On the properties of metastable hypermassive hybrid stars

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

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
Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

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:

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

The late inspiral phase (density, lapse and shift)
Gravitational Waves and Hypermassive Hybrid Stars

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

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 $\rho_0$
The Co-Rotating Frame

Simulation and movie has been produced by Luke Bovard

Note that the angular-velocity distribution in the lower central panel of Fig. 10 refers to the corotating frame and that this frame is rotating at half the angular frequency of the emitted gravitational waves, $\Omega_{GW}$. Because the maximum of the angular velocity $\Omega_{\text{max}}$ is of the order of $\Omega_{GW}/2$ (cf. left panel of Fig. 12), the ring structure in this panel is approximately at zero angular velocity.
Density and Temperature Evolution inside the HMNS

Rest mass density on the equatorial plane

Temperature on the equatorial plane

Hanauske, et.al. PRD, 96(4), 043004 (2017)
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Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{\text{total}} = 2.7 \, M_{\odot}$ in the style of a $(T - \rho)$ QCD phase diagram plot.

The color-coding indicates the radial position $r$ of the corresponding $(T - \rho)$ fluid element measured from the origin of the simulation $(x, y) = (0, 0)$ on the equatorial plane at $z = 0$.

The open triangle marks the maximum value of the temperature while the open diamond indicates the maximum of the density.
Binary Neutron Star Mergers in the QCD Phase Diagram

Evolution of hot and dense matter inside the inner area of a hypermassive neutron star simulated within the LS220 EOS with a total mass of $M_{\text{total}}=2.7 \, M_\odot$ in the style of a $(T, \rho)$ QCD phase diagram plot.

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The angular velocity $\Omega$ in the (3+1)-Split is a combination of the lapse function $\alpha$, the $\phi$-component of the shift vector $\beta^\phi$ and the 3-velocity $v^\phi$ of the fluid (spatial projection of the 4-velocity $u$):

$$\Omega(x, y, z, t) = \frac{u^\phi}{u^t} = \alpha v^\phi - \beta^\phi$$

Focus: Inner core of the differentially rotating HMNS

Temperature

Angular Velocity

Temperature \( (x, y) \) [MeV]

\( \Omega (x, y) \) [kHz]

EOS: LS200, Mass: 1.32 M\(_{\text{Solar}}\), simulation with Pi-symmetry
Time-averaged Rotation Profiles of the HMNSs

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

Soft EoSs:
- Sly
- APR4

Stiff EoSs:
- GNH3
- H4

Hanasuske, et.al. PRD, 96(4), 043004 (2017)
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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 Tolós, 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
    - Prompt phase transition scenario
      Identifying a first-order phase transition in neutron-star mergers through gravitational waves; A Bauswein, NUF Bastian, DB Blaschke, K Chatziioannou, JA Clark, JA Clark, T Fischer, M Oertel; Physical review letters 122 (6), 061102 (2019)
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    - Delayed phase transition scenario
      - Postmerger Gravitational-Wave Signatures of the hadron-quark phase transition in binary compact star mergers; LR Weih, M Hanauske, L Rezzolla; Physical Review Letters 124 (17), 171103 (2020)
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Talk on Monday
M. Hanauske
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
Signatures within the post-merger phase
Phase-transition triggered collapse scenario

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.

ER Most et al., PRL 122 (6), 061101 (2019)
Signatures within the post-merger phase
Phase-transition triggered collapse scenario

Phase difference

$\Delta \phi$ [rad] vs $t - t_{\text{mer}}$ [ms]

$M = 2.8\, M_\odot$
- hadronic
- with quarks

$M = 2.9\, M_\odot$

$\times 10^{-22}$

EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model, leading 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.

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Signatures within the post-merger phase transition triggered collapse scenario. GW waveforms \( h^{+22} \)Instantaneous GW frequencies \( f_{GW} \) Phase difference 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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ER Most, LJ Papenfort, V Dexheimer, M Hanauske, S Schramm, H Stöcker and L. Rezzolla

Physical review letters 122 (6), 061101 (2019)

Density-Temperature-Composition dependent EOS within the CMFq model.
Simulation of total mass $M=2.8 \, M_{\odot}$
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Density-Temperature-Composition dependent EOS within the CMFq model.
Simulation of total mass $M=2.8 \, M_{\odot}$
The last simulation snapshots before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS)

Rest mass density on the equatorial plane

Temperature on the equatorial plane
The last simulation snapshots before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS).
The last simulation snapshot before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS)

Rest mass density on the equatorial plane

Temperature on the equatorial plane
The last simulation snapshot before the apparent horizon is formed inside the HyperMassive Hybrid Star (HMHS).
While the quarks in the bird's head have already rescued themselves from their confinement cage, his body still largely consists of hadronic particles. It is precisely at this point in time that the apparent horizon is formed around the dense and hot head of the strange bird and the free strange quark matter is macroscopically confined by the formation of the black hole.
GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

Self-drawn space-time diagram by R. Penrose (1965)

The swan image in the phase diagram of the QCD

The last picture what an outside observer sees is the frozen picture of a dying swan
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Signatures within the post-merger phase evolution 
Delayed phase transition scenario


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).
Metastable hypermassive hybrid stars as neutron-star merger remnants
The European Physical Journal Special Topics: 1-8 (2021)
Without Phase Transition

With Phase Transition

$t \approx 5.6 \text{ ms}$
Without Phase Transition

With Phase Transition

$t \approx 5.6$ ms
Without Phase Transition

With Phase Transition

\[ t \sim 8 \text{ ms} \]

- DPT, \( \Delta x \approx 189 \text{ m} \)
- DPT, \( \Delta x \approx 237 \text{ m} \)
- NPT, \( \Delta x \approx 237 \text{ m} \)

- Pure–quark phase
- Mixed phase
- Pure–hadron phase
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)