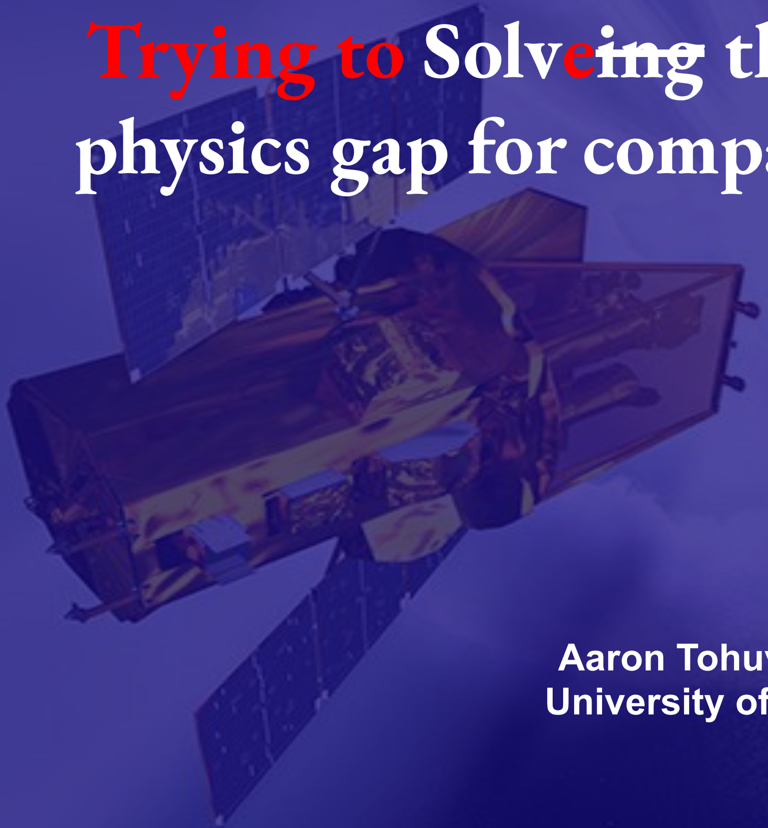
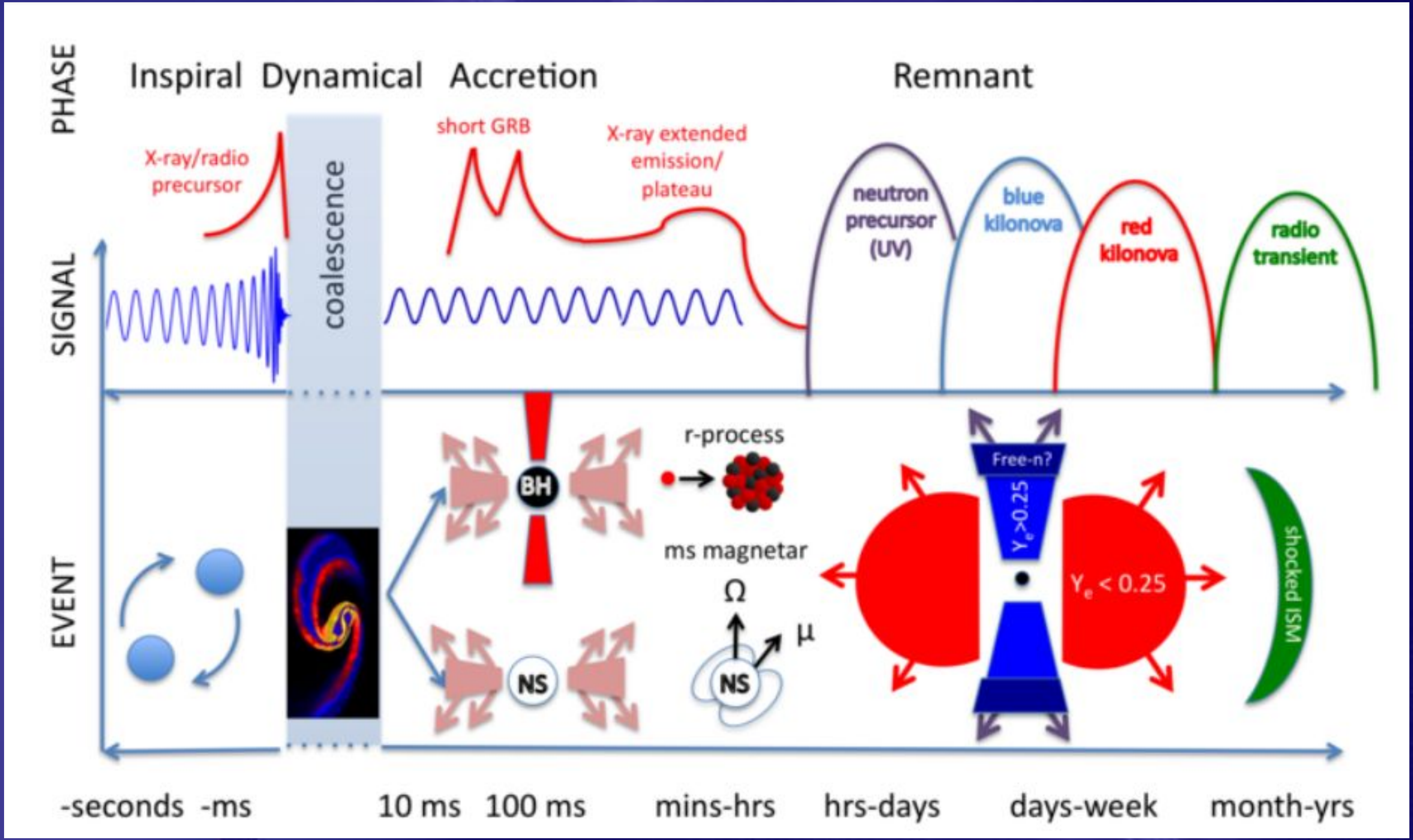
~~Hunting High-Energy Counterparts to Gravitational Wave Events with Swift~~

# Trying to Solve~~ing~~ the 'first few hours' physics gap for compact binary mergers



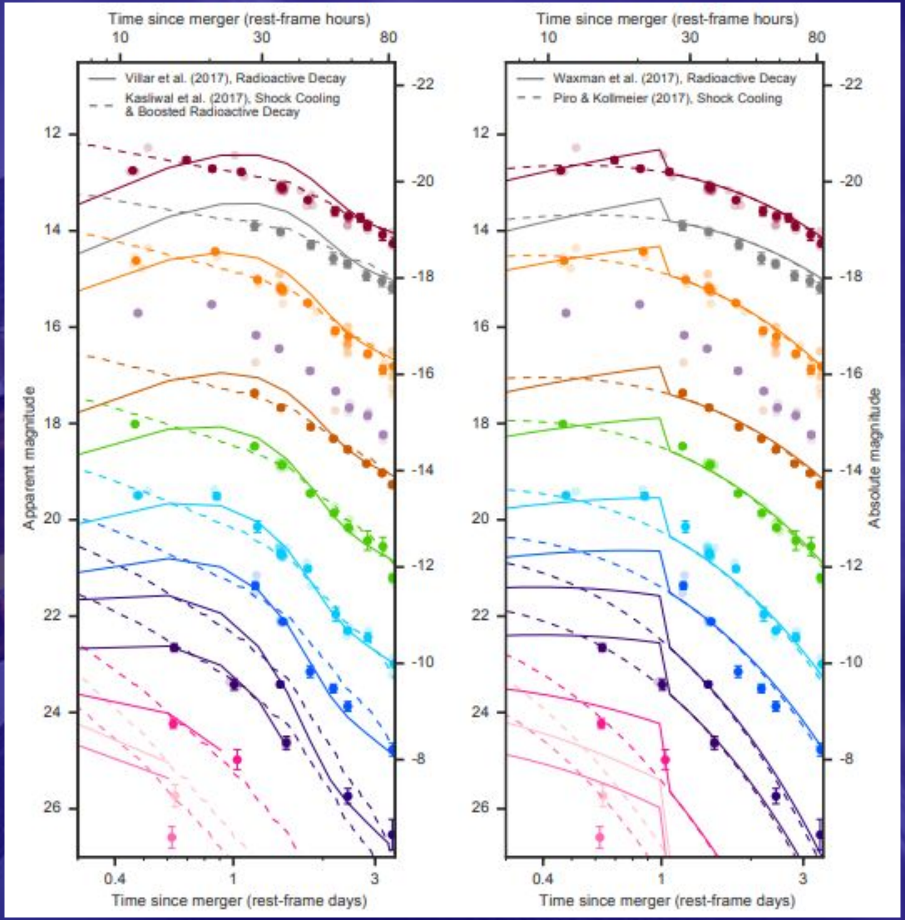

Aaron Tohuvavohu
University of Toronto




Rodriguez + Metzger (2016

# Need for earlier Obs. ---importance of UV

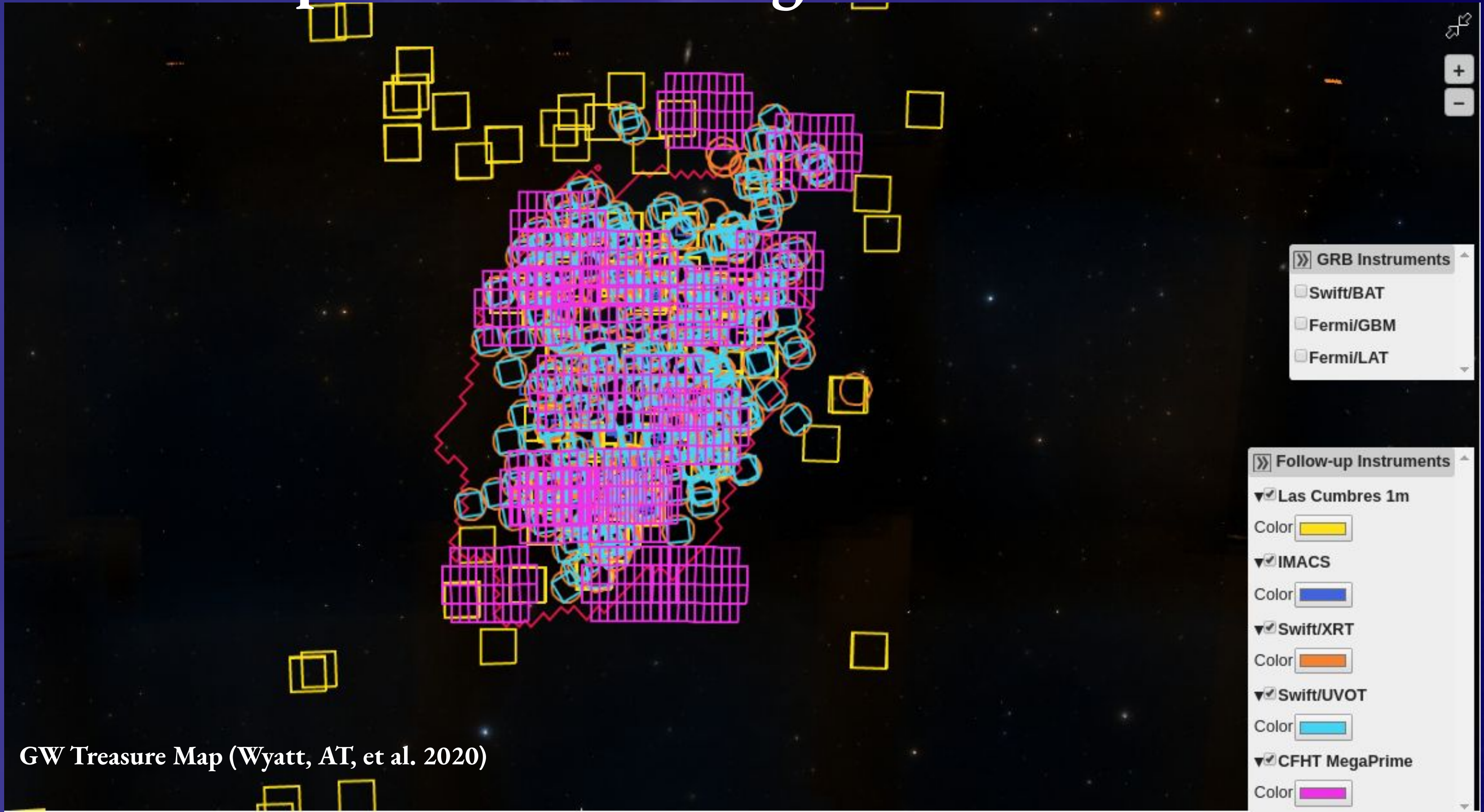
- radioactive decay luminosity model from Villar et al. (2017)
- combined shock cooling - boosted radioactive decay model from Kasliwal et al. (2017).




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

From Arcavi 2018

# Most complete total coverage for NSBH S190814bv




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

# Probability covered as a function of time for S190814bv:


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

# How do we solve this problem?

**(without waiting 5-10 years)**

1. Localize to within the FoV of narrow-field sensitive telescopes (HST, Chandra, Keck, VLT) from the prompt emission alone!

    **What how?**

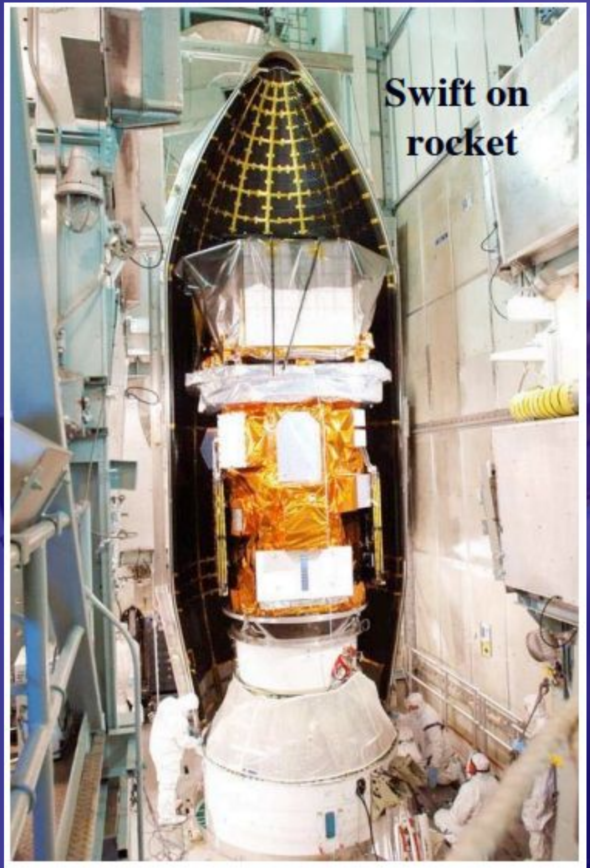
2. Do very early time wide-field searches in X-ray and UV

    **What how?**

3. Coordinate between search groups.

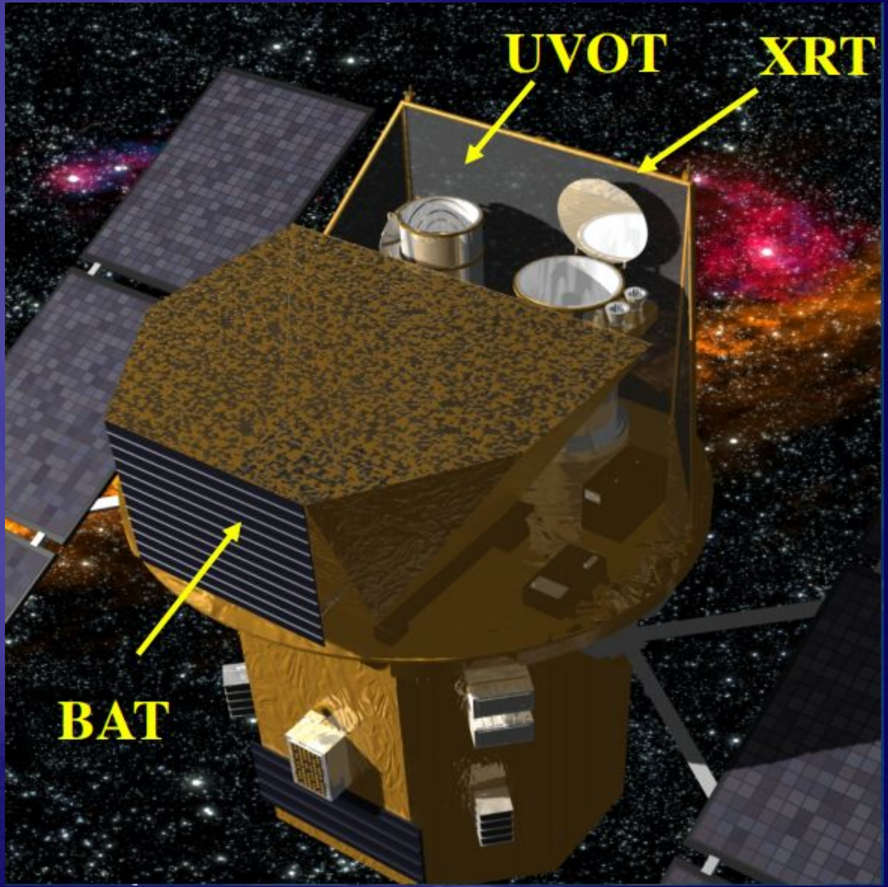
    **What how?**

# The Neil Gehrels *Swift* Observatory (2004-∞)



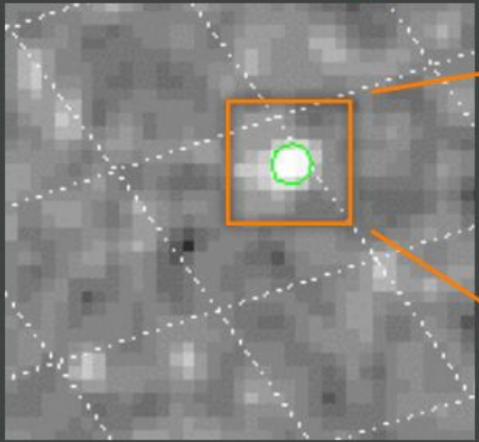

# Instrumentation

- Burst Alert Telescope (BAT)
  - Hard X-rays (15-350 keV)
  - 1/6 of the whole sky (~2 sr.) FoV
  - Localizes ~100 GRB/yr.
  - Arc-minute localization
- X-ray Telescope (XRT)
  - Soft x-rays (0.3-10 keV)
  - 0.12 sq-degree FOV
  - Arc-second localization
  - CCD spectroscopy
- UV/Optical Telescope (UVOT)
  - 170-650 nm
  - 0.08 sq-degree FOV
  - Sub arc-second positions
  - Grism spectroscopy
  - 24th magnitude sensitivity



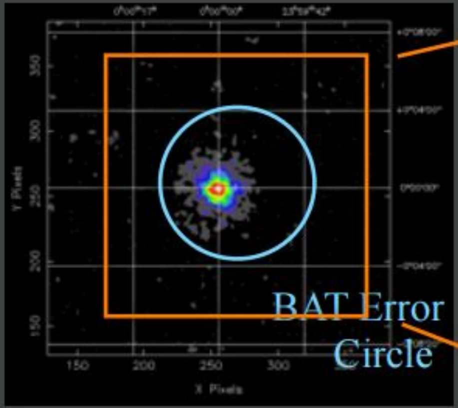
# Swift Localization Sequence

**BAT Burst Image**



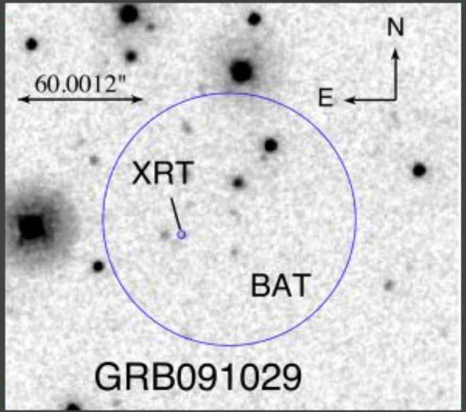
*T~30 sec*

**XRT Image**




*T~100 sec*

**UVOT Image**



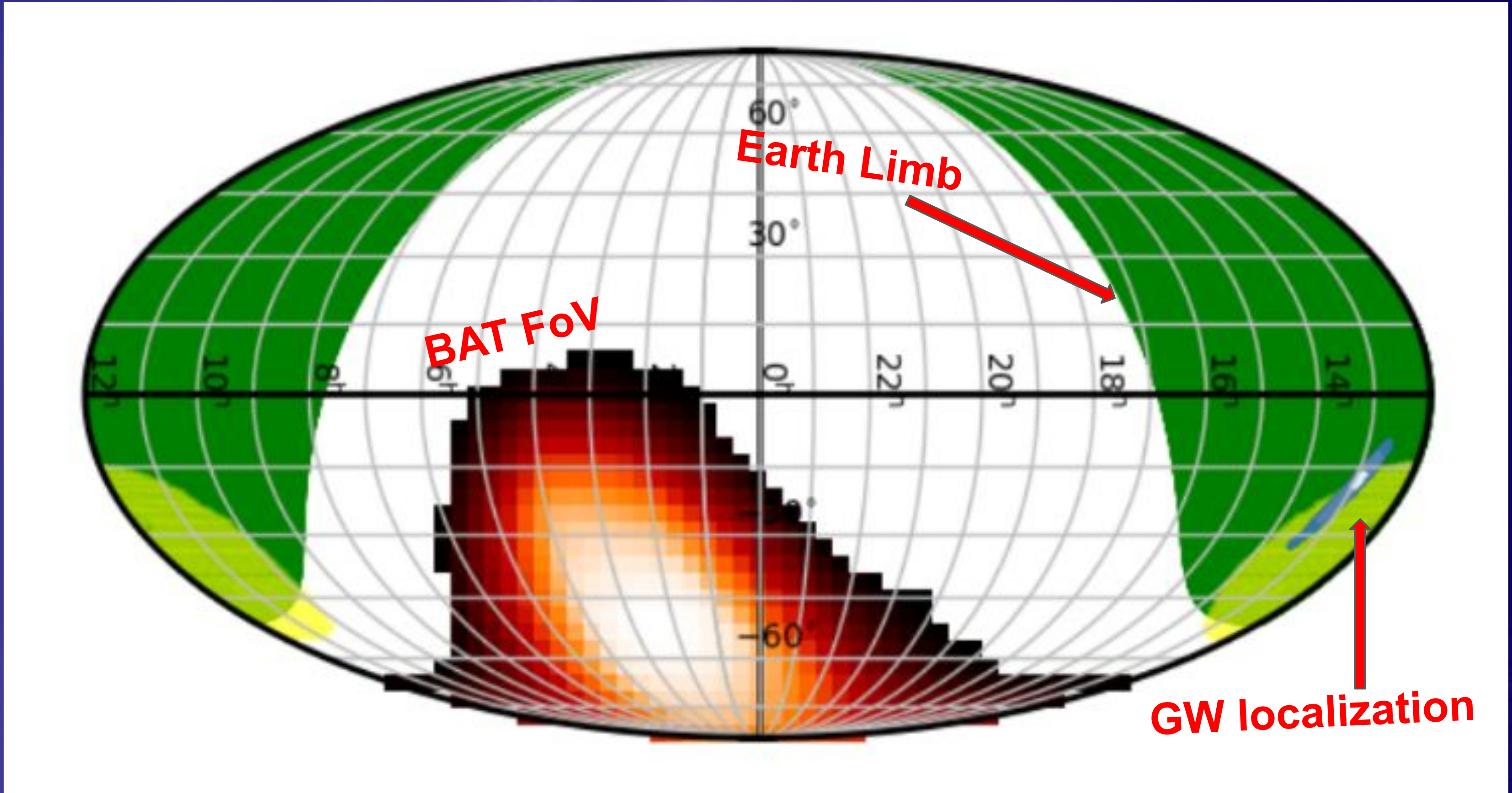

*T~300 sec*

**<4 arcmin**

**< 2 arcsec**

**~0.5 arcsec**

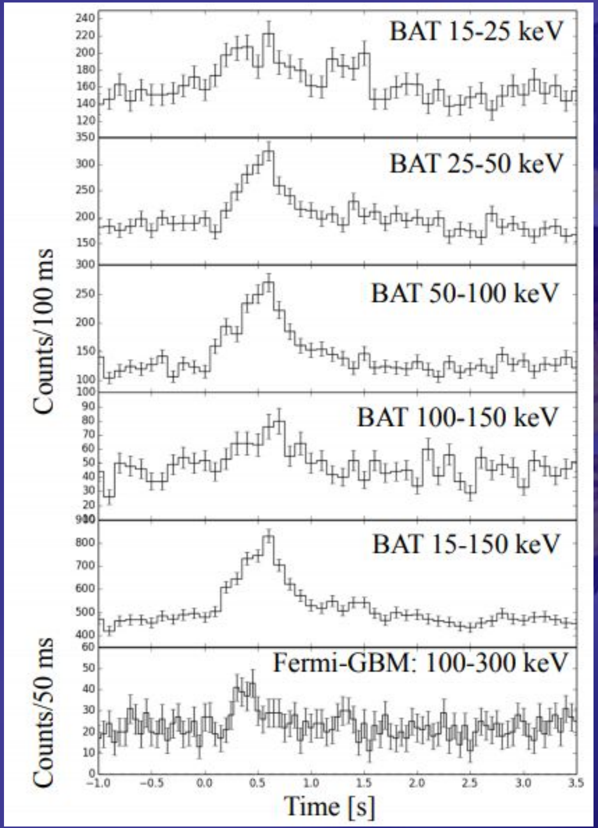
# BAT FoV at GW170817 T0




Amy Lien

# GW170817

(in an alternate universe shifted temporally by 29 minutes)



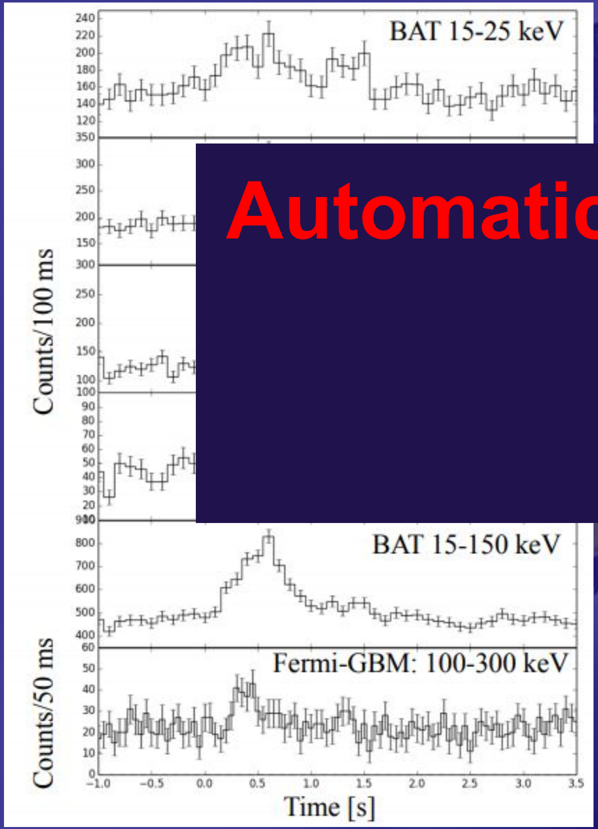

- Light curve shape of GRB 170817A is modeled by fitting.
- Best fit spectral models (Goldstein et al. 2018) are used for the 1st peak and the 2nd peak.
- Using the background data of GRB 170516A.
- 30 degree off-boresight energy response is used.
- Simulated the counts in the BAT standard 80 channels every 100 ms.

23 sigma detection!!!

Sim by **Taka Sakamoto**

# GW170817

(in an alternate universe shifted temporally by 29 minutes)




- Light curve shape of GRB 170817A is modeled by fitting.

23 sigma in Image!!!

**Automatic slew and UVOT and XRT data at T0+62 seconds!**

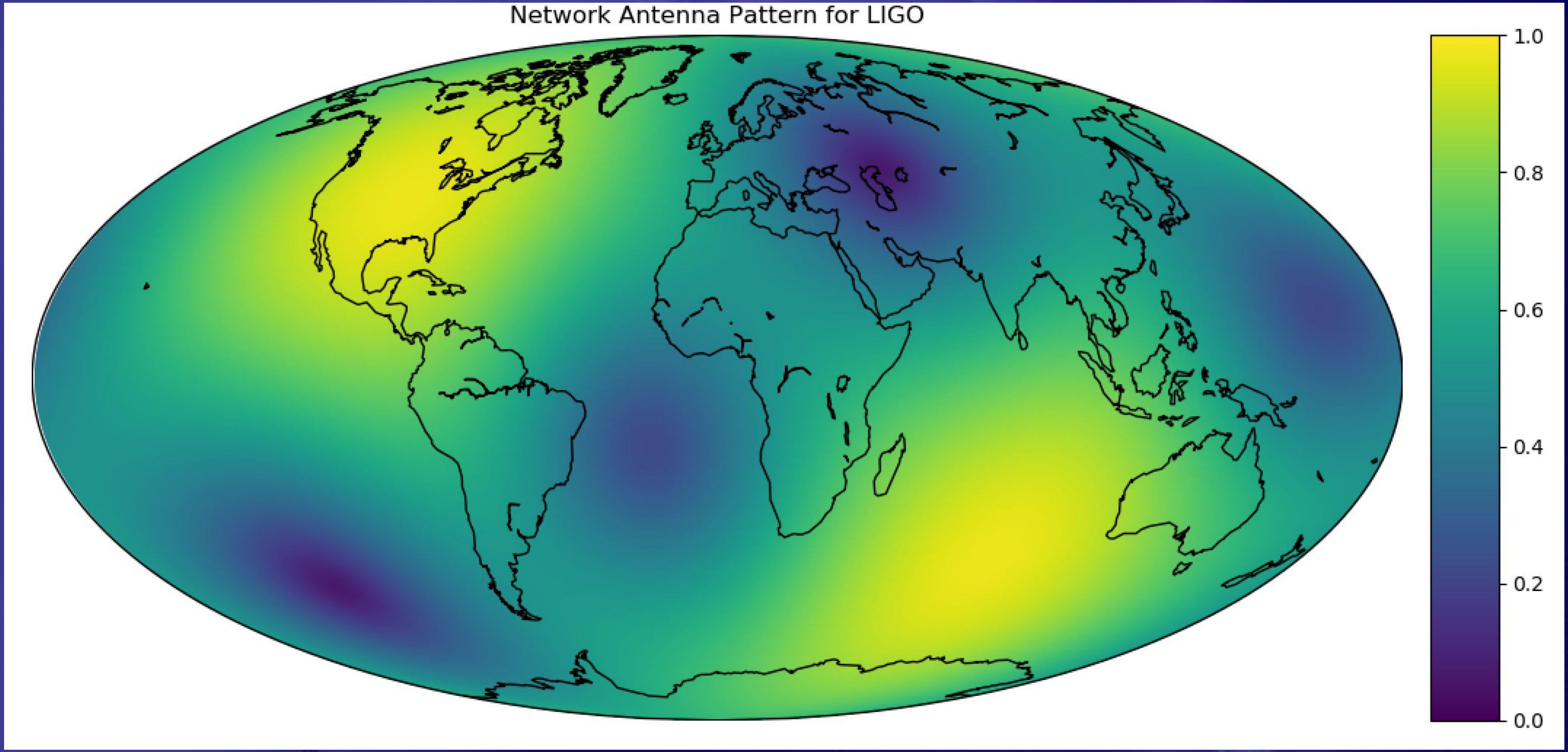
(this is the dream scenario)

response is used.

- Simulated the counts in the BAT standard 80 channels every 100 ms.

Sim by **Taka Sakamoto**

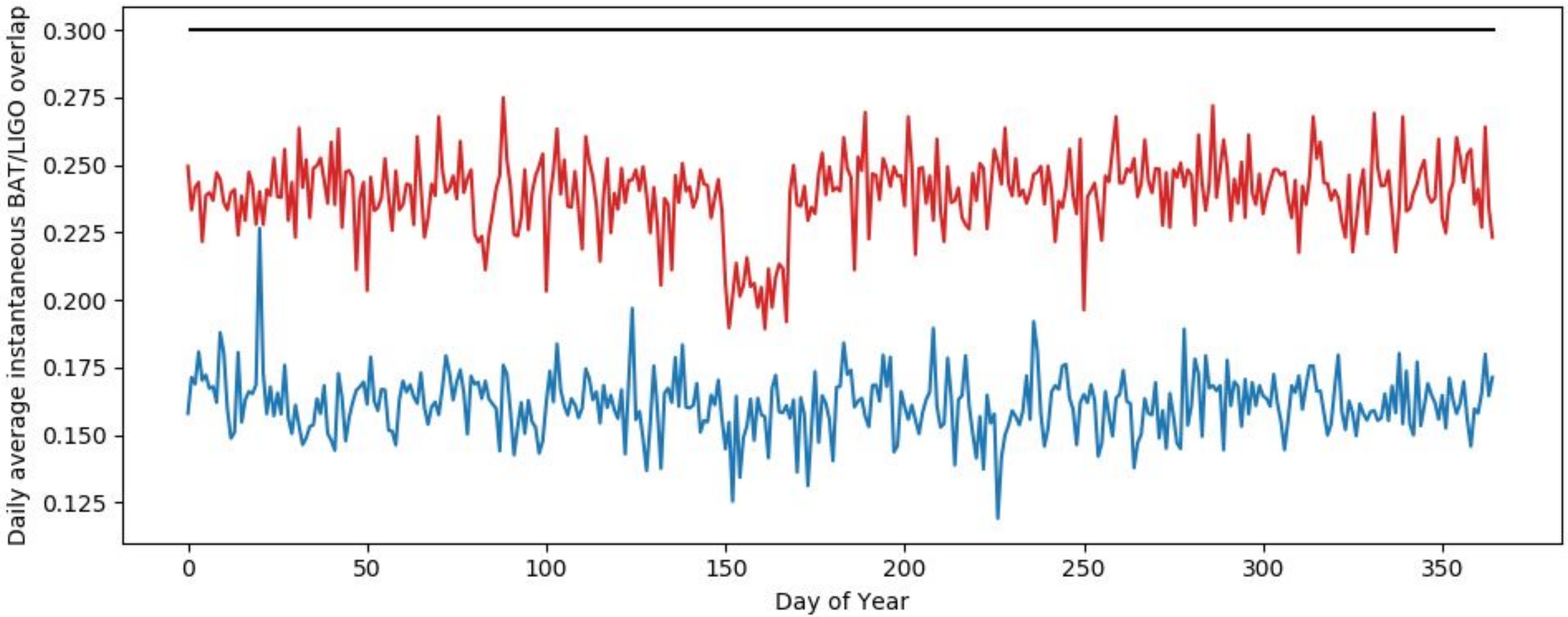
# Just Lamenting?
# Nope, we can optimize for this outcome

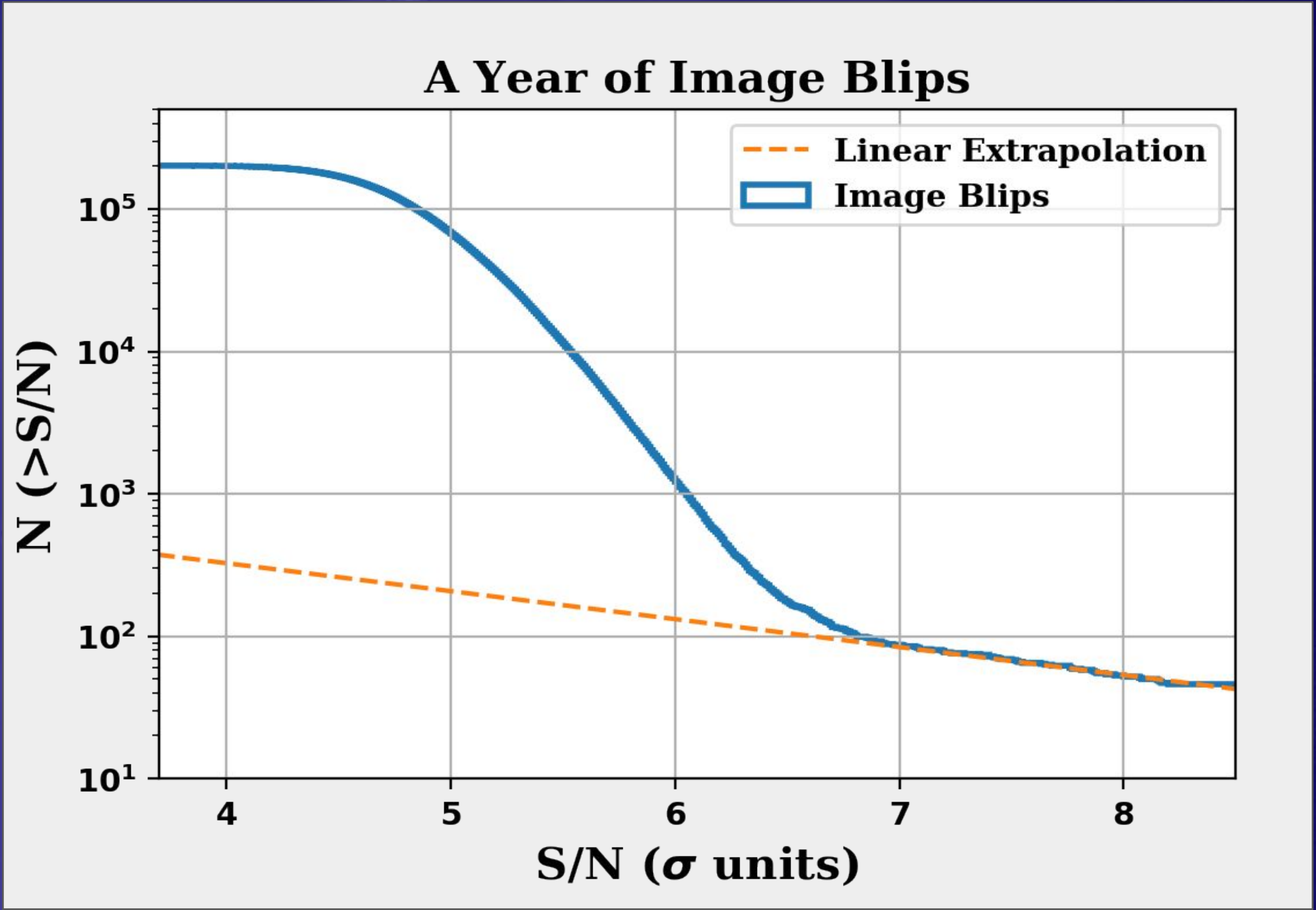


# Chasing the LIGO lobes across the sky:

## Increasing the Coincident GW/GRB yield with Swift/BAT biasing

(AT 2020, in prep)




A Year of Image Blips
Linear Extrapolation
Image Blips
N (>S/N)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
4
5
6
7
8
S/N (σ units)

# Maximum Likelihood Approach

Define full Poisson likelihood for expected counts in each individual detector from bkg. Plus signal model, as a function of energy

$$L = \Pi_{ij}\, p_{ij}$$

Where i iterates of detectors and j iterates over energy bins

$$p_{ij} = \mathrm{Poisson}(n_{ij}; \theta_{ij}) = \theta_{ij}^{\,n\_ij} \exp[-\theta_{ij}] \,/\, n_{ij}!$$

Where $n_{ij}$ is the observed counts in detector i and energy bin j

And $\theta_{ij}$ is the expected number of counts from the model being tested

$$\theta_{ij} = N\_signal_{ij} + N\_bkg_{ij}$$

$$N\_signal_{ij} = S(A_0, \gamma, ra, dec) \times (A\_eff_j \; \square \; f_i)$$

Where $f_i$ is the fraction of the detector that the source illuminates

$N\_bkg_{ij}$ for now is taken from nearby off-time data.

J. Delaunay, AT, et al (in prep)

# BAT Max Likelihood Evaluation

$H_0$: Bkg and S=0

$H_1$: Bkg and S($A_0$,$\gamma$,ra,dec)

$P(\mathrm{data} \mid H_1) \propto L(S, \mathrm{Bkg} \mid \mathrm{data})\, P(S)\, P(\mathrm{Bkg})$

$P(\mathrm{data} \mid H_0) \propto L(\mathrm{Bkg} \mid \mathrm{data})\, P(\mathrm{Bkg})$

P(Bkg) is a gaussian with mode and uncertainty found from a fit to nearby off-time data

Test Statistic:

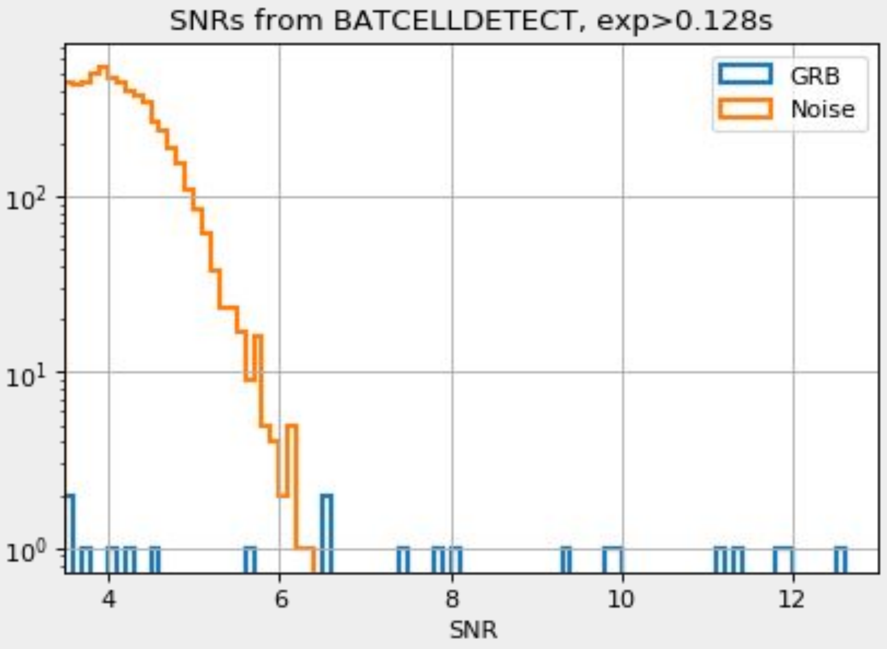
$\underline{\Lambda = 2{*}\log[P(\mathrm{data}|H_1) / P(\mathrm{data}|H_0)]}$

J. Delaunay, AT, et al (in prep)

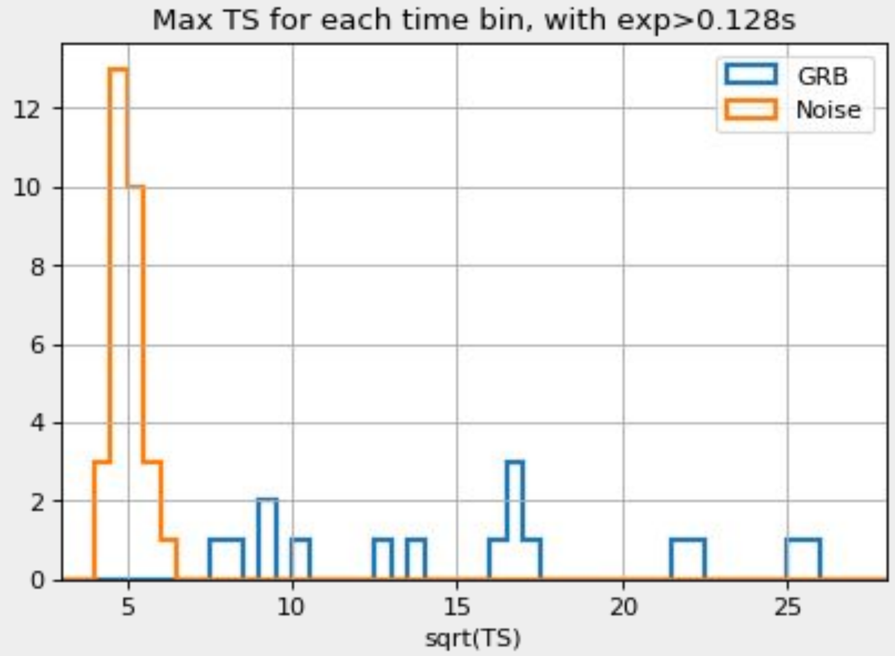
# Example of targeted MaxLogLikelihood

## Around GRB 180805A

**Max SNR = 12.56**




**Max √TS = 25. 86**



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

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

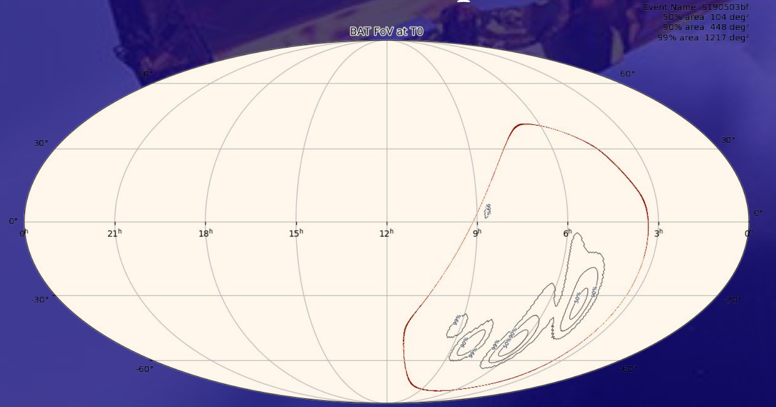
(AT, Palmer, Cenko 2020, in prep )

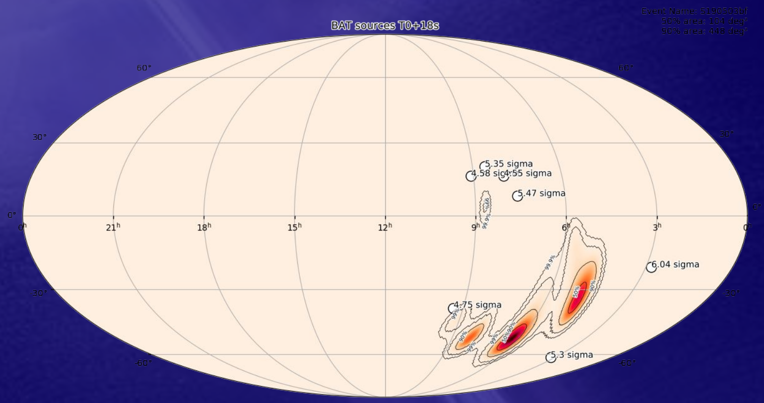
- Autonomously commanding spacecraft in extremely low latency to save temporally coincident event level data
- First ever autonomous commanding of a space telescope for scientific purposes
- Sets the stage for automatic repoint
    - -shhhhhhh

# Joint LVC/BAT sub-threshold search

- MoU signed with LVC : Swift receiving all GW triggers with FAR < 2/day.
- Autonomously commanding spacecraft in extremely low latency to save temporally coincident event level data (GUANO pipeline: AT, Palmer, Cenko 2020, in prep )
- Running sub-threshold maximum likelihood search to look for counterpart.
- GW/GRB coincidences found with joint FAR << 1/month will be reported publicly
- Extends range for GRB 170817 analogue to >120 Mpc, significantly farther for more luminous events.

Example for above threshold BBH S190503bf



# How do we solve this problem?

**(without waiting 5-10 years)**

1. Localize to within the FoV of narrow-field sensitive telescopes (HST, Chandra, Keck, VLT) from the prompt emission alone!

   **What how?**

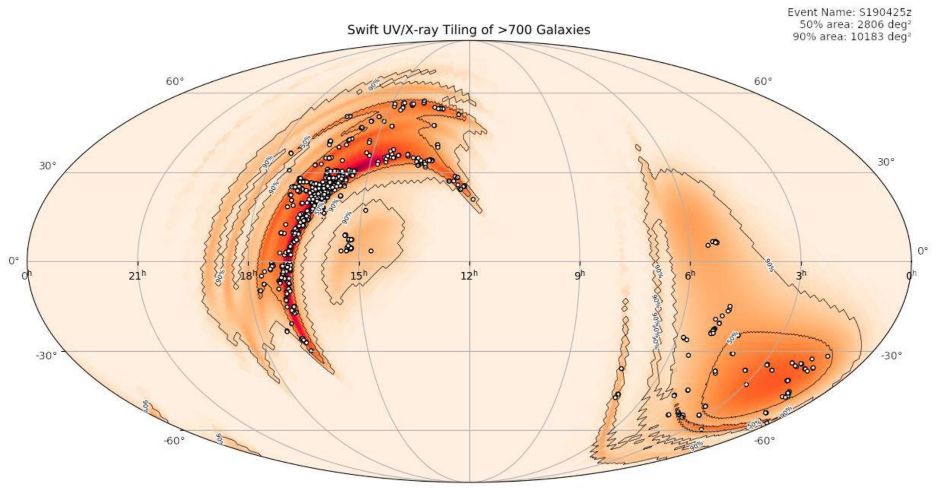
2. Do very early time wide-field searches in X-ray and UV

   **What how?**

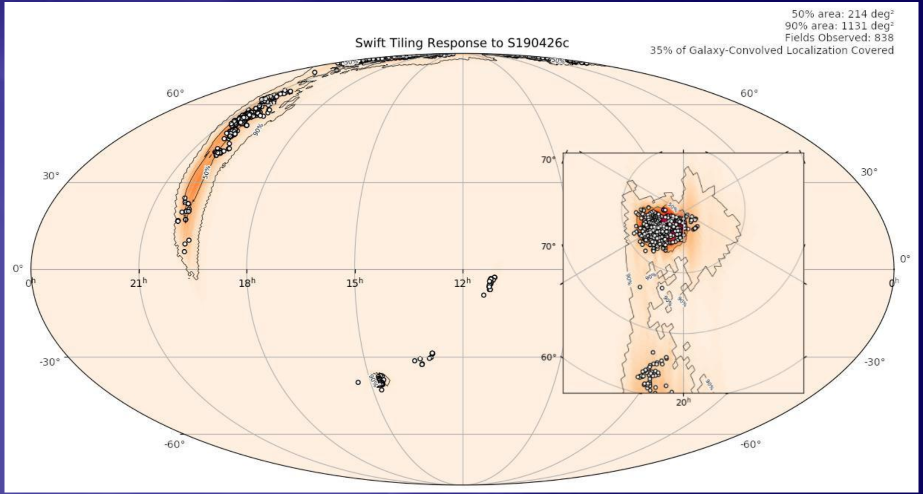
3. Coordinate between search groups.

   **What how?**

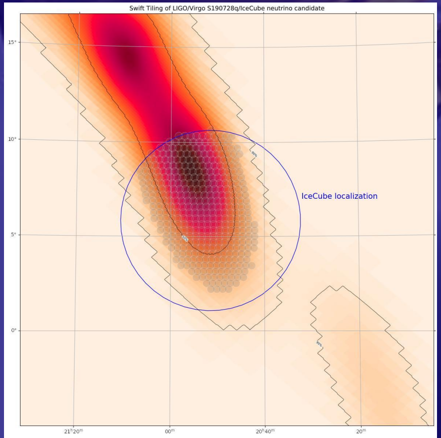
# S190425z



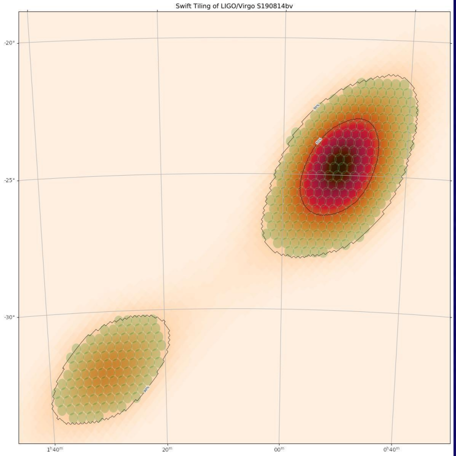

# S190426c




# S190728q/IC-190728A

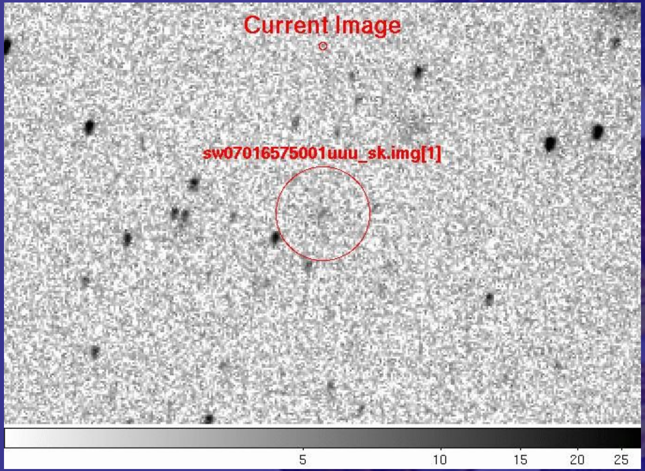



# S190814bv

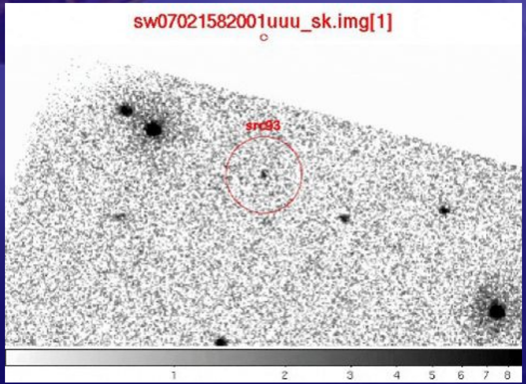


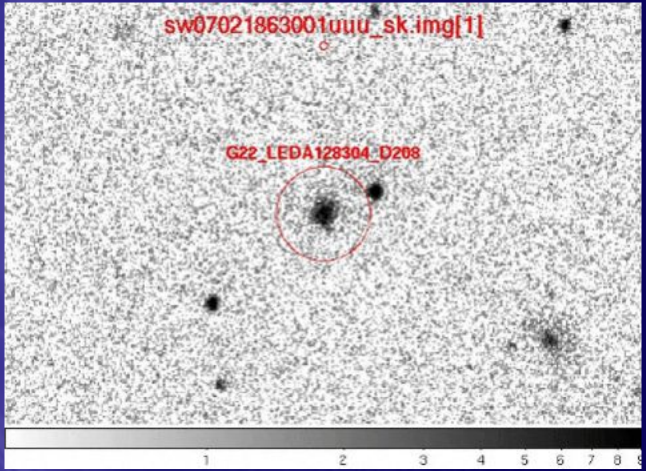
| Name | Classification | Distance (Mpc) | Raw (glxy conv.) prob covered in XRT/UV | BAT prompt coverage |
|---|---|---|---|---|
| S190425z | BNS: (99.9%) | 156 +/- 41 | 1 ( 6.5) % | 10 % |
| S190426c | BNS: (49.3%) Mass Gap: (23.7%) Terrestrial: (14.0%) NSBH: (12.9%) | 377 +/- 100 | 18 (31) % | 10 % |
| S190510g | Terrestrial: (58.0%) BNS: (42.0%) | 227 +/- 92 | 59 (67) % | 0 % |
| S190718y | Terrestrial: (97.9%) BNS: (2.1%) | 227 +/- 165 | 17 (22) % | 15 % |
| S190728q | BBH: (95.4%) Mass Gap: (4.6%) | 874 +/- 171 | 0.6 (95) % *nu | 74 % |
| S190814bv | NSBH: (99.8%) | 267 +/- 52 | 82 (90) % | 100 % |
| S190930t | NSBH: (74.3%) Terrestrial: (25.7%) | 108 +/- 38 | 0.5 (3) % | 11 % |
| S191110af | Burst retracted | NA | 0.07 (25) % | 12 % |
| S191216ap | BBH: (99.1%) | 376 +/- 70 | 2 (3) %, ~99% nu/ɣ | 3 % |
| S200114f | Burst (low freq) | NA | 30 (NA) % | >99.8% |
| S200115j | Mass Gap (with p_ns =1, | 340 +/- 79 | 5 (10) % | 8 % |

# Plenty of ‘new’ UVOT/XRT sources being found.
# Often suffer from lack of template images at sufficient depth in UV and X-ray bands to confidently identify transients.




**Swift J221951-484240**




**Swift J224718-581442 (AT2019sbk)**
**Very Fast UV transient, gone at T0+2 days**
**(perhaps similar to SN 2019bkc?)**

# Swift Gravitational Wave Galaxy Survey

AT, Evans, Kuin, et al. (2020, in prep)

- 5 Million Seconds targeted pre-imaging survey
- >15% of all *Swift* observing time in past year
- 14,251 galaxies
- 4773 individual fields
- 42% of integrated B-band luminosity within 100 Mpc
- X-ray sources to ~4 x $10^{-13}$ erg cm$^{-2}$ s$^{-1}$
- Complete to 5 sigma at 21 mag in u and uvw1

<u>63% Complete as of Today</u> (29/01/20)

# How do we solve this problem?

**(without waiting 5-10 years)**

1. Localize to within the FoV of narrow-field sensitive telescopes (HST, Chandra, Keck, VLT) from the prompt emission alone!

   **What how?**

2. Do very early time wide-field searches in X-ray and UV

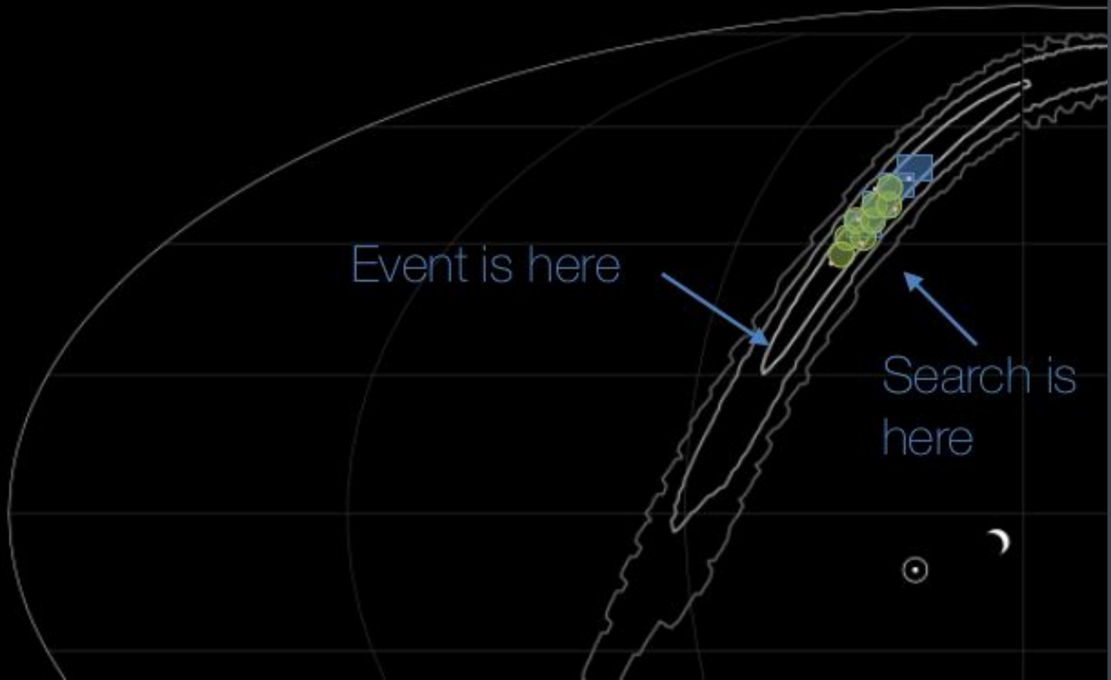
   **What how?**

3. Coordinate between search groups.

   **What how?**

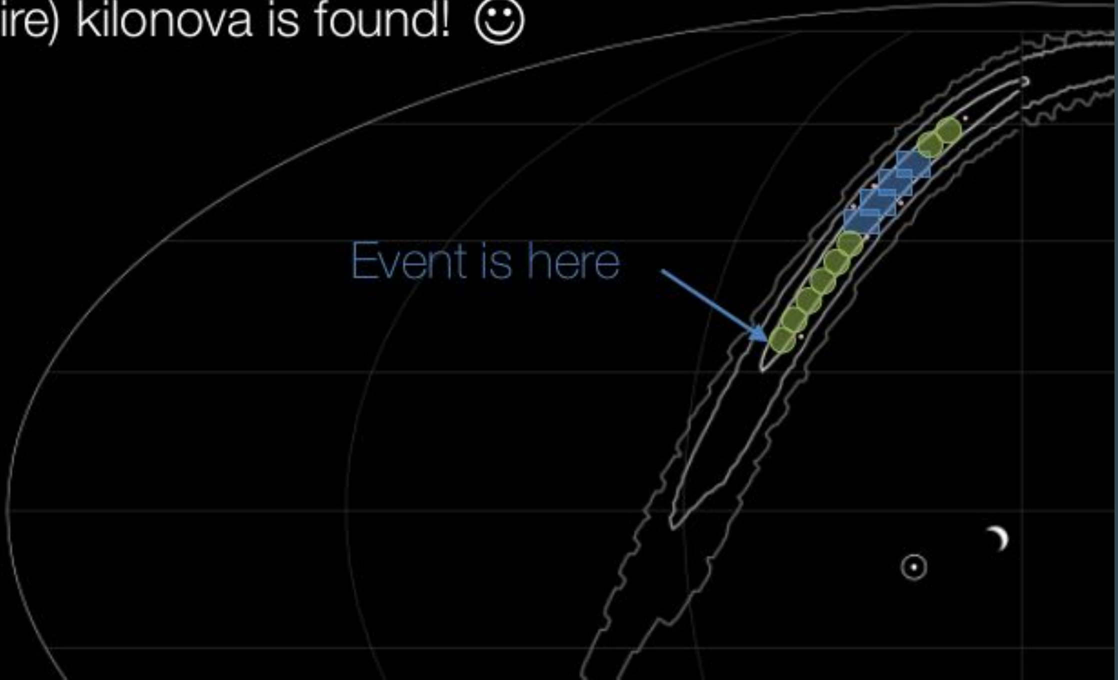
# How to Avoid Unnecessary Overlap in EM Searches?

**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! ☺



# Updates/new features since last community presentation:

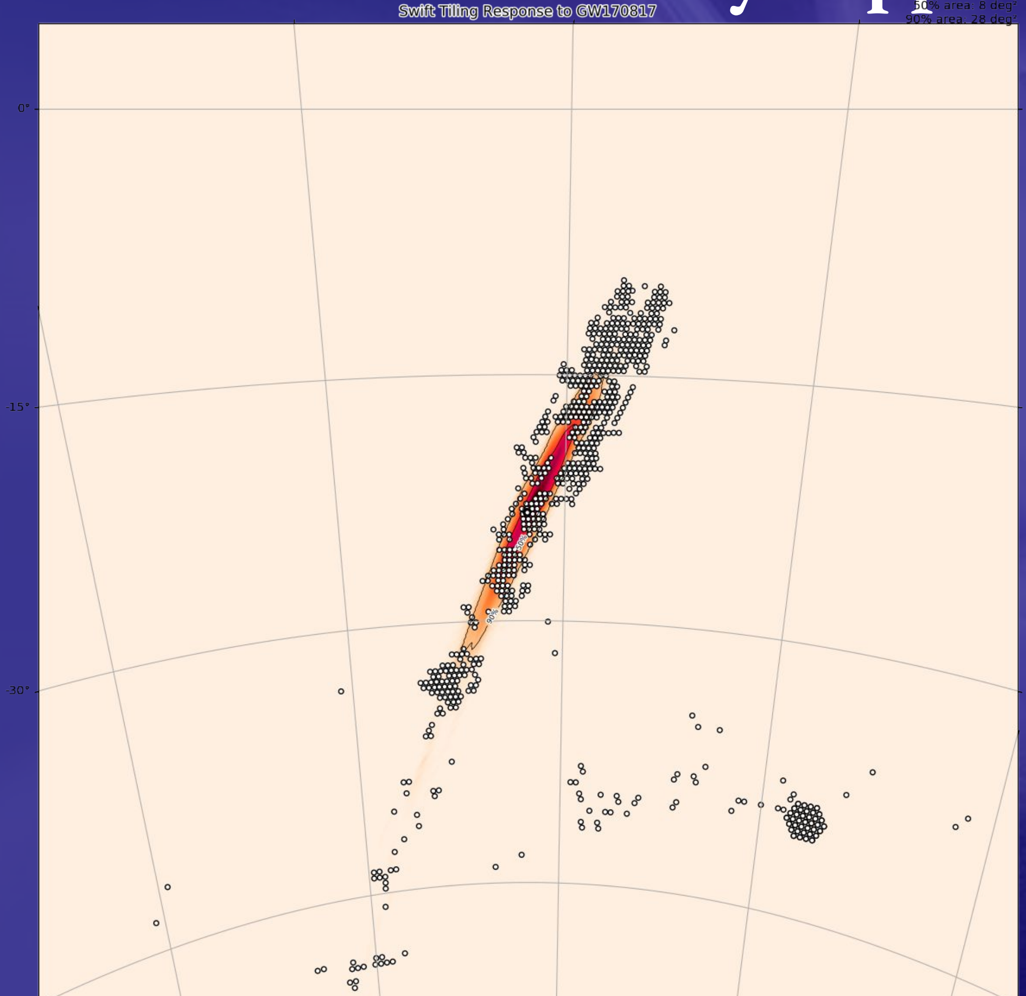
- DOIs and author groups for citing reports
- Tme slider to visualization
- Fermi GBM+LAT automatic coverage map per alert
- Gaining community participation in recent alerts
- Added API tutorial notebooks
- Submitted a paper describing the functionality and inner workings of Treasure Map arXiv:2001.00588
- Added API endpoint for bulk cancellation of scheduled pointings

# Participating Instruments so far in O3:

**Instruments Reporting**

| Name | Pointings reported |
|---|---|
| Swift/XRT | 5464 |
| Swift/UVOT | 3715 |
| Sinistro | 728 |
| ZTF | 207 |
| MMTCam | 119 |
| IMACS_f2_square | 99 |
| MLS10KCCD-CSS | 96 |
| CFHT_MegaPrime | 65 |
| Wise observatory C28 Jay Baum Rich telescope | 32 |
| Wise observatory C18 telescope | 24 |
| Swift_BAT | 23 |
| Spectral | 3 |
| Fermi/GBM | 62 |
| Fermi/LAT | 62 |

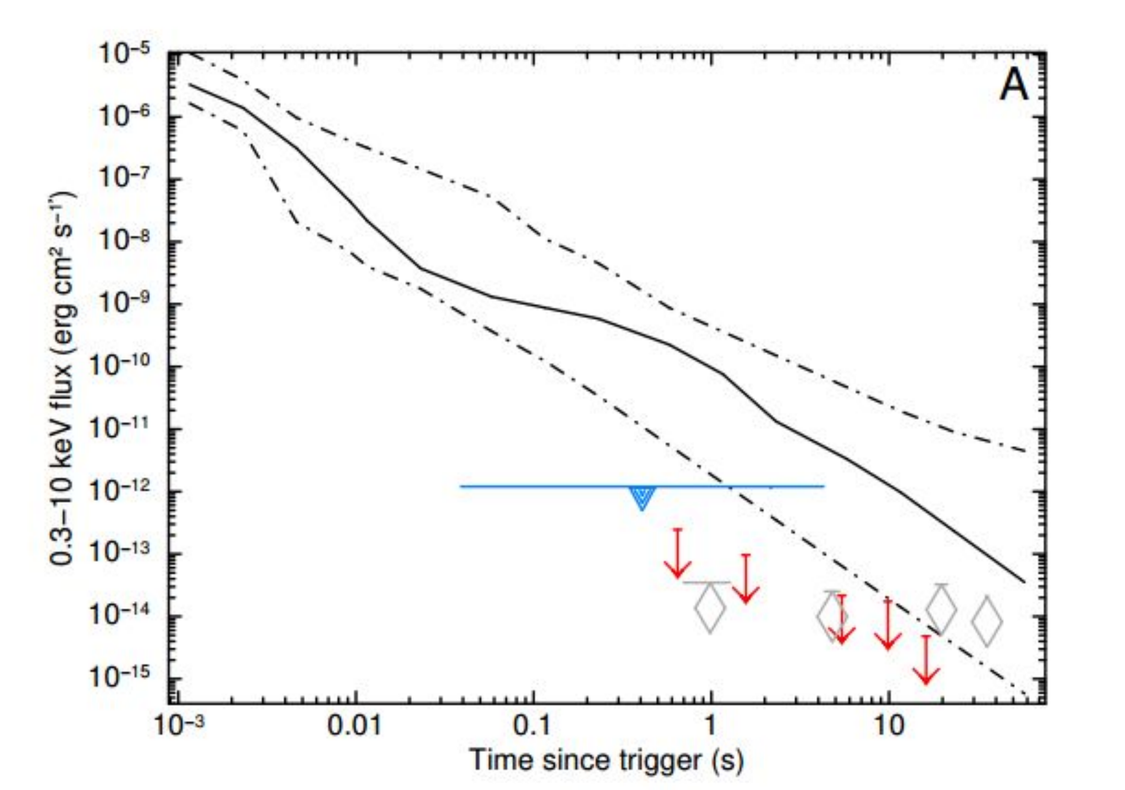
# What actually happened (*Swift* perspective)




- First field imaged at T0+16 minutes
- 741 fields in < 40 hours
- 92% of galaxy convolved localization covered
- Only constraints on X-ray and UV transients in the localization region
- Discovered the UV emission

# XRT early non-detection:

## First indication that this was not an on-axis burst



# What to expect following a public GW trigger:

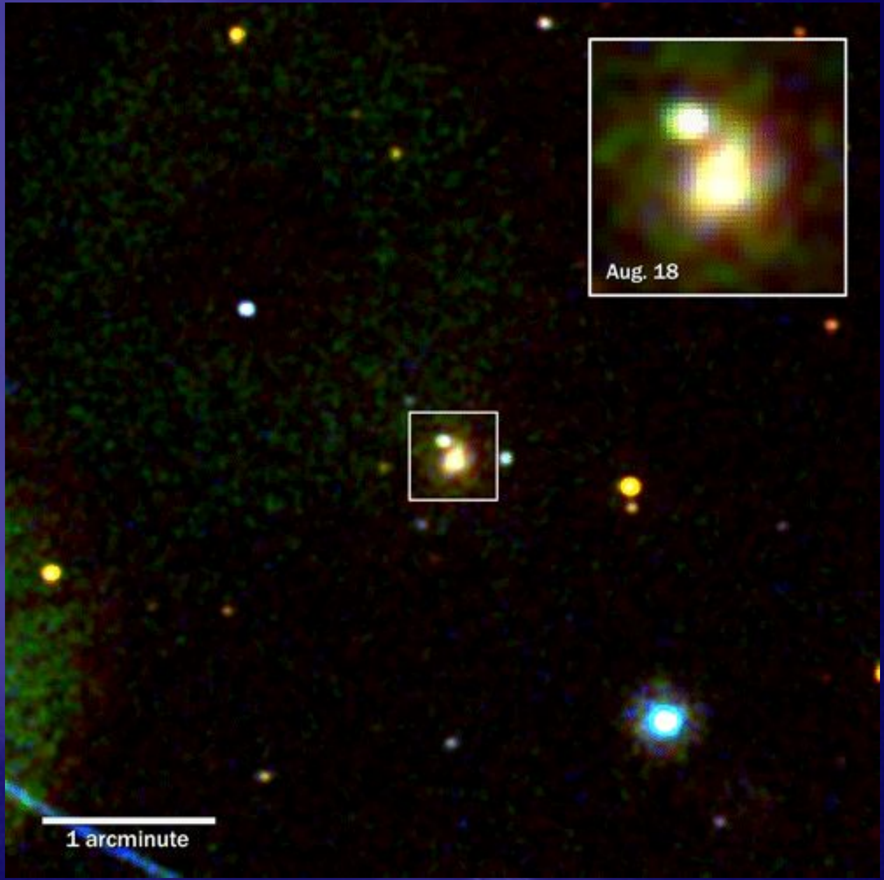
- T0 + 25 minutes: Tiling schedule shared publicly via Treasure Map
- T0 + 30 minutes: Swift UVOT/XRT settles on first target, search begins
- T0 + O(hrs): Sub-threshold BAT search results reported via GCN circular.
- T0 + O(hr) - O(day): XRT counterpart candidates reported automatically via GCN notice.
- T0 + O(hrs) - O(days): Human vetted UVOT/XRT counterpart candidates reported via GCN circular.

Throughout: Rapid X-ray + UV follow-up of promising candidates detected by other instruments.

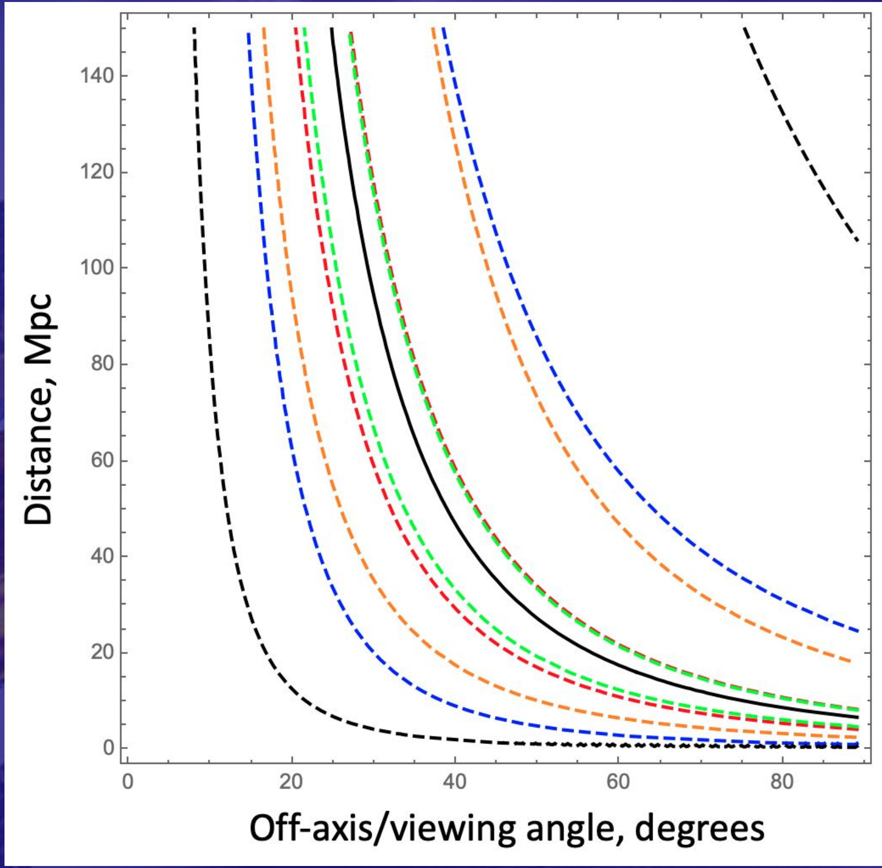
## Submit a ToO

# Swift/UVOT detection of UV bright kilonova

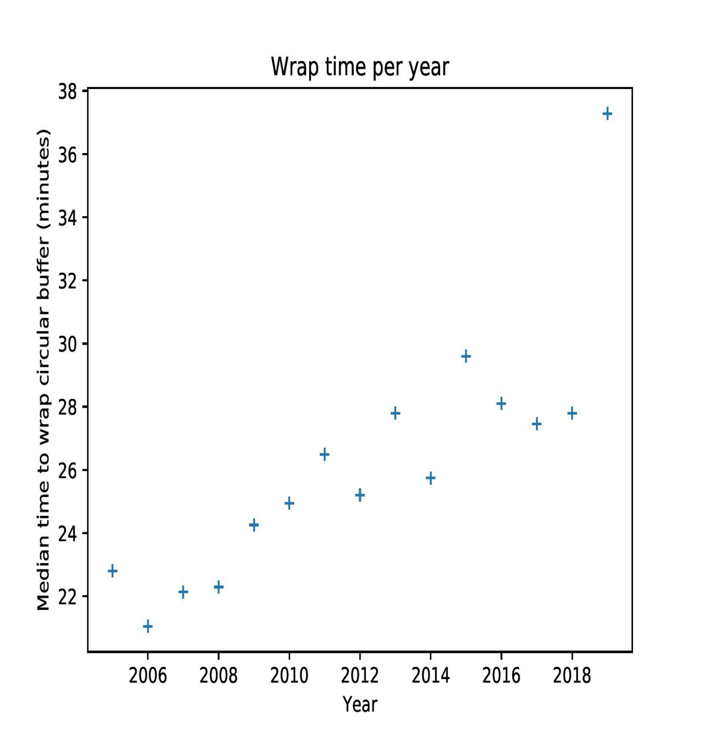
- Swift UV image at T0+15 hours
- Only UV measurement of the kilonova
- UV photometry a critical contribution to kilonova emission modeling

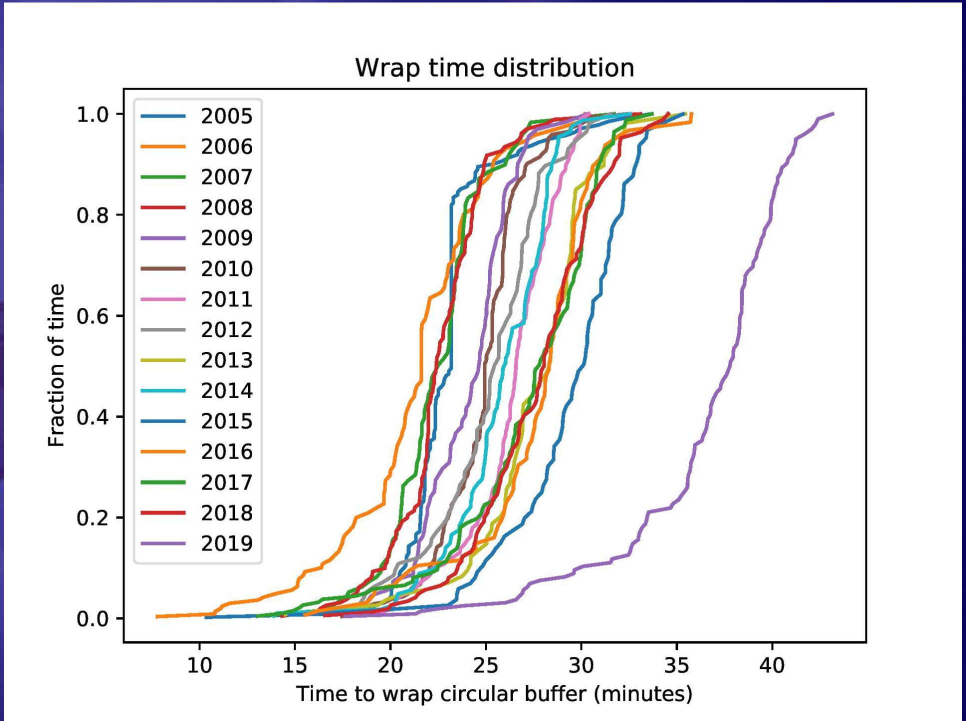


# Recovering an off-axis afterglow with XRT?

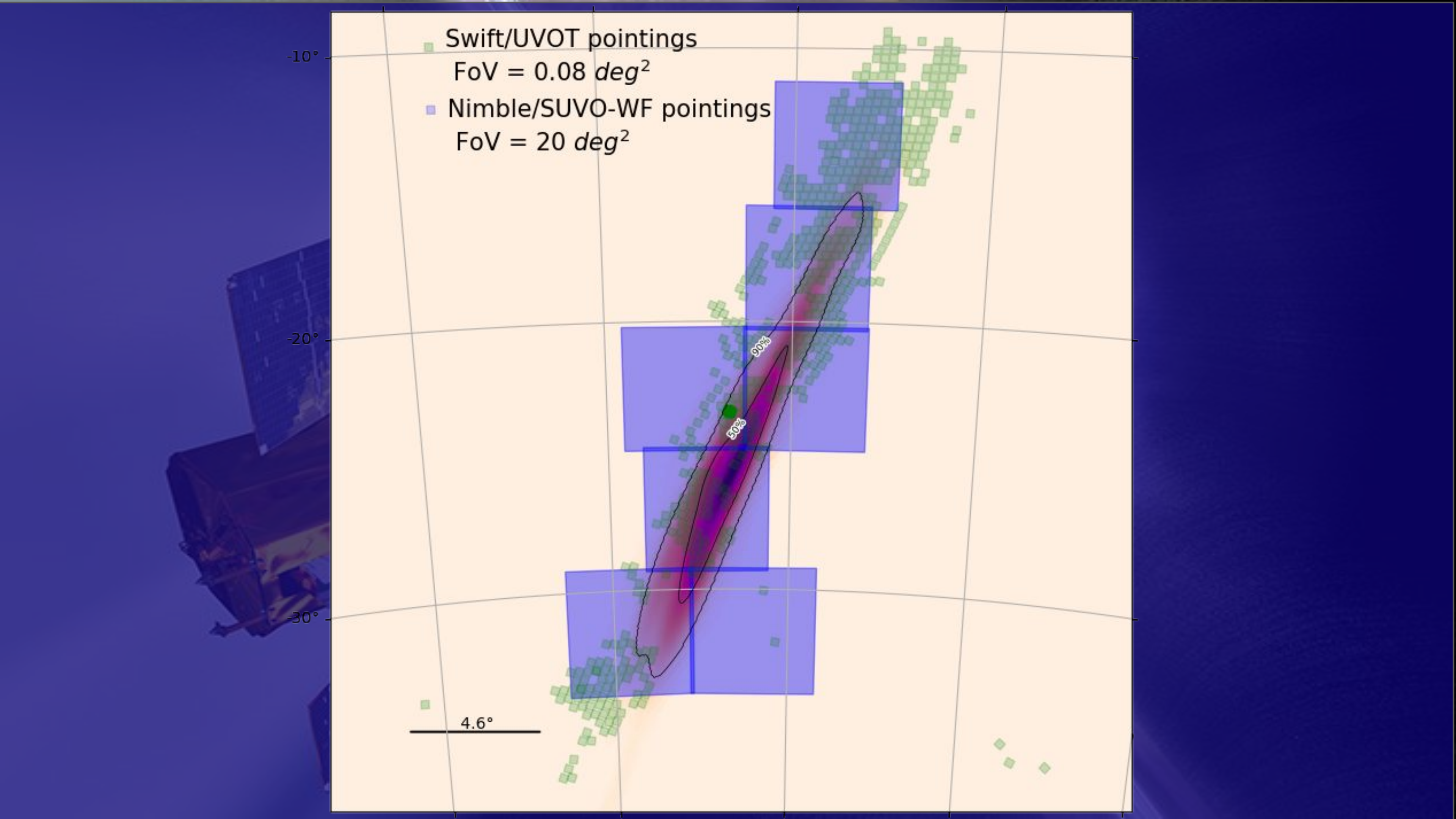



Blue = power-law slope varied, Red = circumburst density varied, Green = E_iso varied


Wrap time per year
Median time to wrap circular buffer (minutes)
22
24
26
28
30
32
34
36
38
2006
2008
2010
2012
2014
2016
2018
Year

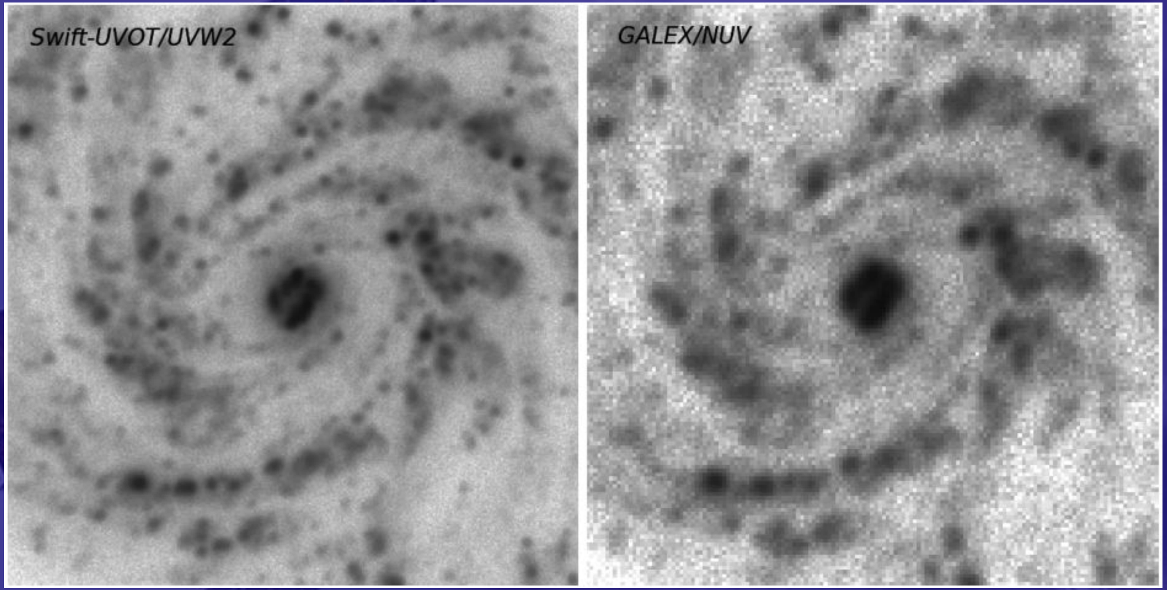

Wrap time distribution
Fraction of time
0.0
0.2
0.4
0.6
0.8
1.0
10
15
20
25
30
35
40
Time to wrap circular buffer (minutes)
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019

D. M. Palmer



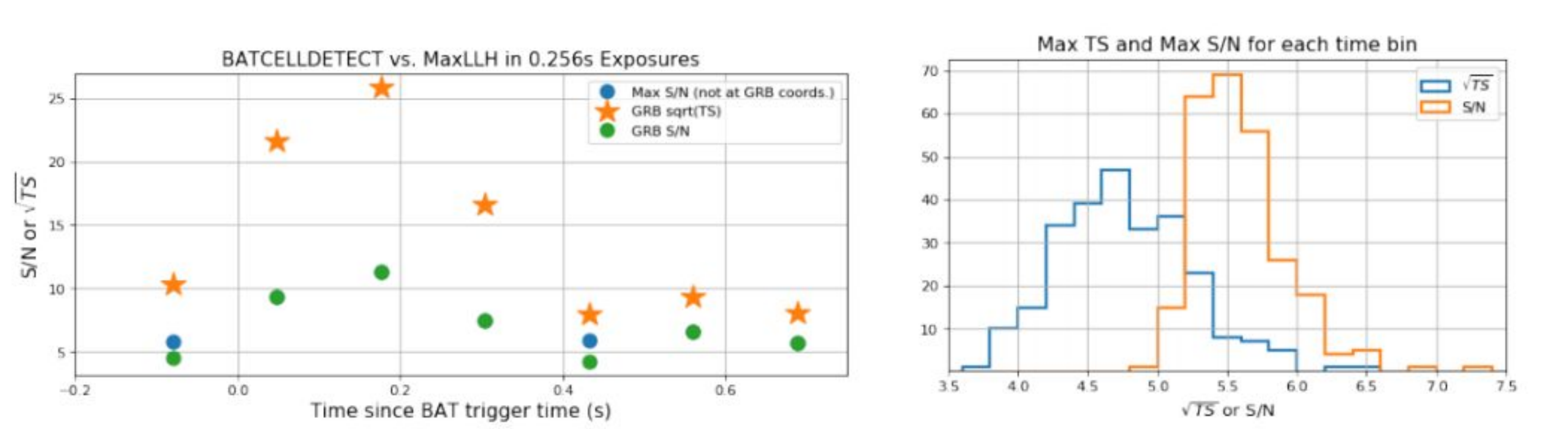
Swift/UVOT pointings
FoV = 0.08 $deg^2$
Nimble/SUVO-WF pointings
FoV = 20 $deg^2$
-10°
-20°
-30°
90%
50%
4.6°

# NGC 4321



# Comparison of MaxLLH vs standard BAT tools

## For the near-threshold short GRB 180805A




J. Delaunay, AT

# Illustrative Rates Estimate

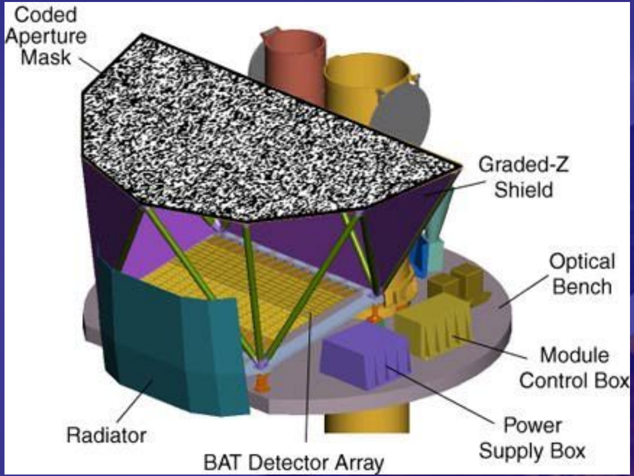
- Assuming $D_{BNS} \leq 120$ Mpc for above-threshold range and BNS rate of 1000 $Gpc^{-3}$ $yr^{-1}$, anticipate ~26 BNS events in the sub-threshold regime (120 Mpc < $D_{BNS} \leq 200$ Mpc, with $3\boldsymbol{\sigma} \leq S \leq 5\boldsymbol{\sigma}$ ). With an (uncorrelated) 70% duty cycle for each detector, this gives 23.5 sub-threshold BNS events + ~3 above-threshold single-detector BNS events per year.

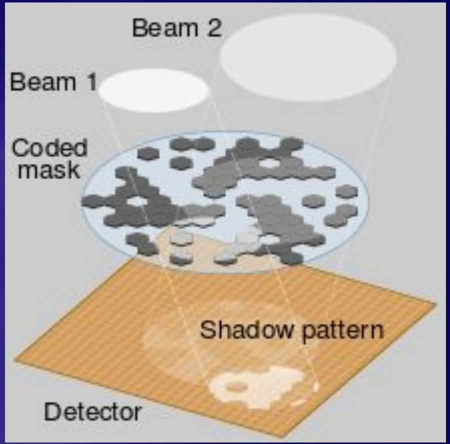
- Duty-cycle averaged sky coverage of BAT (for localization) is 15%, and for detection alone (lower sensitivity) is ~60%. This implies data allowing for few-arcmin localization of **>4 sub-threshold and single-detector events per year** during O3.

- GW170817 detectable to 120 Mpc, ~median **γ**-ray luminosity events detectable to 170 Mpc, brightest (on-axis) **γ**-ray events detectable to far beyond GW sub-threshold range.

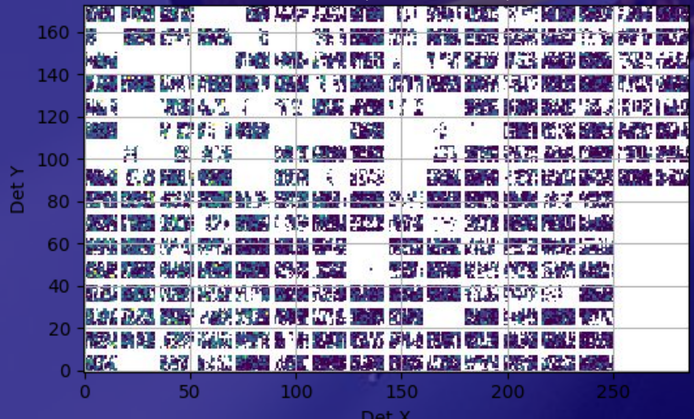
**Conservatively anticipate recovery (w/ few-arcmin localization) of a BAT counterpart for ~2-3 of every 5 real sub-threshold BNS occurring within active BAT FoV during O3b.**

# Burst Alert Telescope
## (magic with shadows)



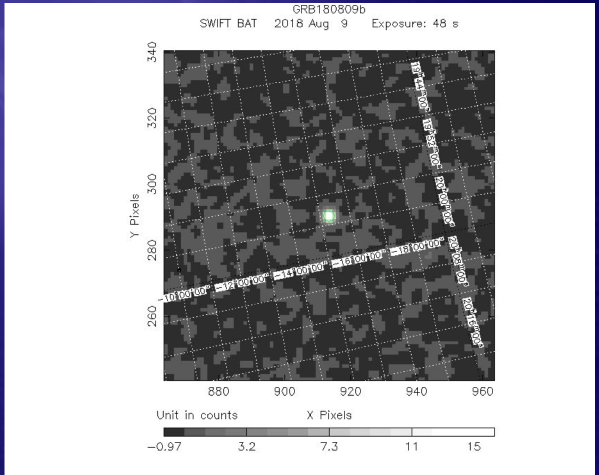




## Data (cts/det)




## FFT w/ mask pattern

## Sky Image



# BAT likelihood cont.

$N\_signal_{ij} = S(A_0,\gamma,ra,dec) \times (A\_eff_j \square f_i)$

$N\_signal_j = \int dN/dE * DRM(E)_j\, dE$

$DRM(E)_j = A_{eff}(E)*$ (Fraction of counts with energy E that land in ebin j)

$N\_signal_{ij} = N\_signal_j * f_i / \Sigma_i f_i$

$L_{ij} = Poiss(Data_{ij} ; Nsig_{ij} + Nbkg_{ij})$

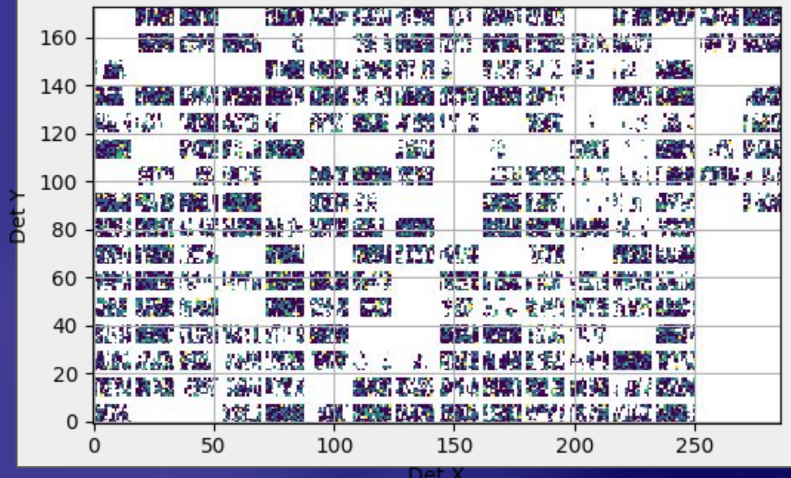
$Nsig_{ij} = Nsig*$(fraction of signal counts in ebin j)$* f_i / \Sigma_i f_i$

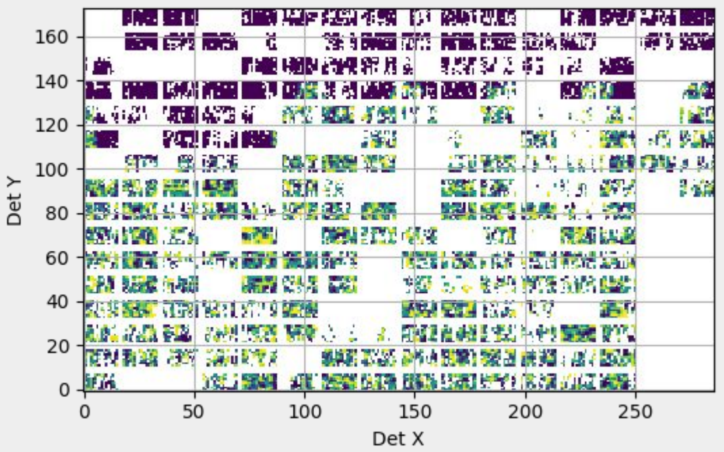
$Nbkg_{ij} =$ (bkg_rate in ebin j)*t_binsize / ndets

$P(B_j) = Norm(bkg\_rate_j ; <bkg_j> \text{ from fits}, \sigma_{j,bkg})$

Maximize over imx, imy, Nsig, plaw_index, bkg_rate for each ebin:

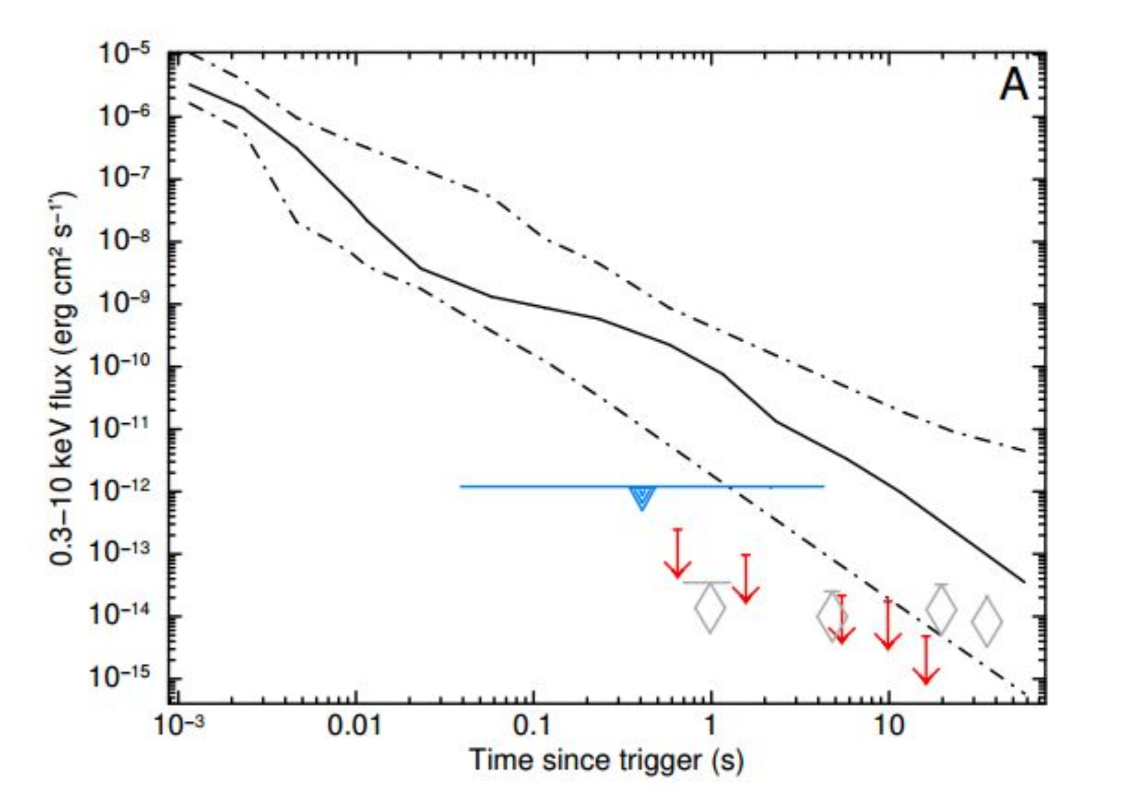
$P(data \mid H_1) \propto \Sigma \log(L_{ij}) + \log(P(B_j))$a



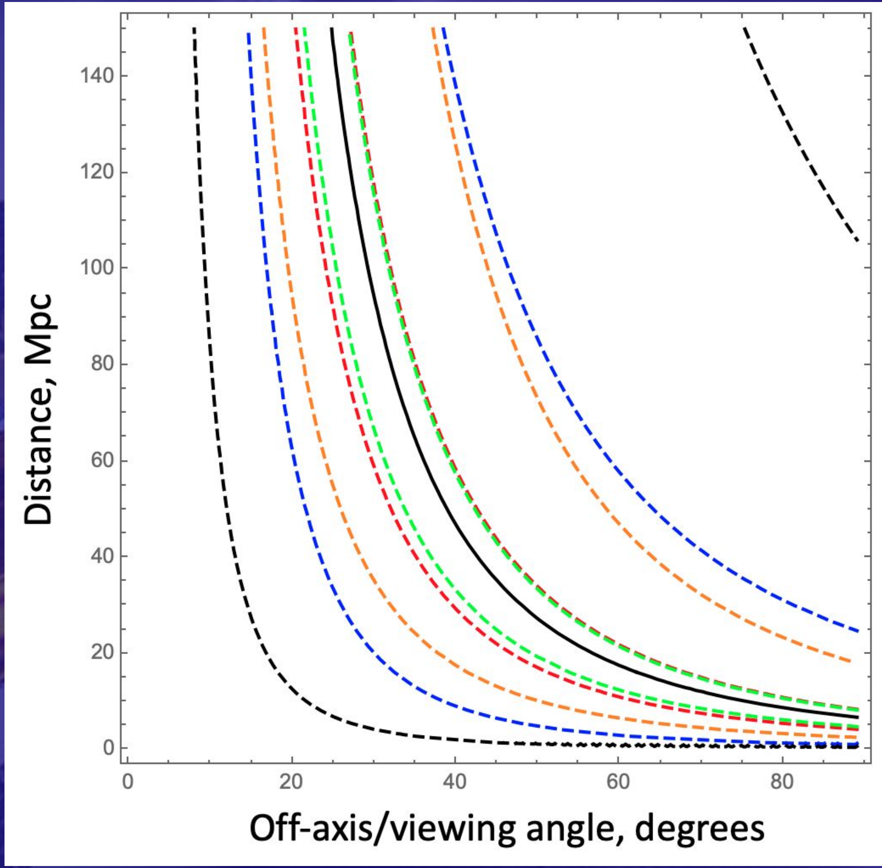



# XRT early non-detection:

## First indication that this was not an on-axis burst



# Recovering an off-axis afterglow with XRT?




Blue = power-law slope varied, Red = circumburst density varied, Green = E_iso varied