Can We Distinguish Low-mass Black Holes in Neutron Star Binaries?

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Abstract

The detection of gravitational waves (GWs) from coalescing binary neutron stars (NS) represents another milestone in gravitational-wave astronomy. However, since LIGO is currently not as sensitive to the merger/ringdown part of the waveform, the possibility that such signals are produced by a black hole (BH)–NS binary can not be easily ruled out without appealing to assumptions about the underlying compact object populations. We review a few astrophysical channels that might produce BHs below $3\,M_\odot$ (roughly the upper bound on the maximum mass of a NS), as well as existing constraints for these channels. We show that, due to the uncertainty in the NS equation of state, it is difficult to distinguish GWs from a binary NS system from those of a BH–NS system with the same component masses, assuming Advanced LIGO sensitivity. This degeneracy can be broken by accumulating statistics from many events to better constrain the equation of state, or by third-generation detectors with higher sensitivity to the late-spiral to post-merger signal. We also discuss the possible differences in electromagnetic (EM) counterparts between binary NS and low-mass BH–NS mergers, arguing that it will be challenging to definitively distinguish the two without better understanding of the underlying astrophysical processes.

Key words: binaries: close – stars: black holes – stars: neutron

1. Introduction

Merging binary neutron stars (NS) have just resoundingly been shown to produce both strong gravitational-wave (GW) signals and copious electromagnetic (EM) emission covering a large frequency range by the recent event GW170817 (Abbott et al. 2017b, 2017c, 2017d; Alexander et al. 2017; Coughlin et al. 2017; Troja et al. 2017; see also, e.g., Kochanek & Piran 1993; Li & Paczynski 1998; Rosswog 2005; Metzger et al. 2010; Metzger & Berger 2012; Ando et al. 2013; Murguia-Berthier et al. 2014). The joint observation of GWs with, for instance, gamma-ray bursts, X-rays, ultraviolet/optical/infrared transients, or radio afterglows is now beginning to provide unprecedented information about the violent dynamics of hot, dense nuclear matter under extreme gravity. With three GW detectors now online, the ability to localize the source of the GW events (albeit within a still rather large window) facilitates identifying EM counterparts (Abbott et al. 2017c, 2017e).

It is natural to assume a compact object is an NS instead of a black hole (BH) if its mass is below the upper bound of a non-rotating NS. Such an assumption has also been supported by the observed mass distribution of NS and BHs in binaries, and applied to distinguish NS–NS and BH–NS binaries through the use of component mass measurements to identify a possible “mass gap” in BHs (Hannam et al. 2013; Littenberg et al. 2015; Mandel et al. 2015). However, the advent of GW astronomy allows us to re-examine preconceptions that might be biased by previously available observations.\textsuperscript{3} In this paper, we consider the possible existence of low-mass BHs (LMBHs) with a mass range that overlaps that of normal NS. We briefly review possible formation channels of such BHs, determine the prospects for identifying them through GW and/or multi-messenger detections, and discuss the implications upon detecting such objects.

2. LMBH Formation Channels

Here we list several possible formation channels to generate LMBHs with masses $<3\,M_\odot$. First, stellar-mass BHs could come from primordial density fluctuations. In the range we are considering ($\sim 1$–$3\,M_\odot$), existing constraints stem from microlensing measurements (Carr et al. 2016), indicating that their mass fraction compared to dark matter is $f \lesssim 5\%$. We expect that the ratio between such LMBHs and normal NS in a galaxy to be

$$f \frac{M_{\text{total}} \Omega_{\text{DM}}}{N_{\text{NS}} M_{\text{NS}}} \approx 330 \frac{M_{\text{total}}}{10^{12} M_\odot} \frac{f}{5\%} \left( \frac{N_{\text{NS}}}{10^8} \frac{M_{\text{NS}}}{1.3 M_\odot} \right)^{-1} \Omega_{\text{DM}} / 0.845,$$

for a Milky Way-like galaxy (the Milky Way values for the total mass, $M_{\text{total}}$, and number of NS, $N_{\text{NS}}$, are estimated in Dehnen & Binney 1998 and Camenzind 2007), where $\Omega_{\text{DM}}$ is the mass fraction of the dark matter in the total matter density. With this upper bound saturated, if the cross-section for dynamically capturing a NS is approximately the same as the one for a BH with similar mass—which should be the case since such capture is dominated by GW emission (East et al. 2012)—it is possible that the merger rate of an LMBH–NS binary is actually greater than the merger rate of dynamically formed NS–NS binaries. Similarly, motivated by the discussion in Capela et al. (2013) and Fuller et al. (2017), NS, white dwarfs, or even main-sequence stars could capture mini-primordial BHs (PBHs)\textsuperscript{4} causing most of the star’s material to be accreted to produce a final BH with stellar mass. It is, however, not clear what fraction of NS could become LMBHs through this process. In fact, a bound on the mini-PBH population was obtained in Capela et al. (2013), assuming that not all NS are destroyed by PBH captures. It has

\textsuperscript{3} Arguably this has already taken place with GW observations revealing the existence of BHs with masses $>20 M_\odot$ (Abbott et al. 2016).

\textsuperscript{4} Here we are referring to PBHs with masses much smaller than one solar mass.
also been proposed that asymmetric dark matter could accumulate in centers of NS through nucleon scattering, and eventually form a seed BH (Goldman & Nussinov 1989; Bramante & Linden 2014; Bramante et al. 2018), providing another scenario for converting an NS to a BH of similar mass.

Another possible way to produce LMBHs is through a supernovae explosion, a standard mechanism for creating compact objects. If the explosion is driven by rapidly growing instabilities (10–20 ms), BH with masses >5 $M_{\odot}$ are expected but slow ones can produce lower masses (Belczynski et al. 2012). To date, observations point to the former option but the existence of a “mass gap” is by no means a definitive fact (Kreidberg et al. 2012).

Additionally, it is also possible that the final BH produced by an NS–NS merger could become subsequently captured in a new LMBH–NS binary. Such hierarchical mergers were discussed in Fishbach et al. (2017) and Gerosa & Berti (2017) from the detection perspective, and in Antonini & Rasio (2016) as a way to estimate the rate of BH–BH mergers. Similarly, NS could gain mass through accretion and collapse to a BH falling in the mass range considered here (Nakamura 1983; Vietri & Stella 1999; MacFadyen et al. 2005; Dermer & Atoyan 2006). Because of the uncertainty in the upper threshold mass of a normal NS, LMBHs formed through NS accretion-induced collapse or collisions can not be easily distinguished from candidates in other channels through mass measurements.

We also note that the range of BH masses allowed by the above channels could also be modified by possible departures from general relativity, the existence of additional fields in nature, and/or exotic compact objects (e.g., Kaup 1968; Liebling & Palenzuela 2012; Cardoso et al. 2016; Mendes & Yang 2017) whose dynamics can yield LMBHs through collapses or mergers. Consequently, through dynamical captures, LMBH–NS systems could be produced with the masses achievable in each possible scenario. Naturally, with such a range of possible formation channels together with current uncertainties as to their likelihood, the rate of LMBH–NS binaries is unknown. Thus, future GW observations of such systems (possibly requiring EM counterparts) will be key to understanding this theoretically possible population.

### 3. Degeneracy of Tidal Effects

We argue that the leading order tidal effects on the GW signal of an inspiraling compact object binary are, in fact, degenerate between an NS–NS and a BH–NS binary, when considering different equations of state (EOSs) of the star (and hence, setting its radius, etc.). We begin by noting that the phase of the inspiral waveform as a function of frequency can be written as (Vines et al. 2011; Sennett et al. 2017)

$$\Psi(f) = \frac{3}{128(\pi M_f)^{5/2}}(1 + \alpha_{1PN} x + ... + \alpha_{5PN} + \alpha_{\text{tide}} x^5 + ...),$$

where $x = (\pi M_f)^{2/3}$, $M_f = (m_1 m_2)^{3/5}/M^{1/5}$, and $M = m_1 + m_2$ is the total mass. The $\alpha_{1PN}, ..., \alpha_{5PN}$ terms encode the various order post-Newtonian (PN) effects, while the leading order tidal correction is given by

$$\alpha_{\text{tide}} = -24 \left[ 1 + 12 \frac{m_2}{m_1} \frac{m_5}{M^2} \Lambda_1 + (1 \leftrightarrow 2) \right],$$

where $\Lambda_1$ and $m_1$ are the dimensionless tidal deformability parameter (normalized by mass to the fifth power) and mass of the first compact object (which here, we will always assume is an NS), respectively, and the second term exchanges these quantities for that of the second compact object (which we take to either be an NS or a BH). It follows from the above that as long as the NS in a BH–NS binary satisfies an EOS that has the tidal deformability of

$$\Lambda_1' = \Lambda_1 + \frac{m_2}{m_1} + \frac{12 m_1 m_2^5}{m_1 + 12 m_2 m_1^5} \Lambda_2,$$

we can not distinguish its inspiral waveform from that of an NS–NS system with $(\Lambda_1, \Lambda_2)$ for the respective stars, up to the leading PN order in tidal corrections.

We can illustrate that this leading order difference in the tidal effects of an NS–NS versus BH–NS system can be readily accommodated into uncertainties in the EOS. To give a concrete example of this, we consider a one parameter family of EOSs given by the SLy equation (Douchin & Haensel 2001) of state at low densities, and a $f = 3$ polytrope at high densities, also roughly consistent with SLy, where the parameter sets the pressure at some reference density (Read et al. 2009; we consider $P = 10^{14}$ to $10^{18}$ dyne cm$^{-2}$ at $\rho = 5 \times 10^{12}$ gm cm$^{-3}$). Then, for a given set of binary parameters, we find the mapping between equations of state in this family such that Equation (4) is satisfied (see Gagnon-Bischoff et al. 2017 for details on computing Love numbers). We show this mapping, in terms of the amount by which the NS radius in the BH–NS binary has to be larger, relative to the

\[\text{Figure 1. Amount by which the NS radius has to be increased—relative to the radius of the corresponding NS in an NS–NS binary with the same masses—for a BH–NS binary to have the same leading order tidal effects. In all of the cases, one NS labeled NS 1 is assumed have a mass of 1.35 \, M_{\odot}, while the different curves correspond to a BH or second NS with a mass ranging from 1 to 2 \, M_{\odot}. The leftmost value of each curve (smallest value of $R_{\text{NS 1}}$) corresponds to the point, where for the family of EOSs considered here, the BH–NS EOS is no longer consistent with a maximum NS mass greater than 2 $M_{\odot}$. Since the corresponding NS–NS EOS is softer, the constraint that the NS–NS EOS is consistent with a maximum NS mass greater than 2 $M_{\odot}$ is stricter, and requires $R_{\text{NS 1}} \geq 11.2$ km.}\]
radius of the corresponding NS in an NS–NS binary, in Figure 1. Typically this increase is less than 2 km. Furthermore, since the tidal effects in a binary NS are dominated by the star of a larger radius, the required increase can be quite small when the smaller object is taken to be the BH. We note in passing that attributing measured tidal effects to a BH–NS binary generically implies a stiffer EOS, and so could be favored, if the softer EOS implied by an NS–NS binary is in tension with other observations (e.g., of the maximum allowed NS mass).

In addition, this mapping assumes we know the component masses exactly, and the uncertainty just lies in the EOS. If we also fold in the uncertainty in component masses (Hannam et al. 2013; Chatziioannou et al. 2014), there is a greater degeneracy.

4. Prospects for GW Detection

As discussed above, the leading order tidal effect is degenerate between LMBH–NS and NS–NS systems, as long as there is sufficient uncertainty in EOS to allow for the mapping in Equation (4). This degeneracy may be resolved in several ways: through the measurement of the next-to-leading PN order tidal effects, as they contain different mass and frequency dependence; through the difference between two types of waveforms in the late-inspiral stage, where the tidal disruption of the NS strongly influences the waveform; or through the accumulation of many NS–NS events and the consequential reduction in the uncertainty of the star’s EOS (notably its radius), to break the degeneracy. Since the effect of PN corrections to tidal effects is ~10%–20%, we focus on the latter two possibilities here.

In order to distinguish the two waveforms $h_{\text{NSNS}}$ and $h_{\text{BHNS}}$, we adopt the measure of

$$S/N^2 = 4 \int df \frac{|h_{\text{NSNS}}(f) - h_{\text{BHNS}}(f)|^2}{S_n(f)},$$

with $S_n(f)$ being the spectra density of Advanced LIGO detector noise. If $S/N^2 \geq 1$, we shall say that the two waveforms are marginally distinguishable (Lindblom et al. 2008). This threshold has to be raised if we require higher statistical significance. The inspiral signals of LMBH–NS and NS–NS waveforms terminate at different respective characteristic frequencies. For an LMBH–NS system, the signal terminates at the cut-off frequency $f_{\text{cut}}$, which is related to the tidal disruption of an NS within a BH–NS binary. For simplicity, in the following estimate we will assume that in LMBH–NS binaries when the star is disrupted, the GW is negligible, and ignore the post-merger part of the waveform for both types of systems. Since Advanced LIGO/VIRGO’s sensitivity degrades considerably at the high frequencies where contact (for NS–NS systems) or disruption (for LMBH–NS systems) occur, a rather good approximation to $S/N^2$ can be readily obtained this way. Based on Shibata et al. (2009), $f_{\text{cut}}$ is actually much higher than the frequency that the NS undergoes during mass shedding, and it depends on the mass ratio of the system and the NS EOS (in particular the NS compactness

7 We note that this fitting formula was obtained using a set of data where the minimum mass ratio was 2. This means that Figure 2 may contain systematic errors due to extrapolation. In fact, there are limited simulations available for the low-mass ratio systems considered here, which motivates future numerical studies within this parameter range.

\[ C = M_{\text{NS}}/R_{\text{NS}}. \] Here, we adopt the fitting formula from Pannarale et al. (2015), under a simplified assumption that the BH is nonspinning

$$f_{\text{cut}} = \frac{1}{M} \sum_{ij} f_{ij} Q^i,$$

where $Q = M_{\text{BH}}/M_{\text{NS}}$ is the mass ratio and $f_{ij}$ are numerical coefficients given in Pannarale et al. (2015). For an NS–NS system, the inspiral ends at the contact frequency, $f_{\text{contact}}$, of the two NS (Damour et al. 2012) is

$$f_{\text{contact}} = \frac{1}{\pi M} \left( \frac{m_1}{M_C} + \frac{m_2}{M_C} \right)^{-3/2}.$$

Equation (5) can then be approximated by

$$S/N^2 \approx 4 \int_{f_{\text{min}}}^{f_{\text{max}}} df \frac{|h_{\text{BS}}(f)|^2}{S_n(f)},$$

where we have used a sky-averaged 3PN inspiral waveform (Kidder 2008) in this range. In Figure 2, we plot $S/N^2$ as a function of the mass ratio of the binary and the radius of the lighter NS. We assume that the binary is at a distance of 100 Mpc, and the mass of the lighter NS is assumed to be $1.35 M_\odot$. Within most of the parameter range we consider here, $S/N^2$ is bounded below ~1.2. The regime with very low $S/N^2$ corresponds to the cases with $f_{\text{cut}} \approx f_{\text{merger}}$. Nevertheless, the distinguishability will be improved if the source is closer, or if we include the post-merger part of the waveform (regarding that there are still significant modeling uncertainties). For example, the S/N of the full post-merger waveform is estimated to be around 1.5 (Clark et al. 2016) for a
of the radius of 1.4
obtained by choosing 400 Hz
NS radius shown
assuming either a high-spin prior or a low-spin prior on the source. The highest
which is above 1 kHz.
increased, relative to the quantity of the corresponding NS in an NS–NS binary
with the same masses, for a BH–NS binary to have the same leading order tidal
effects. This is shown as a function of the mass ratio. In all of the cases, one NS
is assumed have a mass of $M_{\odot} = 1.4 M_{\odot}$. The different curves correspond to
different choices of EOS for the NS–NS binary, and hence the different values
of the radius of $1.4 M_{\odot}$ NS in the NS–NS, as shown in the legend. For comparison,
we also show the Fupper bound constraints on $\Lambda$ from GW170817 assuming either a high-spin prior or a low-spin prior on the source. The highest
NS radius shown (dotted red curve) saturates the former constraint on $\Lambda$, while
the middle value for the NS radius (dotted blue curve) saturates the latter
constraint.

1.35 $M_{\odot}$ + 1.35 $M_{\odot}$ NS binary at a distance of $d = 50$ Mpc
and with the “TM1” EOS, while the S/N contribution from the
dominant mode is significantly lower (Yang et al. 2018),
depending on the EOS.
On the other hand, multiple detections of NS–NS mergers
will be able to constrain the NS EOS, which could help break
the degeneracy indicated by Equation (4). According to
Hinderer et al. (2010), a single Advanced LIGO event from a
distance, $d$, typically constraints $\Lambda$ to an accuracy of

$$
\Delta \Lambda \sim 2.9 \times 10^{1} \left( \frac{M}{2.7 M_{\odot}} \right)^{-2.5} \left( \frac{m_{2}}{m_{1}} \right)^{0.1} \left( \frac{f_{\text{end}}}{500 \text{ Hz}} \right)^{-2.2} \left( \frac{d}{100 \text{ Mpc}} \right)
$$

Assuming a similar end frequency for integration $f_{\text{end}} \sim 500$ Hz as in Hinderer et al. (2010), and an equal mass binary with $M \sim 2.7 M_{\odot}$, we obtain an estimate on the tidal deformability of a star: $\Delta \Lambda_{1}(1.35 M_{\odot}) \sim 2.9 \times 10^{3}$. Assuming
a low-spin prior, GW170817 places on upper bound $\Lambda_{1}(1.4 M_{\odot}) \lesssim 800$ at the 90% confidence level, and an upper bound of $\lesssim 1400$ if the prior is relaxed to allow for high spin (Abbott et al. 2017c). Such constraints on $\Lambda_{1}$ also limit the allowed radius of NS, given the family of EOS assumed in this paper. In Figure 3, we compare this uncertainty in the tidal deformability to the amount by the tidal deformability that has to be changed in order for a BH–NS binary to have the same leading order tidal effects as a corresponding NS–NS binary with the same masses.

With $N$ identical detections, and under the same high-spin prior,
such uncertainty scales as $\Delta \Lambda_{1}(1.4 M_{\odot}) \sim 1.4 \times 10^{3} N^{-1/2}$.
In reality, the component masses and source distances are
different for different events, and it is possible that the best event
of previous $N$ detections dominates the constraint of NS EOS.

In the above discussion, we have not accounted for the effect
of spin, which is particularly important for LMBHs formed
through hierarchical mergers, as they are expected to have
relatively high spin ($\sim 0.7$; Fishbach et al. 2017; Gerosa &
Berti 2017). Such a spin magnitude will generate $\sim 0.15$
mismatch between a nonspinning BH–NS waveform and a
generic precessing waveform if the mass ratio is around 2 (see
Figure 8 of Harry et al. 2014). The relation between
distinguishable mismatch and S/N is discussed in Baird
et al. (2013).

5. Multi-messenger Detection
An important question is whether multi-messenger signals
can help us identify an LMBH. In other words, what are the
possible features of LMBH–NS systems that distinguish them
from NS–NS systems, besides direct GW observation of the
merger waveform? (BH–BH systems in stellar-mass ranges are
not expected to produce EM signals, so the clear presence of
such a signal would favor a system with at least one NS.) We
argue that current limitations in our theoretical understanding
of the underlying astrophysical process giving rise to EM
counterparts make it difficult to clearly distinguish a binary
with only one NS versus a binary with two NS. In what
follows, we discuss several leading counterpart prospects (see
also, e.g., Metzger & Berger 2012), but note that the era of
multi-messenger astronomy will bring an increased under-
standing of them, as well as awareness of further ones.
Several EM counterparts have been proposed that occur
within (tens of) milliseconds prior to merger, including possible
emissions related to crust-cracking due to tidal effects (with
associated luminosities which could reach levels of order $L \approx 10^{48}$ erg s$^{-1}$; Tsang et al. 2012) and magnetosphere
interactions (with associated luminosities which could reach levels
of order $L \approx 10^{43} (B/10^{14} G)^{2}$ erg s$^{-1}$; McWilliams &
Levin 2011; Piro 2012; Palenzuela et al. 2013; Metzger &
Zevin 2016). However, uncertainties in the EOS and magnetization
level of the NS makes distinguishing such signals seem
unlikely.

As the merger proceeds, the star will be disrupted by the
LMBH and give rise promptly to an accreting BH—the most
popular central engine model for a short gamma-ray burst
(sGRB). On the other hand, binary NS can themselves power
a jet, which, as discussed in Murguia-Berthier et al. (2014),
can escape if the jet breaks in a sufficiently short time. Thus,
an sGRB expected to take place nearly coincident with the peak in
GWs would not provide a clear discerning prospect. It is
important to keep in mind that the newly formed massive NS
will reach very high magnetizations ($B \approx 10^{15}$–$10^{17}$ G; Anderson
et al. 2008; Kouchi et al. 2017). If it collapses, large amounts of
energy ($L \approx 10^{49} (B/10^{15} G)^{2}$ erg s$^{-1}$) could be released rather
isotropically (Lehner et al. 2012) setting the stage for possible

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8 The quantity $f_{\text{end}}$ is set to avoid higher PN tidal effects and nonlinear
hydrodynamical coupling. In Hinderer et al. (2010), the fitting formula was
obtained by choosing 400 Hz $\geq f_{\text{end}} \geq 500$ Hz. The end frequency adopted in
Abbott et al. (2017c) is the frequency of the innermost stable circular orbit, which is above 1 kHz.

9 The effective spin of a most rapidly spinning pulsar known so far is $\sim 0.4$
(Hessels et al. 2006).
less -intense high-energy (gamma, X-ray) emissions, which do not necessarily require the observer to be specially aligned. Interestingly, the (short) GRB170817A associated with the GW event GW170817 is less luminous than typical sGRBs (Abbott et al. 2017b). This fact could be explained by the viewing angle but also through different burst mechanisms/models.

The collapse of a hypermassive NS to a BH, however, can take place in a significantly delayed fashion, and the resulting accreting BH state would fit naturally in the “canonical picture” of an accreting BH launching the jet, especially if the jet is Poynting flux dominated. It is tempting to speculate that, in such a paradigm, a significantly delayed sGRB would favor an NS–NS system (as timescales for launching a jet could be around ∼100 ms; e.g., Paschalidis et al. 2015; Ruiz et al. 2016); however, the time required to set the right topology and strength of the magnetic fields required for launching a jet (e.g., McKinney & Blandford 2009) introduces a delay that can potentially blur the differences between a BH-accretion scenario set up promptly after the merger (through BH–NS or NS–NS mergers) or delayed (via an NS–NS merger that produces a long-lived remnant). Furthermore, current uncertainties in key effects like effective viscosity of the forming disk, magnetization levels of the star, accretion characteristics, as well as the sGRB model itself (e.g., Narayan et al. 2001; Piran 2004) currently stand in the way of clearly distinguishing the progenitors based on such a delay.

Another way in which an LMBH–NS may potentially differ from an NS–NS binary is in the amount (and neutron richness) of NS material that is unbound during the merger. This ejecta will undergo r-process nucleosynthesis, building up heavy elements that decay, powering a so-called kilonova/macronova (Li & Paczyński 1998; Kulkarni 2005; Metzger 2017). In a rather spectacular fashion, such observations have been identified as counterparts to GW170817 (e.g., Smartt et al. 2017; Drout et al. 2017). The greater the mass, $M_{ej}$, of material that is ejected, the brighter the transient, and the longer the timescale on which it will peak. In terms of the velocity of the ejecta, such an EM transient will peak on timescales of $t_{peak} \sim 0.3 \left( M_{ej}/0.01 M_{\odot} \right) (v/0.2c)$ days, in the ultraviolet/optical to near-infrared frequencies, with peak luminosities of $L \sim 1.6 \times 10^{41} \left( M_{ej}/0.01 M_{\odot} \right) (v/0.2c)^{2} \mathrm{erg} \, \mathrm{s}^{-1}$ (Barnes & Kasen 2013). On longer timescales of $\sim 2.6 \left( E_{ej}/10^{50} \mathrm{erg} \right)^{1/3} (v/0.2c)^{-5/3}$ years (where $E_{ej}$ is the kinetic energy of the ejecta), there may also be a radio transient associated with the collision of this material with the interstellar medium (Nakar & Piran 2011; Hallinan et al. 2017).

Simulations of NS–NS mergers typically find ejecta of $\lesssim 0.01 M_{\odot}$, with the most ejecta coming from mergers with soft EOSs. With unequal mass ratios (Lehner et al. 2016; Sekiguchi et al. 2016), the ejected material is highly neutron rich, and the amount is on the higher end across EOSs. Higher mass ratio simulations of BH–NS mergers find significant ejecta when the BH has non-negligible spin aligned with the orbital angular momentum and/or the NS has a larger radius (Foucart et al. 2014; Kawaguchi et al. 2016), in which case the amount of ejecta can be up to $\sim 0.1 M_{\odot}$. Hence, an unusually bright ejecta-powered transient would seem to favor an LMBH–NS merger, though a transient consistent with $\lesssim 0.01 M_{\odot}$ ejecta could be attributed to either. We note, however, BH–NS mergers with nearly equal masses are not well studied (see Etienne et al. 2008; Shibata et al. 2009 for some early studies), and further scrutiny will be required to delineate their properties across parameter space.

An additional caveat to the above discussion is that non-negligible NS spin, on the order of $a \sim 0.1$, has also been shown to enhance the amount of ejecta to the level of a few percent of a solar mass (this falls within the allowed range for the spin along the orbital angular momentum estimated in GW170817, notice, however, that the component orthogonal to it is not constrained; East et al. 2016a, 2016b; Dietrich et al. 2017). Orbital eccentricity at the merger can also significantly increase the amount of ejecta (East & Pretorius 2012; Radice et al. 2016), though presumably this will be well constrained by the GW signal.

6. Conclusion

It is conceivable that LMBHs may be produced through PBH capture, supernovae, NS–NS mergers, the collapse of exotic compact objects, or other such phenomena. Therefore, their existence is tightly connected to the astrophysical population/distribution of these seeding objects and the underlying fundamental physics that governs them. Because of the uncertainty in the NS EOS and the degeneracy in the tidal effect of LMBH–NS and NS–NS systems in the inspiral stage, it appears challenging for Advanced LIGO to definitively identify such objects. The ability to differentiate between the two can be improved by better understanding their respective post-merger waveforms, as well as achieving better GW detector sensitivity (Miao et al. 2014, 2017) and accumulating statistics from many detections (Bose et al. 2018; Yang et al. 2018, 2017). The similarities in the potential EM counterparts to the two systems, within theoretical uncertainties, also makes distinguishing them with multi-messenger astronomy challenging, and calls for a better understanding of the underlying astrophysical processes. Such a task of refining models and honing in on the relevant parameter space will benefit tremendously from a dialog with observations as they take place.

If such an LMBH were discovered, the problem of identifying its formation channel would naturally arise. One possible indicator could be the spin of the LMBH—one can compute its prior distributions in each formation channel and compare them with the posterior distributions of each detection. The mass and redshift information of these objects may also help distinguish their origins. Excitingly, third-generation GW detectors will be capable of detecting non-vacuum compact binary mergers up to $z \sim 6$ (Abbott et al. 2017a). If LMBHs are present, even in a small portion of such mergers, they will guide fruitful discoveries in physics and astronomy.

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Erratum: “Can We Distinguish Low-mass Black Holes in Neutron Star Binaries?”
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In the published article, an error was introduced when we computed $S/N_\Delta$ to compare waveforms of binary neutron stars and neutron star–black hole binaries, as shown in Figure 2 therein. After correcting the error, the signal-to-noise ratio ($S/N$) is reduced by roughly a factor of 2. The corrected Figure 2 is shown here, including an updated caption. In addition, in the main text, the sentence “We assume that the binary is at a distance of 100 Mpc” should be corrected to “We assume that the binary is at a distance of 50 Mpc,” and the sentence “Within most of the parameter regime we consider here, $S/N_\Delta$ is bounded below $1/2$ should be refined as, “Within most of the parameter regime we consider here, $S/N_\Delta$ is bounded below 1.”

These corrections do not affect other parts of the paper. We apologize for any possible inconvenience.

Figure 2. $S/N$ computed using Equation (8) and assuming a binary at a distance of 50 Mpc. The mass of NS 1 is assumed to be 1.35 $M_\odot$. This $S/N$ is a function of the radius of the NS 1 and the binary mass ratio. As the $S/N$ is inversely proportional to distance, a 1.35 $M_\odot$+1.35 $M_\odot$ (with NS radius $\sim$12 km) binary event in the Virgo cluster should have an $S/N_\Delta$ around 2.