Usage Report for Fiscal Year 2020

Project Title: BNS merger simulation

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

The first detection of binary neutron star merger event GW170817 opens a new window for exploring the neutron star internal structure and the nuclear equation of state(EOS). As one of the most attractive questions, the EOS at low density(below two nuclear saturation density) could constrain by the laboratory experiments, and the high density(one hundred nuclear saturation density) part could calculate based on the perturbative QCD, but the physics in between is still unclear. Neutron star observations help to fill the gap, especially the GW observations for binary neutron star mergers bring a lot of new information. The mergers are usually divided to two parts: pre-merger and post-merger. The pre-merger(or inspiral)phase contains the information of mass and tidal deformability, which could reveal from parameter estimation from gravitational wave detectors, and they are used to constrain the EOS directly. The post-merger gravitational wave signal has not identified yet, but spectra analysis based on numerical simulation have constructed some new relations(Takami et al. Phys. Rev. Lett. 113 , 091104), which are independent of pre-merger phase. More interesting, deep into the interior of neutron star(beyond 2 saturation density), hadronic description of matter begins to break down and quark degrees of freedom start to emerge.(Baym et al., 2019, ApJL, 855, L1) To describe the physics of high density regime in neutron stars, first-order phase transition and hadron -quark crossover are two simple pictures. As the tidal deformability of neutron stars mainly relate to compactness of each star in binary system, and the neutron stars mass in galactic binary neutron star systems are relatively small (Huang et al., arxiv:1804.03101). The pure hadronic and hadron-quark mixture model may not be distinguished from pre-merger phase. Previously, there were some discussions for first-order phase transition (Bauswein et al., Phys, Rev. Lett 122, 061102; Most et al., Phys, Rev. Lett. 122, 061101). These works showed that the first-order phase transition would increase the f2 peak frequency in the post-merger spectrum, and cost less time to collapse, whereas the tidal deformability was the same if the transition happened only after the merger. The binary neutron star mergers based on hadron-quark crossover have not been explored yet, and we are doing the simulations based on QHC19(Baym et al.,2019, ApJL, 855, L1). The hadron-quark crossover model’s discussion will fill out the puzzle for high density regime of neutron star equation of state.

2. Specific usage status of the system and calculation method

The GRHD simulations for binary neutron star (BNS)merger were based on Lorene and WhiskyTHC codes. Lorene provides tools to solve partial differential equations in numerical relativity by means of multi-domain spectral methods, it could solve TOV equations and make the initial data of binary neutron star. WhiskyTHC is used to solve the evolution equations of general relativistic hydrodynamics (GRHD) in 3D Cartesian coordinates on a curved dynamical background. During the last year as a quick user, I used about 70 percent of core time in BWMPC for the simulations.

３． Result

The simulations were based on tabulated EOS LS220, with initial data generated in symmetric configuration with 1.35 M sun for each star. Since the neutron stars' temperature could increase up to ~100 MeV, one crucial thing is to know how thermal pressure affected the hydro evolution in the post-merger phase. For analyzing this influence, we used two different treatments for the thermal part in simulations. One is using the cold EOS in zero-temperature and additional thermal part. In this formula, pressure in EOS table is only the function of density and internal energy and the temperature given from thermodynamics equations, which based on “ideal-gas”assumption. The other one is the finite-temperature EOS, in which pressure is a function of density, internal energy, and temperature in EOS table. The simulation result shows that post-merger behavior is affected when we use different adiabatic indexes in the simulation and when the index Gamma=2(G2), the most potent peak frequency is near the finite temperature case. Fig.1 shows the maximum density evolution, ρ represent the saturation density for nuclear matter. In the ideal-gas approximation case, a larger thermal index means more thermal pressure contributing to the remnant so that the system could survive longer. Usually, the Gamma=2 for ideal-gas is the high limit since it would cause causality problems if the index is larger. The simulation based on finite-temperature EOS is different from them, which shows a much longer delay time to collapse, indicates that the ideal-gas approximation in the thermal part is not good enough to represent the properties of the real finite-temperature EOS.

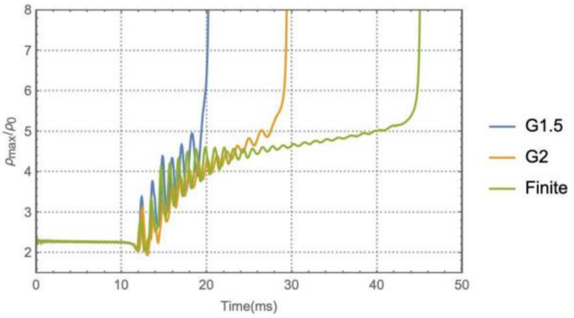

Fig.1

Fig.2 shows the time-domain gravitational wave. In the inspiral phase, all of the three cases are same; since the temperature is almost zero, there is no thermal pressure contribution to neutron stars. After the binary merger, they show different behaviors, one is the delay time to collapse as discussed above, and another one is the shape of the GW template. For a detailed comparison, we analyzed the power spectrum of GW.

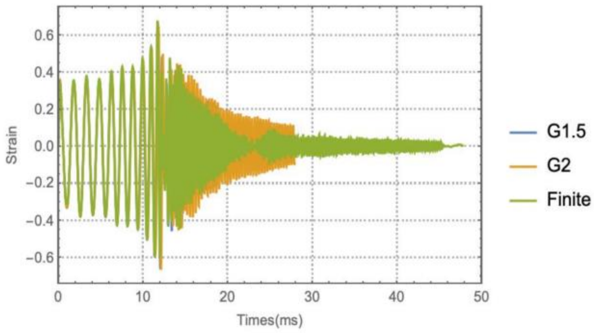

Fig.2

From Fig.3, all of the peaks in G1.5 case shift to higher frequency compared to G2 case. This is because there is more thermal pressure in G2 case, and it makes remnant less compact so that the oscillation frequency would decrease. Also, the G2 case seems to be much closer to the finite-temperature case at the first and second peak, but separate at a higher frequency, it causes the difference shown in the time-domain GW template. As we would like to extend our work to EOS with first-order phase transition and hardon-quark crossover,the simulation based on finite-temperature EOSs would be more reliable when we analyze the post-merger spectrum.

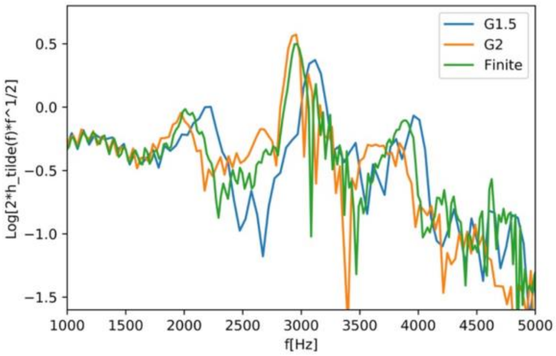

Fig.3

４． Conclusion

The binary neutron stars in inspiral phase are “cold”, so the analyzation based on inspiral phase could reveal the properties of zero-temperature equation of state. However, the thermal effect is very important in the post-merger phase, since it could affect the dynamic of merger remnant and shift the frequency of gravitational wave.

5． Schedule and prospect for the future

We plan to use the WhiskyTHC code to do simulation based on QHC19 and Togashi equation of state(Togashi et al., 2017, Nucl. Phys. A, 961,78). Since the QHC19 is the zero-temperature equation of state, we plan to use ideal-gas approximation for thermal effect in the simulation, with the thermal index 1.5,1.75 and 2, respectively. We will make different initial conditions based on different neutron stars mass and mass ratio, to look for the correlation between the peak shift in post-merger gravitational wave spectrum and the nuclear parameters of hadron-quark crossover model.

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