Usage Report for Fiscal Year 2024

Project Title: General relativistic simulation for binary neutron star merger

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1. Background and purpose of the project, relationship of the project with other projects

The field of neutron star physics is experiencing a "golden age," propelled by revolutionary advancements in multi-messenger astronomy, including gravitational wave detections (e.g., LIGO/Virgo) and electromagnetic counterparts such as kilonovae (observed by JWST and other telescopes). These observations have unveiled unprecedented details about neutron star mergers, yet they now face intrinsic limitations in probing the extreme physics governing neutron star interiors. While multi-messenger data provide critical constraints on the equation of state (EOS) of supranuclear-density matter and the quantum chromodynamic (QCD) phase structure—particularly the hadron-quark phase transition—they remain insufficient to resolve these phenomena conclusively. This observational bottleneck highlights the indispensable role of general relativistic numerical simulations in advancing theoretical understanding and bridging gaps between empirical data and fundamental physics.

Neutron stars in isolation are often modeled under spherical symmetry, but binary mergers involve highly asymmetric, dynamical processes that defy such simplifications. Full general relativistic simulations uniquely capture dynamic features like tidal deformations, shock waves, and post-merger oscillations, which are inaccessible to static or perturbative methods. For example, simulations reveal quasi-periodic oscillations (QPOs) in the post-merger remnant, whose frequency and damping timescale correlate with the EOS and the stability of the remnant (e.g., transient hypermassive neutron stars versus prompt black hole formation). These features encode critical information about the EOS and potential phase transitions in dense matter. A key frontier lies in distinguishing hadronic matter from hybrid configurations with quark cores, as metastable hybrid remnants generate distinct gravitational wave signatures and kilonova emission profiles. Simulations demonstrate that post-merger gravitational waves, combined with electromagnetic signals, can reveal phase transitions by probing the remnant's cooling behavior, oscillation modes, and bulk viscosity—properties tightly linked to the QCD phase diagram at extreme densities.

2. Specific usage status of the system and calculation method

The user usually performs the numerical simulation in mpc with ~1000CPUs for single job. The current calculation resource is suitable. The simulation was based on general relativistic hydrodynamic code WhiskyTHC and Einsteintoolkit. The initial configuration were generated by Lorene and Fuka Code. The detailed configuration is listed below: Our computational approach for hydrodynamics involves the utilization of a finite-volume scheme featuring advanced 5th-order monotonicity-preserving reconstruction techniques. The Riemann problems within the scheme are handled with the Harten-Lax-van Leer-Einfeldt (HLLE) Riemann solver. The evolution of spacetime is computed utilizing the Z4c formulation through the CTGamma code, which implements "1 + log" slicing for the lapse function and "Gamma-driver" shift conditions. The time integration of the hydrodynamics and Einstein equations is carried out with the method of lines, employing a third-order strong-stability-preserving Runge-Kutta scheme, chosen for its efficacy in maintaining stability. We set the Courant-Friedrichs-Lewy (CFL) factor to 0.075. This stringent choice is crucial when implementing flux reconstruction in local-characteristic variables, a technique integral to our adopted monotonicity-preserving scheme. For adaptive-mesh refinement (AMR), we use the Carpet code with seven refinement levels. Our outer boundary is set at 1477 km.

３． Result

In this study, we investigate the equation of state (EOS) of compact stars, focusing on the high-density regime where hadronic matter may transition to quark degrees of freedom. By performing general-relativistic numerical simulations of binary neutron star (BNS) mergers, we explore two viable mechanisms for such transitions: a smooth quark-hadron crossover (QHC) and a strong first-order phase transition (1PT). We introduce the concept of "neutron-quark stars" (NQS), where quark matter emerges at densities below the central density of typical neutron stars, challenging conventional models that assume purely hadronic interiors. Our analysis integrates multi-messenger constraints, including NICER radius measurements, tidal deformability data from GW170817, and theoretical limits from nuclear physics and perturbative QCD (pQCD), to discern observational signatures of these transitions.

EOS MODELS AND NUMERICAL SETUP

We construct three classes of EOSs: (1) purely hadronic models (Togashi and ChEFTex), (2) hybrid models with a 1PT (1PT-NQS), and (3) QHC models. For hadronic EOSs, the Togashi EOS is derived from variational calculations with nuclear forces constrained by experimental data, while the ChEFTex EOS extends chiral effective field theory (ChEFT) results to higher densities using polynomial extrapolations. Both exhibit gradual stiffening but eventually violate causality at extreme densities (5.5n0–6.4n0). For the 1PT-NQS model, we impose a first-order transition starting at 1.8n0, transitioning to a stiff quark-matter EOS with c_s^2 = 2/3c^2. This setup ensures quark cores exist in isolated stars prior to merger—a novel feature compared to prior studies where phase transitions occurred post-merger. For QHC models, we interpolate nuclear and quark-matter EOSs between 1.5n0 and 3.5n0, generating rapid stiffening in the crossover region and sound-speed peaks exceeding the conformal limit (c_s^2 = c^2/3). These models produce stars with radii comparable to or larger than their hadronic counterparts, even for massive neutron stars, aligning with observational preferences for similar radii across masses (1.4–2.1 M☉).

To simulate mergers, we employ the WhiskyTHC code within the Einstein Toolkit framework, using adaptive mesh refinement and finite-volume hydrodynamics. We generate initial data for equal-mass BNS systems with separations of 45 km, resulting in 8–12 orbits before merger. Thermal effects are approximated with a fixed thermal index Γ_th = 2, and we validate numerical uncertainties (e.g., resolution effects) through multi-resolution tests, estimating frequency errors of up to 50 Hz.

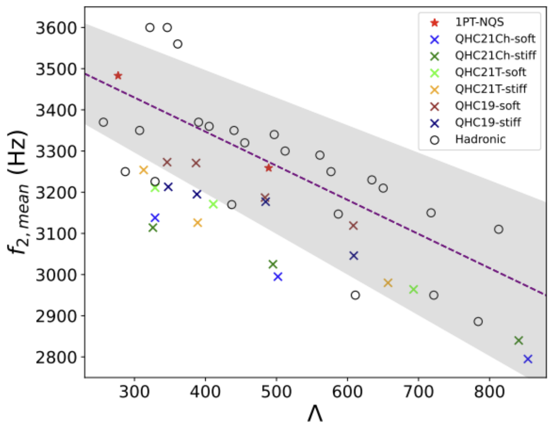
KEY RESULTS

Our simulations reveal distinct post-merger signatures for QHC and 1PT-NQS models. For QHC EOSs, the dominant post-merger gravitational wave (GW) frequency f2 is systematically lower than that of hadronic EOSs with comparable tidal deformability (Λ). This deviation exceeds 200 Hz for strongly stiffened QHC variants, arising from their softer high-density behavior, which reduces the central density and rotational velocity of the remnant. Such differences could be discerned with third-generation GW detectors like the Einstein Telescope if both inspiral and post-merger signals are detected. In contrast, 1PT-NQS models exhibit higher f2 frequencies due to their stiffer quark-matter cores, yet they align with the Λ-f2 relation of hadronic EOSs. This compatibility stems from similar stiffness between hadronic and quark phases in these models, masking the transition in the f2-Λ plane. However, 1PT-NQS systems deviate significantly in the Λ-compactness relation, underscoring the need to combine tidal deformability measurements from BNS mergers with radius constraints (e.g., NICER) to identify such scenarios.

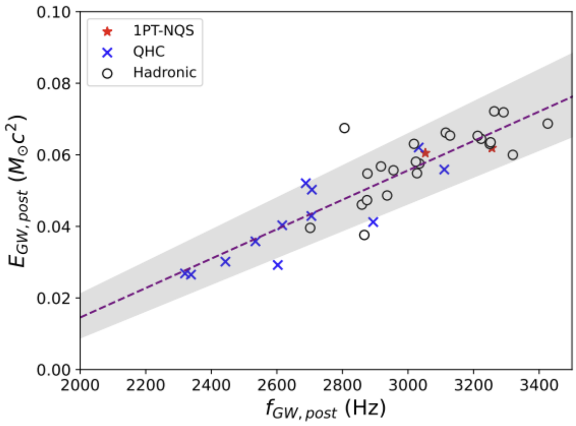
We identify a robust linear correlation between the energy emitted in post-merger GWs (E_GW,post) and the average instantaneous frequency (f_GW,post): E_GW,post ∝ (f_GW,post - 1687). This relation holds across all EOS types and mass ratios, offering a tool to estimate energy release from f2 measurements alone. Additionally, we refine the analysis of angular momentum (J_GW) and energy emission by proposing a modified relation using non-normalized post-merger quantities (subtracting inspiral contributions). This approach enhances sensitivity to EOS differences, particularly for 1PT-NQS models, which exhibit unique trajectories in the J_GW-E_GW plane.

DISCUSSION AND OUTLOOK

Our work highlights the diagnostic potential of post-merger GW signals to probe high-density matter physics. The distinct f2 behaviors of QHC and 1PT-NQS models provide observational benchmarks for future detectors. However, challenges remain in modeling finite-temperature effects, which could lower phase transition densities and amplify frequency differences. We also emphasize the importance of extending simulations to unequal-mass binaries and varying transition densities to explore a broader EOS parameter space.



Relation for post-merger main frequency vs. tidal deformability



Universal relation for post-merger GW energy with its frequency

4. Conclusion

We demonstrate that multi-messenger data—combining GWs, electromagnetic counterparts, and nuclear theory—are essential to unravel the nature of matter at supranuclear densities. The correlations we propose between GW observables and EOS properties pave the way for future studies, particularly as next-generation detectors improve sensitivity to the post-merger signal. Our findings underscore the need for continued advancements in numerical relativity and EOS modeling to fully exploit BNS mergers as cosmic laboratories for quantum chromodynamics.

5. Schedule and prospect for the future

We plan to extend to study the finite-temperature first-order phase transition in the binary neutron star merger. The related research, together with our statistic works on multi-messenger neutron star observation, will give a better clue on the question of hadron-quark transition.

６. If no job was executed, specify the reason.

Fiscal Year 2024 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

[1]Hensh, S., Huang, Y.-J., Kojo, T., Baiotti, L., Takami, K., Nagataki, S., & Sotani, H. (2024). Neutron-quark stars: Discerning viable alternatives for the higher-density part of the equation of state of compact stars. arXiv preprint. arXiv:2407.09446 [astro-ph.HE]. RIKEN-iTHEMS-Report-24.