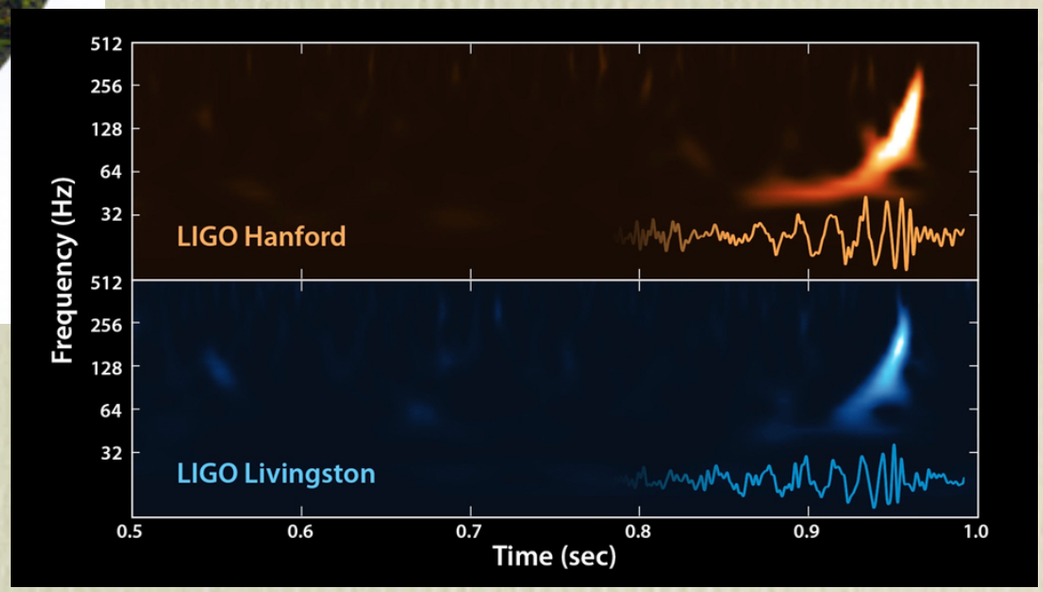
Treasure Map & Treasure TROVE
Infrastructure for Multi-messenger Astronomy

THE GRAVITATIONAL WAVE
TREASURE MAP
treasuremap.space

TROVE: Tool for Rapid Object Vetting and Examination

David Sand
University of Arizona
Observatories Forum, Santa Barbara, Sep 2025

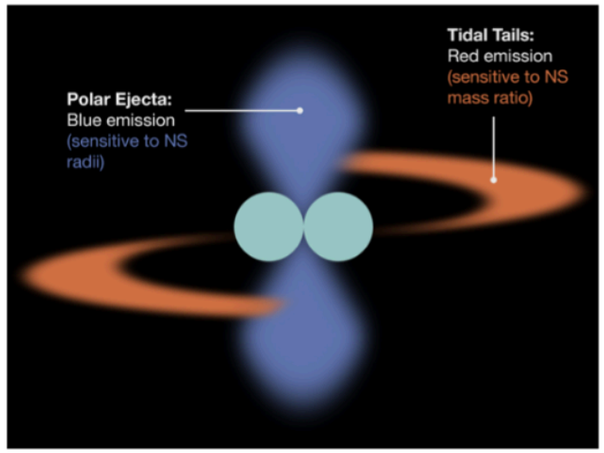
Advanced LIGO + Virgo



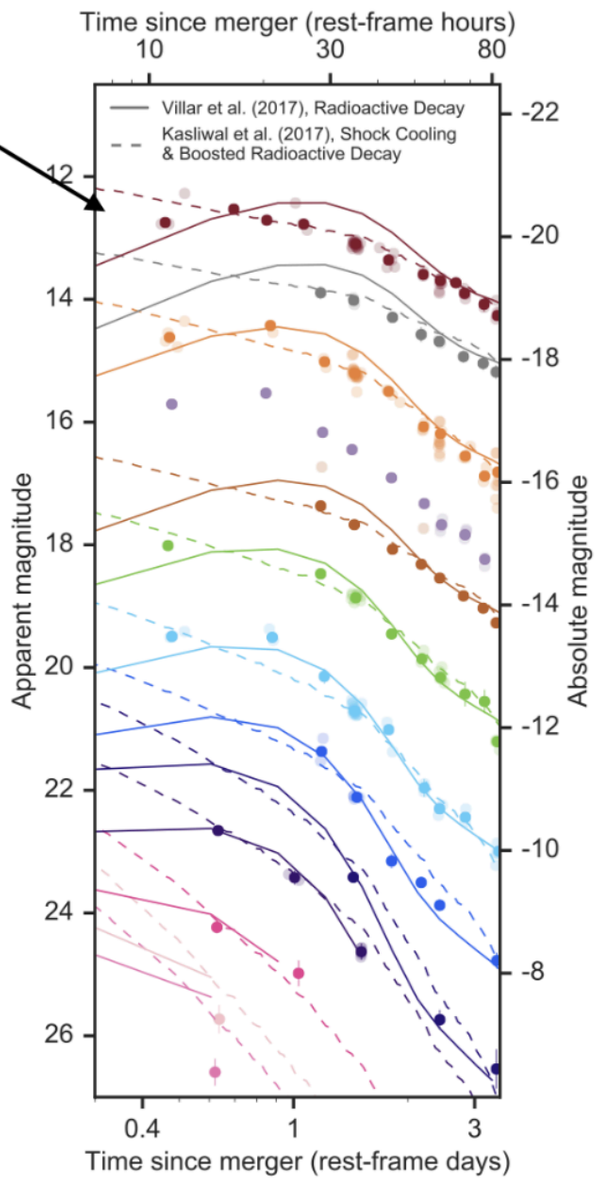
Near Pisa, Italy

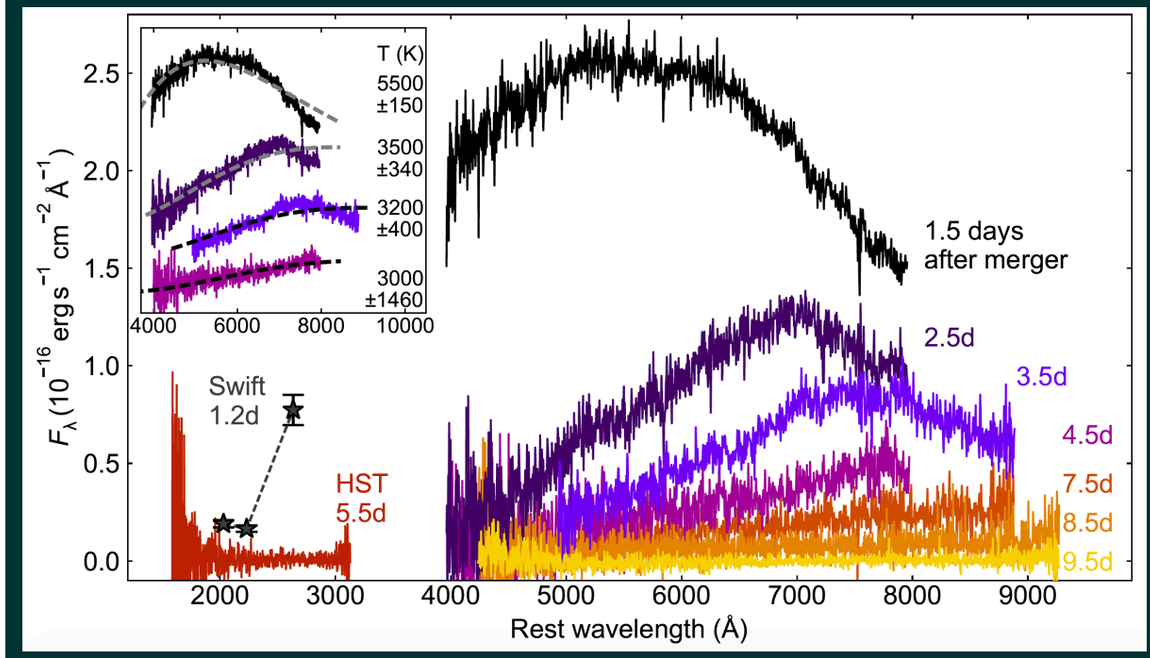
GW Counterparts are faint and fast

Early data can distinguish models.



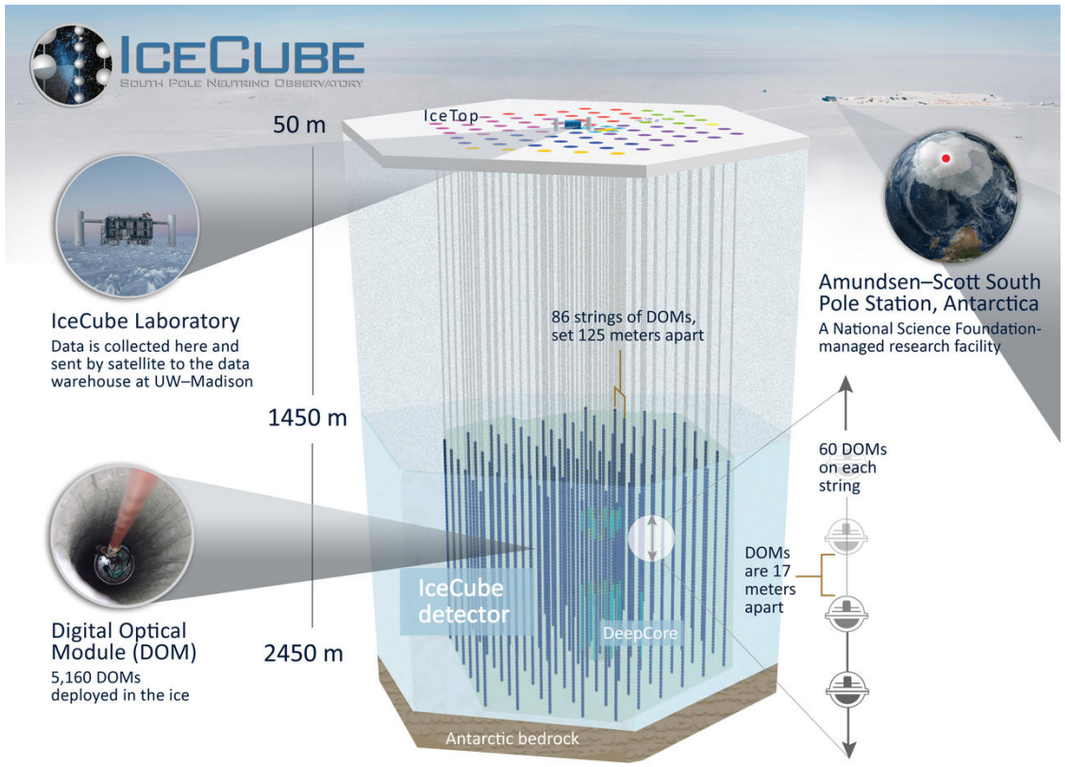
Possible kilonova emission mechanisms

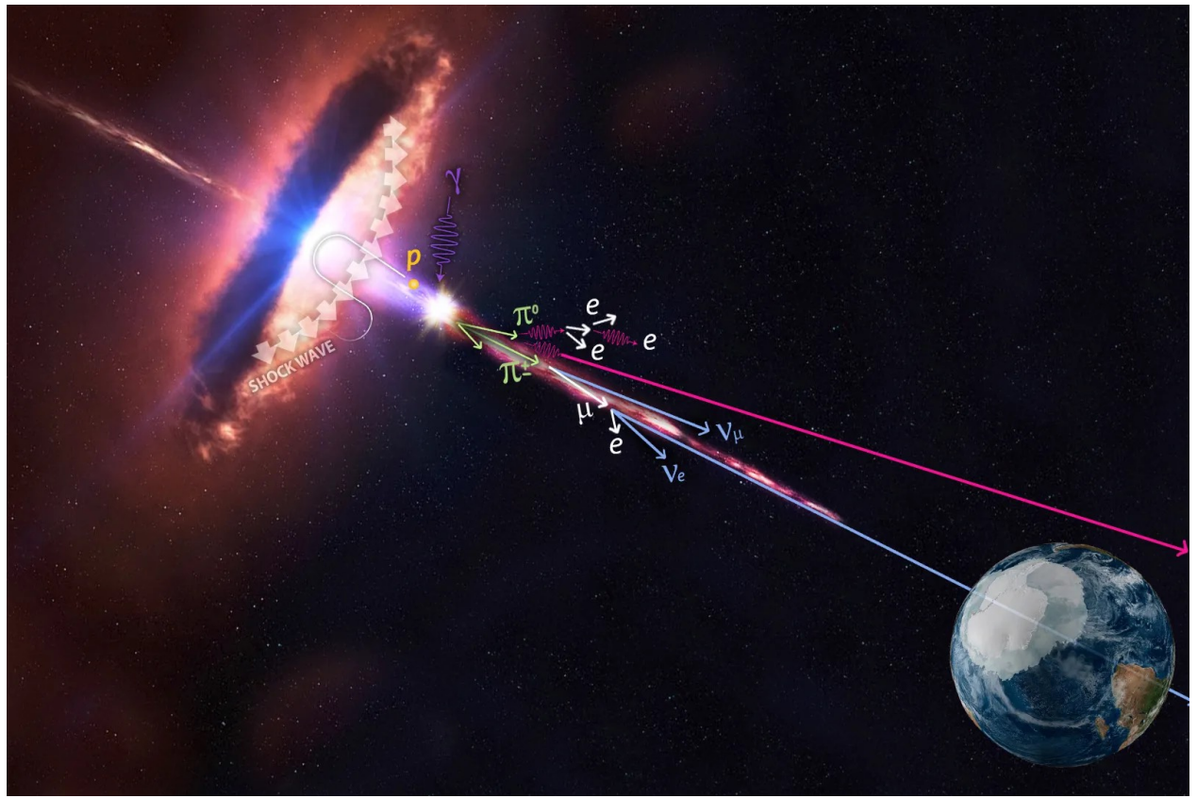




- Science cases: r-process, neutron star equation of state, Hubble constant, explosion physics, etc etc.

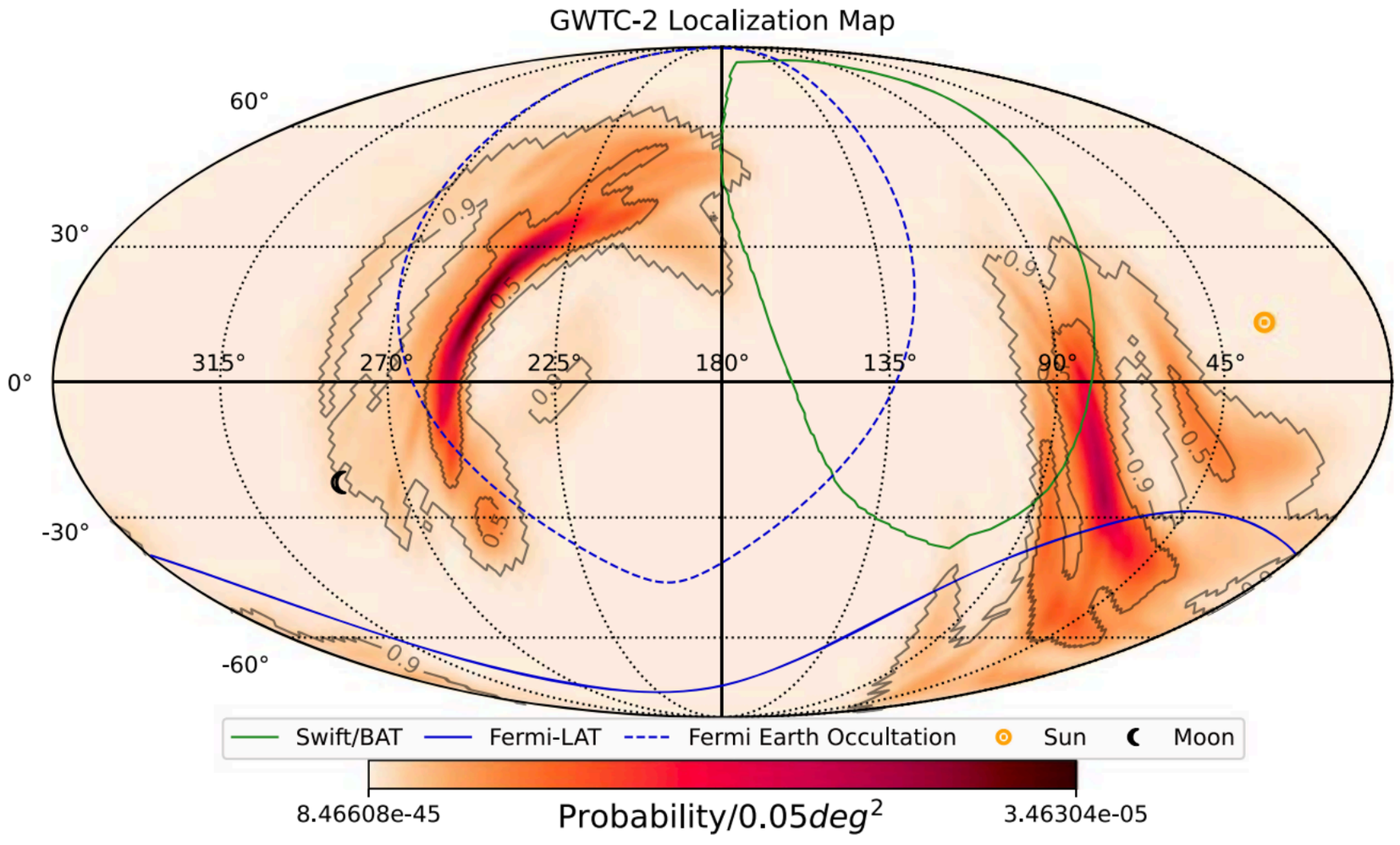
Neutrinos





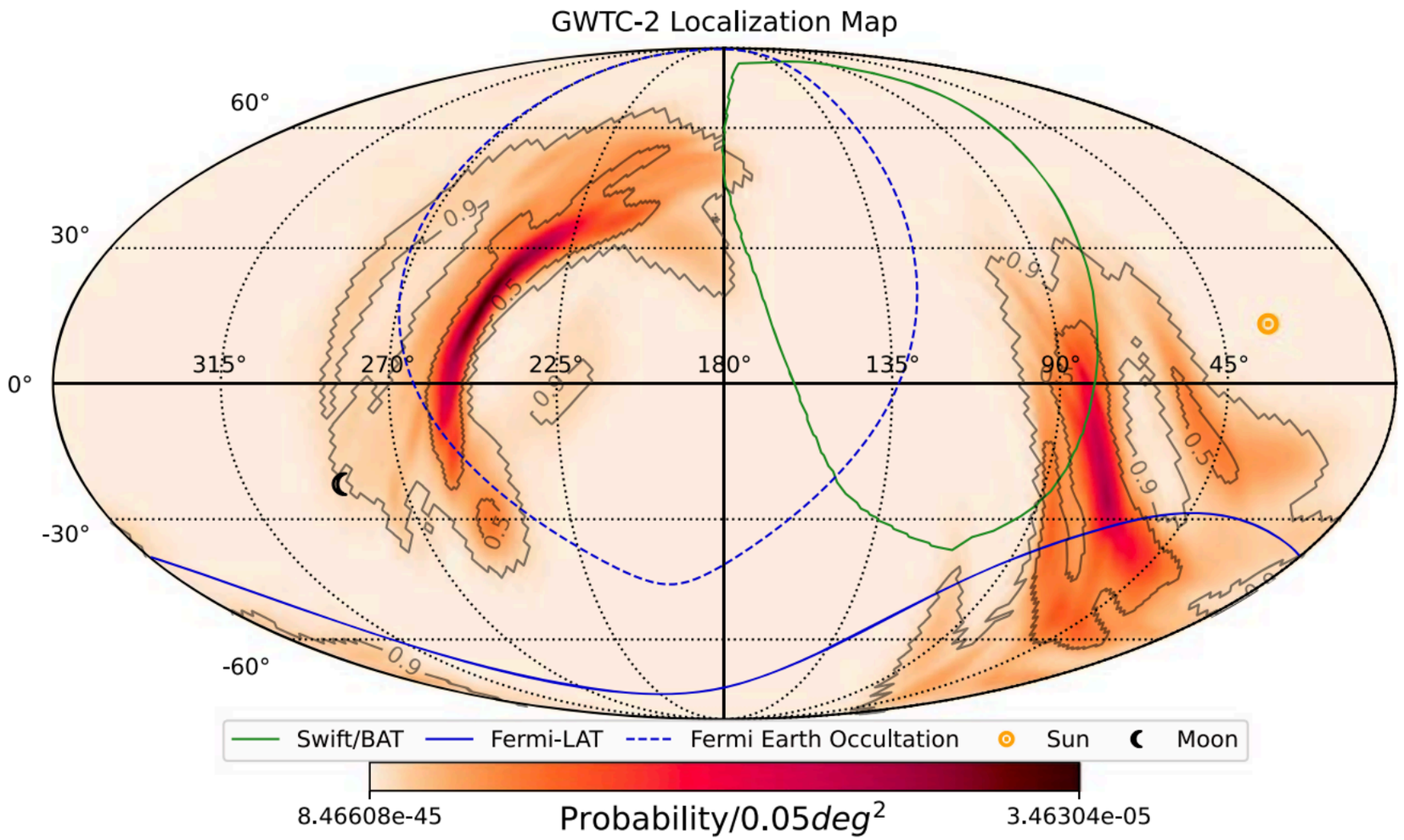
- High-energy neutrinos are produced by the interaction of accelerated cosmic rays with matter or photons. This means they are coming from ‘jetted’ physical scenarios….active galactic nuclei/ blazars, certain types of supernovae, tidal disruption events, etc.
- At least some are coming from blazars, where we are looking ‘down the barrel’ of a supermassive black hole jet.
- But there must be other mechanisms.

Non-localized Events:Many Observational Challenges
1. Large Localizations



- GW190425: BNS with 90% localization of ~8900 deg^2. D=160 Mpc.

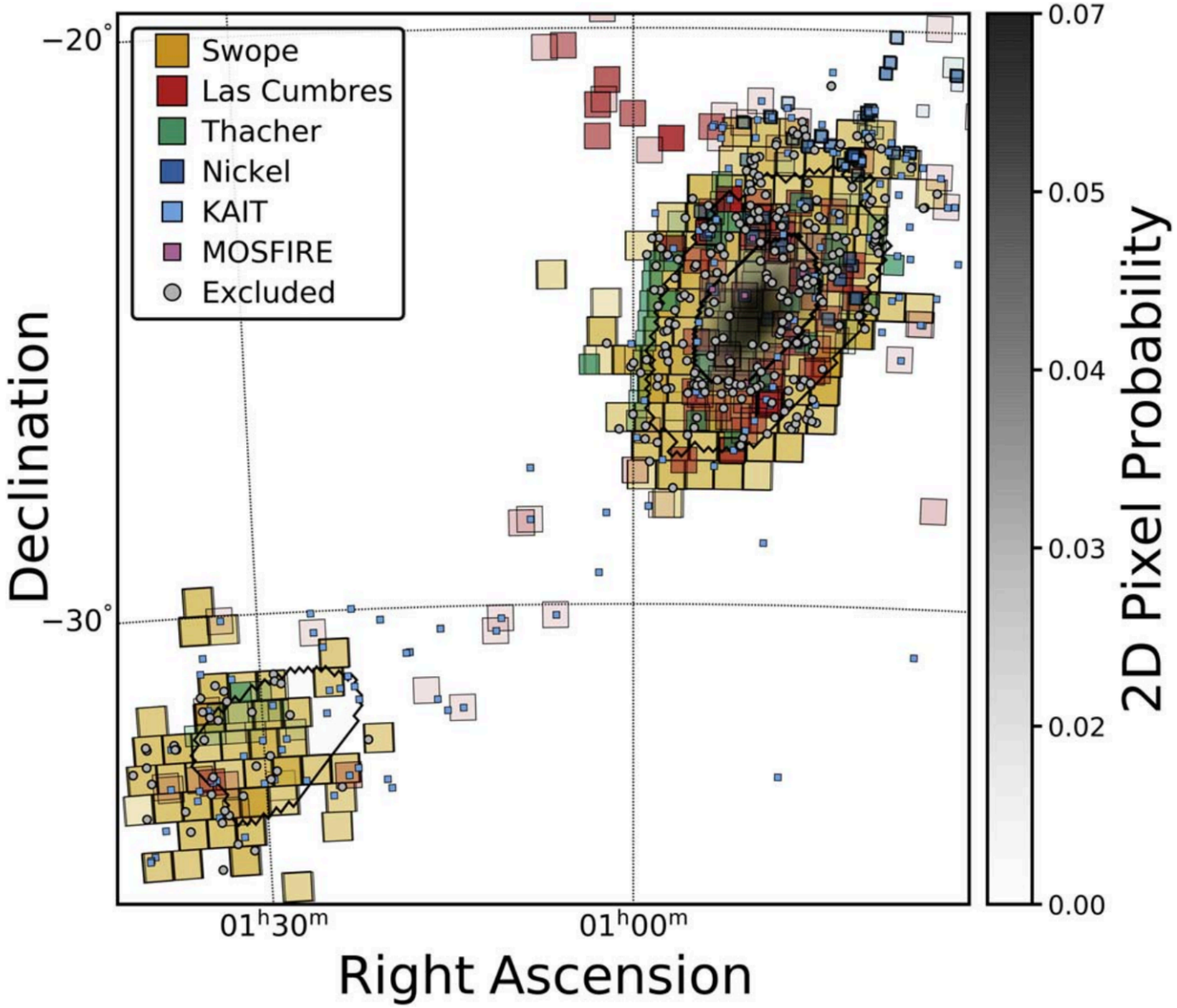
Non-localized Events:Many Observational Challenges
1. Large Localizations, ‘Every man for himself’



- GW190425: BNS with 90% localization of ~8900 deg2. D=160 Mpc.

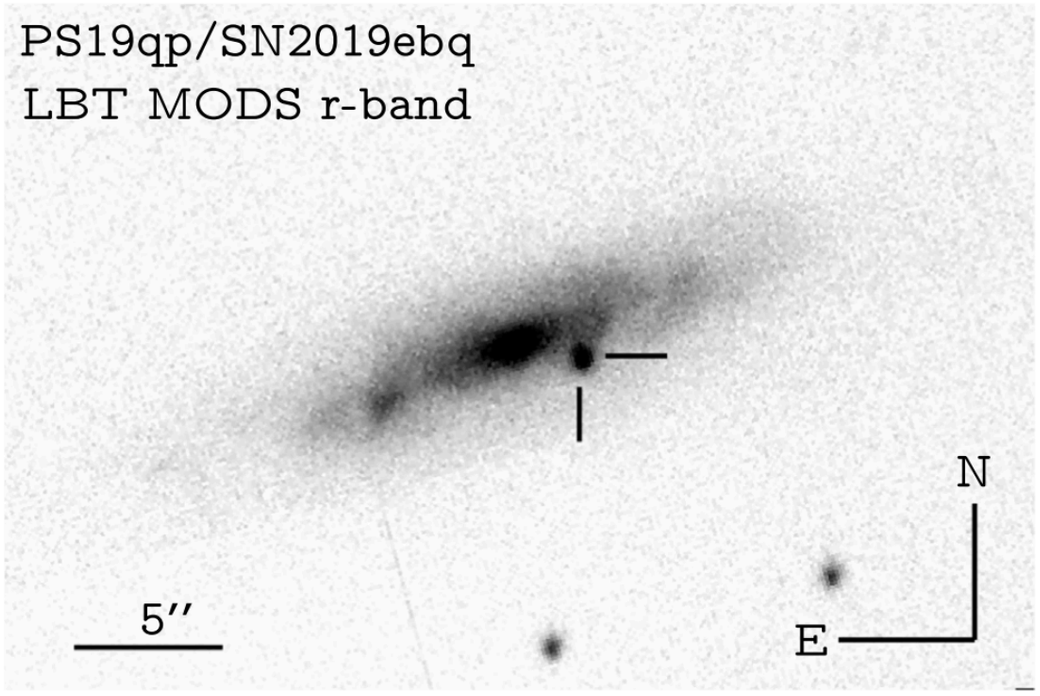
However, more than 5 days after the GW190425 merger, its uncoordinated search covered only 50% of the probability, with some areas observed over 100 times, and some never observed. (Keinan & Arcavi 2025)

Non-localized Events:Many Observational Challenges
2. Many potential candidates

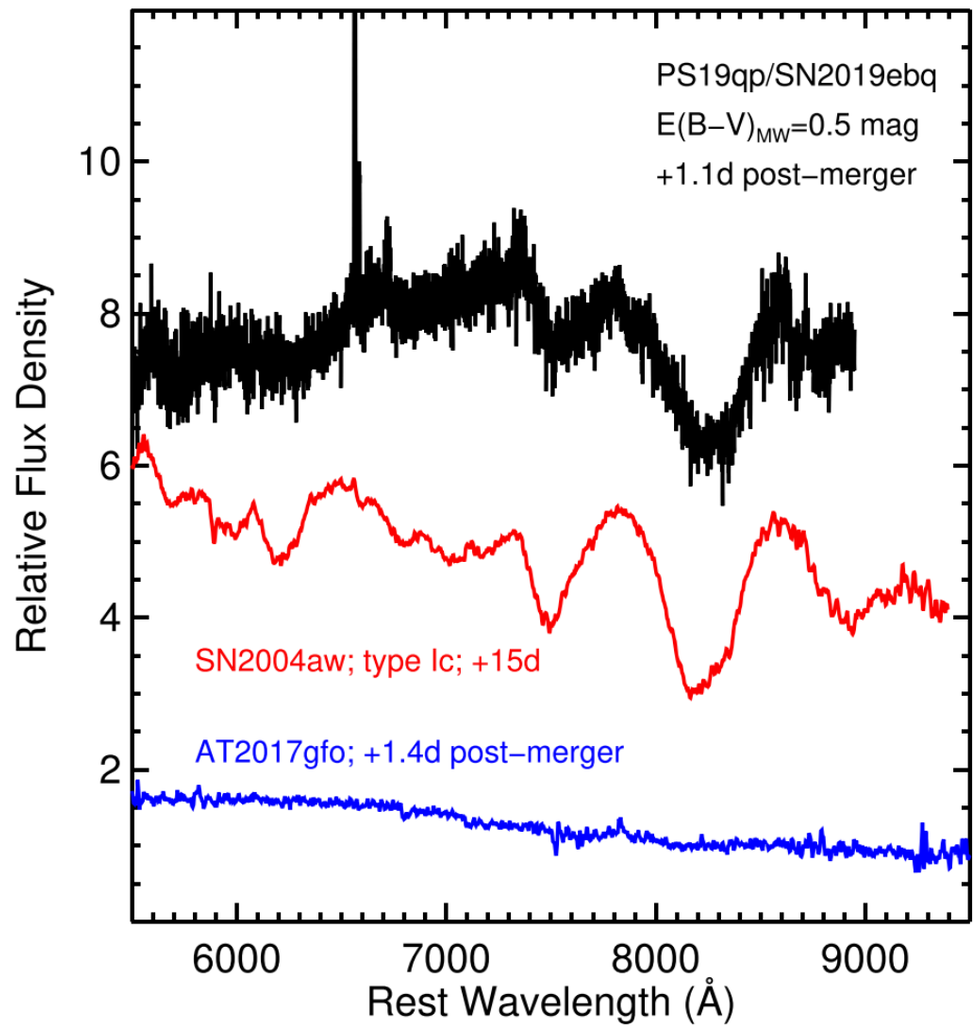


•GW190814: NSBH merger. 51 deg^2 localization. 189 transients in that localization (e.g. Kilpatrick+21).

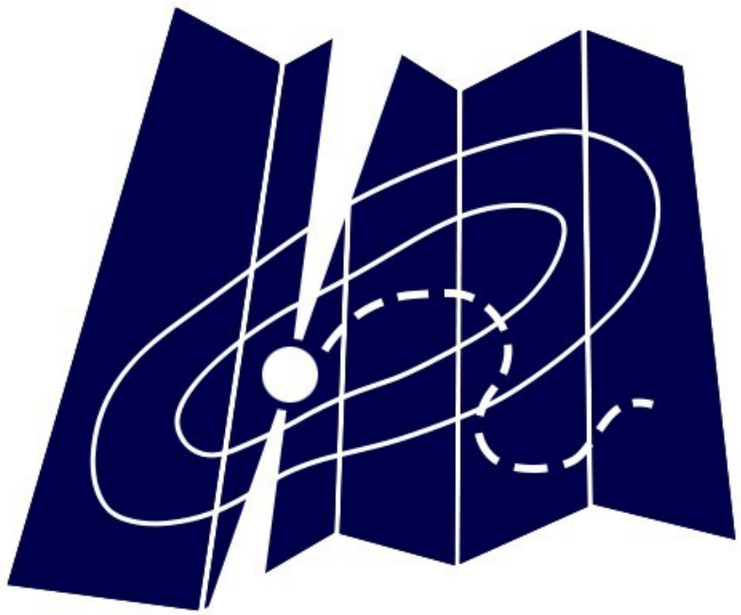
Non-localized Events:Many Observational Challenges
2. Many potential candidates



SAGUARO
Lundquist et al. 2019



- GW190425: BNS with 90% localization of ~8900 deg2. D=160 Mpc.
- 4+ teams got a spectrum of this same transient…wasted 8-10m telescopes time



THE GRAVITATIONAL WAVE
TREASURE MAP
treasuremap.space

Wyatt et al. 2020: ApJ...894..127W

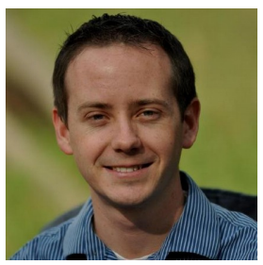
THE GRAVITATIONAL WAVE
TREASURE MAP
treasuremap.space

Wyatt et al. 2020: ApJ...894..127W

Thanks to Sam Wyatt for letting me steal some of his slides.

Treasure Map Team

Samuel Wyatt
David Sand
Iair Arcavi
Aaron Tohuvavohu
Andy Howell
Curtis McCully
Moira Andrews
Joseph Farah
Kathrryn Wynn



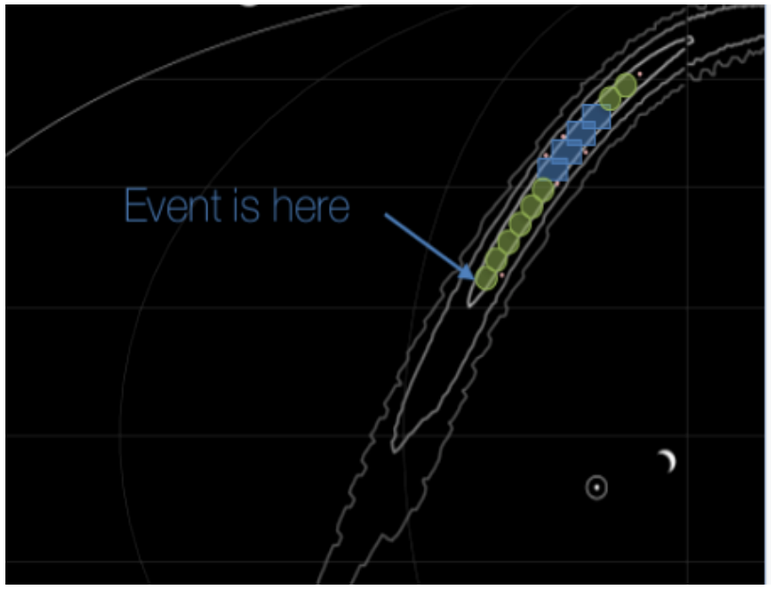
Motivations

Neutron star mergers are rare, and the localizations will be large

Discovery is key

GW Treasure Map

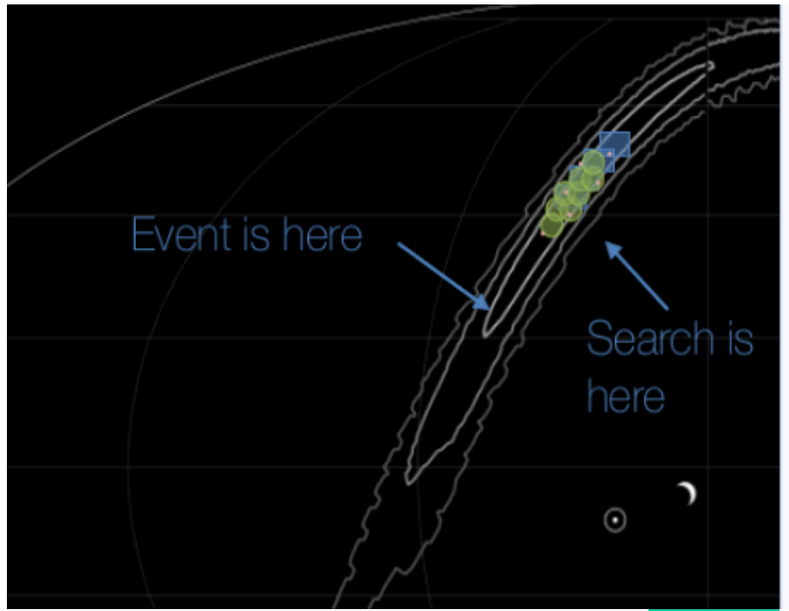
- Ideal Search Scenario
  - Team A submits their planned observations
  - Team B queries Team A's observation strategy via the API, and plans their search around Team A, while also submitting to the Treasure Map



vs.

This

this

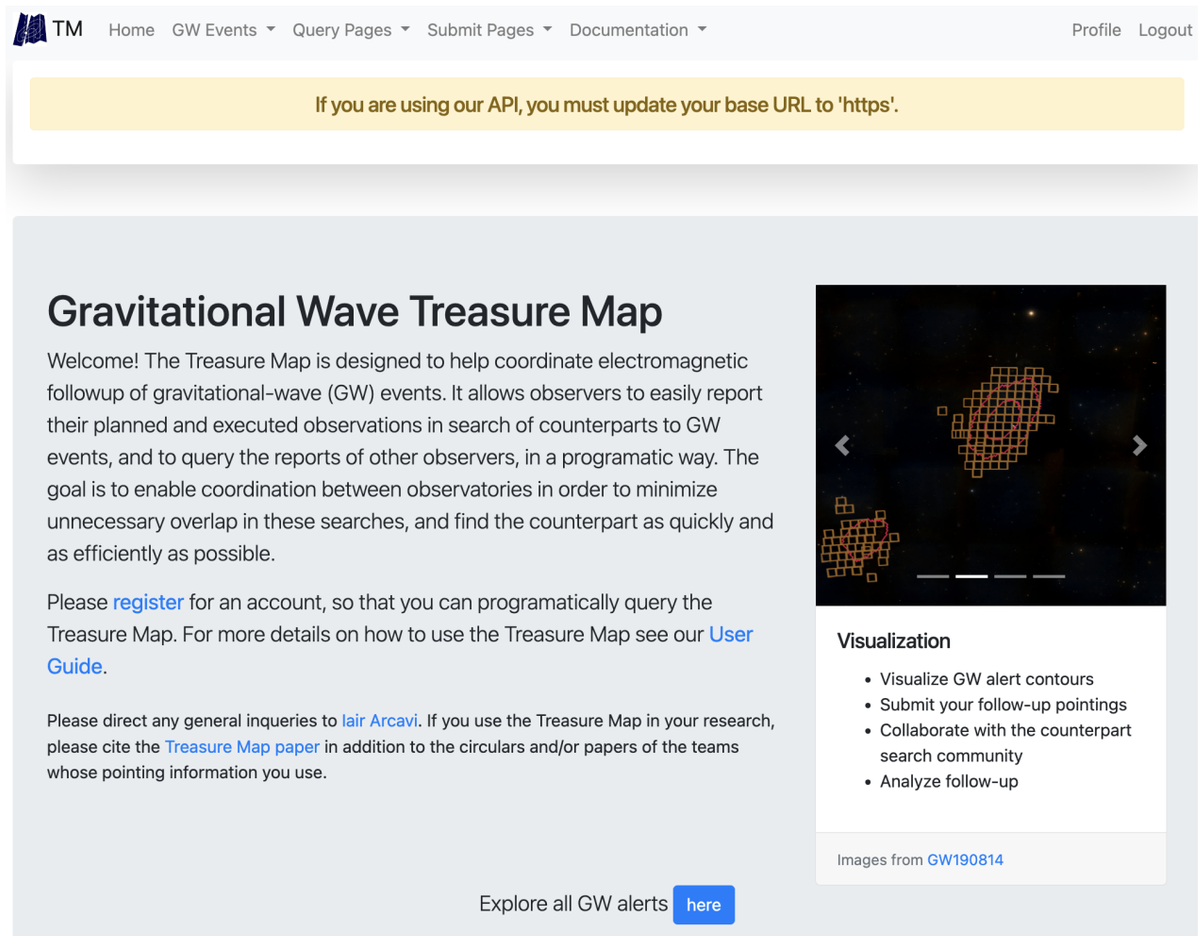


GW Treasure Map

- **Thus there is a need for a service that can:**
  - Host observation strategies
    - submission and querying
  - Offer observing strategy tools:
    - What has been observed?
    - Where is the most optimal area that I can look at this time with my instrument?
- **This can enable real-time observing collaboration between all teams with any instrument.**

GW Treasure Map

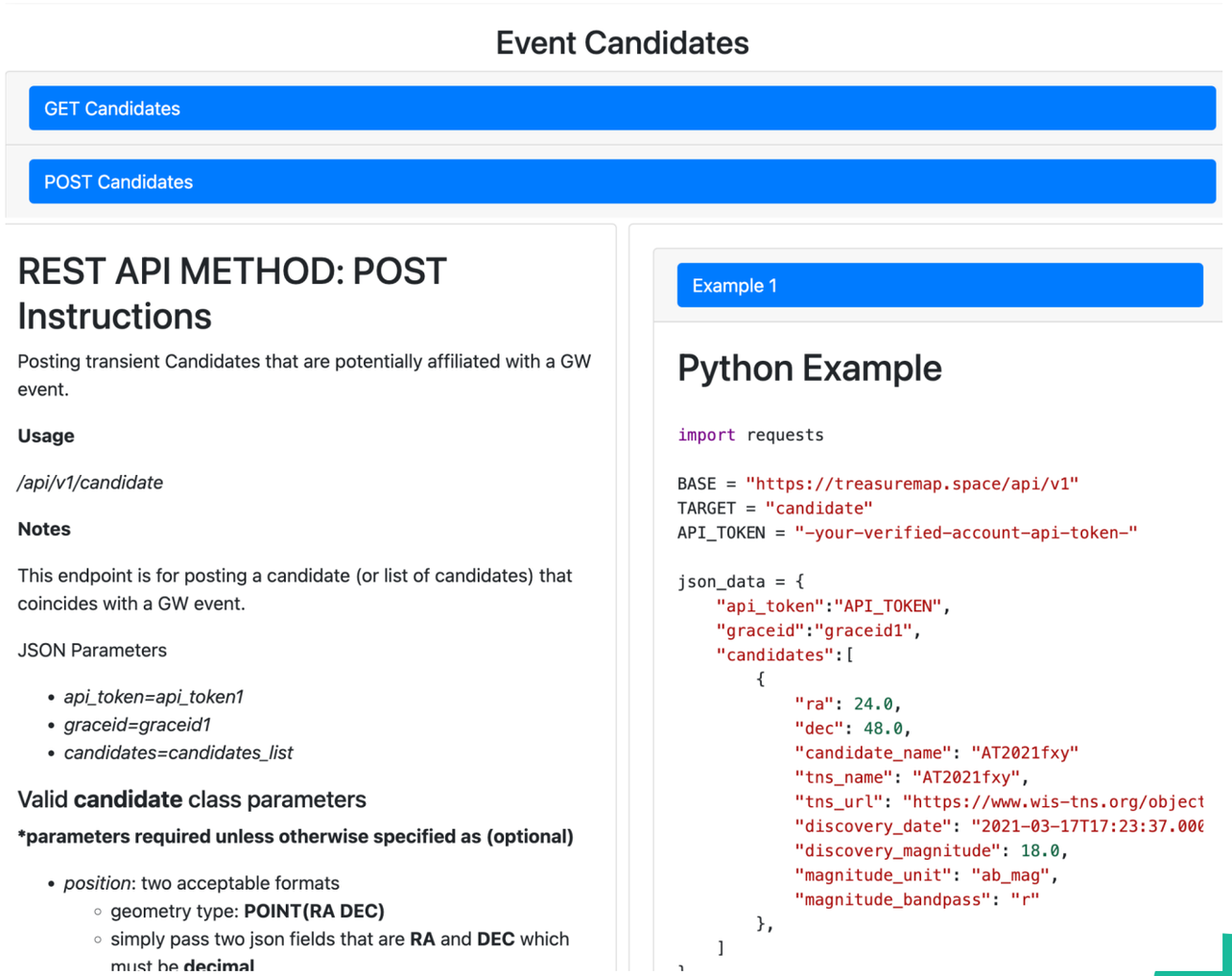
- **Web Based application**
  - User interface+REST API
  - ALADIN visualization interface (does not require account)
  - Web page querying and submitting for:
    - Instruments, Pointings
      - any submission requires Account registration
- API
  - **Account Registration is required**
  - Fully documented with multiple python examples
  - Endpoint suggestions?
  - python API wrapper (gwtm_api) (new!)



GW Treasure Map

REST API

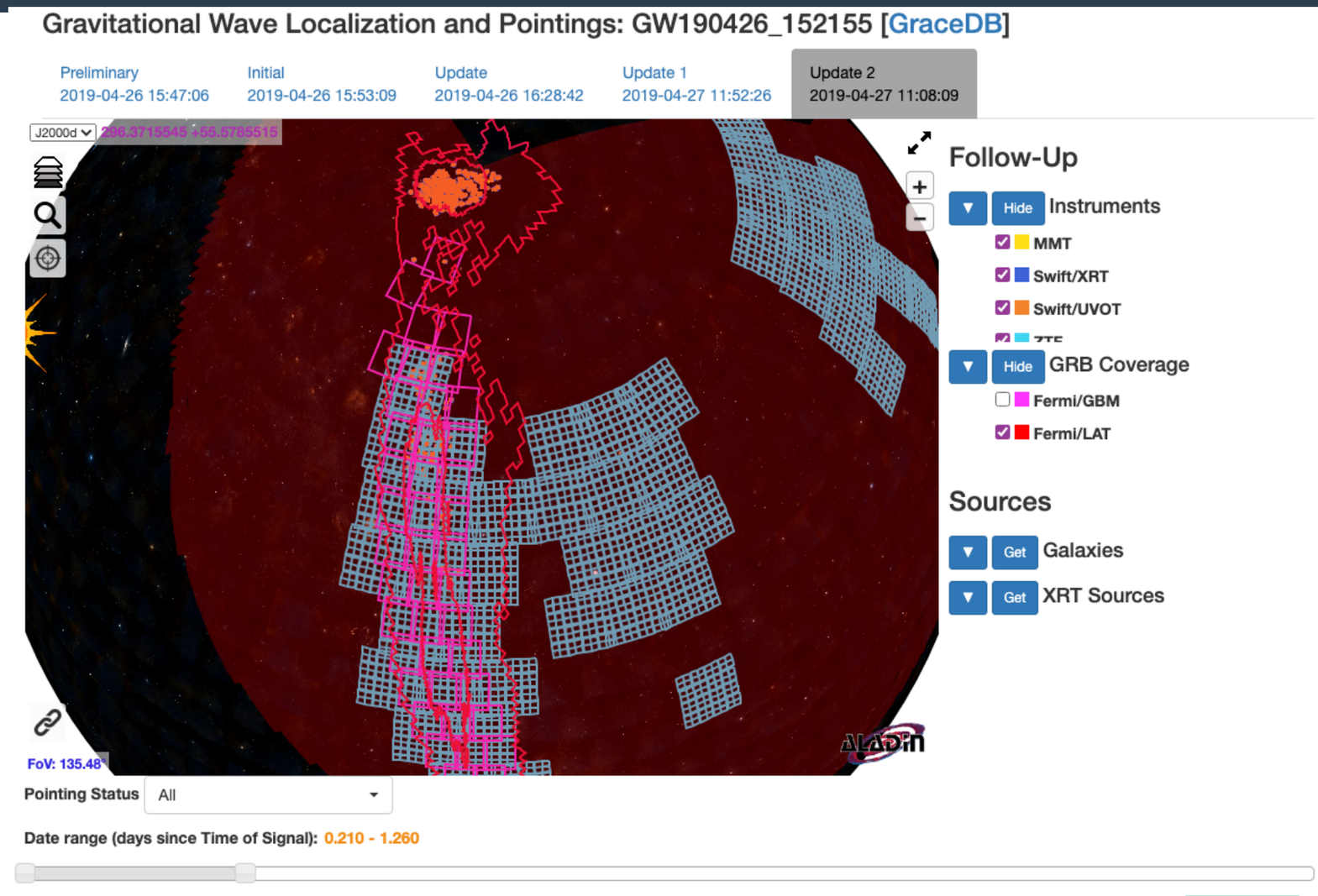
- Ultimately, the primary strength of this tool
  - GET/POST/UPDATE pointing information
    - DOI requests
  - GET Instrument
    - Footprints
  - GET/POST Convolved Galaxies
  - GET/POST/PUT/DELETE candidates
- Fully Documented on the website with ipython notebook tutorials available.



GW Treasure Map

Visualization:

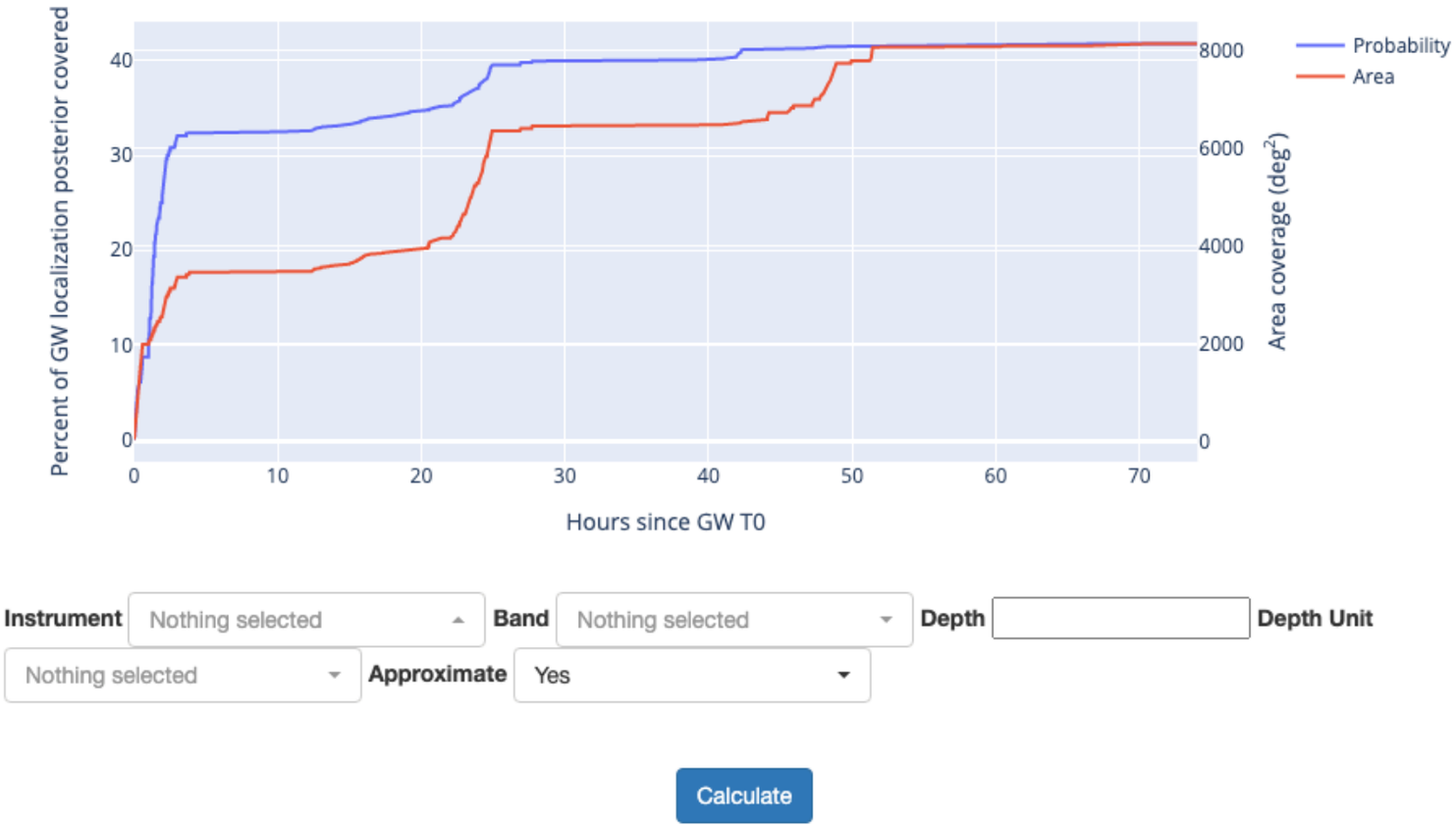
- Interactive ALADIN
  - (BIL, Color Maps, Scroll, Zoom)
- Toggle 90/50 contours and instrument footprints
- Filter pointings
  - (date, range, completed, planned, etc)
- (Someday) Overlay source info:
  - Convolved Galaxies
  - Icecube Nu Track alerts
  - Candidates



GW Treasure Map

Coverage Calculator

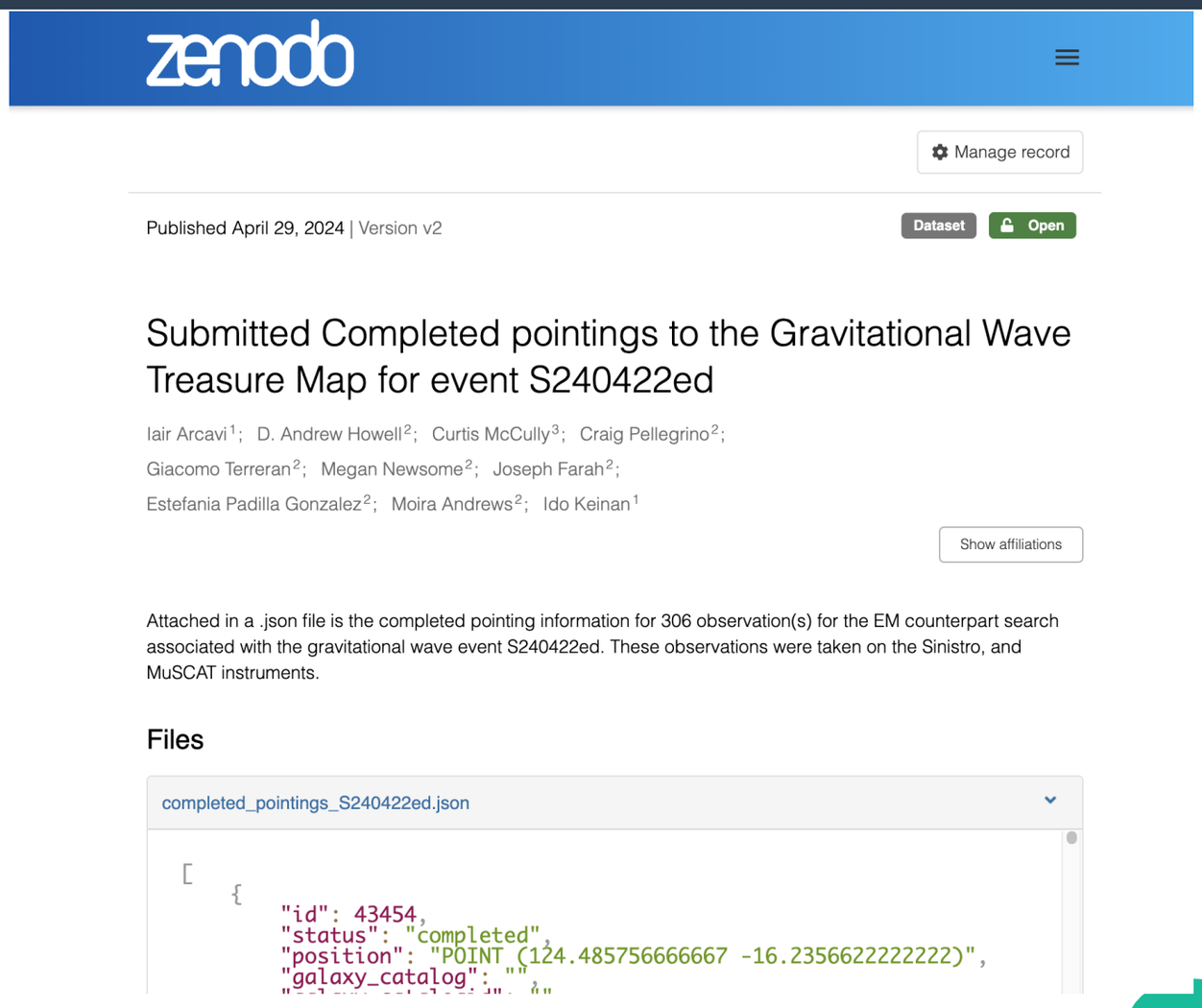
- Calculates the follow-up coverage of the GW localization over time.
- Can limit the coverage calculation based on:
  - Instruments, wavelengths, depths, etc



GW Treasure Map

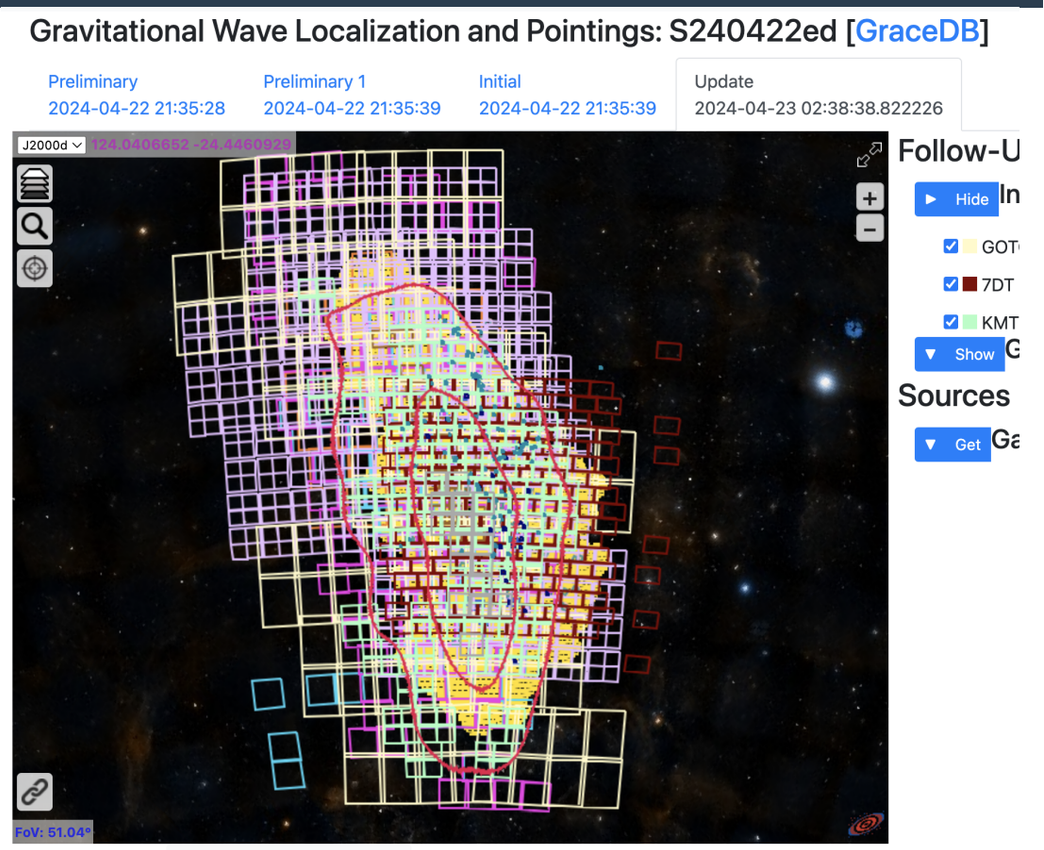
TM Pointings are citeable

- To incentivize collaboration. And to ‘get credit’ for observing even low probability regions
- Pointing DOI’s via zenodo!
  - Digital Object Identifiers are citable
  - API endpoints requesting on submission, and post-facto



GW Treasure Map

- S240422ed (an interesting O4 event, but probably not real)
  - ~2200 completed pointings, up to ~5days after t0.
  - ~70% prob covered within first 6 hours of event at a depth of 20.5mag
  - ~90% covered within first 24hr for all pointings.
- **These pointings were submitted in near real-time**



GW Treasure Map

Current work:

- **NOW RELEASED**: python API wrapper: gwtm_api
- Encompasses most API endpoints for the GWTM in an easier to manage python library (stable)
- Extended capability for follow-up tools as well:
  - visualization, coverage-calc, map renormalization, candidate coverage, more to come!

- https://github.com/TheTreasureMap/gwtm_api

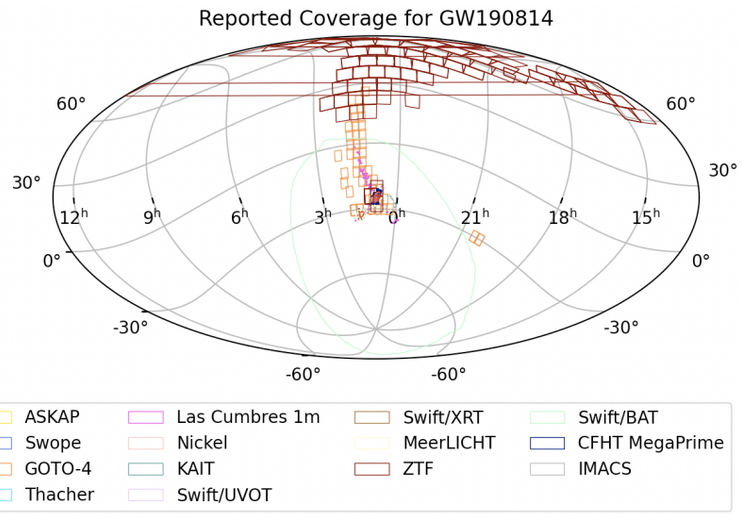
Event Tools

For a given GW event, you can utlize the the `event_tools` library to perform some analytics of a GW event with the data supported on the Treasure Map.

Visualizing coverage

```
import gwtm_api

gwtm_api.event_tools.plot_coverage(graceid="GW190814", api_token=API_TOKEN)
```



The `plot_coverage` function allows you to pass in your own list of pointings, along with caching the queried results so you don't have to hit the API for large queries every time.

```
conda create -n gwtm_api python=3.11
conda activate gwtm_api
python -m pip install gwtm_api
```

GW Treasure Map: What's next for O4

- **Future Implementations**
  - Scheduling suggestions
    - Provide observers with unobserved areas to tile/search with a given instrument footprint
  - Support Candidate follow-up
    - Photometry
    - Spectroscopy

- **Community feature suggestions**
  - We want to hear from our users

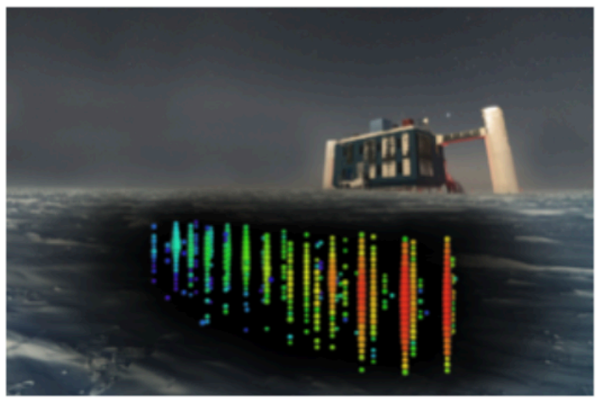
Conclusions

- **Takeaways:**
  - This utility is only as strong as its user base
  - **O4 observations are being reported in ~real-time!**
- Any Questions?

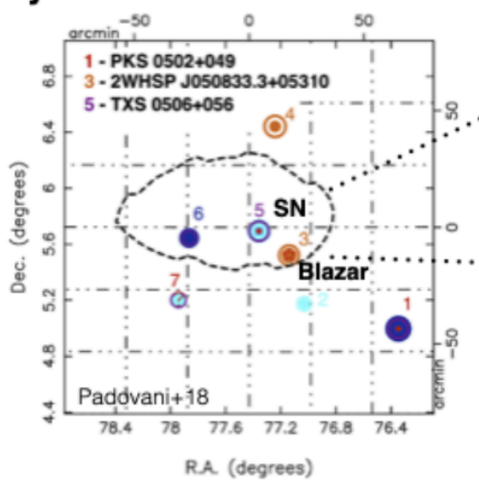
TROVE: Tool for Rapid Object Vetting and Examination

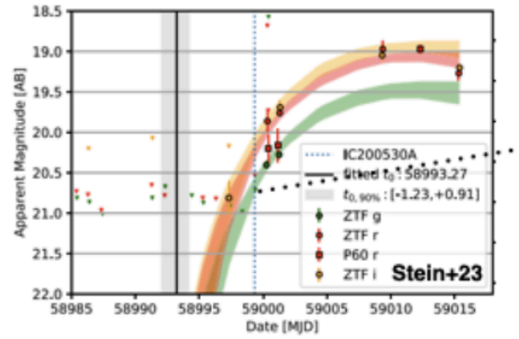
Neutrino Candidate Follow-up & Vetting

Neutrino Alert and Localization

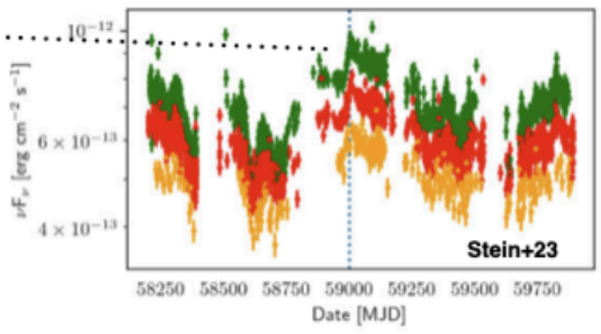


Transient & AGN within Localization: Are they associated with the neutrino?





-Normal SN
-Detection Prior to Neutrino
↳Low Score

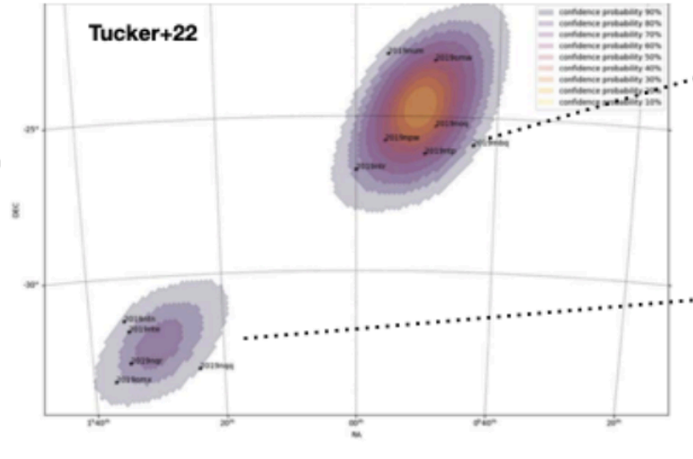


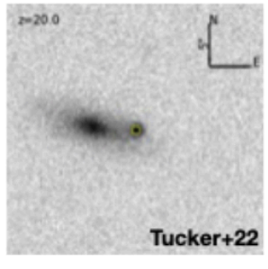
-Blazar Light Curve Before/After Neutrino
-Flaring at Time of Neutrino
↳High Score

GW Candidate Follow-up & Vetting

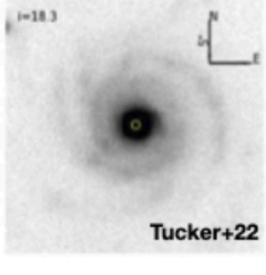
GW Alert and Localization

Many Viable Transients Within Localization

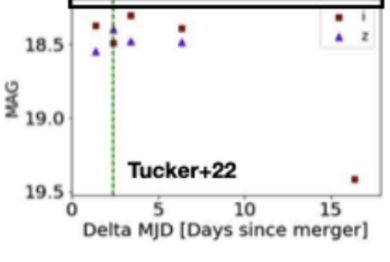




-Host at right distance
-No detection prior to merger
↳High Score



-Transient consistent with AGN position (NS merger)
-Detection prior to merger
↳Low Score



TROVE: Tool for Rapid Object Vetting and Examination

Kate Alexander
University of Arizona

Azalee Bostroem
University of Arizona

Phil Daly
University of Arizona

Wen-fai Fong
Northwestern University

Noah Franz
University of Arizona

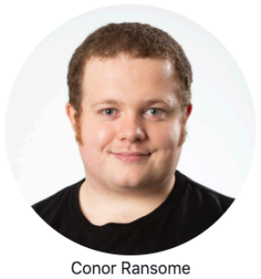
Griffin Hosseinzadeh
UC San Diego

Charlie Kilpatrick
Northwestern University

Michael Lundquist
Keck Observatory

Kerry Paterson
Max Planck Institute for Astronomy

Jillian Rastinejad
University of Maryland



Conor Ransome
University of Arizona

David Sand
University of Arizona

+ Phillip Noel (Here today!)

Manisha Shrestha
University of Arizona

Bhagya Subrayan
University of Arizona

Nicholas Vieira
Northwestern University

TROVE: Tool for Rapid Object Vetting and Examination

Kate Alexander
University of Arizona

Azalee Bostroem
University of Arizona

Phil Daly
University of Arizona

Wen-fai Fong
Northwestern University

Noah Franz
University of Arizona

Griffin Hosseinzadeh
UC San Diego

Charlie Kilpatrick
Northwestern University

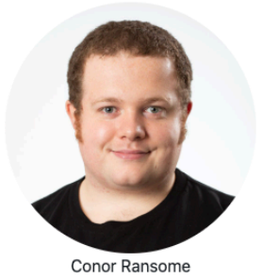
Michael Lundquist
Keck Observatory

Kerry Paterson
Max Planck Institute for Astronomy

Noah Franz
U of Arizona

+ Phillip Noel
(Here today!)

Jillian Rastinejad
University of Maryland



Conor Ransome
University of Arizona

David Sand
University of Arizona

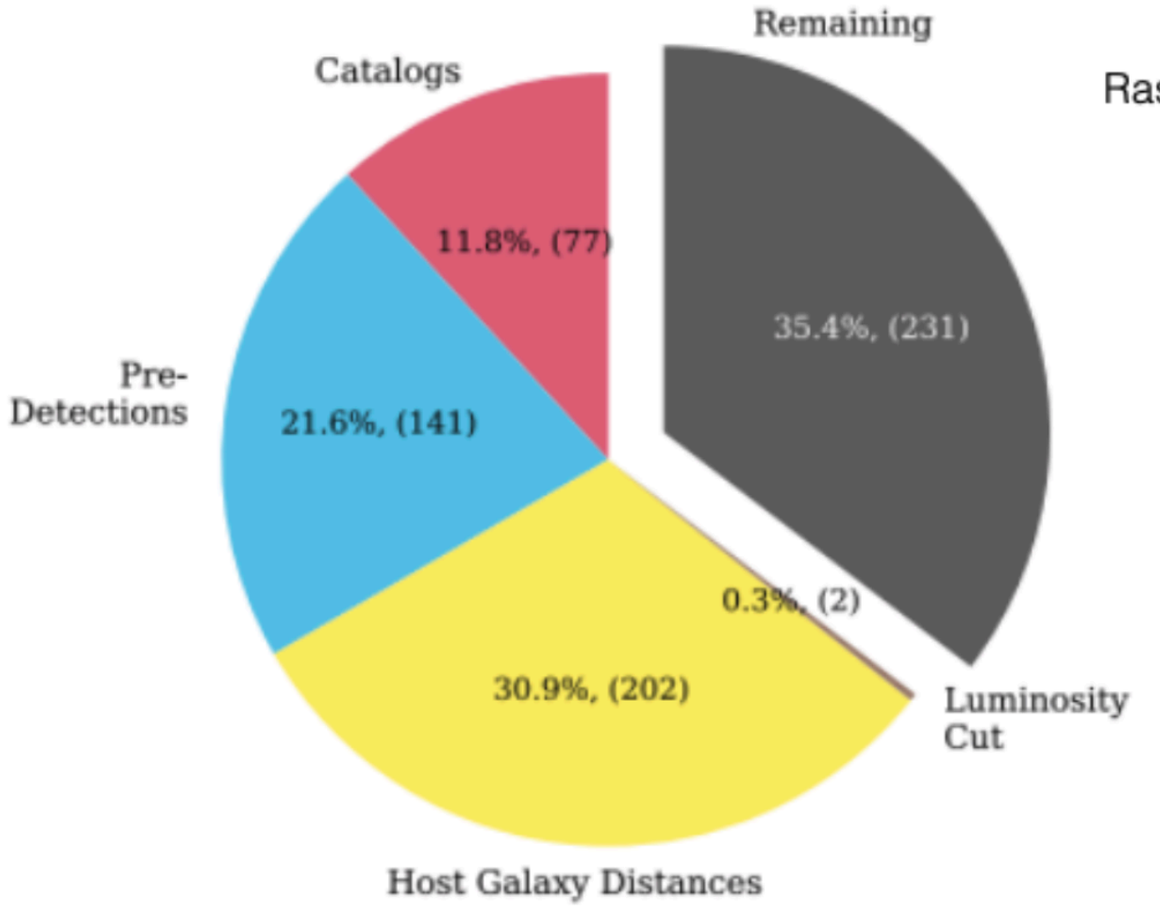
Manisha Shrestha
University of Arizona

Bhagya Subrayan
University of Arizona

Nicholas Vieira
Northwestern University

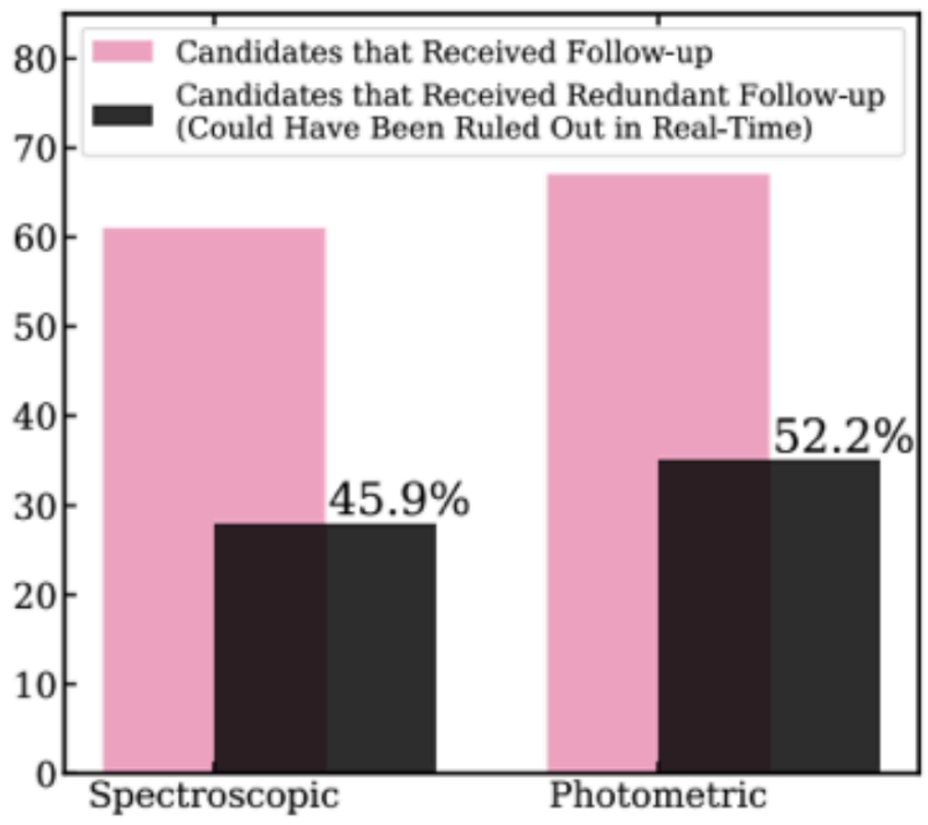
TROVE: The Problem

Real-time Vetting of GW-EM Counterpart Candidates:
Optimizing Follow-up Resources



~65% of all O3 NS candidates culled

Rastinejad+22

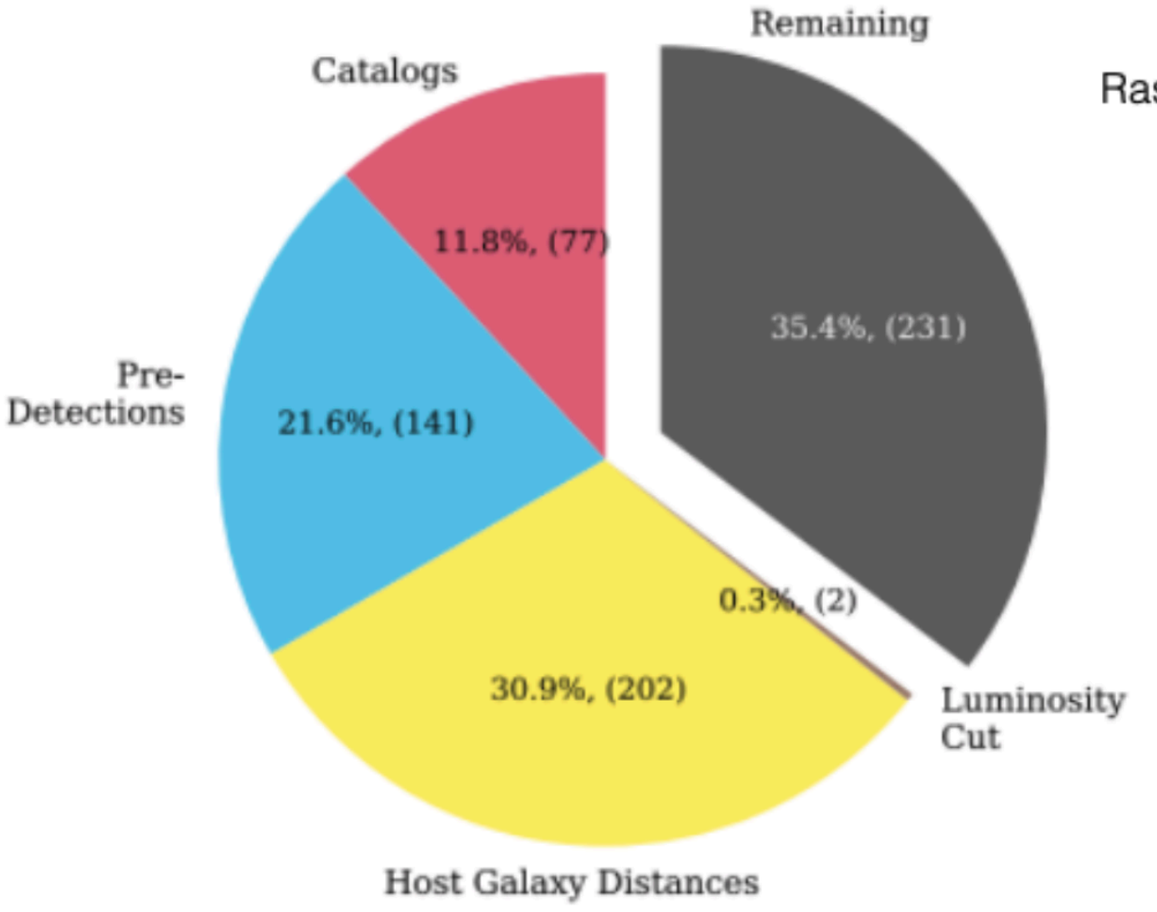


~50% of all candidates that received follow-up did not need it

Real-time vetting of transient would greatly reduce the number of viable counterpart candidates. Rastinejad+22.

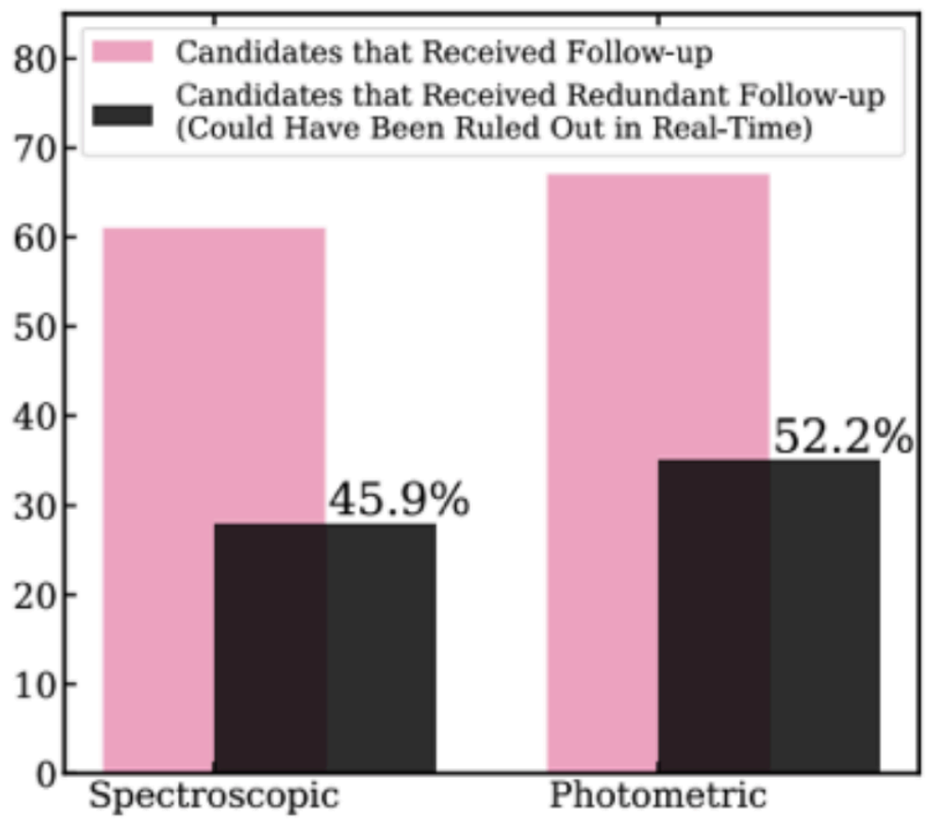
TROVE: The Problem

Real-time Vetting of GW-EM Counterpart Candidates:
Optimizing Follow-up Resources



~65% of all O3 NS candidates culled

Rastinejad+22



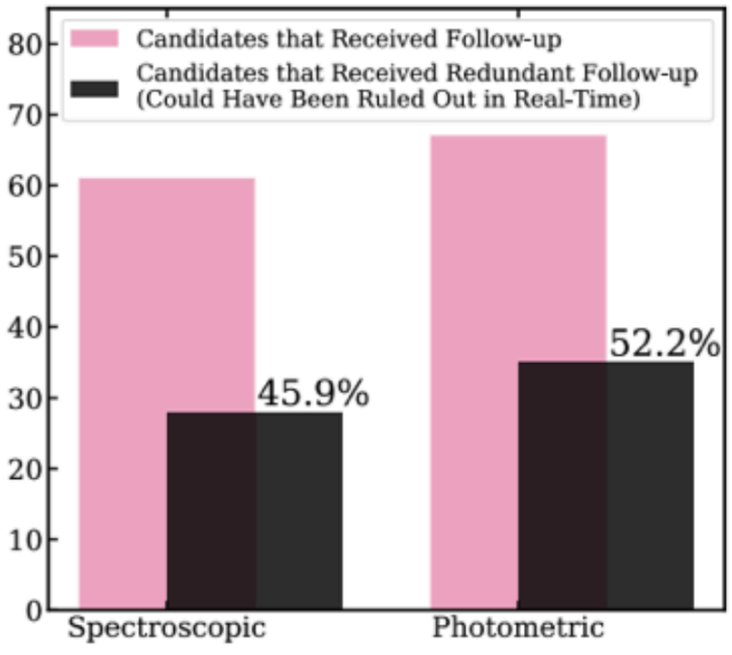
~50% of all candidates that received follow-up did not need it

<u>One goal of the TROVE is to make these vetting resources easy to access in order to level the playing field in MMA.</u> Really important in the ‘heat of the moment’ when decisions must be made and telescopes triggered.

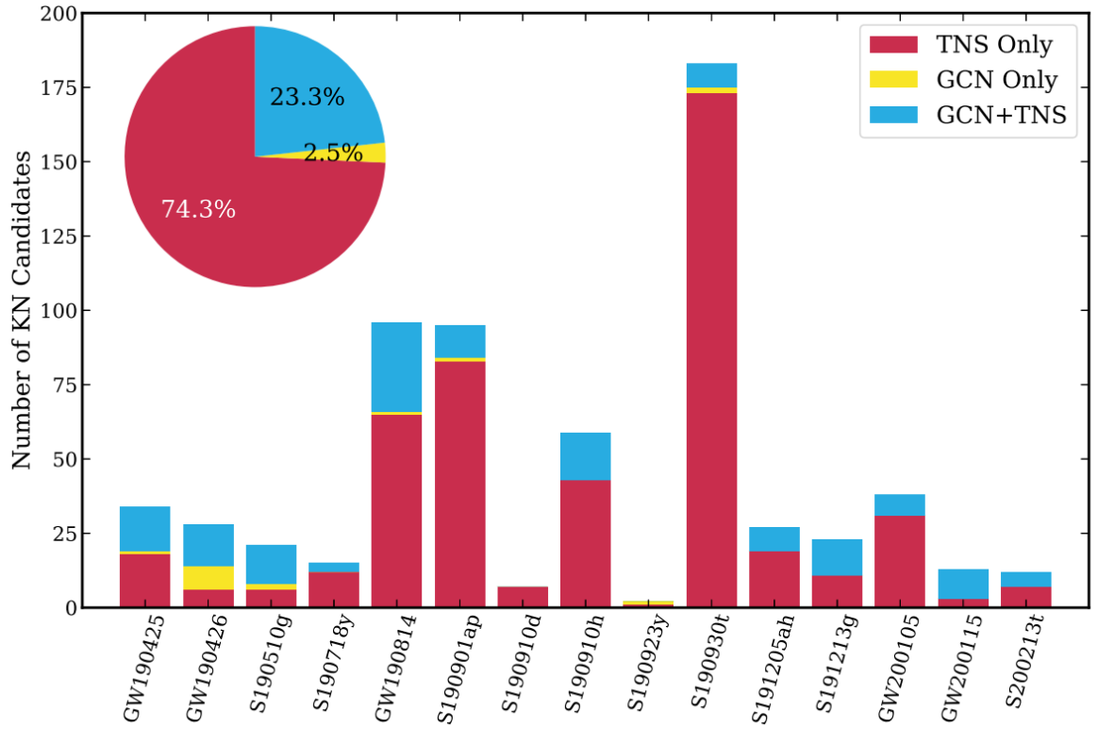
TROVE: So what is vetting?

Use the information you have to check the viability of transients/ variability associated with multi-messenger events.

- In any localization for GWs of ~10+ deg^2 there will inevitably to 10-100s of transients in the localization, but only one can be the counterpart.
- In the end, you *must* get a spectrum or imaging of your candidate to verify that it is associated with the GW.
- Telescope resources are precious, and we tend to all dive in and get a spectrum of the same object. And often that object is a waste of time.



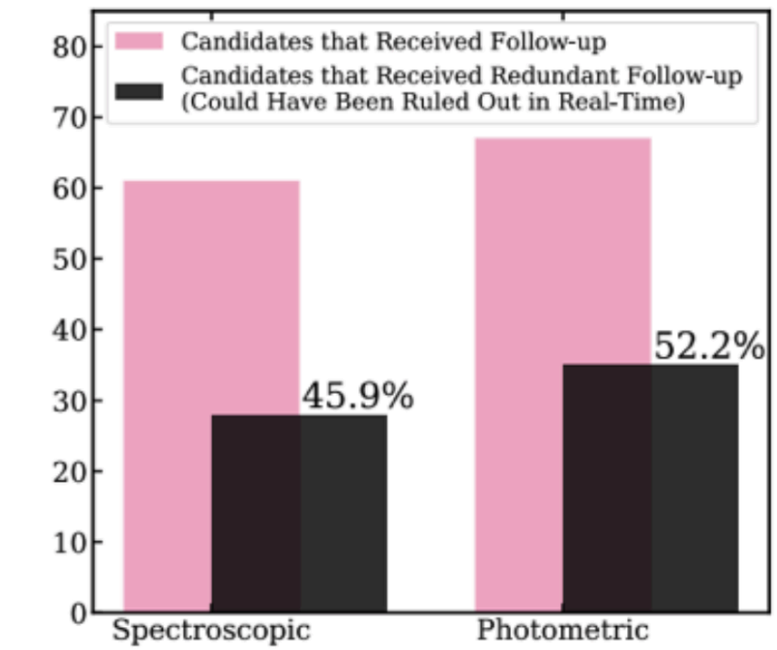
~50% of all candidates that received follow-up did not need it



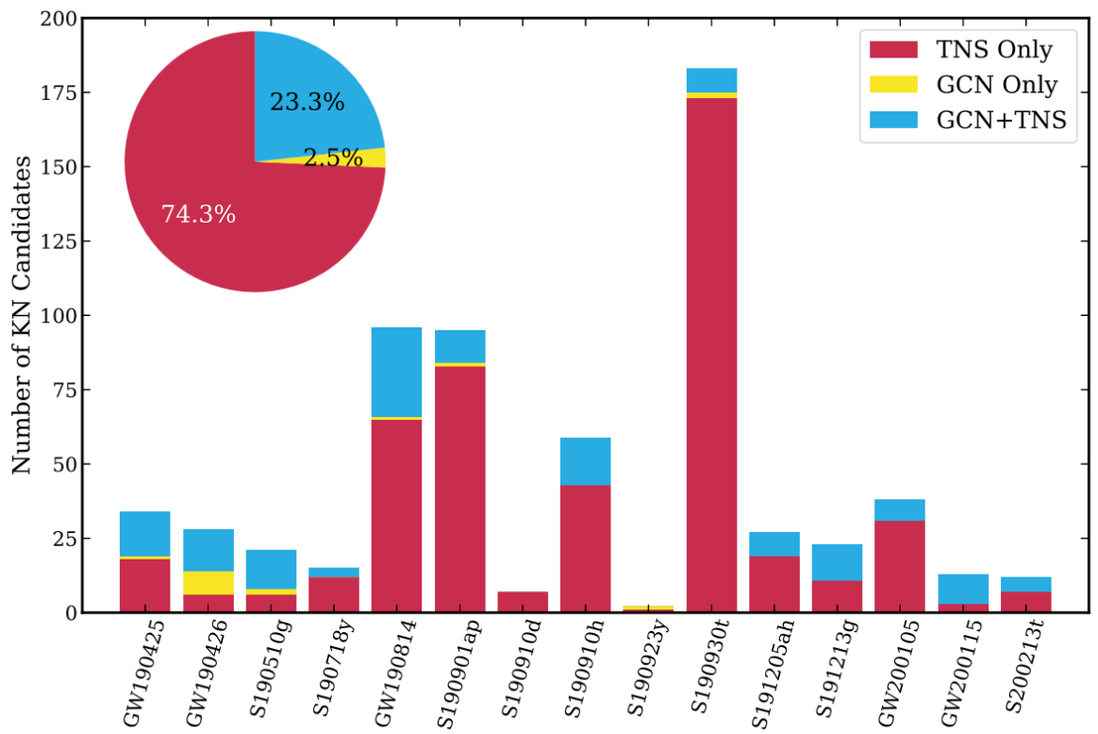
TROVE: So what is vetting?

Use the information you have to check the viability of transients/ variability associated with multi-messenger events.

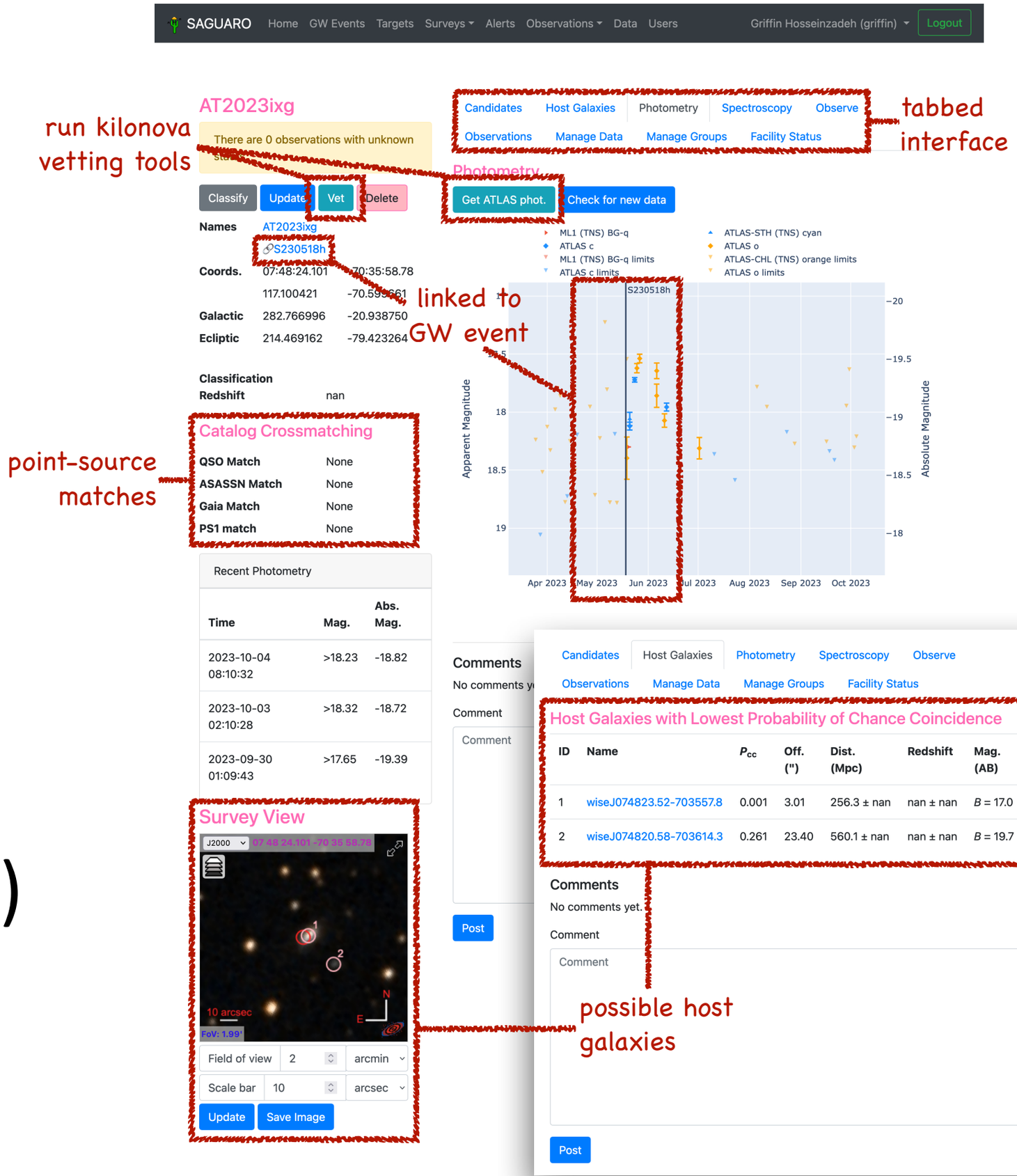
- Cross-check new candidates with catalogs (is the host galaxy at the right distance, is it a known variable object like an AGN or variable star, etc etc)
- Was this transient actually there *before* the GW merger (forced photometry servers)?
- Is the ‘transient’ actually an asteroid (moving object) that is not what we want at all?
- Is the object actually already detected in static deep imaging of the field?
- Very hard to build this infrastructure. Maybe only a couple groups can do it…



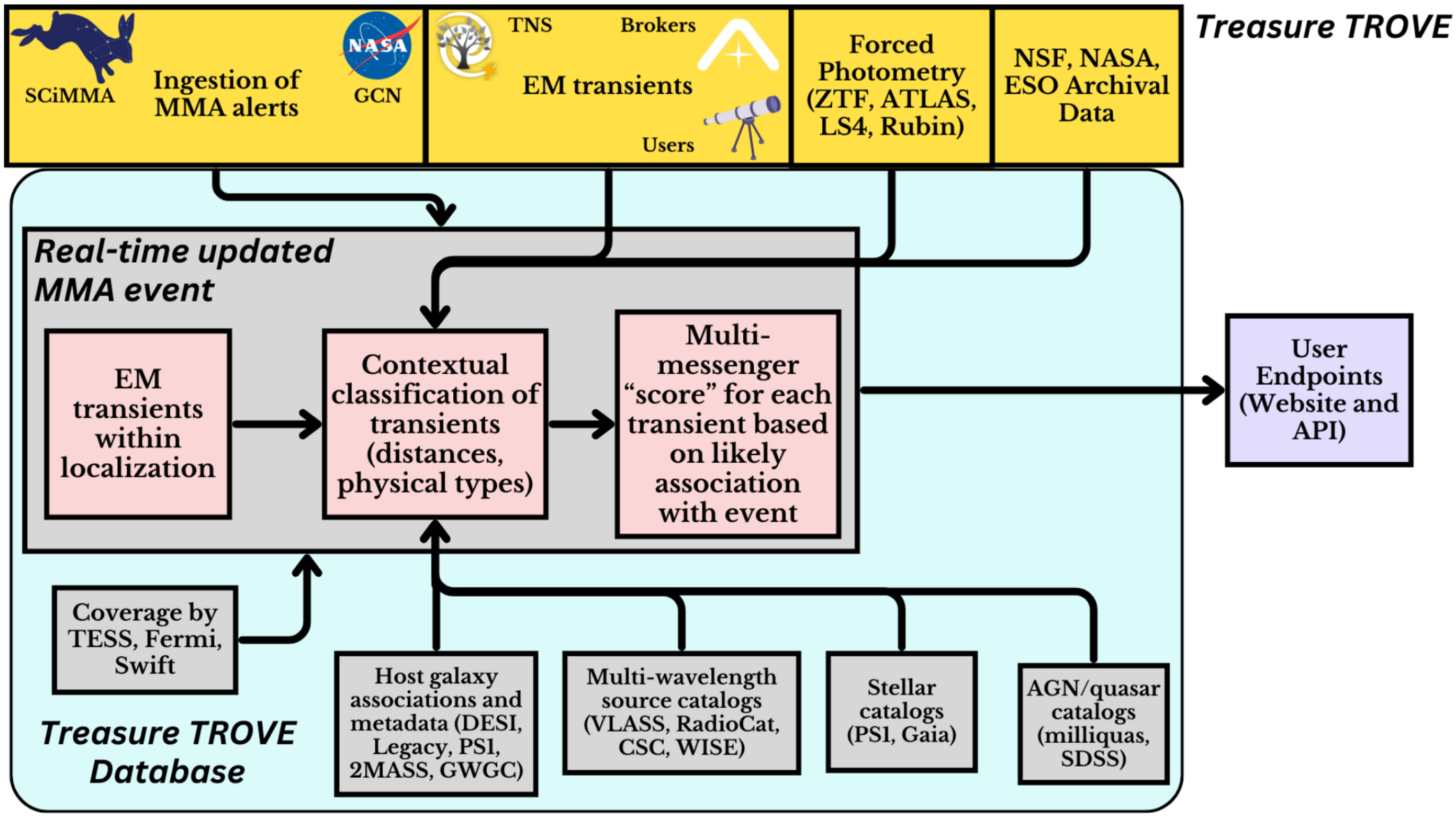
~50% of all candidates that received follow-up did not need it



Aside: First implemented for ‘us’ in SAGUARO TOM (Hosseinzadeh+24)



TROVE: Tool for Rapid Object Vetting & Examination



- Catalogs are spinning on disk (PostgreSQL), and ingested in Q3C (Quad Tree Cube) format for fast cross-matches.

TROVE: Tool for Rapid Object Vetting & Examination

Scoring Elements

$$\text{Score} \propto \sqrt[N]{\prod_{i=1}^{N} \exp\left[\frac{(x_i - \mu_i)^2}{2\sigma_i^2}\right]},$$

- the candidate's position on the sky (i.e., its percentile in the probability map),
- the distance to the candidate, as determined through host galaxy association,
- the luminosity (absolute magnitude) of the candidate,
- the rise and/or decline rate of the candidate's light curve,
- detections at the position of the candidate in imaging taken prior to the event, and
- the candidate's spectroscopic classification, if available.
- Other catalog associations (variable star, AGN, point source, etc)

Scoring still being worked out in detail, but will be from 0 to 1
We want community input and will solicit soon.
We also understand that not everyone will agree on scoring.
Will provide all information necessary to come up with your own score.

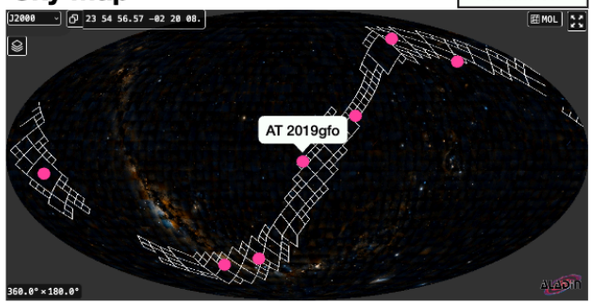
TROVE Website (will be API accessible)

TROVE GW Neutrino GRB Counterparts

S190425z

1/FAR	70 kyr
Distance	158 Mpc
BNS	99%
NSBH	0%
BBH	0%
Terrestrial	0%
HasNS	0%
HasRemnant	0%
HasMassGap	0%

Sky Map ▾ Initial v3



50% Area	2400 deg²
90% Area	9881 deg²

Candidates (34)

+ Report Candidate

Name	Right Asc.	Declination	Probability	Host Dist.	Magnitude	ΔMagnitude	Score ▾
AT 2019gfo	11:46:44.83	+27:24:49.9	82%	140 Mpc	r = 21 (–16)	0.9 mag d^{-1}	93

TROVE GW Neutrino GRB Counterparts

AT 2019gfo

11:46:44.83 +27:24:49.9

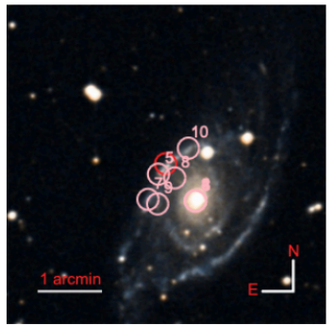
Aliases:
PS19avg

Candidate for:
S240413p

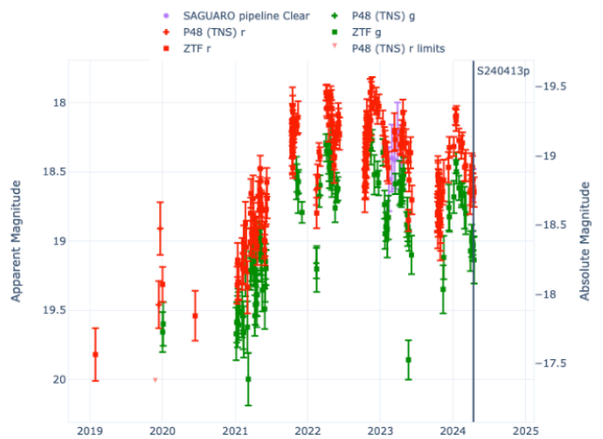
Point Source Matches:
None

Source:
C.B Arthur (U. Arkansas)

Survey View



Photometry + Report Observation



Score Factors

	Target Value	Event Value	Score Factor
Sky Map %ile	82%	—	0.82
Distance	140 Mpc	140 Mpc	1.00
Abs. Mag.	-16.0 mag	-15.5 mag	0.95
Decline Rate	0.9 mag d^{-1}	1.0 mag d^{-1}	0.98
Score			**0.93**

Possible Host Galaxies

#	Name	Pcc	Offset	Distance	Redshift	Magnitude	Source
1	J1464448+2724499	0.02	9.8″	140 Mpc	0.031	19.3	GWGC
2							

TROVE Website v0 in progress

SN2025ulz

Classify | Edit | Share | Delete | Vet

Names	SN2025ulz	
	🔗S250818k	
Coords.	15:51:54.201	+30:54:08.67
	237.975838	30.902408
Galactic	49.509535	50.630027
Ecliptic	225.504783	49.514382

Score Details

S250818k

2D Localization Score: 0.66
Point Source Score (1 or 0): 1
3D Association Score: 0.17
Maximum Luminosity: 4.89 x 10^{41} erg/s
Time of Maximum Light Curve: 26.76 days
Light Curve Slope (positive is brightening): 3.01 mag/day

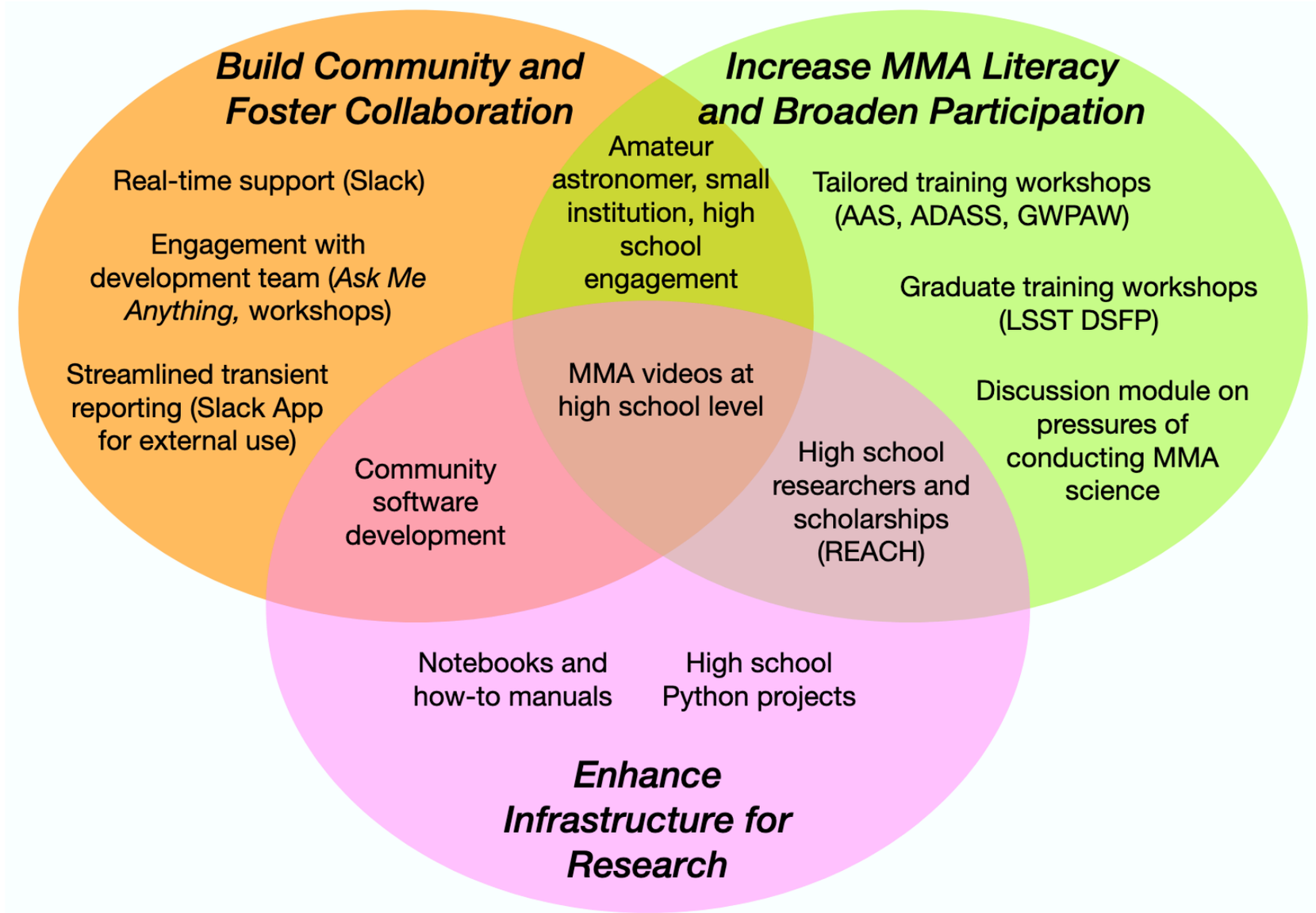
▸ Host Galaxies

▾ Photometry

Things to expect in the next year:

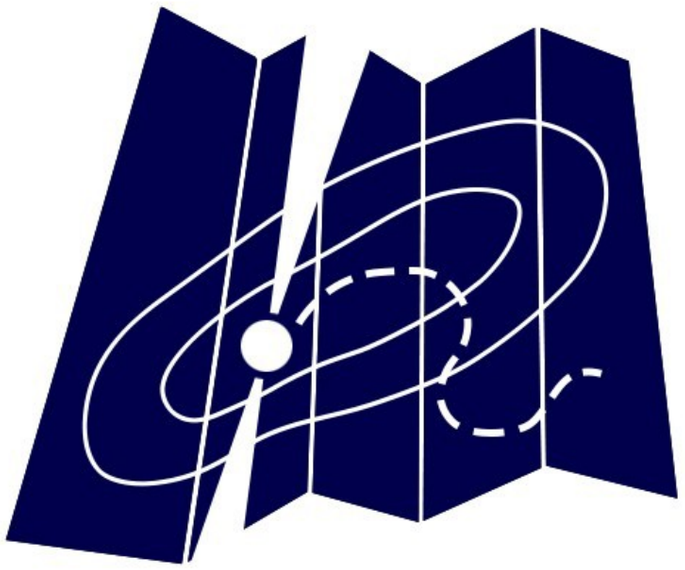
1. Public beta version of the TROVE
2. Paper looking at O3, O4 GW alerts and transient candidates for scoring algorithm development.
3. Paper looking at neutrino scoring based on past events.

TROVE Broader Impacts



- Things to expect in the next year: Slack Channel, Notebooks and how-to manuals. Demonstrations at a conferences near you!

Treasure Map & Treasure TROVE
Infrastructure for Multi-messenger Astronomy



THE GRAVITATIONAL WAVE
TREASURE MAP
treasuremap.space

TROVE: Tool for Rapid Object Vetting and Examination

David Sand
University of Arizona

Observatories Forum, Santa Barbara, Sep 2025

Thank you!!