Strategy for identifying Vera C. Rubin Observatory kilonova candidates for targeted gravitational-wave searches

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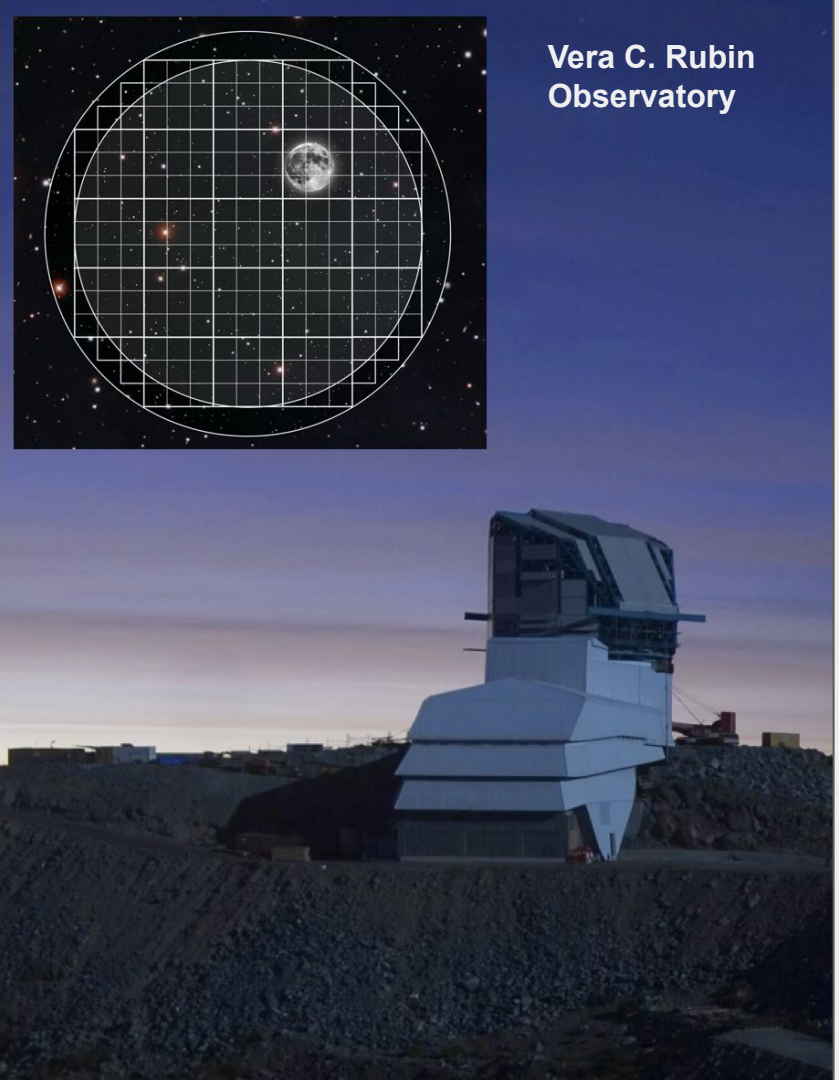
Vera C. Rubin Observatory

LIGO Hanford

KAGRA

Virgo

LIGO Livingston



- LSST will survey the visible Southern Sky every few nights for 10 years
- ~10 million alerts per night - will revolutionize transient astronomy
- Starting very soon! Should begin full survey observations early 2026
- Overlapping observations between Rubin and LVK expected in 2026 - possibility for multi-messenger science!

Usual approach: Target of opportunity (ToO)

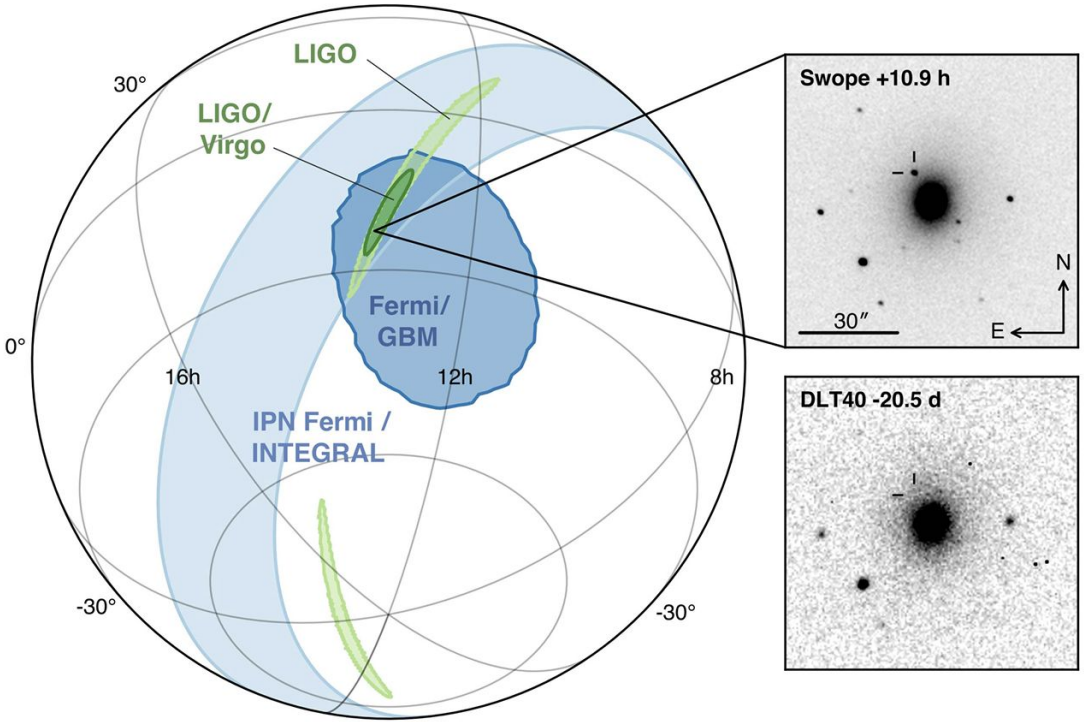


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

Rubin followup to a GW trigger!

GCN Circular 41595

Subject LIGO/Virgo/KAGRA S250725j: Observations with the NSF-DOE Vera C. Rubin Observatory
Event LIGO/Virgo/KAGRA S250725j
Date 2025-08-29T19:02:14Z (2 days ago)
From Sean MacBride at University of Zurich <sean.p.macbride@gmail.com>
Via Web form

Sean MacBride (University of Zurich), Shreya Anand (Stanford University), Erin Howard, Ian Sullivan, David Wang, Lynne Jones, Peter Yoachim, Eric Bellm (University of Washington), Bob Armstrong (Lawrence Livermore National Laboratory), Michael Wood-Vasey (University of Pittsburgh), Alex Drlica-Wagner, Ken Herner (Fermi National Accelerator Laboratory), Gautham Narayan (University of Illinois), Tatiana Acero Cuellar, Federica Bianco (University of Delaware), Bruno Sánchez (Aix Marseille Université), John Banovetz (Lawrence Berkeley National Laboratory), Kris Mortensen, Paulina Venegas, Yijung Kang, Yousuke Utsumi, and Tiago Ribeiro (NSF-DOE Vera C Rubin Observatory), reporting on behalf of NSF-DOE Vera C Rubin Observatory:

We observed the localization region of the binary black hole merger S250725j, reported by LIGO/Virgo/KAGRA (GCN 41154, GCN 41168) with the 9.6 square degree field of view LSST Camera mounted on the 8.4-m Simonyi Survey Telescope at the Vera C. Rubin Observatory. This is the first Target-of-Opportunity observation by Rubin Observatory.

Rubin Observatory is conducting a Science Validation (SV) survey as part of its commissioning activities [1]. During this period, data quality and acquisition rate are variable. Not all data products that will be available during the Legacy Survey of Space and Time (LSST) operations are currently available [2].

Rubin updated science verification strategy + MoU proposal

Rubin will require deep templates to identify transients. Early on such templates may be lacking.

Anais Möller led an effort to develop an updated Rubin Science Verification (SV) strategy with GW/MMT in mind - Recommendations for Enabling Early Multi-Messenger Science - More than 75 signatures

Adopted by Rubin (see https://sitcomtn-005.lsst.io/), providing templates in the declination range [-55, -25] deg on a best effort basis.

MoU between LVK/MMT and Rubin/TVS recently signed to exchange additional information and work on subthreshold searches.

Alternative approach: Targeted GW search to follow up kilonova candidates from Rubin/LSST

Use external astrophysical transients (GRBs/kilonovae) as triggers for a deeper search for GWs

Current existing LVK searches target GRBs and FRBs (e.g., with PyGRB)

We perform simulations to estimate rate of kilonova detections

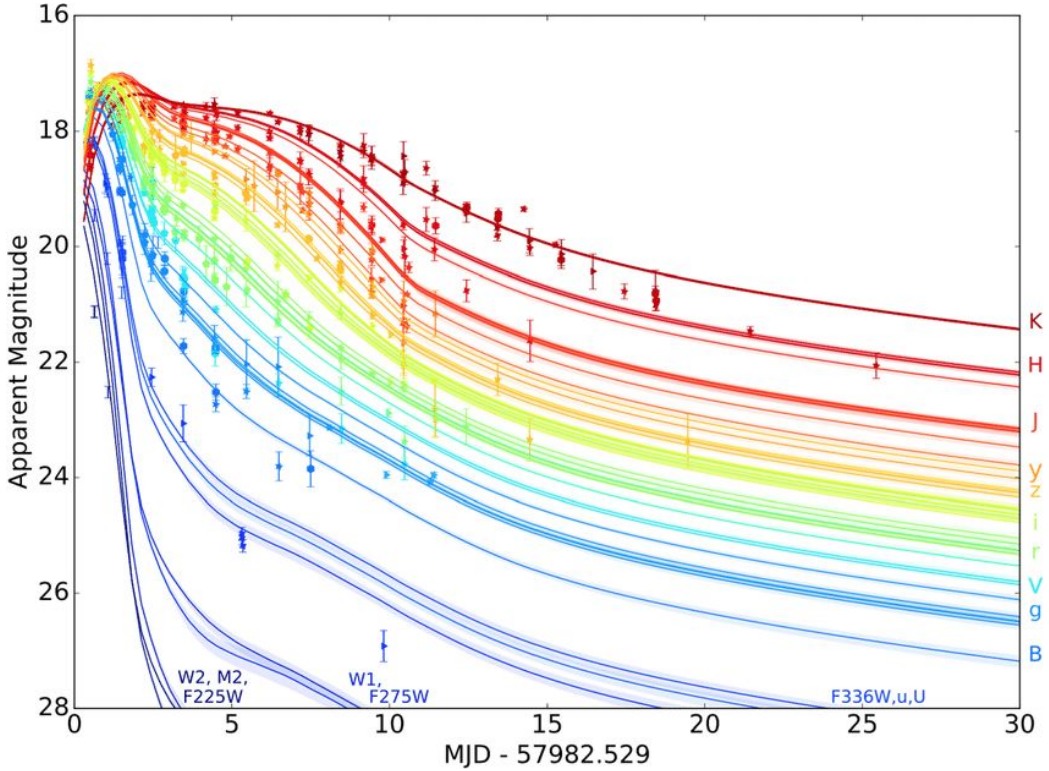
Use latest Rubin/LSST observing strategy

Rubin data processed by FINK broker (Möller et al. 2021)

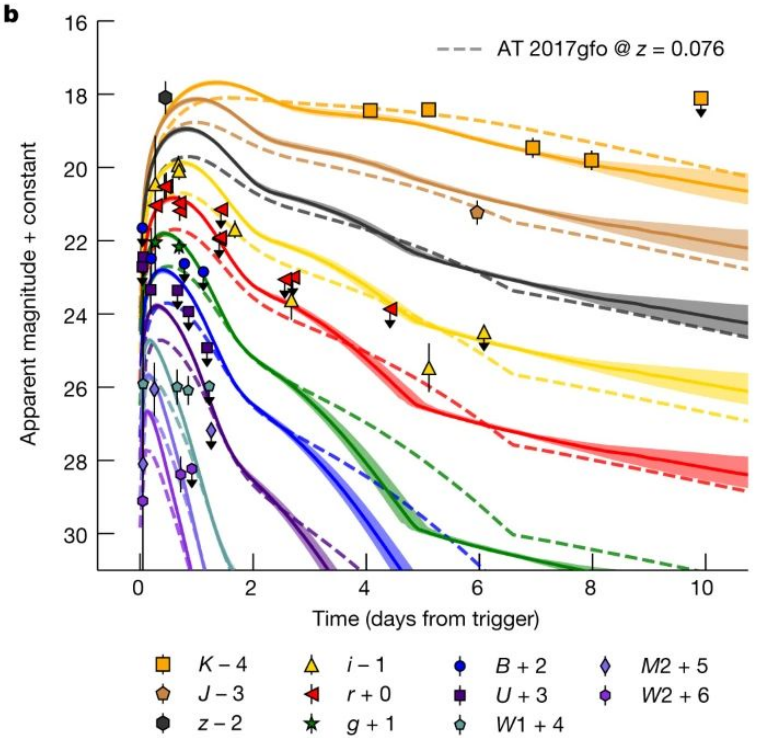
Compare two kilonova light curve models (Kasen & Bulla)

Use archival ZTF data to estimate contamination

Kilonova lightcurves

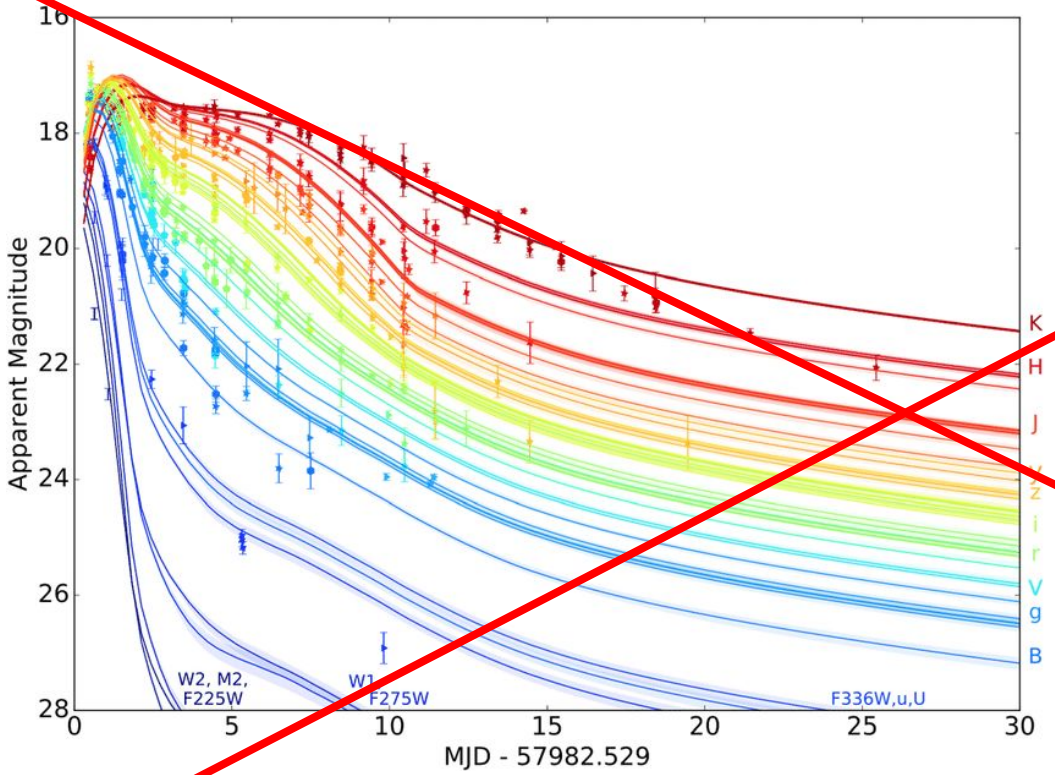


GW170817/AT2017gfo (compilation from Villar et al. 2018)

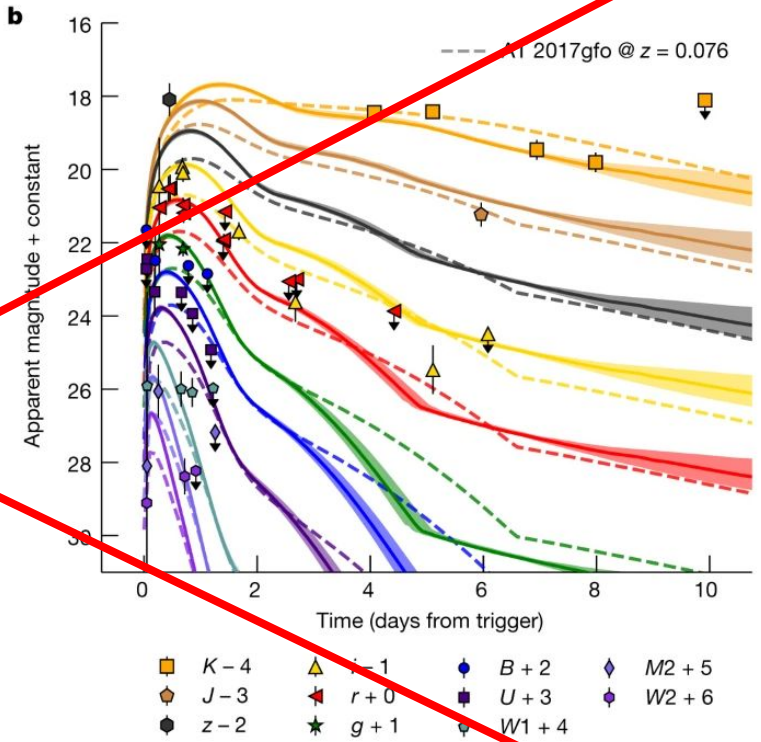


GRB 211211A (Rastinejad et al. 2022)

Kilonova lightcurves

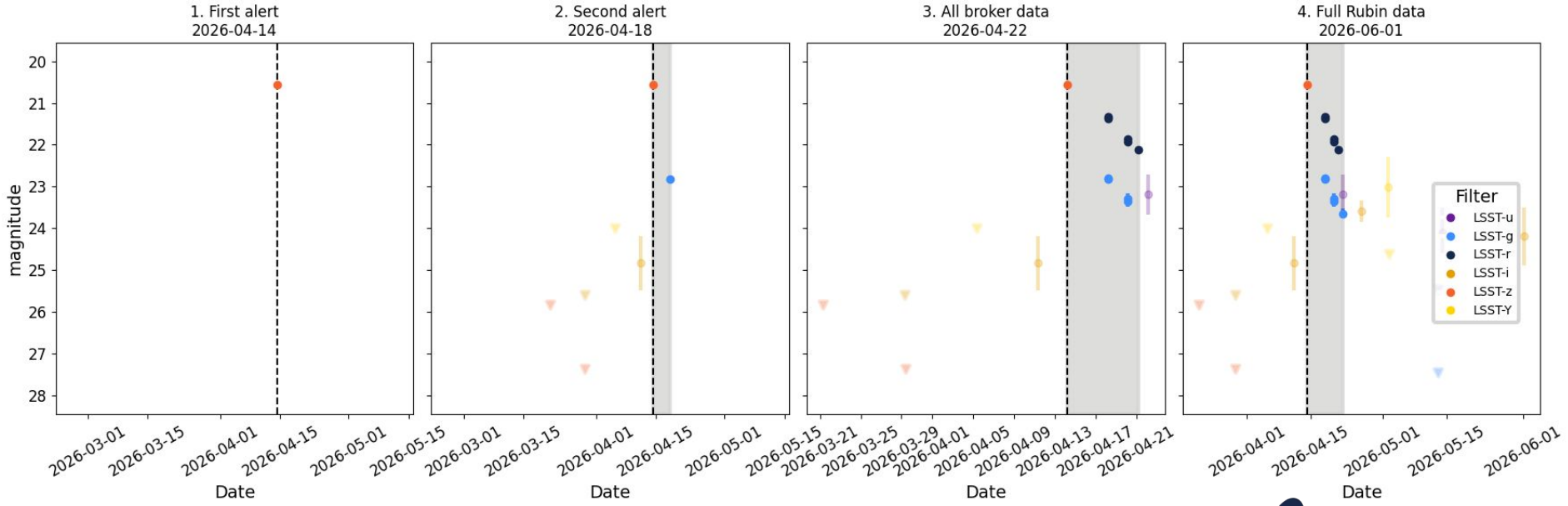


GW170817/AT2017gfo (compilation from Villar et al. 2018)



GRB 211211A (Rastinejad et al. 2022)

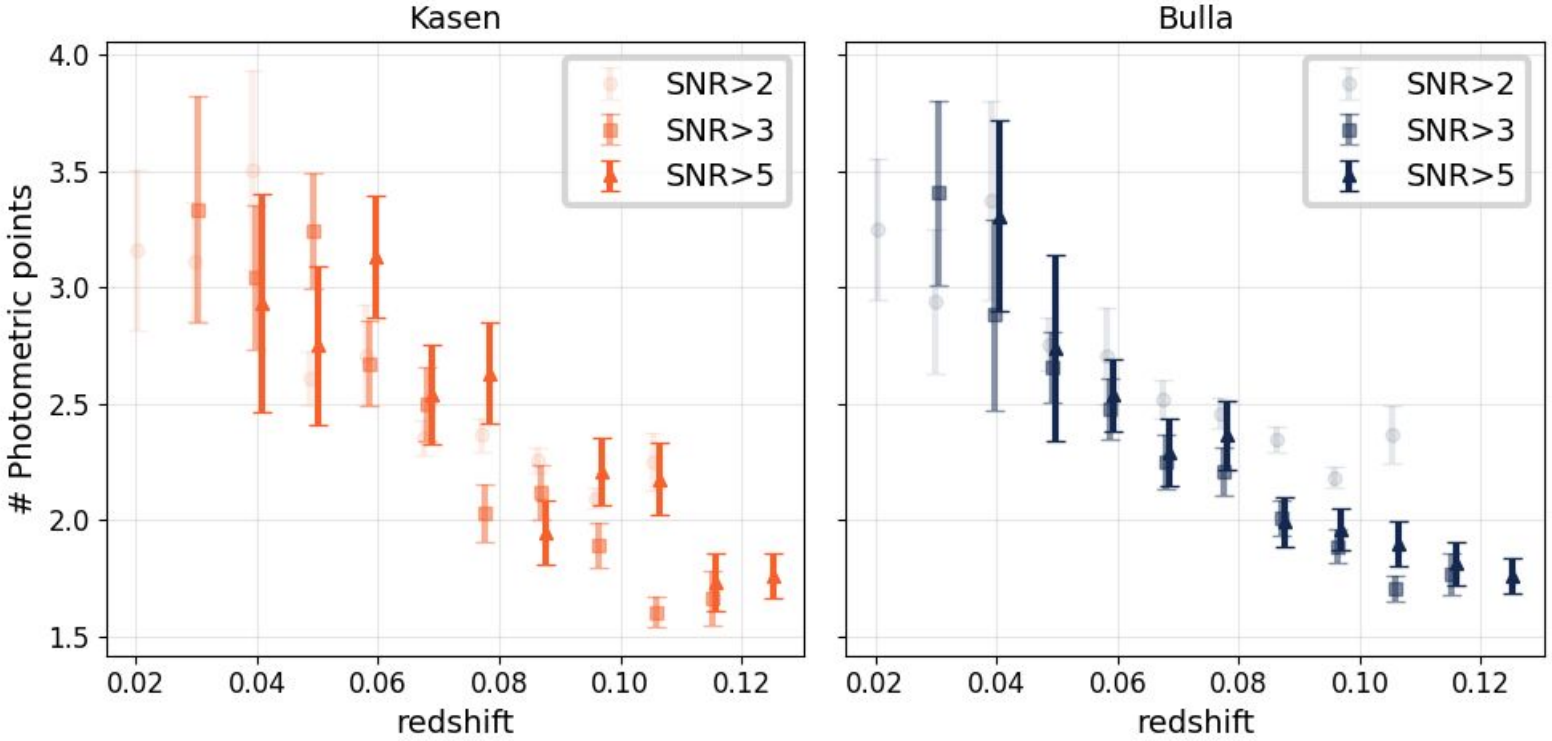
Example kilonova lightcurves from Rubin



Most kilonovae only have 1–2 detections due to survey (LSST) cadence

Average number of detections with redshift

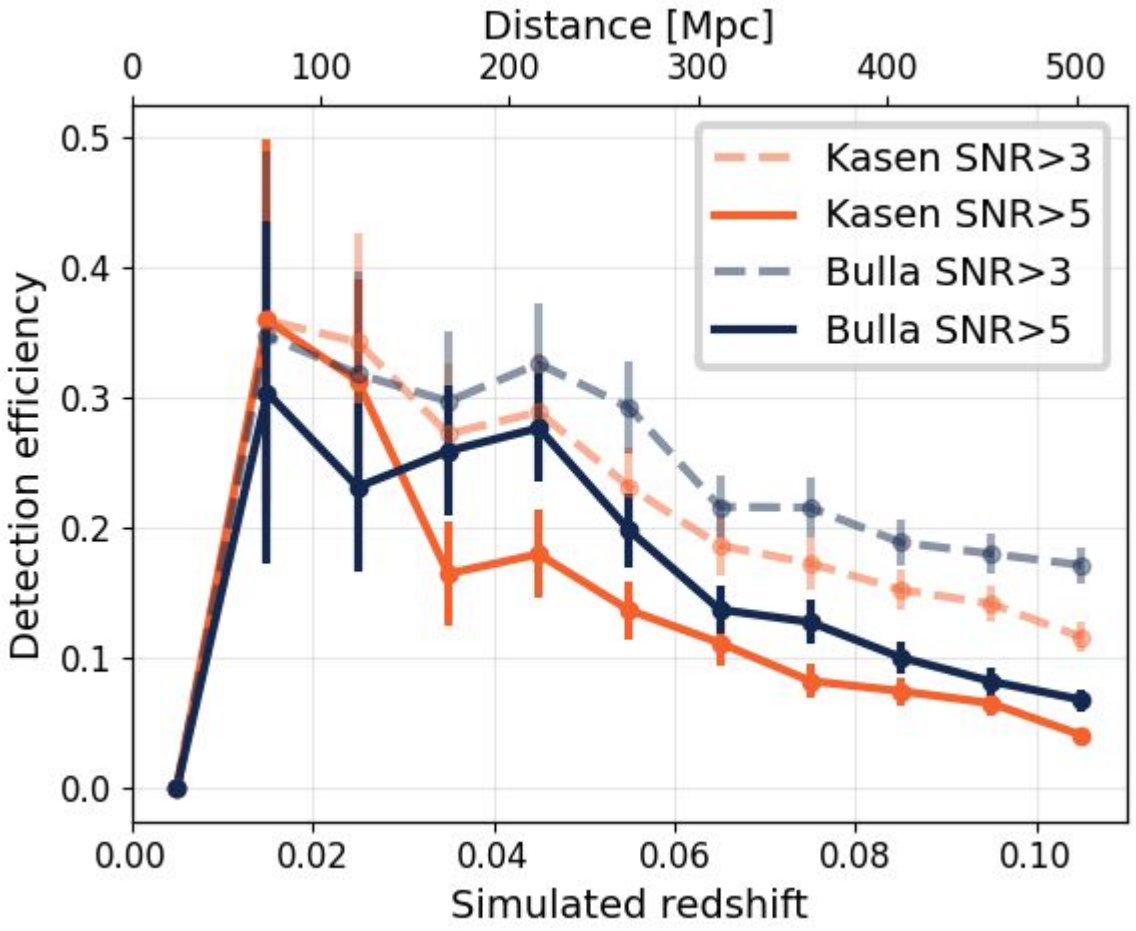
Most kilonova candidates only have a few detections due to being faint + LSST cadence



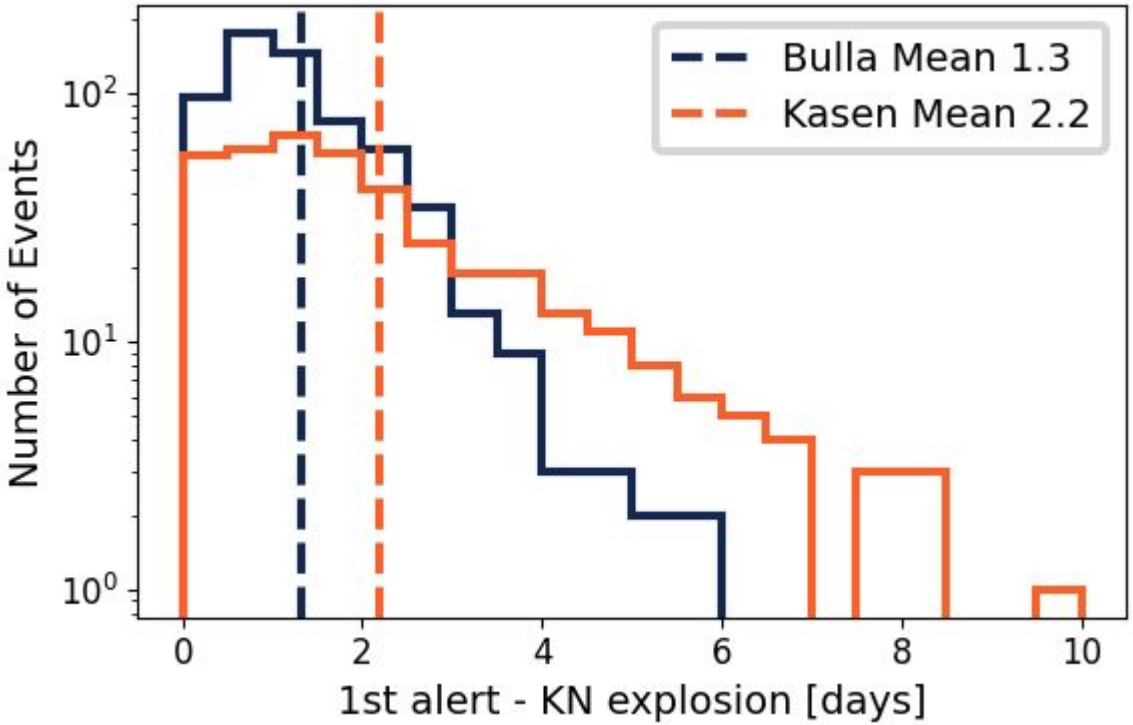
Detection efficiency with redshift

Around 10–20% of kilonovae are detected (at least one alert with SNR > 5)

Most detections in i and r band



Time between neutron star merger and first detection of the kilonova



KNe typically detected ~2 days after neutron star merger

Sets on source window for gravitational wave searches

FINK

Selection criteria & contamination

Kilonovae are faint and fade rapidly. Many contaminants (e..g, supernovae, flare stars, AGN, asteroids)

Need to remove known variable stars, remove known Gaia sources

Target outside the Galactic plane (|b| > 20)

Could be up to ~50 times as many contaminants for Rubin/LSST (based on number of expected alerts).

May be worse in the first year (e.g., uncatalogued variable stars)

Use archival ZTF data to estimate contamination using our criteria

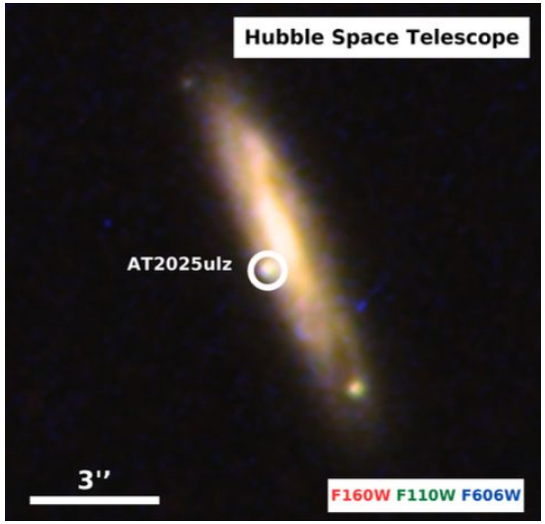
>30 contaminants per month with our strictest selection criteria

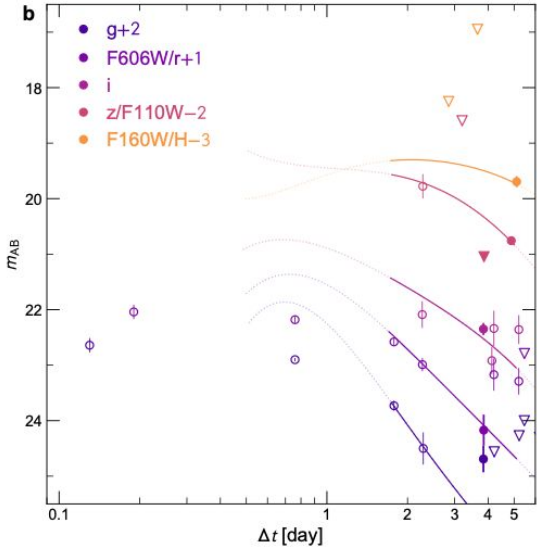
Contamination: Example - S250818k/AT2025ulz

Subthreshold BNS candidate, ZTF detected potential optical counterpart (Stein et al.)

Initially promising kilonova candidate (faint, red, fading rapidly, localised to a host galaxy)

Subsequent follow up led to it being reclassified as most likely an unrelated type IIb supernova





Yang et al. 2025

Conclusions

Overlapping observations between Rubin and LVK provide opportunity to perform a targeted search for kilonova candidates identified by FINK

Kilonovae are typically detected 1-2 days after the neutron star merger (large on-source window), and only have a few detections.

With our search strategy, we find ~30 events per month. Subselect based on distance/sky location, GW data availability

Sample dominated by contamination by other similar transients such as supernovae. True contaminant rates for Rubin/LSST currently unknown, will be well known by O5.

Paper submitted to ApJ

Small team to study contaminant rates in first few months of LSST.

Identify list of candidates for LVK to follow up in 2026

Observing proposal submitted by Liana Rauf et al. to follow up nearby Rubin kilonova candidates with ANU 2.3m