Gravitational Waves from Neutron-Star Mergers - Implications for Nuclear Physics and Cosmology

Michalis Agathos
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

LIGO-Virgo | Frank Elavsky | Northwestern

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PROPERTIES OF NS MATTER

- Cold matter in the interior of NS reaches supra-nuclear densities
- Large uncertainties on matter properties; plethora of viable models

Figure 7

Özel & Freire [arXiv:1603.02698]
see also Lattimer [arXiv:1305.3510]
PROPERTIES OF NS MATTER

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GW SOURCE MODELLING

- The post-Newtonian (PN) expansion gives approximate solutions to the 2-body problem in GR
- Accurate analytic solution for the best part of the inspiral stage
- Simple frequency-domain waveform:

\[
\hat{h}(f) = A f^{-7/6} \cos(2\Phi(f; m_1, m_2) + \phi_0) \quad v = (\pi M f)^{1/3}
\]

\[
\Phi = \left(\frac{v}{c}\right)^{-5} \sum_{i=0}^{N} \left[ \psi_i + \psi^{(1)}_i \ln \frac{v}{c} \right] \left(\frac{v}{c}\right)^i
\]

- Alternative formulation uses effective-one-body (EOB) approach
- Numerical Relativity simulations complete the model close to/during merger, where perturbative expansions fail
MATTER EFFECTS IN BINARY NEUTRON STARS

- Tidal gravitational field of each NS deforms companion
  \[ Q_{ij} = -\lambda(m)\mathcal{E}_{ij} \]

- Extra orbiting quadrupoles induced by NS spins

- **Tidal interactions** are the dominant matter effect for slow-spinning NSs for LIGO/Virgo BNS sources, where spin-induced quadrupoles are expected to be small

- In both cases, the effect magnitudes are determined by the **equation of state (EoS)** of NS matter

- **Post-merger** signal, lifetime and type of remnant (NS/BH) also depend on the “stiffness” of the EoS

- However, post-merger occurs at very high frequencies (>2 kHz), where detector sensitivities are still not good enough

[Hinderer+ arXiv:0911.3535]
Neutron stars are **not** point masses

Strong tidal effects at the end of inspiral deform each NS:

This tidal deformation affects binary orbital evolution (5PN+)

\[
Q_{ij} = -\lambda(m)\mathcal{E}_{ij}
\]

\[
\Phi(f) = \Phi_{PP}(f) + \Phi_{\text{tidal}}(f)
\]

\[
\Phi_{\text{tidal}}(f) = (\pi M f)^{-\frac{5}{3}} \sum_{a=1,2} \frac{3\lambda_a}{128\eta M^5} \left[ -\frac{24}{\chi_a} \left( 1 + \frac{11\eta}{\chi_a} \right) (\pi M f)^{10/3} - \frac{5}{28\chi_a} (3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3) (\pi M f)^{12/3} + \ldots \right]
\]

[Flanagan & Hinderer 2008]

[Damour; Nagar; Villain 2012]

Tidal deformability parameter \( \lambda \) depends on second Love number and radius:

\[
\lambda_a = \lambda(m_a) = \frac{2}{3} k_2 R(m_a)^5 \quad \Lambda_a = \lambda_a/m_a^5
\]
GW170817: A BINARY NEUTRON STAR MERGER

- Coincident observation of GWs and EM signals across the spectrum
- Low-mass binary, consistent with NSs
- Host galaxy identified (NGC 4993)
CONSTRANTS ON TIDAL PARAMETERS

- Sky location fixed to identified EM source
- Two choices of spin priors, up to 0.05 and 0.89 resp.
- Low frequency down to 23 Hz
- Different BNS waveform models, including matter effects

[LVC PRX 9, 011001 (2019)]
LIGO-P1800061
NEW IMPROVED CONSTRAINTS ON TIDAL PARAMETERS

\[ \Lambda = \frac{16 (m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{13 (m_1 + m_2)^5} \]

[Refs: 103, 112, 115, 167, 169, 172]
Work under the additional assumption that GW170817 is a BNS

Both NSs obey the same EOS

Implement this in two independent ways:

- Sample $P(\rho)$ function directly and integrate TOV equations to get macroscopic properties

- Sample $\Lambda$ and use approximately universal relations between macroscopic NS properties: $\Lambda$, $Q$, $C$, as well as correlation between $\Lambda_1$, $\Lambda_2$, $q$ (binary-$\Lambda$ relation) Yagi-Yunes [arXiv:1608.02582], Chatziioannou-Haster-Zimmerman [arXiv:1804.03221]
SPECTRAL PARAMETERIZATION OF $P(\rho)$

➤ Samples the EoS directly as in Carney-Wade-Irwin [arXiv: 1805.11217], based on spectral parametrization of Lindblom [arXiv:1009.0738]

➤ Constraints on $P(\rho)$ function assuming a realistic 4-dim family of EoS

$P(\rho) \sim \rho^\Gamma$

$\Gamma = \Gamma(P; \gamma_i)$, $\gamma_i = (\gamma_1, \gamma_2, \gamma_3, \gamma_4)$

➤ Constraints at 90% CL:

➤ $P(2\rho_{\text{sat}}) \sim 3.5 \times 10^{34}$ dyn/cm$^2$

➤ Stiff EoS region excluded
out this paper we quote symmetric credible intervals. Our
estimated through a linear expansion of
lar masses. The tidal deformability of a
with the results of [106] for soft EOSs and NSs with simi-
posterior shrinks by a factor of
ment. The area of the 90% credible region for the
of [52]. In both cases imposing a common EOS leads to
sic EOS is assumed, but is not excluded from the analysis
region that is naturally excluded when a common realis-
dently, in orange. The shaded region marks the
two tidal deformability parameters are sampled indepen-
directly in an EOS parameter space. We sample uni-
certain prior constraints to be conveniently incorporated in
structure of NSs. We do this using the spectral EOS pa-
tations describing the equilibrium configuration of a spher-
through the Tolman-Oppenheimer-V olkoff (TOV) equa-
parameters and the masses are mapped to a
EOSs [110]. Then for each sample, the four EOS pa-
dic larger values of the tidal deformability parameter and
favored over "stiff" EOSs such as H4 or MS1, which pre-

RESULTS

We begin by demonstrating the improvement in the mea-
Sampling directly in the EOS parameter space allows for
pressures at twice (six times) the nuclear satu-
ties of NSs [19]. The pressure at twice (six times) the nu-

MEASUREMENT OF TIDAL DEFORMATIONS

This choice of prior

LIGO-P1800115

LIGO-P1800115
MASS-RADIUS USING BOTH METHODS

- Radius-mass posteriors are produced by either
  - using $\Lambda$ - C relation:
    \[ R_1 = 10.8^{+2.0}_{-1.7}, \quad R_1 = 10.7^{+2.1}_{-1.5} \]
    or
  - integrating TOV eqns and imposing EoS support at 1.97 Msun (most massive observed NS):
    \[ R_1 = 11.9^{+1.4}_{-1.4}, \quad R_2 = 11.9^{+1.4}_{-1.4} \]

- Parametrized-EoS method cuts out low radii (too soft to support 1.97 Msun)

[LVC PRL 121 161101 (2018)]
LIGO-P1800115
GW170817 data is available in GWOSC

https://www.gw-openscience.org/

Results and posterior samples publicly available at

https://dcc.ligo.org/LIGO-P1800115/public
Need to remove apparent source-dependence from parametrization of matter effects

Choice of parameterisation (or not):

- Phenomenological approach: parameterise effects that enter the gravitational waveform model, see Del Pozzo, MA+ 2013, MA+ 2015
- Fundamental approach: parameterise EOS of NS matter, then GW observables are derived quantities, see Lackey & Wade 2014, Carney+ 2018
- Nonparametric approach: recover functional dependence \( P(\rho) \) or \( \lambda(m) \) (Landry & Essick 2018, MA in prep)

Need very high accuracy in both

- point-mass (PM) baseline model and
- matter effects in the GW waveform
Like BBH, BNS mergers are standard sirens

Unlike BBH, BNS spacetimes are not “scale-symmetric”

In BBH, the effect of redshift is degenerate with a mass rescaling

In BNS, matter properties introduce additional scale that breaks the degeneracy

Only works if we know the EOS (or measure everything together)

Independent EOS measurement with NICER?
DID GW170817 PROMPTLY COLLAPSE TO A BH?

- EM indicates: probably not!
- What can we say with GW signal alone?
  - Threshold-Λ analysis: sample Λ directly
  - Threshold-mass analysis: sample EoS, derive Λ, \( M_{\text{max}} \), \( M_{\text{thr}} \); can impose mass constraints

[MA+ arXiv:1908.05442]
MULTIMESSENGER STUDIES WITH BNS MERGERS

- GW + EM coincident detection (e.g. GW170817) should lead to GW + EM coherent data analysis
- Identification of EM source -> fixed sky location, constr. distance
- EM spectrum -> inclination, intr. source properties
- Modelling via high-res NR simulations w/ microphysics
- e.g. $\Lambda$-M$_{\text{disk}}$ correlation Radice+ ApJL 852:L29 (2018)

EoS cannot be too soft!
INFORMATION FROM THE MERGER AND BEYOND

- PM inspiral + matter effects: clean perturbative formulation
- Violent merger of relativistic balls of matter at supranuclear densities: not so clean... NR input is crucial!
- Characteristic peaks in post-merger
- Modeling post-merger signal is an active research field

[Del Pozzo, Nagar PRD 95 124034 (2017)]
[Dudi+ PRD 98 084061 (2018)]
[Chatziioannou+ PRD 96, 124035 (2017)]
[Breschi, MA+ arXiv:1908.11418 (2019)], ...

[Bernuzzi+ PRD 89 104021 (2014)]
[Bernuzzi+ PRL 115, 091101 (2015)]
[Bauswein+ PRL 108 011101 (2012)]
[Takami+ PRD 91 064001 (2015)]
CONCLUSIONS

- BNS detections can probe properties of cold matter at supranuclear densities
- **GW170817** already gave very interesting results
- Making use of the assumption that NSs obey the same EoS further improves measurements
- Continuously **improving waveform models** with matter effects (TEOBResumS)
- Need high-quality **input from NR** simulations with matter
- Matter breaks scale-invariance and allows for new **standard-siren cosmography**
- Further gain if information from **EM observations** is folded in (coherently and robustly)
- Many more **BNS** detections in O3 and beyond will improve constraints
- Looking forward to results from NICER!
- We are officially in the era of GW astrophysics & cosmology (and even GW nuclear physics?). Posterior samples available online!

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MODELLING MATTER EFFECTS IN THE WAVEFORM

  - Post-Newtonian inspiral + fit to EOB/NR
  - intermediate post-inspiral and merger-ringdown fit to EOB/NR  [Taracchini+ arXiv:1311.2544]
  - spins w/ one-parameter precession effects
- Matter effects
  - PN: Hinderer+, Flanagan+, Poisson+, Ferrari+, Gualtieri+, ...
  - EOB: Damour+, Nagar+, Buonanno+, ...
  - NR simulations: Bernuzzi+, Read+, Rezzolla+, Hotokezaka+, Dietrich+, ...
**“I-LOVE-Q” RELATIONS**

- **NS assumption** allows us to make use of known “universal” relations between NS properties.

- These reduce the dimensionality of parameter space.

- **Λ — Q** relation
  - Yagi-Yunes [arXiv:1302.4499]

- **Λ — C** relation
  - Maseli+ [arXiv:1304.2052],
  - Urbanec+ [arXiv:1301.5925],
  - Yagi-Yunes [arXiv:1608.02582]
TABLE III. Equal-mass BNS configurations considered in this work. From left to right the column reports: the EOS, the gravitational mass of each star, the compactness, the quadrupolar dimensionless Love numbers, the leading-order tidal coupling constant $\tilde{T}_2$, the corresponding value of the quadrupolar “tidal deformability” for each object, $\tilde{\Lambda}_{A,B}$, Eq. (22), the dimensionless spin magnitude and the spin-induced quadrupole momenta $C_{QA,QB}$.

<table>
<thead>
<tr>
<th>Name</th>
<th>EOS</th>
<th>$M_{A,B} [M]$</th>
<th>$C_{A,B}$</th>
<th>$k_{A,B}^{2\tilde{T}}$</th>
<th>$\tilde{\Lambda}_{A,B}$^{2}</th>
<th>$C_{QA,QB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAM:0095</td>
<td>SLy</td>
<td>1.35</td>
<td>0.093</td>
<td>73.51</td>
<td>392</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.093</td>
<td>0.093</td>
</tr>
<tr>
<td>BAM:0039</td>
<td>H4</td>
<td>1.37</td>
<td>0.149</td>
<td>191.34</td>
<td>1020.5</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.149</td>
<td>0.149</td>
</tr>
<tr>
<td>BAM:0064</td>
<td>MS1b</td>
<td>1.35</td>
<td>0.142</td>
<td>289.67</td>
<td>1545</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td>0.142</td>
<td>0.142</td>
</tr>
</tbody>
</table>

FIG. 12. Phasing comparison between BAM and TEOBResumS waveforms for the SLy and MS1b equal-mass BNS configurations of Table III. The EOB and NR waveforms, once aligned during during the early inspiral (approximately over the first 1500 $M$ of evolution), are compatible, within the NR uncertainty (gray area in the figures) essentially up to the NR merger point, defined as the peak of the waveform amplitude $|h_{22}|$. Note however that the errors are larger for the MS1b configuration. The time marked by the vertical green line corresponds to 700Hz. Consideration of spins is also important, as the leftmost panel of Fig. 12 also shows that the EOB-NR phase difference towards merger is acceptably small ($< 1$ rad), but also significantly larger than the NR uncertainty. This illustrates that, for the first time, our NR simulations are finally mature to inform the analytical model with some new, genuinely strong-field, information that can be extracted from them.

The figures show that for the EOB dynamics, we typically underestimate the effect of tides in the last orbit, since the phase of the NR data is evolving faster (stronger tides). However, the opposite is true for BAM:0095. This result is consistent with the ones of Ref. [32] for the same physical configuration (but different simulations, leftmost panel of Fig. 3) where one had already the indication that for compact NS, tidal effects could be slightly overestimated with respect to the corresponding NR description. Informing TEOBResumS with the BAM simulations is outside the scope of the current work. However, we want to stress that this is finally possible with our improved simulations.

IV. CONTRIBUTION OF SELF-SPIN TERMS TO BNS INSPIRAL

Now that we could show the consistency between the TEOBResumS phasing and state-of-the art NR simulations, let us investigate in more detail the effect of spins on long BNS waveforms as predicted by our model. First of all, let us recall that inspiralling BNS systems are not likely to have significant spins. The fastest NS in a confirmed BNS system has dimensionless spins $\tilde{\chi} \approx 0.04$. Another potential BNS system has a NS with spin frequency of 239 Hz, corresponding to dimensionless spin 0.2. The fastest-spinning, isolated, millisecond pulsar observed so far has $\tilde{\chi} = 0.04$. However, it is known that even a spin of 0.03 can lead to systematic biases in the estimated tidal parameters if not incorporated in the waveform model [122,123]. Those analysis are based on PN waveform models. A precise assessment of these biases using TEOBResumS is beyond the scope of the present work and will hopefully be addressed in the future. Since the most important theoretical novelty of TEOBResumS is the incorporation of self-spin effects in resummed form, our aim here is to estimate their effect in terms of time.

TOWARDS A BETTER WAVEFORM MODEL

- New model: TEOBResumS
- PM baseline:
  - EOB, resummed PN expansion of binary dynamics, w/ spin-orbit & spin-spin interactions to high order
  - reliable up to merger
  - higher order modes
  - next-to-quasi-circular corrections
  - Post-adiabatic inspiral (speed-up)

[Nagar+ PRD 98, 104052 (2018)]
[Nagar&Retegno PRD 99 021501 (2019)]

Code publicly available (+examples): https://bitbucket.org/eob_ihes/teobresums
TOWARDS A BETTER WAVEFORM MODEL

- New model: TEOBResumS
- Matter sector:
  - GSF-resummed potential with tides to high order
  - Spin-induced effects in resummed form at NNLO
  - \( l=2,3,4 \) tidal polarizability
  - LO gravitomagnetic tides resummed
  - Universal fits for relations between multipole Love parameters
    [Yagi PRD 89, 043011 (2014)]

[Nagar+ PRD 98, 104052 (2018)]
[Nagar&Retegno PRD 99 021501 (2019)]
[Akcay+ PRD 99, 044051 (2019)]
[Bernuzzi+ PRL 114, 161103 (2015)]

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