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Jia Jie Li, Armen Sedrakian, and Mark Alford

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Relativistic hybrid stars in the light of NICER PSR J0740+6620 radius measurement

Jia Jie Li*

School of Physical Science and Technology, Southwest University, Chongqing 400700, China

Armen Sedrakian†

Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany and
Institute of Theoretical Physics, University of Wrocław, 50-204 Wrocław, Poland

Mark Alford‡

Department of Physics, Washington University, St. Louis, Missouri 63130, USA

We explored the implications of the recent radius determination of PSR J0740+6620 by the NICER experiment combined with the neutron skin measurement by PREX-II experiment and the associated inference of the slope of symmetry energy, for the structure of hybrid stars with a strong first-order phase transition from nucleonic to quark matter. We combine a covariant density-functional nucleonic equation of state (EoS) with a constant speed of sound EoS for quark matter. We show that the radius and tidal deformability ranges obtained from GW170817 can be reconciled with the implication of PREX-II experiment if there is a phase transition to quark matter in the low-mass compact star. In the high-mass segment, the EoS needs to be stiff to comply with the large-radius inference for PSR J0740+6620 and J0030+0451 with masses $M \simeq 2M_\odot$ and $M \simeq 1.4M_\odot$. We show that twin stars are not excluded, but the mass and radius ranges (with $M \geq M_\odot$) are restricted to narrow domains $\Delta M_{\text{twin}} \lesssim 0.05M_\odot$ and $\Delta R_{\text{twin}} \sim 1.0$ km. We also show that the existence of twin configurations is compatible with the light companion in GW190814 event being a hybrid star in the case of values of the sound-speed square $s = 0.6$ and $s = 1/3$.

I. INTRODUCTION

Recent mass measurement of heaviest pulsar to date PSR J0740+6620 [1] which is currently at $2.08^{+0.07}_{-0.07}M_\odot$ and the recent analysis [2, 3] of X-ray data from the NICER experiment which gave the radius estimates $12.39^{+1.30}_{-0.98}$ [2] and $13.71^{+2.61}_{-1.50}$ km [3] and corresponding mass estimates $2.07^{+0.07}_{-0.07}M_\odot$ and $2.08^{+0.09}_{-0.09}M_\odot$ of PSR J0740+6620 open prospects of constraining the properties of dense matter equation of state (EoS), in particular, the possibility of a phase transition at high densities.

The lower bound on the radius of PSR J0740+6620 constrains a highly relevant region of the mass-radius (M - R) diagram of compact stars (CS), which in combination with the determination of the tidal deformability (TD) of a star of mass $\sim 1.4M_\odot$ in the GW170817 event by the LIGO-Virgo Collaboration [4] put significant constraints on the EoS of CS. These require that the stellar EoS must be moderately soft at intermediate densities (to allow for relatively small TDs) and must be stiff enough at high densities (to allow for two-solar mass CSs) (see [5–11]).

Recently, the Lead Radius Experiment Collaboration (PREX-II) reported the most precise measurement yet of the neutron skin thickness of the lead nucleus $R_{\text{skin}}^{208} = 0.283 \pm 0.071$ fm (mean and 1σ standard deviation) in a parity violating electron scattering experiment. [12] Subsequent theoretical analysis [13, 14] based on density-functional theory established values of the symmetry energy E_{sym} and the slope

of nuclear symmetric energy L_{sym} at saturation density (ρ_{sat}) that are consistent with the inferred value of R_{skin}^{208} . Ref. [13] finds $E_{\text{sym}} = 38.1 \pm 4.7$ MeV and $L_{\text{sym}} = 106 \pm 37$ MeV from a family of relativistic (nonlinear, meson-exchange) density functionals (DFs). Ref. [14] expanded the base (and the functional form) of employed DFs to include non-relativistic DFs, relativistic DFs with density-dependent meson-exchange couplings and relativistic point coupling DFs to find $E_{\text{sym}} = 32 \pm 1$ MeV and $L_{\text{sym}} = 54 \pm 8$ MeV. These values include additional requirement on DFs to be consistent with the experimental limits on the dipole polarizability of ^{208}Pb , which prefer DFs predicting a small value of L_{sym} . The large value of L_{sym} found in the first analysis is in potential tension with the various estimates [15–18], whereas the value obtained from the second analysis is within the range inferred previously. Note that the difference between the quoted two values of L_{sym} is 1.37σ which translates to about 83% significance. Since L_{sym} is highly correlated with the stellar radius and tidal deformability, the rather large value found in the first analysis is in potential tension with the GW170817 deformability measurement if one assumes a purely nucleonic composition [13].

Nevertheless, independent of the interpretation of PREX-II experiment, the potential tension outlined above suggests a close examination of compatibility of a large value of L_{sym} with the constraints on compact stars. Here we address the possibility of *first-order phase transition* from nucleonic to quark matter using (a) the radius measurements of two neutron stars by NICER, (b) tidal deformability of GW170817, and (c) a range of values of L_{sym} suggested by Refs. [13, 14].

The composition of matter at high densities achieved in a CS's core remains unknown. One possibility is a deconfinement phase transition from bound states of hadrons to liberated quark states [19]. If the quark matter in a CS's core is relatively soft then its radius and TD are reduced, which could

* jiajili@swu.edu.cn

† sedrakian@fias.uni-frankfurt.de

‡ alford@physics.wustl.edu

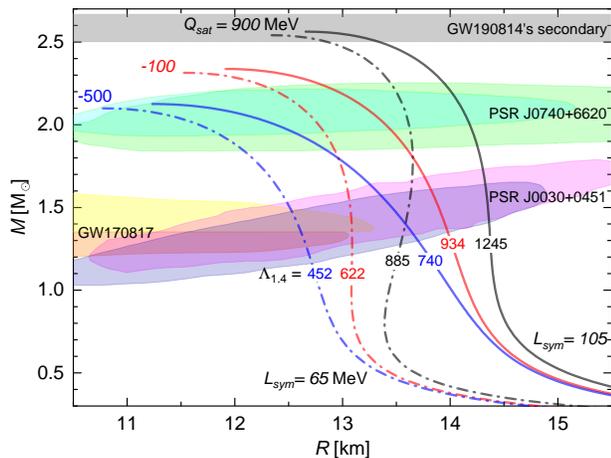


FIG. 1. M - R relation for nucleonic EoS for different pairs of values of Q_{sat} and L_{sym} . In addition we show the TD of a canonical CS for each model. Constraints with 90% credibility from multi-messenger astronomy are shown by color regions [2–4, 37, 38]; see text for details.

avoid the tentative tension between the inferred TDs from the GW170817 event and those predicted by purely hadronic stiff EoS models without a phase transition [20–34]. Of particular interest in this scenario is the emergence of *twin and triplet stars* where one (or two) hybrid stars have the same mass as, but different radius from, a purely hadronic star [21, 25–27, 30, 35, 36]. The more extreme case of triplets will not be discussed here.

With a mass of about $2.1M_{\odot}$ PSR J0740+5620 is the most massive known CS: it is about 50% more massive than PSR J0030+0451. Yet current measurements do not indicate a significant difference in size, see Fig. 1. As mentioned earlier, the generic feature of the first-order phase transition is the softening of the EoS in the vicinity of the transition point, which leads to smaller radii of hybrid stars as compared to the nucleonic ones. Confronting the very massive star’s radius estimation with the possible phase transition in dense matter is thus very timely. This issue has been discussed by [5, 7].

In this work, we apply the setup developed by us earlier [30] to explore the consequences of a strong first-order phase transition from nucleonic to quark matter and the formation of twin stars. The resulting models are then confronted with the newly available data from NICER and PREX-II experiments.

II. CONSTRUCTION OF EOS

To describe low-density matter, we use a covariant density functional (CDF) of nuclear matter in which baryons are coupled to mesons with density-dependent couplings, and adopt as a reference the DDME2 parametrization [39]. The CDF EoS models can be extended by modifying the density-dependence of the couplings [40] such as to map the CDF EoS models onto purely phenomenological ones [41] which are based on an expansion of the energy density of nuclear matter close to the saturation density ρ_{sat} with respect to the

density and isospin asymmetry, i.e.,

$$E(\chi, \delta) \simeq E_{\text{sat}} + \frac{1}{2!} K_{\text{sat}} \chi^2 + \frac{1}{3!} Q_{\text{sat}} \chi^3 + E_{\text{sym}} \delta^2 + L_{\text{sym}} \delta^2 \chi + \mathcal{O}(\chi^4, \chi^2 \delta^2), \quad (1)$$

where $\chi = (\rho - \rho_{\text{sat}})/3\rho_{\text{sat}}$ with ρ and ρ_{sat} being the number density and its value at saturation, $\delta = (\rho_n - \rho_p)/\rho$ where $\rho_{n(p)}$ is the neutron(proton) number density. The coefficients of the expansion are known as *incompressibility* K_{sat} , the *skewness* Q_{sat} , the *symmetry energy* E_{sym} and the *slope parameter* L_{sym} . In this manner the uncertainties in the gross properties of CSs can be quantified in terms of not-well-known higher-order *characteristics of nuclear matter*, specifically Q_{sat} and L_{sym} [40, 41]. The low-order characteristics are fixed at their values predicted by the DDME2 parametrization: $E_{\text{sat}} = -16.14$, $K_{\text{sat}} = 251.15$, $E_{\text{sym}} = 32.31$ MeV and $\rho_{\text{sat}} = 0.152 \text{ fm}^{-3}$. At the same time the CDF provides access to composition of matter which is not fixed in agnostic models based on nuclear characteristics only.

Motivated by this, we construct six representative EoS featuring combinations of three values of $Q_{\text{sat}} = -500, -100, 900$ MeV and two values of $L_{\text{sym}} = 65, 105$ MeV. The value of Q_{sat} controls the high-density behavior of the EoS and, thus, the maximum mass of a static CS [40]. For $Q_{\text{sat}} = -500$ MeV the maximum mass is about $2.1M_{\odot}$, which matches the mass measurement of PSR J0740+6620 [1, 42]; for $Q_{\text{sat}} = -100$ MeV the maximum mass is consistent with the (approximate) *upper limit* on the maximum mass of static CSs $\sim 2.3M_{\odot}$ inferred from the analysis of GW170817 event [43, 44]; finally, for $Q_{\text{sat}} = 900$ MeV the maximum mass is close to $2.5M_{\odot}$, which would be compatible with the mass of the secondary in the GW190814 event [45] and its interpretation as a nucleonic CS [46, 47]. We chose values of L_{sym} corresponding to the central value and the lower range of the 1σ confidence interval (CI) of the PREX-II measurement, $L_{\text{sym}} = 106 \pm 37$ MeV [12, 13]. Note that the recent measurement of the spectra of pions in intermediate energy collisions implies $L_{\text{sym}} = 79.9 \pm 37.6$ MeV [48]. In addition, an analysis based on non-parametric EoS shows that there is a mild tension between the results of Ref. [13] and astrophysical data supplemented by chiral effective field theory results [49].

The M - R relations for our six EoS are shown in Fig. 1 where we also show the current astrophysical observational constraints. We show 90%-credible ellipses from each of the two NICER modeling groups for PSR J0030+0451 and J0740+6620 [2, 3, 37, 38]. We also show 90%-credible regions for each of the two CSs that merged in the gravitational wave event GW170817 [4]. Finally, we show the 90% CI for the mass of the secondary component of GW190814 [45]. A lower limit on average TD $\tilde{\Lambda}_{1.186} \geq 240$ (with binary chirp mass $\mathcal{M} = 1.186 M_{\odot}$) was extracted from the GW170817 event using the observations and modeling of this merger [50, 51]. This limit allows hybrid stars having $R_{1,4}$ radii [24] well below the corresponding NICER limits [37, 38].

The softest EoS model ($Q_{\text{sat}} = -500$, $L_{\text{sym}} = 65$ MeV), which gives $R_{1,4} = 12.58$ km and $\Lambda_{1,4} = 452$ for canonical star, appears as the only model satisfying all three of the M - R constraints. The stiffest EoS model ($Q_{\text{sat}} = 900$, $L_{\text{sym}} = 105$

MeV) which gives $R_{1.4} = 14.37$ km and $\Lambda_{1.4} = 1245$, passes through the upper range of the CIs provided by NICER results. The M - R relations shown in Fig. 1 indicate that one could find a compromise between the requirements of a soft EoS (from GW170817) and relatively large value of L_{sym} implied by the analysis of PREX-II of Ref. [13]. This would be accomplished by an EoS with $L_{\text{sym}} \sim 65$ MeV, which is at the lower end of 1σ range of Ref. [13], and a negative Q_{sat} .

So far we have seen that fairly low values of L_{sym} from the range consistent with the inference [13] from the PREX-II experiment allowed us to build models that are consistent with the known astronomical constraints. However, as we show next, larger values from the experimental range of L_{sym} can be accommodated if a strong first-order phase transition to quark matter is allowed for. We will model below the EoS of the quark phase using the constant-sound-speed (CSS) parametrization [35, 52], which matches well with the predictions based on the Nambu-Jona-Lasinio (NJL) model computations which include vector repulsion [53, 54]. We assume a first-order phase transition with a sharp boundary between the nucleonic and quark phases (which is the case when mixed phases are disfavored by surface tension and electrostatic energy costs [55]). The pressure is then given by [35, 52]

$$p(\varepsilon) = \begin{cases} p_{\text{tran}}, & \varepsilon_{\text{tran}} < \varepsilon < \varepsilon_{\text{tran}} + \Delta\varepsilon, \\ p_{\text{tran}} + s[\varepsilon - (\varepsilon_{\text{tran}} + \Delta\varepsilon)], & \varepsilon_{\text{tran}} + \Delta\varepsilon < \varepsilon, \end{cases} \quad (2)$$

where p_{tran} is the transitional pressure with energy density $\varepsilon_{\text{tran}}$, $\Delta\varepsilon$ is the discontinuity, and s is the square of the sound speed in the quark phase. The possible topologies of hybrid stars in the M - R diagram based on CSS parametrization have been studied [35]. Of particular interest is the case where by an appropriate choice of the parameters p_{tran} , $\Delta\varepsilon$ and s there are two disconnected branches of stars, one with purely nucleonic and the other with hybrid stars. Such topology leads, in particular, to twin configurations where stars have identical masses but different radii [21, 25–27]. The more extreme case of three disconnected branches leads to the formation of triplets, which will not be studied here [36].

Figure 2 illustrates how such a transition to quark matter allows a nuclear EoS with a large L_{sym} to be consistent with astrophysical constraints. We have fixed the nuclear EoS by choosing $L_{\text{sym}} = 65$ and $Q_{\text{sat}} = 900$ MeV. We vary the CSS parameters of the quark matter EoS to explore different sound speeds s , and by varying ρ_{tran} and $\Delta\varepsilon_{\text{tran}}$ we can explore different values of the maximum masses $M_{\text{max}}^{\text{N}}$ and $M_{\text{max}}^{\text{Q}}$ on the nucleonic branch and hybrid branch respectively. In particular, each of the two same-color solid lines differ only by the value of $M_{\text{max}}^{\text{Q}}$.

The sequences shown in Fig. 2 are for $M_{\text{max}}^{\text{Q}}/M_{\odot} = 2.1, 2.3, 2.5$ and $M_{\text{max}}^{\text{N}}/M_{\odot} = 1.0, 1.3$ (corresponding to transition densities $\rho_{\text{tran}}/\rho_{\text{sat}} = 1.81, 2.05$). We see that a stiff nucleonic EoS can be made compatible with the GW170817 constraint if there is a first-order transition to quark matter at densities $\rho_{\text{tran}} \lesssim 2\rho_{\text{sat}}$.

Figure 2 shows, in addition, the sensitivity of results towards varying the value of s for a specific case with fixed maximum masses. Since a reduction of s from its maximal value softens the quark-matter EoS, the M - R curves are shifted to

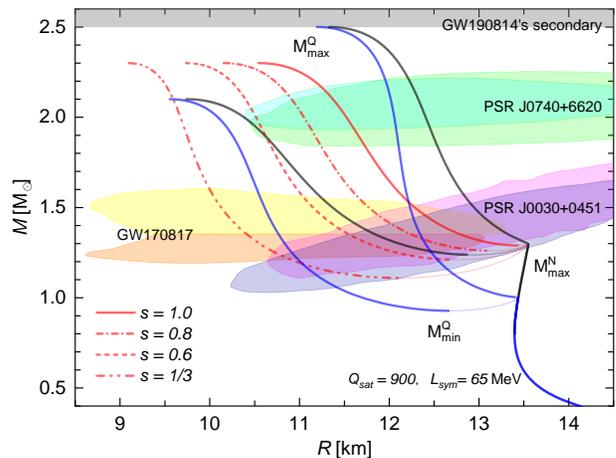


FIG. 2. Illustrative M - R relation for hybrid EoS models. The results are constructed by varying one of the three quantities that fully determine the model at fixed values of two others. These are the maximum masses of quark $M_{\text{max}}^{\text{Q}}$ and nucleonic $M_{\text{max}}^{\text{N}}$ branches and the sound speed square s . The dotted thin lines indicate unstable configurations. All the solid curves correspond to $s = 1.0$. For the remaining curves, the value of s is as indicated in the plot.

the left, eventually putting some of them ($s \lesssim 0.6$) outside of the NICER result for PSR J0740+6620. Note that in Fig. 2 two topologies of M - R curves are present - the connected and disconnected ones, the latter having a region of instability between the nucleonic and hybrid configurations. In the following, we focus on the disconnected topologies.

III. MASS-RADIUS CONSTRAINT FOR HYBRID STARS

To study the occurrence of twin configurations, we select EoSs from the parameter space of our model that have twin configurations and are consistent with both NICER and gravitational wave measurements. Specifically, they yield radii that are above the NICER 90%-confidence lower limit from PSR J0740+6620 and J0030+0451, and below the 90%-confidence upper limit on the radius of a $1.36M_{\odot}$ star from the GW170817 event; (the stellar mass is chosen to the one inferred for equal mass binary.) Fig. 3 shows examples of our exploration of this parameter space. Each of the 4 panels in Fig. 3 has curves for two nuclear EoS (with the values of L_{sym} and Q_{sat} given in each panel title) and a fixed speed of sound in the quark matter EoS (also given in each panel title). Within each panel we vary the remaining parameters of the quark matter EoS (nuclear matter density at the transition ρ_{tran} and energy density jump at the transition $\Delta\varepsilon$) as follows. In each of the two or three plots in each panel, we require the maximum mass on the hybrid branch $M_{\text{max}}^{\text{Q}}$ to have a different value (which can be read off from the y-axis), and in each plot, we show results for two values of $M_{\text{max}}^{\text{N}}$ which span the range within which the M - R curves obey the mass-radius constraints as described in the previous paragraph, and contain twin stars (i.e., a discontinuity between the nucleonic branch and the hybrid branch).

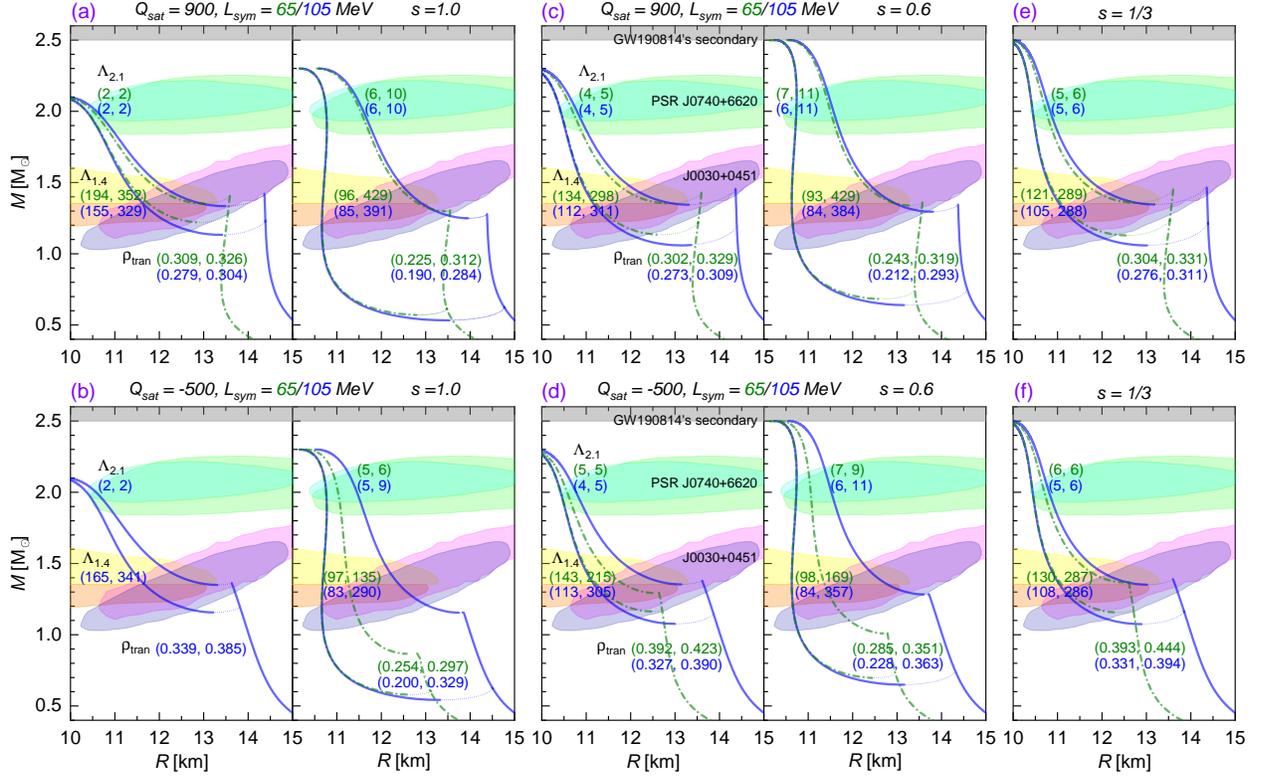


FIG. 3. Constraints on the M - R relation of CSs featuring twin configurations (in some cases the instability region is not resolved on the figure’s scale). Panels (a) and (b): M - R curves for hybrid stars characterized by different maximum mass (attained on the quark branch) for nucleonic EoS with pairs of values of Q_{sat} (-500 and 900 MeV) and L_{sym} (65 and 105 MeV), and quark matter CSS EoS with $s = 1.0$ (in natural units). The ranges of transition density ρ_{tran} in units of fm^{-3} , TDs $\Lambda_{1,4}$ and $\Lambda_{2,1}$ (dimensionless) for a canonical mass $M/M_{\odot} = 1.4$ and massive $M/M_{\odot} = 2.1$ stars respectively are quoted as well. The color-coding of numbers matches that of the curves. Panels (c)-(d) and (e)-(f): same as in (a)-(b), but $s = 0.6$ and $s = 1/3$, respectively.

Let us first focus on the case $s = 1.0$ (Fig. 3(a) and (b)). The following systematics are observed in our setup:

- (i) The stiffer is the nucleonic EoS the larger is the range of masses and radii where twin stars exist; see also Fig. 4 below. Intuitively, this makes sense, as the stiffer nuclear EoS pushes the nucleonic branch to higher radii, further from the hybrid branch.
- (ii) The larger the value $M_{\text{max}}^{\text{Q}}$ the narrower the range of masses where twins exist and the instability region between nucleonic and hybrid stars. A higher value, in the current set-up, requires a smaller $\Delta\varepsilon$ to allow for a steep increase of the mass. Since for our parameter choice the M - R curves pass through the GW170817 90% credible region, the quoted values of TD are consistent with the upper limit set by the GW170817 on this quantity event [4].

Consider next the case of less stiff quark EoS with $s = 0.6$ (Fig. 3(c) and (d)) and $s = 1/3$ (Fig. 3(e) and (f)). The general features found above are replicated in this case as well. However, in this case we find twin solutions for models supporting heavier stars, with $M_{\text{max}}^{\text{Q}}/M_{\odot} \gtrsim 2.3$. Interestingly, the $M_{\text{max}}^{\text{Q}}/M_{\odot} = 2.5$ sequence, in which the light component in the GW190814 would be a hybrid star (see Fig. 3), allows for twin solutions for $s = 0.6, 1/3$ in the considered range $65 \leq L_{\text{sym}} \leq 105$ MeV. Compared to the $s = 1.0$ case for

the same maximum mass $M_{\text{max}}^{\text{Q}}$ the value of $M_{\text{max}}^{\text{N}}$ is shifted upwards significantly which promotes the appearance of twin configurations.

The analysis above shows, among other things, that NICER’s 90% CI for PSR J0740+6620 does not preclude a strong first-order phase transition, which (very robustly) leads to a shift of the radius towards smaller values compared to the case without phase transition. Furthermore, the fact that PREX-II analysis of Ref. [13] indicates $L_{\text{sym}} > 65$ MeV at 68% confidence level and $L_{\text{sym}} > 45$ MeV at 90% corroborates the scenario of such a strong first-order phase transition, as large L_{sym} allows for a large radius of the nucleonic low-mass stars and thus “leaves room” on the M - R diagram for a hybrid branch with a smaller radius that is consistent with astrophysical measurements. In such a scenario the appearance of twin configurations is possible. This leads us to the conclusion that even the relatively low-mass $M/M_{\odot} \leq 1.5$ CSs could be in fact hybrid stars.

Figure 4 shows the values of $M_{\text{max}}^{\text{N}}$ for which twins arise, the mass range of twins ΔM_{twin} defined as the range between $M_{\text{max}}^{\text{N}}$ and the minimum value of a CS mass on the hybrid branch, as well as associated with this mass range intervals of the radius ΔR_{twin} and TD $\Delta\Lambda_{\text{twin}}$ as functions of the parameters defining the EoS. For $s = 1.0$ twin configurations arise

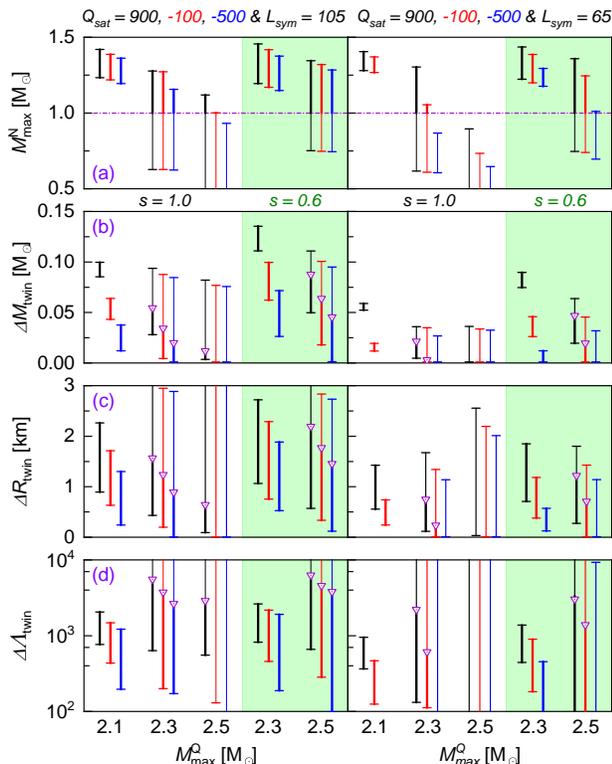


FIG. 4. Ranges of parameters M_{\max}^N , ΔM_{twin} , ΔR_{twin} and $\Delta \Lambda_{\text{twin}}$ characterizing twin configurations (see text for definitions) for EoS constructed using nucleonic matter with pairs of values of Q_{sat} (-500, -100 and 900 MeV) and L_{sym} (65 and 105 MeV) and quark matter with $s = 1.0$ and 0.6 (shaded). The triangles followed by the thin lines correspond to twins with $M \leq 1 M_{\odot}$. See text for discussion.

for $M_{\max}^Q/M_{\odot} \lesssim 2.3$ (within the parameter space explored and excluding twins with $M < 1.0 M_{\odot}$, see below), but for $s = 0.6$ values $M_{\max}^Q/M_{\odot} \sim 2.5$ are obtained. This has implications for the GW190814 event which involved a merger of a $23 M_{\odot}$ black hole with a $\sim 2.6 M_{\odot}$ object. Therefore, this object could have been a hybrid star living on a CS sequence which contains a twin, i.e. the GW190814 event does not exclude twins [for a contrary view see [56]].

In Fig. 4 we see that the range of masses containing twins is small, $\Delta M_{\text{twin}} \lesssim 0.05 M_{\odot}$. For radii, note that the triangles followed by thin lines denote twins with $M < 1 M_{\odot}$. This is a rough threshold below which stars are unlikely to be observed because of their likely instability at the hot proton-neutron-star stage [57, 58]. With that condition, the radius difference of twins is $\Delta R_{\text{twin}} \sim 1$ km for $s = 1.0$; the difference is larger for $s = 0.6$ with ΔR_{twin} reaching up to 3 km. This range is largest for very stiff nucleonic EoS which predict a large radius. The narrow range of masses and modest radius difference for twins is a consequence of the constraint imposed by the large radius of PSR J0740+662, which limits the allowed range of the reduction of the radius of a hybrid star and makes it challenging to distinguish between nucleonic and hybrid stars as $\Delta R_{\text{twin}} = 1$ km requires radius measurement accuracy of less than 10%. However, the difference in the TDs of twins can be several hundred to two thousand, see Fig. 4(d),

therefore studies of Λ_1 - Λ_2 extracted from inspiral phase of CS mergers is a more promising avenue for identifying twins.

IV. CONCLUSIONS

To summarize, we investigated the impact of two recent observational/experimental results, the inference of the radius of PSR J0740+6620 [2, 3] from the X-ray data provided by NICER experiment and of the neutron skin thickness by the PREX-II experiment in conjunction with the DF analysis of Refs. [13, 14], on the static properties of relativistic hybrid stars. The analysis of Ref. [13] gives a value of L_{sym} which is in potential tension with the tidal deformability and radius limits inferred from GW170817 analysis. The L_{sym} value extracted in the analysis of Ref. [14] is within the accepted range and does not pose any tension with multimessenger astrophysics. The above mentioned new results were confronted here with the conjecture of strong first-order phase transition and formation of hybrid stars. In doing so we adopted a density-functional model of nucleonic matter which allows for accurate description of low-density nuclear phenomenology, along with a flexible parameterization of high-density quark matter. Our main finding is that it is possible to account for current astrophysical and nuclear experimental constraints within the scenario of hybrid stars, which can appear as twin configurations, *with a low value of phase transition density from nucleonic to quark matter*. Specifically, in this scenario the first-order phase transition *naturally softens the EoS* at intermediate densities (which is required to avoid the potential tension between the GW170817 event and PREX-II measurement’s interpretation of Ref. [13]) and the assumption of a high sound speed in quark matter *stiffens the EoS at high densities*, which is required to account for $M \gtrsim 2.0 M_{\odot}$ massive CS and the large radius of PSR J0740+6620 (as measured by the NICER analysis teams). We have quantified under which conditions such models may have twin solutions. In particular, for the squared sound speed in quark matter $s = 0.6$ and $s = 1/3$ we find twin stars *and* a large enough maximum mass to allow for a CS in the GW190814 merger event. For low values of s the range of the difference in the radii for twins expands; for example, $\Delta R_{\text{twin}} \sim 1.0$ km found for $s = 1$ become 3 km for $s = 0.6$. In the EoS models where Δ -resonances appear (see [30, 59] and references therein), the EoS softens at intermediate densities and the radius of the star is reduced with consequences for the M - R relation similar to those found here.

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