Usage Report for Fiscal Year 2022

Project Title: Numerical simulation for binary neutron star mergers

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

Multi-messenger astronomy, including gravitational, electromagnetic, and neutrino signals, has started offering new ways of obtaining information on ultra-high-density matter. Observations of the inspiral of a binary neutron-star (BNS) merger may provide information on the equation of state (EOS) at a few times the nuclear saturation number density (n_0), and even higher densities (several times (n_0)) may be investigated through observations of the post-merger phase, where matter is also hotter than in the inspiralling NSs. In the near future, the detection of BNS mergers will happen on a daily basis and this will allow to perform improved statistical analyses also of the properties of their EOS. In particular, the most intense gravitational wave(GW) radiation is produced in regions of the strong gravitational field by coherent movements of masses with large compactness. Therefore, GW naturally becomes the cosmic laboratory for ultra-dense matter. GW in the late inspiral of binary neutron star(BNS) system was detected by Ligo/Virgo detectors in 2017, while the post-merger dynamics have not been observed because of the lack of sensitivity in $2-5$ kHz band. It is possibly detected with higher sensitivity by upgraded Advanced LIGO and third-generation observatories. Post-merger dynamics, which consists of different modes, would provide unique information about the dense matter EOS. To accurately evolve the merger and post-merger dynamics of BNS, it is often necessary to solve Einstein's equation and associated matter field equations. However, these equations are nonlinear partial differential equations, and hence it is impossible to solve them analytically for general problems. Instead, fully general relativistic hydrodynamics simulations are required. My research aims to understand how hadron-quark transition takes place by astrophysical observations. Numerical simulations for BNS mergers build the bridge to connect the EOS of dense matter and the astrophysical observations.

2. Specific usage status of the system and calculation method

We have generated initial data for quasi-equilibrium irrotational BNSs at a separation of 45km (which leads to about 5 - 7 orbits before merger) using the open-source code Lorene. We have performed fully general-relativistic hydrodynamic simulations using the WhysikyTHC code , which is written in the Einstein Toolkit framework . In particular, we have employed a finite-volume scheme with 5-th order monotonicity-preserving reconstruction and the Harten-Lax-van Leer-Einfeldt (HLLE) Riemann solver . The spacetime evolution is calculated in the Z4c formulation through the code, with "1+log" slicing and "Gamma-driver" shift conditions. For the time integration of the coupled set of the hydrodynamic and Einstein equations we have used the method of lines, with a third-order strong-stability-preserving Runge-Kutta scheme with a Courant-Friedrichs-Lewy~(CFL) factor of 0.075 (such a small value is necessary when adopting flux reconstruction in local-characteristic variables using the adopted monotonicity-preserving scheme). The simulation grids with adaptive-mesh refinement are managed through the Carpet code. The simulation domain extends to ~1500km, and we use seven mesh-refinement levels with the finest grid spacing ~230m for our fiducial simulations. During the last year as a quick user, I used about 30 percent core time in total, with 30 nodes and 1200 cores for each submission.

3. Result

We attempted to identify the special features of quark-hadron crossover(QHC, one mechanism of hadron-quark transition) by using the GW in post-merger of BNS. We performed fully general-relativistic simulations adopting two QHC models, QHC19B (named here QHC19-soft), QHC19D (named QHC19-stiff), and the purely hadronic Togashi EOS (see Fig. 1). The QHC19 EOSs in low-density regime is the same as Togashi EOS, but undergo a rapidly stiffening process because of the pauli-blocking effect in the quark level, with density increasing. For this reason, before the merger, the NS properties is almost the same. More differences are expected shown only after the merger. In Fig. 2, we show the maximum density evolution during the merger at four different initial mass (M1.25 means the gravitational mass of each NS is 1.25 solar mass).

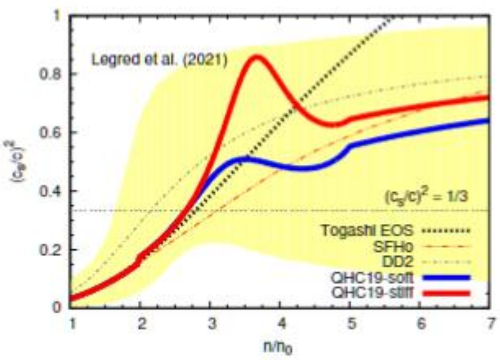

Fig. 1

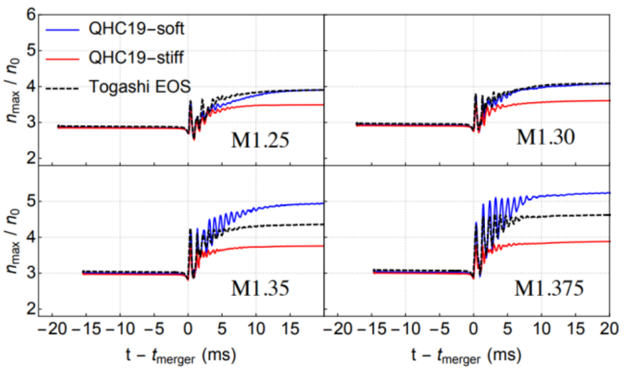

Fig. 2

In QHC19-stiff, the sound speed (and thus pressure support) around 3.5n_0 increases the most; it is then expected that inspiralling stars and merged objects in BNSs with QHC19-stiff are less compact than those with the Togashi or QHC19-soft EOSs, as can be ascertained in Fig. 1: the maximum number density n_max is smaller than for the other EOSs, in the inspiral, after the merger, and (on average) during the merger. Even in our most massive case, n_max for QHC19-soft reaches up only to ~3.8n_0. At such densities, indeed, stiffening due to the crossover is still important.

In QHC19-soft, in contrast, the evolution of n_max is different for binaries of different masses. Since for densities < 3.5n_0 QHC19-soft is stiffer than the Togashi EOS, in our lowest-mass case, M1.25, in which densities higher than $3.5n_0$ are reached only towards the end of our simulations, we see n_max to be always smaller than that for the Togashi EOS. For M1.30, where the maximum density after the merger reaches 3.5-4n_0, the differences between the QHC19-soft and Togashi EOS appear to average out (their sound-speed curves cross around 3.5n_0), leading to similar evolution. For even larger masses, M1.35 and M1.375, during and after the merger, densities greater than $\sim 3.5n_0$ are reached in a wide region, and hence QHC19-soft leads to a considerably more compact merged object.

The oscillations of the merged object produce intense GW emission, characterized by distinct peaks (f_1, f_2, f_3) in the power spectrum. In Fig. 3, we show the GW waveform as well as its spectroscopy. Some similarities and differences between our purely hadronic and QHC models are apparent. While the damping times for post-merger GWs (signalled by the extinguishing of the red color over the whole frequency band in the spectrogram) are seen to be dependent on the EOS, the time interval in which a wide range of frequencies has a lot of power (the time interval in which the spectrogram has a bright band) is shorter for QHC19-stiff. This means that the transient period between the merger and the time when gravitational radiation settles to a well-identified main frequency, f_2, is shorter for QHC19-stiff.

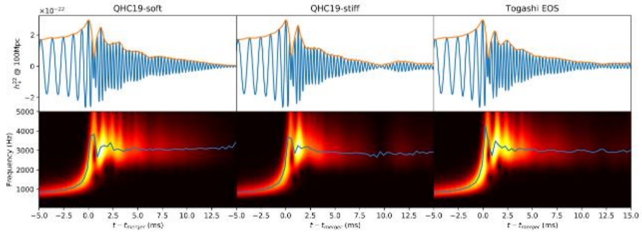

Fig. 3

In Fig. 4, we show the main mode(f_2) frequency in GW spectrum. For all masses, f_2 for QHC19-stiff is lower than for the Togashi EOS, and this is related to the lower compactness of the merged object, which is in turn related to the pronounced peak in sound speed for QHC19-stiff. For QHC19-soft, except for our lowest-mass case, f_2 is higher than that for the Togashi EOS. In models M1.25, f_2 for both QHC19-soft and QHC19-stiff is lower than that for the Togashi EOS. This is due to the fact that quark-matter densities ~ 5n_0, where the QHC EOSs are softer than the Togashi EOS, are not reached, and thus the remnant is less compact. This is a unique feature of the peak in sound speed present in QHC models and is independent of the height of such peak (namely, of the parameters of the specific QHC EOS). Note, however, that, since the stiffening in the crossover domain is strongly affected by the quark-matter EOS it is attached to, even in lower-mass models one may still in principle gain from observations useful information on how quarks are liberated in high-density hadronic matter.

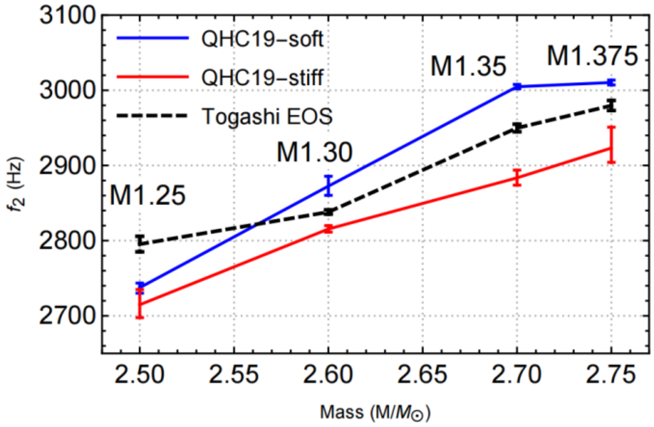

Fig. 4

4． Conclusion

In this work, we performed the first (and fully general-relativistic) simulations of BNS mergers with EOSs based on QHC (QHC19) and discussed how they could be distinguished from purely hadronic EOSs or hybrid quark-hadron EOSs with 1PTs.

We found that a QHC EOS with a pronounced peak in sound speed, like QHC19-stiff, leaves a clear and unique signature in the post-merger main frequency: for any binary mass, f_2 is lower than that of the baseline hadronic EOS, and thus also lower than that expected for EOSs with a 1PT.

Results of this work will become relevant to observations when GWs in the kHz band are surveyed with higher sensitivity by an upgraded Advanced LIGO (A+) and third-generation observatories (e.g., the Einstein Telescope and Cosmic Explorer), also with a specifically optimized design (e.g., NEMO).

5． Schedule and prospect for the future

This work is a first attempt to study in BNS mergers the unique features of QHC EOSs. We plan to extend the analysis in several directions, first of all by adopting the QHC21 EOS, which improves further over QHC19 under the microscopical point of view and which was made public after we finished our simulations. We will explore the relationship between some EOS parameters and observable quantities, as well as finite-temperature effects, expected to be important for the onset of quark saturation.

Fiscal Year 2022 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

Y.-J. Huang, L. Baiotti, T. Kojo, K. Takami, H. Sotani, H. Togashi, T. Hatsuda, S. Nagataki, and Y.-Z. Fan, *Merger and Postmerger of Binary Neutron Stars with a Quark-Hadron Crossover Equation of State*, Phys Rev Lett **129**, 181101 (2022).

[Oral presentation]

Invited talk	Merger and post-merger of binary neutron stars with a quark-hadron crossover equation of state	RIKEN, iTHEMS Nov. 2022
Invited talk	Numerical simulations for binary neutron star mergers	Wuhan Uni. June. 2022
talk	Merger and post-merger of binary neutron stars with a quark-hadron crossover equation of state	The 9th KAGRA International Workshop June. 2022
Invited talk	Merger and post-merger of binary neutron stars with a quark-hadron crossover equation of state	ITP, Goethe Uni. April. 2022