Usage Report for Fiscal Year 2023

Project Title:

Numerical simulation for binary neutron star mergers

Name:

○Yongjia Huang

Laboratory at RIKEN: Interdisciplinary Theoretical and Mathematical Sciences Program

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

The state of strongly interacting matter at exceedingly high density remains one of the long-standing open questions. Neutron star (NS), as it cools down the eons ahead after the birth in the supernova explosion, provides an astrophysical laboratory to investigate the equation of state (EOS) of dense, strongly interacting nuclear matter at zero temperature. In the past five years, there has been some inspiring progress in astrophysical observations on NSs, including the multi-messenger observations of the first binary neutron star merger event GW170817, the accurate mass determination of the very massive object PSR J0740+6620 (i.e., M = 2.08 ± 0.07 M_sun), and the mass-radius measurements of PSR J0030+0451 and PSR J0740+6620 by the Neutron Star Interior Composition Explorer (NICER;. These events/objects comprise the multi-messenger NS data set for our following analysis. On the theoretical side, state-of-the-art ab-initio calculation provides boundary conditions on the EOS for both low and high-density regimes. Currently, calculations using the χ EFT have been achieved with incredibly high precision (the Next-to-Next-to-Next-to leading order, N3LO) for many-body interactions. Thus, the dense matter EOS up to 1.1 ρ sat(nuclear saturation density) is solidly constrained by the N3LO χ EFT calculations. Though the pQCD is only valid at ultra-high density (& 40 ρ sat), the highorder pQCD calculation still provides a reference to the non-perturbative effect at a lower density, with the chemical potential reaching 2.6 GeV, where its missing-higher order truncation error in pQCD is comparable with the uncertainty from χ EFT at 1.1 ρ sat. Such a boundary constraint from pQCD can be pushed to a considerably lower density, even reachable in astrophysical NSs. The information that emerged from various directions reveals that the EOSs, which follow the χ EFT calculation in the low density, are required to undergo a rapid stiffening, and exceed the conformal limit (c2s /c2 ≤ 1/3) to support a massive NS, where cs is the speed of sound inside the NS, and c is the speed of light in vacuum. Subsequently, they must tend to be soft to satisfy the causality-driven constraint from pQCD. Therefore, with the EOS structure determined by taking into account the observational and theoretical constraints, two key questions might be answered: how the quark-hadron transition takes place and whether quark matter core exists in astrophysical NSs.

２. Specific usage status of the system and calculation method

We incorporate the latest χ EFT and pQCD results/constraints in our Bayesian nonparametric inference of NS EOS represented by the feed-forward neural network (FFNN) expansion and then apply such an inference to the current multi-messenger NS data set. Different from the literature that assumes some structures (e.g., bumps, dips, and kinks) in the square of sound speed c2s through a parametric form, our nonparametric representation of EOS is model-agnostic and can directly/robustly extract the structure information from the observation data. The EOS model is constructed on a log-uniform grid in densities between ~ 0.3 ρ sat and 10 ρ sat. We match the constructed EOS to the NS crust EOS up to ~ 0.3 ρ sat. From 0.3 ρ sat to 1.1 − 2 ρ sat, we follow the N3LO χ EFT calculation. At higher densities, the χ EFT calculations are likely broken down. Though the result is weakly dependent on the choice of breakdown density, we define a variable ρ ceft to marginalize the uncertainties, and uniformly sample it from 1.1 ρ sat to 2 ρ sat. Below ρ ceft the EOSs are constrained by the χ EFT calculations. Hence the influence of the different breakdown densities of the χ EFT calculations has been considered in this work. The configuration for numerical simulation is the same as used in the last year.

３. Result

As shown in the panel (a) of Fig. 1, the EOSs below the density of ρ ~ 1.1 ρ sat are well constrained. This is anticipated since the χ EFT theory sets a tight constraint in this range; the sound speed thus lies on the low-value region of the priors. While in the middle region, there is a rapid increase of c2s and the conformal limit has been violated at the 90% credibility. As a reference, the APR EOS with R1.4 = 11.35 km, DD2 EOS with R1.4 = 12.90 km, and H4 EOS with R1.4 = 13.69 km are also shown in panel (b) of Fig. 1, where R1.4 denotes the radius of a 1.4M NS. The rapid stiffening in the medium density, identified in a model-agnostic way, is a natural result required by the observations of NSs with a mass of ~ 2M. After that, the c2s are suppressed in the high-density region (& 4 ρ sat), as a consequence of the inclusion of the pQCD likelihood. Therefore, the hadronic EOS with a monotonically increasing sound speed is disfavored in the high-density region. Specifically, the c2s → 0 only presents near the center of the heaviest NSs, thus does not support the strong first order phase transition in low-mass NSs.

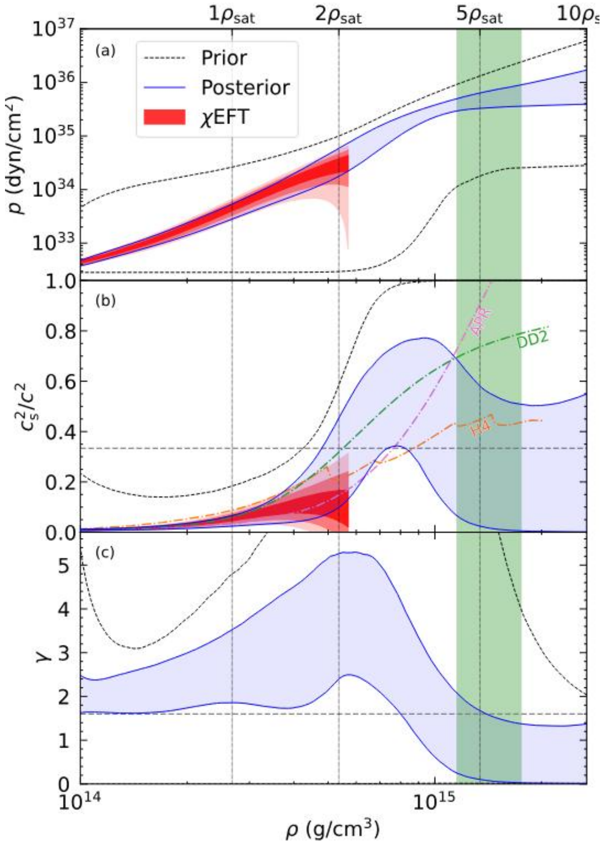

Fig. 1 The 90% credible intervals of the pressure p(panel (a)), the square of sound speed normalized by the squared light speed c2s /c2 (panel (b)) and γ (panel (c), γ ≡ d(ln p)/d(ln e), where e is the energy density.) v.s. rest-mass density.

Benefit from our model-agnostic method in representing EOS, we are able to describe the EOS structure without assuming hadronic model or phase transition take places. Thus, we get the latest constraint for EOS. The multi-messenger constraint finally gave the softest and stiffest allowed EOSs for 1.2 and 1.4 solar mass neutron star. Fig. 2 shows the mass-radius relation for the constraint EOSs.

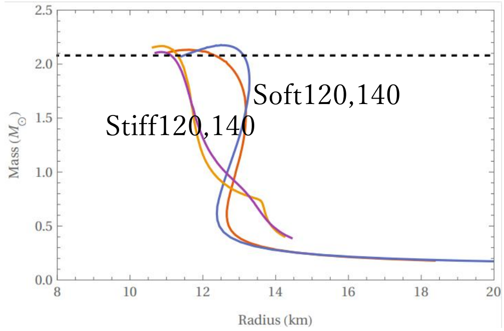

Fig.2 The allowed EOSs for 1.2 and 1.4 solar mass neutron star

Although the range for EOSs are considerably narrow with current observation，it is still hard to be determined well. We used the softest and stiffest EOSs as the reference, and did the numerical simulation for binary neutron star merger. We wanted to see how large the difference from gravitational wave shows after the merger. Fig.3 shows the result, where ~500Hz difference presents, suggested that gravitational wave spectrum is more sensitive to EOS difference than M-R relation. We are planning to construct universal relation between gravitational wave frequency and EOS properties, and get a better criterion for quark matter arising in neutron star.

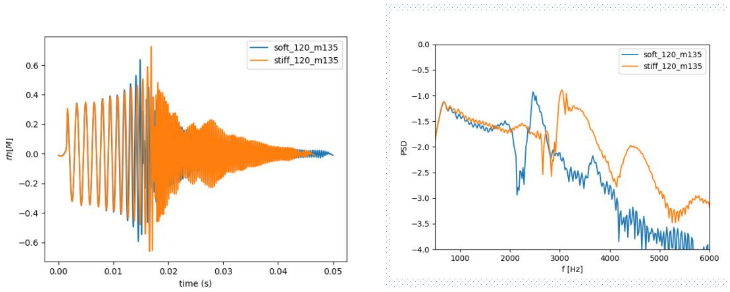

Fig.3 Gravitational wave and its spectrum for softest and stiffest EOS within the constraint

Fiscal Year 2023 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

1. Ming-Zhe Han, Yong-Jia Huang, Shao-Peng Tang, Yi-Zhong Fan,
Plausible presence of new state in neutron stars with masses above 0.98MTOV,
Science Bulletin, 68, 9, 2023.

[Oral presentation]

Seminar April 2023 “Binary neutron star merger with a quark-hardon crossover equation of state” in KIAA, Peking University