

Binary neutron star mergers with a subsolar mass star

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(Received 10 April 2026; accepted 2 September 2026; published 18 September 2026)

While there are a number of proposed formation channels for subsolar mass compact objects, including black holes formed primordially or neutron stars that form in collapsar disks, there have yet to be any conclusive observations of such objects. Motivated by the possibility that, if such objects exist, gravitational waves from binary mergers may reveal them, we study binary neutron star mergers where one star has a subsolar mass in order to determine how well such systems are described by current models and when they could be distinguished from a system with a subsolar mass black hole. We perform fully general-relativistic simulations of a $1.7M_{\odot}$ star merging with a $0.8M_{\odot}$ star, leading to tidal deformabilities of up to $\mathcal{O}(10^4)$ for the latter, and quantify how this affects the merger dynamics and associated gravitation and electromagnetic signals. In this regime, we find mass transfer between the stars, as well as significantly lower disruption frequencies. Though this is not captured by current gravitational waveform models, we conclude that this does not significantly impact the sensitivity of current gravitational wave detectors to these sources. Assuming design sensitivity of the LIGO and Virgo detectors, we find no biases in the recovered intrinsic parameters for signal-to-noise ratios $\lesssim 100$. We also find that the large deformabilities lead to a significant increase in the amount of dynamically ejected matter compared to equal-mass systems, exceeding the predictions of current phenomenological models.

DOI: [10.1103/j5cs-3d6r](https://doi.org/10.1103/j5cs-3d6r)

I. INTRODUCTION

The first detection of a gravitational wave signal from a binary neutron star (BNS) merger, GW170817 [1], was simultaneously observed as GRB170817A and subsequently observed across the electromagnetic spectrum, inaugurating a new era in multimessenger astronomy [2,3] and exploration of the properties of matter at high densities [4–8]. Following this first detection, a second BNS gravitational wave event was observed, GW190425 [9], unfortunately without an observed electromagnetic counterpart. In contrast to GW170817, the total mass of GW190425 was larger than the mass of observed BNS systems in our Galaxy, illustrating the potential of gravitational wave observations to reveal

new populations of systems. Since 2019, despite the unprecedented sensitivity of the LIGO and Virgo detectors, no clear BNS candidates have been reported. However, two recent subthreshold BNS events, GW231109_235456 [10] and S250818k [11], have been associated with potential electromagnetic counterparts [12,13]. In addition, in November 2025, the LIGO-Virgo-KAGRA Collaboration reported the candidate S251112 cm [14], classified as a subsolar mass compact binary merger. If astrophysical, the source frame chirp masses for both S250818k and S251112 cm lie between 0.1 and $0.87M_{\odot}$, which requires the lighter compact object to be below $1M_{\odot}$. The candidate S250818k additionally favors a second component classified as a $\gtrsim 1.0M_{\odot}$ neutron star.

The observation of even a single subsolar mass neutron star would be an important discovery, since the supernova mechanism for forming neutron stars predicts typical masses ranging from 1.2 to $2M_{\odot}$ [15–19]. However, considerable uncertainty remains, especially at the mass range limits. A recent claimed observation of a $0.77M_{\odot}$ neutron star within a supernova remnant [20] suggests that subsolar mass neutron stars could be formed astrophysically. In addition to such tentative observational evidence, theoretical models also predict plausible formation channels for subsolar mass

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neutron stars, for example through fragmentation in gravitationally unstable collapsar disks [21], although significant uncertainties remain.

In this work, we consider a BNS system in which one of the component neutron stars has a mass smaller than $1M_{\odot}$. There have been numerous proposals for primordial formation scenarios for subsolar mass black holes [22], and one important question is how distinguishable a subsolar mass black hole would be from a neutron star in a binary merger. Gravitational wave observations allow for the measurement of the masses and tidal distortions of neutron stars through their imprint on the gravitational waveform [23,24], together providing direct constraints on the equation of state (EOS). Smaller mass neutron stars tend to be more easily deformed by tidal effects, as these objects are less dense than their massive counterparts. EOS models predict that subsolar neutron stars can have dimensionless tidal deformabilities ranging from $\mathcal{O}(10^3)$ for a $1M_{\odot}$ up to $\mathcal{O}(10^6)$ for a $0.1M_{\odot}$ star [25–30]. The constraints on the tidal deformability of neutron stars from GW170817 [4–8] and those on neutron star radius, obtained from the NICER x-ray telescope [31–33], have ruled out a large fraction of the EOS. The observation of low-mass binary systems could provide some of the most stringent constraints on the EOS, as the tidal effects in their gravitational wave signals are more prominent. Thus, detecting a low-mass neutron star would provide tighter constraints on the EOS while offering insights into alternative evolutionary pathways for forming ultralight binaries and challenging current assumptions about neutron star populations.

Previous searches have attempted to look for subsolar mass systems while neglecting the tidal deformability of the system [34,35]. Reference [36] showed that the loss in sensitive volume can be as high as 78.4% for an equal-mass binary system of chirp mass $0.17M_{\odot}$, in a search conducted using binary black hole (BBH) template banks. This loss was calculated under idealized conditions by comparing matches between templates and fiducial signals. In practice, gravitational wave signals are buried in noise, making it likely that the actual sensitivity loss is higher. Therefore, if a nearby subsolar BNS system had merged, the signal might have been missed by previous searches due to reduced sensitivity from not accounting for tidal deformability. More recently, Ref. [37] performed a novel search to explicitly look for subsolar BNS systems to ensure none of the low-mass neutron stars have escaped detection by previous search criteria. After performing a search using the public data from the third observing run of advanced LIGO and Advanced Virgo detectors, no new mergers were detected, and a new upper limit was placed on the merger rate of BNSs. This analysis was subsequently extended to the first part of the fourth observing run (O4a) in Ref. [38], which likewise found no evidence for subsolar BNS mergers, further strengthening the constraints on the merger rate.

Complementary to these searches, recent studies have investigated the prospects for identifying the nature of subsolar compact objects through their gravitational wave signatures, highlighting the role of tidal effects in distinguishing neutron stars from primordial black holes and other exotic compact objects [39,40]. These works suggest that current and near-future detector sensitivities could enable high-confidence measurements of tidal deformability in the subsolar mass regime.

However, both the above-mentioned searches and these forecast studies, as well as standard methods for extracting information about the properties of the binary system from gravitational wave detector data via a coherent Bayesian analysis, rely on accurate gravitational wave approximants throughout the entire parameter space. In principle, numerical-relativity (NR) simulations would be the method of choice for the description of a BNS waveform. However, such simulations come with high computational costs and thus typically only cover the late stage of the inspiral and merger [41–50]. As a result, over the years, the community has developed a range of waveform models for BNS systems [51–60]. One thing that they all have in common is that they are calibrated to numerical simulations close to the merger, where post-Newtonian theory breaks down. While different groups have produced high-quality NR data for BNS configurations in which the individual stars are spinning and covering mass ratios in the range [1.0, 2.0] (see, e.g., Table VII of Ref. [51]), with several addressing the effect of high mass ratios on the dynamics and merger process [43,48,61–64], none of these studies has, to our knowledge, produced NR data for subsolar mass neutron star binaries with individual tidal deformabilities greater than $\mathcal{O}(5000)$. Therefore, estimating the sensitivity of searches to subsolar BNS system is subject to theoretical bias. Furthermore, a reliable analysis of detected gravitational wave signals relies on an accurate theoretical description to cross-correlate measured gravitational strain data with gravitational approximants throughout the entire parameter space. If the waveform models used were inaccurate, this would lead to a systematic bias in the extraction of information from the observed data [65–68]. In fact, even for well-measured events such as GW170817, the inferred mass posteriors exhibit extended tails toward lower masses that fall outside the regime in which current models are calibrated (see Fig. 4 of Ref. [1]). The posterior sampling for GW231109_235456 [10] also extends into the subsolar mass regime. This further highlights the importance of developing waveform models that remain reliable across the full parameter space, including regions that have not yet been directly probed by observations.

In this paper, we follow the evolution of subsolar BNS systems with individual tidal deformabilities of up to $\mathcal{O}(10^4)$ and try to answer the following questions. (i) What is the impact of having such large tidal deformabilities on the merger dynamics and associated gravitational

signal? We find that matter effects lead to noticeably lower disruption frequencies, in the sensitive band of current gravitational wave detectors, which are inaccurately described by current gravitational wave models. (ii) Do current gravitational wave models used in LIGO-Virgo-KAGRA analyses lead to a significant loss of sensitivity? We find that the missing physics in current gravitational wave models does not significantly impact the sensitivity of the current generation of ground-based detectors. For all the configurations considered, the mismatch between our numerical simulations and state-of-the-art waveform models remains below $\sim 7 \times 10^{-4}$. This is presumably because the signal detectable by current ground-based detectors contains negligible power at merger frequencies. (iii) Do current gravitational wave models lead to biases in estimation of the source properties? We also perform parameter estimation and find no biases in the effective tidal deformability of the binary. In particular, assuming design sensitivity of the LIGO and Virgo detectors, for network signal-to-noise ratios (SNRs) below 105, we find that all intrinsic parameters are recovered within 1σ (i.e., 1 standard deviation).

Although the mass alone of a subsolar compact object cannot unambiguously determine whether it is a neutron star or a black hole, the tidal deformability provides a powerful discriminant. A confident measurement of a large tidal deformability would be incompatible with a black hole interpretation and thus would provide clear evidence for the presence of a neutron star. In this paper, we also explore to what extent such a distinction could be achieved with current gravitational wave detectors and find that, assuming the smaller object would be a black hole, the companion neutron star would have an inferred tidal deformability in tension with constraints from other observations.

The remainder of the paper is organized as follows. Details about the numerical setup and the different configurations considered are described in Sec. II. We present a qualitative discussion of the merger dynamics in Sec. III and extract information about the ejecta and remnant properties in Sec. III A. In Sec. III C, we compare the extracted gravitational wave signals to a set of state-of-the-art gravitational wave models and in Sec. III D, we perform an injection study to understand possible systematic biases. We conclude in Sec. IV. We discuss the accuracy of our simulations and provide more numerical details in Appendix A. Throughout this paper we use physical units for ease of comparison, unless otherwise stated.

II. METHODS AND CONFIGURATIONS

A. Numerical setup

We simulate BNS mergers by evolving the Einstein equations coupled to hydrodynamics using the code described in Ref. [69]. We discretize the Einstein field equations in the generalized harmonic formulation using

fourth-order accurate finite differences and time integration. We model the neutron star matter as a perfect fluid and evolve the general-relativistic Euler equations in conservative form using high-resolution shock-capturing techniques. We use the same methods and parameters for evolving BNS binaries as in Ref. [50]. Our simulations use box-in-box adaptive mesh refinement provided by the PAMR library [70]. We typically use seven levels of mesh refinement in our simulations, unless otherwise noted. We provide details on numerical resolution and convergence in Appendix A.

B. Initial configurations

We use quasicircular BNS initial data constructed with the Frankfurt University/Kadath (FUKA) initial data code suite [71], which is based on an extended version of the KADATH spectral solver library [72]. The set of hydrodynamical evolution equations is closed by an EOS connecting pressure p to specific internal energy ϵ and rest mass density ρ , i.e., $p = p(\rho, \epsilon)$. We focus on two different equations of state, namely, cold piecewise polytropic fits [73] approximating the SLy2 [17] and BSk21 [74] EOS. The latter is a prototypical stiff EOS predicting a radius of $R_{1.4} \sim 12.59$ km for a $1.4M_\odot$ neutron star, while the former is softer with $R_{1.4} \sim 11.76$ km [73]. These EOS give maximum masses of $2.053M_\odot$ for SLy2 and $2.274M_\odot$ for BSk21 for nonspinning stars and are consistent with pulsar observations [75–79] and with both electromagnetic and gravitational wave observations [6,80–84] of the BNS event GW170817 [85], as well as the gravitational wave observations of GW190814 [86] and GW190425 [87].

Thermal effects are added to the zero-temperature polytrope with an additional pressure contribution of the form $p_{\text{th}} = (\Gamma_{\text{th}} - 1)\rho\epsilon_{\text{th}}$, where ϵ_{th} denotes the excess specific energy compared to the cold value at the same density. We use $\Gamma_{\text{th}} = 1.75$, motivated by studies comparing nonzero-temperature EOS such as Refs. [88,89].

We focus on one nonspinning BNS configuration with a total mass of $M = 2.5M_\odot$ and a mass ratio $q = 0.39$, corresponding to individual gravitational masses of $M_A = 1.8M_\odot$ and $M_B = 0.7M_\odot$. The resulting chirp mass is $\mathcal{M} \sim 0.95M_\odot$, which lies on the edge of both the standard and subsolar mass compact binary template banks used for searches in O4 [90,91]. The value of the mass ratio was chosen to enhance tidal effects. We choose an initial separation of ~ 50 km, which corresponds to an initial gravitational wave frequency of 483 Hz, approximately 10 orbital periods before merger. We perform eccentricity reduction as described in Ref. [92] and reduce the initial orbital eccentricity to $\lesssim 10^{-3}$.

For comparison, we also simulate an equal-mass ($q = 1$) BNS with the same total mass, using the BSk21 EOS. The initial separation is also 50 km, approximately 10 orbital periods before merger.

TABLE I. Properties of our BNS simulations. The columns give the equation of state, the individual neutron star gravitational masses $M_{A,B}$, the mass ratio q , the individual radii $R_{A,B}$, tidal deformabilities $\Lambda_{A,B}$, the effective tidal deformability of binary $\tilde{\Lambda}$, residual orbital eccentricity e , and initial gravitational wave frequency f . The neutron stars are nonspinning.

EOS	$M_A(M_\odot)$	$M_B(M_\odot)$	q	R_A (km)	R_B (km)	Λ_A	Λ_B	$\tilde{\Lambda}$	e	f (Hz)
BSk21	1.8	0.7	0.39	12.49	12.26	101	1.88×10^4	1403	8×10^{-4}	483
SLy2	1.8	0.7	0.39	11.34	12.03	42	1.50×10^4	1066	10^{-3}	483
BSk21	1.25	1.25	1.0	12.53	12.53	1023	1023	1023	10^{-3}	473

III. RESULTS

We follow the evolution of the two types of BNS systems distinguished by their respective EOS. We summarize the properties of each binary in Table I. In Fig. 1, we present 2D snapshots of the density for the dynamical evolutions of the BSk21 system in the EOS equatorial plane. In Fig. 2, we show the rest mass surrounding the subsolar neutron star as a function of time and frequency. Initially ($t = 0$ ms or $f = 483$ Hz), the objects are separated by a coordinate distance of ~ 50 km. The radii of the neutron stars are $R_{0.7} \sim 12.26$ and $R_{1.8} \sim 12.49$ km, and their tidal deformabilities $\Lambda_{0.7} = 1.88 \times 10^4$ and $\Lambda_{1.8} = 101$. The second column (top row) of Fig. 1 shows the system at $t = 10$ ms or $f = 520$ Hz, i.e., ~ 2.5 orbits after the beginning of the simulation. At time $t \sim 30$ ms or $f \sim 720$ Hz, the smaller neutron star starts undergoing mass transfer. The merger occurs at $t = 35$ ms, or equivalently ~ 990 Hz, by which time the smaller neutron star has lost roughly 4% of its initial mass to the primary. The final remnant is a long-lived

massive neutron star that does not collapse within the timescales of our simulations (up to ~ 10 ms postmerger). The snapshot at $t = 30$ ms shows that the smaller neutron star is highly deformed. This deformation, while being coordinate dependent, is due to the large tidal deformability of the smaller neutron star, which results in the star being disrupted at a lower frequency. The softer SLy2 EOS case undergoes a similar evolution, except the mass transfer and merger happen roughly 1.3 ms later, corresponding to a slightly higher merger frequency of ~ 1050 Hz. This shift in merger frequency between the two EOS, corresponding to a change in the tidal deformability of the secondary, illustrates that the onset of mass transfer is sensitive to the compactness of the secondary. Together with the mass-ratio dependence discussed in Sec. III A, this suggests that mass transfer will commence progressively earlier in the inspiral, i.e., at lower orbital frequency, for binaries with either a larger mass ratio or more tidally deformed secondary, as expected from simple Roche-lobe-type arguments for tidal disruption in binaries.

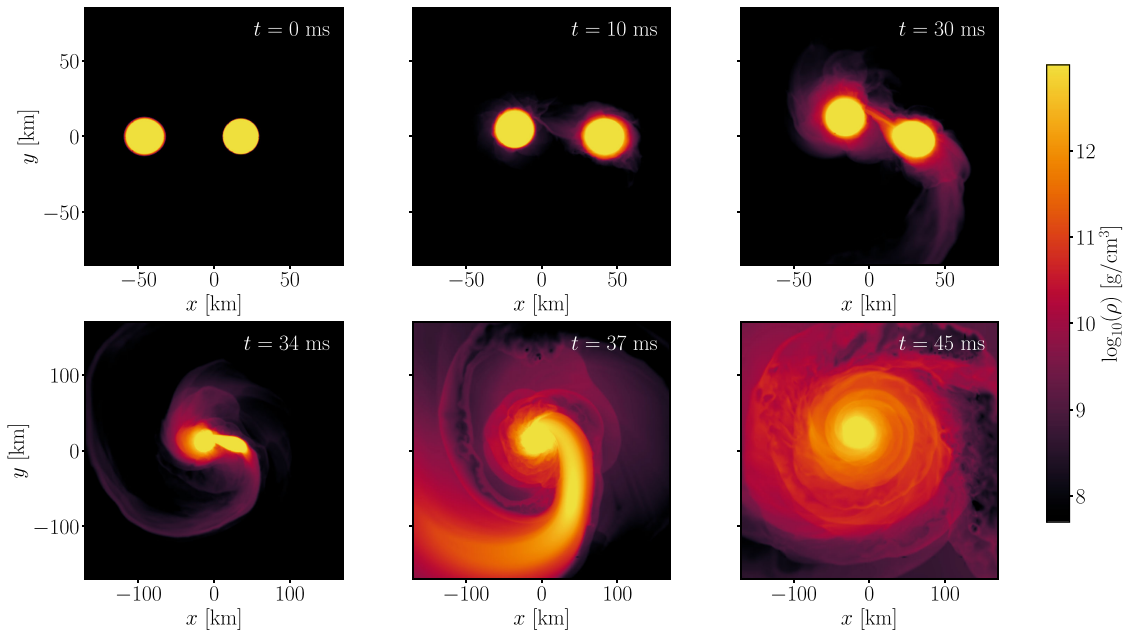


FIG. 1. Rest mass density profile in the equatorial plane on a logarithmic scale at different times for the BSk21 simulation. Note that the bottom row is enlarged (by a factor of 2) compared to the top row.

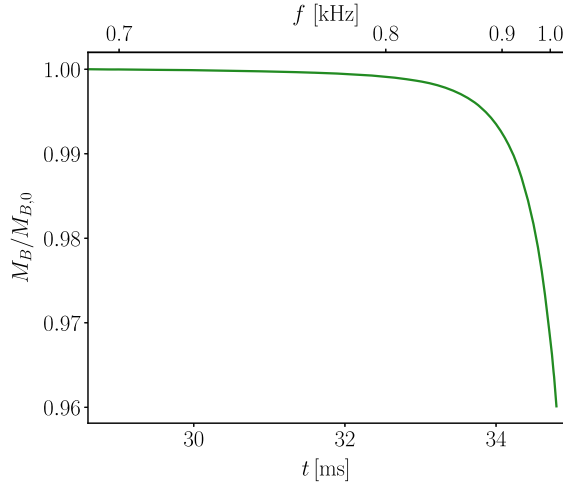


FIG. 2. Change in the total rest mass surrounding the subsolar neutron star for the BSk21 simulation as a function of time. We also show the corresponding gravitational wave frequency at the top. We only show the mass evolution from ~ 28 ms onward as the mass does not vary much before then.

In the following, we characterize the postmerger remnants, unbound material, and the gravitational wave signals. Combining the gravitational waveforms from the numerical simulations with analytical waveforms, we construct hybrid waveforms and estimate the measurability of the dimensionless tidal deformability of the neutron stars by advanced gravitational wave detectors.

A. Ejecta and remnant properties

In this section, we examine the postmerger distribution of matter. To characterize the postmerger ejected matter, we use the integrated rest mass density ρ residing outside some given radius

$$M_0(> r) = \int_{>r} \rho u^t \sqrt{-g} d^3x, \quad (1)$$

where u^t is the t component of the fluid 4-velocity. Postmerger, part of the rest mass will become unbound and escape to infinity. We flag fluid elements as unbound if $u_t < -1$ and the radial component of the velocity is positive. From the value of u_t , we can also determine the distribution of the rest mass M_0 over values of the velocity at infinity v_∞ .

Comparing the two different EOS, we find in Fig. 3 that the stiffer BSk21 EOS produces slightly more unbound matter than the softer SLy2 EOS: 4×10^{-2} versus $3.5 \times 10^{-2} M_\odot$. This trend in the ejecta differs from previous studies of BNS mergers [50,93–95]. One possible explanation is that, for equal-mass or mildly asymmetric binaries, shock heating is the dominant mass-ejection mechanism for neutron stars with soft EOS, whereas tidal interactions dominate for stiff EOS. However, the efficiency of shock heating decreases as the binary mass ratio departs from unity, while tidal effects become more important. For stiff EOS, where tidal interactions are already the primary driver of dynamical mass ejection, increasing mass asymmetry simply amplifies their role as also found in Ref. [96].

We also investigate the dependence on mass ratio by performing an equal-mass BSk21 simulation with the same total mass as our unequal-mass cases. In this setup, we find that the amount of unbound material is $\sim 1.3 \times 10^{-3} M_\odot$, i.e., it decreases by a factor of approximately 30 compared to $q = 0.39$. For comparison, we apply the fitting formulas from Ref. [62] and find good agreement in the equal-mass case. However, for the unequal-mass configuration, the fitting formula underestimates the amount of unbound material by a factor of about 6. This comparison allows us to partially disentangle the role of the mass ratio from that

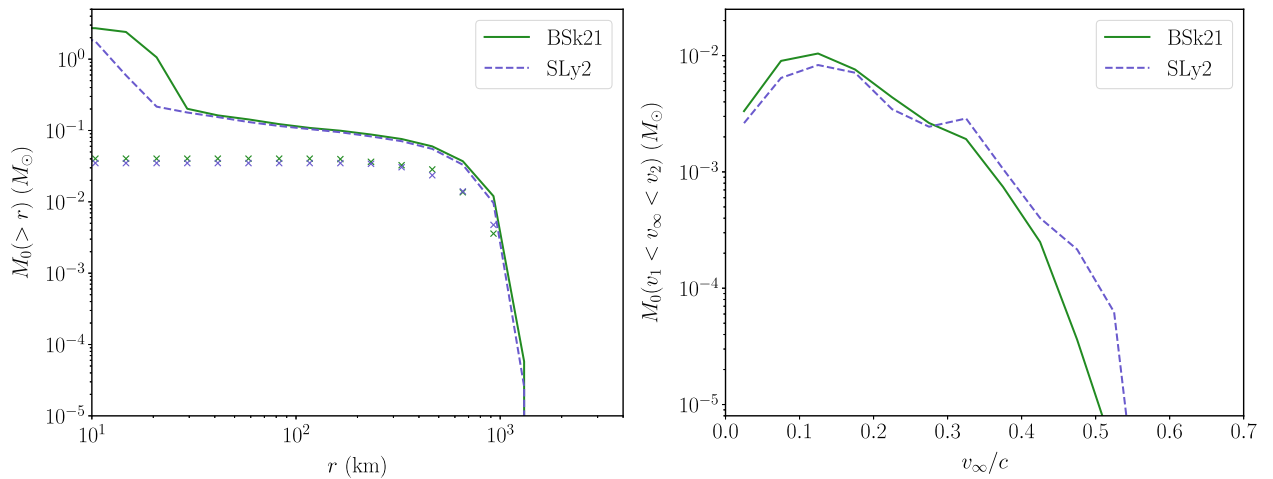


FIG. 3. Left: the amount of rest mass outside a given coordinate radius from the center of mass for the postmerger remnant for mergers of BNSs with various EOS. The solid curves show the total amount, while the points show just the unbound rest mass. Right: the amount of unbound rest mass binned by the velocity at infinity, with each bin of width $0.05c$.

of the subsolar nature of the secondary. The qualitative features we observe, strong tidal disruption, mass transfer prior to merger, and a one-armed spiral matter distribution, are consistent with the general behavior found in previous studies of asymmetric BNS and neutron star–black hole (NSBH) mergers [43,48,61–64,97] that do not specifically consider a subsolar mass of the secondary. However, the fact that the fitting formula of Ref. [62], calibrated against binaries with more moderate mass ratios and neutron star masses, reproduces the equal-mass ejecta well but underestimates the unequal-mass ejecta by a factor of ~ 6 suggests that a simple extrapolation of standard mass ratios trends is insufficient in this regime. One could then attribute the excess ejecta to the extreme tidal deformability of the subsolar star ($\Lambda_B \simeq 1.9 \times 10^4$, well outside the range probed in previous mass-ratio studies).

As a further cross-check, we compare our results to the dynamical ejecta fitting formula of Ref. [98], which is calibrated against a larger set of BNS simulations, including more asymmetric mass ratios. This fitting formula overestimates the amount of unbound material by a factor ~ 2 in both equal- and unequal-mass cases. This is in contrast with the formula of Ref. [62], whose accuracy differs sharply between the two mass ratios. This suggests that mass-ratio trends are captured more robustly by formulas calibrated over a broader range of mass ratios and is consistent with attributing the larger disagreement found with Ref. [62] to its modeling of the equation of state and mass-ratio-dependent (shock-driven) ejecta component, rather than to the tidal contribution.

We do note that the ejecta masses reported here should be interpreted with caution as our simulations do not include detailed neutrino transport, magnetic fields, or realistic nuclear microphysics and our results should be viewed primarily as illustrating trends with EOS stiffness and mass ratio within our modeling framework rather than as precise predictions of the ejecta properties. The agreement with the fitting formulas of Ref. [62] in the equal-mass case provides some confidence that the overall magnitude of the ejecta is reasonable, though quantitative predictions for the ejecta mass and velocity distribution are generally sensitive to the microphysics.

B. Gravitational waves

To study the gravitational wave signal, we decompose the polarizations (h_+ , $h_\times$) into (ℓ, m) multipoles as

$$h_+(t) - ih_\times(t) = \frac{1}{D_L} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} h_{\ell m}(t) {}_{-2}Y_{\ell m}(t, \phi), \quad (2)$$

where D_L is the luminosity distance to source, ${}_{-2}Y_{\ell m}$ are the $s = -2$ spin-weighted spherical harmonics, and ι and ϕ are the inclination and azimuthal angles that define the orientation of the binary with respect to the observer. Each

mode $h_{\ell m}(t)$ can be written in terms of a real time-domain amplitude $A_{\ell m}(t)$ and phase $\phi_{\ell m}(t)$ as

$$h_{\ell m}(t) = A_{\ell m}(t) e^{-i\phi_{\ell m}(t)}, \quad (3)$$

giving a gravitational wave frequency

$$\omega_{\ell m}(t) = \frac{d}{dt} \phi_{\ell m}(t). \quad (4)$$

The gravitational wave strain modes are related to the Newman-Penrose scalar Ψ_4 modes $\Psi_{4,\ell m}$ through $\ddot{h}_{\ell m} = \Psi_{4,\ell m}$. We extract the gravitational radiation by evaluating the Newman-Penrose scalar modes $\Psi_{4,\ell m}$ at different extraction radii in the wave zone, and integrate the above equation to obtain the strain using the fixed frequency integration method [99]. The leading-order quadrupolar modes $\ell, m = 2, \pm 2$ are dominant in our case.

Figure 4 shows the plus polarization h_+ for an optimally oriented, face-on source located at 100 Mpc for the two EOS considered, aligned in phase and time at 500 Hz. We also show the gravitational wave frequency evolution. The peak frequencies, defined as the instantaneous frequencies at which the amplitude of the strain is maximal, are 990 and 1050 Hz for BSk21 and SLy2, respectively. For comparison, the contact frequencies, defined as when the binary separation equals the sum of the components' radii, are ~ 745 and ~ 810 Hz, respectively (see Appendix A of Ref. [100] for a detailed definition). Since the merger frequencies of these configurations lie within the sensitive band of ground-based detectors, we next study how well current gravitational wave models capture large tidal effects.

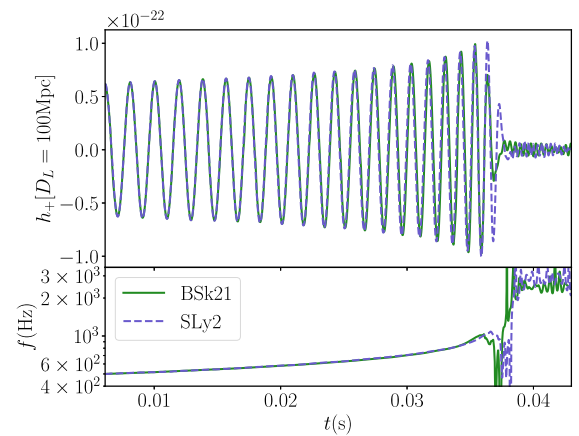


FIG. 4. We show the plus polarization of the gravitational wave radiation (top) of the BNS mergers when observed face-on at 100 Mpc for two equations of state. The bottom panel shows the corresponding gravitational wave frequency. The waveforms are aligned in phase and time at a reference frequency of 500 Hz.

C. Comparison with existing gravitational wave models

The numerical simulations produced in this paper consist of subsolar BNS simulations with large tidal effects and low eccentricity initial data (below 10^{-3}). It is therefore natural to explore the performance of state-of-the-art inspiral-merger-ringdown BNS waveform models, which in contrast to BBH models, need to include tidal effects. We focus on two major waveform-model families, namely, the SEOB and IMRPhenom models. The first waveform model we consider is IMRPhenomXAS_NRTidalv3, which employs the frequency-domain aligned spin IMRPhenomXAS [101] model as its BBH baseline and augments it with tidal effects using the closed-form NRTidalv3 [51] prescription. The model is designed to cover the ranges $m_{1,2} \in [0.5, 3.0]M_\odot$ and $\Lambda_{1,2} \in [0, 20000]$, a range well suited to our study. However, we note that, within the suite of numerical simulations that were used to calibrate the model, only two were unequal-mass systems with a subsolar mass secondary ($0.98M_\odot$ and $0.90M_\odot$, and with tidal deformabilities ~ 2600 and ~ 4600 , respectively). Within the SEOB family, we consider two models that incorporate tidal effects in different ways. The first is SEOBNRv5_ROM_NRTidalv3, which similar to the IMRPhenomXAS model, augments the BBH approximant SEOBNRv5_ROM [102] with the NRTidalv3 prescription. The second model, SEOBNRv5THM [52], builds on the BBH approximant SEOBNRv5HM [102] and includes the same tidal information as NRTidalv3, apart from an extension of the dynamical tides formalism to spin-aligned neutron stars [52]. It also includes a calibrated merger time and a phenomenological model for the premerger waveform of the late inspiral which is calibrated to a large set of NR waveforms. The NRTidalv3 and SEOBNRv5THM not only differ in their treatment of the merger, but also in the fact that, in the former, tidal effects are added in the frequency domain, while in the latter, they are incorporated in the time domain. Given that noticeable differences between these models have been observed for mass ratios greater than 2, yielding mismatches up to 10^{-2} [52], it is particularly interesting to study which model best describes our numerical waveforms.

In order to make meaningful statements, the waveform models are compared against complete BNS waveforms that are constructed by stitching together our numerical waveforms, covering the last ~ 10 orbits up to merger and extending through postmerger phase, with inspiral waveforms (calculated from 20 Hz) obtained with respective waveform model. In particular, we hybridize the semi-analytical and NR waveforms by following the procedure outlined in Refs. [42,65,103]. We first align the semi-analytical (SA) and NR waveforms which employ the same binary parameters by minimizing the integral

$$\mathcal{I}(\delta t, \delta \phi) = \int_{t_i}^{t_f} dt |\phi_{\text{NR}} - \phi_{\text{SA}}(t + \delta t) + \delta \phi|, \quad (5)$$

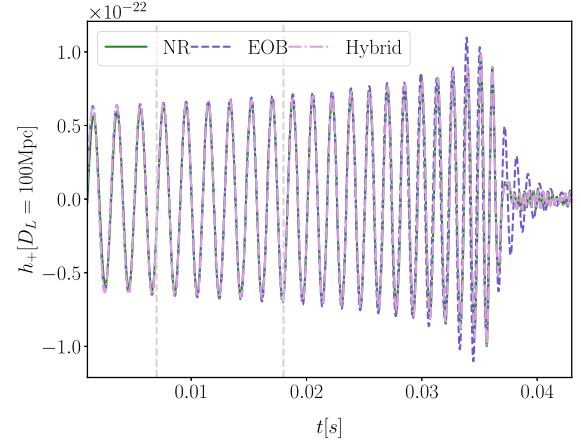


FIG. 5. Hybridization of the BSk21 configuration with the SEOBNRv5_ROM_NRTidalv3 model. The alignment interval is marked by vertical dashed lines. The SEOBNRv5_ROM_NRTidalv3 EOB waveform is shown as a purple dashed curve and the NR waveform as a green solid curve. The final hybrid combines the long inspiral from the EOB waveform, which includes several hundred cycles (not shown in the figure), and the late inspiral, as well as the postmerger phase of the NR waveform.

where $\delta\phi$ and δt are the relative phase and time shifts, and ϕ_{NR} and ϕ_{SA} denote the phases of the NR and in this case tidal effective one body (EOB) or IMRPhenom waveform. The alignment is done in a time window $[t_i, t_f]$ that corresponds to the frequency window $[500, 565]$ Hz.¹ Once the waveforms are aligned, we perform a smooth transition from the semianalytical to the NR waveform within the interval,

$$h_{\text{hyb}}(t) = \begin{cases} h_{\text{SA}}(t')e^{i\phi} & t \leq t_i \\ h_{\text{NR}}H(t) + h_{\text{SA}}(t')e^{i\phi}[1 - H(t)] & t_i \leq t \leq t_f \\ h_{\text{NR}}(t) & t \geq t_f \end{cases}, \quad (6)$$

where $t' = t + \delta t$, and $H(t)$ is the Hann window function,

$$H(t) := \frac{1}{2} \left[1 - \cos \left(\pi \frac{t - t_i}{t_f - t_i} \right) \right]. \quad (7)$$

In Fig. 5, we present, as an example, the hybrid construction for the BSk21 configuration and SEOBNRv5_ROM_NRTidalv3, with the alignment marked by vertical dashed lines. The discrepancy between the numerical simulation and the waveform model in the merger and postmerger part of the waveform arises because NRTidalv3 tapers the entire waveform past $7.5f_{\text{est}}$, where f_{est} is the

¹The lower bound of the window is driven by the initial frequency of simulations and the upper bound is arbitrary, but we have verified that the results do not sensitively depend on the window we choose.

estimated merger frequency [51]. This is also the reason for the sudden decrease in amplitude of the waveform in the late inspiral [52].

Using these hybrid waveforms, we can now assess the gravitational wave models by computing the mismatch between the hybrid waveforms and semianalytical gravitational wave models. We compute the mismatch according to

$$\bar{F} = 1 - \max_{\phi_c, t_c} \frac{(h_{\text{SA}}(\phi_c, t_c) | h_{\text{hyb}})}{\sqrt{(h_{\text{SA}} | h_{\text{SA}})(h_{\text{hyb}} | h_{\text{hyb}})}}, \quad (8)$$

where ϕ_c and t_c are arbitrary phase and time shifts, between approximants and the hybrid waveforms. The noise-weighted overlap is defined as

$$(h_1 | h_2) = 4\mathcal{R} \int_{f_{\min}}^{f_{\max}} \frac{\tilde{h}_1(f) \tilde{h}_2^*(f)}{S_n(f)} df, \quad (9)$$

where the tilde denotes the Fourier transform, $S_n(f)$ is the spectral density of the detector noise, and f is the gravitational wave frequency (in the frequency domain). We use the Advanced LIGO, zero-detuning, high-power (aLIGO_ZERO_DET_high_P) noise curve [104] with a fixed $f_{\min} = 30$ Hz and a variable $f_{\max}$ ranging from 500 up to 3000 Hz. We compute the mismatch for our hybrid waveforms against the IMRPhenomXAS_NRTidalv3, SEOBNRv5_ROM_NRTidalv3, SEOBNRv5THM, and SEOBNRv5_ROM waveform models. Each hybrid is compared against the baseline waveform model it was hybridized with, so that any contribution to the mismatch arises solely from differences between the numerical simulations and the corresponding waveform model. The results for each EOS are shown in Fig. 6. Generally, we find that all waveform models, including the BBH waveform SEOBNRv5_ROM, perform well. For all EOS, the mismatch remains below 4×10^{-3} , even for maximum frequencies at or above the merger frequency. Note also that the softer EOS gives mismatches which are roughly of the same order of magnitude than the stiffer EOS, despite tidal effects being

smaller. We emphasize that this is a nontrivial result since the parameters considered here lie outside the region of parameter space against which these waveform models were calibrated. Another noteworthy result is that changing the BBH baseline between SEOBNRv5_ROM_NRTidalv3 and IMRPhenomXAS_NRTidalv3 plays only a minor role in the mismatches, as was already pointed out in Ref. [52]. This is not surprising as the two models agree in the low spin limit. We also note that the SEOBNRv5THM mismatches are comparable to the NRTidalv3 approximant. The differences between the approximants are most likely due to the way the merger is handled in these two models, with SEOBNRv5THM merging for example later than NRTidalv3 for the Sly2 system. Finally, for the BSk21 EOS we observe that the BBH approximant SEOBNRv5_ROM yields smaller mismatches than the tidal models up to roughly 750 Hz, i.e., before the onset of mass transfer. At first sight, this may appear counterintuitive, since tidal effects are already present in the system. However, at these frequencies the tidal contributions to the phase evolution remain small, and differences between models are dominated by subtle amplitude and normalization effects rather than genuine tidal dynamics. In particular, the BBH and tidal approximants are constructed and normalized differently. Since the mismatch is computed using normalized waveforms, small differences in amplitude modeling can influence the result. As a consequence, the BBH model can yield slightly smaller mismatches in this regime despite omitting tidal physics. Once tidal effects become dynamically important, around the onset of mass transfer, the tidal models begin to outperform the BBH approximant, as expected. To better disentangle normalization effects from genuine waveform disagreement, we present two complementary diagnostics in Appendix B.

Using these results, we can also provide a rough estimate of the SNR above which a particular waveform model will yield biases. In particular, if two waveforms fulfill the criterion [105–108]

$$\bar{F} < n_p / (2q^2) \quad (10)$$

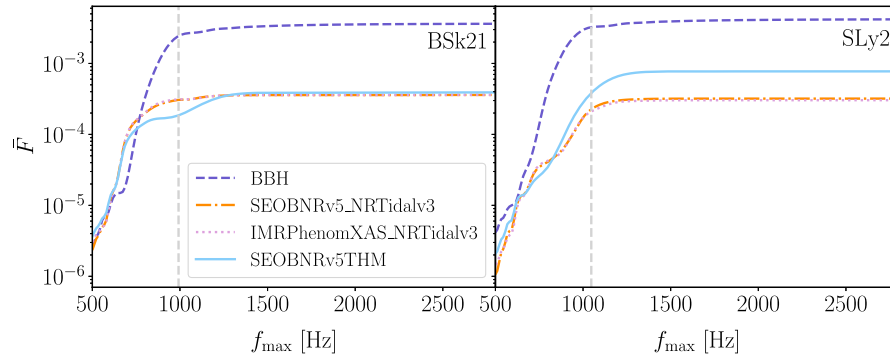


FIG. 6. Mismatches between different waveform models and our hybrid waveforms for the two different EOS (BSk21 on the left, and SLy2 on the right), computed according to Eq. (8) with a fixed $f_{\min} = 20$ Hz and a variable maximum frequency $f_{\max}$. We mark the merger frequency with a vertical dashed line.

for a given power spectral density, where n_p is total number of intrinsic parameters and ρ is the SNR, then they are deemed indistinguishable. Applying this to the BBH model, we find that the single detector SNR required to distinguish our hybrid waveform from the BBH one is ~ 41 for the BSk21 and ~ 39 for the SLy2 configuration. While this criterion is simple to evaluate, there are several problems that affect its usefulness in practice and make it in general too conservative. Namely, if it is violated, biases can, but need not arise [109] (see Ref. [110] for a suggestion on how to improve this criterion). In the next section, we perform Bayesian inference, allowing us to properly answer beyond which SNR a particular waveform model that is used as a template in parameter estimation yields biased posterior distributions for the hybrid signals.

D. Parameter estimation

We now perform an injection study to understand possible biases during parameter estimation for subsolar BNS systems. We consider a three-detector network consisting of the LIGO and Virgo detectors. Given $h_{\ell m}(t)$, the distance to the source, the angles (ι, ϕ) , $h_{+,\times}$ from Eq. (2), and the detector response functions $F_{+,\times}$, the observed strain is

$$h(t) = h_+(t)F_+(\alpha, \delta, \phi_p) + h_\times(t)F_\times(\alpha, \delta, \phi_p), \quad (11)$$

where $F_{+,\times}$ depend on the source's sky location (right ascension α and declination δ) and the polarization angle ϕ_p of the source relative to the interferometer.

We inject the BSk21 hybrid waveforms discussed in Sec. III C, starting from 20 Hz, and do not consider the softer EOS further. We consider SEOBNRv5_ROM_NRTidalv3 and the SEOBNRv5_ROM BBH model. We do not consider the IMRPhenomXAS_NRTidalv3 model as the baseline BBH models agree in the low spin limit. Despite the promising mismatches, we also do not consider SEOBNRv5THM as it is not yet implemented in the LALSuite package [111]. We assume the design sensitivity of Advanced LIGO and Advanced Virgo. We inject waveforms with a network SNR of $\rho_{\text{net}} \sim 35$, corresponding to an optimistic scenario similar to GW170817 [85]. In Table II, we list the extrinsic parameters of injected signals. Because the high-frequency content of the

postmerger portion of the gravitational wave reaches ~ 2400 Hz, we produce injections with a sampling rate of 16384 Hz, which corresponds to a high-frequency cutoff of 8192 Hz. We recover with a sampling rate of 8192 Hz and a maximum frequency of $f_{\text{high}} = 3500$ Hz, i.e., above the waveform termination. All injections start at a frequency of 20 Hz, while our Bayesian analysis uses a low cutoff frequency of $f_{\text{low}} = 30$ Hz to generate template waveforms. In all cases, we perform zero noise injections, as this allows us to obtain posteriors that do not depend on a specific noise realization, therefore isolating systematic errors.

We perform Bayesian inference using Bilby [112–114] and analyze 256 s of data. We use a multibanded likelihood calculation to speed up the computation and the sampling algorithm used is nested sampling with the DYNesty sampler [115]. For the analysis, we assume uniform prior distributions in the interval $[0.5, 1000]M_\odot$ for component masses and $[-0.05, 0.05]$ for both dimensionless aligned spins. We also assume a uniform prior distribution for the individual tidal deformabilities between $[0, 2 \times 10^4]$. For all other parameters, we use priors similar to other gravitational wave analyses; see, e.g., Ref. [82]. As a check that our pipeline works properly, we additionally inject a SEOBNRv5_ROM_NRTidalv3 waveform constructed using the same parameters as for the hybrid construction of BSk21 with that model, and we recover this injection with the same model. We label this additional injection SEOBNRv5_ROM_NRTidalv3_same_inj and do not expect to see biases for this setup, which will provide a useful point of comparison.

In Fig. 7, we show the results for the BSk21 EOS, where we show the 2D and 1D marginalized probability densities for a subset of the recovered posterior distributions, namely, the chirp mass $\mathcal{M}$, the mass ratio q , and the dimensionless tidal deformability $\tilde{\Lambda}$. In the 2D contour plots, we show the 90% confidence intervals. The dotted lines and crosses mark the injected values. Through the comparison with SEOBNRv5_ROM_NRTidalv3_inj_same, we find that our employed setup is able to recover the injected parameters reliably and that all injected parameters are recovered within the 90% confidence interval. Using our hybrid waveform all parameters are recovered within the 90% confidence interval, without biases. We find that the network SNR beyond which the tidal deformability deviates from its injected value by more than 1σ is ~ 105 . The lack of bias despite the tidal models not capturing the earlier onset of mass transfer is because of the lower sensitivity of the detectors at such frequencies. Indeed, we did a recovery with a lower upper cutoff frequency of 1792 Hz and found that the results of the parameter estimation are almost identical, suggesting that the lack of postmerger content in the models used for parameter estimation has no significant impact. These results are in agreement with Ref. [65] and consistent with the expectation that the postmerger will have negligible impact on parameter recovery with the current generation of gravitational wave

TABLE II. Values of extrinsic parameters used for the injections.

Parameter	Label	Value
Phase at 30 Hz	ϕ	5.46 rad
Right ascension	α	3.86 rad
Declination	δ	-1.155 rad
Inclination	ι	0 rad
Polarization angle	ψ	0.081 rad
Merger time at geocenter	t_c	1 369 419 318 s

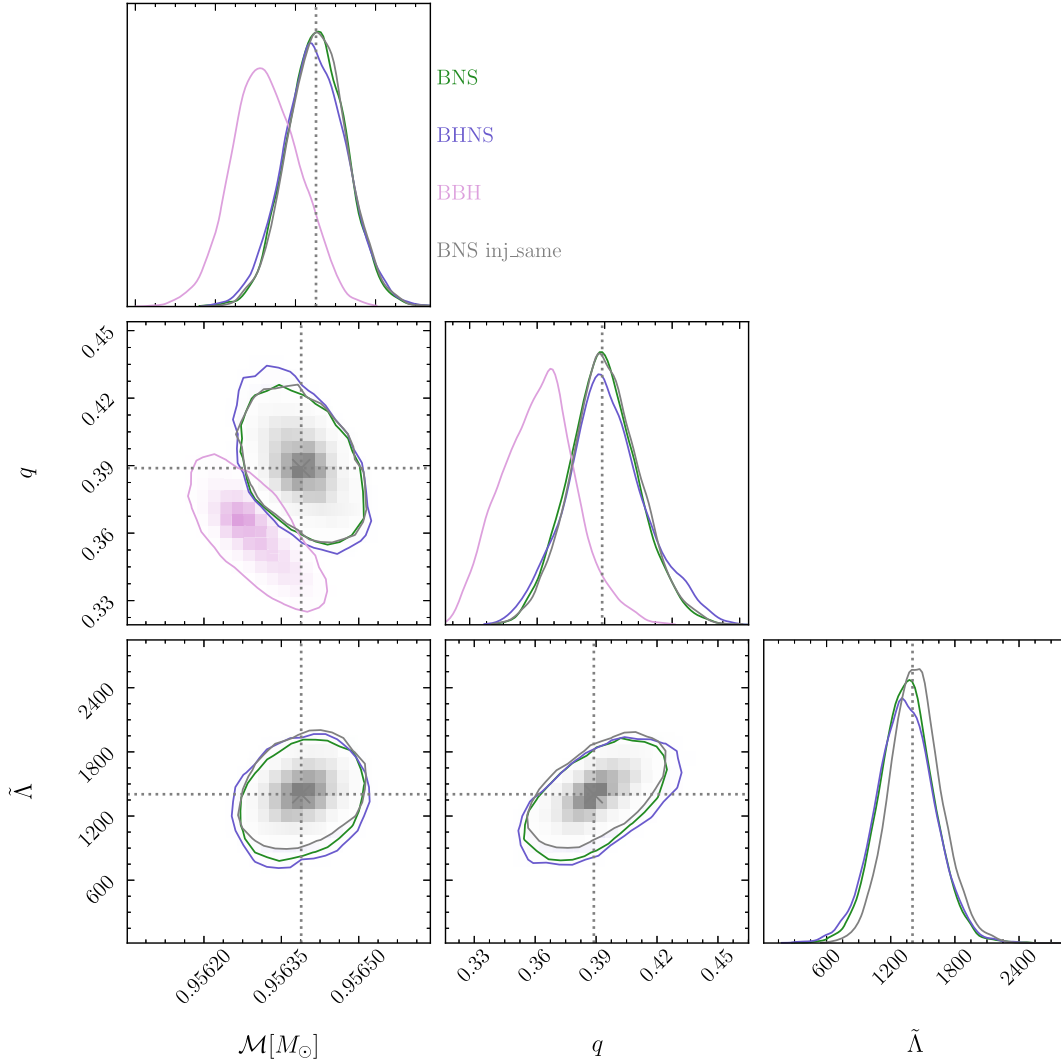


FIG. 7. The marginalized 1D and 2D posterior probability distributions for chirp mass $\mathcal{M}$, mass ratio q , and tidal deformability $\tilde{\Lambda}$ for the BSk21 configuration. Recoveries labeled by BNS (green), BHNS (blue), and BBH (pink) use different approximations to recover our hybridized waveform, which is a combination of the SEOBNRv5_ROM_NRTidalv3 model and our numerical simulation. The BNS inj_same (gray) uses for injection and recovery the SEOBNRv5_ROM_NRTidalv3 model with the same source parameters as the hybrid. The latter serves as validation for our injection setup. The injected source parameters are marked with dotted lines and crosses. Contours show the 90% credible regions in 2D and the corresponding intervals in the 1D posteriors. The log Bayes factors $\ln \mathcal{B}$, relative to the BNS model are 0.4 and -8.2 for the BHNS and BBH model, respectively.

detectors [116]. Note that, in agreement with Refs. [100,117], we find a positive correlation between q and $\tilde{\Lambda}$. Overall, our results suggest that if we were to observe a subsolar event, current waveform models would accurately identify the event as containing a subsolar object.

We also show results when assuming the smaller object is a black hole (i.e., that its tidal deformability is zero).² We

²Note that we do not use the black hole–neutron star (BHNS) waveform model of the SEOBNRv4 model family, but instead force tidal deformability of the smaller object in the BNS model to vanish. The reason for this is that the current BHNS model requires the larger object to be the black hole.

find small biases in the chirp mass and mass ratio, in addition to the tidal deformability, although within 1σ . Finally, we also recover with the BBH waveform model SEOBNRv5_ROM and find larger biases in the chirp mass and mass ratio, although within 2σ . Note that, even under the BBH interpretation, the analysis would still point to the presence of a subsolar mass object.

The evidence for whether there is one or two neutron stars in the system is quantified with the log Bayes factor between the BNS and BHNS model. Focusing on a SNR of 35, we find a log Bayes factor of 0.40 in favor of the BHNS model, meaning the BHNS model is marginally preferred, but the evidence is inconclusive. This is consistent with

Ref. [118], which showed that the leading-order tidal effects on the gravitational wave signal of an inspiraling compact object binary are in fact degenerate between a BNS and a BHNS binary, so long as there is sufficient uncertainty in the EOS. However, if we take the median recovered value for the mass of neutron star $M_A = 1.80M_\odot$ and assume the EOS is BSk21 or SLy2, then this would imply a tidal deformability of 98 or 43, respectively, which is incompatible with the median recovered value for $\Lambda_A = 990^{+380}_{-345}$. That is, no EOS allowed by prior constraints would give such a high value of Λ . Thus, once realistic EOS constraints are incorporated, the BHNS interpretation becomes disfavored. Similarly, computing the log Bayes factor between the BBH and BNS model, we find the BNS model is strongly favored with a log Bayes factor of 8.2.

IV. DISCUSSION AND CONCLUSION

In this work, we have presented results from fully relativistic hydrodynamic simulations of quasicircular BNS systems in which one of the component masses is subsolar. We considered two different EOS governing the perfect fluid model for the stars, allowing for individual tidal deformabilities up to 10^4 . Our focus was on quantifying the impact of large tidal deformabilities on the gravitational wave signal, and in this first study, we have neglected the effects of magnetic fields, neutrinos, and realistic nuclear microphysics.

Due to the relatively large mass ratio, we find that tidal effects are significant. For example, the smaller mass star can start to transfer mass to its more massive companion even during the late inspiral. We also find that the amount of dynamically ejected material is on the order of a few times $10^{-2}M_\odot$, largely independent of the EOS considered. This corresponds to an increase by a factor of ≈ 30 compared to an equal-mass binary with the same total mass, in disagreement with predictions from phenomenological relations for the ejecta and disk masses derived from typical BNS simulations with supersolar mass neutron stars.

We next investigated the impact of large tidal deformabilities on the gravitational wave signal and found that matter effects lead to significantly lower disruption frequencies, on the order of 700 Hz—i.e., well within the sensitive band of current gravitational wave detectors. Motivated by this, we examined whether current gravitational wave models would suffer from a loss of sensitivity or introduce biases in the estimation of source properties. To address this, we constructed complete inspiral-merger-ringdown BNS waveforms by combining state-of-the-art EOB and IMRPhenom models for the inspiral with our numerical relativity simulations for the late inspiral and merger. The resulting waveforms show mismatches with state-of-the-art models below 4×10^{-3} , indicating that such signals would not be missed by current searches, as the

differences predominantly show up at the higher frequencies that contribute less to the SNR.

We then injected these hybrid waveforms into fiducial data streams of the LIGO and Virgo detectors and performed parameter estimation using various waveform models. We found that neglecting all tidal effects in the waveform model leads to biases in the inferred chirp mass and mass ratio for an observation with a SNR of 35. However, the data would favor a BNS template over a BBH model. Conversely, assuming that the lighter object is a black hole introduces small biases in the recovered intrinsic parameters, and the data would instead favor a BHNS model. However, in that case, the inferred tidal deformability for the larger mass neutron star would be in tension with observations.

When recovering the signal with waveform models that include closed-form tidal corrections, we did not find any biases in the recovered chirp mass, mass ratio, and effective tidal deformability, all consistent within the 90% credible intervals. We further determined that the network SNR at which the inferred tidal deformability would deviate from its injected value by more than 1 standard deviation is approximately 105, corresponding to the upper range of expected SNRs for a GW170817-like event in the O5 observing run [119]. Given the expected increase in detector sensitivity, our results suggest that current waveform systematics are unlikely to be a limiting factor for typical O5 detections, but may become relevant for particularly loud events. This highlights the need for continued improvement of BNS waveform models, especially in the late inspiral, merger, and postmerger regimes where tidal effects become increasingly important and current models transition to BBH-like templates.

Overall, we hope that our results can serve as an initial testing ground for future gravitational wave and electromagnetic modeling of subsolar BNS mergers. However, more simulations for various mass ratios, EOS, and spins, as well as simulations including realistic nuclear microphysics are needed to draw a more complete picture.

ACKNOWLEDGMENTS

It is a pleasure to thank Samuel D. Tootle, Harald Pfeiffer, and Konrad Topolski for their assistance constructing the initial data used here; Anna Puercher, Adrian Abac, and Marcus Haberland for help setting up the parameter estimation runs; Lami Suleiman for providing tabular equations of state; and Alan Tsz-Lok Lam, Hao-Jui Kuan, Reed Essick, Marcus Haberland, and Tim Dietrich for helpful discussions regarding various aspects of this project. W.E. acknowledges support from a Natural Sciences and Engineering Research Council of Canada Discovery Grant and an Ontario Ministry of Colleges and Universities Early Researcher Award. J.R. acknowledges support from the National Science Foundation Grant No. PHY-2409736. This research was supported in part by Perimeter Institute for Theoretical Physics. Research at

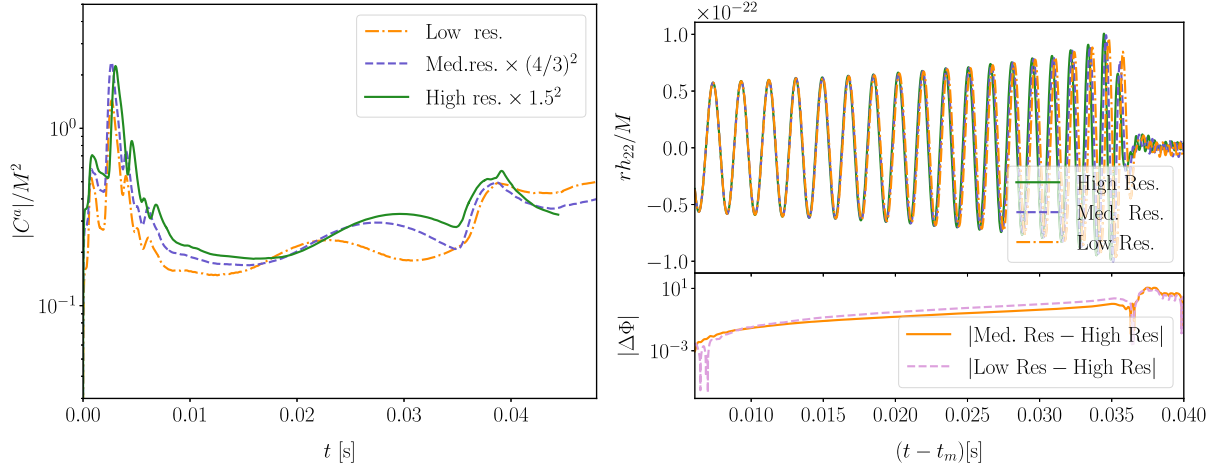


FIG. 8. Left: volume integrated norm of the generalized harmonic constraint violation C^a as a function of time for the BNS system for BSk21 EOS. The values have been scaled assuming second-order convergence, though at early times the convergence is closer to first order. Right: gravitational wave radiation from the low, medium, and high resolutions aligned in phase and time at 500 Hz (top) and the corresponding accumulated dephasing between the low and medium and low and high resolutions (bottom).

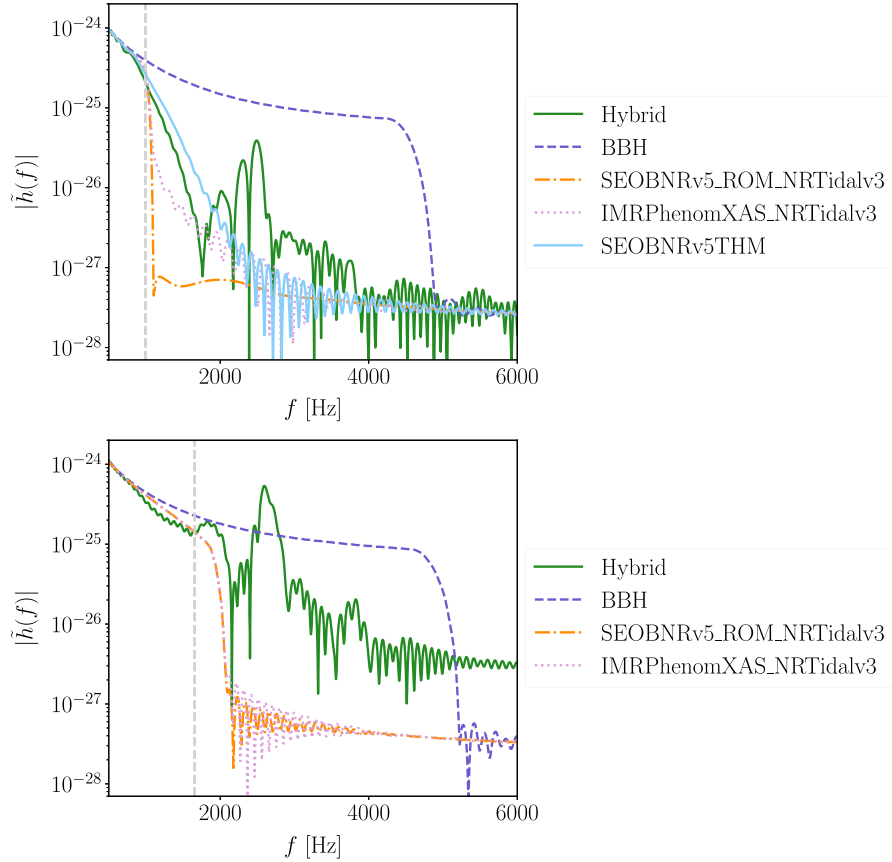


FIG. 9. The frequency-domain hybridized and analytical waveforms as a function of frequency for the BSk21 EOS. Top: the unequal-mass system presented in main text. Bottom: the results when evolving an equal mass system with the same total mass. The dashed gray lines mark the merger frequency. We find that the agreement is better up to larger frequencies for the equal-mass case, because the tidal effects are smaller.

Perimeter Institute is supported in part by the Government of Canada through the Department of Innovation, Science and Economic Development and by the Province of Ontario through the Ministry of Colleges and Universities. Computations were performed on the Urania and Hypatia HPC system at the Max Planck Computing and Data Facility. This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: NUMERICAL CONVERGENCE AND ERROR ESTIMATES

For the BNS mergers considered in this paper, we perform simulations with seven levels of refinement where the finest level has a linear grid spacing of $dx \sim 0.033M$, and each successive level has a linear grid spacing that is twice as coarse. In the left panel of Fig. 8, we show the norm of the generalized harmonic constraint violation, integrated over the domain as a function of time. For the BSk21 EOS, we also perform a convergence study with grid spacing that is $3/4$ and $2/3 \times$ as large, which is shown in Fig. 8. All results in the main text are from the lowest resolution. Although at early times, the order of

convergence is closer to first order, presumably from high-frequency noise (junk radiation) in the initial data which may engage the shock-capturing scheme, at later times, the convergence is consistent with roughly second order, as expected from our numerical scheme in the absence of shocks. The right panel of Fig. 8 shows the waveforms for all resolutions (top panel) and the dephasing between low or medium and high resolution (bottom panel) which accumulates to roughly 2 and 1 rad at merger, defined as the time at which the complex amplitude of the high-resolution waveform peaks. The dephasing is roughly first-order convergent.

As a consistency check, we perform simulations for an equal-mass system with the same total mass. Again, focusing on the BSk21 EOS, we hybridize the waveform as described in the main text. In Fig. 9, we present the frequency-domain hybridized and analytical waveforms. We find that the equal-mass system agrees with analytical waveforms up to larger frequencies. This is confirmed by computing the mismatches between hybrid and analytical waveforms, which we show for both the equal and unequal mass case in Fig. 10. From this figure, one can also see that the gravitational wave signal in the 2–3 kHz frequency range, coming from the postmerger oscillations, is significantly weaker in the unequal mass case compared to the equal-mass case.

As a final consistency check, we perform parameter estimation on the hybrid waveform for the equal-mass case. We choose a distance that gives a similar SNR to the one

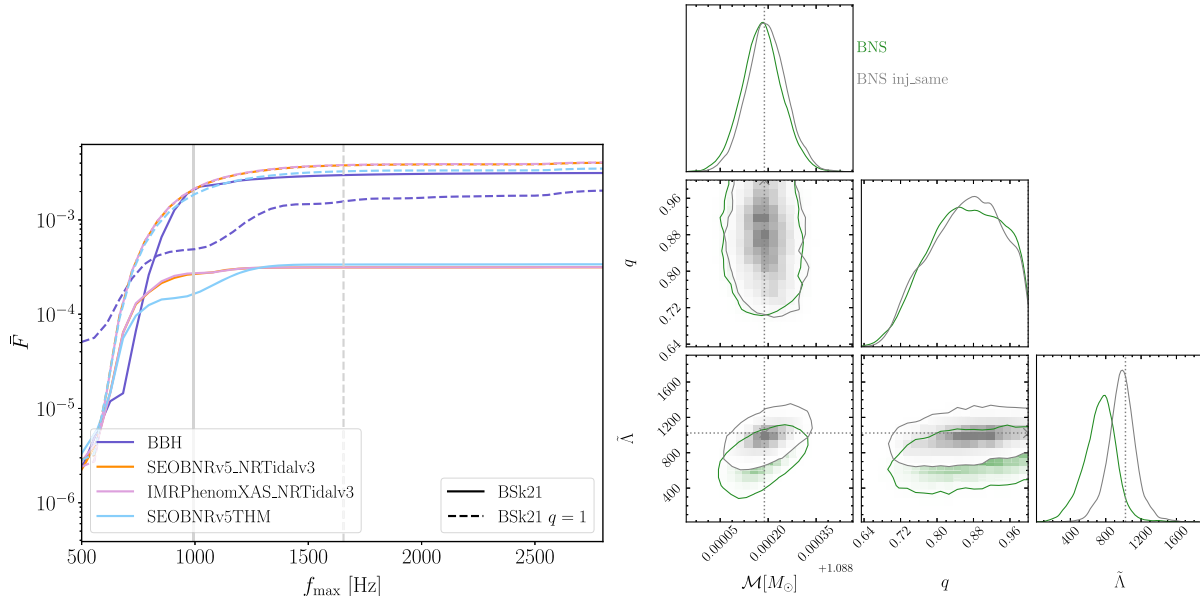


FIG. 10. Left: mismatches between different waveform models and our hybrid waveforms computed as in Fig. 6, but for the equal mass (dashed lines) and unequal mass (solid lines) with the BSk21 EOS. Right: the marginalized 1D and 2D posterior probability distributions for chirp mass $\mathcal{M}$, mass ratio q , and tidal deformability $\tilde{\Lambda}$ for the equal-mass BSk21 configuration. The recovery labeled by BNS (green) uses a different approximation to recover our hybridized waveform which is a combination of the SEOBNRv5_ROM_NRTidalv3 model and our numerical simulation. The BNS inj_same (gray) uses for injection and recovery the SEOBNRv5_ROM_NRTidalv3 model with the same source parameters as the hybrid.

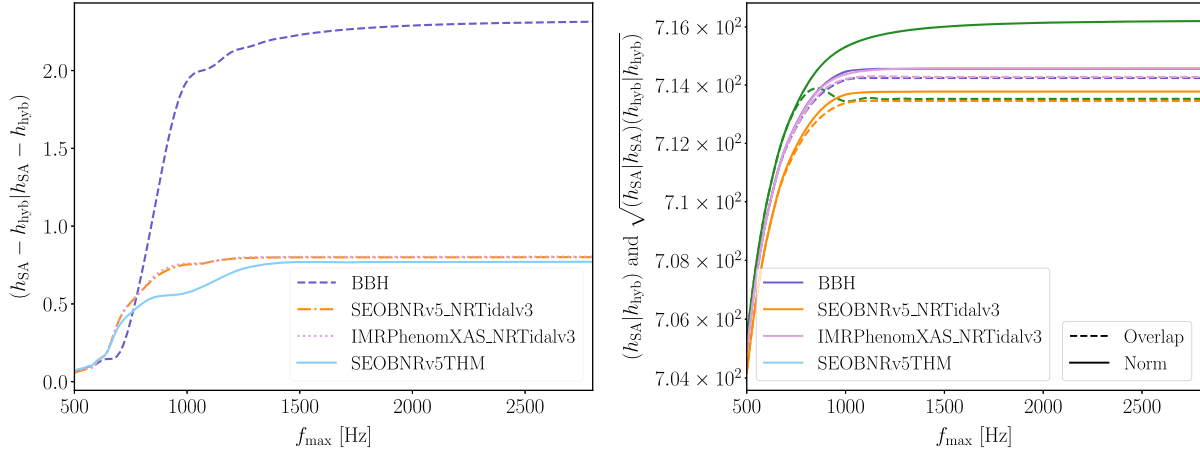


FIG. 11. Left: a match-based estimate of the size of waveform differences at a fixed distance of 100 Mpc, as a function of upper cutoff frequency for the BSK21 EOS. Right: the unnormalized overlap between the semianalytical and hybrid waveforms ($h_{\text{SA}}|h_{\text{hyb}}$), and the geometric mean amplitude of the two signals ($h_{\text{SA/hyb}}|h_{\text{SA/hyb}}$), as a function of the upper cutoff frequency, for the BSK21 EOS.

considered in the main text. We use similar priors and show the results in Fig. 10. As mentioned above, the masses and spins are well recovered; however, although the injected value of the effective tidal deformability is within the 90% confidence interval, there is a small bias toward lower effective tidal deformability. This is consistent with the results found in Ref. [65] and is likely due to the accumulated phase difference between our hybrid and analytical waveform in the late inspiral. This is further justified by the observation that the posteriors are nearly identical when analyzing the signal with a lower cutoff frequency, again in agreement with with Ref. [65].

APPENDIX B: NORMALIZATION EFFECTS AND ALTERNATIVE OVERLAP MEASURES

In this appendix, we present additional diagnostics to clarify why, for the BSK21 EOS, the BBH approximant SEOBNRv5_ROM yields smaller mismatches than the tidal models before the onset of significant mass transfer.

While the standard mismatch provides a convenient and widely used measure of waveform agreement, it involves an implicit normalization that can obscure the relative impact of amplitude differences, particularly in regimes where tidal effects are still subdominant. To better disentangle normalization effects from genuine waveform disagreement, we therefore consider alternative measures that more directly quantify the noise-weighted difference between waveforms.

First, in the left panel of Fig. 11 we show the quantity

$$(h_{\text{SA}} - h_{\text{hyb}}|h_{\text{SA}} - h_{\text{hyb}}), \quad (\text{B1})$$

evaluated at a fixed reference distance of 100 Mpc. This measure more directly maps onto the likelihood weighting in parameter estimation, since it quantifies the noise-weighted squared difference between signals without the additional normalization inherent in the mismatch. We find that, in the low-frequency regime, where the BBH approximant also exhibits slightly smaller mismatches, the squared difference is correspondingly small, indicating that tidal contributions to the signal remain subdominant there. At higher frequencies, however, the tidal models show improved agreement as expected once tidal effects become significant.

Second, in the right panel of Fig. 11, we show the unnormalized overlap between the semianalytical and hybrid waveforms, and the geometric mean amplitude of the two signals, as a function of the upper cutoff frequency. This figure makes explicit how the cumulative disagreement builds up with frequency while avoiding the rescaling present in the standard mismatch definition. This again indicates that the apparent better agreement at low frequencies of the BBH model is primarily driven by normalization effects, rather than improved physical agreement with the hybrid waveform.

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