Equation-of-state influence on neutron-star mergers

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Outline

- Motivation
- Equation of state of high-density matter and the mass-radius relation of neutron stars
- Code details
- Neutron star mergers: general outcome
- Gravitational waves → Advanced LIGO, Advanced Virgo
- Results: equation of state dependence of the GW signal
- Interpretation
- Summary and conclusions
Equation of state of high-density matter

Beta equilibrium, zero temperature
Equation of state of high-density matter only incompletely known

→ neutron star properties unknown

→ survey of EoS dependence of neutron-star mergers

→ measure EoS from gravitational-wave signal of neutron-star mergers

→ **functional dependence !!!!**
Code details

- 47 microphysical EoS (12 include thermal effects consistently), including two strange quark matter EoSs (distinguishable by other observational features)
- without any selection procedure
- 3D Relativistic Smooth Particle Hydrodynamics
- spatial conformal flatness (+ postNewtonian backreaction)
- from quasi-equilibrium orbit about three revolutions before merging
- initially cold neutron stars in neutrinoless beta-equilibrium
- nonrotating velocity profile
- default resolution of 340,000 SPH particle
Dynamics

Inspiral of NS binary

\[ \text{~100 Myrs} \]

Neutron star merger

\[ \text{dependent on EoS, } M_{\text{tot}} \]

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

\[ \text{dependent on EoS, } M_{\text{tot}} \]

10-100 ms

Rigidly rotating (supermassive) NS

Delayed collapse to a BH + torus

\[ \text{GW } f=\mu\text{Hz...kHz } \rightarrow \text{ binary masses} \]

\[ \text{GW kHz} \]
Expected binary parameters

Observations suggest:

~ equal-mass binaries with $M_{\text{tot}} \approx 2.6 \ M_{\odot}$ most abundant in binary population

(in agreement with population synthesis studies)

=> focus on $1.35-1.35 \ M_{\odot}$
Inspiral of NS binary

~100 Myrs

Neutron star merger

dependent on EoS, $M_{tot}$

Prompt formation of a BH + torus

dependent on EoS, $M_{tot}$

Formation of a differentially rotating massive NS

dependent on EoS, $M_{tot}$

Rigidly rotating (supermassive) NS

Delayed collapse to a BH + torus

GW $f=\mu\text{Hz...kHz}$ → binary masses

GW kHz

10-100 ms
• Movie 1.2-1.35 (Temperature)
Movie 1.35-1.35 (density, equatorial plane)
General outcome

for 1.35-1.35 $M_{\text{sun}}$ binaries
(most abundant according to population synthesis studies)

42 out of 47 models lead to the formation of a differentially rotating object
Gravitational-wave amplitude

via quadrupole formula

1.35-1.35 $M_{\text{sun}}$, Shen EoS
Gravitational-wave spectra

- Pronounced peak in the kHz range as a robust feature of all models forming a differentially rotating NS

Sensitivity curves:
- Red dashed: Advanced LIGO
- Black dashed: Einstein Telescope

thick line: full signal
thin line: postmerger signal
Connect EoS and GW signal:

Mass-radius relations of nonrotating neutron stars
Stellar parameters of nonrotating NSs = integral EoS property
Candidate EoS cover the full range of stellar parameters
for all EoS 1.35-1.35 $M_{\text{sun}}$ binaries: $f_{\text{peak}}$ vs. properties of nonrotating NS
Radius of the maximum-mass configuration

1.35-1.35 binaries

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Radius of a $1.6 \, M_{\text{sun}}$ star

1.35-1.35 binaries

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Radius of a 1.6 $M_{\text{sun}}$ star

For the accepted models:

- **Maximum scatter from fit:**
  - $\sim 100$ meters

- Triangle: strange quark matter (distinguishable by other observations)
- Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Maximum-mass (of nonrotating NSs)

1.35-1.35 binaries

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Central density of maximum-mass NS

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Pressure at 1.85 nuclear density

1.35-1.35 binaries

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Sound speed at 1.85 nuclear density

1.35-1.35 binaries

Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects
Variation of binary parameter

$M_1$ and $M_2$ measurable from GW inspiral signal

Note: for the different total binary masses different radii of nonrotating NSs represent better choice (involved density regimes)

Squares: 1.2 - 1.2
Circles: 1.2 – 1.5
Crosses: 1.35 - 1.35
Diamonds: 1.5 - 1.5

(subset of EoSs)
Evolution of maximum density

Sly4
1.35 \( M_{\text{sun}} \)

Shen

Remnant \( \sim 2.6 \ M_{\text{sun}} \)
Crucial for usability:

- Out to which distance the postmerger signal can be detected?
  → 20-45 Mpc with Advanced LIGO → 0.01 – 1 events/yr (conservative)
  → much more with late inspiral signal

- To which accuracy $f_{\text{peak}}$ can be determined?
  → about 30-50 Hz (from Fisher information matrix)

- (binary masses, merger time, distance ... known from inspiral)
Remarks:

- Peak frequency coincides within a few per cent with results of fully relativistic calculations (without trend, depends also on exact implementation of EoS)
- Some EoS might be ruled out by nuclear physics → reduces scatter
- Our method is robust with respect to uncertainties in the determination of the binary masses
- Alternative: EoS from GW inspiral signal: ~1 km accuracy but higher event rate (Read et al. 2009)
- Multiple detections with different total binary masses highly interesting
Why such a scaling?

GW spectrum (pre- and post-merger)
1.35-1.35 $M_{\odot}$, Shen EoS

Fourier transform of the pressure
in the equatorial plane

Stergioulas et al. (2011)
Eigenfunction of the pressure at $f_{peak}$
Fundamental quadrupolar fluid mode

for Newtonian uniform-density stars:

\[ f \propto \sqrt{\frac{M}{R^3}} \]

still valid for relativistic, rotating stars with arbitrary EoS

\[ \Rightarrow f_{\text{peak}} \propto R_{\text{remnant}}^{-3/2} \]

if remnant size correlates with the radius of nonrotating stars

\[ \Rightarrow f_{\text{peak}} \propto R_{\text{TOV}}^{-3/2} \]

Figure 1. The numerically obtained $f$-mode frequencies plotted as functions of the mean stellar density ($M$ and $R$ are in km and $\omega_{f-\text{mode}}$ in kHz).

Andersson & Kokkotas 1998
Radius of the remnant

$R_{\text{remnant}} = \text{sphere enclosing } 2.6 \, M_{\text{sun}} \text{ rest mass}$
$f_{\text{peak}}$ [kHz]

$(2.6/(R_{1.6})^3)^{(1/2)}$ [geom. units]

$\rightarrow$ linear scaling
Summary and conclusions

- Survey of equation of state influence on neutron star mergers
- Generic outcome of 1.35-1.35 $M_{\odot}$ merger: formation of a differentially rotating NS
- Pronounced peak in the GW spectrum
- Peak frequency scales very well with the radius of a nonrotating NS with 1.6 $M_{\odot}$
- Neutron star radii can be measure with an accuracy of 100-200 meters
- Correlations / constraints for other EoS properties

          Bauswein et al., PRD 86, 063001 (2012)
          Stergioulas et al., MNRAS 418, 427 (2011)