GRAVITATIONAL WAVES PROBING QUARK MATTER CROSSOVER*

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Received 12 September 2022, accepted 23 September 2022, published online 14 December 2022

It is likely that a change from nuclear to quark matter (QM) in the neutron star (NS) cores is a continuous crossover. Importantly, the *ab initio* estimates of the equations of state (EOSs) in the low-density nuclear region and in the high-density QCD region are both soft, and so the EOS at the intermediate-density region must inevitably be stiff to support massive NSs as observed by the Shapiro time delay. Thus, the first-order phase transition that tends to make the EOS softer is severely constrained. The possible impact of the presence of QM on the gravitational wave signals has already been discussed under an assumption of a strong first-order phase transition for the QM onset. Here, we show that the gravitational wave signals are sensitive enough to detect the QM cores even if the transitional change is a smooth crossover. The early gravitational collapse is induced mainly by rapid softening, not by a discontinuity from the first-order phase transition.

DOI:10.5506/APhysPolBSupp.16.1-A100

1. A big unknown

The QCD phase diagram has many unknowns such as the QCD Critical Point, the fate of the Lifshitz point (*i.e.*, the onset of the quasi-long-range order as a remnant of spatially modulated states), the texture of a family of color-superconducting phases, and so on. Among various unresolved issues, the biggest unknown on the QCD phase digram, in my opinion, is how nuclear matter (NM) will be taken over by quark matter (QM); see Fig. 1. In old days, a first-order phase transition was postulated, but today, we are too wise to be blind against such folklore.

First, we have learned the nature of phase transition at high T and low density, where a smooth crossover has been established based on the first-principles QCD calculations. Even though physical degrees of freedom are

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

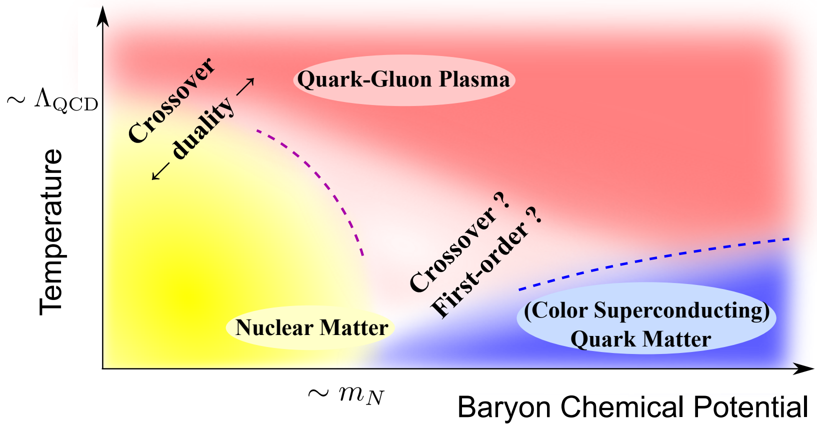

Fig. 1. The QCD phase diagram; the change from nuclear to quark matter is not understood yet.

totally different between the hadronic phase and the quark–gluon plasma (QGP), they are connected without any jump in thermodynamics, which is extremely nontrivial. In a sense, the first-order phase transition would be the easiest to develop our imagination about the underlying mechanism like a bag model, which could be the reason why an assumption of the first-order phase transition was accepted in the Stone Age. In the case of smooth crossover, the transitional region is both hadron-like and QCD-like; that is, it can be reasonably approximated by an interacting gas of hadrons, and at the same time, by an interacting gas of quarks and gluons, which realizes a sort of duality.

Actually, what is the definition of QGP at all? If we perfectly knew the hadronic interactions at any T, and if we were clever enough to perform non-perturbative calculations of thermodynamics in terms of interacting hadrons, would there be any obvious breakdown of theory? Probably in this way we could go to as high T as a few times the pseudo-critical temperature in terms of hadrons. However, if we stuck to the hadronic language, the calculations would be impossibly complicated, and there, the resummed perturbation theory of QCD in terms of quarks and gluons would be even simpler. Then, we can call such a situation deconfined QCD matter for convenience. In other words, the QGP is a proxy of interacting (meson-dominating) hadrons. So, I would say, the concept of the QGP itself is blurred due to the crossover nature that is presumably rooted to the duality.

Next, turning to the state of dense baryonic matter, we are aware of the reality of quark–hadron continuity, which may well be regarded as a high-density counterpart of the duality seen at high T. In the large-$N_{\rm c}$ limit, the gas of free QM has a pressure of $\mathcal{O}(N_{\rm c})$, and one may think that the pressure of the baryonic gas should scale as $\mathcal{O}(1)$ due to color confinement. However, it is known that the baryon interactions are strong of $\mathcal{O}(N_c)$ and the baryonic pressure including both the kinetic and the interaction energies should become $\mathcal{O}(N_c)$, *i.e.*, the same as the QM scaling. Microscopically, the inter-baryon interactions arise from meson exchanges or exchanges of quarks and anti-quarks, which accounts for the N_c dependence of the baryonic pressure. This argument known as Quarkyonic Matter is very profound. The gas of strongly interacting baryons is indistinguishable from the gas of quarks and the duality seems to hold. These observations imply that the nature of transition may be quite similar to the high-T crossover and QM could be defined by something that is more conveniently approximated by QCD calculations in terms of quarks and gluons.

Finally, we note that the QCD-based calculations already exist, and at a glance, the uncertainty looks out of control in the density region relevant to the neutron star (NS) physics. However, the uncertainty lies in the direction to make the equation of state (EOS) even softer, and too soft EOSs are immediately excluded from the existence of the two-solar-mass NSs. Therefore, in practice, the uncertainty in the pQCD calculations is under theoretical control.

With such precious wisdom as listed here, we should evolve our thinking to a modernized version in the contemporary age.

2. EOS of our belief

It is still a challenge to exclude the possibility of the first-order phase transition. If its strength is sufficiently weak, it can occur anywhere. In this case, however, the current experimental data do not have the resolution to make any observable difference, and our terminology, "crossover", includes such EOS with invisibly weak first-order phase transition. Another chance to have a strong first-order phase transition is that it may occur at unphysically high density that would not affect any observables including the gravitational waves. For this scenario to be justified, the pQCD calculations should describe not only the soft EOS branch but also a hard branch unless its validity is lost. There is also a logical possibility that cannot be ruled out in principle; that is, the EOSs may become very stiff before/after a (strong) first-order phase transition so that the stiffness can compensate for the softening effect from the first-order phase transition. Since the underlying physics for the rapid stiffening is unclear, we would not consider the last possibility here.

Figure 2 shows the EOS candidates that I believe in. The crossover EOS is constructed from the matching condition with three EOSs: the low-density region should be consistent with the chiral effective theory (χEFT), the intermediate region should be within the range of the EOS distribution inferred from the NS experimental data (processed by the Bayesian analysis as well as the machine-learning technique), and the high-density region should agree with the pQCD results. Then, the crossover point is uniquely fixed by the position where the intermediate branch and the extrapolated pQCD branch meet. This crossover EOS is my personal favorite, and honestly speaking, I cannot imagine anything else as a realistic candidate.

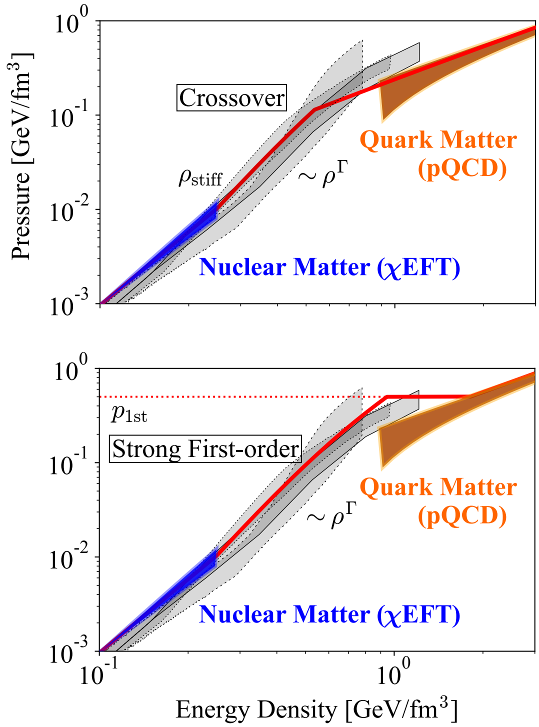

Fig. 2. (Color online) Two typical EOSs; the upper figure shows the EOS in the crossover scenario and the lower one in the first-order transition scenario. The blue/dark gray band at the low-density side represents the χEFT estimates and the orange/gray band at the high-density side represents the pQCD results. The light gray regions indicate the EOSs inferred from the NS experimental data. The intermediate EOS is parametrized by a polytrope, $p = K\rho^\Gamma$, where ρ is the density and Γ is chosen to be 3.5. The separation point, $\rho_{\rm stiff}$, between the χEFT and the intermediate regions is also an unknown parameter that was taken as $\rho_{\rm stiff} = 1.6\rho_0$ with the saturation density ρ_0.

Still, the first-order phase transition scenario is presented in Fig. 2. As a matter of fact, in this case, the presence of phase transition is completely irrelevant, for there is no way to see it at all. Now, the intriguing question is whether these two different EOSs could cause any sizable effect in the gravitational wave signals or not. Our answer is affirmative, fortunately.

3. What to see

The gravitational wave signals as shown in Fig. 3 (from Ref. [1]) are composed of several distinct pieces. The earliest (*i.e.*, the left in the horizontal axis) is from the inspiral stage of two NSs making circular rotations around each other. They loose the energy and the angular momentum by the emission of the gravitational wave, and their distance becomes shorter and shorter. At last, they merge to produce a massive NS beyond the stability bound. The rapidly oscillating signals after the merger, which is usually referred to as the post-merger stage, come from the rapid rotation and deformation of this transient NS that will eventually go to a blackhole after the gravitational collapse.

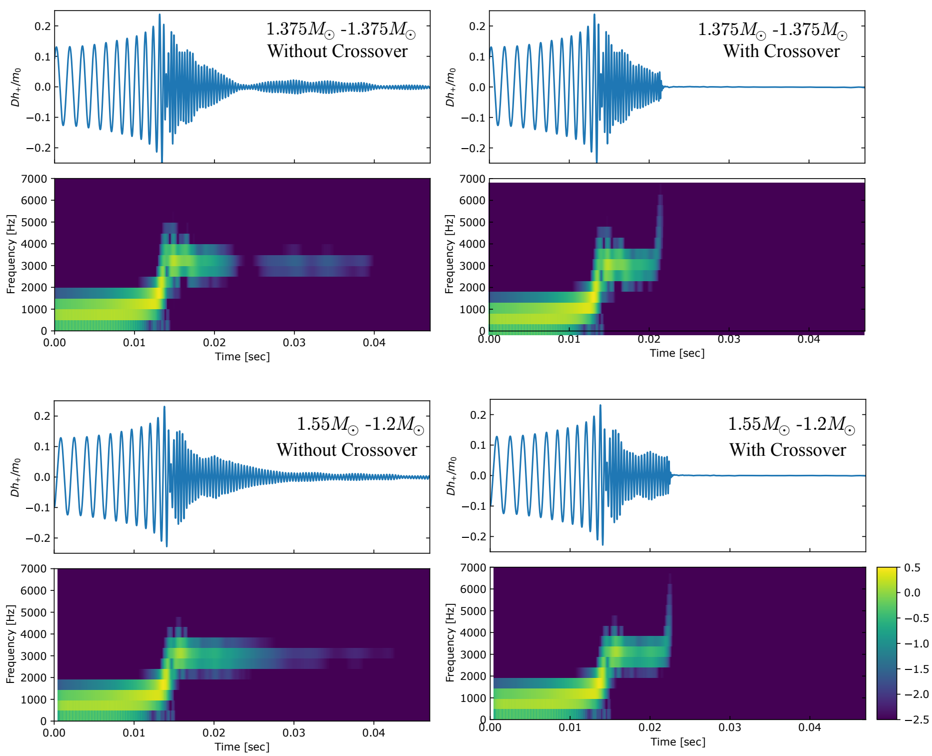

Fig. 3. The gravitational wave signals with the crossover EOS (left) with two equal masses (upper) and unequal masses (lower). The same for the case without crossover (right).

Interestingly, the comparison between the left and the right columns in Fig. 3 clearly indicates a qualitative difference in the post-merger stage. The life-time between the merger and the blackhole formation is far shorter if the

NS cores have QM with crossover. An important lesson we can learn is that the early gravitational collapse is induced by the fact that the EOS in the pQCD branch is soft, not by the singularity associated with the phase transition (see Refs. [2–4] for simulation with the first-order transition). Therefore, if the post-merger dynamics will be analyzed by the future upgraded detectors, we can distinguish two scenarios of the presence and the absence of the QM cores in the NSs. Here, we recall that our definition of QM is matter well approximated by the pQCD calculations, and so our QM EOS is inevitably soft by definition. One should be careful about this point; some authors adopt a different definition of QM and their QM EOS often looks stiff due to interactions beyond the perturbative regime. Such EOSs, in our definition, belong to the nuclear terrain.

Finally, we shall mention the possible constraints from the mass ratio. For all the results in Fig. 3, the total mass was set as $2.75M_{\odot}$ in accord to GW170817, and we compared two situations of equal masses with $1.375M_{\odot}$–$1.375M_{\odot}$ (upper panels) and of unequal masses with $1.55M_{\odot}$–$1.2M_{\odot}$ (lower panels). These different mass ratios lead to almost identical patterns of the gravitational waves. Nevertheless, we found a significant difference. In fact, it is crucial to check the consistency with the observed kilonova, AT2017gfo, that is an electromagnetic counterpart of GW170817. The kilonova parameters are essential for the r-process to synthesize heavy elements and it is established that the ejected mass from the kilonova is $\sim 0.05M_{\odot}$. This means that the remnant mass should be greater than $0.05M_{\odot}$ that is to be ejected. In our simulation, the equal-mass case did not pass this test, while the unequal-mass case is acceptable. In the future, the mass ratio will be fixed by better data in the inspiral stage, and if the corresponding kilonova will be detected, we can impose an additional constraint on the EOS from the kilonova and the remnant mass after the gravitational collapse.

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