Fantastic B~~ea~~ur~~sts~~ and ~~Where~~ How to Find Them

Aaron Tohuvavohu
(University of Toronto)

And the BAT-GUANO and Treasure Map teams

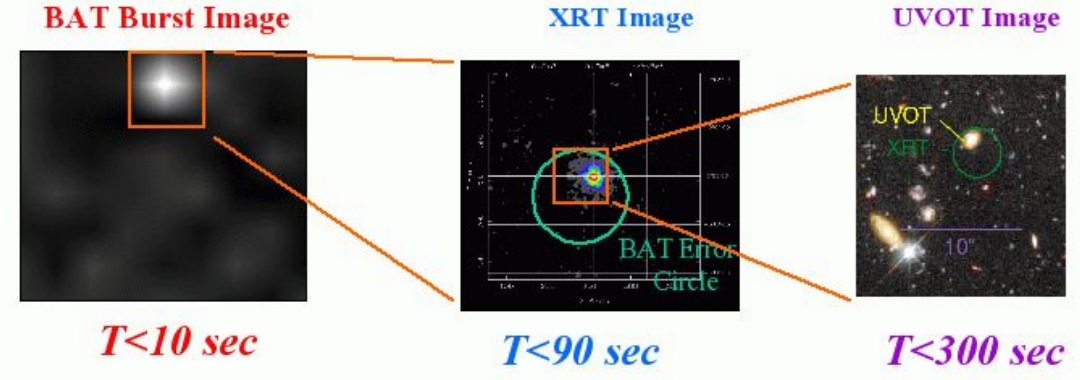
The 3 most important things for GRBs

1. **Location**
2. **Location**
3. Low-latency **Location**

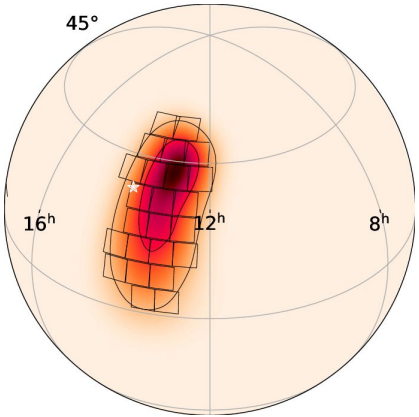
Need a localization small enough for multi-wavelength characterization (<a few arcmin)

Two approaches:

Best Case: Localize from prompt emission alone



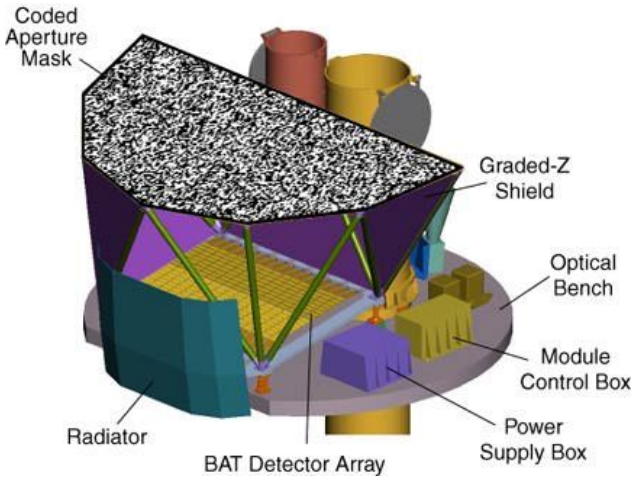
Most missions here: Expect wide-field off-band searches of large localization regions



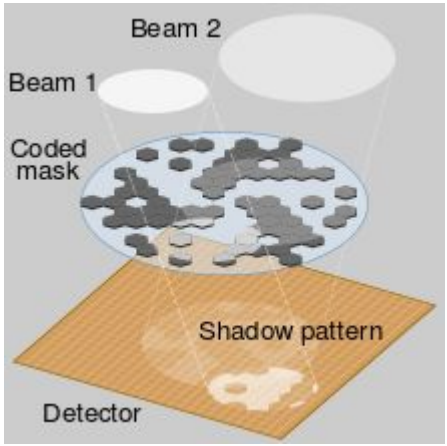
Credit: Leo Singer, probably

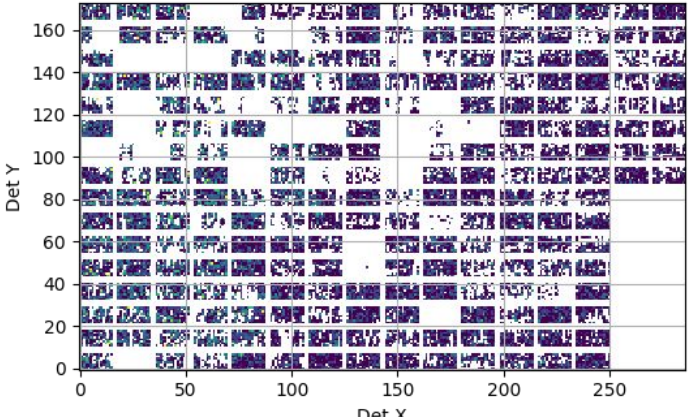
Swift Burst Alert Telescope

(shadowgrams)

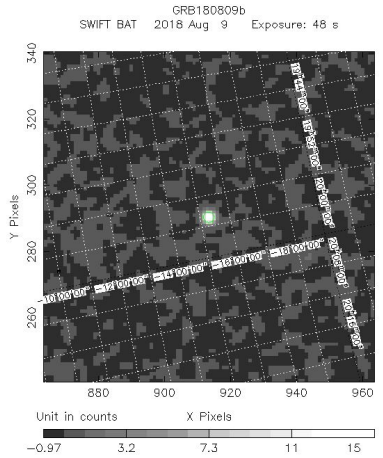


- Hard X-rays (15-350 keV)
- 1/6 of the whole sky (~2 sr.) FoV
- Localizes ~100 GRB/yr onboard
- Prompt Arc-minute localization



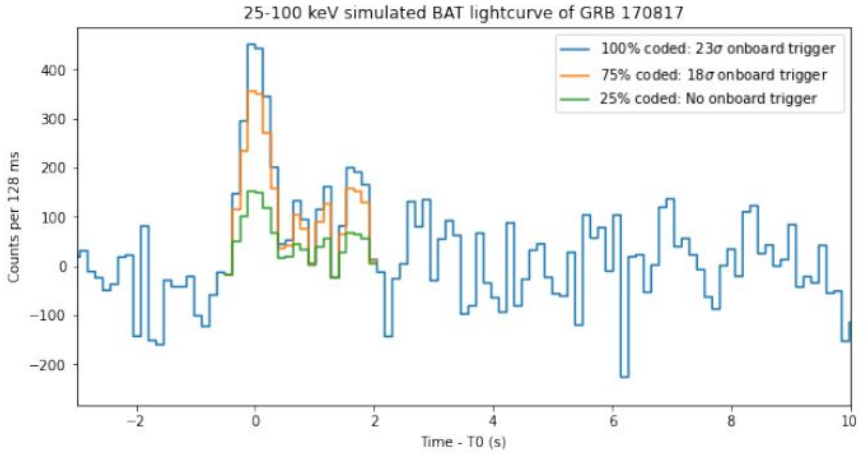


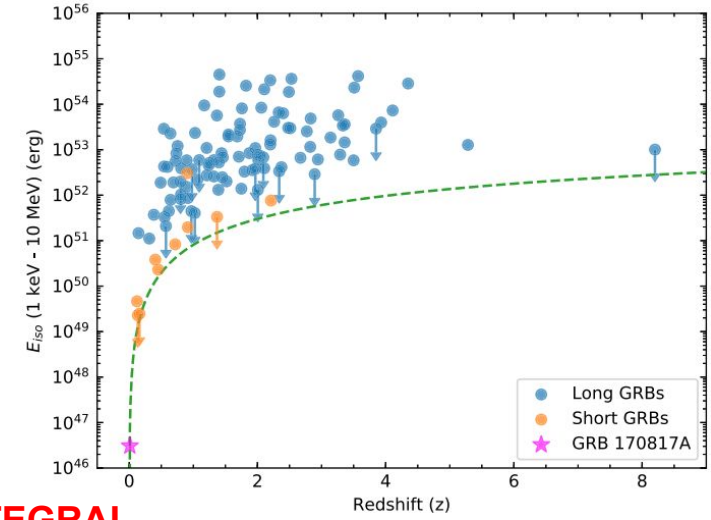
Correlation and FFT w/ mask pattern



Intrinsic capability of BAT

- With event data (each count tagged with time, photon energy, detector) can perform shadowgram, or other sensitive GRB searches
- Simulations show GRB 170817-like burst recoverable out to ~100 Mpc, almost 2x as far as any other instrument
- Only BAT can provide prompt arcmin localization for pointed follow-up at very early times, window to crucial physics
- BAT localization alone provides unique host galaxy ID in local universe





Undetectable for Fermi/INTEGRAL beyond ~60-70 Mpc!!!

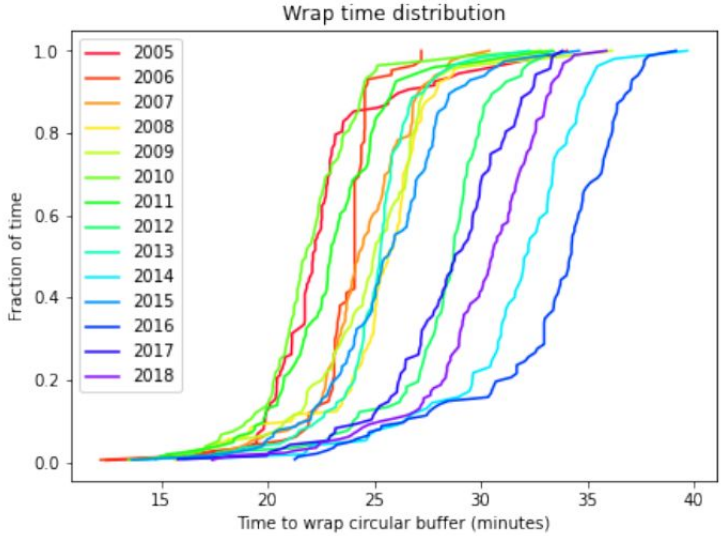
The Problem: Required Data Don't Make it to the Ground

- *Swift* mission design was for prompt (~seconds) ID and location of bursts
  - No requirement for non real-time analysis

- BAT effective area very large→ High Data Volume
- Antenna is bandwidth limited and onboard recorders are insufficient

- Result: For ~15 years BAT has relied on onboard real-time analyses to find GRBs
  - No targeted searches
  - No way to assess completeness/selection effects of onboard trigger algorithms

- **Data we need are saved to an onboard ring buffer. If we can get to it in time, and get it to the ground, great science is possible!**

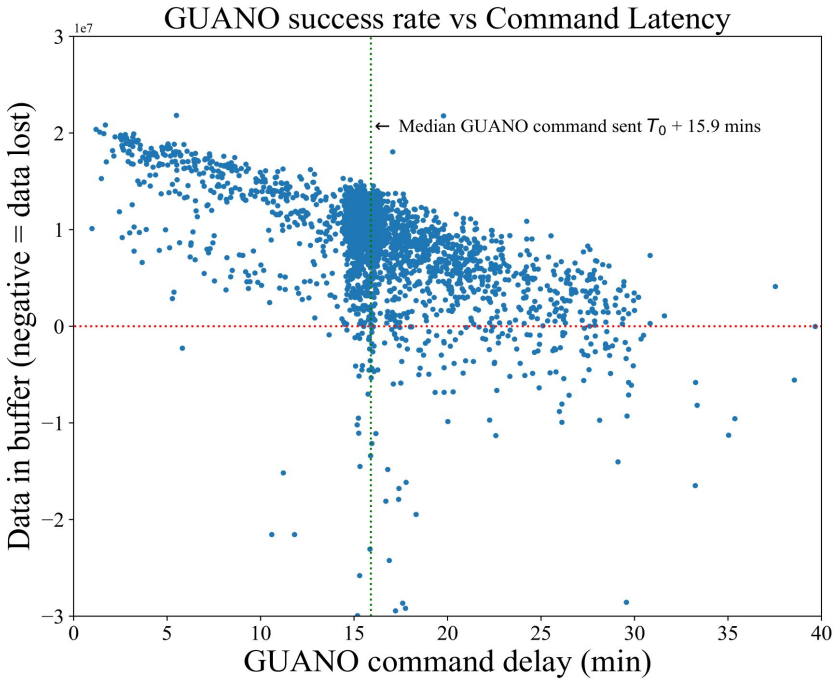


"Fast response" commanding was ~2-4 hours!!!!!

Gamma-ray Urgent Archiver for Novel Opportunities (GUANO):

Swift/BAT dumps on demand to enable sensitive sub-threshold GRB searches

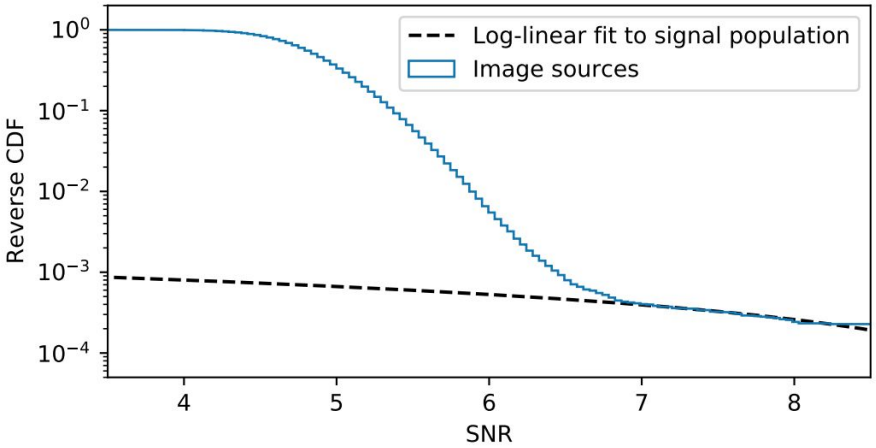
(AT, Kennea, DeLaunay, et al. 2020: 2005.01751)

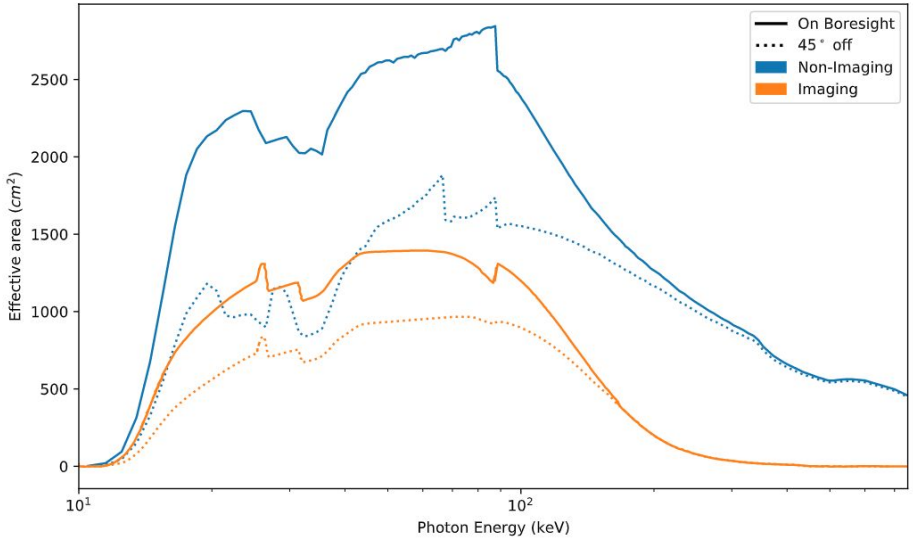


- **Autonomously commanding spacecraft in extremely low latency to save temporally coincident event level data. ~5x/day**
- **First ever autonomous on-demand commanding of a space telescope for scientific purposes**
- **Commanding infrastructure also now used for very low-latency ToO repoint with narrow-field *Swift* instruments**
  - **On target to FRBs in O(10) minutes**

Now can do imaging, but...

- Large Image Noise population ⟶
- Rejection of uncoded counts on detector, which contain information
- Neglects energy information associated with each count
- Pays a mask-weighting A_{eff} efficiency factor
- Lower A_{eff} at higher energies due to mask transmission⟶ Lower sensitivity to short hard GRBs

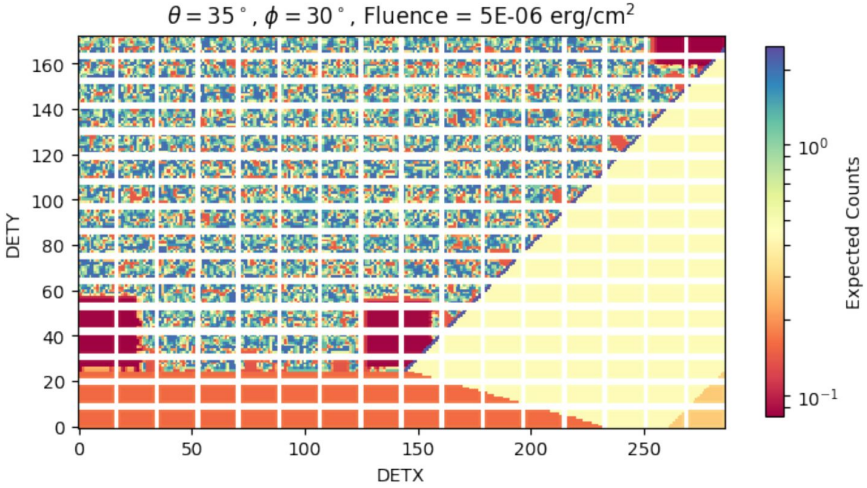


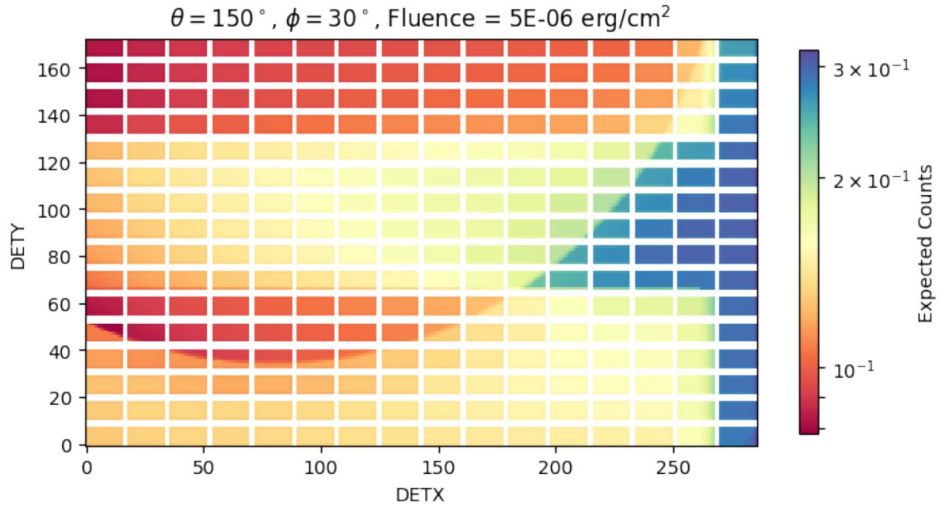


NITRATES (Non-Imaging Transient Reconstruction And TEmporal Search):

A new maximum likelihood Analysis Framework for BAT data

- Using the GUANO data, and bursts with known positions and spectra, we calibrate the BAT out-of-FoV response for the first time.
- GRBs are fully forward modelled through the instrument response, and resultant shadowgrams are produced
- These data models are compared to the observed data with a likelihood test
- 3-5 x more sensitive than imaging

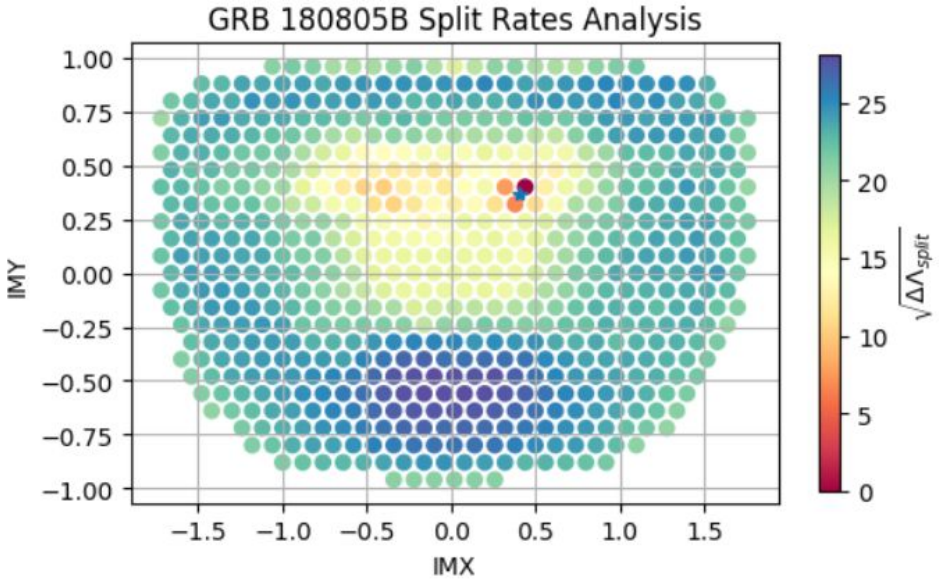


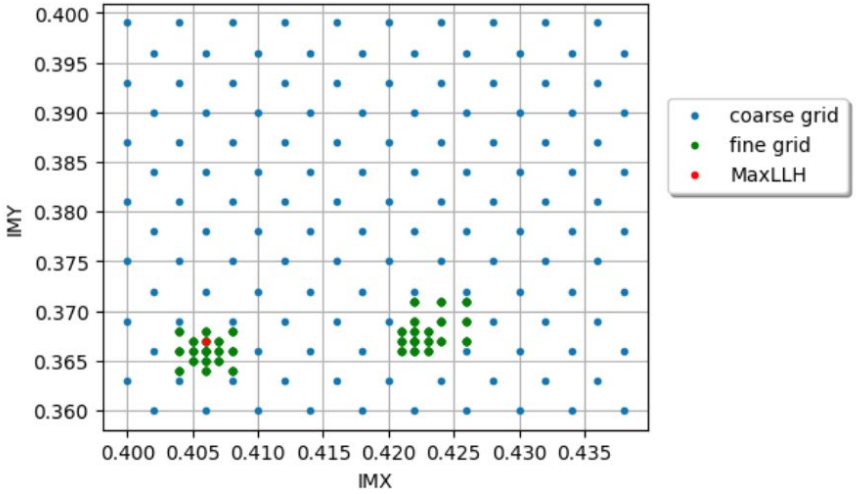


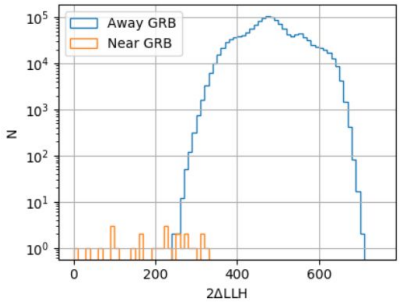
J. DeLaunay + AT, 2021

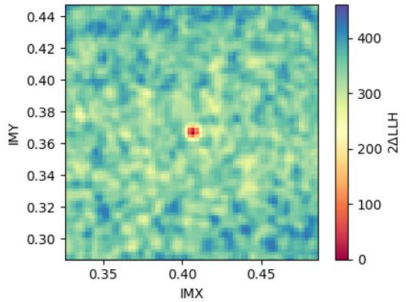
NITRATES:

- **The spatial parameter space to search is massive: FOV ~7000 deg^2 and PSF ~20 arcmin.**
- **Response varies very rapidly across the FoV. Can't possible search every location in low-latency.**
- **Need spatial seeding and intelligent stage-refined localization tests.**
- **Even with seeding ~500 CPU hours required.**









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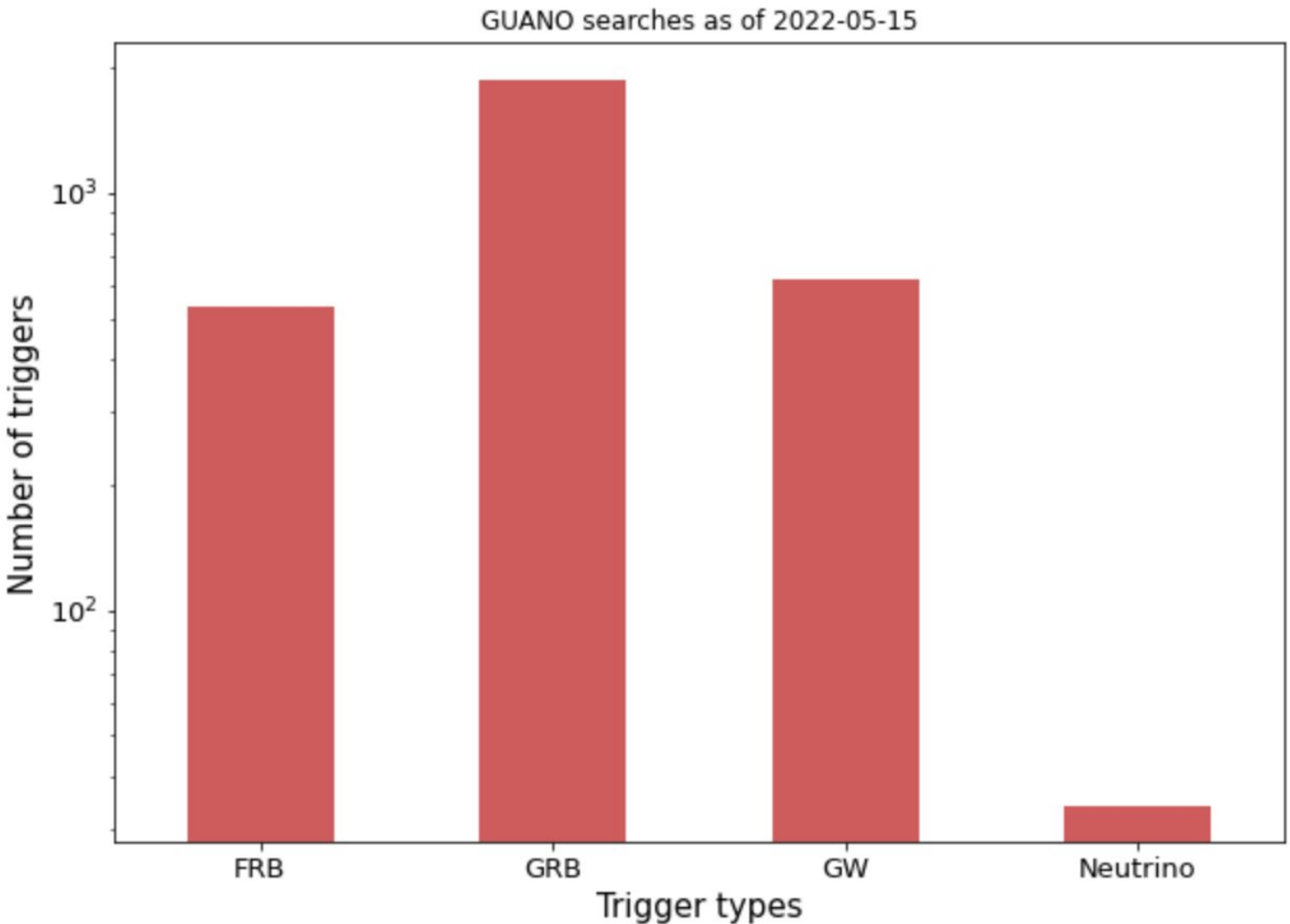
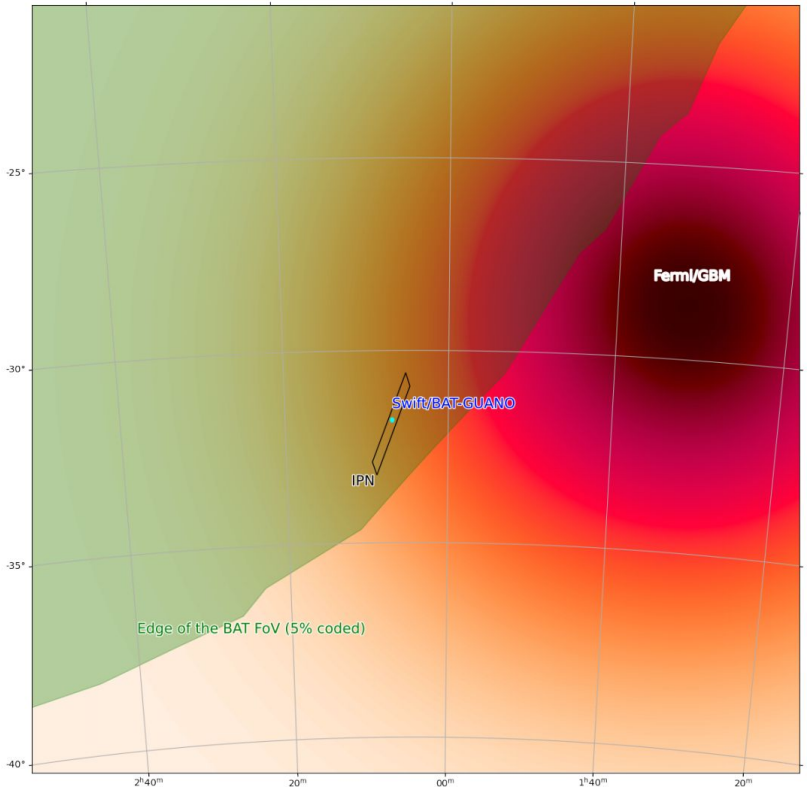

GUANO searches as of 2022-05-15
Number of triggers
10^3
10^2
FRB
GRB
GW
Neutrino
Trigger types

External GRB triggered search results:

- Since Feb 2020: Triggering on GRBs detected by Fermi, INTEGRAL, CALET, GECAM, **YOUR MISSION HERE**
- These GRBs have either large (~100-1000 deg^2) or no localizations
- GUANO has recovered **arcminute localizations for 33 GRBs** to date (~1/month).
  - **>15% of all arcmin localized GRBs.**
- Higher short GRB recovery fraction
  - 25% vs 10% for BAT onboard
- Localizations distributed to community for follow-up in O(hours) via GCN
  - 22 of 33 got prompt follow-up
  - **14 afterglows discovered**



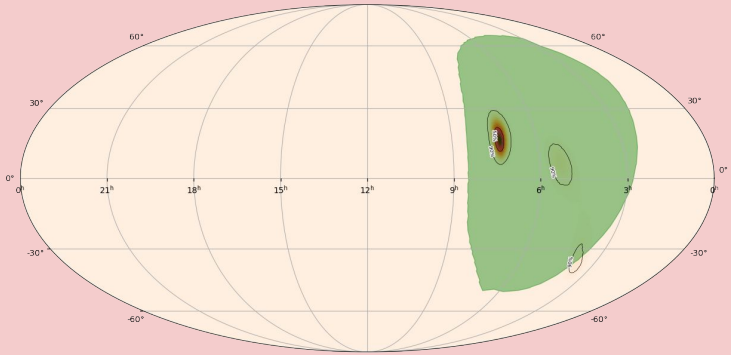
Many localizations unrecoverable with conventional imaging

Search Sensitivity

Using this method and GBM data the flux and light curve shape, computed detection horizon for a GRB 170817A-like burst via injections

Max distance for 90% recoverability
- **At FoV center ~ 115 Mpc**
- **45deg off center ~ 90 Mpc**

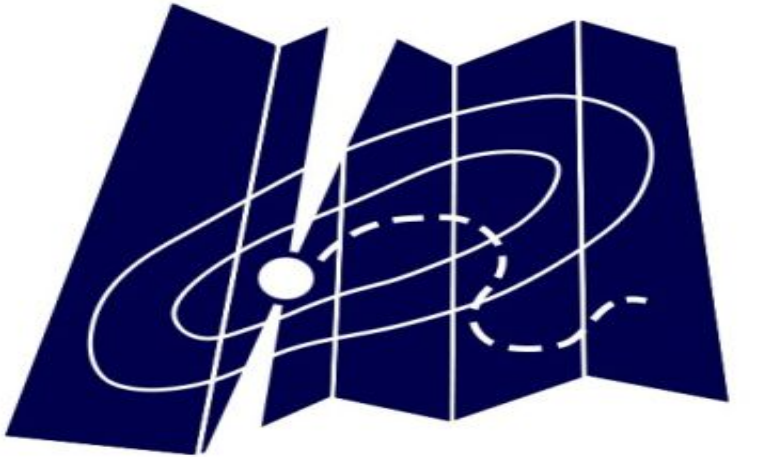
S200114f



- GW alert S200114f had >99% of its localization probability inside BAT's FoV
- Found upper limit flux for event by averaging position dependent sensitivity over skymap
- Assuming a power-law index of -1.32 found 14-195 keV flux sensitivities of
  - 2.1 x 10^{-7} erg cm^{-2} for 0.256s timescale
  - 8.1 x 10^{-8} erg cm^{-2} for 1.024s timescale

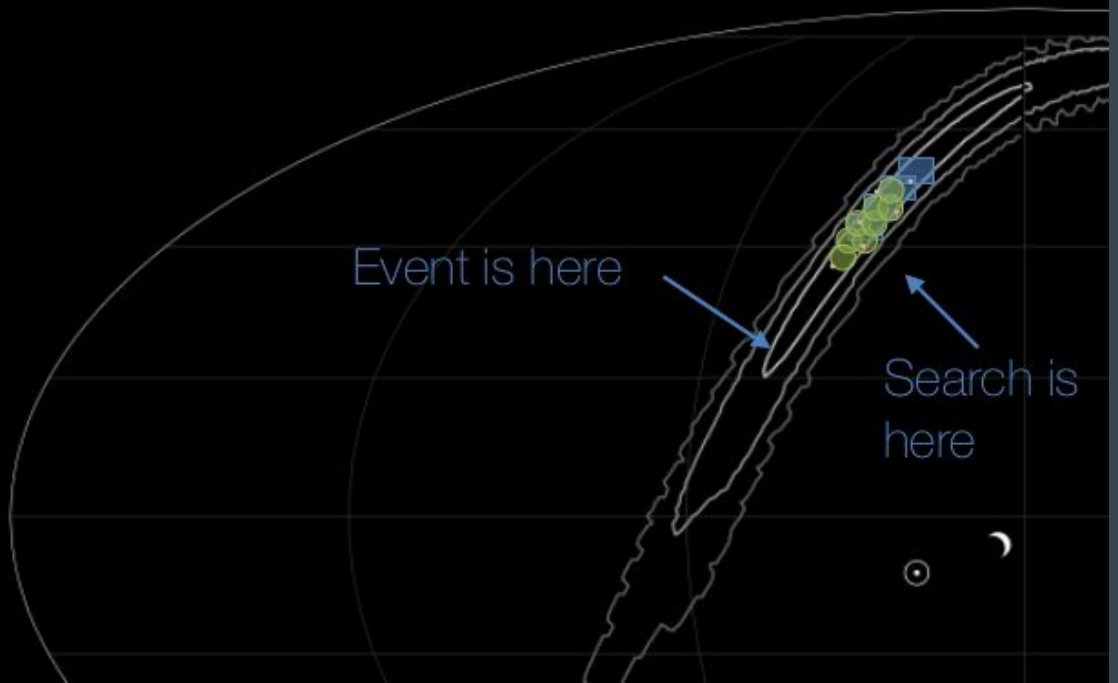
For Reference
- BAT onboard detection to ~ 65 Mpc at center of FoV
- GBM onboard detection to ~ 50 Mpc
- GBM targeted search ground analysis to < 70 Mpc

The Future of Treasure Map with GRBs?



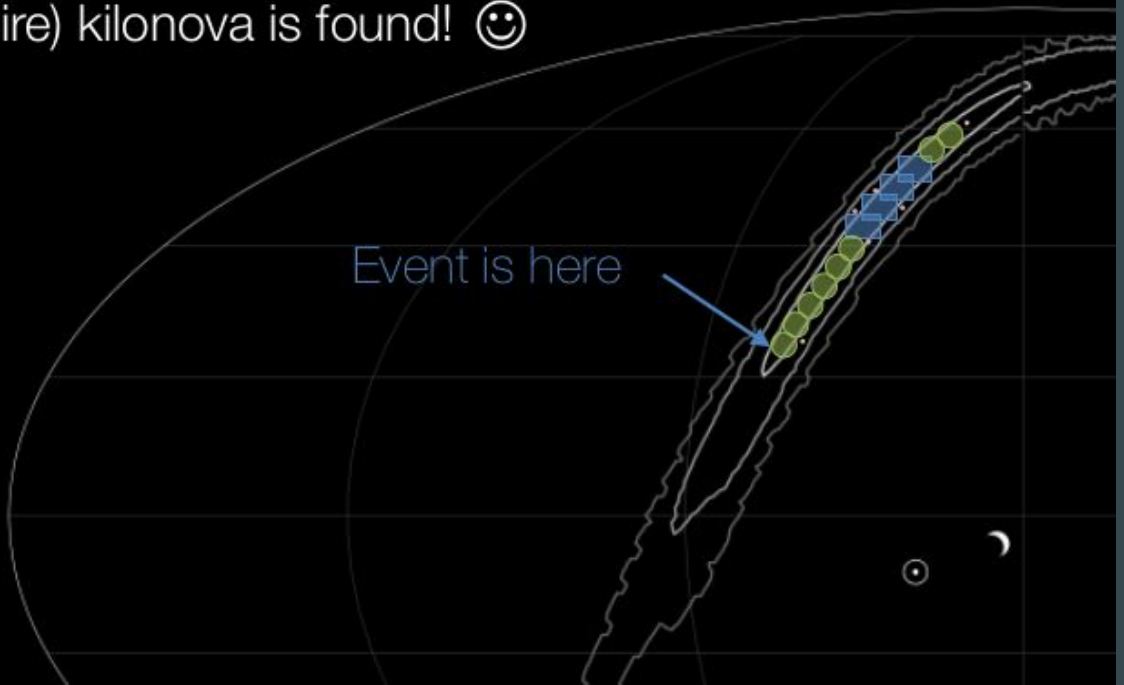
How to Avoid Unnecessary Overlap in EM Searches?

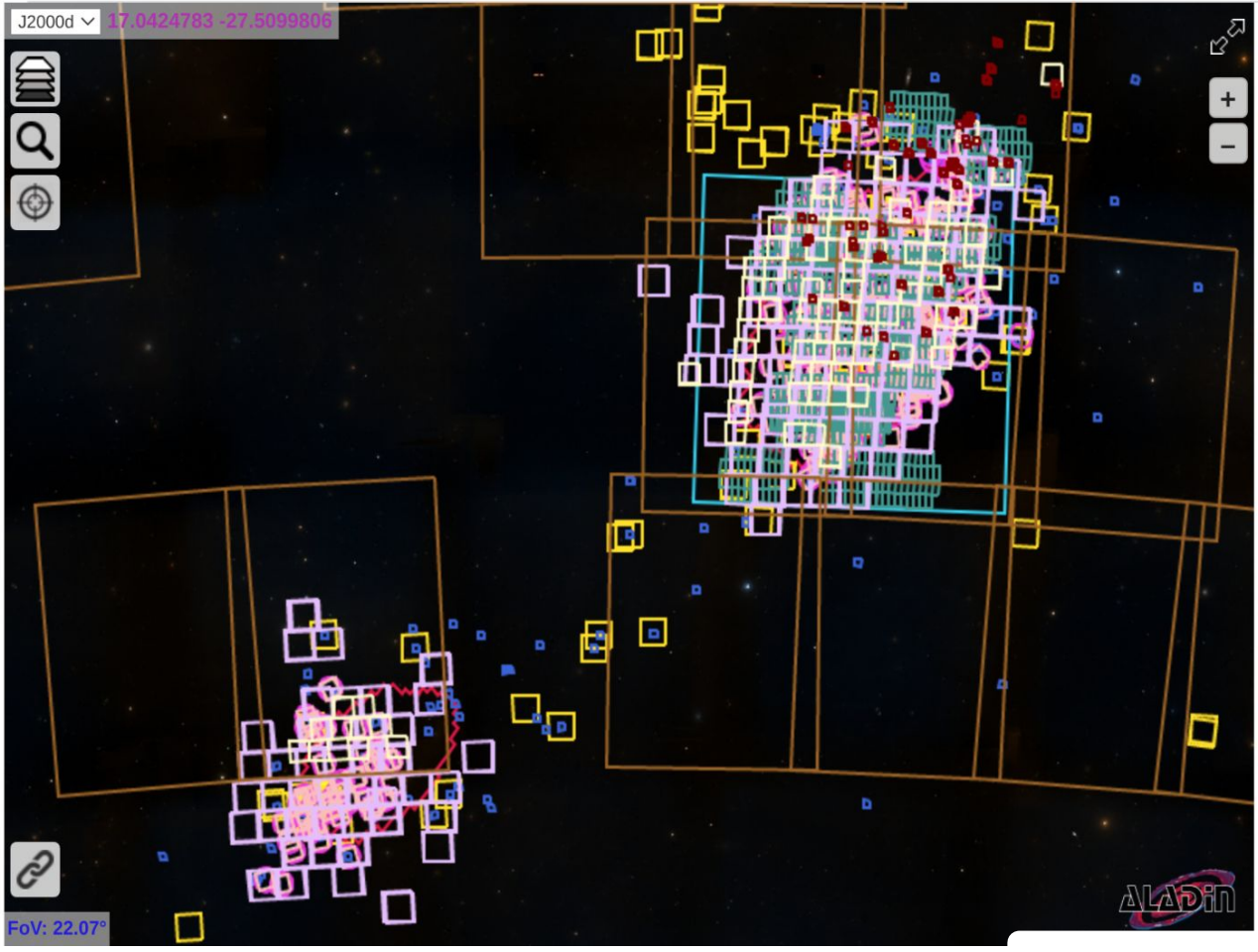
Typical Scenario:
Everyone observes the highest probability region.
Early (or entire) kilonova is missed ☹



How to Avoid Unnecessary Overlap in EM Searches?

Desired Scenario:
Resources are put to good use to cover more of the probability region.
Early (or entire) kilonova is found! ☺





Follow-Up

Hide Instruments

- Las Cumbres 1m
- KAIT
- IMACS

Show GRB Coverage

- Swift/BAT
- Fermi/GBM
- Fermi/LAT

Sources

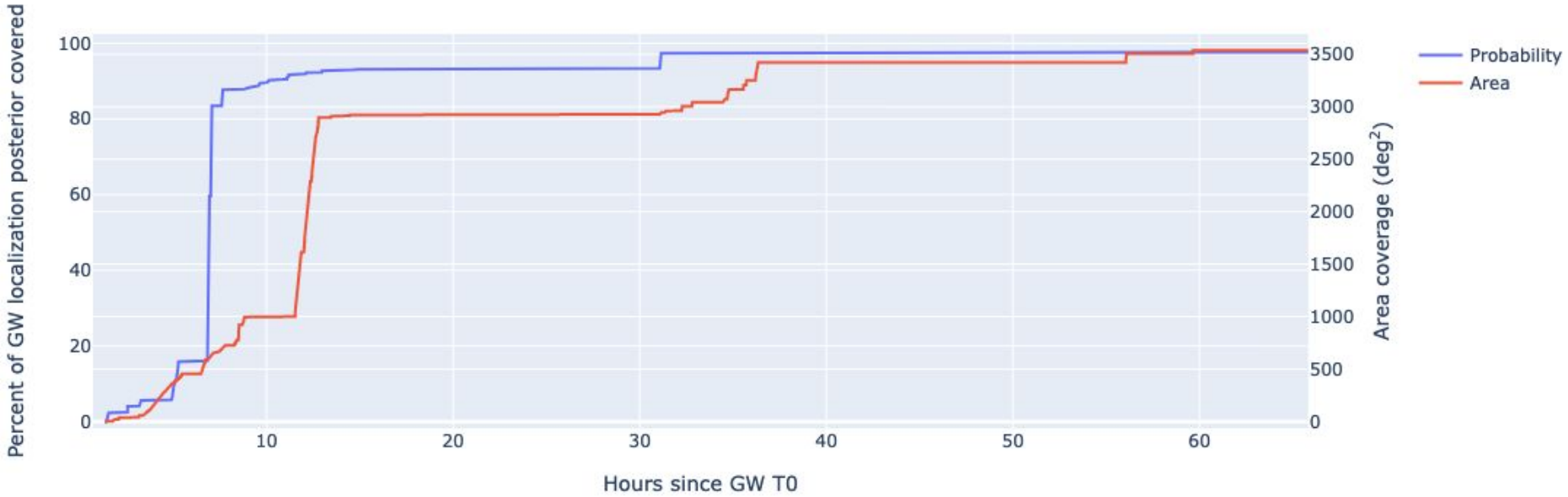
Get Galaxies

Hide XRT Sources

- SCIMMA XRT Sources

GW Treasure Map (Wyatt, AT, et al. 2020): http://treasuremap.space

>4000 search exposures
>20 instruments spanning radio → gamma


Percent of GW localization posterior covered
100
80
60
40
20
0
10
20
30
40
50
60
Hours since GW T0
3500
3000
2500
2000
1500
1000
500
0
Area coverage (deg²)
Probability
Area

Other coming/planned features

- Serve candidate counterpart information in map **DONE**
- Auto ingest TESS (+ other wide-field stare) coverage **prototype working**
- Serve Nu/gamma/GW convolved localization maps **done for one event**
- Serve suggested tiling and pointing plans to users **prototype working**
- Support IVOA scheduling/visibility query API format (obsLocTAP)
- TOM Toolkit plugin Support