B09: Probing strong-interaction matter with GW from neutron-star mergers

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CRC-TR 211 Strong-interaction matter under extreme conditions

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Motivation and goals

Third-generation gravitational wave (GW) detectors will capture numerous high-SNR post-merger events per year, demanding state-of-the-art binary neutron star (BNS) simulations to constrain dense QCD models.

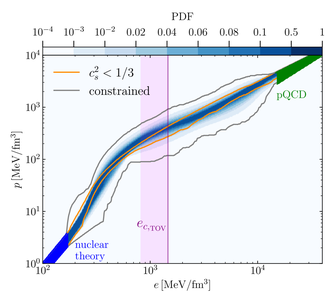
We combine **Equation of State (EoS) modeling** with **General Realtivistic Magnetohydrodynamic (GRMHD) simulations** of BNS mergers to probe dense matter imprints on **GW from kilohertz (kHz) to megahertz (MHz)** frequencies:

- to infer the EoS and QCD phases from kHz-range post-merger GW ringdown slopes,
- extend nonperturbative QCD EoS models to include kaon condensation and color superconductivity,
- to predict MHz-band GW signatures by embedding a subgrid and substep relativistic-hydro scheme for bubble dynamics into GRMHD,
- build a chiral effective model with the nucleon's parity partner to link chiral transitions, the EoS, and neutrino emission.

This project brings together A03, A08, A09 and B03, B04, B07 to synergize EoS modeling and multi-physics simulations across neutron-star mergers and cosmological phase transitions.

Highlights from the second funding period

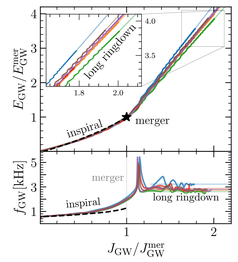
Generic neutron-star EoS modeling



S. Altiparmak et al., Astrophys. J.Lett. 939 (2022) 2, L34

- Developed code to sample millions of valid EoSs to derive distributions of neutron-star sound speed, mass–radius, and tidal deformability.
  S. Altiparmak et al., Astrophys.J.Lett. 939 (2022) 2, L34
- Revealed that light stars feature stiff cores and central sound-speed peaks, whereas heavy stars have soft cores and stiff envelopes.
  C. Ecker and L. Rezzolla, Astrophys.J.Lett. 939 (2022) 2, L35

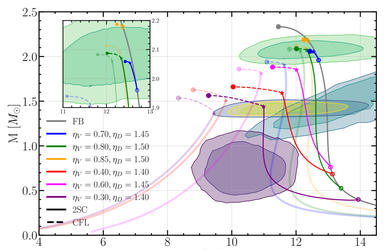
GWs from BNS mergers



C. Ecker et al., Nature Commun. 16 (2025) 1, 1320

- BNS merger simulations uncover a tight correlation between the late-time ("long ringdown") energy-to-angular-momentum loss ratio and the EoS properties.
- Applying this correlation to post-merger GW signals reduces EoS uncertainty at supra–nuclear densities, making the long ringdown a powerful probe of neutron-star core matter for third-generation detectors.
  C. Ecker et al., Nature Commun. 16 (2025) 1, 1320

Color-Superconducting (CSC) Phases in Neutron Stars



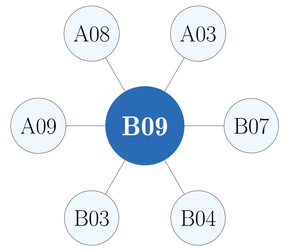
H. Gholami et al., PRD 111 (2025) 103034

- Renormalization-group consistent treatment of CSC phases in the Nambu–Jona-Lasinio model.
  H. Gholami et al., PRD 111 (2025) 014006
- Analyzed impact of CSC phases on EoS, speed of sound, maximum diquark gap, and the mass-radius relation for neutron stars.
- Constructed hybrid-star models with CSC phases complying with present astrophysical constraints.
  J.-E. Christian et al., arXiv:2503.13626

Publications and theses

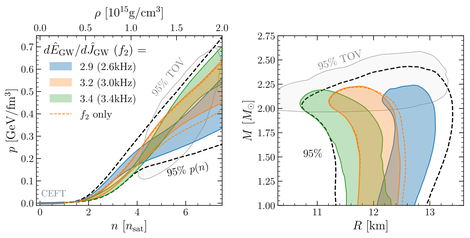
Dissertations	3	3	Done | Ongoing
Theses	3	4	M.Sc. | B.Sc.
Publications	34	6	Published | Pre-print

Project connections



Project plan

kHz GWs from BNS mergers

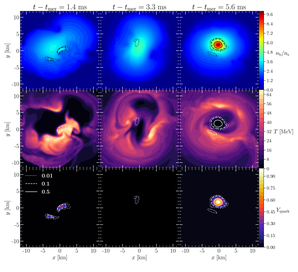


C. Ecker et al., Nature Commun. 16 (2025) 1, 1320

Determine properties of dense QCD matter via kHz GWs from BNS mergers by

- extending composition-agnostic EoS sampling to finite temperatures, integrating EoS ensembles in BNS merger simulations,
- extending PyCBC with BNS post-merger templates linked to GPU-accelerated GRACE simulations of long ringdown slope,
- developing holographic QCD-based models incorporating color-superconducting and kaon-condensed phases for implementation in BNS merger simulations.

MHz GWs from BNS mergers

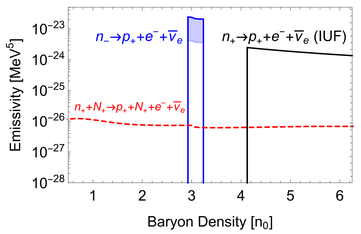


S. Tootle et al., SciPost Phys. 13 (2022) 109

Calculate the first quantitative predictions of the MHz GWs from BNS mergers by

- modeling numerically the growth and collision of quark bubbles and to construct a subgrid and substep model of their dynamics,
- implementing the subgrid/step model in binary merger simulations and compute the MHz contribution to the GW signal,
- determining the microscopical signatures of the phase transition, the corresponding MHz GW spectrum, and their observability by high-frequency GW detectors.

Impact of the chiral phase transition and electroweak response



Brodie and Pisarski, arXiv:2501.02055

Develop the chiral parity doublet model with electroweak coupling for astrophysical and cosmological applications by

- extending EoS to high density, temperature, isospin, and lepton fraction, study chiral phase transition for neutron stars and early Universe cosmology,
- confronting with astrophysical data on neutron stars, QCD lattice data, and heavy-ion data from dilepton production,
- calculating neutrino emissivities and transport properties as input for neutron star merger simulations.

Expected key advances

- Determine the potential of inferring EoS and various phases of QCD matter from BNS post-merger GWs in the kHz range by simulating the long ringdown slope.
- Generalize non-perturbative approaches to the QCD EoS to include condensed phases of confined (kaon condensation) and deconfined matter (color superconductivity).
- Integrate a subgrid/substep special-relativistic hydrodynamics model of detonation-/deflagration-driven bubble dynamics into a GRMHD code to simulate phase-transition bubble nucleation in BNS mergers and assess their MHz GW signatures.
- Establish a unified chiral effective model including the nucleon's parity partner to explore the impact of a chiral phase transition on the EoS and its implications for the electroweak response and neutrino emission in neutron-star mergers.

Available	Requested
Senior scientists: 5	
	Post-doctoral researchers: 1
Doctoral researchers: 2	Doctoral researchers: 2

DFG Deutsche Forschungsgemeinschaft