How loud are neutron star mergers?

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We present results from the first large parameter study of neutron star mergers using fully general relativistic simulations with finite-temperature microphysical equations of state and neutrino cooling. We consider equal and unequal-mass binaries drawn from the galactic population and simulate each binary with three different equations of state. Our focus is on the emission of energy and angular momentum in gravitational waves in the postmerger phase. We find that the emitted gravitational-wave energy in the first ~10 ms of the life of the resulting hypermassive neutron star (HMNS) is about twice the energy emitted over the entire inspiral history of the binary. The total radiated energy per binary mass is comparable to or larger than that of nonspinning black hole inspiral-mergers. About 0.8 – 2.5 % of the binary mass-energy is emitted at kHz frequencies in the early HMNS evolution. We find a clear dependence of the postmerger GW emission on binary configuration and equation of state and show that it can be encoded as a broad function of the binary tidal coupling constant κ2: Our results also demonstrate that the dimensionless spin of black holes resulting from subsequent HMNS collapse are limited to ≤ 0.7 – 0.8. This may significantly impact the neutrino pair annihilation mechanism for powering short gamma-ray bursts (sGRB).

I. INTRODUCTION

Gravitational wave (GW) astronomy has been inaugurated by the first direct detection of GWs from a binary black hole (BH) merger by Advanced LIGO [1]. Another primary source for Advanced LIGO is the GW-driven inspiral and merger of binary neutron stars (BNS). A possible outcome of the merger is the formation of a hot, differentially rotating hypermassive neutron star (HMNS), which may survive for many tens of milliseconds before collapsing to a BH, e.g. [2,6]. Observations of NSs with mass ~2M⊙ [7,8] and of BNSs with individual masses ~1.35M⊙ favor the HMNS scenario as the initial outcome. The stiff nuclear equation of state (EOS) in combination with differential rotation at least temporarily prevents collapse to a BH [10]. GW emission is expected to depend on the interplay of several physical ingredients: relativistic (magneto)hydrodynamics (M)HD, nonlinear gravity, finite-temperature effects in the nuclear EOS, neutrino cooling, and angular momentum redistribution (via viscosity or (M)HD). Fully general relativistic (GR) simulations that include realistic microphysics (i.e. nuclear and neutrino physics) are the only reliable means to study postmerger evolution and its GW emission.

In this work, we present results from a new and largest-to-date set of BNS configurations simulated in full numerical relativity with temperature-dependent microphysical EOS and neutrino physics. Our configurations are representative of galactic BNS systems. We consider three different EOS broadly consistent with observational and experimental constraints. We focus on the postmerger evolution and its GW emission, and show for the first time that the HMNS phase is the most GW-luminous phase in the entire history of BNS systems. Soft EOS and HMNS masses close to (but below) the prompt collapse threshold are the most luminous. BHs resulting from HMNSs that survive for ≥ 10 ms are robustly limited to dimensionless spins ≤ 0.7. Larger spins are obtained if the merger remnant collapses promptly or within 1 – 2 dynamical times of merger.

II. BINARY CONFIGURATIONS AND SIMULATIONS

The properties of the considered binary configurations are summarized in Tab. I. We choose equal and unequal-mass configurations guided by observed galactic BNS systems [9]. Configurations *-135135, *-136125, *-140120, and *-144139 reproduce the NS masses in the binaries identified by B2127+11C (and B1534+12), J1906+0746, J1756-2251 (and J1829+2456), and B1913+13, respectively. We simulate these binaries using three different nuclear EOS, referred to as LS220 [12], DD2 [13], and SFHo [14]. They span a reasonable range of radii and maximum gravitational masses for non-spinning NSs: DD2 has MTOVmax ~ 2.42M⊙ and radius R1.35M⊙ ~ 13.2 km;
SFHo and LS220 have similar $M_{\text{TOV}}^{\text{max}} \sim 2.05 M_\odot$, but $R_{1.35M_\odot} \sim 11.9$ km (SFHo) and $R_{1.35M_\odot} \sim 12.7$ km (LS220). We refer to EOS with larger $R_{1.35M_\odot}$ as being “stiffer”, since at fixed mass, a stiffer EOS results in lower central densities and larger NS radii. All three EOS provide maximum cold NS masses greater than $2 M_\odot$, which puts them in agreement with the maximum observed NS mass $1.4 M_\odot$. SFHo and LS220 fall within the NS mass radius relation predicted by [15], while DD2 has a somewhat larger radius. SFHo and DD2 both agree with microscopic neutron matter calculations [16], but LS220 falls outside of the favored region.

We compute conformally-flat initial data for our simulations, assuming quasicircular orbits and irrotational flow [17]. They are characterized by the Arnowitt-Deser-Misner (ADM) mass-energy $M_{\text{ADM}}$ and angular momentum $J_{\text{ADM}}$. The initial separation is 40 km ($\sim 3$ orbits to merger). The spacetime is evolved with the Z4c formulation [18], coupled with GRHD and a neutrino leakage scheme [19]. We employ the Einstein Toolkit [20] with the CTeGamma spacetime solver and the WhiskyTHC GRHD code [21]. We use the high-order MP5 reconstruction implemented in WhiskyTHC to ensure that the effect of numerical dissipation is minimized. The Courant-Friedrichs-Lewy factor is set to $0.15$ to guarantee the positivity preserving property of the limiter described in [21]. Dynamical evolutions are carried out with linear resolution of $\Delta x \sim 295$ m for a total time of $\sim 60$ ms after merger, and with $\Delta x \sim 185$ m for 20 ms after merger. Our grid consists of 6 refinement levels with the coarsest being a cube of linear extent $1024 M_\odot \sim 1512$ km. To reduce our computational cost, we impose symmetry across the $xy$-plane and, for equal mass models, we assume $\pi$-symmetry. Model LS220-135135 is simulated also without leakage. The GWs are extracted from the spin-weighted multipolar decomposition of the Weyl scalar $\Psi_4$ on a sphere placed at $200 M_\odot \approx 295$ km.

In all simulations but SFHo-144139, we observe the formation of a HMNS. We define the merger time $t_0$ as the time of waveform peak amplitude [22], time periods of $N$ ms after $t_0$ are indicated as $t_N$. Figure 1 shows the evolution of the maximum rest-mass density $\rho_{\text{max}}(t)$ for all models and snapshots of the temperature $T$ and rest-mass density $\rho$ in the orbital plane at representative times for LS220-135135 (with leakage).

During merger, the two NS cores come into contact and merge to a single core within $\sim t_{10}$. $\rho_{\text{max}}$ increases by up to a factor 1.5–2 and oscillates violently. Note that for a given total mass, stiffer EOS have smaller $\rho_{\text{max}}$. Additionally, the oscillations in $\rho_{\text{max}}$ have higher ampli-
tude when the configuration is closer to the prompt collapse threshold and when $p_{\text{max}}$ is larger. The evolution from the initial two-core structure into a more axisymmetric single-core HMNS is due to hydrodynamic angular momentum redistribution and dissipation by shock heating and GW emission [3]. The extreme nonaxisymmetric shape and the increase in density result in very efficient GW emission [22].

Temperatures as high as $\sim 50$ MeV are reached in the interface between the NSs (Fig. 1). Physically, we expect these temperatures to be somewhat lower, because at very high resolutions and when MHD is included, [23] showed that a fraction of the shear flow energy created at contact is converted into magnetic field energy. In our simulations, instead, the unresolved shear energy is converted into heat by our finite-volume scheme. This corresponds to a case in which no large-scale dynamo is activated and the locally generated magnetic field dissipates.

As the merger and the early HMNS evolution proceed, we observe hot streams of matter being squeezed out of the interface between the two NSs. Part of this material becomes unbound while the rest forms a thick torus around the merger remnant. As the two NS cores merge, the core remains relatively cold, with $T \sim 10$ MeV, while the temperature peaks at around $\sim 50$ MeV at densities of $\sim 3 - 5 \times 10^{14}$ g cm$^{-3}$. Even at these lower densities, the EOS is only mildly affected by thermal effects [10].

The high mass of SFHo-144139, combined with the particularly soft EOS, results in prompt collapse at merger. We observe BH formation within the simulated time also for LS220-1365125, LS220-135135, LS220-144139, SFHo-135135. It is interesting to note that LS220 and SFHo have similar cold non-spinning NS maximum masses, but SFHo HMNSs collapse much more quickly. This is due to their more compact postmerger configuration, which leads to a more rapid evolution toward instability [10]. We list the remnant BH masses and spins in Tab. I. The properties of the accretion disks will be discussed elsewhere [24].

### III. GW ENERGY AND ANGULAR MOMENTUM

The energy radiated in GWs over the entire history of the binary up to the start of our simulations ($t = 0$), is (in $G = c = 1$) $E_{\text{GW},i} = M - M_{\text{ADM}}$, where $M = M_A + M_B$ is the binary gravitational mass at infinite separation. From the $\Psi_4$ projections we compute the waveform multipoles $h_{\ell m}(t)$ up to $\ell = \ell_{\text{max}} = 8$, and, using Eqns. (15) and (16) of [25], the energy and angular momentum emitted in GWs during our simulations, $\Delta E_{\text{GW}}(t)$ and $\Delta J_{\text{GW}}(t)$, respectively. The total emitted energy over inspiral, merger, and postmerger evolution to time $t$ is then $E_{\text{GW}}(t) = E_{\text{GW},i} + \Delta E_{\text{GW}}(t)$. Similarly, the binary angular momentum to time $t$ is given by $J(t) = J_{\text{ADM}} - \Delta J_{\text{GW}}(t)$. We report both quantities normalized by $M$ at different times in Tab. I.

A gauge-invariant way to represent the HMNS GW emission is to consider binding energy vs. angular momentum curves in analogy to the approach proposed in [25, 26]. Working with quantities per reduced mass, we define $E_b = -E_{\text{GW}}/(M\nu)$ and $j = J/(M^2\nu)$ with the symmetric mass ratio $\nu = M_A M_B/M^2 \approx 1/4$. Representative examples of $E_b(j)$ curves are shown in Fig. 2. The binary evolution starts at large $j$ (large separations) and at small negative $E_b$, accounting for the energy radiated

### TABLE I. BNS properties (EOS, individual isolation masses, total baryonic mass of the binary, ADM quantities, dimensionless tidal coupling constant, e.g. [11]) and the dimensionless radiated GW energy per binary mass $E_{\text{GW}}/M$ and the mass-rescaled angular momentum $J/M^2$ at $t_0$ (merger) and $t_{20}$ (N ms after merger). For configurations collapsing to a BH we also report $E_{\text{GW}}/M$ and $J/M^2$ as computed $\sim t$ ms after collapse and the BH irreducible mass and dimensionless angular momentum as measured by the horizon finder. All numbers are from simulations with $\Delta x = 295$ m. The total binary mass is $M = M_A + M_B$. Configurations are named according to EOS and masses $M_A, M_B$.

| EOS | $M_A$ | $M_B$ | $M_b$ | $M_{\text{ADM}}$ | $J_{\text{ADM}}$ | $\kappa_t^2$ | $E_{\text{GW}}(t)/M \times 10^2$ | $J(t)/M^2 \times 10^4$ | $E_{\text{GW}}/M \times 2^10$ | $M_{\text{BH}}$ | $\alpha_{\text{BH}}$ | $\psi_{\text{GW}}$ |
|-----|-------|-------|-------|------------------|------------------|-----------|-------------------------------|-----------------|-----------------|----------------|-----------------|----------------|
| DD2 | 1.40  | 1.20  | 2.829 | 5.276            | 6.537            | 203       | 1.27 2.13 2.17 2.18           | 8.87 7.95 7.90 7.89 | -               | -               | -               | -               |
| DD2 | 1.365 | 1.25  | 2.843 | 5.289            | 6.639            | 194       | 1.34 2.24 2.29 2.30           | 8.87 7.91 7.86 7.83 | -               | -               | -               | -               |
| DD2 | 1.35  | 1.35  | 2.946 | 6.73             | 7.015            | 162       | 1.37 2.56 2.58 2.60           | 8.75 7.57 7.54 7.53 | -               | -               | -               | -               |
| DD2 | 1.44  | 1.39  | 3.100 | 2.799            | 7.589            | 124       | 1.46 2.90 2.95 2.97           | 8.60 7.29 7.25 7.23 | -               | -               | -               | -               |
| LS220 | 1.40 | 1.20  | 2.830 | 2.574            | 6.540            | 159       | 1.34 2.09 2.31 2.35           | 8.79 8.03 7.81 7.78 | -               | -               | -               | -               |
| LS220 | 1.365 | 1.25  | 2.846 | 2.588            | 6.623            | 151       | 1.38 2.89 3.05 3.12           | 8.76 7.35 7.20 7.15 | -               | -               | -               | -               |
| LS220 | 1.35  | 1.35  | 2.947 | 2.671            | 7.000            | 125       | 1.46 3.32 3.63 -              | 8.65 7.0 6.81 -     | 3.80 6.68 2.40 5.44 | -               | -               |
| LS220 | 1.44  | 1.39  | 3.102 | 2.797            | 7.570            | 94        | 1.52 - - -                     | 8.51 - - - -       | 3.68 6.92 2.70 7.04 | -               | -               |
| SFHo | 1.40  | 1.20  | 2.850 | 2.573            | 6.525            | 115       | 1.53 3.21 3.37 3.48           | 8.47 7.06 6.92 6.84 | -               | -               | -               | -               |
| SFHo | 1.365 | 1.25  | 2.868 | 2.589            | 6.615            | 110       | 1.52 3.61 3.80 3.94           | 8.47 6.78 6.63 6.53 | -               | -               | -               | -               |
| SFHo | 1.35  | 1.35  | 2.972 | 2.674            | 7.018            | 89        | 1.59 - - -                     | 8.38 - - - -       | 3.77 8.66 2.56 6.83 | -               | -               |
| SFHo | 1.44  | 1.39  | 3.133 | 2.801            | 7.581            | 67        | 1.66 - - -                     | 8.26 - - - -       | 2.27 7.86 2.79 8.08 | -               | -               |
considerations hold also for configurations like LS220-
energy BH collisions up to \( \sim M \) aligned spins can emit up to 13% of
down (BH binary inspiral-merger (cf. Fig. 2). This fractional energy emission is comparable
to the collapse threshold that collapses soon after merger

\( t \) (or \( t_c \approx t_\text{coll} \)), lower rather than higher masses favor GW energy/angular momentum emission (cf. LS220-144139 vs. LS220-135135 and SFHo-135135 vs. SFHo-136125).

The dimensionless mass-rescaled angular momentum available at merger is in the range \( 3.3 \lesssim j(t_0) \lesssim 3.6 \) (0.83 \( \lesssim J(t_0)/M^2 \lesssim 0.89 \)); this range is representative of a large sample of EOS, masses, and mass ratios [11, 22]. The GW emission during the early HMNS evolution reduces these values by 11–22%, depending on binary configuration and EOS. The late-time value of \( J(t)/M^2 \) is the largest spin \( a_\text{BH} \) that the remnant BH can have (assuming no disk is produced). For HMNSs that collapse within \( t_{50} \), an upper limit for the BH spin parameter is \( \max(a_\text{BH}) \lesssim 0.7 \) \( \lesssim 2.8 \) for \( \nu = 1/4 \), cf. Fig. 2. The angular momentum evolution of HMNSs that are stable beyond \( t_{50} \) is expected to be significantly affected by MHD angular redistribution and breaking and is presently highly uncertain.

Runs at higher-resolution (HR) show that our results are robust and actually conservative: the GW luminosity is typically underestimated due to numerical dissipation at low resolution. The HMNS collapse time \( t_c \) can vary by a few milliseconds for configurations close to the collapse threshold, e.g. LS220-144139 has \( t_c \sim t_{50} \) for \( \Delta x = 185 \) m runs, while \( t_c \sim 290 \) m. The respective \( E_{\text{GW}}(t_{20}) \) variation is, at most, \( \lesssim 10\% \) at HR. However, because a HMNS that collapses earlier also emits more GWs early on, the timescale of the main GW emission remains \( \sim t_{20} \).

IV. DISCUSSION

We demonstrate for the first time that, due to the extreme densities and nonaxisymmetry of the early post-merger phase, generic BNS mergers can reach large GW luminosity corresponding to \( L_{\text{GW}} \sim 6 \times 10^{55} \text{erg s}^{-1} \), with typical emission timescale of \( \sim t_{10} \) (compare with [2]).
Our results lead us to the conjecture that the maximum postmerger GW emission efficiency is attained by a configuration in which EOS and binary mass are such that the HMNS is slightly below the prompt collapse threshold and supported for $\sim t_{10}$. Such configurations can be identified by investigating the dependence on the coupling constant for tidal interactions. The latter is defined by investigating the dependence on the coupling constant.

The simulations were performed on the Caltech computer Zwicky (NSF PHY-0960291), on NSF XSEDE (TG-PHY100033), and on NSF/NCSA Blue Waters (NSF PRAC ACI-1440083). LR and PM were supported by NASA Einstein Postdoctoral Fellowships under grant numbers PF3-140114 and PF5-160140, respectively.

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