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Remnant baryon mass in neutron star-black hole mergers: predictions for binary neutron star mimickers and rapidly spinning black holes

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Gravitational-wave (GW) and electromagnetic (EM) signals from the merger of a Neutron Star (NS) and a Black Hole (BH) are a highly anticipated discovery. We present a simple formula, validated with 75 simulations, that distinguishes between potential merger outcomes and predicts the baryon mass left outside of the BH after merger. Our formula describes critical unexplored regimes: comparable masses with non-spinning BHs, and higher BH spins, and is essential in assessing whether events such as GW170817 could be NS-BH systems instead of NS-NS mergers.

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Introduction In this new era of gravitational wave (GW) astronomy, the observation of the merger of a neutron star (NS) and black hole (BH) binary in GWs and/or electromagnetic (EM) emission remains amongst the most anticipated discoveries yet to happen [1]. NSBH mergers simultaneously involve strong-field gravity, supradense nuclear matter, complex microphysics, and powerful EM phenomena due to the delayed matter outflows at different timescales and frequencies. Understanding the detailed merger processes and multi-messenger signatures involved has been a longstanding challenge at the forefront of nuclear physics and astrophysics.

Moreover, GW and EM measurements of GW170817 ([2–4] and references therein) indicate that it was most likely the first discovery of a binary neutron star (NSNS) merger. However, observations only allowed us to conclude definitively that: i) at least one NS was involved in the merger from ultraviolet-optical-infrared observations (e.g., [5–16]), and ii) the other object in the progenitor binary had a comparable mass from GW measurements [2, 17], and is thus probably, but not certainly, a NS. This highlights the urgent need, addressed here and in a complementary paper focusing on observables [18], to model both GW and EM observables of NSBH mergers, in particular in the equal-mass regime, and to distinguish them from NSNS mergers.

Progress on modeling the rich non-linear physics of NSBH mergers relies on numerical simulations within a general-relativistic framework. Simulations show that the NS is either torn apart by the BH’s tidal forces or plunges into the BH, depending on the mass ratio, spins, and the NS Equation-of-State (EoS). If the NS is disrupted, most of the matter is accreted onto the BH within a few milliseconds. The remaining material forms an accretion disk and bound tidal tail around the final BH, or is ejected by the merger, as illustrated in Fig. 1. Nuclear reactions in the debris disk and ejecta, neutrino winds, and relativistic outflows are examples of processes that power EM transients such as kilonovae (e.g., [19–23]) and short gamma-ray bursts (SGRBs, e.g., [24, 25]).

The baryon mass outside the BH ~ 10 ms after merger, which we refer to as the remnant mass M^{rem} here, is an

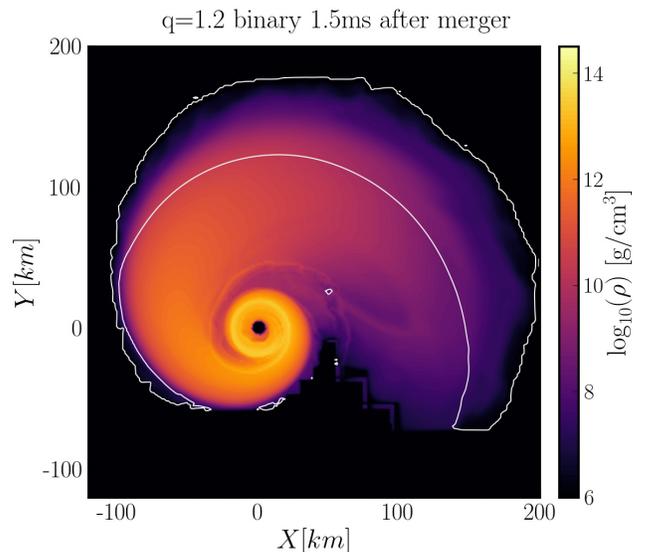


FIG. 1. *Baryon density 1.5 ms after a nonspinning NSBH merger with mass ratio $Q = 1.2$, in the equatorial plane. The white contour encloses the small amount of unbound material $M_{\text{ej}} \sim 5 \times 10^{-4} M_{\odot}$. The remnant mass for such a system is significantly overestimated by the previous prediction of FF12 [26] but well-described by the new model developed here.*

important quantitative diagnostic, as first shown in Foucart 2012 [26], hereafter FF12. Critically, M^{rem} impacts the observables of the plethora of possible EM counterparts, and their detectability by current EM facilities. For instance, M^{rem} , as introduced by FF12, is currently used when triggering EM follow-up searches by alerts sent by the LIGO and Virgo detectors (see the method outlined in [27]). M^{rem} also determines whether matter is available to power a SGRB or a kilonova, and is critical for predicting the mass and proper-

ties of merger outflows (see also [28]). Another application is GW measurements: tidal disruption (i.e. $M^{\text{rem}} \neq 0$) leads to a distinct shutoff in the signal [29–31] that depends on the long-sought after EoS of NS matter.

Previous work on modelling NSBH mergers has focused on mass ratios $Q = M_{\text{BH}}/M_{\text{NS}} \gtrsim 3$, with M_{BH} and M_{NS} the gravitational masses of the compact objects in isolation (see [32–36] and references therein). This range corresponds to astrophysical formation scenarios through supernova explosions in a progenitor binary that predict a gap between NS and BH masses [37, 38]. Comparable-mass binaries with a single NS could involve a primordial BH [39], a BH born in a prior NSNS merger that formed a binary through dynamical interactions in a dense cluster or galactic core (see the review in [40]), or an exotic BH-like object (see [40, 41] for possible BH mimickers).

In this paper we develop a new simple, ready-to-use prediction for the range of masses, NS radii, and BH spins leading to tidal disruption, as well as M^{rem} for NSBH mergers. Our results cover previously unmodelled binary parameters: comparable masses and high BH spins. The former are critical to distinguish NSBH from NSNS mergers. The latter are of particular interest for astrophysics and for constraining fundamental axion-like particles [42]. Our model’s dependence on the binary parameters is derived from physical tidal disruption and symmetry considerations, with free coefficients calibrated to results from numerical-relativity (NR) simulations. The NR data include two novel simulations of comparable-mass binaries ($Q = 1, 1.2$), to be described in detail in an upcoming paper, a case with high BH spin [43], and several systems with a composition- and temperature-dependent EoS for the NS matter [35, 36].

The new regions in parameter space covered here are essential: the model of FF12 leads to substantially inaccurate results outside of the range of binary parameters for which it was calibrated. Specifically, we show that the remnant mass is significantly lower for nearly equal-mass NSBH mergers than expected from FF12, which is thus inadequate to assess whether GW170817 is in fact a NSBH merger mimicking a NSNS binary. By contrast, M^{rem} is substantially higher for large BH spins than previously predicted by FF12, which would lead to missing potential EM counterparts for multi-messenger studies.

We also discuss a further important application of our results: verifying the reliability of numerical simulations by comparing remnant mass predictions from different NR codes. This is a pressing open problem that has not yet been addressed for NSBH mergers.

Numerical simulations We consider results from 75 NR simulations performed with three different evolution codes compiled from [33, 35, 36, 43–48] (See Supplemental Material at [URL] for simulation details). Each simulation is parameterized by three dimensionless quantities: the mass ratio $Q \geq 1$, the dimensionless BH spin $\chi_{\text{BH}} = c|\mathbf{S}|/(GM_{\text{BH}}^2)$, where \mathbf{S} is the spin angular momentum, and the NS’s compaction $C_{\text{NS}} = GM_{\text{NS}}/(R_{\text{NS}}c^2)$, where R_{NS} is the NS’s areal radius that depends on the EoS. Effects of precession, NS spin, orbital eccentricity, and magnetic fields are not con-

sidered. Precessing systems can be approximately mapped onto aligned-spin systems [49], while aligned NS spins and non-zero eccentricities can significantly enhance M^{rem} , but only for extreme systems formed through dynamical capture [50, 51]. Low dimensionless spins on the NS or residual eccentricities (a few percents or less) are not expected to cause large changes in M_{rem} . Magnetic fields are critical to the post-merger evolution, but do not affect much the merger dynamics itself [52, 53], the epoch most relevant here. Our simulations cover the range $Q \in [1, 7]$, $\chi_{\text{BH}} \in [-0.5, 0.97]$, and $C_{\text{NS}} \in [0.13, 0.182]$ and include 44 systems not used in FF12, with 11 cases outside the range of validity of FF12, and 12 systems with tabulated composition- and temperature-dependent EoS. We focus on the normalized remnant mass

$$\hat{M}^{\text{rem}} = M^{\text{rem}}/M_{\text{NS}}^b, \quad (1)$$

where M_{NS}^b is the baryonic mass of the initial NS. Since most simulation results do not have error bars, we estimate the errors σ_{NR} in \hat{M}^{rem} based on a few simulations where well-determined errors were computed (see FF12 for details). The resulting error estimate combines a 10% relative error and a 1% absolute error in the mass measurements:

$$\sigma_{\text{NR}} = \left[\left(\frac{\hat{M}_{\text{rem, NR}}}{10} \right)^2 + \left(\frac{1}{100} \right)^2 \right]^{1/2}. \quad (2)$$

Model for the remnant baryon mass Our model for \hat{M}^{rem} relies on physical insights about tidal disruption [26] together with novel symmetry considerations. For $Q \rightarrow \infty$, the NS tidally disrupts if it overflows its Roche lobe outside the radius of the innermost stable circular orbit (ISCO) of the BH, where its motion transitions from an inspiral to a rapid plunge. The normalized ISCO radius $\hat{R}_{\text{ISCO}} = R_{\text{ISCO}}/M_{\text{BH}}$ is, for $Q \rightarrow \infty$,

$$\hat{R}_{\text{ISCO}} = 3 + Z_2 - \text{sgn}(\chi_{\text{BH}}) \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}, \quad (3)$$

with $Z_1 = 1 + (1 - \chi_{\text{BH}}^2)^{1/3}[(1 + \chi_{\text{BH}})^{1/3} + (1 - \chi_{\text{BH}})^{1/3}]$ and $Z_2 = \sqrt{3\chi_{\text{BH}}^2 + Z_1^2}$ [54]. The ratio of R_{ISCO} to the NS radius can be expressed as $R_{\text{ISCO}}/R_{\text{NS}} = \hat{R}_{\text{ISCO}} Q C_{\text{NS}}$. Our model is given by

$$\hat{M}_{\text{model}}^{\text{rem}} = \left[\text{Max} \left(\alpha \frac{1 - 2C_{\text{NS}}}{\eta^{1/3}} - \beta \hat{R}_{\text{ISCO}} \frac{C_{\text{NS}}}{\eta} + \gamma, 0 \right) \right]^\delta \quad (4)$$

with free parameters $(\alpha, \beta, \gamma, \delta)$. A zero $\hat{M}_{\text{model}}^{\text{rem}}$ corresponds to no tidal disruption. The first term in(4) is proportional to the normalized disruption separation $d_{\text{dis}}/R_{\text{NS}} = (3Q)^{1/3}$ from Newtonian physics multiplied by $(1 - 2C_{\text{NS}})$ to account for the fact that a BH (having an effective $C_{\text{BH}} = 1/2$ when non-spinning) cannot be tidally disrupted. The second term scales as $R_{\text{ISCO}}/R_{\text{NS}}$ as $Q \rightarrow \infty$. The parameters (γ, δ) represent nonlinear effects not accounted for by the simple physical considerations. Importantly, while our tidal-disruption considerations in limiting regimes suggest a dependence on the mass ratio Q , our result (4) depends instead on the *symmetric*

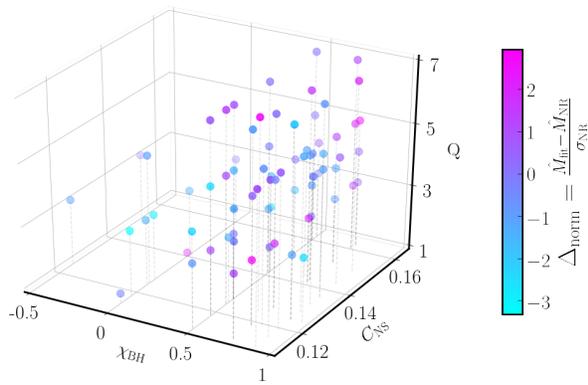


FIG. 2. Differences between NR results and the model (4) weighted by the estimated NR error as a function of the mass ratio, NS compaction, and BH spin. Magenta (cyan) color corresponds to an over-(under-) estimate of \hat{M}_{rem} .

mass ratio $\eta = Q/(1+Q)^2$ to enforce a symmetry of many observables in the general relativistic two-body problem: invariance under exchanging the bodies' labels. This property becomes explicit in post-Newtonian expansions where η characterizes many mass-ratio effects, but is obscured in the large- Q limit where η becomes equivalent to Q^{-1} . Restoring that symmetry often renders results derived for $Q \rightarrow \infty$ surprisingly accurate when compared to NR data for $Q \sim 1$ (see e.g. [55, 56]); accordingly we have replaced Q^{-1} by η in the consideration leading to Eq. (4).

To determine the free parameters in (4), we define a figure-of-merit Δ_{norm} that accounts for the uncertainty in the NR data as the difference between $\hat{M}_{\text{model}}^{\text{rem}}$ computed from a model and the NR result, relative to the estimated σ_{NR} :

$$\Delta_{\text{norm}} = \frac{\hat{M}_{\text{model}}^{\text{rem}} - \hat{M}_{\text{NR}}^{\text{rem}}}{\sigma_{\text{NR}}}. \quad (5)$$

Minimizing the root-mean-square of Δ_{norm} leads to

$$\alpha = 0.406, \quad \beta = 0.139, \quad \gamma = 0.255, \quad \delta = 1.761. \quad (6)$$

The root-mean-square error in the model is $\Delta_{\text{norm}} \sim 1.4$, and Figure 2 illustrates that our resulting prediction performs well across the 3D binary parameter space covered by simulations.

Our model will critically help differentiate NSNS from low-mass NSBH mergers, requiring our prediction remains robust for $Q \sim 1$ binaries. We find that the vast improvement over FF12 for $Q \sim 1$ comes from accounting for the two-body symmetry of vacuum gravity by using η in the theoretical basis of (4); the new parameters γ, δ are not necessary to improve the $Q \sim 1$ predictions. The physical consequence of replacing Q^{-1} by η is that for $Q \sim 1$ the ISCO-term becomes larger, thus leading to more material falling into the BH. A larger ISCO for small Q than computed for $Q \rightarrow \infty$ is expected on physical grounds: (i) the NS's plunge, although not well-defined in this limit, would begin at an effective ISCO of the two-body spacetime (e.g. [57]), and (ii) the NS matter accreted at merger causes the BH to grow, which moves

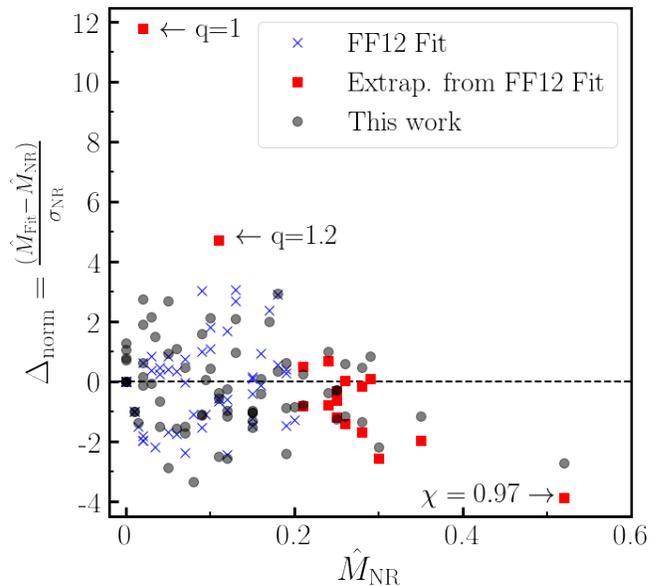


FIG. 3. Normalized errors in the remnant mass predictions versus NR results. Blue crosses indicate results for FF12 within its range of validity, red squares for FF12 outside that range, and grey circles are from our new model (4). The normalization factor σ_{NR} is a combination of a 10% relative error and 0.01 absolute error in \hat{M}_{NR} (Eq. 2), approximating the unknown NR errors.

the ISCO for the remaining material outwards [58] and leads to a larger fractional change in the ISCO location for smaller Q . We further verify that our result is not overly dependent on the two simulations with $Q < 2$ by re-fitting (4) but ignoring simulations with $Q < 2$. We find that this modified fit is as consistent with the low- Q NR simulations as (4) with (6) obtained using all NR results. Figure 3 shows that this is not the case for the model of FF12, which was derived for a narrower range of parameters ($Q \geq 3, \hat{M}_{\text{rem}} \leq 0.2$). While FF12 continues to work well within that range, it substantially overestimates M^{rem} for $Q \sim 1$, even if re-calibrated using the latest numerical results.

Cases with large remnant masses or, equivalently, large BH spins are another key regime for multimessenger observations and fundamental physics. For capturing the merger outcome in this limit, it is necessary to introduce the nonlinearity parameters (γ, δ) . These nonlinear effects are missing from FF12 and enable our new model to correctly predict larger M_{rem} for rapidly spinning BHs than FF12, a result more favorable to the production of electromagnetic counterparts.

We next discuss an interesting application of our model as a benchmark for verifying that different NR codes predict broadly consistent M^{rem} . Figure 4 summarizes our findings: over the range of binary parameters for which data from multiple collaborations is available, there is no systematic bias associated with the NR code used. Our standard fit performs equally well on SACRA and SpEC simulations, while fits calibrated to the results of only one code predict the results of the other in regions of parameter space where simulations

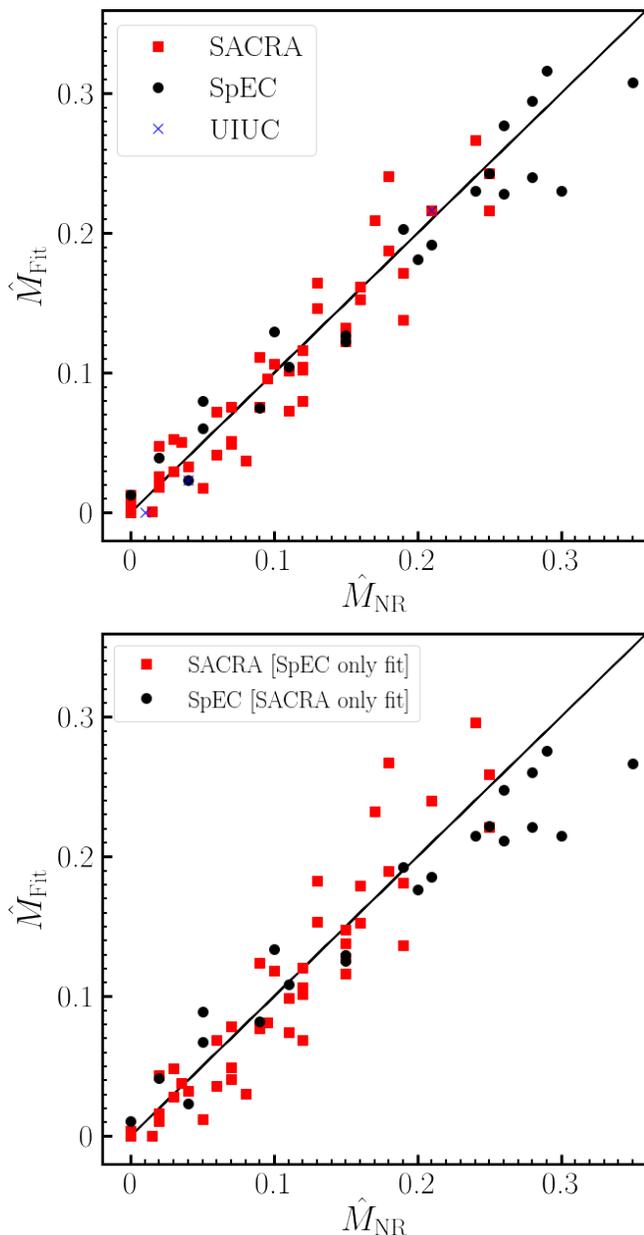


FIG. 4. Remnant baryon masses for all simulations used in this work, split by evolution code: SACRA (red squares), SpEC (black circles), and the UIUC code (blue crosses). Different codes measure remnant baryon masses to within the model’s accuracy. The top panel shows results for the fit presented in this paper. The bottom panel shows results for the SpEC simulations using a fit calibrated to SACRA simulations only, and vice-versa.

from both codes are available (the SpEC simulations with $\hat{M}_{\text{fit}} > 0.2$ all have $\chi_{\text{BH}} \geq 0.9$, while the SACRA simulations with $\hat{M}_{\text{fit}} > 0.2$ all have $C_{\text{NS}} = 0.131$, parts of the parameter space not explored by the other code). While this comparison is not as direct as one based on identical initial data, it advantageously uses a large number of numerical results rather than comparing isolated examples, and increases

our confidence in the reliability of NR simulations to within the accuracy of our model.

We further study an alternative model that depends on the properties of NS matter through the dimensionless quadrupolar tidal deformability of the NS, $\Lambda = (2/3)k_2 C_{\text{NS}}^{-5}$ (with k_2 the tidal Love number), which is the best-measured EoS parameter of a slowly-spinning NS from GW data [2, 17, 59]. Defining $\rho = (15\Lambda)^{-1/5}$, so that $\rho \approx C_{\text{NS}}$, we use

$$\hat{M}_{\Lambda}^{\text{rem}} = \left[\text{Max} \left(\alpha \frac{1-2\rho}{\eta^{-1/3}} - \beta \hat{R}_{\text{ISCO}} \frac{\rho}{\eta} + \gamma, 0 \right) \right]^{\delta}, \quad (7)$$

with the best-fit parameters $\alpha = 0.308$, $\beta = 0.124$, $\gamma = 0.283$, and $\delta = 1.536$. This prediction performs as well as the compaction-based model (4) for $M_{\text{rem}} \leq 0.2M_{\odot}$, but has larger errors for simulations using single-polytrope equations of state and producing more massive remnants. We find that using approximately universal relations for $C(\Lambda)$ [60, 61] in (4) performs similarly to (7). In that case, larger errors for single polytropes are expected, as the properties of NSs for single-polytrope EoSs are not well-described by universal relations. While (4) is a priori preferable, the Λ -based model captures well the limit between disrupting and non-disrupting systems, is advantageous for rapid GW analysis, and may be less accurate solely for unphysical EoSs.

Discussion A key application of the new model for the remnant mass outside the BH, (4) and (6), is to derive limits on the range of binary parameters leading to the disruption of a NS, as shown in Fig. 5. For the previously unexplored $Q \sim 1$ systems, the remnant masses are significantly lower than predicted by FF12, and some compact neutron stars can entirely avoid disruption. Accordingly, our new model is essential for assessing whether an observed NSNS merger could instead be a NSBH merger. We discuss the implications of our results for the pressing question of whether GW170817 could have been a NSBH system in a companion paper [18]. For large Q , our new model is important for triggering rapid electromagnetic follow-up observations that would be missed when using FF12.

Conclusion. This paper provides a simple new formula for computationally inexpensive yet reliable estimates of M_{rem} for NSBH mergers across a wide range of parameters, including important regimes not previously considered. The average relative error in the remnant mass prediction is $\sim 15\%$ for binaries with $Q \in [1, 7]$, $\chi_{\text{BH}} \in [-0.5, 0.9]$, and $M_{\text{rem}} \lesssim 0.3M_{\text{NS}}^b$. This paper is already guiding the choice of progenitor parameters for NR simulations, and detailed models of EM counterparts and GW emission [62, 63], a requisite for identifying and characterizing NSBH mergers. Differences between FF12 and our new results also emphasize the need for numerical simulations in yet-unexplored regions of parameter space to test and optimize semi-analytical models – especially $Q \sim 1$ NSBH systems with significant BH spins that currently remain unexplored.

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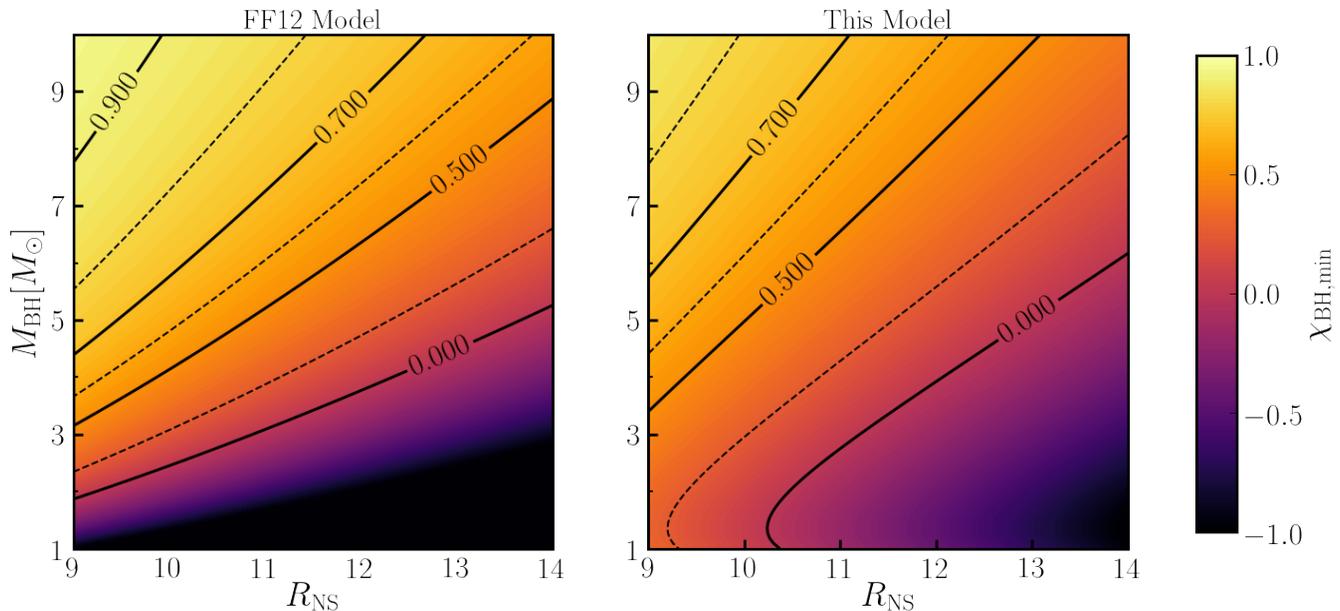


FIG. 5. Minimum aligned component of the BH spin required for a $1.35M_{\odot}$ NS to disrupt, as a function of NS radius and BH mass. We show results for the model from FF12 (left), and our new formula (right). Solid black curves are contours of constant $\chi_{\text{BH,min}} = 0, 0.5, 0.7, 0.9$, while dashed black curves are for $\chi_{\text{BH,min}} = 0.25, 0.6, 0.8$. The new results are less favorable to disruption for near-equal mass systems, and more favorable for large mass ratios.

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