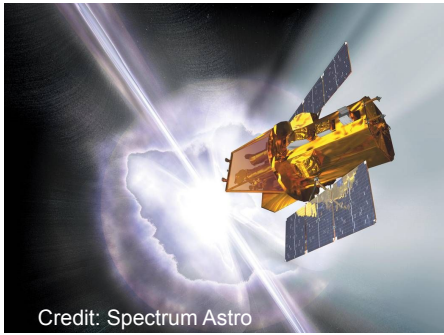
Swift-BAT GUANO and NITRATES



Jimmy DeLaunay
Penn State
jjd330@psu.edu

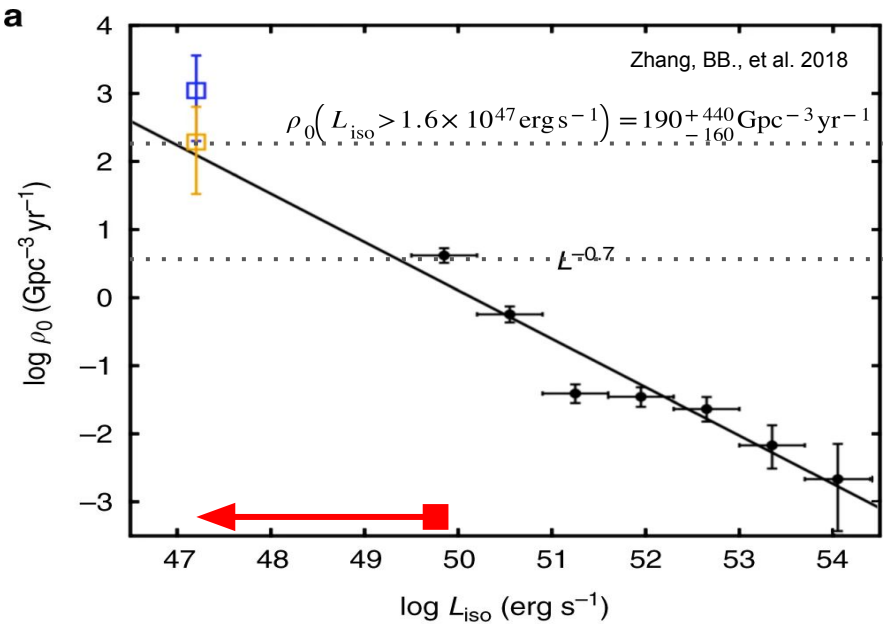
Swift BAT-Guano Team: Jamie Kennea (PSU), Tyler Parsotan (GSFC), Gayathri Raman (PSU), Samuele Ronchini (PSU), Aaron Tohuvavohu (U Toronto)

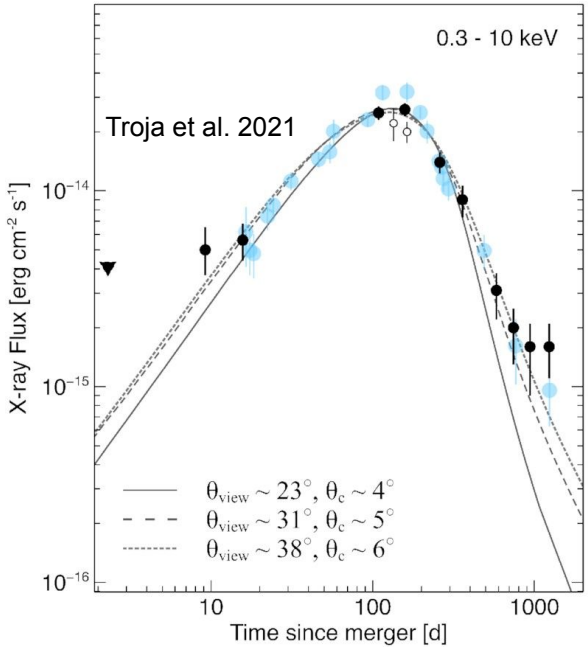
3rd Astro-COLIBRI Workshop
Institut Pascal, France
September 16th 2024

PennState

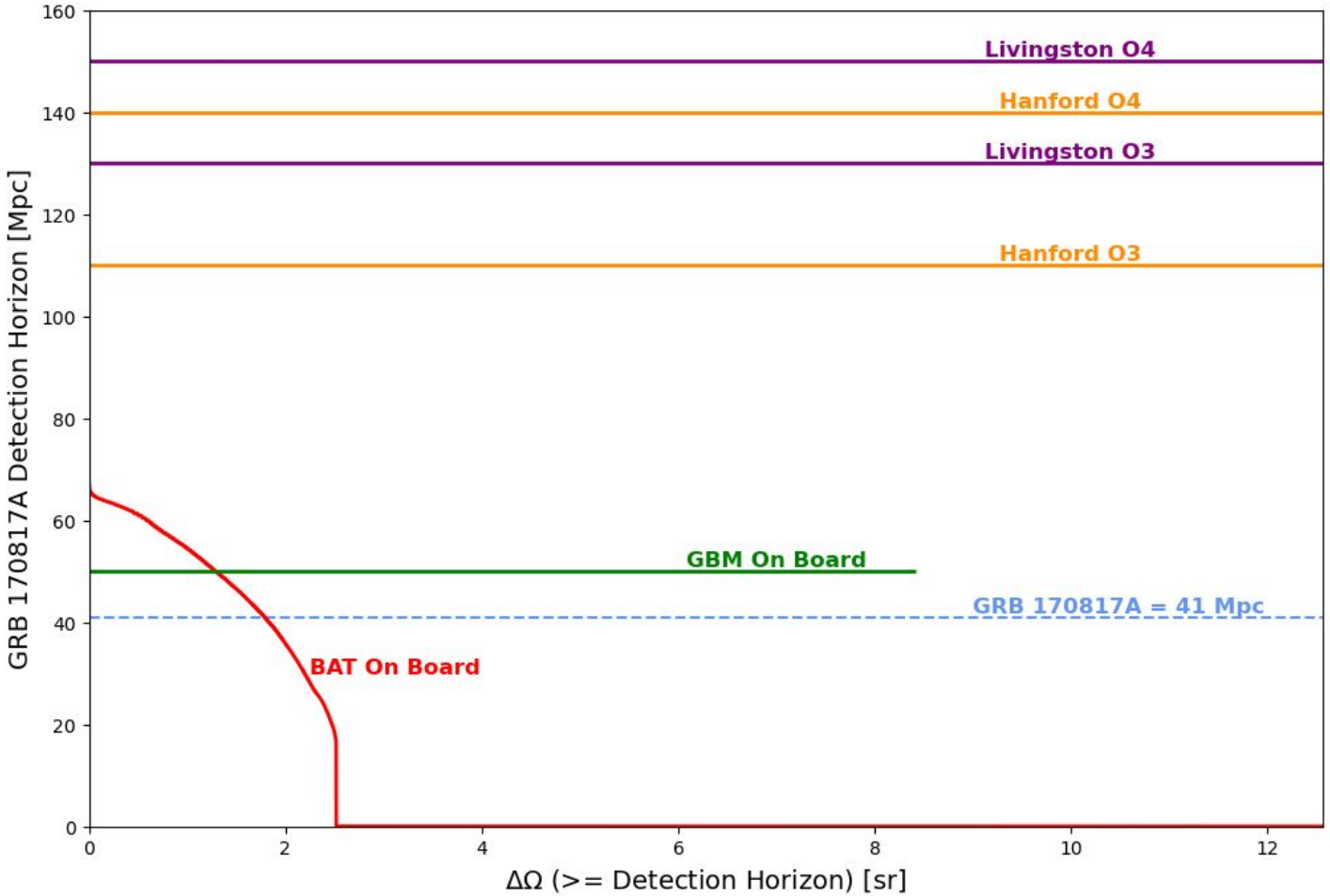
GRB 170817A

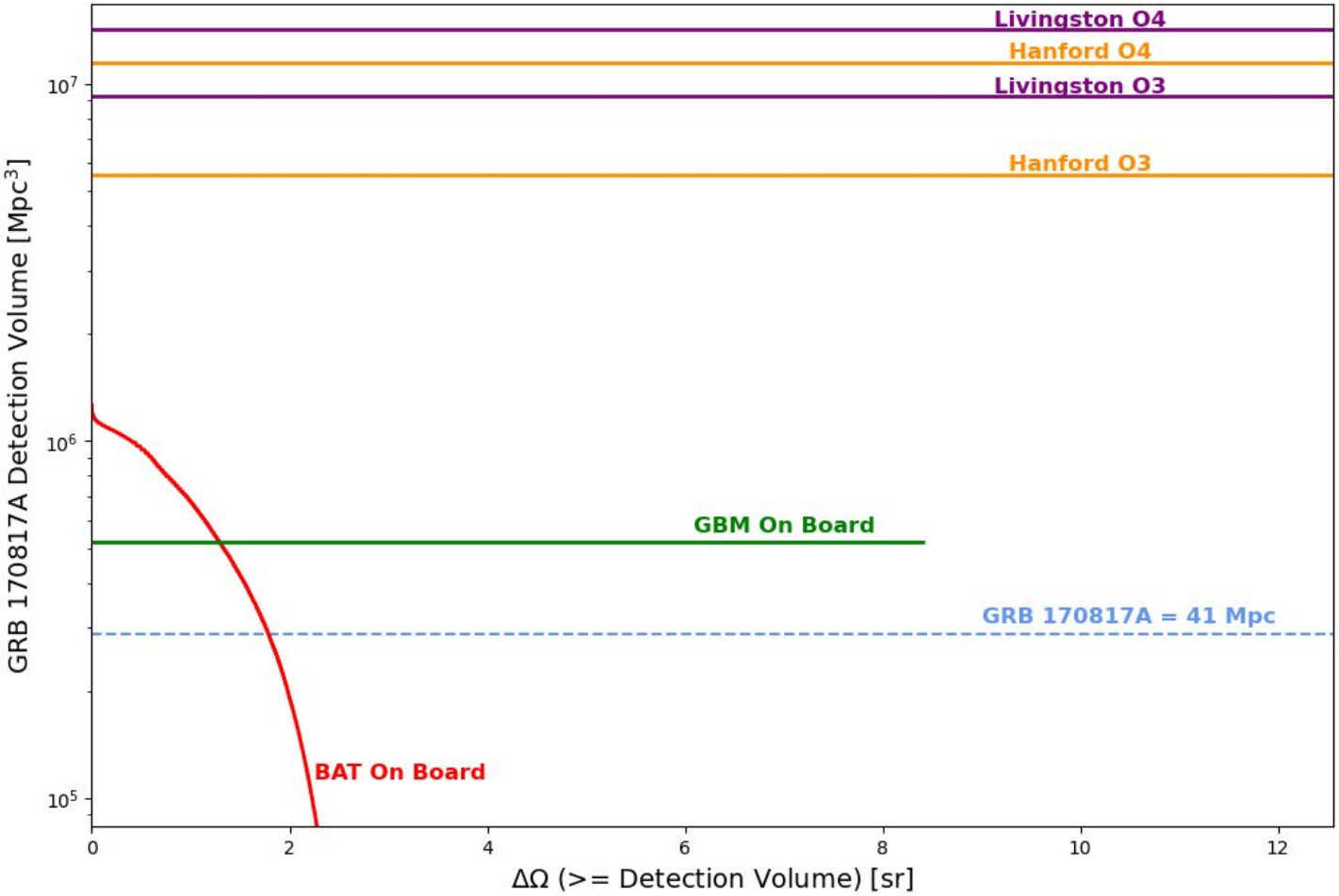
- Closest measured SGRB distance
- Measured fluence just under the median for GBM SGRBs
- By far the lowest measured L_{iso}
- Possible population of low-luminosity SGRBs





- Structured jet viewed off-axis gives best agreement with afterglow data
  - “Normal” jet pointed away from us
- Off-axis afterglow has characteristic initial, rising X-ray afterglow


Livingston O4
Hanford O4
Livingston O3
Hanford O3
GBM On Board
GRB 170817A = 41 Mpc
BAT On Board
GRB 170817A Detection Horizon [Mpc]
ΔΩ (>= Detection Horizon) [sr]
0
20
40
60
80
100
120
140
160
0
2
4
6
8
10
12


Livingston O4
Hanford O4
Livingston O3
Hanford O3
GBM On Board
GRB 170817A = 41 Mpc
BAT On Board
GRB 170817A Detection Volume [Mpc³]
ΔΩ (>= Detection Volume) [sr]
10⁷
10⁶
10⁵
0
2
4
6
8
10
12

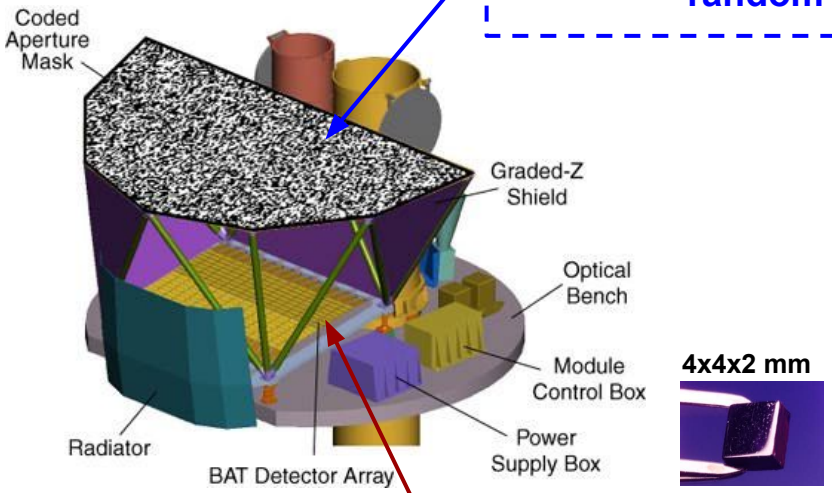
GUANO - Gamma-ray Urgent Archiver for Novel Opportunities

Tohuvavohu et al. (2020).

- Time tagged event (TTE) data normally only available around onboard triggered GRBs
- GUANO allows for TTE data to be available on command
  - 90 - 200 s of data around time of interest
- Command needs to be prompt (<30 minutes)
  - Event buffer lasts ~30 minutes
- Allows for additional and more sensitive searches to be possible on the ground
  - Better imaging, mosaic imaging during slews, **better analyses**
- Started in O3
- Dumping data for GRBs, GWs, Neutrinos, FRBs
  - **Dozens of additional arcminute localized GRBs!**

How BAT Works - A Coded mask imager (15 - 350 keV)

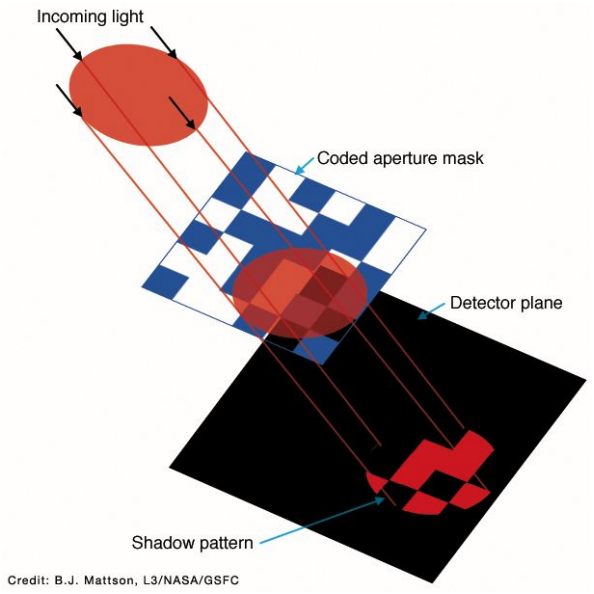
Aperture Mask is 50% open and consists of ~50,000 lead tiles in a random pattern



32,768 CZT Detectors in Array

Energy Resolution of CZT Detectors: ~5 keV @ 60 keV

Basic Concept



- Constructs images via a balanced cross-correlation technique
- Creates an image on board whenever there's a rate excess
- Localizes sources to a few arcminutes

NITRATES - Non Imaging Transient Reconstruction and TEmporal Search

DeLaunay & Tohuvavohu 2022

Using BAT TTE data for a certain time interval, data binned by detector and energy

- Uses 9 energy bins ranging from 15 keV to 350 keV

N_{ij} = number of counts in detector, i and energy bin, j

$\lambda_{ij}(\boldsymbol{\Theta})$ = number of expected counts from model(s), given model parameters $\boldsymbol{\Theta}$

$$l_{ij}\,(\boldsymbol{\Theta}|N_{ij}) = \text{Poisson}(N_{ij}\,;\,\lambda_{ij}(\boldsymbol{\Theta}))$$

$$\text{LLH}\,(\boldsymbol{\Theta}|\mathbf{N}) = \sum_i \sum_j \ln[\, l_{ij}\,(\boldsymbol{\Theta}|N_{ij})\,]$$

Count sources to model:
Diffuse: Cosmic x-ray background (CXB), local particle background
Point Sources: Known steady(ish) sources, transient sources (GRBs)

GRB Search

Looking for new PS not in off-time bkg fit

Likelihood Ratio Test Statistic

$$\Lambda = -2(\,\text{LLH}(\,\boldsymbol{\Theta}_{\text{Bkg}}|\mathbf{N}) - \max[\,\text{LLH}(\boldsymbol{\Theta}_{\text{Sig}},\,\boldsymbol{\Theta}_{\text{Bkg}}|\mathbf{N})\,]\,)$$

NITRATES - Non Imaging Transient Reconstruction and TEmporal Search

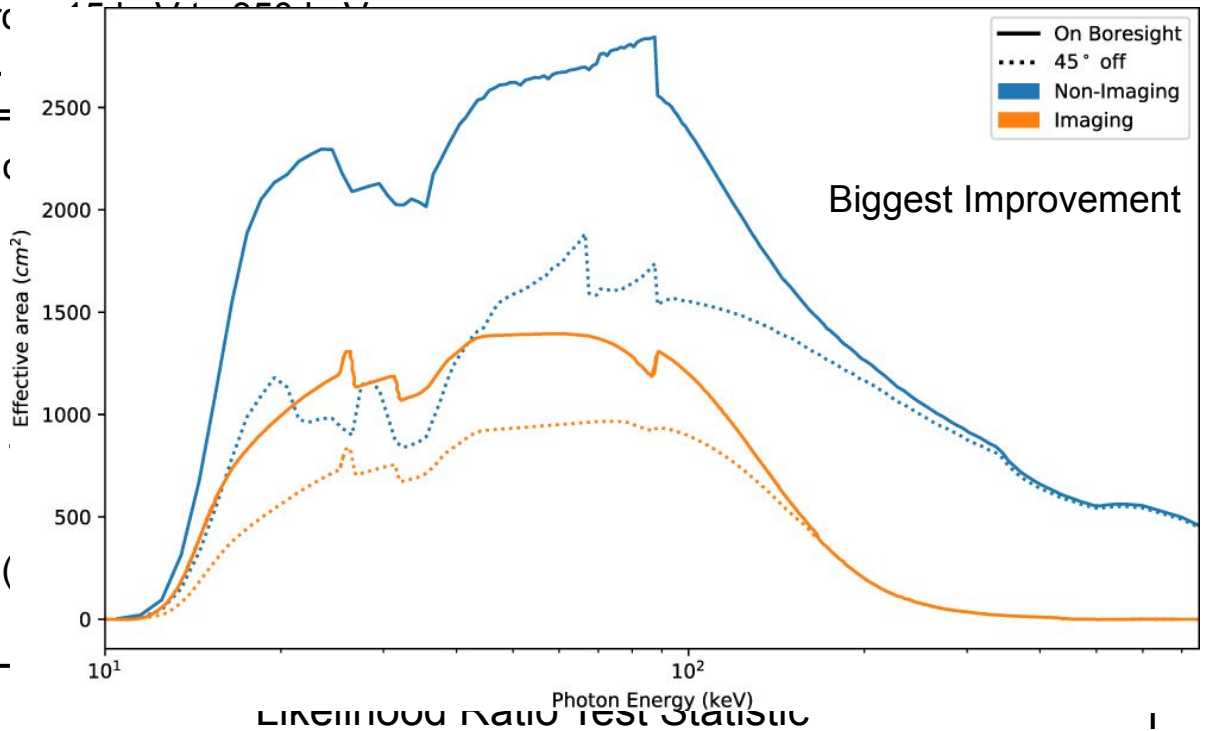
DeLaunay & Tohuvavohu 2022

Using BAT TTE data for a certain time interval, data binned by detector and energy

- Uses 9 energy bins ranging fr

N_{ij} =

$\lambda_{ij}(\Theta)$ = number



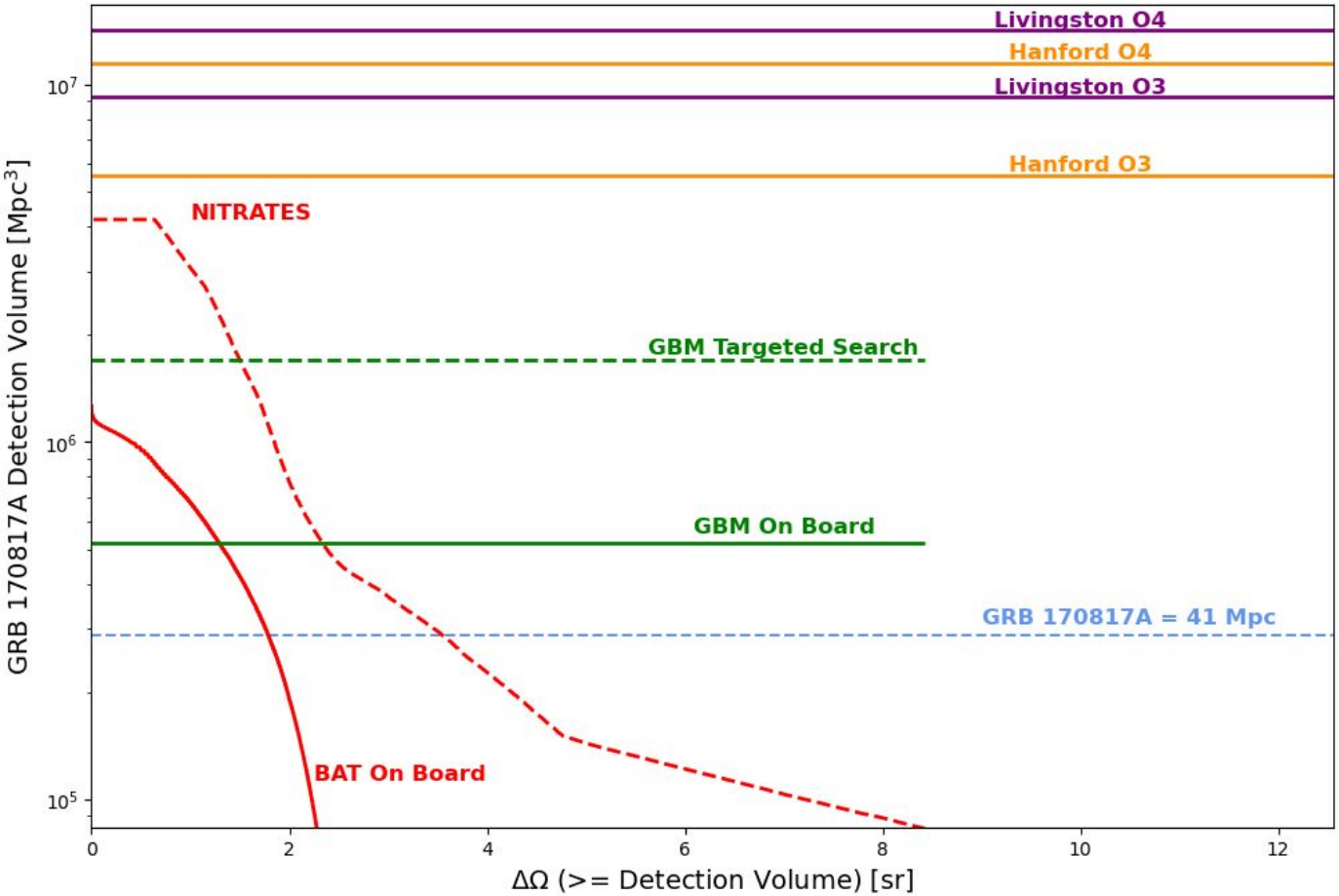
Count sources to model:
Diffuse: Cosmic x-ray background (
Point Sources: Known steady(ish)

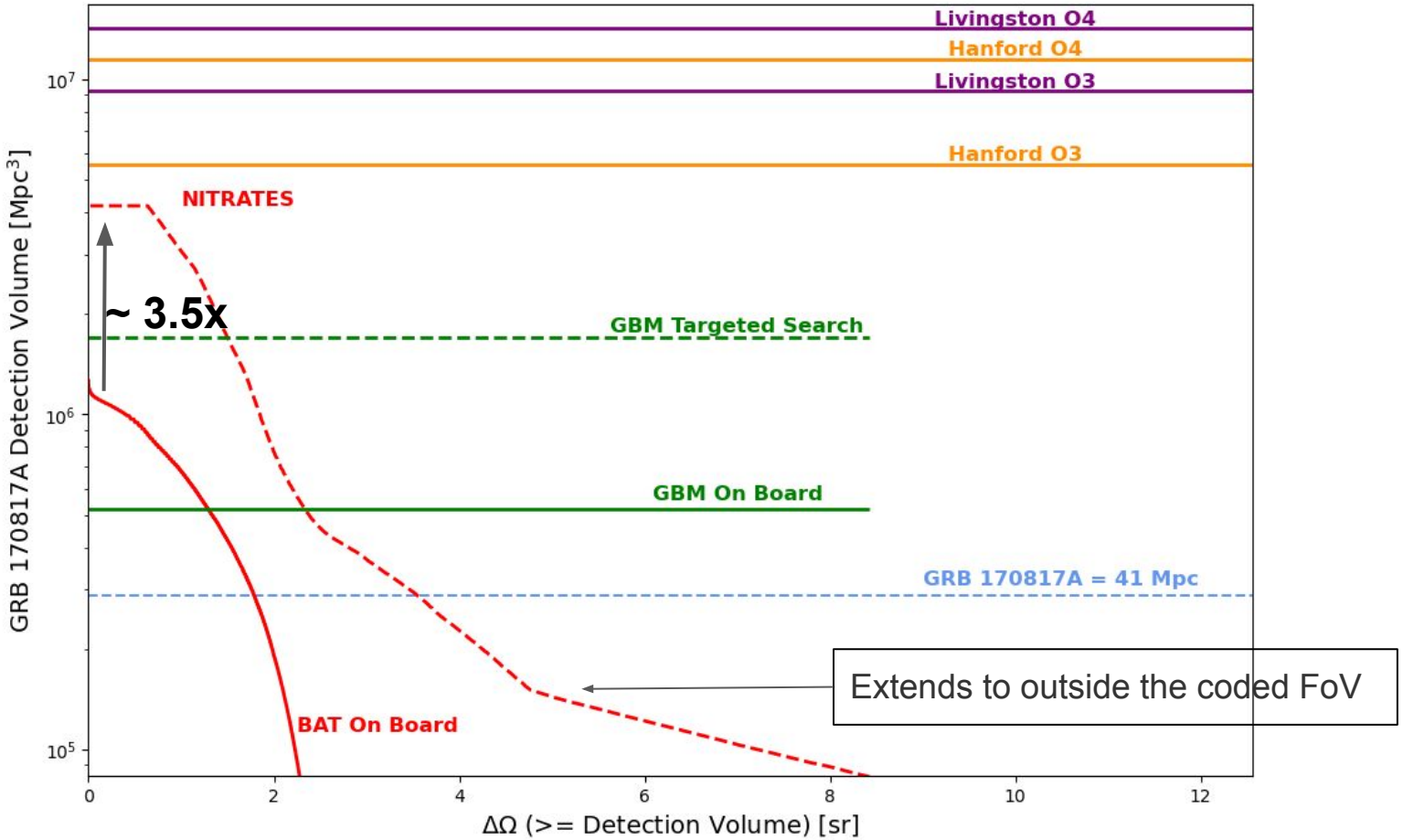
GRB Search

Looking for new PS not in off-time bkg fit

Likelihood Ratio Test Statistic

$$\Lambda = -2(LLH(\Theta_{Bkg}|\mathbf{N}) - \max[LLH(\Theta_{Sig}, \Theta_{Bkg}|\mathbf{N})])$$


Livingston O4
Hanford O4
Livingston O3
Hanford O3
NITRATES
GBM Targeted Search
GBM On Board
GRB 170817A = 41 Mpc
BAT On Board
10^7
10^6
10^5
GRB 170817A Detection Volume [Mpc^3]
0
2
4
6
8
10
12
ΔΩ (>= Detection Volume) [sr]


Livingston O4
Hanford O4
Livingston O3
Hanford O3
NITRATES
~ 3.5x
GBM Targeted Search
GBM On Board
GRB 170817A = 41 Mpc
BAT On Board
Extends to outside the coded FoV
GRB 170817A Detection Volume [Mpc^3]
10^7
10^6
10^5
0
2
4
6
8
10
12
ΔΩ (>= Detection Volume) [sr]

5x all sky

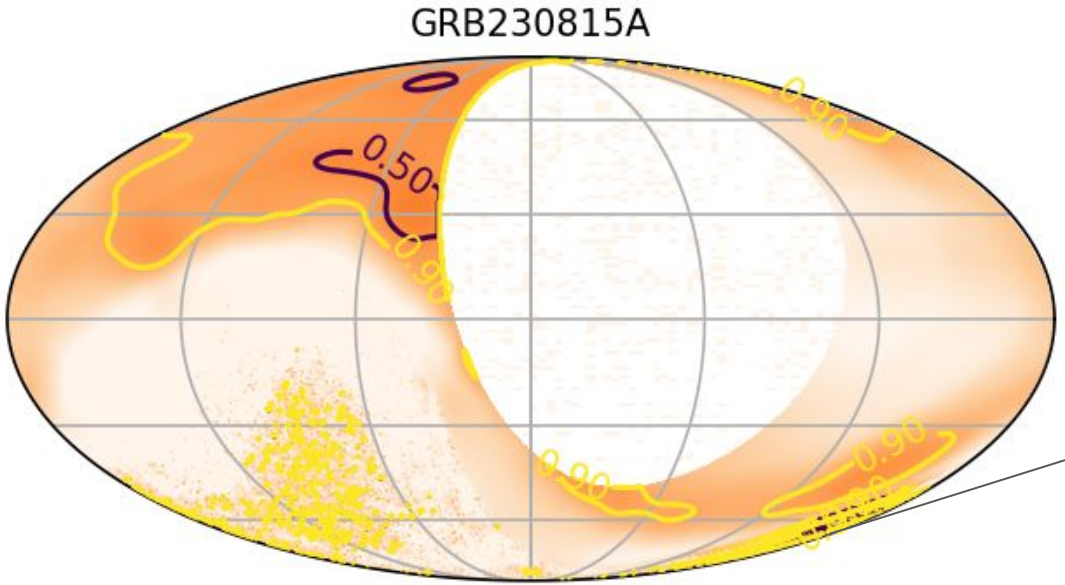
Localization

Best case scenario - ~3 arcminute circle

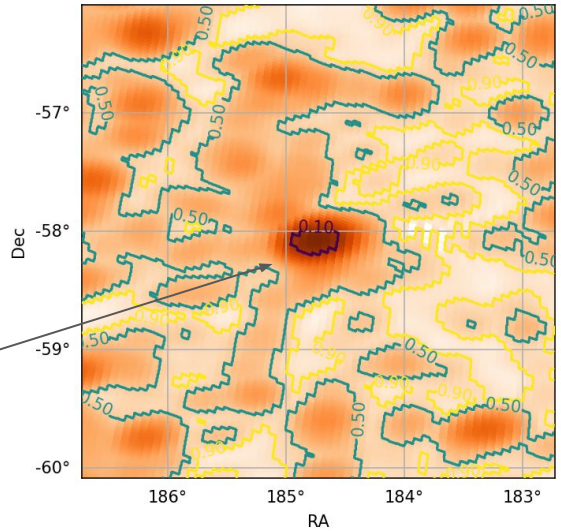
Localization

Best case scenario - ~3 arcminute circle

Worst case scenario -



Zoom in on GRB/max LLH position

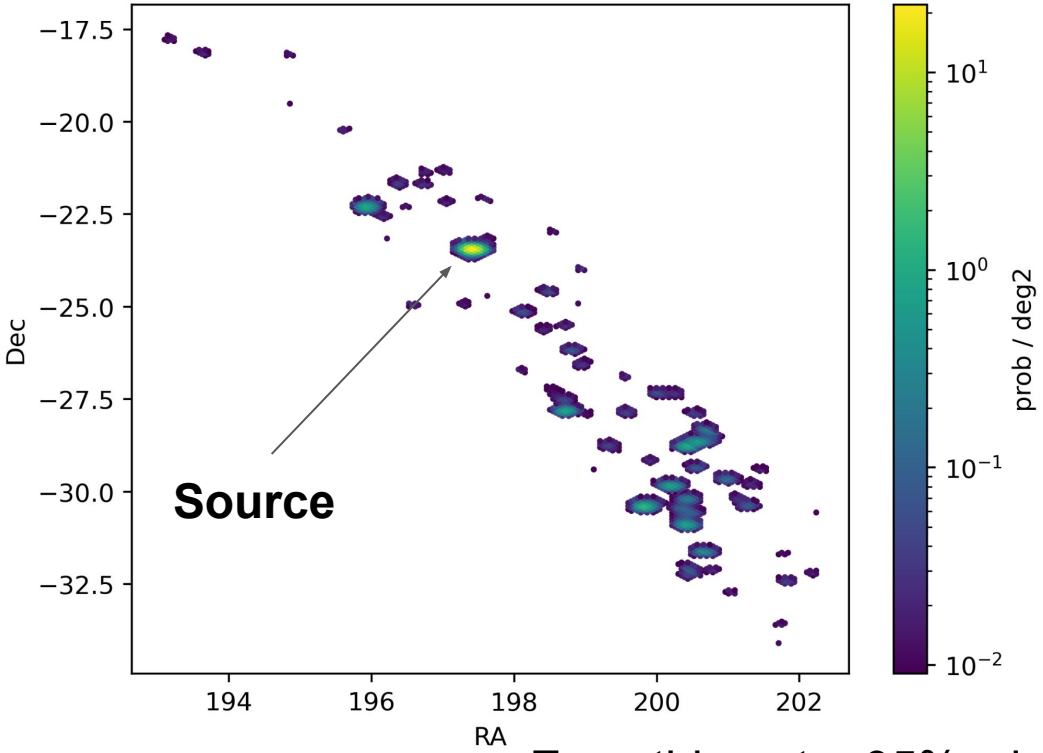


50% area = 600 deg^2

90% area = 5,700 deg^2

FWHM ~ ⅓ deg

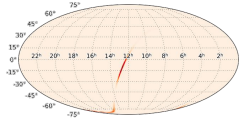
What if GRB 170817A were in the BAT coded FoV at 90 Mpc?



Everything at < 95% c.l.

NITRATES ground trigger and messy skymap,
also skymap joined with GW skymap

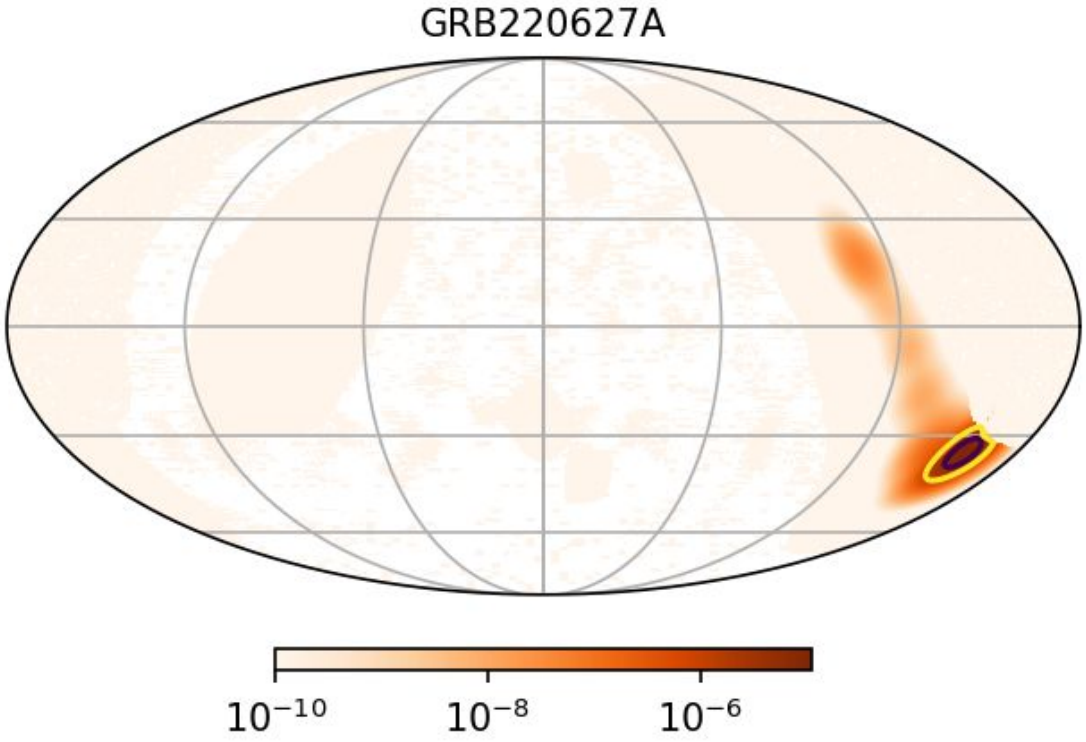
Alert sent out to world at ~2-8 hours



- GW170817 LH skymap
  - 50% area = 48 deg2
  - 90% area = 189 deg2

- Combine with NITRATES mess
  - 50% area = 0.036 deg2
  - 90% area = 1.2 deg2

Best Case Outside of Coded Field of View



50% area = 50 deg^2
90% area = 160 deg^2

BAT-GUANO GCN Kafka Alerts

These notices are published on the GCN Kafka topic `gcn.notices.swift.bat.guano`.

Detailed Description and Examples

Type	Contents	Latency
Alert	Detection of a burst	5 min - 4 hours
Localization	Arcminute position or HEALPix map	30 min - 5 hours
Retraction	Retraction of an alert or localization	4 hours - 1 day

Examples here

More info https://gcn.nasa.gov/missions/swift

HEALPix maps will be in MOC format

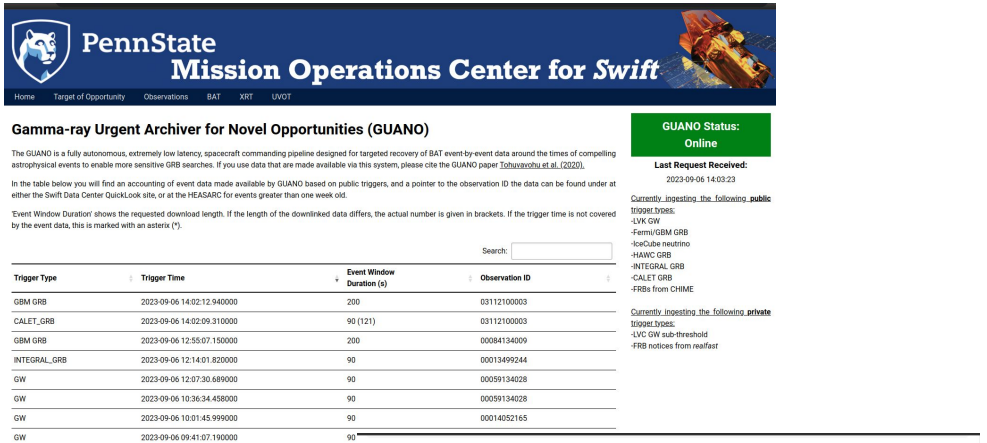
- Joint sub-threshold GW-GRB detections will be sent out by LVK over GCN
  - If joint FAR < 1/month (after trials correction) using RAVEN formalism
  - Combined skymaps
  - See more here https://emfollow.docs.ligo.org/userguide/content.htm

external_coinc	
gcn_notice_id	`{583417860, 583327924}`
ivorn	External IVORN identification field
observatory	`{Fermi,Swift}`
search	`{GRB,SubGRB}`
time_difference	Time between source and external event in seconds
time_coincidence_far	Estimated coincidence false alarm rate in Hz using timing
time_sky_position_coincidence_far	Estimated coincidence false alarm rate in Hz using timing and sky position
combined_skymap	The contents of a sky map produced by combining the GW skymap and the external coincidence skymap in a multi-order FITS format as a Base64-encoded string.

How to find GUANO data

GUANO triggers can be found here
Observation ID can be used to find the data on the
- archive (if > 2 weeks old)
- quicklook (if < 2 weeks old)

Or swift_tools API can be used to query and fetch GUANO and other Swift data



PennState Mission Operations Center for *Swift*

Home | Target of Opportunity | Observations | BAT | XRT | UVOT

Gamma-ray Urgent Archiver for Novel Opportunities (GUANO)

The GUANO is a fully autonomous, extremely low latency, spacecraft commanding pipeline designed for targeted recovery of BAT event-by-event data around the times of compelling astrophysical events to enable more sensitive GRB searches. If you use data that are made available via this system, please cite the GUANO paper Tohuvavohu et al. (2020).

In the table below you will find an accounting of event data made available by GUANO based on public triggers, and a pointer to the observation ID the data can be found under at either the Swift Data Center QuickLook site, or at the HEASARC for events greater than one week old.

'Event Window Duration' shows the requested download length. If the length of the downlinked data differs, the actual number is given in brackets. If the trigger time is not covered by the event data, this is marked with an asterix (*).

GUANO Status: Online

Last Request Received:
2023-09-06 14:03:23

Currently ingesting the following **public** trigger types:
-LVK GW
-Fermi/GBM GRB
-IceCube neutrino
-HAWC GRB
-INTEGRAL GRB
-CALET GRB
-FRBs from CHIME

Currently ingesting the following **private** trigger types:
-LVC GW sub-threshold
-FRB notices from *realfast*

Search:

Trigger Type	Trigger Time	Event Window Duration (s)	Observation ID
GBM GRB	2023-09-06 14:02:12.940000	200	03112100003
CALET_GRB	2023-09-06 14:02:09.310000	90 (121)	03112100003
GBM GRB	2023-09-06 12:55:07.150000	200	00084134009
INTEGRAL_GRB	2023-09-06 12:14:01.820000	90	00013499244
GW	2023-09-06 12:07:30.689000	90	00059134028
GW	2023-09-06 10:36:34.458000	90	00059134028
GW	2023-09-06 10:01:45.999000	90	00014052165
GW	2023-09-06 09:41:07.190000	90	
GBM GRB	2023-09-06 09:21:25	20(	

Fetching GUANO data for a specific triggers or date ranges

The above example show fetching recent triggers, what about for date ranges, or specific times. Here we'll give a few examples of how to search for GUANO triggers using time searches. Firstly, let's see what GUANO dumps occrred during Jan 1st, 2022:

```
guano = GUANO(begin="2022-01-01", end="2022-01-02", limit=100)
guano
```

Trigger Type	Trigger Time	Offset (s)	Window Duration (s)	Observation ID
GBM GRB	2022-01-01 08:57:39	50	200	00014979001
GBM GRB	2022-01-01 07:16:20	50	200	00031306080
INTEGRAL_GRB	2022-01-01 05:11:22	0	90 (1202)	01091527000

So on Jan 1st, 2022 there were three GUANO dumps, 2 Fermi/GBM detected GRBs and one INTEGRAL GRB. By default, GBM GRBs are dumped for 200s and INTEGRAL GRBs are dumped for 90s. However, in this case you can see that the actual amount of event data for the INTEGRAL GRB was 1202s. Let's look into why, by taking a look at the `Swift_GUANO_Data` object associated with that trigger.

```
guano[-1].data
```

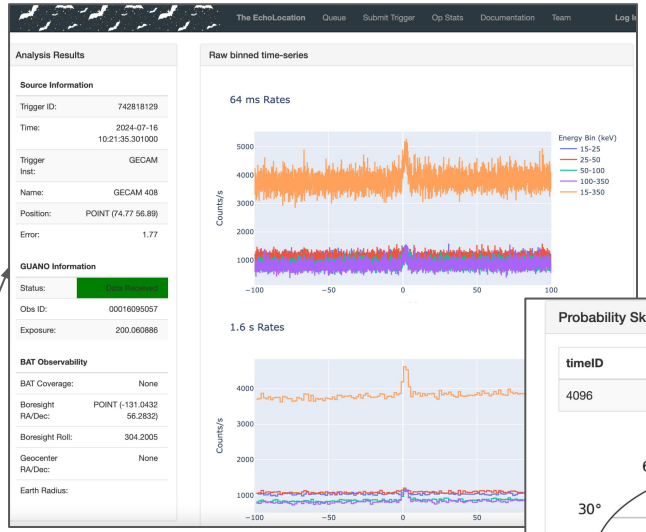
Parameter	Value
obsid	01091527000
triggertime	2022-01-01 05:11:22
begin	2022-01-01 05:06:11.642365
end	2022-01-01 05:26:13.749165
exposure	1202.1068
filenames	sw01091527000bevshsp_uf.evt
gti	2022-01-01 05:06:11.642365 - 2022-01-01 05:26:13.749165 (0:20:02)
all_gtis	2022-01-01 05:06:11.642365 - 2022-01-01 05:26:13.749165 (0:20:02)
acs	mixed
utcf	-28.357940673828125

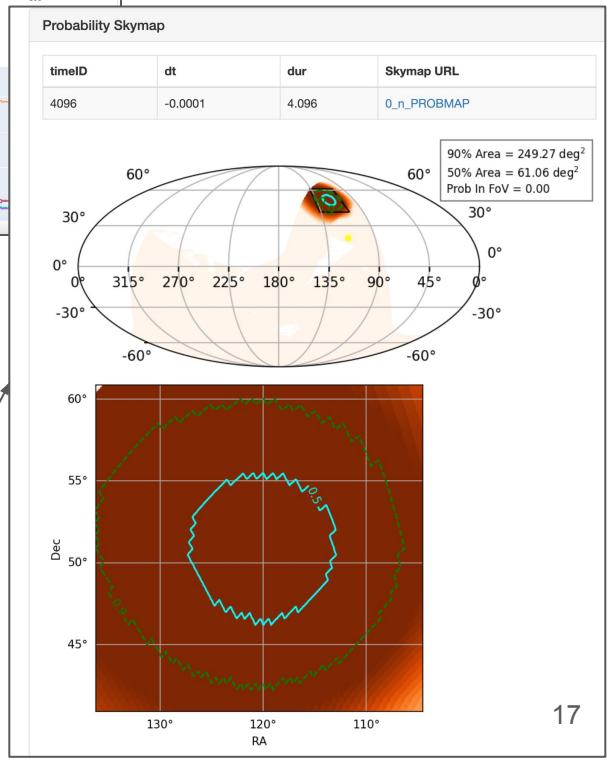
How to find NITRATES results

Go to https://guano.swift.psu.edu/

Click on the trigger you're interested in to view its report page

Will have basic figures, like the LC and BAT FoV on the sky





Along with NITRATES products, such as intermediate results, best fit points, and the localization

Find more info in the documentation

Results are preliminary
Feedback is welcome

Tools to analyze BAT data

- Standard BAT tools
  - HEASOFT FTOOLS
    - Analysis help
  - New python package to do custom analysis on long exposure survey data
    - BatAnalysis (Parsotan et. al. 2024)
    - Support for TTE data being added
- NITRATES
  - NITRATES python package
  - 500 GB of required response files found here
  - Only supports TTE data at the moment
  - Much more efficient version that runs on continuous rates data products in the works
    - Won't require HPC cluster, < 1 GB of response files
    - Won't be capable of arcminute-scale localizations
  - Recommendations for public friendly tools are very welcome!

Summary

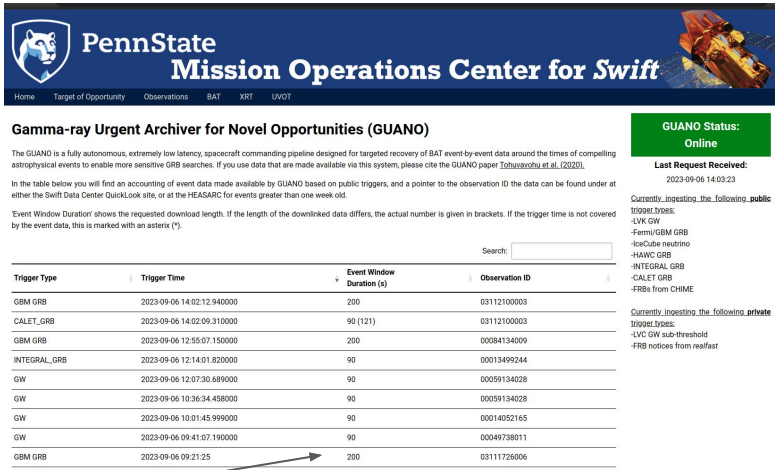
- GRB 170817A showed that off-axis GRBs can be detected
  - Many more opportunities for joint GRB-GW detections
- Need more sensitive GRB searches
- GUANO enables ground analyses
- NITRATES great increases detection horizon to GRB 170817A-like bursts
- Listen for GUANO and LVK joint Kafka notices and be ready for messy skymaps
- Check out our live results at https://guano.swift.psu.edu, check out the documentation to see how to receive and use probability skymaps
- Feel free to contact us if you're interested in working with GUANO data or the NITRATES analysis

Backups

GUANO - Gamma-ray Urgent Archiver for Novel Opportunities

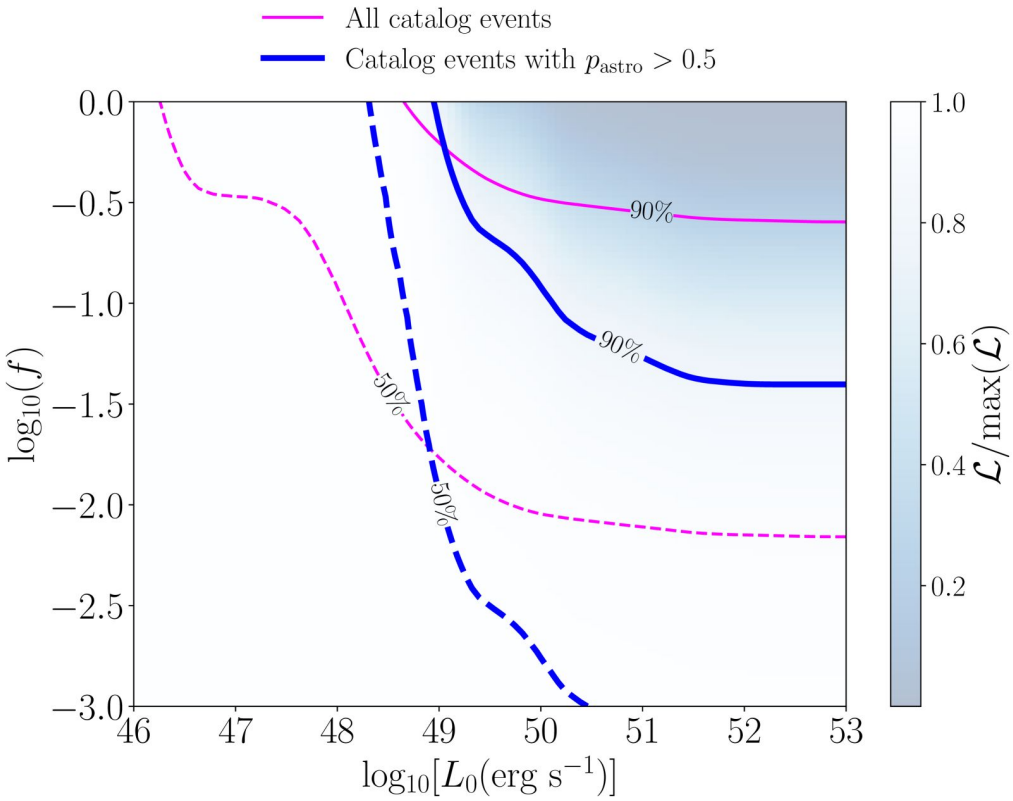
[Tohuvavohu et al. (2020).]

- Time tagged event (TTE) data normally only available around onboard triggered GRBs
- GUANO allows for TTE data to be available on command
  - 90 - 200 s of data around time of interest
- Command needs to be prompt (<30 minutes)
  - Event buffer lasts ~30 minutes
- Allows for additional and more sensitive searches to be possible on the ground
  - Better imaging, mosaic imaging during slews, **better analyses**
- Started in O3
- Dumping data for GRBs, GWs, Neutrinos, FRBs
- See https://www.swift.psu.edu/guano/ for triggers to GUANO
- If you're interested in adding triggers to GUANO contact
  - Jamie Kennea - jak51@psu.edu
  - Aaron Tohuvavohu - aaron.tohu@gmail.com



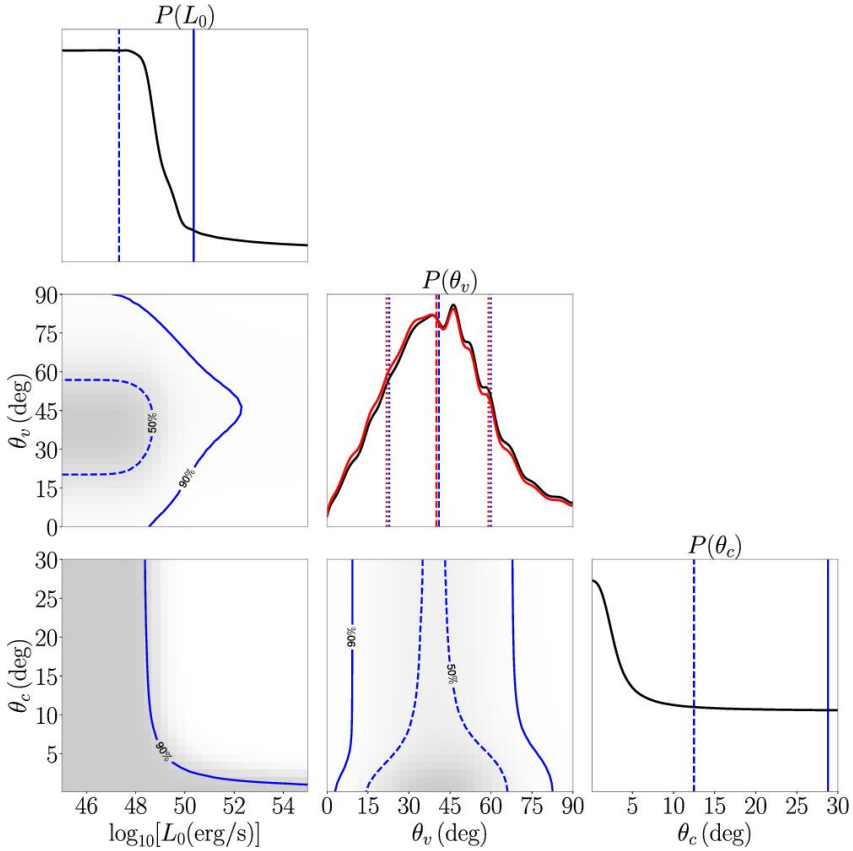
Recent Results - O3 Archival

- Ran NITRATES on all O3 GW events with GUANO data
- Found nothing significant
- Population limits set on prompt emission from BBH mergers
  - f = fraction of BBHs with emission
- Raman et al. 2024 https://arxiv.org/abs/2407.12867

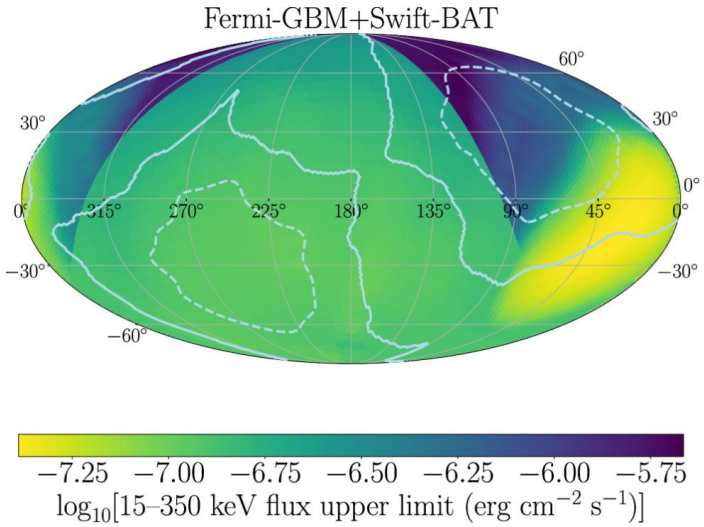


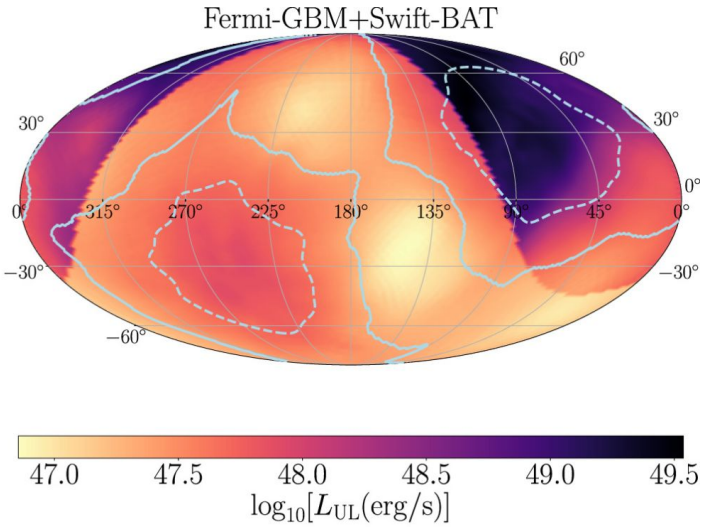
Recent Results - GW230529

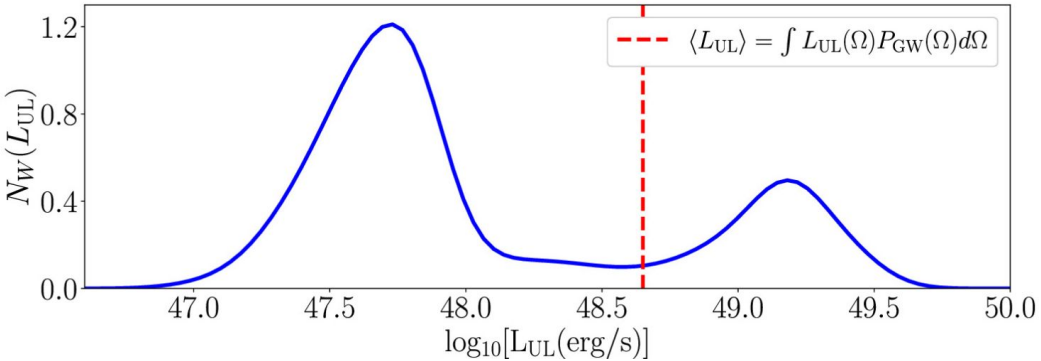
- Full sky upper limits set by Swift BAT and Fermi GBM for the likely NSBH merger GW230529 (large localization)
- Using GW inference results as priors, able to set limits on jet properties
- [Ronchini et al. 2024]



Gaussian Jet Profile


Fermi-GBM+Swift-BAT
60°
30°
0°
−30°
−60°
315°
270°
225°
180°
135°
90°
45°
−7.25 −7.00 −6.75 −6.50 −6.25 −6.00 −5.75
log10[15–350 keV flux upper limit (erg cm−2 s−1)]

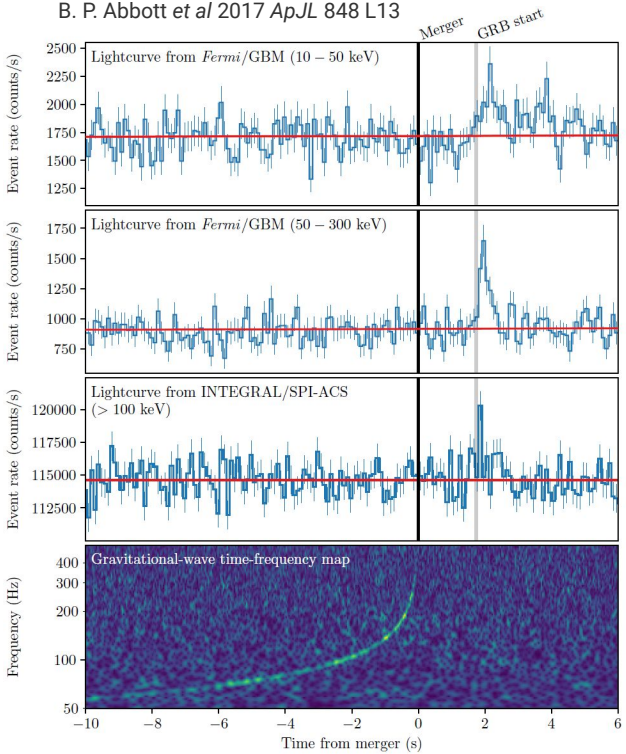

Fermi-GBM+Swift-BAT
60°
30°
0°
−30°
−60°
315°
270°
225°
180°
135°
90°
45°
47.0 47.5 48.0 48.5 49.0 49.5
log10[LUL(erg/s)]

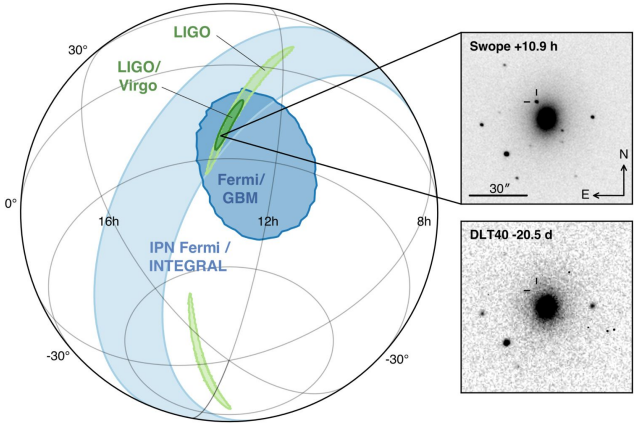

⟨LUL⟩ = ∫ LUL(Ω)PGW(Ω)dΩ
NW(LUL)
1.2
0.8
0.4
0.0
47.0 47.5 48.0 48.5 49.0 49.5 50.0
log10[LUL(erg/s)]

GRB/GW 170817

- First detection of GWs from a BNS merger
- 1.7 s later short GRB observed
- First high-energy multi-messenger detection
- Confirmation that BNS mergers are a short GRB progenitor

B. P. Abbott *et al* 2017 *ApJL* 848 L13



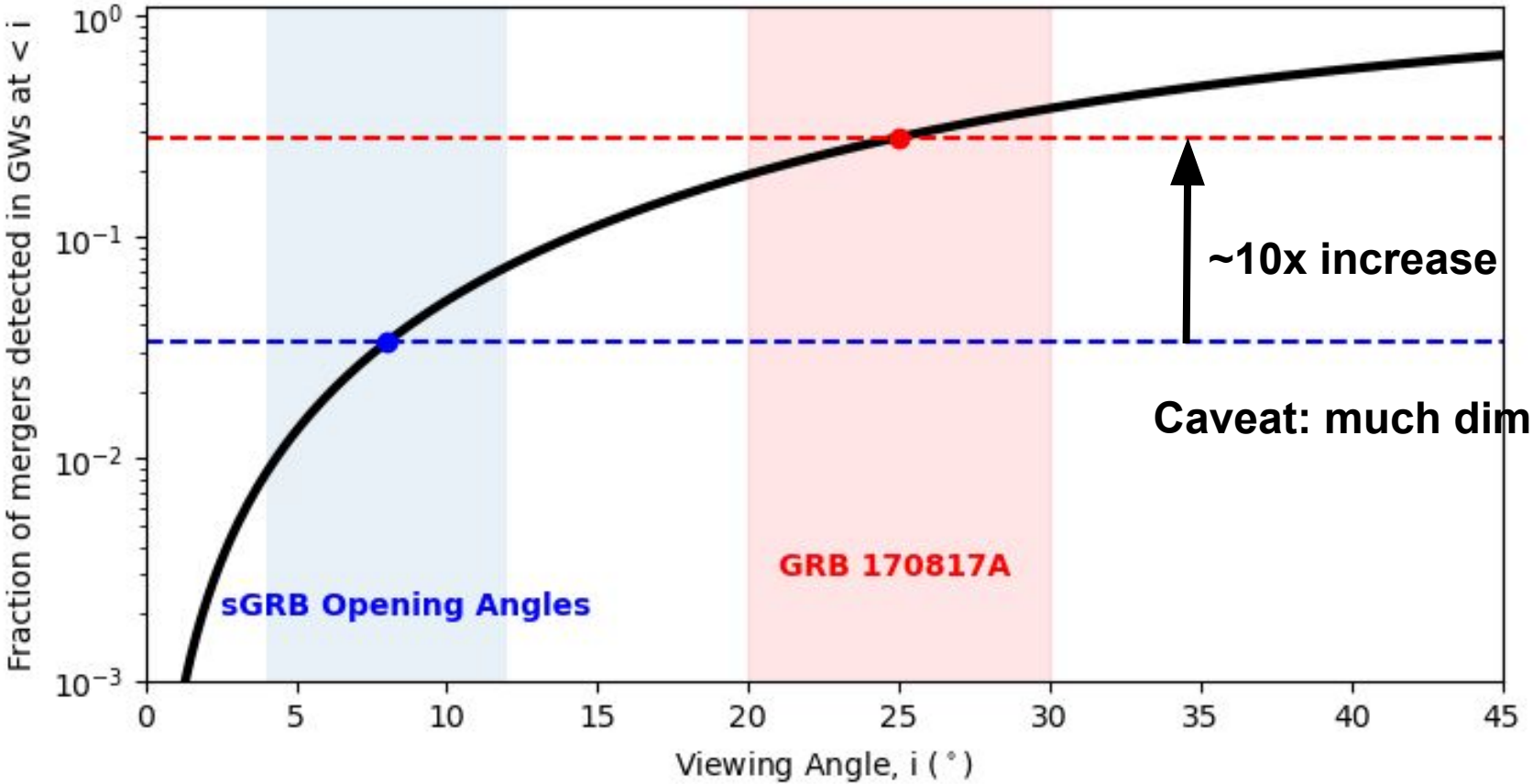


B. P. Abbott *et al* 2017 *ApJL* 848 L12

<11 hours post merger bright optical signal localized to NGC 4993, a galaxy ~40 Mpc away

Widespread scientific implications

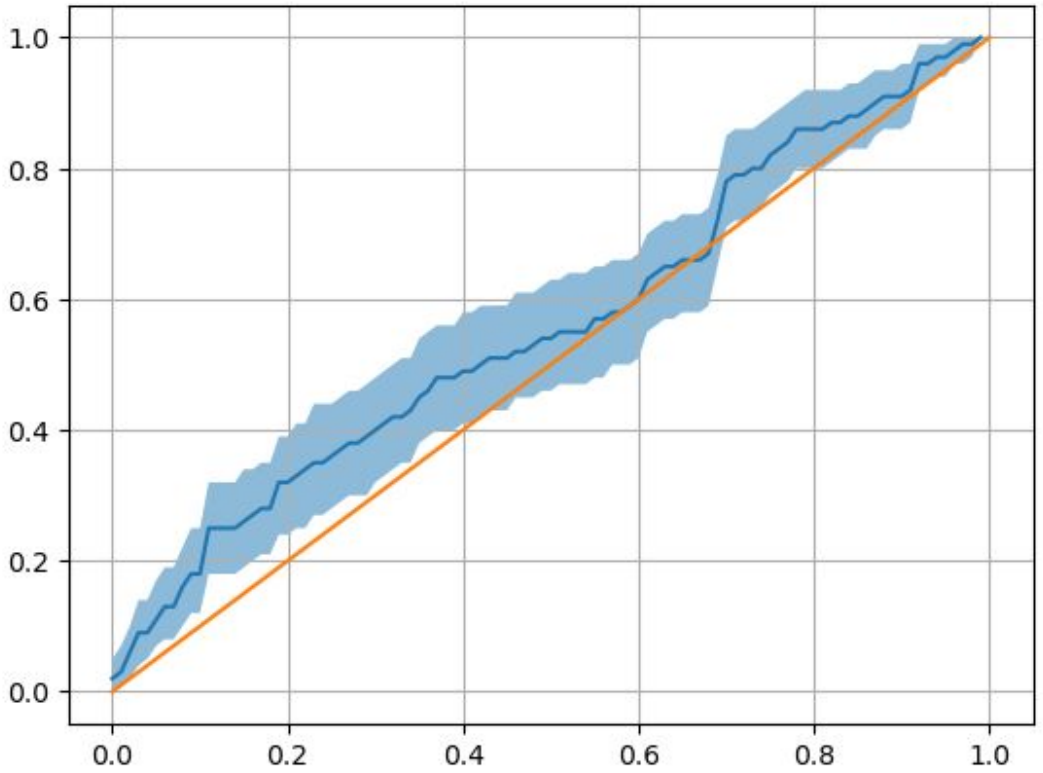
- Gold origin from r-process nucleosynthesis
- Measurement of speed of gravity
- Measurement of hubble constant …


Fraction of mergers detected in GWs at < i
10^0
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
35
40
45
Viewing Angle, i (°)
sGRB Opening Angles
GRB 170817A
~10x increase
Caveat: much dimmer

P-P plot of NITRATES skymaps

In order to sample the prior space, a random position is drawn in instrument coordinates then the closest GRB is chosen and a random time bin of that GRB.
This is done 100 times, a P-P plot is made, then this is repeated 1000 times.
The median of the 1000 trials is plotted and the error band contains 90% of the trials

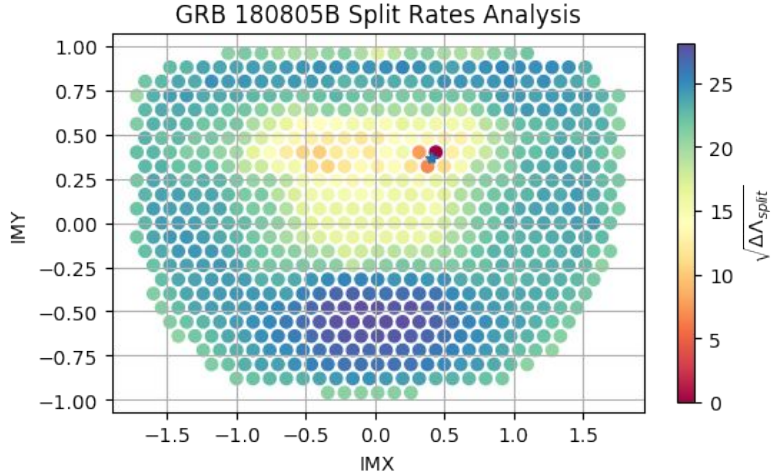
~250 skymaps from ~30 GRBs used here

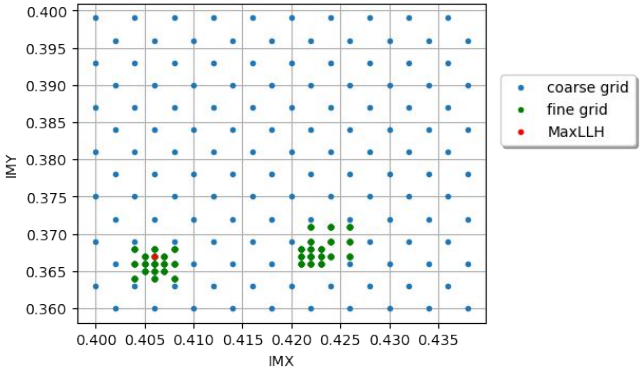


Computational Expense

Very large Parameter space

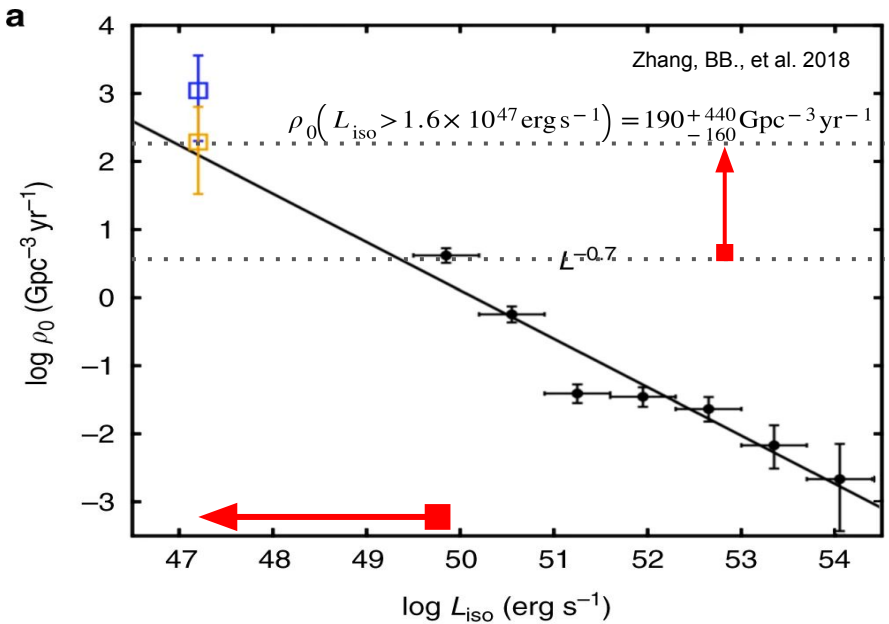
- Inside coded FoV, position point spacing needs to be < PSF size
  - PSF ≈ ⅓ deg, FoV ≈ 7,000 deg^2
- Seeding analyses and recursive grid search
- ~200 core-hours per analysis
- Runs on 2 clusters
  - PSU roar
  - NASA NCCS





GRB 170817A

- Closest measured SGRB distance
- Measured fluence just under the median for GBM SGRBs
- By far the lowest measured L_{iso}
- Possible population of low-luminosity SGRBs



Two Component Emission

Main Hard Peak

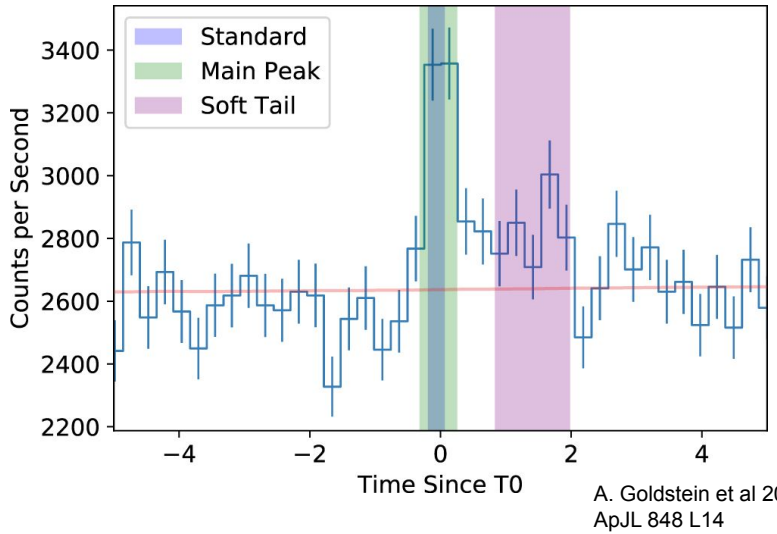
Normal sGRB emission

E_{peak} = 185 keV

Soft Tail

Best fit by thermal spectrum

kT = 10.3 keV



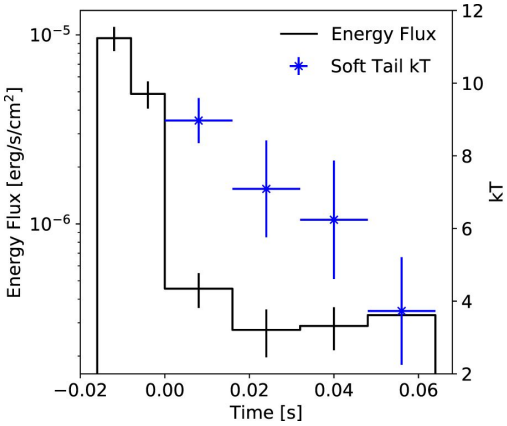
A. Goldstein et al 2017
ApJL 848 L14

Main peak fluence larger than soft tail by a factor of ~3

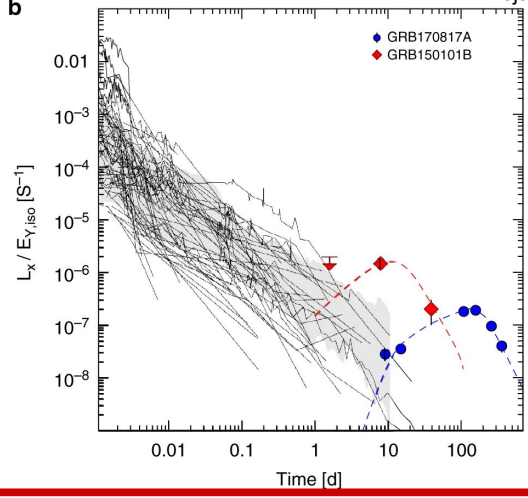
A Second Low-Luminosity SGRB

GRB 150101B has several similarities to GRB 170817A
- Short hard spike followed by soft tail
- Bright optical transient
- Late rising X-ray afterglow

With some slight differences
- Further away, z = 0.134, D_L ~ 650 Mpc
- $L_{iso} \gtrsim$ 2 orders of magnitude larger
- Shorter, T_{90} ~ 0.08 s



Burns et al. 2018



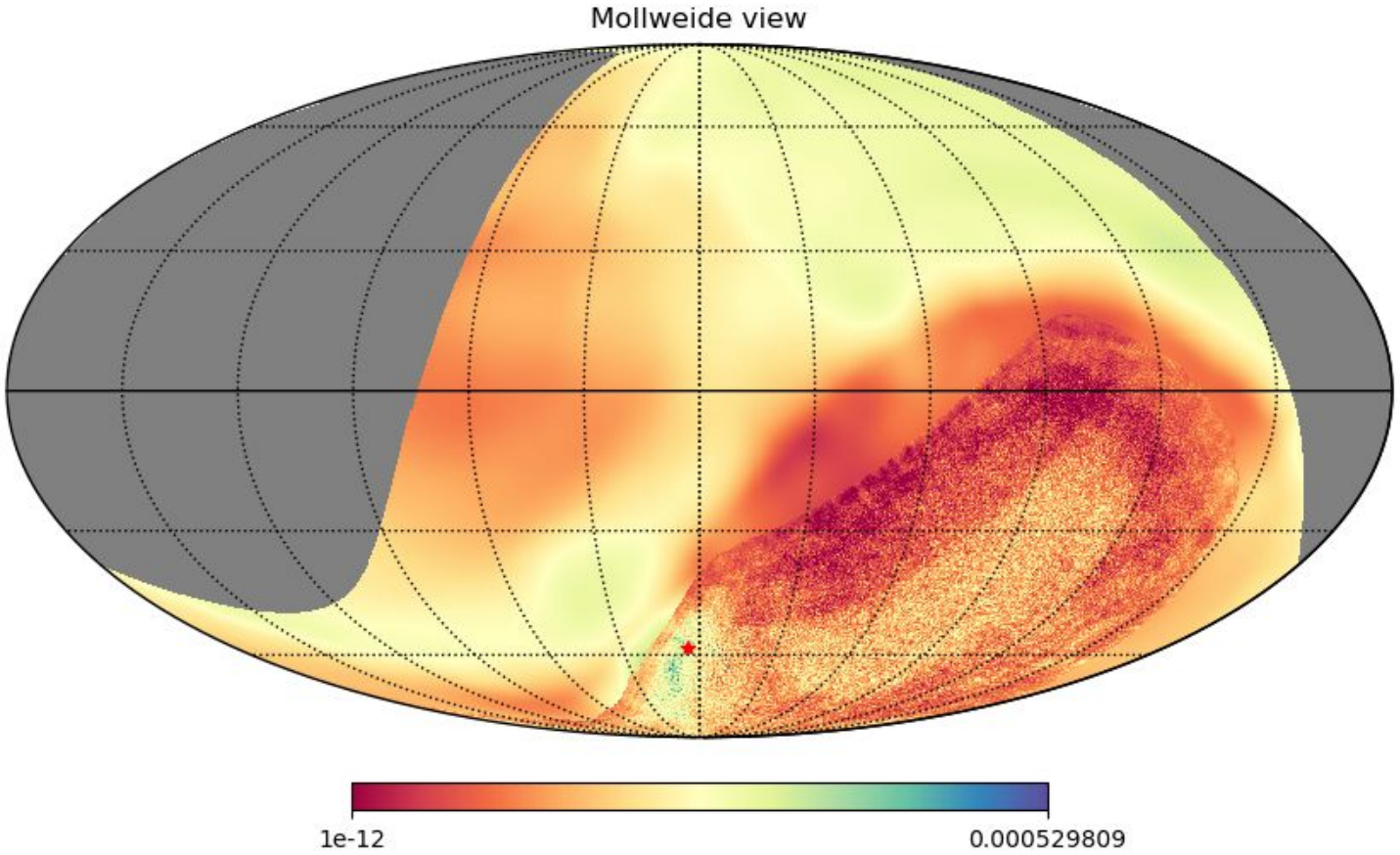
Troja et al. 2018

A structured jet model with a Gaussian profile was fit to the X-ray afterglow (Troja et al. 2018)
- Consistent with a typical SGRB jet pointed elsewhere
- Gaussian jet width ~ 3°
- Viewing angle ~ 13°

Being less off-axis may explain the differences

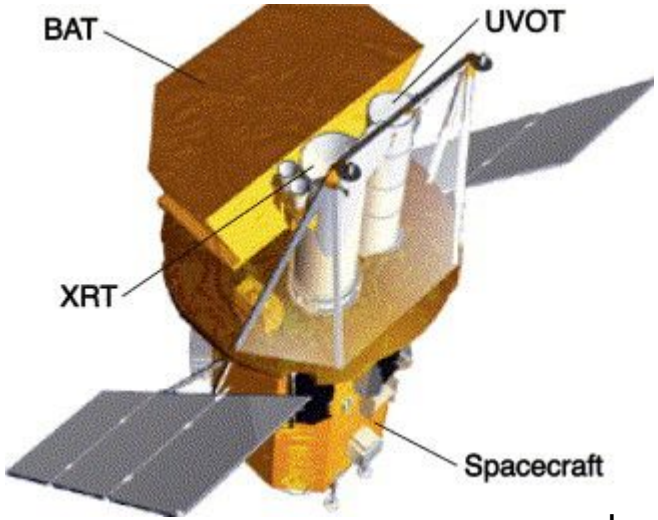
Prompt emission mechanism still not clear, but there is an emerging population → Need more sensitive searches

GRB 230815A



The Neil Gehrels Swift Observatory

- Designed to detect GRBs and observe the early afterglow
- Can re-point “swiftly”, ~ 1 minute
  - Previously hours



Gehrels 2004

Instruments

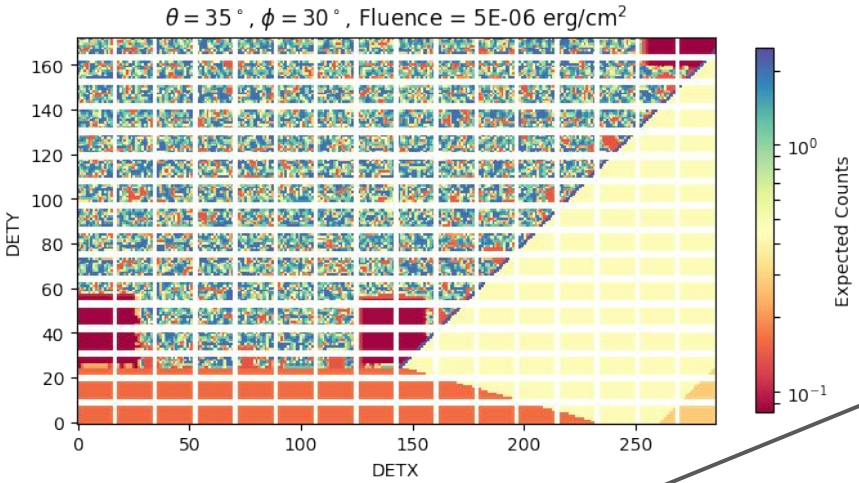
Burst Alert Telescope (BAT)
- Coded mask imager (15 - 150 keV)
  - Unmasked response up to 500 keV
- Detects and localizes GRBs (a few arcmins)
- Large FoV, ~ 2 st

X-Ray Telescope (XRT)
- 0.3 - 10 keV
- CCD spectroscopy
- Localizations of a few arcseconds

UV/Optical Telescope (UVOT)
- 170 - 650 nm
- Capable of sub-arcsecond localization

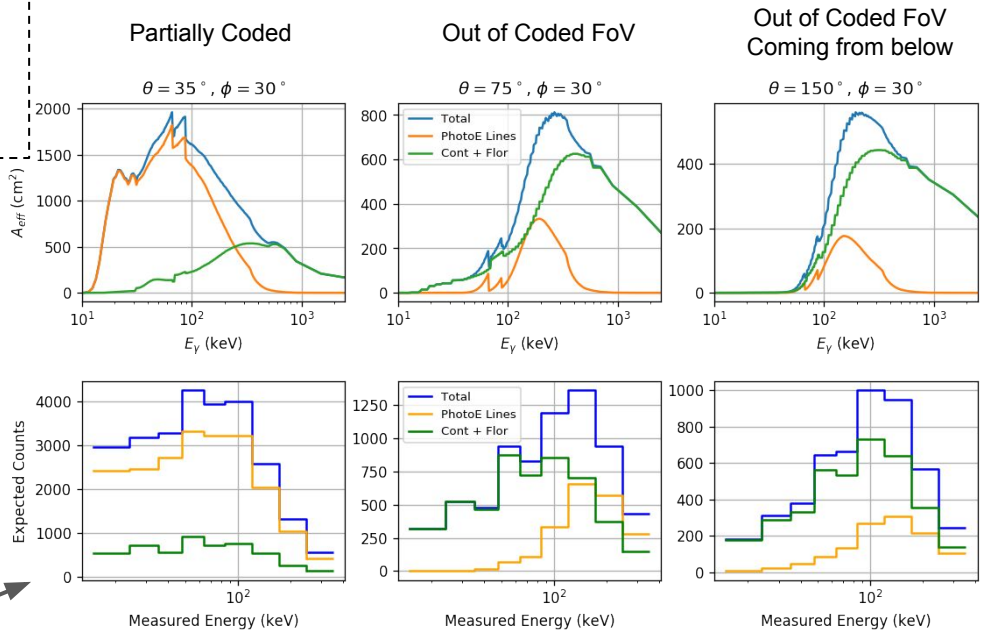
- Launched Nov. 2004
- >1000 GRBs detected
- Swift Mission Operations Center at Penn State

- $t_i(\theta, \phi, E_\gamma)$ is calculated on the fly, except for photon paths through the mask.
- Using the Swift software the fraction each detector is not blocked by the mask, f_i is calculated for a given source position.
- f_i calculated and stored for the entire coded FoV
  - Grid spacing ≈ ⅓ PSF size
  - $t_i(\theta, \phi, E_\gamma) = f_i + (1 - f_i)\, t_{pb}$



Same flux and position as

The total A_{eff} over all detectors and split between the direct and indirect components



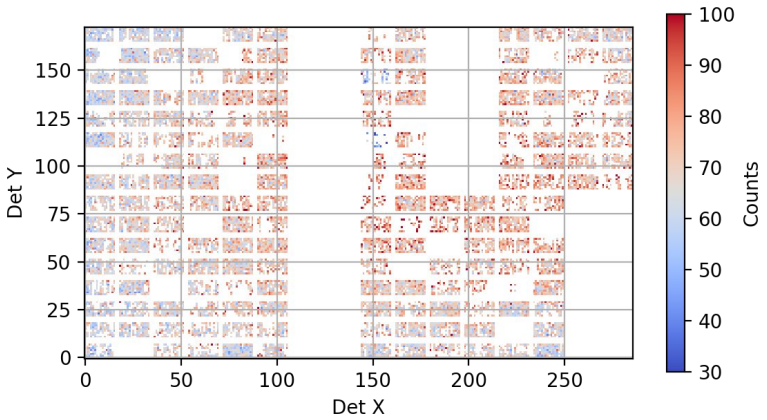
Expected counts from the PS model with a cutoff power-law spectra with γ = 0.5, E_{peak} = 350 keV, and a 10 keV - 1000 keV fluence of 5×10^{-6} erg cm^{-2} .

How BAT Works

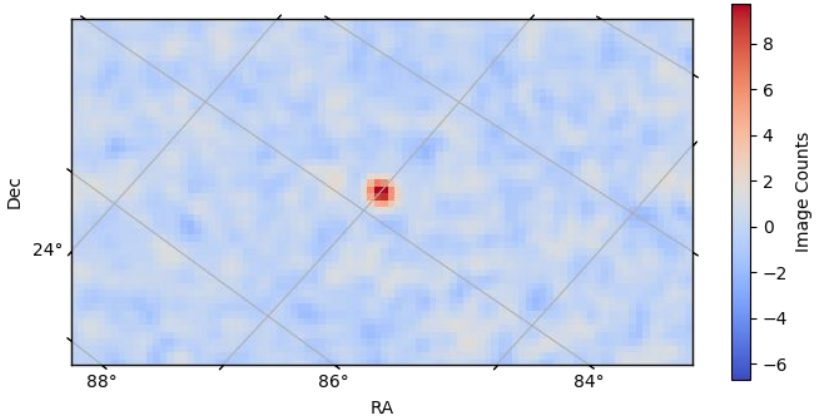
Cross-correlate with Mask Pattern

Crab in Detector Space

Detector Plane Image (DPI)



Crab in Sky Space



Mask-Weighted Counts
Gaussian noise centered around 0 where there's no source
Automatic Bkg subtraction

Zoomed in
Full FoV is ~2 sr

What if GRB 170817A were in the BAT coded FoV at 40 Mpc?

What if GRB 170817A were in the BAT coded FoV at 40 Mpc?

Onboard trigger and
arcmin-scale localization

XRT, UVOT observations and alert sent
to the world at < 1 minute

What if GRB 170817A were in the BAT coded FoV at 40 Mpc?

Onboard trigger and
arcmin-scale localization

XRT, UVOT observations and alert sent
to the world at < 1 minute

What if GRB 170817A were in the BAT coded FoV at 70 Mpc?

What if GRB 170817A were in the BAT coded FoV at 40 Mpc?

Onboard trigger and
arcmin-scale localization

XRT, UVOT observations and alert sent
to the world at < 1 minute

What if GRB 170817A were in the BAT coded FoV at 70 Mpc?

NITRATES ground trigger and arcmin-scale localization

Alert sent out to world at ~2-8 hours

XRT, UVOT observations at alert + ~1 hour

What if GRB 170817A were in the BAT coded FoV at 90 Mpc?

What if GRB 170817A were in the BAT coded FoV at 90 Mpc?

NITRATES ground trigger and messy skymap,
also skymap joined with GW skymap

Alert sent out to world at ~2-8 hours