Project Title:

Numerical simulation for binary neutron star merger

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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 us new ways of obtaining information on ultra-high-density matter. Observations of the inspiral of a binary neutron-star (BNS) merger may provide us with information on the equation of state (EOS) at a few times the nuclear saturation density (n_0 = 0.16 fm^{-3}), 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 next ten years or so, 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. It is quite helpful to study the state of matter at extremely high density and temperature, which is one of the most exciting long-standing open questions, with numerical simulations of BNS merger. Furthermore, it is especially useful to explore how quark-hadron transitions may occur. We presents the first study of quark-hadron crossover (QHC) in (fully) general-relativistic binary-neutron-star (BNS) merger simulations in this project.

2. Specific usage status of the system and calculation method

We have generated initial data for quasiequilibrium irrotational BNSs at a separation of 45km using the open-source code Lorene. We have performed fully general-relativistic hydrodynamic simulations using the WhiskyTHC code, which is written in the Einsteintoolkit framework. In particular, we have employed a finite-volume scheme with 5th-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 CTGamma 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. The simulation grids with adaptive-mesh refinement are managed through the Carpet code . The simulation box extends to ~1477 km, and we use seven mesh-refinement levels with the finest resolution of ~231 m.

3. Result

We performed simulations adopting two QHC models, QHC19B (named here QHC19-soft), QHC19D (named QHC19-stiff), and the purely hadronic Togashi EOS. Reference shows QHC EOSs for 4 parameter sets (A, B, C, D), relative to the way of connecting the hadron and quark EOSs. Set A, however, is not discussed here because it leads to an EOS with too small a maximum mass for NSs, and among the remaining three sets, for simplicity we have chosen only two: the softest and stiffest ones in the crossover region.

The QHC19 and Togashi EOSs differ substantially only for nB(Baryon number density) ≳3n0, and, since the maximum values of nB in our inspiralling NSs are around 3n0, the properties (like the tidal deformability of stars built with the above different EOSs and their dynamics during the inspiral differ of less than 1%. Even with the approximately same pre-merger configuration, we find the post-merger dynamic is strongly correlated with the high-density EOSs, which are determined by the detail of QHC. Fig.1 shows the square of sound speed of QHC EOSs and some purely hadronic EOSs. The typical feature for QHC EOS is a peak in sound speed, which generally stiffens the EOS in low-density regime.

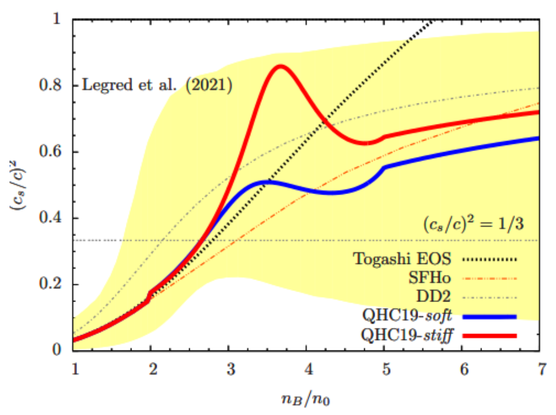

Fig. 1 Square of sound speed normliazed to the speed of light, c_s^2/c^2 = dP/de, for our QHC EOSs with soft and stiff sets of quark model parameters and for representative hadronic EOSs: Togashi EOS, SFHo , and DD2 .The yellow band is the allowed region from multi-messenger observation in the model-agnostic approach. The conformal limit, c_s^2=c^2/3, which should be reached in the high-density limit, is also shown as a guide.

In QHC19-stiff, the sound speed (and thus pressure support) around 3.5n0 increases the most, and it is then expected that stars and merged objects in BNS described through QHC19-stiff are less compact than those described through the Togashi or QHC19-soft EOSs, as can be ascertained in Fig. 2: nmax is smaller than for the other EOSs, in both the inspiral, after the merger, and (on average) during the merger. In the most massive case considered here, nmax reaches up only to ≈ 3.8n0. At such densities, indeed, stiffening due to the crossover is important. In QHC19-soft, on the other hand, binaries of different masses show different evolution of nmax. Since for densities ≲3.5n0, QHC19-soft is stiffer than the Togashi EOS, in our lowest-mass case, M1.25, in which densities higher than 3.5n0 are reached only towards the end of our simulations, we see nmax to be always smaller than that for the Togashi EOS. The trend changes in higher-mass configurations. For M1.30, where the maximum density after the merger reaches 3.5−4n0, the differences in the QHC19-soft and Togashi EOS appear to average out (their sound-speed curves cross around 3.5n0, cf. Fig. 1), leading to similar evolution for these models (top right panel of Fig. 2). For even larger masses, models M1.35 and M1.375 (bottom panels of Fig. 2), during and after the merger densities greater than 3.5n0 are reached in a wide region, and hence QHC19-soft leads to a considerably considerably more compact merged object.

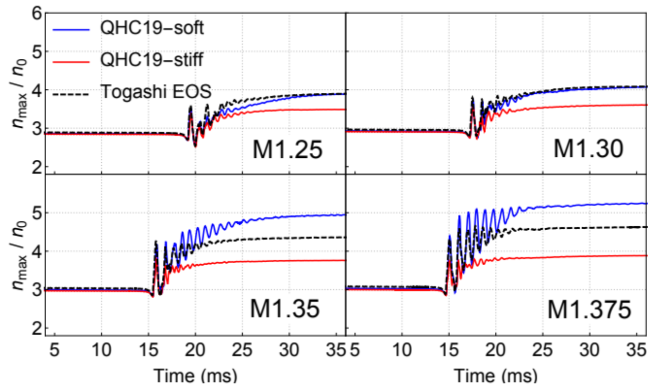

Fig. 2 Evolution of the maximum number density for simulations employing the QHC19 and Togashi EOS with different initial masses.

We study the effects of such stiffening on the frequency, f2, of the main peak in the post-merger gravitational wave (GW) spectrum as Fig. 3 shows. Comparing the values of f2 for different EOSs and BNS masses gives us important clues on how to discriminate observationally different types quark dynamics in the high-density end of EOSs.

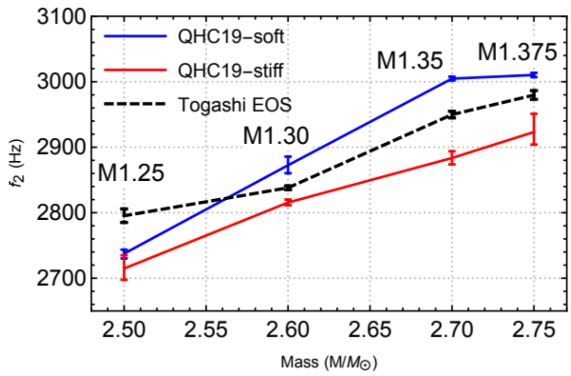

Fig. 3 Relation between f2 and the total mass of BNS. Compared with the purely hadronic Togashi EOS, f2 is higher (lower) for QHC19-soft (QHC19-stiff) in high-mass configurations, while in the lowest-mass configuration f2 is lower for both QHC models.

Our main findings are: i) in relatively low-mass binaries, the stiffening characteristic of QHC models results generically in a lower f2 than that expected form the corresponding purely hadronic EOS and thus also from EOSs with first-order phase transitions, which predict more compact remnants (and therefore higher f2) after the transition; ii) in higher-mass binaries, QHC models with pronounced peaks in sound speed are similarly distinguishable in a clear way from the corresponding purely hadronic EOS or from EOSs with first-order phase transitions, while QHC models with more moderate sound-speed peaks may be difficult to distinguish from EOSs exhibiting weak first-order phase transitions.

4. Conclusion

In the project this year, we performed the first (and fully general-relativistic) simulations of BNS mergers with EOSs based on quark-hadron crossover and discussed how they could be distinguished from purely hadronic EOSs or hybrid quark-hadron EOSs with first-order phase transitions. We have found that for some EOS models and binary-mass ranges it would be relatively simple to discriminate observationally. In particular, 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, f2 is lower than that of the baseline hadronic EOS, and thus also lower than that expected for EOSs with a first-order phase transition.

5. Schedule and prospect for the future

We plan to extend the analysis in several directions, first of all by adopting the recent QHC21 EOS, which was made public after we finished our simulations. We will explore the relation between some EOS parameters and the stiffness of the EOSs, as well as finite-temperature effects, expected to be important for the onset of quark saturation. We also plan to perform simulations of unequal-mass binaries and study the role of QHC EOSs on mass ejecta.

6. If no job was executed, specify the reaso