Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers

Parallel session: Numerical Relativity and Gravitational Wave Observations
05.07.2021, 17:50

In collaboration with Lukas Weih, Elias R. Most, Jens Papenfort, Luke Bovard, Gloria Montana, Laura Tolos, Jan Steinheimer, Anton Motornenko, Veronica Dexheimer, Horst Stöcker, and Luciano Rezzolla
Einstein’s theory of general relativity and the resulting general relativistic conservation laws for energy-momentum in connection with the rest-mass conservation are the theoretical groundings of neutron star binary mergers:

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}
\]

\[
\nabla_\mu (\rho u^\mu) = 0, \\
\nabla_\nu T^{\mu\nu} = 0.
\]

(3+1) decomposition of spacetime

\[
g_{\mu\nu} = \begin{pmatrix}
-\alpha^2 + \beta_i \beta^i & \beta_i \\
\beta_i & \gamma_{ij}
\end{pmatrix}
\]

\[
d\tau^2 = \alpha^2 (t', x') dt'^2 \\
x^i_{t+dt} = x^i_t - \beta^i (t, x') dt
\]
The Hadron-Quark Phase Transition

The QCD Phase Diagram

Lattice QCD

Credits: Jan Steinheimer

neutron  proton
The QCD – Phase Transition and the Interior of a Hybrid Star

Gravitational Waves and Hypermassive Hybrid Stars

ALF2-EOS: Mixed phase region starts at $3\rho_0$ (see red curve), initial NS mass: $1.35 \, M_{\odot}$

Hanauske, et.al. PRD, 96(4), 043004 (2017)

Gravitational wave amplitude at a distance of 50 Mpc

Rest mass density distribution $\rho(x,y)$ in the equatorial plane in units of the nuclear matter density $\rho_0$
Time Evolution of the GW-Spectrum

The power spectral density profile of the post-merger emission is characterized by several distinct frequencies. After approximately 5 ms after merger, the only remaining dominant frequency is the $f_2$-frequency (See e.g. L. Rezzolla and K. Takami, PRD, 93(12), 124051 (2016)).

Unfortunately, due to the low sensitivity at high gravitational wave frequencies, no post-merger signal has been found in GW170817.

But advanced detectors / next-generation detectors might be able to detect!!?
Time-averaged Rotation Profiles of the HMNSs

**Talk on Thursday**

*On the properties of metastable hypermassive hybrid stars*

Parallel session
**Neutron stars: Dense matter in compact stars, 08.07.2021, 18:10**

Time-averaged rotation profiles for different EoS
Low mass runs (solid curves), high mass runs (dashed curves).

Hanauske, et.al. PRD, 96(4), 043004 (2017)

**Soft EoSs:**
- Sly
- APR4

**Stiff EoSs:**
- GNH3
- H4
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Can we detect the quark-gluon plasma with gravitational waves?

• Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
  - Signatures within the late inspiral phase (premerger signals)
    • Constraining twin stars with GW170817; G Montana, L Tolòs, M Hanauske, L Rezzolla; Physical Review D 99 (10), 103009 (2019)
  - Signatures within the post-merger phase evolution
    • Phase-transition triggered collapse scenario
      Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers; ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker, L. Rezzolla; Physical review letters 122 (6), 061101 (2019)
    • Delayed phase transition scenario
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GW waveforms $h_{+}^{22}$

Instantaneous GW frequencies $f_{GW}$

Phase transition leads to a very hot and dense quark core that, when it collapses to a black hole, produces a ringdown signal different from the hadronic one.

EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model with (red) and without (black) phase transition.

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Phase difference $\Delta \phi$

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Density-Temperature-Composition dependent EOS within the CMFQ model.
Simulation of total mass $M=2.8 M_{\text{solar}}$
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The deconfinement phase transition in neutron-star mergers. The European Physical Journal A 56 (2), 1-11 (2020)

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Maximum value of the rest-mass density vs time for three binary neutron star simulations. Black curve without a phase transition (NPT) and blue/red with a Gibbs-like hadron-quark phase transition (DPT: standard/low resolution). Blue-shaded regions mark the different phases of the EOS (mixed phase and pure-quark phase).
Without Phase Transition

With Phase Transition

Without Phase Transition

With Phase Transition

Strain $h^+$ (top) and its spectrogram (bottom) for the binary neutron star simulation of the delayed phase transition scenario. In the top panel the different shadings mark the times when the HMHS core enters the mixed and pure quark phases. In the bottom panels, the white lines trace the maximum of the spectrograms, while the red lines show the instantaneous gravitational-wave frequency.
How to detect the hadron-quark phase transition with gravitational waves

Total gravitational wave spectrum (left NPT, right DPT), PRL 124, 171103 (2020)
Metastable hypermassive hybrid stars as neutron-star merger remnants

The European Physical Journal Special Topics: 1-8 (2021)
Due to the large $m=1$ mode of the emitted gravitational wave in the DPT case, a qualitative difference to the NPT scenario might be observable in future by focusing on the $h_{+}^{12}$ gravitational wave mode during the post-merger evolution.
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Gravitational-wave signatures of the hadron-quark phase transition in binary compact star mergers
Two brand new articles

Signatures of deconfined quark phases in binary neutron star mergers.

Liebling, Steven L., Carlos Palenzuela, and Luis Lehner.
Effects of high density phase transitions on neutron star dynamics.
Classical and Quantum Gravity 38.11 (2021): 115007.
The different Phases of a Binary Compact Star Merger Event

- Late inspiral and merger phase
- Transient early postmerger phase
- Postmerger phase
- Collapse to the Kerr black hole and ringdown phase

Wiener Walzer
Disco-Fox
Merengue
Tango

$h_+ \times 10^{22} [50 \text{ Mpc}]$

Wy exactly these dances? Details in

"Binary Compact Star Mergers and the Phase Diagram of Quantum Chromodynamics", Matthias Hanauske and Horst Stöcker, Discoveries at the Frontiers of Science, 107-132; Springer, Cham (2020)

Talk on Thursday
General Relativity in the Theater of the Absurd
Parallel session: Education Teaching Einsteinian Physics to School Students
08.07.2021, 17:20

https://itp.uni-frankfurt.de/~hanauske/TanzNeutronensterne.mp4