Merger and Postmerger of Binary Neutron Stars with a Quark-Hadron Crossover Equation of State

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Golden era for neutron star physics

At the death of stars, nuclear fusion stops and cannot create enough pressure to compete with stellar gravity. Depending on the mass of the progenitor, neutron stars(NS), composed of the densest matter in the universe, might form after the collapse. However, not simply as its name suggests, the composition of neutron stars is long-controversial. Such a situation has changed in recent years. By measuring the bulk properties of neutron stars, such as mass, radius, and tidal deformability, the equation of states(EOS) in zero temperature can be explored reversely.

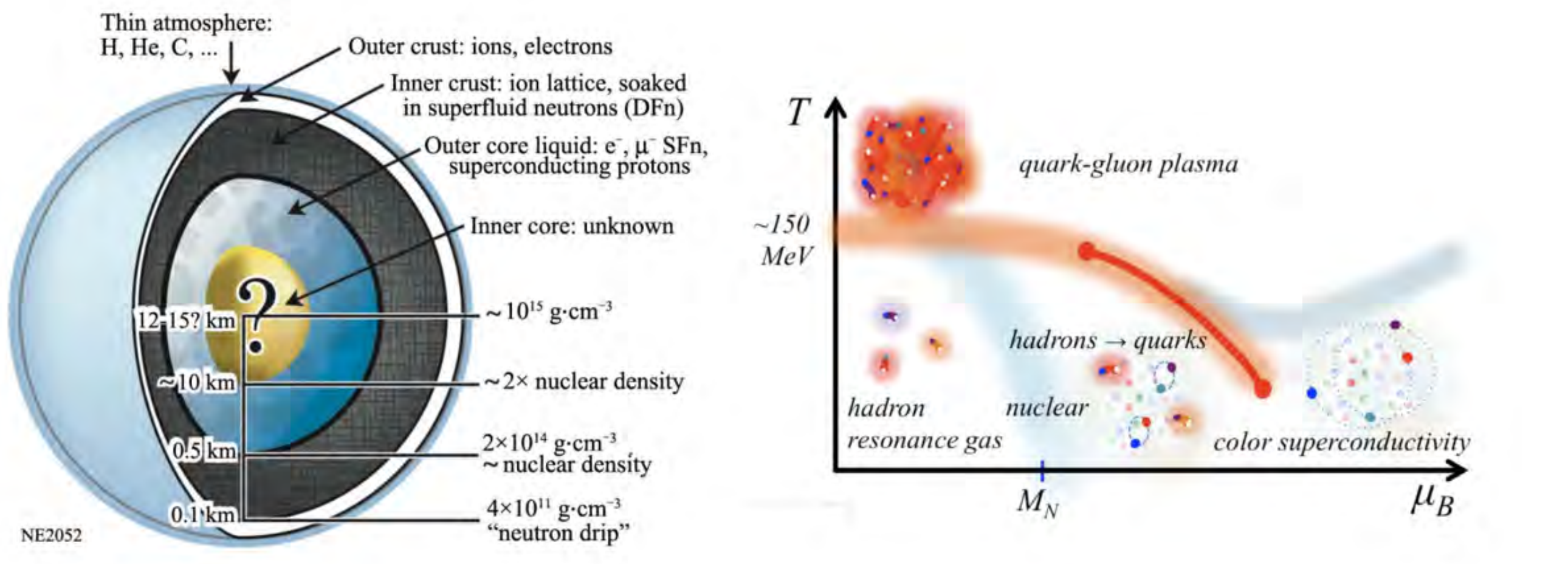

Fig.1 Left: The schematic plot for neutron star composition. Figure is taken from https://heasarc.gsfc.nasa.gov/Images/nicer/ **Right:** QCD phase diagram in finite temperature [2]. Neutron star observation is currently the only window to explore the matter in high chemical potential and zero temperature.

From neutron star observation to equation of state

In the past five years, there have been some inspiring progress in astrophysical observations on NSs, including the multi-messenger observations of the first binary neutron star(BNS) merger event GW170817, the accurate mass determination of the very massive object PSR J0740+6620 (i.e., $M = 2.08 \pm 0.07 M_{\odot}$), and the mass-radius measurements of PSR J0030+0451 and PSR J0740+6620 by the Neutron Star Interior Composition Explorer (NICER). These observations, together with Bayesian non-parametric inference technology, help to describe the dense matter EOS in detail.

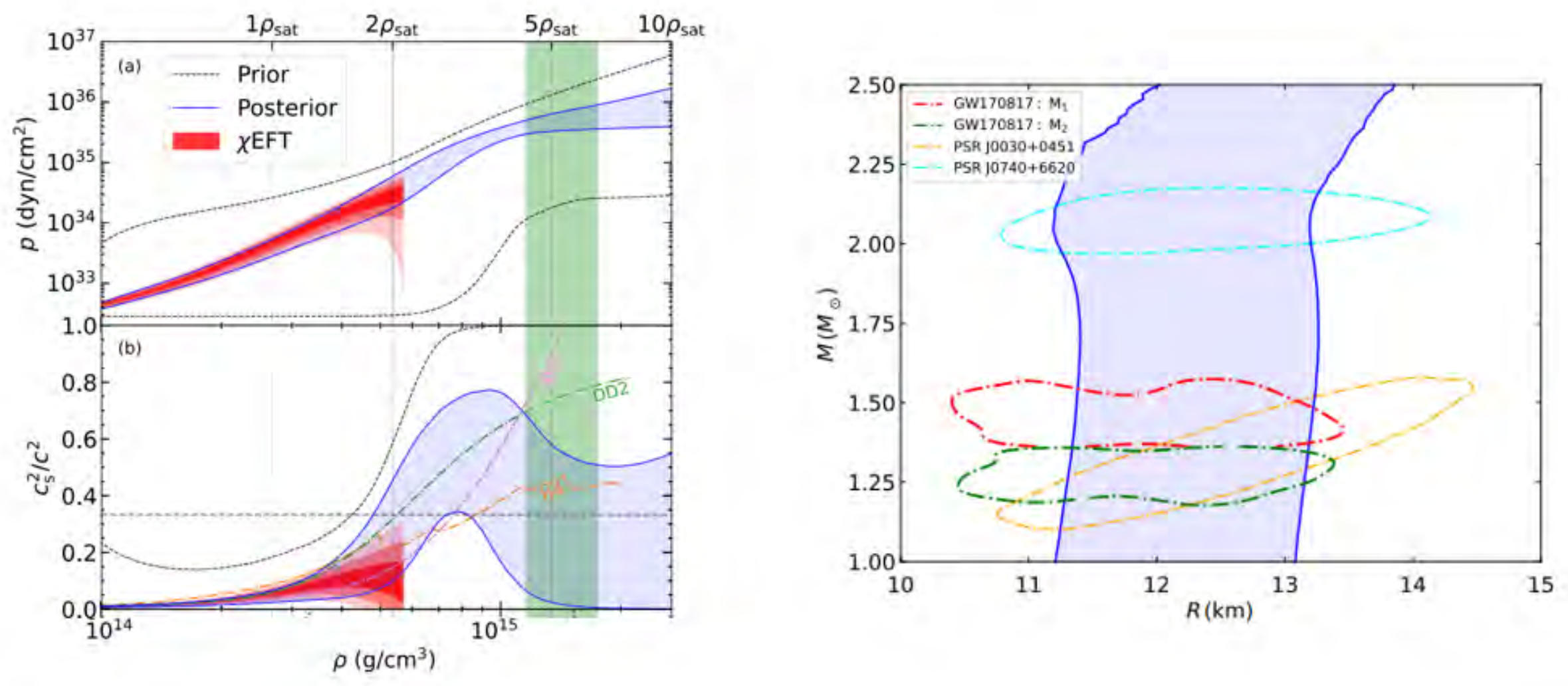

Fig.2 Left: Constraint to dense matter EOS and its sound speed by incorporating the NS observations. Red region shows theoretical bound of chiral effective theory calculation for hadronic EOS in low density. **Right:** Posterior for mass-radius constraints from different observations and their combined result [3].

Many-body interaction described by chiral effective theory calculation and nuclear experiment suggests the neutron star EOS should not be too stiff below two nuclear saturation densities. On the other hand, hadronic matter at several nuclear saturation densities has already overlapped, suggesting the hadron-quark transition should occur in massive NSs. However, if such a transition is first-order, it always makes the EOS softer. Therefore, both of these reasons make it challenging to support a massive NS.

Quark-hadron crossover equation of state

Motivated by the result that QCD transition at zero chemical potential and finite temperature is not a real phase transition but an analytical crossover. In zero temperature and high chemical potential (or baryon density), quark-hadron crossover(QHC) EOSs describe the matter in the region of the hadron-quark mixed phase with a smooth crossover. It is worth noting that such a transition could stiffen the EOSs, thus naturally supporting a massive neutron star even with a soft hadronic EOS.

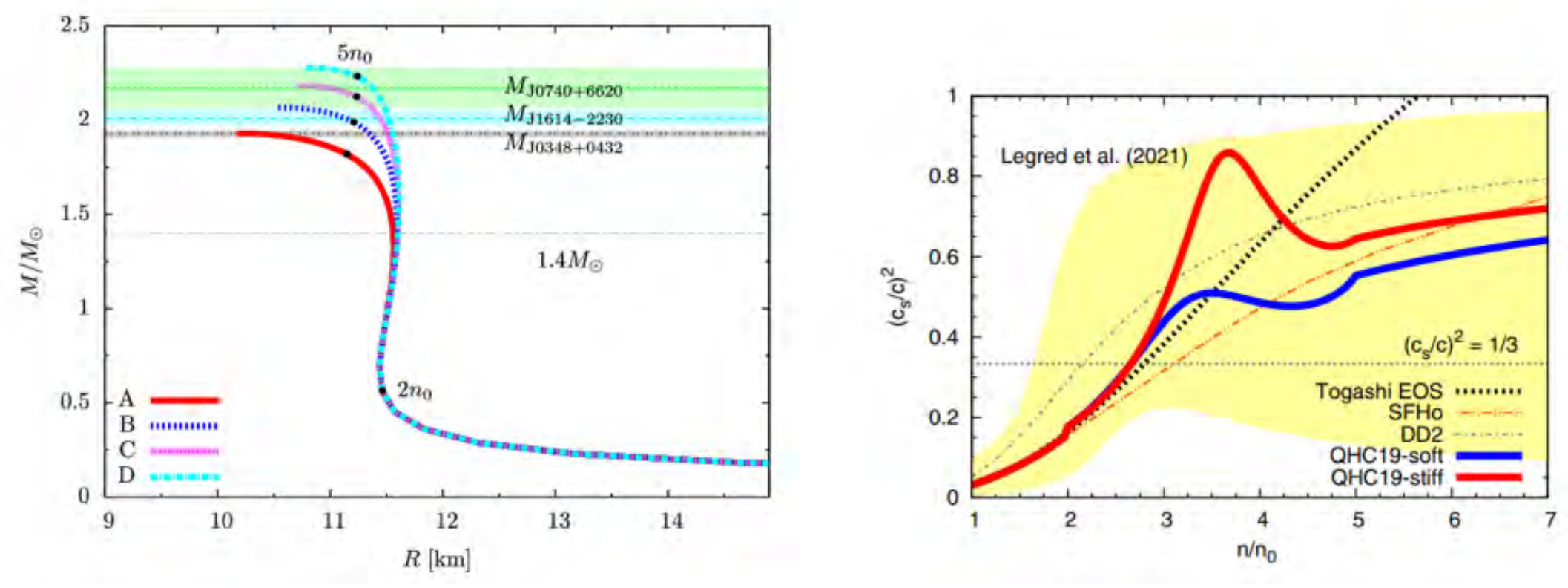

Fig.3 Left: Mass-radius relation for QHC19 EOSs of the parameter sets A–D[1]. The stiffening in crossover could support a more massive neutron star, while the radius of low-mass NSs are the same. **Right:** Square of sound speed normalized to the speed of light. QHC19 models generally show a peak structure [4].

QHC provides a self-consistent interpretation for the existence of massive neutron stars together with soft hadronic EOS. However, it is required to verify whether the crossover occurs inside NSs with observation. Since an exotic core composed of hadron-quark mixed matter in the QHC picture may not change the global structure (like radius, tidal deformability) of NSs in equilibrium, we design the astrophysical experiment by exploring the dynamics modes during BNS merger.

Numerical simulation for binary neutron stars merger

Due to the energy dissipation from the gravitational wave, BNS would finally be merged. After the BNS merger, the GW signal is expected to be detected with the third-generation detectors in the 2030s.

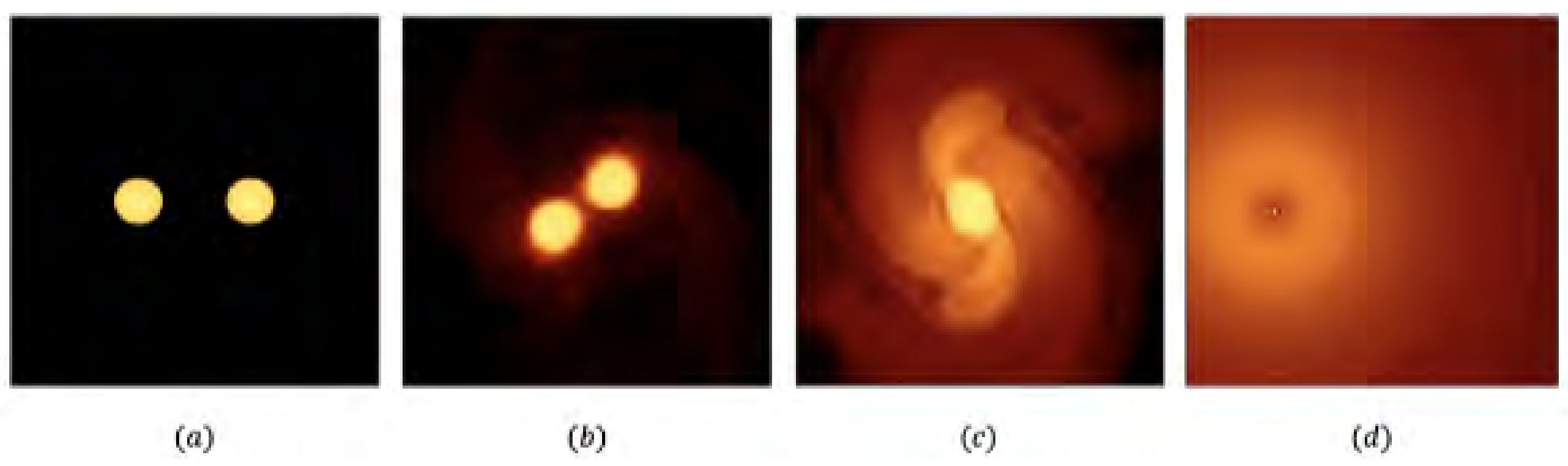

Fig.4 Simulation of binary neutron star merger. (a) Two neutron stars at initial separation of 45km. (b) During the last inspiral, tidal force changes the shape of neutron stars and disrupt the matter in atmosphere. (c) After the merger, a hypermassive neutron star in differential rotating momentarily forms. Bar-deformed structure contributes to the main mode of GW. (d) With angular momentum transferring to outside, merger remnant collapse to the black hole.

We present the first fully general-relativistic BNS merger simulations with QHC EOSs. Among the QHC19 models that support the two solar mass neutron stars, we selected the softest (QHC19-soft) and stiffest (QHC19-stiff) one and considered different NS masses (from 1.25 to 1.375 solar mass). Because of the consistency between the density of crossover starts and the central density of each NS, the cases with the same total masses showed the same properties during inspiral. While the density increased after the merger, the evolution of the merger remnant was dominant by QHC.

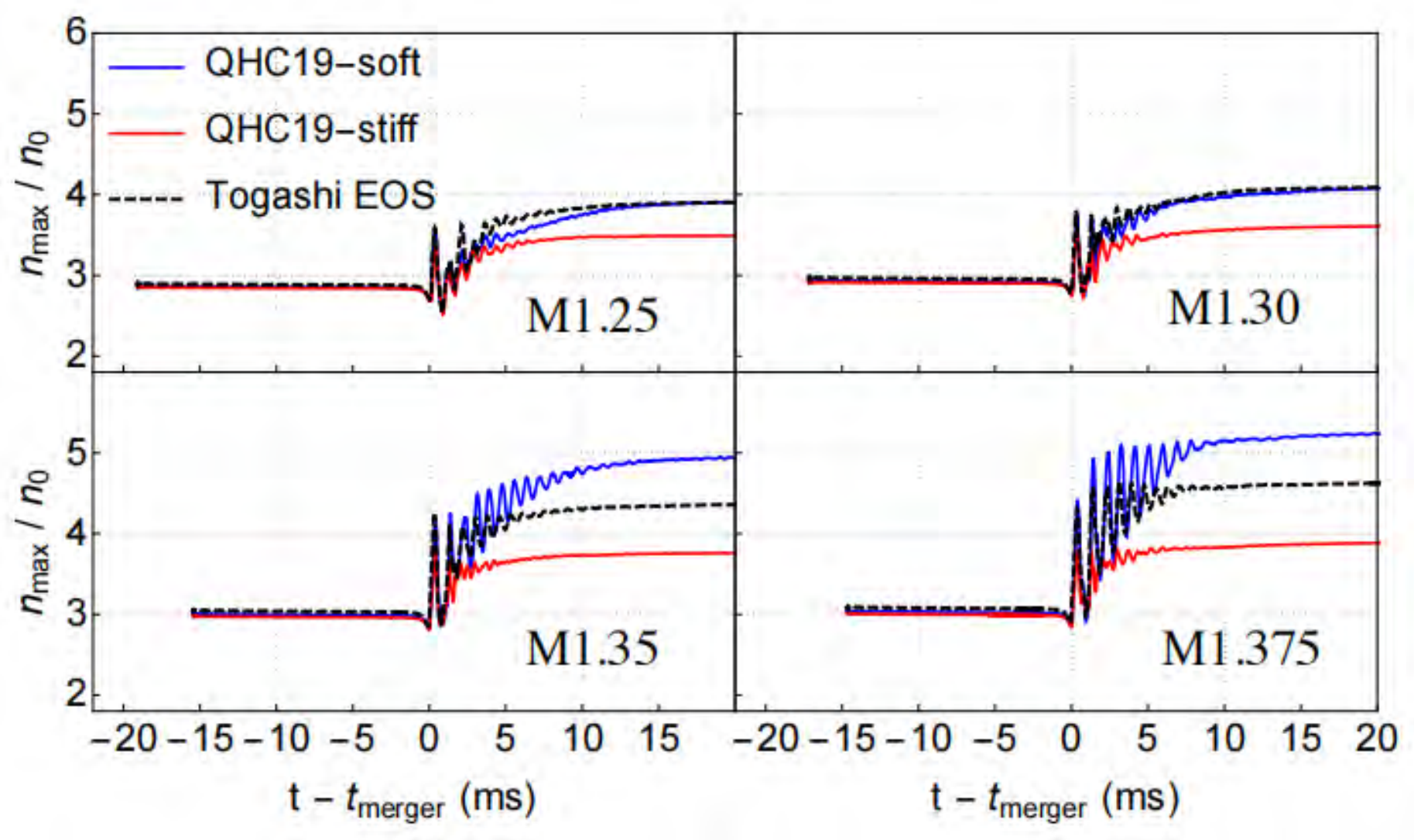

Fig.5 Evolution of the maximum number density for simulations [4].

Maximum density evolution during the merger shows clear order of EOS stiffness. We confirm the frequency of the primary mode in the GW spectrum following the relation in quantitative, thus providing a unique observable quantity to explore how the hadron-quark transition takes place.

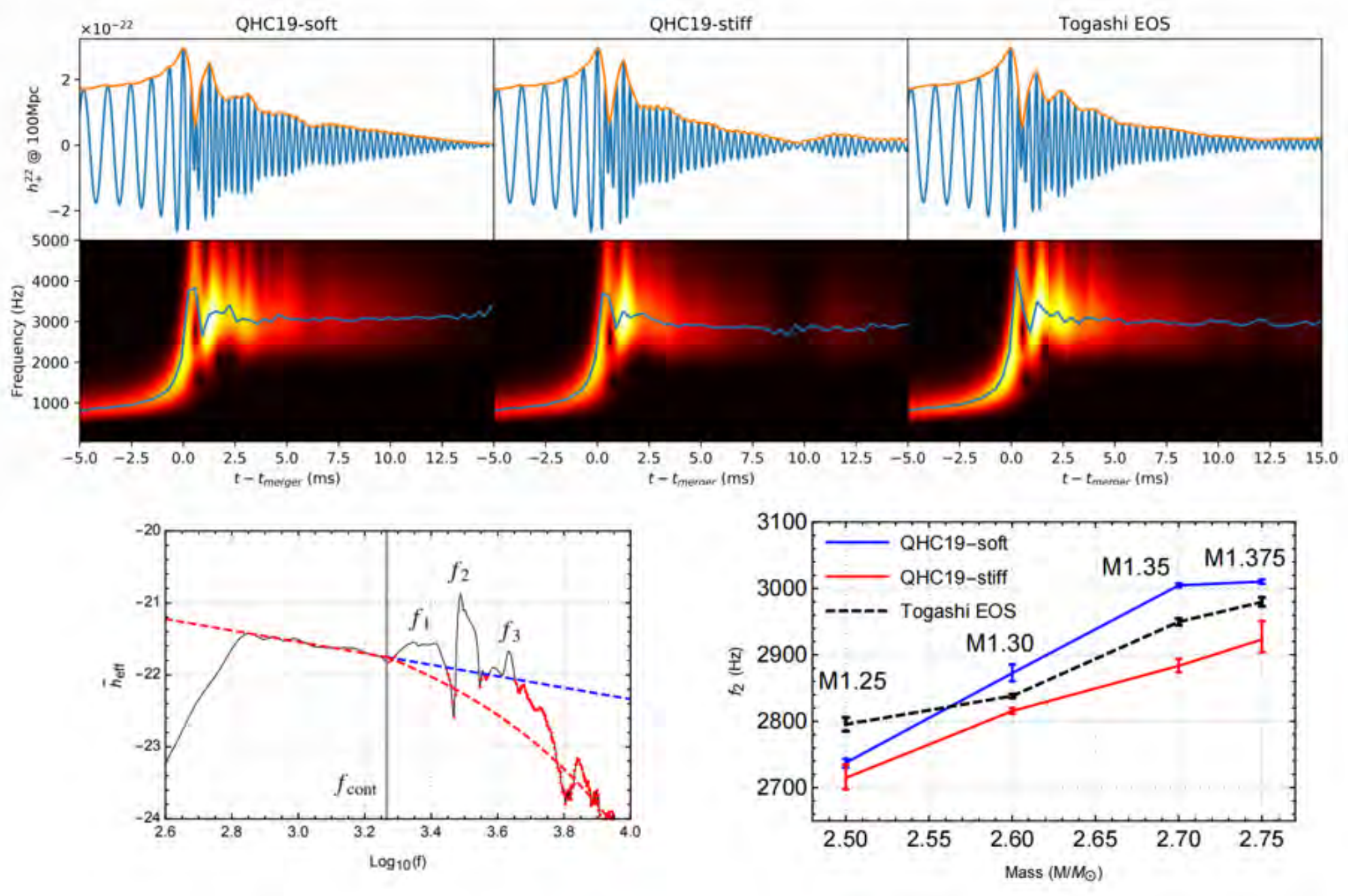

Fig.6 Top: Fundamental and dominant harmonic mode (l = m = 2) of GW and its spectrogram. **Bottom Left:** The spectrum of GW during BNS merger. **Bottom Right:** Relation between f2 and the total mass of the binary [4].

References

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