Kilonova Detectability with Wide-field Instruments

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Abstract

Kilonovae are ultraviolet, optical, and infrared transients powered by the radioactive decay of heavy elements following a neutron star merger. Joint observations of kilonovae and gravitational waves can offer key constraints on the source of Galactic r-process enrichment, among other astrophysical topics. However, robust constraints on heavy element production require rapid kilonova detection (within ~1 day of merger) as well as multiwavelength observations across multiple epochs. In this study, we quantify the ability of 13 wide-field-of-view instruments to detect kilonovae, leveraging a large grid of over 900 radiative transfer simulations with 54 viewing angles per simulation. We consider both current and upcoming instruments, collectively spanning the full kilonova spectrum. The Roman Space Telescope has the highest redshift reach of any instrument in the study, observing kilonovae out to z ~ 1 within the first day post-merger. We demonstrate that BlackGEM, DECam, GOTO, the Vera C. Rubin Observatory’s LSST, ULTRASAT, VISTA, and WINTER can observe some kilonovae out to z ~ 0.1 (~475 Mpc), while DDOTI, MeerLICHT, PRIME, Swift/UVOT, and ZTF are confined to more nearby observations. Furthermore, we provide a framework to infer kilonova ejecta properties following nondetections and explore variation in detectability with these ejecta parameters.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Neutron stars (1108); Transient detection (1957); Radiative transfer simulations (1967)

Supporting material: figure set

1. Introduction

Neutron star mergers have long been invoked as a cosmic source of heavy elements, produced through rapid neutron capture (r-process) nucleosynthesis (Lattimer & Schramm 1974; Lattimer et al. 1977; Symbalisty & Schramm 1982; Eichler et al. 1989; Freiburghaus et al. 1999; Côté et al. 2018). Heavy lanthanides and actinides fuse in material gravitationally unbound during the coalescence of either binary neutron stars (BNSs) or neutron star–black hole (NSBH) binaries with near-equal mass ratios (Metzger 2019). The residual radioactive decay of these r-process elements spurs electromagnetic emission, called a kilonova (Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010).

Kilonova emission spans ultraviolet, optical, and near-infrared wavelengths (UVOIR), with shorter-wavelength “blue” emission fading within a day of merger, giving way to “red” emission persisting for over a week (e.g., see Metzger 2019). Observations of a kilonova’s rapid evolution can reveal the role of neutron star mergers in Galactic r-process enrichment, while holding promise for additional discoveries in cosmology, nuclear physics, and stellar astrophysics.

Gamma-ray burst emission may also accompany a neutron star merger (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1992), with later theories (Fryer et al. 1999; Popham et al. 1999) linking neutron star mergers to short-duration gamma-ray bursts (sGRBs)—transient signals with hard gamma-ray emission that persist for less than two seconds (Norris et al. 1984; Kouveliotou et al. 1993). Numerous follow-up observations of sGRBs reveal viable kilonova candidates (Perley et al. 2009; Berger et al. 2013; Tanvir et al. 2013; Yang et al. 2015; Jin et al. 2016, 2020; Gompertz et al. 2018; Troja et al. 2018, 2019a; Ascenzi et al. 2019; Lamb et al. 2019; Rossi et al. 2020; Fong et al. 2021; O’Connor et al. 2021; Rastinejad et al. 2021), strengthening the theorized connection between sGRBs, kilonovae, and neutron star mergers. Astronomers solidified this connection with the joint detection of gravitational-wave (GW) event GW170817 (Abbott et al. 2017c), GRB 170817A (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017), and kilonova AT 2017gfo (Andreoni et al. 2017; Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017; Covino et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasliwal et al. 2017; Lipunov et al. 2017; Nicholl et al. 2017; Pian
et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Troja et al. 2017; Usumi et al. 2017; Valenti et al. 2017). GW170817 also serves as the first GW detection containing a neutron star (Abbott et al. 2017c) and the first multi-messenger detection with GWs (Abbott et al. 2017d).

Several serendipitous circumstances allowed for detection of the kilonova associated to GW170817. The source’s comparatively tight sky localization (31 deg² at 90% credible level; LVC 2017: Abbott et al. 2020b) combined with its nearby distance estimate (40 ± 8 Mpc; LVC 2017) promoted prompt detection of a UVOIR counterpart within 12 hr post-merger (Arcavi et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; Lipunov et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Valenti et al. 2017). Due to its nearby distance, GW170817 was confined to a localization volume of ~520 Mpc³ at the 90% credible level (LVC 2017), leaving only a few dozen plausible host galaxies, which were efficiently observed with galaxy-targeted observations. Additionally, GW170817’s favorable viewing angle (<20°; Ghirlanda et al. 2019; Troja et al. 2019b) aided coincident detection of an sGRB without excessive afterglow contamination of the kilonova signal.

However, detecting a kilonova at greater distances becomes increasingly difficult, often requiring the use of wide-field-of-view (FoV) instruments. For example, large sky localization, exacerbated by the lack of coincident sGRB detection, spurred fruitless counterpart searches (Coughlin et al. 2019; Hosseinzadeh et al. 2019; Paterson et al. 2021) following the GW detection of GW190425 (LVC 2019; Abbott et al. 2020a). This BNS merger’s sky localization was constrained to a massive 10,183 deg² at the 90% credible level (LVC 2019), requiring an area of the sky over 300 times the size of GW170817’s localization to be rapidly searched for transient signals. Additionally, the source was more distant than GW170817 (155°–45 Mpc; LVC 2019) and confined to a larger localization volume (9.7 × 10⁶ Mpc³; LVC 2019), making efficient galaxy-targeted kilonova searches unfeasible.

As GW detector sensitivity increases, wide-field instruments will remain necessary tools for kilonova detection. The advent of more sensitive GW detectors will lead to compact binary merger detection at greater distances, which jointly increases the sky volume required for counterpart searches in addition to reducing the effectiveness of galaxy-targeted searches. In the third Observing Run (O3) of advanced LIGO (Aasi et al. 2015) and advanced Virgo (Acernese et al. 2015), the average redshift horizon of a 1.4 M⊙ + 1.4 M⊙ BNS was 300 Mpc, 240 Mpc, and 100 Mpc for the LIGO Livingston, LIGO Hanford, and Virgo detectors, respectively. We note that mergers comprising more massive objects (e.g., NSBHs) are detectable at even greater distances.

The fourth Observing Run (O4) will considerably increase the sensitivity, with BNS horizon redshifts anticipated to increase to 360–430 Mpc, 200–270 Mpc, and 70–290 Mpc for advanced LIGO, advanced Virgo, and KAGRA (Akutsu et al. 2019), respectively (Abbott et al. 2020b). Furthermore, in the 2030s, proposed third-generation GW detectors including Einstein Telescope (Punturo et al. 2010) and Cosmic Explorer (Abbott et al. 2017a) will detect BNS mergers out to cosmological redshifts of z ~ 4 and z ~ 10, respectively (Hall & Evans 2019), far beyond the reaches of currently existing instruments.

Although sky localization is expected to significantly improve with larger networks of GW detectors (Schutz 2011; Nissanke et al. 2013; Abbott et al. 2020b), localization estimates will still encompass significant areas of the sky. In O4, the four-detector network of advanced LIGO, advanced Virgo, and KAGRA will observe BNS (NSBH) systems with a median sky localization area of 33 deg² (50 deg²) and volume of 52,000 Mpc³ (430,000 Mpc³), encapsulating thousands of plausible host galaxies (Abbott et al. 2020b). Moreover, the addition of a fifth GW detector in India will improve sky localization areas by approximately a factor of two (Pankow et al. 2018). However, even in the era of third-generation GW detectors, sky localization areas will remain large for distant BNS mergers, with more than 50% of BNS mergers at z ≥ 0.4 constrained to localization areas in excess of 100 deg² with a network of three Cosmic Explorer instruments (Mills et al. 2018). Therefore, wide-field instruments will remain a necessary tool for kilonova detection into the 2030s.

In this paper, we assess kilonova detectability with 13 wide-field instruments, quantifying the redshift out to which kilonovae are detectable for a variety of filters. This study builds upon previous detectability studies (Scolnic et al. 2018) by employing the Los Alamos National Laboratory (LANL) grid of radiative transfer kilonova simulations (Wollaeger et al. 2021) to explore detectability for a diverse range of kilonova ejecta masses, velocities, morphologies, compositions, and inclinations.

We describe the set of wide-field instruments selected for the study in Section 2 and then quantify the typical redshift reach of each instrument in Section 3. In Section 4, we explore how each instrument’s ability to observe a kilonova varies with ejecta properties. We build upon these results in Section 5 to provide a framework for inferring kilonova properties from non-detections. We summarize each instrument’s capacity for kilonova detection in Section 6 and offer suggestions for future kilonova searches in Section 7. Throughout the study, we adopt a standard Λ-CDM cosmology with parameters H₀ = 67.4 km s⁻¹ Mpc⁻¹, Ωₐ₀ = 0.315, and Ωₗ = 0.685 (Planck Collaboration et al. 2020). Data products and software produced through this study are available on GitHub.13

## 2. Wide-field Instruments

The optimal observing strategy for multiwavelength follow-up of LIGO/Virgo/KAGRA candidate events is an evolving science (e.g., Kasliwal & Nissanke 2014; Gehrels et al. 2016; Artale et al. 2020), and varies greatly depending on the instrument FoV, wavelength range, and sensitivity (see, e.g., Gehrels et al. 2015; Bartos et al. 2016; Cowperthwaite et al. 2019; Graham et al. 2019). Wide-field instruments provide the ability for rapid searches of GW sky localization regions with high cadence. In the next decade, a number of ground- and space-based facilities will be dedicated to these types of follow-up, enabling the ability to cover large sky regions in a short amount of time. We base our kilonova detectability study on a selection of current and future wide-field instruments with planned follow-up of LIGO/Virgo/KAGRA candidate events. In addition, we include instruments that have the sensitivity and wavelength coverage to contribute significantly to the kilonova detection rate, but that lack a formal GW follow-up strategy (i.e., LSST, Roman; Cowperthwaite et al. 2019; Foley et al. 2019; Andreoni et al. 2021b).

We note that this study is focused on the ability of wide-field instruments to detect kilonovae arising from poorly localized

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13 https://github.com/eachase/kilonova_detectability/
mergers. We primarily focus on kilonova searches following a 
LIGO/Virgo/KAGRA candidate BNS or NSBH event. How-
ever, the results of this study apply to kilonova searches 
following sGRB detections with large sky localization areas, 
such as some sGRBs detected with the Fermi Gamma-Ray 
Burnt Monitor (Goldstein et al. 2020). The follow-up strategy 
for well-localized events is significantly different (as it does not 
require covering large sky areas), and is beyond the scope of 
this work.

All instruments in this study are either already active or plan to 
see first light within the 2020s, in the advanced ground-based GW 
detector era. Our study includes several existing instruments such as 
the Deca-Degree Optical Transient Imager (DDOTI; Watson et al. 2016), 
de the Dark Energy Camera (DECam; Flaugher et al. 2015), the Gravitational-wave Optical Transient 
Observer (GOTO; Dyer et al. 2018, 2020), MeerLICHT (Bloemen et al. 2015), Swift’s Ultra-Violet Optical Telescope (UVOT; Roming et al. 2005), the Visible and Infrared Survey Telescope for 
Astronomy (VISTA; Sutherland et al. 2015), and the Zwicky Transient Facility (ZTF; Bellm et al. 2019). In addition, we include numerous near-term instruments such as BlackGEM 
(Bloemen et al. 2015), the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST; Ivezic et al. 2019), the PRime- 
focus Infrared Microlensing Experiment (PRIME17), the Nancy Grace Roman Space Telescope (Roman; Spergel et al. 2015), the Ultraviolet Transient Astronomy Satellite (ULTRASAT; Sagiv et al. 2014), and the Wide-Field Infrared Transient 
Explorer (WINTER; Lomax et al. 2020). This study is not a 
comprehensive list of all wide-field instruments available 
in the coming decade.

The selected wide-field instruments span UVOIR wave- 
lengths (≈2000–22000 Å) typical of kilonova emission. The 3σ 
limiting magnitudes were compiled from the literature based 
either on the instrument design sensitivity (i.e., BlackGEM, 
LSST, PRIME, Roman, ULTRASAT, WINTER) or the instrument performance during previous LIGO/Virgo obser-
ving runs (i.e., DECam, DDOTI, GOTO, MeerLICHT, UVOT, 
VISTA, ZTF). For instruments that have already demonstrated 
their capability to effectively cover GW localization regions, 
we focus our study on the filters used in those searches. The 
filter selection17 and limiting magnitudes are outlined here for 
each instrument (see also Table 1).

BlackGEM—BlackGEM is a planned array of wide-field 
optical telescopes located at the La Silla Observatory in Chile. 
It will initially consist of three 0.65 m optical telescopes, each 
with a 2.7 deg² FoV (Bloemen et al. 2015; Groth 2019). Each 
telescope is equipped with a six-slot (ugriz and broad q) filter 
wheel. The main focus of the BlackGEM mission is the follow-up 
of LIGO/Virgo/KAGRA candidate events, with a goal of 
achieving a cadence of two hours on low-latency sky localization 
using the u, q, and i filters. In order to determine the most sensitive 
filters for kilonova detection, we also include g, r, and z in our 
study. The 3σ limiting magnitude for a 300 s integration time 
under photometric observing conditions (1σ seeing) is q ≲ 23 mag 
(P. Groth 2021, private communication).

DDOTI—DDOTI is a wide-field, robotic imager located at the 
Observatorio Astronómico Nacional (OAN) in Sierra San Pedro 
Mártir, Mexico (Watson et al. 2016). The instrument comprises 
six 28 cm telescopes with a combined 69 deg² FoV. DDOTI 
produces unfiltered images, referred to as the w-band. It has previously been used in the follow-up of GW190814 (Thakur et al. 2020). Based on DDOTI follow-up during O3 (Becerra et al. 2021), we adopt a median exposure time of ≈2 hr, yielding a median 10σ limiting magnitude w ≳ 20.5 mag.

DECam—DECam is mounted on the 4 m Victor M. Blanco 
telescope at the Cerro Tololo Inter-American Observatory 
(CTIO) in Chile. The instrument has approximately a 3 deg² 
FoV, and was designed for the purpose of wide-field optical 
(ugrizy) surveys (Flaugher et al. 2015; Kessler et al. 2015; 
Soares-Santos et al. 2016). Electromagnetic follow-up of 
LIGO/Virgo candidate events has been carried out in previous 
observing runs by the Dark Energy Survey GW (DES GW) 
Collaboration (e.g., Soares-Santos et al. 2016, 2017; Andreoni et al. 2020; Herner et al. 2020; Morgan et al. 2020) using the i- 
and z-bands. In this work, we focus on kilonova detection by 
DECam at these wavelengths.

GOTO—At design specifications, GOTO will include an array of 
16 × 40 cm telescopes on two robotic mounts (producing a 
160 deg² FoV) at two separate locations in Spain and Australia, 
allowing for coverage of both hemispheres (Dyer et al. 2018, 
2020; Dyer 2020; Steeghs et al. 2022). A prototype, referred to as 
GOTO-4 (18 deg² FoV), was instituted in La Palma, Spain in 
2017 with an initial array of four telescopes. This was upgraded to 
an eight-telescope array in 2020 (GOTO-8), yielding a 40 deg² 
FoV (Dyer et al. 2020). The prototype mission, GOTO-4, has 
demonstrated its capability to cover large GW localization regions 
during O3 with good sensitivity to optical transients (Gompertz et al. 2020). In a 360 s integration time, GOTO can reach depths of 
L ≳ 21.0 mag (B. Gompertz & M. Dyer 2021, private 
communication; Steeghs et al. 2022), where L is a wide-band 
filter,18 approximately equivalent to g + r.

LSST—The Vera C. Rubin Observatory, currently under 
construction on Cerro Pachon in Chile, is anticipated to begin 
survey operations in 2023. The observatory consists of an 8.4 
m wide-field optical telescope covering a 9.6 deg² FoV. The 
Rubin Observatory’s LSST will survey half the sky every three 
nights in the ugrizy filters. The planned Wide–Fast–Deep 
(WFD) survey will reach r ≳ 24.2 mag (assuming 
amass r ~ 1.2) for a 30 s integration time (Ivezic et al. 2019).

Despite the lack of a formal GW follow-up strategy, we have included 
LSST within this study to highlight the sensitivity of the WFD 
survey (see also, e.g., Scolnic et al. 2018; Cowperthwaite et al. 
2019; Andreoni et al. 2021b) in order to encourage GW follow-
up and demonstrate the prospect of serendipitous detection.

MeerLICHT—MeerLICHT is a fully robotic 0.65 m optical 
telescope located at the South African Astronomical Observa-
tory (SAAO) in Sutherland, South Africa (Bloemen et al. 
2015). MeerLICHT was designed as the prototype instrument 
for the BlackGEM array (Groth 2019). The telescope has a 
2.7 deg² FoV, and covers the same ugrizy wavelengths 
as BlackGEM. MeerLICHT has been used for GW follow-up 
during past LIGO/Virgo observing runs (e.g., GW190814; de 
Wet et al. 2021) with observations in the u, q, and i filters. For 
comparison to BlackGEM, we likewise include the g, r, and z 
filters in our study. MeerLICHT is limited by sky background 
in 60 s exposures, yielding a limiting magnitude q ≳ 20.6 mag.

17 When available, filter response functions were taken from the SVO Filter Profile Service (Rodrigo & Solano 2020). The filter response functions for 
BlackGEM, DDOTI, GOTO, MeerLICHT, PRIME, and WINTER were 
obtained through private communication with the instrument teams.

18 https://github.com/GOTO-OBS/public_resources/tree/main/throughput
Table 1
Kilonova Detectability Metrics for Wide-field Instruments

| Instrument      | FoV (deg²) | Exp. Time (s) | Filter | λlim (Å) | mlim (AB) | z50%   | z95%   | z50% References |
|-----------------|------------|---------------|--------|----------|-----------|--------|--------|------------------|
| BlackGEM        | 8.1        | 300           | u      | 3800     | 21.5      | 0.037  | 0.013  | 0.091 1          |
|                 |            |               | g      | 4850     | 22.6      | 0.057  | 0.011  | 0.21   |
|                 |            |               | q      | 5800     | 23.0      | 0.072  | 0.027  | 0.23   |
|                 |            |               | r      | 6250     | 22.3      | 0.052  | 0.022  | 0.14   |
|                 |            |               | i      | 7650     | 21.8      | 0.044  | 0.015  | 0.13   |
|                 |            |               | z      | 9150     | 20.7      | 0.025  | 0.011  | 0.069  |
| DDOTI           | 69         | 7200          | w      | 6190     | 20.5      | 0.023  | 0.0083 | 0.073 2, 3      |
| DECam           | ∼3         | 90            | i      | 7870     | 22.5      | 0.058  | 0.022  | 0.18   4, 5     |
|                 |            |               | z      | 9220     | 21.8      | 0.042  | 0.014  | 0.12   |
| GOTO            | 40b        | 360           | L      | 5730     | 21.0      | 0.029  | 0.0097 | 0.097 6, 7      |
| LSST            | 9.6        | 30            | u      | 3690     | 23.6      | 0.078  | 0.012  | 0.28   8        |
|                 |            |               | g      | 4830     | 24.7      | 0.14   | 0.035  | 0.48   |
|                 |            |               | r      | 6220     | 24.2      | 0.12   | 0.043  | 0.43   |
|                 |            |               | i      | 7570     | 23.8      | 0.099  | 0.038  | 0.31   |
|                 |            |               | z      | 8700     | 23.2      | 0.079  | 0.029  | 0.24   |
|                 |            |               | y      | 9700     | 22.3      | 0.052  | 0.021  | 0.14   |
| MeerLICHT       | 2.7        | 60            | u      | 3800     | 19.1      | 0.013  | 0.0052 | 0.035 1, 9     |
|                 |            |               | g      | 4850     | 20.2      | 0.019  | 0.0032 | 0.073  |
|                 |            |               | r      | 5800     | 20.6      | 0.024  | 0.010  | 0.074  |
|                 |            |               | i      | 6250     | 19.9      | 0.019  | 0.0067 | 0.046  |
|                 |            |               | z      | 7650     | 19.4      | 0.016  | 0.0053 | 0.047  |
|                 |            |               | y      | 9150     | 18.3      | 0.0085 | 0.0023 | 0.024  |
| PRIME           | 1.56       | 100           | Z      | 9030     | 20.5      | 0.023  | 0.0099 | 0.067 10       |
|                 |            |               | Y      | 10200    | 20.0      | 0.019  | 0.0079 | 0.048  |
|                 |            |               | J      | 12400    | 19.6      | 0.017  | 0.0067 | 0.044  |
|                 |            |               | H      | 16300    | 18.4      | 0.0088 | 0.0023 | 0.023  |
| Roman           | 0.28       | 67            | R      | 6160     | 26.2      | 0.29   | 0.10   | 0.96   11, 12   |
|                 |            |               | Z      | 8720     | 25.7      | 0.24   | 0.10   | 0.79   |
|                 |            |               | Y      | 10600    | 25.6      | 0.23   | 0.10   | 0.79   |
|                 |            |               | J      | 12900    | 25.5      | 0.22   | 0.10   | 0.65   |
|                 |            |               | H      | 15800    | 25.4      | 0.22   | 0.095  | 0.48   |
|                 |            |               | F      | 18400    | 24.9      | 0.17   | 0.037  | 0.38   |
| Swift/UVOT      | 0.08       | 80            | u      | 3500     | 19.9      | 0.015  | 0.0019 | 0.061 13       |
| ULTRASAT        | 200        | 900           | NUV    | 2550     | 22.3      | 0.022  | 0.0022 | 0.10   14b      |
| VISTA           | 1.6        | 360           | Y      | 10200    | 21.5      | 0.038  | 0.012  | 0.094 15, 16   |
|                 |            |               | J      | 12600    | 21.0      | 0.032  | 0.011  | 0.071  |
|                 |            |               | H      | 16500    | 21.0      | 0.031  | 0.011  | 0.068  |
|                 |            |               | Ks     | 21400    | 20.0      | 0.018  | 0.007  | 0.045  |
| WINTER          | 1.0        | 360           | Y      | 10200    | 21.5      | 0.038  | 0.012  | 0.093 17, 18   |
|                 |            |               | J      | 12500    | 21.3      | 0.036  | 0.012  | 0.075  |
|                 |            |               | Hr     | 15800    | 20.5      | 0.023  | 0.010  | 0.052  |
| ZTF             | 47         | 30            | g      | 4770     | 20.8      | 0.025  | 0.0063 | 0.092 19       |
|                 |            |               | r      | 6420     | 20.6      | 0.024  | 0.0092 | 0.074  |
|                 |            |               | i      | 8320     | 19.9      | 0.019  | 0.0061 | 0.059  |

Notes. The column labeled z50% represents the maximum redshift at which 50% of LANL kilonova models are observable at any one time in a given band. Columns labeled z95% and z50% enumerate similar redshifts for 95% and 5% of modeled kilonovae, respectively.

a 10σ limiting magnitude.
b FoV of one GOTO-8 system.

References. (1) P. Groot (2021, private communication); (2) Thakur et al. (2020); (3) Boccera et al. (2021); (4) Kessler et al. (2013); (5) Soares-Santos et al. (2016); (6) B. Gompertz & M. Dyer (2021, private communication); (7) Dyer (2020); (8) Ivezic et al. (2019); (9) de Wet et al. (2021); (10) T. Sumi (2021, private communication); (11) Scolnic et al. (2018); (12) Hounsell et al. (2018); (13) Oates et al. (2021); (14) Sagiv et al. (2014); (15) McMahon et al. (2013); (16) Banerji et al. (2015); (17) N. Lourie & D. Frostig (2021, private communication); (18) Frostig et al. (2022); (19) Bellm et al. (2019).
**PRIME**—PRIME is a 1.8 m wide-field infrared telescope under construction at SAAO. The telescope has a 1.56 deg² FoV and covers wavelengths ZYJHK. In a 100 s integration time PRIME reaches depths of $z \gtrsim 20.5$ mag and $y \gtrsim 20.0$ mag (T. Sumi 2021, private communication).

**Roman**—The 2.4 m Roman Space Telescope (formerly WFIRST), with planned launch no later than 2027, will cover a 0.28 deg² FoV (~200 times larger than the Hubble Space Telescope (HST); Sp Berger et al. 2015). The Wide Field Instrument (WFI) is sensitive to optical/infrared wavelengths between 5000 and 20000 Å. In this study, we focus on the RZYJH filters. We have chosen to include Roman within this study in order to encourage GW follow-up (see also Foley et al. 2019) and demonstrate its sensitivity to kilonovae out to cosmological distances. The instrument sensitivity is adopted following Hounsell et al. (2018) and Scolnic et al. (2018).

**UVOT**—The UVOT on board the Neil Gehrels Swift Observatory has a wavelength coverage of 1600–8000 Å and a 0.08 deg² FoV (Roming et al. 2005). Despite its smaller FoV, Swift is able to cover large regions of the sky in ~24 hr with a rapid response (a few hours) to LIGO/Virgo alerts (Evans et al. 2016, 2017; Klingler et al. 2019, 2021; Page et al. 2020). In addition, Swift has the added benefit of simultaneous X-ray coverage from the X-ray Telescope. UVOT follow-up has been optimized for its smaller FoV by targeting galaxies with high probabilities of being the host, ensuring they are completely within the FoV (Klingler et al. 2019). The large majority of UVOT tiles are observed with the $u$-band, and therefore we focus our analysis on this filter. Based on GW follow-up during O3, we adopt a median 5σ limiting magnitude $u \gtrsim 19.9$ mag (Oates et al. 2021).

**ULTRASAT**—ULTRASAT is an ultraviolet telescope with planned launch to geostationary orbit in 2024. The instrument will have a 200 deg² FoV and cover wavelengths between 2200 and 2800 Å, referred to as NUV for near-ultraviolet. The estimated limiting magnitude in 900 s integration time is NUV $\gtrsim 22.3$ mag. Since ULTRASAT does not have a publicly available filter function, we approximated the filter response functions using a top-hat function between 2200 and 2800 Å.

**VISTA**—VISTA is a 4 m wide-field survey telescope equipped with the VISTA infraRed CAMera (VIRCAM) covering wavelengths ZYJHKs, with a 1.6 deg² FoV (Sutherland et al. 2015). VISTA is located at the Cerro Paranal Observatory in Chile, and operated by the European Southern Observatory (ESO). Follow-up of LIGO/Virgo candidate events has largely occurred through the VISTA Near infraRed Observations Uncovering Gravitational wave Events (VIRGOUGE) project in the $Y$, $J$, and $K_s$ filters (e.g., Tanvir et al. 2017; Ackley et al. 2020). The 5σ limiting magnitudes were taken from the Vista Hemisphere Survey (McMahon et al. 2013; Banerji et al. 2015) and rescaled to a 360 s exposure time, yielding $Y \gtrsim 21.5$ mag, $J \gtrsim 21.0$ mag, $H \gtrsim 21.0$ mag, and $K_s \gtrsim 20.0$ mag.

**WINTER**—WINTER is a new infrared instrument, with planned first light in late 2021 (Frostig et al. 2020, 2022; Lourie et al. 2020). WINTER will use a 1 m robotic telescope located at the Palomar Observatory in California, USA. The instrument has a ~1 deg² FoV and covers infrared wavelengths YJHK. In a 360 s integration time, WINTER reaches 5σ depth $Y \gtrsim 21.5$ mag, $J \gtrsim 21.3$ mag, and $H \gtrsim 20.5$ mag (N. Lourie & D. Frostig 2021, private communication).

**ZTF**—ZTF employs a wide-field camera (47 deg² FoV) on the Palomar 48 in (P48) Oschin (Schmidt) telescope in San Diego County, California, USA (Bellm et al. 2019). Using 30 s exposures, it can cover 3760 deg² hr⁻¹ to limiting magnitude $r \gtrsim 20.6$ mag (Graham et al. 2019). This capability makes ZTF an effective tool for kilonova searches, both for GW candidate events (Coughlin et al. 2019; Kasliwal et al. 2020) and serendipitous discovery (Andreoni et al. 2021a).

We note that the follow-up strategy and sensitivity of these instruments vary greatly depending on a number of factors, such as the observing conditions, sky location, and the size of the GW localization region. The sensitivity assumed in this work is considered to be an approximate limiting magnitude for GW follow-up, while noting that this sensitivity is variable day-to-day for each ground-based instrument. We also note that the limiting magnitudes are computed for “snapshot” exposures, and more sensitive images can be obtained by stacking multiple exposures over the course of a night. Figure 1 displays the assumed limiting magnitudes, indicating separate filters by their effective wavelength. For consistency, we compute effective wavelengths from all filter response functions using Equation (1) of King (1952). These instruments provide an excellent coverage of the range of wavelengths expected for kilonovae. In Table 1, we present the FoV, typical exposure time of GW tiling, filter effective wavelengths, and limiting magnitudes for each instrument.

### 3. Assessing Kilonova Detectability

We employ the LANL grid of kilonova simulations (Wollaeger et al. 2021) to assess each instrument’s ability to observe a kilonova. Rather than limiting our study to AT 2017gfo-like kilonovae, these radiative transfer simulations span a wide range of ejecta parameters, including expected values from both BNS and NSBH progenitors. The LANL simulations are two-component, multidimensional, axisymmetric kilonova models, generated with the Monte Carlo radiative transfer code SuperNu (Wollaeger et al. 2013; Wollaeger & van Rossum 2014). These simulations rely on nucleosynthesis results from the WinNet code (Korobkin et al. 2012; Winteler et al. 2012) in addition to a set of tabulated binned opacities (Fontes et al. 2020) from the LANL suite of atomic physics codes (Fontes et al. 2015). The most recent LANL grid of kilonova simulations (Wollaeger et al. 2021) includes a full set of lanthanides and fourth-row elements, some of which were not included in previous data sets (Wollaeger et al. 2018).

These radiative transfer simulations simultaneously evolve two ejecta components: a dynamical ejecta component and a wind ejecta one. The dynamical ejecta component is initiated with a low electron fraction ($Y_e = 0.04$) and corresponds to the lanthanide-rich or “red” emission. This component has composition consistent with the robust “strong” $r$-process pattern such as the one repeatedly found in metal-poor $r$-process enriched stars and in the solar $r$-process residuals (Sneden et al. 2009; Holmbeck et al. 2020). The second, lanthanide-poor wind ejecta component corresponds to the “blue” kilonova emission and is primarily composed of wind-driven ejecta from the post-merger accretion disk. The wind ejecta is initiated with two separate wind compositions, representing either high-latitude $(Y_e = 0.37)$ or mid-latitude...
(Ye = 0.27) wind composition, consistent with winds induced by a wide range of post-merger remnants (Lippuner et al. 2017; Wollaeger et al. 2021). Dynamical ejecta is initiated with a toroidal morphology, constrained near the binary’s orbital plane, while the wind ejecta is modeled by either a spherical or “peanut-shaped” geometry (Korobkin et al. 2021). Figure 2 presents the two morphological configurations used in the simulation set. Models span five ejecta masses (0.001, 0.003, 0.01, 0.03, and 0.1 M⊙) and three ejecta velocities (0.05c, 0.15c, and 0.3c) for each component, covering the full range of kilonova properties anticipated from numerical simulations (see Wollaeger et al. 2021 and references therein). By considering all possible combinations of ejecta properties, the LANL grid includes 900 kilonova simulations. The full set of simulation parameters are compiled in Table 2.

These 900 simulations have previously been used to estimate kilonova properties associated with follow-up of GW190814 (Thakur et al. 2020) and GW200115 (Dichiara et al. 2021), in addition to targeted observations of two cosmological sGRBs (Bruni et al. 2021; O’Connor et al. 2021). Additionally, the LANL simulation grid is the basis for an active learning-based approach to a kilonova light-curve surrogate modeling and parameter estimation framework (Ristic et al. 2022).

All 900 multidimensional simulations are rendered in 54 viewing angles, each subtending an equal solid angle of 4π/54 sr. In this study, we use spectra from all 54 viewing angle renditions to quantify detectability, making the generous assumption that a GW event has equal probability of detection at all viewing angles. This differs from kilonova searches aimed at sGRBs, such as in O’Connor et al. (2021), where we limit our simulation grid to face-on viewing angles (θ_e < 15°) as sGRBs are typically detected on-axis. By including all 54 viewing angles of the 900 LANL kilonova simulations, our detectability study incorporates a full suite of 48,600 kilonova models.

Each model includes a set of time-dependent spectra, which are converted to light curves by computing a magnitude associated with each spectrum. Spectra are not simulated for the first three hours post-merger (rest frame). We render each simulated set of spectra into a light curve for various redshifts, z, and for a broad range of filters with corresponding wavelength-dependent bandpass filter functions, R(λ0). Magnitudes are computed according to

\[ m_{AB} = -2.5 \log_{10} \left( \frac{1}{c} \int_{0}^{\infty} f(\lambda_0(1+z)^{-1}) R(\lambda_0) \lambda_0^{-1} d\lambda_0 \right) \]

where \( \lambda_0 \) is the observed wavelength in cm, \( c \) is the speed of light in cm s\(^{-1}\), and \( f(\lambda_0) \) is the wavelength-dependent spectral flux density in erg s\(^{-1}\) cm\(^{-2}\) (Hogg et al. 2002; Blanton et al. 2003). In Equation (1), we account for cosmological K-corrections (Humason et al. 1956; Oke & Sandage 1968) by converting rest-frame spectral emission to observer-frame wavelengths.

We define a kilonova as detectable in a given filter if it outshines the limiting magnitude of the filter, as listed in Table 1. Then, we trace the detectability’s variation with redshift by considering light curves at various cosmological distances. Figure 3 displays detectability constraints for two representative filters: the LSST r-band (optical) and the Roman Space Telescope’s H-band (near-infrared). We present detectability, defined as the fraction of detectable kilonova simulations, as a
function of both redshift and observer-frame time. Detectability in the LSST/r-band peaks around 12 hr post-merger, then rapidly decreases over time. However, the higher wavelength Roman/H-band reaches peak detectability two days post-merger, with 5% of nearby (<1 Gpc) kilonovae detectable over two weeks after merger. For comparison, Figure 3 includes detectability constraints for AT 2017gfo-like kilonovae, computed from spectroscopic data (Chornock et al. 2017; Cowperthwaite et al. 2017; Nicholl et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017).21 We do not present AT 2017gfo-like detectability within 12 hr of merger, because no spectra were collected at this point in the kilonova evolution. Our AT 2017gfo-like detectability metrics are broadly consistent with previous studies (Scolnic et al. 2018; Rastinejad et al. 2021). Similar figures for all filters in Table 1 are available in the Supplemental Materials.

Table 2

Properties of LANL Kilonova Simulations (Adapted from Wollaeger et al. 2021)

| Property                          | Values                                      |
|----------------------------------|---------------------------------------------|
| Dynamical ejecta mass           | {0.001, 0.003, 0.01, 0.03, 0.1} $M_\odot$   |
| Wind ejecta mass                | {0.001, 0.003, 0.01, 0.03, 0.1} $M_\odot$   |
| Dynamical ejecta velocity       | 0.05c, 0.15c, 0.3c                          |
| Wind ejecta velocity            | 0.05c, 0.15c, 0.3c                          |
| Dynamical ejecta morphology     | toroidal (T; Cassini oval family; Korobkin et al. 2021) |
| Wind ejecta morphology          | spherical (S) or “peanut” (P; Cassini oval family; Korobkin et al. 2021) |
| Dynamical ejecta composition    | initial $Y_e = 0.04$ (see Table 2 in Wollaeger et al. 2021) |
| Wind ejecta composition         | initial $Y_e = 0.27$ or 0.37 (see Table 2 in Wollaeger et al. 2021) |

21 Compiled from Guillochon et al. (2017).

Figure 2. Schematics of the two combined morphologies used in the simulation grid (Wollaeger et al. 2021). All models have a toroidal (T, red) dynamical ejecta, 450 models are simulated with a spherical wind (S, blue), and 450 models are simulated with a peanut-shaped wind (P, blue). Each component is varied over the mass–velocity grid in Table 2, and hence is not necessarily drawn to scale here (adapted from Korobkin et al. 2021 and Wollaeger et al. 2021).

Figure 3. Detectability constraints for two filters: LSST/r-band (top) and Roman/H-band (bottom). Contours indicate the fraction of 48,600 simulated kilonovae (900 simulations each rendered at 54 viewing angles) with apparent magnitudes brighter than the limiting magnitude in each filter, for a given redshift and observer-frame time. The three white contours demarcate regions where 5%, 50%, and 95% of simulated kilonovae are detectable. The magenta curve represents each filter’s ability to detect AT 2017gfo-like kilonovae. The complete figure set (13 images) is available in the online journal. (The complete figure set (13 images) is available.)

For each filter, we compute the maximum redshift at which 50% of simulated kilonovae are detectable at any one time, $z_{50\%}$, called the “typical redshift reach.” With this definition, we ascribe
a typical redshift reach of $z_{50\%}=0.12$ and $z_{50\%}=0.22$ to the LSST/r-band and Roman/H-band in Figure 3, respectively. Table 1 lists the typical redshift reaches for all instruments and filters, in addition to compiling maximum detectable redshifts for both 95% and 5% of simulated kilonovae as $z_{95\%}$ and $z_{5\%}$, respectively.

Additionally, Figure 4 compares the typical redshift reach for all instruments in this study, highlighting the differences as a function of their effective wavelengths (see Table 1). Typical redshift reaches vary from $z_{50\%}=0.0085$ ($\sim$38 Mpc) for the MeerLICHT/\textit{z}-band up to $z_{50\%}=0.29$ ($\sim$1.5 Gpc) for the Roman/R-band. As anticipated, the typical redshift reach for each instrument correlates significantly with the limiting magnitude distribution in Figure 1. We remind the reader that simulated light curves are not available earlier than three hours post-merger (rest frame), resulting in no detectability predictions in this time range. This omission may bias the detectability estimates of short-wavelength (ultraviolet) filters, such as the ULTRASAT/NUV-band, LSST/u-band, and UVOT/u-band.

### 4. Detectability Variations with Kilonova Properties

The typical redshift reach often varies significantly with kilonova properties, such as the ejecta mass or velocity. Larger ejecta masses generally result in more luminous kilonova emission, allowing for detection at higher redshifts, while kilonovae containing lower ejecta masses are only detectable at nearby distances. This mass dependence makes it difficult to determine whether a GW candidate event will produce an observable kilonova for a given instrument. Robust detectability metrics are further muddled by compounding degeneracies with other parameters such as velocity of the expanding ejecta, viewing angle, and composition.

Differing kilonova properties induce variations in kilonova detectability. For example, a kilonova with large wind ejecta mass and small dynamical ejecta mass may be easily detectable in the ultraviolet but difficult to observe in near-infrared filters, while other kilonova parameters may produce emission that is primarily detectable in the infrared. Shorter-wavelength filters probe the wind ejecta, with peak emission in optical wavelengths at early times. At the short-wavelength extreme, ultraviolet instruments capture the early structure of the outermost wind-driven ejecta (Arcavi 2018; Banerjee et al. 2020). However, these short-wavelength filters offer little insight into the dynamical ejecta, which peaks at redder wavelengths. Additionally, a filter’s variation with kilonova parameters depends on the source redshift: high-redshift kilonova emission is shifted to longer wavelengths, requiring consequently redder filters to capture variability in dynamical ejecta mass. If kilonova properties are unknown, multiband observations across UVOIR wavelengths are necessary to maximize the probability of kilonova detection.

Figure 5 demonstrates the variation in kilonova detectability in the Roman/H-band for different ejecta masses. The left (right) column restricts the simulation set to one dynamical (wind) ejecta mass, while allowing all other parameters to vary, resulting in 9720 simulations per panel (180 simulations each with 54 viewing angles). In the left column, dynamical ejecta mass varies from the smallest (0.001 $M_{\odot}$) to the largest (0.1 $M_{\odot}$) values in the LANL simulation grid. Larger ejecta masses enhance detectability, as 50% of simulations with dynamical ejecta masses of 0.1 $M_{\odot}$ are detectable out to $z=0.31$, with peak emission three days post-merger. Smaller ejecta masses induce both dimmer emission and an earlier peak (e.g., Kasen et al. 2017), as shown by the diminished late-time detectability and smaller typical redshift reach ($z=0.16$) for dynamical ejecta masses of 0.001 $M_{\odot}$.

However, a small subset of kilonovae with low dynamical ejecta...
masses remain detectable at redshifts $z > 0.3$, consistent with the addition of a large wind ejecta mass. The variation is a bit more pronounced for wind ejecta: 50% of simulated kilonovae with large wind ejecta masses ($0.1 M_e$) are detectable out to $z = 0.37$, while less than 5% of those with low wind ejecta mass ($0.001 M_e$) are detectable at such high redshifts. Additionally, as kilonova emission at higher redshift ($z \geq 0.4$) is proportionally shifted to longer wavelengths, the Roman/H-band becomes less effective at detecting emission from mergers with high dynamical ejecta mass. As a result, variation with dynamical ejecta mass decreases with redshift.

Different wavelength bands exhibit varying dependence on ejecta mass. Similarly to in the near-infrared (Roman/H-band), detectability at optical and ultraviolet wavelengths varies significantly with wind ejecta masses. However, optical and ultraviolet bands show little variability with dynamical ejecta masses. We define the variable $v$ to quantify a given filter’s sensitivity to a kilonova property such as ejecta mass. As an example, we can quantify the Roman/H-band’s dependence on wind ejecta mass by comparing the 50% detectability contours (dotted lines) in Figure 5. We label the 50% detectability contours for the lowest ejecta mass (top panel) and the highest ejecta mass (bottom panel) as $g(t)$ and $f(t)$, respectively. We then quantify variability with mass as

$$v = \frac{1}{2} \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{[f(t) - g(t)] dt}{\int_{t_{\text{min}}}^{t_{\text{max}}} [f(t) + g(t)] dt},$$

integrating from the shortest rest-frame time, $t_{\text{min}} = 0.125$ day, to a maximum time of $t_{\text{max}} = 20$ days. Values of $v$ close to zero indicate negligible variation with a given parameter, while higher values of $v$ indicate a significant dependence. There is no upper limit on $v$, although we note that a value of $v = 1$ corresponds to a threefold enhancement in $z_{50\%}$ between two subsets of parameters (i.e., $f(t) = 3g(t)$). Based on the 50%
contours in Figure 5, the Roman/H-band produces $v = 0.91$ for dynamical ejecta mass (left column) and $v = 0.94$ for wind ejecta mass (right column), suggesting that the Roman/H-band’s detectability is slightly more dependent on wind ejecta mass than on dynamical ejecta mass.

Figure 6 presents the variability scores for all filters in Figure 4 as a function of both dynamical ejecta mass (purple) and wind ejecta mass (orange). As anticipated, variability with dynamical ejecta mass increases with filter wavelength, while variability with wind ejecta mass decreases with wavelength. Ultraviolet filters exhibit the largest dependence on wind ejecta mass, with the UVOT/u-band and ULTRASAT/NUV-band both yielding $v = 1.7$. The PRIME/H-band demonstrates the largest variability with dynamical ejecta mass, with $v = 1.3$. Variability scores directly relate to a filter’s ability to constrain a given parameter from photometric observations (see Section 5).

The interplay between various kilonova parameters must be considered to fully capture variations in detectability. For example, masses for both dynamical and wind ejecta alter kilonova emission and thus affect detectability. We explore the interrelation of dynamical and wind ejecta masses in Figure 7, using the Roman/H-band as an example. The top (bottom) panel restricts total ejecta mass to the lowest (highest) simulated mass, where total mass is the sum of both dynamical and wind ejecta masses. In both panels, the total mass is fixed while composition, morphology, viewing angles, and ejecta velocities vary, resulting in 1944 simulations in each panel (36 simulations each rendered at 54 viewing angles). Total mass significantly alters kilonova detectability in the Roman/H-band, with a variability $v = 1.6$ between the total masses of 0.002 $M_\odot$ (top panel) and 0.2 $M_\odot$ (bottom panel). Kilonovae with higher total ejecta masses are detectable at significantly higher redshifts than their low-mass counterparts.

In addition to mass, other properties of neutron star mergers affect kilonova detectability. Luminosity may vary with viewing angle due to morphological effects (Korobkin et al. 2021) and lanthanide curtaining (Kasen et al. 2015). Additionally, ejecta composition significantly alters detectability in some filters, as lanthanide-poor ejecta yields significantly less luminous emission in the redder optical and infrared filters than lanthanide-rich ejecta. Ejecta velocity also has a pronounced effect on detectability, with higher ejecta velocities leading to earlier peak emission and subsequently more luminous kilonovae (e.g., Kasen et al. 2017). Numerous other factors alter simulated light curves and kilonova detectability including thermalization of decay products and nuclear mass models (Lippuner & Roberts 2015; Hotokezaka & Nakar 2020). Considerably more uncertain nuclear physics may be propagated by allowing synthesized r-process abundance patterns to differ from the robust “strong” pattern, as done in Barnes et al. (2021) and Zhu et al. (2021).

5. Inferring Kilonova Properties with Wide-field Observations

We can leverage parameter-dependent variations in kilonova detectability to infer ejecta properties and guide future observations. By coupling nondetections in wide-field transient searches with the kilonova detectability metrics presented in this work, constraints can be placed on kilonova ejecta properties. Nondetections are particularly constraining when a very large fraction of the GW sky localization is covered by multiple instruments or filters in a short period of time. To explore this, we consider observations in the Roman/H-band taking place two days post-trigger for a merger with a predicted redshift of $z = 0.2$ (an ambitious $\sim 1$ Gpc for current GW detectors). If these observations yield no transient detection, the total ejecta mass of an associated kilonova can be constrained to lower values. This relationship is supported by Figure 7,
because nearly 100% of simulated kilonovae with total ejecta masses of 0.2 $M_\odot$ are detectable two days post-merger at $z = 0.2$, while no kilonovae with total ejecta masses of 0.002 $M_\odot$ are detectable. Thus, a nondetection rules out the presence of a kilonova with the highest ejecta mass included in the simulation grid at $z = 0.2$.

This method has previously been employed by Thakur et al. (2020) to constrain parameters for a plausible kilonova associated with GW190814 (Abbott et al. 2020c). The authors compare upper limits from wide-field searches (including DDOTI) to the LANL kilonova grid, ruling out the presence of a high-mass ($> 0.1 M_\odot$) and fast-moving (mean velocity $> 0.3c$) wind ejecta. Total ejecta masses $\geq 0.2 M_\odot$ are also strongly disfavored by the upper limits. A similar method was used by Dichiara et al. (2021) to constrain kilonova ejecta properties from an upper-limit observation following GW200115 (Abbott et al. 2021b).

Nondetections in wide-field searches may also guide subsequent observing schedules. For example, assume that you are planning additional follow-up observations after a nondetection in the BlackGEM/$q$-band at 12 hr post-merger for an event at $z = 0.05$ ($\sim 230$ Mpc) that has not been detected by any other instrument. Of all the instruments in this study intended to follow up GW candidate events (i.e., not including LSST or Roman), an additional BlackGEM observation is best suited for follow-up observations in this example. This conclusion was reached by searching the 48,600 LANL kilonova models to identify kilonovae that are undetectable with BlackGEM at this redshift and time, but detectable with other instruments at 36 hr post-merger. Based on the LANL kilonova grid, 8% of simulated kilonovae are detectable 36 hr post-merger in the BlackGEM/$q$-band, but not detectable in the same band 12 hr post-merger. No other filter considered in this study (other than LSST or Roman) results in more than 8% of detectable kilonovae 36 hr post-merger, following a BlackGEM/$q$-band nondetection at 12 hr post-merger. A selection of detectable light curves is highlighted in the right panel of Figure 8, suggesting the presence of high-mass ($> 0.1 M_\odot$) and slow-moving (mean velocity $< 0.15c$) wind ejecta. BlackGEM’s $q$-band does not offer strong constraints on dynamical ejecta properties, consistent with the discussion in Section 4 and Figure 6. DECam can also provide useful follow-up observations after a nondetection at 12 hr, with 6% of simulated kilonovae detectable in DECam, but not BlackGEM at the aforementioned times. Several instruments, including DDOTI, GOTO, VISTA, and PRIME, have negligible probability of detecting a kilonova at $z = 0.05$ following a BlackGEM nondetection. However, we note that both LSST and Roman have the highest probability of detecting a kilonova in this scenario, further highlighting their utility in kilonova searches.

We performed a similar analysis assuming a nondetection with WINTER ($J$-band) 12 hr post-merger for a GW event at $z = 0.05$ ($\sim 230$ Mpc). Again, we searched the 48,600 LANL kilonova models for kilonovae that are undetectable with the WINTER/$J$-band at this redshift and time, but detectable with other instruments between 12 and 36 hr post-merger. Based on the LANL kilonova grid, 16% of simulated kilonovae are detectable with the WINTER/$J$-band 36 hr post-merger but not detectable 12 hr post-merger. These light curves are highlighted in the right panel of Figure 8. The WINTER nondetection and subsequent detection are consistent with large ejecta masses, with over 70% of orange light curves in Figure 8 corresponding to total ejecta masses $\geq 0.1 M_\odot$. WINTER’S $J$-band offers constraints on both dynamical and wind ejecta parameters, as expected from Figure 6. In addition to WINTER, several instruments in this study are capable of observing kilonovae following a WINTER nondetection. For example, over 40% of simulated light curves are observable in the BlackGEM/$q$-band at 36 hr post-merger following a WINTER nondetection 24 hr earlier. Additional instruments have nonzero probabilities of detecting a kilonova under this scenario: GOTO can observe 6% of simulated kilonovae following a WINTER nondetection, DDOTI can observe 12%, VISTA can observe 15%, ZTF can observe 3%, and ULTRASAT can observe 1%.

These examples demonstrate how nondetections offer powerful constraints on kilonova ejecta properties. However, targeted observations with large-aperture telescopes are better suited to sample kilonova emission after an initial detection in a wide-field search, providing multiband observations over the duration of kilonova evolution. The LANL set of kilonova models provides a rich data set for thorough statistical analysis and optimization of kilonova observing strategies, beyond the study of nondetections in wide-field surveys, which we reserve for future work. In addition, we refer the reader to several other studies on the efficacy of Bayesian parameter estimation to infer...
kilonova parameters (i.e., Villar et al. 2017; Coughlin et al. 2018; Barbieri et al. 2019; Heinzel et al. 2021; Nicholl et al. 2021; Ristic et al. 2022).

6. Instrument Results

In this section, we briefly summarize each instrument’s capacity for kilonova detection. We describe the accessible redshifts for each filter and the most probable times for kilonova detection. Additional figures for each instrument are presented in the Supplemental Materials.

BlackGEM—BlackGEM’s optical and near-infrared filters are well suited to detect kilonova emission, especially within two days post-merger. The broad $q$-band provides the best opportunities for detection, with 50% of simulated kilonovae detectable at $z = 0.072$ ($\sim$340 Mpc) and kilonovae with high wind ejecta mass detectable out to $z \sim 0.2$. Our results largely support BlackGEM’s plan to follow up with the $u, q,$ and $i$ filters. However, we note that the $q$-band increases the detectable kilonova parameter space at later times ($t \geq 2$ days). As an example, nearly 10% of modeled kilonovae at $z = 0.01$ ($\sim$45 Mpc) are only observable in the $q$-band at $t = 4$ days (observer frame) and not observable in any other BlackGEM filters.

DDOTI—DDOTI’s $w$ filter can detect 50% of simulated kilonovae out to $z = 0.023$ ($\sim$100 Mpc), with a peak detectability $12$ hr post-merger. DDOTI can follow up some LIGO/Virgo/KAGRA candidate events with inferred redshifts out to $z = 0.073$ ($\sim$340 Mpc).

DECam—DECam’s $i$- and $z$-bands are sensitive to kilonova detection, reaching $z_{50\%} = 0.058$ ($\sim$270 Mpc) and 0.042 ($\sim$190 Mpc), respectively. The $i$-band may be more useful for kilonova searches than the $z$-band, because nearly all simulated kilonovae detectable in the $z$-band are also detectable in the $i$-band, regardless of time and redshift. DECam is able to observe kilonovae with high ejecta mass out to $z = 0.18$ ($\sim$900 Mpc).

GOTO—GOTO’s $L$-band achieves $z_{50\%} = 0.029$ ($\sim$130 Mpc), with peak detectability $\sim$8 hr post-merger. GOTO is able to follow up high wind ejecta mass LIGO/Virgo/KAGRA candidate events with inferred redshifts out to $z = 0.097$ ($\sim$460 Mpc).

LSST—LSST can observe the most distant kilonovae of all other ground-based instruments in the study. The $g$-band has the highest typical redshift reach, with $z_{50\%} = 0.14$ peaking $\sim$8 hr post-merger. We especially encourage the use of LSST’s $g, r,$ and $i$ filters for follow-up of relatively distant LIGO/Virgo/KAGRA candidate events ($z = 0.15–0.5$) that may not be observable with other ground-based, wide-field instruments.

MeerLICHT—Similarly to BlackGEM, MeerLICHT’s broad $q$ filter is the most sensitive at detecting kilonovae. MeerLICHT has better chances to observe kilonovae located at $z < 0.074$ ($\sim$345 Mpc). For comparison, BlackGEM can detect kilonovae at over twice the distance of MeerLICHT.

PRIME—This ground-based infrared instrument is useful for late-time kilonova searches, with peak detectability between one and eight days post-merger. The most sensitive filter reaches $z_{50\%} = 0.023$ ($\sim$100 Mpc), with some kilonovae with high ejecta mass detectable out to $z = 0.067$ ($\sim$300 Mpc). Additionally, the PRIME/$H$-band may offer strong constraints on dynamical ejecta masses.

Roman—Roman provides an excellent tool for kilonova detection and GW follow-up. The Roman/$R$-band is the most sensitive filter in our study, reaching $z_{50\%} = 0.29$ with some kilonovae detectable out to $z \sim 1$. However, Roman’s relatively small FoV precludes follow-up of GW candidate events with large localization areas. We encourage the use of the Roman Space Telescope for GW follow-up (see also Foley et al. 2019), especially for distant and/or well-localized candidate events.

UVOT—Swift/UVOT’s $u$-band reaches $z_{50\%} = 0.015$ ($\sim$70 Mpc), with a peak detectability around four hours post-merger. The $u$-band is well suited to follow up LIGO/Virgo/KAGRA candidates out to $z = 0.061$ ($\sim$280 Mpc). UVOT’s detectability estimates may be biased by the lack of simulated light curves within three hours post-merger.

ULTRASAT—ULTRASAT provides an excellent tool for early kilonova detection. Its 200 deg$^2$ NUV filter can detect 50% of simulated kilonovae out to $z = 0.022$ ($\sim$100 Mpc), with mergers with high wind ejecta mass detectable out to $z = 0.1$ within the first 12 hr post-merger. We caution the reader in their interpretation of ULTRASAT results. This study is based on an approximate ULTRASAT filter, because no finalized filter is publicly available. Furthermore, we anticipate that ULTRASAT’s detectability estimate would increase with the availability of simulated light curves before three hours.

VISTA—VISTA is one of the most sensitive ground-based infrared facilities in the study, with $z_{50\%} = 0.038$ ($\sim$170 Mpc) for the $Y$-band. VISTA is able to follow up LIGO/Virgo/KAGRA candidate events with high ejecta mass out to $z = 0.094$ ($\sim$450 Mpc) one day post-merger. Additionally, VISTA observations may provide strong constraints on dynamical ejecta masses.
WINTER—Similarly to VISTA, WINTER is one of the most sensitive ground-based infrared facilities in the study, with $z_{50\%} = 0.038$ ($\sim 170$ Mpc) for the Y-band. WINTER is capable of following up some nearby (within $\sim 100$ Mpc) mergers over two weeks post-merger. WINTER can observe kilonovae with high ejecta mass out to $z = 0.093$ ($\sim 440$ Mpc) one day post-merger, in addition to offering tight constraints on dynamical ejecta mass. Our results are generally consistent with the detectability estimates presented in Frostig et al. (2022).

ZTF—ZTF is well suited to searching large sky localization regions for relatively nearby kilonovae ($z \lesssim 0.1$), with a typical redshift reach of $z = 0.02$ ($\sim 100$ Mpc) in the g-, r-, and i-bands. ZTF is able to detect a subset of kilonovae with high ejecta mass out to $z = 0.094$ ($\sim 445$ Mpc).

7. Discussion and Conclusions

This study explores kilonova searches with current and upcoming wide-field instruments. This analysis relies on the LANL grid of kilonova simulations (Wollaeger et al. 2021), a set of 48,600 radiative transfer models that span a variety of ejecta parameters. Based on these simulations, we quantify each instrument’s ability to detect a kilonova, recording the fraction of observable kilonovae from the simulation grid for various times and redshifts. The 44 filters in this study have significant variations in their typical redshift reach; ultraviolet filters are restricted to observing nearby kilonovae ($z < 0.3$), while the Roman Space Telescope can observe a subset of kilonovae out to $z \sim 1$. We concentrate on wide-field kilonova searches following a GW candidate event, although the conclusions of this study are equally relevant to kilonova searches following poorly localized short GRBs. Additionally, the framework presented in this study is easily adaptable, and can be applied to searches performed by more sensitive instruments with smaller FoV (e.g., Gemini, Keck, GTC, VLT, SALT, HST, JWST) following the detection of a kilonova. Additionally, we remind the reader that the facilities studied in this work do not constitute a comprehensive selection of wide-field instruments.

Detecting, analyzing, and modeling kilonovae is a new and evolving science; many uncertainties remain after only a single confident multi-messenger observation with GWs (Abbott et al. 2017d). As a result, the models that lay the foundation of this study rely on numerous physical assumptions, including the use of a specific nuclear mass model (the finite-range droplet model, Möller et al. 1995) and decay product thermalization (Barnes et al. 2016; Rosswog et al. 2017). While the LANL grid of kilonova models covers a wide range of kilonova parameters (see Section 3 and Table 2), this simulation grid does not span all possible ejecta scenarios. For instance, the simulations do not encompass all possible variations in ejecta morphology (Korobkin et al. 2021) or composition (Even et al. 2020). We also ignore changes in the detected UVOIR emission due to extinction or the presence of contamination from either an sGRB afterglow or the host galaxy, which will be expanded upon in a future work.

Our work produces results that are consistent with the detectability study presented by Scolnic et al. (2018), which determined kilonova detectability using an AT 2017gfo-like model. Scolnic et al. (2018) predict a redshift range of $z = 0.02$–0.25 for LSST, consistent with our redshift range of $z = 0.035$–0.48 for the most sensitive LSST filter. Our results are also broadly consistent with the detectability estimates presented by Rastinejad et al. (2021), which leveraged three kilonova models (in addition to AT 2017gfo) to infer the maximum redshift of kilonova detection.

Similarly to Scolnic et al. (2018), we focus only on the ability of these instruments to detect a kilonova, and not its unambiguous identification (as this outcome depends on multi-epoch observations across a range of filters). Wide-field searches are likely to uncover numerous other transient signals (e.g., supernovae), potentially masquerading as a kilonova signal (see Cowperthwaite & Berger 2015 for a discussion of kilonova contaminants). LIGO/Virgo/KAGRA candidate events constrained to large localization volumes are increasingly likely to reveal false positive kilonova candidates, further necessitating the need for repeated observations of each field to rapidly distinguish a kilonova candidate. In future work, we intend to provide methods to disentangle kilonova candidates from other transients with a limited number of photometric observations.

We caution the reader in the interpretation of our results and emphasize that the typical redshift reach presented in Table 1 and Figure 4 refer to the redshifts at which 50% of simulated kilonovae are detectable. This is not equivalent to the probability of detection for the full population of kilonovae. For example, our results claim that 50% of simulated kilonovae are observable in the LSST/r-band at $z = 0.12$. This does not imply that the LSST/r-band has a 50% probability of observing a kilonova at $z = 0.12$. Such a statement relies on a realistic astrophysical distribution of kilonova ejecta properties, while our study is based on a uniformly sampled grid of models. This study could be expanded to draw from a distribution of kilonova models with the availability of more robust models for binary neutron star populations, neutron star equation of state, and mappings between compact object progenitors and ejecta. Additionally, this work could be further expanded to include redshift-dependent rates of neutron star mergers and associated GW detection.

Multiband observations capture variability in kilonova emission and provide tighter constraints on kilonova properties, such as the composition and ejecta mass. Once a kilonova is identified, targeted follow-up observations at several wave-lengths (and times) are necessary to constrain ejecta properties. Additionally, instruments must be distributed in geographically disparate locations, similarly to the Las Cumbres Observatory Global Telescope Network (Brown et al. 2013), to maximize the probability of kilonova detection. Instrument response time may also vary significantly based on the location of a neutron star merger on the sky. We stress the utility of both ground-based and space-based detectors to allow for rapid follow-up post-trigger, aiding in kilonova detection.

Kilonova searches also benefit from a variety of fields of view and exposure times, such as the collection of instruments in this study. Wide-FoV instruments with short exposure times are best suited to rapidly scan the sky for GW candidate events localized to large regions of the sky, while smaller FoV instruments with longer exposure times are better suited for well-localized (\(\lesssim 10\) deg\(^2\)) events. For example, while the Roman Space Telescope has the largest typical redshift reach in this study, less sensitive, wider FoV instruments are better able to follow up GW candidate events with large localization areas.

Based on the results of our study, we present the following findings to guide observing strategies and commissioning of future instruments.
1. This study demonstrates the utility of a diversity of wide-field instruments to search for kilonovae following GW detections. This includes a variety in instrument location, sensitivity, FoV, cadence, exposure time, and wavelength coverage. Additionally, rapid dissemination of both GW and electromagnetic search results is critical to optimize counterpart searches among this diverse array of instruments.

2. Early observations increase the probability of observing a kilonova, especially at ultraviolet and optical wavelengths. Based on the results in this study, we stress the importance of early-time observations for kilonova detection. Although not a focus of this study, we note that early observations offer the most stringent constraints on wind ejecta properties.

3. More sensitive wide-field ultraviolet instruments are needed for kilonova detection as LIGO/Virgo/KAGRA reach design sensitivity. The ultraviolet instruments in this study can observe only a small fraction of kilonovae beyond $z \sim 0.1$, which is equivalent to the BNS horizon redshift of advanced LIGO at design sensitivity (Abbott et al. 2020b).

4. We promote the construction of additional wide-field near-infrared instruments. Compared to optical instruments, few ground-based near-infrared instruments are available for GW follow-up, potentially reducing the probability of kilonova detection. Near-infrared instruments hold immense promise for kilonova detection, because they are able to detect kilonovae within several days post-merger as opposed to the limited timescale accessible to ultraviolet and optical instruments.

5. We recommend using this work as a guide for scheduling future kilonova observations. We encourage observations if a nonzero number of simulated kilonovae are detectable at a given time and redshift based on the figures in the Supplemental Materials. To meet observational and programmatic needs, observing teams may select a fraction of detectable kilonovae (i.e., 5%, 50%) as a threshold to guide GW follow-up searches.

6. Low-latency GW products, such as sky localization and distance estimates, should be used to alter observing strategies. We recommend comparing low-latency distance estimates with the detectability estimates provided in this work.

The current and upcoming wide-field instruments in this study are well poised to observe kilonovae coincident with GW events in the advanced detector era. However, the landscape of multi-messenger astronomy with GWs will change through the construction of new detectors. Sky localization will improve as additional GW detectors are commissioned (Abbott et al. 2020b), allowing larger-aperture instruments to cover higher percentages of the localization region. Simultaneously, enhanced GW detector sensitivity will reveal neutron star mergers at cosmic distances previously inaccessible through GWs alone, with the Einstein Telescope and Cosmic Explorer detecting BNS mergers at redshifts out to $z \sim 4$ and $z \sim 10$, respectively (Hall & Evans 2019). To match the increase in GW detector sensitivity, innovative UVOIR instruments must be constructed to observe kilonovae in the era of third-generation GW detectors.

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