

LETTER • OPEN ACCESS

CoRe database of binary neutron star merger waveforms

To cite this article: Tim Dietrich *et al* 2018 *Class. Quantum Grav.* **35** 24LT01

View the [article online](#) for updates and enhancements.

Recent citations

- [GW190425: Observation of a Compact Binary Coalescence with Total Mass \$3.4 M_{\odot}\$](#)
B. P. Abbott *et al.*
- [The Reliability of the Low-latency Estimation of Binary Neutron Star Chirp Mass](#)
Sylvia Biscoveanu *et al.*
- [Phase transitions in neutron stars and their links to gravitational waves](#)
Milva G Orsaria *et al.*






IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Letter

CoRe database of binary neutron star merger waveforms

Tim Dietrich^{1,2}, David Radice^{3,4}, Sebastiano Bernuzzi^{5,6},
Francesco Zappa^{2,5}, Albino Perego^{6,7}, Bernd Brügmann⁵,
Swami Vivekanandji Chaurasia⁵, Reetika Dudi⁵,
Wolfgang Tichy⁸ and Maximiliano Ujevic⁹

¹ Nikhef, Science Park, 1098 XG Amsterdam, Netherlands

² Max Planck Institute for Gravitational Physics (Albert Einstein Institute),
Am Mühlenberg 1, Potsdam 14476, Germany

³ Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540,
United States of America

⁴ Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane,
Princeton, NJ 08544, United States of America

⁵ Theoretical Physics Institute, University of Jena, 07743 Jena, Germany

⁶ Istituto Nazionale di Fisica Nucleare, Sezione Milano Bicocca, gruppo collegato di
Parma, I-43124 Parma, Italy

⁷ Dipartimento di Fisica, Università degli Studi di Milano Bicocca,
Piazza della Scienza 3, 20126 Milano, Italy

⁸ Department of Physics, Florida Atlantic University, Boca Raton, FL 33431,
United States of America

⁹ Centro de Ciências Naturais e Humanas, Universidade Federal do ABC,
09210-170, Santo André, São Paulo, Brazil

E-mail: diet.tim@gmail.com

Received 14 September 2018, revised 16 October 2018

Accepted for publication 26 October 2018

Published 13 November 2018



CrossMark

Abstract


We present the computational relativity (CoRe) collaboration's public database of gravitational waveforms from binary neutron star mergers. The database currently contains 367 waveforms from numerical simulations that are consistent with general relativity and that employ constraint satisfying initial data in hydrodynamical equilibrium. It spans 164 physically distinct configuration with different binary parameters (total binary mass, mass-ratio, initial separation, eccentricity, and stars' spins) and simulated physics. Waveforms computed at multiple grid resolutions and extraction radii are provided for controlling numerical uncertainties. We also release an exemplary



Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

set of 18 hybrid waveforms constructed with a state-of-art effective-one-body model spanning the frequency band of advanced gravitational-wave detectors. We outline present and future applications of the database to gravitational-wave astronomy.

Keywords: numerical relativity, gravitational wave astronomy, neutron stars

 Supplementary material for this article is available [online](#)

(Some figures may appear in colour only in the online journal)

The era of gravitational-wave (GW) astronomy has been inaugurated with the direct detection of GWs from binary black hole (BBH) mergers [1–5] soon followed by the breakthrough observation of GWs and electromagnetic (EM) signals from a binary neutron star (BNS) collision [6–9].

Numerical relativity (NR) is the fundamental tool to study GWs from systems in the strong-field regime, and it has crucially supported the first discoveries. In particular, different NR groups have publicly released BBH simulation data [10–12]. These catalogs have been the cornerstone of many scientific results. They have been used to improve our understanding of the merger dynamics [13–18], to develop waveform models [19–26] including surrogates [27, 28], and to validate LIGO-Virgo parameter estimation pipelines [29, 30].

Following the first successful BNS merger simulations in full general relativity [31, 32], the NR community has made tremendous progresses on several aspects of the problem: (i) the exploration of the effect of different equations of state (EOSs), total mass and mass-ratio on the merger dynamics [33–39]; (ii) the development of many-orbits simulations for high-precision GW modeling [40–46]; (iii) the exploration of BNS mergers from eccentric orbits and dynamical collisions [47–51]; (iv) the inclusion of aligned spins and spin-precession effects [49, 52–59]; (v) the simulation of magnetic effects in connection to gamma-ray bursts engines [60–68]; (vi) the study of finite-temperature and composition effects using a microphysical descriptions of NS matter together with neutrino transport [65, 69–74]; (vii) the study of mass ejecta and EM counterparts [37, 38, 51, 54, 73, 75–81]. New frontiers in BNS merger simulations are the inclusion of general-relativistic radiation hydrodynamics [74, 82, 83] and viscous hydrodynamics effects [84–88].

Since 2009 our team has contributed to some of the research lines mentioned above. Here, we present the largest-to-date public database of BNS waveforms composed of new simulations and those published in [34, 37, 43, 45, 52, 54, 56, 58, 84, 89–97]. The combined set of simulations required about 150 million CPU-hours on supercomputers in Europe and the United States. We publicly release these data with the goal of supporting researchers and further developments in the field of GW astronomy (www.computational-relativity.org). We plan to extend the database with waveforms from upcoming simulations and from other groups/codes.

This article describes the simulation methods in $3 + 1$ NR, summarizes the quality of the computed waveforms and the key parameters that characterize the GW, and concludes outlining some of the many applications. We use geometrized units $c = G = 1$ and express results in terms of solar masses ($M_{\odot} = 1.9889 \times 10^{33}$ g) if not otherwise stated. Conversion factors to CGS are $[L] = GM_{\odot}/c^2 \simeq 1.47670 \times 10^5$ cm and $[T] = GM_{\odot}/c^3 \simeq 4.92549 \times 10^{-6}$ s.

1. Simulation methods

1.1. Initial data

Initial data are constructed by solving the Einstein constraint equations in the conformal thin sandwich formalism and by imposing hydrodynamical equilibrium for the star fluid [98–100]. The fluid’s flow is chosen to be either irrotational [101], or prescribed according to the constant rotational velocity formalism [102, 103]. Binaries in quasi-circular orbits are built imposing a helical Killing vector [104], whereas for eccentric orbits an approximate ‘heliptical’ Killing vector is used [56, 105]. We use either the public `Lorene` [106] or the `SGRID` [56, 103, 107] code. Both codes use multi-domain pseudo-spectral methods with surface fitting coordinates [104, 108].

1.2. Evolutions

Dynamical simulations are performed using free-evolution schemes for the Einstein equations and general relativistic hydrodynamics (GRHD). For the spacetime, we employ either the BSSNOK [109–111] formalism or the Z4c formalism [112–116]. The latter has improved constraint propagation and damping properties with respect to BSSNOK, especially in matter simulations [112, 116]. We use the moving puncture gauge [117–121], which can handle automatically the gravitational collapse without the need for excision [122–124]. GRHD is solved in flux-conservative form [125]. Some mergers are simulated with microphysical EOS and neutrino cooling is taken into account with a leakage scheme. Viscous effects in GR are also simulated in a few cases using the large eddy scheme (GRLES) developed in [84].

We use two different NR codes: `BAM` [126–128] and `THC` [42, 129–133]. Both codes use a simple mesh refinement scheme whereby the grid hierarchy is composed of nested Cartesian boxes, some of which can be moved to track the orbital motion of the stars [127, 134, 135]. The grid setup is controlled by the resolution Δx in the finest levels. The finest refinement levels cover entirely the NSs during the inspiral. The other levels are constructed by progressively coarsening the resolution by factors of two and extend to the wave-extraction zone. Discretization is based on fourth (or higher) order finite-differencing stencils and GRHD is handled with either standard finite-volume or high-order finite-differencing high-resolution shock-capturing methods. The hydrodynamical flux is computed with the local Lax–Friedrichs, Roe, or Harten–Lax–van Leer-contact flux scheme employing a number of different flux limiters; details and cross validations have been presented in, e.g. [40, 42, 43]. The `THC` code also implements a neutrino leakage scheme and the GRLES [51, 84].

1.3. Wave extraction

GWs are extracted on coordinate spheres with radius r using the spin-weighted $s = -2$ spherical harmonics decomposition of the Weyl scalar Ψ_4 , e.g. [127]. Some of the `THC` simulations employ the Cauchy characteristic extraction technique to obtain Ψ_4 at future null infinity [136]. The metric multipoles are reconstructed using the fixed frequency method [137]. We release the $\ell = m = 2$ metric multipole h_{22} as a function of the coordinate time t and of the retarded time $u = t - r_*$, e.g. equation (17) of [43], where $r_*(r)$ is the tortoise coordinate defined by assuming r is the isotropic radius and using the binary total mass for the Schwarzschild spacetime. We also release the GW energy and angular momentum emitted during the simulation that are computed as in [138, 139]. Our waveforms are extracted at different extraction radii and can be further extrapolated to obtain null-infinity estimates, e.g. [40, 140, 141].

2. Input physics

BNS simulations require several assumptions on the NS fluid and input models describing the matter interactions. The yet unknown EOS is among the most important quantities determining the NS properties and the binary dynamics. It determines the tidal deformations and interactions of the stars during the inspiral [142–146], the lifetime and rotation frequency of the merger remnant [36, 93, 147–149], and the amount of unbound matter ejected during the merger process, e.g. [38, 75, 76, 90]. We release data for 15 different EOSs. Two EOSs are polytropic models with adiabatic index $\Gamma = 2$ [52]. Nine EOSs are zero-temperature nuclear physics models represented by piecewise polytropic fits [150]. They are augmented with a Γ -law pressure component during the simulation to approximate temperature effects [151]. Five EOSs are tabulated finite-temperature microphysical models developed in [152–156], which we also release. Finite-temperature effects are crucial during and after merger, when compressional and shock heating are present, e.g. [38, 69, 72, 157, 158].

The role of magnetic fields on the post-merger dynamics is currently a key open question [61, 68, 84, 86, 88, 159, 160]. Large magnetic field instabilities might cause turbulence and induce viscosity, potentially affecting the merger remnant, mass outflows and the GW emission. Also, while not directly relevant for GW emission on the dynamical timescale of our simulations, neutrino transport plays a crucial role in the merger remnant, e.g. [35, 38, 51, 65, 69, 70, 72, 79, 81]. We plan to include more data from simulations with advanced radiation transport schemes and magnetic field effects as robust NR results become available.

3. Waveform parameters

Figure 1 summarizes our database in terms of the main parameters that characterize the GWs.

3.1. Binary mass

In contrast to BBHs, BNS dynamics cannot be rescaled by the binary total mass (A, B label the NSs)

$$M = M_A + M_B, \quad (1)$$

since M enters the description of tidal interactions during the inspiral and determines the merger remnant.

Formation scenarios and the constraints from GW170817 indicate that NS masses lie within $\sim 1.0\text{--}2.3M_\odot$ [66, 87, 161–164]. Current observations range from $\sim 1.0M_\odot$ [165, 166] to $\sim 2.0M_\odot$ [167, 168] or possibly even $\sim 2.3M_\odot$ [169], with BNS masses varying in $\sim 2.5\text{--}2.9M_\odot$ [170, 171]. The wide mass range in our database fully covers the observational and a large fraction of the theoretical limits.

GWs from a $M = 3.2M_\odot$ merger are shown in figure 2 (upper right panel). High-mass mergers likely result in a prompt BH formation; while high-mass BNS emit strong GWs, they are EM faint due to smaller ejecta and disk masses [76, 148, 172, 173].

3.2. Mass ratio

The mass ratio

$$q = \frac{M_A}{M_B} \geq 1, \quad (2)$$

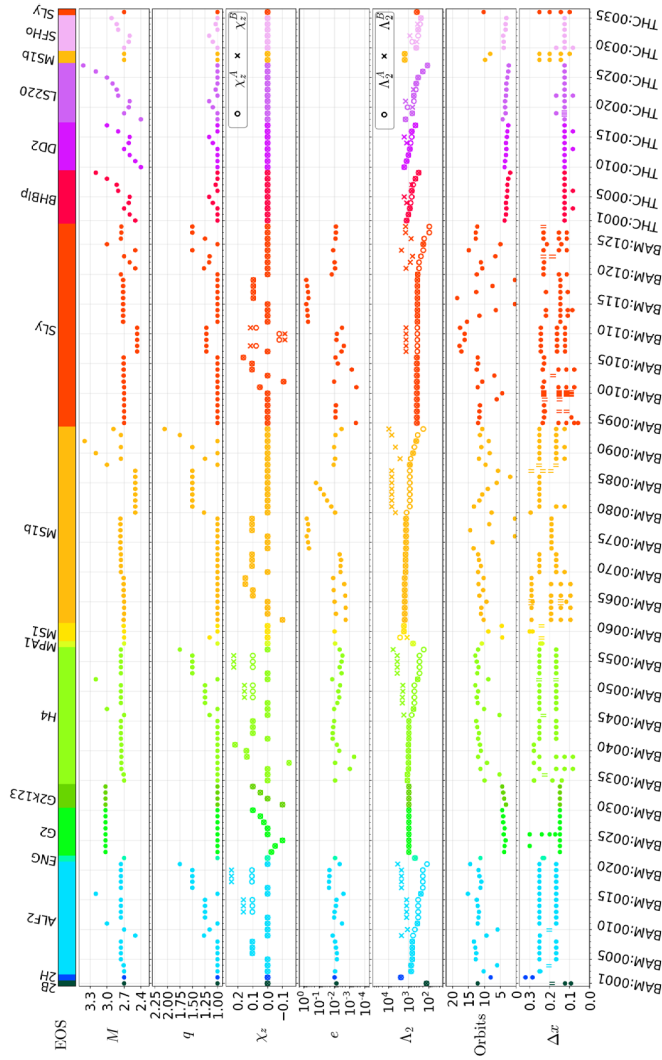


Figure 1. Simulations currently contained in the CoRe database. We present the total mass M , the mass ratio q , the individual dimensionless spins $\chi_z^{A,B}$, the eccentricity e [no eccentricity measurement is given for too short simulations], the individual quadrupolar tidal parameters $\Lambda_2^{A,B}$, the number of orbits [note that for highly eccentric orbits close to head-on, the number of orbits can drop below 1], and the employed resolution Δx of the finest level covering the entire NS for different configurations. Different colored markers refer to different EOS, see top color bar. In the last panel we also include simulations with different grid resolutions and numerical methods (fluxes, mesh refinement strategies etc.); simulations of a fixed configuration performed at the same resolutions but using different methods are marked with vertical bars in this panel. Overall we include 51 unpublished simulations in the current version of the database, while the remaining simulations have been already published in [34, 37, 43, 45, 52, 54, 56, 58, 84, 89–97]. New simulations include setups with larger eccentricities, higher spin values, and larger total masses compared to the ones presently available in the literature.

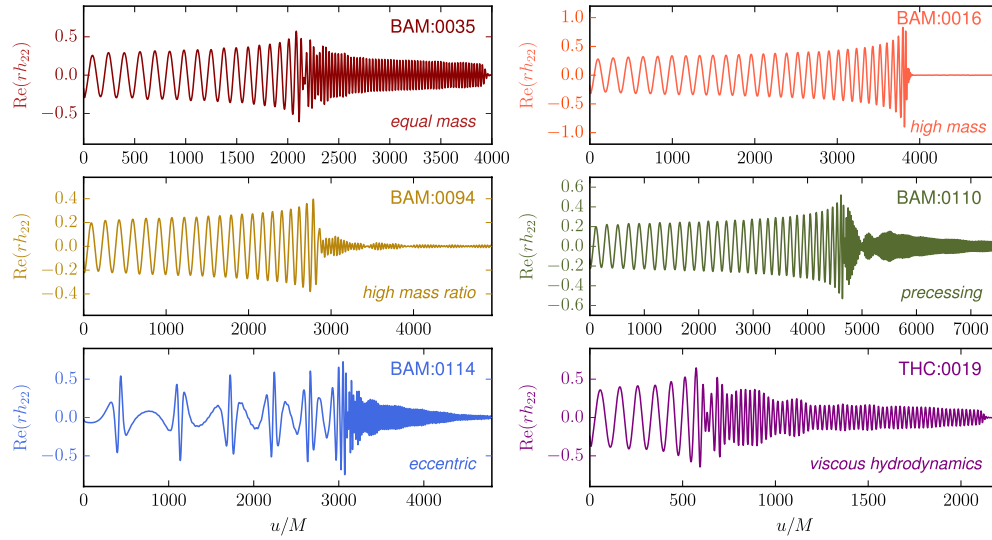


Figure 2. Waveforms from the database showing a baseline equal mass case (upper left panel), and the influence of total mass (upper right panel), mass ratio (middle left panel), spins (middle right panel), eccentricity (lower left panel), and EOS (bottom right panel).

has a clear imprint on the GW/EM signals: BNS with larger q are less luminous in GWs [54, 96, 145], but their larger mass ejecta can power bright EM transients [38, 54, 174]. The isolated NS mass distribution permits mass ratios up to $q_{\max} \simeq 2.3$, but population synthesis models predicts lower values $q_{\max} \simeq 1.8\text{--}1.9$ [56, 175]. The largest observed mass ratio in BNSs is $q \sim 1.3$ [176, 177]. The CoRe database contains data with mass ratios up to $q = 2.1$, which is the largest simulated so far [37, 56]. In this simulation the companion NS is tidally disrupted during the merger leading to postmerger GWs with small amplitude (figure 2, middle left panel).

3.3. Spins

The dimensionless spin of a NS in a binary can be defined as

$$\chi_A = \frac{\mathbf{S}_A}{M_A^2}, \quad (3)$$

where the angular momentum \mathbf{S}_A is computed from the isolated NS with the same EOS, rotational velocity, and baryonic mass as the constituents of the binary [52, 54, 56]. The maximum NS spin is not precisely known, since it depends on the EOS, but existing EOS models predict breakup spins below $|\chi| \sim 0.7$, corresponding to spin periods of less than 1 ms [178]. The fastest spinning NS in a BNS system is PSR J1946+ 2052 [179] which will have $|\chi| \sim 0.05$ at merger.

For spins parallel to orbital angular momentum (say z -direction), the effective spin [180]

$$\chi_{\text{eff}} = \frac{M_A}{M} \chi_z^A + \frac{M_B}{M} \chi_z^B - \frac{38}{113} \frac{M_A M_B}{M^2} (\chi_z^A + \chi_z^B), \quad (4)$$

is the quantity determining the leading-order spin-orbit effects on the phase evolution of the binary. Spin-orbit interactions quantitatively change the inspiral-merger and remnant

dynamics [52, 181, 182]. Neglecting their effect can bias the GW parameter estimation [183–185]. Spin-precession effects in BNS have been first simulated in [56, 58]; the computed GW signal is shown in figure 2 (middle right panel).

3.4. Eccentricity

The emission of GWs causes field binaries to circularize to eccentricities $e \lesssim 10^{-5}$ by the time they enter the LIGO-Virgo band [186]. Therefore, for an accurate modeling of the GWs, it is important to simulate small eccentricity binaries. The residual (numerical) eccentricity of the initial data can be reduced to $e \lesssim 10^{-3} - 10^{-4}$ using an iterative procedure [56, 187, 188], which we employed for a subset of our configurations.

On the contrary, dynamically assembled BNSs or those belonging to hierarchical triplets could be highly eccentric even at the time of merger [189, 190]. An example of a highly eccentric merger with $e = 0.6$ is shown in figure 2 (bottom left panel). The bursts in the GW amplitude are caused by the close encounters of the two stars. These encounters also induce f -mode oscillations which allow an independent constraint of the EOS for upcoming 3rd generation GW detectors [47, 191, 192]¹⁰.

3.5. Tidal parameters

Tidal interactions in the post-Newtonian (PN) formalism are described by a multipolar set of parameters proportional to the relativistic Love numbers [142–144, 193]. The dominant effect depends on the gravitoelectric quadrupolar Love numbers k_2^A and the compactness C_A of the NS through the expression $\Lambda_2^A = 2k_2^A/(3C_A^5)$. Tidal interactions are attractive and enter at leading PN order in the GW phasing evolution through the combination [146, 194–196],

$$\tilde{\Lambda} = \frac{16}{13} \left[\frac{(M_A + 12M_B)M_A^4}{(M_A + M_B)^5} \Lambda_2^A + (A \leftrightarrow B) \right]. \quad (5)$$

The tidal parameter $\tilde{\Lambda}$ is a key quantity to characterize the non-perturbative regime of the merger dynamics as shown in [34, 96, 197] and discussed below. Furthermore, it provides a simple but effective parameterization of the characteristic GW post-merger frequencies [38, 91, 198] and of the disk mass [94].

The value of $\tilde{\Lambda}$ for GW170817 is constrained to be $\lesssim 630$ on the basis of the analysis of the GW signal alone [6, 199]. In addition, [94, 200] suggested that the observation of an EM counterpart to GW170817 allows to place a lower bound on the tidal deformability of $\tilde{\Lambda} \gtrsim 400$, [94], or $\tilde{\Lambda} \gtrsim 200$, [200]. Further constraints arise from the theoretical modeling of matter near nuclear density, e.g. [201], other astrophysical observations, e.g. [162, 202–205], and from the combination of all these constraints by considering a large set of possible nuclear physics EOSs, e.g. [206, 207].

4. Data quality

Waveforms' error budgets based on convergence tests and finite radius extraction have been presented in [40, 42, 43, 45, 97, 130, 131]. Phase convergence is typically observed for about 10–15 orbits at sufficiently high resolutions, corresponding to about $\gtrsim 96$ grid points per NS

¹⁰ To allow the study of f -oscillations with constraint solved data, the database contains 21 simulations of 14 different configurations with various eccentricities. These include BAM:0116 which is up to our knowledge to date the longest NR simulation, covering 172 ms.

diameter. The error due to finite-radius extraction dominates in the early part of the simulations, but truncation errors increase towards merger and afterwards where the uncertainty is the largest [40]. Typical accumulated phase errors up to merger are estimated as $\delta\phi \sim 0.2\text{--}1.5$ rad for simulations in which convergence can be proven. We stress, however, that the lowest resolutions employed in our runs are not convergent and do not give quantitatively reliable results for multiple orbits. Post-merger GWs are typically less accurate, but monotonic behavior with grid resolution can be observed at sufficiently high resolutions, e.g. [93]. Our post-merger data are sufficiently robust to infer the energy and frequency content, e.g. [91, 93, 96].

We assessed systematic errors due to the use of nonlinear numerical schemes used for GRHD [130, 139] with extensive testing of different algorithms and/or extensive code comparisons. We have tested consistency between BAM and THC for datasets: BAM:0097 and THC:0036, BAM:0063 and THC:0029, BAM:0064 and THC:0028, using exactly the same initial data; see the supplementary material (stacks.iop.org/CQG/35/24LT01/mmedia) for further details. We found that phase differences are below the estimated uncertainties. A simple polytropic EOS setup has also been compared to results obtained with the SpEC code [208–210] with similar results [211].

We stress that all of our waveforms are computed using constraint-satisfying initial data in hydrostatic equilibrium. Constraint-violating and/or non-hydrostatic initial data exhibits large unphysical fluid oscillations that contaminate the GW signals. These oscillations are significantly reduced and converge to zero if equilibrium is imposed [97]; see the supplementary material for further details and discussions. Systematic errors generated by the initial data were studied by comparing the evolution of a binary produced by SGRID and Lorene using the same evolution setup (BAM:0026, BAM:0027) [52]. Differences in the GW phase and collapse time to a black hole were found to be compatible with those expected from finite grid resolutions effects.

5. Applications

The CoRe waveform database has wide applicability to the study of strong-field BNS dynamics and for GW astronomy.

Our simulations showed that, despite the complexity of the physics involved, the main quantities characterizing the merger dynamics, like the mass-rescaled GW frequency and the binding energy per unit mass, are determined by parameters like $\tilde{\Lambda}$, emerging from perturbative (PN and effective-one-body, EOB) analysis [34, 91]. About 100 simulations of the CoRe database were used to compute the total GW luminosity in terms of tidal parameters and the mass-ratio for *all* BNS with aligned spins $|\chi_z| \lesssim 0.14$, and to set upper limits on the total emitted energy [96]. The current database includes simulations beyond $|\chi_z| \lesssim 0.14$ and will therefore allow for an update of quasi-universal relations derived for irrotational or low-spinning binaries.

A related application is the study of the merger outcome. NR data are crucial to understand the formation of massive NS remnant [35, 160, 212] and prompt black hole formation at merger [148, 213, 214]. To allow such a study we have performed for the release of the database 18 new simulations with total binary masses $M \geq 3.0 M_\odot$ for different EOSs.

The data we provide can be used to verify and develop inspiral-merger waveform models for LIGO-Virgo analysis. BAM simulations have already been used in the development of the TeOBResum model [89]. Further analytical-numerical comparisons showed that state-of-art tidal EOB models might underestimate tidal effects at merger for stiff EOS and small M [95].

Our *spinning* BNS are currently used to test the performances of the `TEOBResumS` model [20, 215].

High-resolution `BAM` simulations (`BAM:0037`, `BAM:0064`, `BAM:0095`) were employed to construct the tidal phase model `NRtidal` [45, 97, 185]. The latter is a closed-form expression fitting the inspiral-merger GW composed of `PN`, `TEOBResum`, and `NR` data used to augment any `BBH` waveform model with tidal effects [185]. Notably, `NRtidal` was used in the LIGO-Virgo analysis of `GW170817` [6, 199, 216–218], and other groups are using similar approaches for GW modeling [219].

A main open challenge is the modeling of GWs from merger remnants [148, 149, 198, 220–226]. Several features of the signal are understood, but quantitative models are missing. We anticipate that `CoRe` data will be used to develop new post-merger models to be employed for the analysis of data from current and third-generation detectors. The latter are the most promising observatories to capture high-frequency GW signals, e.g. [92, 93, 227].

Our data can also be injected in synthetic detector noise to test parameter estimation pipelines, similarly to what was done for `BBHs` [30]. For `BNSs`, however, complete waveforms spanning thousands of GW cycles during the inspiral and tens of GW post-merger cycles would be needed. To address the problem, we generate hybrid waveforms combining analytical models and `NR` data and covering the frequency range of ground-based interferometers [228] (see also [197, 229, 230]). We release 18 of these hybrids corresponding to equal, unequal masses and spinning `BNSs`. Details about all configurations for which hybrids are made publicly available are given in [185].

The `CoRe` database will have a reach beyond the applications we have just discussed. In the future, we plan to include more quantities from our simulations. For example, mass outflows ejected during merger, e.g. [38, 51, 72, 75, 76, 81, 88, 90, 174], and disk masses and profiles [94]. These data will be crucial for the interpretation of EM counterparts.

Acknowledgments

We thank A Nagar and S Ossokine for discussions and A Sternbeck at TPI Jena for technical help.

TD acknowledges support by the European Unions Horizon 2020 research and innovation program under grant agreement No 749145, `BNSmergers`. DR acknowledges support from a Frank and Peggy Taplin Membership at the Institute for Advanced Study and the Max-Planck/Princeton Center (MPPC) for Plasma Physics (NSF PHY-1523261). SB acknowledges support by the European Union’s H2020 under ERC Starting Grant, grant agreement no. `BinGraSp-714626`. AP acknowledges support from the INFN initiative High Performance data Network funded by CIPE. RD and BB were supported by DFG grant BR 2176/5-1. SVC and RD were supported by the DFG Research Training Group 1523/2 ‘Quantum and Gravitational Fields’. WT was supported by the National Science Foundation under grants PHY-1305387 and PHY-1707227.

Computations were performed on the supercomputer SuperMUC at the LRZ (Munich) under the project number `pr48pu`, Jureca (Jülich) under the project number `HPO21`, on the supercomputers Bridges, Comet, and Stampede (NSF XSEDE allocation TG-PHY160025), on NSF/NCSA Blue Waters (NSF PRAC ACI-1440083), on Marconi (PRACE proposal 2016153522 and ISCRA-B project number `HP10B2PL6K`), on the Hydra and Draco clusters of the Max Planck Computing and Data Facility, the compute cluster Minerva of the Max-Planck Institute for Gravitational Physics, and on the ARA cluster of the University of Jena.

ORCID iDs

Tim Dietrich  <https://orcid.org/0000-0003-2374-307X>

David Radice  <https://orcid.org/0000-0001-6982-1008>

Swami Vivekanandji Chaurasia  <https://orcid.org/0000-0003-1312-6924>

References

- [1] Abbott B P *et al* 2016 Observation of gravitational waves from a binary black hole merger *Phys. Rev. Lett.* **116** 061102
- [2] Abbott B P *et al* 2016 GW151226: observation of gravitational waves from a 22-solar-mass binary black hole coalescence *Phys. Rev. Lett.* **116** 241103
- [3] Abbott B P *et al* 2017 GW170104: observation of a 50-solar-mass binary black hole coalescence at redshift 0.2 *Phys. Rev. Lett.* **118** 221101
- [4] Abbott B P *et al* 2017 GW170814: a three-detector observation of gravitational waves from a binary black hole coalescence *Phys. Rev. Lett.* **119** 141101
- [5] Abbott B P *et al* 2017 GW170608: observation of a 19-solar-mass binary black hole coalescence *Astrophys. J.* **851** L35
- [6] Abbott B P *et al* 2017 GW170817: observation of gravitational waves from a binary neutron star inspiral *Phys. Rev. Lett.* **119** 161101
- [7] Abbott B P *et al* 2017 Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A *Astrophys. J.* **848** L13
- [8] Abbott B P *et al* 2017 Multi-messenger observations of a binary neutron star merger *Astrophys. J.* **848** L12
- [9] Coulter D A *et al* 2017 Swope supernova survey 2017a (SSS17a), the optical counterpart to a gravitational wave source *Science* **358** 1556
- [10] Mroue A H *et al* 2013 A catalog of 174 binary black-hole simulations for gravitational-wave astronomy *Phys. Rev. Lett.* **111** 241104
- [11] Healy J, Lousto C O, Zlochower Y and Campanelli M 2017 The RIT binary black hole simulations catalog *Class. Quantum Grav.* **34** 224001
- [12] Jani K, Healy J, Clark J A, London L, Laguna P and Shoemaker D 2016 Georgia tech catalog of gravitational waveforms *Class. Quantum Grav.* **33** 204001
- [13] Lousto C O and Zlochower Y 2014 Black hole binary remnant mass and spin: a new phenomenological formula *Phys. Rev. D* **89** 104052
- [14] Le Tiec A *et al* 2013 Periastron advance in spinning black hole binaries: gravitational self-force from numerical relativity *Phys. Rev. D* **88** 124027
- [15] Nagar A, Damour T, Reisswig C and Pollney D 2016 Energetics and phasing of nonprecessing spinning coalescing black hole binaries *Phys. Rev. D* **93** 044046
- [16] Varma V, Ajith P, Husa S, Bustillo J C, Hannam M and Prerer M 2014 Gravitational-wave observations of binary black holes: effect of nonquadrupole modes *Phys. Rev. D* **90** 124004
- [17] Keitel D *et al* 2017 The most powerful astrophysical events: gravitational-wave peak luminosity of binary black holes as predicted by numerical relativity *Phys. Rev. D* **96** 024006
- [18] Gerosa D and Moore C J 2016 Black hole kicks as new gravitational wave observables *Phys. Rev. Lett.* **117** 011101
- [19] Pan Y *et al* 2014 Inspiral-merger-ringdown waveforms of spinning, precessing black-hole binaries in the effective-one-body formalism *Phys. Rev. D* **89** 084006
- [20] Damour T and Nagar A 2014 New effective-one-body description of coalescing nonprecessing spinning black-hole binaries *Phys. Rev. D* **90** 044018
- [21] Taracchini A *et al* 2014 Effective-one-body model for black-hole binaries with generic mass ratios and spins *Phys. Rev. D* **89** 061502
- [22] Husa S, Khan S, Hannam M, Pürrer M, Ohme F, Jiménez Forteza X and Bohé A 2016 Frequency-domain gravitational waves from nonprecessing black-hole binaries. I. New numerical waveforms and anatomy of the signal *Phys. Rev. D* **93** 044006
- [23] Pürrer M 2016 Frequency domain reduced order model of aligned-spin effective-one-body waveforms with generic mass-ratios and spins *Phys. Rev. D* **93** 064041

- [24] Babak S, Taracchini A and Buonanno A 2017 Validating the effective-one-body model of spinning, precessing binary black holes against numerical relativity *Phys. Rev. D* **95** 024010
- [25] Bohé A *et al* 2017 Improved effective-one-body model of spinning, nonprecessing binary black holes for the era of gravitational-wave astrophysics with advanced detectors *Phys. Rev. D* **95** 044028
- [26] Huerta E A *et al* 2017 Complete waveform model for compact binaries on eccentric orbits *Phys. Rev. D* **95** 024038
- [27] Field S E, Galley C R, Hesthaven J S, Kaye J and Tiglio M 2014 Fast prediction and evaluation of gravitational waveforms using surrogate models *Phys. Rev. X* **4** 031006
- [28] Blackman J, Field S E, Galley C R, Szilgyi B, Scheel M A, Tiglio M and Hemberger D A 2015 Fast and accurate prediction of numerical relativity waveforms from binary black hole coalescences using surrogate models *Phys. Rev. Lett.* **115** 121102
- [29] Abbott B P *et al* 2016 Directly comparing GW150914 with numerical solutions of Einsteins equations for binary black hole coalescence *Phys. Rev. D* **94** 064035
- [30] Abbott B P *et al* 2017 Effects of waveform model systematics on the interpretation of GW150914 *Class. Quantum Grav.* **34** 104002
- [31] Shibata M and Uryu K 2000 Simulation of merging binary neutron stars in full general relativity: $\Gamma = 2$ case *Phys. Rev. D* **61** 064001
- [32] Shibata M 1999 Fully general relativistic simulation of coalescing binary neutron stars: preparatory tests *Phys. Rev. D* **60** 104052
- [33] Hotokezaka K, Kyutoku K, Okawa H, Shibata M and Kiuchi K 2011 Binary neutron star mergers: dependence on the nuclear equation of state *Phys. Rev. D* **83** 124008
- [34] Bernuzzi S, Nagar A, Balmelli S, Dietrich T and Ujevic M 2014 Quasi-universal properties of neutron star mergers *Phys. Rev. Lett.* **112** 201101
- [35] Foucart F, Haas R, Duez M D, O'Connor E, Ott C D, Roberts L, Kidder L E, Lippuner J, Pfeiffer H P and Scheel M A 2016 Low mass binary neutron star mergers : gravitational waves and neutrino emission *Phys. Rev. D* **93** 044019
- [36] Bernuzzi S, Radice D, Ott C D, Roberts L F, Moesta P and Galeazzi F 2016 How loud are neutron star mergers? *Phys. Rev. D* **94** 024023
- [37] Dietrich T, Ujevic M, Tichy W, Bernuzzi S and Brüggmann B 2017 Gravitational waves and mass ejecta from binary neutron star mergers: effect of the mass-ratio *Phys. Rev. D* **95** 024029
- [38] Lehner L, Liebling S L, Palenzuela C, Caballero O L, O'Connor E, Anderson M and Neilsen D 2016 Unequal mass binary neutron star mergers and multimessenger signals *Class. Quantum Grav.* **33** 184002
- [39] Sekiguchi Y, Kiuchi K, Kyutoku K, Shibata M and Taniguchi K 2016 Dynamical mass ejection from the merger of asymmetric binary neutron stars: radiation-hydrodynamics study in general relativity *Phys. Rev. D* **93** 124046
- [40] Bernuzzi S, Thierfelder M and Brüggmann B 2012 Accuracy of numerical relativity waveforms from binary neutron star mergers and their comparison with post-Newtonian waveforms *Phys. Rev. D* **85** 104030
- [41] Hotokezaka K, Kyutoku K and Shibata M 2013 Exploring tidal effects of coalescing binary neutron stars in numerical relativity *Phys. Rev. D* **87** 044001
- [42] Radice D, Rezzolla L and Galeazzi F 2014 Beyond second-order convergence in simulations of binary neutron stars in full general-relativity *Mon. Not. R. Astron. Soc.* **437** L46–50
- [43] Bernuzzi S and Dietrich T 2016 Gravitational waveforms from binary neutron star mergers with high-order weighted-essentially-nonscillatory schemes in numerical relativity *Phys. Rev. D* **94** 064062
- [44] Hotokezaka K, Kyutoku K, Okawa H and Shibata M 2015 Exploring tidal effects of coalescing binary neutron stars in numerical relativity. II. Long-term simulations *Phys. Rev. D* **91** 064060
- [45] Dietrich T, Bernuzzi S and Tichy W 2017 Closed-form tidal approximants for binary neutron star gravitational waveforms constructed from high-resolution numerical relativity simulations *Phys. Rev. D* **96** 121501
- [46] Kiuchi K, Kawaguchi K, Kyutoku K, Sekiguchi Y, Shibata M and Taniguchi K 2017 Sub-radian-accuracy gravitational waveforms of coalescing binary neutron stars in numerical relativity *Phys. Rev. D* **96** 084060
- [47] Gold R, Bernuzzi S, Thierfelder M, Brüggmann B and Pretorius F 2012 Eccentric binary neutron star mergers *Phys. Rev. D* **86** 121501
- [48] East W E and Pretorius F 2012 Dynamical capture binary neutron star mergers *Astrophys. J.* **760** L4

- [49] East W E, Paschalidis V, Pretorius F and Shapiro S L 2016 Relativistic simulations of eccentric binary neutron star mergers: one-arm spiral instability and effects of neutron star spin *Phys. Rev. D* **93** 024011
- [50] East W E, Paschalidis V and Pretorius F 2016 Equation of state effects and one-arm spiral instability in hypermassive neutron stars formed in eccentric neutron star mergers *Class. Quantum Grav.* **33** 244004
- [51] Radice D, Galeazzi F, Lippuner J, Roberts L F, Ott C D and Rezzolla L 2016 Dynamical mass ejection from binary neutron star mergers *Mon. Not. R. Astron. Soc.* **460** 3255–71
- [52] Bernuzzi S, Dietrich T, Tichy W and Brüggmann B 2014 Mergers of binary neutron stars with realistic spin *Phys. Rev. D* **89** 104021
- [53] Kastaun W, Galeazzi F, Alic D, Rezzolla L and Font J A 2013 On the black hole from merging binary neutron stars: how fast can it spin? *Phys. Rev. D* **88** 021501
- [54] Dietrich T, Bernuzzi S, Ujevic M and Tichy W 2017 Gravitational waves and mass ejecta from binary neutron star mergers: effect of the stars' rotation *Phys. Rev. D* **95** 044045
- [55] Kastaun W, Ciolfi R, Endrizzi A and Giacomazzo B 2017 Structure of stable binary neutron star merger remnants: role of initial spin *Phys. Rev. D* **96** 043019
- [56] Dietrich T, Moldenhauer N, Johnson-McDaniel N K, Bernuzzi S, Markakis C M, Brüggmann B and Tichy W 2015 Binary neutron stars with generic spin, eccentricity, mass ratio, and compactness—quasi-equilibrium sequences and first evolutions *Phys. Rev. D* **92** 124007
- [57] Tacik N *et al* 2015 Binary neutron stars with arbitrary spins in numerical relativity *Phys. Rev. D* **92** 124012
- Tacik N *et al* 2016 *Phys. Rev. D* **94** 049903 (erratum)
- [58] Dietrich T, Bernuzzi S, Brüggmann B, Ujevic M and Tichy W 2018 Numerical relativity simulations of precessing binary neutron star mergers *Phys. Rev. D* **97** 064002
- [59] Tsatsin P and Marronetti P 2013 Initial data for neutron star binaries with arbitrary spins *Phys. Rev. D* **88** 064060
- [60] Anderson M *et al* 2008 Magnetized neutron star mergers and gravitational wave signals *Phys. Rev. Lett.* **100** 191101
- [61] Giacomazzo B, Rezzolla L and Baiotti L 2011 Accurate evolutions of inspiralling and magnetized neutron-stars: equal-mass binaries *Phys. Rev. D* **83** 044014
- [62] Rezzolla L *et al* 2011 The missing link: merging neutron stars naturally produce jet-like structures and can power short gamma-ray bursts *Astrophys. J.* **732** L6
- [63] Palenzuela C *et al* 2013 Gravitational and electromagnetic outputs from binary neutron star mergers *Phys. Rev. Lett.* **111** 061105
- [64] Kiuchi K, Kyutoku K, Sekiguchi Y, Shibata M and Wada T 2014 High resolution numerical-relativity simulations for the merger of binary magnetized neutron stars *Phys. Rev. D* **90** 041502
- [65] Palenzuela C, Liebling S L, Neilsen D, Lehner L and Caballero O L, O'Connor E and Anderson M 2015 Effects of the microphysical equation of state in the mergers of magnetized neutron stars with neutrino cooling *Phys. Rev. D* **92** 044045
- [66] Ruiz M, Shapiro S L and Tsokaros A 2018 GW170817, general relativistic magnetohydrodynamic simulations and the neutron star maximum mass *Phys. Rev. D* **97** 021501
- [67] Ciolfi R, Kastaun W, Giacomazzo B, Endrizzi A, Siegel D M and Perna R 2017 General relativistic magnetohydrodynamic simulations of binary neutron star mergers forming a long-lived neutron star *Phys. Rev. D* **95** 063016
- [68] Kiuchi K, Kyutoku K, Sekiguchi Y and Shibata M 2018 Global simulations of strongly magnetized remnant massive neutron stars formed in binary neutron star mergers *Phys. Rev. D* **97** 124039
- [69] Sekiguchi Y, Kiuchi K, Kyutoku K and Shibata M 2011 Gravitational waves and neutrino emission from the merger of binary neutron stars *Phys. Rev. Lett.* **107** 051102
- [70] Galeazzi F, Kastaun W, Rezzolla L and Font J A 2013 Implementation of a simplified approach to radiative transfer in general relativity *Phys. Rev. D* **88** 064009
- [71] Neilsen D *et al* 2014 Magnetized neutron stars with realistic equations of state and neutrino cooling *Phys. Rev. D* **89** 104029
- [72] Sekiguchi Y, Kiuchi K, Kyutoku K and Shibata M 2015 Dynamical mass ejection from binary neutron star mergers: radiation-hydrodynamics study in general relativity *Phys. Rev. D* **91** 064059
- [73] Foucart F, O'Connor E, Roberts L, Kidder L E, Pfeiffer H P and Scheel M A 2016 Impact of an improved neutrino energy estimate on outflows in neutron star merger simulations *Phys. Rev. D* **94** 123016

- [74] Foucart F 2018 Monte-Carlo closure for moment-based transport schemes in general relativistic radiation hydrodynamics simulations *Mon. Not. R. Astron. Soc.* **475** 4186–207
- [75] Hotokezaka K *et al* 2013 The mass ejection from the merger of binary neutron stars *Phys. Rev. D* **87** 024001
- [76] Bauswein A, Goriely S and Janka H-T 2013 Systematics of dynamical mass ejection, nucleosynthesis and radioactively powered electromagnetic signals from neutron-star mergers *Astrophys. J.* **773** 78
- [77] Wanajo S, Sekiguchi Y, Nishimura N, Kiuchi K, Kyutoku K and Shibata M 2014 Production of all the *r*-process nuclides in the dynamical ejecta of neutron star mergers *Astrophys. J.* **789** L39
- [78] Fujibayashi S, Sekiguchi Y, Kiuchi K and Shibata M 2017 Properties of neutrino-driven ejecta from the remnant of a binary neutron star merger: pure radiation hydrodynamics case *Astrophys. J.* **846** 114
- [79] Perego A, Radice D and Bernuzzi S 2017 AT2017gfo: an anisotropic and three-component Kilonova counterpart of GW170817 *Astrophys. J.* **850** L37
- [80] Hotokezaka K, Beniamini P and Piran T 2018 Neutron star mergers as sites of *r*-process nucleosynthesis and short gamma-ray bursts *Int. J. Mod. Phys. D* **27** 1842005
- [81] Bovard L, Martin D, Guercilena F, Arcones A, Rezzolla L and Korobkin O 2017 *r*-process nucleosynthesis from matter ejected in binary neutron star mergers *Phys. Rev. D* **96** 124005
- [82] Shibata M and Sekiguchi Y 2012 Radiation magnetohydrodynamics for black hole-torus system in full general relativity: a step toward physical simulation *Prog. Theor. Phys.* **127** 535
- [83] Foucart F, O'Connor E, Roberts L, Duez M D, Haas R, Kidder L E, Ott C D, Pfeiffer H P, Scheel M A and Szilagy B 2015 Post-merger evolution of a neutron star-black hole binary with neutrino transport *Phys. Rev. D* **91** 124021
- [84] Radice D 2017 General-relativistic large-eddy simulations of binary neutron star mergers *Astrophys. J.* **838** L2
- [85] Shibata M, Kiuchi K and Sekiguchi Y-I 2017 General relativistic viscous hydrodynamics of differentially rotating neutron stars *Phys. Rev. D* **95** 083005
- [86] Shibata M and Kiuchi K 2017 Gravitational waves from remnant massive neutron stars of binary neutron star merger: viscous hydrodynamics effects *Phys. Rev. D* **95** 123003
- [87] Shibata M, Fujibayashi S, Hotokezaka K, Kiuchi K, Kyutoku K, Sekiguchi Y and Tanaka M 2017 Modeling GW170817 based on numerical relativity and its implications *Phys. Rev. D* **96** 123012
- [88] Fujibayashi S, Kiuchi K, Nishimura N, Sekiguchi Y and Shibata M 2018 Mass ejection from the remnant of a binary neutron star merger: viscous-radiation hydrodynamics study *Astrophys. J.* **860** 64
- [89] Bernuzzi S, Nagar A, Dietrich T and Damour T 2015 Modeling the dynamics of tidally interacting binary neutron stars up to the merger *Phys. Rev. Lett.* **114** 161103
- [90] Dietrich T, Bernuzzi S, Ujevic M and Brüggmann B 2015 Numerical relativity simulations of neutron star merger remnants using conservative mesh refinement *Phys. Rev. D* **91** 124041
- [91] Bernuzzi S, Dietrich T and Nagar A 2015 Modeling the complete gravitational wave spectrum of neutron star mergers *Phys. Rev. Lett.* **115** 091101
- [92] Radice D, Bernuzzi S and Ott C D 2016 One-armed spiral instability in neutron star mergers and its detectability in gravitational waves *Phys. Rev. D* **94** 064011
- [93] Radice D, Bernuzzi S, Del Pozzo W, Roberts L F and Ott C D 2017 Probing extreme-density matter with gravitational wave observations of binary neutron star merger remnants *Astrophys. J.* **842** L10
- [94] Radice D, Perego A, Zappa F and Bernuzzi S 2018 GW170817: joint constraint on the neutron star equation of state from multimessenger observations *Astrophys. J.* **852** L29
- [95] Dietrich T and Hinderer T 2017 Comprehensive comparison of numerical relativity and effective-one-body results to inform improvements in waveform models for binary neutron star systems *Phys. Rev. D* **95** 124006
- [96] Zappa F, Bernuzzi S, Radice D, Perego A and Dietrich T 2018 Gravitational-wave luminosity of binary neutron stars mergers *Phys. Rev. Lett.* **120** 111101
- [97] Dietrich T, Bernuzzi S, Brüggmann B and Tichy W 2018 High-resolution numerical relativity simulations of spinning binary neutron star mergers *26th Euromicro Int. Conf. on Parallel, Distributed and Network-based Processing* pp 682–9
- [98] Wilson J R and Mathews G J 1995 Instabilities in close neutron star binaries *Phys. Rev. Lett.* **75** 4161–4

- [99] Wilson J R, Mathews G J and Marronetti P 1996 Relativistic numerical model for close neutron star binaries *Phys. Rev. D* **54** 1317–31
- [100] York J W Jr 1999 Conformal ‘thin sandwich’ data for the initial-value problem *Phys. Rev. Lett.* **82** 1350–3
- [101] Bonazzola S, Gourgoulhon E and Marck J-A 1999 Numerical models of irrotational binary neutron stars in general relativity *Phys. Rev. Lett.* **82** 892–5
- [102] Tichy W 2011 Initial data for binary neutron stars with arbitrary spins *Phys. Rev. D* **84** 024041
- [103] Tichy W 2012 Constructing quasi-equilibrium initial data for binary neutron stars with arbitrary spins *Phys. Rev. D* **86** 064024
- [104] Gourgoulhon E, Grandclément P, Taniguchi K, Marck J-A and Bonazzola S 2001 Quasiequilibrium sequences of synchronized and irrotational binary neutron stars in general relativity: 1. Method and tests *Phys. Rev. D* **63** 064029
- [105] Moldenhauer N, Markakis C M, Johnson-McDaniel N K, Tichy W and Brüggmann B 2014 Initial data for binary neutron stars with adjustable eccentricity *Phys. Rev. D* **90** 084043
- [106] Gourgoulhon E, Grandclément P, Marck J-A, Novak J and Taniguchi K Paris Observatory, Meudon section—LUTH laboratory <http://www.lorene.obspm.fr/>
- [107] Tichy W 2009 A new numerical method to construct binary neutron star initial data *Class. Quantum Grav.* **26** 175018
- [108] Ansorg M 2007 Multi-domain spectral method for initial data of arbitrary binaries in general relativity *Class. Quantum Grav.* **24** S1–4
- [109] Nakamura T, Oohara K and Kojima Y 1987 General relativistic collapse to black holes and gravitational waves from black holes *Prog. Theor. Phys. Suppl.* **90** 1–218
- [110] Shibata M and Nakamura T 1995 Evolution of three-dimensional gravitational waves: harmonic slicing case *Phys. Rev. D* **52** 5428–44
- [111] Baumgarte T W and Shapiro S L 1999 On the numerical integration of Einstein’s field equations *Phys. Rev. D* **59** 024007
- [112] Bernuzzi S and Hilditch D 2010 Constraint violation in free evolution schemes: comparing BSSNOK with a conformal decomposition of Z4 *Phys. Rev. D* **81** 084003
- [113] Ruiz M, Hilditch D and Bernuzzi S 2011 Constraint preserving boundary conditions for the Z4c formulation of general relativity *Phys. Rev. D* **83** 024025
- [114] Weyhausen A, Bernuzzi S and Hilditch D 2012 Constraint damping for the Z4c formulation of general relativity *Phys. Rev. D* **85** 024038
- [115] Cao Z and Hilditch D 2012 Numerical stability of the Z4c formulation of general relativity *Phys. Rev. D* **85** 124032
- [116] Hilditch D *et al* 2013 Compact binary evolutions with the Z4c formulation *Phys. Rev. D* **88** 084057
- [117] Bona C, Massó J, Stela J and Seidel E 1996 A class of hyperbolic gauge conditions *The Seventh Marcel Grossmann Meeting: on Recent Developments in Theoretical and Experimental General Relativity, Gravitation and Relativistic Field Theories* ed R T Jantzen *et al* (Singapore: World Scientific)
- [118] Alcubierre M *et al* 2003 Gauge conditions for long term numerical black hole evolutions without excision *Phys. Rev. D* **67** 084023
- [119] van Meter J R, Baker J G, Koppitz M and Choi D-I 2006 How to move a black hole without excision: gauge conditions for the numerical evolution of a moving puncture *Phys. Rev. D* **73** 124011
- [120] Campanelli M, Lousto C O, Marronetti P and Zlochower Y 2006 Accurate evolutions of orbiting black-hole binaries without excision *Phys. Rev. Lett.* **96** 111101
- [121] Baker J G, Centrella J, Choi D-I, Koppitz M and van Meter J 2006 Gravitational wave extraction from an inspiraling configuration of merging black holes *Phys. Rev. Lett.* **96** 111102
- [122] Baiotti L, Hawke I and Rezzolla L 2007 On the gravitational radiation from the collapse of neutron stars to rotating black holes *Class. Quantum Grav.* **24** S187–206
- [123] Thierfelder M, Bernuzzi S, Hilditch D, Brüggmann B and Rezzolla L 2011 The trumpet solution from spherical gravitational collapse with puncture gauges *Phys. Rev. D* **83** 064022
- [124] Dietrich T and Bernuzzi S 2015 Simulations of rotating neutron star collapse with the puncture gauge: end state and gravitational waveforms *Phys. Rev. D* **91** 044039
- [125] Banyuls F, Font J A, Ibanez J M A, Martí J M A and Miralles J A 1997 Numerical 3+1 general relativistic hydrodynamics: a local characteristic approach *Astrophys. J.* **476** 221
- [126] Brüggmann B, Tichy W and Jansen N 2004 Numerical simulation of orbiting black holes *Phys. Rev. Lett.* **92** 211101

- [127] Brüggmann B *et al* 2008 Calibration of moving puncture simulations *Phys. Rev. D* **77** 024027
- [128] Thierfelder M, Bernuzzi S and Brüggmann B 2011 Numerical relativity simulations of binary neutron stars *Phys. Rev. D* **84** 044012
- [129] Radice D and Rezzolla L 2012 THC: a new high-order finite-difference high-resolution shock-capturing code for special-relativistic hydrodynamics *Astron. Astrophys.* **547** A26
- [130] Radice D, Rezzolla L and Galeazzi F 2014 High-order fully general-relativistic hydrodynamics: new approaches and tests *Class. Quantum Grav.* **31** 075012
- [131] Radice D, Rezzolla L and Galeazzi F 2015 High-order numerical-relativity simulations of binary neutron stars *ASP Conf. Ser.* **498** 121–6
- [132] Pollney D, Reisswig C, Schnetter E, Dorband N and Diener P 2011 High accuracy binary black hole simulations with an extended wave zone *Phys. Rev. D* **83** 044045
- [133] Löffler F *et al* 2012 The Einstein toolkit: a community computational infrastructure for relativistic astrophysics *Class. Quantum Grav.* **29** 115001
- [134] Berger M J and Olinger J 1984 Adaptive mesh refinement for hyperbolic partial differential equations *J. Comput. Phys.* **53** 484
- [135] Schnetter E, Hawley S H and Hawke I 2004 Evolutions in 3D numerical relativity using fixed mesh refinement *Class. Quantum Grav.* **21** 1465–88
- [136] Reisswig C, Bishop N T, Pollney D and Szilagyi B 2009 Unambiguous determination of gravitational waveforms from binary black hole mergers *Phys. Rev. Lett.* **103** 221101
- [137] Reisswig C and Pollney D 2011 Notes on the integration of numerical relativity waveforms *Class. Quantum Grav.* **28** 195015
- [138] Damour T, Nagar A, Pollney D and Reisswig C 2012 Energy versus angular momentum in black hole binaries *Phys. Rev. Lett.* **108** 131101
- [139] Bernuzzi S, Nagar A, Thierfelder M and Brüggmann B 2012 Tidal effects in binary neutron star coalescence *Phys. Rev. D* **86** 044030
- [140] Scheel M A *et al* 2009 High-accuracy waveforms for binary black hole inspiral, merger and ringdown *Phys. Rev. D* **79** 024003
- [141] Reisswig C, Bishop N T, Pollney D and Szilagyi B 2010 Characteristic extraction in numerical relativity: binary black hole merger waveforms at null infinity *Class. Quantum Grav.* **27** 075014
- [142] Damour T 1983 Gravitational radiation and the motion of compact bodies *Gravitational Radiation* ed N Deruelle and T Piran (Amsterdam: North-Holland) pp 59–144
- [143] Hinderer T 2008 Tidal love numbers of neutron stars *Astrophys. J.* **677** 1216–20
- [144] Damour T and Nagar A 2009 An improved analytical description of inspiralling and coalescing black-hole binaries *Phys. Rev. D* **79** 081503
- [145] Hinderer T, Lackey B D, Lang R N and Read J S 2010 Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral *Phys. Rev. D* **81** 123016
- [146] Damour T, Nagar A and Villain L 2012 Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals *Phys. Rev. D* **85** 123007
- [147] Bauswein A and Janka H-T 2012 Measuring neutron-star properties via gravitational waves from binary mergers *Phys. Rev. Lett.* **108** 011101
- [148] Hotokezaka K *et al* 2013 Remnant massive neutron stars of binary neutron star mergers: evolution process and gravitational waveform *Phys. Rev. D* **88** 044026
- [149] Takami K, Rezzolla L and Baiotti L 2014 Constraining the equation of state of neutron stars from binary mergers *Phys. Rev. Lett.* **113** 091104
- [150] Read J S, Lackey B D, Owen B J and Friedman J L 2009 Constraints on a phenomenologically parameterized neutron- star equation of state *Phys. Rev. D* **79** 124032
- [151] Shibata M, Taniguchi K and Uryu K 2005 Merger of binary neutron stars with realistic equations of state in full general relativity *Phys. Rev. D* **71** 084021
- [152] Lattimer J M and Swesty F D 1991 A Generalized equation of state for hot, dense matter *Nucl. Phys. A* **535** 331–76
- [153] Typel S, Ropke G, Klahn T, Blaschke D and Wolter H H 2010 Composition and thermodynamics of nuclear matter with light clusters *Phys. Rev. C* **81** 015803
- [154] Hempel M and Schaffner-Bielich J 2010 Statistical model for a complete supernova equation of state *Nucl. Phys. A* **837** 210–54
- [155] Steiner A W, Hempel M and Fischer T 2013 Core-collapse supernova equations of state based on neutron star observations *Astrophys. J.* **774** 17

- [156] Banik S, Hempel M and Bandyopadhyay D 2014 New hyperon equations of state for supernovae and neutron stars in density-dependent Hadron field theory *Astrophys. J. Suppl.* **214** 22
- [157] Bauswein A, Janka H-T and Oechslin R 2010 Testing approximations of thermal effects in neutron star merger simulations *Phys. Rev. D* **82** 084043
- [158] Kaplan J D *et al* 2014 The influence of thermal pressure on equilibrium models of hypermassive neutron star merger remnants *Astrophys. J.* **790** 19
- [159] Kawamura T, Giacomazzo B, Kastaun W, Ciolfi R, Endrizzi A, Baiotti L and Perna R 2016 Binary neutron star mergers and short gamma-ray bursts: effects of magnetic field orientation, equation of state and mass ratio *Phys. Rev. D* **94** 064012
- [160] Radice D, Perego A, Bernuzzi S and Zhang B 2018 Long-lived remnants from binary neutron star mergers *Mon. Not. R. Astron. Soc.* **481** 3670–82
- [161] Lattimer J M 2012 The nuclear equation of state and neutron star masses *Annu. Rev. Nucl. Part. Sci.* **62** 485–515
- [162] Ozel F and Freire P 2016 Masses, radii and equation of state of neutron stars *Annu. Rev. Astron. Astrophys.* **54** 401
- [163] Rezzolla L, Most E R and Weih L R 2018 Using gravitational-wave observations and quasi-universal relations to constrain the maximum mass of neutron stars *Astrophys. J.* **852** L25
- [164] Margalit B and Metzger B D 2017 Constraining the maximum mass of neutron stars from multimessenger observations of GW170817 *Astrophys. J.* **850** L19
- [165] Rawls M L, Orosz J A, McClintock J E, Torres M A P, Bailyn C D and Buxton M M 2011 Refined neutron-star mass determinations for six eclipsing x-ray pulsar binaries *Astrophys. J.* **730** 25
- [166] Ozel F, Psaltis D, Narayan R and Villarreal A S 2012 On the mass distribution and birth masses of neutron stars *Astrophys. J.* **757** 55
- [167] Demorest P, Pennucci T, Ransom S, Roberts M and Hessels J 2010 Shapiro delay measurement of a two solar mass neutron star *Nature* **467** 1081–3
- [168] Antoniadis J *et al* 2013 A massive pulsar in a compact relativistic binary *Science* **340** 6131
- [169] Linares M, Shahbaz T and Casares J 2018 Peering into the dark side: magnesium lines establish a massive neutron star in PSR J2215+5135 *Astrophys. J.* **859** 54
- [170] Lattimer J M Observed neutron star masses www.stellarcollapse.org/nsmasses
- [171] Huang Y-J, Jiang J-L, Li X, Jin Z-P, Fan Y-Z and Wei D-M 2018 Total gravitational mass of the Galactic double neutron star systems: evidence for a bimodal distribution (arXiv:1804.03101)
- [172] Giacomazzo B, Perna R, Rezzolla L, Troja E and Lazzati D 2013 Compact binary progenitors of short gamma-ray bursts *Astrophys. J.* **762** L18
- [173] Ruiz M and Shapiro S L 2017 General relativistic magnetohydrodynamics simulations of prompt-collapse neutron star mergers: the absence of jets *Phys. Rev. D* **96** 084063
- [174] Dietrich T and Ujevic M 2017 Modeling dynamical ejecta from binary neutron star mergers and implications for electromagnetic counterparts *Class. Quantum Grav.* **34** 105014
- [175] Dominik M, Belczynski K, Fryer C, Holz D, Berti E, Bulik T, Mandel I and O’Shaughnessy R 2012 Double compact objects I: the significance of the common envelope on merger rates *Astrophys. J.* **759** 52
- [176] Martinez J G, Stovall K, Freire P C C, Deneva J S, Jenet F A, McLaughlin M A, Bagchi M, Bates S D and Ridolfi A 2015 Pulsar J0453+1559: a double neutron star system with a large mass asymmetry *Astrophys. J.* **812** 143
- [177] Lazarus P *et al* 2016 Einstein@home discovery of a double-neutron star binary in the PALFA survey *Astrophys. J.* **831** 150
- [178] Lo K-W and Lin L-M 2011 The spin parameter of uniformly rotating compact stars *Astrophys. J.* **728** 12
- [179] Stovall K *et al* 2018 PALFA discovery of a highly relativistic double neutron star binary *Astrophys. J.* **854** L22
- [180] Buonanno A, Chen Y-B and Vallisneri M 2003 Detecting gravitational waves from precessing binaries of spinning compact objects: adiabatic limit *Phys. Rev. D* **67** 104025
- Buonanno A, Chen Y-B and Vallisneri M 2006 *Phys. Rev. D* **74** 029904 (erratum)
- [181] Damour T 2001 Coalescence of two spinning black holes: an effective one-body approach *Phys. Rev. D* **64** 124013
- [182] Campanelli M, Lousto C O and Zlochower Y 2006 Spin-orbit interactions in black-hole binaries *Phys. Rev. D* **74** 084023

- [183] Harry I and Hinderer T 2018 Observing and measuring the neutron-star equation-of-state in spinning binary neutron star systems *Class. Quantum Grav.* **35** 145010
- [184] Agathos M, Meidam J, Del Pozzo W, Li T G F, Tompitak M, Veitch J, Vitale S and Van Den Broeck C 2015 Constraining the neutron star equation of state with gravitational wave signals from coalescing binary neutron stars *Phys. Rev. D* **92** 023012
- [185] Dietrich T *et al* 2018 Matter imprints in waveform models for neutron star binaries: tidal and self-spin effects (arXiv:1804.02235)
- [186] Peters P C 1964 Gravitational radiation and the motion of two point masses *Phys. Rev.* **136** B1224–32
- [187] Pfeiffer H P, Brown D A, Kidder L E, Lindblom L, Lovelace G and Scheel M A 2007 Reducing orbital eccentricity in binary black hole simulations *Class. Quantum Grav.* **24** S59–82
- [188] Kyutoku K, Shibata M and Taniguchi K 2014 Reducing orbital eccentricity in initial data of binary neutron stars *Phys. Rev. D* **90** 064006
- [189] Bonetti M, Perego A, Capelo P R, Dotti M and Miller M C 2018 r -process nucleosynthesis in the early universe through fast mergers of compact binaries in triple systems *Publ. Astron. Soc. Aust.* **35** 17
- [190] Lee W H, Ramirez-Ruiz E and van de Ven G 2010 Short gamma-ray bursts from dynamically-assembled compact binaries in globular clusters: pathways, rates, hydrodynamics and cosmological setting *Astrophys. J.* **720** 953–75
- [191] Chirenti C, Gold R and Miller M C 2017 Gravitational waves from f-modes excited by the inspiral of highly eccentric neutron star binaries *Astrophys. J.* **837** 67
- [192] Chaurasia S V, Dietrich T, Johnson-McDaniel N K, Ujevic M, Tichy W and Brüggmann B 2018 Gravitational waves and mass ejecta from binary neutron star mergers: effect of large eccentricities (arXiv:1807.06857)
- [193] Binnington T and Poisson E 2009 Relativistic theory of tidal Love numbers *Phys. Rev. D* **80** 084018
- [194] Flanagan E E and Hinderer T 2008 Constraining neutron star tidal Love numbers with gravitational wave detectors *Phys. Rev. D* **77** 021502
- [195] Damour T and Nagar A 2009 Relativistic tidal properties of neutron stars *Phys. Rev. D* **80** 084035
- [196] Favata M 2014 Systematic parameter errors in inspiraling neutron star binaries *Phys. Rev. Lett.* **112** 101101
- [197] Read J S *et al* 2013 Matter effects on binary neutron star waveforms *Phys. Rev. D* **88** 044042
- [198] Rezzolla L and Takami K 2016 Gravitational-wave signal from binary neutron stars: a systematic analysis of the spectral properties *Phys. Rev. D* **93** 124051
- [199] Abbott B P *et al* 2018 Properties of the binary neutron star merger GW170817 (arXiv:1805.11579)
- [200] Coughlin M W *et al* 2018 Constraints on the neutron star equation of state from at2017gfo using radiative transfer simulations *Mon. Not. R. Astron. Soc.* **480** 3871–8
- [201] Schaffner-Bielich J 2008 Hypernuclear physics for neutron stars *Nucl. Phys. A* **804** 309–21
- [202] Ozel F and Psaltis D 2009 Reconstructing the neutron-star equation of state from astrophysical measurements *Phys. Rev. D* **80** 103003
- [203] Neuhauser R, Hambaryan V V, Hohle M M and Eisenbeiss T 2012 Constraints on the equation-of-state of neutron stars from nearby neutron star observations *J. Phys.: Conf. Ser.* **337** 012073
- [204] Steiner A W, Lattimer J M and Brown E F 2013 The neutron star mass-radius relation and the equation of state of dense matter *Astrophys. J.* **765** L5
- [205] Watts A L *et al* 2016 Colloquium: Measuring the neutron star equation of state using x-ray timing *Rev. Mod. Phys.* **88** 021001
- [206] Annala E, Gorda T, Kurkela A and Vuorinen A 2018 Gravitational-wave constraints on the neutron-star-matter equation of state *Phys. Rev. Lett.* **120** 172703
- [207] Most E R, Weih L R, Rezzolla L and Schaffner-Bielich J 2018 New constraints on radii and tidal deformabilities of neutron stars from GW170817 *Phys. Rev. Lett.* **120** 261103
- [208] Scheel M A, Pfeiffer H P, Lindblom L, Kidder L E, Rinne O and Teukolsky S A 2006 Solving Einstein's equations with dual coordinate frames *Phys. Rev. D* **74** 104006
- [209] Szilagyi B, Lindblom L and Scheel M A 2009 Simulations of binary black hole mergers using spectral methods *Phys. Rev. D* **80** 124010

- [210] Buchman L T, Pfeiffer H P, Scheel M A and Szilagy B 2012 Simulations of non-equal mass black hole binaries with spectral methods *Phys. Rev. D* **86** 084033
- [211] Haas R *et al* 2016 Simulations of inspiraling and merging double neutron stars using the spectral Einstein code *Phys. Rev. D* **93** 124062
- [212] Giacomazzo B and Perna R 2013 Formation of stable magnetars from binary neutron star mergers *Astrophys. J.* **771** L26
- [213] Kiuchi K, Sekiguchi Y, Shibata M and Taniguchi K 2010 Exploring binary-neutron-star-merger scenario of short- gamma-ray bursts by gravitational-wave observation *Phys. Rev. Lett.* **104** 141101
- [214] Bauswein A, Baumgarte T W and Janka H T 2013 Prompt merger collapse and the maximum mass of neutron stars *Phys. Rev. Lett.* **111** 131101
- [215] Nagar A *et al* 2018 Time-domain effective-one-body gravitational waveforms for coalescing compact binaries with nonprecessing spins, tides and self-spin effects
- [216] Chatziioannou K, Haster C-J and Zimmerman A 2018 Measuring the neutron star tidal deformability with equation-of-state-independent relations and gravitational waves *Phys. Rev. D* **97** 104036
- [217] Abbott B P *et al* 2018 GW170817: measurements of neutron star radii and equation of state *Phys. Rev. Lett.* **121** 161101
- [218] Dai L, Venumadhav T and Zackay B 2018 Parameter estimation for GW170817 using relative binning (arXiv:1806.08793)
- [219] Kawaguchi K, Kiuchi K, Kyutoku K, Sekiguchi Y, Shibata M and Taniguchi K 2018 Frequency-domain gravitational waveform models for inspiraling binary neutron stars *Phys. Rev. D* **97** 044044
- [220] Bauswein A, Janka H T, Hebeler K and Schwenk A 2012 Equation-of-state dependence of the gravitational-wave signal from the ring-down phase of neutron-star mergers *Phys. Rev. D* **86** 063001
- [221] Bauswein A, Stergioulas N and Janka H-T 2014 Revealing the high-density equation of state through binary neutron star mergers *Phys. Rev. D* **90** 023002
- [222] Takami K, Rezzolla L and Baiotti L 2015 Spectral properties of the post-merger gravitational-wave signal from binary neutron stars *Phys. Rev. D* **91** 064001
- [223] Bauswein A and Stergioulas N 2015 Unified picture of the post-merger dynamics and gravitational wave emission in neutron star mergers *Phys. Rev. D* **91** 124056
- [224] Clark J A, Bauswein A, Stergioulas N and Shoemaker D 2016 Observing gravitational waves from the post-merger phase Of binary neutron star coalescence *Class. Quantum Grav.* **33** 085003
- [225] Bose S, Chakravarti K, Rezzolla L, Sathyaprakash B S and Takami K 2018 Neutron-star radius from a population of binary neutron star mergers *Phys. Rev. Lett.* **120** 031102
- [226] Chatziioannou K, Clark J A, Bauswein A, Millhouse M, Littenberg T B and Cornish N 2017 Inferring the post-merger gravitational wave emission from binary neutron star coalescences *Phys. Rev. D* **96** 124035
- [227] Clark J *et al* 2014 Prospects for high frequency burst searches following binary neutron star coalescence with advanced gravitational wave detectors *Phys. Rev. D* **90** 062004
- [228] Dudi R, Pannarale F, Dietrich T, Hannam M, Bernuzzi S, Ohme F and Bruegmann B 2018 Relevance of tidal effects and post-merger dynamics for binary neutron star parameter estimation *Phys. Rev. D* **98** 084061
- [229] Read J S *et al* 2009 Measuring the neutron star equation of state with gravitational wave observations *Phys. Rev. D* **79** 124033
- [230] Hotokezaka K, Kyutoku K, Sekiguchi Y-I and Shibata M 2016 Measurability of the tidal deformability by gravitational waves from coalescing binary neutron stars *Phys. Rev. D* **93** 064082