Filling the Mass Gap: How Kilonova Observations Can Unveil the Nature of the Compact Object Merging with the Neutron Star

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Abstract

In this Letter we focus on the peculiar case of a coalescing compact-object binary whose chirp mass is compatible both with a neutron star–neutron star system, with the black hole in the range defined as the “mass gap.” Some models of core-collapse supernovae predict the formation of such low-mass black holes and a recent observation seems to confirm their existence. Here we show that the nature of the companion to the neutron star can be inferred from the properties of the kilonova emission once we know the chirp mass, which is the best constrained parameter inferred from the gravitational signal in low-latency searches. In particular, we find that the kilonova in the black hole–neutron star case is far more luminous than in the neutron star–neutron star case, even when the black hole is nonspinning. The difference in the kilonova brightness arises primarily from the mass ejected during the merger. Indeed, in the considered interval of chirp masses, the mass ejection in double neutron star mergers is at its worst as the system promptly forms a black hole. Instead mass ejection for the black hole–neutron star case is at its best as the neutron stars have low mass/large deformability. The kilonovae from black hole–neutron star systems can differ by two to three magnitudes. The outcome is only marginally dependent on the equation of state. The difference is above the systematics in the modeling.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Black holes (162); Compact binary stars (283); Gamma-ray bursts (629); Gravitational waves (678)

1. Introduction

During the O1 and O2 observing runs, the LIGO Scientific Collaboration and Virgo Collaboration (LVC) detected gravitational wave (GW) signals from 10 coalescing stellar-mass black hole binaries (BHBH) and a neutron star binary system (NSNS), the latter accompanied by a multiwavelength electromagnetic (EM) counterpart (Abbott et al. 2017b, 2017c; The LIGO Scientific Collaboration & the Virgo Collaboration 2018a). At the time of writing, as the third observing run (O3) is in progress, the LVC reported the detection of two probable black hole–neutron star (BHNS) binary merger candidates (S190814bv—The LIGO Scientific Collaboration & the Virgo Collaboration 2019a, and S190910d—The LIGO Scientific Collaboration & the Virgo Collaboration 2019b), plus candidates with a lower probability of being actual astrophysical events.5 Before the beginning of O3, the estimated BHNS detection rate for this run was in the range of 0.04–12 yr−1 (Dominik et al. 2015). At the time of writing, there are no indications of observed EM counterparts associated with these candidates (Coughlin et al. 2019; for S190814bv see, e.g., Klotz 2019; Soares-Santos 2019; Srivastav 2019, for S190910d see, e.g., Crisp 2019; Pereyra 2019).

From a theoretical point of view, BHNS mergers can be accompanied by an EM counterpart as in the NSNS case. This occurs when the NS is (at least partially) tidally disrupted before crossing the BH event horizon (Shibata & Taniguchi 2011). Tidal disruption is favored in binaries with low mass ratio q = M1/M2 and large NS tidal deformability ΛNS (corresponding to a small NS mass and/or to a “stiff” equation of state). A high black hole spin,6 which brings the last stable circular orbit of the binary closer to the BH horizon, also greatly enhances the tidal disruption (Shibata & Taniguchi 2011; Kawaguchi et al. 2016; Foucart et al. 2018; Barbieri et al. 2019a, 2019b). The unbound NS material (“ejecta”) is thought to produce kilonova emission (Lattimer & Schramm 1974; Li & Paczynski 1998; Metzger 2017). Moreover, Shapiro (2017), Paschalidis (2017), and Ruiz et al. (2018) showed that after a BHNS merger a relativistic jet can be launched, powering a short gamma-ray burst (sGRB; Eichler et al. 1989; Narayan et al. 1992) and GRB afterglow emission (Sari et al. 1998; D’Avanzo et al. 2018; Ghirlanda et al. 2018; Salaña et al. 2019).

The BH mass distribution observed so far in coalescing binaries is broad (The LIGO Scientific Collaboration et al. 2018b), extending up to 50–10^6 M⊙ with the lightest BH carrying a mass 7.6±4.3 M⊙ close to the mean BH mass observed in Galactic X-ray binaries of ~7.8 ± 1.2 M⊙ ( Özel et al. 2010). Double NS systems observed so far carry masses in the interval 1.165 M⊙–1.590 M⊙ (Zhang et al. 2019), and the NS with the highest and best estimated mass is the radio pulsar J0740+6620 with MNS = 2.14±0.10 M⊙ in a low-mass binary (Cromartie et al. 2019). Thus, observations appear to indicate a discontinuity between the observed mass distributions of NSs and stellar BHs, called “mass gap,” located approximately between 3 M⊙ (the maximum NS mass inferred from causality arguments) and ~5 M⊙ (Lattimer & Prakash 2001). However, Thompson et al. (2019) recently reported the

5 We defer to the LIGO/Virgo O3 Public Alerts webpage https://gracedb.ligo.org/superevents/public/O3/ for a complete list of current candidates.

6 We use the term “spin” to indicate the dimensionless spin parameter, 7 We refer to the LIGO/Virgo O3 Public Alerts webpage https://gracedb.ligo.org/superevents/public/O3/ for a complete list of current candidates.
The discovery of a BH with mass $3.3^{+2.8}_{-0.7} M_{\odot}$ in a noninteracting binary system with a red giant.

The mass spectrum of compact objects depends sensitively on the mass of the carbon–oxygen core at the end of stellar evolution, on the compactness of the collapsing core at bounce and on the supernova (SN) explosion engine. Belczynski et al. (2012) and Fryer et al. (2012) showed that, in the presence of a significant amount of fallback, explosions happening over a large interval of post-bounce times lead to a continuous range in remnant masses. By contrast explosions happening predominantly within a few hundreds of milliseconds after bounce, characterized by negligible amounts of fallback material, produce more easily the mass gap. Interestingly, at the time of writing, the LVC reported event candidates with binaries having at least one component in the mass gap (The LIGO Scientific Collaboration & the Virgo Collaboration 2019c, 2019d).

It is known that the binary chirp mass $M_c$, a combination of the masses of the two components, is one of the best measured parameters encoded in the GW signal. It is the prime parameter used to identify in low-latency searches the nature of the binary —whether the system hosts two NSs, two stellar BHs, or a BH and an NS. Interestingly, we note that if the NS and BH mass spectra join to form a continuum, i.e., there is no “mass gap” between BH and NS mass distributions (as Thompson et al. 2019a, 2019b seem to indicate), there exists a range of values of the chirp mass $M_c$ where the nature of the binary cannot be identified uniquely based on the chirp mass only (see also Mandel et al. 2015). In particular, hereafter we call “ambiguous” the chirp masses whose values are compatible with either an NSNS or a light BHNS system (see Figure 1).

In this Letter, we aim at answering the following question: can EM observations of coalescing binaries in this “ambiguous” chirp mass interval help to disentangle their nature and narrow down the uncertainties on the existence of a mass gap? To this purpose, we study the properties of the kilonova emission of NSNS and BHNS systems which fall in this “ambiguous” chirp mass interval, using the semianalytical model presented in Barbieri et al. (2019a, 2019b).

2. “Ambiguous” Chirp Masses

The binary chirp mass is defined as

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

where $M_1$ and $M_2$ are the masses of the two component stars (we take $M_1 \geq M_2$). LVC public alerts follow a classification scheme to communicate probabilistic estimates of the nature of the merging system to the community. The scheme classifies as “BNS” any system with both masses $M_1$ and $M_2$ smaller than $3 M_{\odot}$; as “BBH” any system with both $M_1$ and $M_2$ larger than $5 M_{\odot}$; as “NSBH” any system with $M_1 > 5 M_{\odot}$ and $M_2 < 3 M_{\odot}$, and as “MassGap” any system with at least one component carrying a mass between 3 and 5 $M_{\odot}$. An additional “Terrestrial” category is defined to represent triggers that are not of astrophysical origin (i.e., false alarms).

In this work we follow a slightly different classification. We assume the SFHo equation of state (EoS), for which the maximum mass of a nonrotating NS is $M_{\text{max}}^{\text{NS}} = 2.058 M_{\odot}$ (Steiner et al. 2013). We also fix the minimum NS mass to $M_{\text{min}}^{\text{NS}} = 1 M_{\odot}$ (≈10% lower than the value found in Suwa et al. 2018). We thus classify as “NSNS” those systems with both $M_1$ and $M_2$ between 1 and $2.058 M_{\odot}$ (yellow region in Figure 1); “BBHNS” those with $M_1 > 5 M_{\odot}$ and $M_2 < 2.058 M_{\odot}$ (green region); “BBBH” those with both masses above $5 M_{\odot}$ as in the LVC classification (purple region). Considering that compact objects populating the mass gap have masses larger than $M_{\text{max}}^{\text{NS}}$, we assume these to be stellar-origin BHs. In Figure 1 we divide the “MassGap” region in three subregions: “BH+gap” for those systems with a BH above $5 M_{\odot}$ and a BH in the gap; “gap+gap” for those with two BHs in the gap; “gap+NS” for those with a BH in the gap and an NS.

Two limiting values of the chirp mass can be identified: $M_{c,\text{min}} = 1.233 M_{\odot}$ is the chirp mass corresponding to a gap +NS binary with $M_{\text{NS}} = M_{\text{min}}^{\text{NS}}$ and $M_{\text{BH}} = M_{\text{max}}^{\text{NS}}$ (red line). All GW events with chirp mass below $M_{c,\text{min}}$ are NSNS mergers. Similarly, $M_{c,\text{max}}^{\text{NSNS}} = 1.792 M_{\odot}$ is the chirp mass corresponding to an NSNS binary with both NSs having the maximum allowed mass (blue line). Events with chirp mass above $M_{c,\text{max}}^{\text{NSNS}}$ cannot be produced by an NSNS merger. Events with chirp mass between $M_{c,\text{min}}$ and $M_{c,\text{max}}$ can be either NSNS or gap+NS mergers (green–orange lines), i.e., they are “ambiguous.”

3. Computation of Ejecta Properties from BHNS and NSNS Mergers

During the final phase of an NSNS merger, tidal forces lead to a partial disruption of the stars, producing an outflow of neutron-rich material. When the crusts of the two NS impact each other, compression, shock heating, and potentially neutrino ablation cause an additional outflow (Bauswein et al. 2013; Hotokezaka et al. 2013; Radice et al. 2016; Dietrich et al. 2017; Beloborodov et al. 2018). The released NS material can be divided into two components: the dynamical ejecta,

![Figure 1.](image-url)
gravitationally unbound, that leave the merger region, and a bound component, which forms an accretion disk around the merger remnant. On longer timescales, other outflows originate from the disk: faster ejecta produced by magnetic pressure and neutrino-matter interaction during the initial neutrino-cooling-dominated accretion phase (we call these “wind ejecta”), and slower but more massive ejecta produced by viscous processes in the disk, especially during the advection-dominated phase (Dessart et al. 2009; Metzger & Fernández 2014; Perego et al. 2014; Just et al. 2015; Siegel & Metzger 2017—we call these “secular ejecta”). Substantial differences in the ejecta properties arise depending on the postmerger scenario (see, i.e., Kawaguchi et al. 2019).

In order to calculate dynamical ejecta and disk mass from an NSNS merger we adopt the fitting formulae reported in Radice et al. (2018), which are calibrated on a large suite of high-resolution GRHD simulations. Both quantities depend on the NS masses and tidal deformabilities. We also adopt their formula for the dynamical ejecta mass-weighted average asymptotic velocity $v_{\text{dyn}}$.

The NS tidal disruption can occur also in BHNS mergers. If the NS is disrupted outside the innermost stable circular orbit, then the released material remains outside the BH in the form of a crescent (e.g., Kawaguchi et al. 2016), otherwise the NS plunges directly onto the BH. We adopt the fitting formula from Foucart et al. (2018) to calculate the total mass remaining outside the BH, $M_{\text{out}}$. This quantity depends on the BH mass and spin, and on the NS mass, tidal deformability and baryonic mass $M_{\text{NS}}$. We adopt the formulae in Kawaguchi et al. (2016) to calculate the dynamical ejecta mass and average velocity $v_{\text{dyn}}$ in this case. $M_{\text{dyn}}$ depends on the BH mass and spin, the NS mass, baryonic mass, and compactness $C_{\text{NS}}$, and on the angle $\chi_{\text{ini}}$ between the binary total angular momentum and the BH spin. We assume $\chi_{\text{ini}} = 0$. $v_{\text{dyn}}$ depends only on the mass ratio $q = M_{\text{BH}}/M_{\text{NS}}$. We proceed as in Barbieri et al. (2019b) to calculate $C_{\text{NS}}$ from $\Lambda_{\text{NS}}$ and $M_{\text{NS}}$ from $M_{\text{NS}}$ and $C_{\text{NS}}$. We then calculate the disk mass as $M_{\text{disk}} = \max[M_{\text{out}} - M_{\text{dyn}}, 0]$. As in Barbieri et al. (2019b) we assume that $M_{\text{dyn}}$ cannot exceed 30% $M_{\text{out}}$, considering recent BHNS simulations presented in Foucart et al. (2019).

In what follows, we conservatively assume the BH to be nonspinning ($\chi_{\text{BH}} = 0$), corresponding to the worst condition for ejecta production.

### 4. Ejecta Properties for “Ambiguous” Chirp Masses

In Figure 2 we show the dynamical ejecta and disk masses on the $(M_1, M_2)$ plane along lines of constant $M_c$. We limit the $y$-axis to $M_{\text{NS}}^{\text{max}}$ as we focus on systems that contain at least one NS. It is apparent that NSNS configurations compatible with “ambiguous” chirp masses do not produce dynamical ejecta

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9. We note that Kiuchi et al. (2019) showed that the predictions from these formulae might underestimate the produced disk mass in binaries with large mass ratios. However, they consider the case with $M_{\text{NS},1} = 1.55 M_\odot$ and $M_{\text{NS},2} = 1.2 M_\odot$, thus low-mass/largely deformable NSs. Instead, as can be seen in Figure 2, we consider systems with $M_{\text{NS},1} > 1.65 M_\odot$ and $M_{\text{NS},2} > 1.35 M_\odot$. Therefore, the NSs in our systems are less deformable and we expect that the underestimation reported in Kiuchi et al. (2019) is less significant.

8. Among the corotating configurations. Indeed the counter-rotating cases ($\chi_{\text{BH}} < 0$) are the worst conditions in absolute, more often leading to a direct plunge. However, counter-rotating configurations are not expected for field binaries but for the dynamically formed ones, that represent a negligible contribution to the merger rate (Ye et al. 2019).

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Figure 2. Dynamical ejecta (top panel) and accretion disk (bottom panel) masses for different values of the binary chirp mass $M_{\text{c}}$. We assume the SFHo EOS ($M_{\text{NS}}^{\text{max}} = 2.058 M_\odot$) and nonspinning BHs ($\chi_{\text{BH}} = 0$). The vertical red line separates NSNS configurations (left) and BHNS ones (right). Each line corresponds to a $M_{\text{c}}$ (reported on it). The pink shadowed area is the region where differences of the ejecta mass for the BHNS and NSNS cases are larger than systematic errors. The yellow stars indicate the BHNS systems with the NS having a “representative” mass of $1.4 M_\odot$.
larger than the systematic errors. The uncertainties on the fitting formulae for NSNS are $\Delta M_{\text{NS NS}}^{\text{dyn}} = 0.5 M_{\text{dyn}} + 5 \times 10^{-3} M_\odot$ and $\Delta M_{\text{disk}}^\text{NS NS} = 0.5 M_{\text{disk}} + 5 \times 10^{-4} M_\odot$ (Radice et al. 2018).

The uncertainties on the fitting formulae for BHNS are $\Delta M_{\text{BHNS}}^{\text{dyn}} = 0.2 M_{\text{dyn}}$ (Kawaguchi et al. 2016) and $\Delta M_{\text{e out}} = 0.1 M_{\text{out}}$ (Foucart et al. 2018). Therefore, being $M_{\text{disk}}^{\text{BHNS}} = M_{\text{out}} - M_{\text{dyn}}^{\text{BHNS}}$, we assume its uncertainty to be $\Delta M_{\text{disk}}^{\text{BHNS}} = \sqrt{(\Delta M_{\text{out}})^2 + (\Delta M_{\text{dyn}}^{\text{BHNS}})^2}$. We define

$$\sigma_{\text{dyn}} = \frac{\Delta M_{\text{NS NS}}^{\text{dyn}}}{\sqrt{(\Delta M_{\text{NS NS}}^{\text{dyn}})^2 + (\Delta M_{\text{Dyn}}^{\text{BHNS}})^2}}$$

and

$$\sigma_{\text{disk}} = \sqrt{(\Delta M_{\text{NS NS}}^{\text{disk}})^2 + (\Delta M_{\text{disk}}^{\text{BHNS}})^2)}.$$  

We indicate, as the pink shadowed area in Figure 2, the regions where the differences in the mass of dynamical ejecta and disk for the BHNS and NSNS cases are greater than or equal to $\sigma_{\text{dyn}}$ and $\sigma_{\text{disk}}$, respectively. In these regions the ejecta mass differences are larger than the systematic errors.

Figure 3 summarizes the differences between two representative NSNS and BHNS systems with “ambiguous” chirp masses (cases II and III in the figure), and also a “GW170817-like” NSNS case, for comparison. For the latter we consider an NSNS system with masses 1.46 $M_\odot$ and 1.27 $M_\odot$.

Merger (I) produces relatively low-mass dynamical ejecta at all latitudes, with a preferentially equatorial angular distribution $\propto \sin^3 \theta$, where $\theta$ is the polar angle (Perego et al. 2017). The accretion disk is massive and $\sim 20\%$ of its mass is unbound in the form of secular ejecta, with a similar angular distribution as for the dynamical ones, while $\sim 5\%$ of its mass goes into the wind ejecta, mostly confined in the polar region ($\theta < \pi/3$ rad—Perego et al. 2017). After the merger, an intermediate state with a hyper-massive NS could exist before collapsing to a BH (gray central object represented in Figure 3(I)). The strong neutrino winds produced in this state interact with the ejecta, increasing the electron fraction $Y_e$ or, equivalently, lowering the opacity.

We consider a system with 2 $M_\odot$ and 1.6 $M_\odot$ stars (II) as our representative NSNS merger in the “ambiguous” chirp mass range. As explained above, in this case we expect no dynamical ejecta and a low-mass accretion disk, resulting in low-mass wind and secular ejecta. The merger remnant collapses promptly to a BH. The absence of an intermediate hyper-massive NS state implies little neutrino wind, giving a low $Y_e$ in the ejecta (Kawaguchi et al. 2019).

Finally, as BHNS merger in the “ambiguous” chirp mass range we consider a system with $M_{\text{BH}} = 3 M_\odot$ and $M_{\text{NS}} = 1.1 M_\odot$ (III). In BHNS mergers, the dynamical ejecta have a crescent-like shape, extending into half of the equatorial plane and limited to the region with $\theta < 0.3$ rad (Kawaguchi et al. 2016). In the considered system, the dynamical ejecta and accretion disk are massive. Due to the lack of a neutrino wind, the fraction of accretion disk flowing into wind ejecta is lower than in the NSNS case (we assume $\sim 1\%$). The disk fraction that goes into secular ejecta is the same as in the NSNS case. As a consequence, the secular ejecta are massive, while the wind ejecta have low mass. The ejecta $Y_e$ is lower than the NSNS case.

Therefore, with the ejecta properties being substantially different for the NSNS and BHNS cases in the “ambiguous” chirp mass range, we expect the kilonova light curves to present important differences as well.

5. Kilonova Model

The neutron-rich material ejected in NSNS and BHNS mergers is an ideal site for $r$-process nucleosynthesis, which produces the heaviest elements in the universe (Lattimer & Schramm 1974; Eichler et al. 1989; Korobkin et al. 2012; Wanajo et al. 2014). The synthesized nuclei are unstable and they decay radioactively, powering the kilonova emission (Li & Paczyński 1998; Metzger et al. 2010; Kasen et al. 2013).

We compute the kilonova light curves using the composite semianalytical model presented in Barbieri et al. (2019a, 2019b) (in part based on Grossman et al. 2014; Martin et al. 2015; Perego et al. 2017). For the NSNS cases we assume the model parameters (ejecta geometry, opacity, and the fractions of $M_{\text{disk}}$ that go into wind and secular ejecta) as in Perego et al. (2017). The model has been tested on GW170817: using the parameters inferred for this event (Abbott et al. 2017a; Perego et al. 2017), we obtain multiwavelength light curves consistent with the observed ones (Villar et al. 2017,
For BHNS systems we assume the same model parameters as in Barbieri et al. (2019a, 2019b) based on Just et al. 2015; Kawaguchi et al. 2016; Fernández et al. 2017.

The kilonova light curves are highly degenerate with respect to binary parameters. Thus, it is impossible to infer the system properties from the kilonova light curve alone. This degeneracy can be (at least partially) broken using information from GW analysis. In particular, the measurement of the binary chirp mass reduces the number of parameters by one. Leaving, i.e., $M_1$ as a free parameter, $M_2$ is constrained by the measured $M_c$.

6. Kilonovae for “Ambiguous” Chirp Masses

In Figure 4 we show the envelope of the kilonova light curves expected from NSNS and BHNS mergers, for four selected values of the chirp mass. We consider emission in the $g$ (509 nm) and $K$ (2143 nm) bands and the figure shows the absolute magnitude as a function of time. For all the “ambiguous” chirp masses the fitting formulae from Radice et al. (2018) in NSNS mergers predict no dynamical ejecta and a minimum allowed disk mass $M_{\text{disk}} = 10^{-3} M_\odot$. Thus we have a single light curve for NSNS mergers, and we can expect that these events would not produce kilonovae brighter than shown in Figure 4.

For BHNS mergers there exists a range of light curves for each $M_c$, arising from the different combinations of the component masses, producing different ejecta properties. For $M_c = 1.45 M_\odot$ (panels (1a)–(1b)) all kilonovae from BHNS mergers are much brighter at every time than that from NSNS mergers. Therefore a single observation in one of these bands would allow us in principle to distinguish the nature of the merging system.

At higher values of the chirp mass, there is only a small overlap between the BHNS and NSNS cases, at the bottom of the BHNS envelope. Therefore, except for observed light curves at low absolute magnitudes, it should be always possible...
to distinguish the nature of the merging system by the sole kilonova brightness. We note that the disentangling of the nature of the binary is optimal when $M_c = 1.45 M_\odot$ (panels (1a)–(1b)). In this case, as shown in Figure 2, the mass interval of the ejecta from BHNS mergers is the narrowest, and this in turn leads to the narrowest spread in the kilonova light curves.

The prediction of BHNS kilonovae as bright or brighter than NSNS ones is presented in Kawaguchi et al. (2019). They find that BHNS kilonovae are brighter in the near-infrared $K$-band, due to the smaller electron fraction $Y_e$ in the ejecta owing to the lack of strong neutrino irradiation from the central remnant. In the $i$ band, Kawaguchi et al. (2019) find that NSNS configurations ending with the formation of a supermassive NS leads to brighter kilonovae than the BHNS case. This is due to the strong neutrino emission produced in this case, that increases $Y_e$ in the ejecta. However, in their study they compare sundry BHNS and NSNS configurations not selected on the bases of the chirp mass. By contrast, in our work, we compare BHNS and NSNS mergers at fixed chirp mass. This requirement restricts the NSNS binary configurations to cases producing no dynamical ejecta and very low mass disks. Therefore, whatever the value of $Y_e$ in the ejecta from the NSNS merger is, the mass propelled in the merger is so low that almost all the BHNS kilonovae are brighter, at all wavelengths.

For other comparisons between NSNS and BHNS merger outcomes and studies on distinguishing the nature of merging compact binaries see Hinderer et al. (2019) and Coughlin & Dietrich (2019), who considered an unconventional BH companion with mass of $\sim 1.4 M_\odot$, thus below the maximum NS mass.

As a visual comparison we also show the kilonovae for BHNS binaries having an NS with a “representative” mass of $1.4 M_\odot$ (aqua/magenta lines). For $M_c = 1.45 M_\odot$ such a binary does not exist, while for $M_c = 1.75 M_\odot$ it is fated to a direct plunge, thus there is no kilonova.

We remark that the kilonova light curves from BHNS are inferred assuming nonspinning BHs ($\chi_{BH} = 0$). As explained in Barbieri et al. (2019a, 2019b), increasing the BH spin (fixing all the other parameters) leads to more massive ejecta and, consequently, more luminous kilonovae. Therefore, if the BHs have a nonzero spin, our argument would be even stronger. As an example, for $\chi_{BH} \gtrsim 0.5$ all light curves from BHNS kilonovae would be brighter than those from NSNS binaries in each band and at any time, in this critical range of “ambiguous” chirp masses.

7. Conclusion

The detection of a BHNS coalescence could be the next ground-breaking discovery in multimessenger astronomy. At the time of writing, there are promising GW candidates detected by the LVC during the observation run O3. The associated detection of an electromagnetic signal from these new GW sources might contribute to our understanding of the physical processes that power the multilwavelength EM emission (Gompertz et al. 2018; Rossi et al. 2019, and references therein).

From the GW signal, one of the best constrained parameters in low latency is the binary chirp mass, a combination of the masses of the two components. This parameter is currently used to classify the binary, whether the system hosts two NSs, two stellar BHs, or a BH and an NS. In the present Letter, we point out that in absence of a “mass gap” between the NS and BH mass distributions (as Thompson et al. 2019 seem to indicate), there exists a range of $M_c$ (as shown in Figure 1) for which it is not possible to distinguish the nature of the binary on the basis of the chirp mass measurement alone. For the SFHo EoS adopted in this analysis, we find that the values of the chirp mass between $1.233 M_\odot$ and $1.792 M_\odot$ are compatible either with NSNS and BHNS systems.

In this Letter we show that the observation of the kilonova emission from these systems can break the degeneracy in the “ambiguous” chirp mass range, and constrain the nature of the merging system. We find that kilonova emission shows substantial differences in the luminosity and temporal evolution in NSNS and BHNS systems (see Figure 4). In particular, the BHNS case is far more luminous than the NSNS case, even when the BH is nonspinning. This happens because in this “ambiguous” $M_c$ range the NSNS configurations represent the worst cases for ejecta production, while the BHNS configurations represent the best ones. It is important to note that, when the differences of the ejecta mass for the BHNS and NSNS cases are substantial, they are larger than the systematic errors in the modeling. Therefore, observing the kilonova associated with such an event is of fundamental importance to break the degeneracy on the nature of the merging system. Furthermore, if the observed kilonova is compatible with a BHNS merger, this would provide evidence in support of the existence of low-mass BHs, filling the “mass gap.”

This work illustrates the potential of multimessenger observations of compact binary mergers, and the importance of an efficient exchange of information between the GW and EM communities (Biscoveanu et al. 2019; Margalit & Metzger 2019).

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9 Offline GW signal analysis could provide more precise information. This would lead to stronger constraints on the component masses that could allow us to distinguish the nature of the merging system using GW alone, in some cases.
