

The background of the slide is an abstract watercolor wash in various shades of blue, ranging from light sky blue to deep cerulean and indigo. The texture is soft and painterly, with visible brushstrokes and color blending. The watercolor is more concentrated on the left side, fading into a lighter blue and then white on the right side.

Rubin Target-of-Opportunity program: Past, Present, and Future

Shreya Anand
(KIPAC-Rubin fellow, Stanford University)

IceCube Particle Astrophysics Symposium
University of Wisconsin, Madison
Oct 13-15, 2026

Outline

1. The Present: Overview of the Rubin Target-of-Opportunity program
2. The Past Rubin ToO follow-ups
 - 3I/ATLAS: An interstellar object
 - S250725j: A well-localized BBH merger candidate
 - S251112cm: A subsolar mass merger candidate
 - IC250708A: A high-energy neutrino candidate (later retracted)
3. The (near) Future: Rubin ToO 2026 recommendations

The background of the slide is a blue watercolor wash, with darker blue and teal tones on the left and right sides, and a lighter, almost white, area on the right side where the text is located.

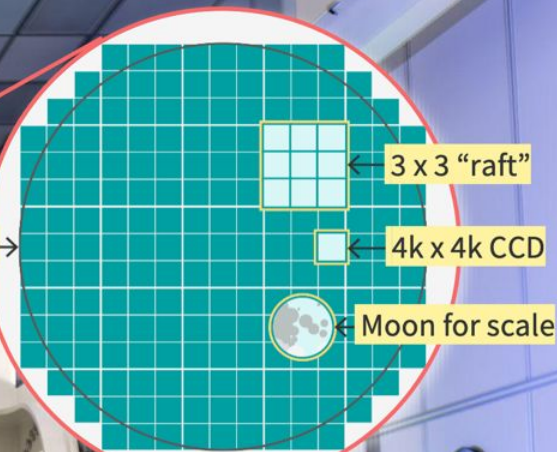
The Present: Overview of the Rubin Target-of-Opportunity program

Largest camera in the world

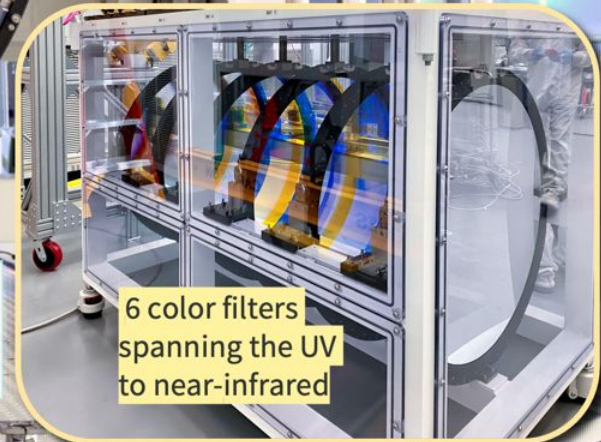
★ 3200 megapixels ★

LSST Camera

3.5-degree
Field of view →
(45x the full
moon)



Built at the the SLAC National
Accelerator Laboratory

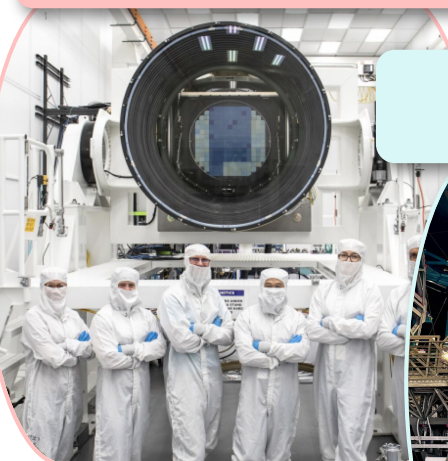


LSST: Capturing the dynamic sky

The greatest astronomical movie of all time

Wide Field of View

Largest digital camera ever built

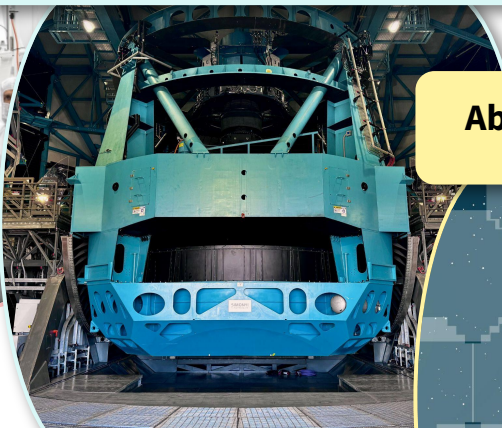


J. Orrell/SLAC National Accelerator Lab



Speed

Novel three-mirror design

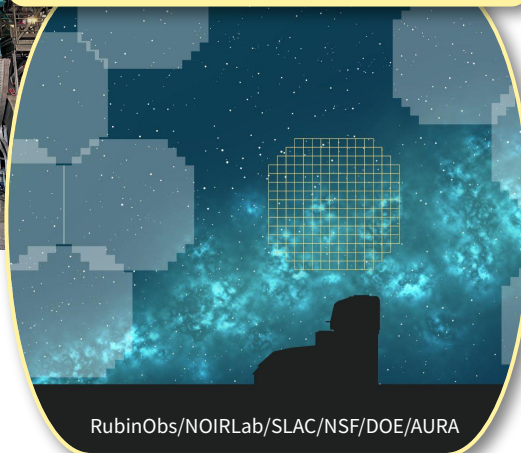


RubinObs/NOIRLab/SLAC/NSF/DOE/AURA



Ability to see faint objects

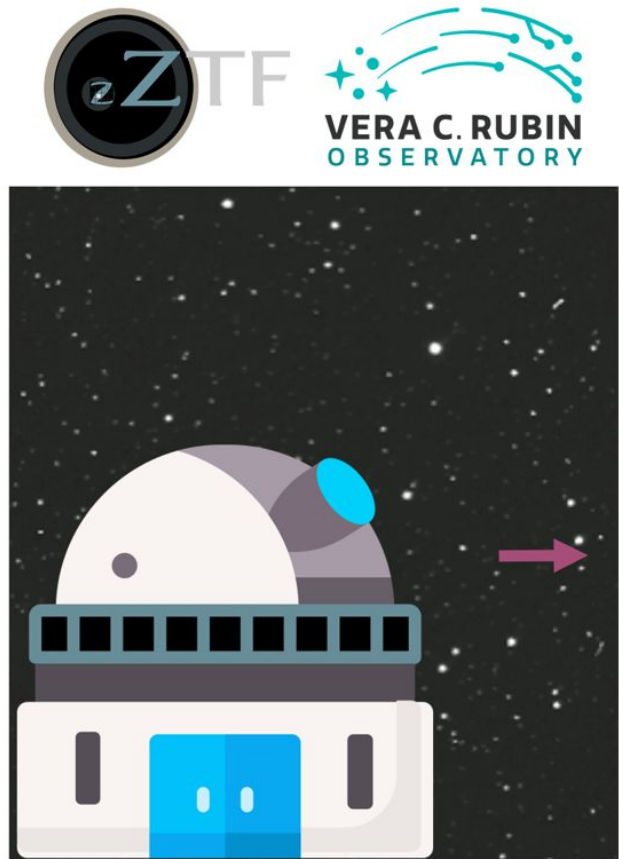
Across the entire Southern sky



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA

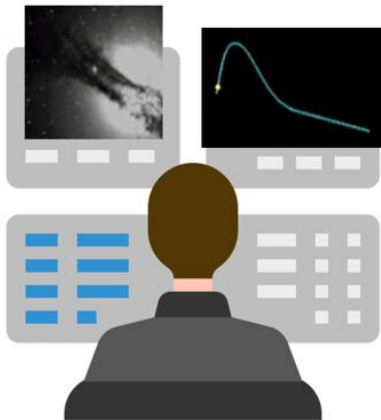


Alert Brokers: how the data gets from Rubin to you!



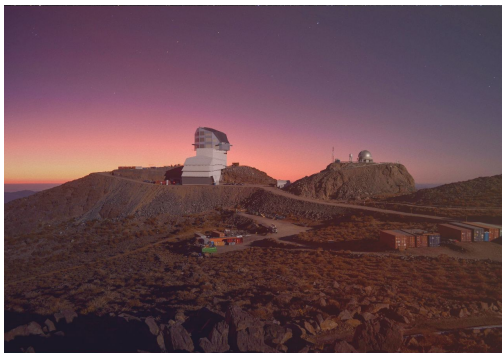
ALeRCE
Automatic Learning for the
Rapid Classification of Events

20 TB per night!!



Credits: ESA/Hubble & NASA, B. Merin; P. Nugent (LBNL),
Supernova Cosmology Project; Flaticon, Freepik, Gowi

Paving the way for a Rubin ToO program



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

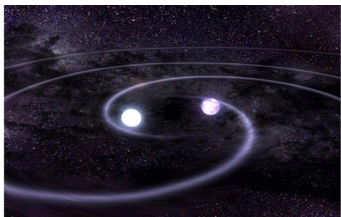
Igor Andreoni, Raffaella Margutti, John Banovetz, Sarah Greenstreet, Claire-Alice Hebert, Tim Lister, Antonella Palmese, Silvia Piranomonte, S. J. Smartt, Graham P. Smith, Robert Stein, Tomas Ahumada, Shreya Anand, Katie Auchettl, Michele T. Bannister, Eric C. Bellm, Joshua S. Bloom, Bryce T. Bolin, 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 Hosseinzadeh, Maryam Hussaini, Dina Ibrahimzade, Luca Izzo, R. Lynne Jones, Yijung Kang, Mansi M. Kasliwal, Matthew Knight, Keerthi Kunnumkal, 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, Huel Sears, Darryl Z. Seligman, Ritwik Sharma, Manisha Shrestha, Simran, Michael C. Stroh, Giacomo Terreran, 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.

See also other papers: Margutti+2015, Margutti+2018, Andreoni+2022

Rubin Target-of-Opportunity: Science Drivers



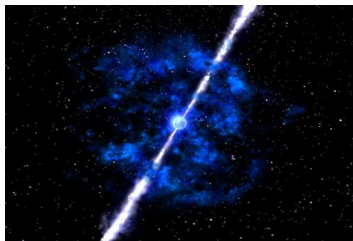
Gravitational Waves (75% of time allocation!)

- Binary neutron star mergers
- Neutron star—black hole mergers
- Binary black hole mergers
- Subsolar mass mergers
- Lensed binary neutron star mergers



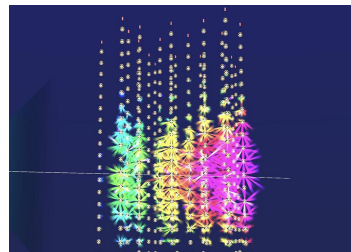
Solar system objects

- Potentially hazardous asteroids
- Interstellar objects



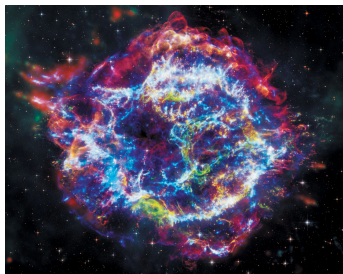
Gamma-ray bursts

- Short GRBs
- Merger-driven GRBs
- High-energy GRBs
- Ultralong GRBs



High energy neutrinos

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



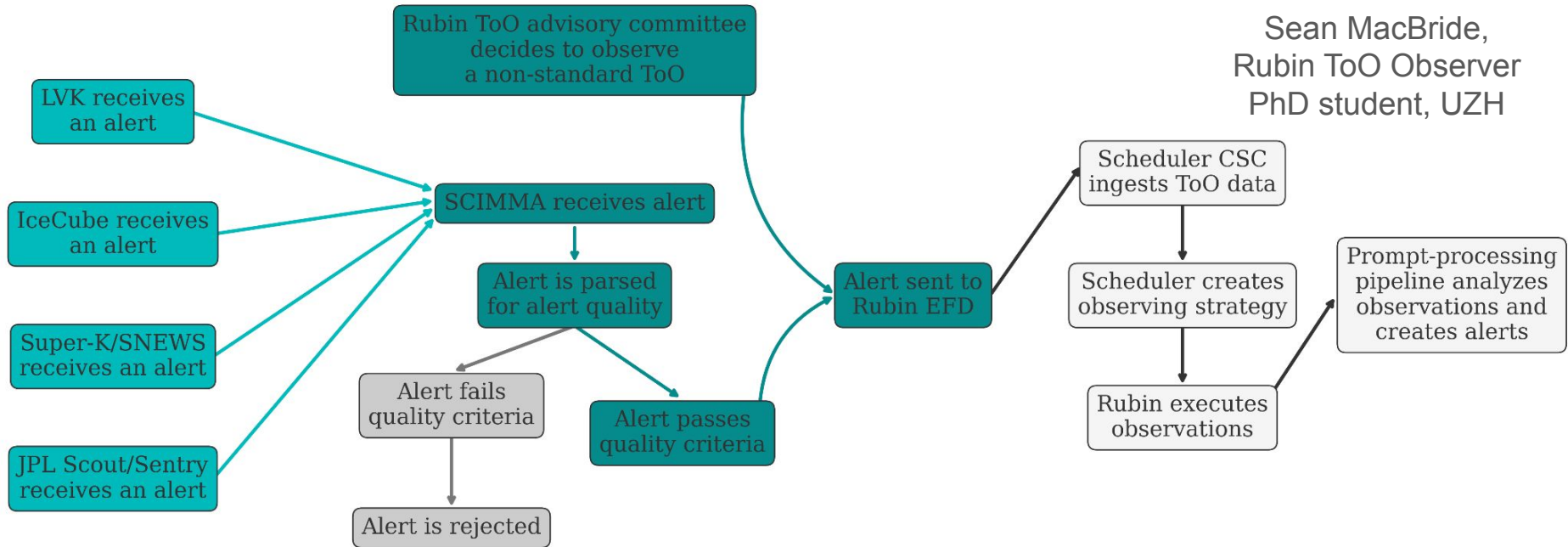
Other rare events

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

Rubin ToO workflow



Sean MacBride,
Rubin ToO Observer
PhD student, UZH



Timeline of Rubin Observatory Operations in Response to a ToO

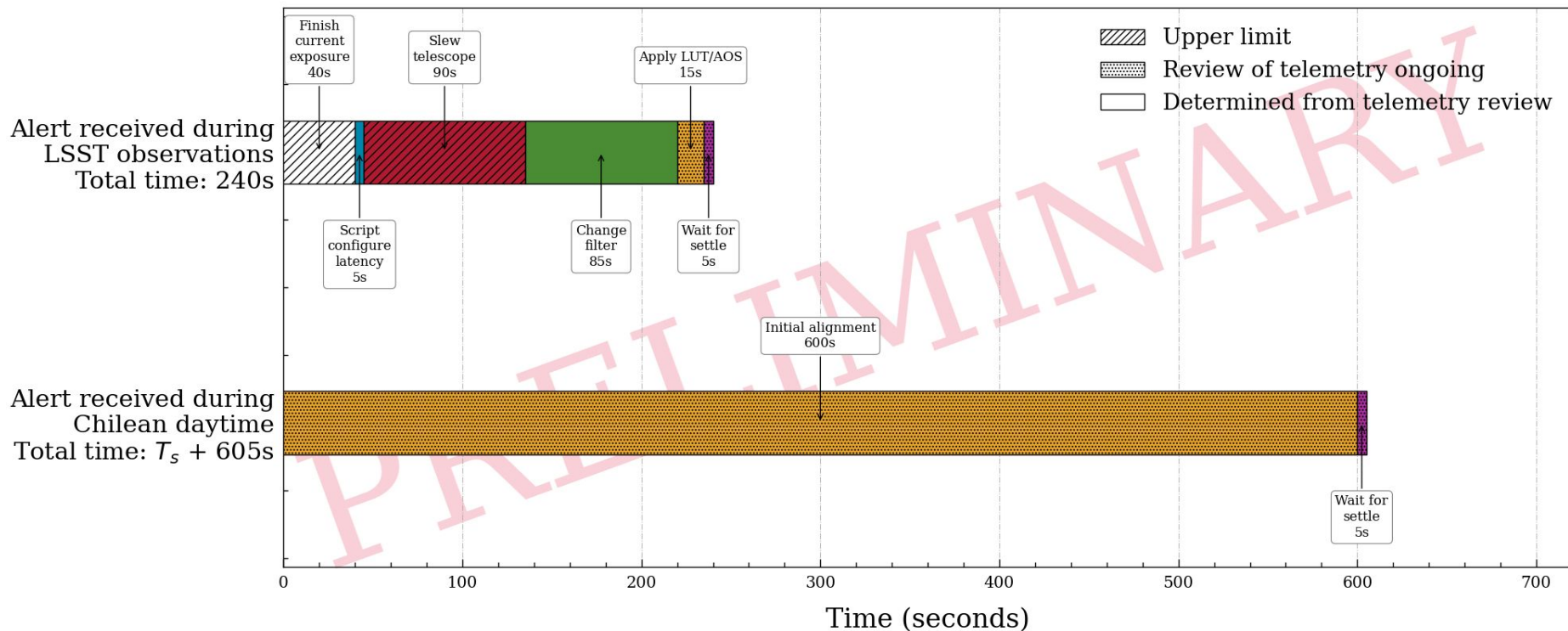


Figure credit: S. MacBride

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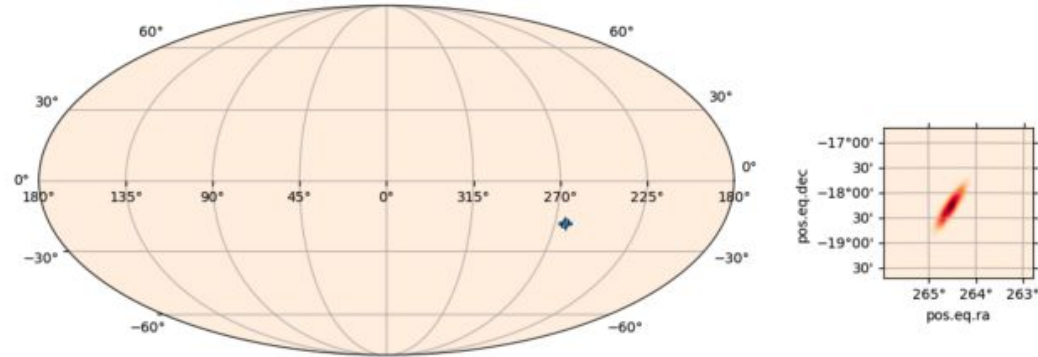
The Past: Rubin ToOs during commissioning,
early operations, and operations

The ToO System in Action

<u>Alert (source)</u>	<u>Comment</u>
3I/ATLAS (PHA)	Observations taken on July 12, 2025. Supported the first Rubin Project Science paper with LSSTCam (Chandler+2026).
S250725j (GW)	Observations taken on July 28, 2025. Additional observations planned, but curtailed by weather.
S251112cm (GW)	Observations taken from November 14-22, 2025. Imaged $\sim 800 \text{ deg}^2$ in two bands to $m_{g,i} \sim 24$ in three hours. Paper nearly complete (Anand+, in prep.)
IceCube-20250708A (HE-neutrino)	Observations taken starting on July 9, 2026. Later classified as a non-astrophysical event from muons produced in a cosmic-ray shower.

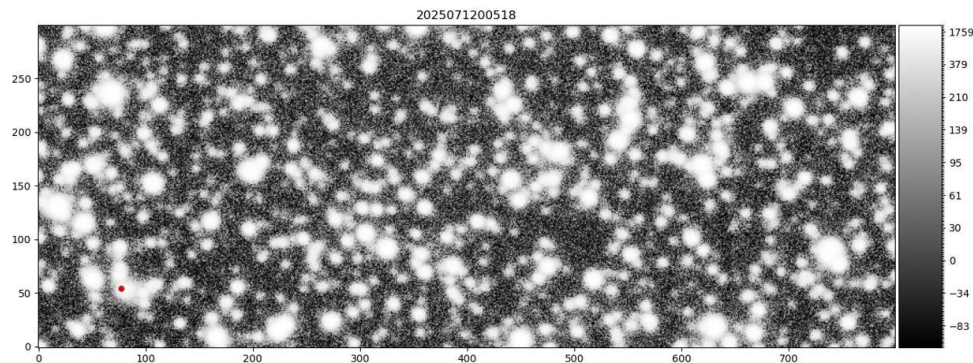
3I/ATLAS: Rubin observations of an interstellar object

- 3rd interstellar object passing through the solar system!
- Rubin began observations on 2025-07-12
- 4 visits total, of 30s images spanning ugrizY filters
- Results published in Chandler et al. 2026



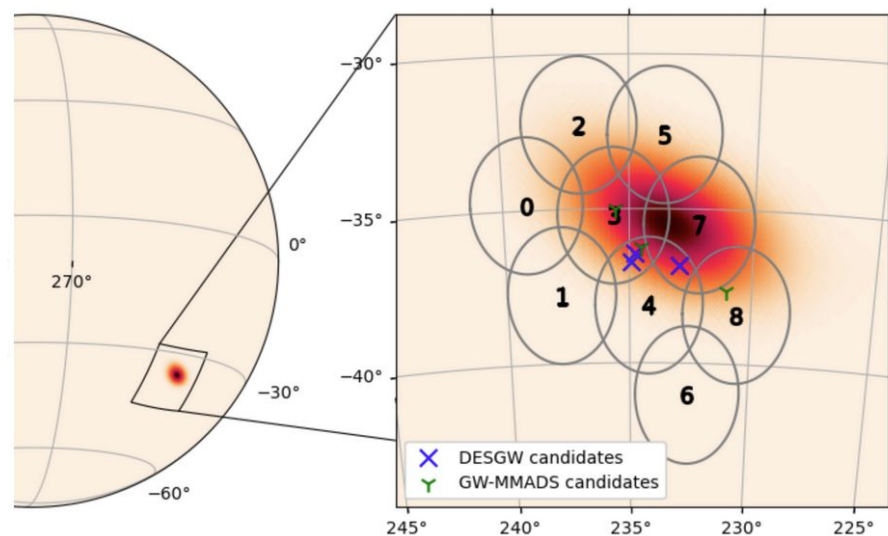
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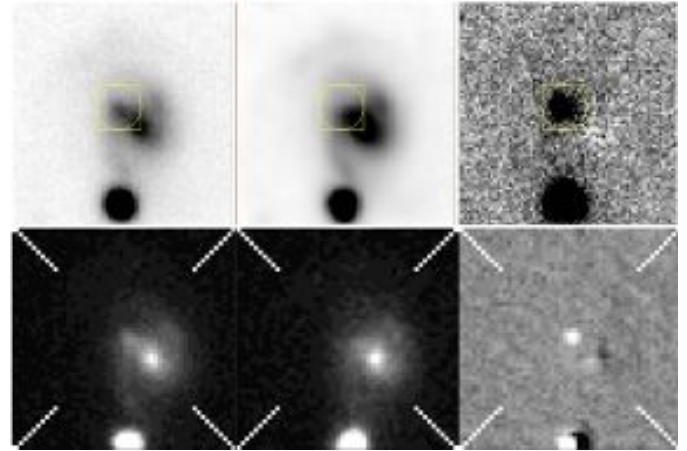
S250725j: Rubin follow-up of a well-localized BBH merger

- Localized to 19 sq. deg., $d=380\pm 93$ Mpc
- BBH merger candidate ($>99\%$) 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 ~ 24 th mag (r-band)



S250725j: challenges and takeaways

- Custom image subtraction with DECam templates
- Issues from astrometric matching and crowded stellar fields (low gal. lat.)
- Recovery of previously reported candidates (MacBride+2025 GCN 41595)
- Further follow-up epochs cancelled due to poor weather at the Summit and engineering priorities

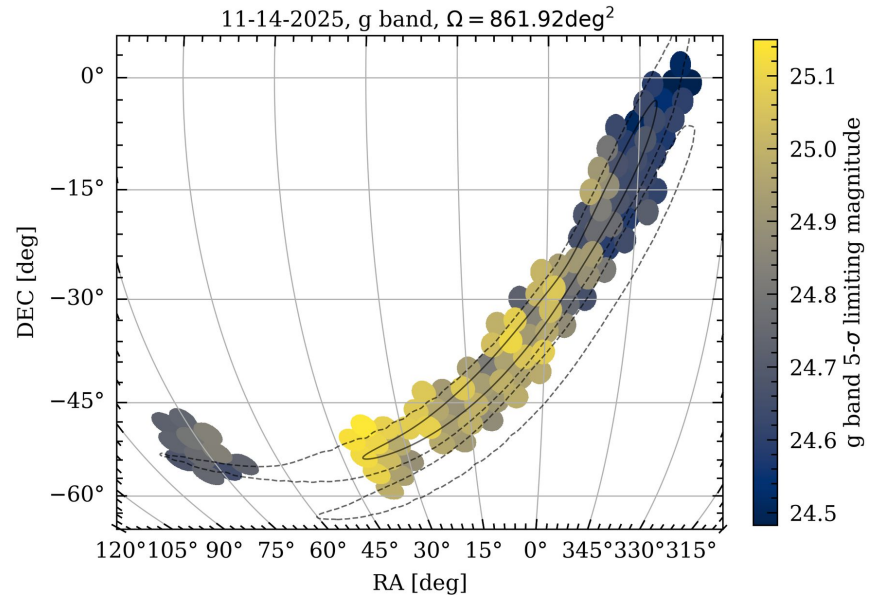


Rubin images of AT2025sib

<https://gcn.nasa.gov/circulars/41595>

S251112cm: Rubin observation statistics

- SSM merger candidate, $M_{\text{chirp}} < 0.87 \text{ Msun}$
- Observations started 2 nights after merger (ToO advisory board activation)
- Cumulative probability coverage: $\sim 39\%$ (70% region targeted)
- 30s images taken in g- and i-bands
- Four epochs of observations taken on nights 0, 2, 4, and 6 after 2025-11-14
- Median depth: $\sim 24.4 \text{ mag (g)}$ and $\sim 23.6 \text{ mag (i)}$
- Unprecedented mapping speed: covered $\sim 800 \text{ sq. deg.}$ in 2 bands in $\sim 3 \text{ hrs!}$



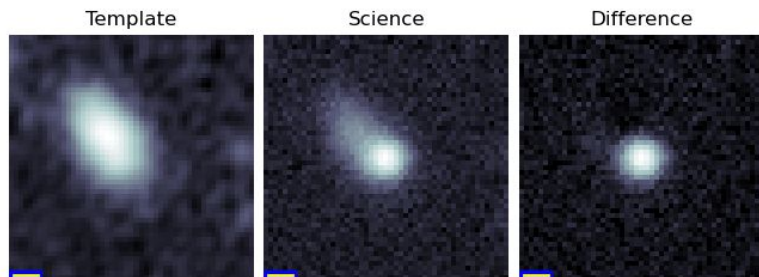
S251112cm: Filtering out impostors

8.7 million alerts!

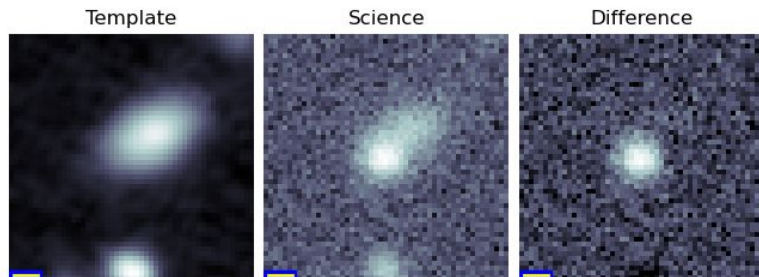


S251112cm: We found real transients!

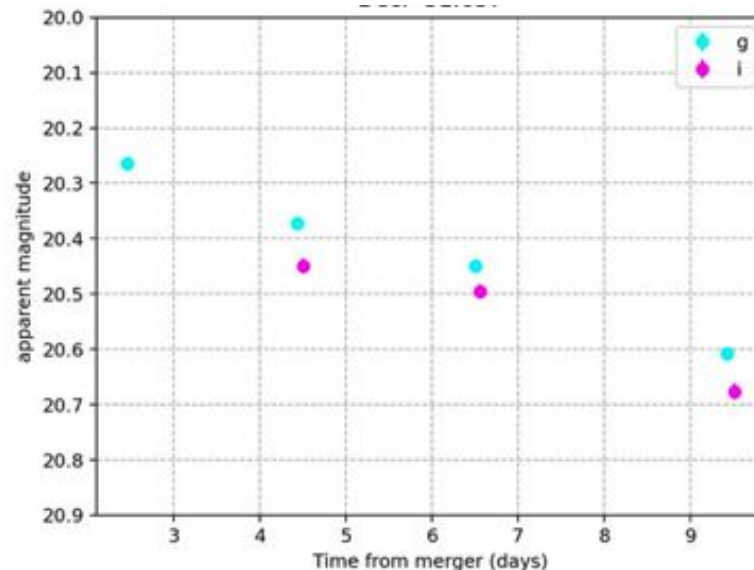
After visually inspecting ~7000 cutouts!



g-band image



i-band image



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

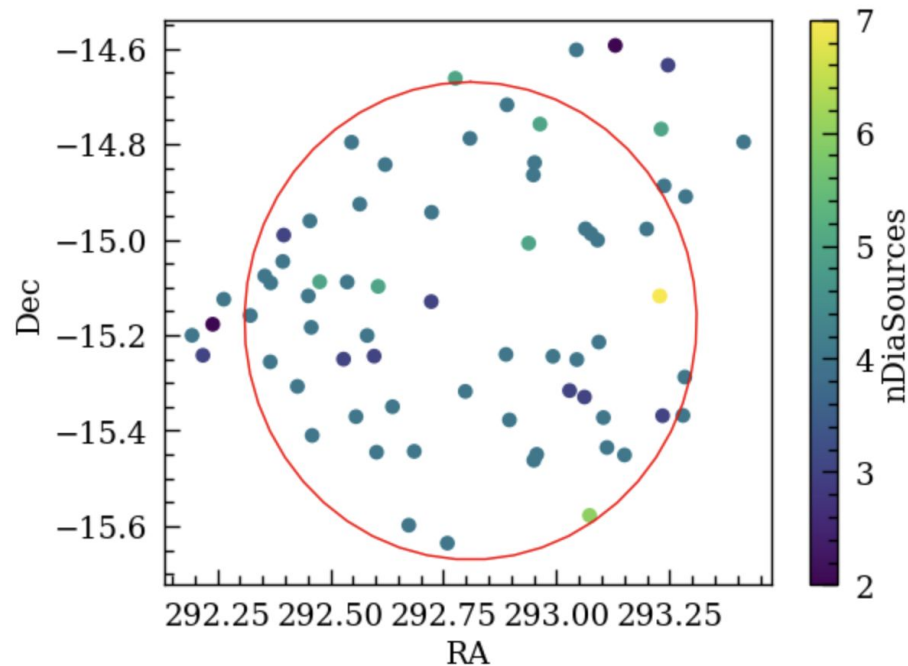
Summary: transient-like candidates from search

- ~70 candidates in our DECam-Rubin shortlist
 - 0 kilonova-like candidates or SSM counterpart candidates
 - GCNs: MacBride+2025 (GCN 42707), SA+2025 (GCN 42357)
- Separate search with Rubin-Rubin, using last epoch as template
 - ~10 candidates in final shortlist
 - 0 kilonova-like candidates or SSM counterpart candidates

Systematic filtering yields a digestible number of Rubin candidates!

IC260708A: First Activation for a High Energy Neutrino

- IceCube reported a high-energy neutrino event (IceCube-20260708A) on July 8th, 2026.
- Rubin observations between July 9-13th
- Minimal deployed templates in one band (z) $\rightarrow$ alerts
- Custom template building, offline processing initiated.



The localization of IceCube-20260708A (red), and the recovered candidates from offline Rubin processing.

IC260708A: Retraction

- This alert was later associated with muons from a cosmic ray shower.
- Retractions were not implemented; development ongoing
- Test of offline processing capabilities



The 90% localization region of IceCube-20260708A (white) and the incremental template quality in the region for each patch-tract combination, here shown for g-band.

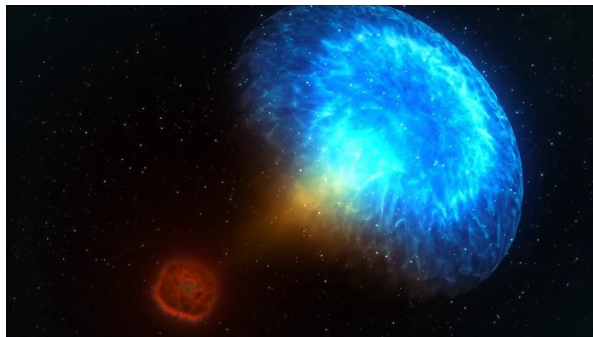
Insights from past Rubin ToO campaigns

- Rubin is very capable of tiling GW events with $A > 500$ sq. deg!
- $g-i$ filter choice is effective in distinguishing KNe from contaminants; other filters to be considered
- “Silver strategy” sensitive to most KN models; delay to get on sky hinders sensitivity
- DECam-Rubin subtractions are effective!
- Digestible number of candidates (< 100) from wide-area campaign!

The background of the slide is a watercolor-style wash of various shades of blue, ranging from deep navy to light sky blue, with some darker, almost black, veins and textures. The wash is more concentrated on the left side and fades towards the right.

The Future: Rubin ToO 2026 recommendations

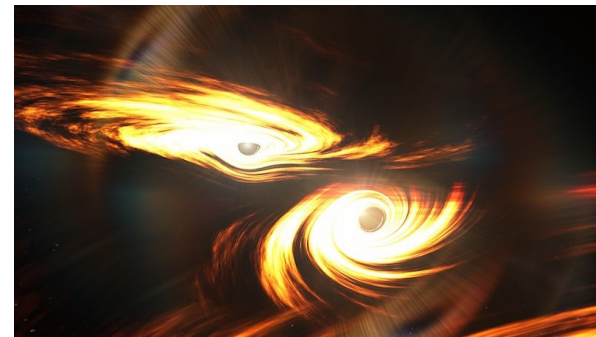
Gravitational waves: science goals with Rubin



Binary neutron star / Neutron
star–black hole mergers
(NASA GSFC / CI Lab)



Subsolar mass mergers
(Caltech / K. Miller and R. Hurt
(IPAC))



Binary black hole mergers
(Mark Myers, ARC Centre of
Excellence for Gravitational Wave
Discovery (OzGrav))

Gravitational Waves: Intermediate Run 1

BNS NSBH BBH
Annual detection rates

O4 HLV 2^{+4}_{-2} 4^{+9}_{-4} 240^{+290}_{-140}

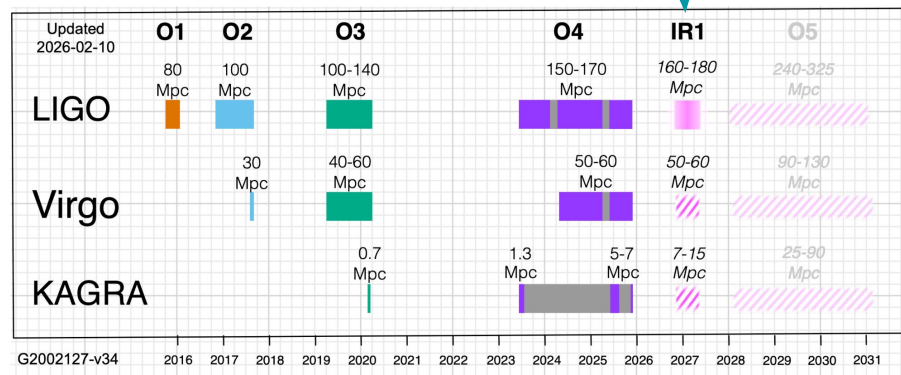
Localization areas (sq. deg.)

O4 HLV 1420^{+310}_{-250} 2150^{+380}_{-310} 1837^{+55}_{-48}

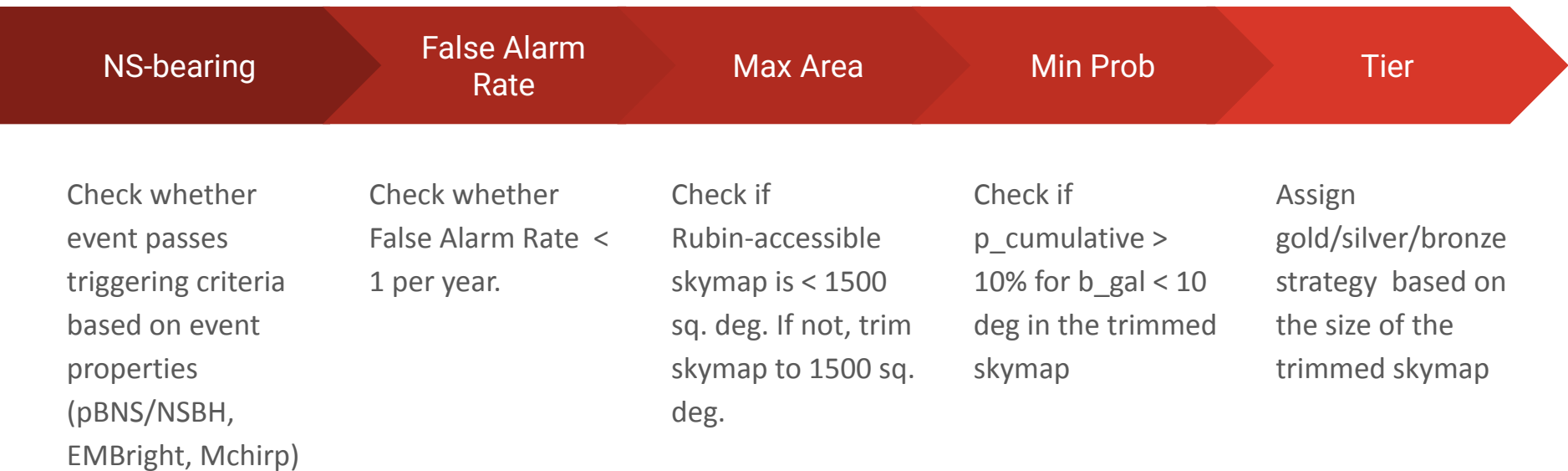
Median distances (Mpc)

O4 HLV 266^{+33}_{-44} 471^{+49}_{-55} 1987^{+37}_{-42}

We are here!

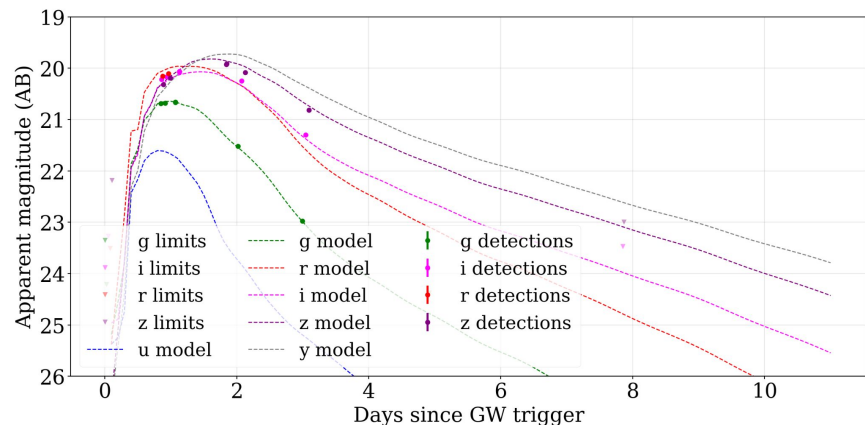


Rubin triggering decision tree (BNS mergers)

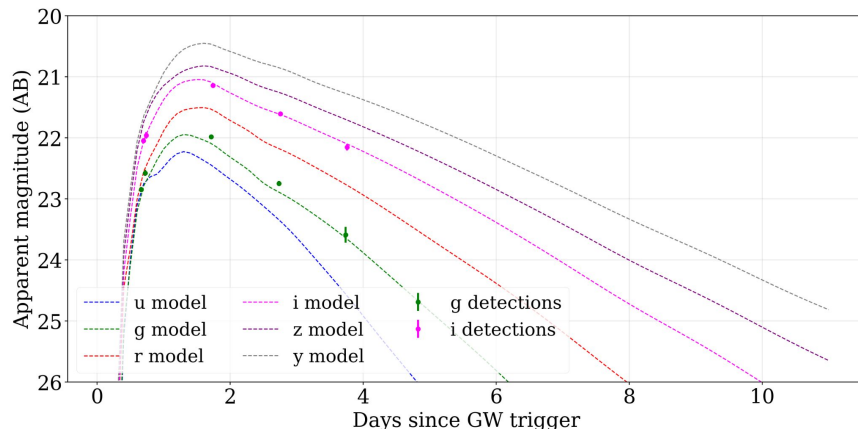


Rubin's strategy for kilonova identification

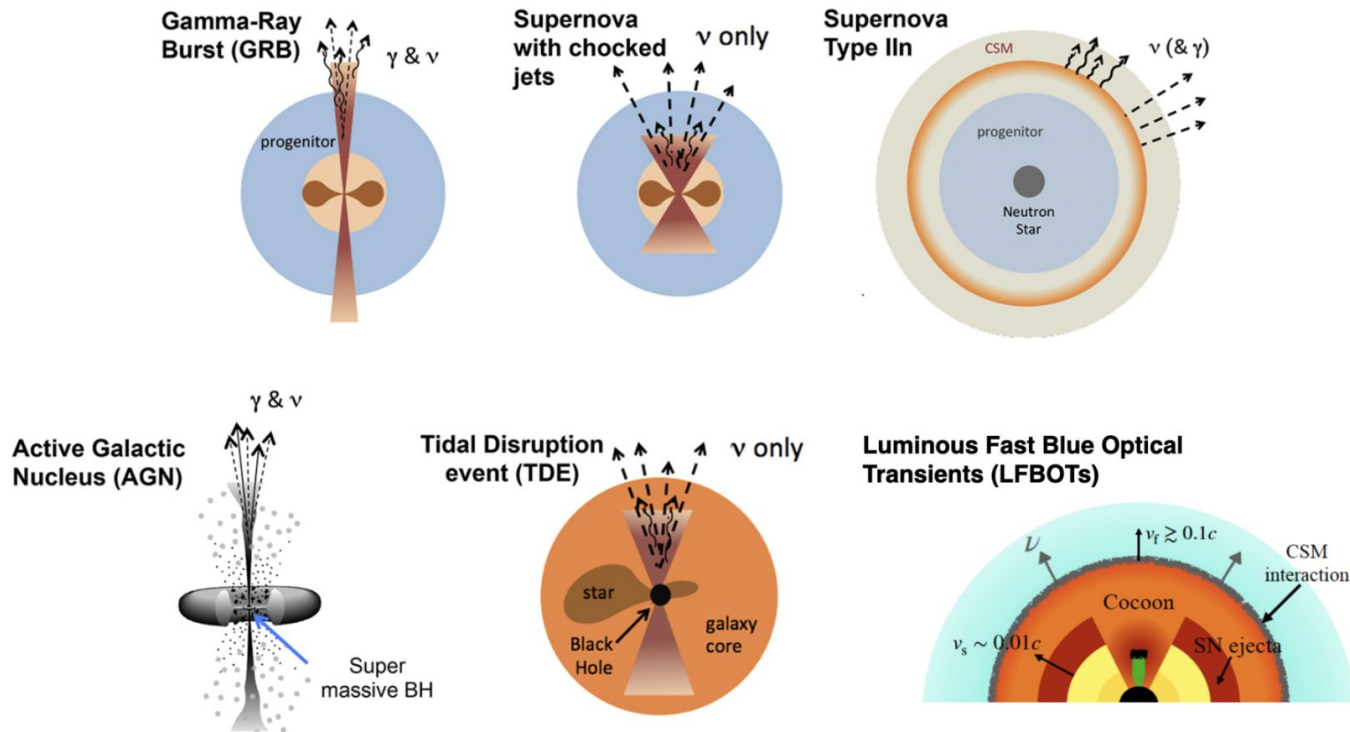
Proposed 4-filter gold strategy for BNS kilonova at 250 Mpc



Proposed 2-filter silver strategy for NSBH kilonova at 350 Mpc



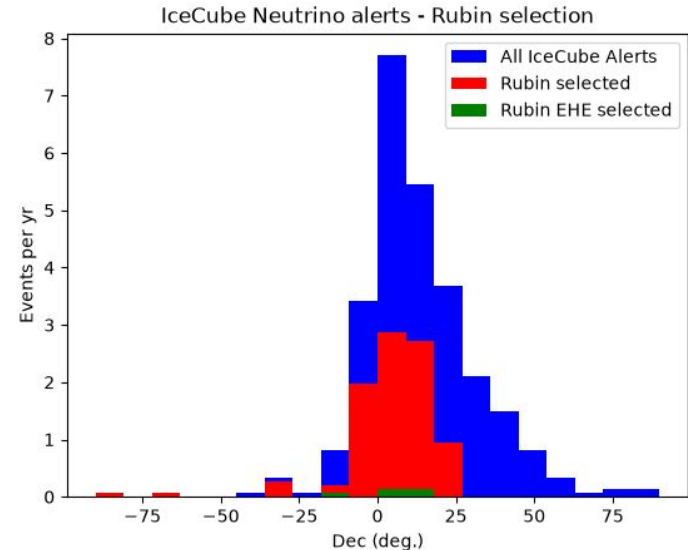
High Energy Neutrinos: Astrophysical Sources



Adapted from Bartos (2018) and Guarini et al (2022).

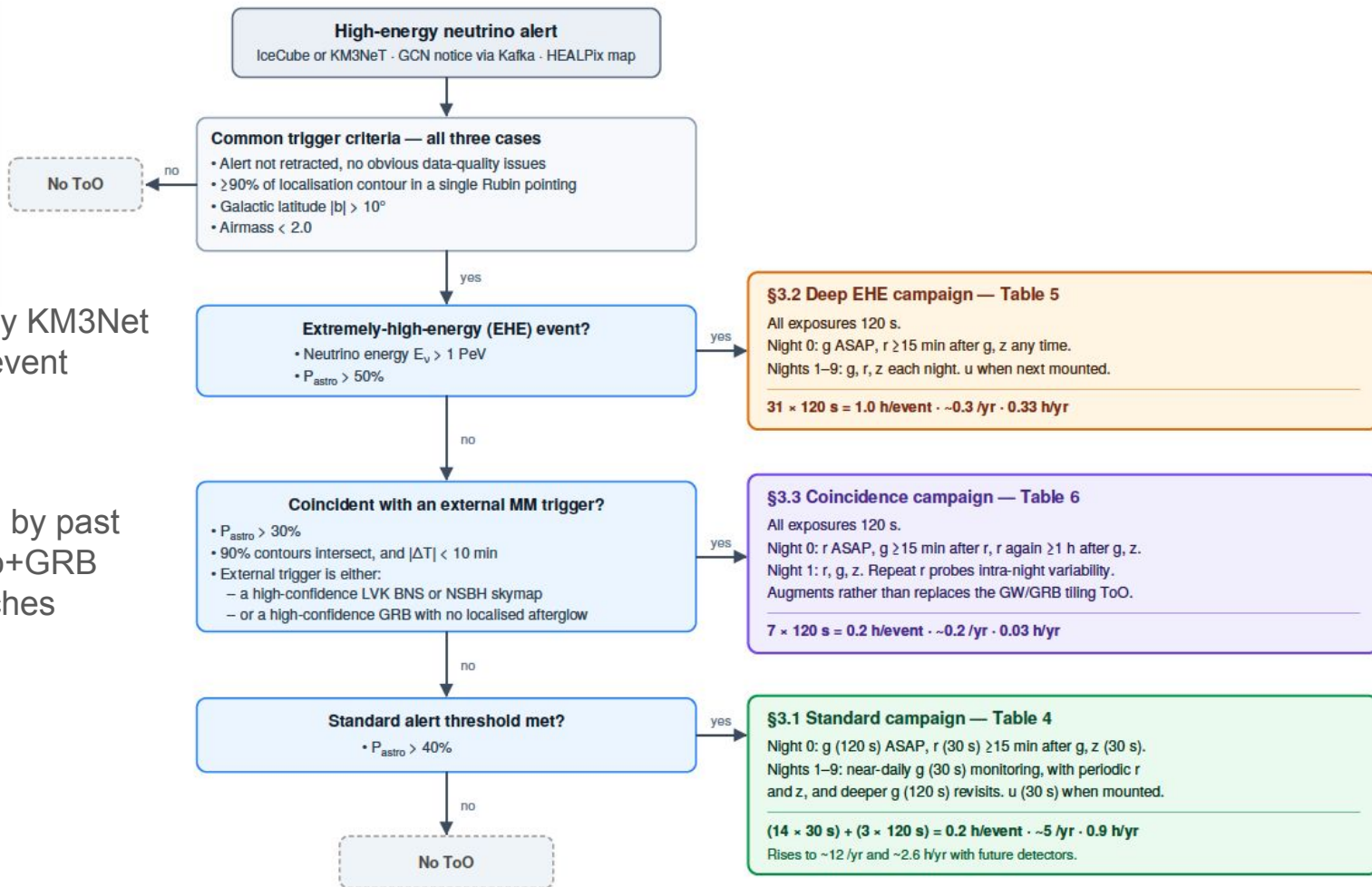
High Energy Neutrinos: proposed program

- Rubin can cover most neutrino localizations in a **single pointing**
- Reaches a depth of 24.5 mag, needed to find neutrino counterparts out to $z > 0.5$
- A comprehensive follow-up campaign for every accessible $P_{\text{astro}} > 40\%$ neutrino track
- Includes KM3Net triggering!



Motivated by KM3Net
EHE event

Motivated by past
Neutrino+GRB
searches



Gamma Ray Bursts: Science Goals with Rubin

Science case lead: Ahumada

Break the tension:

Binary merger rate
vs
r-process enrichment

GRB Progenitor science

- Mergers
- Collapsars
- Magnetars
- TDEs

Origin of

Very High Energy
emission (>100 GeV) and
Extragalactic Background
Light (EBL) attenuation.

Selected
cases

Short GRBs

Merger-driven long GRBs

High Energy GRBs

GRBs coincident with local galaxy cluster

GRBs with prompt polarization

Kilonova science
&
r-process
nucleosynthesis

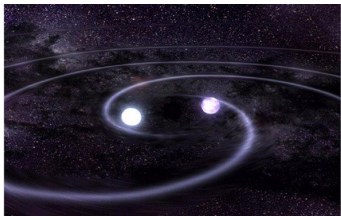
Host Galaxy:

- **Redshift**
- Natal kicks
- Population studies

Fundamental GRB physics

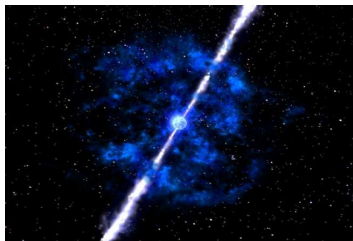
- Jets structure
- Magnetic fields
- Origin of gamma-ray photons
- Central engine

Rubin Target-of-Opportunity: Science Drivers



Gravitational Waves (75% of time allocation!)

- Binary neutron star mergers
- Neutron star—black hole mergers
- Binary black hole mergers
- Subsolar mass mergers
- Lensed binary neutron star mergers



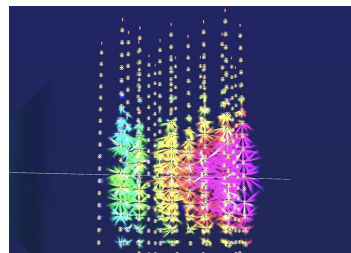
Gamma-ray bursts

- Short GRBs
- Merger-driven GRBs
- High-energy GRBs
- Ultralong GRBs



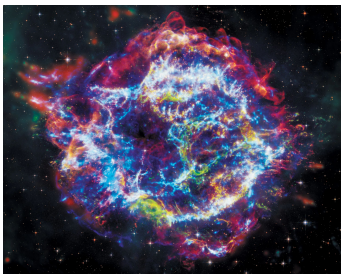
Solar system objects

- Potentially hazardous asteroids
- Interstellar objects



High energy neutrinos

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



Other rare events

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

Other Rubin ToO cases

- Near-Earth Objects
- Lensed BNS mergers / GRBs
- Galactic Supernova
- Unidentified GW Sources: detected with the Burst search rather than the compact binary coalescence (CBC) searches
 - Under the purview of the **ToO advisory board**

Takeaways: The Rubin ToO program

- 3% of LSST is dedicated to ToOs!
- Rubin has already performed 4 ToO campaigns thus far (1 ISO, 2 GWs, 1 neutrino)
- Rubin ToO 2026 report draft is nearly complete (lead by R. Margutti)
 - Soon to be released, pending approval of the Rubin SCOC and leadership
- Goal: find the next multi-messenger counterpart with Rubin!

Extra Slides

Important Recent Developments from Neutrino-land

'Ultrahigh Energy' Neutrino Found With a Telescope Under the Sea

It's the most energetic particle of its kind ever discovered, and scientists have no idea where it came from.

Listen · 6:22 min

Share full article



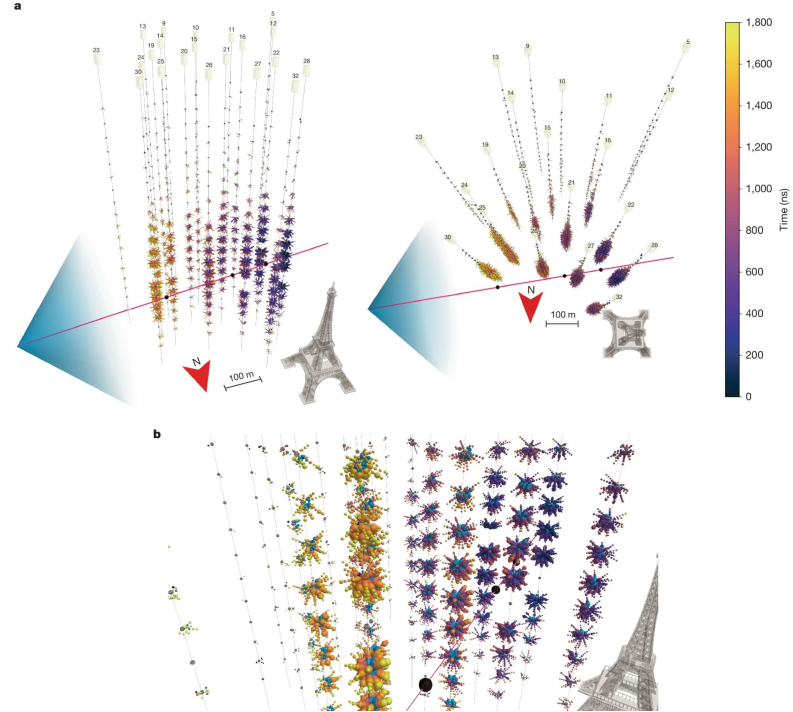
Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

<https://doi.org/10.1038/s41586-024-08543-1>

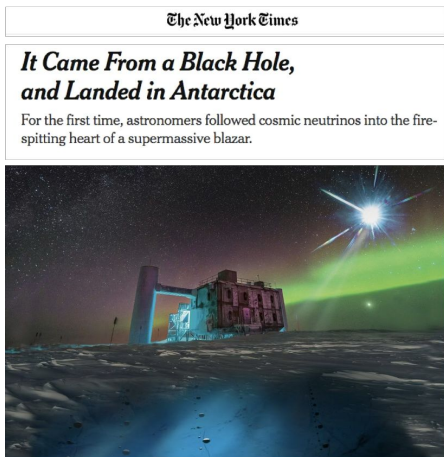
The KM3NeT Collaboration[✉]

Received: 19 August 2024



Astrophysical neutrino flux extends up to ~ 100 PeV

Neutrino follow-up can confirm OR exclude associations



Credit: Science/IceCube

GCN Circular 39631

Subject IceCube-250309A - IceCube observation of a high-energy neutrino candidate track-like event
Event [IceCube-250309A](#)
Date 2025-03-09T11:48:28Z (a year ago)
From A. Zegarelli at Ruhr University Bochum <azegarelli@icecube.wisc.edu>
Via Web form

The IceCube Collaboration (<http://icecube.wisc.edu/>) reports:

The inferred neutrino energy of this alert is ~ 4 PeV, making it the fourth-highest energy known detection by IceCube over the past decade.

The alert coincides with the Fermi GRB250309B (Fermi-GBM trigger 763198715 at 07:38:30.66 on 09 March 2025; https://gcn.gsfc.nasa.gov/other/763198715_fermi) with a time delay of 145.91 seconds relative to the GRB trigger time. The angular distance to the most updated reconstruction released by the GBM team, which has a 1 σ statistical error of 1.60 deg, is 0.77 degrees. An alternative algorithm results in a shifted direction (<https://gcn.nasa.gov/circulars/39629>) with an angular distance from the best fit neutrino direction of 3.18 degrees and has a 1 σ statistical error of 1.3 degree and a systematic error of 1 degree.

We strongly encourage follow-up observations of the neutrino region of interest and the uncertainty region of GRB250309B.

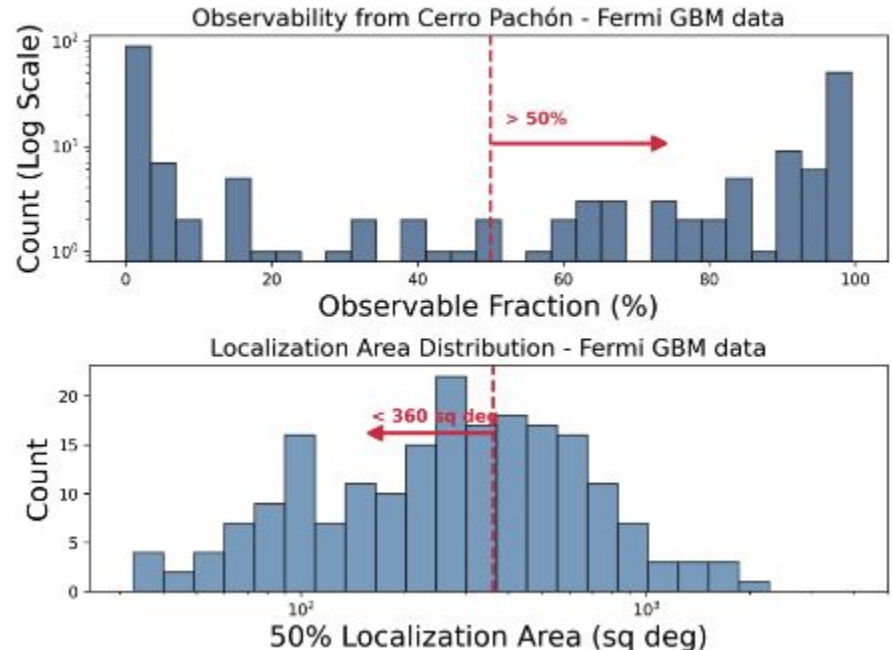
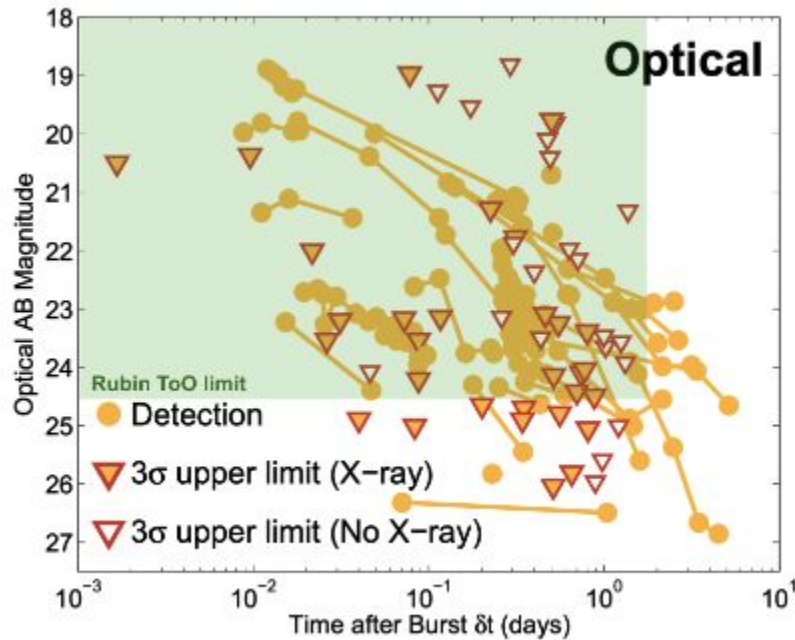
GCN Circular 39639

Subject GRB250309B: One candidate counterpart from the Zwicky Transient Facility
Event [GRB 250309B](#)
Date 2025-03-09T18:25:09Z (a year ago)
Edited On 2025-03-09T19:31:58Z (a year ago)
From Robert David Stein at JSI <rdstein@umd.edu>
Edited By Judith Racusin at NASA/GSFC <judith.racusin@nasa.gov> on behalf of Robert David Stein at JSI <rdstein@umd.edu>
Via Web form

Robert Stein (JSI), Tomas Ahumada (Caltech), Jannis Necker, Akshay Erhanalodi (DESY), and Anna Franckowiak (Ruhr University Bochum), Jesper Sollerman (Stockholm) report:

We note that ZTF25aaivtjt/[AT2025dws](#) is located 2.24 degrees from the center of the neutrino localisation. If this is indeed the afterglow, then the offset to the reported neutrino uncertainty region is $>5 \sigma$, suggesting that the neutrino and GRB are not associated.

Gamma-ray bursts: justification for Rubin

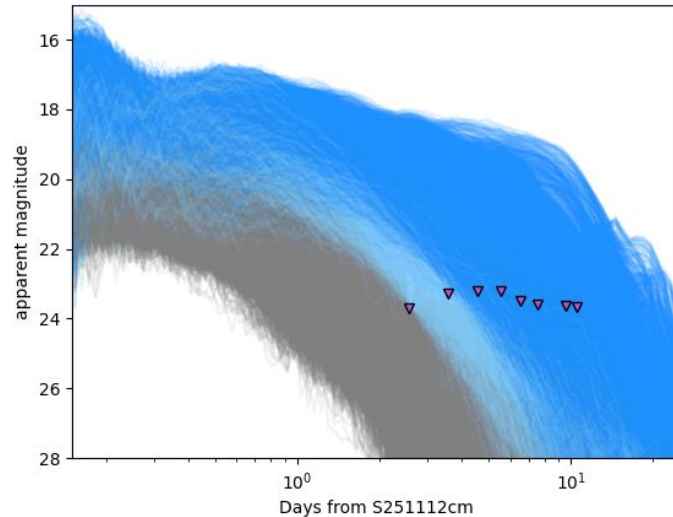


Gravitational Waves: IR1 updates to Rubin ToOs

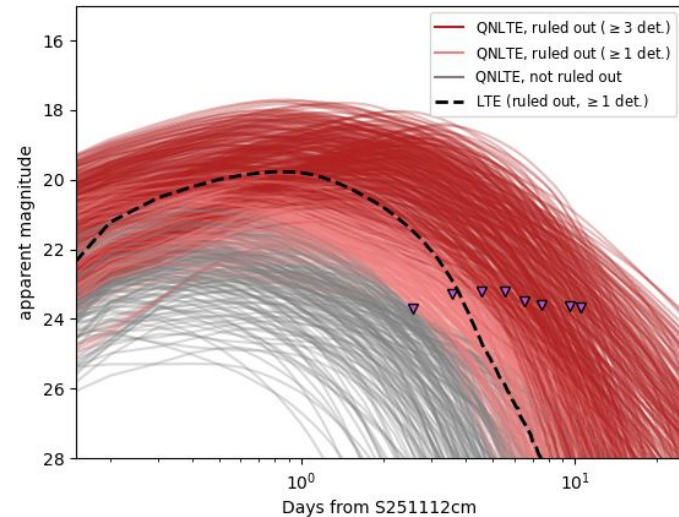
- Fully automated triggering and strategy execution
- Triggering on poorly localized GW events
- Inclusion of binned chirp mass information in triggering criteria
- Changes to the requested observing strategies (filters, cadence, etc)
- Triggering on high-significance SSM merger candidates
- Lack of Rubin templates → DECAM templates

Constraints on kilonova models

POSSIS constraints

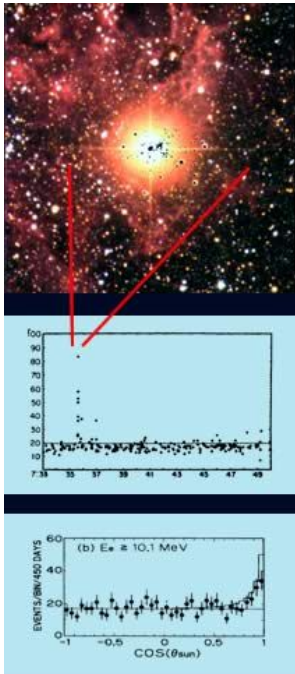


Sedona QNLTE constraints



>45% of the BNS kilonova models in the POSSIS and Sedona model grids (Brethauer+2026, Bulla+2023) are ruled out by requiring 3 non-detections in 2 filters.

Next Galactic supernova will be the event of the century



- Reminder: MeV neutrinos are emitted at time of supernova explosion
- Triangulation from global network of neutrino detectors will lead to a warning alert (“SNEWS”).
- Neutrino region likely to be $O(\sim 25)$ sq. deg.
- 1 alert in Rubin era if we are lucky ($p \sim 15\%$)
- Considerable scientific gain in catching shock breakout early -> Rubin FoV essential!

Rubin ToO 2024 recommendations

