Signatures of quark-hadron phase transitions in neutron-star mergers

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The two-body problem in GR

- For BHs we know what to expect:
  \[ \text{BH} + \text{BH} \rightarrow \text{BH} + \text{GWs} \]

- For NSs the question is more subtle: hyper-massive neutron star (HMNS), ie
  \[ \text{NS} + \text{NS} \rightarrow \text{HMNS}+\ldots\ ? \rightarrow \text{BH}+\ldots \]

- HMNS phase can provide clear information on EOS

- BH+torus system may tell us on the central engine of GRBs
The two-body problem in GR

- For BHs we know what to expect:
  \[ \text{BH} + \text{BH} \rightarrow \text{BH} + \text{GWs} \]

- For NSs the question is more subtle: the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:
  \[ \text{NS} + \text{NS} \rightarrow \text{HMNS} + \ldots \rightarrow \text{BH} + \text{torus} + \ldots \rightarrow \text{BH} + \text{GWs} \]

- ejected matter undergoes nucleosynthesis of heavy elements
A prototypical simulation with possibly the best code looks like this…

merger $\rightarrow$ HMNS $\rightarrow$ BH + torus
Anatomy of GW signal

GNH3, $\bar{M} = 1.350 M_\odot$
Anatomy of GW signal

- **Chirp signal**
- **Transient**
- **Post-merger (HMNS)**
- **Black-hole formation (ringdown)**

**Postmerger signal**: peculiar of binary NSs
In frequency space

Read et al. (2013)
GW170817: the first binary neutron-star system

- Unfortunately only the inspiral signal was detected.
- Fortunately this was sufficient to set a number of constraints on max. mass, tidal deformability, radii, etc.
- Gold mine is in the post-merger for there is a lot of information there, also about phase transitions!
What we can do nowadays

Extracting information from the EOS


There are “lines”

This is GW spectroscopy!
A spectroscopic approach to the EOS


merge

frequency
A spectroscopic approach to the EOS


merger frequency
Phase transitions and their signatures

Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel (2019)
Strangeness is expected in neutron stars both in the inspiral (hyperons) and possibly after merger (strange quarks?)

Isolated neutron stars probe a small fraction of phase diagram

Neutron-star binary mergers reach temperatures up to 80 MeV and probe regions complementary to experiments
Modelling the EOS

- EOS based on Chiral Mean Field (CMF) and nonlinear SU(3) sigma model
- Includes hyperons and quarks that can be turned on/off
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures
• EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.

• Quarks appear at sufficiently large temperatures and densities.
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• Quarks appear at sufficiently large temperatures and densities.

• For EOS without quarks, the dynamics is very similar, but no PT.
Comparing with the phase diagram

- Phase diagram with quark fraction
Comparing with the phase diagram

- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time
Comparing with the phase diagram

- Reported are the evolution of the max. temperature and density.
- Quarks appear already early on, but only in small fractions.
- Once sufficient density is reached, a full phase transition takes place.
In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.

- Note the phase difference is **zero** in the inspiral.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.
Gravitational-wave emission

**“low-mass” binary**

In low-mass binary, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.

**“high-mass” binary**

In high-mass binary, phase transition takes place rapidly after ~ 5 ms. Waveforms are similar but ringdown is different (free fall for PT).

Observing mismatch between inspiral (fully hadronic) and post-merger (phase transition): clear signature of a PT.
Conclusions

✴ Spectra of post-merger shows peaks, some "quasi-universal".

✴ When used together with tens of observations, they will set tight constraints on EOS: radius known with ~1 km precision.

✴ **GW170817** has already provided new limits on

\[
2.01^{+0.04}_{-0.04} \leq \frac{M_{\text{TOV}}}{M_\odot} \lesssim 2.16^{+0.17}_{-0.15} \quad \text{maximum mass}
\]
\[
12.00 < R_{1.4}/\text{km} < 13.45 \quad \tilde{\Lambda}_{1.4} > 375 \quad \text{radius, tidal deformability}
\]

✴ **GWs**: new probe of high-density matter and of QCD to be used in conjunction with laboratory experiments.

✴ A phase transition after a BNS merger leaves a GW signature and opens a gate to access quark matter beyond accelerators.