Modern compact star observations and the quark matter equation of state

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Abstract

We present a hybrid equation of state (EoS) for dense matter that satisfies phenomenological constraints from modern compact star (CS) observations which indicate high maximum masses ($M \sim 2 M_\odot$) and large radii ($R > 12$ km). The corresponding isospin symmetric EoS is consistent with flow data analyses of heavy-ion collisions and a deconfinement transition at ~ 0.55 fm^{-3}. The quark matter phase is described by a 3-flavor Nambu–Jona-Lasinio model that accounts for scalar diquark condensation and vector meson interactions while the nuclear matter phase is obtained within the Dirac-Brueckner-Hartree-Fock (DBHF) approach using the Bonn-A potential. We demonstrate that both pure neutron stars and neutron stars with quark matter cores (QCSs) are consistent with modern CS observations. Hybrid star configurations with a CFL quark core are unstable.

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1 Introduction

Recently, new observational limits for the mass and the mass-radius relationship of compact stars have been obtained which provide stringent constraints on the equation of state of strongly interacting matter at high densities, see [1] and references therein. In particular, the high mass of $M = 2.1 \pm 0.2 \ M_{\odot}$ for the pulsar J0751+1807 in a neutron star - white dwarf binary system [2] and the large radius of $R > 12$ km for the isolated neutron star RX J1856.5-3754 (shorthand: RX J1856) [3] point to a stiff equation of state at high densities. Measurements of high masses are also reported for compact stars in low-mass X-ray binaries (LMXBs) as, e.g., $M = 2.0 \pm 0.1 \ M_{\odot}$ for the compact object in 4U 1636-536 [4]. For another LMXB, EXO 0748-676, constraints for the mass $M \geq 2.10 \pm 0.28 \ M_{\odot}$ *and* the radius $R \geq 13.8 \pm 0.18$ km have been reported [5]. The status of these data is, however, unclear since the observation of a gravitational redshift $z = 0.35$ in the X-ray burst spectra [6] could not be confirmed thereafter despite numerous attempts [7]. We exclude possible constraints from LMXBs from the discussion in the present paper as their status is not settled and they would not tighten the mass and mass-radius limits provided by J0751+1807 and RX J1856, respectively. It has been argued [3,5] that deconfined quark matter cannot exist in the centers of compact stars with masses and radii as reported for these objects. In view of recent works on the quark matter EoS, however, this claim appears to be premature [8].

In the present paper, we demonstrate that the present-day knowledge of hydrodynamical properties of dense matter allows to construct hybrid EsoS with a critical density of the deconfinement phase transition low enough to allow for extended quark matter cores and stiff enough to comply with the new mass measurements of compact stars. It has been shown recently by Alford et al. [9] that hybrid stars can masquerade as neutron stars once the parameters of a generic phenomenological quark matter EoS have been chosen appropriately. While in [9] the APR EoS [10] for the hadronic phase has been used, we base our investigation on a nuclear EoS obtained from the ab initio DBHF approach using the Bonn A potential [11,12] which results in star configurations with larger radii and masses. The DBHF EoS is soft at moderate densities (compressibility K=230 MeV) [11,13] but tends to become stiffer at high densities. At densities up to 2-3 times nuclear saturation density it is in agreement with constraints from heavy ion collisions based on collective flow [14,15] and kaon production [16]. However, at higher densities this EoS seems to be too repulsive concernig the flow constraint. As we will show in the present paper, the problems of this EoS with an early onset of the nuclear direct Urca (DU) process and a violation of the flow constraint for heavy-ion collisions at high densities can be solved by adopting a phase transition to quark matter.

We have no first principle information from QCD about the quark matter EoS

in the nonperturbative domain close to the chiral/ deconfinement transition at zero temperature and finite density which would be required for an ab-initio study of the problem whether deconfined quark matter can exist in neutron stars or not. Therefore it is desireable to develop microscopic approaches to the quark matter EoS on the basis of effective models implementing, as far as possible, QCD symmetries into the model Lagrangian. The Lagrangian of the Nambu–Jona-Lasinio (NJL) type models has chiral symmetry which is dynamically broken in the nonperturbative vacuum and restored at finite temperatures in accordance with lattice QCD simulations. Therefore, the application of the NJL model to finite densities where presently no reliable lattice QCD simulations exist, can be regarded as state-of-the-art for present dense quark matter studies, see [18] and references therein.

In contrast to Ref. [9] we base our investigation on a three-flavor chiral quark model with selfconsistently determined quark masses and pairing gaps [19] similar to the parallel developments in Refs. [20,21]. This approach has the advantage that it allows, e.g., to distinguish two- and three-flavor phases in quark matter (for a first discussion, see [22]) and to allow conclusions about the presence of gapless phases at zero temperature as a function of the coupling strengths in the current-current-type interaction of the model Lagrangian [23]. Moreover, we will investigate the question of the stability of neutron stars with a color superconducting quark matter core in the celebrated CFL phase, for which a number of phenomenological applications have been studied, in particular the cooling problem [24,25,26,27], gamma-ray bursts [28,29], and superbursts [30]. We will confirm in this work the earlier result by Buballa et al. [31] that a CFL quark matter core renders the hybrid star unstable.

Here we generalize the model [19] by including an isoscalar vector meson current which, similar to the Walecka model for nuclear matter, leads to a stiffening of the quark matter EoS. Increasing the scalar diquark coupling constant leads to a lowering of the phase transition density. It is the aim of the present work to determine the unknown coupling strengths in both these channels such that an optimal hybrid star EoS is obtained. It fulfills all recently developed constraints from modern compact star observations [1,5] while providing sufficient softness of the isospin-symmetric limit of this EoS as required from the analysis of heavy-ion collision transverse flow data [14,15] and K^+ production data [16].

2   Equation of state

The thermodynamics of the deconfined quark matter phase is described within a three-flavor quark model of Nambu–Jona-Lasinio (NJL) type. The path-integral representation of the partition function is given by

$$Z(T,\hat{\mu}) = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\int\limits_0^\beta d\tau \int d^3x \left[\bar{q}\left(i\slashed{\partial} - \hat{m} + \hat{\mu}\gamma^0\right)q + \mathcal{L}_{\text{int}}\right]\right\}, \quad (1)$$

$$\mathcal{L}_{\text{int}} = G_S\left[\sum_{a=0,3,8}(\bar{q}\tau_a q)^2 - \eta_V(\bar{q}\gamma^0 q)^2\right.$$
$$\left. +\eta_D\sum_{A=2,5,7}(\bar{q}i\gamma_5\tau_A\lambda_A C\bar{q}^T)(q^T iC\gamma_5\tau_A\lambda_A q),\right], \quad (2)$$

where $\hat{\mu}$ and $\hat{m} = \text{diag}_f(m_u, m_d, m_s)$ are the diagonal chemical potential and current quark mass matrices. For $a = 0$, $\tau_0 = (2/3)^{1/2}\mathbf{1}_f$, otherwise τ_a and λ_a are Gell-Mann matrices acting in flavor and color spaces, respectively. $C = i\gamma^2\gamma^0$ is the charge conjugation operator and $\bar{q} = q^\dagger\gamma^0$. G_S, η_V, and η_D determine the coupling strengths of the interactions.

The interaction terms represent current-current interactions in the color singlet scalar and vector meson channels, and the scalar color antitriplet diquark channel. In the choice of the four-fermion interaction channels we have omitted the pseudoscalar quark-antiquark terms, which should be present in a chirally symmetric Lagrangian. These terms do not contribute to the thermodynamic properties of the deconfined quark matter phase at the mean-field (Hartree) level [32] to which we restrict the discussion in the present paper. The Lorentz three-current, $\nu \in \{1,2,3\} : (\bar{q}\gamma^\nu q)^2$, vanishes in the static ground state of matter and is therefore omitted. The model is similar to the models in [19,20,21], except that we include also the isoscalar vector meson channel. We follow the argument given in [19], that the $U_A(1)$ symmetry breaking in the pseudoscalar isoscalar meson sector is dominated by quantum fluctuations and no 't Hooft determinant interaction needs to be adopted for its realization.

After bosonization using Hubbard-Stratonovich transformations, we obtain an exact transformation of the original partition function (1). The transformed expression constitutes the starting point for powerful approximations, defined as truncations of the Taylor expanded action functional to different orders in the collective boson fields. In the following, we use the mean-field (MF) approximation. This means that the bosonic functional integrals are omitted and the collective fields are fixed at the extremum of the action. The corresponding mean-field thermodynamic potential, from which all thermodynamic quantities can be derived, is given by

$$\Omega_{MF}(T,\mu) = -\frac{1}{\beta V}\ln Z_{MF}(T,\mu)$$
$$= \frac{1}{8G_S}\left[\sum_{i=u,d,s}(m_i^* - m_i)^2 - \frac{2}{\eta_V}(2\omega_0^2 + \phi_0^2) + \frac{2}{\eta_D}\sum_{A=2,5,7}|\Delta_{AA}|^2\right]$$

$$-\int \frac{d^3p}{(2\pi)^3} \sum_{a=1}^{18} \left[E_a + 2T \ln\left(1 + e^{-E_a/T}\right) \right] + \Omega_l - \Omega_0 \ . \qquad (3)$$

Here, Ω_l is the thermodynamic potential for electrons and muons, and Ω_0 is a divergent term that is subtracted in order to get zero pressure and energy density in vacuum ($T = \mu = 0$). The quasiparticle dispersion relations, $E_a(p)$, are the eigenvalues of the Hermitian matrix

$$\mathcal{M} = \begin{bmatrix} -\vec{\gamma} \cdot \vec{p} - \hat{m}^* + \gamma^0 \hat{\mu}^* & \gamma_5 \tau_A \lambda_A \Delta_{AA} \\ -\gamma_5 \tau_A \lambda_A \Delta_{AA}^* & -\vec{\gamma}^T \cdot \vec{p} + \hat{m}^* - \gamma^0 \hat{\mu}^* \end{bmatrix}, \qquad (4)$$

in color, flavor, Dirac, and Nambu-Gorkov space. Here, Δ_{AA} are the diquark gaps. $\hat{m}^*$ is the diagonal renormalized mass matrix and $\hat{\mu}^*$ the renormalized chemical potential matrix, $\hat{\mu}^* = \mathrm{diag}_f(\mu_u - G_S\eta_V\omega_0, \mu_d - G_S\eta_V\omega_0, \mu_s - G_S\eta_V\phi_0)$. The gaps and the renormalized masses are determined by minimization of the mean-field thermodynamic potential (3), subject to charge neutrality constraints which depend on the application we consider. In the (approximately) isospin symmetric situation of a heavy-ion collision, the color charges are neutralized, while the electric charge in general is non-zero. For matter in β-equilibrium, also the electric charge is neutralized. For further details, see [19,20,21].

We consider η_D as a free parameter of the quark matter model, to be tuned with the present phenomenological constraints on the high-density EoS. Similarly, the relation between the coupling in the scalar and vector meson channels, η_V, is considered as a free parameter of the model. The remaining degrees of freedom are fixed according to the NJL model parameterization in Table I of [33], where a fit to low-energy phenomenological results has been made.

A consistent relativistic approach to the quark hadron phase transition where the hadrons appear as bound states of quarks is not yet developed. First steps in the direction of such a unified approach to quark-hadron matter have been accomplished within the NJL model in [34]. In this paper, however, the role of quark exchange interactions between hadrons (Pauli principle on the quark level) has yet been disregarded. As has been demonstrated within a nonrelativistic potential model approach, these contributions may be essential for a proper understanding of the short-range repulsion [35] as well as the asymmetry energy at high-densities [36]. In the present work we apply a so-called two-phase description where the nuclear matter phase is described within the relativistic Dirac-Brueckner-Hartree-Fock (DBHF) approach considered in [1] and the transition to the quark matter phase is obtained by a Maxwell construction. The critical chemical potential of the phase transition is obtained from the equality of hadronic and quark matter pressures. A discussion of the reliability of the Maxwell construction for the case of a set of conserved
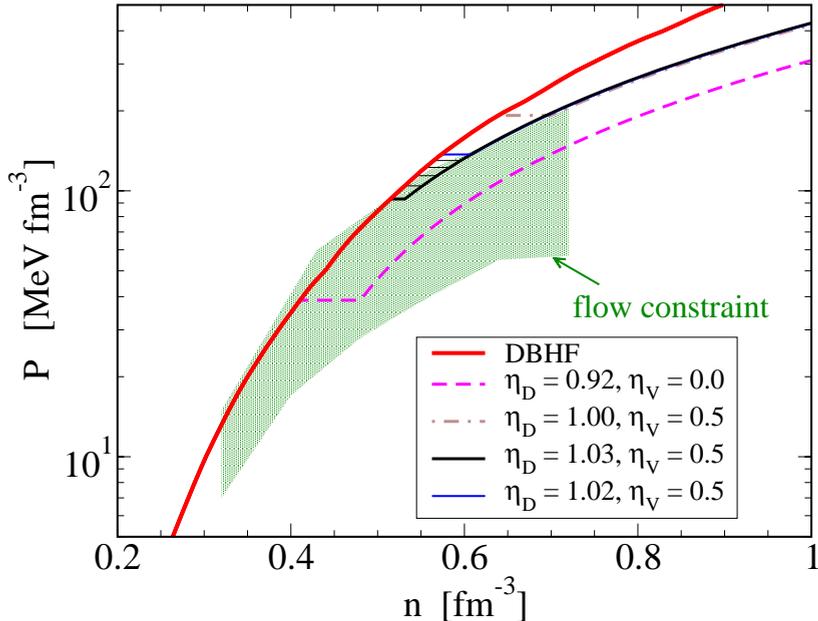
charges is discussed in [37].

Fig. 1. Pressure vs. density of the isospin symmetric EoS for different values of the relative coupling strengths η_D and η_V. The behaviour of elliptic flow in heavy-ion collisions is related to the EoS of isospin symmetric matter. The upper and lower limits for the stiffness deduced from such analyses are indicated in the figure (shaded region). The quark matter EoS favored by the flow constraint has a vector coupling $\eta_V = 0.50$ and a diquark coupling between $\eta_D = 1.02$ (blue solid line) and $\eta_D = 1.03$ (black fat solid line); results for four intermediate values $\eta_D = 1.022 \ldots 1.028$ are also shown (thin solid lines).

The baryon density as derivative of the pressure with respect to the baryochemical potential exhibits a jump at the phase transition, as shown for isospin-symmetric matter in Fig. 1. As can be seen in that Figure, a slight variation of the quark matter model parameters η_D and η_V results in considerable changes of the critical density for the phase transition and the behaviour of the pressure (stiffness) at high densities. There appears the problem of a proper choice of these parameters which we suggest to solve by applying the flow constraint [14] to symmetric matter, shown as the hatched area in Fig.1. At first we fix the vector coupling by demanding that the high density behavior of the hybrid EoS should be as stiff as possible but still in accordance with the flow constraint. We obtain $\eta_V = 0.50$, independent of the choice of the scalar diquark coupling. The latter we want to determine such that the problem of the violation of the flow constraint for the DBHF EoS in symmetric nuclear matter at high densities is resolved by the phase transition to quark matter. The optimal choice for η_D is thus between 1.02 and 1.03. In the following we will investigate the compatibility of the now defined hybrid star equation of

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state with CS constraints.

3 Astrophysical constraints on the high-density EoS

Recently, observations of compact objects have resulted in new limits for masses and radii which put stringent constraints on the high-density behaviour of the nuclear matter EoS, see [1].

Particularly demanding data come from the pulsar PSR J0751+1807 with a lower mass limit of $M \geq 1.9 \, M_\odot$ [2], and the isolated compact star RX J1856 with a mass-radius relationship supporting a radius exceeding 13.5 km for typical masses below 1.4 $M_\odot$ or masses above 1.9 $M_\odot$ for stars with radii $R \leq 12$ km [3]. In Fig.2 we display these constraints together with lines of constant gravitational redshift.

The above constraints have to be explained by any reliable CS EoS, i.e. the mass radius relation resulting from a corresponding solution of the Tolman-Oppenheimer-Volkoff equations has to touch each of the regions shown in Fig. 2. This is well fulfilled for the purely hadronic DBHF EoS.

It is widely assumed that if quark matter would exist in CSs, the maximum mass would be significantly lower than for nuclear matter stars (NMS). This argumentation has been used to claim that quark matter in neutron stars is in contradiction with observations [5].

As we will show in this work, large hybrid star masses can be obtained for sufficiently stiff quark matter EsoS. In this case, the corresponding hybrid (NJL+DBHF) QCS sequence is not necessarily ruled out by phenomenology. The stiffness of the quark matter EoS can be significantly increased when the vector meson interaction of the NJL model introduced in Section 2 is active. The maximum value of the vector coupling which is still in accordance with the upper limit extrapolation of the flow constraint, $\eta_V = 0.50$, see Fig. 1, allows a maximum mass of 2.1 $M_\odot$. With this choice the constraints from PSR J0751+1807 and RX J1856 displayed in Fig. 2 can be fulfilled.

The maximum mass is rather inert to changes of the diquark coupling η_D whereas the critical mass for the occurrence of a quark matter core gets significantly lowered by increasing the value of η_D. For example, the choice of η_D in the range $1.02 - 1.03$ corresponds to critical star masses from 1.35 $M_\odot$ to 1.0 $M_\odot$, see Fig. 2.

Another robust statement from our studies of the hybrid EoS is that the occurrence of a CFL quark matter core renders the compact star unstable.

This confirms an earlier findings by Baldo et al. [17] and Buballa et al.[31] for slightly different hybrid EsoS.

An additional test to the mass-radius relation could be provided by a measurement of the gravitational redshift. We note that the redshift z=0.35 found for EXO 0748-676 [6], which could not be confirmed by further measurements [7], would be in accordance with both NMS and QCS interpretations. A measurement of $z \geq 0.5$ could not be accommodated with the QCS model suggested here, while the NMS would not be invalidated by redshift measurements up to $z = 0.6$.
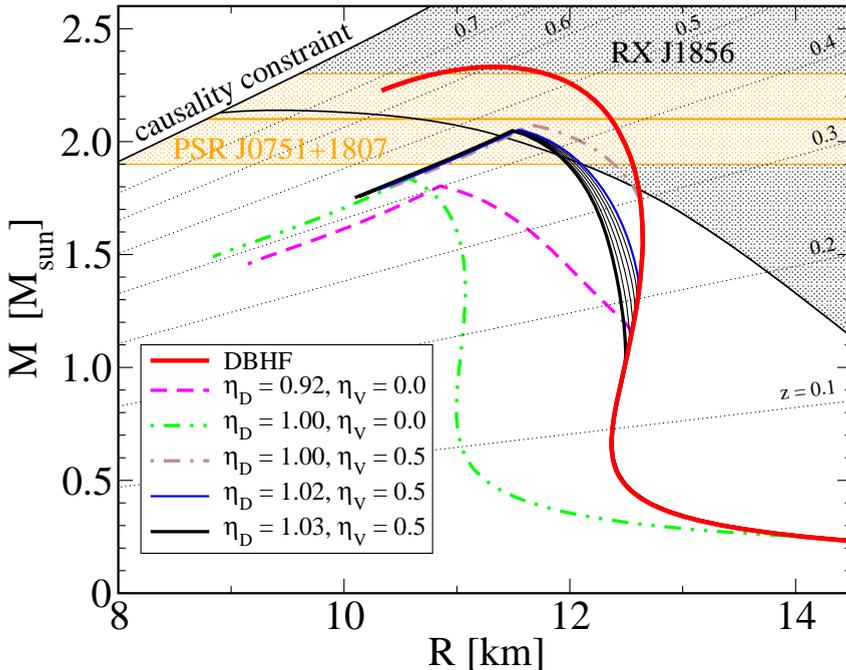

Fig. 2. Mass - radius relationship for CS sequences corresponding to a nuclear matter EoS (DBHF) and different hybrid star EsoS (DBHF+NJL), see text. Indicated are also the constraint on the mass from the pulsar J0751+1807 [2] and on the mass-radius relationship from the isolated neutron star RX J1856 [3] Present constraints on the mass-radius relation of CSs do not rule out hybrid stars. The dotted lines indicate the gravitational redshift, $z = (1 - 2GM/R)^{-1/2} - 1$, of photons emitted from the compact star surface.

Next we want to discuss the question whether measurements of the moment of inertia (MoI) I might serve as a tool to distinguish pure NMS from QCS models. Due to the discovery of the relativistic double pulsar PSR J0737+3039 a measurement of the MoI became a possibility and has been recently discussed as another constraint on the EoS of compact stars, assuming that future mea-
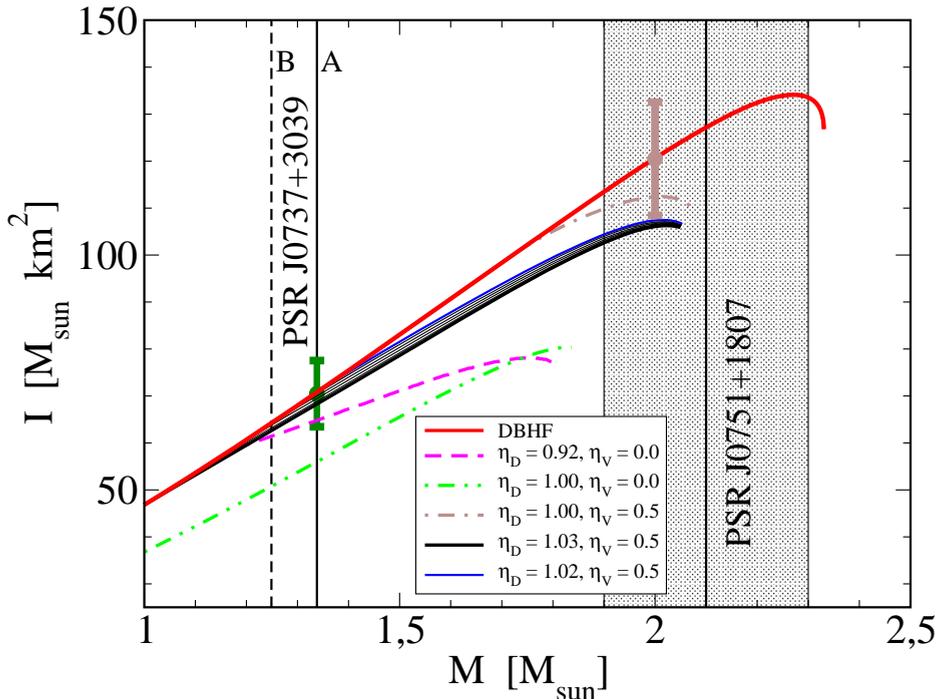
Fig. 3. Moment of inertia vs. the gravitational mass for the compact star EsoS discussed in the text. The highlighted mass regions correspond to the double pulsar J0737+3039 A+B and the pulsar J0751+1807. We also show anticipated data points with error bars corresponding to a measurement with a 1 σ level of 10%.

surements will exhibit an error of only about 10% [47,48]. In our calculations we follow the definition of the MoI given in Ref. [46] and show the results for the EsoS of the present paper in Fig. 3. Due to the fact that the mass 1.338 $M_{\odot}$ of PSR J0737+3039 A is in the vicinity of the suggested critical mass region, the quark matter core is small and the expected MoI of the hybrid star will be practically indistinguishable from that of a pure hadronic one. The situation would improve if the MoI could be measured for more massive objects because the difference in the MoI of both alternative models for masses as high as 2 $M_{\odot}$ could reach the 10% accuracy level.

Finally we would like to discuss the question whether there are observables suited to distinguish between pure neutron stars and those with a quark matter interior. As we have seen in the previous results, the hydrodynamic behavior of the hybrid star EoS has to be rather similar to that of pure hadronic matter in order to allow for sufficiently large masses. If so, the moment of inertia and other mechanical properties of the resulting stars will turn out to be indistinguishable to the level of a few percent. A different situation might occur for CS cooling where the transport properties and thus the excitation spectra of the dense matter play the essential role. As an example, pairing

gaps of the order of an MeV or below will not affect the thermodynamics but are sufficiently large to influence on neutrino cooling processes. Let us discuss the example of the direct Urca (DU) process.

If the DU process would occur in hadronic matter, it would give rise to a fast cooling and result in a strong sensitivity to slightest mass changes of the corresponding compact object. Therefore, it should not occur in CSs with masses below 1.5 $M_\odot$, as this would provide a cooling rate that is inconsistent with CS population syntheses [38,39]. If on the other hand the DU process does *not* occur in a hadronic star, one would require that young, fast coolers such as Vela and 3C58 should have a rather large mass, again in contradiction with the present population syntheses.

A possible resolution to this hadronic cooling problem could be a phase transition to quark matter with moderately enhanced cooling. This has been demonstrated for hybrid stars with a 2SC+X quark matter phase [40] which is in accordance with all presently known cooling constraints [39]. The physical nature of the hypothetical X-gap is, however, not yet clarified. A discussion of this issue can be found in Refs. [41,42].

For the DBHF EoS the DU threshold is at $n_{\mathrm{DU}} = 0.375$ fm^{-3} corresponding to a CS mass of $M_{\mathrm{DU}} = 1.26\ M_\odot$, see Fig. 4. The hybrid EoS presented in this work has a critical density for the quark matter phase transition which is below n_{DU} provided a value $\eta_D \geq 1.024$ is chosen.

Thus for the parameter values $\eta_V = 0.50$ and $\eta_D \gtrsim 1.024$ the present EoS for hybrid star matter fulfills all modern observational constraints discussed above.

4   Summary

We have investigated the compatibility of present constraints on the high density EoS with the concept of CSs possessing a QM core. The hadronic part of the EoS was taken from the DBHF approach, while the QM EoS is provided by a chiral NJL-type quark model with current-current interactions in the color singlet (isoscalar) scalar and vector meson channels as well as in the color antitriplet scalar diquark channels. The finite vector meson coupling enables us to describe large hybrid star masses by stiffening the QM EoS, whereas the chosen value for the diquark coupling ensures a sufficiently early phase transition to QM in order to avoid the activation of DU cooling within the hadronic shell of the hybrid star. Since the high density QM part of the EoS is softer than the corresponding pure hadronic EoS also the flow constraint is fulfilled in this scenario. We discussed the possibility to distinguish between
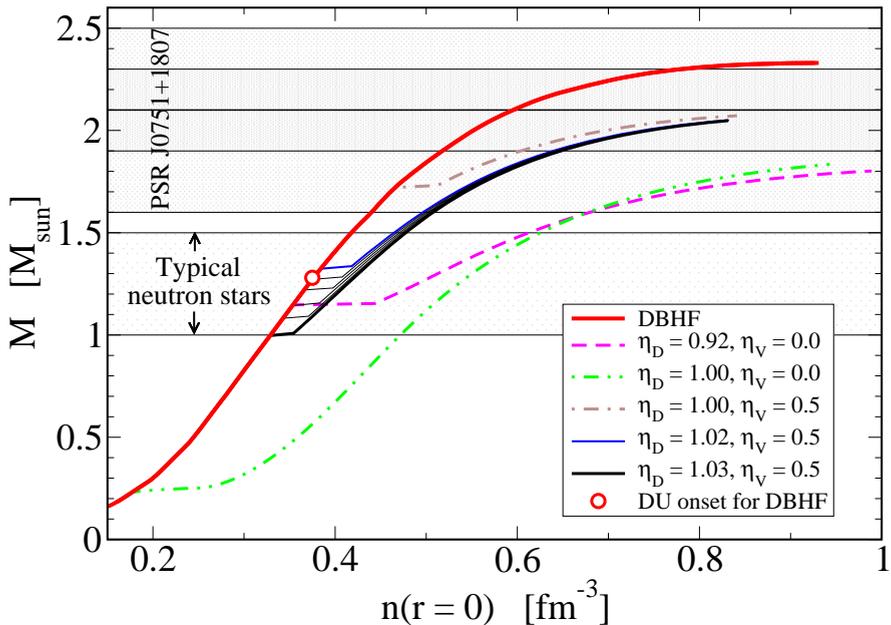
Fig. 4. Compact star masses vs. the central density for different values of the relative coupling strengths η_D and η_V, see Section 2. In a pure neutron (DBHF) star, DU processes occur for $M > M_{DU} = 1.26~M_\odot$ (circle). The maximum mass of hybrid star configurations depends mainly on the relative strength of the vector meson coupling, η_V, while the transition density depends on η_V and η_D.

pure NSs and hybrid stars by hypothetical data from successful measurements of the MoI for stars of a given mass. It turned out, that this would be possible for rather massive objects ($M \approx 2.0~M_\odot$) provided the standard deviation of the measurements is less than 10%, as expected for PSR J0737+3039 A.

As our main result we conclude that *no present phenomenological finding bears a strong argument against the presence of a QM core inside NSs.* Moreover, we demonstrated that problems with cooling and flow which appear as weak points of a purely hadronic EoS at large densities can be resolved in a natural way when a transition to QM occurs at not too large densities.

The most common argument against the presence of QM in CSs, resulting from the *prejudice* of the softness of QM EsoS, is no longer valid if we account for a vector meson interaction channel which stiffens the EoS. The earlier finding that CFL quark matter cannot be found in stable hybrid stars has been reconfirmed and appears thus as a severe constraint for phenomenological scenarios of compact star evolution.

However, there is a discrepancy between the phenomenologically deduced values of the coupling constants $(\eta_D, \eta_V)_{\text{phen}} = (1.024, 0.5)$ and those expected

from the Fierz rearrangement argument $(\eta_D, \eta_V)_{\text{Fierz}} = (0.75, 0.5)$. It is necessary to repeat the present study for more realistic microscopic approaches to the QCD EoS taking into account, e.g., that QCD interactions are nonlocal and momentum-dependent. One possible strategy could consist in the application of nonlocal, separable models [49,50] which can be generalized to use covariant formfactors [51,52] to be adjusted such that Lattice QCD results on the momentum dependence of the quark selfenergies [53] could be reproduced. Moreover, one should go beyond the mean-field level of description and treat hadrons as bound states of quarks. This would allow to model the hadron-to-quark-matter phase transition in a more consistent way as the dissolution of hadronic bound states into correlations in the continuum of quark matter.

Acknowledgments

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