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Quark mass effects on the stability of hybrid stars

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Abstract

We perform a study of the possible existence of hybrid stars with color superconducting quark cores using a specific hadronic model in a combination with an NJL-type quark model. It is shown that the constituent mass of the non-strange quarks in vacuum is a very important parameter that controls the beginning of the hadron–quark phase transition. At relatively small values of the mass, the first quark phase that appears is the two-flavor color superconducting (2SC) phase which, at larger densities, is replaced by the color-flavor locked (CFL) phase. At large values of the mass, on the other hand, the phase transition goes from the hadronic phase directly into the CFL phase avoiding the 2SC phase. It appears, however, that the only stable hybrid stars obtained are those with the 2SC quark cores.

1. Introduction

At low temperatures and high densities, strongly interacting matter is expected to be a color superconductor. The prediction that the related energy gaps could be of the order of 100 MeV in quark matter at densities of a few times nuclear matter density [1,2] evoked many theoretical studies of color superconducting matter at intermediate and high densities, suggesting that the structure of the QCD phase diagram could be very rich (for reviews see, e.g., Refs. [3–6]). Most prominent are the two-flavor color superconducting (2SC) phase where only up and down quarks are paired and the color-flavor locked (CFL) phase where up, down and strange quarks participate in a diquark condensate.

Since the temperatures attained in heavy-ion collisions are probably too high to produce color superconducting phases, compact stars seem to be the most promising objects to test these ideas empirically. Therefore, many theoretical investigations have been performed to identify possible signals of color superconducting quark matter in the interior of stars. At this point, obviously the first question is whether the equation of state of strongly interacting matter allows for the existence of quark cores inside stars (which should be called hybrid stars then). This question has already

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been addressed in several works using different approaches with taking the effects of color superconductivity into account (see, for example, Refs. [7–11]).

Since it is a very difficult task to construct an equation of state for hadronic and quark matter on the same footing, usually a hybrid equation of state is employed. This consists in taking some realistic hadronic equation of state and combining it with some description of deconfined quark matter. The phase transition point is thereby determined using the criterion of maximal pressure. Studies employing a bag-model description of quark-matter phases often show reasonable windows in parameter space where hybrid stars could exist. Moreover, bag-model studies revealed that a diquark condensation in color superconducting phases, although it contributes only to subleading order to the pressure, could have a large effect on the hadron–quark phase transition [12] and on the properties of compact stars [7] because the bag constant cancels out most of the leading μ^4 term. On the other hand, bag-model calculations miss possible effects of the density and phase dependence of the quark masses, diquark gaps and the bag constant. Several authors have therefore employed NJL-type quark models where these effects can be studied.

Two early investigations in this direction were performed in Refs. [13,14]. It was shown that quarks can possibly exist in a hadron–quark mixed phase inside a star, but not in a pure quark core. This result could be traced back to the effective bag constant and the effective strange quark mass, which are dynamically generated quantities in NJL-type models and which are usually quite large. These investigations, however, did not include the possibility of diquark condensation. By including such effects, the authors of Refs. [10,11] found stable hybrid stars with pure quark cores using an NJL description of the quark phase. This is in contrast to the findings of Ref. [9] where no stable configurations containing a pure quark core were found even if color superconductivity was taken into account.

As our knowledge based on first principles about the quark phase at relevant densities is rather limited and we have to rely on model studies, it is very important to sort out the physical reasons for these, at first sight contradictory, findings. We will thereby concentrate on the differences between the approaches of Ref. [9] and Ref. [11], since this already suffices to show the main point. The most obvious difference between these two studies is the fact that the quark-matter equation of state has been derived within a two-flavor model in Ref. [11] and within a three-flavor model in Ref. [9]. In fact, it was found by the latter that the hadron–quark phase transition takes place only if strange quarks play a non-negligible role in quark matter. In particular, if diquark condensates were included, the transition always went directly to the CFL phase, whereas the 2SC phase did not appear. This is in qualitative agreement with earlier arguments given in Ref. [15] where it was claimed that the 2SC phase is never favored if electric and color neutrality is imposed, as required for compact stars. However, since the strange quarks are relatively heavy, it was found in Ref. [9] that their emergence causes a strong increase of the energy density at the phase transition point, rendering the would-be hybrid star unstable against collapse.

This problem did not arise in Ref. [11] where strange quarks have not been taken into account. Here the energy density increases only slightly due to the quark degrees of freedom and the resulting hybrid equation of state can accommodate stable compact stars with pure quark-matter cores. However, in view of Ref. [9], one may ask whether this result would persist if strange quarks were added to this model. One may also wonder, how a hadron–quark phase transition in Ref. [11] without strange quarks was possible at all.

Let us begin with the second question. A priori, there are two possible sources of the observed differences: the hadronic part and the quark part of the equation of state. Since our firm knowledge about the hadronic part is limited to the vicinity of the nuclear matter saturation point, there can be large differences in the behavior at higher densities. To get an idea about the variations, the authors of Ref. [9] have employed three rather different hadronic equations of state. Thus, although yet another hadronic equation of state has been used in Ref. [11], the essential difference is more likely to come from the quark part.

In fact, if we compare the vacuum properties of the two NJL models, we see that the constituent masses of the up and down quarks are $M_u^{\mathrm{vac}} = 368$ MeV in Ref. [9], but only 314 MeV in Ref. [11]. If these were non-interacting constituent quarks, this would mean that the quark gas reaches zero pressure only at $\mu_B = 3M_u^{\mathrm{vac}} \simeq 1100$ MeV in the former, but already at the nucleon mass in the latter case. From this point of view, it appears plausible that it is much harder for the heavier quarks of Ref. [9] to compete with hadronic matter than for the lighter ones of Ref. [11]. In an NJL model, the quarks are of course interacting and their masses at large densities are much smaller than in vacuum. Nevertheless, as we will see below, the net effect is quite similar.

To investigate this point more carefully (as well as the question about the influence of the strange quarks), we consider the following NJL type quark model defined by the Lagrangian density

$$\mathcal{L} = \bar\psi(i\partial\!\!\!/ - \hat m)\psi + \mathcal{L}_{q\bar q} + \mathcal{L}_{qq}, \tag{1}$$

where ψ denotes a quark field with three flavors and three colors. The mass matrix $\hat m$ has the form $\hat m = \mathrm{diag}(m_u, m_d, m_s)$ in flavor space. The interaction splits into a quark–quark part

$$\mathcal{L}_{qq} = H \sum_{A=2,5,7} \sum_{A'=2,5,7} \left(\bar\psi i\gamma_5 \tau_A \lambda_{A'} C \bar\psi^{\mathrm{T}}\right) \times \left(\psi^{\mathrm{T}} C i\gamma_5 \tau_A \lambda_{A'} \psi\right) \tag{2}$$

and a quark–antiquark part

$$\mathcal{L}_{q\bar q} = G \sum_{a=0}^{8} \left[(\bar\psi \tau_a \psi)^2 + (\bar\psi i\gamma_5 \tau_a \psi)^2\right] - K\left[\det{}_f\left(\bar\psi(1+\gamma_5)\psi\right) + \det{}_f\left(\bar\psi(1-\gamma_5)\psi\right)\right]. \tag{3}$$

Here τ_i and λ_j are $SU(3)$-(Gell-Mann-)matrices in flavor and color space, respectively. $\tau_0 = \sqrt{2/3}\mathbb{1}_f$ is proportional to the unit matrix in flavor space. The same three-flavor model has been employed in Ref. [9].[1]

To study the quark mass dependence, we use two different parameter sets throughout the following analysis. The first one (hereafter "RKH") is taken from Ref. [18] and is the parameter set employed in Ref. [9], while the second set (hereafter "HK") is taken from Ref. [19]. Both sets have been fixed by fitting the masses and decay constants of pseudoscalar mesons, but it turns out that the HK fit results in somewhat smaller constituent masses in vacuum. In particular, $M_u^{\mathrm{vac}} = 335$ MeV which is 33 MeV smaller than the RKH value of 368 MeV used in Ref. [9]. This is still 21 MeV larger than the vacuum mass in Ref. [11]. For the value of the coupling constant in the diquark channel, H, which cannot be determined from meson properties, we use the same prescription as in Ref. [9] for both sets of parameters, i.e., we take the same value as for the coupling constant in the scalar quark–antiquark channel, G. For comparison, we also consider normal, i.e., color non-superconducting quark matter, $H = 0$. However, we do not consider the possibility of the intermediate strengths (e.g., $H \simeq 3G/4$) that may give rise to the recently proposed gapless phases [20,21].

To describe the hadronic phase we will restrict ourselves to the (relatively stiff) equation of state derived in Ref. [22], which has been employed in Ref. [11]. The effect of choosing other hadronic equations of state will briefly be discussed in Section 4.

2. Hybrid equation of state

By specifying the models for the description of hadron and quark matter, we can now determine when the phase transitions between different phases happen. We restrict ourselves to the study of sharp phase transitions between neutral homogeneous phases of hadronic and quark matter. This is partially motivated by the results of Ref. [23] where it was found that a quark–hadron mixed phase is unlikely to be stable for reasonable values of the surface tension, and by the findings in Ref. [17] concerning mixed phases of color superconducting quark matter.

In Fig. 1 the pressure of electrically and color neutral hadronic and quark matter in beta equilibrium is displayed as a function of the baryon chemical potential. The dash-dotted line corresponds to the hadronic equation of state [22]. The other lines correspond to NJL quark matter in the normal phase (dotted), or in a color superconducting phase. Here we have indicated the part which belongs to the 2SC phase by a dashed line and the part which belongs to the CFL phase by a solid line. Since the two solutions cross each other at the 2SC–CFL transition point, the slope of the pressure increases discontinuously, which is clearly visible in the figure. Physically this is related to a sudden increase of the baryon number density due to the fact that the number of strange quarks jumps from almost

[1] For a more detailed analysis of electrically and color neutralquark matter within this model, see also Refs. [16,17].

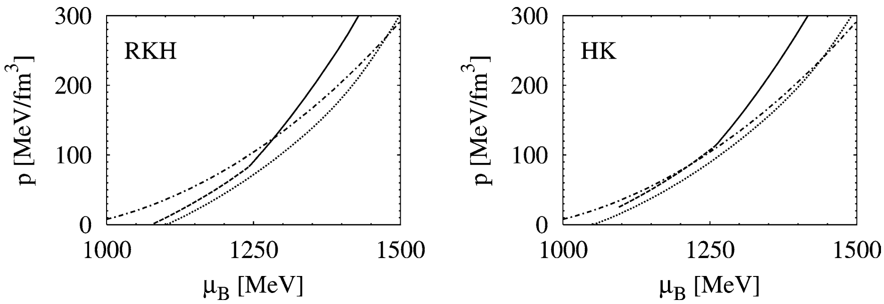

Fig. 1. Pressure of electrically and color neutral matter in beta equilibrium as a function of baryon chemical potential. Dash-dotted line: hadronic matter [22]. The other lines correspond to NJL quark matter in the normal (dotted), 2SC (dashed) or CFL phase (solid), obtained with the parameter sets RKH [18] (left panel) or HK [19] (right panel).

Table 1
Various quantities related to the phase transitions identified in Fig. 1: critical baryon chemical potential, and baryon and energy densities below (1) and above (2) the phase transition

Phase transition	μ_B [MeV]	$\rho_B^{(1)}/\rho_0$	$\rho_B^{(2)}/\rho_0$	$\epsilon^{(1)}$ [MeV/fm^3]	$\epsilon^{(2)}$ [MeV/fm^3]
hadronic → RKH(CFL)	1284	3.6	6.0	657	1188
hadronic → RKH(N)	1477	5.4	7.9	1092	1701
hadronic → HK(2SC)	1216	3.0	3.4	536	627
HK(2SC) → HK(CFL)	1260	4.0	5.7	746	1117
hadronic → HK(N)	1441	5.1	6.5	1000	1353

zero in the 2SC phase to 1/3 of the total quark number in the CFL phase. In contrast, there is no such behavior in the normal quark matter phase where the strange quarks come in smoothly.

Now, the points of phase transitions are easily read off as the points of equal pressure, i.e., the points where the lines $p(\mu_B)$ cross. The results are summarized in Table 1. We begin our discussion with the left panel of Fig. 1 where the quark equations of state are based on the RKH parameter set. This is the parameter set used in Ref. [9] for the description of quark matter.

We find that the hadron–quark phase transitions occur for both, normal and color superconducting quark matter, although, of course, the presence of diquark condensates lowers the critical chemical potential substantially. In both cases, the phase transition is triggered, to a large extent, by the appearance of strange quarks in the system. In absence of diquark coupling, the transition to normal quark phase happens only at relatively large chemical potential that lies well above the strange quark threshold, $\mu_B^{\text{th}} \simeq 1300$ MeV. At the corresponding critical potential, there are about 25% strange quarks.

In the case of color superconducting quark matter, a phase transition happens much earlier, leading directly to the CFL phase and avoiding an intermediate 2SC phase. This is related to the kink in $p(\mu_B)$ at the 2SC–CFL transition point which strongly accelerates the phase transition from the hadronic phase. As pointed out above, the kink in the pressure dependence is associated with the sudden appearance of a large amount of strange quarks in the CFL phase. In contrast, the diquark condensation in the 2SC color superconducting phase practically does not change the slope of the pressure curve. Instead, it leads only to a moderate shift of the curve as a whole which can be attributed to an additional binding due to the formation of Cooper pairs. Thus, the use of the RKH parameter set seems to leave no chance for the presence of the 2SC phase in neutral strongly interacting matter. This is in agreement with the conclusions of Ref. [9].

It turns out, however, that the validity of this statement depends strongly on the value of the constituent mass of the non-strange quarks in vacuum. As argued above, the latter controls the point of zero pressure in the NJL model. Thus, the main effect of a smaller light quark constituent mass in vacuum is to shift the pres-

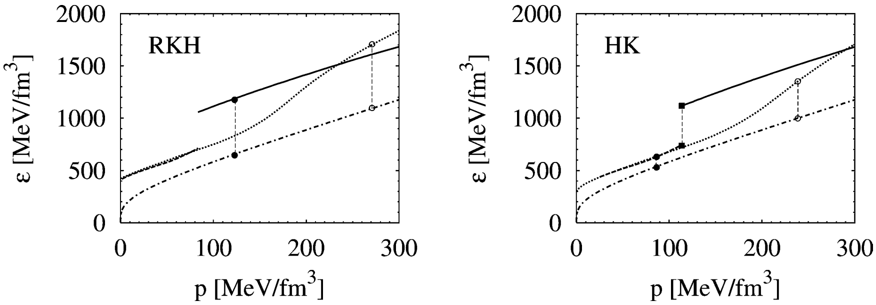

Fig. 2. Energy density as a function of pressure for the hadronic equation of state [22] (dash-dotted lines) and NJL quark matter obtained with parameter sets RKH [18] (left panel) and HK [19] (right panel): normal quark phase (dotted), 2SC (dashed), CFL (solid). The points with the thin vertical lines indicate the positions of the phase transitions.

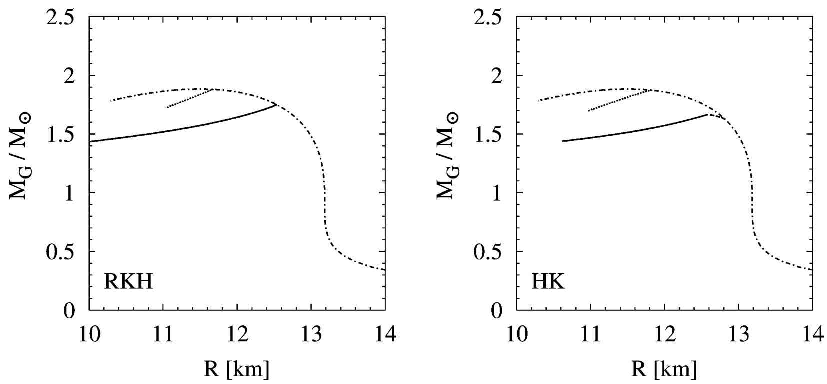

Fig. 3. Gravitational masses of static compact stars as functions of the radius for the different equations of state. The dash-dotted lines indicate the results for a purely hadronic star. The other lines indicate the presence of a quark phase in the center: normal phase (dotted), 2SC dashed, CFL (solid). The quark phases in the left panel have been calculated with parameter set RKH, those in the right panel with parameter set HK.

sure curves to lower chemical potentials. This can be seen by comparing the results on the left-hand side of Fig. 1 with the curves displayed in the right panel where we employed the parameter set HK. There, as a result of the shift, we indeed get a phase transition into the 2SC phase before that is replaced by the CFL phase at a somewhat higher chemical potential (see Table 1 for details). Although the window is rather small, it makes a qualitative difference for compact stars, as we will discuss below.

The equations of state, i.e., the energy density as a function of pressure, for the various phases are presented in Fig. 2. At the first-order phase transition boundaries the density and, hence, the energy density increases discontinuously. The corresponding values are listed in Table 1. As one can see, in most cases the discontinuity is rather large. The only exception is the hadron-2SC transition where the jump of the energy density is relatively small.

3. Star structure

For a given equation of state, $\epsilon = \epsilon(p)$, the gravitational mass M_G of a static compact star as a function of its radius R can be obtained by solving the Tolman–Oppenheimer–Volkoff equation [24]. The resulting curves for the hadronic and hybrid equations of state constructed above are displayed in Fig. 3. The dash-dotted lines indicate the results for a purely hadronic star. For a more realistic description of the crust, i.e., the region of subnuclear matter densities, we have employed the equations of state of Baym, Pethick and Sutherland [25] for $\rho_B < 0.001\ \mathrm{fm}^{-3}$ and

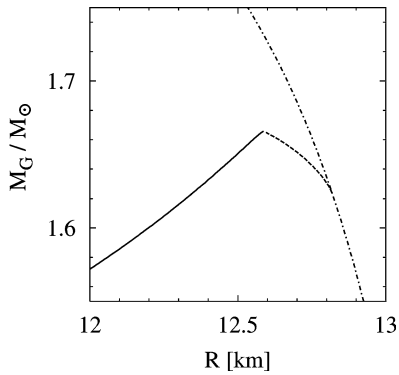

Fig. 4. Enlarged detail of the right panel of Fig. 3, showing the emergence of a color superconducting quark core in a compact star calculated with the hybrid equation of state obtained with the NJL parameter set HK. The meaning of the various line types is the same as in Fig. 3.

of Negele and Vautherin [26] for 0.001 $\mathrm{fm}^{-3} < \rho_B <$ 0.08 fm^{-3}. The configurations containing a normal quark matter core are indicated by dotted lines and those with a color superconducting core in the CFL phase by solid lines. As we noted earlier, in the case of the HK quark equation of state (right panel), there is a phase transition from hadronic matter to the 2SC phase, followed by a second phase transition to the CFL phase. Here we have indicated the part of the curve which corresponds to a 2SC phase (but not yet a CFL phase) in the center of the star by a dashed line. This part of the figure is also presented in an enlarged form in Fig. 4.

The onset of a quark matter phase in the center of the star implies of course a deviation from the corresponding hadronic matter curve. Because of the discontinuous energy density at the phase transition point (see Table 1 and Fig. 2) this is always related to a cusp in the mass-radius relation. These cusps are clearly visible in Figs. 3 and 4. However, for all transitions to normal or to CFL quark matter the effect is so strong that the star is rendered unstable. This is exactly what has been observed in Ref. [9].

On the other hand, at the hadron-2SC phase transition (Fig. 4) the star remains stable. This proves that stable hybrid stars are possible within the NJL model, even if strange quarks are included. However, as soon as the 2SC–CFL phase transition takes place, the star becomes unstable. Therefore, in this example, hybrid stars only exist in a small mass window between 1.62 and 1.66 $M_\odot$. Nevertheless, the maximum radius of the 2SC core in a stable configuration is 3.5 km, about one quarter of the total radius of the star.

Although our assumption of sharp phase transitions between homogeneous neutral phases seems well justified, since for the transition from hadronic to quark matter as well as for the transition from the 2SC to the CFL phase surface energy effects are likely to favor a homogeneous interface [17,23], we cannot completely exclude the existence of mixed hadronic–quark phases. In that case the energy density would not jump, but continuously interpolate between the hadronic and the quark solution. As a consequence, the cusps in Figs. 3 and 4 would be smoothened out and the instability would not occur immediately at the onset of the mixed phase. We expect, however, that in this case the star would become unstable before the mixed phase turns into a pure quark phase if this is the CFL or normal quark matter phase.

4. Discussion

In this Letter, we continued the systematic study of Refs. [7–11] in search of possible constructions of hybrid stars with color superconducting quark matter in their interior. In order to understand the striking differences in the conclusions of Ref. [9], where no stable hybrid star constructions were found, and Ref. [11], where the hybrid stars with the 2SC quark cores were the most natural constructions, we considered a combination of a specific hadronic equation of state with two different equations of state for quark matter. Without much of a limitation, we used only constructions with sharp boundaries between different phases of matter.

While the hadronic equation of state is without any doubt a very important input in the constructions of hybrid baryonic matter, here we concentrate mostly on the role of the quark equations of state. In bag models, like in Ref. [7], these are mainly determined by the values of the bag constant, the diquark gap, and the strange quark mass. In NJL-type models, the quarks acquire effective (“constituent”) masses through dynamical breaking of chiral symmetry. Although this is in some way related to an effective bag constant, the effect is more complex and cannot be described by a single density independent number. In particular, the strange and the non-strange sectors partially decouple.

In the present Letter we show that a very important parameter in NJL-type models of quark matter is the value of the constituent mass of the *non-strange* quarks in vacuum. This parameter controls the value of the baryon chemical potential at which the pressure is zero. For example, decreasing (increasing) the mass parameter has the effect of shifting the whole dependence of the pressure to smaller (larger) values of the baryon chemical potential and thereby the hadron–quark phase transition to lower (higher) densities. Therefore, for relatively small values of the mass, the first quark phase that appears with increasing baryon density is the two-flavor color superconducting (2SC) phase which is eventually replaced by the color-flavor locked (CFL) phase at higher densities. For large values of the mass, on the other hand, the phase transition goes from the hadronic phase directly into the CFL phase avoiding the 2SC phase.

This difference turned out to be crucial for the stability of hybrid stars. We found that hybrid stars, if they exist, have a quark core in the 2SC phase and contain only a small fraction of strange quarks. Also, our study suggests that the size of a quark matter core inside a hybrid star is very sensitive to the choice of the non-strange quark mass parameter in the NJL model. In particular, when one goes from the "small" mass limit, as in Ref. [11], to the "large" mass limit, as in Ref. [9], the quark core radius changes from being very large to vanishing.

In the NJL model studied here, we find no stable stars with either CFL or normal quark matter cores. This is the opposite of the prediction of Ref. [15] where it was argued that there is no 2SC phase in compact stars. Let us be more precise: performing a Taylor expansion in the strange quark mass, the authors of Ref. [15] found that in beta-equilibrated electrically and color neutral quark matter the 2SC phase is always less favored than the CFL phase or normal quark matter. From this observation they concluded that the 2SC phase is absent in compact stars. In contrast to this result, it was shown in Ref. [16] in the framework of the NJL model that neutral 2SC matter could be the most favored quark phase in a certain regime. However, the authors argued that this interval might disappear if the hadronic phase is included more properly. This is indeed what we found for parameter set RKH, while for parameter set HK the 2SC phase survives only in a tiny window. Nevertheless, if Nature chooses to be similar to this equation of state, it will be this tiny window which gives rise to hybrid stars, whereas the CFL phase would be never present in compact stars.

At this point we should ask, to what extent our results, which are based on two examples can be considered as a general feature. To address this, let us briefly come back to the dependence on the hadronic equation of state. As mentioned earlier, in Ref. [9] three different hadronic equations of state have been considered. For the stiffest one, obtained within a microscopic Brueckner–Hartree–Fock calculation without hyperons [27], the results are in qualitative agreement with ours if the quark phase is described by the RKH equation of state. The two other hadronic equations of state employed in Ref. [9] are softer, thus rendering a transition to quark matter less favorable. In fact, for the softest equation of state, based on a Brueckner–Hartree–Fock calculation with hyperons [28], no phase transition was found at all, while for the intermediate one, based on a relativistic mean-field model [29], a phase transition took place only if diquark pairing was taken into account. Employing these three hadronic equations of state, we found that none of the results reported in Ref. [9] changes qualitatively if the NJL parameters HK are used instead of RKH. In particular, in none of these cases there is an intermediate 2SC phase and there are no stable hybrid stars.

Both, an intermediate 2SC phase and stable hybrid stars, thus appear as rather exceptional cases which we only obtained if the very stiff hadronic equation of state based on Ref. [22] is combined with the HK quark equation of state. The constituent mass of the non-strange quarks thereby plays a key role. Note in addition that our choice $H = G$ for the diquark coupling constant is likely to be an upper limit. With a smaller coupling, there would be less binding in the 2SC phase and eventually the small window of stable hybrid stars which is seen in Fig. 4 may close. On the other hand, if we further decrease the constituent mass of the non-strange quarks, the window could become wider. Similarly, a larger constituent mass of the strange quarks would render the CFL phase less favored and thereby help stabilizing the 2SC phase. A systematic study in all these directions still remains to be done. This should also include the consideration of other color superconducting phases which have not been taken into account here.

Whereas the question about details of the hadron–quark phase transition is thus strongly dependent on both, the hadronic equation of state and the choice of the parameters for the quark phase, all NJL-model calculations so far agree that there is no stable hybrid star with a quark core in the CFL phase or in the normal phase with a large fraction of strange quarks. As mentioned earlier, this observation, which is in contrast to the bag-model results of Ref. [7], can be explained by the fact that the dynamically generated effective bag constants and effective strange quark masses of the NJL model are in general quite large. Also, the fact that these effective quantities depend on the phase and are therefore different for normal, 2SC and CFL quark matter leads to important differences to the bag model (see Ref. [9]).

Finally, it should be reminded that our results rely on the assumption that the NJL model parameters which have been fitted in vacuum can be applied to dense matter. It is of course possible that this is not the case. Hence our arguments could also be turned around. The observation, e.g., of a compact star with a CFL quark matter core or even a pure strange quark star would convincingly demonstrate that the quark-matter phase is not well described by an NJL-type model with parameters which are fixed in vacuum.

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