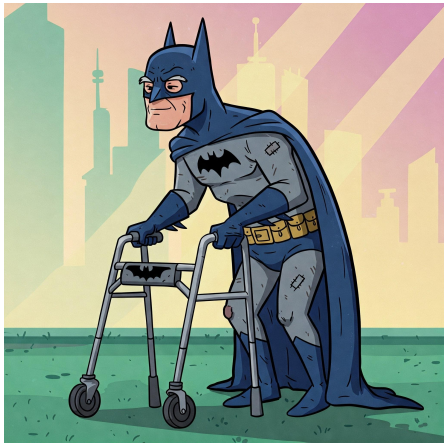
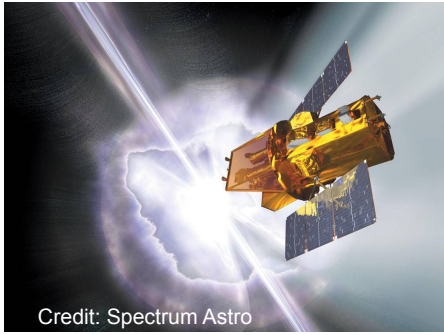
Teaching an old BAT new tricks: New analysis methods and results with Swift/BAT-GUANO





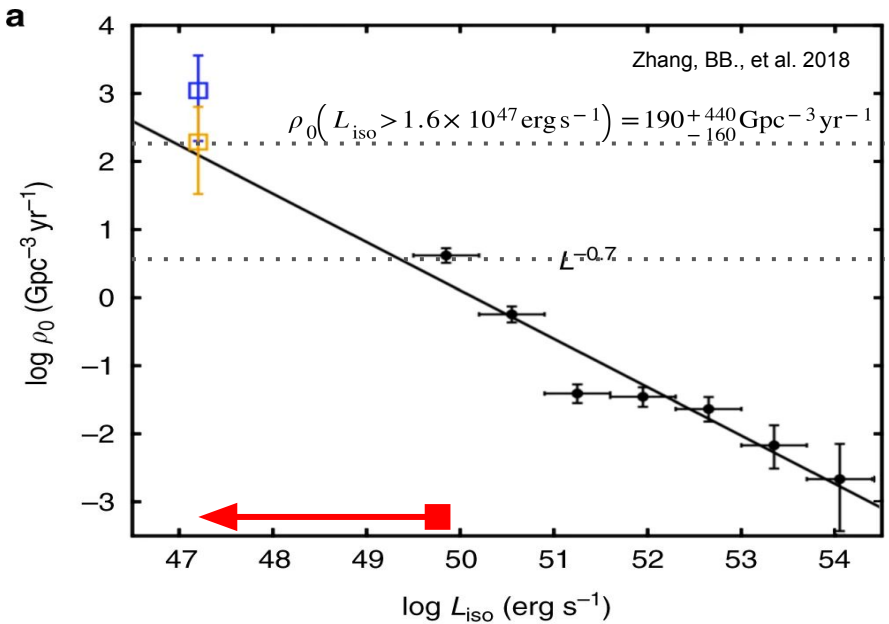
Jimmy DeLaunay
Penn State
jjd330@psu.edu

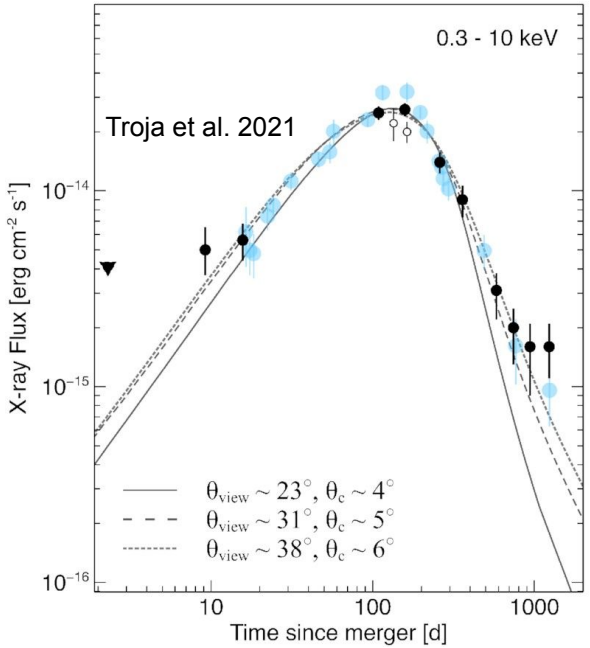
Swift BAT-Guano Team: Jamie Kennea (PSU), Tyler Parsotan (GSFC), Gayathri Raman (PSU), Samuele Ronchini (PSU), Aaron Tohuvavohu (Caltech)

Swift 20
Florence, Italy
March 25th 2025

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

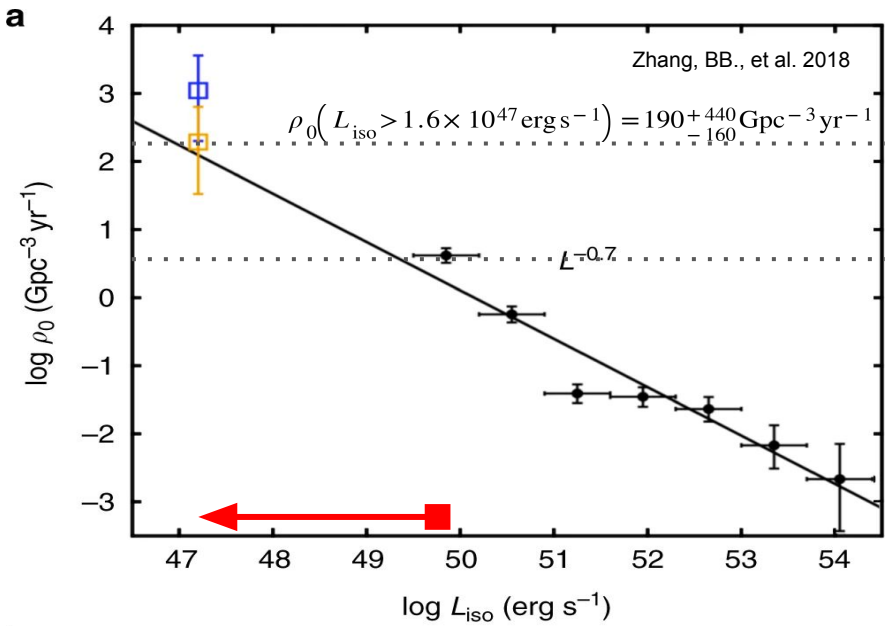


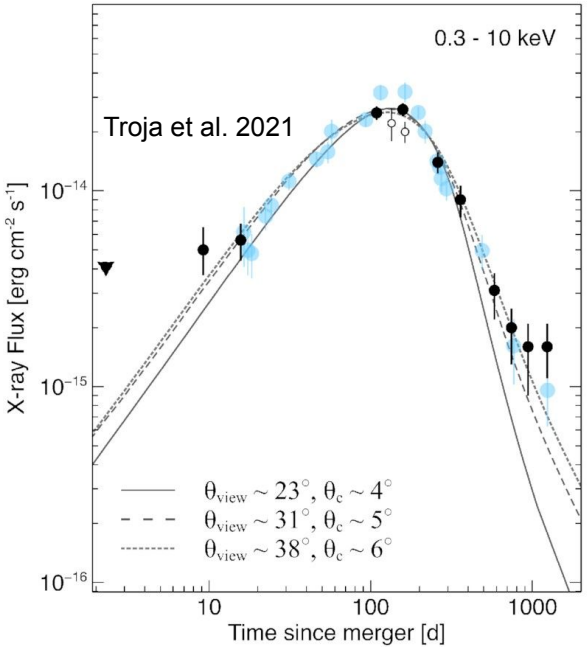


- Structured jet viewed off-axis gives best agreement with afterglow data
  - “Normal” jet pointed away from us
- Off-axis afterglow has characteristic initial, rising X-ray afterglow

GRB 170817A

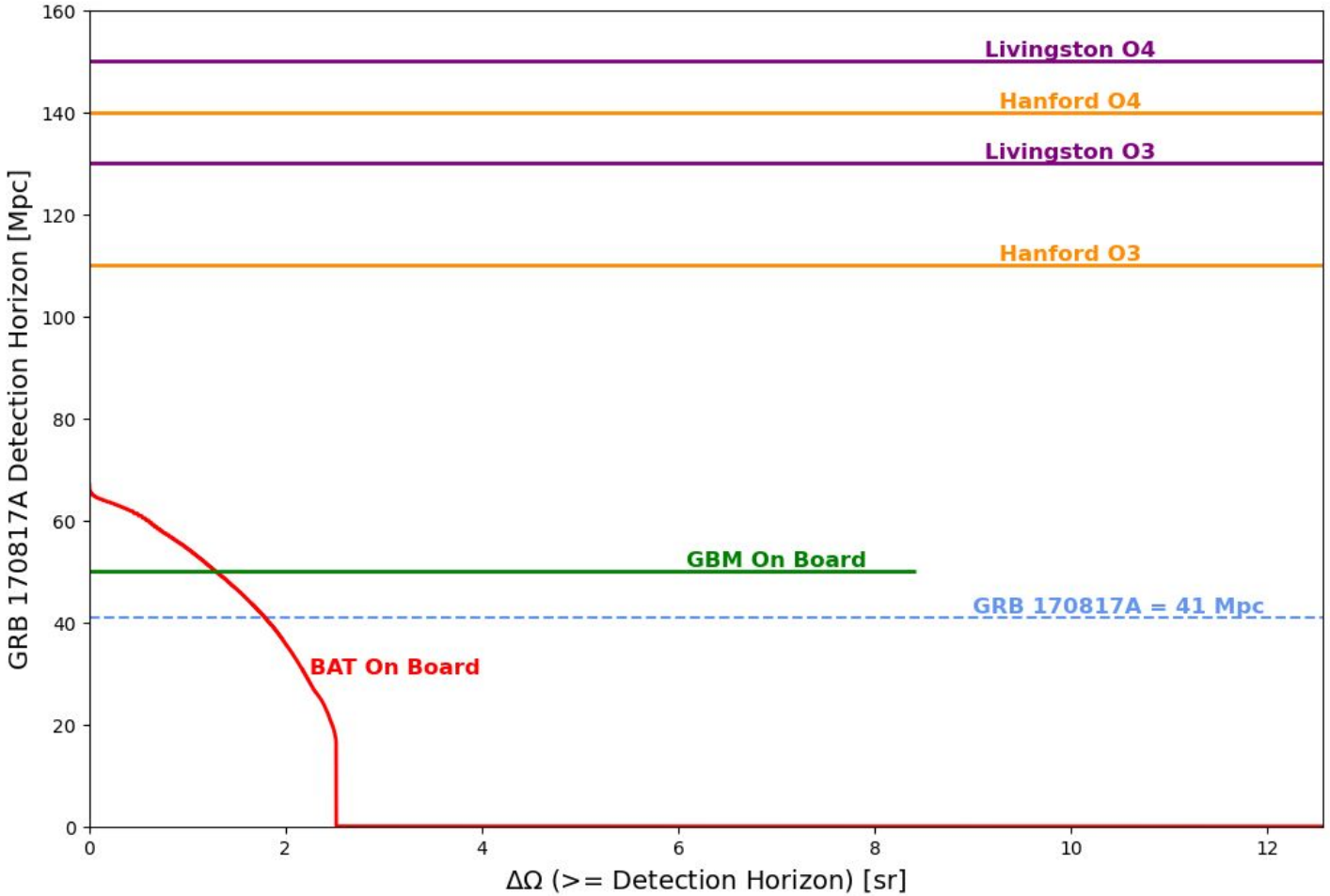
- Closest measured SGRB distance
- Measured fluence just under the median for GBM SGRBs
- By far the lowest measured L_{iso}
- Possible population of low-luminosity SGRBs

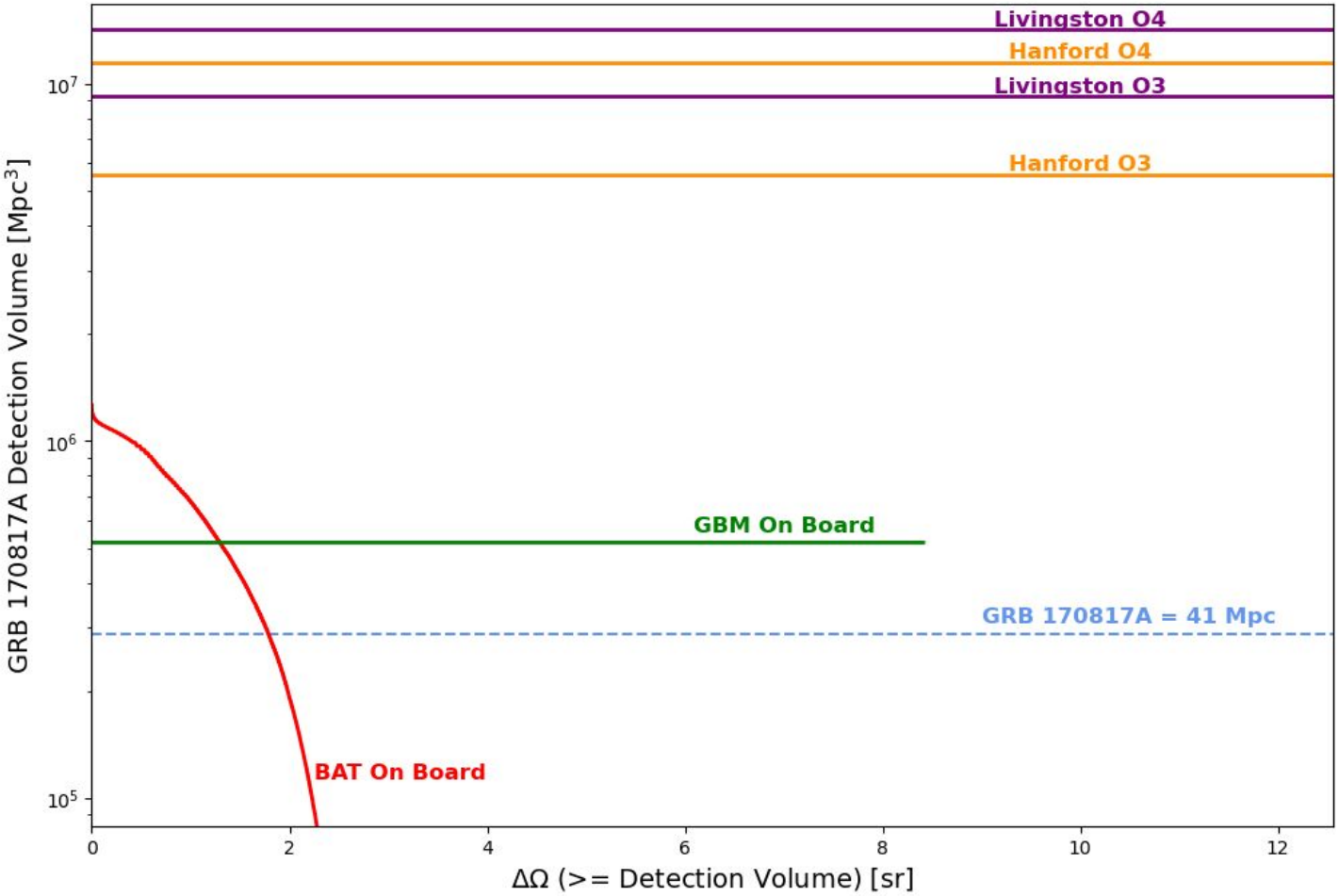




- Structured jet viewed off-axis gives best agreement with afterglow data
  - “Normal” jet pointed away from us
- Off-axis afterglow has characteristic initial, rising X-ray afterglow

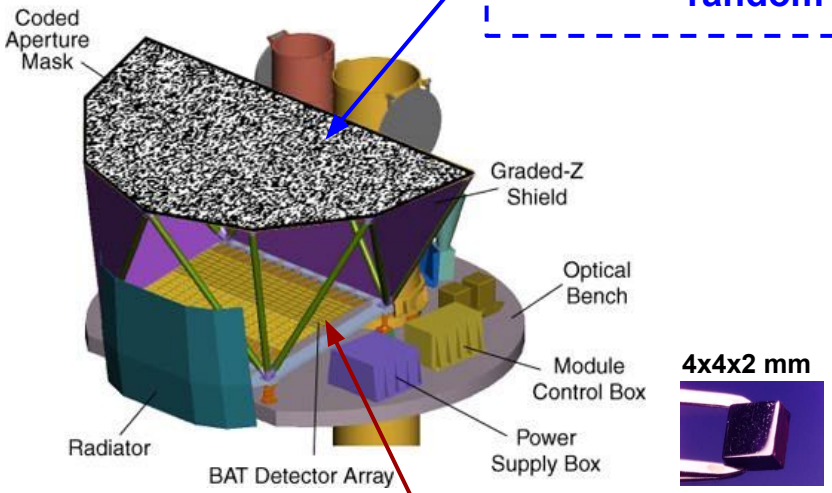
We can detect off-axis prompt emission!


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

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

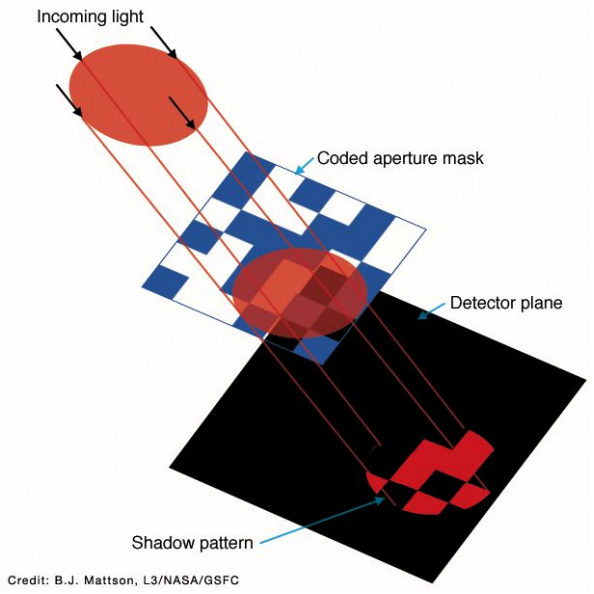
Aperture Mask is 50% open and consists of ~50,000 lead tiles in a random pattern



32,768 CZT Detectors in Array

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

Basic Concept

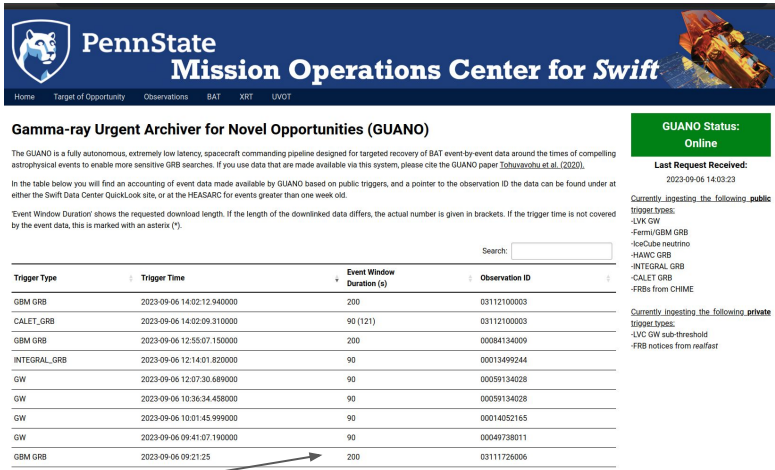


- Constructs images via a balanced cross-correlation technique
- Creates an image on board whenever there's a rate excess
- Localizes sources to a few arcminutes

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
  - Jimmy DeLaunay - jjd330@psu.edu



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

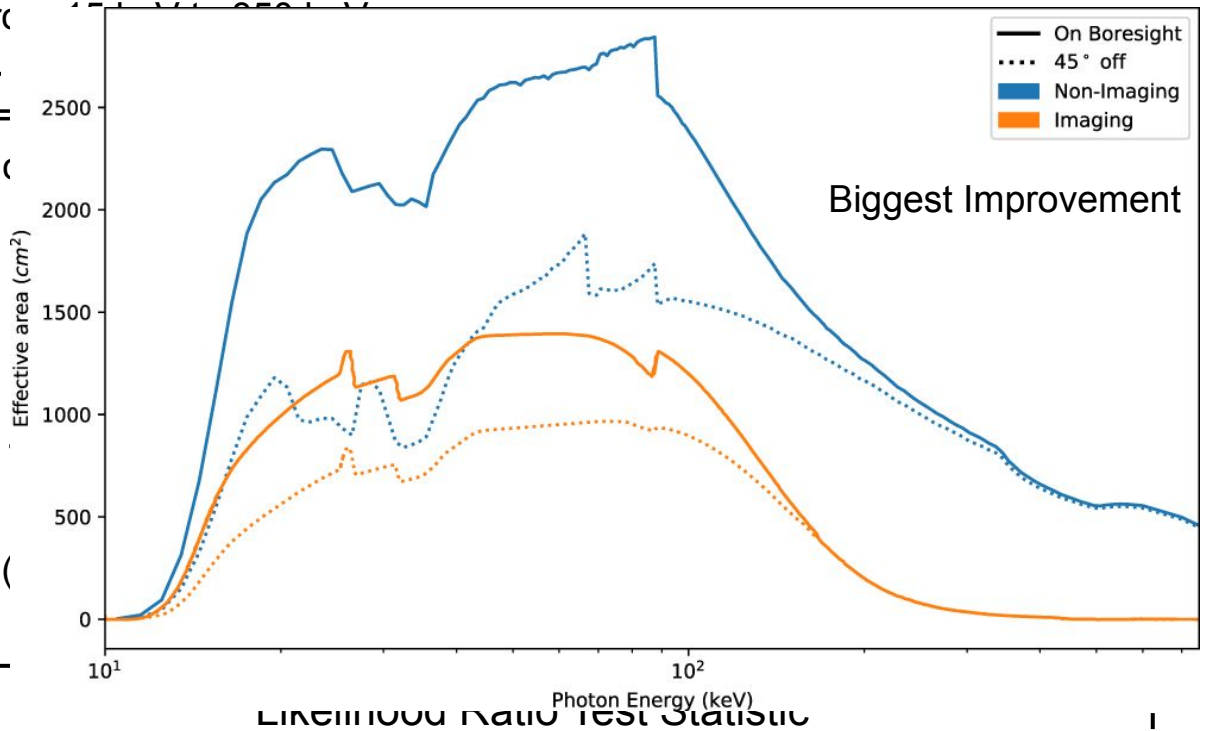
DeLaunay & Tohuvavohu 2022

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



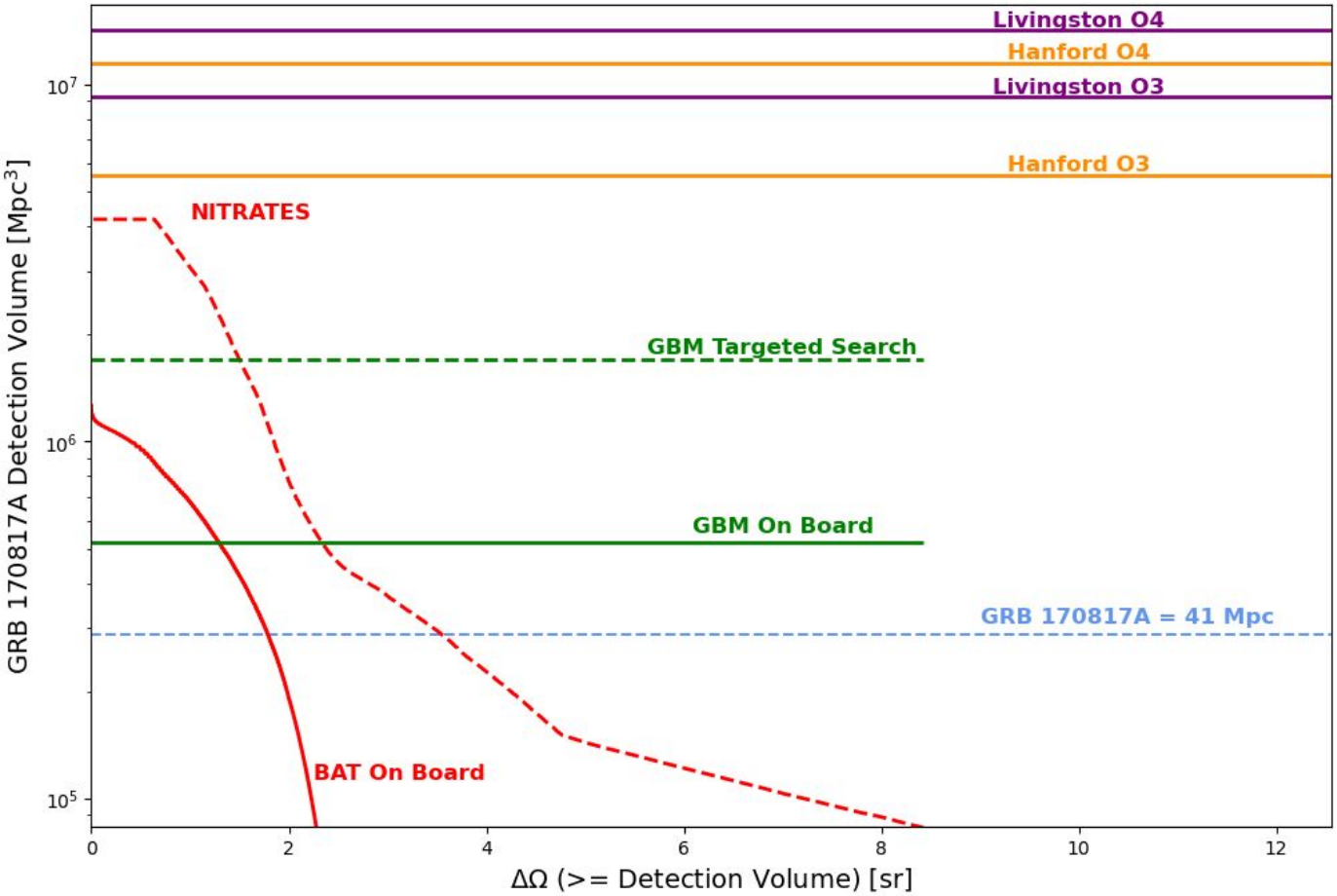
Count sources to model:
Diffuse: Cosmic x-ray background (
Point Sources: Known steady(ish)

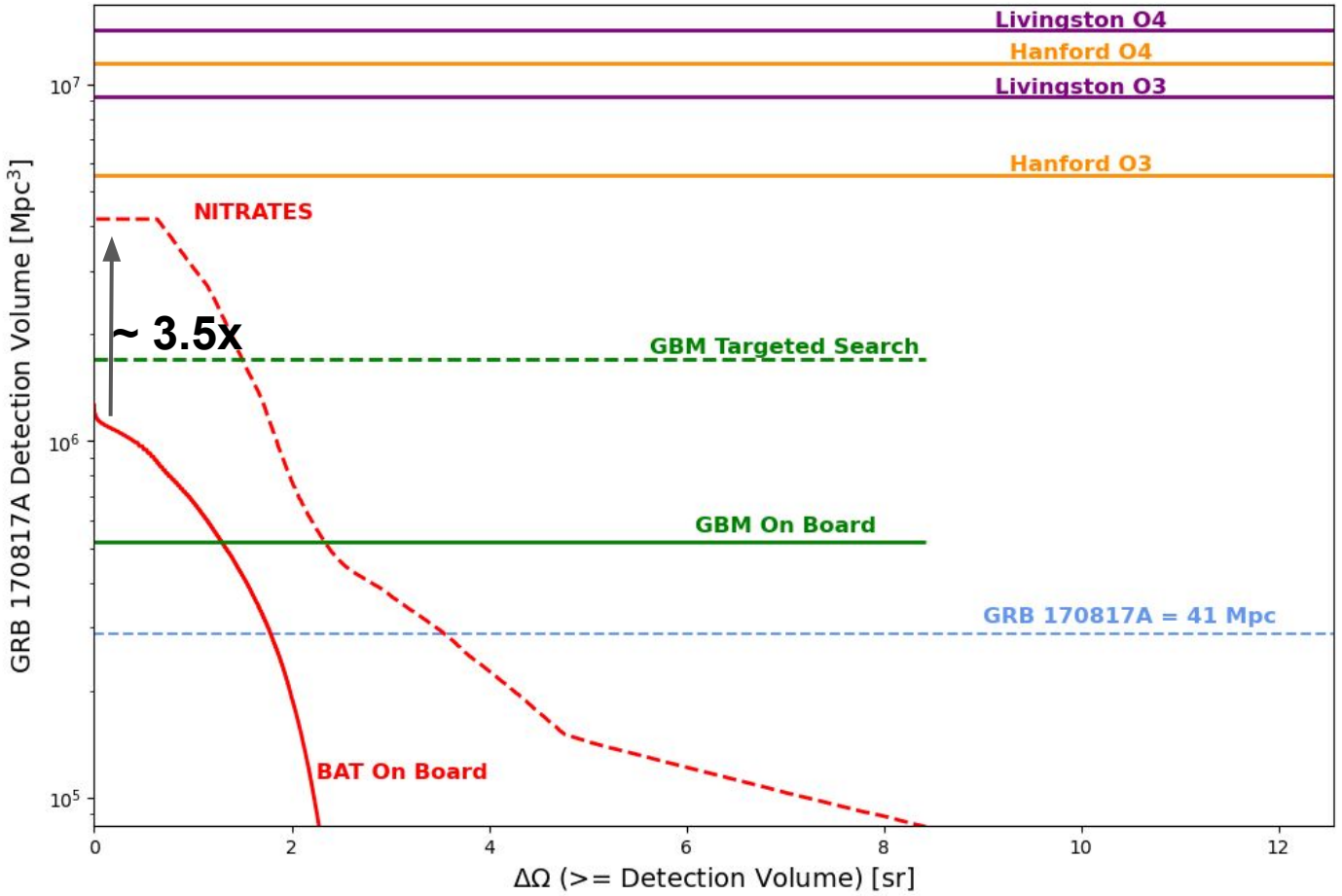
GRB Search

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
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

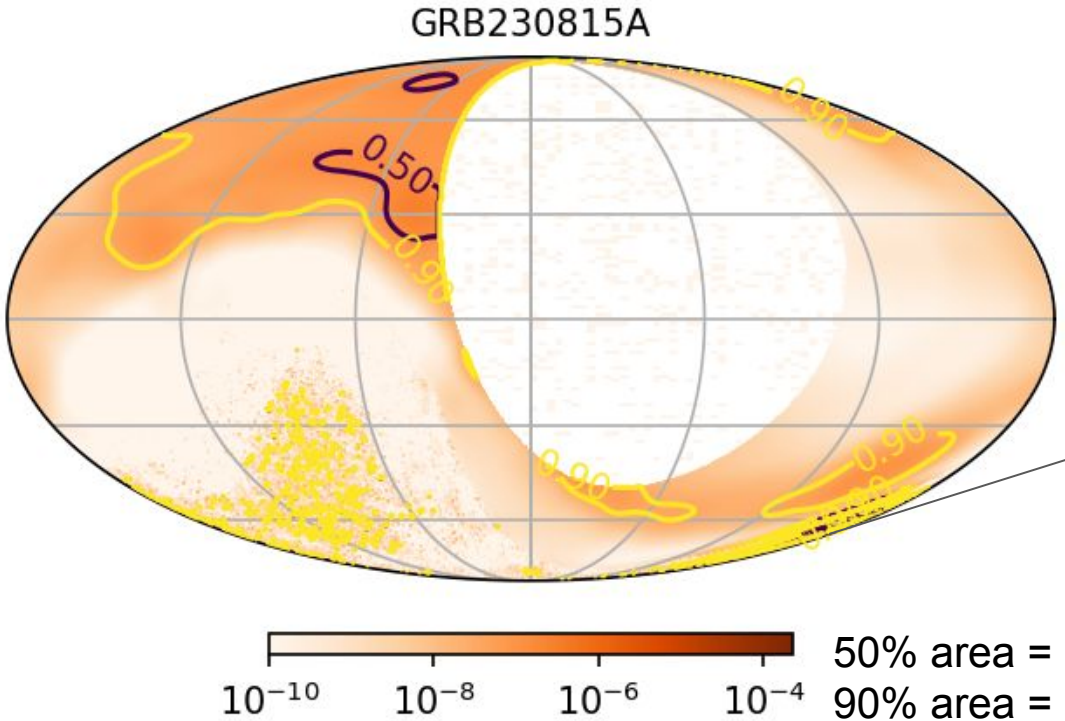
Localization

Best case scenario - ~3 arcminute circle

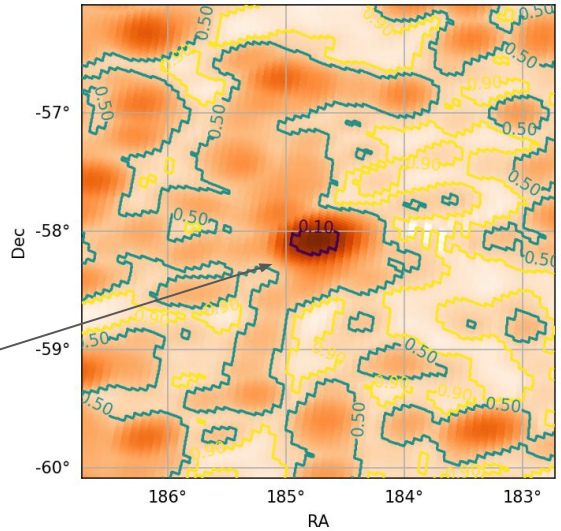
Localization

Best case scenario - ~3 arcminute circle

Worst case scenario -



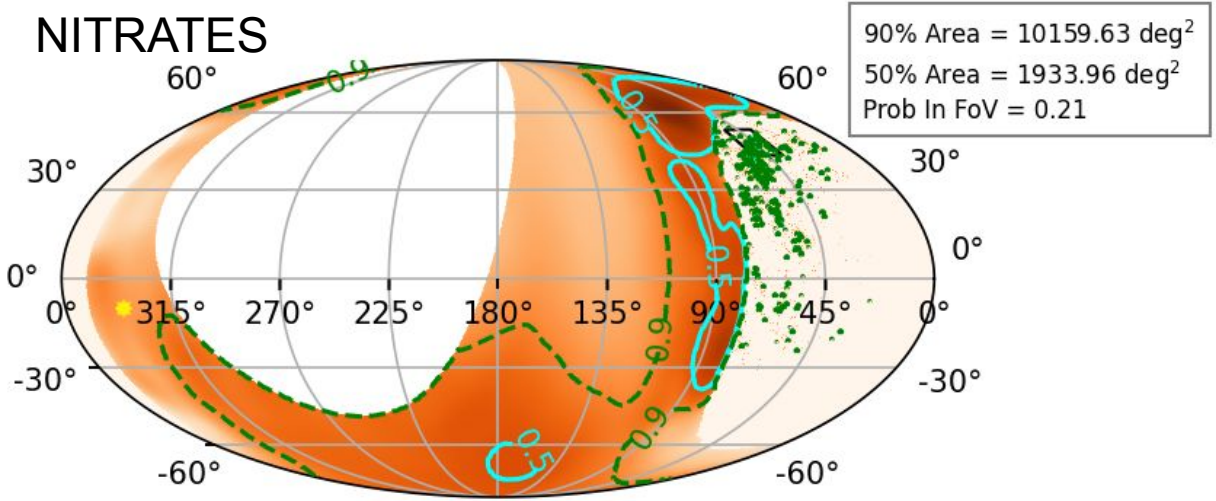
Zoom in on GRB/max LLH position



50% area = 600 deg^2
90% area = 5,700 deg^2

FWHM ~ ⅓ deg

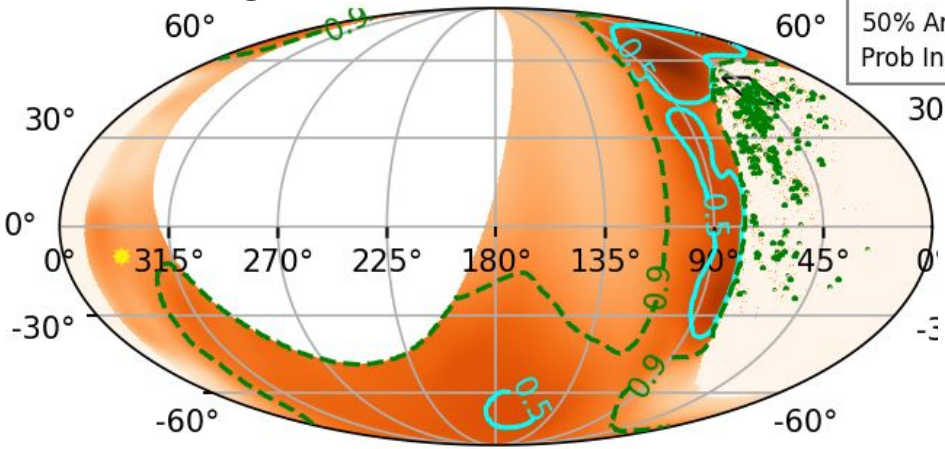
NITRATES



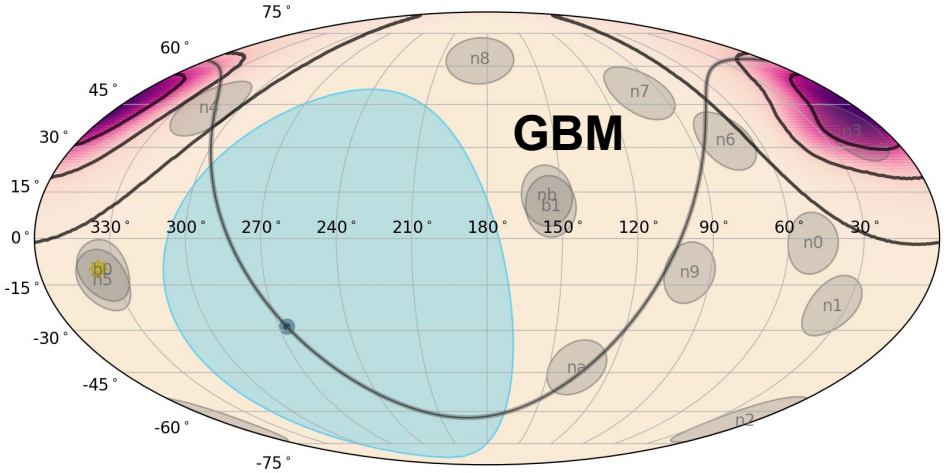
Short GRB 250223B

Short GRB 250223B

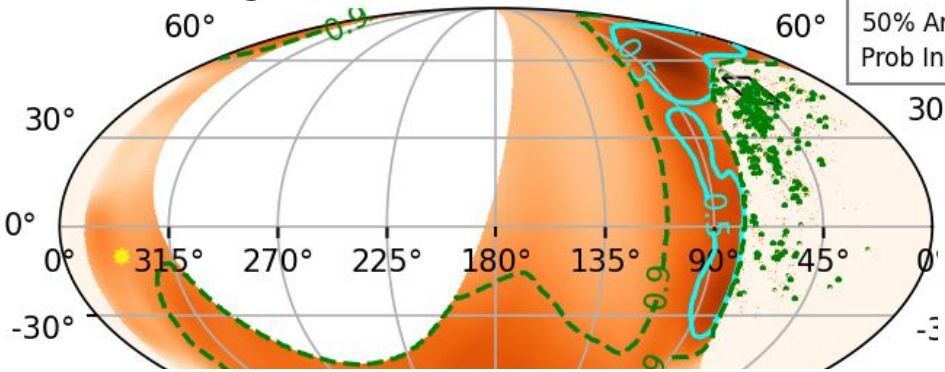
NITRATES



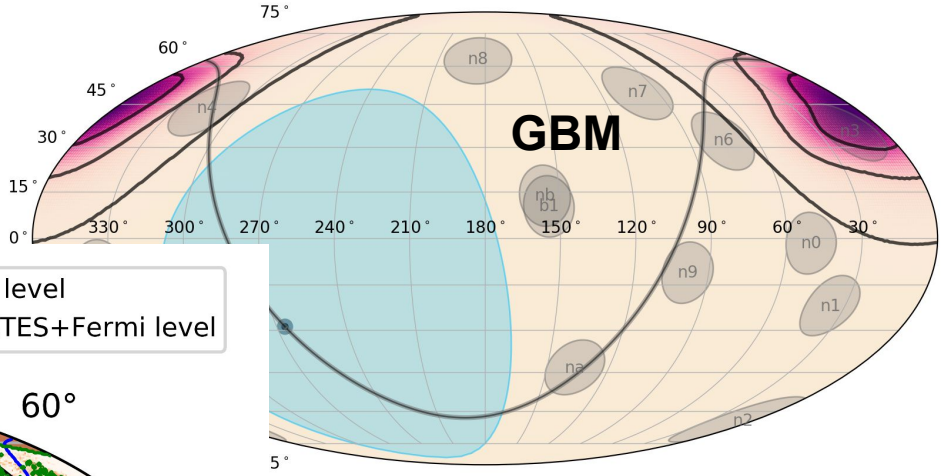
GBM

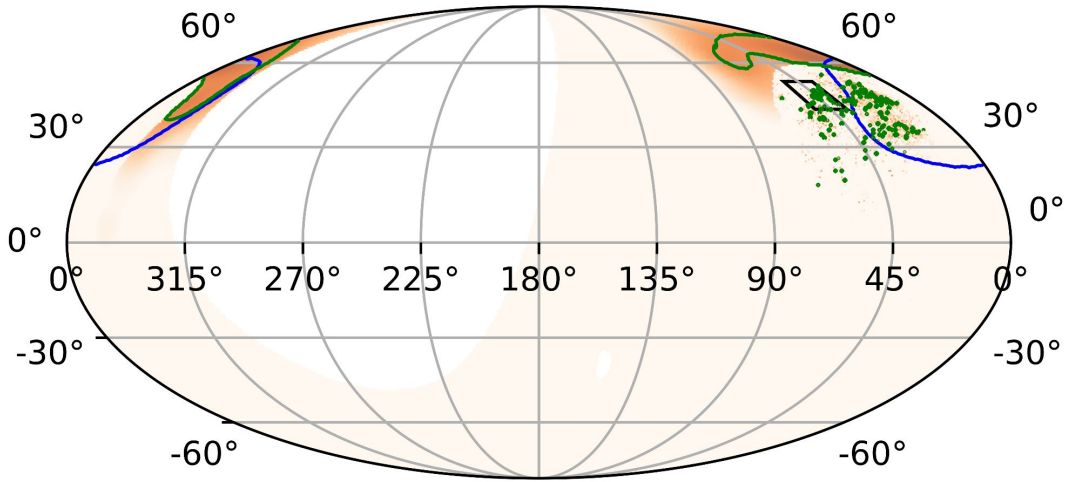


NITRATES



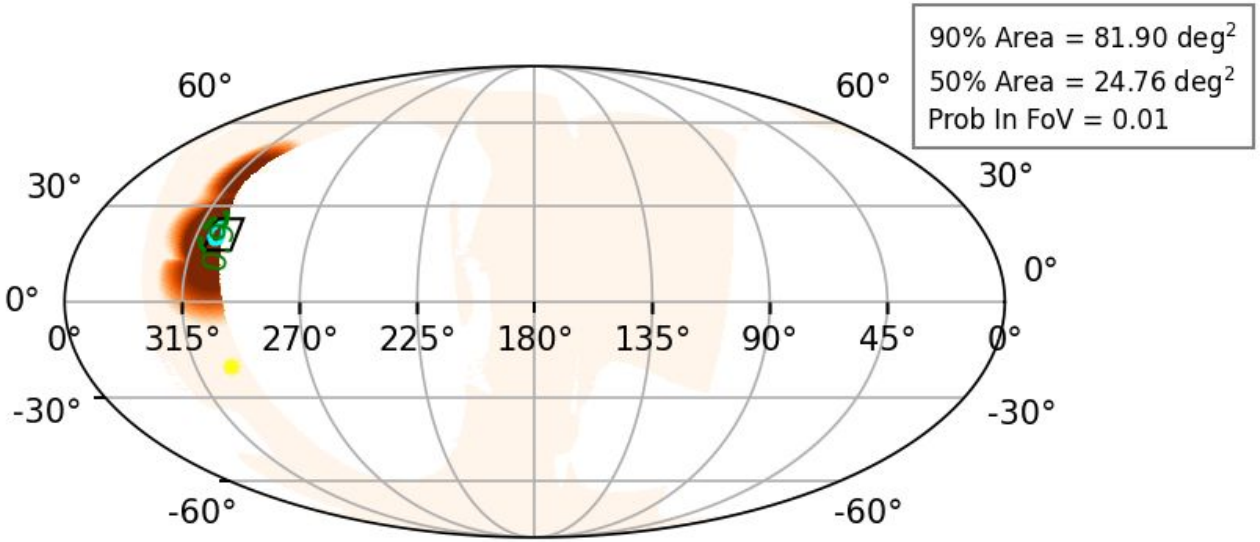
Short GRB 250223B



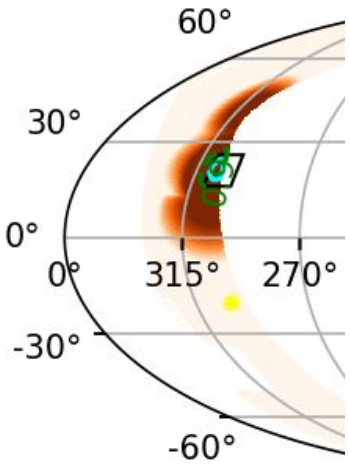


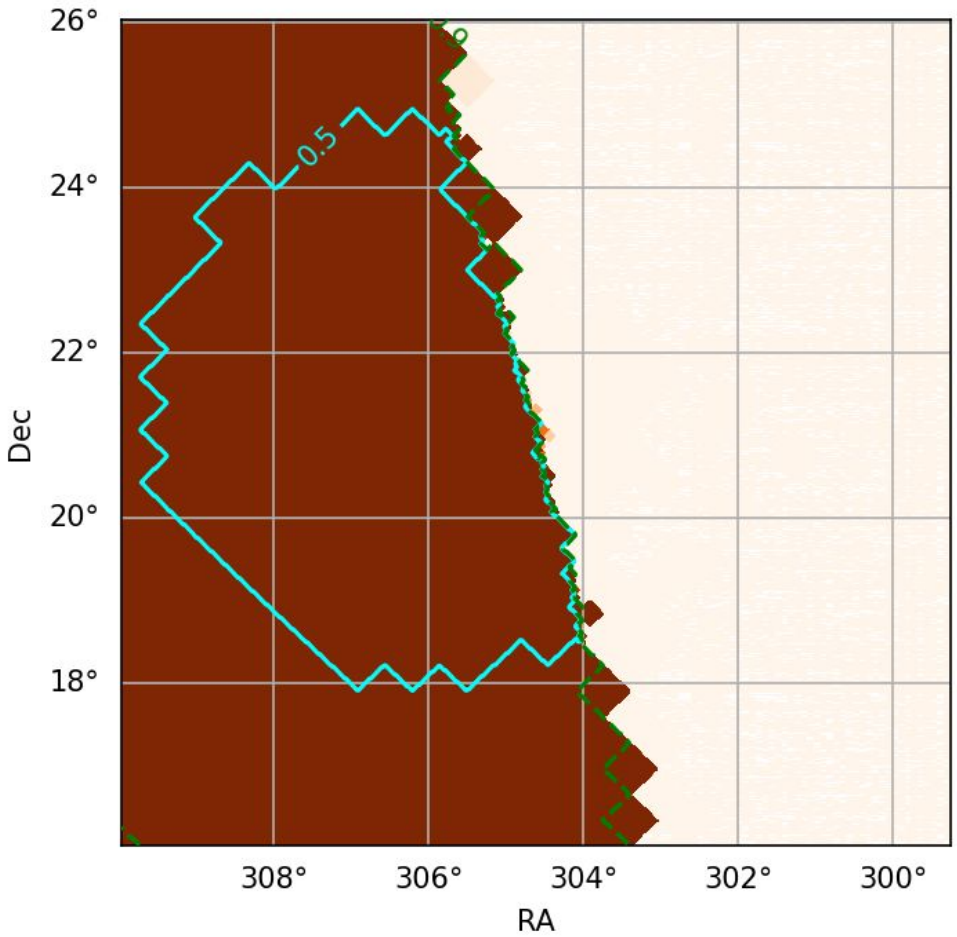
>50% of probability distributed across small “islands”

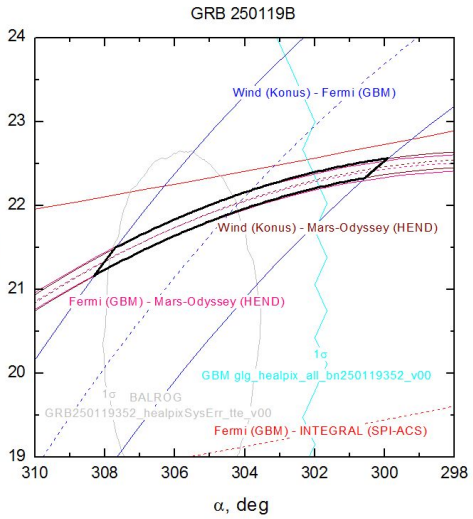
Best Case Outside of Coded Field of View - GRB 250119B



Best Case Outside of Coded Field of View - GRB 250119B

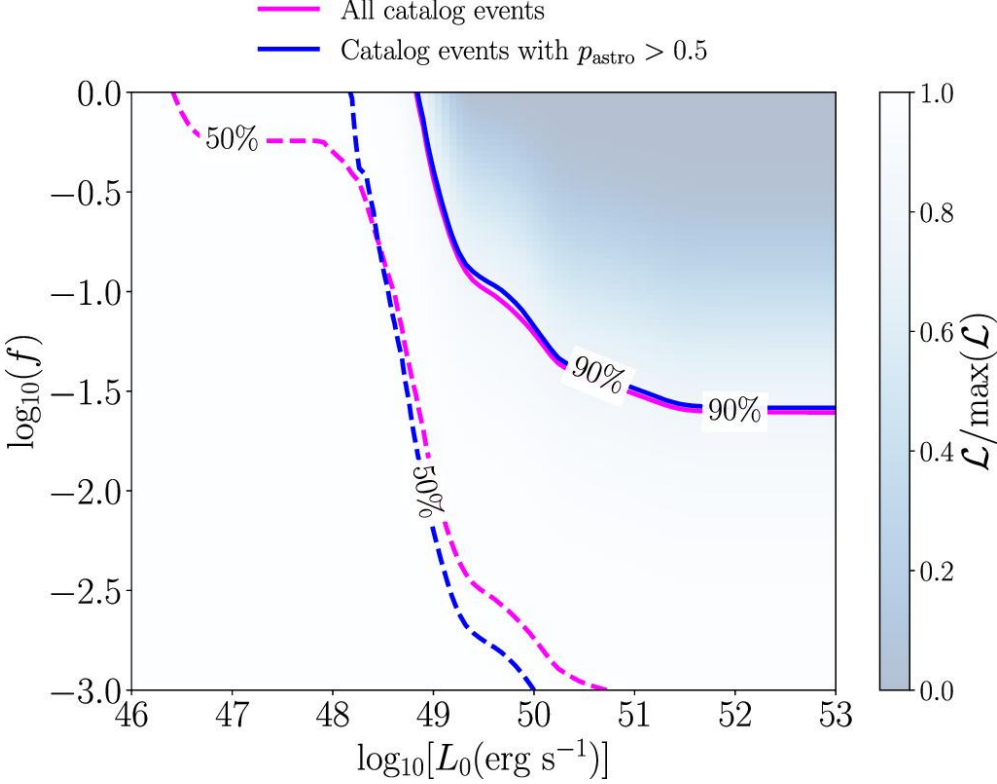






GUANO+NITRATES Results

- Increased the rate of arcminute localized short GRBs by BAT by ~50%!
  - First sGRB mm afterglow GRB 211106A
  - Laskar et al 2022
- O3 GW-GRB archival search
  - Population limits set on prompt GRB emission from BBH mergers
  - Raman et al. 2025
- NITRATES+GBM upper limits for NSBH GW230529 used to constrain jet geometry of possible GRB
  - Ronchini et al. 2024

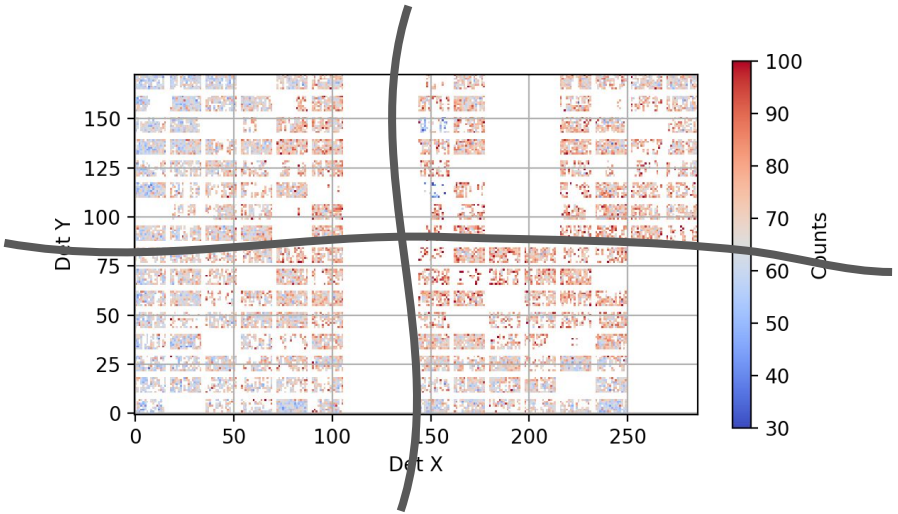


Raman et al. 2025

See **Samuele Ronchini's** talk tomorrow morning for more about Swift's GW efforts!

What if there’s no event data?

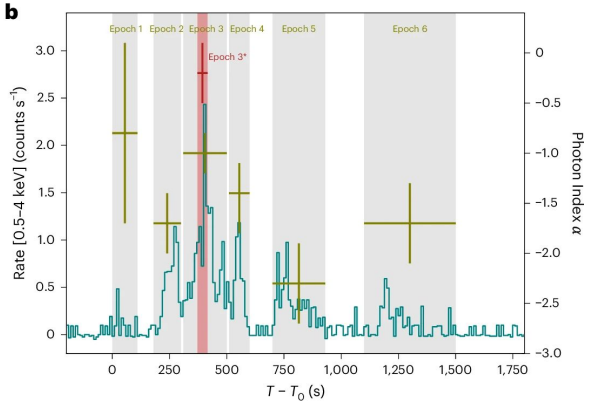
- GUANO relies on an external trigger, what if there was none (or it was too late)
- Continuous rates data for each quadrant of detector array
- Can apply the NITRATES analysis
  - 4 big detectors instead of 32k
- Can get a coarse localization



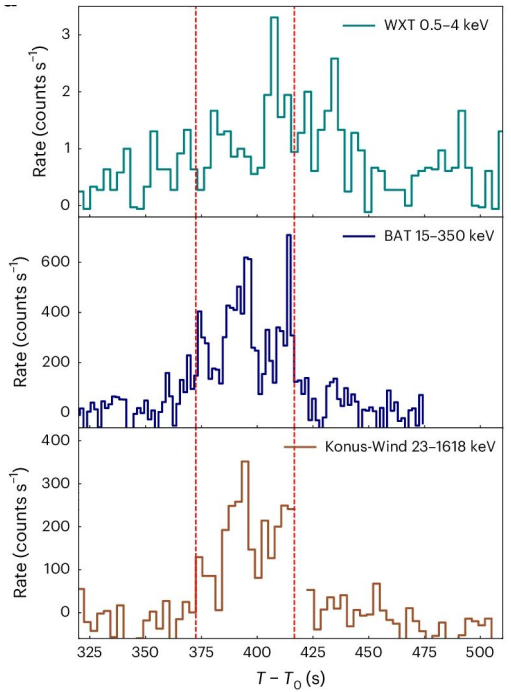
EP240315a - a high-z GRB with early soft X-rays

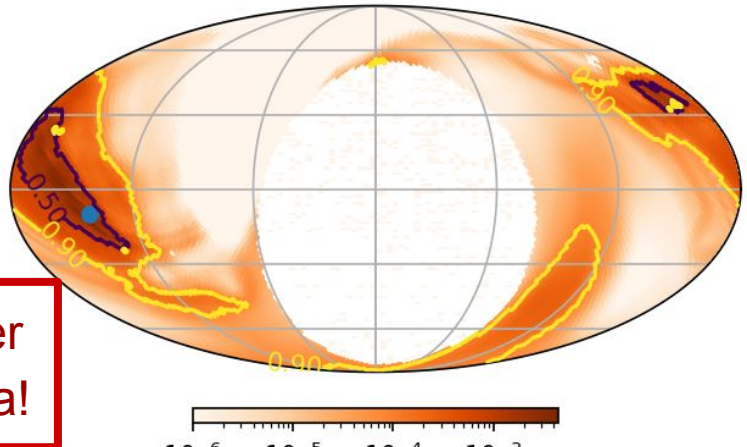
Used this “quad-rates” analysis to

- Localize GRB 240315C
  - confirmed same origin as EP240315a
- Perform joint spectral fit with EP and Konus
- Set gamma-ray upper limits during other epochs



Liu, Y et. al. 2025





50% area = 1,060 deg2
90% area = 6,400 deg2

See **Yuan Liu’s** talk earlier today for more EP240315a!

Looking forward!

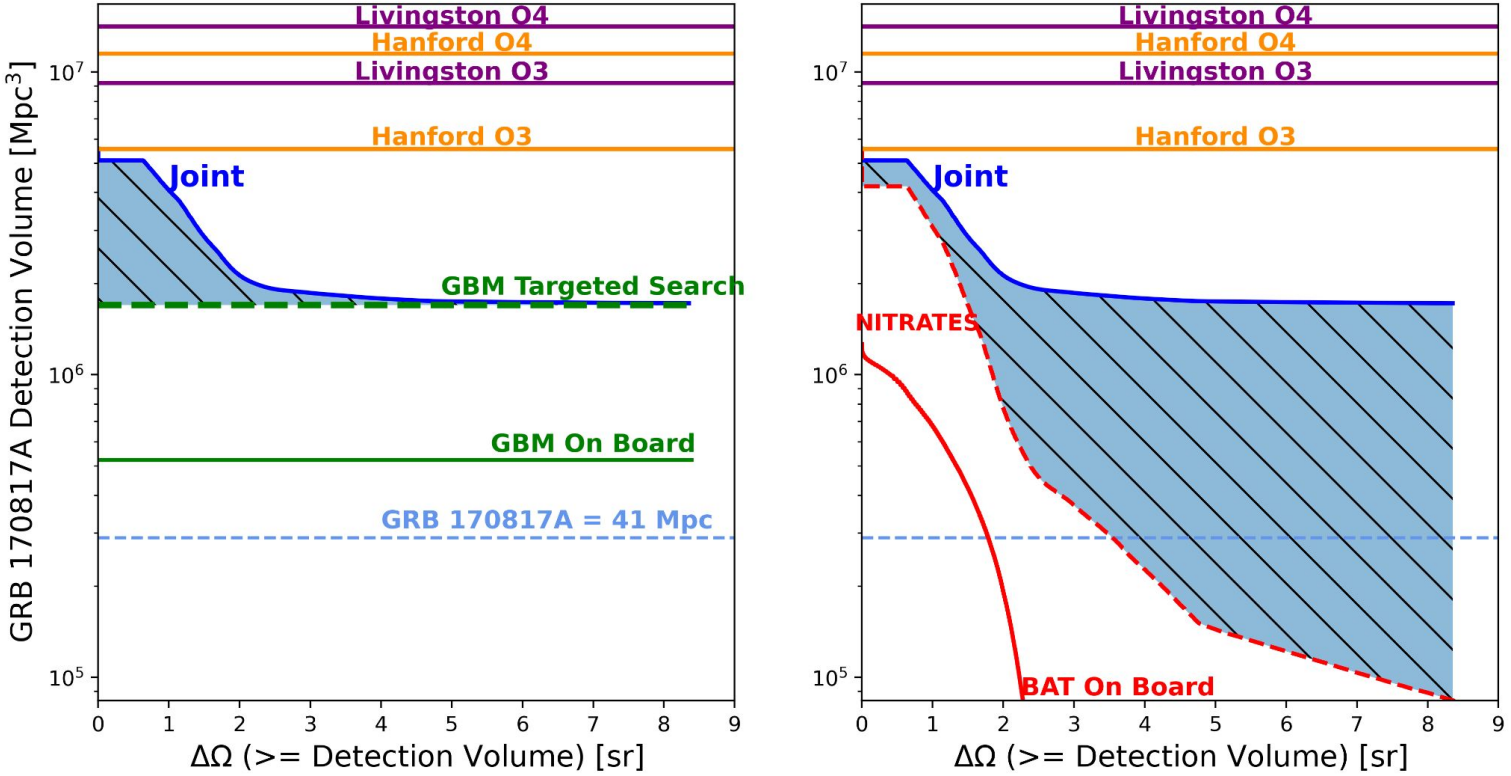
Like the LVK GW-Network,

With a likelihood framework, a GRB network is simple*

$$LLH^{\text{GRB-Network}}(\Theta_{GRB}) = \sum_i^{\text{GRB-Monitors}} LLH_i(\Theta_{GRB}, \Theta_{BKG,i})$$

* just needs accurate cross calibration of responses

Joint NITRATES-GBM analysis in development



- Estimated gain from joint Aeff
- Can also reject local noise transients and improved localizations

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

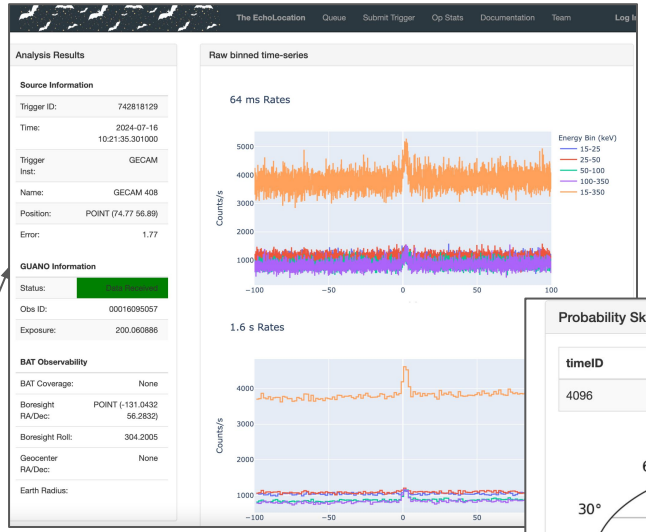
external_coinc	
gcn_notice_id	`{583417860, 583327924}`
ivorn	External IVORN identification field
observatory	`{Fermi,Swift}`
search	`{GRB,SubGRB}`
time_difference	Time between source and external event in seconds
time_coincidence_far	Estimated coincidence false alarm rate in Hz using timing
time_sky_position_coincidence_far	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.

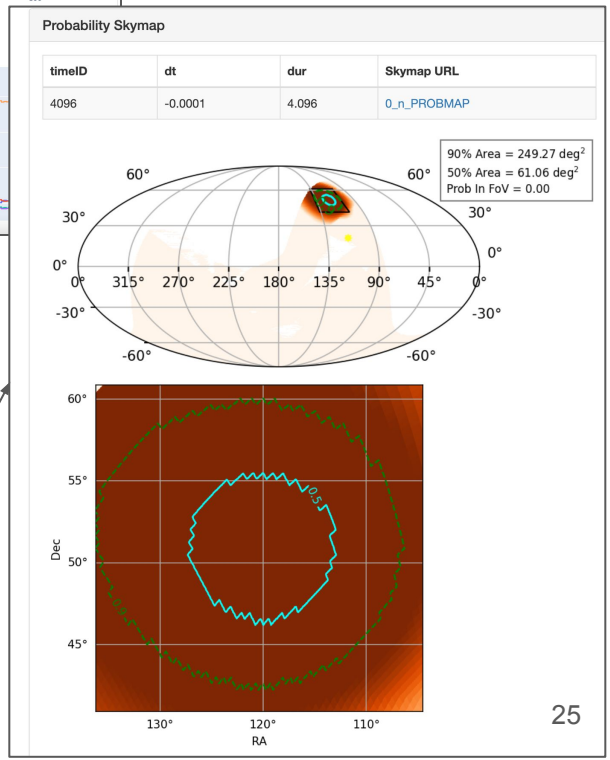
How to find NITRATES results

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

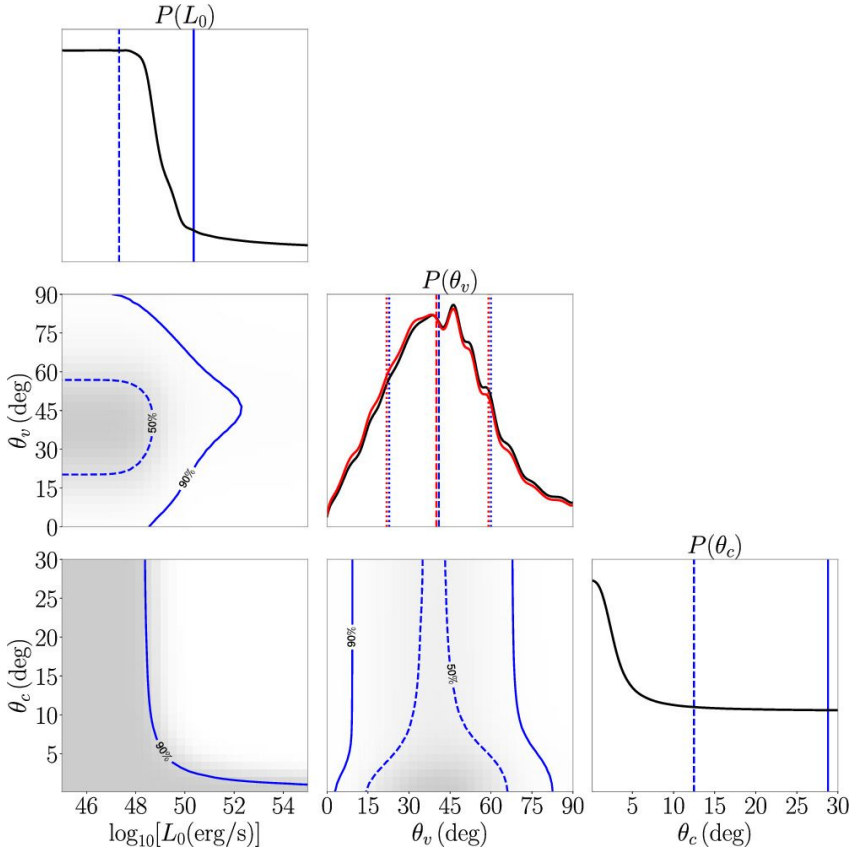
Summary

- 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
- With detections and upper limits, getting physics results
- 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 , see documentation on how to get and use NITRATES skymaps
- More analysis techniques that can applied to more data and more instruments in development!

Backups

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]

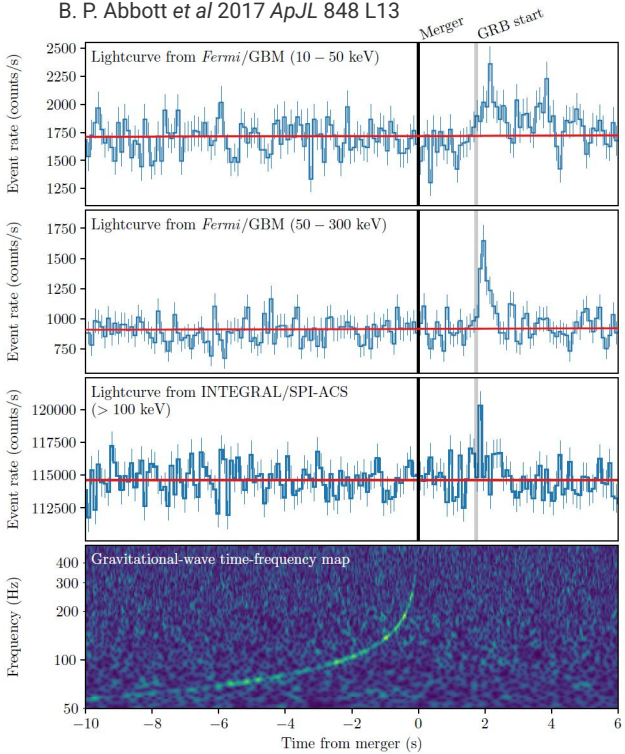


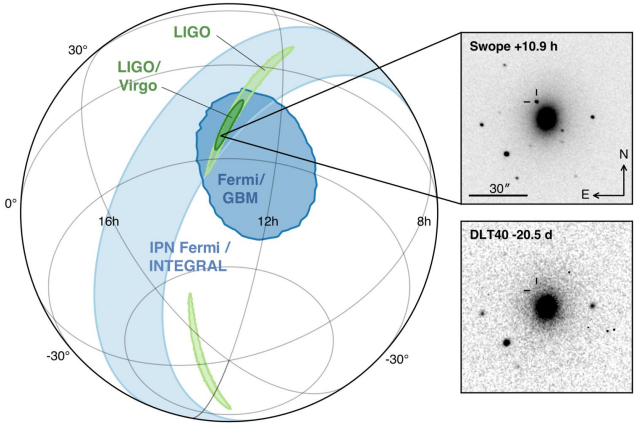
Gaussian Jet Profile

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



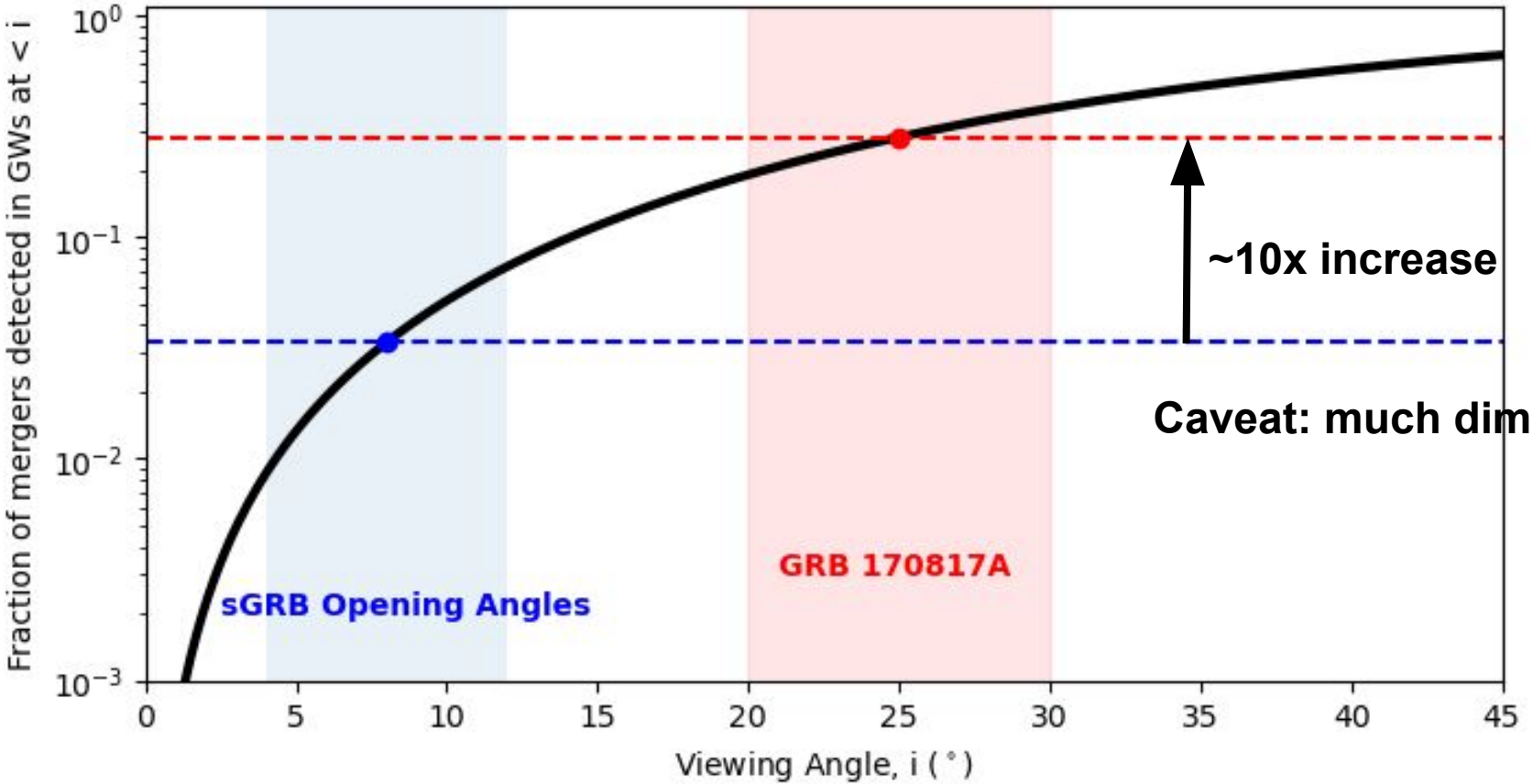


B. P. Abbott *et al* 2017 *ApJL* 848 L12

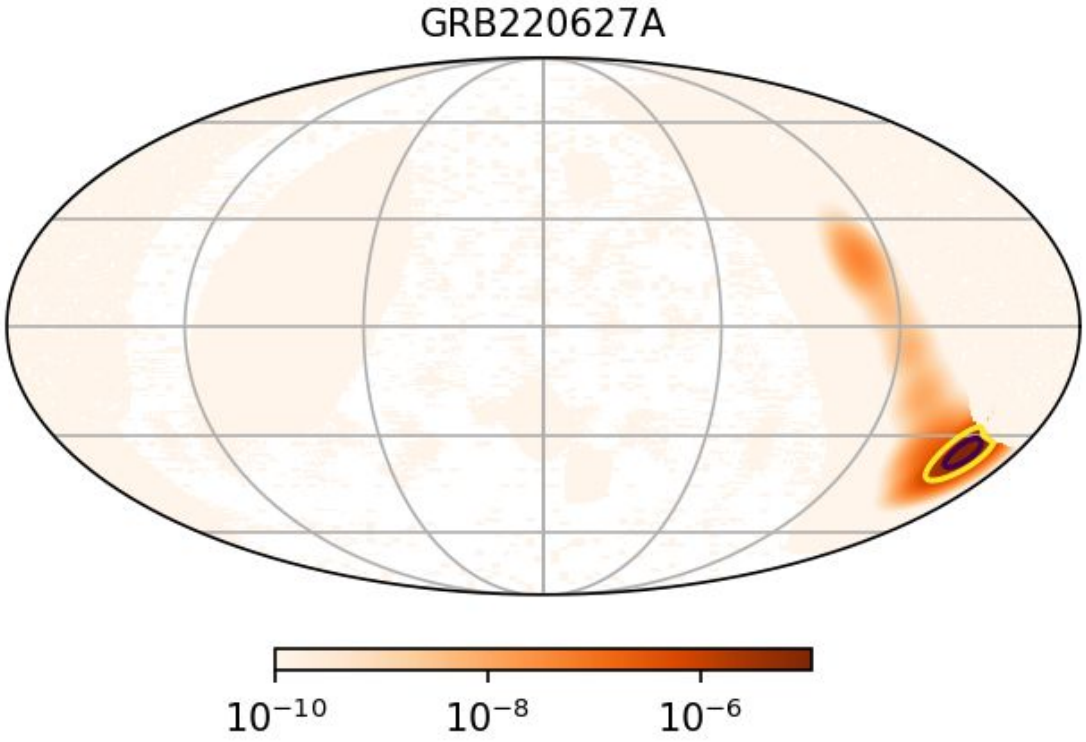
<11 hours post merger bright optical signal localized to NGC 4993, a galaxy ~40 Mpc away

Widespread scientific implications

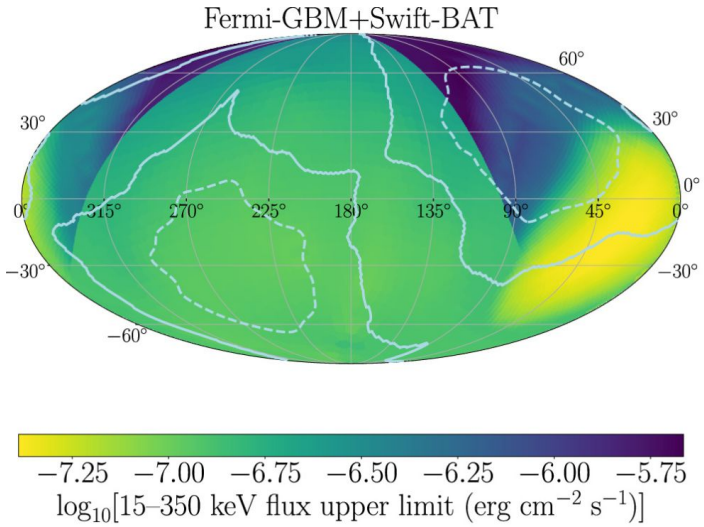
- Gold origin from r-process nucleosynthesis
- Measurement of speed of gravity
- Measurement of hubble constant …

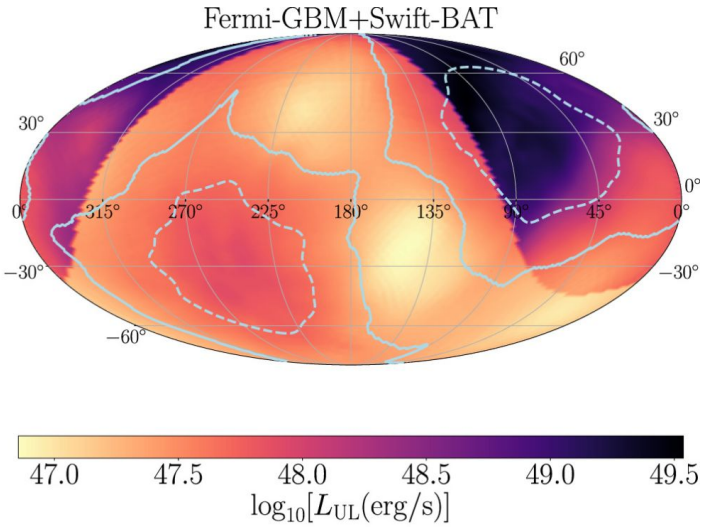

Fraction of mergers detected in GWs at < i
10^0
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
30
35
40
45
Viewing Angle, i (°)
sGRB Opening Angles
GRB 170817A
~10x increase
Caveat: much dimmer

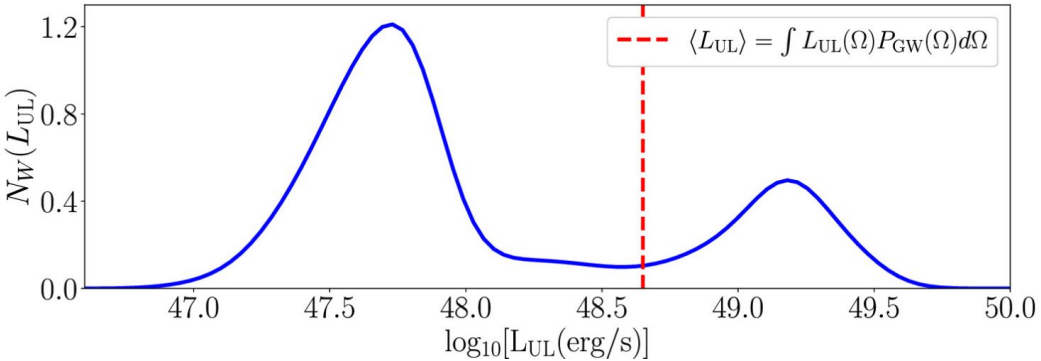
Best Case Outside of Coded Field of View



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


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)]

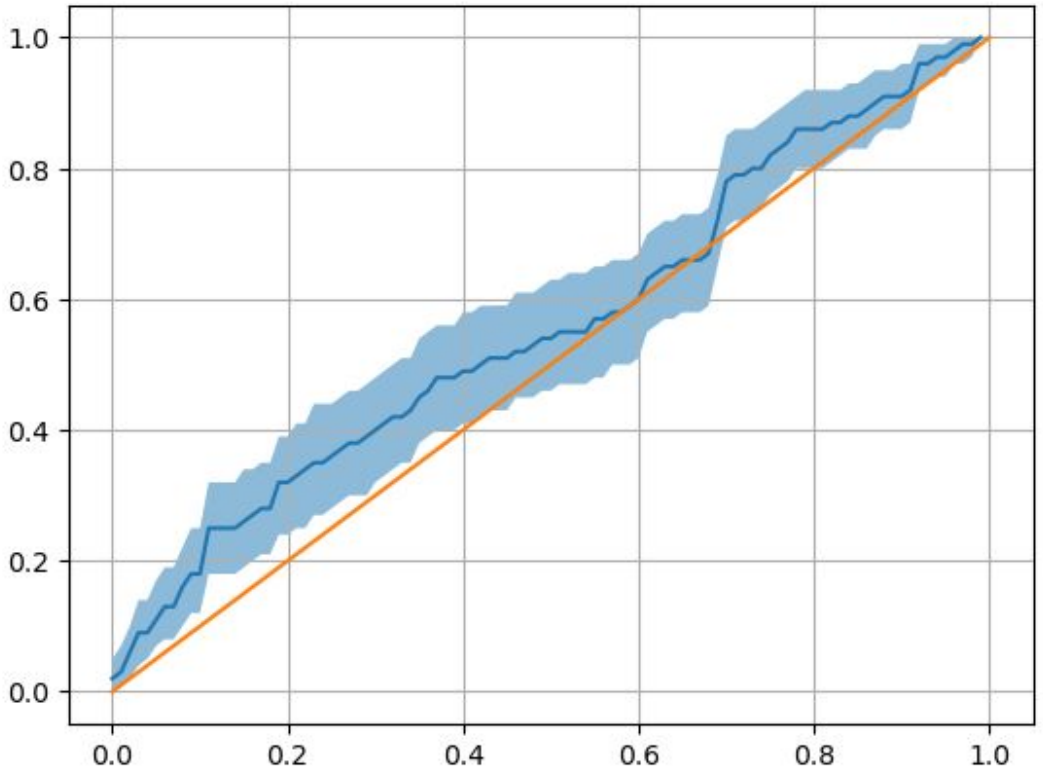

Fermi-GBM+Swift-BAT
60°
30°
0°
−30°
−60°
315°
270°
225°
180°
135°
90°
45°
47.0 47.5 48.0 48.5 49.0 49.5
log10[LUL(erg/s)]


⟨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)]

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

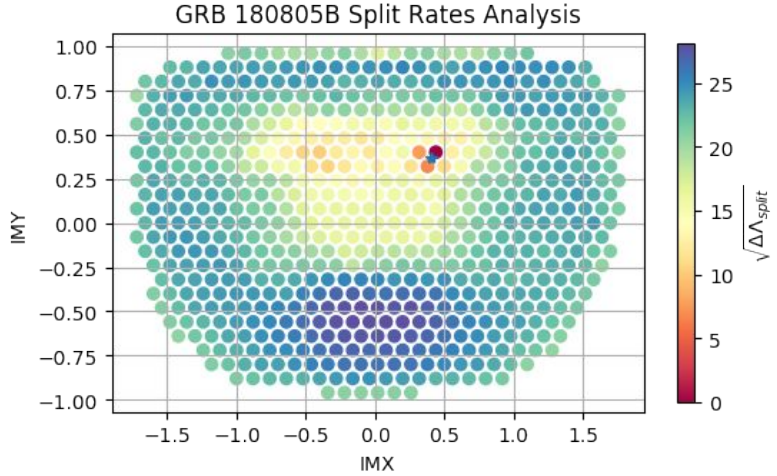
~250 skymaps from ~30 GRBs used here

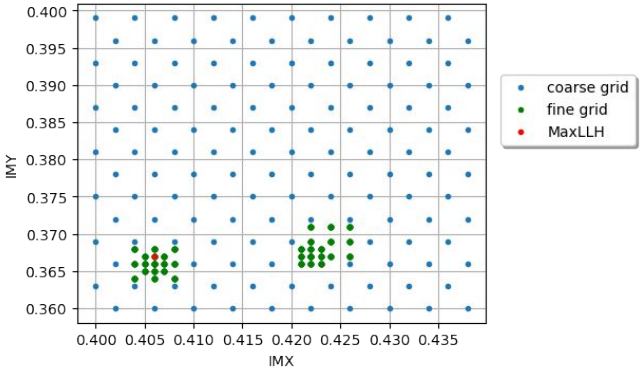


Computational Expense

Very large Parameter space

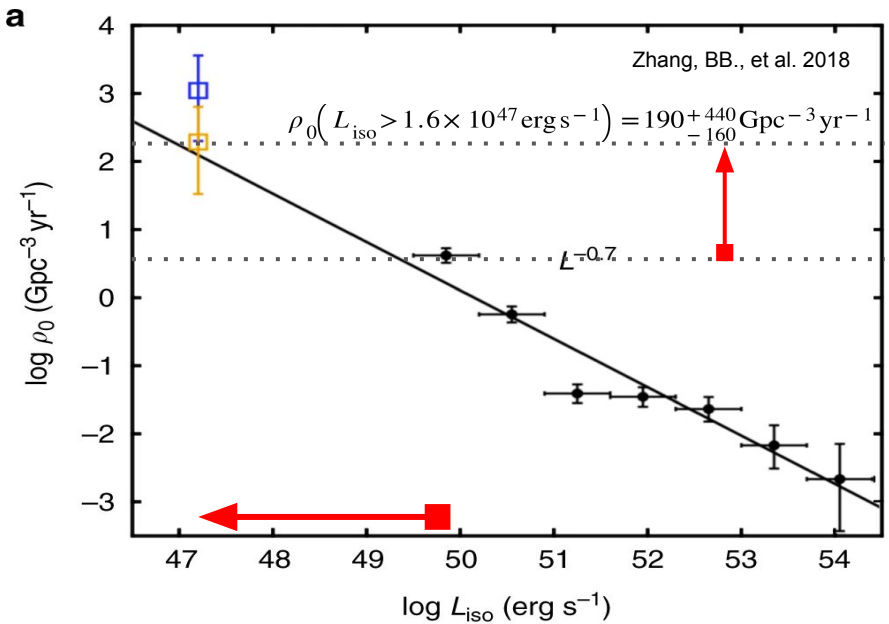
- Inside coded FoV, position point spacing needs to be < PSF size
  - PSF ≈ ⅓ deg, FoV ≈ 7,000 deg^2
- Seeding analyses and recursive grid search
- ~200 core-hours per analysis
- Runs on 2 clusters
  - PSU roar
  - NASA NCCS





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

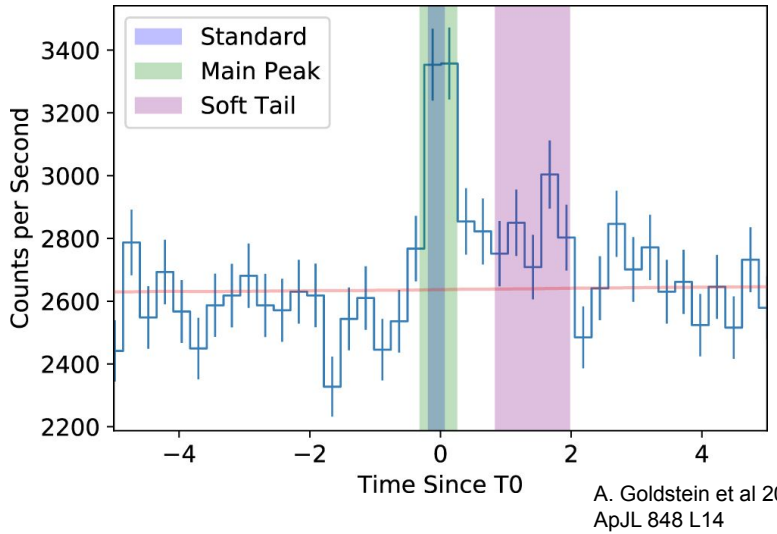
Normal sGRB emission

E_{peak} = 185 keV

Soft Tail

Best fit by thermal spectrum

kT = 10.3 keV



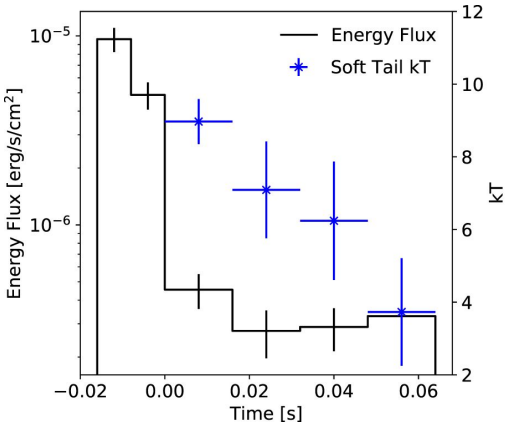
A. Goldstein et al 2017
ApJL 848 L14

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

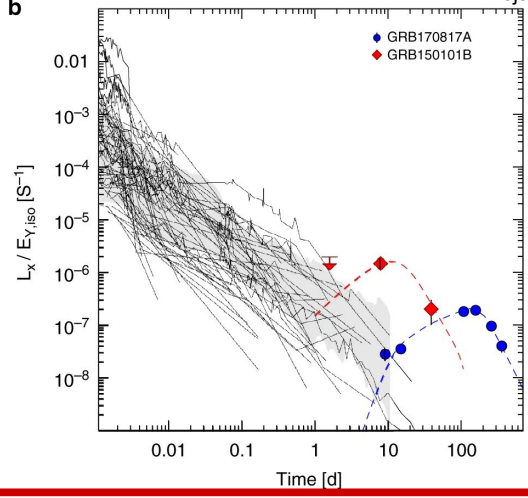
A Second Low-Luminosity SGRB

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



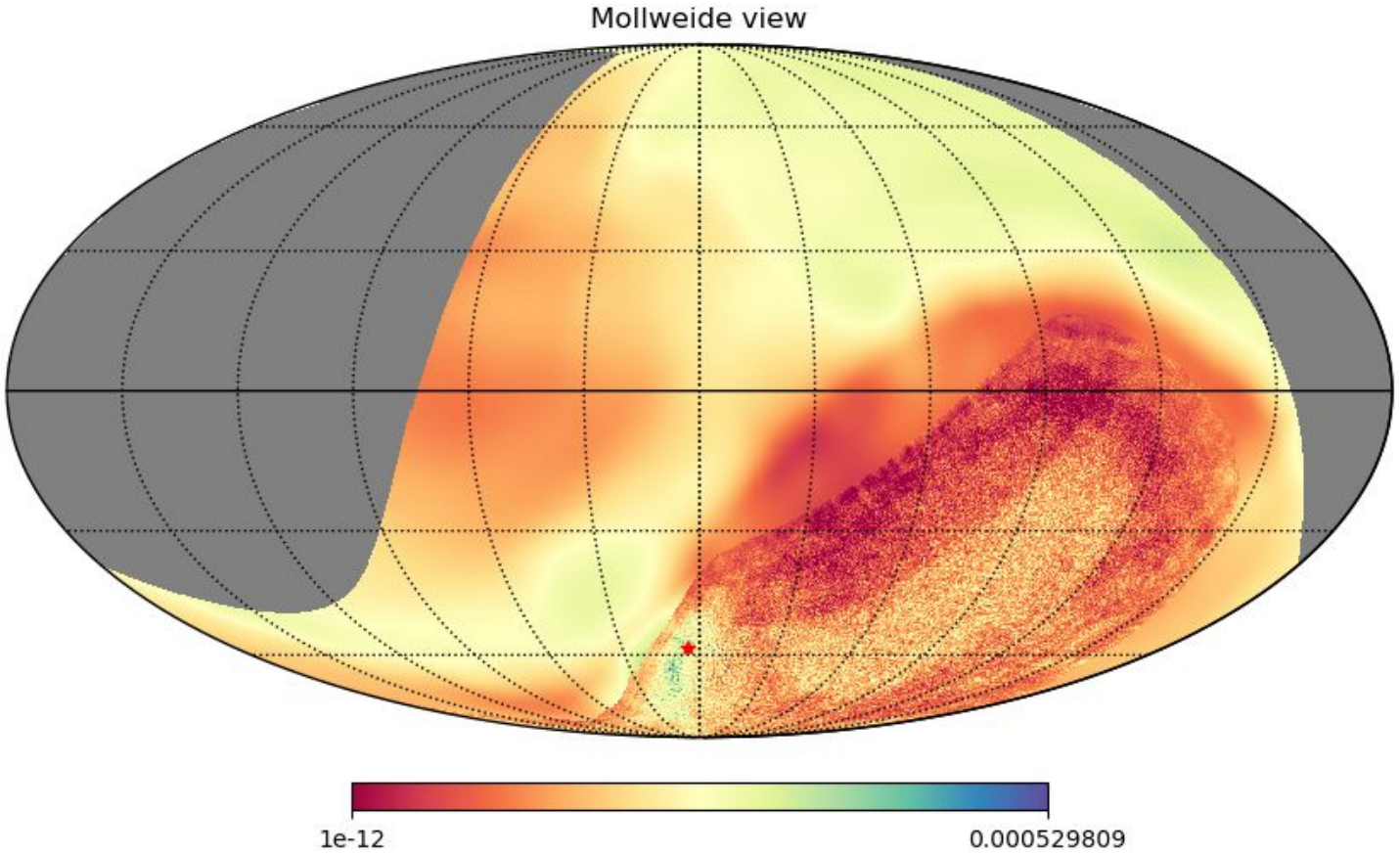
Troja et al. 2018

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

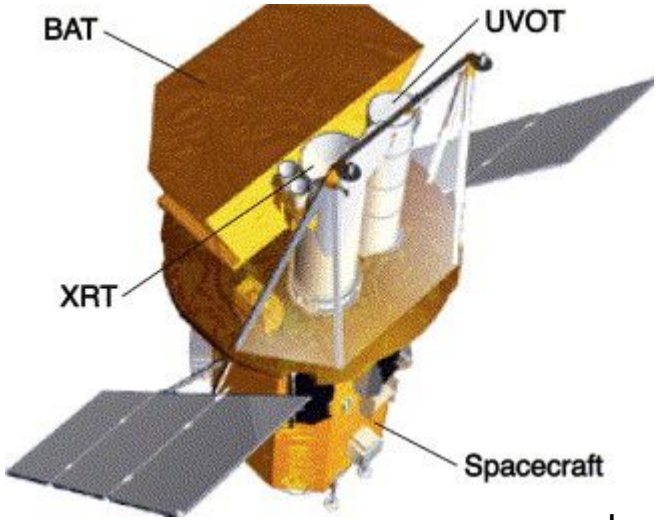
Prompt emission mechanism still not clear, but there is an emerging population → Need more sensitive searches

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

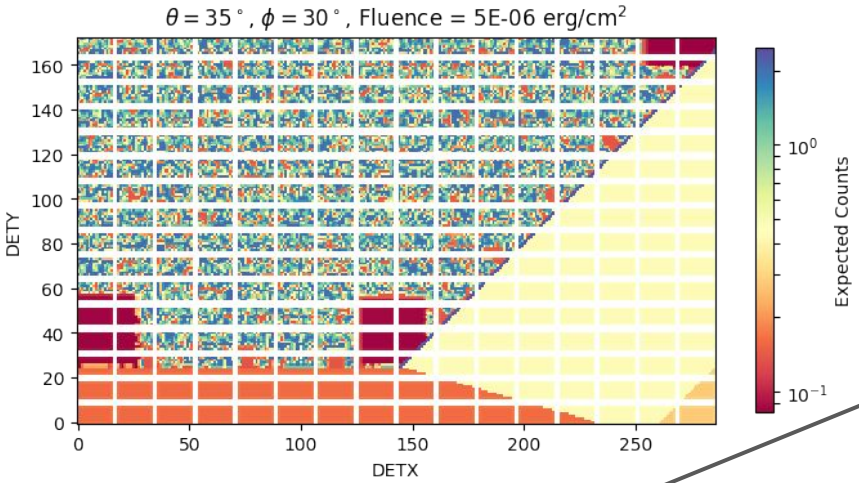
Burst Alert Telescope (BAT)
- Coded mask imager (15 - 150 keV)
  - Unmasked response up to 500 keV
- Detects and localizes GRBs (a few arcmins)
- Large FoV, ~ 2 st

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

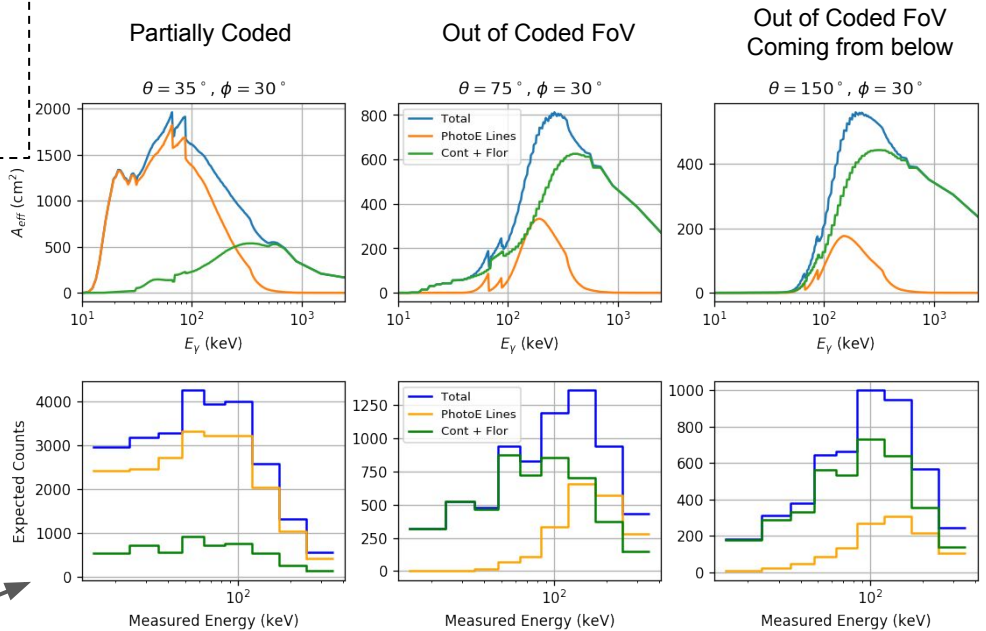
- Launched Nov. 2004
- >1000 GRBs detected
- Swift Mission Operations Center at Penn State

- $t_i(\theta, \phi, E_\gamma)$ 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



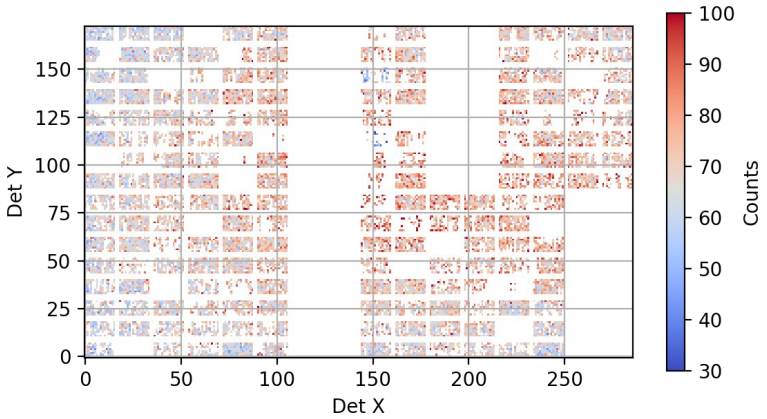
Expected counts from the PS model with a cutoff power-law spectra with γ = 0.5, E_{peak} = 350 keV, and a 10 keV - 1000 keV fluence of 5×10^{-6} erg cm^{-2} .

How BAT Works

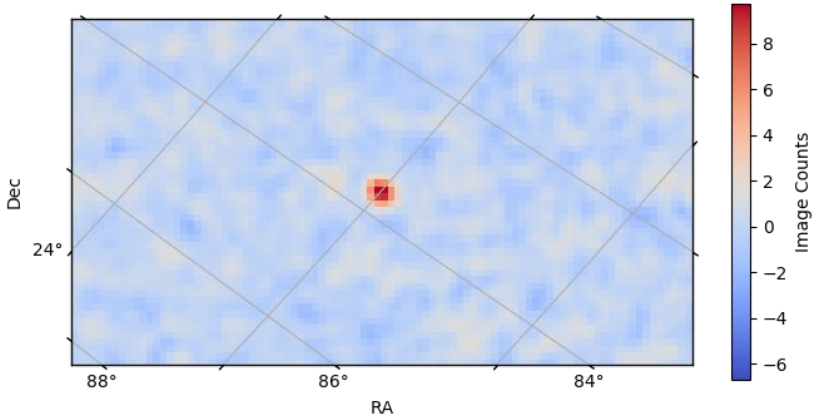
Cross-correlate with Mask Pattern

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

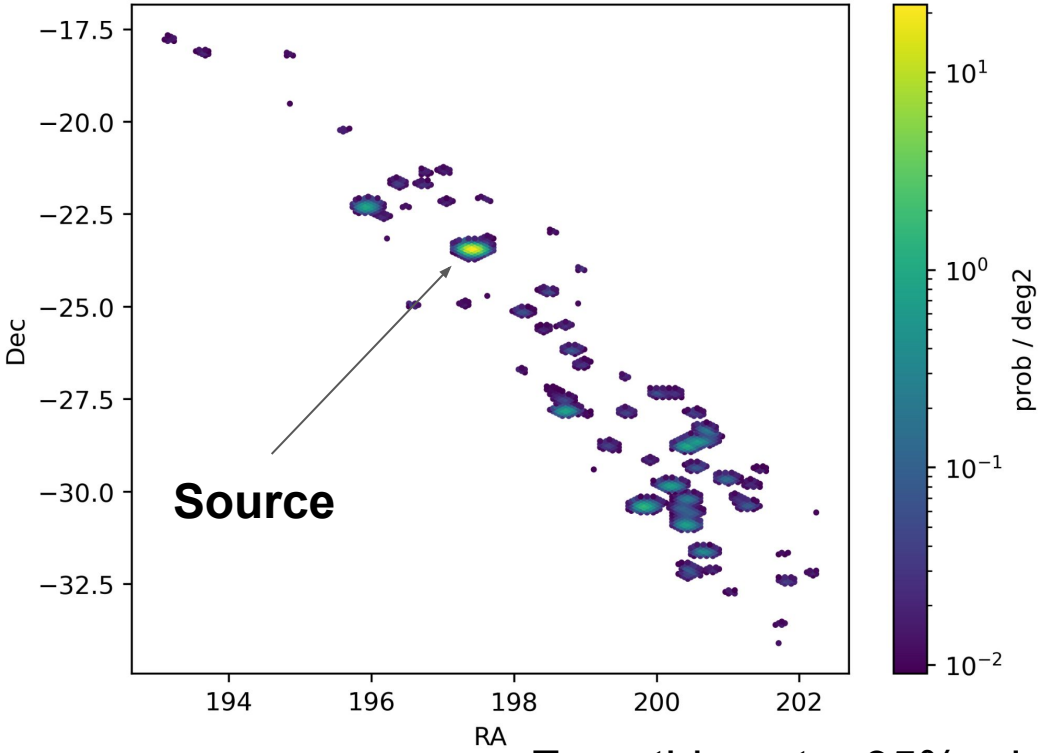
What if GRB 170817A were in the BAT coded FoV at 90 Mpc?

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

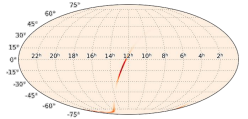
What if GRB 170817A were in the BAT coded FoV at 90 Mpc?



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