Title: Seeing into the immediate post-merger environment of a neutron star collision

Speakers: Aaron Tohuvavohu

Series: Particle Physics

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Abstract: The rich EM phenomenology in the seconds, minutes, and hours just before, during, and after a compact object merger encodes the magnetization of the binary components, the nature of the post-merger remnant, the neutron star equation of state, the free neutron abundance, and a wide array of other compelling physics. Unfortunately, the requirement to search, find, and classify an electromagnetic counterpart within the large GW localization regions before targeted follow-up with sensitive instruments can begin, excludes access to these earliest times, even for the most well localized GW sources. The ability to promptly localize a GW source to within the field-of-view of a narrow-field sensitive facility, would enable extraordinary science. I will discuss the science cases that require extremely early time observations, and the coordination, instruments, and analyses necessary to achieve it. These include gamma-ray imaging, novel data analysis techniques, pre-merger GW detection, faster space telescopes, and new experiments.

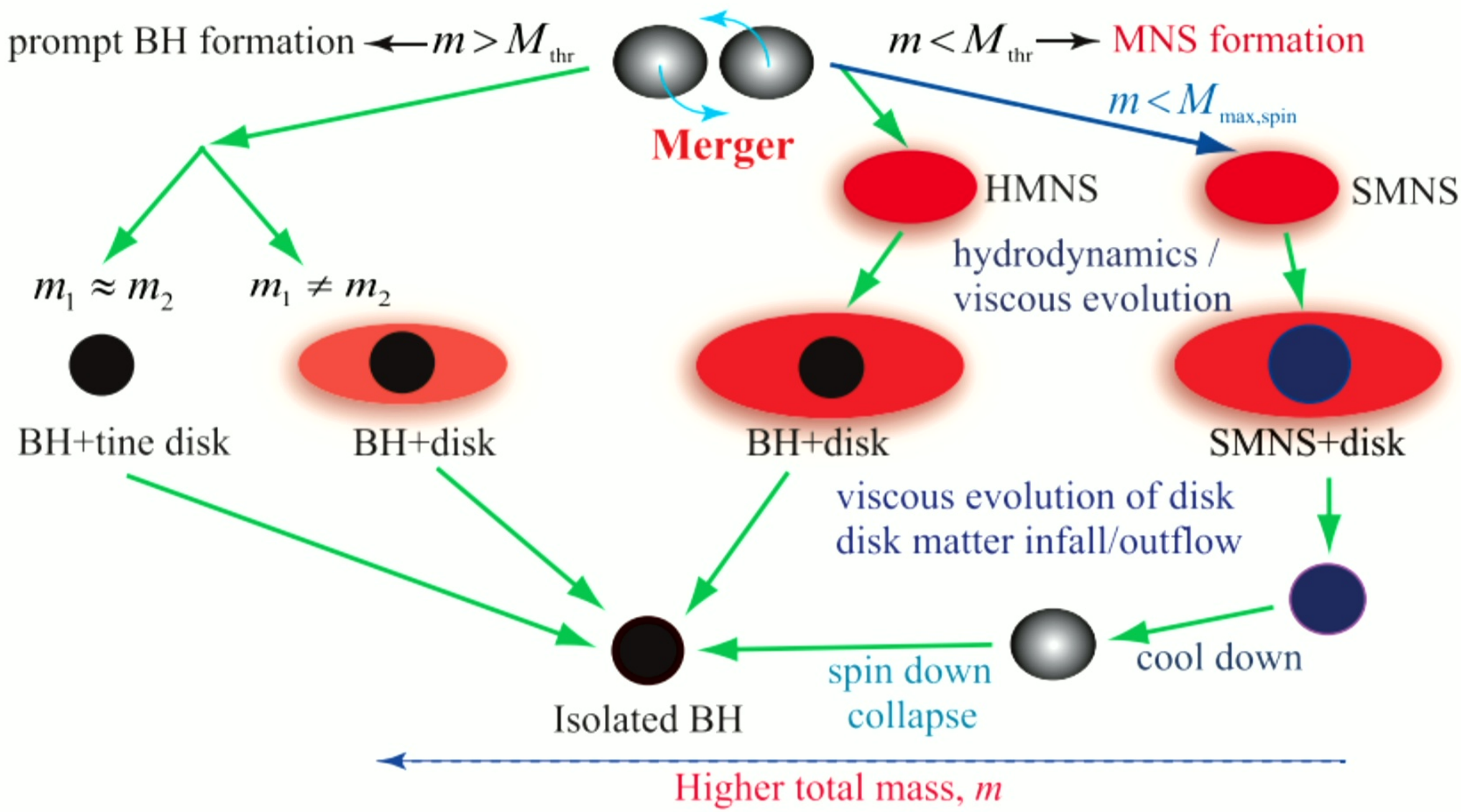
Zoom link https://pitp.zoom.us/j/96186614241?pwd=R0xpT0dDZVZzek5RT0x4Q1c3Z1RuUT09

Seeing into the immediate post-merger environment of a neutron star collision

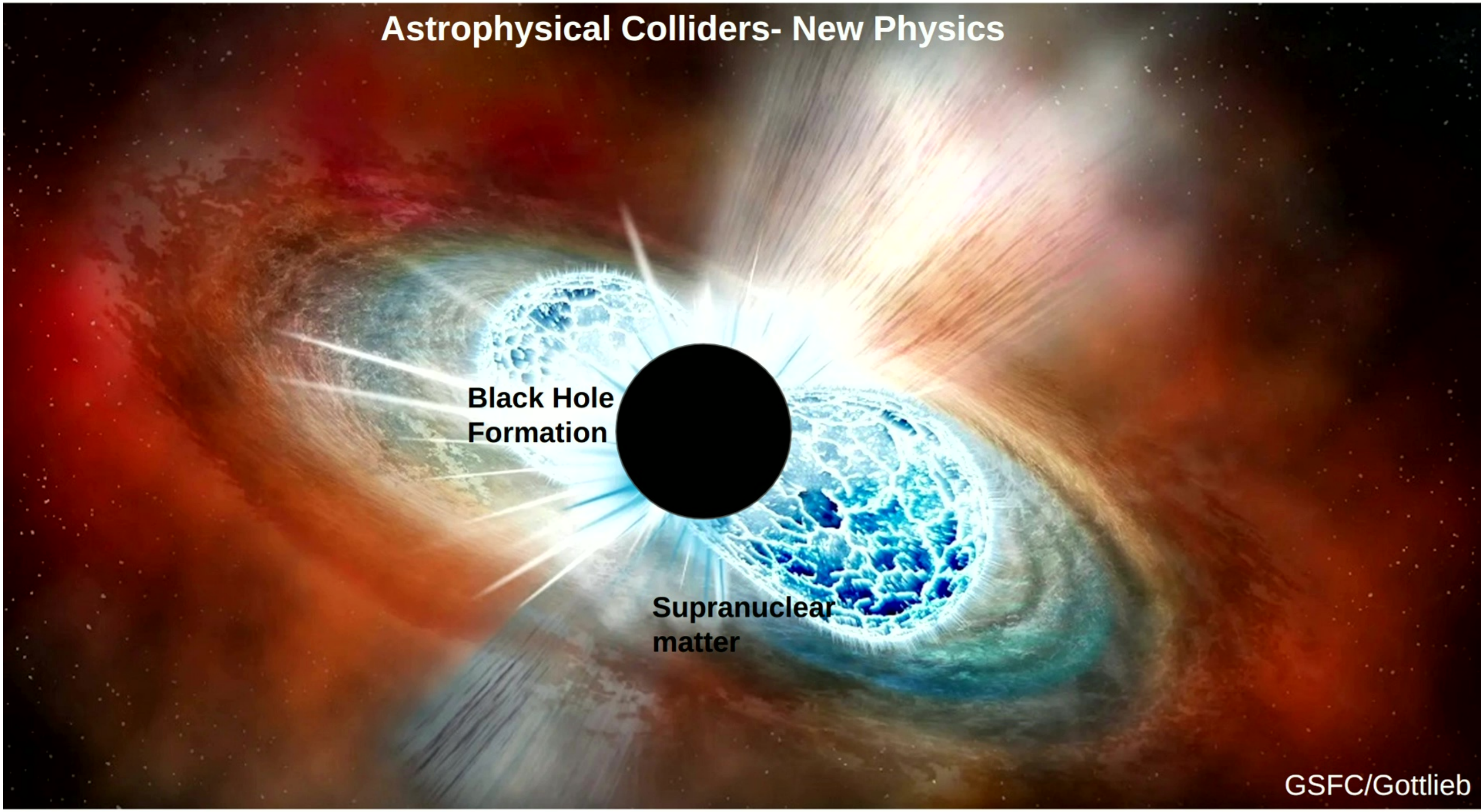
Aaron Tohuvavohu

UNIVERSITY OF TORONTO

DUNLAP INSTITUTE *for* ASTRONOMY & ASTROPHYSICS



Shibata 2019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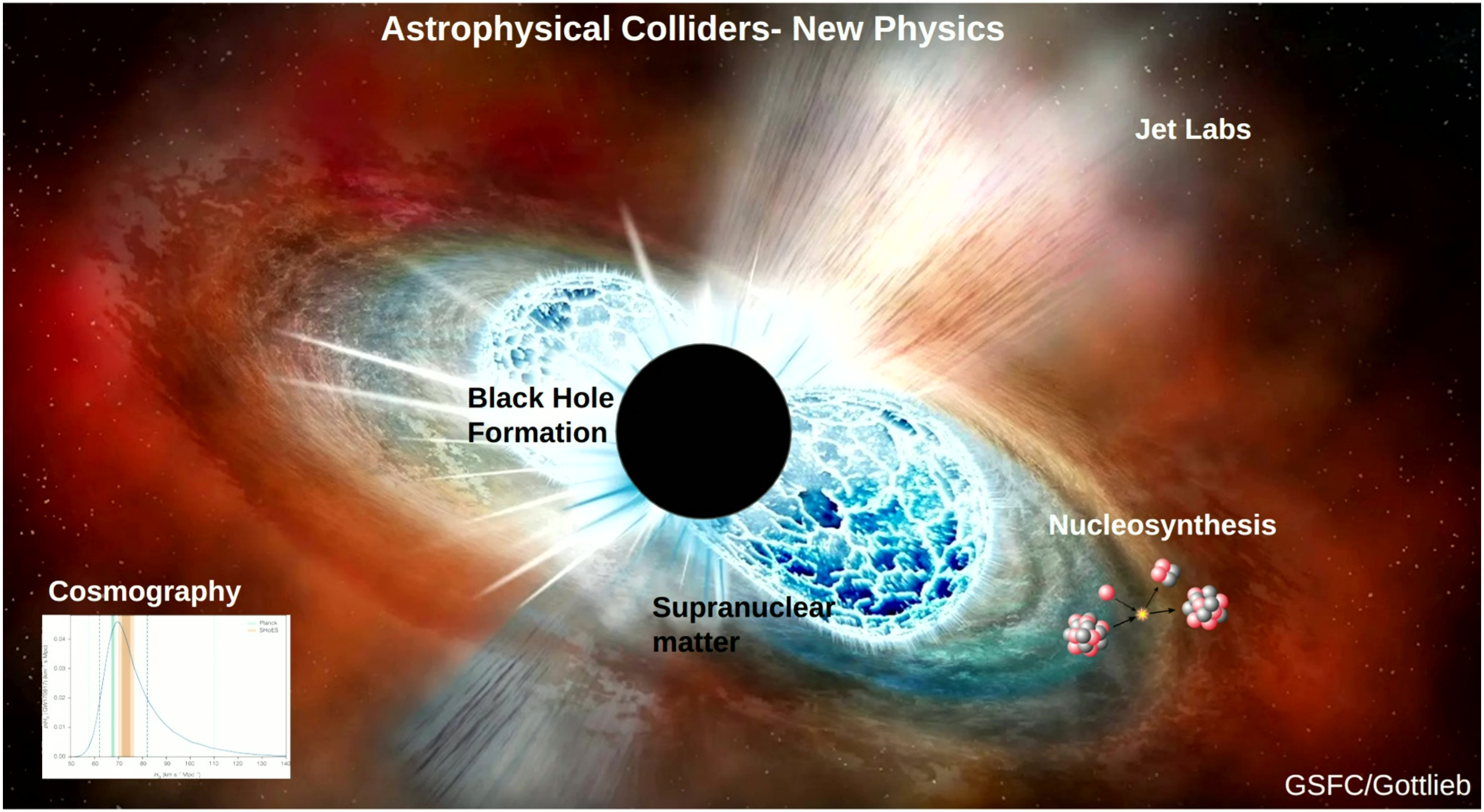
Black Hole
Formation
Supranuclear
matter
GSFC/Gottlieb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Jet Labs
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Formation
Nucleosynthesis
Cosmography
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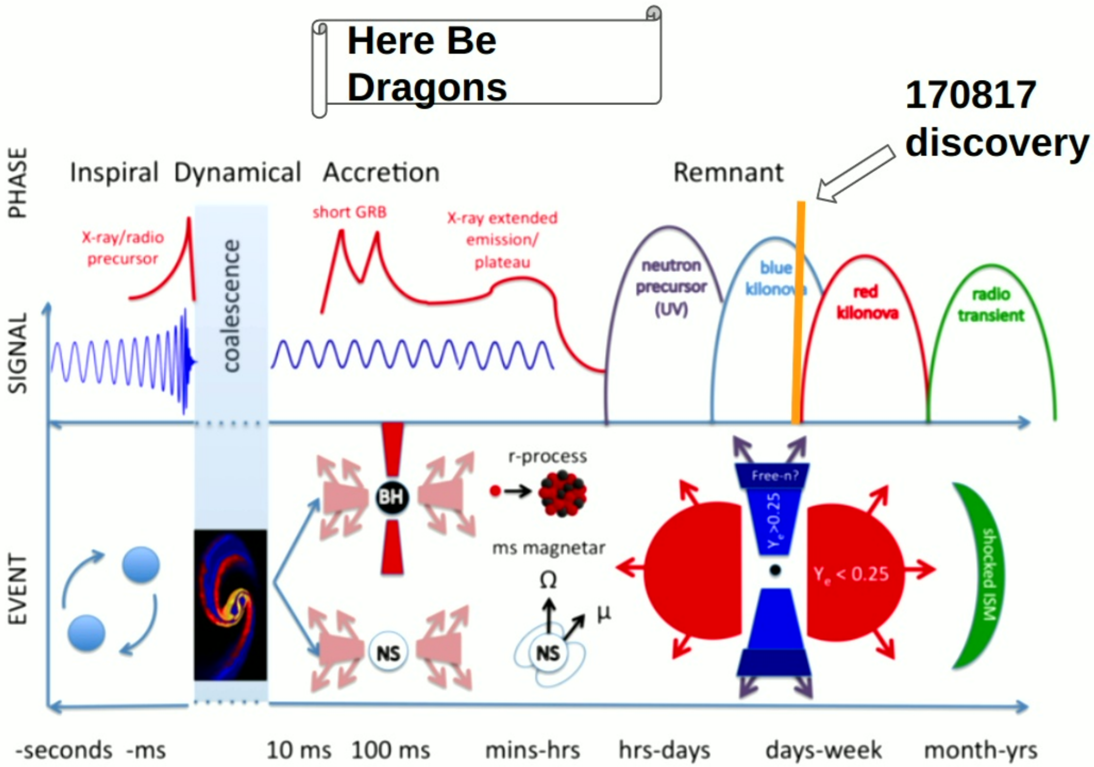
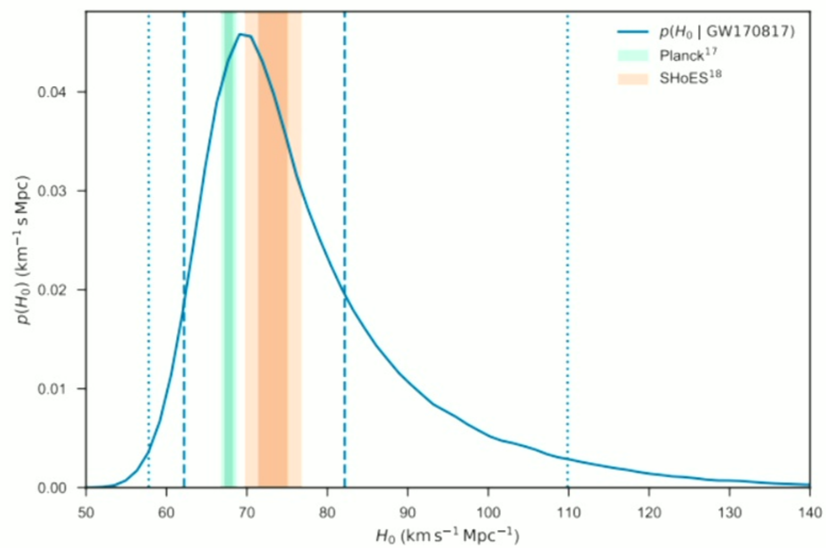
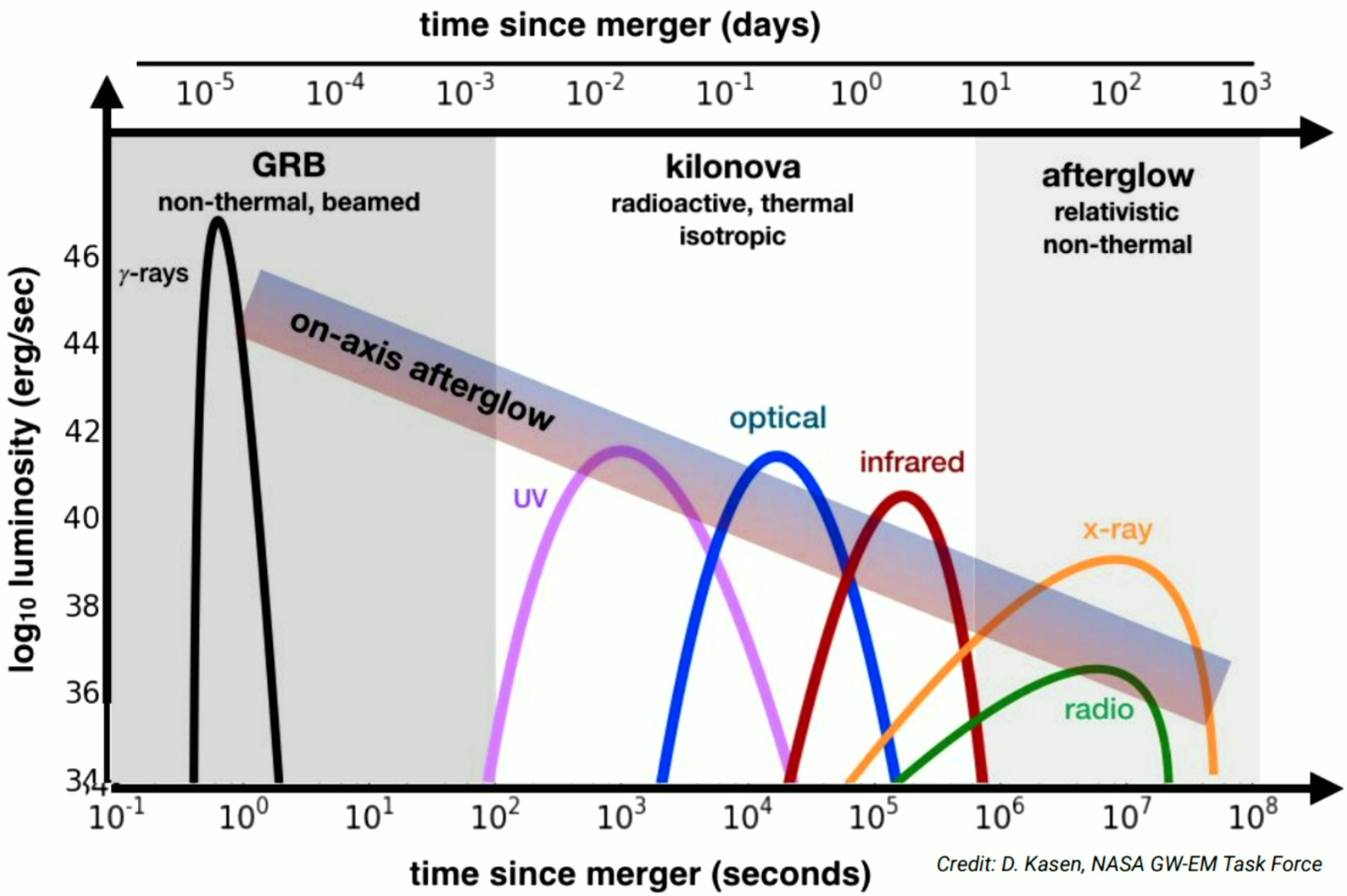


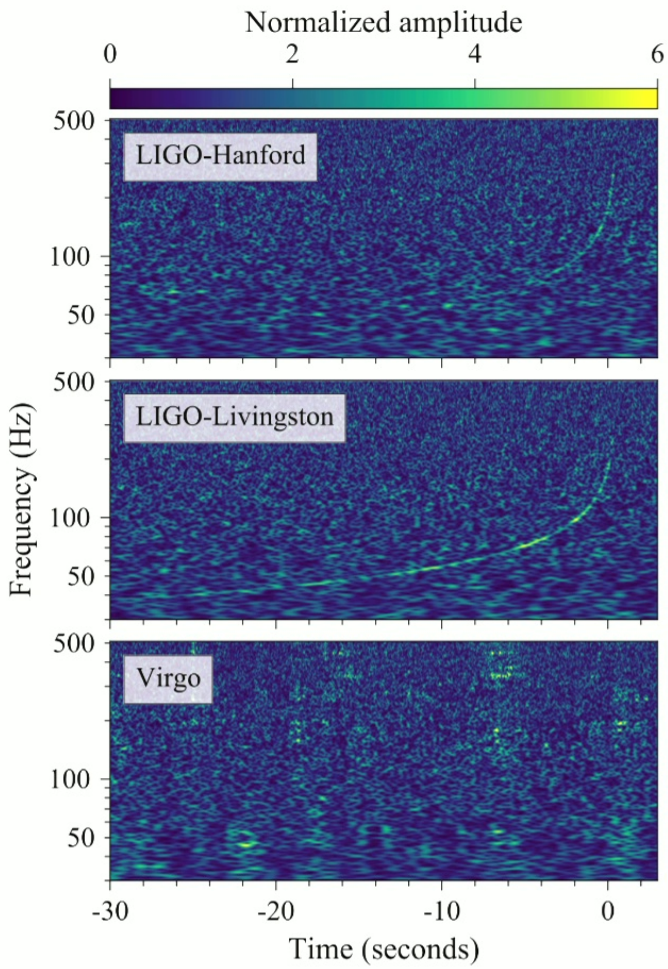
Fernandez + Metzger (2016)

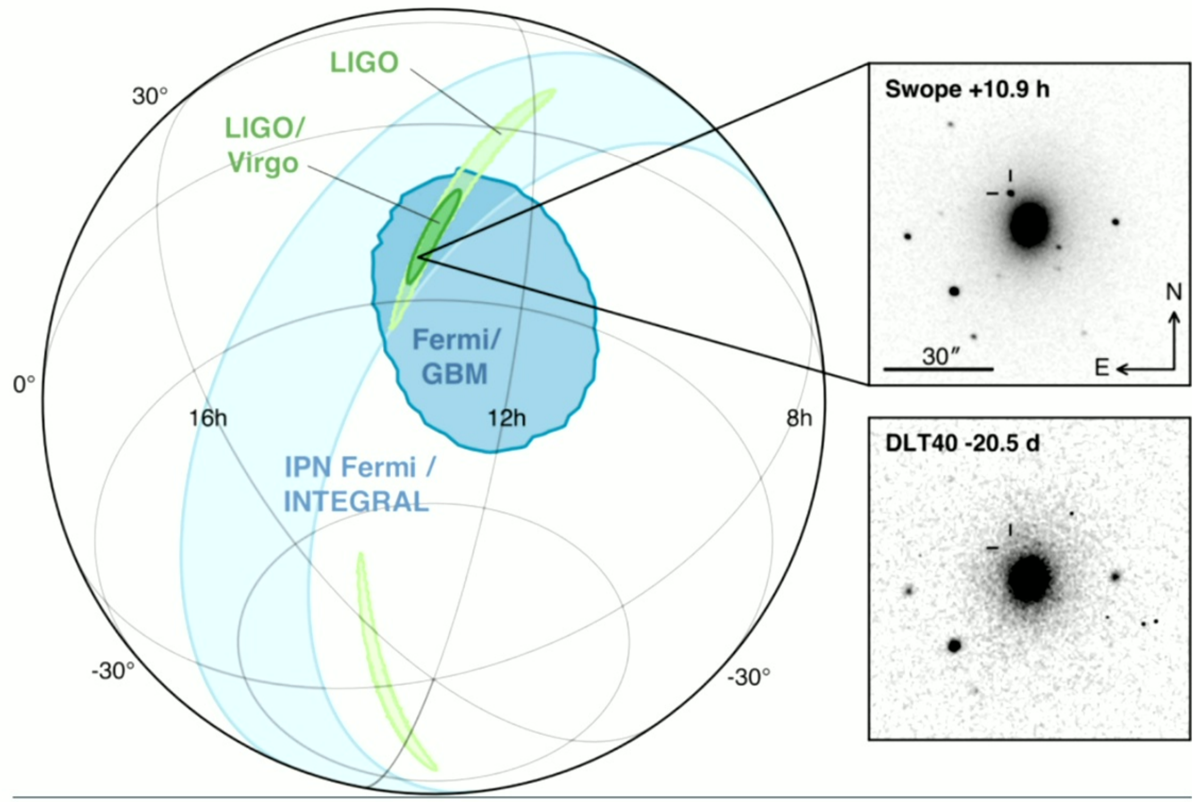


LVC et al. (2017)


time since merger (days)
10-5 10-4 10-3 10-2 10-1 100 101 102 103
GRB
non-thermal, beamed
kilonova
radioactive, thermal
isotropic
afterglow
relativistic
non-thermal
γ-rays
on-axis afterglow
optical
infrared
UV
x-ray
radio
log10 luminosity (erg/sec)
46
44
42
40
38
36
34
10-1 100 101 102 103 104 105 106 107 108
time since merger (seconds)
Credit: D. Kasen, NASA GW-EM Task Force

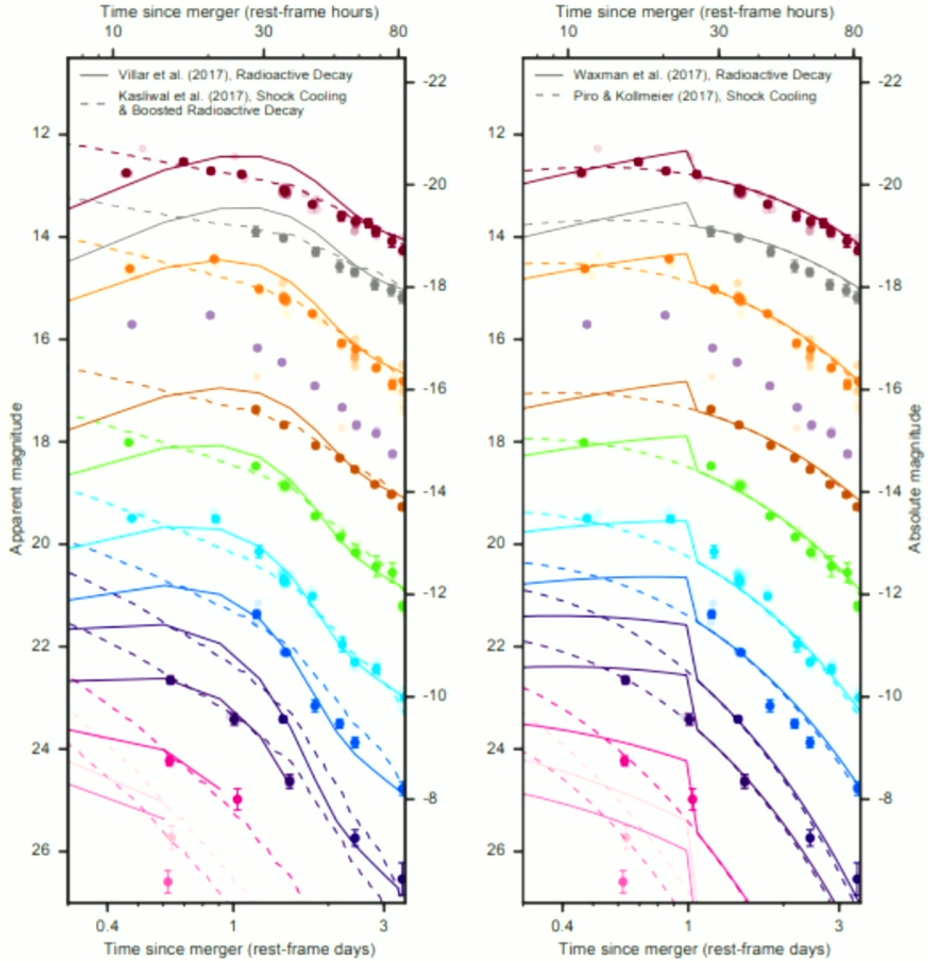
We were incredibly lucky in 2017





One example: Early UV observations required to break model degeneracy

- **radioactive decay luminosity model**
- **combined shock cooling - boosted radioactive decay**



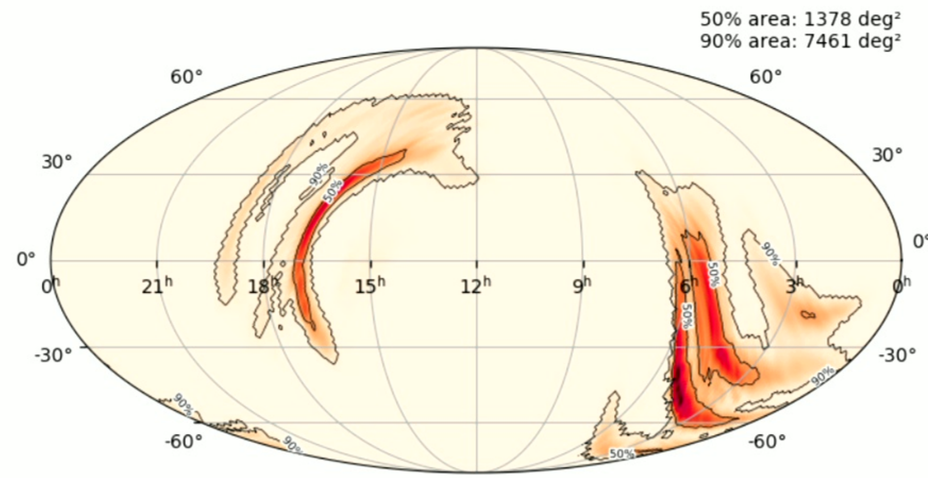
- **single-component radioactive decay luminosity model from Waxman et al. (2017)**
- **shock cooling model from Piro & Kollmeier (2017).**

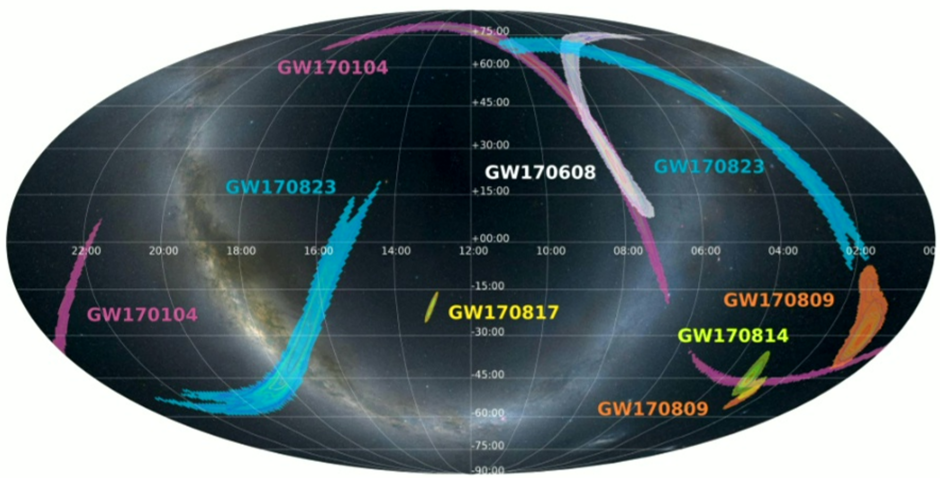
Arcavi 2018

Just a few Open Questions:

- What is the remnant, NS or BH, for the typical NS merger?
- How does the outcome of nucleosynthesis depend on the remnant?
- What is the maximum mass of a neutron star, equation of state?
- What is the GRB jet formation condition? Launching efficiency?
- What determines the jet's energy, Lorentz factor, opening angle?
- Your favorite question about accretion, black hole formation, compact objects, supra-nuclear matter, ultra-relativistic flows…

Why is this hard?
GW localizations are poor!

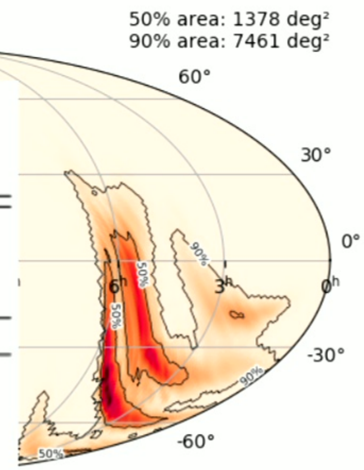


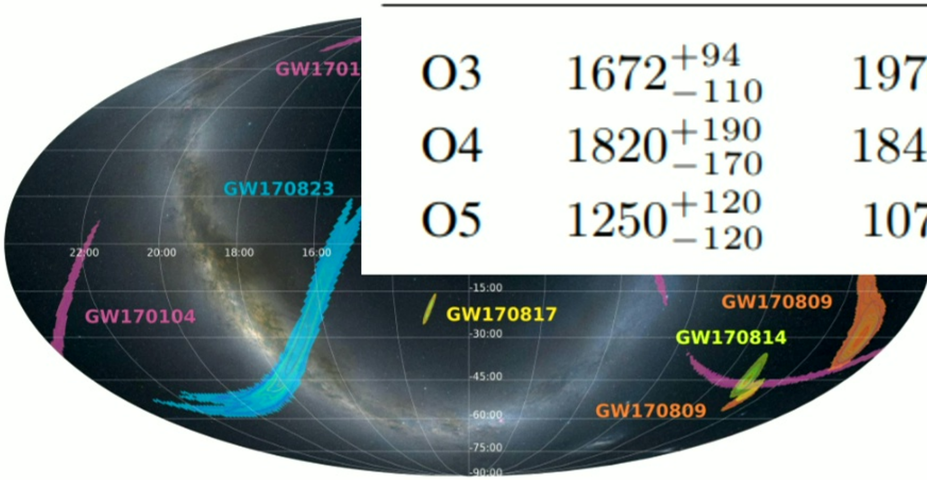


Why is this hard?
GW localiz

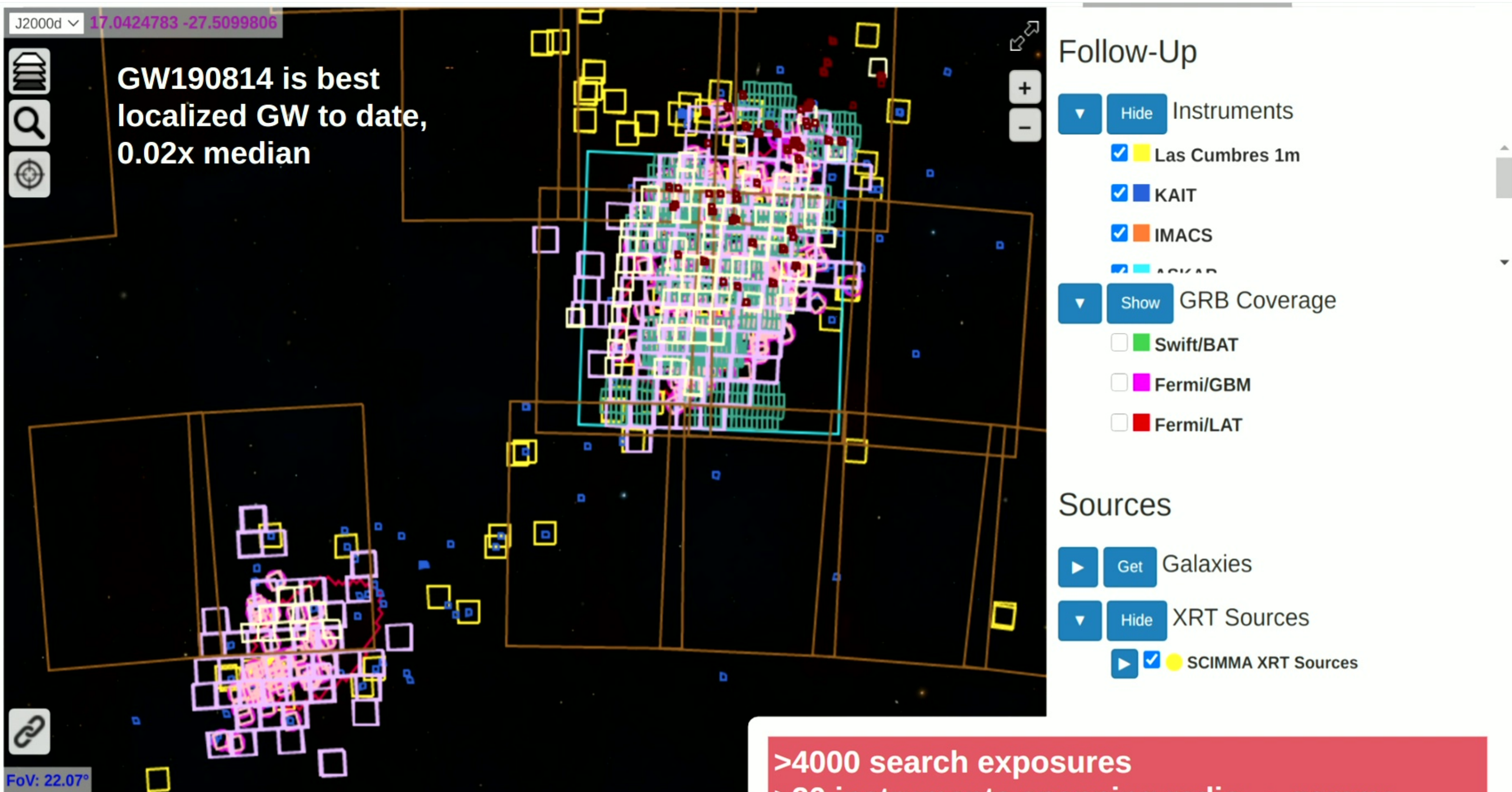
Table 2. Summary Statistics for O3, O4, and O5.

Run	BNS	NSBH	BBH
	Median 90% credible area (deg^2) [a]		
O3	1672^{+94}_{-110}	1970^{+110}_{-110}	1069^{+43}_{-41}
O4	1820^{+190}_{-170}	1840^{+150}_{-150}	335^{+28}_{-17}
O5	1250^{+120}_{-120}	1076^{+65}_{-75}	$230.3^{+7.8}_{-6.4}$





Petrov,Singer, et al. 2021



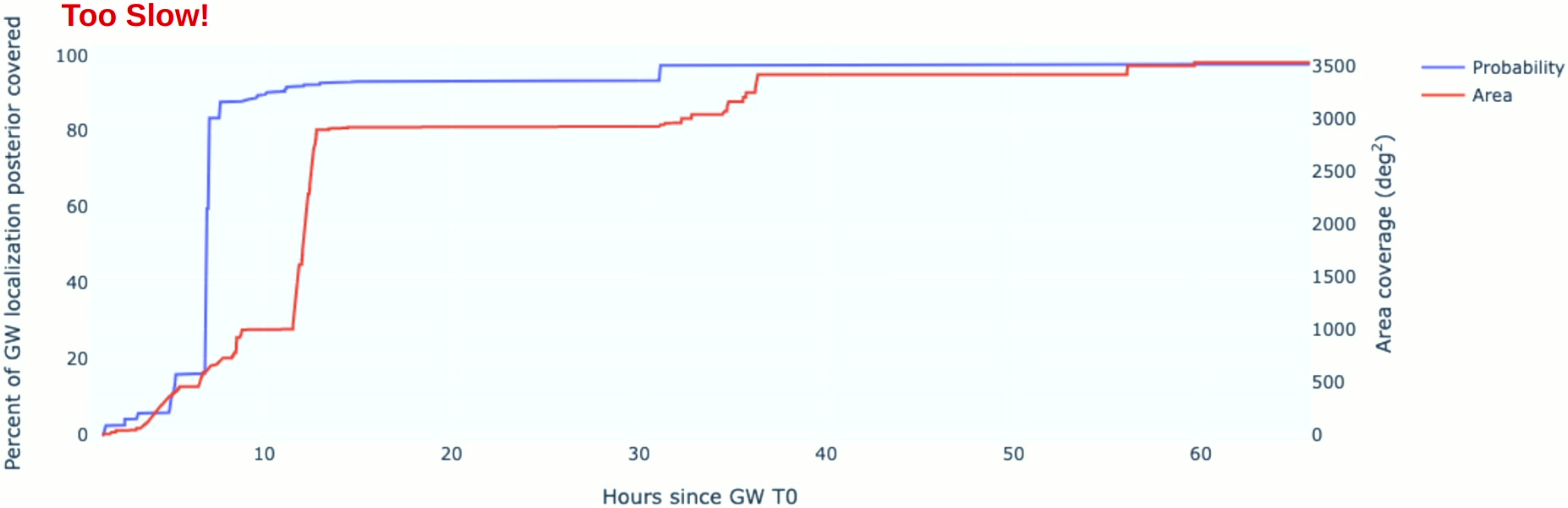
>4000 search exposures
>20 instruments spanning radio → gamma

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

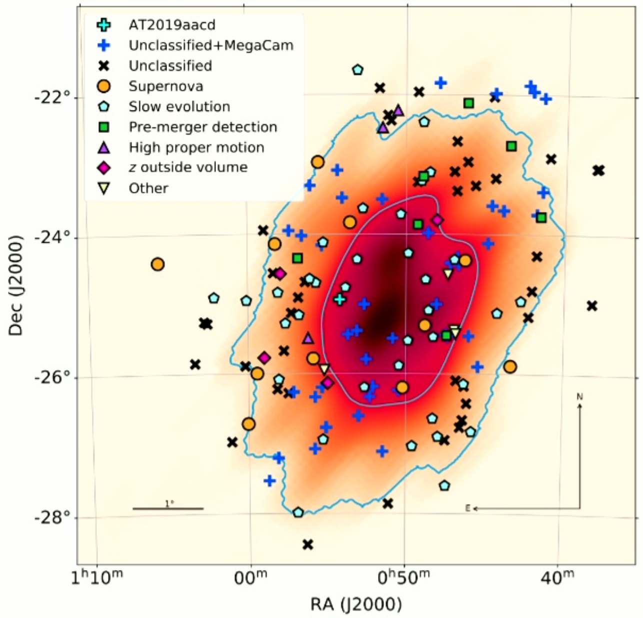
Skymap coverage for GW190814:

All wavelengths (optical dominant)

ZTF powerful….Still Too Slow!

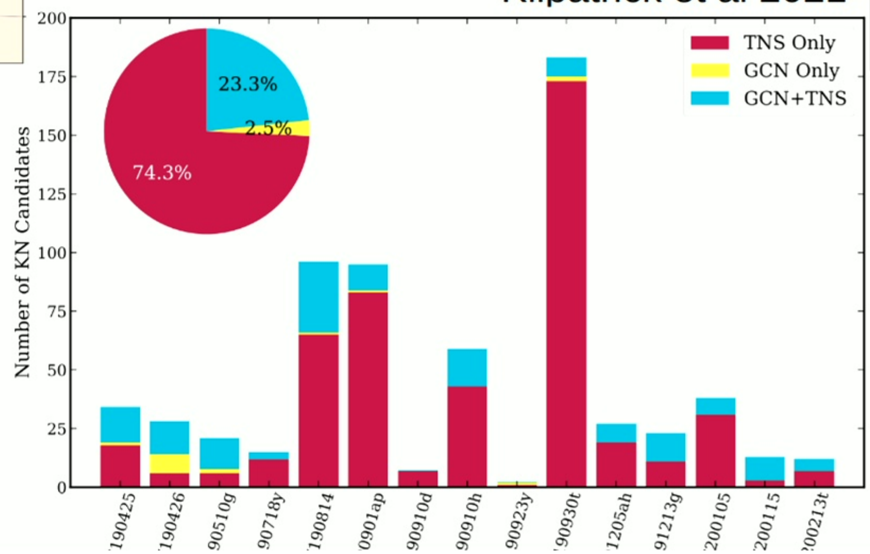


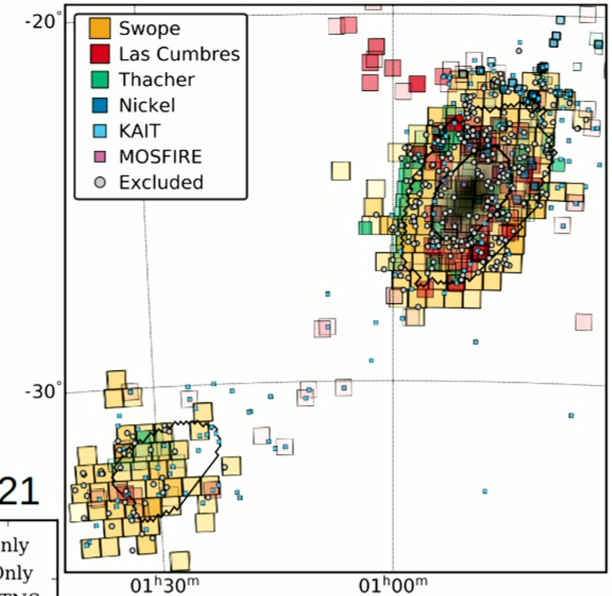
The wide-field search is only the first step…



Vieira et al 2020

Kilpatrick et al 2021

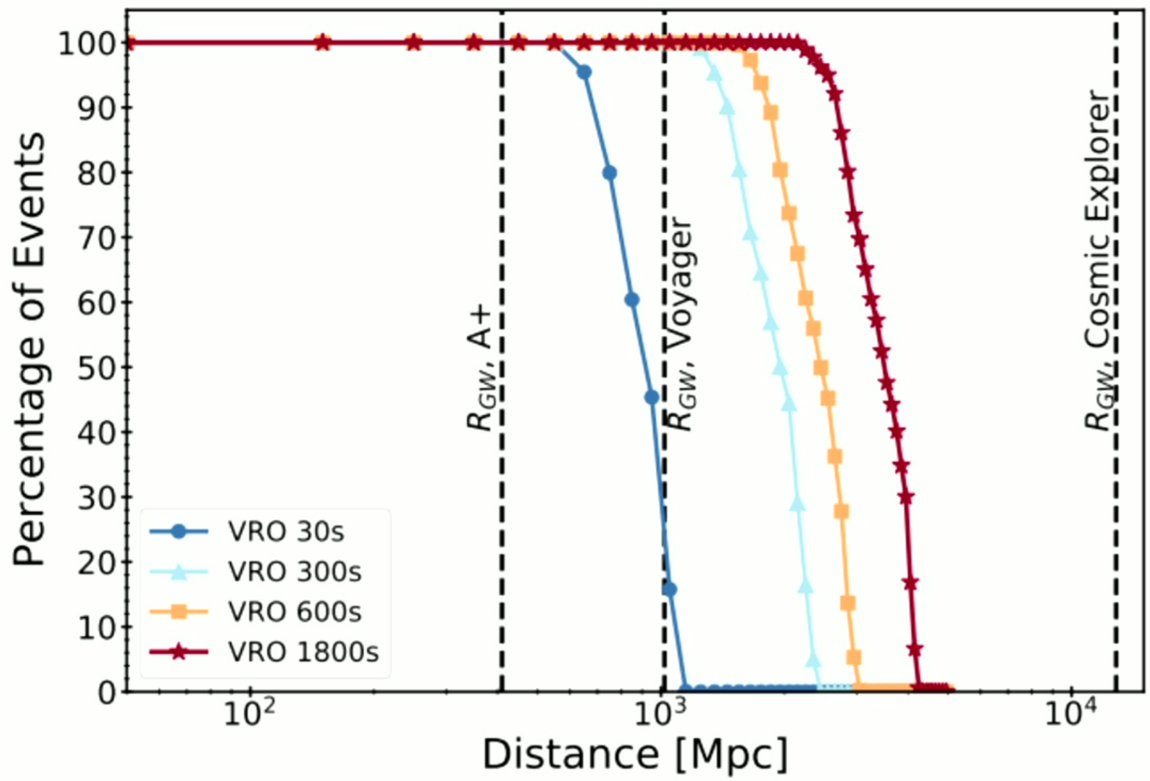




Rastinejad et al. 2022

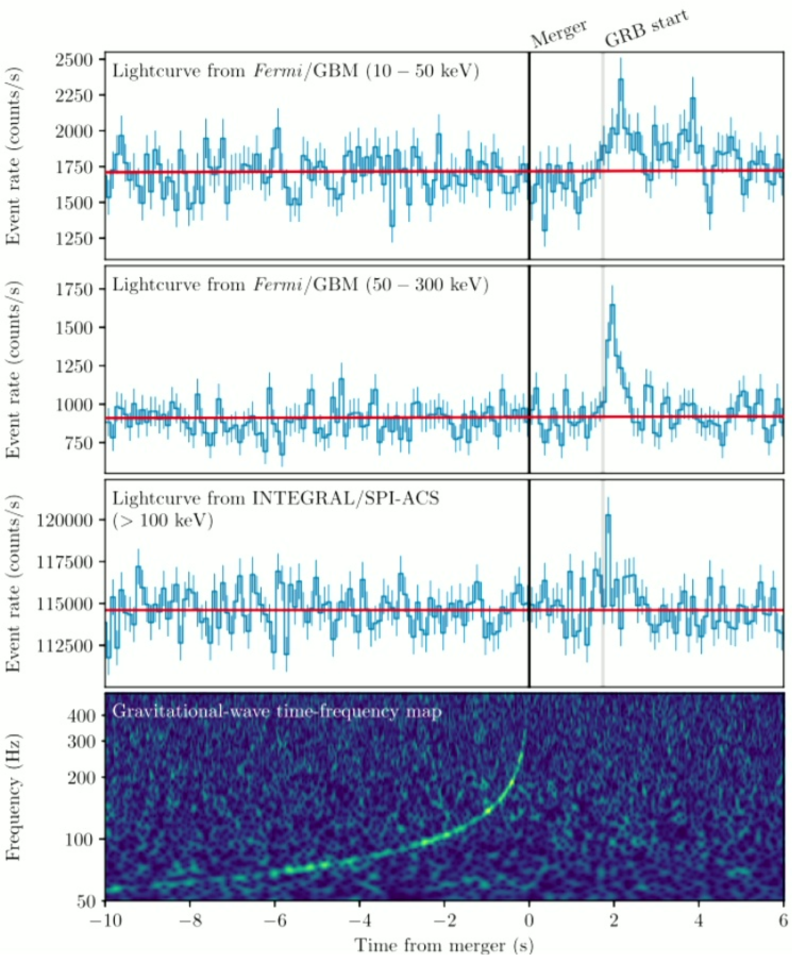
So, wide-field UVOIR searches are too slow… But there are also other problems:

Kilonova is intrinsically too faint for discovery at cosmological distances.

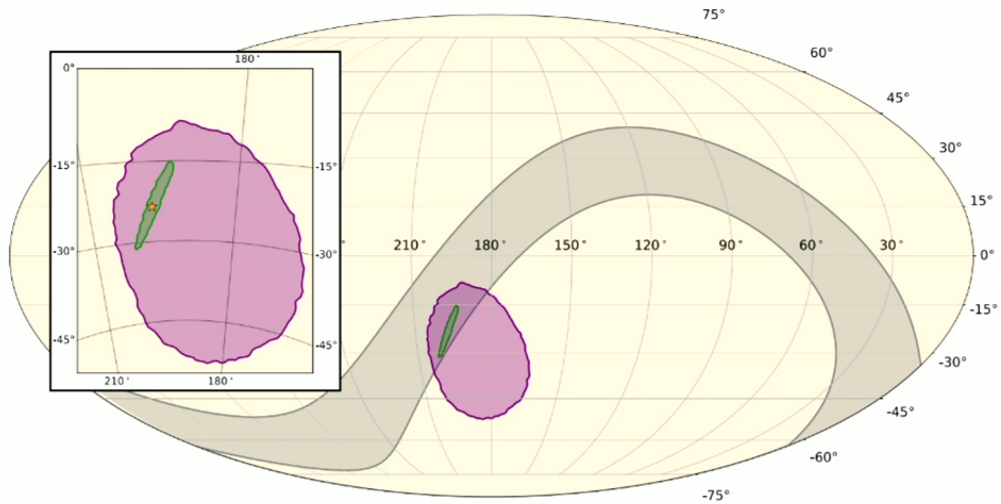


Chen et al, 2021

Why do we want to do sensitive (targeted) GRB searches?

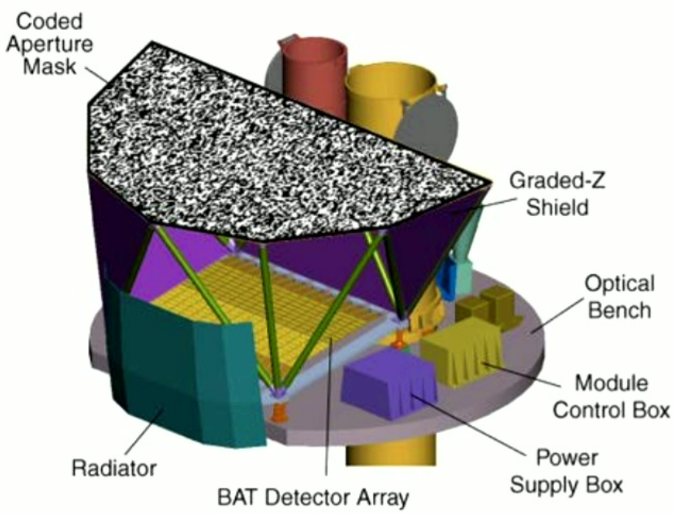


All (most) sky, all the time, prompt signal allows prompt localization, unambiguous temporal association (no classification problem)

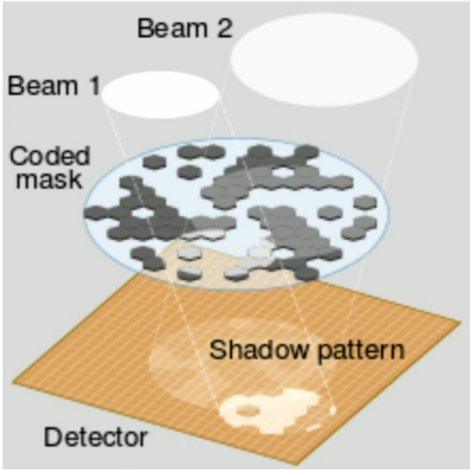


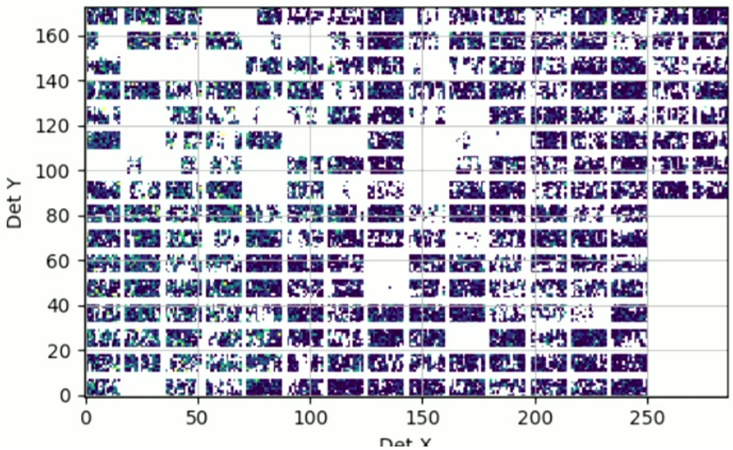
LVC, Fermi/GBM, INTEGRAL 2017

Burst Alert Telescope
(shadowgrams)

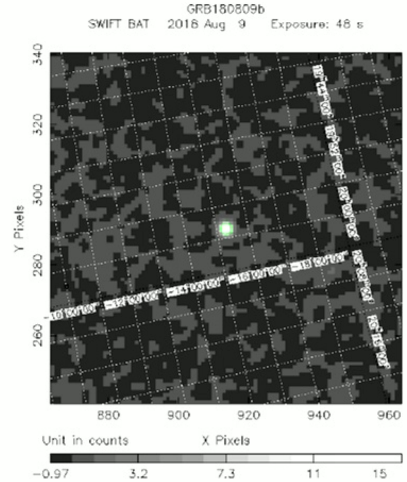


- Hard X-rays (15-350 keV)
- 1/6 of the whole sky (~2 sr.) FoV
- Localizes ~100 GRB/yr onboard
- Prompt Arc-minute localization



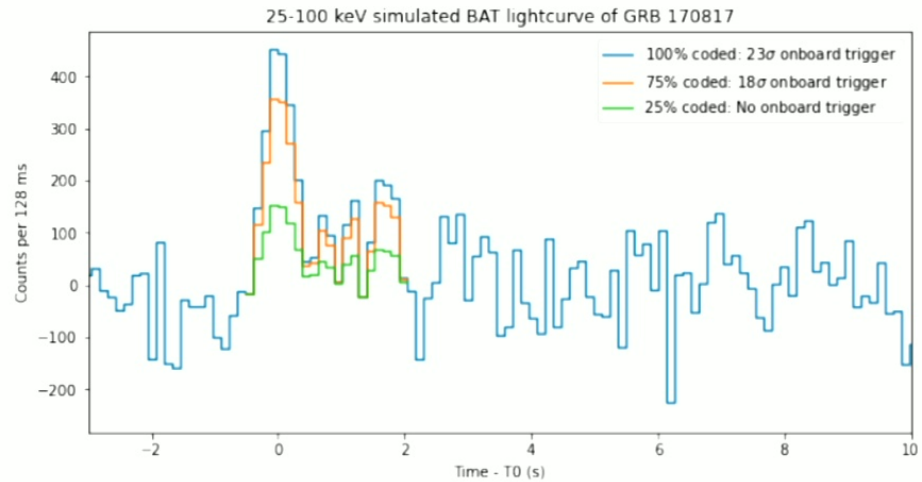


Correlation and FFT w/ mask pattern

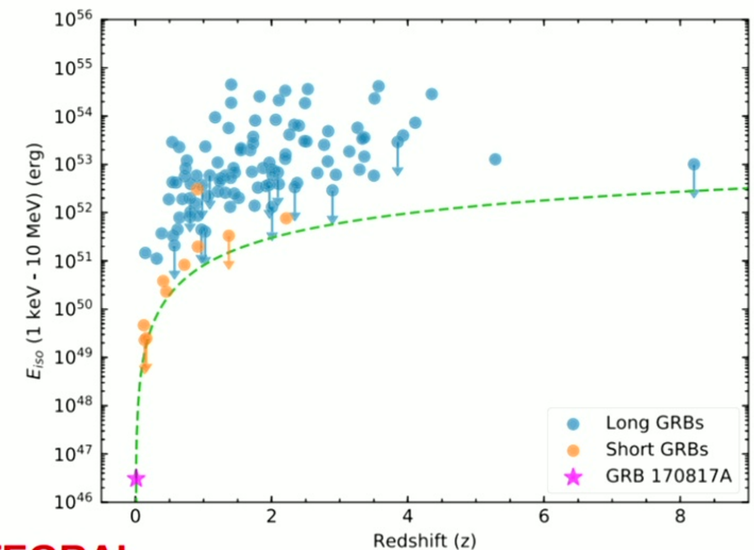


Intrinsic capability of BAT

- 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

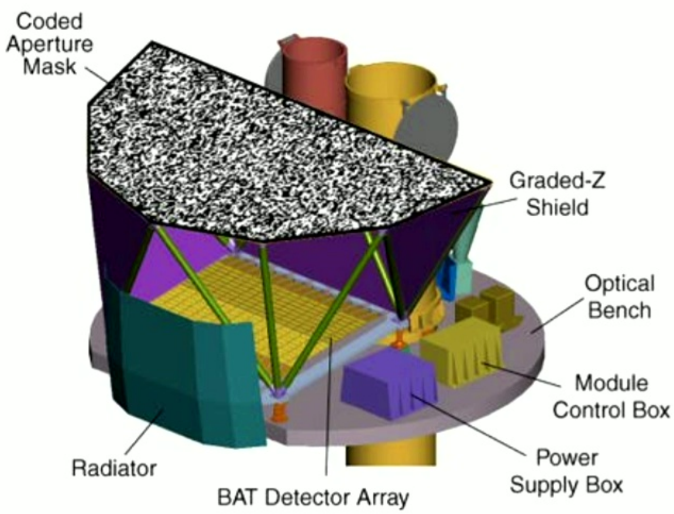


- Only BAT can provide prompt arcmin localization for pointed follow-up at very early times, window to crucial physics

- BAT localization alone provides unique host galaxy ID in local universe

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

Burst Alert Telescope
(shadowgrams)



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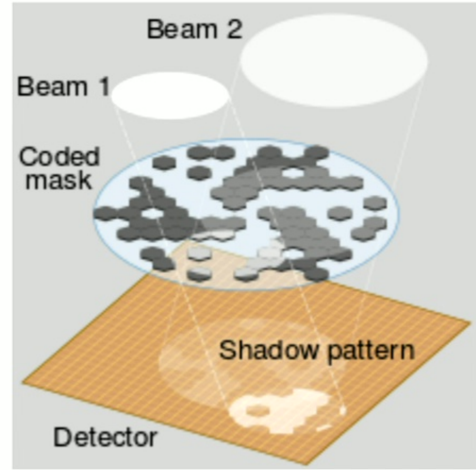

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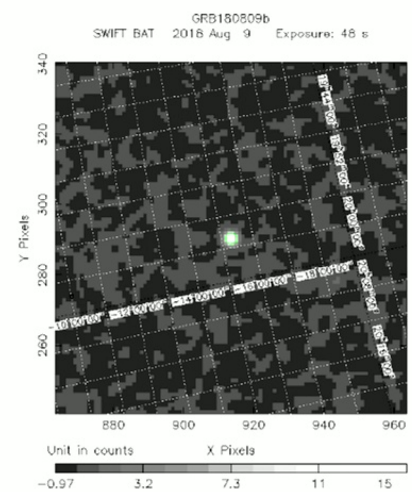


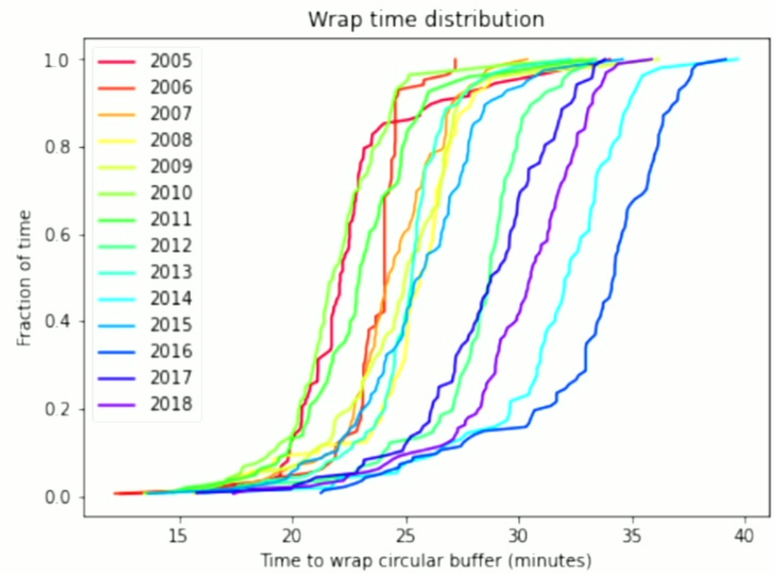
The Problem: Required Data Don't Make it to the Ground

- *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

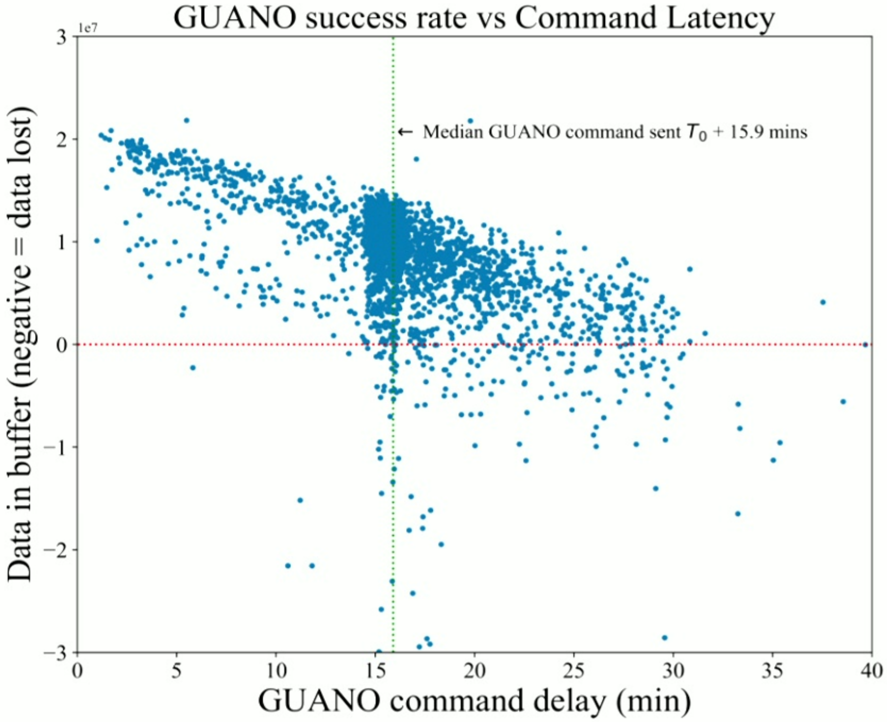
- **Data we need are saved to an onboard ring buffer. If we can get to it in time, and get it to the ground, great science is possible!**



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

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

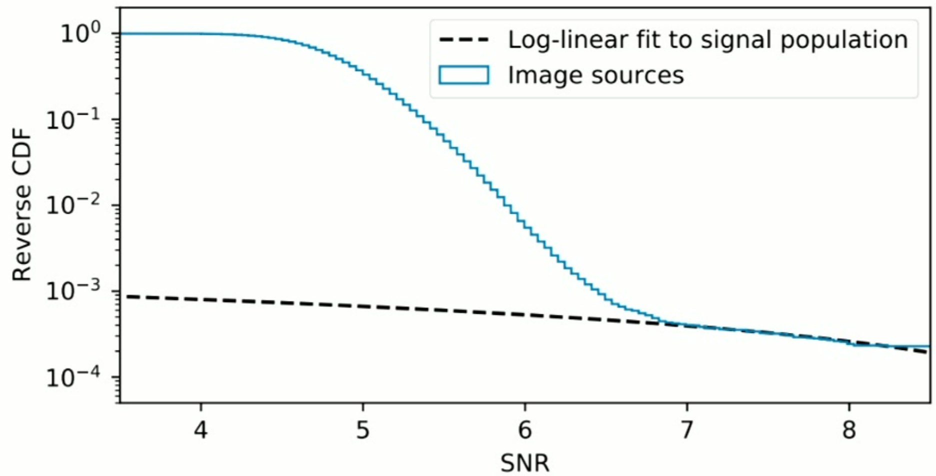
Swift/BAT dumps on demand to enable sensitive sub-threshold GRB searches
(AT, Kennea, DeLaunay, et al. 2020)



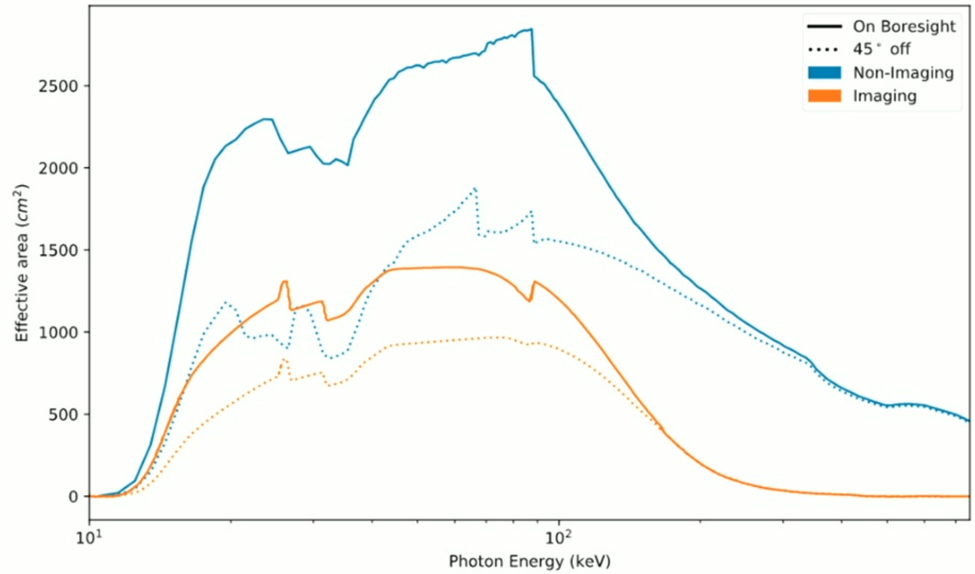
- **Autonomously commanding spacecraft in extremely low latency to save temporally coincident event level data. ~5x/day**
- **First ever autonomous on-demand commanding of a space telescope for scientific purposes**
- **Commanding infrastructure also now used for very low-latency ToO repoint with narrow-field *Swift* instruments**
  - **On target to FRBs in O(1) minutes**

Now can do imaging, but...

- Large Image Noise population →



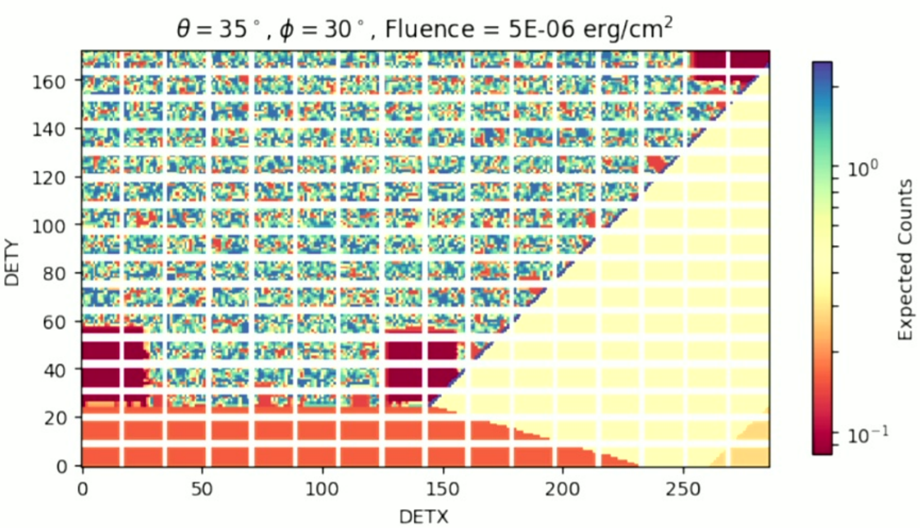
- Rejection of uncoded counts on detector, which contain information
- Neglects energy information associated with each count
- Pays a mask-weighting A_{eff} efficiency factor
- Lower A_{eff} at higher energies due to mask transmission→ Lower sensitivity to short hard GRBs

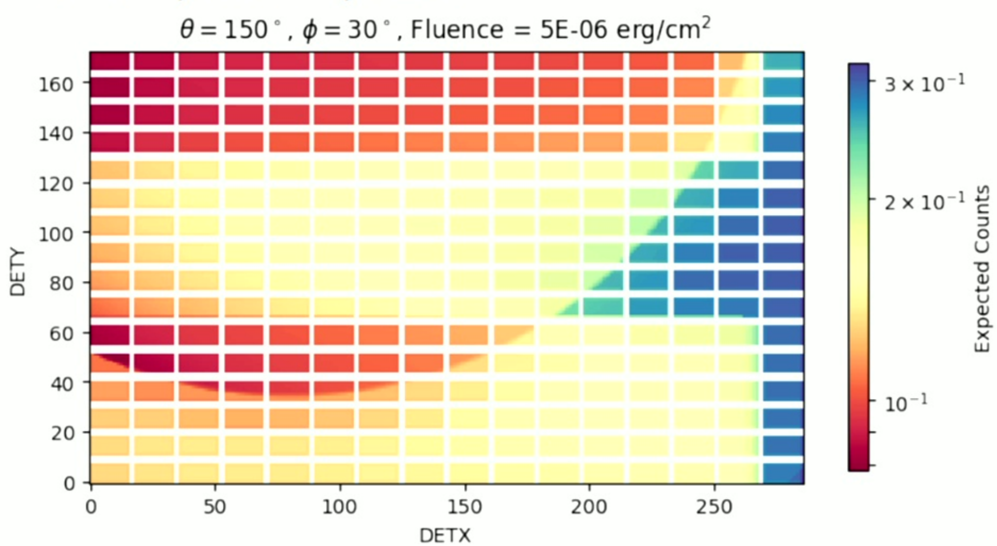


NITRATES (Non-Imaging Transient Reconstruction And TEmporal Search):

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-∞ x more sensitive than imaging,** dep on source spectrum+position



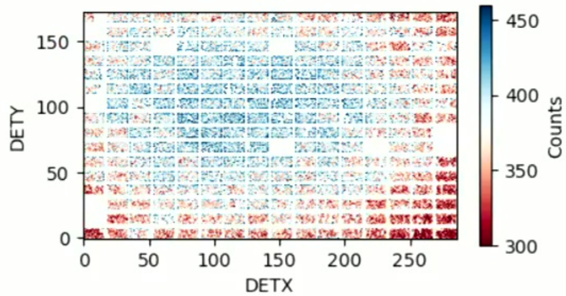


J. DeLaunay + AT, 2022

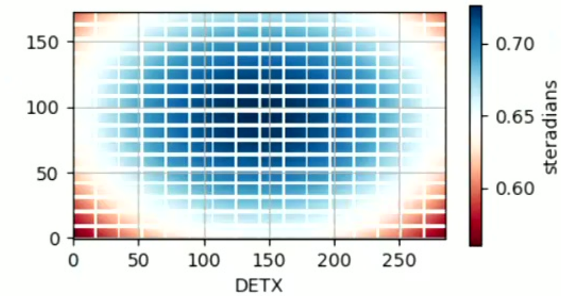
Diffuse Model

- 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

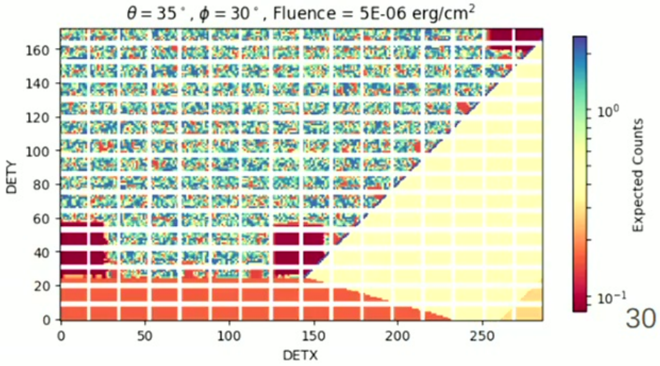
For a cutoff power-law spectrum
$\Theta^{PS} = \{\theta, \phi, A, E_{peak}, \gamma\}$

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



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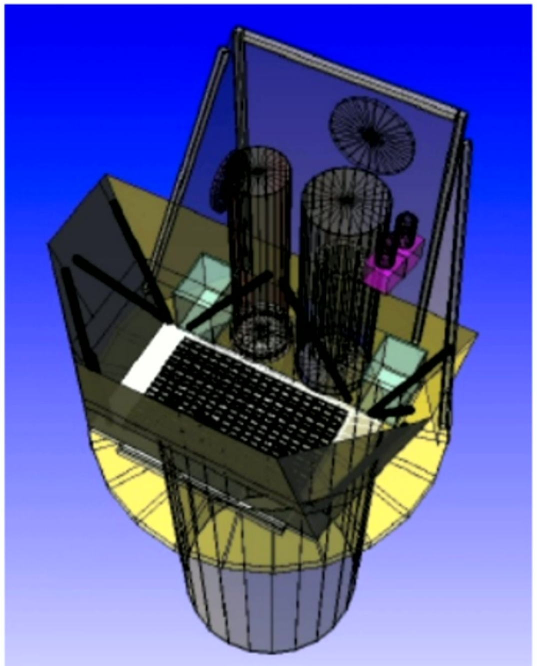

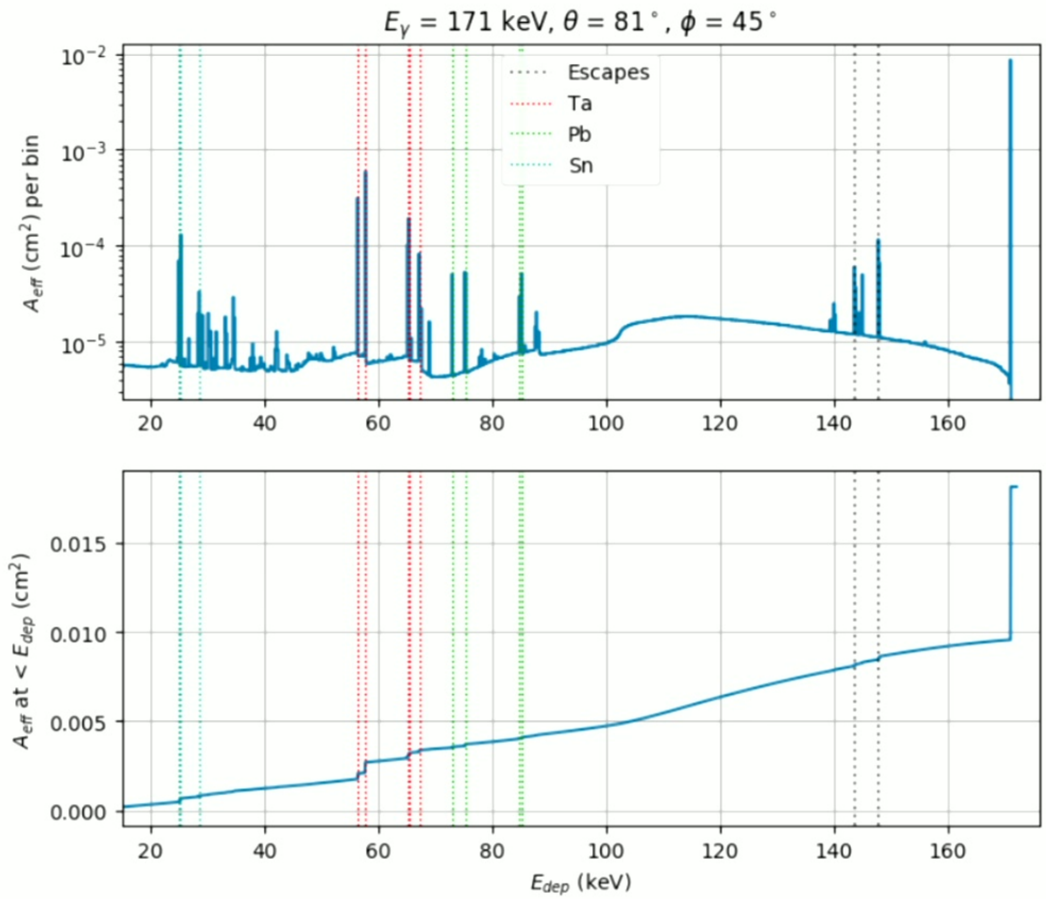
E_γ = 171 keV, θ = 81°, ϕ = 45°
Escapes
Ta
Pb
Sn
A_{eff} (cm^2) per bin
A_{eff} at < E_{dep} (cm^2)
E_{dep} (keV)

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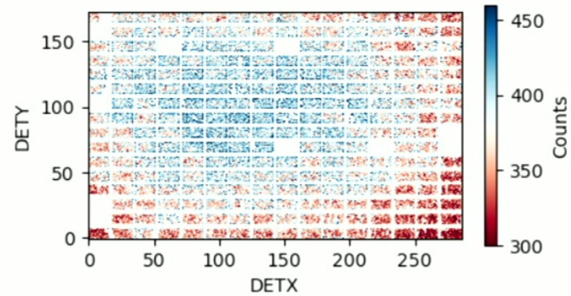
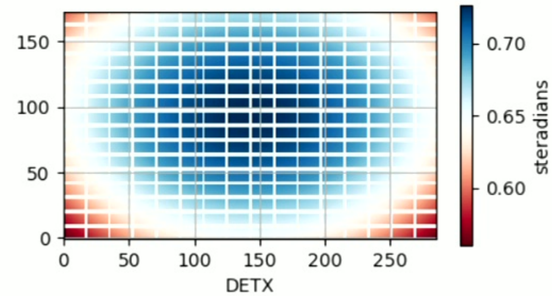
≈1300 s of exposure with no bright sources



Ω_i



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ϕ_j^b = rate per det. per Ω_i

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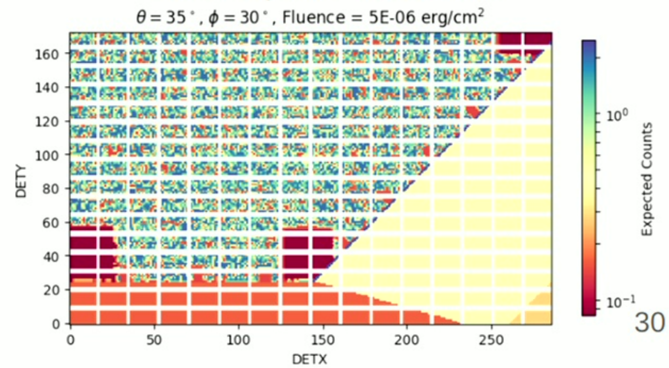
Example PS Model



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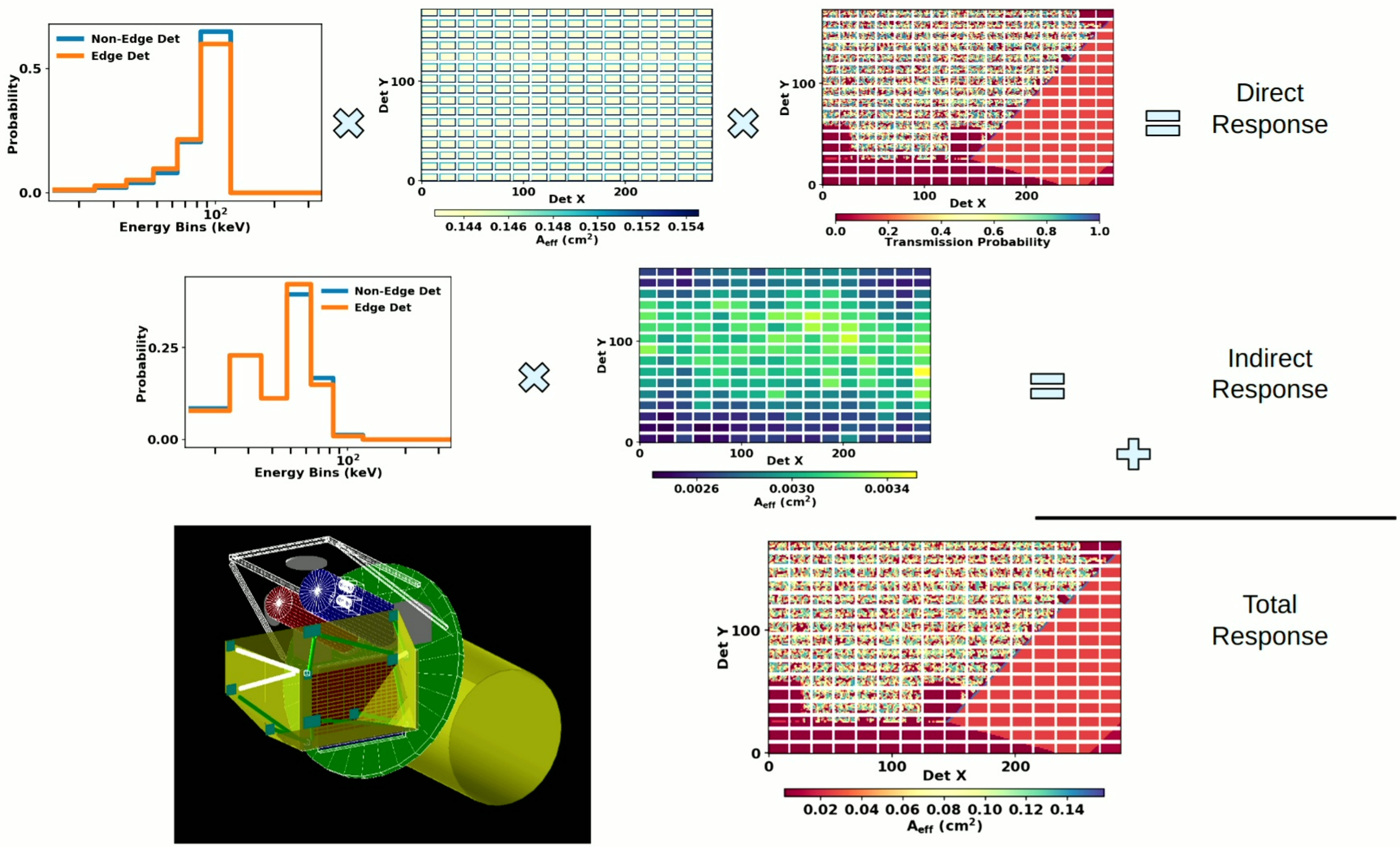
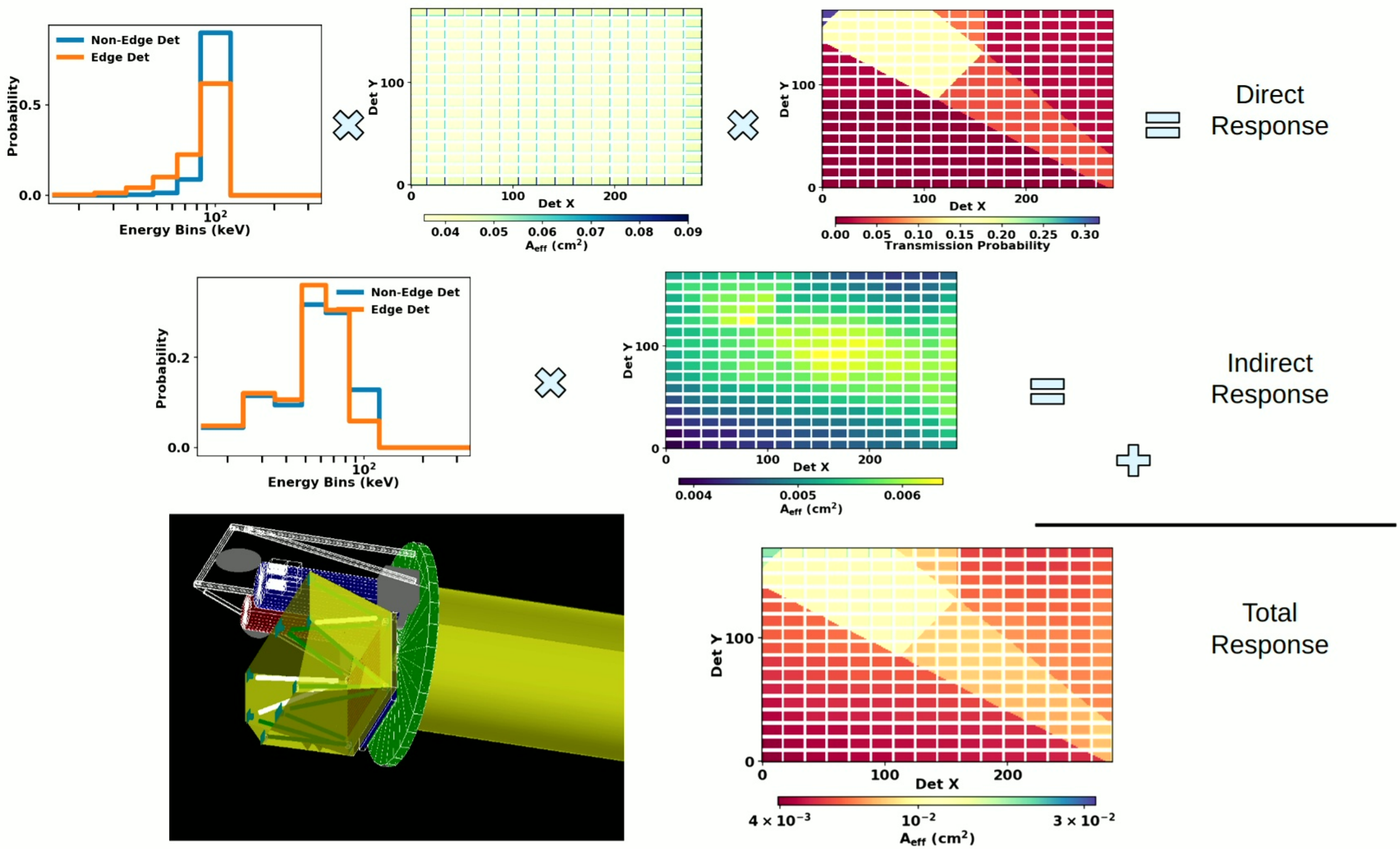
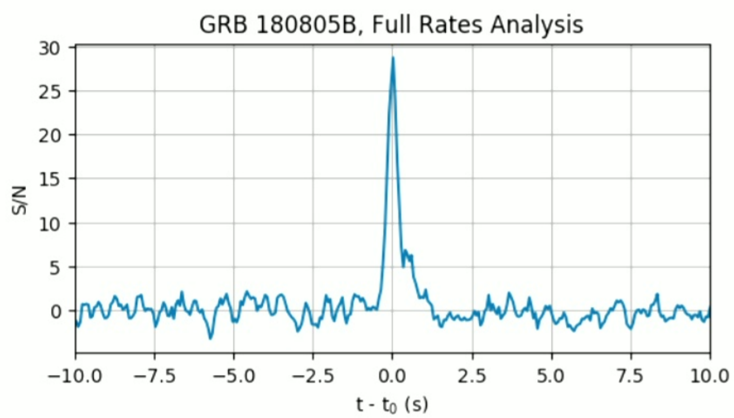

Non-Edge Det
Edge Det
Probability
Energy Bins (keV)
Det Y
Det X
A_eff (cm²)
Transmission Probability
Direct Response
Indirect Response
Total Response


Non-Edge Det
Edge Det
Probability
Energy Bins (keV)
Det Y
Det X
Aeff (cm2)
Transmission Probability
Direct Response
Indirect Response
Total Response

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



0.256 s time bins

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

Full Rates Analysis

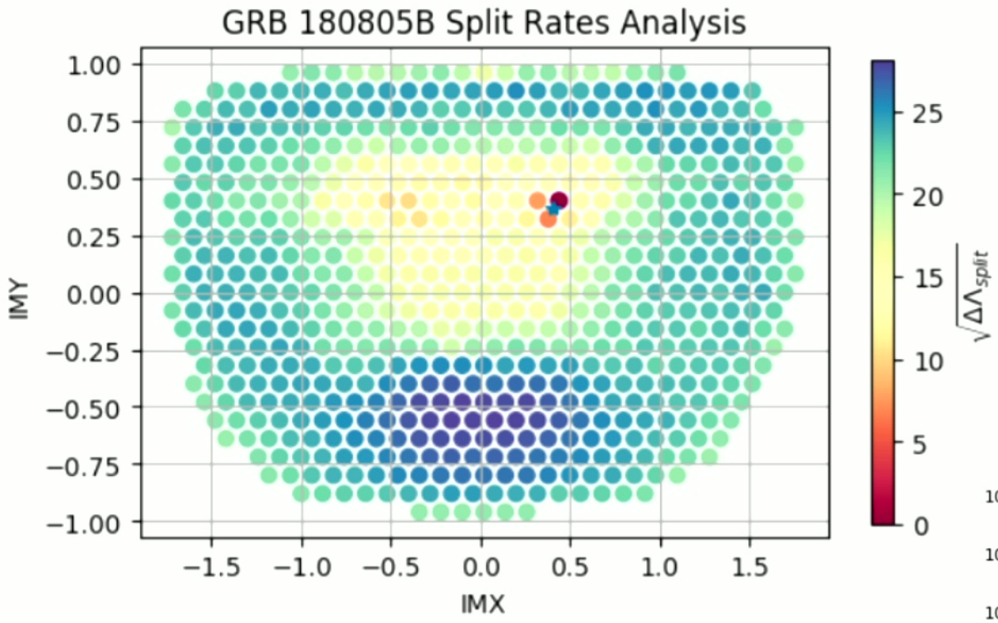
- Using the counts from all detectors and energy bins, excesses above background are checked for in all of the time bins.
- The few bins with the highest S/N for each duration size are kept as time seeds.
- N_{bkg} and σ_{bkg} are calculated using a linear fit to the rates.

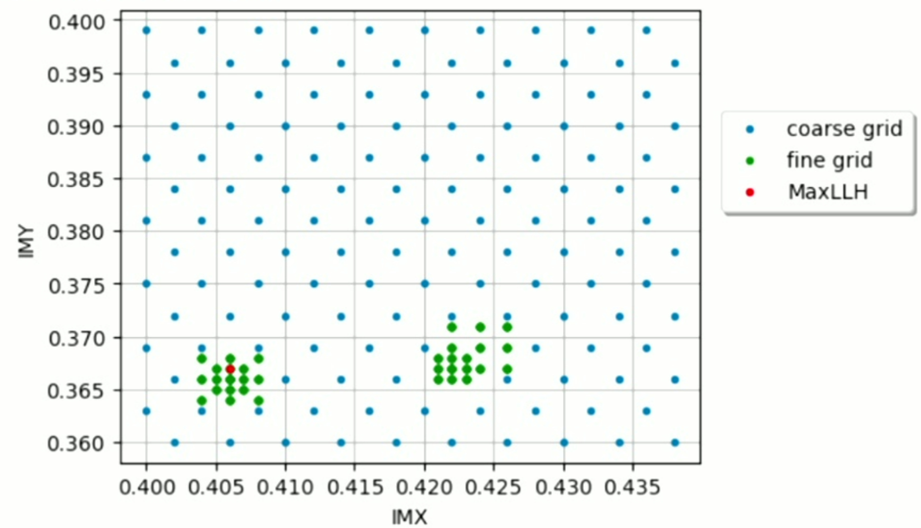
$$S/N_i^{rates} = \frac{N_i - N_{bkg}}{\sqrt{N_{bkg}^2 + \sigma_{bkg}^2}}$$

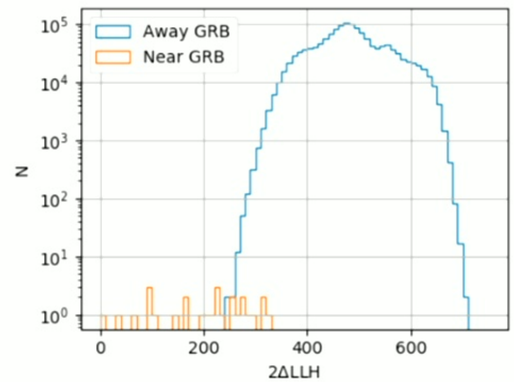
<100 time bins

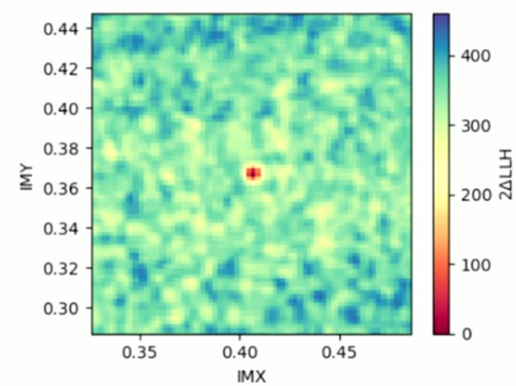
NITRATES:

- The spatial parameter space to search is massive: FOV ~7000 deg^2 and PSF <20 arcmin.
- Can't possibly search every location in low-latency.
- Need spatial seeding and intelligent stage-refined localization tests.
- Even with seeding ~500 CPU hours required.





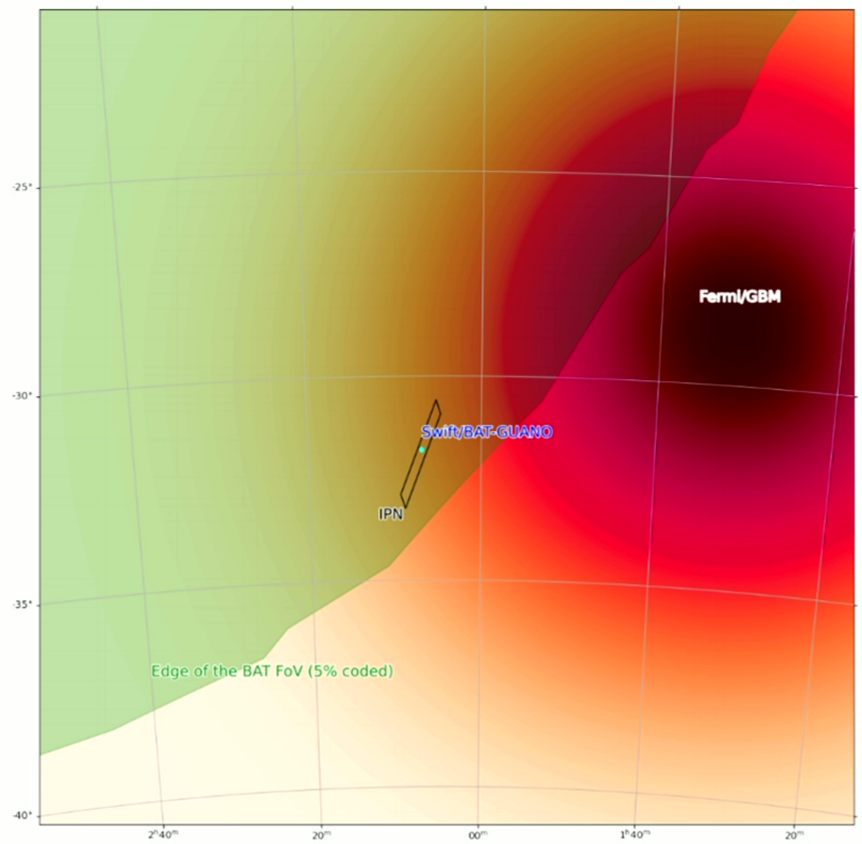




J. DeLaunay + AT, 2022

External GRB triggered search results:

- Since Feb 2020: Triggering on GRBs detected by Fermi, INTEGRAL, CALET, HAWC
- These GRBs have either large (~100-1000 deg^2) or no localizations
- GUANO has discovered **arcminute localizations for 34 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
  - 23 of 34 got prompt follow-up
  - **15 afterglows discovered**



Many localizations unrecoverable with conventional imaging

Coherent GW-GRB joint search

MoU between LVK + GUANO, to combine the spatio-temporal and parametric. information from the GW and GRB data streams.

$$Z = FAR_{gw} FAR_{grb} \Delta t \quad (5)$$

where FAR_{gw} and FAR_{grb} are FARs of their respective experiments. This statistic can be mapped to a joint FAR since each individual FAR is drawn from a uniform distribution

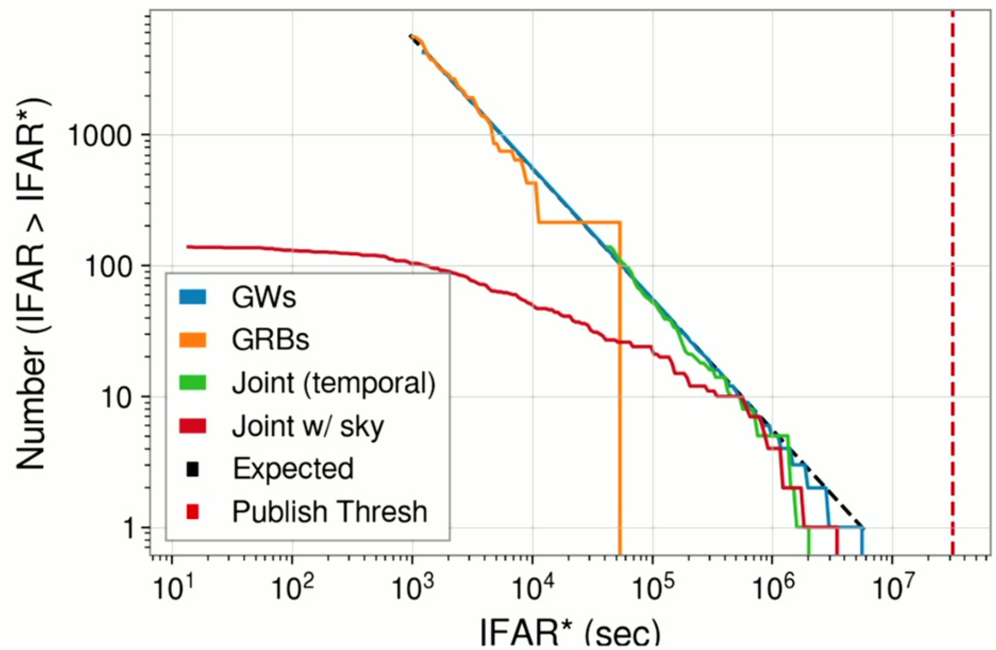
$$FAR_t(Z) = \int_0^{Z_{max}} p(FAR_{grb}\Delta t \leq Z/FAR_{gw}) dFAR_{gw} \quad (6)$$

$$= \int_0^Z dFAR_{gw} + \int_Z^{Z_{max}} Z/FAR_{gw} dFAR_{gw} \quad (7)$$

$$= Z\,(1 + \ln(Z_{max}/Z)) \quad (8)$$

where $Z_{max} = FAR_{gw,max} FAR_{grb,max} \Delta t$. A final coincidence FAR_c with sky map information can be made by dividing by (3) similarly to (1) to get

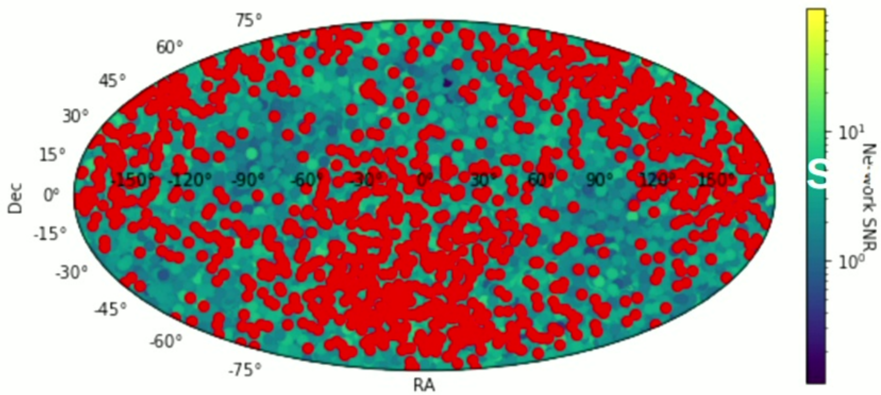
$$FAR_c = FAR_t / I_\Omega. \quad (9)$$



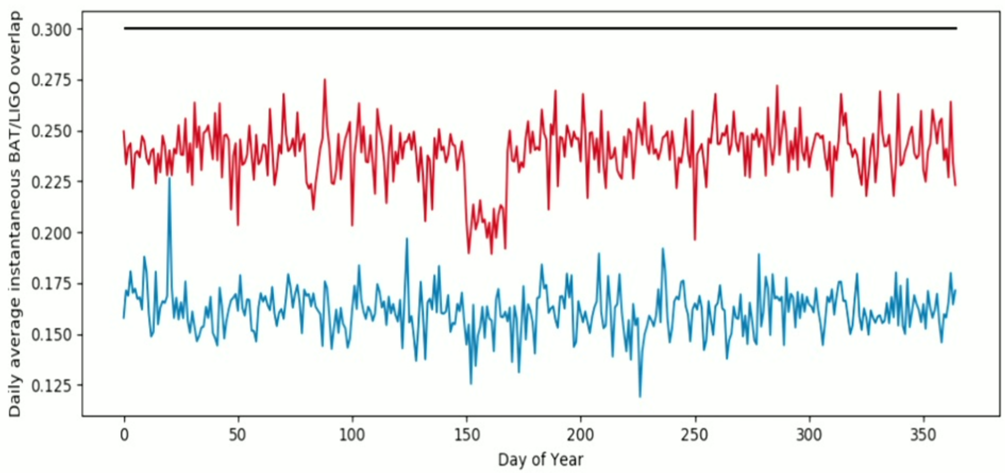
$$\mathcal{I}_{\mathbf{\Omega}} = \int \frac{P(\mathbf{\Omega}|\widehat{t_c}, D_{\rm GW}, \mathcal{H}^{\rm S}_{\rm GW}) P(\mathbf{\Omega}|\widehat{t_c}, D_{\rm EM}, \mathcal{H}^{\rm S}_{\rm EM})}{P(\mathbf{\Omega}|\mathcal{H}^{\rm S})} d\mathbf{\Omega}\,.$$

But The BAT coded FoV Doesn't Cover the Whole Sky… Schedule Intelligently!

Sky Dist with O4 LVK PSDs



Detection fraction for different *Swift* schedules



Coherent GW-GRB joint search

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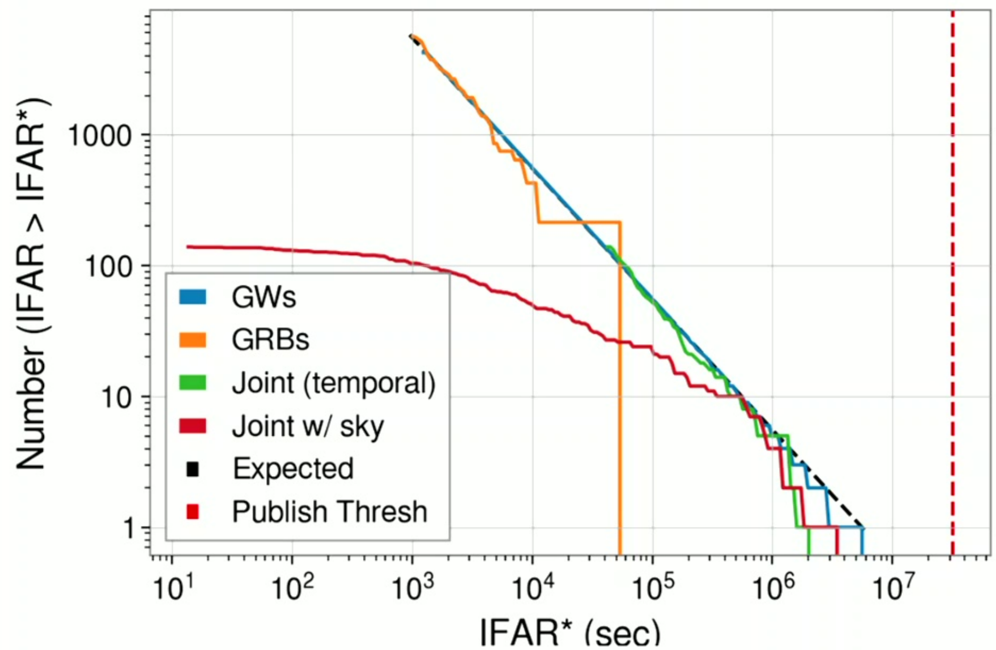
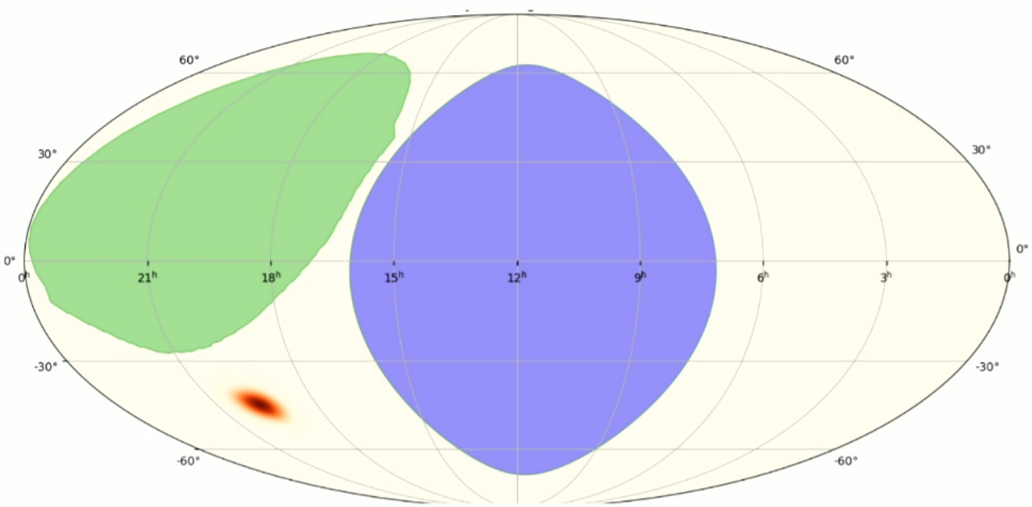
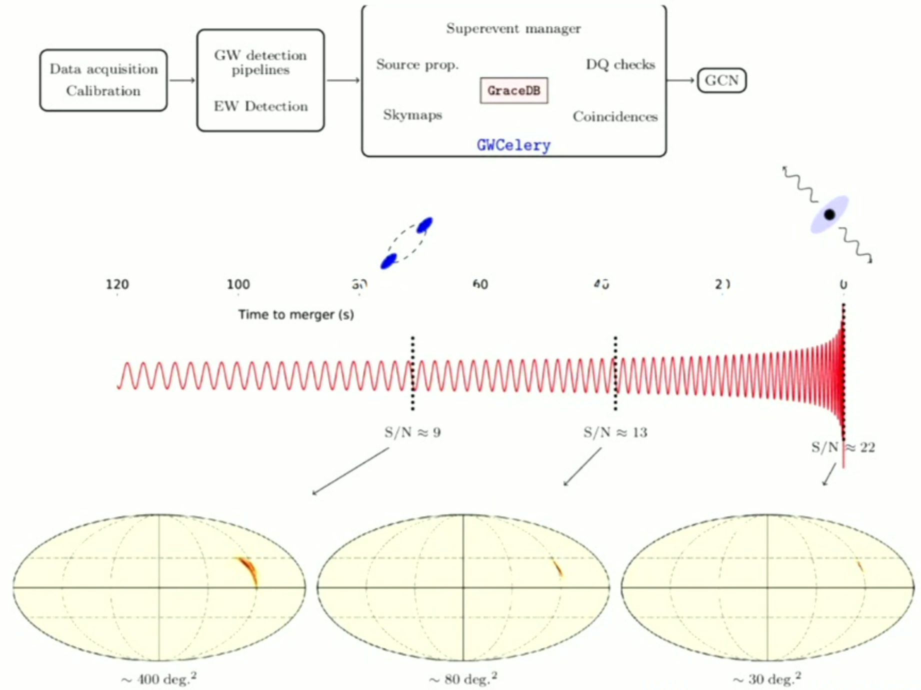


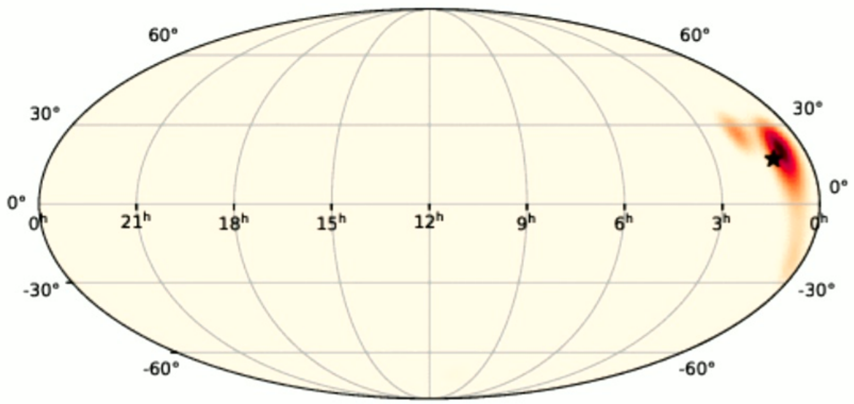
$$\mathcal{I}_{\mathbf{\Omega}} = \int \frac{P(\mathbf{\Omega}|\widehat{t_c}, D_{\rm GW}, \mathcal{H}^{\rm S}_{\rm GW}) P(\mathbf{\Omega}|\widehat{t_c}, D_{\rm EM}, \mathcal{H}^{\rm S}_{\rm EM})}{P(\mathbf{\Omega}|\mathcal{H}^{\rm S})} \, d\mathbf{\Omega}\,.$$

Put BAT FOV on GW localization region before T0

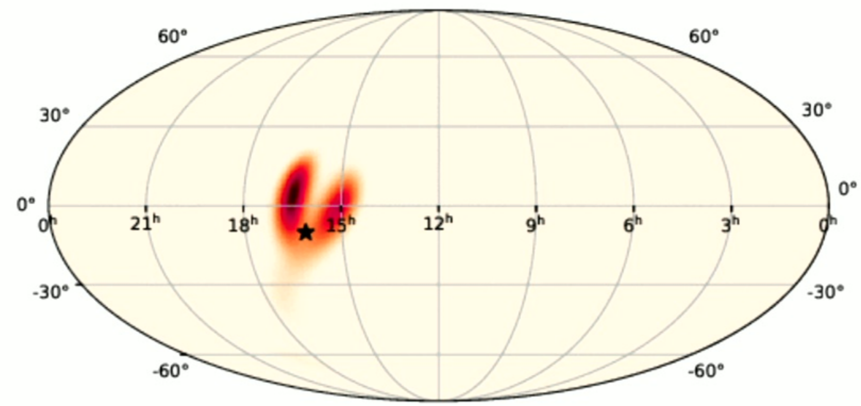




Magee et al. 2021



60°
60°
30°
30°
0°
0°
0h
21h
18h
15h
12h
9h
6h
3h
0h
-30°
-30°
-60°
-60°



60°
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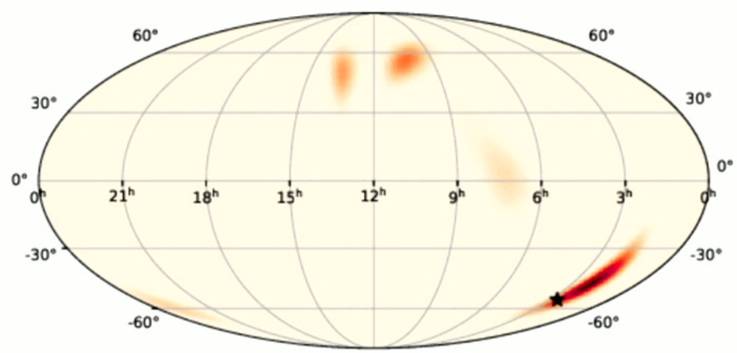
15h
12h
9h
6h
3h
0h
-30°
-30°
-60°
-60°



60°
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0h
21h
18h
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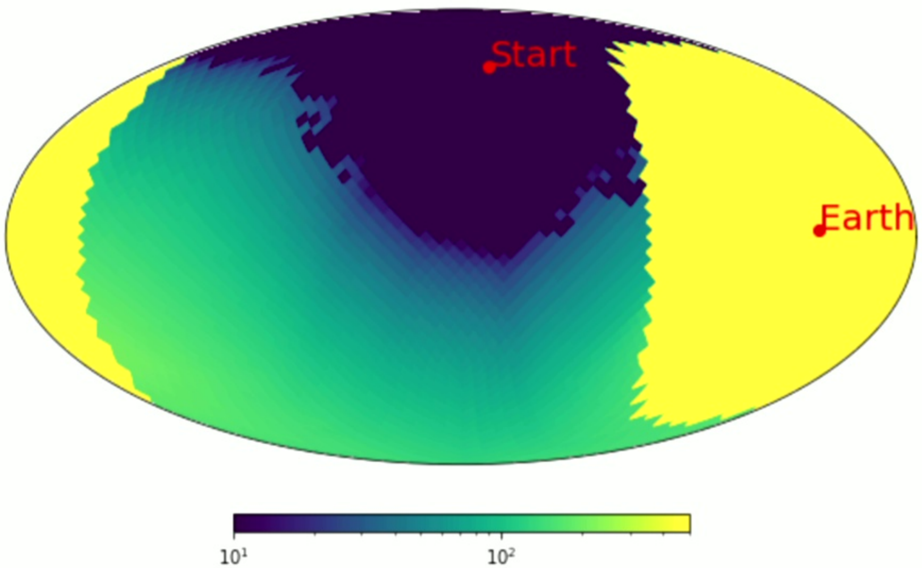
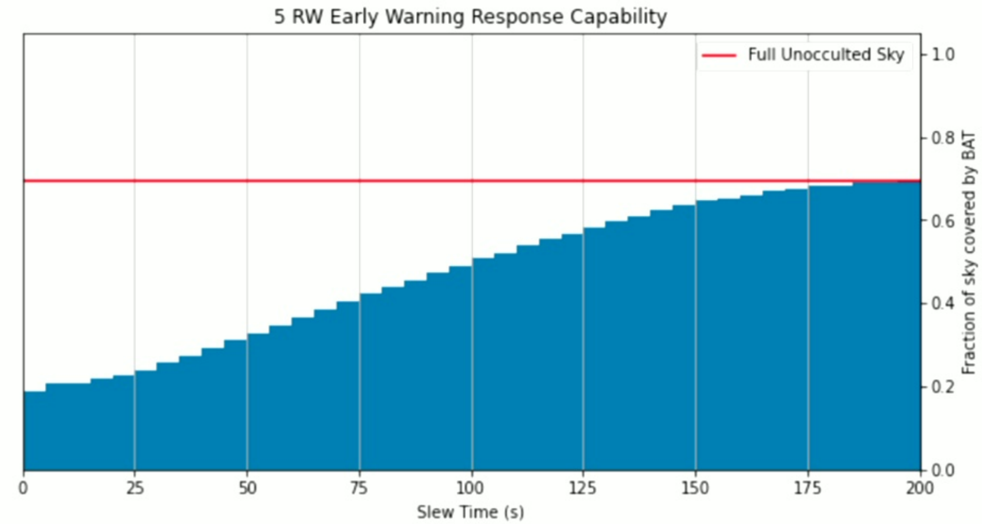
12h
9h
6h
3h
0h
-30°
-30°
-60°
-60°

Space-based Early Warning Response!

Put BAT FOV on GW localization region before T0





Is this actually possible?

Yes: Command latency is now 10 seconds

X-ray and UV observations of a bright non-repeating FRB at T0+236 seconds

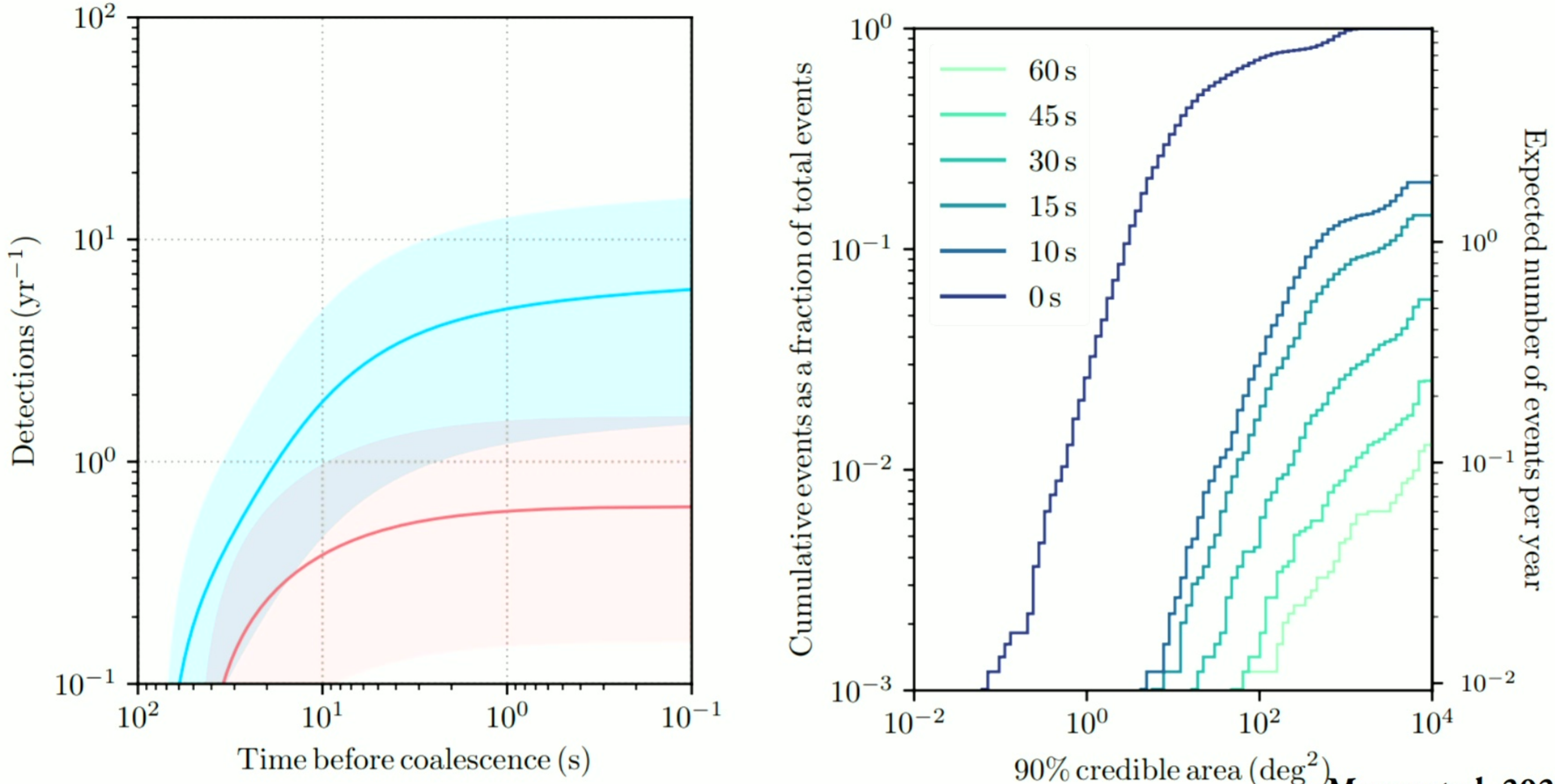
ATel #16233; ***Aaron Tohuvavohu (U Toronto), Jamie Kennea (Penn State), Phil Evans (U Leicester), James DeLaunay (Penn State)***

*on **7 Sep 2023; 13:54 UT***

Credential Certification: Aaron Tohuvavohu (a.tohuvavohu@mail.utoronto.ca)

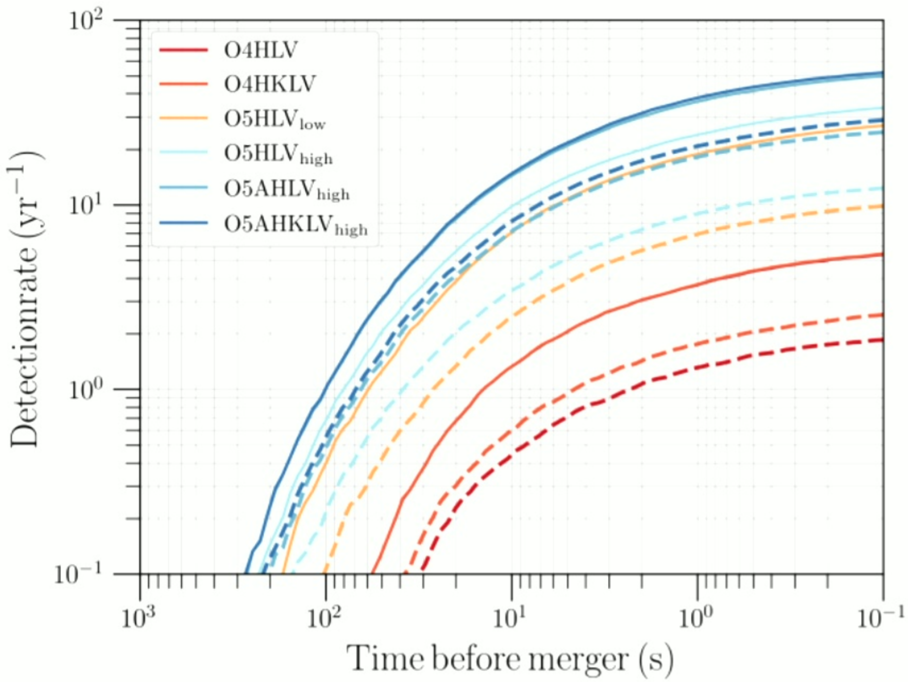
O4 Prospects for Early Warning Response?

Not good…tech demo for future runs



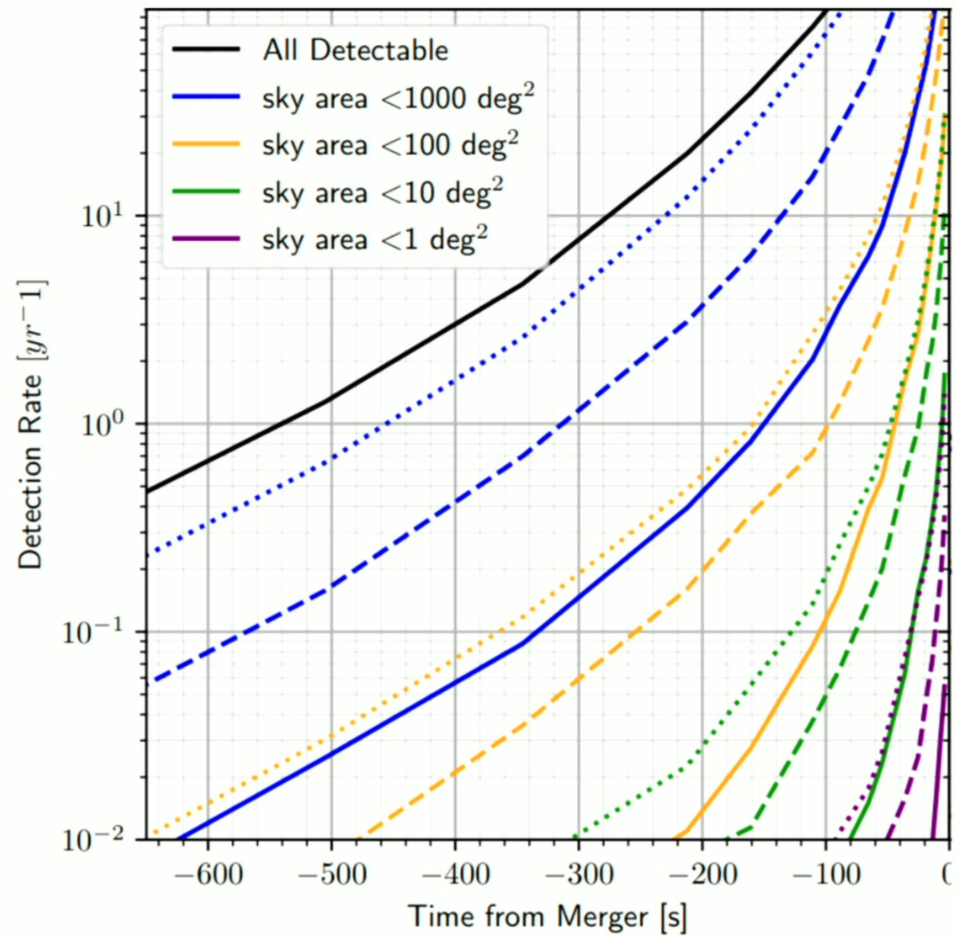
Magee et al. 2021

But things start to look better in O5



Magee and Borhanian 2022

And for 2.5 G detectors (Voyager/A#) Early 2030s



Nitz et al. 2020


QUVIK
Quick Ultra-Violet
Kilonovae Surveyor
CZECH AEROSPACE RESEARCH CENTRE
$30 M Euro cost-cap
Funded for Launch!
Timed for O5

120 kg smallsat

35 cm aperture

1 deg^2 FoV

<2.5" PSF FWHM

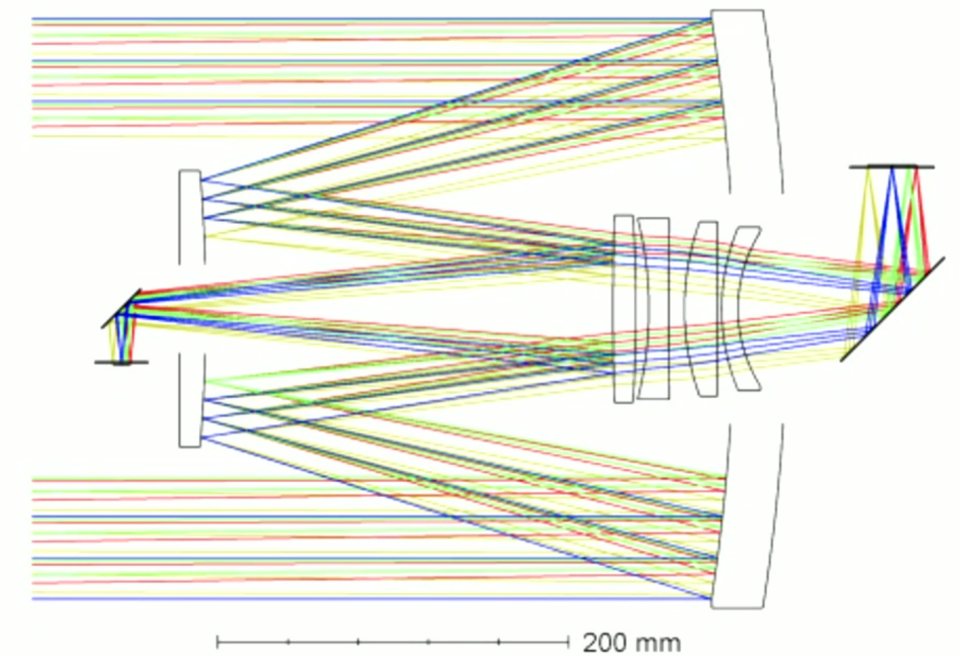
NUV band (230-340 nm)

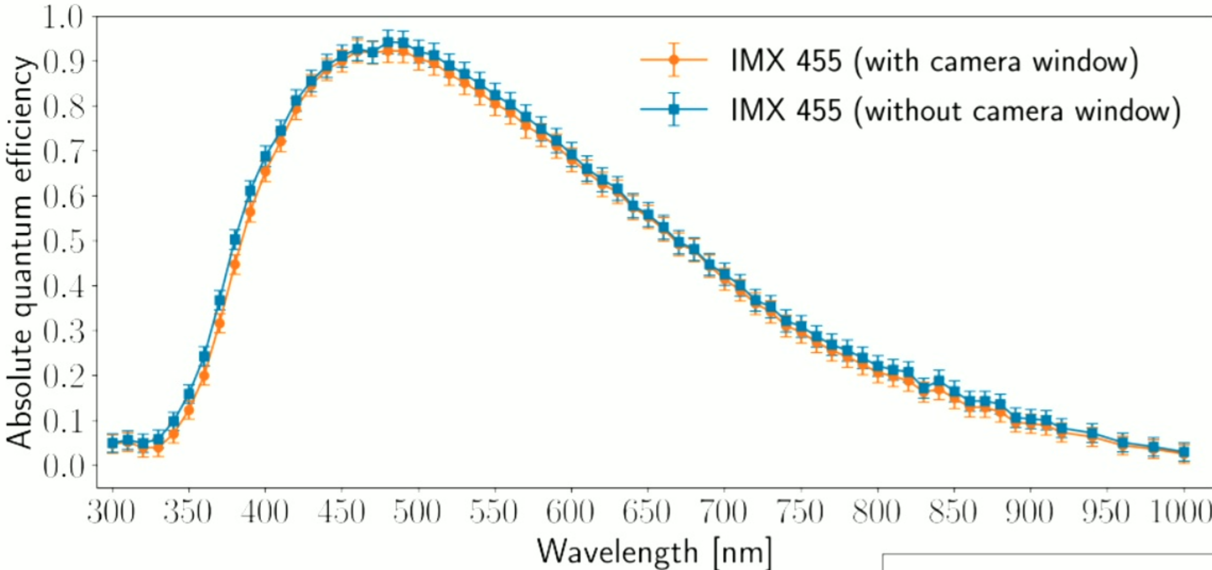
FUV band (140-190 nm)

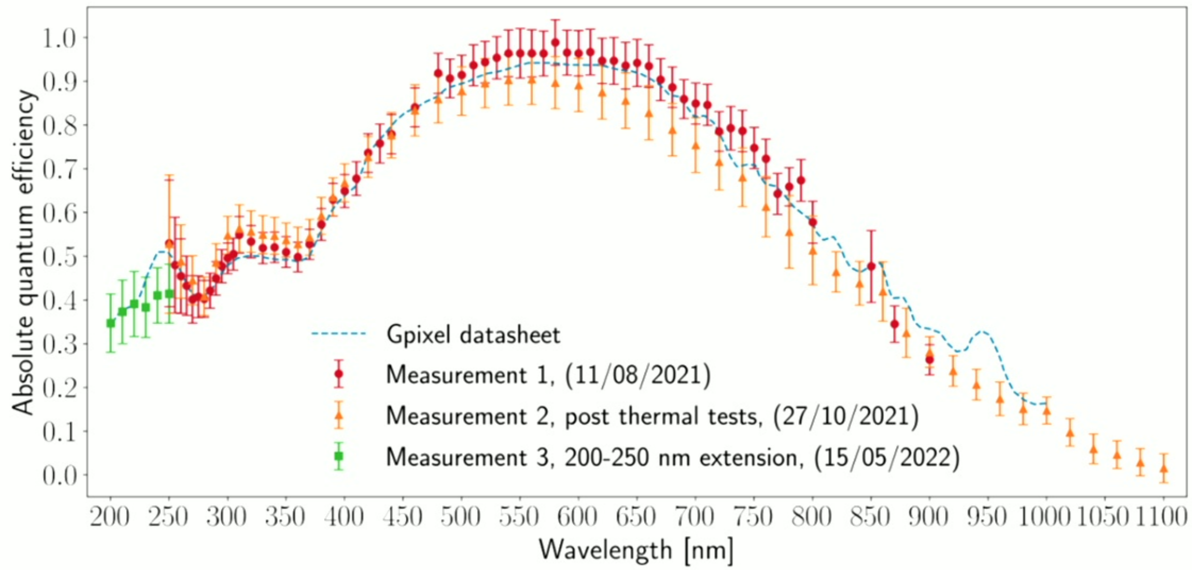
22.5 AB mag (SNR 5 in 1000s)

3 year mission

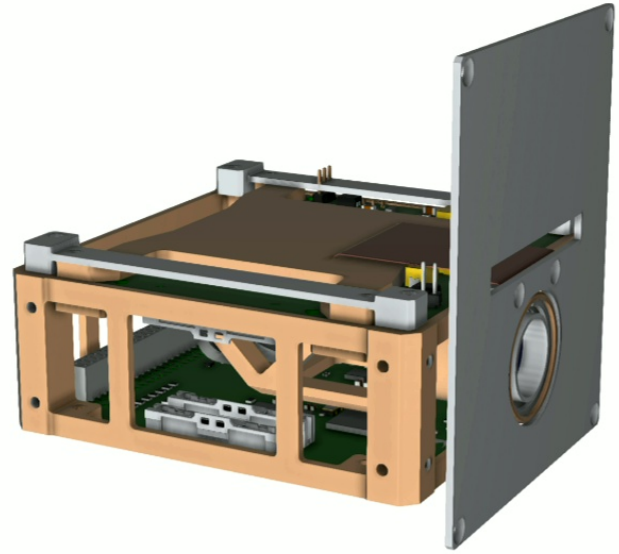
15 minute ToO response to target from ground trigger

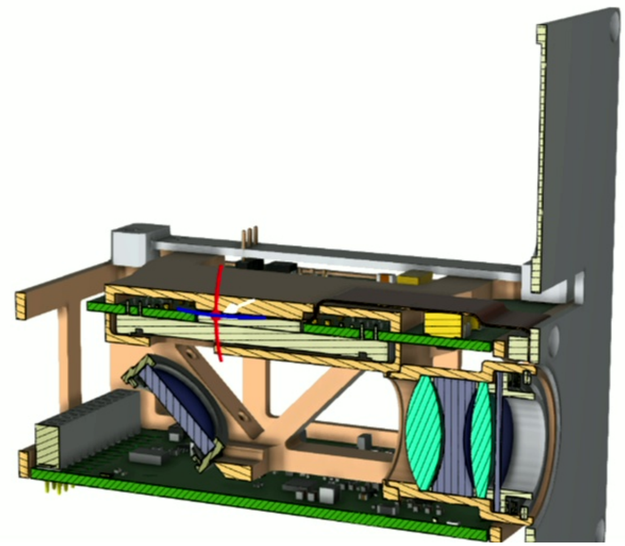



IMX 455 (with camera window)
IMX 455 (without camera window)
Absolute quantum efficiency
Wavelength [nm]


Gpixel datasheet
Measurement 1, (11/08/2021)
Measurement 2, post thermal tests, (27/10/2021)
Measurement 3, 200-250 nm extension, (15/05/2022)
Absolute quantum efficiency
Wavelength [nm]

LUVCam: A high performance, low cost, UV camera system



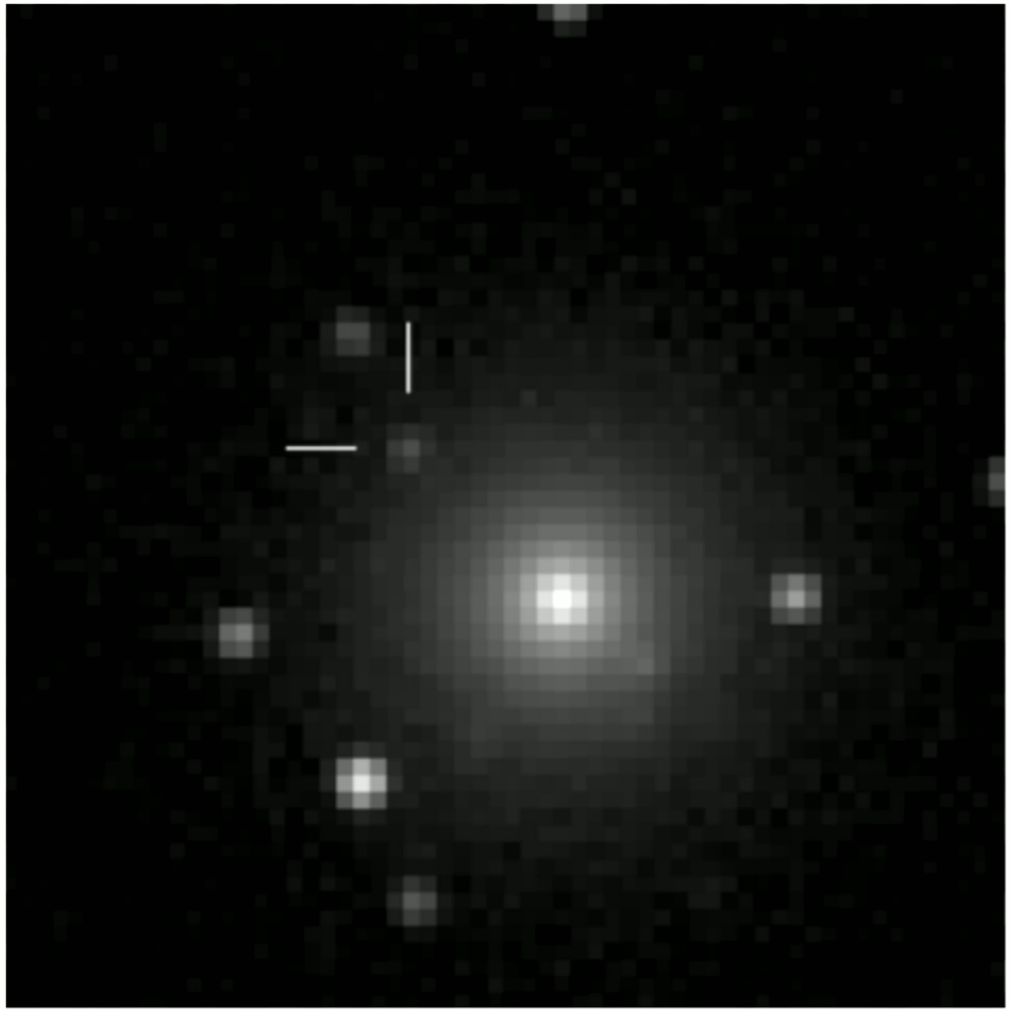


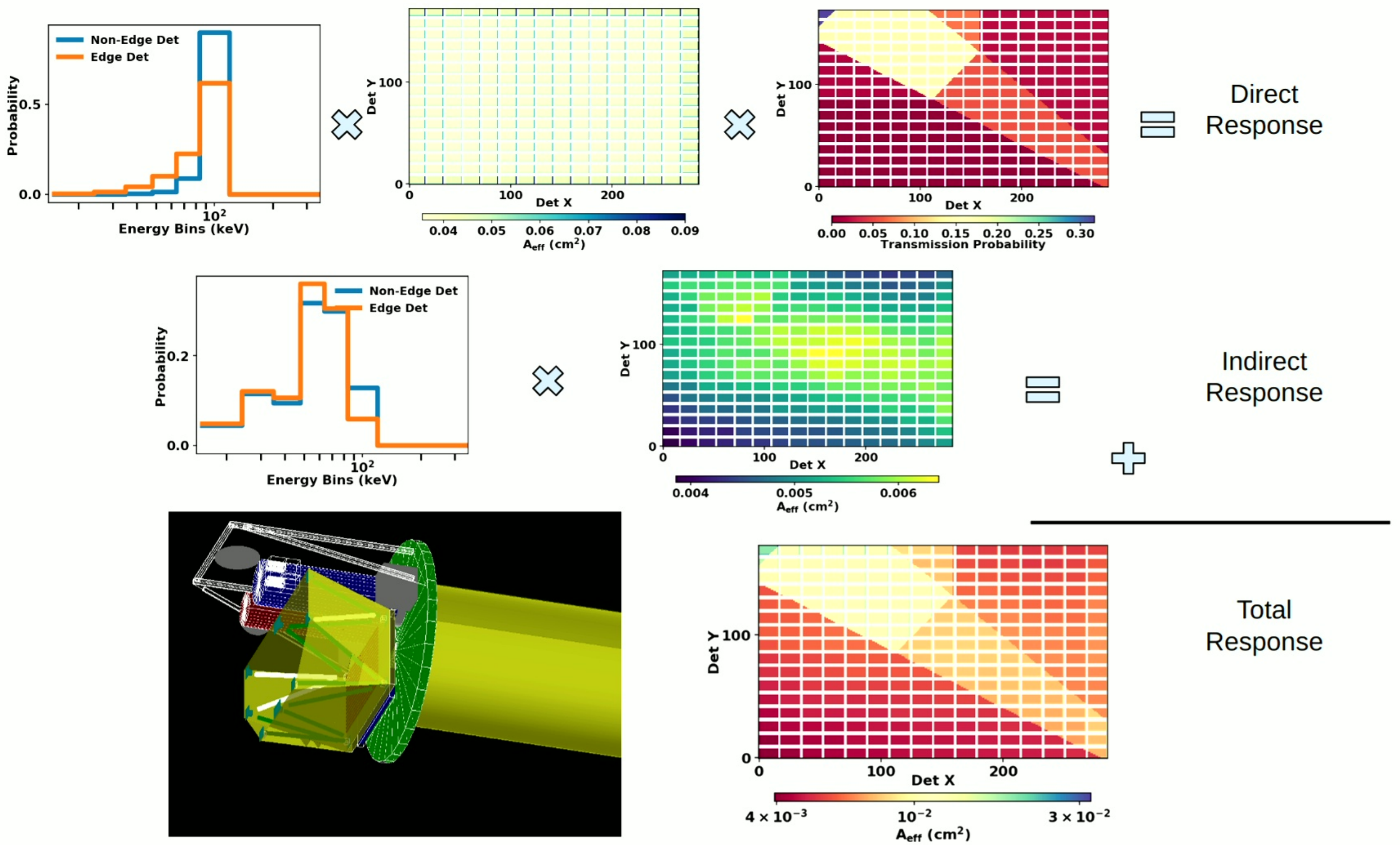
Watching Mergers Live

- New data products for **old space telescopes**.
- Novel data analysis techniques, **hard calibration**
- Two supercomputers, millions of CPU/hours per year, burst computing on HPC
- Two new command+control schemes for space telescopes
- Comms infrastructure challenges, RF engineering, bureaucratic barriers
- Coherent multi-messenger searches, new statistical techniques for data combination, cross-collaboration communication+sharing
- Negative Latency GW detections: faster plumbing
- **New space telescopes**, new cameras, new technology.
- **Lots of passionate people**

Maybe we'll pull it off?

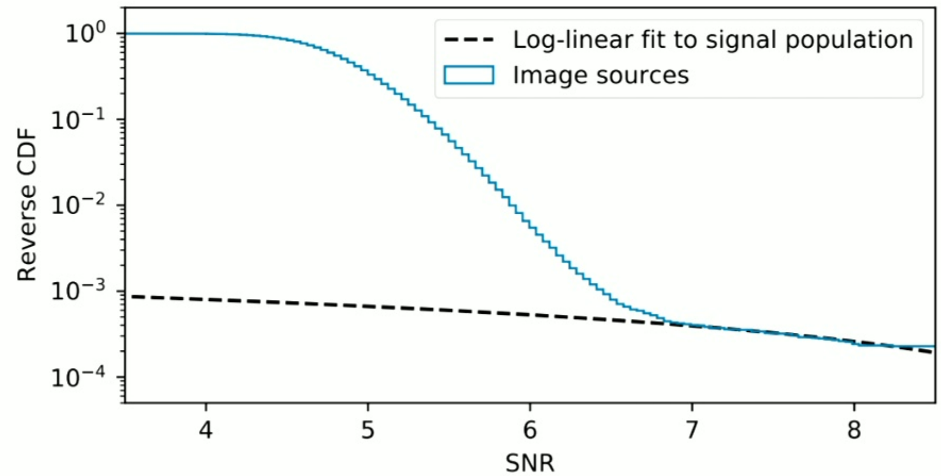
QUVIK Far-UV image of kilonova at 200 Mpc, T0+15 min

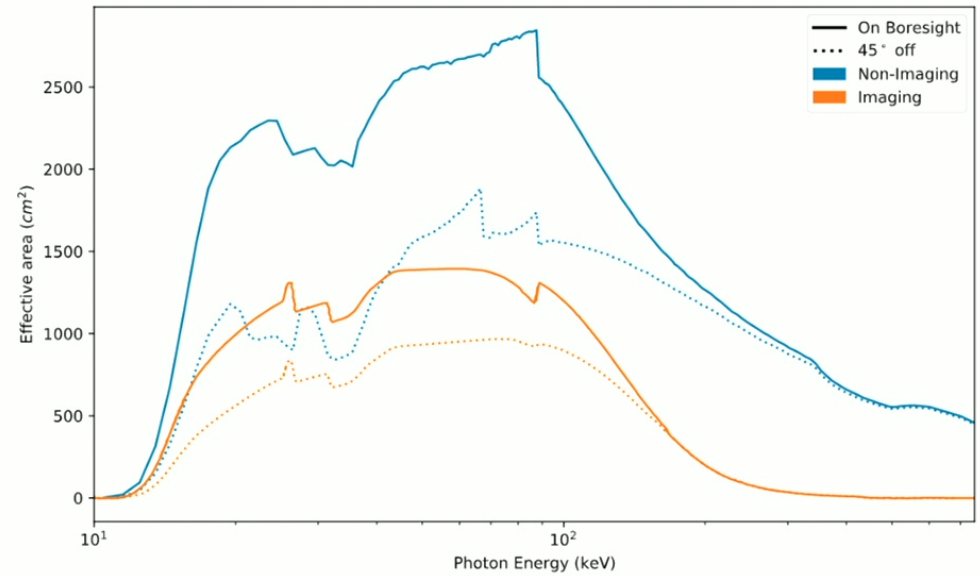



Non-Edge Det
Edge Det
Probability
0.5
0.0
10^2
Energy Bins (keV)
Det Y
100
0
Det X
200
0.04 0.05 0.06 0.07 0.08 0.09
A_{eff} (cm^2)
0.00 0.05 0.10 0.15 0.20 0.25 0.30
Transmission Probability
Direct
Response
Non-Edge Det
Edge Det
Probability
0.2
0.0
10^2
Energy Bins (keV)
0.004 0.005 0.006
A_{eff} (cm^2)
Indirect
Response
Total
Response
4×10^{-3} 10^{-2} 3×10^{-2}
A_{eff} (cm^2)

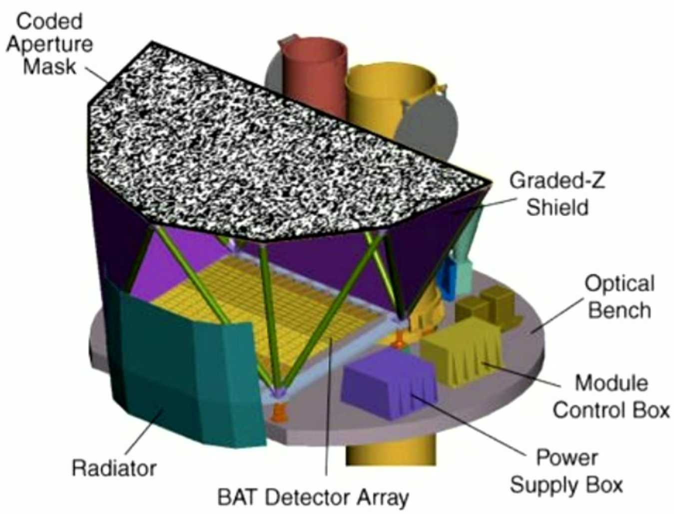
Now can do imaging, but...

- 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

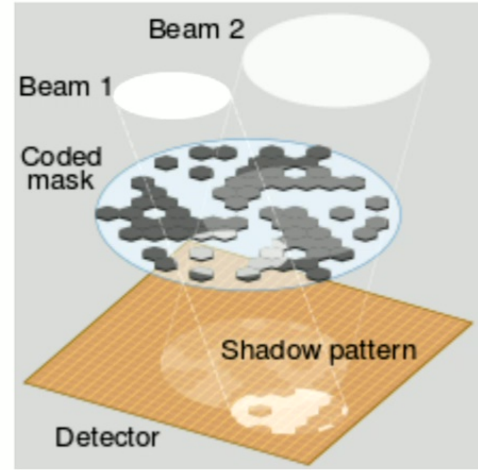




Burst Alert Telescope
(shadowgrams)



- 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