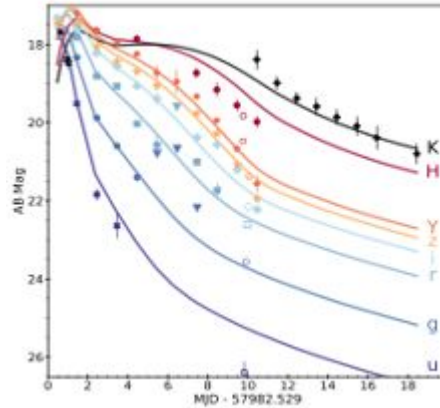
The background of the slide is a vibrant blue watercolor wash, with darker tones on the left and lighter, more translucent washes on the right. The texture is organic and fluid, resembling ink or paint on paper. In the top left corner, there is a small, solid blue rectangular mark.

Computing hurdles in wide-field target-of-opportunity searches with ZTF and Rubin

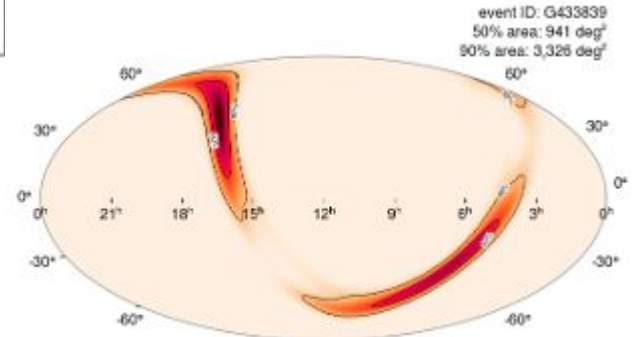
Shreya Anand

LSST-DA Catalyst Fellow - Stanford University
HTC26: MMA Computing Challenges
Tuesday, June 9, 2026

Challenges in conducting EM counterpart searches



FAINT, FAST, and RED!



DECam $g < 24$

ZTF $g < 20.5$

DES,
2.5 deg²



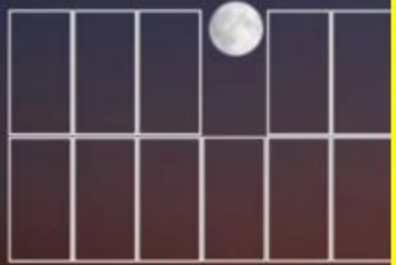
PS1, 7 deg²



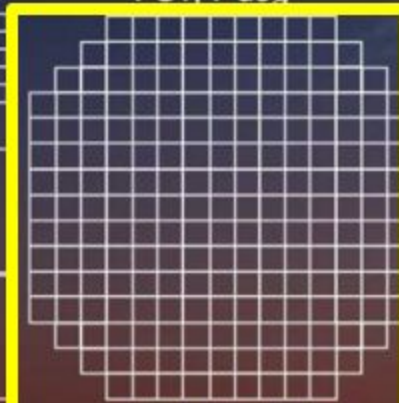
SDSS,
3 deg²



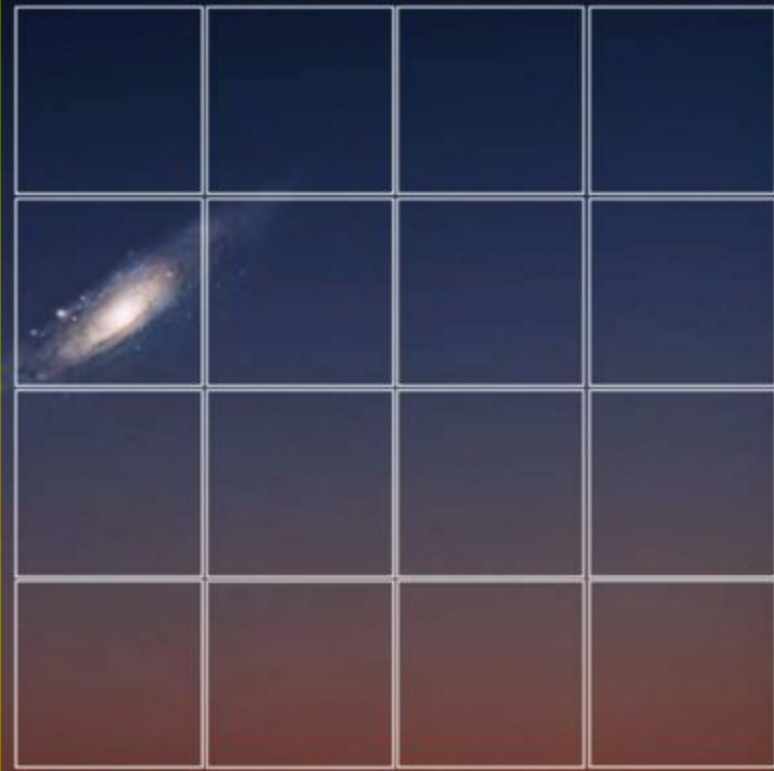
PTF/IPTF, 7.3 deg²



LSST, 9.6 deg²



ZTF, 47 deg²

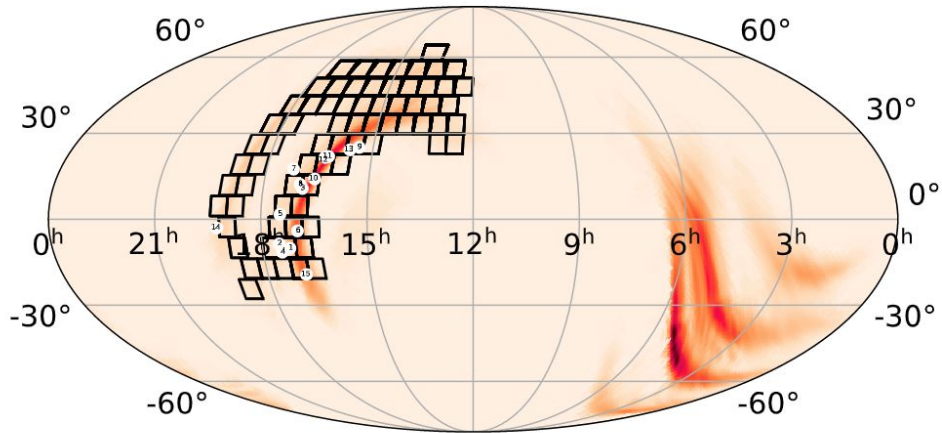


Modified from Laher+17

LSST $g < 25$

1 deg

GW scheduling algorithms

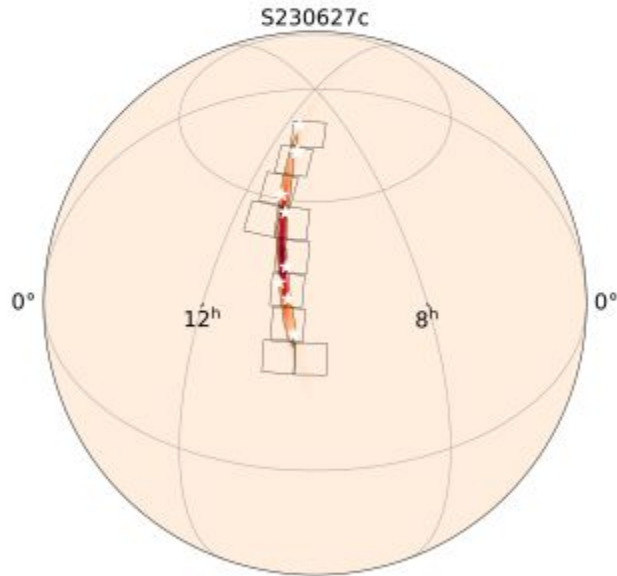


- Complex optimization problem involving:
 - Probability within skymap
 - Observable fields
 - Moon distance
 - Airmass

Initial transient filtering

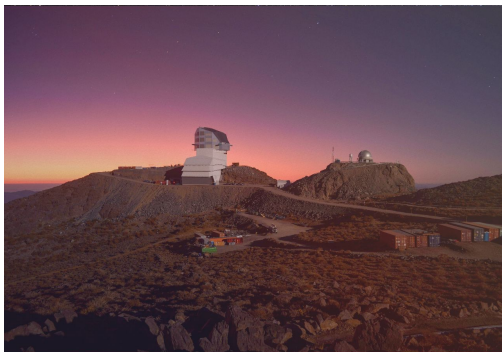


Kilonova filtering



- Inconsistent distance - comparing host redshift to GW distance
- Old - temporally coincident with GW
- Red - photometric color evolution
- Slow - photometric evolution rate
- Rock - asteroid-like
- Stellar - within 2 arcsec of a star; variability
- AGN - WISE colors of host galaxy; variability
- Bogus - image artifact
- Spectrum - inconsistent spectroscopic classification

Rubin ToO 2024 workshop report



Rubin ToO 2024: Envisioning the Vera C. Rubin Observatory LSST Target of Opportunity program

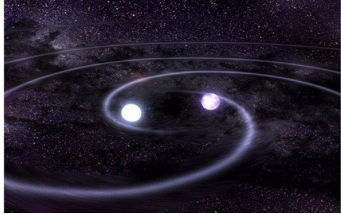
Igor Andreoni, Raffaella Margutti, John Banovetz, Sarah Greenstreet, Claire-Alice Hebert, Tim Lister, Antonella Palmese, Silvia Piranomonte, S. J. Smartt, Graham P. Smith, Robert Stein, Tomas Ahumada, Shreya Anand, Katie Auchetti, Michele T. Bannister, Eric C. Bellm, Joshua S. Bloom, Bryce T. Bolin, Clecio R. Bom, Daniel Brethauer, Melissa J. Brucker, David A.H. Buckley, Poonam Chandra, Ryan Chornock, Eric Christensen, Jeff Cooke, Alessandra Corsi, Michael W. Coughlin, Bolivia Cuevas-Otahola, D'Ammando Filippo, Biwei Dai, S. Dhawan, Alexei V. Filippenko, Ryan J. Foley, Anna Franckowiak, Andreja Gomboc, Benjamin P. Gompertz, Leanne P. Guy, Nandini Hazra, Christopher Hernandez, Griffin Hossainzadeh, Maryam Hussaini, Dina Ibrahimzade, Luca Izzo, R. Lynne Jones, Yijung Kang, Mansi M. Kasliwal, Matthew Knight, Keerthi Kunnumkai, Gavin P Lamb, Natalie LeBaron, Cassandra Lejoly, Andrew J. Levan, Sean MacBride, Franco Mallia, Alex I. Malz, Adam A. Miller, J. C. Mora, Gautham Narayan, Nayana A.J., Matt Nicholl, Tiffany Nichols, S. R. Oates, Akshay Panayada, Fabio Ragosta, Tiago Ribeiro, Dan Ryczanowski, Nikhil Sarin, Megan E. Schwamb, Hueli Sears, Darryl Z. Seligman, Ritwik Sharma, Manisha Shrestha, Simran, Michael C. Stroh, Giacomo Terzeran, Aishwarya Linesh Thakur, Aum Trivedi, J. Anthony Tyson, Yousuke Utsumi, Aprajita Verma, V. Ashley Villar, Kathryn Volk, Meet J. Vyas, Amanda R. Wasserman, J. Craig Wheeler, Peter Yoachim, Angela Zegarelli, Federica Bianco

Upto 3% of Rubin's time
available for ToOs!

The Legacy Survey of Space and Time (LSST) at Vera C. Rubin Observatory is planned to begin in the Fall of 2025. The LSST survey cadence has been designed via a community-driven process regulated by the Survey Cadence Optimization Committee (SCOC), which recommended up to 3% of the observing time to carry out Target of Opportunity (ToO) observations. Experts from the scientific community, Rubin Observatory personnel, and members of the SCOC were brought together to deliver a recommendation for the implementation of the ToO program during a workshop held in March 2024. Four main science cases were identified: gravitational wave multi-messenger astronomy, high energy neutrinos, Galactic supernovae, and small potentially hazardous asteroids possible impactors. Additional science cases were identified and briefly addressed in the documents, including lensed or poorly localized gamma-ray bursts and twilight discoveries. Trigger prioritization, automated response, and detailed strategies were discussed for each science case. This document represents the outcome of the Rubin ToO 2024 workshop, with additional contributions from members of the Rubin Science Collaborations. The implementation of the selection criteria and strategies presented in this document has been endorsed in the SCOC Phase 3 Recommendations document (PSTN-056). Although the ToO program is still to be finalized, this document serves as a baseline plan for ToO observations with the Rubin Observatory.

It has since been endorsed by the Survey Cadence Optimization Committee!

Rubin Target-of-Opportunity: Science Drivers

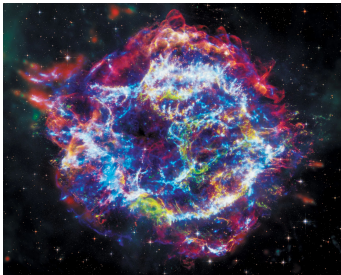


Gravitational Waves

- Binary neutron star mergers
- Neutron star–black hole mergers
- Binary black hole mergers
- Lensed binary neutron star mergers

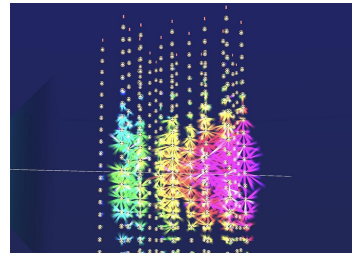


Potentially Hazardous Asteroids



Other rare events

- Galactic supernovae
- Gravitational Wave burst events
- Gravitationally lensed gamma-ray bursts



High energy neutrinos

- Neutron star mergers
- Core-collapse supernovae
- Active Galactic Nuclei
- Tidal disruption events

Rubin ToO workflow

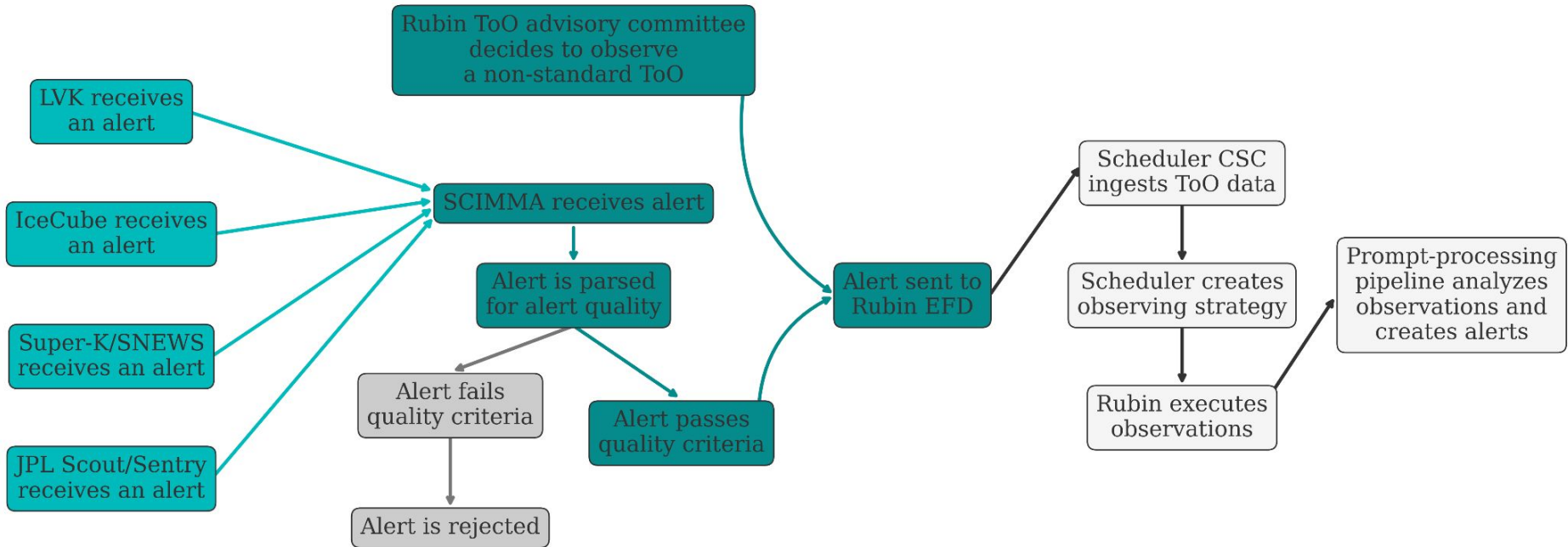
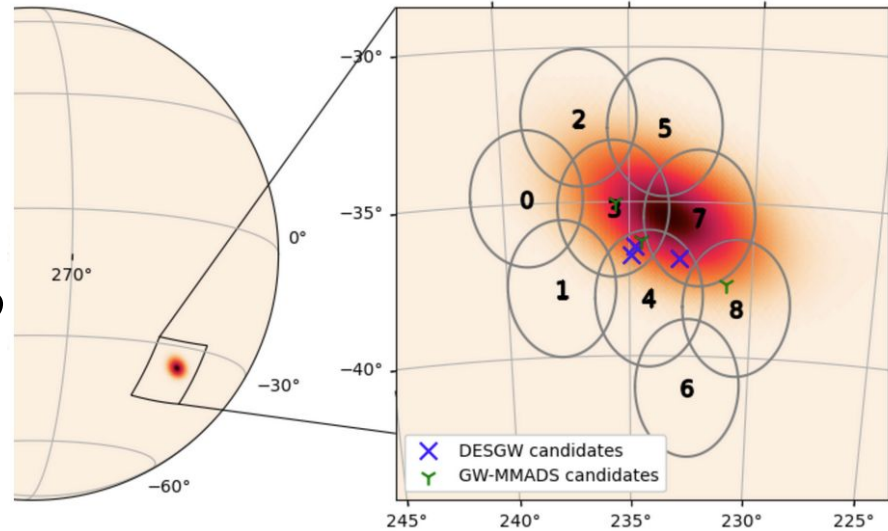


Figure credit: S. MacBride; see <https://rtn-098.lsst.io/> for more details

S250725j: Rubin follow-up of a well-localized BBH merger

- Localized to 19 sq. deg.,
 $d=380\pm 93$ Mpc
- BBH merger candidate with a
chirp mass between 11-22 M_{sun}
- Observations started 2025-07-29
- 9 Rubin pointings covered 94%
of the credible region
- u-r-i filter strategy to a depth of
 $\sim 24^{\text{th}}$ mag (r-band)



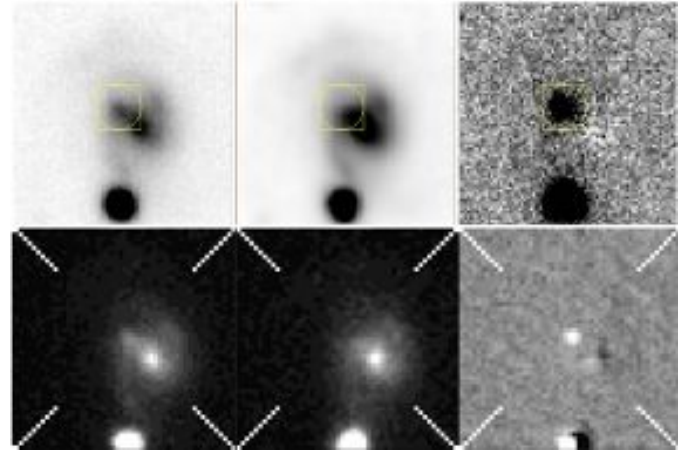
Custom ToO image processing

- Challenge: no existing Rubin templates!*
- Offline custom image processing task (developed by Bob Armstrong and Erin Howard) to create DECam templates from DES, DELVE and DECADE datasets run on US Data Facility
- LSST's standard data release production pipeline used to get difference images and photometry

*This will continue to be a significant challenge during IR1!

S250725j: challenges and takeaways

- First demo that the pipeline works!
- Issues from astrometric matching and crowded stellar fields
- Successful recovery of previously reported candidates
- Further follow-up epochs cancelled due to poor weather - additional analysis not possible

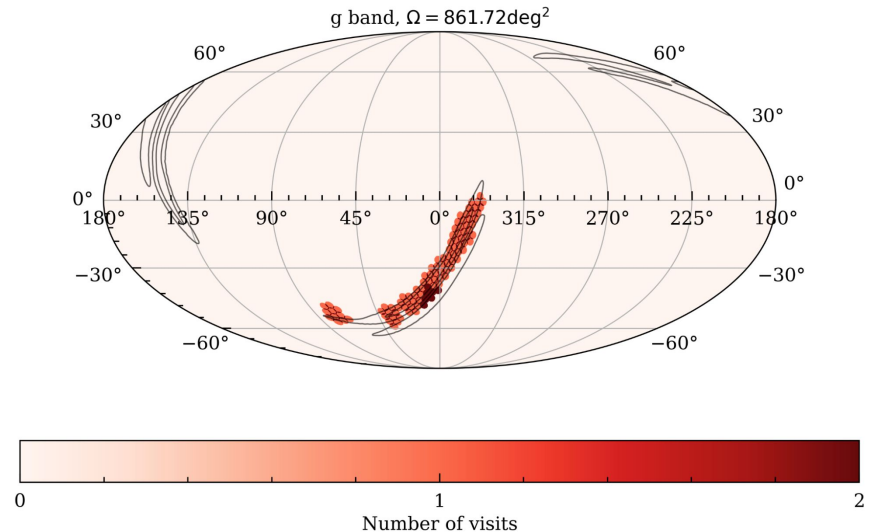


Rubin images of AT2025sib

(MacBride+2025 GCN 41595)

S251112cm: Rubin follow-up of a subsolar mass merger candidate

- Localized to 1681 sq. deg., distance of 93 Mpc
- Given exceptional nature of event, Rubin leadership and ToO advisory committee decided to trigger!
- Cumulative probability coverage: ~39%
- Four epochs of observations taken on nights 0, 2, 4, and 6 after 2025-11-14
- Median depth: ~24.4 mag (g) and ~23.6 mag (i) in 30 s images
- Unprecedented mapping speed: covered ~800 sq. deg. in 2 bands in ~3 hrs!
- See also recent papers: Vieira+2026, Hall+2026



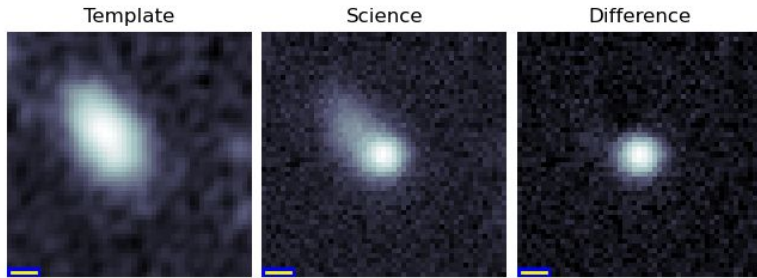
Filtering out impostors

8.7 million alerts!

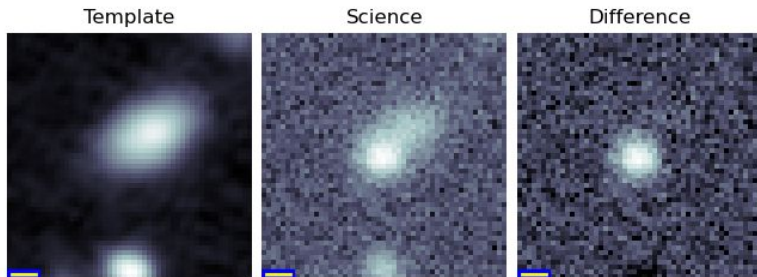


We found real transients...

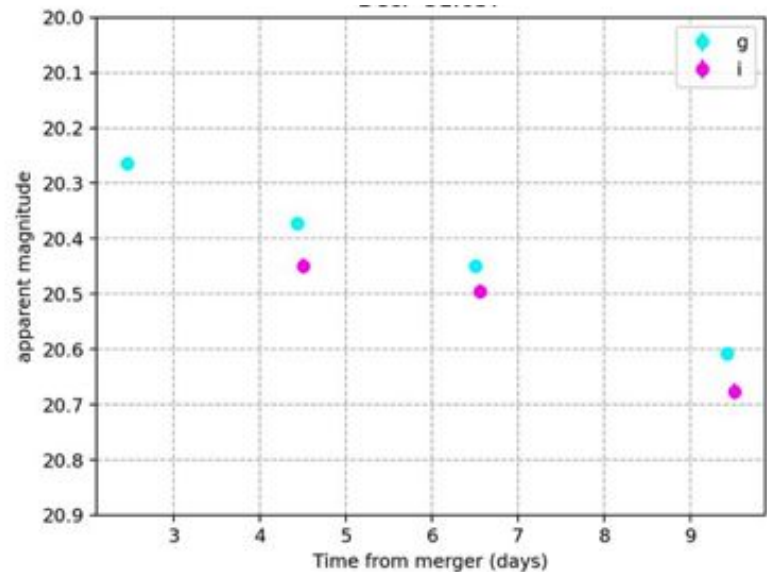
After visually inspecting ~7000 cutouts!



g-band image



i-band image



[AT2025adin](#), 30" away from a NED galaxy within the GW volume; first seen by GOTO¹⁵

Summary: transient-like candidates from search

- ~70 candidates in our final shortlist
 - 32 candidates with high photo-z
 - 15 of these candidates were detected by other surveys
 - 0 kilonova-like candidates
- GCNs: MacBride+2025 (GCN 42707), SA+2025 (GCN 42357)
- Rubin paper in prep, to come out in advance of IR1

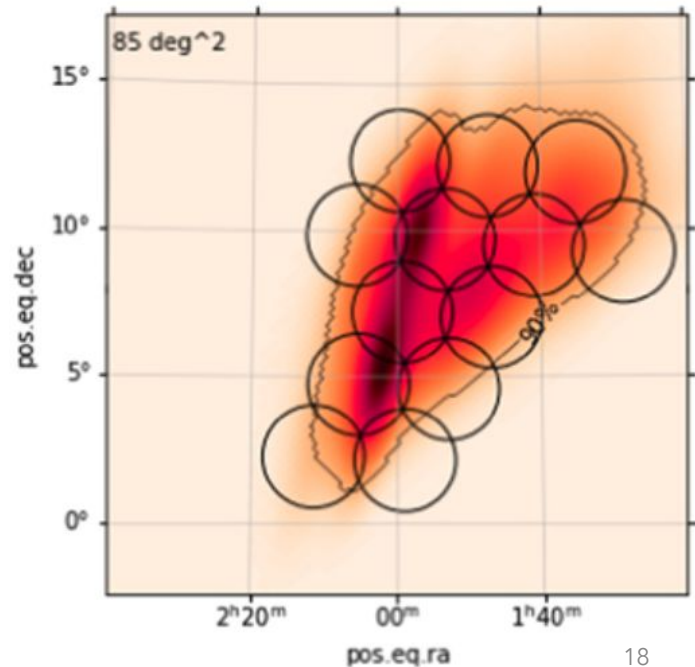
Systematic filtering yields a digestible number of Rubin candidates!

Rubin ToO 2026 workshop

- Revised Rubin follow-up recommendations in light of:
 - Low rates of NS-bearing mergers expected in IR1
 - Lessons learned from past Rubin GW follow-ups
 - Tests of Rubin's performance in mock simulated follow-ups and on-sky
- Plan for filtering alerts to find the next kilonova

Rubin ToOs during IR1: scheduling observations

- Tiling large sky areas
 - Optimize probability coverage, observability, other constraints
- Automated triggering:
 - Need to evaluate real-time simulated observing strategies
 - Ingest events based on properties available in GW Kafka alert packet



Example criteria for automated triggering

Resulting triggering criteria:

[1] GW event with $P(\text{BNS}+\text{NSBH}) > 90\%$ OR $\text{hasNS} \geq 50\%$ OR $\text{HasRemnant} \geq 10\%$ OR $\text{Mchirp} < 2.3$ OR $(2.3 < \text{Mchirp} < 5.5 \text{ AND } P(\text{BNS}+\text{NSBH}) > 0.1)$ [2] FAR < 1 event per year (FAR < $1.6e-8$ Hz)

Strategy:

[1] Rubin will cover the $\Omega = 500 \text{ deg}^2$ highest probability region accessible to Rubin (whether this is the total 90% sky localization area or not).

[2] Query DECam $\Omega = 500 \text{ deg}^2$ area and decide between z or i (which of the two filters has best coverage in terms of depth and area). If querying DECam in real-time is not possible, pick i -band)

[3] Night 0,1,2,3: one scan of $\Omega = 500 \text{ deg}^2$ with $g+i$ (or $g+z$, depending on the outcome of point 2) 120 second exposure in each filter (~5.02 hrs). Note: this is very similar to our “Silver event” strategy, the only difference being the deeper images during Night 0.

Rubin ToOs during IR1: image processing

- Lack of template coverage for the accessible sky
 - Rubin-DECam processing needs to be run in real-time (custom pipeline was resource intensive)
 - Artifact mitigation for Rubin-DECam
- Deeper exposures
 - Longer exposures than 30s results in different kinds of artifacts (crosstalk, overflowing pixels) that need to be filtered out
 - Real-time co-adds are not computationally feasible at the moment

Rubin ToOs during IR1: alert filtering

- Vision: implement base-level “bronze” community filter to identify all real, astrophysical transients within localization
- In practice: need to work with each alert broker to implement filtering
- Challenges: functionality for “archival” queries on update skymaps in brokers, filtering to a digestible number of candidates

Lots to iron out in advance of IR1!



Thank you!