PennState
Eberly College of Science

NEIL GEHRELS *SWIFT* OBSERVATORY

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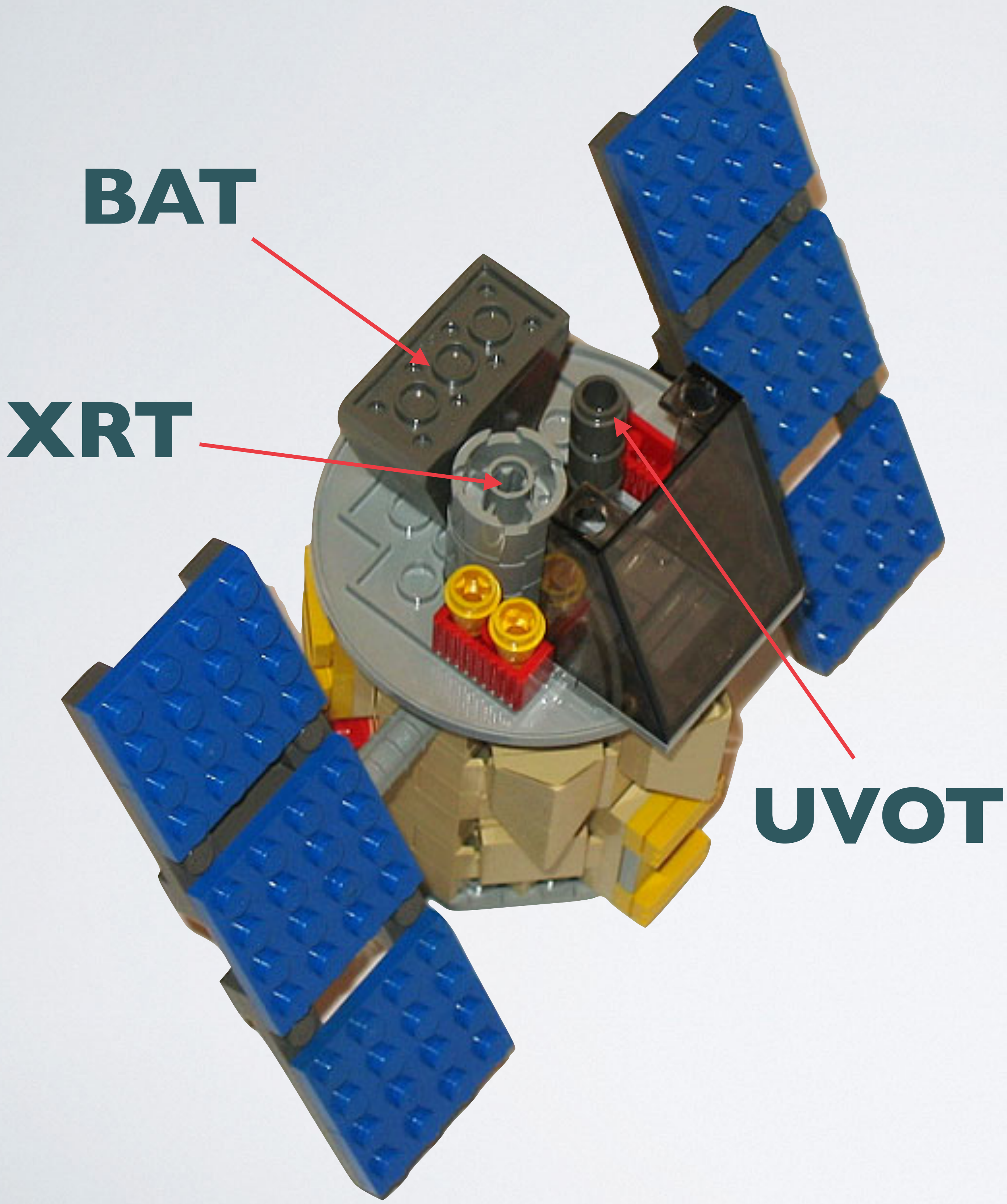
NEIL GEHRELS *SWIFT* OBSERVATORY

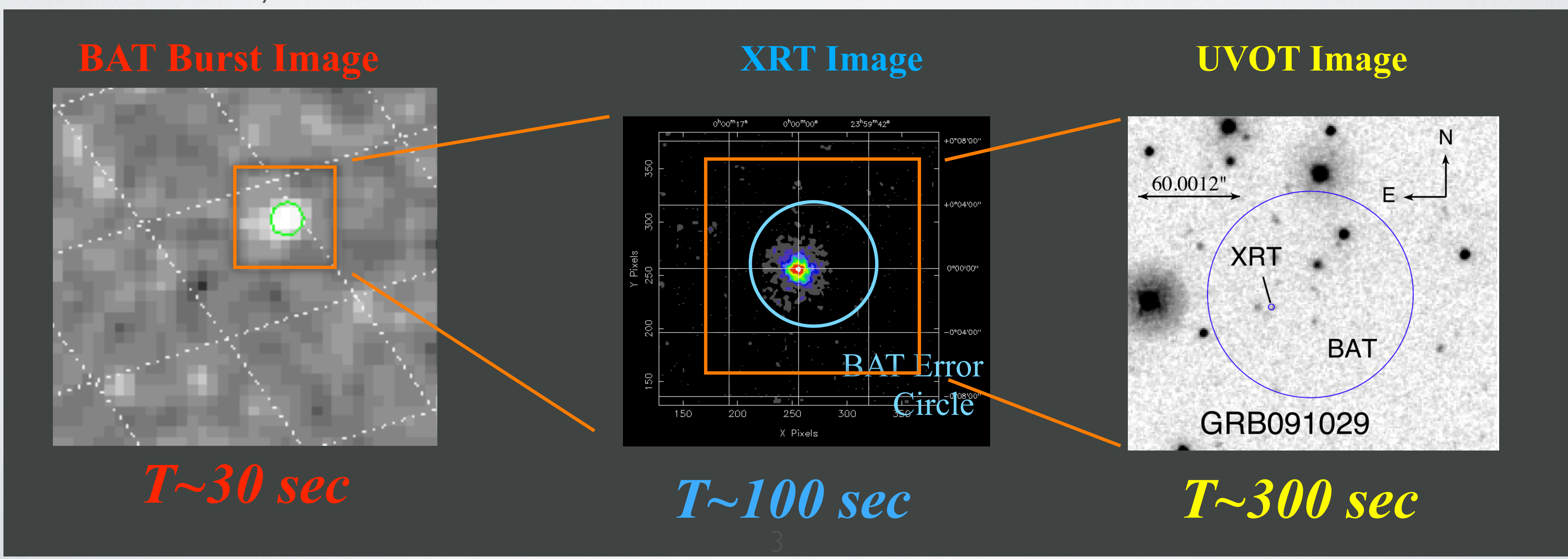


- **Burst Alert Telescope (BAT)**
  - "Hard X-ray" 15-150 keV
  - 2 sr field of view (1/6th of sky)
  - CdZnTe detectors
  - Detects ~100 GRBs per year
- **X-Ray Telescope (XRT)**
  - "Soft X-ray" 0.3-10 keV
  - 23.8 arcminute diameter FOV (~0.12 sq degree)
  - few arcsecond (as good as 1.8") positions
  - CCD spectroscopy
- **UV/Optical Telescope (UVOT)**
  - 170 – 650 nm
  - 17 arcminute width square FOV (~0.8 sq degree)
  - Sub-arcsecond positions
  - Grism spectroscopy
  - 6 UV/optical broad-band filters
  - 22nd mag sensitivity (filtered)

LEGO Swift credit: https://brickshelf.com/cgi-bin/gallery.cgi?f=114876

SWIFT DETECTS A GRB

1. Burst Alert Telescope triggers on GRB, calculates position to ~ 1- 3 arc-minutes, Sends a text message to team!
2. Spacecraft autonomously slews to GRB position in 1-2 minutes.
3. X-ray Telescope: ~ 5-6 arcsec prompt, ~1.3-3.5 arc-sec position after a few minutes
4. UV/Optical Telescope images field
5. The Swift team analyzes the data in real time and sends out GCN Circular to the community in ~5 - 20 minutes.



WHAT MAKES SWIFT UNIQUE

- **Multi-wavelength observations -** Hard X-ray/ X-ray / Optical / UV all in one package, simultaneously, makes Swift both powerful broad look at objects, but and also broadens the possible science as UV astronomy becomes more in demand.

- **Transient discovery -** BAT is a hard X-ray transient all-sky (in a day) monitor. Triggers on GRBs, SGRs, LMXBs, SFXTs. BAT transient monitor tracks brightness of hundreds of X-ray sources, and discovers new transients.

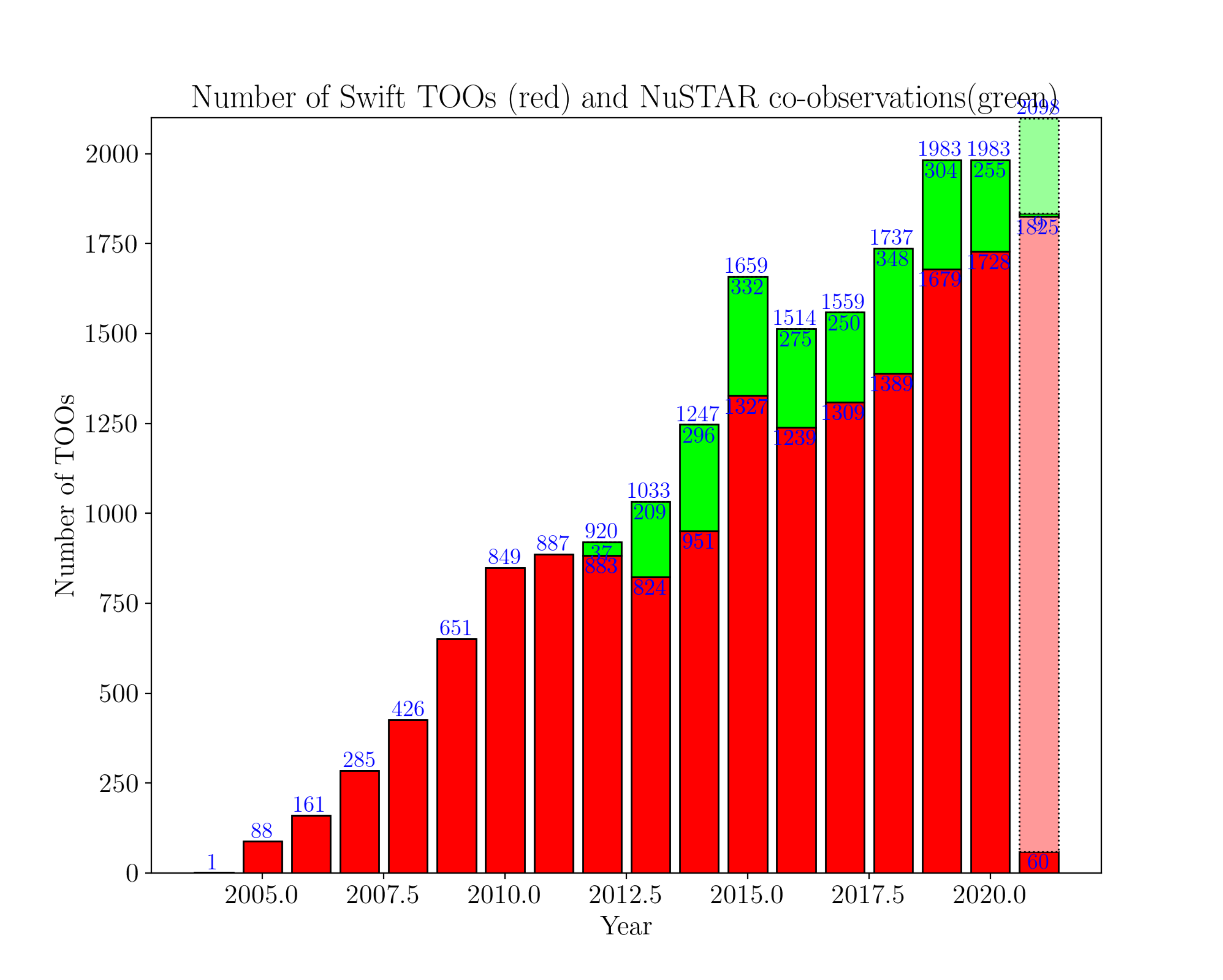
- **Rapid slewing -** gets you to a GRB fast. Also allows for **very high efficiency** of operations (75%, despite being in LEO and spending time in SAA). Also allows **time domain astrophysics** due to ability to perform high cadence high sensitivity monitoring.

- **Constantly evolving ground and onboard software -** we don't stand still evolving the operations concept. We're now capable of faster and more complex observations than ever before, enabling **large scale tiling** for LIGO follow-up, automated rapid response to external triggers.

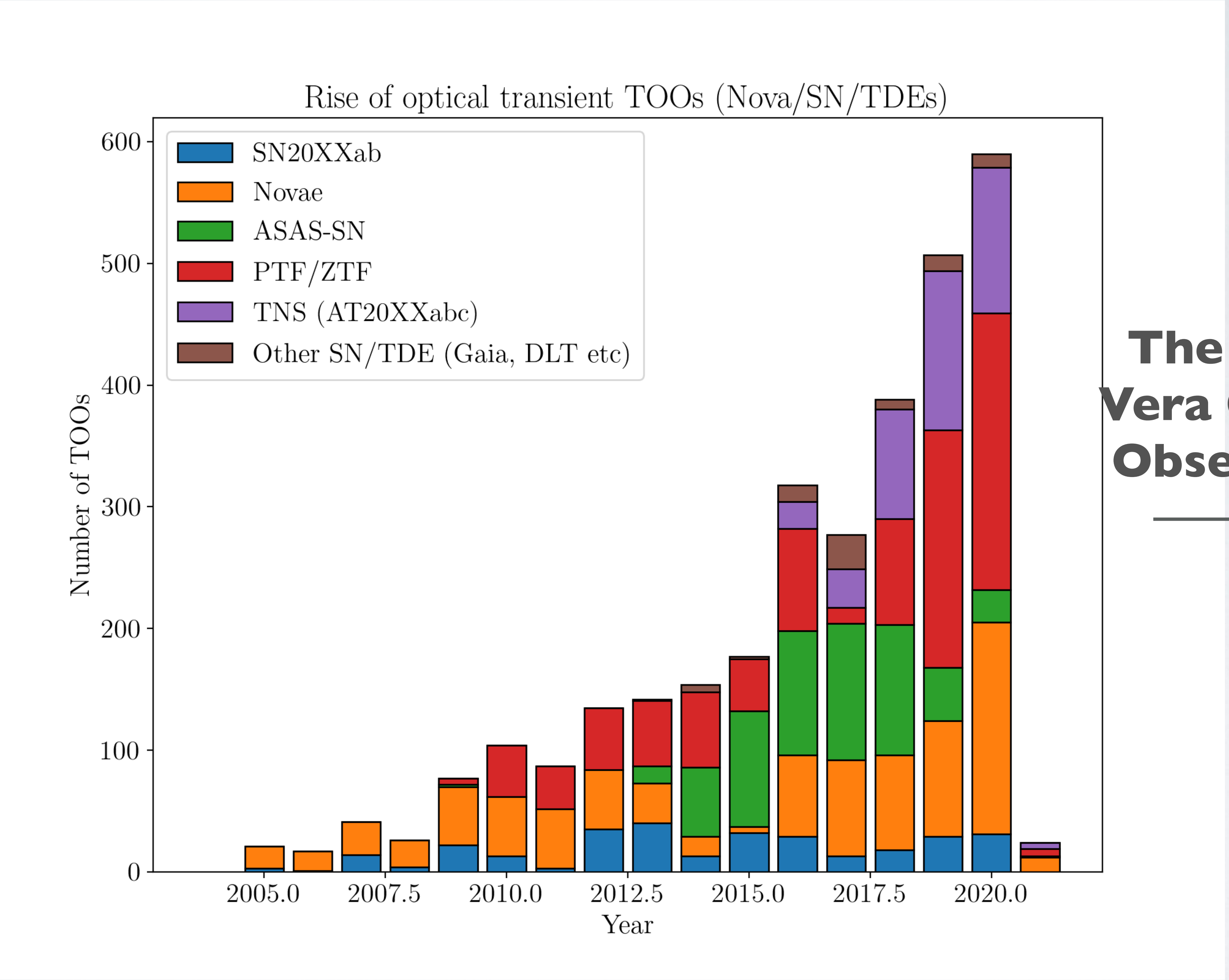
- **Motivated and agile team -** with the aid of software automation, Swift can be run by a small team on call 24/7, to respond rapidly to latest TOOs.

- **Open and broad TOO program with open data program -** Our TOO program is extremely open, with low rejection rates, and our data is made public ASAP - **no proprietary period.**

SWIFT RECIEVES A LOT OF TOOS



WHAT'S BEHIND THE RISE IN TOOS?



The future: Vera C. Rubin Observatory

?

See Peter Browns talk from Tuesday's Swift session for discussion of Swift Supernova science.

SCIENCE FROM SWIFT OPERATIONS EVOLUTION

- No doubt that large amount of TOOs have delivered a huge breadth of Swift Science.
  - We are no longer just *"The GRB Mission"* but are now to most people*"The TOO Mission"*.
- Discussion of all Swift science highlights is beyond the scope of a 15 minute talk! See excellent talk by Patrizia Caraveo at the Tuesday Swift AAS session, for a good overview of science, plus the other excellent talks at that session.
- For the rest of the talk I will discuss how key changes to Swift operations have enabled new science opportunities.
- First up - how we have enabled Multi-messenger astrophysics with Swift.

MULTI-MESSENGER ASTROPHYSICS

- Neil Gehrels' excitement about the possibility of detection of Gravitational Waves mean Swift has been in the Multi-Messenger game for longer than most.
- First Swift Multi-messenger observations started in 2011 with observations of IceCube Neutrino triggers (e.g. Evans et al., 2015).
- First Swift observations of a LIGO trigger were in 2011 when we observed the "Big Dog" event, before the Advanced LIGO era (Evans+ 2012).
    - *The paper on this only had 818 authors!*

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SWIFT FOLLOW-UP OBSERVATIONS OF CANDIDATE GRAVITATIONAL-WAVE TRANSIENT EVENTS

P. A. Evans[1], J. K. Fridriksson[2], N. Gehrels[3], J. Homan[2], J. P. Osborne[1], M. Siegel[4], A. Beardmore[1], P. Handbauer[5], J. Gelbord[4], J. A. Kennea[4], M. Smith[4], Q. Zhu[4], and
The LIGO Scientific Collaboration and Virgo Collaboration,
J. Aasi[6], J. Abadie[6], B. P. Abbott[6], R. Abbott[6], T. D. Abbott[7], M. Abernathy[8], T. Accadia[9], F. Acernese[10,11], C. Adams[12], T. Adams[13], P. Addesso[14], R. Adhikari[6], C. Affeldt[15,16], M. Agathos[17], K. Agatsuma[18], P. Ajith[6], B. Allen[15,16,19], A. Allocca[20,21], E. Amador Ceron[19], D. Amariutei[22], S. B. Anderson[6], W. G. Anderson[19], K. Arai[6], M. C. Araya[6], S. Ast[15,16], S. M. Aston[12], P. Astone[23], D. Atkinson[24], P. Aufmuth[15,16], C. Aulbert[15,16], B. E. Aylott[25], S. Babak[26], P. Baker[27], G. Ballardin[28], S. Ballmer[29], Y. Bao[22],

Evans et al. (2012) (where et al. = 817 people)

Monthly Notices of the Royal Astronomical Society
MNRAS 448, 2210–2223 (2015)
doi:10.1093/mnras/stv136

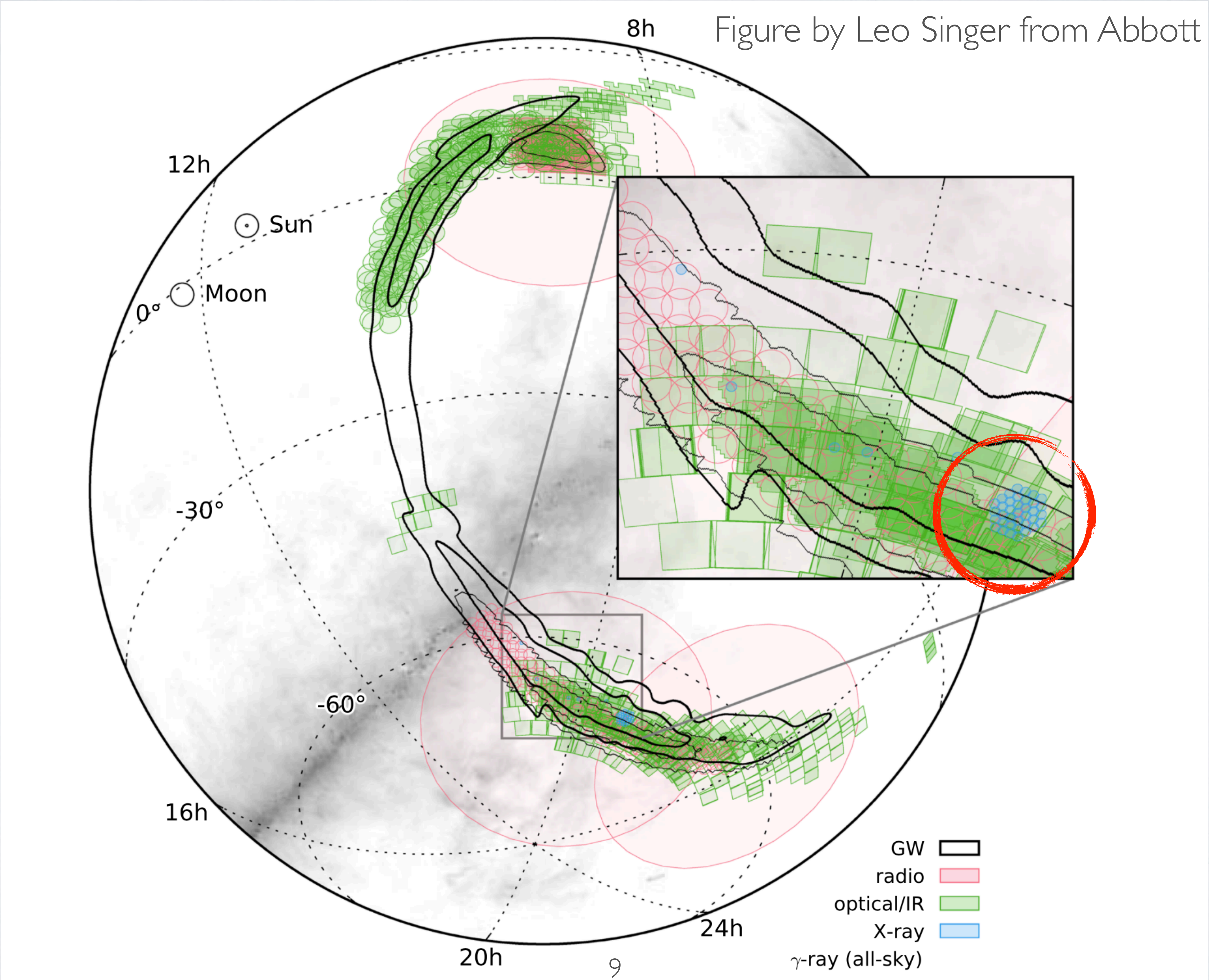
***Swift* follow-up of IceCube triggers, and implications for the Advanced-LIGO era**

P. A. Evans,[1★] J. P. Osborne,[1] J. A. Kennea,[2] M. Smith,[3] D. M. Palmer,[4] N. Gehrels,[5] J. M. Gelbord,[6,7] A. Homeier,[8] M. Voge,[8] N. L. Strotjohann,[8,9] D. F. Cowen,[10] S. Böser,[11] M. Kowalski[8,9] and A. Stasik[9]

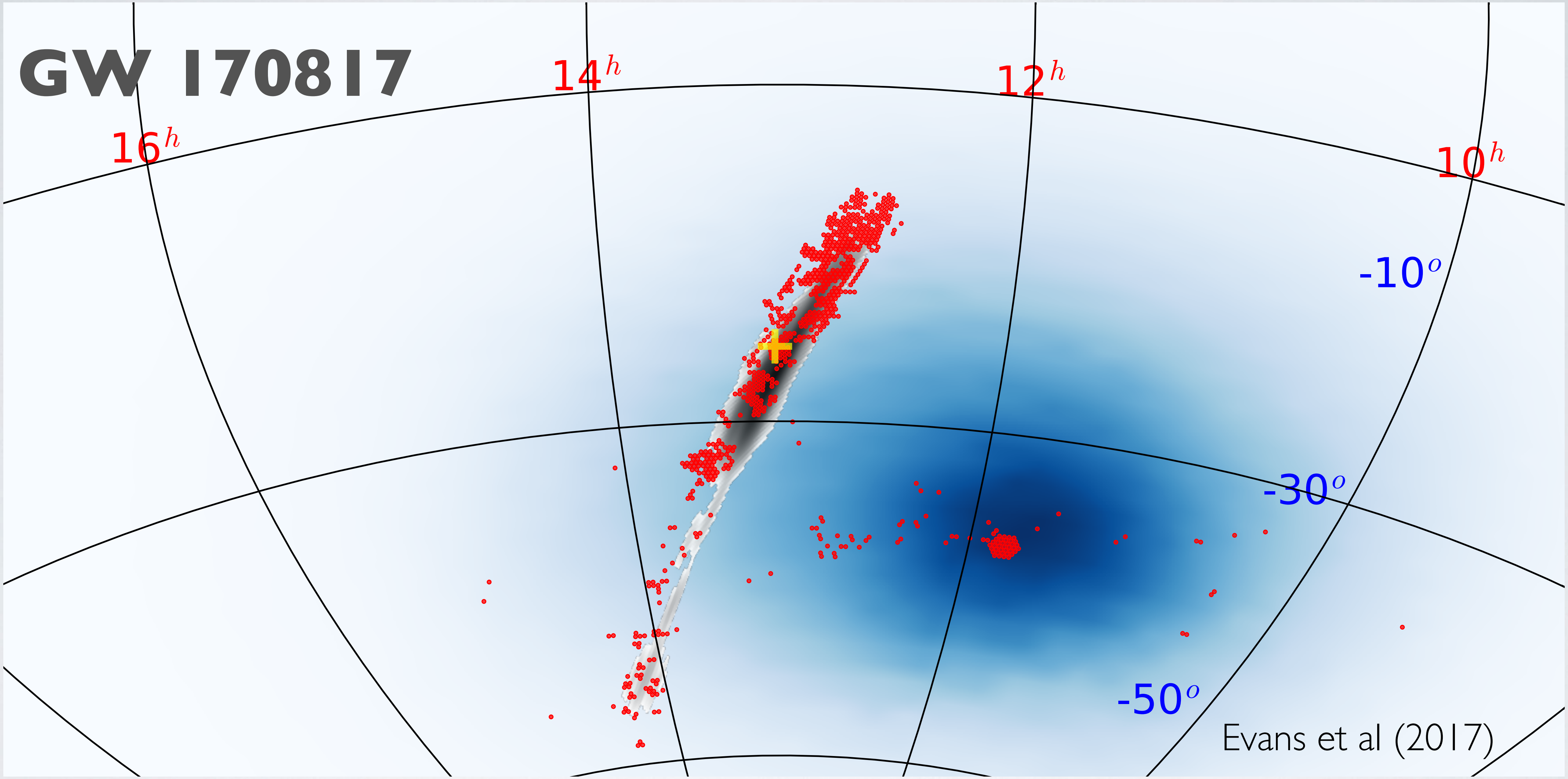
IceCube/Swift paper: Evans et al. (2015)

GW150914 SWIFT FOLLOW-UP

Figure by Leo Singer from Abbott et al. (2016)

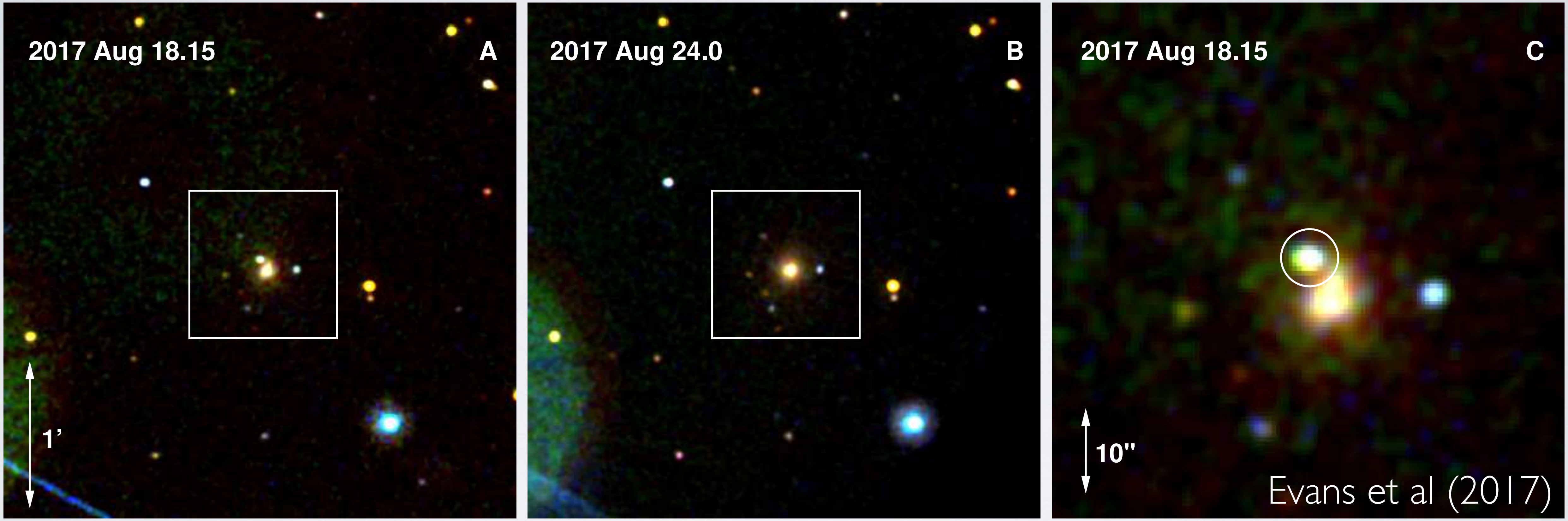


TILING LIGO ERROR REGIONS



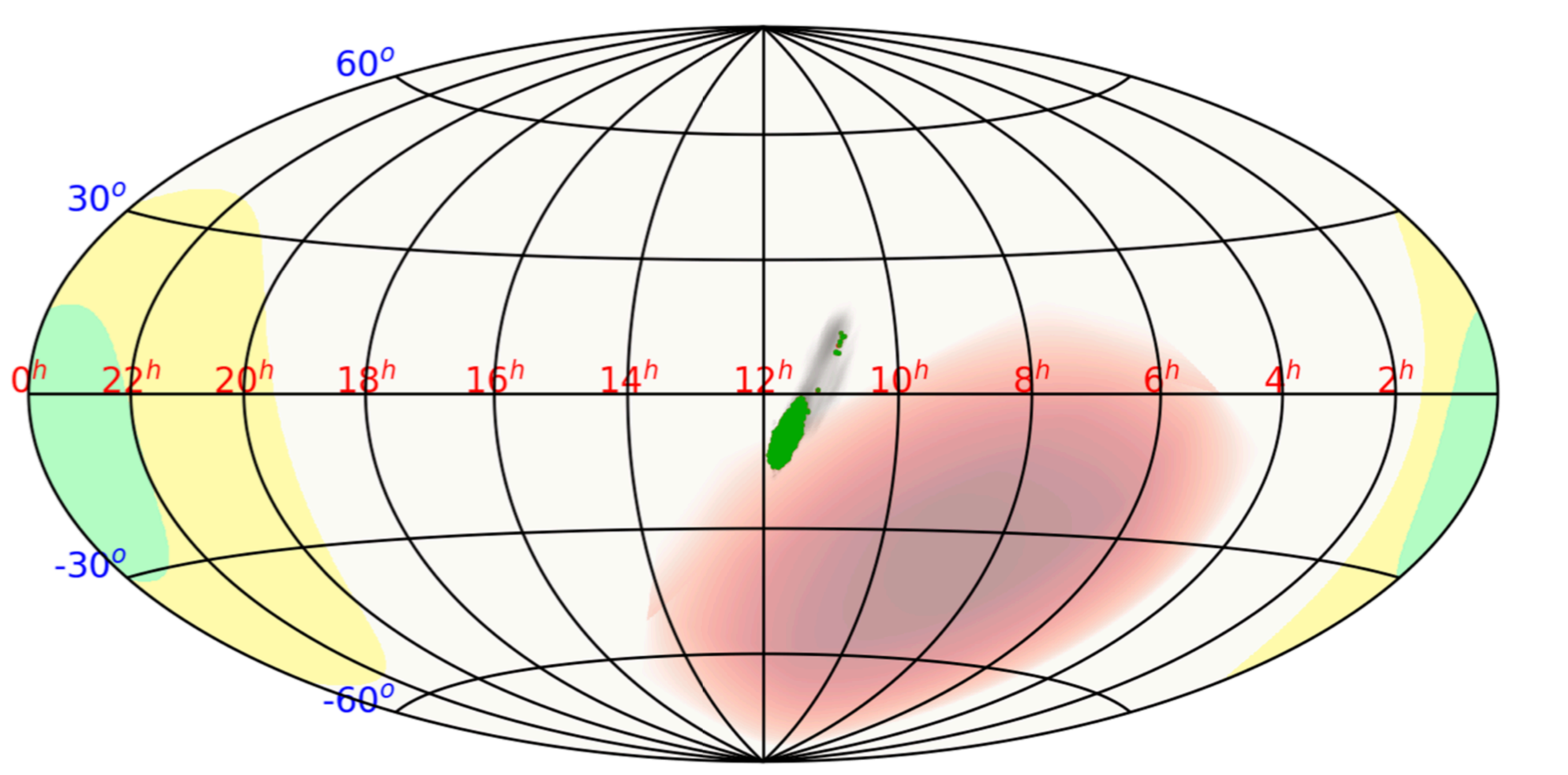
- GW170817:
  - New software allowed us to re-write the science plan on the fly to observe many fields to search for counterpart.
  - 744 fields observed by Swift.
  - 92% of distance-weighted GW localization covered.

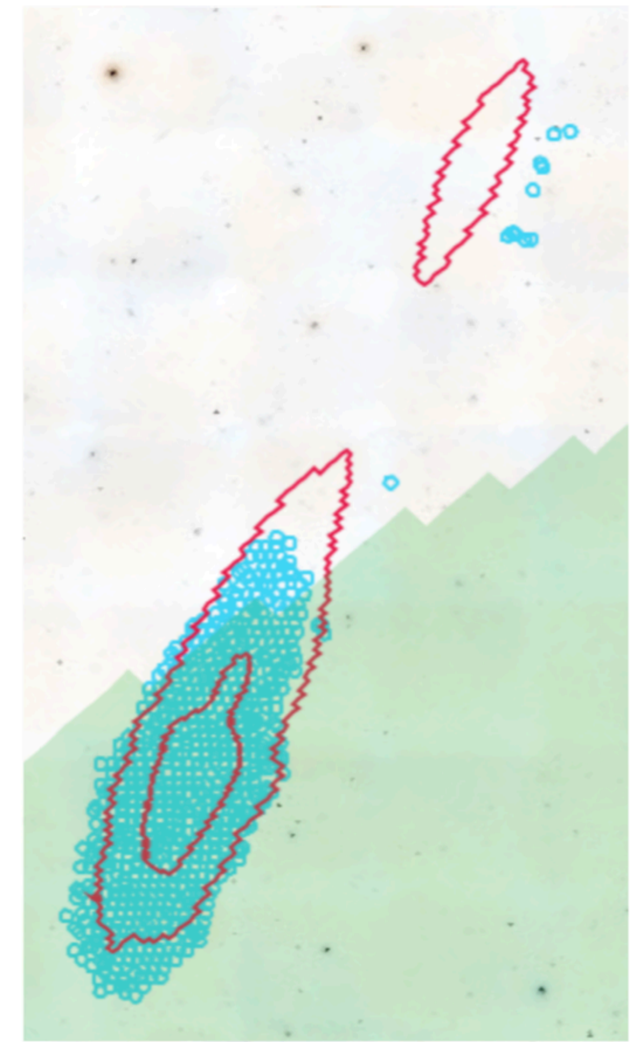
SWIFT UVOT DETECTION OF AT2017GFO



- Initial measure u = 18.2 +/- 0.1 mag (AB)
- Object in NGC 4993
- Monitoring show that the UV rapidly faded.
- No XRT detection of emission from optical transient.

O3 RESULT: S200224A

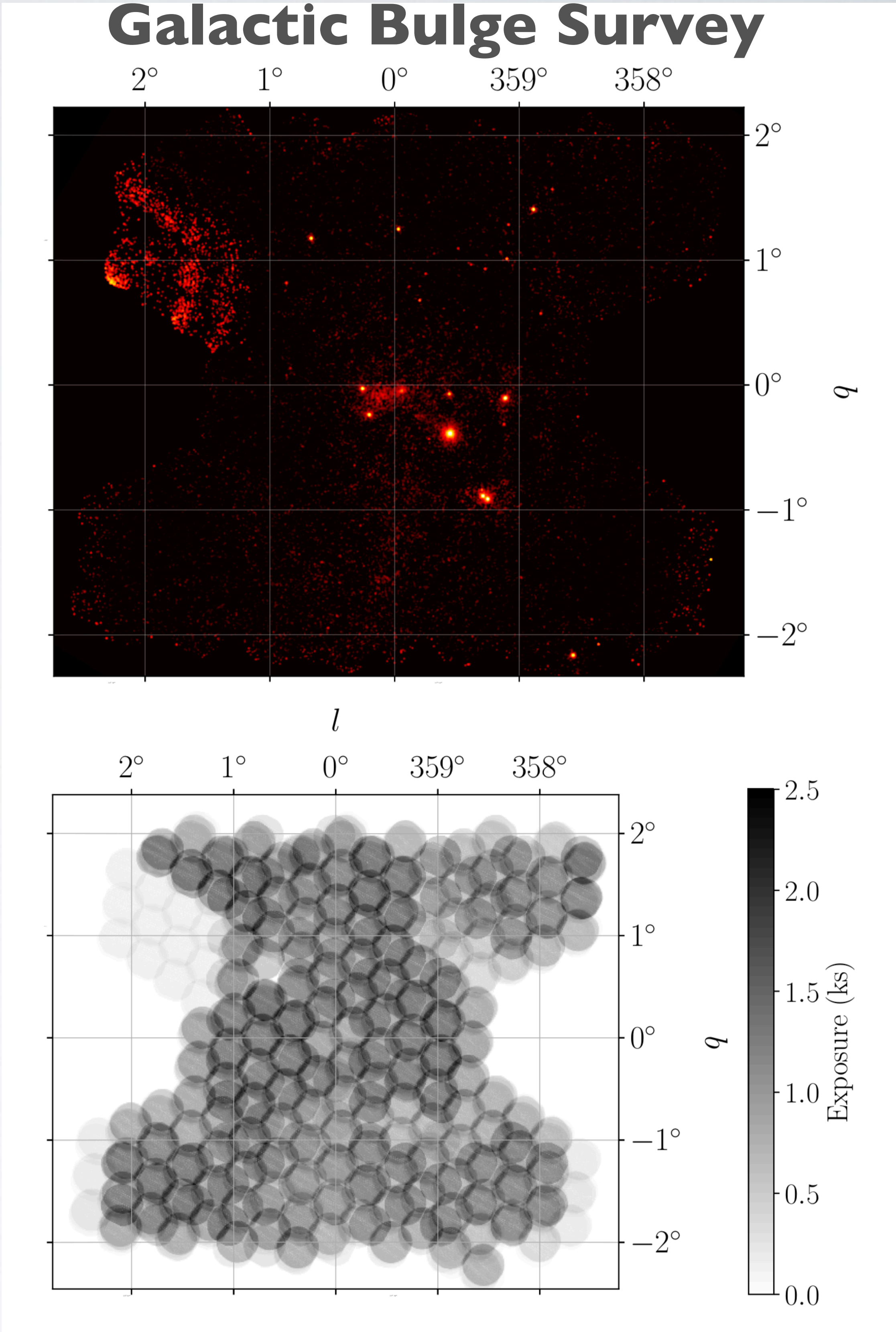




- Image from Klinger et al. (2020)
- S200224A is a BH-BH merger
- Covered 79.2% (X-ray) and 62.4% (UV) of the GW error region.
- No candidates seen. Upper limit on isotropic-equivalent blast wave energy = 4.1 x 10^51 erg (assuming GRB like parameters)

HIGH CADENCE SYNOPTIC SURVEYS WITH SWIFT

- Newly developed planning software allowed us to schedule very short observations, not previously possible.
  - Now possible to schedule observations with Swift as short at 60s (previously 300s was minimum)
- Although this functionality was developed to meet the need for covering very large error regions (e.g. LIGO), a new usage came out of it, high cadence synoptic surveys.
- Examples:
  - Swift SMC Survey (S-CUBED) - 144 obervations that cover the optical extent of the SMC every week, with 60s exposure (e.g. Kennea+, 2018) .
  - Swift Galactic Bulge Survey - 100+ observations of 60-120s exposures covering the Galactic bulge every 2 weeks to look for VFXTs (e.g. Shaw+ 2020, Baharamian+ 2021)



Images from Baharamian+ (2021)

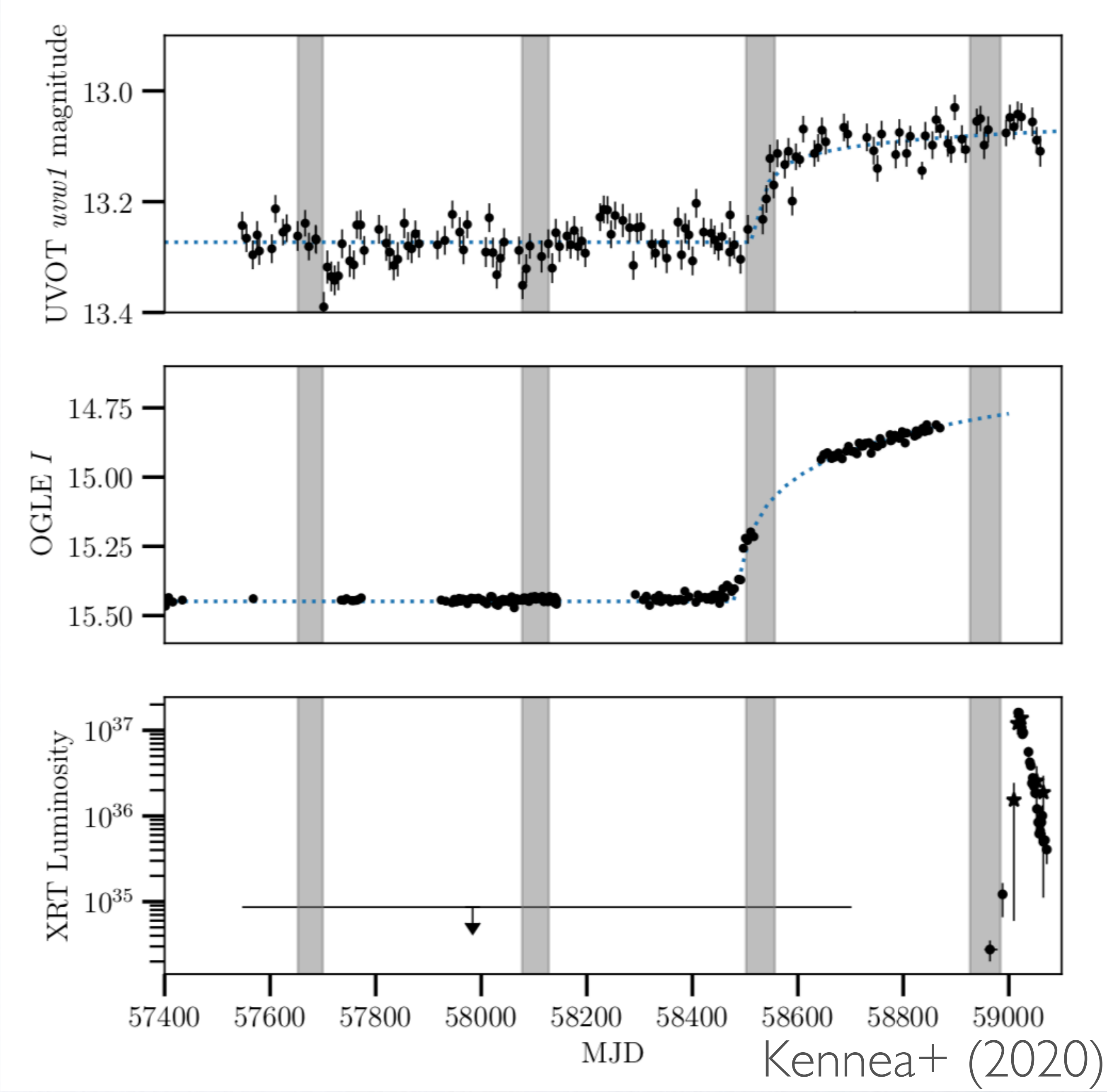
MOTIVATION FOR SHALLOW X-RAY SURVEYS

- Swift's XRT has a low background, making it sensitive to detecting point sources at relatively low fluxes - **5-10 counts is a good detection**.

- For S-CUBED Survey 60s exposure allows detection of a NS binary in the SMC at 1-2% Eddington Luminosity.

- Selected science results from S-CUBED so far:
  - Early detection of super-Eddington outburst from SMC X-3 (e.g.)(Townsend+ 2017)
  - Discovery of Be/X-ray binary system in SMC with WD companion (Coe+ 2020)
  - Discovery of a Type-I X-ray outburst in a long period Be/X-ray binary, which began on the first periastron passage after after the formation of the circumstellar disk (Kennea+ 2020).

Swift J004516.6–734703



Kennea+ (2020)

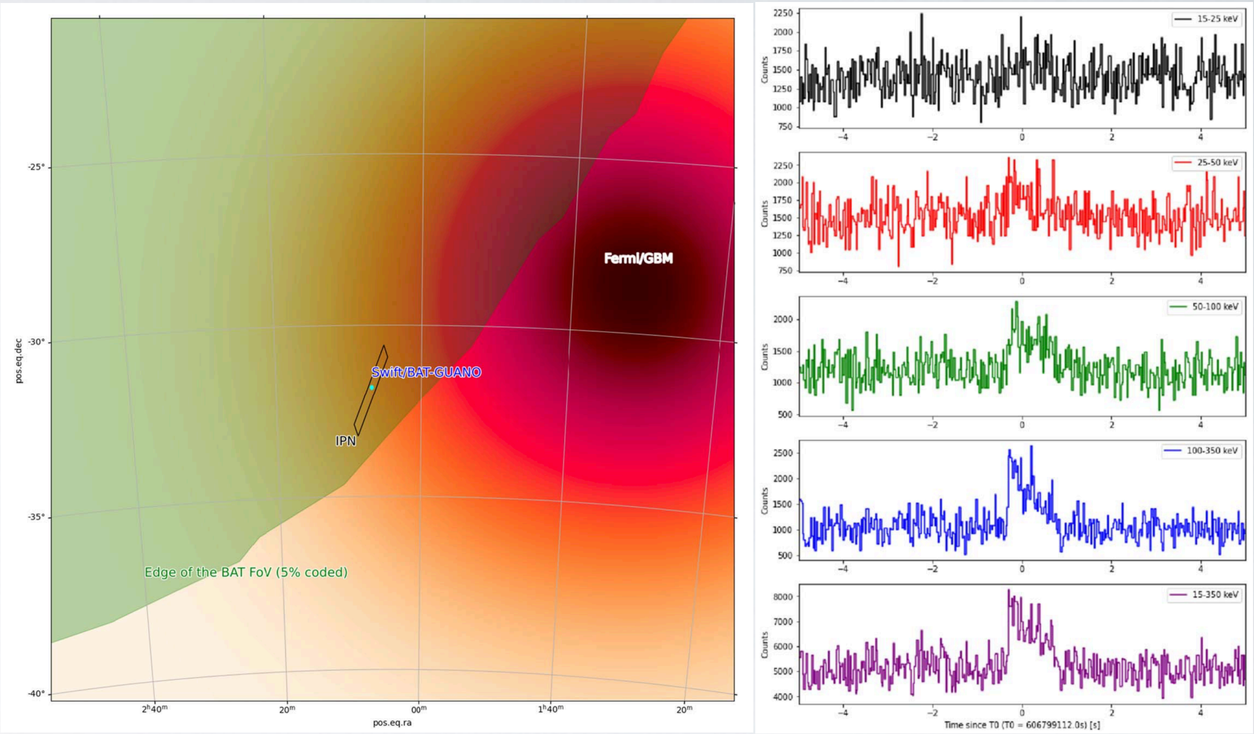
BAT *GUANO*

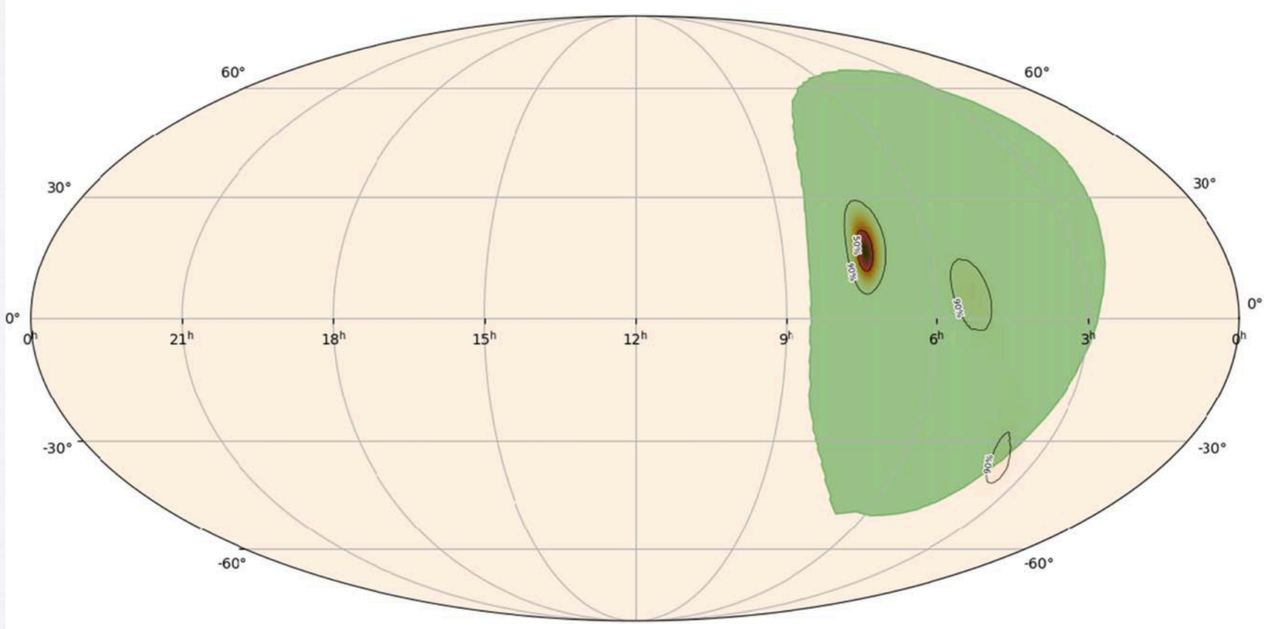
- BAT has a complex trigger algorithm to find GRBs, but it is not 100% successful, especially if GRB is near the edge of the field of view. However, these GRBs can be found if we analyze BAT event data. However, there are two caveats:
  - BAT event data take up too much bandwidth to downlink, so are normally lost.
  - BAT event data exist in a transient buffer which contains 25-35 minutes of BAT event data, so to retrieve it you have to act fast.
- Enter the **Gamma-ray Urgent Archiver for Novel Opportunities** (*GUANO*)
  - *GUANO* commands Swift to dump the event buffer based on external triggers, e.g. GRBs from other missions, multi-messenger triggers.
  - As data event data only exists on-board for 25-30 minutes, need to command Swift quickly.
  - Using groundstation passes we would only successfully downlink 1 in 6 *GUANO* triggers.
  - Swift MOC developed a first of it’s kind automated TDRSS scheduling and commanding system.
    - Swift Operations Team members and the GUANO system can request TDRSS passes >=14 mins in the future
    - Commands are sent by automated MOC computers 24/7. Whole system can work with no human-in-the-loop.

GUANO RESULTS

- *GUANO* so far utilized for the following science:
  - Localization of Fermi/GBM GRBs that did not trigger Swift.
  - Example of GRB 200325A (right), we were able to localize it arc-minute accuracy with GUANO data.
  - Results show that we can obtain arc-minute (or better with follow-up) localizations of 10-20% more GRBs than possible with just BAT triggering.
  - 10 months of GRB chasing with GUANO we have localized 10 GRBs, 2 of which are short.
- BAT is the most sensitive detector of sGRBs, when they are in the BAT FOV.
  - Whenever LIGO triggers, *GUANO* dumps BAT event data, in order to enable the most sensitive search for prompt emission from GW triggers.
  - In addition triggering of *GUANO* with LIGO sub-threshold triggers can enable correlated sub-threshold searches for events that might not be strong enough to trigger either LIGO or BAT.
  - In the case of S200114f, 99.7% fo the GW probability was covered by BAT FOV, and event data was dumped through *GUANO*.
- *GUANO* data used in detection of GRB 200415A AKA giant Magnetar Flare in NGC 253 (Oliver Roberts' talk yesterday in GRB session)

GRB 200325A





Results from Tohuvavohu et al. (2020)

FUTURE DEVELOPMENTS FOR SWIFT

- We're not done… coming soon:
  - **TOO API (2021)**
    - Simple API interface for querying Swift Visibility, previous observations and for submitting TOO requests.
    - TOO submission API is expected to plug into transient event brokers and TOMs, in order to allow automated submission of TOOs and criterion based TOO submission (e.g. submit TOOs based on transients from Rubin Observatory that meet certain criteria defined by TOO requester).
    - Allow submitting of Healpix based probability maps for transients, rather than simple RA/Dec/Radius.
  - **Auto-TOO (2021+)**
    - The final frontier for Swift regarding TOOs - in order to observe targets as quickly as possible, we are working on a system that allows Swift to safely observe TOO targets ASAP without a human-in-the loop.
    - Example: Rapid response follow-up for non-Swift triggers such as FRBs, GW events and FRBs at very short timescales (~15 mins).

CONCLUSIONS

- Swift's multi-wavelength instrument complement, rapid slewing and flexible software platform have allowed it to evolve from a GRB mission into a rapid response time domain astrophysics mission.
- Lesson from Swift for future missions:
  - Start with a flexible and robotic platform, with high levels of automation
  - Never stop re-writing your operations software
  - Combinations of relatively mediocre and recycled instruments with a platform such Swift's can open new opportunities in astrophysics.
  - Open data policies and open TOO acceptance policy lead to a mission in high demand with a high science impact.
    - Neil's original paper on Swift has been cited in 2300 refereed papers (~150/year since publication). Many more papers use Swift data and don't cite this.
- For more Swift science results, please review talks given at Tuesday's session, and plenty of other talks on Swift at AAS!