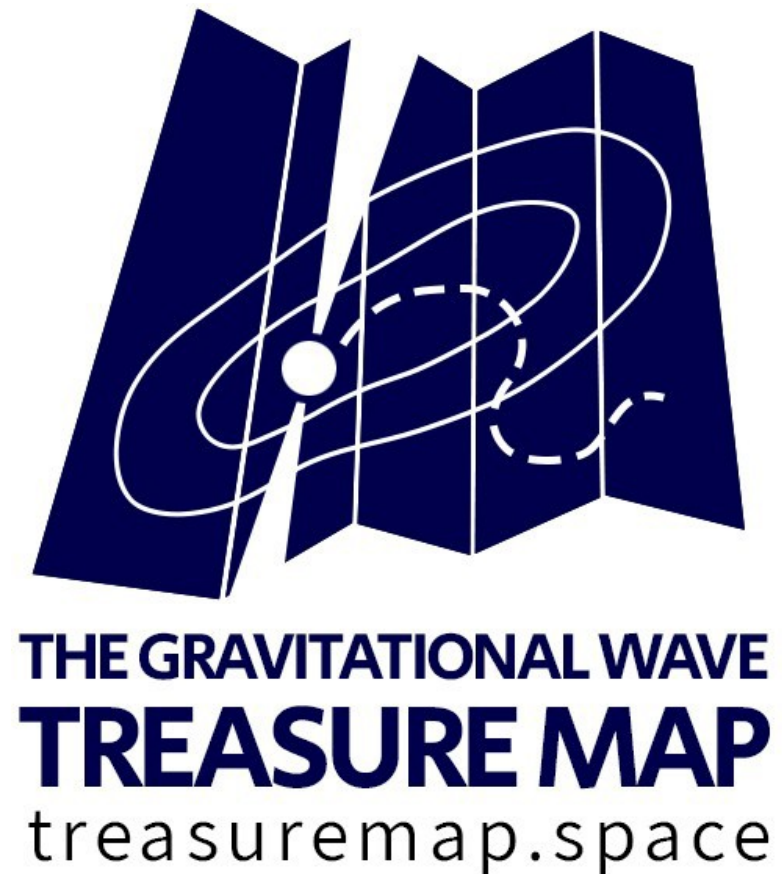


Treasure Map & Treasure TROVE

Infrastructure for Multi-messenger Astronomy



**TROVE: Tool for Rapid Object Vetting
and Examination**

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



Advanced LIGO + Virgo



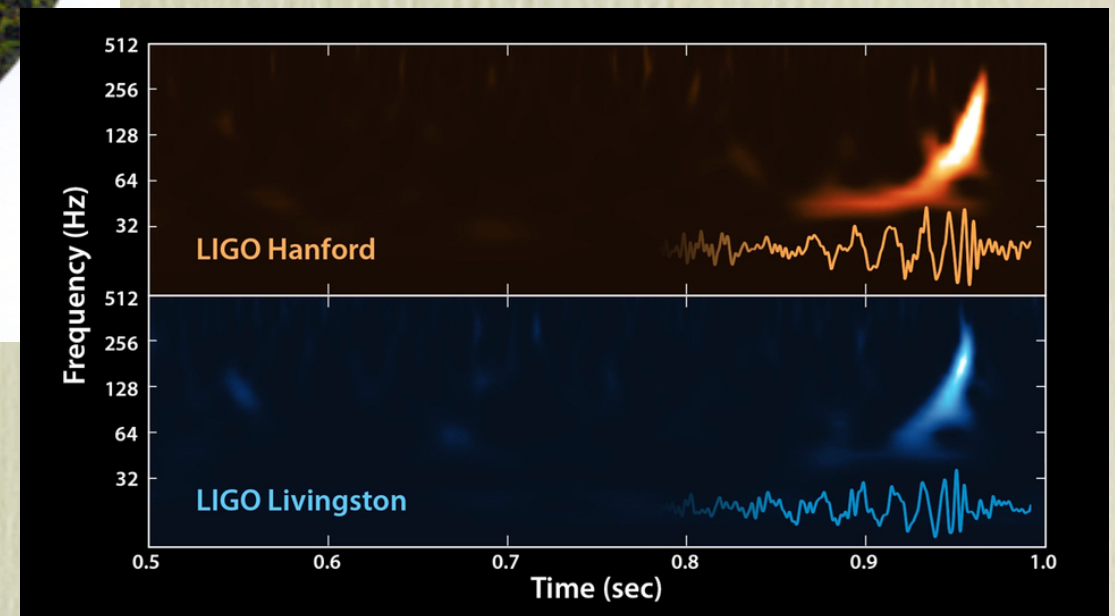
Hanford, Washington



Livingston, Louisiana

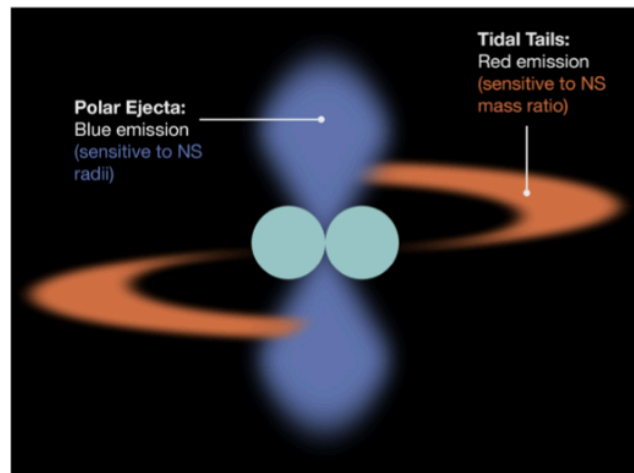


Near Pisa, Italy



GW Counterparts are faint and fast

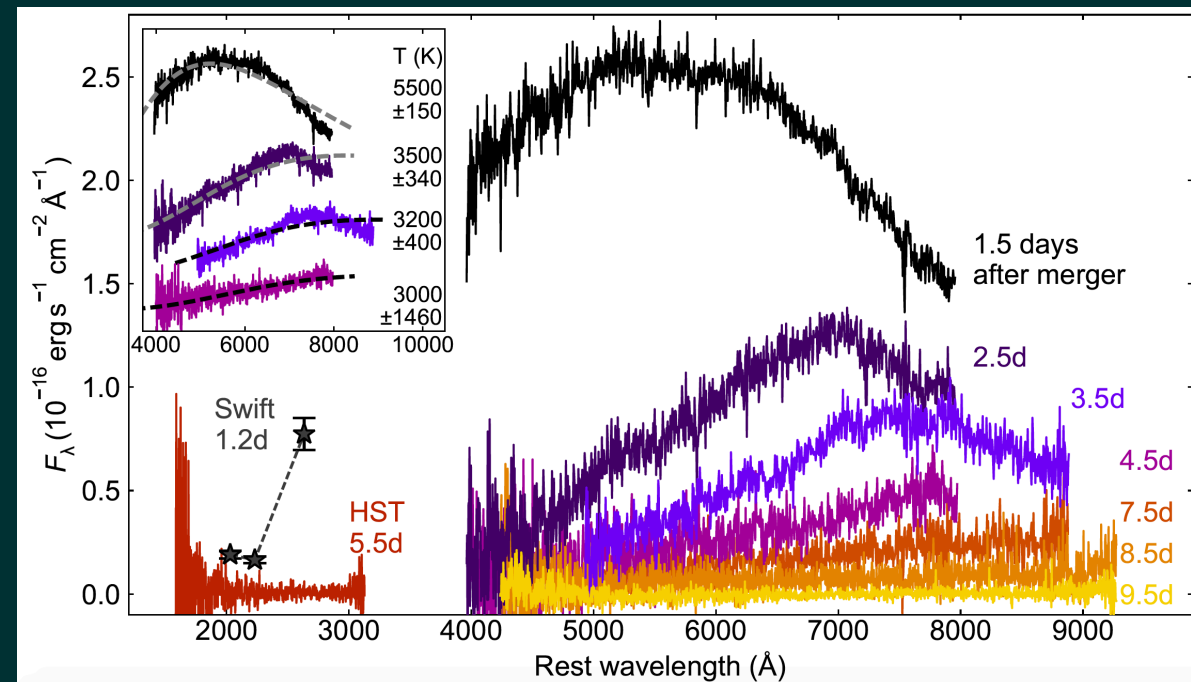
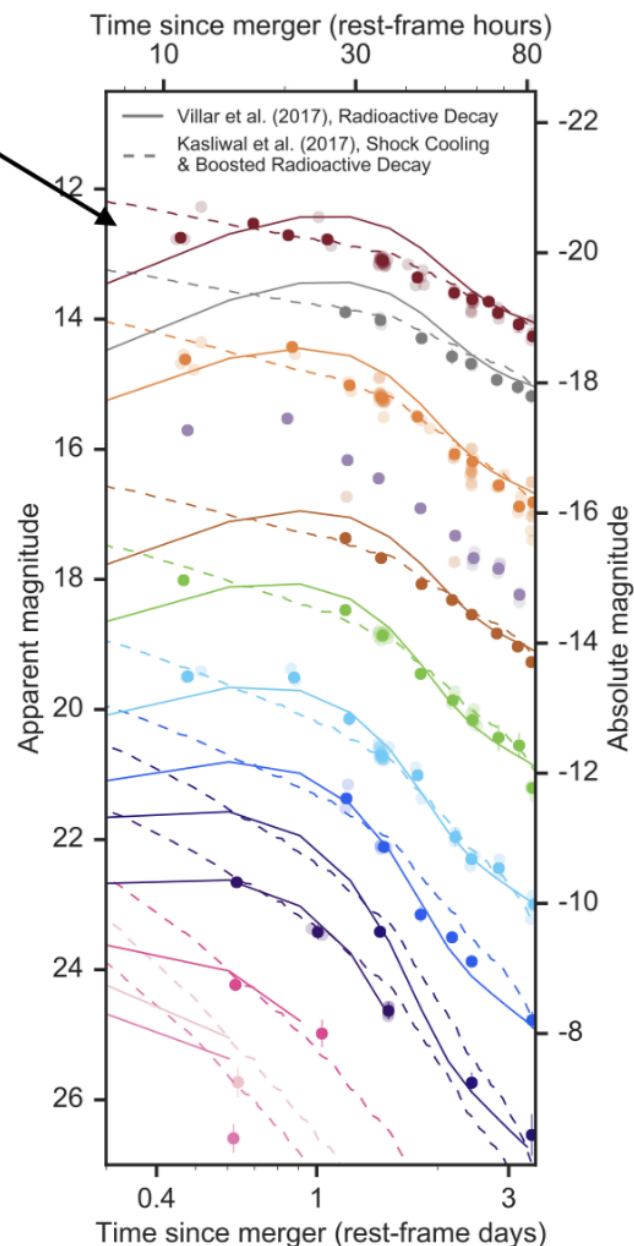
Early data can distinguish models.



Possible kilonova emission mechanisms

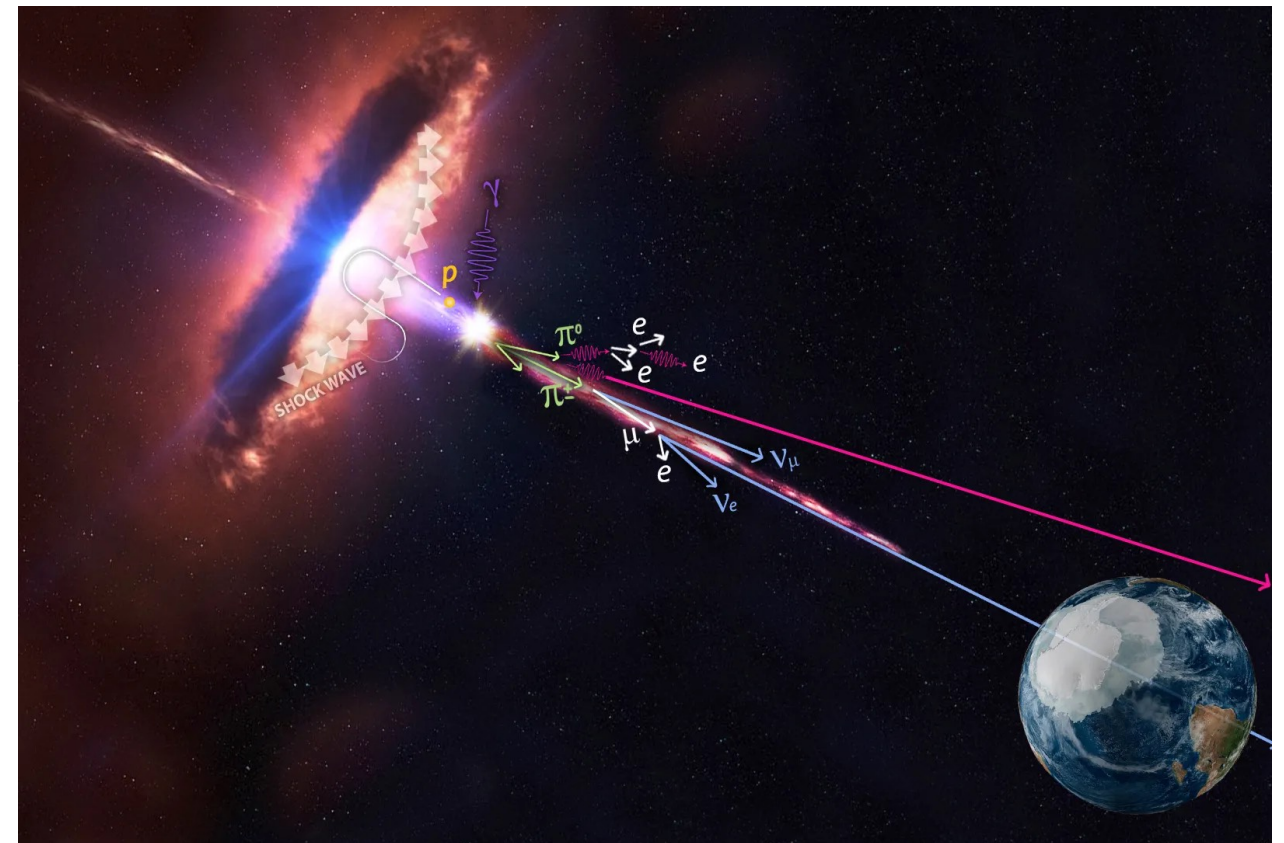
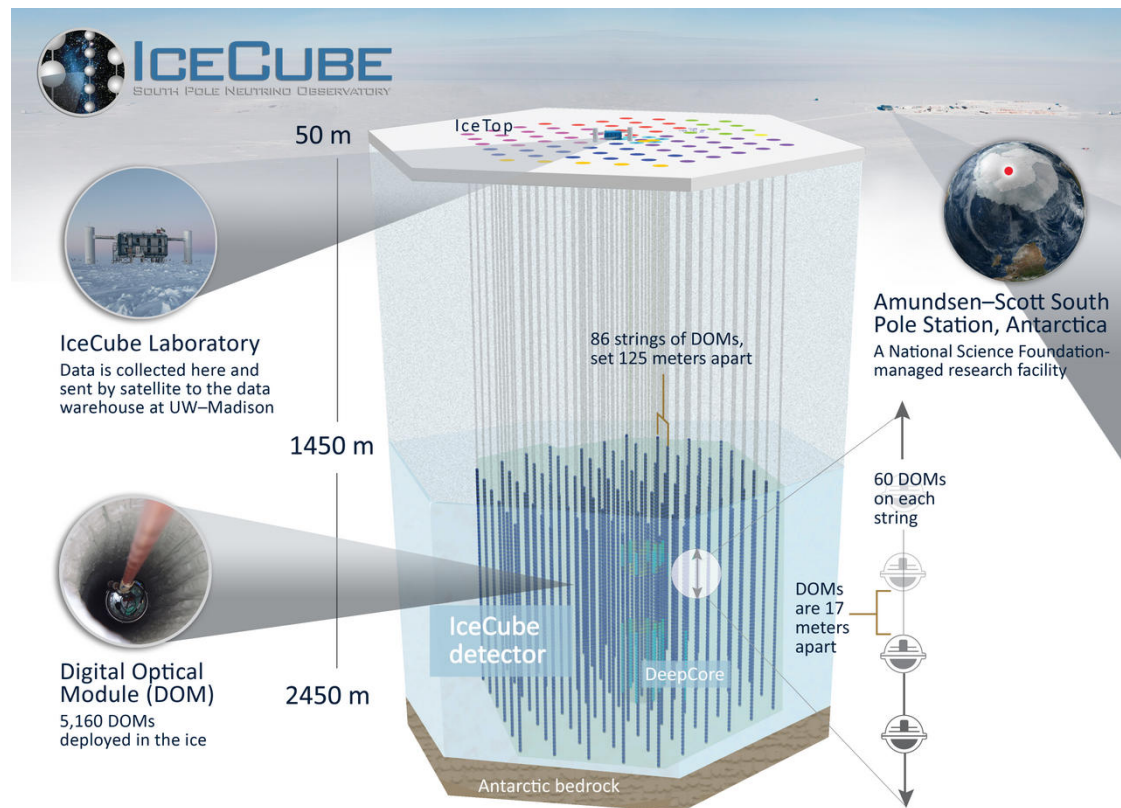


Tidal Tails:
Red emission
(sensitive to NS mass ratio)



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

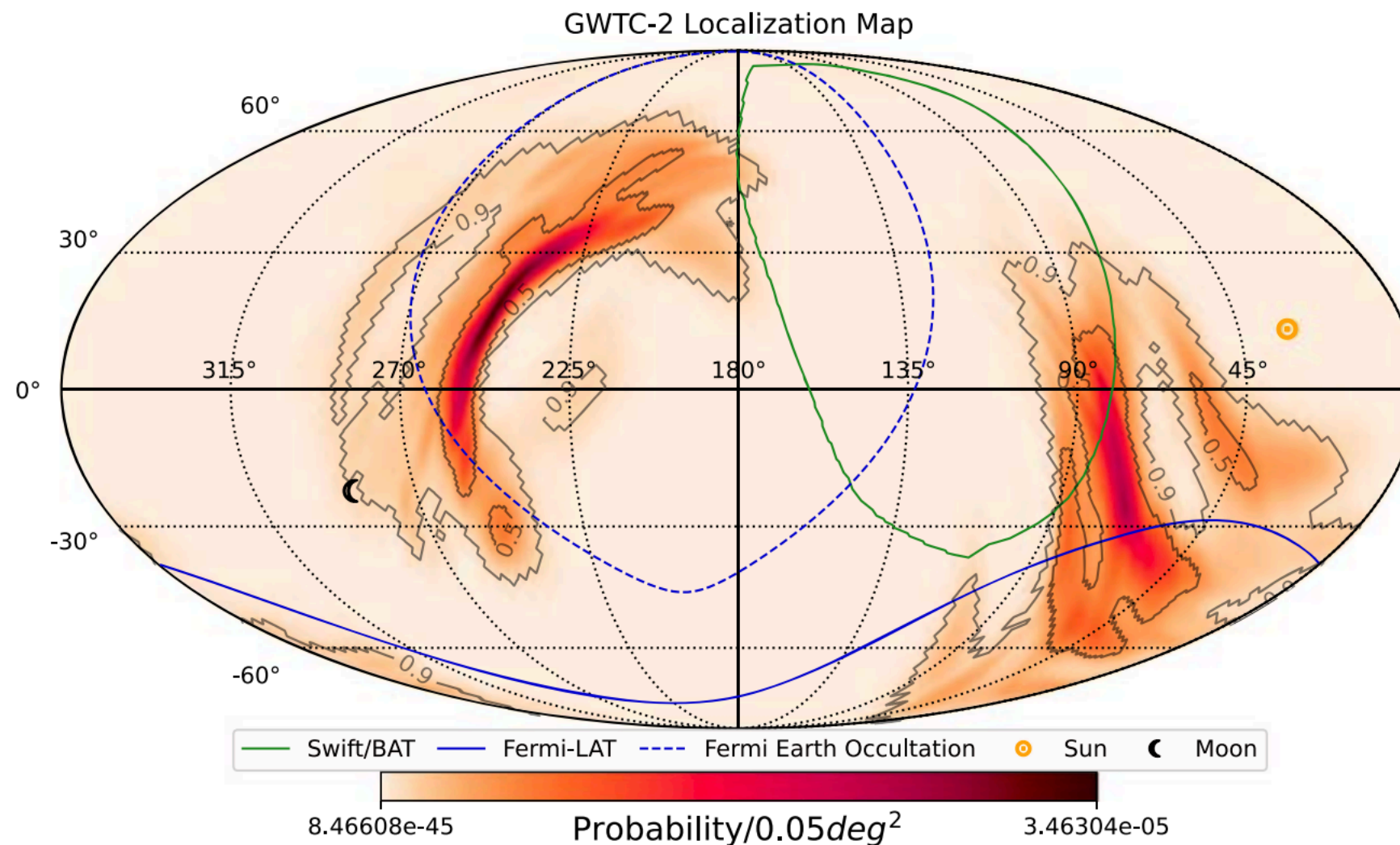
Neutrinos



- 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

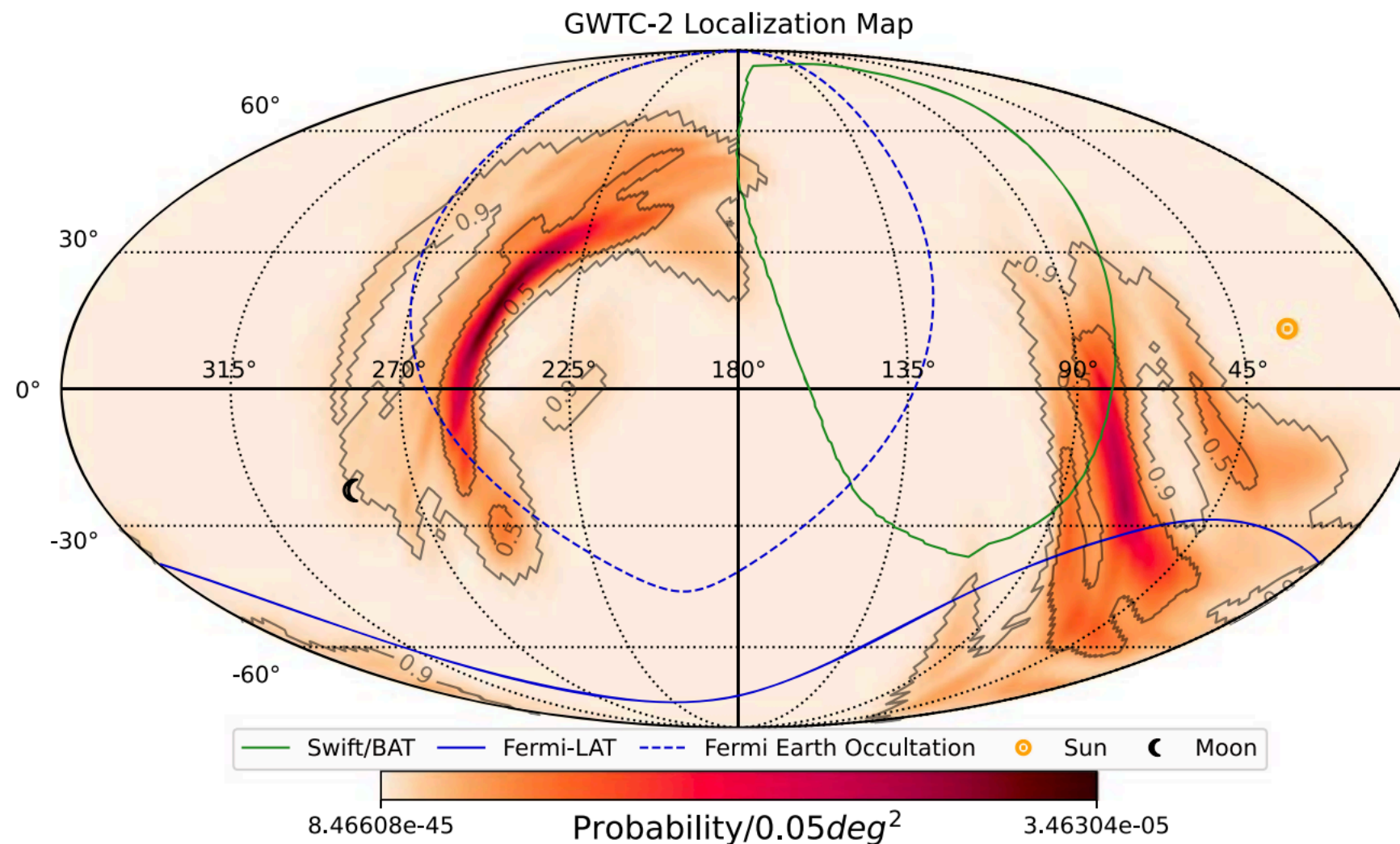
1. Large Localizations



- GW190425: BNS with 90% localization of $\sim 8900 \text{ deg}^2$. $D=160 \text{ Mpc}$.

Non-localized Events: Many Observational Challenges

1. Large Localizations, 'Every man for himself'

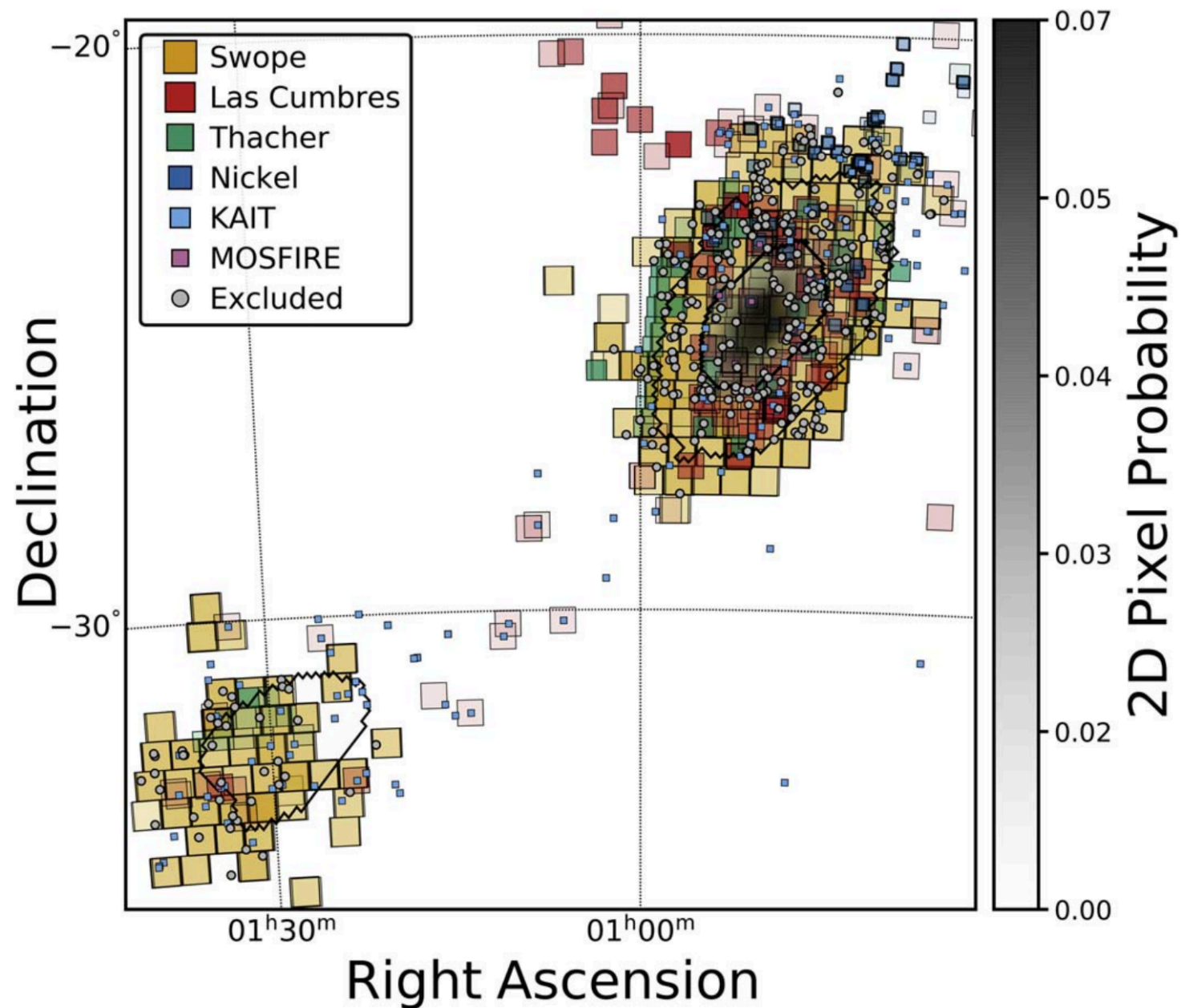


- GW190425: BNS with 90% localization of ~ 8900 deg². $D=160$ Mpc.

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

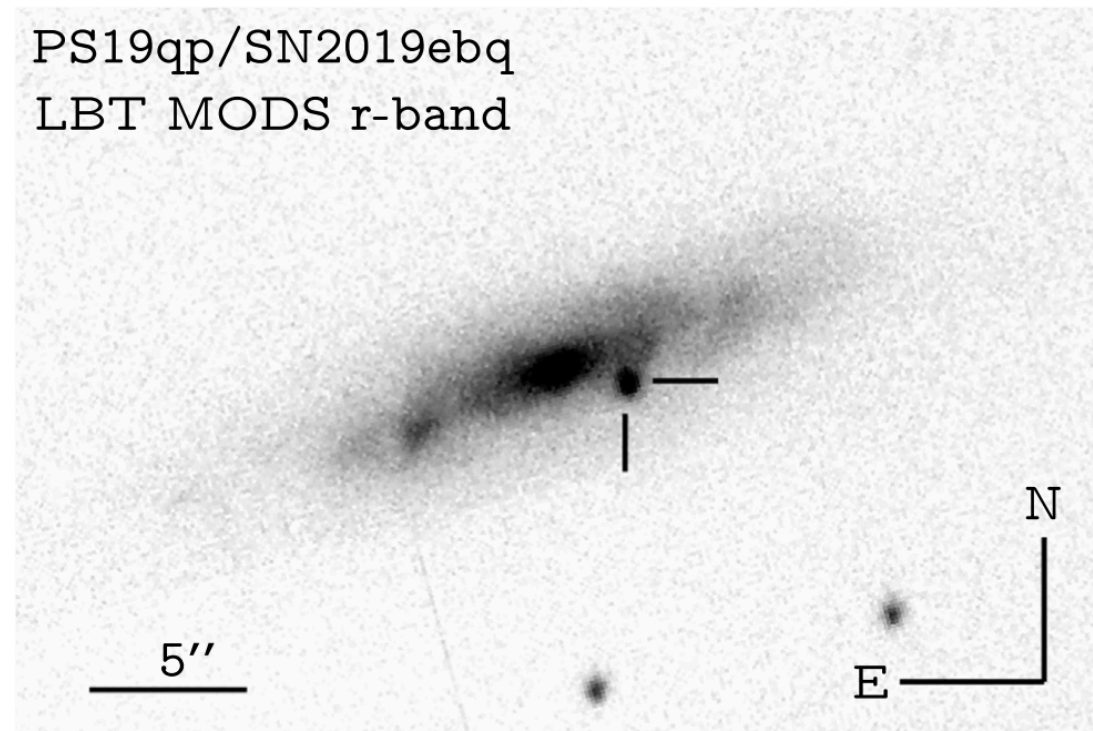
2. Many potential candidates



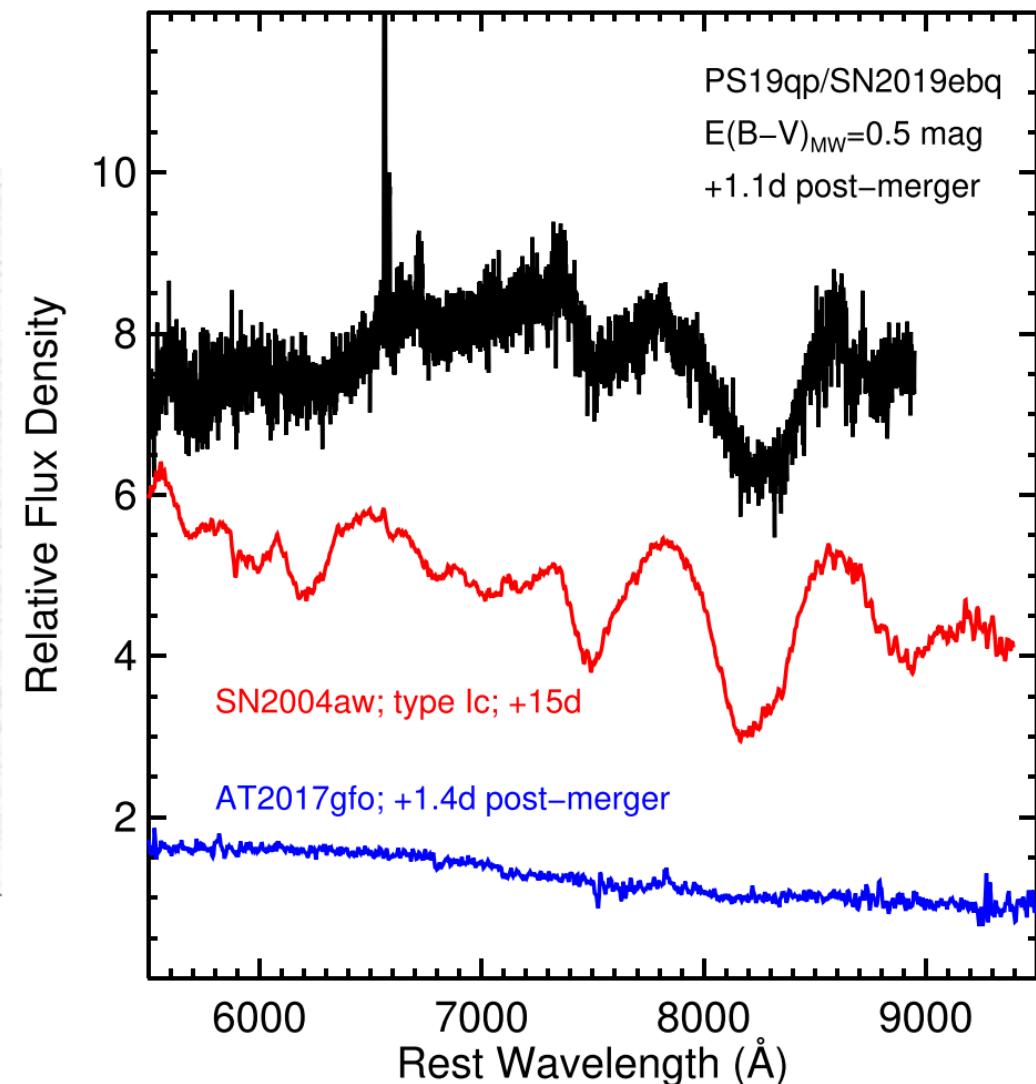
- GW190814: NSBH merger. 51 deg² localization. 189 transients in that localization (e.g. Kilpatrick+21).

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

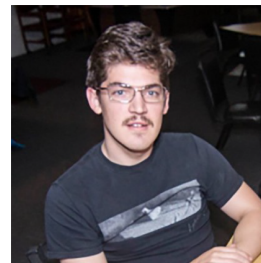
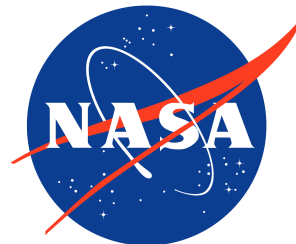
Andy Howell

Curtis McCully

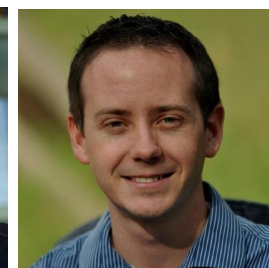
Moirra Andrews

Joseph Farah

Kathrryn Wynn



UNIVERSITY OF
TORONTO



Motivations

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

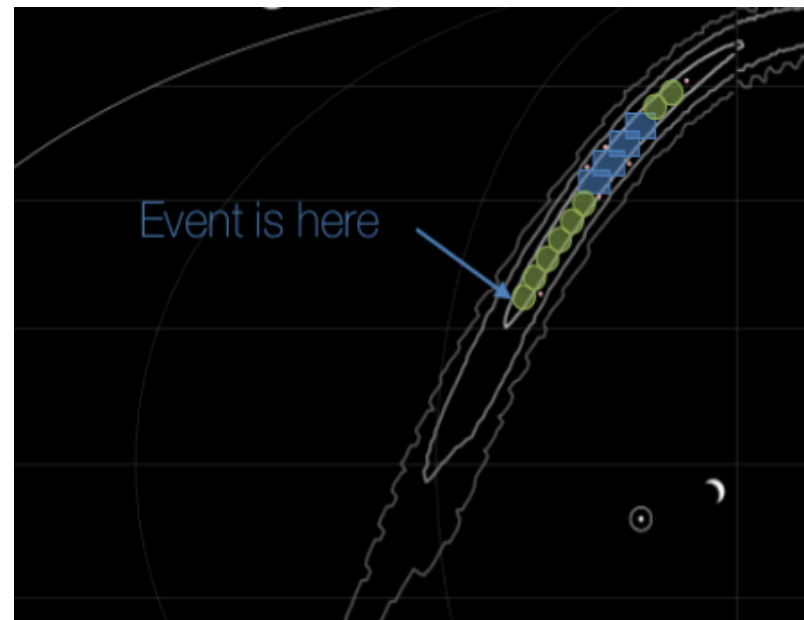
Discovery is key



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



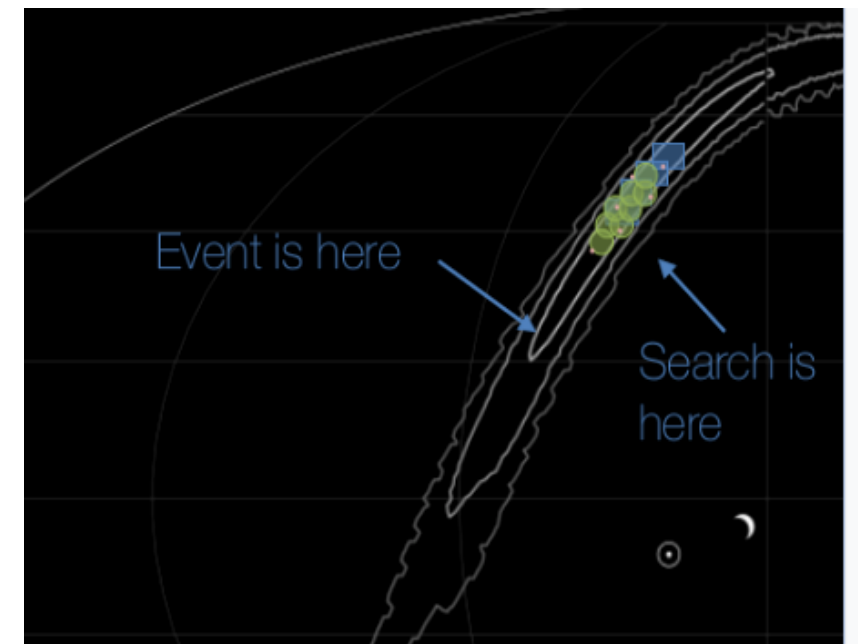
← This



vs.



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!)

TM Home GW Events Query Pages Submit Pages Documentation Profile Logout

If you are using our API, you must update your base URL to 'https'.

Gravitational Wave Treasure Map

Welcome! The Treasure Map is designed to help coordinate electromagnetic followup of gravitational-wave (GW) events. It allows observers to easily report their planned and executed observations in search of counterparts to GW events, and to query the reports of other observers, in a programatic way. The goal is to enable coordination between observatories in order to minimize unnecessary overlap in these searches, and find the counterpart as quickly and as efficiently as possible.

Please [register](#) for an account, so that you can programatically query the Treasure Map. For more details on how to use the Treasure Map see our [User Guide](#).

Please direct any general inquiries to [Iair Arcavi](#). If you use the Treasure Map in your research, please cite the [Treasure Map paper](#) in addition to the circulars and/or papers of the teams whose pointing information you use.

Visualization

- Visualize GW alert contours
- Submit your follow-up pointings
- Collaborate with the counterpart search community
- Analyze follow-up

Explore all GW alerts [here](#)

Images from [GW190814](#)

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.

Event Candidates

GET Candidates

POST Candidates

REST API METHOD: POST Instructions

Posting transient Candidates that are potentially affiliated with a GW event.

Usage

`/api/v1/candidate`

Notes

This endpoint is for posting a candidate (or list of candidates) that coincides with a GW event.

JSON Parameters

- `api_token=api_token1`
- `graceid=graceid1`
- `candidates=candidates_list`

Valid candidate class parameters

***parameters required unless otherwise specified as (optional)**

- `position`: two acceptable formats
 - geometry type: **POINT(RA DEC)**
 - simply pass two json fields that are **RA** and **DEC** which must be **decimal**

Example 1

Python Example

```
import requests

BASE = "https://treasuremap.space/api/v1"
TARGET = "candidate"
API_TOKEN = "-your-verified-account-api-token-"

json_data = {
    "api_token": "API_TOKEN",
    "graceid": "graceid1",
    "candidates": [
        {
            "ra": 24.0,
            "dec": 48.0,
            "candidate_name": "AT2021fxy",
            "tns_name": "AT2021fxy",
            "tns_url": "https://www.wis-tns.org/object",
            "discovery_date": "2021-03-17T17:23:37.000",
            "discovery_magnitude": 18.0,
            "magnitude_unit": "ab_mag",
            "magnitude_bandpass": "r"
        }
    ]
}
```



GW Treasure Map



Gravitational Wave Localization and Pointings: GW190426_152155 [GraceDB]

Preliminary	Initial	Update	Update 1	Update 2
2019-04-26 15:47:06	2019-04-26 15:53:09	2019-04-26 16:28:42	2019-04-27 11:52:26	2019-04-27 11:08:09



Visualization:

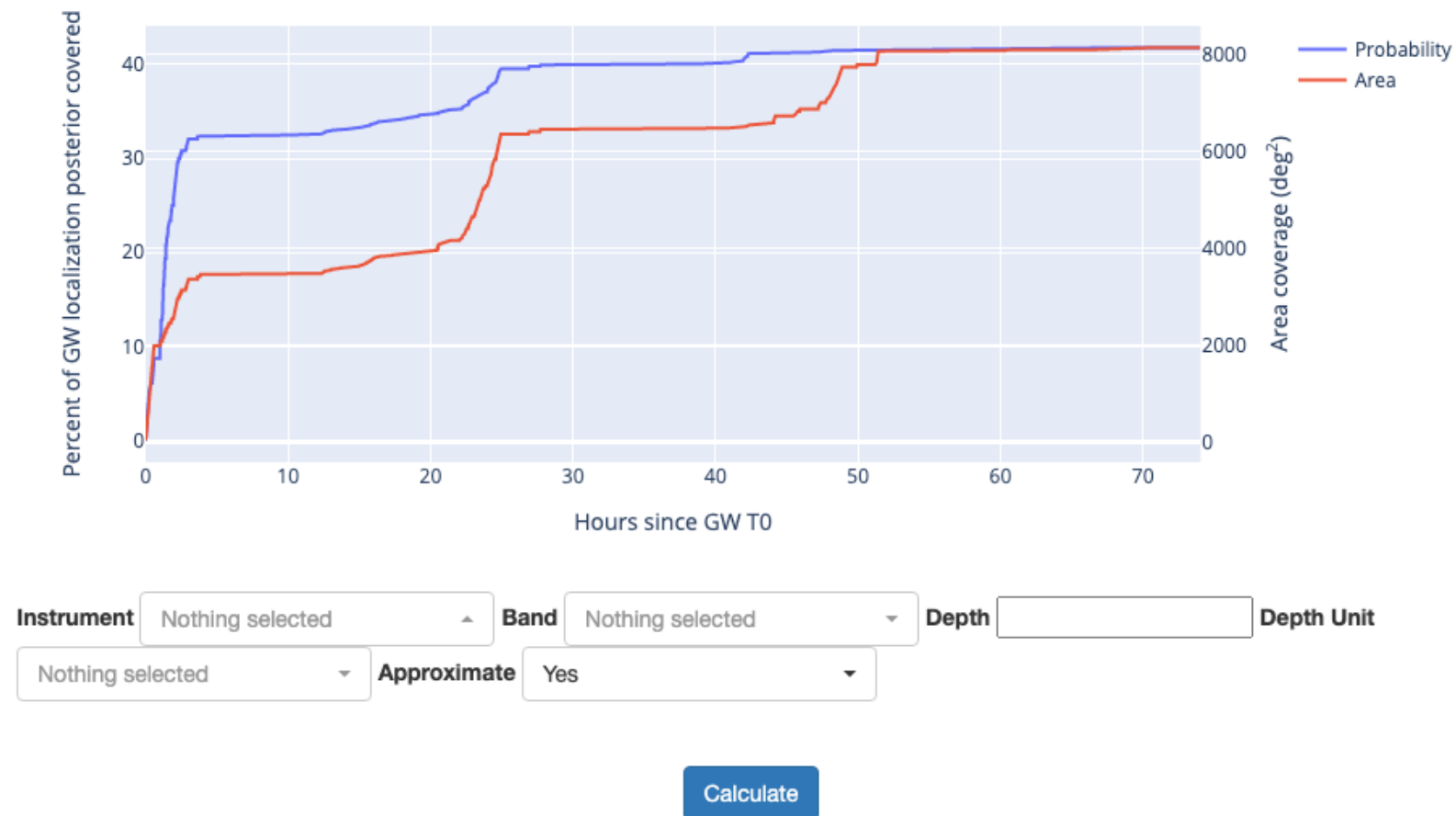
- Interactive ALADIN
 - (BIL, Color Maps, Scroll, Zoom)
- Toggle 90/50 contours and instrument footprints
- Filter pointings
 - (date, range, completed, planned, etc)
- (Someday) Overlay source info:
 - Convolved Galaxies
 - Icecube Nu Track alerts
 - Candidates

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

zenodo

Manage record

Published April 29, 2024 | Version v2

Dataset

Open

Submitted Completed pointings to the Gravitational Wave Treasure Map for event S240422ed

Iair Arcavi¹; D. Andrew Howell²; Curtis McCully³; Craig Pellegrino²;
Giacomo Terreran²; Megan Newsome²; Joseph Farah²;
Estefania Padilla Gonzalez²; Moira Andrews²; Ido Keinan¹

Show affiliations

Attached in a .json file is the completed pointing information for 306 observation(s) for the EM counterpart search associated with the gravitational wave event S240422ed. These observations were taken on the Sinistro, and MuSCAT instruments.

Files

completed_pointings_S240422ed.json

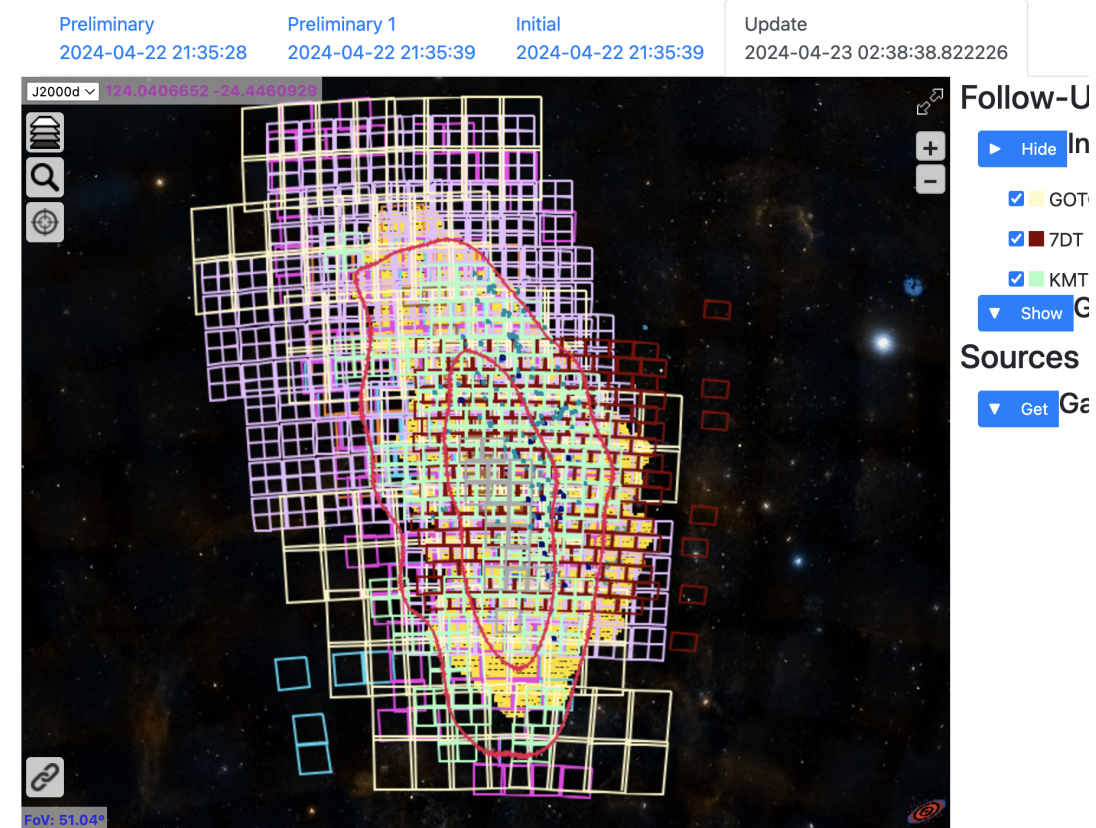
```
[
  {
    "id": 43454,
    "status": "completed",
    "position": "POINT (124.485756666667 -16.2356622222222)",
    "galaxy_catalog": ""
  }
]
```

GW Treasure Map

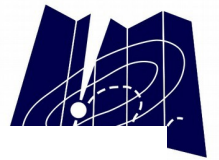


- S240422ed (an interesting 04 event, but probably not real)
 - ~2200 completed pointings, up to ~5days after t0.
 - ~70% prob covered within first 6 hours of event at a depth of 20.5mag
 - ~90% covered within first 24hr for all pointings.
- These pointings were submitted in near real-time

Gravitational Wave Localization and Pointings: S240422ed [[GraceDB](#)]



GW Treasure Map



WAVE
IAP
space

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

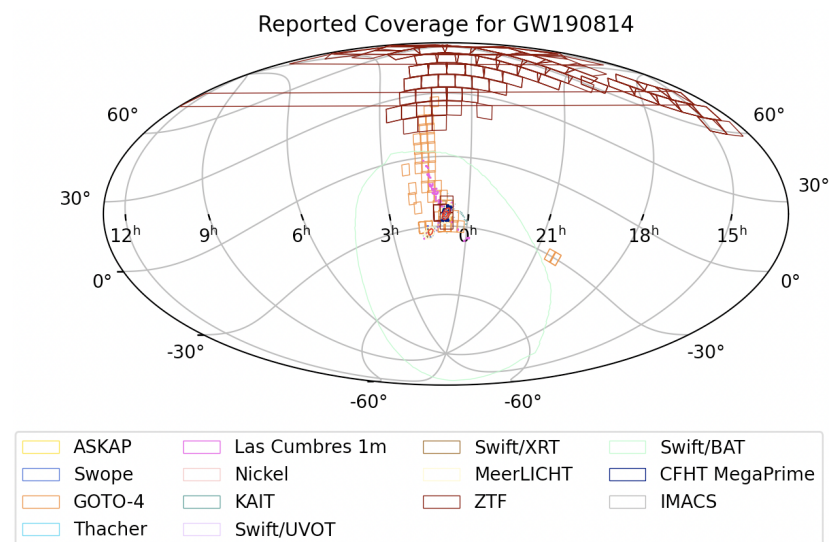
Event Tools

For a given GW event, you can utilize 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
 - **04 observations are being reported in ~real-time!**
- Any Questions?

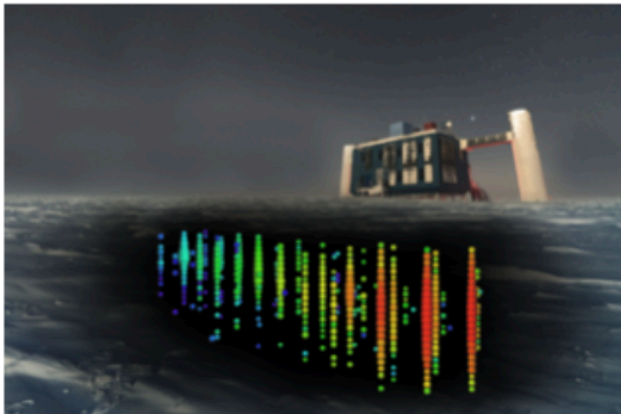


TROVE: Tool for Rapid Object Vetting and Examination

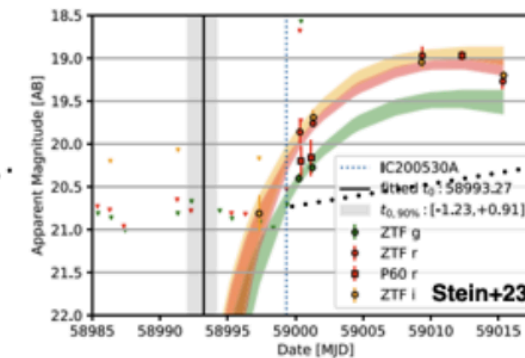
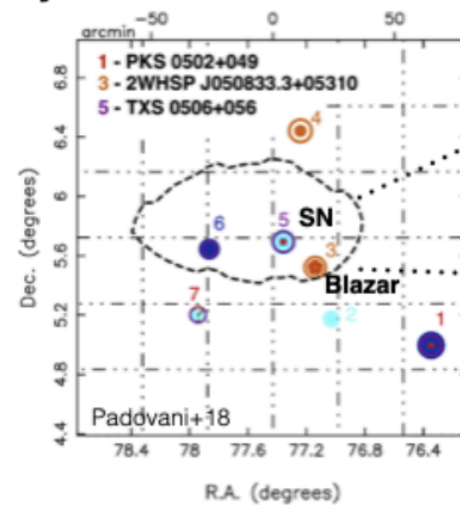


Neutrino Candidate Follow-up & Vetting

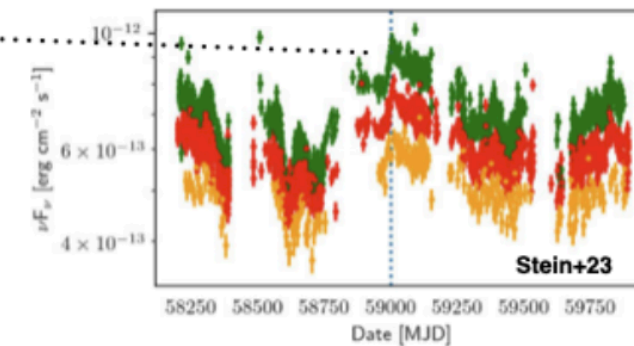
Neutrino Alert and Localization



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



-Normal SN
-Detection Prior to Neutrino
↳ Low Score



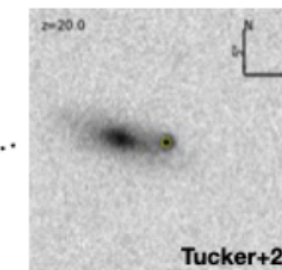
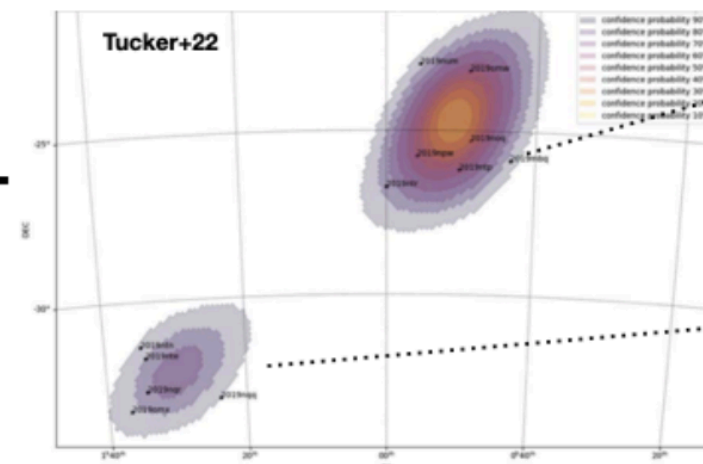
-Blazar Light Curve Before/After Neutrino
-Flaring at Time of Neutrino
↳ High Score

GW Candidate Follow-up & Vetting

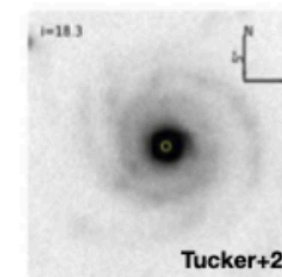
GW Alert and Localization



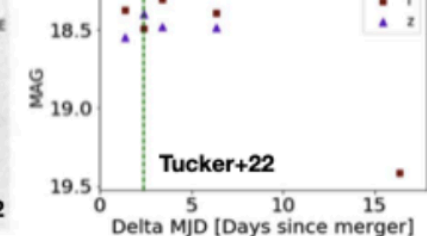
Many Viable Transients Within Localization



-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



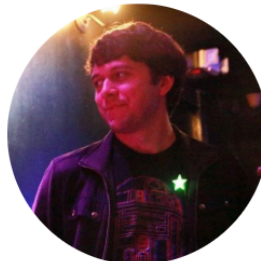
Phil Daly
University of Arizona



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



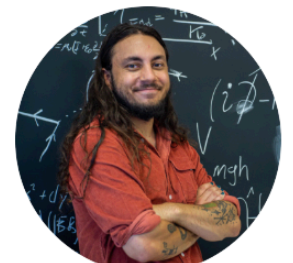
David Sand
University of Arizona



Manisha Shrestha
University of Arizona



Bhagya Subrayan
University of Arizona



Nicholas Vieira
Northwestern University

**+ Phillip Noel
(Here today!)**

TROVE: Tool for Rapid Object Vetting and Examination



Kate Alexander
University of Arizona



Azalee Bostroem
University of Arizona



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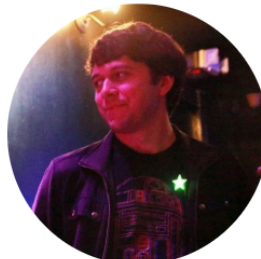
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**Noah Franz
U of Arizona**

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University of Arizona



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University of Arizona



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University of Arizona



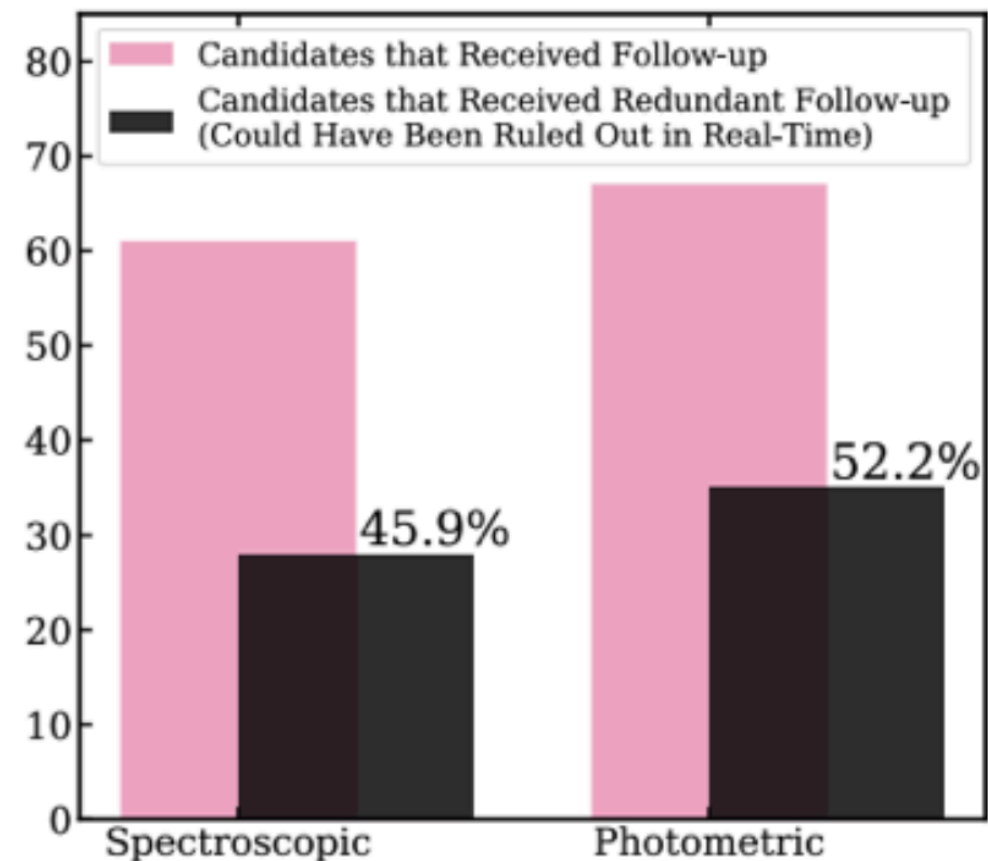
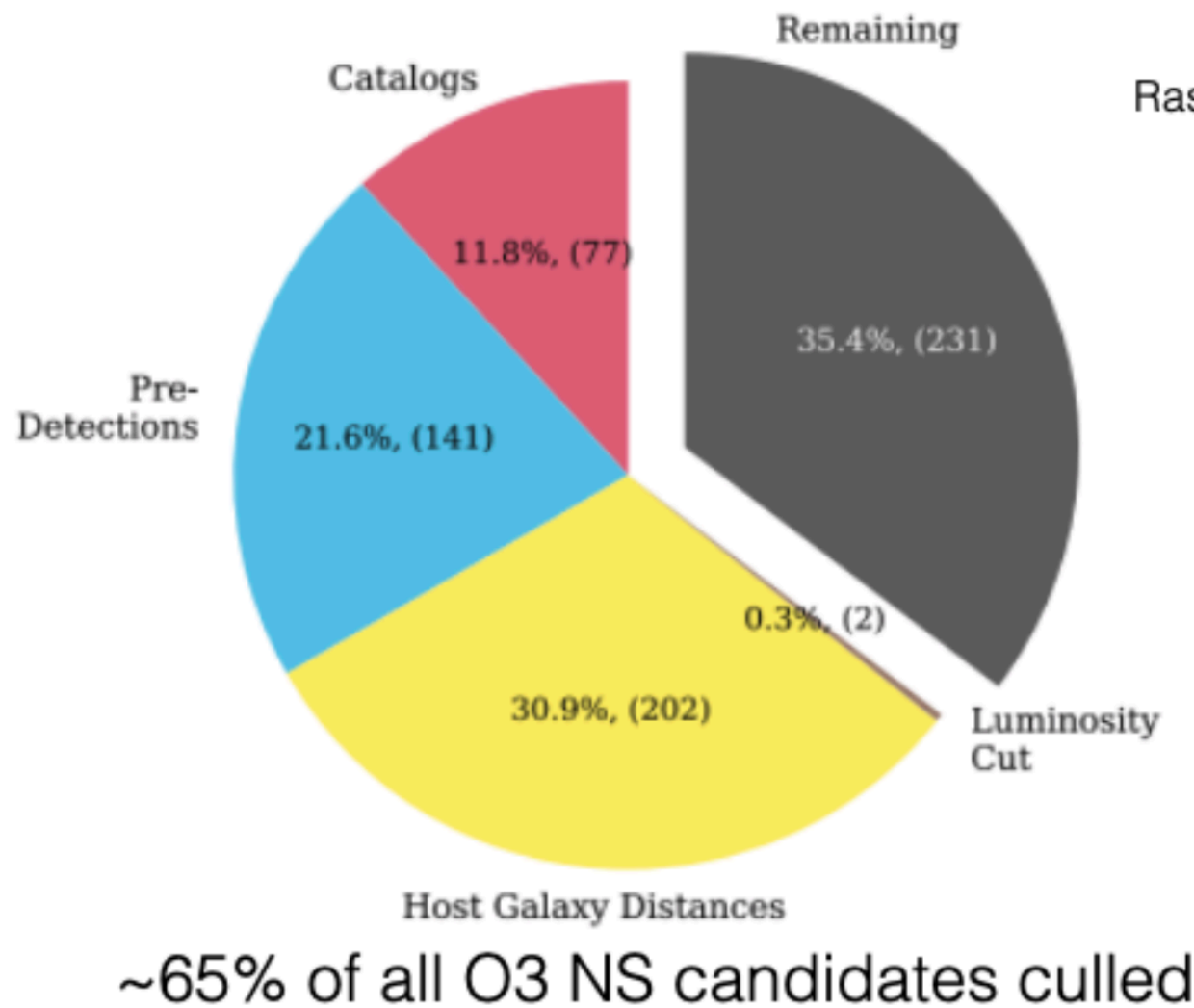
Bhagya Subrayan
University of Arizona



Nicholas Vieira
Northwestern University

TROVE: The Problem

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

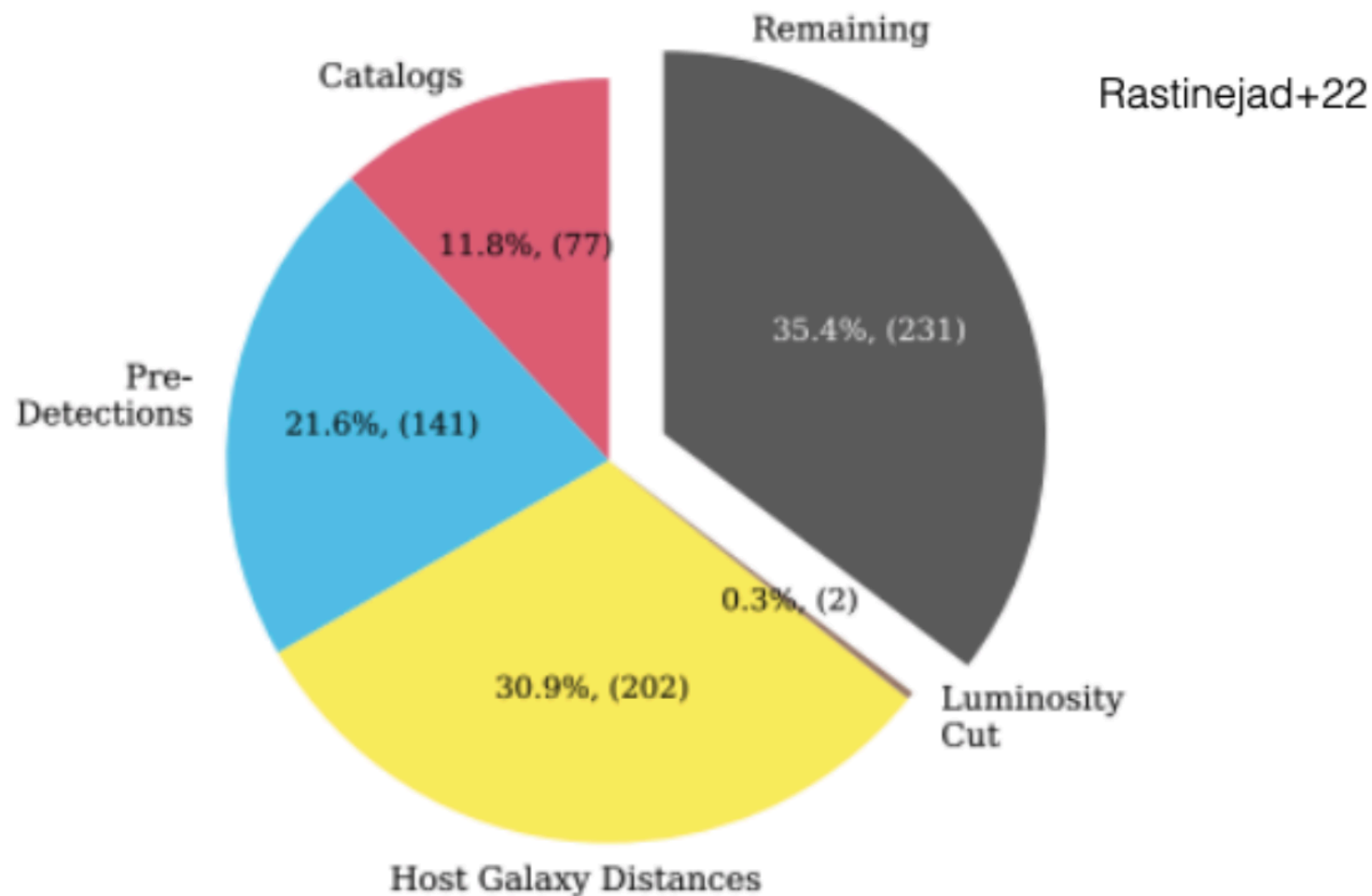


~50% of all candidates that received follow-up did not need it

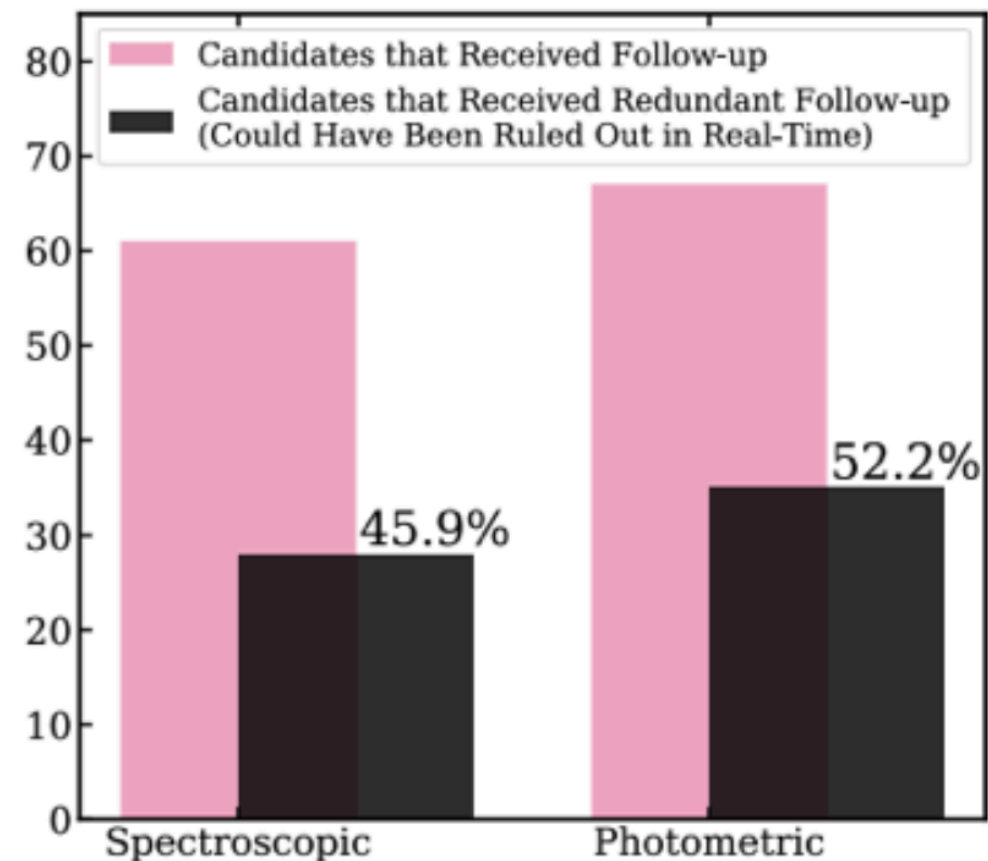
Real-time vetting of transient would greatly reduce the number of viable counterpart candidates. Rastinejad+22.

TROVE: The Problem

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



~65% of all O3 NS candidates culled



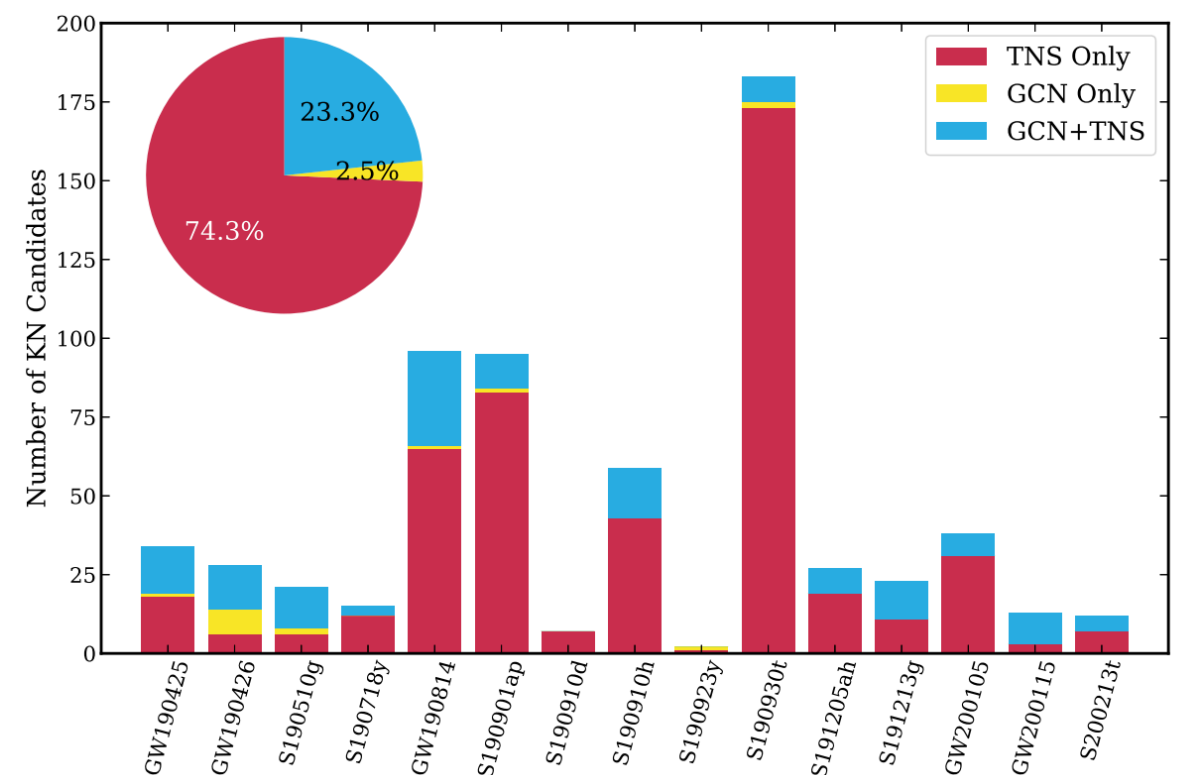
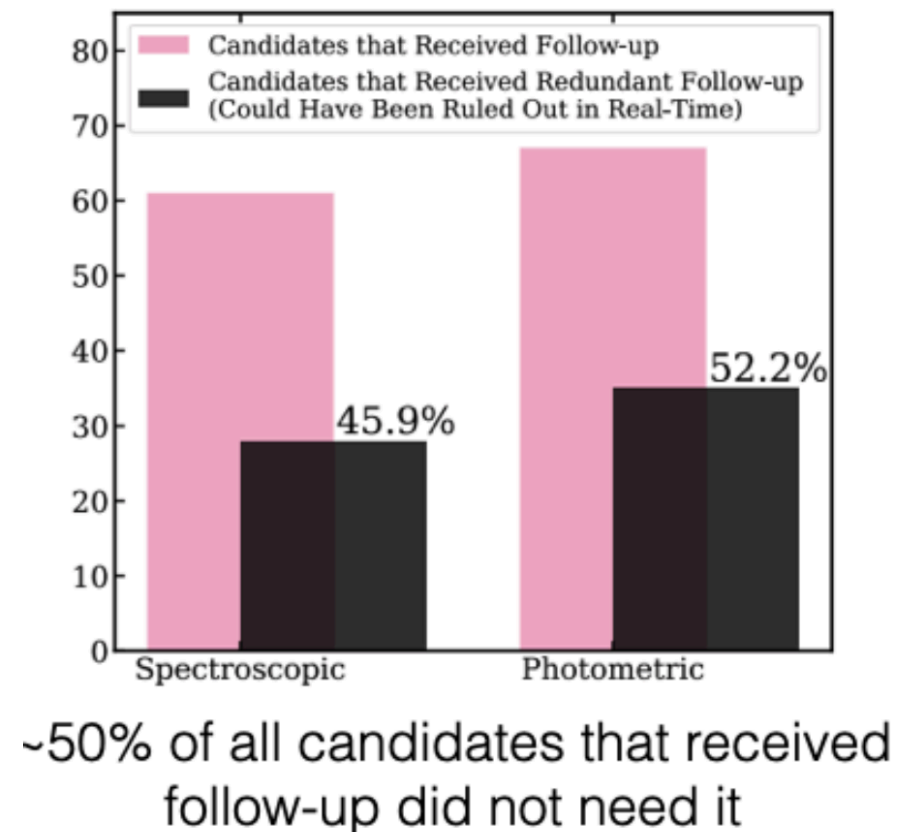
~50% of all candidates that received follow-up did not need it

One goal of the TROVE is to make these vetting resources easy to access in order to level the playing field in MMA. 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.

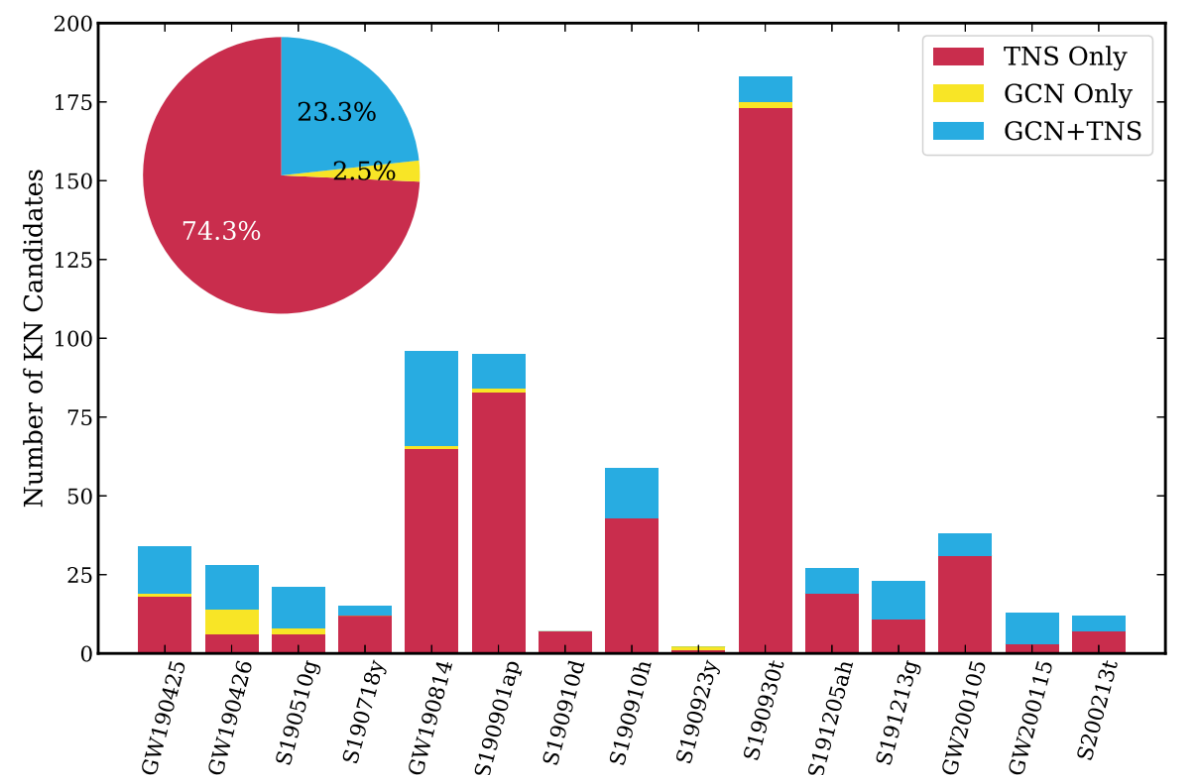
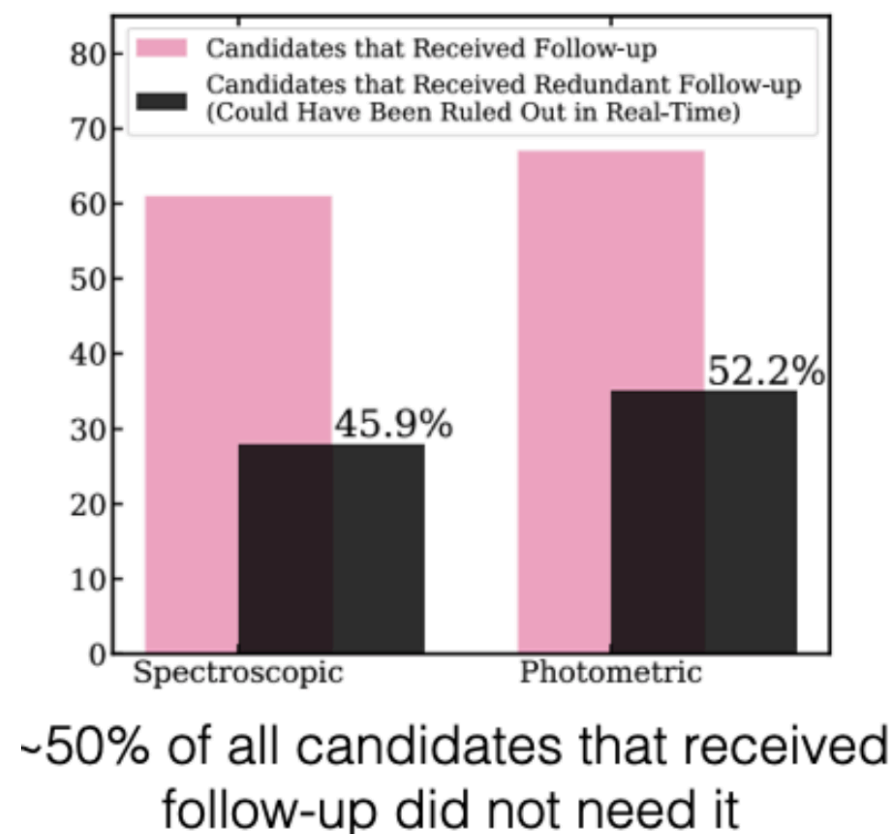
- In any localization for GWs of $\sim 10+$ deg² there will inevitably be 10-100s of transients in the localization, but only one can be the counterpart.
- In the end, you **must** get a spectrum or imaging of your candidate to verify that it is associated with the GW.
- Telescope resources are precious, and we tend to all dive in and get a spectrum of the same object. And often that object is a waste of time.



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...



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

run kilonova vetting tools

AT2023ixg

There are 0 observations with unknown status

Classify Update Vet Delete

Names AT2023ixg S230518h

Coords. 07:48:24.101 -70:35:58.78
117.100421 -70.599661

Galactic 282.766996 -20.938750

Ecliptic 214.469162 -79.423264

Classification
Redshift nan

Catalog Crossmatching

QSO Match None
ASASSN Match None
Gaia Match None
PS1 match None

Recent Photometry

Time	Mag.	Abs. Mag.
2023-10-04 08:10:32	>18.23	-18.82
2023-10-03 02:10:28	>18.32	-18.72
2023-09-30 01:09:43	>17.65	-19.39

Comments

No comments yet

Comment

Comment

Post

tabbed interface

Candidates Host Galaxies Photometry Spectroscopy Observe
Observations Manage Data Manage Groups Facility Status

Get ATLAS phot. Check for new data

linked to GW event

point-source matches

possible host galaxies

Host Galaxies with Lowest Probability of Chance Coincidence

ID	Name	P_{cc}	Off. (")	Dist. (Mpc)	Redshift	Mag. (AB)	Source
1	wiseJ074823.52-703557.8	0.001	3.01	256.3 ± nan	nan ± nan	B = 17.0	GLADE
2	wiseJ074820.58-703614.3	0.261	23.40	560.1 ± nan	nan ± nan	B = 19.7	GLADE

Comments

No comments yet

Comment

Comment

Post

Survey View

J2000 07 48 24.101 -70 35 58.78

10 arcsec

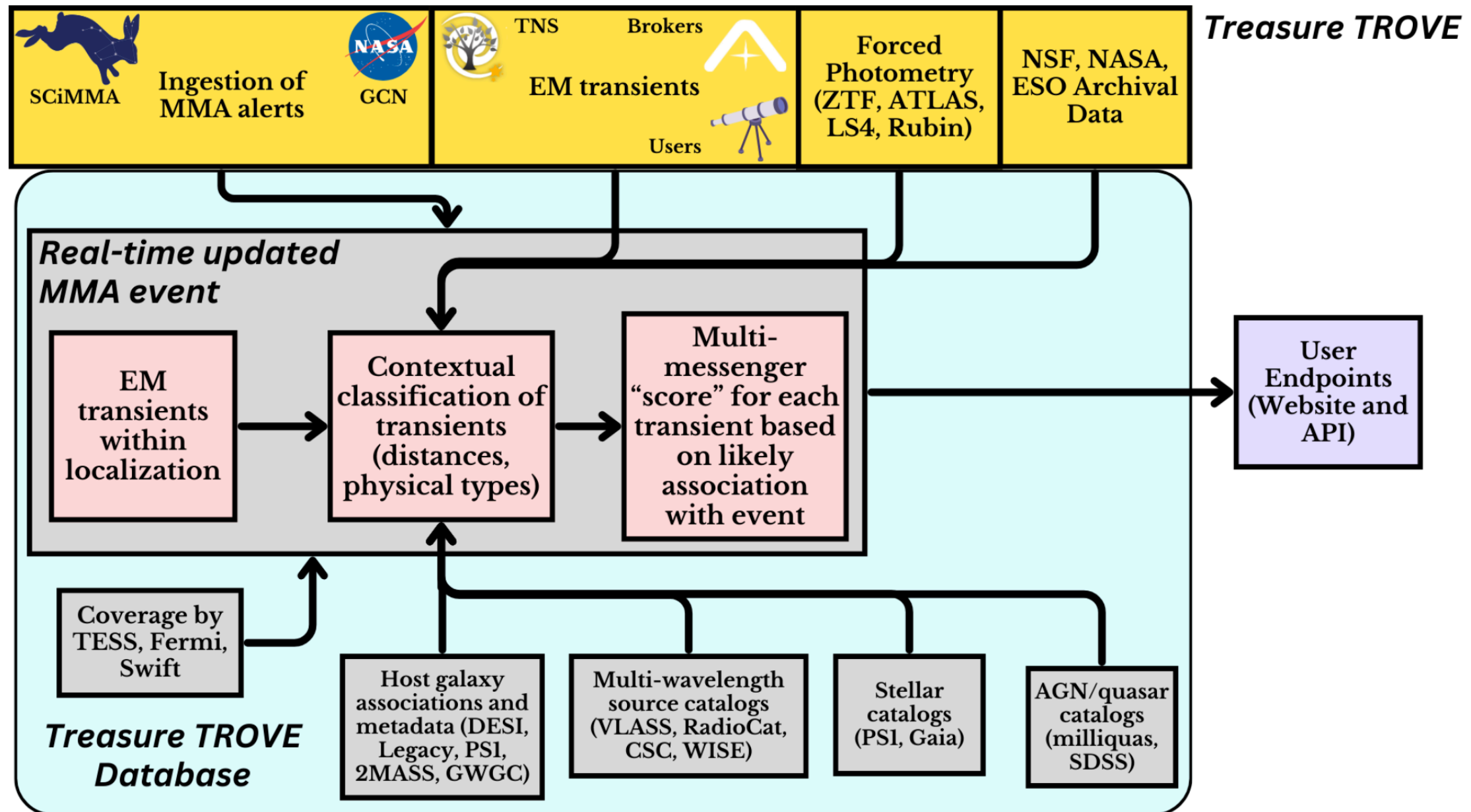
FoV: 1.99'

Field of view 2 arcmin

Scale bar 10 arcsec

Update Save Image

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)

[illegible]




TROVE

GW

Neutrino

GRB

Counterparts



AT 2019gfo

11:46:44.83 +27:24:49.9

Aliases:

PS19avg

Candidate for:

S240413p

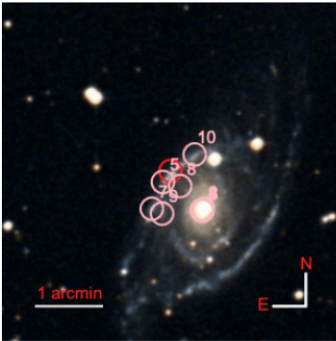
Point Source Matches:

None

Source:

C.B Arthur (U. Arkansas)

Survey View

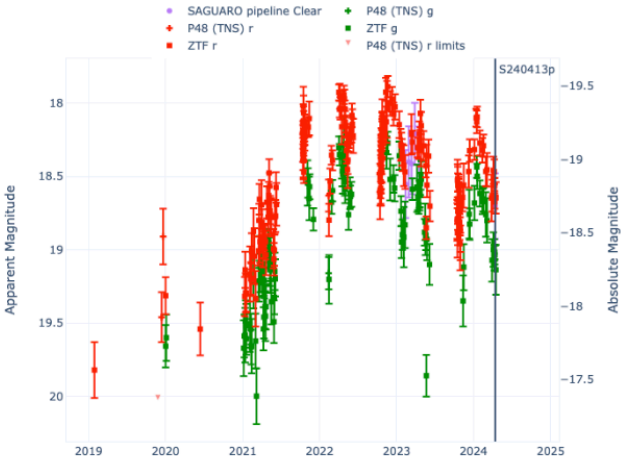


Possible Host Galaxies

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

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

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: 4.89×10^{41} erg/s

Time of Maximum Light Curve: 26.76 days

Light Curve Slope (positive is brightening): 3.01 mag/day

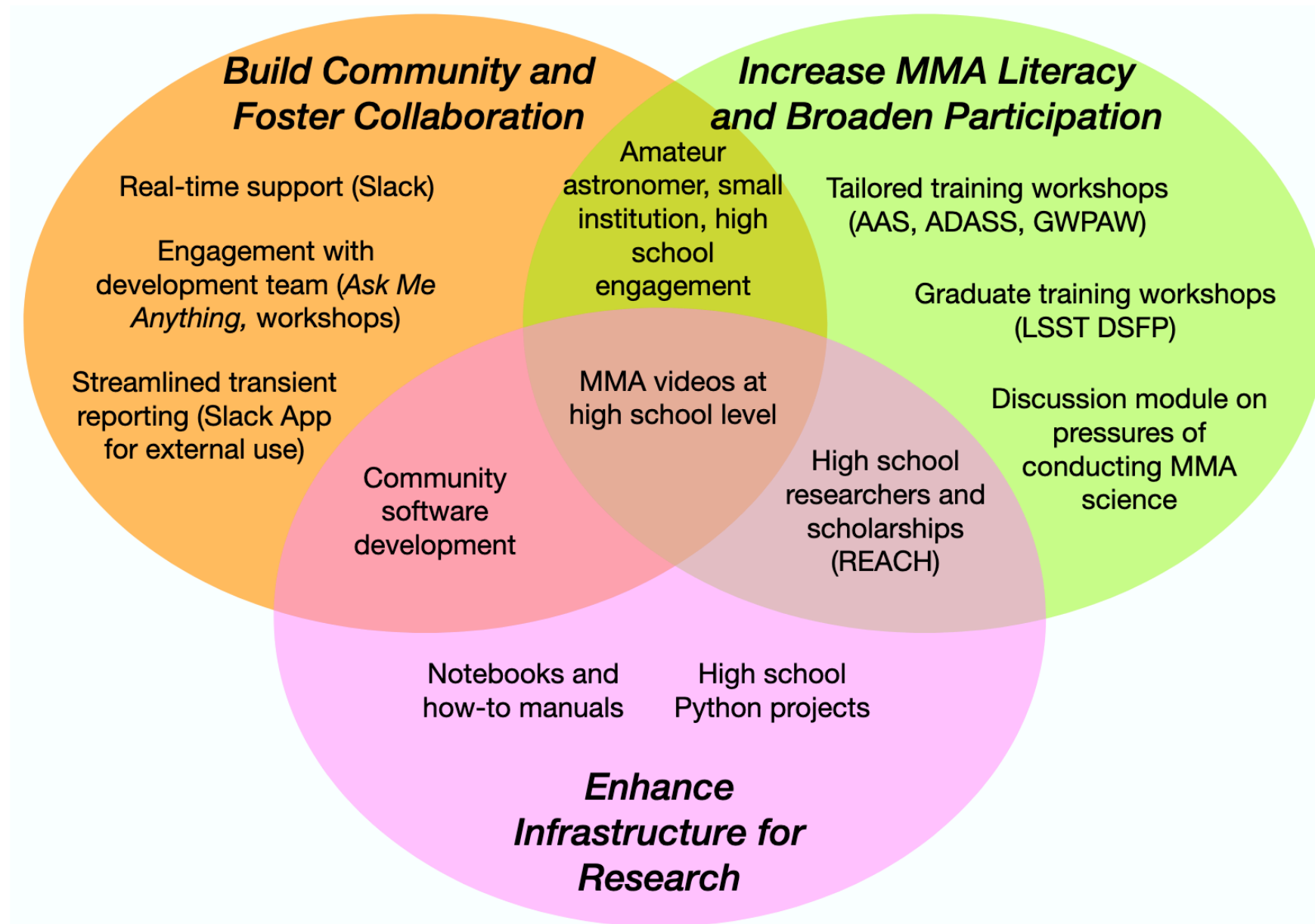
► [Host Galaxies](#)

▼ [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.

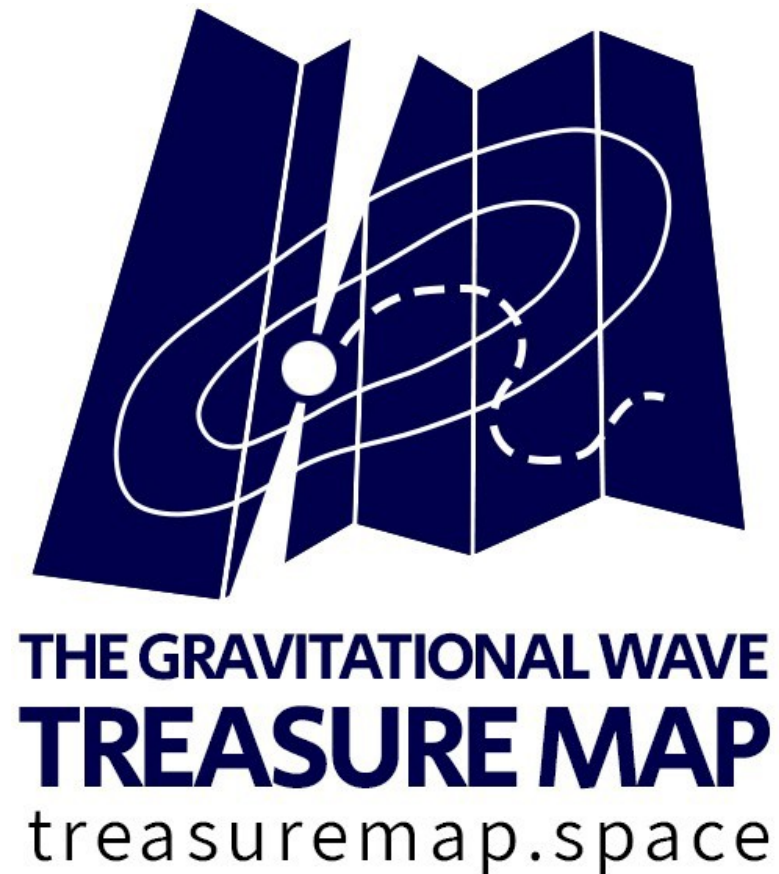
TROVE Broader Impacts



- 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



**TROVE: Tool for Rapid Object Vetting
and Examination**

Thank you!!

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