Kilonova and Optical Afterglow from Binary Neutron Star Mergers. I. Luminosity Function and Color Evolution

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Abstract

In the first work of this series, we adopt a GW170817-like viewing-angle-dependent kilonova model and the standard afterglow model with a light-curve distribution based on the properties of cosmological short gamma-ray burst afterglows to simulate the luminosity functions and color evolution of both kilonovae and optical afterglow emissions from binary neutron star (BNS) mergers. We find that ~10% of the nearly-on-axis afterglows are brighter than the associated kilonovae at the peak time. These kilonovae would be significantly polluted by the associated afterglow emission. Only at large viewing angles with sin θr ≥ 0.20, the electromagnetic signals of most BNS mergers would be kilonova-dominated and some off-axis afterglows may emerge at ~5–10 days after the mergers. At a brightness dimmer than ~23–24 mag, according to their luminosity functions, the number of afterglows is much larger than that of kilonovae. Because the search depth of the present survey projects is <22 mag, the number of afterglow events that are detected via serendipitous observations would be much higher than that of kilonova events, consistent with the current observations. For the foreseeable survey projects (e.g., Mephisto, WFST, and LSST), whose search depths can reach ≥23–24 mag, the detection rate of kilonovae could have the same order of magnitude as afterglows. We also find that it may be difficult to use the fading rate in a single band to directly identify kilonovae and afterglows among various fast-evolving transients by serendipitous surveys. However, the color evolution between the optical and infrared bands can identify them because the color evolution patterns of these phenomena are unique compared with those of other fast-evolving transients.

Unified Astronomy Thesaurus concepts: Gravitational waves (678); Neutron stars (1108); Gamma-ray bursts (629)

1. Introduction

Binary neutron star (BNS) and neutron star–black hole (NSBH) mergers are the prime gravitational wave (GW) sources for current and future ground-based GW detectors (Abbott et al. 2020). They have been proposed to be the progenitors of short gamma-ray bursts (sGRBs; Paczynski 1986; Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992; Zhang 2018), their associated broadband afterglows,8 and kilonova emission. The merger of BNS or NSBH would drive an ultrarelativistic jet that may be powered by accretion of a massive remnant disk onto the newly formed BH or NS after the merger (Rezzolla et al. 2011; Paschalidis et al. 2015; Ruiz et al. 2016). The interaction of the relativistic jet with the ambient medium generates multifrequency nonthermal afterglow emission ranging from radio to X-rays (Rees & Meszaros 1992; Meszaros & Rees 1993; Mészáros & Rees 1997; Paczynski & Rhoads 1993; Sari et al. 1998).

Because the radiation of afterglow is beamed, if the viewing angle is far outside the core of the relativistic jet, the afterglow would have a low peak luminosity and a delayed light-curve rise. In addition to the beamed sGRB and its afterglow, an amount of neutron-rich matter is isotropically released, which undergoes rapid neutron capture (r-process) nucleosynthesis (Lattimer & Schramm 1974, 1976; Symbalisty & Schramm 1982). The radioactive decay of r-process nuclei powers a rapidly evolving thermal kilonova in the ultraviolet, optical, and infrared bands.9

The first BNS merger GW event, GW170817 (Abbott et al. 2017a), was detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO; Aasi et al. 2015) and by Virgo (Acernese et al. 2015). At ~1.7 s after the merger, GRB170817A with a duration of ~2 s was triggered by the Fermi GRB Monitor (Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017; Zhang et al. 2018), and the associated kilonova AT2017gfo was discovered in the host galaxy NGC 4993 ~11 hr later (Abbott et al. 2017c; Arcavi et al. 2017; Coulter et al. 2017; Drout et al. 2017; Evans et al. 2017; Kasliwal et al. 2017; Kilpatrick et al. 2017; Pian et al. 2017; Smartt et al. 2017; Lamb et al. 2019a).

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off-axis multiwavelength afterglow (from radio to X-ray) was detected, with a luminosity peaking at ~200 days (Margutti et al. 2017; Troja et al. 2017; Lazzati et al. 2018; Lyman et al. 2018; Ghirlanda et al. 2019). The multimessenger observations of this event provided smoking-gun evidence for the BNS merger origin of sGRBs. Abbott et al. (2021) recently reported observations of GWs from two NSBH mergers. Despite many efforts for follow-up observations, no confirmed kilonova or afterglow candidate was identified (e.g., Coughlin et al. 2020a; Anand et al. 2021), which may suggest that the two NSBH merger events were plunging events without tidal disruption of the NSs. This may suggest that the two NSBH merger events were plunging events without tidal disruption of the NSs (e.g., Virgili et al. 2011; Wanderman & Piran 2015; Sun et al. 2017; Prentice et al. 2018; Rest et al. 2018; McBrien et al. 2021). However, none of these events has been firmly identified as a kilonova. Andreoni et al. (2021) reported a few independent optically discovered GRB afterglows without any detection of kilonova candidates.

In this series of two papers, we study the observation properties and survey strategies of optical counterparts of BNS mergers. In the first paper of the series, we study the observation properties of a kilonova and of the afterglow of BNS mergers, including luminosity functions, viewing-angle-dependent light curves, and color evolution. In the second paper of the series (Zhu et al. 2021c, Paper II), based on the results of the first paper, we study how likely it is that the kilonovae and afterglows from BNS mergers can be discovered in future observations, and what the best strategy would be to discover them for wide-field surveys. This paper is organized as follows. We discuss the properties of kilonovae and afterglows, and constrain the physical parameters by observations available so far in Section 2. We simulate luminosity distributions of kilonovae and afterglows, and discuss their brightness ratio at different bands in Section 3. In Section 4 we focus on the color evolution properties of kilonovae and compare them with other well-known fast-evolving transients. The color evolution of kilonova-contaminated afterglows is also analyzed. We summarize our results with a discussion in Section 5.

### 2. Modeling

In order to simulate the luminosity functions of the kilonovae and afterglows of BNS mergers and the detectability of optical EM counterparts from BNS mergers (Paper II), one needs to know the redshift distribution of BNS mergers in the universe and the cosmological radiation properties for both kilonovae and optical afterglows.

#### 2.1. Redshift Distribution

In principle, the observed system parameter and redshift distributions for BNS mergers should be the results of the convolution of both the intrinsic system parameters and the redshift distribution. In this paper, we ignore the possible redshift evolution of the BNS system parameters (e.g., Sun et al. 2015) to allow us to separately discuss the parameter distributions and the redshift distribution of BNS systems, where $z$ is the redshift. The number density per unit time for BNS mergers at a given redshift $z$ can be estimated as

$$\frac{dN_{\text{BNS}}}{dz} = \frac{\rho_{0,\text{BNS}} f(z) dV(z)}{1 + z},$$

where $\rho_{0,\text{BNS}}$ is the local BNS event rate density, and $f(z)$ is a dimensionless redshift distribution factor. The comoving volume element $dV(z)/dz$ in Equation (1) is

$$\frac{dV}{dz} = \frac{4\pi D_L^2}{H_0 (1 + z)^2 \sqrt{\Omega_\Lambda + \Omega_m (1 + z)^3}},$$

where $c$ is the speed of light and $D_L$ is the luminosity distance, which is expressed as

$$D_L = \frac{(1 + z)}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_\Lambda + \Omega_m (1 + z)^3}}.$$

BNS mergers would occur after a delay timescale with respect to the star formation history. Main types of delay-time distributions include the Gaussian delay model (Virgili et al. 2011), the log-normal delay model (Wanderman & Piran 2015), and the power-law delay model (Virgili et al. 2011). Sun et al. (2015) suggested that the log-normal delay model is one of the favored delay-time models to explain sGRB observations. Hereafter, we adopt the log-normal delay model as our merger
delay model, whose analytical fitting expression of \( f(z) \) is adopted as Equation (A8) of Zhu et al. (2021e).

2.2. EM Emissions

2.2.1. Optical Afterglow Emission

We first collect a sample of cosmological sGRB afterglows from Fong et al. (2015) and Rastinejad et al. (2021), and constrain the afterglow physical parameters based on these afterglow samples. As shown in Figure 1, the gray points denote the rest-frame X-ray, optical, and radio light curves of the currently detected sGRB afterglows (not including GRB 170817A). In order to obtain simulated afterglow light curves, we briefly adopt the Gaussian structured jet model (e.g., Zhang & Mészáros 2002), which was favored by the observations of GRB170817A afterglow (e.g., Alexander et al. 2017; Lamb & Kobayashi 2018; Lazzati et al. 2018; Mooley et al. 2018; Troja et al. 2018, 2020; Xie et al. 2018; Ghirlanda et al. 2019; Ryan et al. 2020), i.e.,

\[
E(\theta) = E_0 \exp \left( -\frac{\theta^2}{2\theta_c^2} \right),
\]

where \( E_0 = E_j/(1 - \cos \theta_c) \) is the on-axis equivalent isotropic energy, \( E_j \) is the one-side jet energy, and \( \theta_c \) is the characteristic core angle. We adopt a narrow jet structure, where we set \( \theta_c \sim 3^\circ \) based on recent simulations (e.g., Lamb et al. 2022) and observations inferred from the sGRB population (e.g., Jin et al. 2018; Lamb et al. 2019b). Furthermore, the spectra of the standard synchrotron emission from relativistic electrons are employed following Sari et al. (1998), Kumar & Zhang (2015), and Zhang (2018). For more details of the afterglow modeling that we applied to calculate the sGRB light curves along the line of sight, see Appendix C in Zhu et al. (2020). We constrain the ranges of afterglow parameters, including \( E_\gamma \), the circum-burst number density \( n \), the power-law index of the electron
distribution $p$, and the fractions of shock energy carried by electrons $\varepsilon_e$ and by magnetic fields $\varepsilon_B$ to fit the cosmological multiband afterglow light curves. We assume that each parameter is independent, while the viewing angle $\theta_v$ follows a random distribution between $0$ to $\theta_c$. We present the $3\sigma$ simulated region shown as the gray regions in Figure 1. The simulated afterglow light curves can basically reproduce the observed cosmological sGRB afterglows in the X-ray, optical, and radio bands. The distributions of these afterglow parameters, which are consistent with the constraints by Fong et al. (2015), Wang et al. (2015), Wu & MacFadyen (2019), and O’Connor et al. (2020), are listed in Table 1.

### 2.2.2. Kilonova Emission

The comprehensive observations of frequency-dependent light curves and time-dependent spectra for AT2017gfo indicate that they cannot be explained by only one single radioactivity-powered component. At least two emission components (Cowperthwaite et al. 2017; Kasen et al. 2017; Perego et al. 2017; Tanaka et al. 2017; Villar et al. 2017; Kawaguchi et al. 2018; Wanajo 2018; Wu et al. 2019) or a model invoking energy injection (Ai et al. 2018; Li et al. 2018; Yu et al. 2018; Ren et al. 2019) are required to account for the data of AT2017gfo. Up to now, in addition to AT2017gfo, which showed relatively complete observations of kilonova properties, no kilonova candidate was found in O3, and other potential kilonova candidates were detected in superposition with decaying sGRB afterglows.

It is predicted that a kilonova emission diversity should exist because of the different mass ratios (e.g., Dietrich & Ujevic 2017), different types of merger remnants (e.g., Kasen et al. 2015; Fujibayashi et al. 2017; Gill et al. 2019; Kawaguchi et al. 2020, 2021), and potential energy injections into the ejecta (Yu et al. 2013; Metzger & Piro 2014; Ma et al. 2018). The statistical analysis of kilonova emission in sGRB afterglows revealed that the kilonova brightness may have a wide range of distribution and hence confirmed that kilonova emission should be diverse (Gompertz et al. 2018; Ascenzi et al. 2019; Rossi et al. 2020; Rastinejad et al. 2021). However, on the one hand, kilonova emission is predicted to be highly dependent on viewing angle (e.g., Kasen et al. 2015; Martin et al. 2015; Wollaeger et al. 2018, 2021; Barbieri et al. 2019; Bulla 2019; Darbha & Kasen 2020; Zhu et al. 2020; Korobkin et al. 2021), so that one can only observe these kilonova candidates in sGRB afterglows when the line of sight is close to the jet axis. On the other hand, due to the scarce and ambiguous observational data, it is hard to use these limited data to model light curves of cosmological kilonovae.\footnote{Kasliwal et al. (2020) and Mohite et al. (2022) combined the results of GW detections and the nondetections of EM counterparts in O3 to constrain the kilonova luminosity function.}

\begin{table}
\centering
\small
\caption{Afterglow Parameter Distribution Using the Gaussian Jet Model}
\begin{tabular}{ll}
\hline
Parameter & Distribution \\
\hline
$E_j$ & $\log_{10}E_j/\text{erg} \sim N(49.3, 0.4^2)$ \\
$\theta_v$ & $\theta_v/\text{deg} \sim N(3, 0.5^2)$ \\
$p$ & $p \sim N(2.25, 0.2^2)$ \\
$\varepsilon_e$ & $\log_{10}\varepsilon_e \sim N(-1, 0.3^2)$ \\
$\varepsilon_B$ & $\log_{10}\varepsilon_B \sim N(-3, 0.4^2)$ \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image1}
\caption{Multiwavelength observed kilonova data (colored points) of AT2017gfo and our fitting model (colored lines). Kilonova data were collected from Andreoni et al. (2017), Arcavi et al. (2017), Coughlin et al. (2017), Cowperthwaite et al. (2017), Díaz et al. (2017), Drout et al. (2017), Evans et al. (2017), Hu et al. (2017), Valenti et al. (2017), Pozanenko et al. (2018), Shappee et al. (2017), Smartt et al. (2017), Tanvir et al. (2017), Troja et al. (2017), Usman et al. (2017), and Villar et al. (2017).}
\end{figure}

Furthermore, dust echoes from some sGRBs occurring in star-forming galaxies may be much brighter than kilonova, so that they would also affect observations of kilonova candidates from the on-axis view (Lu et al. 2021).\footnote{We note that Dietrich et al. (2020) recently considered another type of wind ejecta component based on the model of POSSIS.}

In Figures 1 and 3 we show the multiwavelength light curves of GRB170817A in the rest frame and their predicted on-axis afterglow light curves. The physical parameters of GRB170817A are directly adopted from the best-fitting result from Troja et al. (2020). When we compare the on-axis multiwavelength light curves of GRB170817A with other cosmological sGRB...
afterglows, the physical properties of the X-ray and optical afterglow of GRB170817A are typical for sGRB afterglows. This result was also recently confirmed by Sala et al. (2019) and Wu & MacFadyen (2019). For an on-axis configuration, AT2017gfo is fainter than the predicted associated afterglow and also fainter than most of cosmological sGRB afterglows. If GW170817 is an on-axis event, the kilonova emission would emerge as a fast-evolving bump in the bright afterglow emission at \( \sim 1 \) day after the merger. The brightness of the afterglow should be more diverse than that of kilonova in the universe. The detectability of a kilonova would be significantly affected by the brightness of the associated afterglow. We generate a cosmological BNS population, investigate under which circumstances one can observe a clear kilonova signal without the pollution from an associated afterglow, and predict model-dependent magnitude distributions (luminosity functions) of BNS kilonovae and afterglows.

### 3.1. Viewing-angle-dependent Properties

The gri bands are typically used by current and future survey projects (e.g., the ZTF; the Multichannel Photometric Survey Telescope, abbreviated Mephisto; the Wide Field
Survey Telescope, abbreviated WFST; and the Large Synoptic Survey Telescope, abbreviated LSST,\textsuperscript{13} LSST Science Collaboration et al. 2009; Graham et al. 2019; X.-Z. Er et al. 2022, in preparation; X. Kong et al. 2022, in preparation), while some survey instruments (e.g., the Wide Field Infrared Survey Telescope, abbreviated WFIRST\textsuperscript{14}, and the Wide Field Infrared Transient Explorer; Hounsell et al. 2018; Lourie et al. 2020; Frostig et al. 2022) that were designed for dedicated follow-up observations in the near-infrared bands (e.g., $J$ and $H$ bands) will operate in the near future. As shown in Figure 3, we plot the on-axis kilonova and afterglow light curves in the $griJ$ bands. The luminosity ratios of afterglow and kilonova are shown at the bottom of each panel of Figure 3. We find that for the on-axis case, only $\lesssim 50\%$ afterglows are dimmer than the associated kilonovae at the kilonova peak time, in which case the kilonovae could be identified as a fast-evolving significant bump on top of the afterglow light curve. More specifically, $\sim 15\%$ of the kilonovae would be more than ten times as bright as the associated afterglows, while $\sim 35\%$ of the on-axis kilonovae would be brighter than the afterglows by a factor of $\sim 1$–10. The brightness of $\gtrsim 50\%$ of the afterglows is always higher than that of the associated kilonovae, especially during the early and late stages. In this case, kilonova emission would be outshone by the afterglow emission and is difficult to identified. When the potential kilonova emission in afterglow emission is to be identified via optical serendipitous observations (e.g., Berger et al. 2013; Jin et al. 2015; Ahumada et al. 2021; Wu et al. 2021), a few criteria are required: 1. the event is nearby so that the observed emission can last for $\gtrsim 1$–2 days, 2. the early-stage afterglow light curve has a high-cadence record, and 3. a significant excess of kilonova emission with respect to the afterglow light curve. The best detection period would be a few days after the BNS mergers, when the afterglow-to-kilonova luminosity ratio reaches the minimum value. Meanwhile, we find that the infrared bands, e.g., $i$ and $J$, are better for searching and identifying kilonovae from afterglow light curves, thanks to the longer durations for kilonova emission in redder bands.

Because the afterglow radiation is significantly beamed due to the relativistic outflow, the afterglow light curve would highly depend on the viewing direction. Figure 4 shows the kilonova and afterglow light curves with different viewing directions in the $r$ band. One can conclude that the larger the viewing angle, the fainter the afterglow emission and the more significant the kilonova contribution. For the afterglow emission with $\sin \theta_v \lesssim 0.10$ ($\theta_v \lesssim 2 \theta_c$), the EM signals from most BNS mergers would still be dominated by afterglow. Observations of kilonovae with $\sin \theta_v \lesssim 0.20$ may easily be polluted by the associated afterglows, because observable kilonovae would always emerge as a fast-evolving bump on top of the afterglow emissions. When $\sin \theta_v \gtrsim 0.20$, the peak luminosity of kilonova emission from most BNS mergers is always much brighter than the afterglow luminosity at $\sim 1$ day

\textsuperscript{13} LSST has been newly named the Vera Rubin Observatory.

\textsuperscript{14} WFIRST has been newly named the Nancy Grace Roman Space Telescope.

Figure 4. Similar to Figure 3, but for the $r$-band afterglow light curves considering several different viewing angles, including $\sin \theta_v = 0, 0.05, 0.1, 0.2, 0.3,$ and 0.4.
after the merger. In this case, it is only when the kilonova becomes dim, i.e., after ∼5–10 days, that one can observe the off-axis jet afterglow.

### 3.2. Luminosity Function

With the redshift distribution $f(z)$, we randomly simulate a group of $n_{\text{sim}} = 5 \times 10^6$ BNS events in the universe based on Equation (1). The distribution of the viewing angle $\theta$, is adopted to be uniform. We simulate the viewing-angle-dependent kilonova and afterglow emissions for each simulated BNS event based on the kilonova and afterglow models described in the previous section. We emphasize that the magnitudes of the kilonova and afterglow emissions represent emergent magnitudes obtained in the Earth frame in the following discussion.

The left panel of Figure 5 shows the probability density functions (PDFs) of the kilonova peak absolute magnitude and the absolute magnitude for the associated afterglow at the kilonova peak time in $griJ$ bands. We note that the following calculations and discussions for afterglows should be conservative considering that the luminosity function of the afterglow is calculated at the peak time of the associated kilonova. One can see that compared with afterglow emission, the magnitude distribution of kilonova has a much narrower distribution. The absolute magnitude distribution of a kilonova is mainly peaked at ∼16 mag. Meanwhile, the redder the observing band, the narrower the magnitude distribution and the higher the luminosity. The distribution spans ∼3 mag in the optical, while it spans ∼1–2 mag in the infrared. For afterglows (including on-axis and off-axis cases), a small fraction (∼10%) of the afterglows would be brighter than kilonovae at the kilonova peak time. As discussed in Section 3.1, these EM signals from BNS mergers should be afterglow-dominated events, which are always observed near the polar direction. Because off-axis afterglows always have a much lower brightness than kilonovae, most EM signatures from BNS mergers along the line of sight should be dominated by kilonovae.

In the middle and right panel of Figure 5, after considering the cosmological redshift distribution of the BNS mergers, we show the PDFs and cumulative distributions for the apparent magnitudes of kilonova and afterglow in different bands. One can see that the maximum possible apparent magnitude for cosmological kilonovae is ∼27–28 mag. The distribution range of the apparent magnitude of kilonovae is still narrower than that of the afterglows. For the wide-field survey projects whose search depths are relatively shallow, one can detect bright afterglows with a relatively higher probability than kilonovae. More specifically, for a search depth of ∼20–21 mag (∼23–24 mag), the detection probability of afterglows by survey projects is ∼10–50 (∼1–5) times that of kilonovae. Only if the search depth reaches ∼24–25 mag can one discover a similar number of kilonova and afterglow events. The ZTF has a search depth of 20.8 mag (21.6 mag) with an exposure time of 30 s (300 s) in the $g$ band. In 13 months of ZTF science validation, Andreoni et al. (2021) reported seven independent optically discovered GRB afterglows without any detection of kilonova candidates. Two of these discovered afterglows were inferred to be associated with an SGRB. One of these two events likely originated from a collapsar (Ahumada et al. 2021; Rossi et al. 2022; Zhang et al. 2021). These searches by the ZTF were supported by our simulation results. Mephisto, WFST, and LSST will have a search depth of 22.4 mag (24.2 mag), 23.0 mag (24.2 mag), and 25.1 mag (26.2 mag) with an exposure time of 30 s (300 s) in the $g$ band. It is expected that the detection rate of kilonovae could have the same order of magnitude as that of afterglows via serendipitous observations in the era of Mephisto, WFST, LSST, and so on.

We will discuss the specific detection rates of kilonova and afterglow by GW-triggered target-of-opportunity observations and serendipitous observations with different search magnitudes in Paper II in detail.

### 4. Color Evolution

In this section, we discuss the color evolution of kilonova and afterglow emissions, which would be helpful to identify these transients using future multiv wavelength observations. Despite the fast evolution of kilonova and afterglow emissions, some of these transients might have been recorded in the...
archival data of survey projects. Color evolution analyses might help to identify them if multicolor data are available.

In Figure 6 we show the griJ-band fading rates of AT2017gfo, the total emission of the modeled GW170817-like kilonova, and afterglow along three lines of sight (i.e., sin$\theta_v = 0.0, 0.1, \text{and} 0.2$), and some other well-studied rapid-evolving transients, including AT2018cow (Prentice et al. 2018; Perley et al. 2019), AT2018kzr (McBrien et al. 2019), ATLAS19dqr (Chen et al. 2020), and SN2004eo (supernova Ia; Mazzali et al. 2008). The fading rate of each transient is fitted by a polynomial function. One can directly use fading rates to reject supernovae, which comprise the majority of the transient survey background. The wide range of kilonova model grids from Dietrich et al. (2020) showed that the fading rates of the simulated kilonova populations are almost faster than 0.3 mag day$^{-1}$. Thus, Andreoni et al. (2021, 2022a) intended to select kilonova and afterglow candidates from the ZT survey database using the pipeline of ZTFReST (Andreoni et al. 2022a; a ZTF software to search for kilonovae and fast-evolving transients) by considering that the recorded sources have significant fading rates faster than 0.3 mag day$^{-1}$. However, as shown in Figure 6, this selection condition may hardly directly identify kilonovae from discovered fast-evolving transients in the survey data set. Compared with other fast-evolving optical transients except for SN Ia, AT2017gfo and the total emission of GW170817-like kilonova plus afterglow have a relatively higher fading rate at the early stage ($\sim$1 day), especially in the optical bands. For example, if all kilonovae were GW170817-like, for the g band, the highest fading rate of kilonovae could reach $\sim$2 mag day$^{-1}$, while other transients always have a fading rate $\lesssim$1 mag day$^{-1}$. After $\sim$1–1.5 days, the optical fading rate of AT2017gfo would be similar to the rates of AT2018cow and AT2018kzr. Thus, this requires the cadence time of survey projects to be shorter than $\sim$1–2 days. By only using g or r bands to search for kilonovae, if the survey projects miss their early-stage observations, one cannot use the fading rate to identify GW170817-like kilonovae from fast-evolving transients. A fraction of kilonova populations in the universe might have a relatively slower evolution at the early stage compared with AT2017gfo. We note that distinguishing these more slowly evolving kilonova populations from numerous types of fast-evolving transients by measuring single-band fading rates may still be difficult, even if the serendipitous survey projects do not miss the early-stage observations.

![Figure 6. The griJ-band fading rates of AT2017gfo (red lines), AT2018cow (green lines), AT2018kzr (blue lines), ATLAS19dqr (orange lines), SN2004eo (SN Ia; black lines), and the total emission of our modeled GW170817-like kilonova and afterglow along different lines of sight (dash-dotted lines).](image-url)
Furthermore, it may be hard to use the infrared fading rate to identify a kilonova because all the transients have similar decay rates.

Next, we discuss the color evolution of AT2017gfo and other optical transients. In Figure 7 we plot the color evolution patterns in the $g - r$, $g - i$, $g - J$, $r - i$, $r - J$, and $i - J$ color–time spaces. The data points with different colors correspond to different transients, and the lines are given by the kilonova model for different viewing angles. As shown in Figure 7, these optical transients except for AT2017gfo have a relatively small color difference between two bands (which is always smaller than ~0.5 mag) and a slowly evolving color evolution. The color evolution of a kilonova is unique compared with the color evolution patterns of other transients. For two colors with a large difference between the high-frequency and low-frequency bands, the difference increases with time for the kilonova total color evolution would be dominated by the kilonova and becomes significant when the difference between two optical bands is larger. For some detected (near) on-axis afterglow events, one can use their color evolutions to test the existence of the associated kilonovae, when the kilonova contribution is small in the observed light curve.

5. Summary and Conclusion

We have carried out a detailed simulation to explore the viewing-angle-dependent properties of a kilonova and afterglow from BNS mergers. By assuming that all kilonovae are similar to AT2017gfo, but are viewed from different viewing angles, we explore the detectability of kilonovae in comparison with sGRB

We plot the color evolution patterns of our modeled kilonova and the total emission of kilonova plus afterglow for different viewing angles, as shown in Figure 8. In general, the color evolution of the afterglow is constant because its radiation is nonthermal, but a kilonova has a significant color evolution. For the on-axis case, because the optical flux is dominated by afterglow at early times, the total color evolution is approximately constant and only appears as a small evolution a few days after the explosion when the kilonova emission becomes significant. As the viewing angle becomes larger, the total color evolution would be dominated by the kilonova and would evolve significantly. The color evolution becomes more significant when the difference between two optical bands is larger. For some detected (near) on-axis afterglow events, one can use their color evolutions to test the existence of the associated kilonovae, when the kilonova contribution is small in the observed light curve.

15 We note that long GRB (lGRB) afterglows and GRB-associated supernovae from collaspsars could also be directly discovered by optical serendipitous observations (e.g., Androoni et al. 2022a). The color evolution of lGRB afterglows would be constant as well, similar to that of sGRB afterglows. However, the GRB-associated supernovae would emerge on the top of the lGRB afterglow light curves much later than kilonovae emerged from sGRB afterglow light curves, so that GRB-associated supernovae and kilonovae can be easily distinguished.
afterglows from BNSs. We found that for an on-axis view, the brightness of the afterglow at early and late stages is always higher than that of the associated kilonova. Only about half of the on-axis afterglows are dimmer than the associated kilonovae at the kilonova peak time, in which case the kilonova could be identified as a fast-evolving bump on the afterglow light curve. The best detection period for the on-axis view to search for the potential kilonova signal from an afterglow is a few days after the BNS merger. Infrared bands are better suited for searching and identifying kilonovae from the afterglow light curves because the kilonova emission lasts longer in the infrared band. Only if $\sin \theta_{\text{a}} \lesssim 0.20$ would the EM signals of most BNS mergers be dominated by a kilonova. In this case, the off-axis afterglow would emerge $\sim 5–10$ days after the BNS mergers.

Figure 8. Color evolution patterns of our modeled GW170817-like kilonova (left subpanels) and total emission of GW170817-like kilonova plus afterglow (right subpanels) in $g - r$, $g - i$, $g - J$, $r - i$, $r - J$, and $i - J$ color–time spaces. The dash-dotted gray lines represent the color evolution of the afterglow. The corresponding values of $\sin \theta_{\text{a}}$ for different color lines are shown in the label of each panel.
We simulated the kilonova and afterglow luminosity functions at the kilonova peak time. The absolute magnitude distribution of kilonova peaks at $\sim -16$ mag but spans by $\sim 3$ mag in optical and $\sim 1$–2 mag in infrared. The spans are caused by the anisotropic distribution of different ejecta components. We note that the properties of cosmological kilonovae are assumed to be GW170817-like. However, the mass of the kilonova ejecta, especially for polar-dominated lanthanide-free neutrino-driven wind ejecta, which may determine the peak luminosity of the kilonova, could be dependent on the survival time of the remnant NS (e.g., Kasen et al. 2015; Fujibayashi et al. 2017; Gill et al. 2019). In addition, the possible additional energy injection from the remnant black hole via fall-back accretion (Rosswog 2007) or the Blandford-Payne mechanism (Ma et al. 2018), or from a long-lived NS through magnetic spindown (Yu et al. 2013; Metzger & Piro 2014) may enhance the brightness of the kilonova. Because the BNS kilonova emission may display significant diversity and NSBH kilonovae will also contribute to the kilonova magnitude distribution (Zhu et al. 2021e), it is expected that the cosmological kilonova luminosity function should be more complicated than our simulation result. We also showed that the afterglows have a wider magnitude distribution than kilonovae. A small fraction ($\sim 10\%$) of the afterglow would be brighter than a kilonova at the kilonova peak time, so that most BNS mergers should be kilonova-dominated. The possible presence of bright afterglow emission may significantly affect the detectability of nearby kilonovae.

After involving the cosmological redshift distribution of BNS mergers, we showed that the maximum possible apparent magnitude for cosmological kilonovae is $\sim 27$–28 mag. The distribution range of the apparent magnitude for afterglows is wider than that of kilonovae. For a brightness that is dimmer than $\sim 23$–24 mag, the afterglow luminosity function is much higher than that of a kilonova. Even though the EM signatures from most of the BNS mergers along the line of sight are kilonova-dominated, our result showed that the most expected EM signal from BNS mergers by serendipitous observations is afterglow rather than kilonova because the search depth for almost all current and foreseeable future survey projects is shallower than $\sim 22$–23 mag. It can be predicted that the number of afterglow events that are detected via serendipitous observations would be much higher than that of kilonova events. Thanks to the improved cadence, the ZTF has discovered a few independent optically discovered SGRB afterglows without detecting any kilonova candidate. These observation results reported by Andreoni et al. (2021) might support our calculations. It is expected that the detection rate of kilonovae could have the same order of magnitude as afterglows via serendipitous observations in the era of Mephisto, WFST, LSST, and so on, thanks to the unprecedented improvements of the survey detectabilities.

Because kilonovae and afterglows evolve rapidly, some candidates may be recorded in the database of survey projects without a prompt detection. We found that it may be difficult to use the fading rate in a single band to directly identify kilonovae and afterglows among the various fast-evolving transients by serendipitous observations, especially if the observations have missed the peak. However, by overplotting other examples of supernovae and fast-evolving transients on the plot that have optical and infrared follow-up observations to resemble kilonova evolution timescales, we find that one can use the color evolution to identify kilonovae and afterglows thanks to their unique color evolution patterns compared with those of other fast-evolving transients. The color evolution for kilonova emissions is usually more significant between an optical and an infrared band, e.g., $g - i$, $g - J$, and $r - j$. Thus, we show that at least two detection epochs in two different exposure filters (especially between an optical and an infrared band) may be used to directly search for and identify kilonova and afterglows during surveys.

Lamb & Kobayashi (2017) and Lamb et al. (2018) explored the detectability of sGRB afterglows by considering different jet structures. Their results for the detection rate of sGRB afterglows were obtained by comparing the distribution of peak afterglows and the threshold of survey projects. Cowperthwaite et al. (2019), Andreoni et al. (2022a), Frostig et al. (2022), and Andreoni et al. (2022b) focused on the studies of the search strategy and the detection rates for BNS or/and NSBH kilonovae by GW-triggered target-of-opportunity observations. Scolnic et al. (2018) considered a few current and upcoming survey projects to estimate the detection rate of kilonovae via serendipitous observations by adopting a specific cadence library for each survey project. Their trigger requirement was set as “at least two filter bands have at least one observation with $S/N > 5$”. However, because most kilonovae may have been recorded with only one observation (e.g., Zhu et al. 2021e; Almualla et al. 2021) and hence, would lack the color evolution information, this requirement may be difficult to reject other fast-evolving transients. Sagüés Carracedo et al. (2021), Andreoni et al. (2021), and Almualla et al. (2021) adopted the pipeline of ZTFReST to search for kilonovae and other fast-evolving transients through serendipitous observations. However, as shown in Figure 6, the selection requirement of the pipeline (fading rates faster than 0.3 mag day$^{-1}$) may hardly directly identify kilonovae from other fast-evolving transients in the survey data set. Zhu et al. (2021e) explored the epochs of revisits and the detection rate of NSBH kilonovae and afterglows by both serendipitous observations and GW-triggered target-of-opportunity observations for various survey projects. Many works in the literature have discussed the search strategy and detection rate of BNS kilonova in detail, but without considering the effect of the associated afterglow emission. In Paper II, we will investigate in detail the optical search strategy and detection rate of both kilonova and optical afterglow events from BNS mergers.

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Software: POSSIS (Bulla 2019; Coughlin et al. 2020b); Matlab, https://www.mathworks.com; Python, https://www.python.org.
Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17
Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, ApJL, 848, L15
Scolnic, D., Kessler, R., Brout, D., et al. 2018, ApJL, 852, L3
Shappee, B. J., Simon, J. D., Drout, M. R., et al. 2017, Sci, 358, 1574
Smartt, S. J., Chen, T. W., Jerkstrand, A., et al. 2017, Natur, 551, 75
Sun, H., Li, Y., Zhang, B.-B., et al. 2019, ApJ, 886, 129
Sun, H., Zhang, B., & Gao, H. 2017, ApJ, 835, 7
Sun, H., Zhang, B., & Li, Z. 2015, ApJ, 812, 33
Symbalisty, E., & Schramm, D. N. 1982, ApL, 22, 143
Tanaka, M., Kato, D., Gaigalas, G., & Kawaguchi, K. 2020, MNRAS, 496, 1369
Tanaka, M., Utsumi, Y., Mazzali, P. A., et al. 2017, PASJ, 69, 102
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, ApJL, 848, L27
Troja, E., Castro-Tirado, A. J., Becerra González, J., et al. 2019, MNRAS, 489, 2104
Troja, E., Piro, L., Ryan, G., et al. 2018, MNRAS, 478, L18
Troja, E., Piro, L., van Eerten, H., et al. 2017, Natur, 551, 71
Troja, E., van Eerten, H., Zhang, B., et al. 2020, MNRAS, 498, 5643
Utsumi, Y., Tanaka, M., Tominaga, N., et al. 2017, PASJ, 69, 101
Valenti, S., Sand, D. J., Yang, S., et al. 2017, ApJL, 848, L24
Villar, V. A., Guillot, S., Berger, E., et al. 2017, ApJL, 851, L21
Virgili, F. J., Zhang, B., O’Brien, P., & Troja, E. 2011, ApJ, 727, 109
Wanajo, S. 2018, ApJ, 868, 65
Wanderman, D., & Piran, T. 2015, MNRAS, 448, 3026
Wang, X.-G., Zhang, B., Liang, E.-W., et al. 2015, ApJL, 219, 9

Wollaeger, R. T., Fryer, C. L., Chase, E. A., et al. 2021, ApJ, 918, 10
Wollaeger, R. T., Korobkin, O., Fontes, C. J., et al. 2018, MNRAS, 478, 3298
Wu, G.-L., Yu, Y.-W., & Zhu, J.-P. 2021, A&A, 654, A124
Wu, M.-R., Barnes, J., Martínez-Pinedo, G., & Metzger, B. D. 2019, PhRvL, 122, 062701
Wu, Y., & MacFadyen, A. 2019, ApJL, 880, L23
Xiao, D., Zhang, B.-B., & Dai, Z.-G. 2019, ApJL, 879, L7
Xie, X., Zrake, J., & MacFadyen, A. 2018, ApJ, 863, 58
Xue, Y. Q., Zheng, X. C., Li, Y., et al. 2019, Natur, 568, 198
Yang, B., Jin, Z.-P., Li, X., et al. 2015, NatCo, 6, 7323
Yu, Y.-W., Liu, L.-D., & Dai, Z.-G. 2018, ApJ, 861, 114
Yu, Y.-W., Zhang, B., & Gao, H. 2013, ApJL, 776, L40
Yuan, Y., Lü, H.-J., Yuan, H.-Y., et al. 2021, ApJ, 912, 14
Zhang, B. 2013, ApJL, 763, L22
Zhang, B. 2018, The Physics of Gamma-Ray Bursts (Cambridge: Cambridge Univ. Press)
Zhang, B., & Mészáros, P. 2002, ApJ, 571, 866
Zhang, B. B., Liu, Z. K., Peng, Z. K., et al. 2021, NatAs, 5, 911
Zhang, B. B., Zhang, B., Sun, H., et al. 2018, NatCo, 9, 447
Zhu, J.-P., Wang, K., & Zhang, B. 2021a, ApJL, 917, L28
Zhu, J.-P., Wang, K., Zhang, B., et al. 2021b, ApJL, 911, L19
Zhu, J.-P., Wu, S., Qin, Y., et al. 2022, ApJ, 928, 167
Zhu, J.-P., Wu, S., Yang, Y.-P., et al. 2021c, arXiv:2110.10469
Zhu, J.-P., Wu, S., Yang, Y.-P., et al. 2021d, ApJ, 921, 156
Zhu, J.-P., Wu, S., Yang, Y.-P., et al. 2021e, ApJL, 917, 24
Zhu, J.-P., Yang, Y.-P., Liu, L.-D., et al. 2020, ApJ, 897, 20
Zhu, J.-P., Zhang, B., Yu, Y.-W., & Gao, H. 2021f, ApJL, 906, L11

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