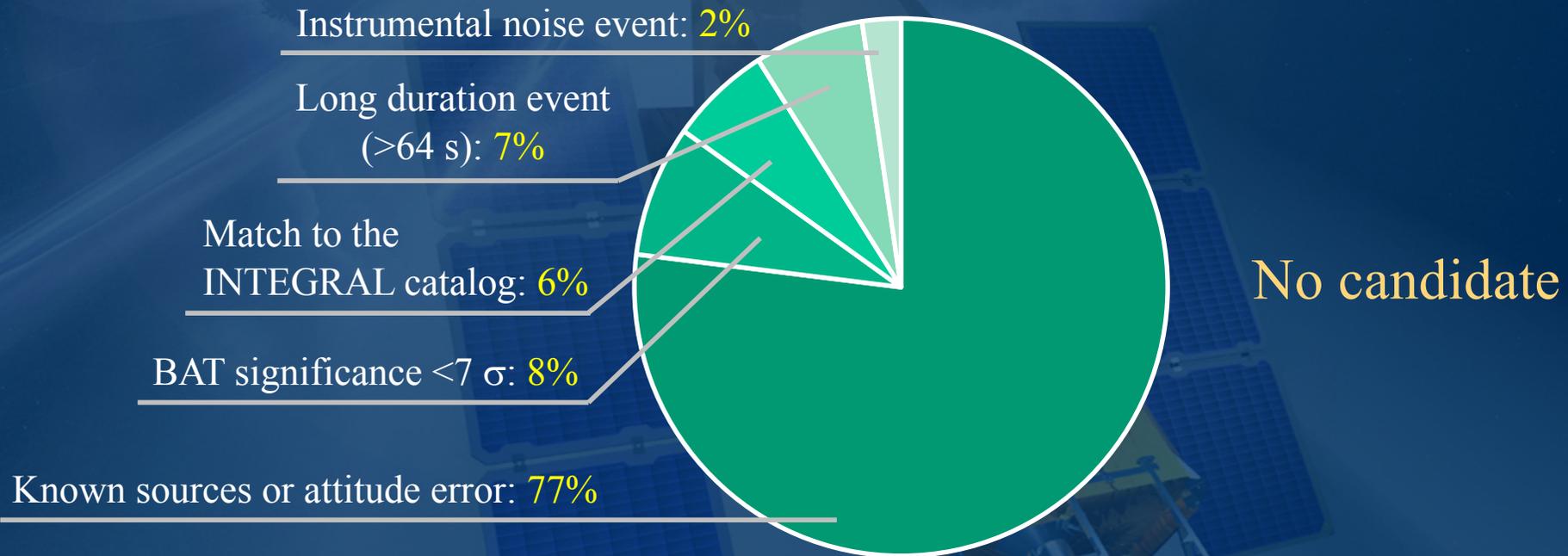
Search for Non-GRB Triggers

GW 170817-like event could be treated as “non GRB”
since no X-ray detection is very rare for GRBs.

2245 on-board triggers (14 years)

1024 Non-GRB triggers

1221 GRB triggers



Search for GRB Triggers

GW 170817-like event has bright UV/optical detection,
but no or weak X-ray detection

2245 on-board triggers (14 years)

1024 Non-GRB triggers

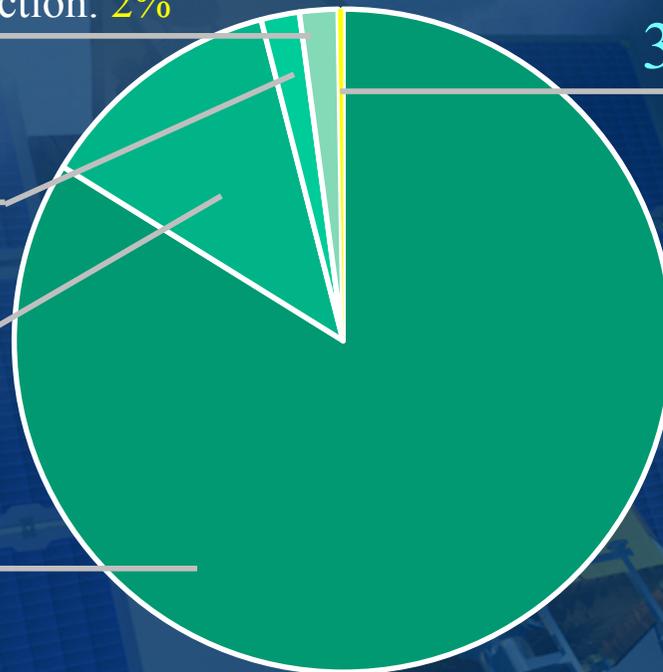
1221 GRB triggers

No UV/optical detection: 2%

Long duration event
(>64 s): 2%

No prompt XRT
observation ($T_0 < 200$ s): 12%

X-ray detection: 84%



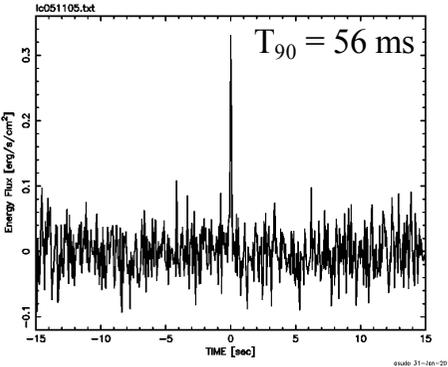
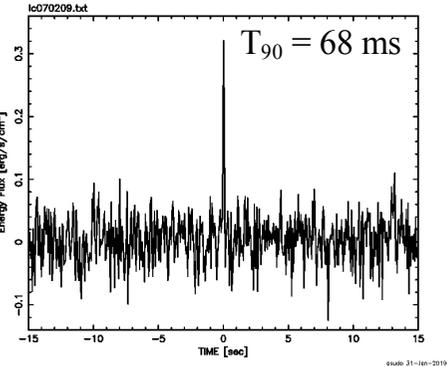
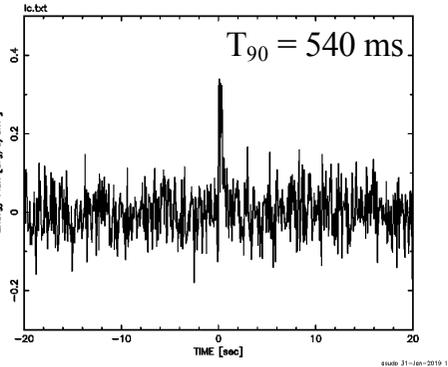
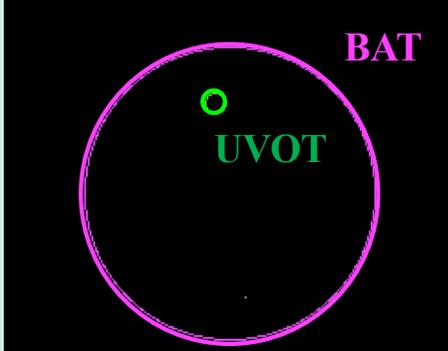
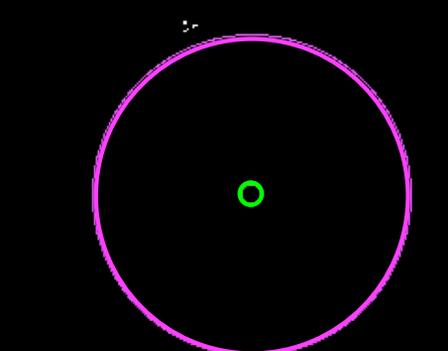
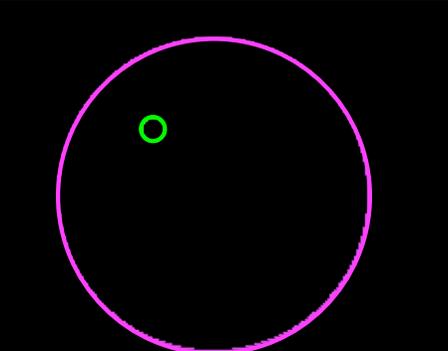
3 candidate events!

Three Candidate Events

BAT

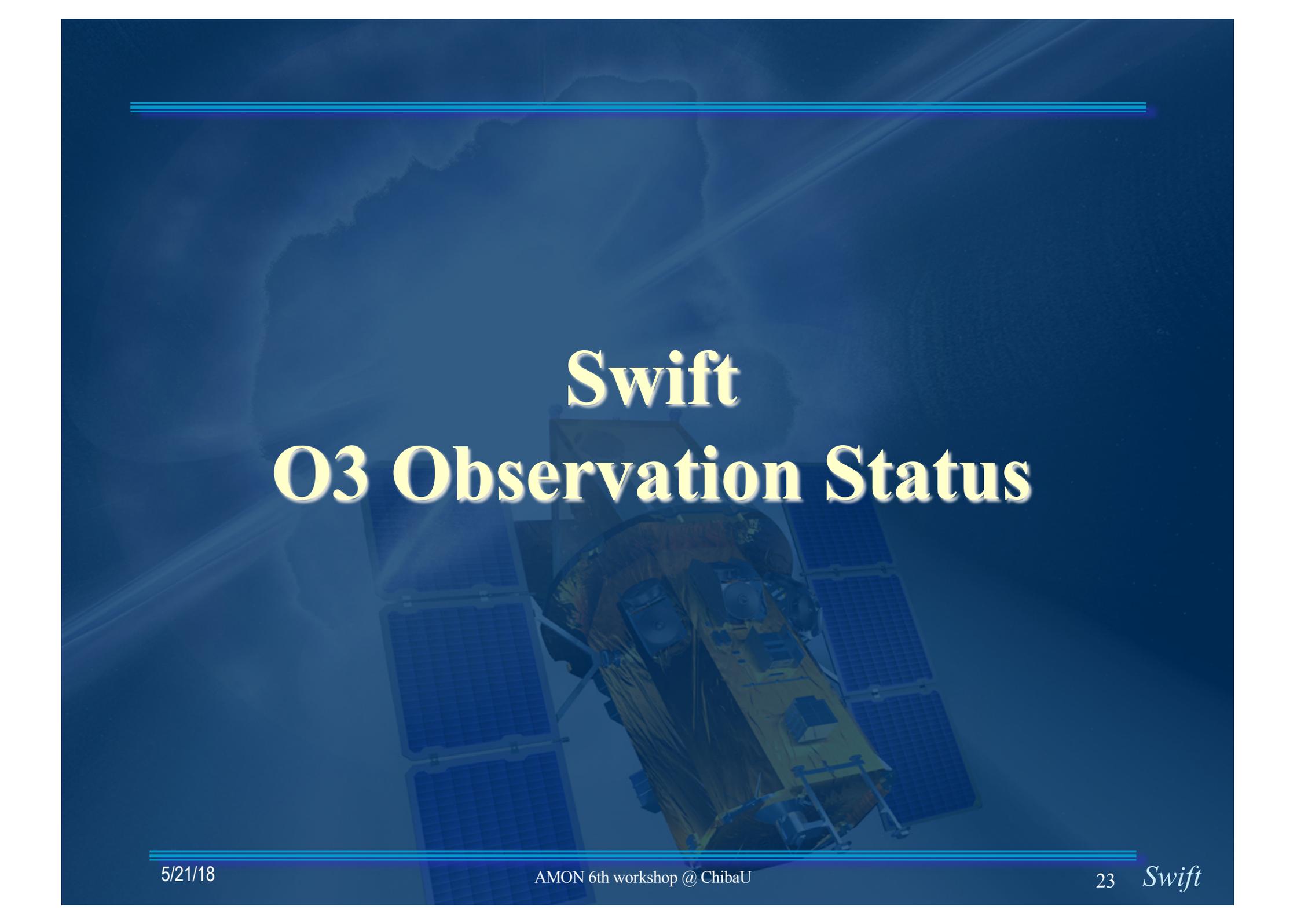
UVOT

XRT

GRB 051105A	GRB 070209	GRB 090305A
 <p>Energy Flux [erg/s/cm²]</p> <p>TIME [sec]</p> <p>$T_{90} = 56$ ms</p>	 <p>Energy Flux [erg/s/cm²]</p> <p>TIME [sec]</p> <p>$T_{90} = 68$ ms</p>	 <p>Energy Flux [erg/s/cm²]</p> <p>TIME [sec]</p> <p>$T_{90} = 540$ ms</p>
<p>Detection: 20.12 mag (UVW2) $T_0 + 87$ Note: reported on the UVOT GRB catalog</p>	<p>Detection: 18.14 mag (V) $T_0 + 71$ Note: reported on the UVOT GRB catalog</p>	<p>Detection 19.48 mag (V) $T_0 + 62$ Note: reported on the UVOT GRB catalog</p>
 <p>BAT</p> <p>UVOT</p> <p>No detection</p>	 <p>No detection</p>	 <p>No detection</p>

Summary (1)

- **Three candidate events** similar characteristics to EM of GW170817 are found in 14 years of Swift operation. The fraction of such events is **0.24%**, and they are very rare.
- At the distance of GW170817, the estimated event rate of NS merger is **0.4-14 events in 14 years** (Abbott et al. 2018). Therefore, our number of three candidates are consistent with the rate.

A faint, artistic rendering of the Swift satellite in space, showing its solar panels and instruments, set against a dark blue background with a nebula-like pattern. The satellite is positioned centrally, slightly below the main title.

Swift

O3 Observation Status

Swift Follow-up Strategy of O3 run

- CBC triggers with a modest (>0.25) probability of containing a NS
 - 800 fields or 90% of galaxy-convolved prob. for 80 s each
 - Re-observe 500 s per field (up to 4 days)
 - CBC triggers with a low (<0.25) probability of containing a NS
 - No follow-up (unless FAR $< 1/10$ yr and the galaxy convolved probability region of >0.50 within 24 hours)
 - CBC triggers with zero probability of containing a NS
 - No follow-up (unless FAR $< 1/10$ yr and LV error region $< 10 \text{ deg}^2$)
-
- Swift Gravitational Wave Galaxy Survey (PI: Tohuvavohu)
 - Pre-imaging 5000 of the brightest galaxies within 100 Mpc, to provide X-ray and UV templates for transient searches.
 - XRT results: <http://www.swift.ac.uk/LVC/>
 - BAT event data downlink by command

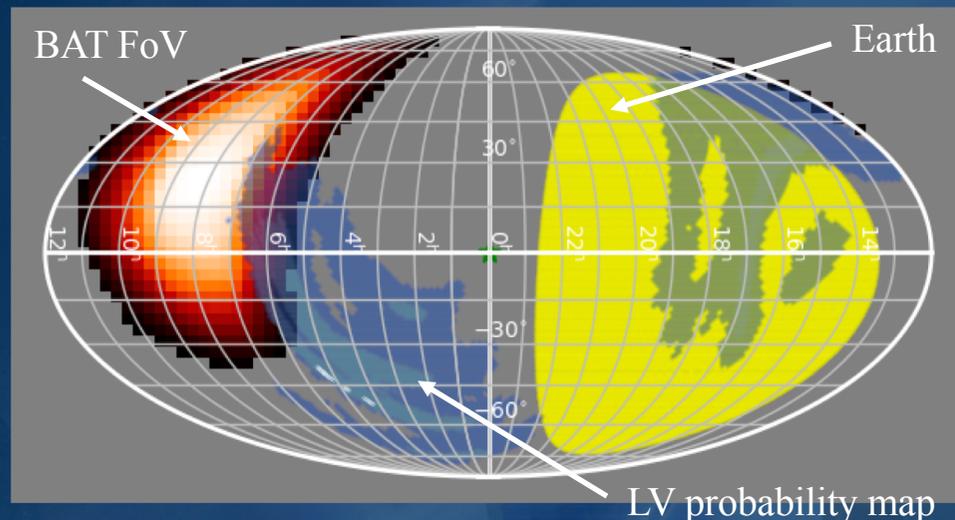
Summary of O3 GW Events

GW	T ₀ (GW) UTC	Event Type	FAR [yr]	L _d [Mpc]	BAT Sum Prob [%]	Swift NFI
S190408an	2019-04-08 18:18:02.288	BBH	<1/100	1473 ± 358	0.02	No
S190412m	2019-04-12 05:30:44.166	BBH	<1/100	812 ± 194	0.28	No
S190421ar	2019-04-21 21:38:56.251	Terrestrial	1/2	2281 ± 697	23.09	No
S190425z	2019-04-25 08:18:05.017	BNS	1/(7 x 10 ⁴)	155 ± 45	11.78	Yes
S190426c	2019-04-26 15:21:55.337	NSBH	1/1.6	375 ± 108	4.51	Yes
S190503bf	2019-05-03 18:54:04.294	BBH	1/19	421 ± 105	99.75	No
S190510g	2019-05-10 02:59:39.292	BNS	1/37	269 ± 108	0.95	Yes
S190512at	2019-05-12 18:07:14.422	BBH	1/16	1331 ± 341	0	No
S190513bm	2019-05-13 20:54:28.747	BBH	1/(1 x 10 ⁵)	1987 ± 501	0	No
S190517h	2019-05-17 05:51:01.831	BBH	1/13	2950 ± 1038	5.34	No

S190425z

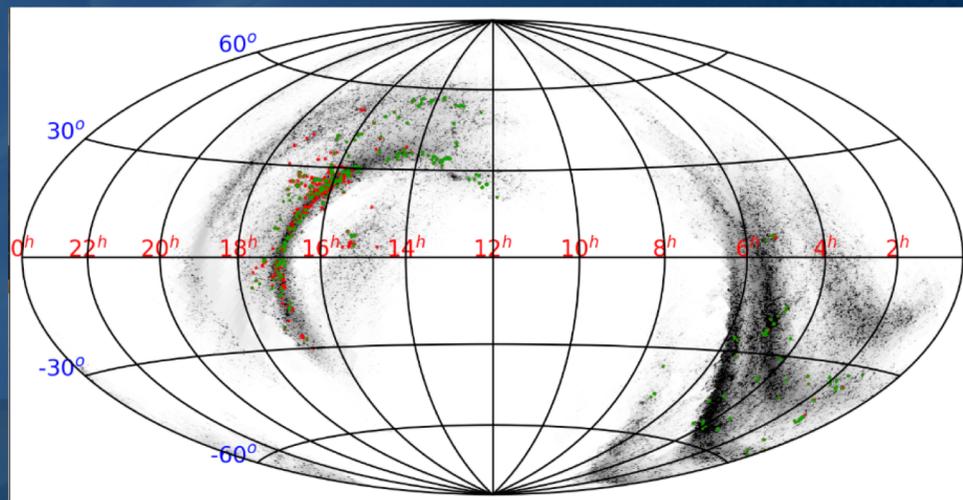
BAT FoV at $T_0(\text{GW})$

Summed LV probability within the BAT FoV: **11.8%**

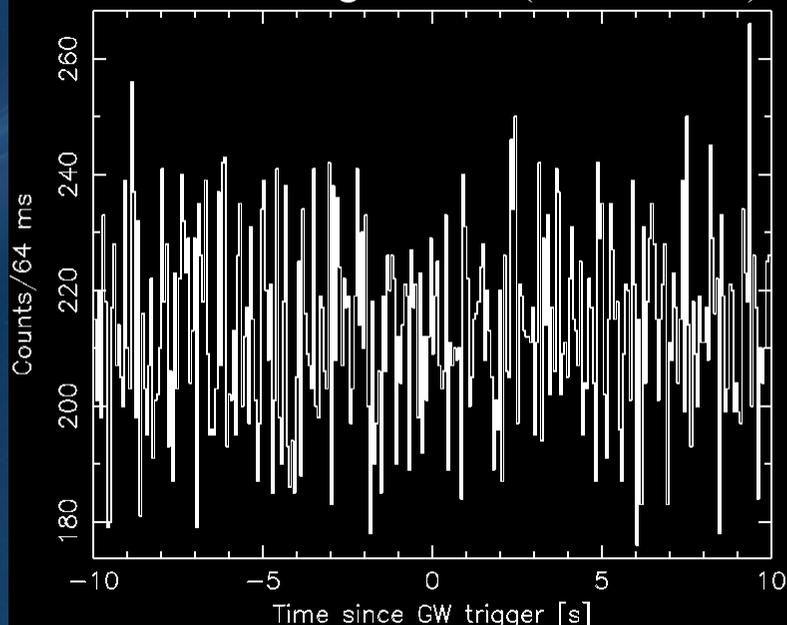


Swift XRT observed fields

(Green: observed XRT fields, Red: planned but not observed)



BAT 64 ms light curve (15-350 keV)



406 observed fields (1% of LV prob.)

- No prompt γ -ray detection
- Possible UVOT source (GCN circ. 24296)
 - No X-ray emission
 - No X-ray/UV emission at Oct 21/22 UT, 2018
 - Not confirmed by other ground telescopes (note: there is a M2-dwarf star near UVOT position)

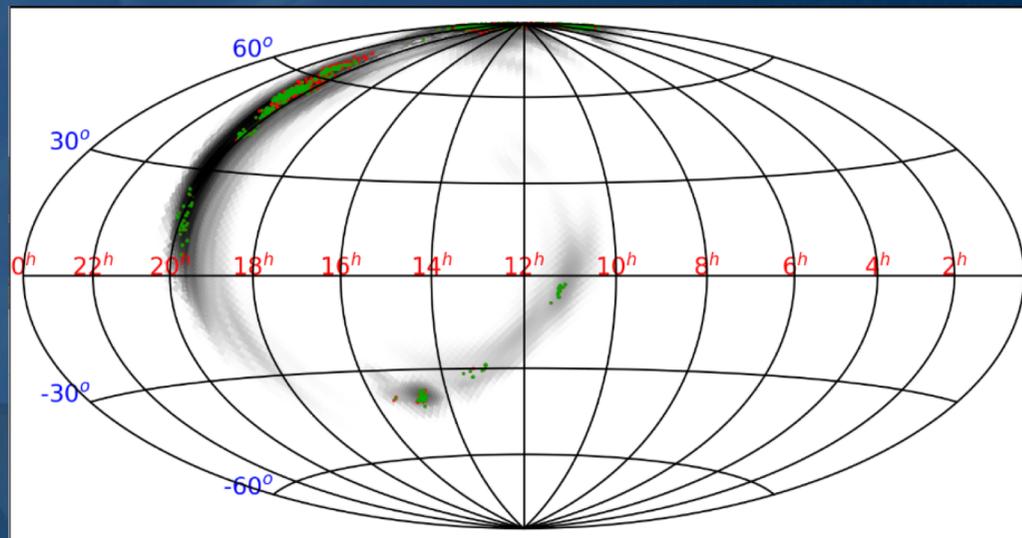
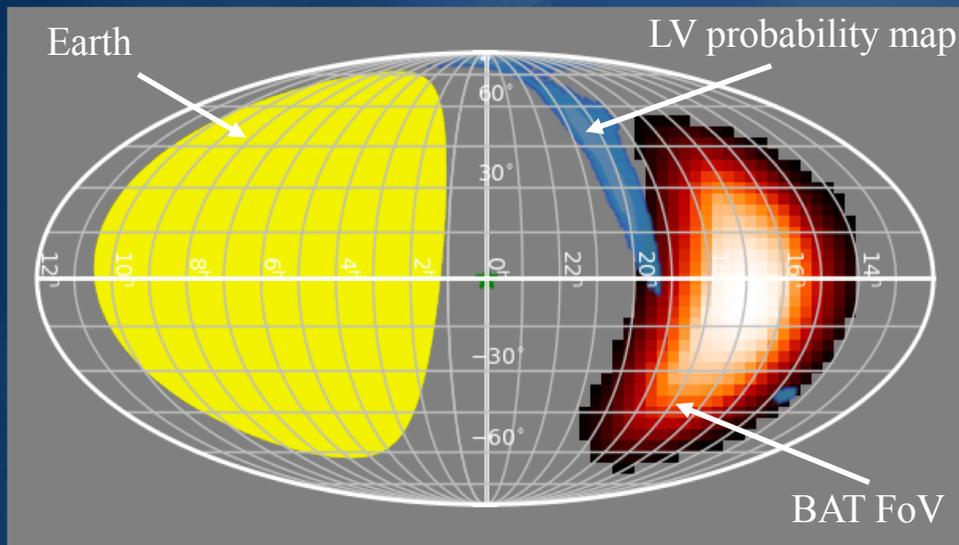
S190426c

BAT FoV at T_0 (GW)

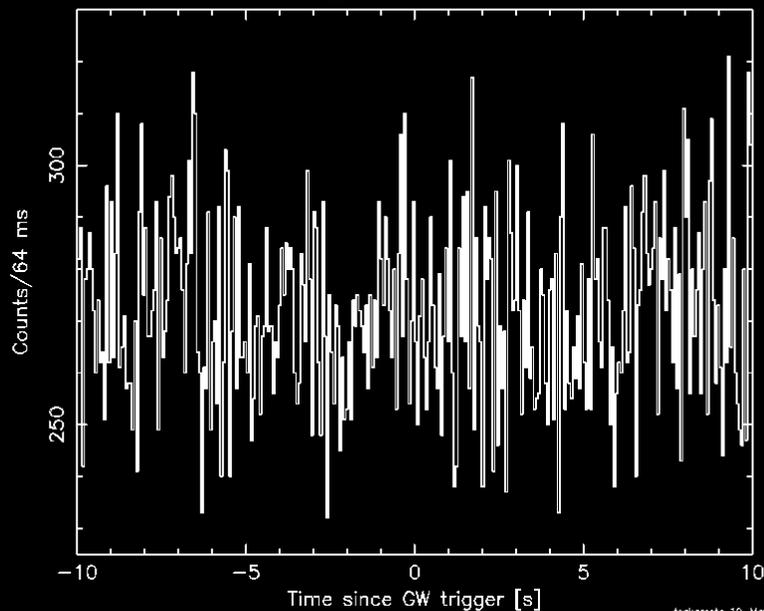
Summed LV probability within the BAT FoV: 4.51%

Swift XRT observed fields

(Green: observed XRT fields, Red: planned but not observed)



BAT 64 ms light curve (15-350 keV)



894 observed fields (18% LV prob.)

- No prompt γ -ray detection
- 114 X-ray sources detected (probably none of them are the EM candidate)

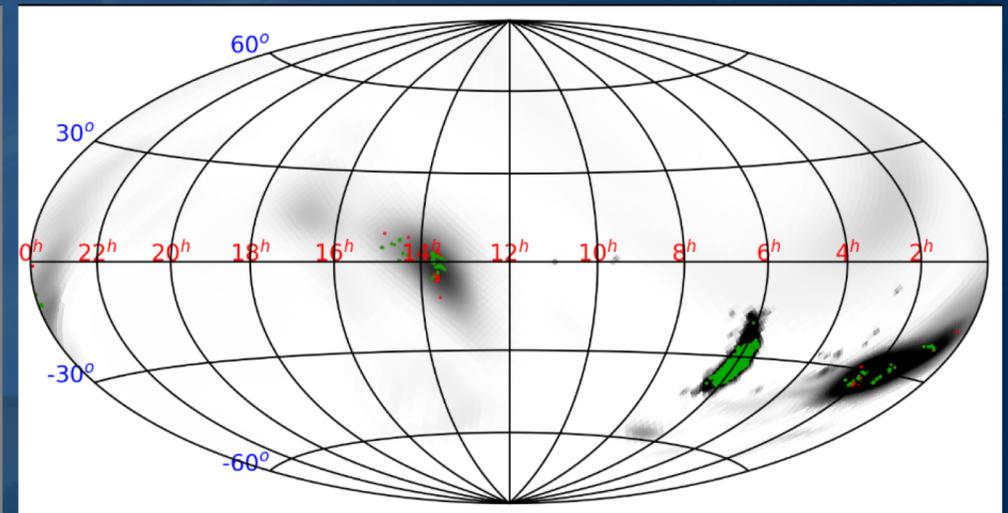
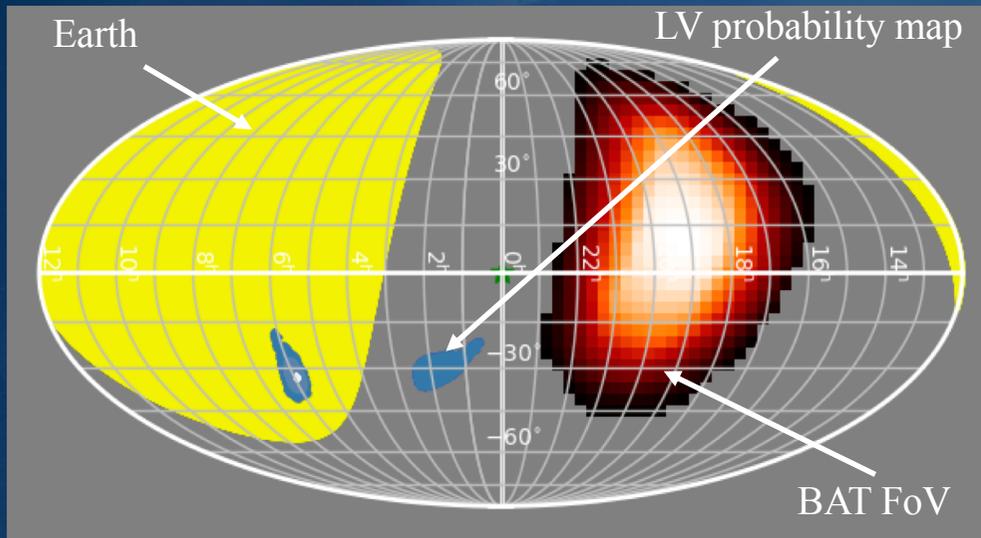
S190510g

BAT FoV at $T_0(\text{GW})$

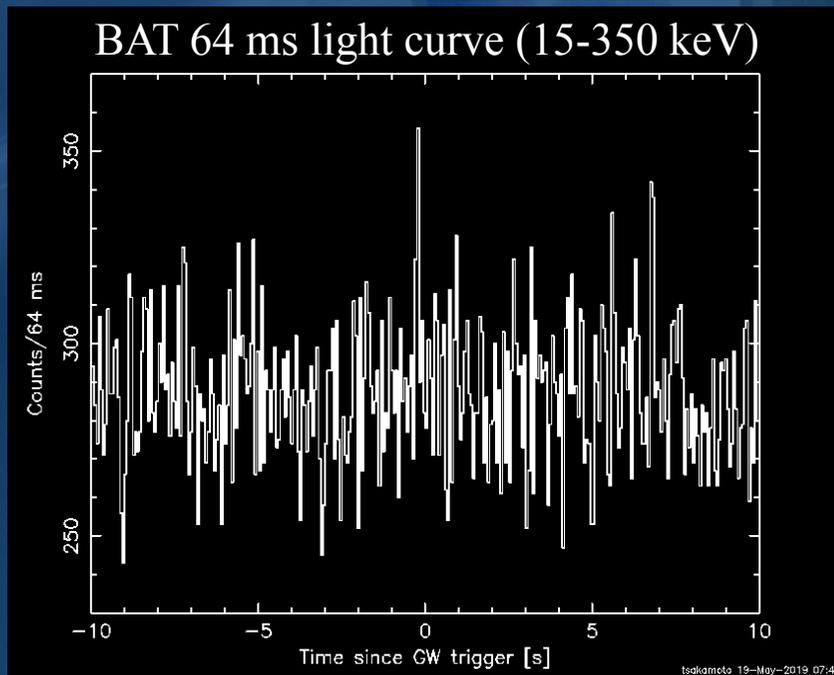
Summed LV probability within the BAT FoV: **0.95%**

Swift XRT observed fields

(Green: observed XRT fields, Red: planned but not observed)



997 observed fields (59% LV prob.)



- No prompt γ -ray detection
- 33 X-ray sources detected (probably none of them are the EM candidate)
 - $3\sigma_{\text{UL}}$: 3×10^{-12} erg/cm²/s (0.3-10 keV)

Summary (2)

- Swift/BAT is powerful all sky hard X-ray monitor to search for the prompt gamma-ray emission associated with GW.
- Swift will do ~ 1000 pointing observations for the LV triggers with the NS containing probability of >0.25 .
- Three GW events (S190425z, S190426c, S190510g) were followed up by Swift. So far, no obvious EM counterpart.

Yamada Conference LXXI: Gamma-ray Bursts in the Gravitational Wave Era 2019

Date: October 28 – November 1, 2019

Venue: Red Brick Warehouse, Yokohama, Japan

URL: <http://yokohamagrb2019.wikidot.com/>

- Registration and abstract submission are opened!
(due June 15)
- Book your hotel ASAP!!

Confirmed invited speakers:

- | | |
|---|--------------------------------------|
| - M. Branchesi (Gran Sasso Sci. Inst.) | - R.-Y. Liu (DESY) |
| - J. Burgess (Max-Planck-Inst.) | - D. Perley (Liverpool J. Moores U.) |
| - E. Burns (NASA/GSFC/USRA) | - J. Selsing (U. of Copenhagen) |
| - P. D'Avanzo (INAF) | - P. Shawhan (U. of Maryland) |
| - H. van Eerten (U. of Bath) | - D. Siegel (Columbia U.) |
| - A. van der Horst (George Washington U.) | - K. Toma (Tohoku U.) |
| - K. Hotokezaka (Princeton U.) | - T. Totani (U. of Tokyo) |
| - T. Kajita (ICRR/U. of Tokyo) | - E. Troja (NASA/GSFC/UMCP) |
| - K. Kiuchi (Kyoto U.) | - K. Wiersema (U. of Warwick) |
| - M. Kole (U. of Geneva) | - B. Zhang (U. of Nevada) |

SOC: L. Amati, K. Asano, J.-L. Atteia, B. Cenko, V. Connaughton, Y. Fukazawa, J. Greiner, K. Ioka, N. Kanda, N. Kawai, P. Meszaros, K. Murase, P. O'Brien, T. Piran, J. Racusin, L. Singer, N. Tanvir, K. Toma, E. Troja,

X.-Y. Wang, R. Yamazaki, D. Yonetoku, M. Yoshida, B. Zhang

LOC: S. Kisaka, T. Sakamoto (Chair), M. Serino, S. Sugita

