Searching for GRBs Coincident with Gravitational Waves with Swift BAT-GUANO

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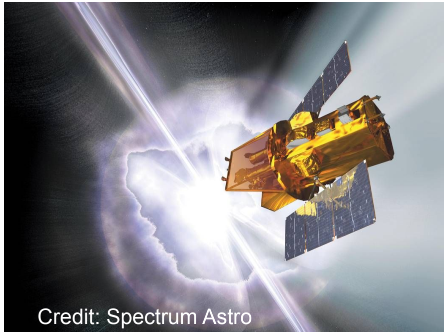
TeVPA 2023
Napoli, Italy
September 13th 2023

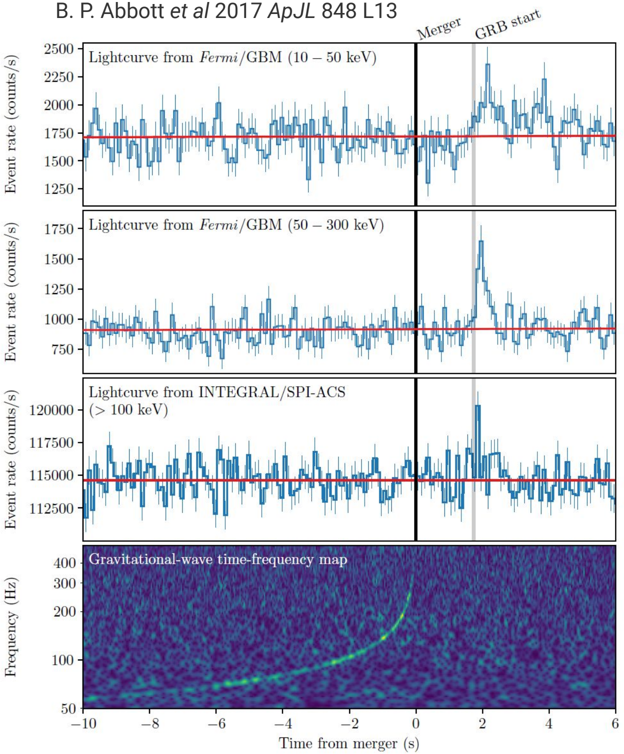
THE UNIVERSITY OF ALABAMA


Credit: Spectrum Astro

GW/GRB 170817

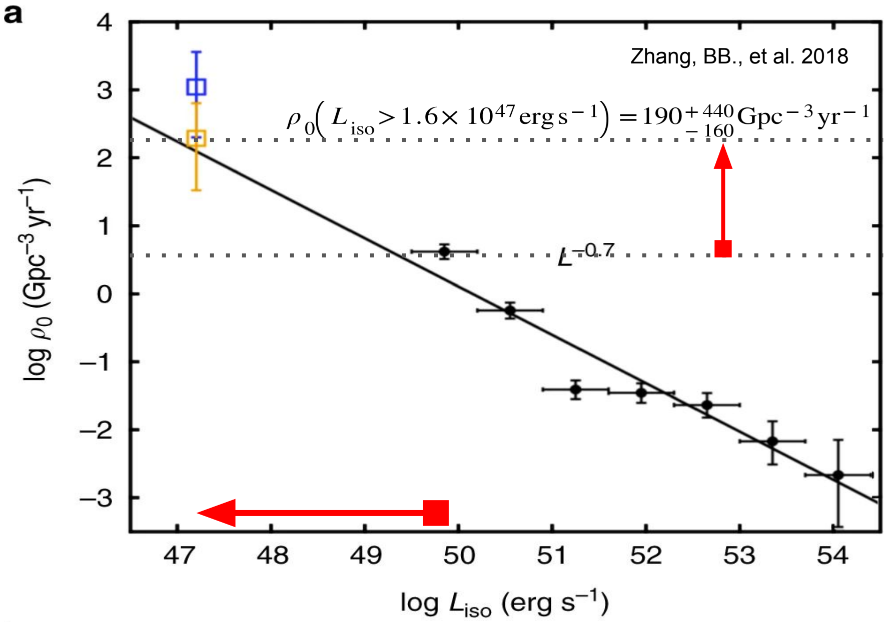
First ever GW-EM multi-messenger Signal!
BNS Merger

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

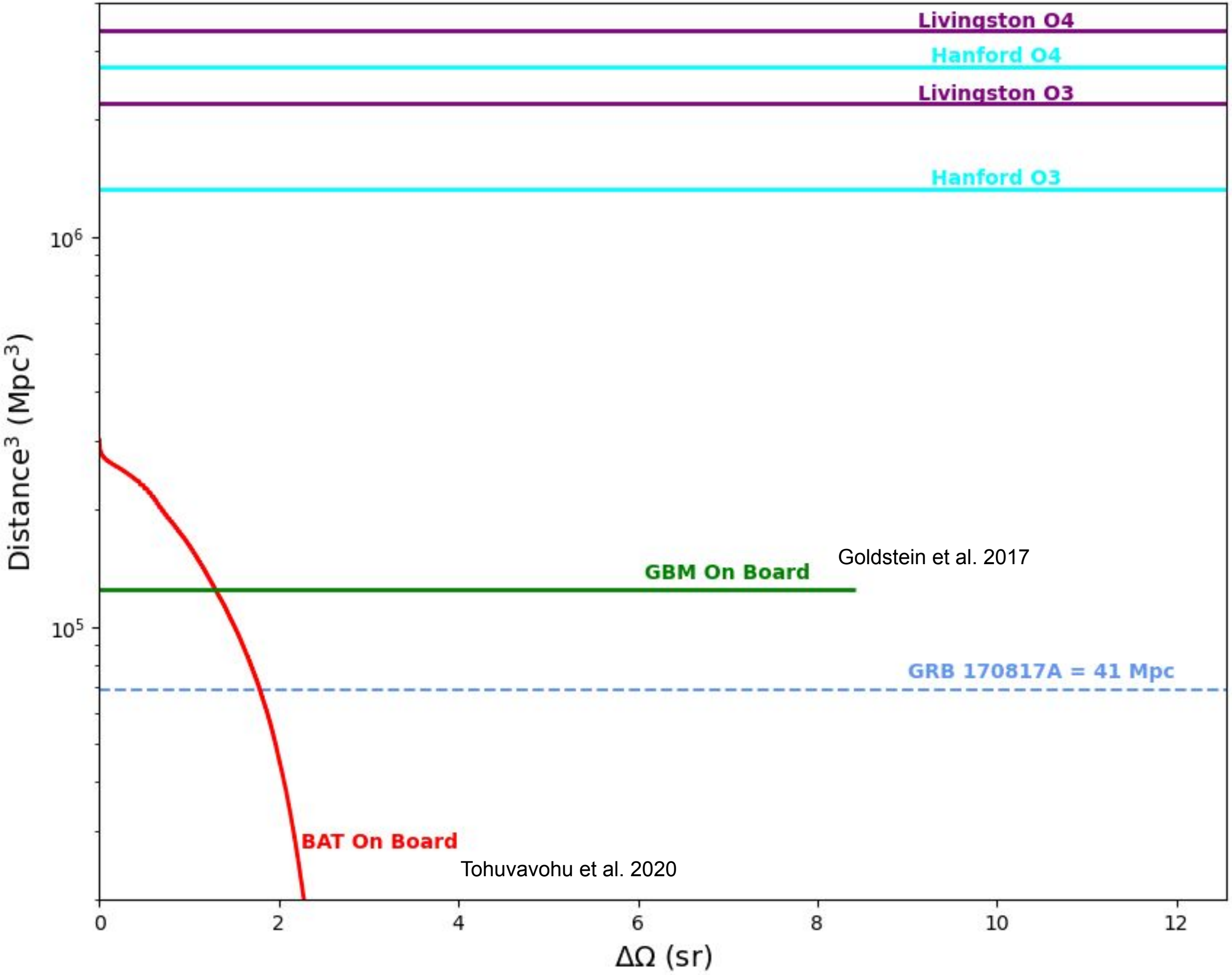


GRB 170817A

- 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



Maximum detection distance for a GRB like GRB 170817A



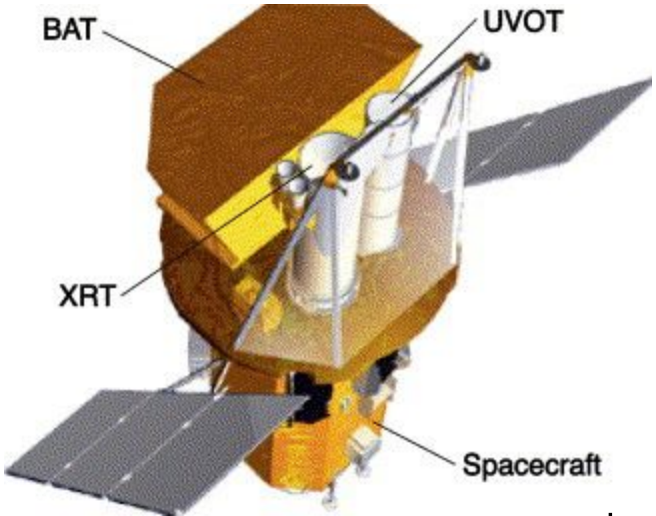
BNS Range

Goldstein et al. 2017

Tohuvavohu et al. 2020

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

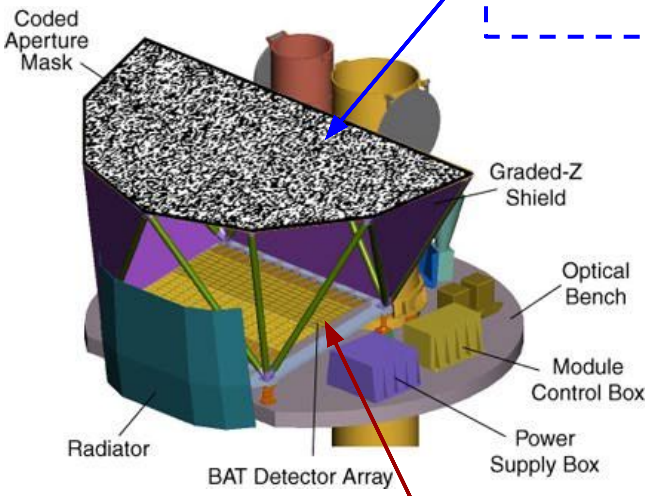
UV/Optical Telescope (UVOT)

- 170 - 650 nm
- Capable of sub-arcsecond localization

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

How BAT Works

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

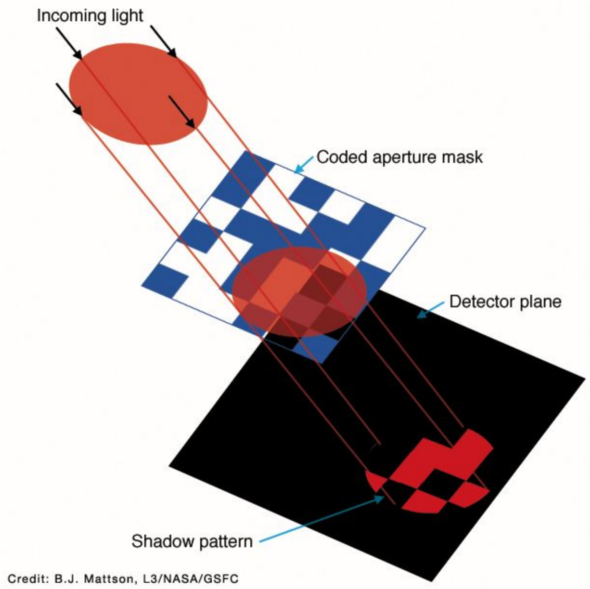


4x4x2 mm

32,768 CZT Detectors in Array

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

Basic Concept

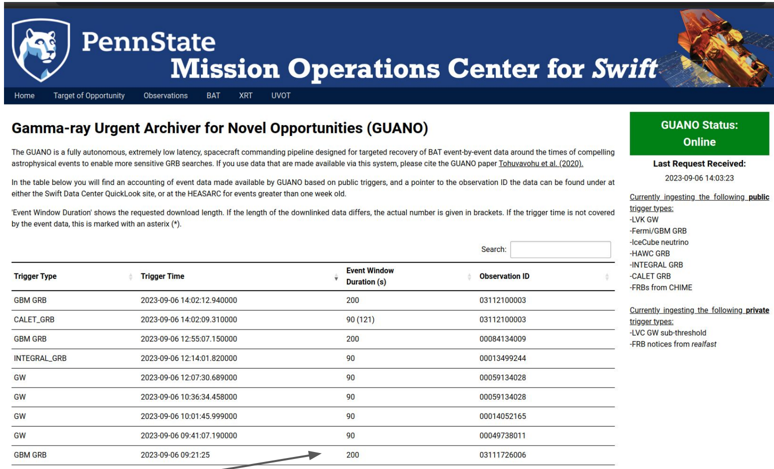


- Constructs images via a balanced cross-correlation technique
- Creates an image on board whenever there's a rate excess

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



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 (*).

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	00049738011
GBM GRB	2023-09-06 09:21:25	200	03111726006

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*

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

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

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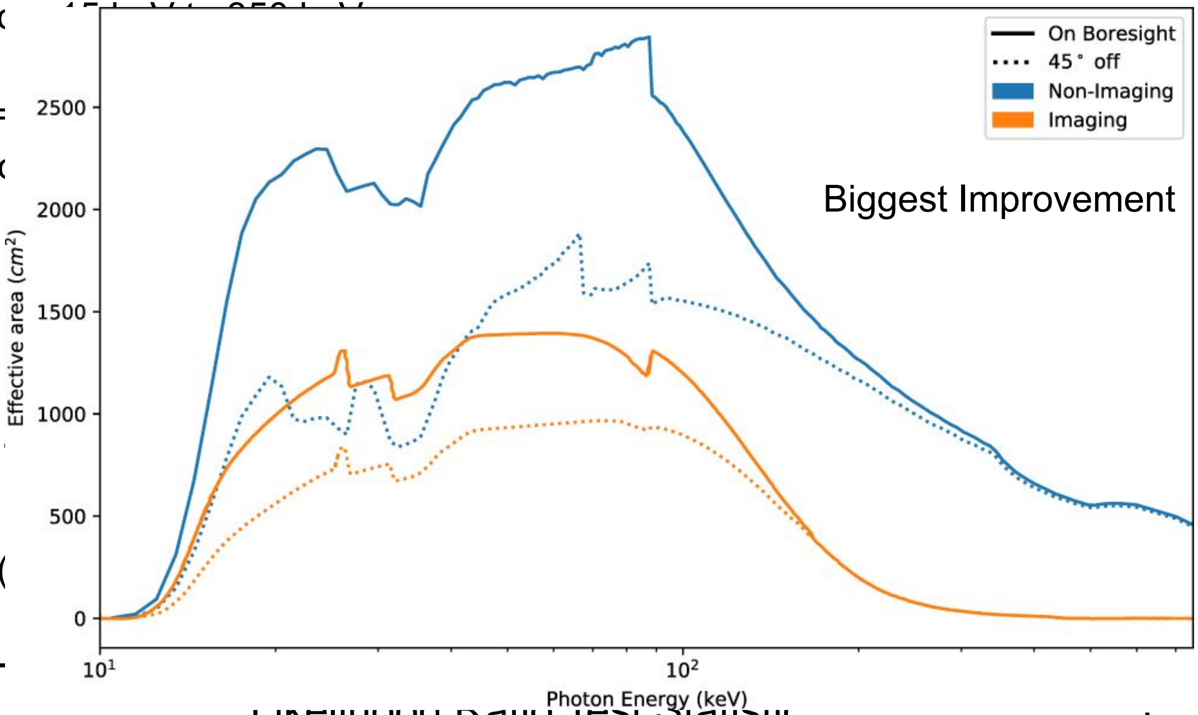
N_{ij} =

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



Count sources to model:
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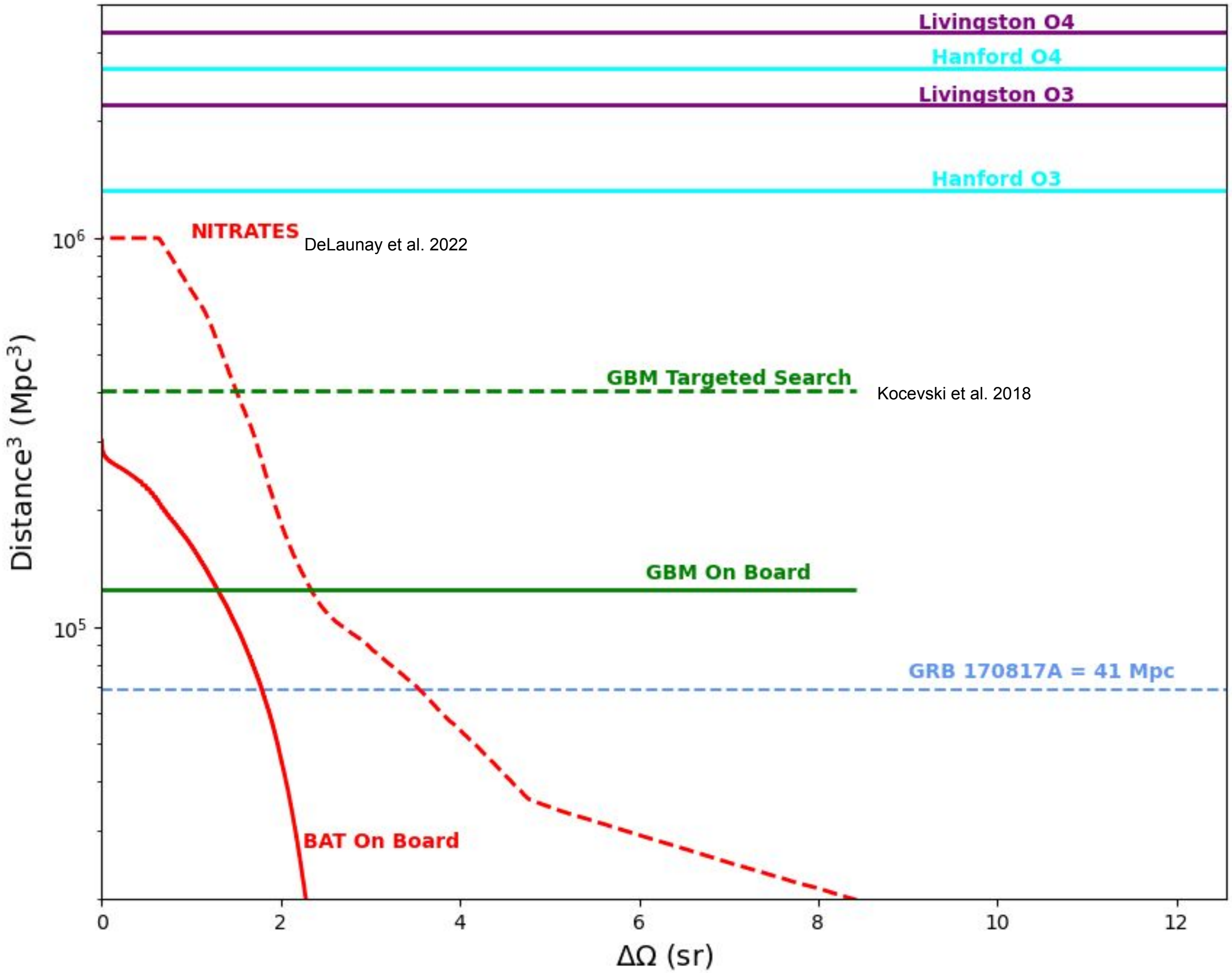
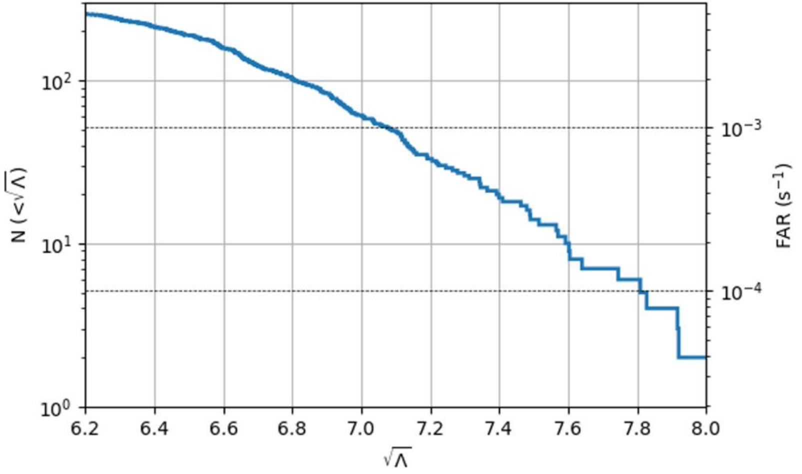
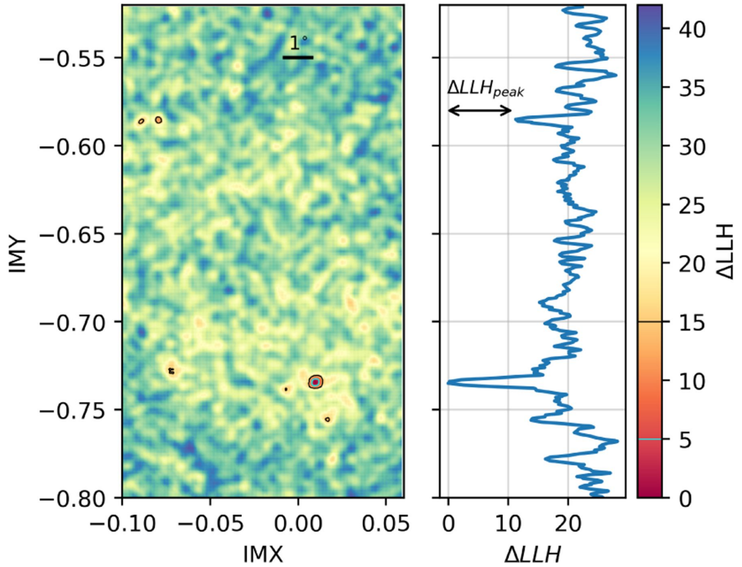


Livingston O4
Hanford O4
Livingston O3
Hanford O3
NITRATES
DeLaunay et al. 2022
GBM Targeted Search
Kocevski et al. 2018
GBM On Board
GRB 170817A = 41 Mpc
BAT On Board
Distance^3 (Mpc^3)
10^6
10^5
0
2
4
6
8
10
12
ΔΩ (sr)

NITRATES Outputs

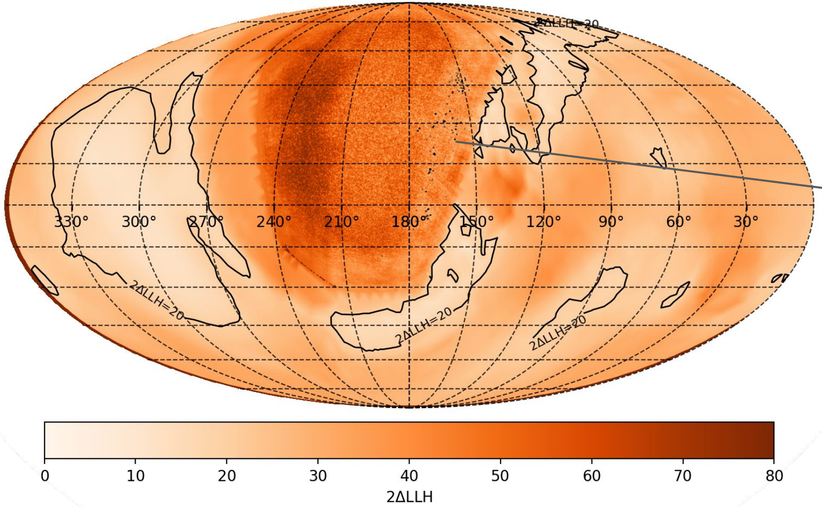
- $\sqrt{\Lambda}$
  - Measure of preference for PS transient origin over bkg
  - Mapped to a FAR
  - ~>8 is a detection
- ΔLLH_{out}
  - Max(LLH(in FoV)) - Max(LLH(out FoV))
  - Measure of preference that source is outside the coded FoV
  - ~< 0 likely out FoV
- ΔLLH_{peak}
  - Difference between max(LLH) and next highest separate LLH mode
  - How likely source is localized to a single arcminute-scale circle
  - > 10 confident localization
  - ~5-10 marginal



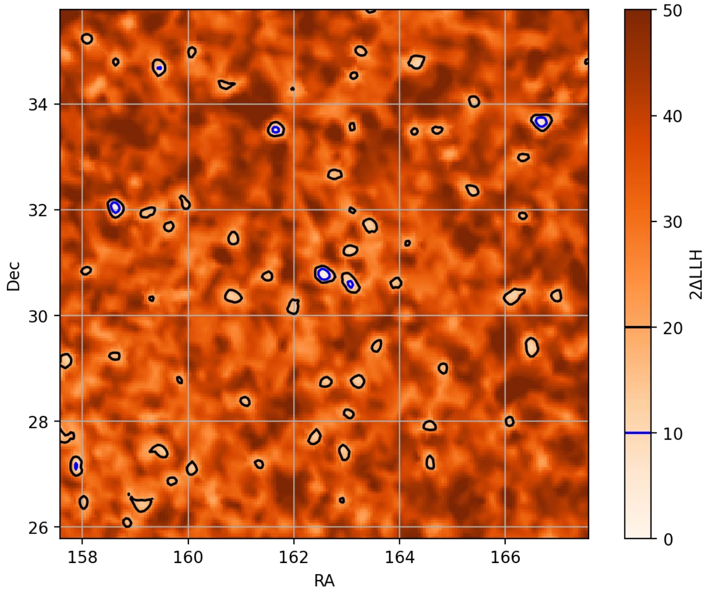


Probability Skymap - work in progress

GRB 220822A - short and weak
Fermi Trigger 714440939
$\sqrt{\Lambda}$ = 9.69, ΔLLH_{out} = 7, ΔLLH_{peak} = 0.2



zoom in



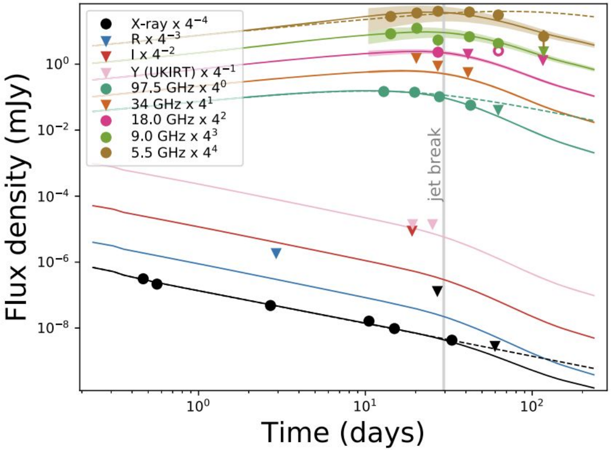
2ΔLLH = 20 ~> 90% containment

Suggestions on how best to show/communicate this are welcome

NITRATES Detected GRBs (missed onboard)

In the last 3 years of operations, NITRATES has successfully

- Provided arcminute localizations for around 32 in FoV events
    - Including 7 short GRBs
- Many confident detections of out of FoV GRBs
- Afterglows identified: 13 X-ray
- Redshifts identified for 2



Laskar et al 2022
First sGRB mm afterglow
GRB 211106A

Keep an eye out for our GCN Circulars!

If you're interested in working with NITRATES/GUANO contact us,

- Me: delauj2@gmail.com
- Aaron Tohuvavohu: aaron.tohu@gmail.com

BAT-GUANO 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

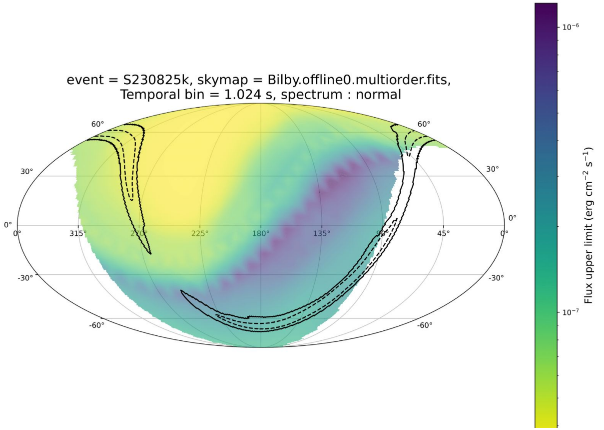
Examples here

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

O4 Status

- Running Nitrates around every GW alert (above and sub threshold)
  - -10 s to +20 s, time scales 0.128 s - 16.384 s
- Computationally expensive
  - ~400 core-hours per search
- Running on 2 clusters
  - Roar collab at Penn State
  - NCCS - NASA
- Upper limit GCN circulars for above threshold GWs

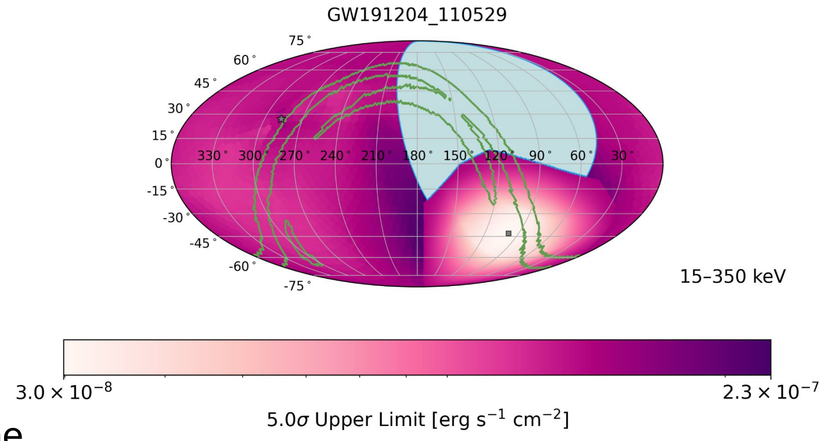
- Joint sub-threshold GW-GRB detections will be sent out by LVK over GCN
  - If joint FAR < 1/month (after trials correction) using RAVEN formalism
  - See more here https://emfollow.docs.ligo.org/userguide/content.html



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.

GRB-GW Science Group

- Joint working group between Swift, Fermi, IPN, and LVK members
- Work on joint alerts and publications
    - Overall goal to increase collaborative efforts between detectors
- Has resulted in several joint publications
    - Most recent: A Joint Fermi-GBM and Swift-BAT Analysis of Gravitational-Wave Candidates from the Third Gravitational-wave Observing Run
    - https://arxiv.org/abs/2308.13666
- If you want to know feel free to contact our chair
    - Samuele Ronchini - sjs8171@psu.edu



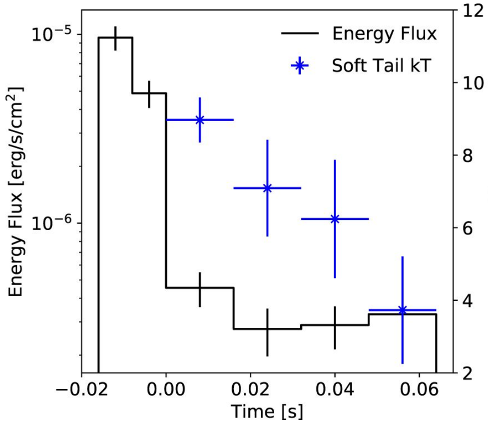
Data Release: https://zenodo.org/record/8101645

Backups

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

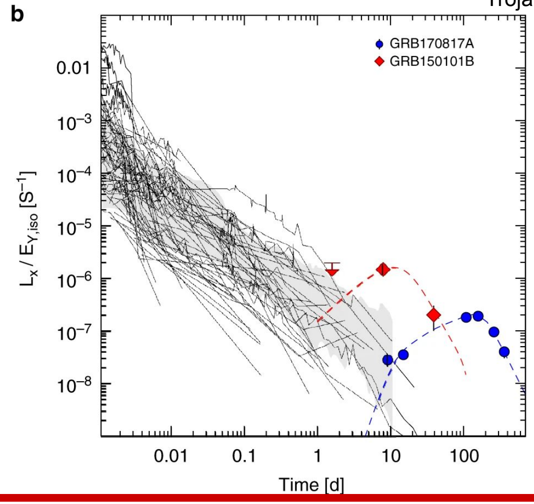


Burns et al. 2018

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

Troja et al. 2018

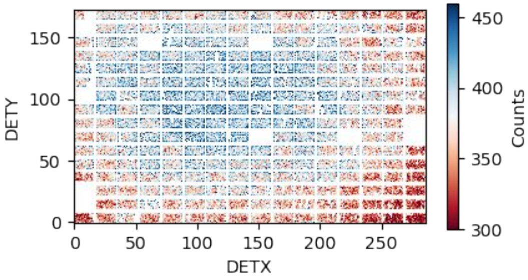


Prompt emission mechanism still not clear, but there is an emerging population → Need more sensitive searches

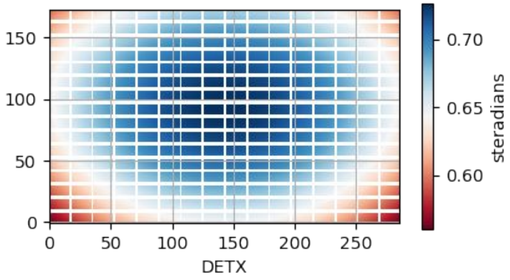
Diffuse Model

- CXB shining through mask openings creates spatial pattern across detector plane
- CXB photons that travel through mask tiles or shield and cosmic ray induced photons do not create any particular spatial pattern
- Two parameters per Ebin

≈1300 s of exposure with no bright sources



Ω_i



$$\lambda_{ij}^{diff} = (\Omega_i\, \phi_j^b + r_j^b)T$$

ϕ_j^b = rate per det. per Ω_i

r_j^b = rate per det.

Ω_i = unblocked solid angle for detector i

T = duration

Point Source Model

Sky Position: (θ, ϕ)

Spectra: Norm (A) and shape parameters

For a cutoff power-law spectrum

$\mathbf{\Theta}^{PS} = \{\theta, \phi, A, E_{peak}, \gamma\}$

Detector Response

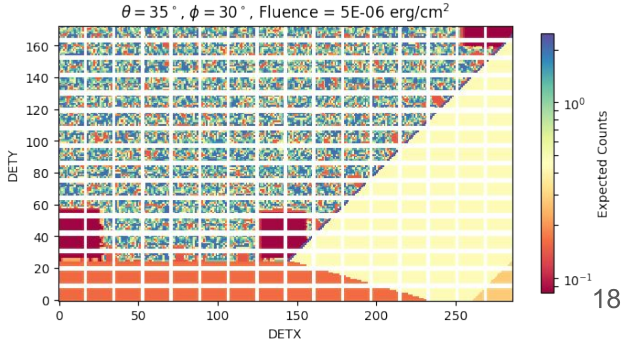
$R_j(E_\gamma) = w_j A_{eff}(E_\gamma)$

w_j is the probability of count falling in Ebin j, $\sum w_j = 1$

For a photon spectra, $f(E_\gamma)$

$$\lambda_{ij}^{PS} = T \int f(E_\gamma)\, R_{ij}(E_\gamma)\, dE_\gamma$$

Example PS Model



GRB Search

We want to know how much the Signal+Bkg hypothesis is favored over the Bkg-only hypothesis (Null)

Signal is a GRB-like transient Point Source

Bkg is the best fit model to nearby off-time data

Likelihood Ratio Test Statistic

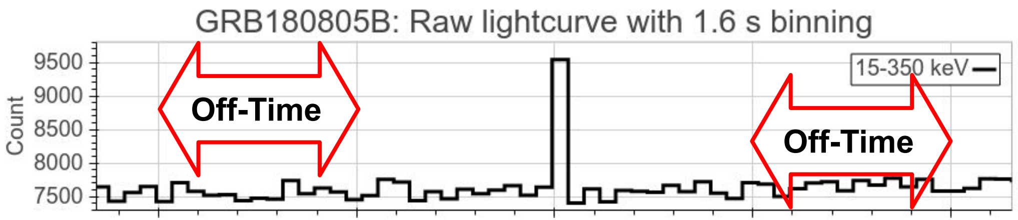
$$\Lambda = -2(\, LLH(\, \boldsymbol{\Theta}_{Bkg} | \mathbf{N}) - \max[\, LLH(\boldsymbol{\Theta}_{Sig}, \boldsymbol{\Theta}_{Bkg} | \mathbf{N}) \,]\,)$$

To find Λ, $LLH(\boldsymbol{\Theta}_{Sig}, \boldsymbol{\Theta}_{Bkg}|\mathbf{N})$ needs to be maximized over $\boldsymbol{\Theta}_{Sig}$, which includes source position (θ, ϕ), spectral shape, and spectral norm (A). $\boldsymbol{\Theta}_{Bkg}$ is kept fixed to its off-time fit values.

Off-Time Background Fit

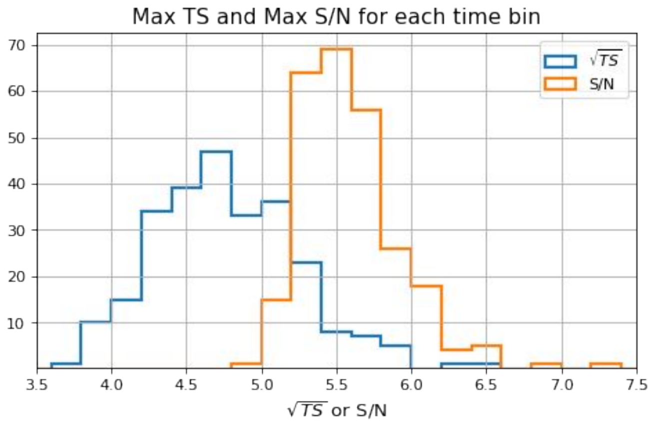
- Use data around time of interest, excluding a small window around it
- Use a diffuse model + a PS model for any known bright sources in the FoV
    - ~15 sources are "bright"

LLH maximized over "A" for grid of positions and spectral shape parameters.
Position parameter space is huge!
PSF ≈ ⅓ deg, FoV ≈ 7,000 deg^2
Typical search uses ~500 cpu hours
Seeding analyses used to narrow down parameter space



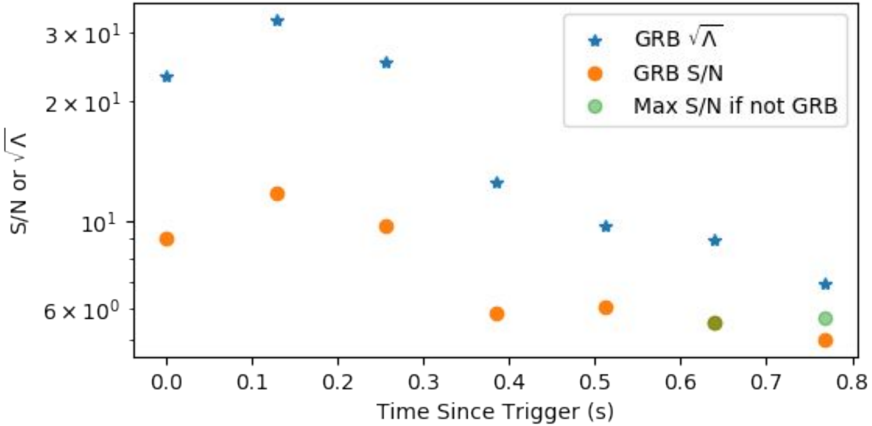
Example Results

For a bunch of durations of data without signal, an image was made and Λ was found



Under the Null-Hypothesis, √Λ is a comparable measure to the imaging S/N

GRB 180805B, 0.256 s time bins



√Λ found for 7 time bins around the trigger time with the image S/N for comparison. Max LLH was found at GRB position in each time bin.

Search sensitivity found via simulated injections for a GRB 170817A-like burst

Max distance for 90% recoverability

- At FoV center ~ 100 Mpc !
- 45deg off center ~ 71 Mpc !

For Reference

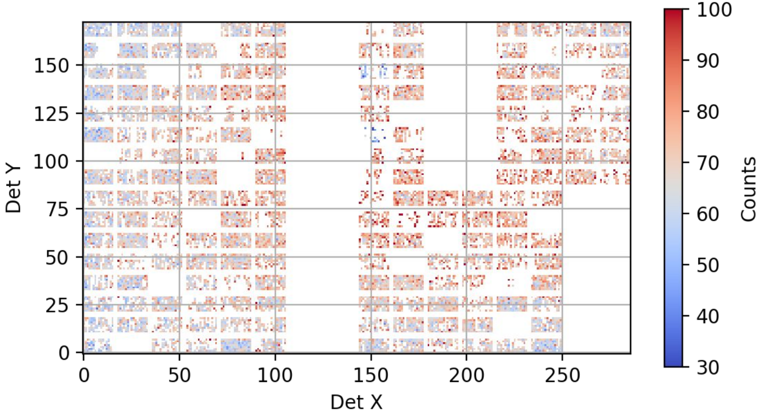
- BAT onboard detection out to ~ 67 Mpc at center of FoV
- GBM onboard detection out to ~ 50 Mpc
- GBM ground analysis out to ~ 74 Mpc

How BAT Works

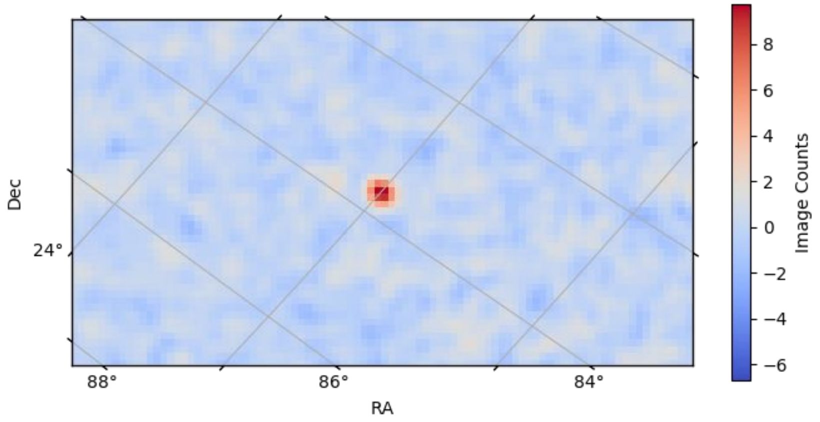
Cross-correlate with Mask Pattern

Crab in Detector Space

Detector Plane Image (DPI)



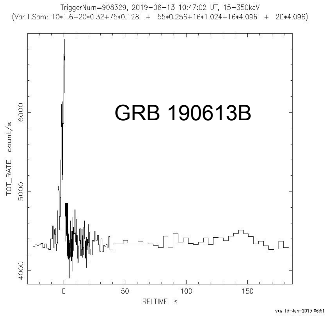
Crab in Sky Space

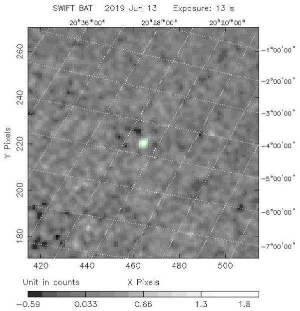


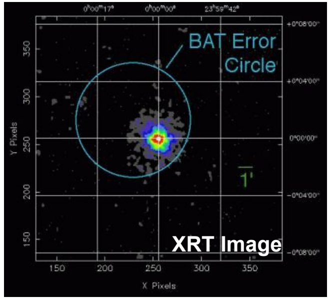
Mask-Weighted Counts
Gaussian noise centered around 0 where there's no source
Automatic Bkg subtraction

Zoomed in
Full FoV is ~2 sr

BAT Searching For GRBs







BAT monitors the count rate

Sudden rate increase
"Rate Trigger"

or

64s go by
"Image Trigger"

Make Image Search for new Point Source

S/N > 7

GRB Detected! Slew and observe afterglow

Reported to astronomical community in ≲ 1 min

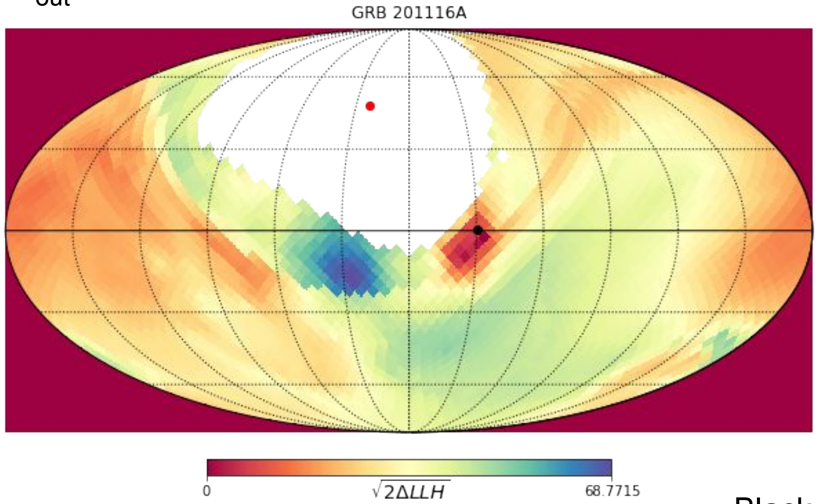
≈20 min of BAT time-tagged event (TTE) data is saved

Out of FoV GRBs

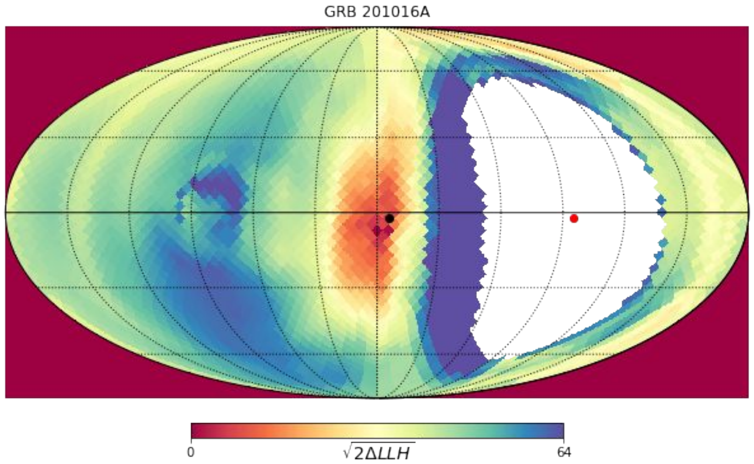
- Impossible to image here
- Most important part is to test if burst is in or outside coded FoV
- Response here is still rough, BAT wasn't designed for this
- Some localization is possible for brighter bursts
- ΔLLH_{out} = max(LLH in FoV) - max(LLH out FoV)

- GRB 201016A was very bright
  - Fluence ~ 10^{-4} erg cm^{-2}
- Orientation was very suboptimal for BAT
  - θ ~ 90deg
  - LLH still did a good job localizing

ΔLLH_{out} ~ -500



ΔLLH_{out} ~ -1630



Black dot is GBM localization

Constructing The Response

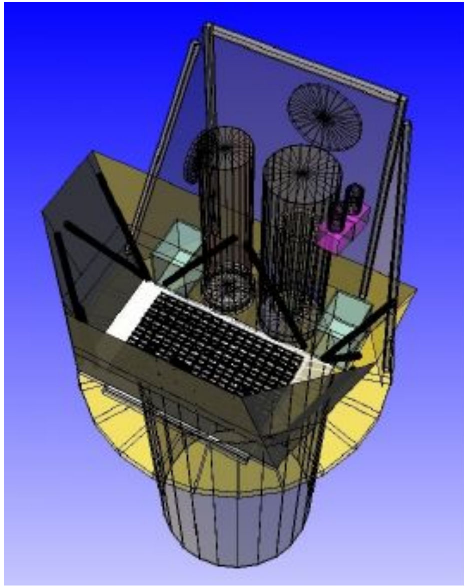
Want a per detector response that supports the whole sky and photon energies ~10 keV - ~5 MeV

Separate into 2 parts

- Indirect response
  - Photon first interacts with another part of the craft
  - Mostly Compton scattering and fluorescence lines from the shield
- Direct response
  - Photon makes it to detector unimpeded

Direct response changes more quickly with sky position, especially in the coded FoV

Swift Mass Model (SwiMM)



Use SwiMM and Geant4 to simulate photon fluxes at a set of photon energies and sky positions. Use results to build responses.

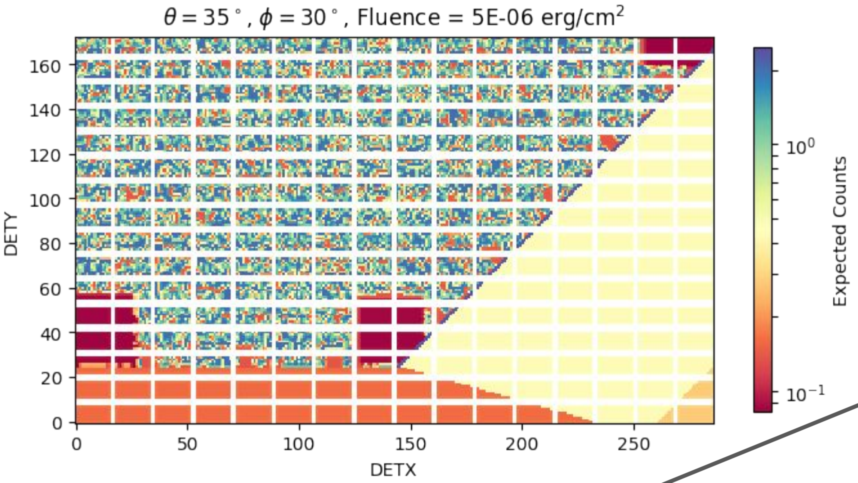
Do simulations with whole mass model to make the indirect responses

For direct response, remove all elements of the mass model besides the detectors and nearby elements.
Will need to adjust this response by the transmission probability.

$$R_{ij}(\theta, \phi, E_\gamma) = R_{ij}^{indirect}(\theta, \phi, E_\gamma) + t_i(\theta, \phi, E_\gamma) \times R_{ij}^{direct'}(\theta, \phi, E_\gamma)$$

Where: t_i = transmission probability to detector i

- $t_i(\theta, \phi, E_\gamma)$ 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
    - $t_i(\theta, \phi, E_\gamma) = f_i + (1 - f_i)\, t_{pb}$



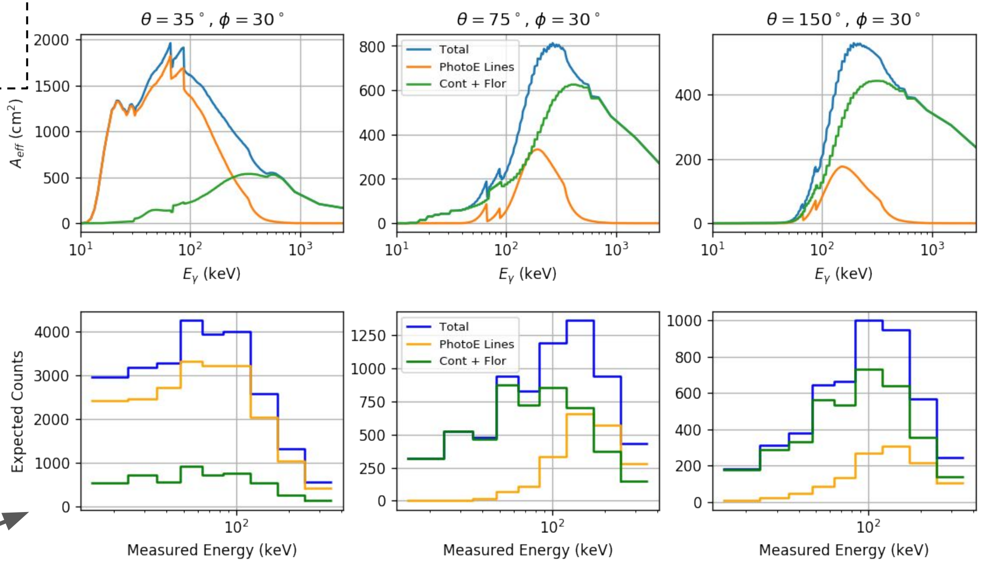
Same flux and position as

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

Partially Coded

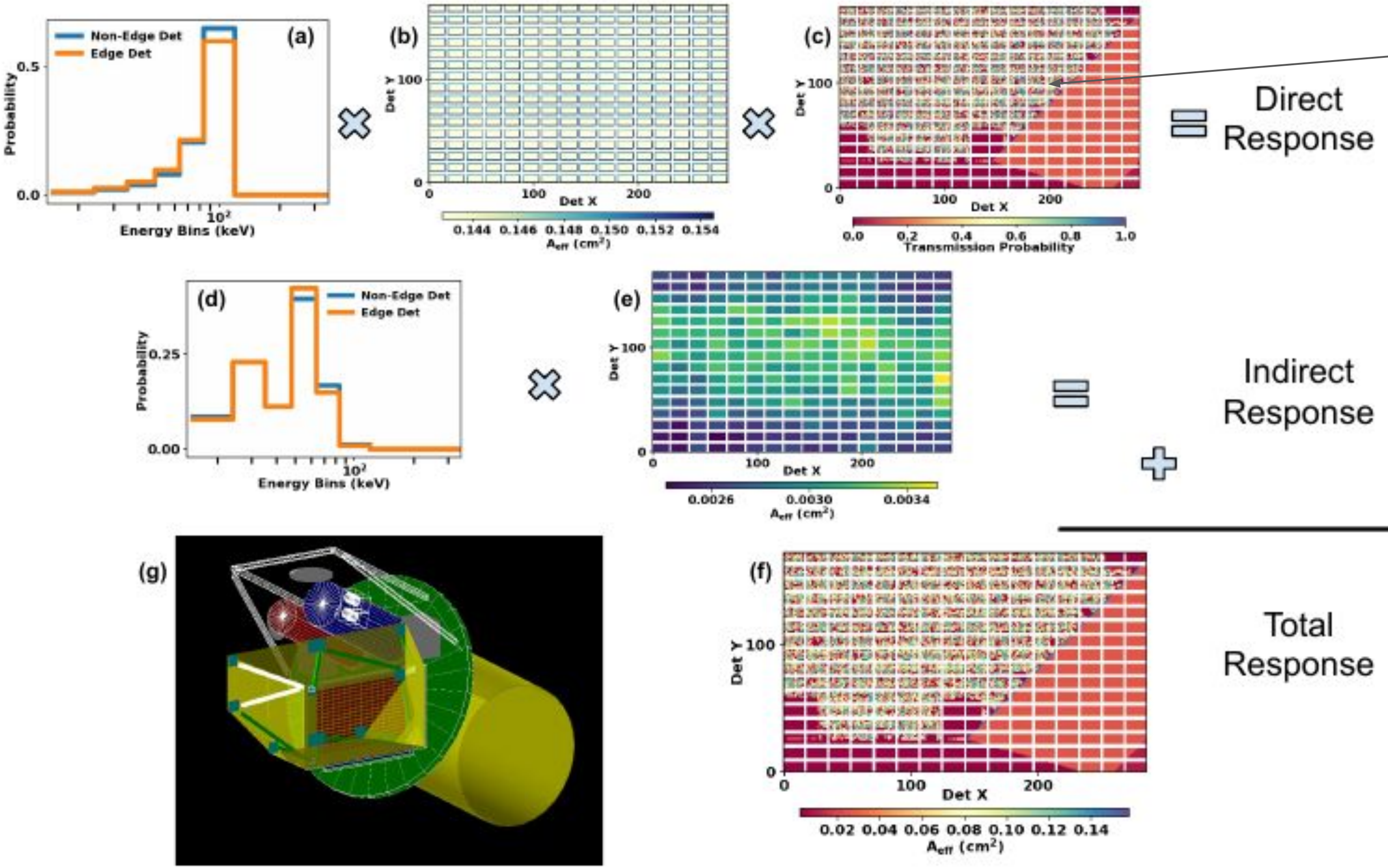
Out of Coded FoV

Out of Coded FoV Coming from below



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} .

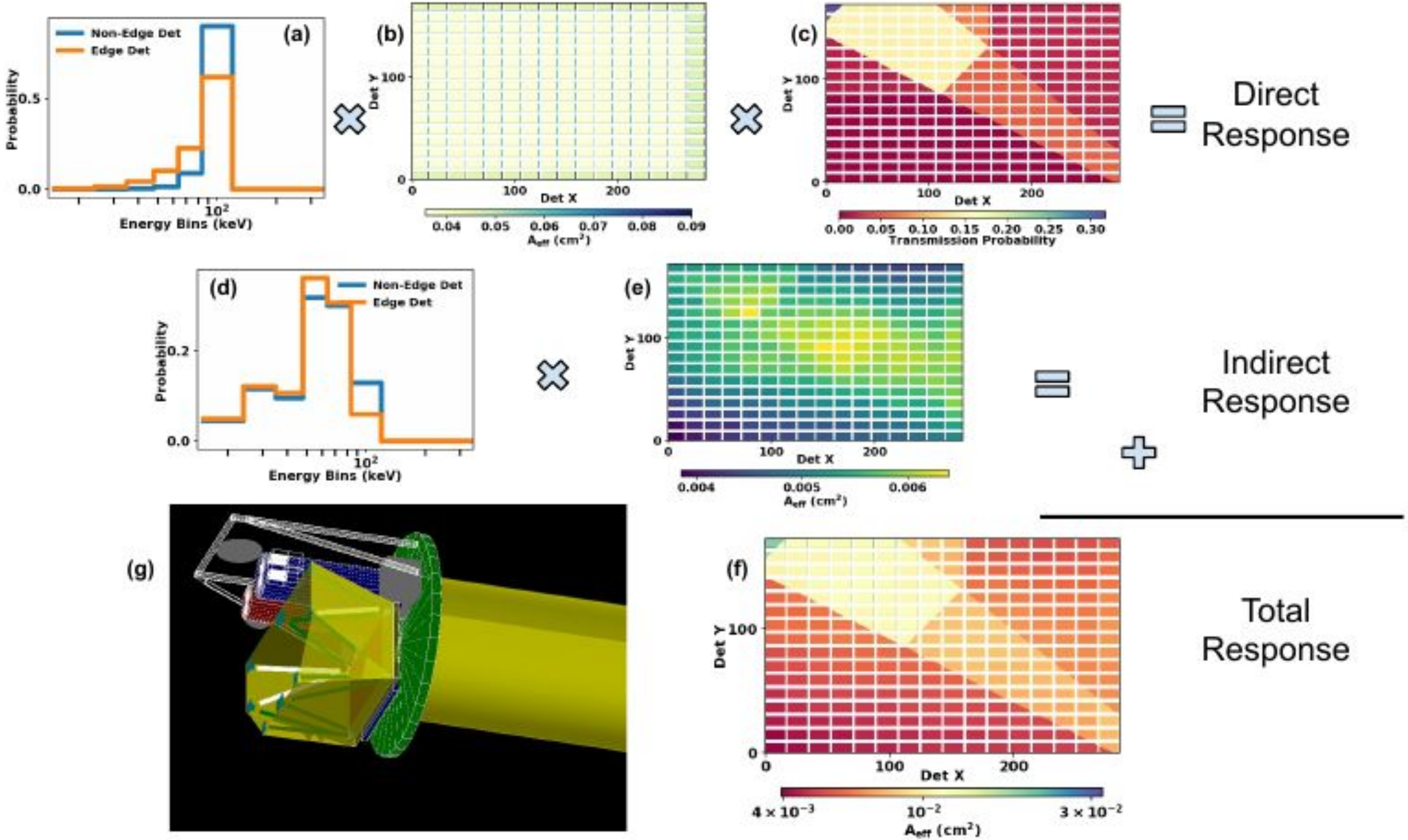
Construction of 100.5 keV Photon Response, Theta 35°



t_i in coded region includes shadowded fraction of each det, which is precomputed and stored.

Similar dets are grouped together when going from depth dists. to responses with charge trapping and other effects included.

Construction of 100.5 keV Photon Response, Theta 75°



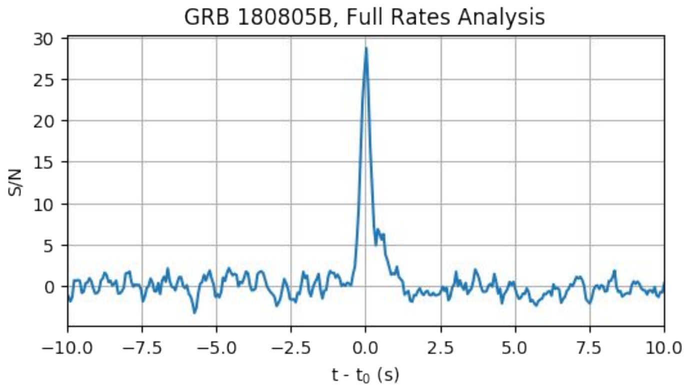
Targeted Search Pipeline

- Pipeline to run GRB search around some external trigger time
- Includes simpler analyses for seeding to find interesting times and cut down position parameter space

Searches for GRB-like emission in time bins around some time of interest, t_0

- Tests durations of 0.128 s, 0.256 s, …, 16.384 s
- For each duration time bins are made from t_0 - 20 s to t_0 + 20 s, with a step of ¼ the duration

>1000 time bins



0.256 s time bins

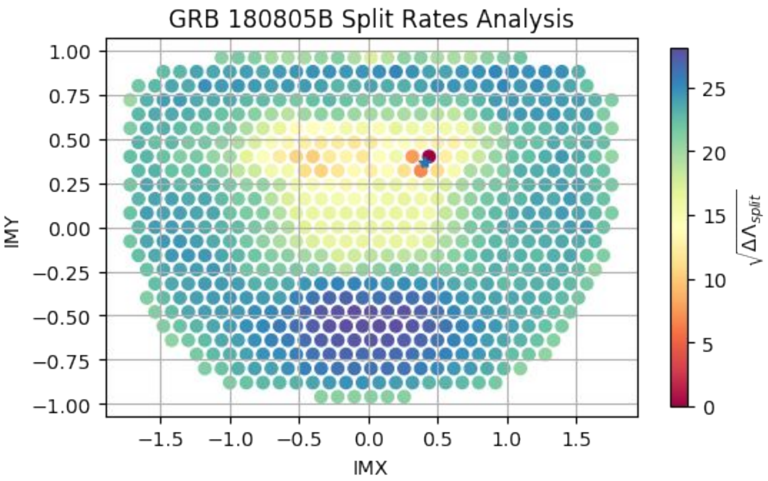
Full Rates Analysis

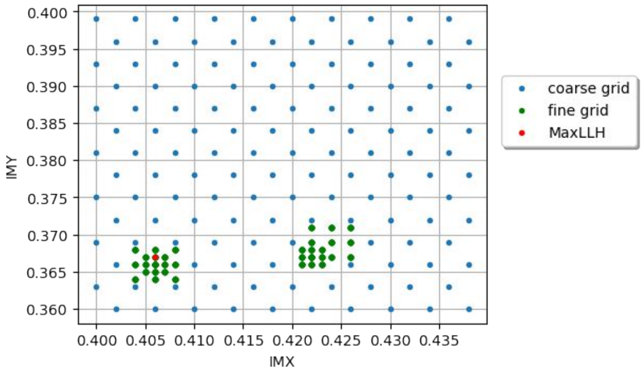
- Using the counts from all detectors and energy bins, excesses above background are checked for in all of the time bins.
- The few bins with the highest S/N for each duration size are kept as time seeds.
- N_{bkg} and σ_{bkg} are calculated using a linear fit to the rates.

$$S/N_i^{rates} = \frac{N_i - N_{bkg}}{\sqrt{N_{bkg}^2 + \sigma_{bkg}^2}}$$

<100 time bins

Targeted Search Pipeline





<100 time bin seeds

Split Detector Rates Analysis

- In order to get spatial seeds, a simplified likelihood is used where instead of making each detector its own bin, only 2 det bins are used: coded and uncoded dets
- Enough counts to use Gaussian approximation of LLH
- Λ_{split} = -2(LLH^{split} ($\boldsymbol{\Theta}_{Bkg,}$A=0 | **N**) - max[LLH^{split} ($\boldsymbol{\Theta}_{Bkg,}\boldsymbol{\Theta}_{sig}$ | **N**)])
- Time seeds are chosen using the max $\sqrt{\Lambda_{split}}$ from each incoming time bin, with ≤ 8 kept
- For each remaining time bin, the coded FoV is split up into squares in imx, imy. Squares are chosen as position seeds based on the nearby $\Delta\Lambda_{split} = \max(\Lambda_{split}) - \Lambda_{split}$ values, choosing ~8% - 35% of the FoV.
- No position seeds are chosen for out of the FoV, whole region is done

≤ 8 time bin seeds

Square Scanning

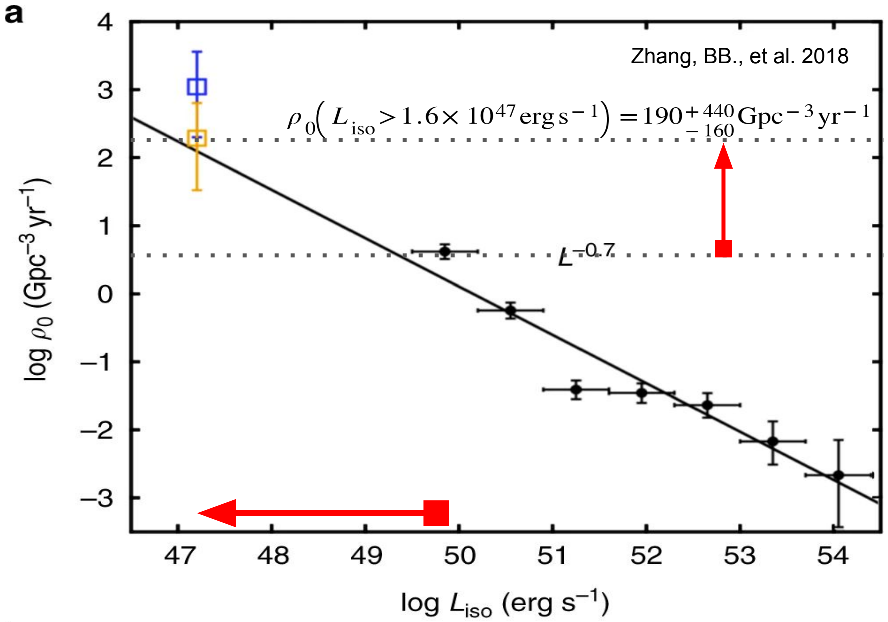
- In each square seed, the nLLH is minimized over a coarse and staggered imx, imy grid
- Then around largest LLH spots, a finer grid and more spectral points are used

Out of Coded FoV

For each time bin the LLH is optimized at each pixel position of an Nside 16 Healpix map that's at < 5% partial coding

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

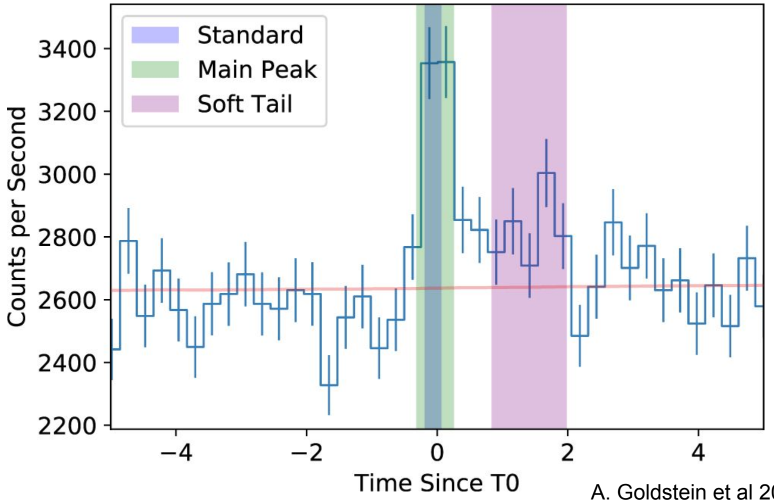
Normal sGRB emission

E_{peak} = 185 keV

Soft Tail

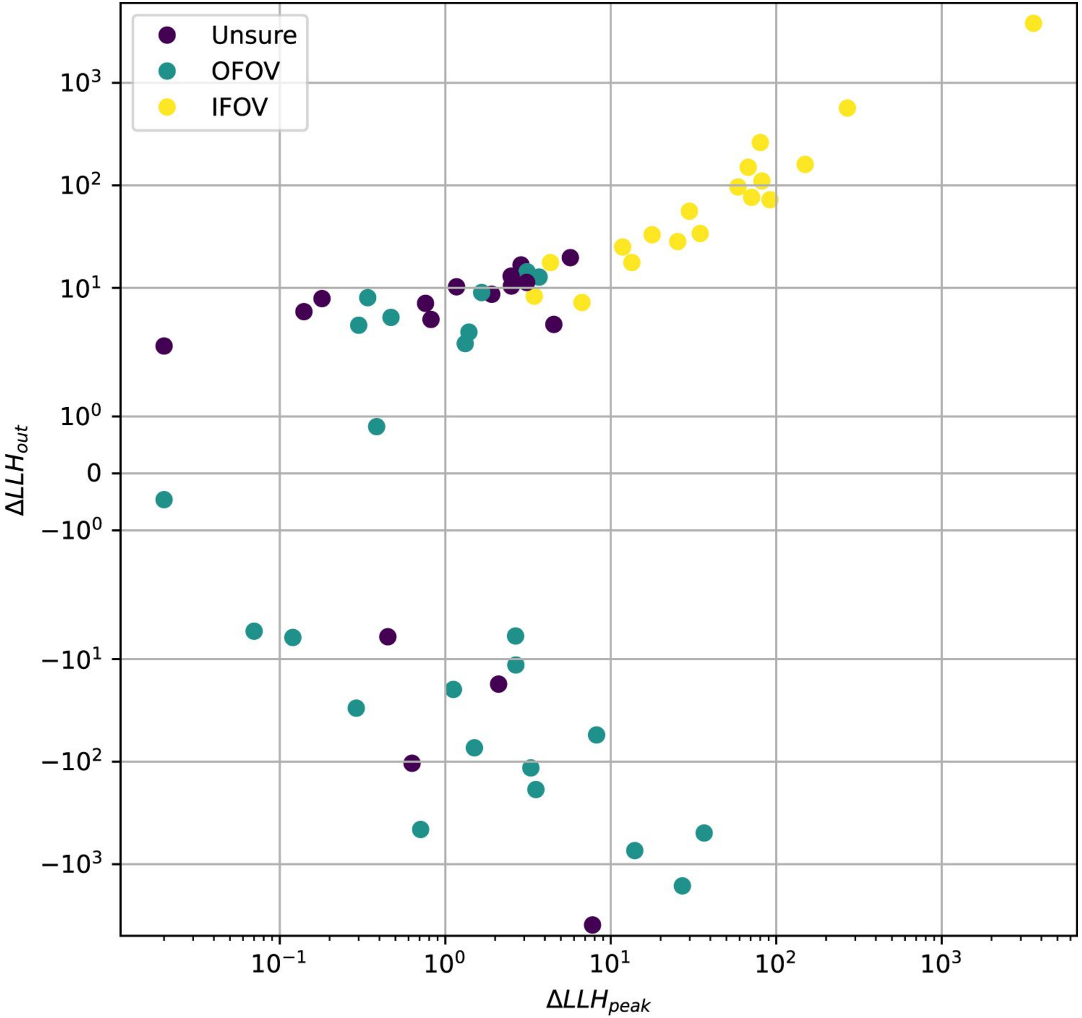
Best fit by thermal spectrum

kT = 10.3 keV



A. Goldstein et al 2017
ApJL 848 L14

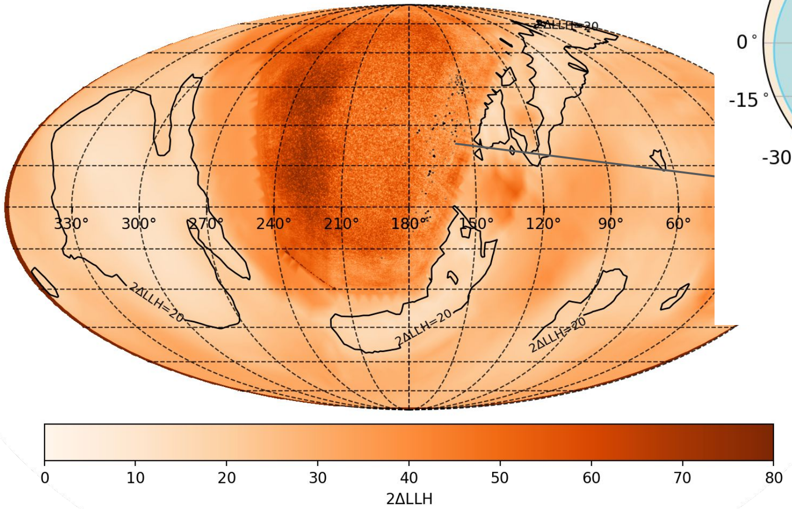
Main peak fluence larger than soft tail by a factor of ~3

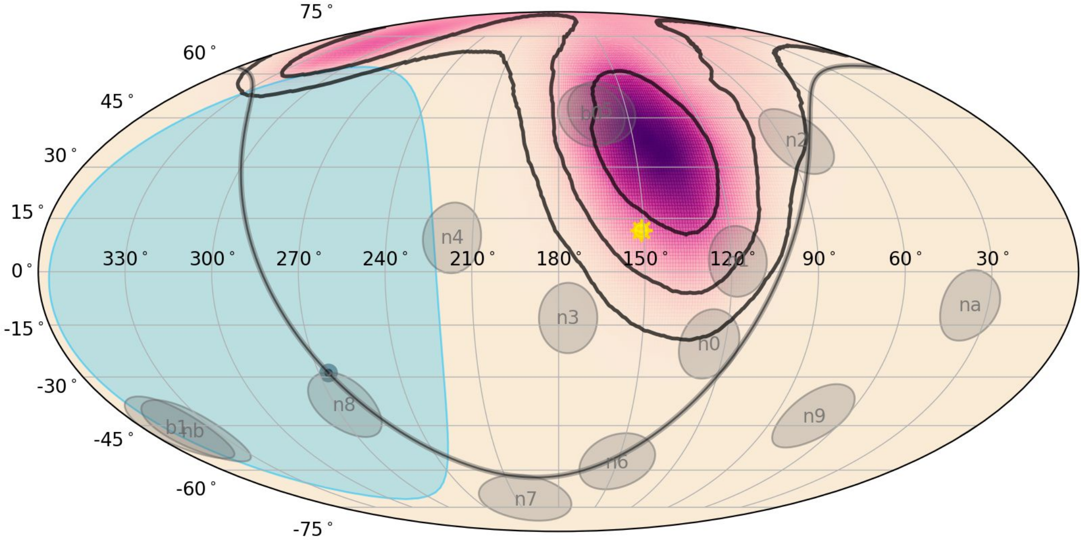


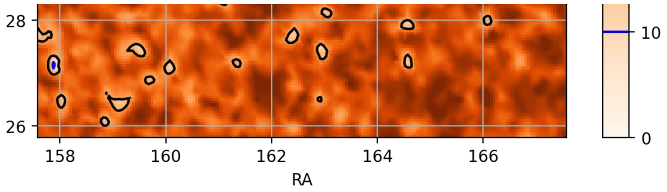
Unsure
OFOV
IFOV
10^3
10^2
10^1
10^0
0
-10^0
-10^1
-10^2
-10^3
ΔLLH_{out}
10^{-1}
10^0
10^1
10^2
10^3
ΔLLH_{peak}

Skymap - work in progress

GRB 220822A
Fermi Trigger 714440939
$\sqrt{\Lambda}$ = 9.69, ΔLLH_{out} = 7, ΔLLH_{peak} = 0.2



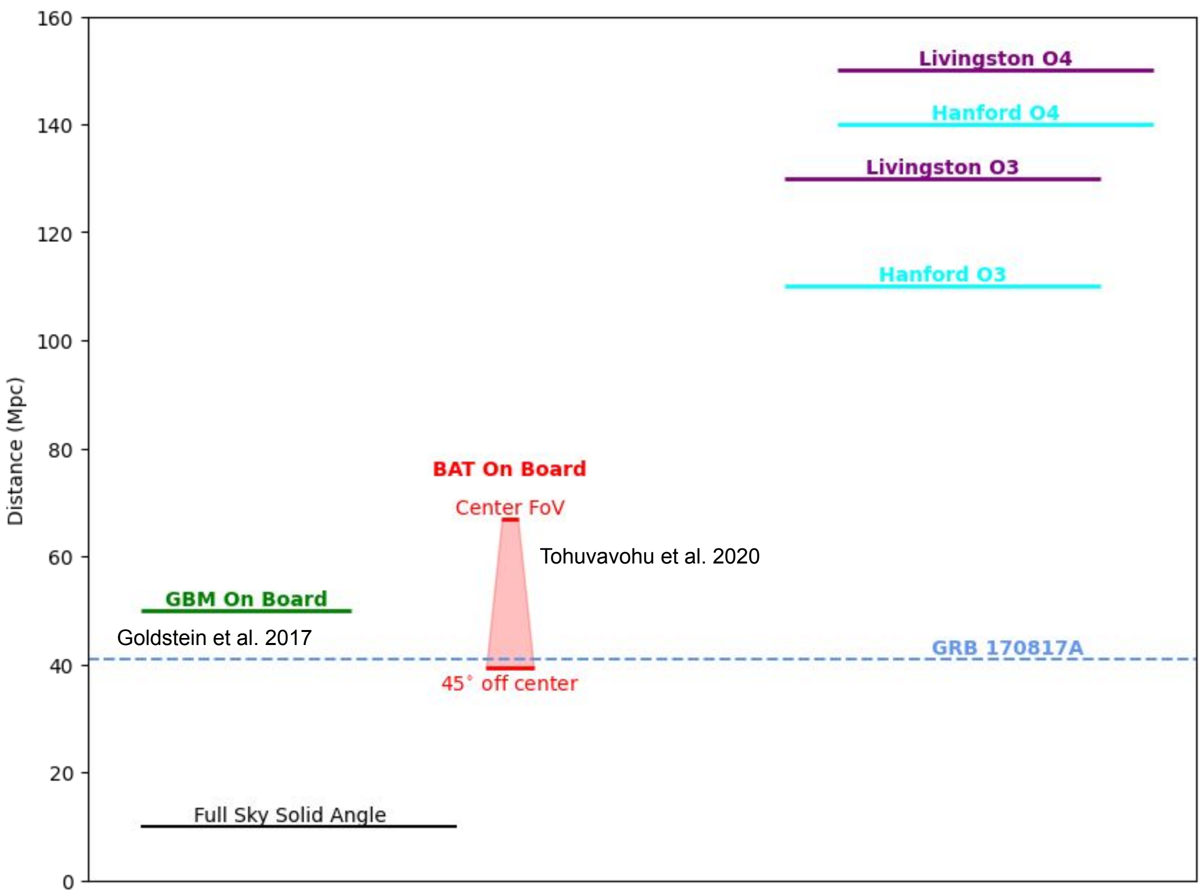




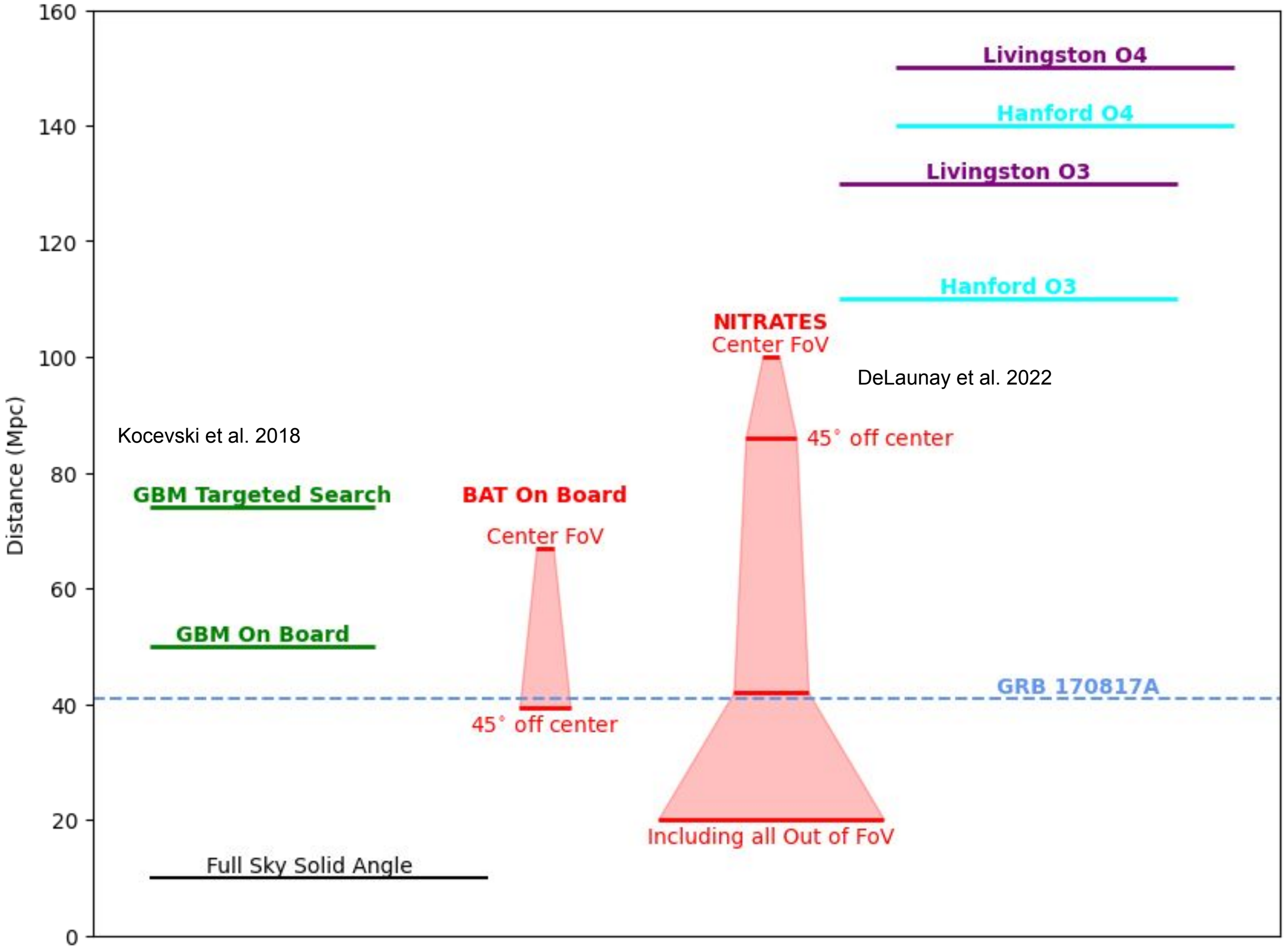
2ΔLLH = 20 ~> 90% containment

Suggestions on how best to show/communicate this are welcome

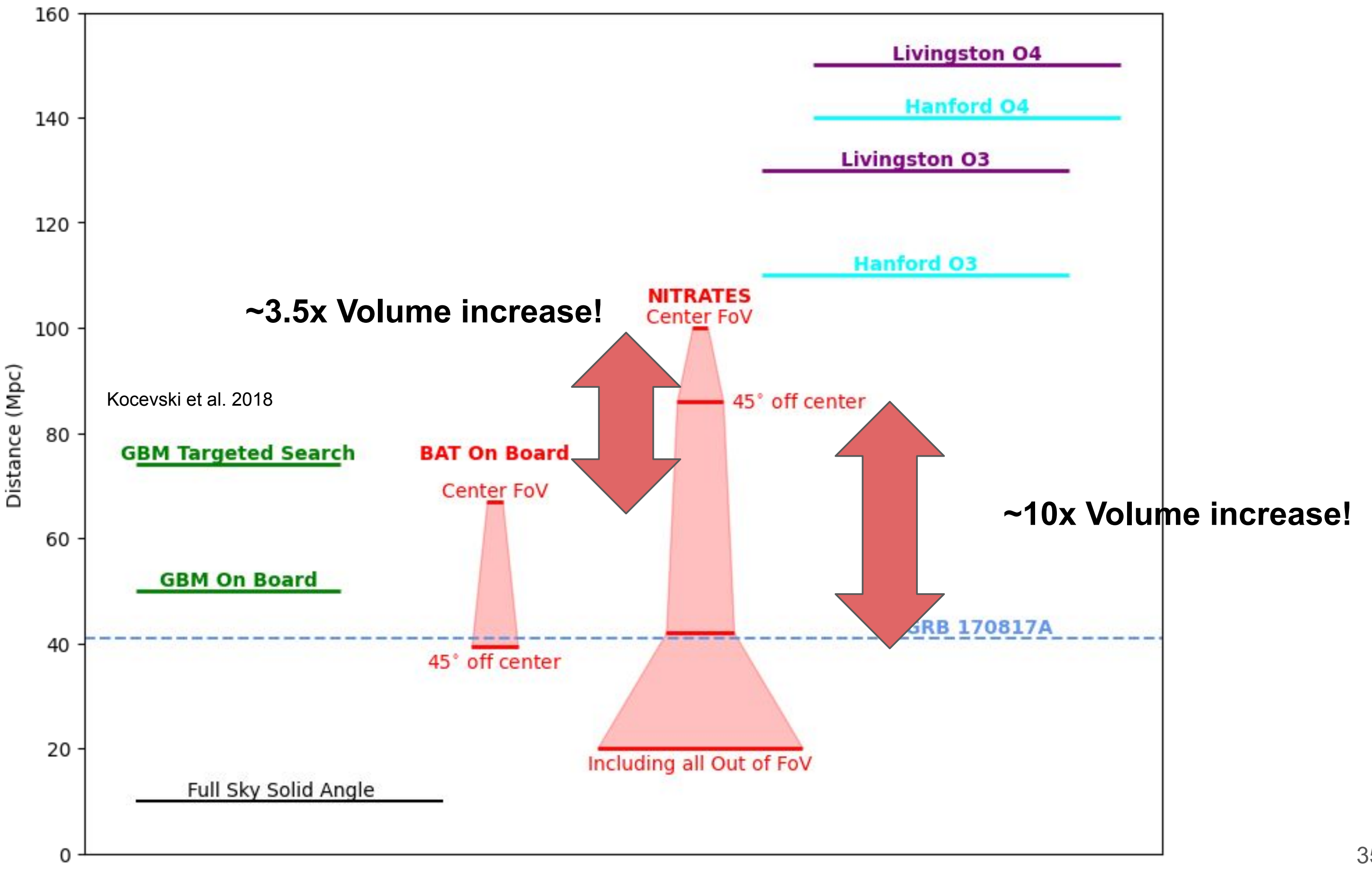
Maximum detection distance for a GRB like GRB 170817A



BNS Range



Livingston O4
Hanford O4
Livingston O3
Hanford O3
NITRATES
Center FoV
DeLaunay et al. 2022
45° off center
Kocevski et al. 2018
GBM Targeted Search
BAT On Board
Center FoV
GBM On Board
GRB 170817A
45° off center
Including all Out of FoV
Full Sky Solid Angle
Distance (Mpc)
160
140
120
100
80
60
40
20
0



160
140
120
100
80
60
40
20
0
Distance (Mpc)
Livingston O4
Hanford O4
Livingston O3
Hanford O3
~3.5x Volume increase!
NITRATES
Center FoV
45° off center
Kocevski et al. 2018
GBM Targeted Search
BAT On Board
Center FoV
~10x Volume increase!
GBM On Board
GRB 170817A
45° off center
Including all Out of FoV
Full Sky Solid Angle