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Discerning the binary neutron star or neutron star-black hole nature of GW170817 with gravitational wave and electromagnetic observations

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The discovery of GW170817 with gravitational waves (GWs) and electromagnetic (EM) radiation is prompting new questions in strong-gravity astrophysics. Importantly, it remains unknown whether the progenitor of the merger comprised two neutron stars (NSs), or a NS and a black hole (BH). Using new numerical-relativity simulations and incorporating modeling uncertainties we produce novel GW and EM observables for NS-BH mergers with similar masses. A joint analysis of GW and EM measurements reveals that if GW170817 is a NS-BH merger, $\lesssim 40\%$ of the GW parameters are compatible with EM observations.

Introduction. The recent gravitational-wave (GW) and electromagnetic (EM) measurements of GW170817 [2–6], a neutron-star (NS) binary merger, have enabled critical insights into gravity, high-energy astrophysics, nuclear physics, and cosmology. Notably however, measurements so far have not conclusively shown that the progenitor binary comprised two NSs. From only GW observations, the masses of the individual compact objects are consistent with those of NSs measured through EM observations [7]. Furthermore, under the restrictive assumption of small spins, signatures from tidal effects suggest that (at least one of) the compact objects had finite size, albeit with a large statistical uncertainty [7–9]. From EM measurements alone, the discovery of a kilonova, an optical-infrared transient powered by rapid neutron-capture nucleosynthesis (e.g., [10–15]), indicates that the merger involved at least one NS [1, 16–27]. Thus, an important open question is whether the progenitor binary was a NS-NS or indeed, a NS and a black hole (BH) or exotic compact object with comparable mass. A major limitation in answering this question has been the absence of predicted GW and EM observables for similar mass NS-BH systems. While such low-mass BHs are not expected from standard astrophysical channels, they could in principle form in a prior merger or from primordial fluctuations in the early Universe [28]; alternatively, they could be exotic ultracompact objects (see, e.g., [29]).

To address this question, this paper presents the first direct comparison between the GW and EM signatures of NS-NS and NS-BH mergers with identical mass ratios (see [30] for an initial exploration). First, using new numerical relativity (NR) simulations of non-spinning NS-NS and NS-BH mergers with an identical composition-dependent NS equation-of-state (EoS) as our benchmark, we provide GW and EM observables (GW phase evolution and EM kilonova bolometric lightcurves) for mergers with mass ratios of 1 and 1.2. We then apply our methods to GW170817. Incorporating the large uncertainties in GW and EM modeling as well as in the EoS of NS matter, we show that current *EM-only* observations rule out a NS-BH merger, applicable to most EoSs, with mass ratio one. We cannot, however, rule out a NS-BH merger of mass ratio 1.2. We demonstrate that a *joint* analysis of GW and EM measurements leads to significantly improved constraints on the nature of the progenitor and enables us to compute, for the first time, a quantitative probability that a NS-BH merger are consistent with GW170817. Our methods provide orthogonal constraints to those GW and EM analyses that assume a NS-NS progenitor and focus on the nature of the remnant [31–36]. For NS-NS mergers, the remnant may be either a stable or metastable NS or a BH surrounded by an accretion disk; for NS-BH binaries, the remnant can only be a BH.

Numerical-relativity simulations. We analyze four new NR simulations of nonspinning NS-NS and NS-BH mergers with mass ratios $Q = 1, 1.2$ ($1.2M_\odot + 1.44M_\odot$ and $1.44M_\odot + 1.44M_\odot$, with the BH as the more massive object for NS-BH mergers). We use the tabulated composition- and temperature-dependent 'DD2' EoS [37] for the NS matter, for which $R_{\rm NS} = 13$km for a $1.4M_\odot$ star, and solely consider low-eccentricity systems ($e \lesssim 10^{-3}$). Simulations are performed using the general-relativistic radiation hydrodynamics code SpEC [38–40], with a two-moment approxi-

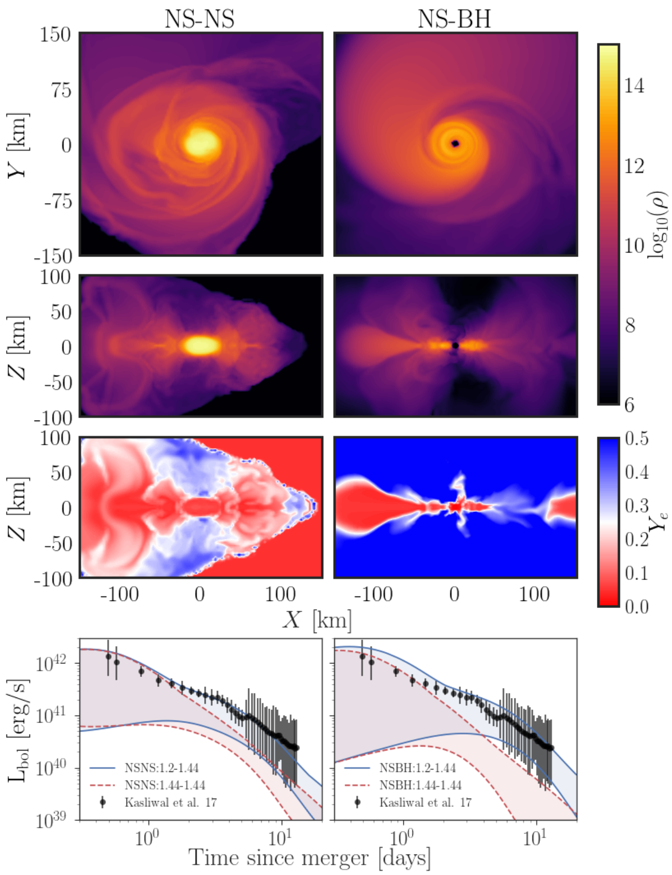

FIG. 1. *One-to-one comparison of NS-NS and NS-BH* with $Q = 1.2$ and the DD2 EoS. *Upper panels*: Matter density (cgs units) and composition (electron fraction Y_e), 3ms after merger for our NS-NS (left) and NS-BH (right) simulations. Low-density, high-Y_e polar regions are not resolved numerically in the NS-BH simulation. *Lower panels:* Kilonova bolometric lightcurves (blue), including results for our $Q = 1$ simulations (red). Shaded regions indicate the large uncertainties in the modelling. We assume that the total ejecta mass is 10–50% of $M_{\rm rem}$ measured in the simulations and the dynamical ejecta, and that the fraction of the blue component is $\sim 0 - 90\%$, to conservatively take into account uncertainties in the composition of the post-merger outflows (see text). The data with error bars from observations of GW170817 are taken from [1].

mate neutrino transport algorithm [41, 42]. We measure the mass, composition, and velocity of the matter outflows during the merger for all simulations, and $M_{\rm rem}$, the post-merger remnant mass excluding the final object. For the $Q = 1.2$ systems, we also extract the GWs. The top panels of Fig. 1 shows the result of the merger: matter surrounding a hypermassive NS or BH for the NS-NS or NS-BH systems respectively. For $Q = 1$ (1.2) we measure $M_{\rm rem} \sim 0.08\,(0.15) M_\odot$ for the NS-NS binaries and $M_{\rm rem} \sim 0.03 (0.13) M_\odot$ for the NS-BH binaries. In all simulations, a small amount of cold, neutron-rich material is dynamically ejected in the equatorial plane by the merger: $0.002 M_\odot$ ($0.004 M_\odot$) for NS-NS, and less than $0.001 M_\odot$ for NS-BH binaries. Less neutron-rich polar ejecta is observed, but in the absence of magnetic fields

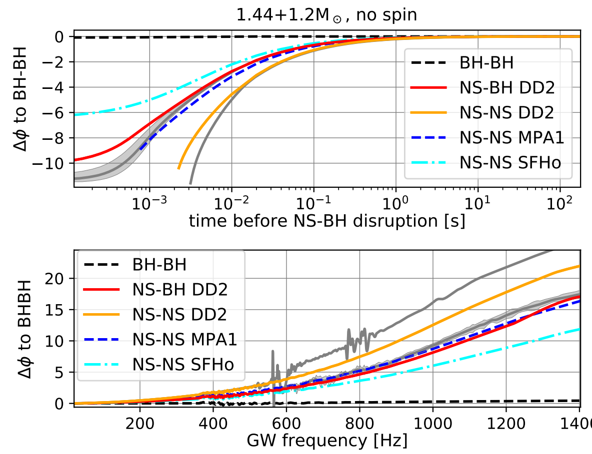

FIG. 2. *Tidal effects during an inspiral* in the GW phase when compared to a BH-BH as a function of time (top) and GW frequency (bottom) for a $1.2M_\odot - 1.44M_\odot$ system. Grey curves are our new NR results, with the shaded region indicating the numerical uncertainties (for NS-NS we have only one resolution); curves with legends are the predictions from the model SEOBNRv4T. Tidal effects accelerate the phase accumulation, hence the different signs when comparing to a BH-BH at the same time or frequency.

its mass is negligible (and not resolved in the simulations); see [43]. Note that none of our simulations produce a relativistic jet, e.g., as observed for GW170817 [44, 45], which is unsurprising given that our simulations do not include any MHD effects (see [46] for incipient jets in a NS-BH simulation).

Tidal effects in the GWs. For binaries comprising compact objects of only a few solar masses with similar signal-to-noise ratios as GW170817, current GW detectors are sensitive only to the GWs generated during their inspiral [7]. In contrast to vacuum BH-BH mergers, an important signature of NS matter in the GWs is due to tidal effects, where the objects' deformations produce a small change in the GWs. The dominant tidal GW signatures are characterized by a combination of each object's EoS-dependent tidal deformability [47] $\lambda = (2/3) k_2 R^5/G$, where G is Newton's constant, and k_2 and R are the Love number and radius.

Measurements of GW source parameters are very sensitive to the GW phase evolution (e.g., [48–50]). Figure 2 illustrates the impact of tidal effects on the GW phasing over an inspiral (up to peak GW amplitude) for a $1.44M_\odot - 1.2M_\odot$ binary. Grey curves show the results from the new NR simulations where the grey shaded region indicates the uncertainty due to finite resolution; the data were extended to low frequencies by matching to a theoretical model (known as SEOBNRv4T [51, 52]), where tidal effects are described analytically and thus apply to both NS-NS and NS-BH. The zero-line in Figure 2 is a BBH GW constructed by matching NR data from the SXS catalog [53, 54] to the theoretical SEOBNRv4 model [55–57] at low frequency. As can be seen from Fig. 2 a NS-BH binary with the relatively stiff DD2 EoS (grey shaded region) may have similar tidal effects as a NS-NS binary with a softer EoS (smaller NS radius). Together with the large statistical errors in the GW measurements, this makes it difficult to distinguish such systems (see the supplementary material for additional comparisons).

GW170817 GW constraints The GW-only analysis of GW170817 without the restriction to low spins in [7] constrains the mass-weighted combination of tidal deformabilities $\tilde{\Lambda} = 16/(13M_{\rm tot}^5)[(1+12/Q)\lambda_1 + (1+12Q)\lambda_2]$, where $M_{\rm tot}$ is the total mass of the binary, to be $\tilde{\Lambda} < 630$. A value within these bounds could be either due to a BBH ($\tilde{\Lambda} = 0$), a NS-BH with $\tilde{\Lambda} = 16\lambda(1+12Q)/(13M_{\rm tot}^5)$, or a NS-NS system. Altogether the GW measurements can only rule out NS-BH inspirals with EoSs in extreme corners of the possible parameter space. When specializing to the more restrictive assumption of low spins, the results of [7, 9] are still consistent with a wide range of NS-BH binaries, including both of our simulations with the DD2 EoS (a paper on GW inference is in preparation).

EM Kilonova observables for NS-BH and NS-NS mergers. For our case studies, we construct kilonova bolometric lightcurves, arguably the most robust examples of EM observables, to compare with our results in the ultraviolet-optical-infrared (UVOIR). However, the methods presented here could be extended to any prompt emission and afterglow lightcurves associated with the short γ-ray burst (SGRB) that followed GW170817. The UVOIR lightcurve depends critically on the mass, composition and velocity of different types of matter outflow from NS-NS or NS-BH mergers [10, 13, 14], the nature of the remnant (e.g., [58, 59]), as well as the inclination viewing angle to the binary (e.g., [60]).

We expect to measure two types of outflows for our particular simulations: dynamical ejecta associated with tidal tails in the binaries' equatorial plane and winds from the remnant accretion disk. The latter are strongly dependent on the remnant, with an expected ejected mass $M_{\rm wind} \sim (0.1-0.5)M_{\rm rem}$ [61, 62]. Given the measured mass of the disk and dynamical ejecta, disk winds thus dominate the mass budget of the outflows.

Based on the simulations, we compute kilonova bolometric lightcurves including conservative estimates for uncertainties in the unknown microphysics associated with the EM modelling. For simplicity, we use a two-component model that assumes there are low and high opacity components responsible for "blue" and "red"-coloured components respectively in the lightcurves (e.g., [20, 63]). The blue and red components are the lanthanide-free and lanthanide-rich ejecta, respectively, roughly corresponding to $Y_e \gtrsim 0.25$ and $\lesssim 0.25$ [64, 65]. We solve for the evolution of the ejecta thermal energy with radiative cooling and radioactive heating [66]. For each component, we assume that the ejecta with a total mass of $M_{\rm ej}$ expands homologously with an initial density profile of $\rho \propto r^{-1}$ ($\propto r^{-5}$) for the inner (outer) part, where r is the radius of the expanding ejecta. These two parts are separated by a characteristic velocity $v_{\rm ej}$. We further assume a constant opacity with values taken from the range of 0.1–$1\,{\rm cm}^2/{\rm g}$ and 5–$10\,{\rm cm}^2/{\rm g}$ for the blue and red components respectively [67–69].

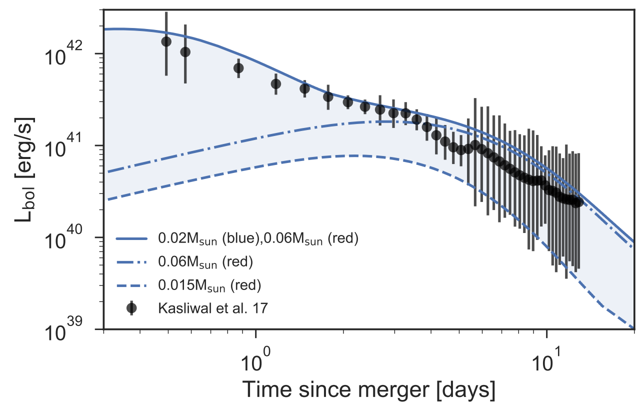

FIG. 3. *Inferred ejecta properties required to produce the bolometric UVOIR lightcurve associated with the GW170817 progenitor.* The dotted and dashed lines show the lanthanide-rich component assuming 30% of the $(0.05-0.2M_\odot)$ remnant mass is ejected (the range in disk mass is given in our model [72] and the estimated ejected percentage by simulations in [62, 73]). The solid lines are the combined results from both red and blue components.

To map from the simulations to the kilonova light curves, we assume that the total ejecta mass $M_{\rm ej}$ is $M_{\rm dy} + \epsilon M_{\rm rem}$, where $M_{\rm dy}$ is the mass of the dynamical ejecta and $\epsilon = 0.1$ and 0.5 for the lower and upper bounds. We select the fraction of the blue component for the disk outflow to range from 0 (lower bound) to the value with which the slope of the bolometric light curve is consistent with the observed data (upper bound). For the dynamical ejecta, note that we use the mass with $Y_e > 0.25$ obtained directly from the simulations. For our NS-BH simulations we obtain the upper bounds in the lower panels of Fig. 1 when assuming $(M_{\rm ej,red}, M_{\rm ej,blue})$ amount to $(0.048, 0.027)M_\odot$ and $(0.002, 0.018)M_\odot$ for $Q = 1.2, 1$ respectively. The lower bounds assume $(M_{\rm ej,red}, M_{\rm ej,blue}) = (0.015, 0)M_\odot$ and $(0.002, 0)M_\odot$ for $Q = 1.2, 1$ respectively. Correspondingly, for our NS-NS simulations, the upper bounds in Fig. 1 assume $(M_{\rm ej,red}, M_{\rm ej,blue}) = (0.032, 0.02)M_\odot$ and $(0.006, 0.02)M_\odot$, while the lower bounds correspond to $(M_{\rm ej,red}, M_{\rm ej,blue}) = (0.12, 10^{-4})M_\odot$ and $(0.006, 2\times 10^{-4})M_\odot$ for $Q = 1.2, 1$ respectively. We use the electron and γ-ray heating rates of radioactive r-process nuclei given by [70] and take into account the thermalization efficiencies of γ and β rays [71]. Here we neglect the contribution of α-decay and spontaneous fission.

The bottom panels of Figure 1 illustrate our results for the kilonova bolometric lightcurves for our merger simulations in light of the UVOIR observations of GW170817 [1]. The width of each lightcurve represents the modelling uncertainties discussed above, and uncertainties in the composition of the outflows discussed below. We find that the EM observations are *inconsistent* with equal-mass NS-NS and NS-BH mergers with a DD2 EoS. They are, however, consistent with both our $Q = 1.2$ NS-NS and NS-BH mergers.

GW170817 kilonova constraints. Figure 3 shows necessary ejecta properties to produce the UVOIR lightcurve associated with GW170817. The required ejecta mass can plausibly be produced by any remnant with $M_{\rm rem} \gtrsim 0.1 M_\odot$ (assuming $\sim 50\%$ of the disk is unbound). Specifically, we show that the lanthanide-rich component of the lightcurve can be produced assuming 30% of $0.2 M_\odot$ remnant mass, given by our model [72] and simulations by [62, 73], is ejected from a NS-BH merger; see [74, 75] for an alternative approach to compute photometric lightcurves for the contribution from dynamical ejecta. As discussed in [1, 16–27], the main difficulty is to produce the $\sim 0.02 M_\odot$ of fast ($v \sim 0.2$-$0.3c$), hot ejecta with a high electron fraction $Y_e \gtrsim 0.25$ required to explain the blue kilonova associated with GW170817. While none of our simulations produce such ejecta during merger, it could be produced in the shear region between two merging NSs, though only for finely-tuned parameters [76]: if the NSs' compactness is too high, the merger results in a prompt collapse to a BH preventing significant outflows, while if it is too low, the collision is insufficiently violent yielding only a small amount of hot polar ejecta (as in our simulations). Simulations of NS-NS mergers with masses compatible with GW170817 and compactness maximizing the production of hot ejecta are necessary to determine whether such a NS-NS merger scenario can underly the blue kilonova emission associated with GW170817.

Can the blue kilonova be produced by a NSBH merger? While such systems do not generate polar-shocked material, they produce hot, fast ejecta through post-merger disk outflows. Outflows of the required mass, velocity, and composition are not seen in current simulations; yet these simulations suffer from important limitations. Hydrodynamics simulations of NS-BH mergers [41] show high-Y_e disk winds but an insufficient amount of ejected mass; when including magnetic fields, large amounts of fast, hot ejecta have been measured [77], but its exact mass and composition will only be known once we have simulations that include both magnetic fields and neutrino transport. Long-term magnetohydrodynamics (MHD) evolutions of the remnant using idealized initial conditions (axisymmetric, cold, neutron-rich tori) have found fast MHD-driven outflows [62, 73] but with a low Y_e; however, with initial conditions taken from merger simulations, 2D viscous hydrodynamics evolutions find outflows with higher Y_e [78] than for the idealized setup. The properties of post-merger disk outflows in NS-BH systems thus remain highly uncertain. MHD effects during disk circularization and/or post-merger evolutions may still be the source of significant high-Y_e outflows.

Although these EM modelling uncertainties prevent us from setting stringent constraints on the progenitor of GW170817, we can at least rule out any binary systems that produce remnants with $M_{\rm rem} \lesssim 0.1 M_\odot$. For NS-BH binaries, this critically excludes equal mass systems with $R_{\rm NS} \lesssim 13\,{\rm km}$, and compact stars ($R_{\rm NS} \lesssim 11\,{\rm km}$) at all mass ratios, but not large stars in asymmetric-mass binaries (see below and supplementary material).

Joint GW and EM analysis of GW170817: a NS-BH merger? When interpreting the GW and EM observations of GW170817 separately, a NS-BH binary is consistent with the measurements. Here, we show that combining GW and EM measurables yields substantially more interesting constraints on the possibility and parameters of a NS-BH progenitor. We take the posterior distributions for the effective inspiral spin $\chi_{\rm eff}$ [79], Q, and $\tilde{\Lambda}$ obtained from the GW analysis with high-spin priors from [7]. Assuming a NS-BH system (zero NS spin and BH tidal deformability) and $M_{\rm BH} \geq M_{\rm NS}$, we convert these parameters at fixed masses to $\Lambda_{\rm NS} = \lambda (m_{\rm NS} c^2)^{-5} = 13\tilde{\Lambda}/[16(1{+}12Q)]$ and the BH's spin parameter $\chi_{\rm BH} = (1+Q)\chi_{\rm eff}/Q$. Next, we apply a quasi-universal relation to obtain the NS's compactness C from $\Lambda_{\rm NS}$ [80] (see also [81]). Finally, we substitute the GW information on parameters into our model [72] that predicts the remnant mass $M_{\rm rem}$ for a given set of progenitor parameters $(C, Q, \chi_{\rm BH})$. Binning these results yields the posterior distribution of Q and $M_{\rm rem}$ for a NS-BH progenitor of GW170817 shown in Fig 4. We find that nearly 40% of the probability distribution is at $M_{\rm rem} > 0.1 M_\odot$, the minimum requirement set by the EM constraints (taking into account a $\sim 0.02 M_\odot$ uncertainty in the model for $M_{\rm rem}$); see the supplemental material for the marginalized probability for a given $M_{\rm rem}$. Figure 5 (left) shows the marginalized posterior distribution of Q and $R_{\rm NS}$ for GW170817, restricted to binaries satisfying our conservative constraint $M_{\rm rem} > 0.1 M_\odot$. We also show (right) results assuming a possible tighter constraint to illustrate the potential impact of more accurate numerical simulations of post-merger accretion disks in the near future. The region of parameter space favored by both EM and GW constraints includes equal mass systems with large neutron stars ($R_{\rm NS} \sim 14\,{\rm km}$, also at present still consistent with nuclear physics constraints [82]), as well as more asymmetric systems with more compact stars [e.g., $R_{\rm NS} \sim (12-13)\,{\rm km}$ for $Q \sim 1.5$].

Discussion We have presented the first direct comparison of NS-NS and NS-BH mergers with identical mass ratios using the results of four new numerical relativity simulations. We showed that, taking into account the large uncertainties in modelling and the EoS of NS matter, current GW-only or EM-only observations can rule out a NS-BH merger only in extreme corners of the parameter space, e.g., in mass ratio and EoS. Importantly, we demonstrate a novel method of jointly analyzing GW and EM measurements to address the open question of whether one can quantitatively distinguish a NS-NS merger from a NS-BH (or very compact exotic compact object) with comparable mass. This allows us to determine, for the first time, a quantitative probability that a NS-BH merger is consistent with GW170817.

Our analysis is implementable for future NS binary mergers with measurable GW and EM radiation, allowing us to establish both the nature of the progenitor and remnant for sin-

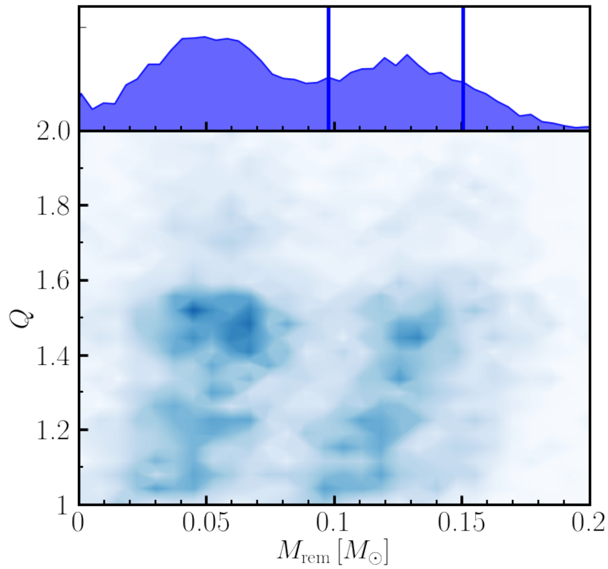

FIG. 4. *Posterior distribution function of Q and predicted $M_{\rm rem}$ for GW170817 assuming a NS-BH* merger with $M_{\rm BH} \geq M_{\rm NS}$. The top panel shows the marginalized distribution function of $M_{\rm rem}$, with the solid lines showing the 60% and 90% confidence intervals. The double-peaked distribution is a result of the features present in the $\tilde{\Lambda}$ posteriors.

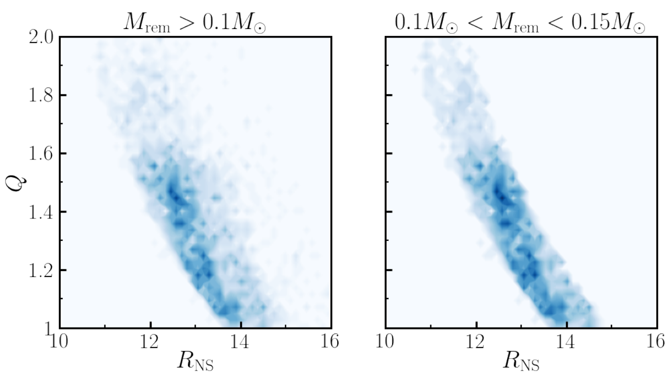

FIG. 5. *Marginalized probability distribution of NS radii [km] and binary mass ratios for GW170817 assuming a NS-BH progenitor* and using quasi-universal relations between $R_{\rm NS}$ and $\Lambda_{\rm NS}$ [80]. *Left:* current EM constraints exclude systems with $M_{\rm rem} < 0.1 M_\odot$, and *right*: possible impact of potential tighter constraints from improved modelling in the near future.

gle and populations of events. We expect our methods should improve as simulations continue to incorporate a multitude of micro-physics, reducing the wide systematic errors in the modelling of EM measurables. In particular, our ability to predict kilonova lightcurves is severely limited by current uncertainties in the properties of the post-merger disk winds that dominate the mass budget of the outflows for near-equal mass systems. Recent progress in 3D simulations of post-merger remnants promise significant improvements in modelling capabilities in the near future [62, 73].

GW measurements are also anticipated to improve as the detectors become more sensitive (although GW170817 already had a high signal-to-noise), and in the more distant future may also observe direct signatures from the tidal disruption or plunge of a NS-BH system or a NS-NS post-merger. Further, our analysis can readily incorporate constraints on NS matter from nuclear- and astrophysics (e.g., the PREX-II experiment [83] and the NICER mission [84]), which will substantially sharpen the conclusions. For example, for GW170817, imposing a realistic upper bound on the NS radius would immediately rule out large parts of the NS-BH parameter space still allowed by GW and EM observations.

In conclusion, while we have focused here on the GW and EM signatures for a restricted set of NS-BH mergers, our methods have broader applications, and follow-up work with more comprehensive studies and more realistic physics is ongoing.

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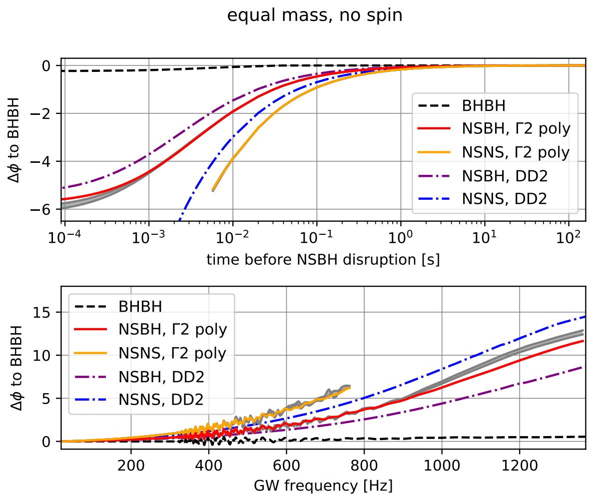

FIG. 6. *GW phase comparisons in an equal-mass case*. All curves with legends are using the SEOBNRv4T model, shaded regions indicate the uncertainty range of NR results due to finite resolution. Note that the grey shading indicating the NR result around the orange NSNS curve is barely visible on the scale of the plot. For the DD2 cases the total mass is $M = 2.88 M_\odot$, while the other curves correspond to $M = 2.8 M_\odot$.

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Supplemental material

Tidal effects in the GW phasing for $Q = 1$. Figure 6 shows a similar phasing comparison as in Fig. 2 but for equal-mass binaries. The interesting aspect of this comparison is that for the case with a $\Gamma = 2$ polytropic EoS we have accurate NR data for all types of binaries with a total mass of $M = 2.8 M_\odot$. For binary with the DD2 EoS discussed in the main text, $M = 2.88 M_\odot$.

Probability of remnant mass amount for a NS-BH progenitor of GW170817. The results of the combined analysis based on [7, 72] illustrated in Fig.4 can be further marginalized over the mass ratio using [7]. We thus obtain the probability that a NSBH progenitor for GW170817 produced a given amount of remnant mass as shown in Fig. 7. As systems with $< 0.1\, M_\odot$ of ejecta mass fail to produce the observed EM lightcurve, even under the very conservative assumptions discussed in the main text, our results show that a $\lesssim 40\%$ probability is associated with GW170817 being a NS-BH merger. When more refined EM modelling becomes available in the future, Fig. 7 can be used to set tighter constraints on the probability associated with a NS-BH progenitor for GW170817.

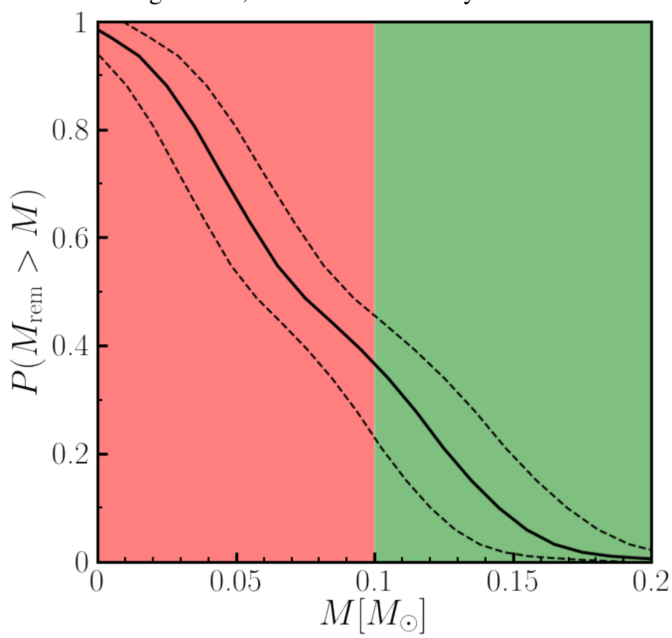

FIG. 7. *Probability that GW170817 produces a remnant mass greater than a given value, if it is a NSBH merger*. We show results for the model of [72] (solid line), as well as 1-σ errors in that formula (dashed lines).