Strange stars with a mirror-dark-matter core confronting with the observations of compact stars

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We investigate the structure and the tidal deformability of strange stars with a mirror-dark-matter core for the standard MIT bag model. We find that to explain the observations of GW170817, PSR J0740 + 6620 and PSR J0030 + 0451 simultaneously, strange stars in GW170817 should have a mirror-dark-matter core although it is unnecessary for PSR J0740 + 6620 and PSR J0030 + 0451 to contain one. More generally, our study leads to the result that for the standard MIT bag model, the observations of compact stars mentioned above could serve as evidence for the existence of a dark-matter core inside strange stars.

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I. INTRODUCTION

As hypothesized by Itoh [1], Bodmer [2], Witten [3], and Terazawa [4], strange quark matter (SQM) consisting of up (u), down (d) and strange (s) quarks and electrons may be the true ground state of baryonic matter. According to this hypothesis, compact stars made entirely of SQM, referred to as strange stars (SSs), ought to exist in the Universe [5–11].

Yang *et al.* [11,12] found that both for the standard MIT bag model and for the density dependent quark mass model, the existence of SSs is ruled out by the dimensionless tidal deformability of a 1.4 $M_\odot$ star of GW170817 [$\Lambda(1.4) = 190^{+390}_{-120}$] [13,14] and the mass of PSR J0740 + 6620 (which was first reported as $2.14^{+0.10}_{-0.09}$ $M_\odot$ for a 68.3% credibility interval [15], and the constraint that the maximum mass of SSs must be greater than 2.14 $M_\odot$ is employed in Refs. [11,12]). Although the mass of PSR J0740 + 6620 has been updated recently to be 2.08 ± 0.07 $M_\odot$ [16], the above conclusions for the standard MIT bag model [12] are not changed if one employs the constraint that the maximum mass of SSs must be greater than 2.08 $M_\odot$, which can be seen from Figs. 1 and 2 in Sec. IV of this paper.

Nevertheless, Yang *et al.* [11,12] demonstrated that if non-Newtonian gravity effects are considered, SSs can exist for certain ranges of the values of the non-Newtonian gravity parameter. In this paper, instead of employing the non-Newtonian gravity effects, we propose an alternative explanation to the above-mentioned astrophysical observations which supposes that SSs have a mirror-dark-matter (MDM) core.

Compact stars might contain a dark-matter core made of self-interacting dark matter [19–21]. Neutron stars (NSs) with a dark-matter core have been studied extensively [22–38]. SSs with a dark-matter core have also been studied [39,40]. Especially, neutron stars with a MDM core have been studied [41,42]. Ciarcelluti and Sandin [42] found that the discrepancy between the mass and radius data of EXO 0748-676 [43] and the group 4U 1608-52, 4U 1820-30 and EXO 1745-248 can be interpreted as the signature of a dark-matter core inside them. One key point of their work is that a MDM core inside NSs leads to an apparent softening of the equation of state (EOS), and the relative amount of MDM in NSs strongly effects the mass-radius relationship of the star. Another key point is that the equilibrium sequence of NSs is nonunique and history dependent, because the relative amount of MDM trapped in each NS could be different, which depends on the individual history, starting from the formation of the progenitor star and continuing through the evolutionary phases until present age.

In this paper, we will study the structure and the tidal deformability of SSs with a MDM core and explain not only the observations of the tidal deformability of GW170817 and the mass of PSR J0740 + 6620, but also the mass and radius of PSR J0030 + 0451 derived from NICER observations [17,18]. Moreover, the radius of PSR J0740 + 6620 derived from NICER and XMM-Newton observations recently [44,45] is also discussed.

This paper is organized as follows: In Sec. II, we briefly review the EOS of SQM and MDM. In Sec. III, we present the theoretical framework of the structure and the tidal deformability of SSs with a MDM core. In Sec. IV,

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numerical results and discussions are presented. Finally, the summary and conclusions are given in Sec. V.

II. EQUATION OF STATE OF SQM AND MDM

Following Yang *et al.* [12], we briefly review the phenomenological model for the equation of state (EOS) employed in this paper, namely, the standard MIT bag model [5–7,10]. In that model, u and d quarks are treated as massless particles but s quarks have a finite mass, m_s. First-order perturbative corrections in the strong interaction coupling constant α_S are taken into account.

The thermodynamic potential for the u, d and s quarks, and for the electrons are given by [6,12]

$$\Omega_u = -\frac{\mu_u^4}{4\pi^2}\left(1-\frac{2\alpha_S}{\pi}\right), \tag{1}$$

$$\Omega_d = -\frac{\mu_d^4}{4\pi^2}\left(1-\frac{2\alpha_S}{\pi}\right), \tag{2}$$

$$\begin{aligned}\Omega_s = -\frac{1}{4\pi^2}\Bigg\{&\mu_s\sqrt{\mu_s^2-m_s^2}\left(\mu_s^2-\frac{5}{2}m_s^2\right)+\frac{3}{2}m_s^4 f(u_s,m_s)\\ &-\frac{2\alpha_S}{\pi}\Bigg[3\left(\mu_s\sqrt{\mu_s^2-m_s^2}-m_s^2 f(u_s,m_s)\right)^2\\ &-2(\mu_s^2-m_s^2)^2-3m_s^4\ln^2\frac{m_s}{\mu_s}\\ &+6\ln\frac{\sigma}{\mu_s}\left(\mu_s m_s^2\sqrt{\mu_s^2-m_s^2}-m_s^4 f(u_s,m_s)\right)\Bigg]\Bigg\},\end{aligned} \tag{3}$$

$$\Omega_e = -\frac{\mu_e^4}{12\pi^2}, \tag{4}$$

where $f(u_s,m_s)\equiv\ln[(\mu_s+\sqrt{\mu_s^2-m_s^2})/m_s]$. The quantity σ $(=300\ \mathrm{MeV})$ is a renormalization constant whose value is of the order of the chemical potential of strange quarks, μ_s. Values of $m_s=93$ and $m_s=150$ MeV have been considered for the strange quark mass in our calculations [46].

The number density of each species is given by

$$n_i = -\frac{\partial\Omega_i}{\partial\mu_i}, \tag{5}$$

where μ_i ($i=u$, d, s, e) are the chemical potentials. For SQM, chemical equilibrium is maintained by the weak interaction, which leads for the chemical potentials to the following conditions:

$$\mu_d = \mu_s, \tag{6}$$

$$\mu_s = \mu_u + \mu_e. \tag{7}$$

The electric charge neutrality condition is given by

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0. \tag{8}$$

The energy density is given by

$$\epsilon_Q = \sum_{i=u,d,s,e}(\Omega_i+\mu_i n_i)+B, \tag{9}$$

and the corresponding pressure is obtained from

$$p_Q = -\sum_{i=u,d,s,e}\Omega_i - B, \tag{10}$$

where B denotes the bag constant.

Mirror dark matter (MDM) is a kind of stable and self-interacting dark matter candidate that emerges from the parity symmetric extension of the standard model of particles [47]. The idea of the possible existence of MDM can be traced back to 1956, when Lee and Yang proposed that the weak interactions is not parity symmetric [48], they also pointed out that, even if the interactions of the known particle were to violate parity, the symmetry could be restored if a set of mirror particles existed. For details about MDM, see Refs. [49–59].

In the minimal parity-symmetric extension of the standard model [47,60], the group structure is $G\otimes G$, where G is the gauge group of the standard model. In this model the two sectors are described by the same Lagrangians, but where ordinary particles have left-handed interactions, mirror particles have right-handed interactions. Thus, the microphysics of MDM is the same as that of ordinary matter. In our study, SQM made of up (u), down (d) and strange (s) quarks and electrons (e) is supposed to be the true ground state of baryonic matter. As a result, its mirror twin made of mirror up (u'), mirror down (d') and mirror strange (s') quarks and mirror electrons (e') (i.e., the mirror strange quark matter, which is the composition of the MDM core considered in this paper) is the true ground state of the mirror partner of baryonic matter. Since the microphysics of the mirror strange quark matter is the same as that of SQM, we could use the same EOS for SQM and MDM.

MDM could interact with ordinary matter via gravity. Besides gravity, the two sectors could interact by other means, for instance, photon-mirror photon kinetic mixing. With a mixing of strength (ϵ) of order 10^{-9}, MDM can fulfill all constraints imposed by cosmological observations including those from the cosmic microwave background and big bang nucleosynthesis [36,59]. The effect of such weak interactions on equilibrium structure of a compact star should be small and can be ignored [41]. The interactions between quarks and mirror quarks has not been studied so far. However, if such interactions exist, it is reasonable to suppose that they are weak and can also be ignored in our study.[1] Therefore, we will consider only the gravitational interaction between SQM and MDM in this paper.

III. THE STRUCTURE AND TIDAL DEFORMABILITY OF STRANGE STARS WITH A MDM CORE

In the following, we use geometrized units $G = c = 1$, and use the subscript Q for SQM and D for MDM.

To study the properties of SSs with a MDM core, we employ a two-fluid formalism where SQM and MDM sectors do not interact directly. However, these two sectors interact through the gravitational interaction in this formalism.

In the two-fluid formalism, the Tolman-Oppenheimer-Volkoff (TOV) equations are, e.g., [35,36,41,42]

$$\frac{dm(r)}{dr} = 4\pi\epsilon(r)r^2, \tag{11}$$

$$\frac{dp_Q(r)}{dr} = -\frac{[m(r) + 4\pi r^3 p(r)][\epsilon_Q(r) + p_Q(r)]}{r[r - 2m(r)]}, \tag{12}$$

$$\frac{dp_D(r)}{dr} = -\frac{[m(r) + 4\pi r^3 p(r)][\epsilon_D(r) + p_D(r)]}{r[r - 2m(r)]}, \tag{13}$$

where

$$\epsilon(r) = \epsilon_Q(r) + \epsilon_D(r), \tag{14}$$

$$p(r) = p_Q(r) + p_D(r). \tag{15}$$

The dimensionless tidal deformability is defined as $\Lambda \equiv \lambda/M^5$, where λ denotes the tidal deformability parameter, which can be expressed in terms of the dimensionless tidal Love number k_2 as $\lambda = \frac{2}{3}k_2R^5$ [63–66]. Thus, one has

$$\Lambda = \frac{2}{3}k_2\beta^{-5}, \tag{16}$$

where β is compactness of the star, and it is defined as $\beta \equiv M/R$.

In the two-fluid formalism, the tidal Love number k_2 can be calculated using the expression [67]

$$k_2 = \frac{8}{5}\frac{\beta^5 z}{F}, \tag{17}$$

with

$$z \equiv (1 - 2\beta)^2[2 - y_R + 2\beta(y_R - 1)], \tag{18}$$

and

$$F \equiv 6\beta(2 - y_R) + 6\beta^2(5y_R - 8) + 4\beta^3(13 - 11y_R) + 4\beta^4(3y_R - 2) + 8\beta^5(1 + y_R) + 3z\ln(1 - 2\beta). \tag{19}$$

In Eqs. (18) and (19), $y_R \equiv y(R) - 4\pi R^3\epsilon_s/M$, where $y(R)$ is the value of $y(r)$ at the surface of the star, and the second term of the right-hand side exists because there is a nonzero energy density ϵ_s just inside the surface of SSs [68]. The quantity $y(r)$ satisfies the differential equation

$$\frac{dy(r)}{dr} = -\frac{y(r)^2}{r} - \frac{y(r) - 6}{r - 2m(r)} - rQ(r), \tag{20}$$

with, e.g., [35,36]

$$Q(r) \equiv \frac{4\pi r}{r - 2m(r)}\left[[5 - y(r)]\epsilon(r) + [9 + y(r)]p(r) + \frac{\epsilon_Q(r) + p_Q(r)}{\partial p_Q(r)/\partial\epsilon_Q(r)} + \frac{\epsilon_D(r) + p_D(r)}{\partial p_D(r)/\partial\epsilon_D(r)}\right] - 4\left[\frac{m(r) + 4\pi r^3 p(r)}{r[r - 2m(r)]}\right]^2. \tag{21}$$

For a given EOS of SQM and MDM, Eq. (20) can be calculated together with the TOV equations [Eqs. (11)–(13)] with the boundary conditions $y(0) = 2$, $m(0) = 0$, $p_Q(R) = 0$, $p_D(R_D) = 0$ [R_D is the radius of the MDM core] for a given SQM pressure at the center of the star $p_Q(0)$ and a given MDM pressure at the center of the star $p_D(0)$.

Note that there is another energy density jump ϵ_{sD} at the surface of the MDM core. Therefore, a correction of $-4\pi R_D^3\epsilon_{sD}/M(R_D)$ is added to $y(R_D)$.

IV. RESULTS AND DISCUSSIONS

We investigate the allowed parameter space of the standard MIT bag model according to the following five constraints, e.g., [11,12,69–72].

First, the existence of SSs is based on the idea that the presence of strange quarks lowers the energy per baryon of a mixture of u, d and s quarks in beta equilibrium below the energy of the most stable atomic nucleus, ^{56}Fe ($E/A \sim 930$ MeV) [3]. This constraint results in the three-flavor lines shown in Figs. 1 and 2.

The second constraint is given by assuming that non-strange quark matter (i.e., two-flavor quark matter made of

[1]Neutron-mirror neutron ($n - n'$) mass mixing have been studied [61,62], and the possibility that the ordinary neutron stars, via $n - n'$ conversion, can develop the mirror matter cores in their interiors has been discussed [38]. However, in Ref. [38], the authors pointed out that the transformation to mirror matter should be suppressed in SQM because SQM is self-bound (as strandard nuclei), and the transition to mirror nuclear matter should give no energy gain.

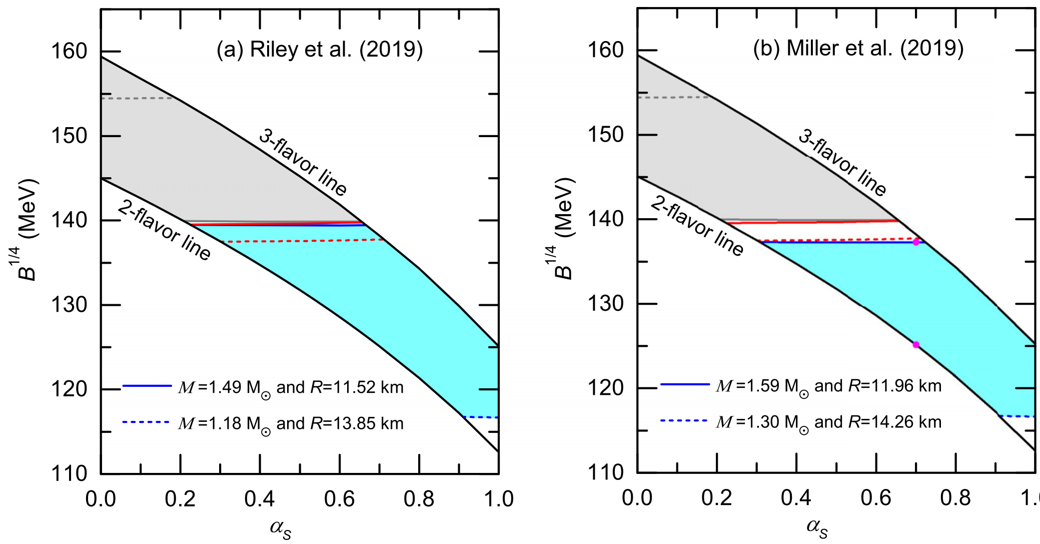

FIG. 1. Constraints on the parameters of the EOS of SQM, namely, $B^{1/4}$ and α_S for SSs without a MDM core for a strange quark mass of $m_s = 93$ MeV. The gray solid and dashed lines are for $\Lambda(1.4) = 580$ and $\Lambda(1.4) = 190$, respectively. The red solid and dashed lines are for $M_{\max} = 2.08\ M_\odot$ and $M_{\max} = 2.14\ M_\odot$, respectively. The gray-shadowed areas corresponds to the allowed parameter space according to the dimensionless tidal deformability of a 1.4 $M_\odot$ star of GW170817 [$\Lambda(1.4) = 190^{+390}_{-120}$]. The cyan-shadowed areas indicate the parameter space which satisfies both $M_{\max} \geq 2.08\ M_\odot$ and the observational data of NICER for PSR J0030 + 0451 [(a) for the analysis by Riley *et al.* [17] and (b) for Miller *et al.* [18]]. The magenta dots in (b) mark the two parameter sets of ($B^{1/4}$(MeV), α_S) [namely, (125.1,0.7) and (137.3, 0.7)], which will be employed for our discussions in Figs. 3 and 4.

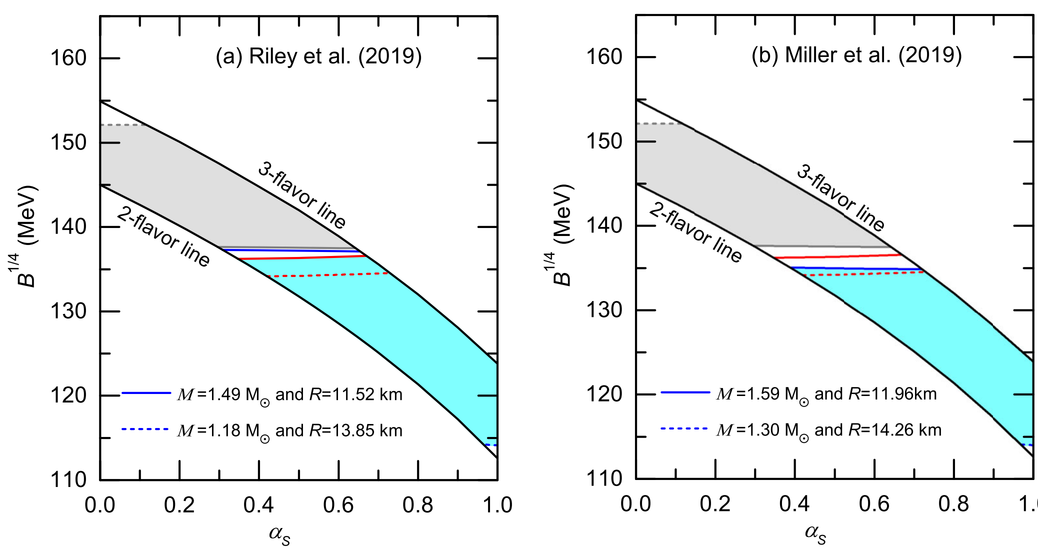

FIG. 2. Constraints on $B^{1/4}$ and α_S for SSs without a MDM core. The only difference between this figure and Fig. 1 is that this figure is for a strange quark mass of $m_s = 150$ MeV (remember that Fig. 1 is for $m_s = 93$ MeV).

only u and d quarks) in bulk has an energy per baryon higher than the one of ^{56}Fe, plus a 4 MeV correction coming from surface effects [5,9,72]. By imposing $E/A \geq 934$ MeV on nonstrange quark matter, one ensures that atomic nuclei do not dissolve into their constituent quarks. This leads to the two-flavor lines in Figs. 1 and 2. The areas between the three-flavor lines and the two-flavor lines in Figs. 1 and 2 show the allowed $B^{1/4}$-α_S parameter regions where the first and the second constraints described just above are fulfilled.

The above two constraints are from nuclear structure. As we discuss the constraints from astrophysics in the following, these two constraints must be fulfilled, which means that we are only interested in the regions between the three-flavor lines and the two-flavor lines in the following.

The third constraint follows from the tidal deformability observation of GW170817, $\Lambda(1.4) = 190^{+390}_{-120}$, where $\Lambda(1.4)$ is the dimensionless tidal deformability of a 1.4 $M_\odot$ star. The parameter regions satisfying this constraint correspond to the gray-shadowed areas in Figs. 1 and 2.

The fourth constraint is from the observational data of NICER for the isolated pulsar PSR J0030 + 0451. The NICER observations produced two independent measurements of the pulsar's mass and equatorial radius: $M = 1.34^{+0.15}_{-0.16}\ M_\odot$ and $R_{\mathrm{eq}} = 12.71^{+1.14}_{-1.19}$ km [17], and $M = 1.44^{+0.15}_{-0.14}\ M_\odot$ and $R_{\mathrm{eq}} = 13.02^{+1.24}_{-1.06}$ km [18]. In Figs. 1 and 2, these data on the M-R plane are translated into the $B^{1/4}$-α_S space. The blue lines in Figs. 1(a) and 2(a) are for ($M(M_\odot)$, R(km)) sets (1.49, 11.52) and (1.18, 13.85), which correspond to the data given by Riley *et al.* [17]. The blue lines in Figs. 1(b) and 2(b) are for (1.59, 11.96) and (1.30, 14.26), which come from the data given by Miller *et al.* [18]. Thus, the areas between the blue solid lines and blue dashed lines are the allowed $B^{1/4}$-α_S parameter regions resulting from the mass and radius constraints of PSR J0030 + 0451.

The fifth constraint is that the maximum mass of SSs must be greater than the mass of PSR J0740 + 6620, which was first reported as $2.14^{+0.10}_{-0.09}\ M_\odot$ [15], and was recently updated to $2.08 \pm 0.07\ M_\odot$ [16] (for a 68.3% credibility interval). In this paper, we will use $M_{\max} \geq 2.08\ M_\odot$. By employing this constraint, the allowed parameter space is limited to the regions below the red solid lines in Figs. 1 and 2. For comparison, the $M_{\max} = 2.14\ M_\odot$ line (the red dashed line) is also presented in Figs. 1 and 2.[2]

The cyan-shadowed areas in Figs. 1 and 2 show the parameter space which satisfies both the fourth and fifth constraints mentioned above. In Figs. 1(a), 1(b) and 2(b), the cyan-shadowed areas are the regions between the blue solid lines and blue dashed lines, which are the same regions as that restricted by the fourth constraint. This is because the red solid lines (for $M_{\max} = 2.08\ M_\odot$) are above the blue solid lines. However, in Fig. 2(a), the red solid line (for $M_{\max} = 2.08\ M_\odot$) serves as the upper boundary of the cyan-shadowed area since it is under the blue solid line.

Here we want to stress that Figs. 1 and 2 are plotted for SSs without a MDM core. As can be seen from Figs. 1 and 2, the cyan-shadowed area does not overlap with the gray-shadowed area, which means that SSs without a MDM core cannot agree with the observations of GW170817, PSR J0740 + 6620 and PSR J0030 + 0451 simultaneously.

[2] $M_{\max} \geq 2.14\ M_\odot$ is employed in our previous papers [11,12]. As can be seen from Figs. 1 and 2, when it is changed to $M_{\max} \geq 2.08\ M_\odot$, the conclusion drawn in Ref. [12] that the existence of SSs is ruled out for the standard MIT bag model by the observed dimensionless tidal deformability of a 1.4 $M_\odot$ star of GW170817 and the mass of PSR J0740 + 6620 remains correct.

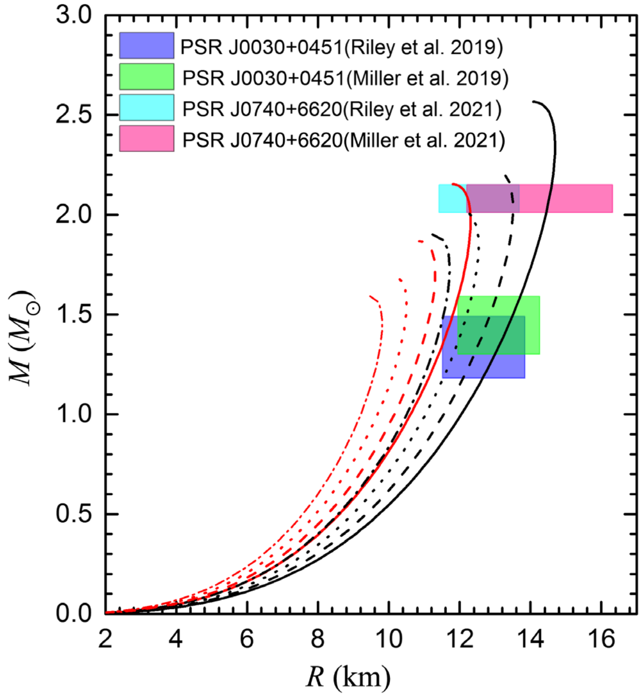

FIG. 3. The mass-radius relation of SSs for a strange quark mass of $m_s = 93$ MeV. The black lines are for $\alpha_S = 0.7$ and $B^{1/4} = 125.1$ MeV, and the red lines are for $\alpha_S = 0.7$ and $B^{1/4} = 137.3$ MeV. The solid, dashed, dotted, dash-dotted lines are for the mass fraction of MDM $f_D = 0$, 10%, 20%, and 30%, respectively. The blue and green regions show the mass and radius estimates of PSR J0030 + 0451 derived from NICER data by Riley *et al.* [17] ($R = 12.71^{+1.14}_{-1.19}$ km, $M = 1.34^{+0.15}_{-0.16}\ M_\odot$) and Miller *et al.* [18] ($R = 13.02^{+1.24}_{-1.06}$ km, $M = 1.44^{+0.15}_{-0.14}\ M_\odot$), respectively. The cyan and pink regions show the mass of PSR J0740 + 6620 ($2.08 \pm 0.07\ M_\odot$ [16]), and the radius of it derived from NICER and XMM-Newton data by Riley *et al.* [44] ($12.39^{+1.30}_{-0.98}$ km) and Miller *et al.* [45] ($13.7^{+2.6}_{-1.5}$ km), respectively.

Figure 3 shows the mass-radius relation of SSs for $m_s = 93$ MeV with various values of f_D for two sets of SQM parameters [$B^{1/4}$(MeV), α_S] [namely, (125.1, 0.7) and (137.3, 0.7), which are marked as magenta dots in Fig. 1(b)]. The mass fraction of MDM (f_D) is defined by $f_D \equiv M_D/M$, where M is the total mass of the star and M_D is the mass of the MDM core. As can be seen in Fig. 3, for given values of the SQM parameters [$B^{1/4}$(MeV), α_S], both the maximum mass and the radius of the 1.4 $M_\odot$ star decrease with the increasing of f_D.

It can be found in Fig. 3 that for SSs without a MDM core (i.e., $f_D = 0$) and with $\alpha_S = 0.7$, both the maximum mass and the radius of the 1.4 $M_\odot$ star increase as the value of $B^{1/4}$ decreases. The red solid line, which is for $\alpha_S = 0.7$ and $B^{1/4} = 125.1$ MeV, can well satisfy the observational data for PSR J0030 + 0451 given by Riley *et al.* [17], while it can only marginally satisfy that given by Miller *et al.* [18] (this result can also be found from Fig. 1). However, the black solid line, which is for $\alpha_S = 0.7$ and

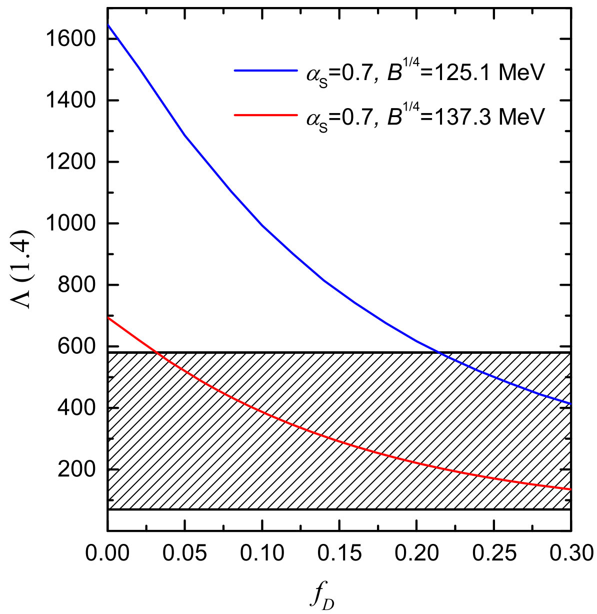

FIG. 4. Relation between the dimensionless tidal deformability of a 1.4 $M_\odot$ star [$\Lambda(1.4)$] and the mass fraction of MDM (f_D) for a strange quark mass of $m_s = 93$ MeV. The shaded region corresponds to $70 < \Lambda(1.4) < 580$, which is given by the observation of GW170817.

$B^{1/4} = 137.3$ MeV, can satisfy both of these observational data for PSR J0030 + 0451 very well. We also find in Fig. 3 that the red solid line can well satisfy the recently observed radius data of PSR J0740 + 6620 given by Riley *et al.* [44] ($12.39^{+1.30}_{-0.98}$ km), but it can only marginally satisfy that given by Miller *et al.* [45] ($13.7^{+2.6}_{-1.5}$ km). On the other hand, the black solid line can well satisfy both of these observational data for PSR J0740 + 6620. Considering the above-mentioned similar behavior in the explanation of the observational data for PSR J0030 + 0451 and PSR J0740 + 6620, it is reasonable to assume that when the constraint from the observational data for PSR J0030 + 0451 is fulfilled, the recently observed radius data of PSR J0740 + 6620 could be explained, too. For convenience, we will only focus on the discussion of the constraint from PSR J0030 + 0451, and will no longer discuss the constraint from the observed radius data of PSR J0740 + 6620.

Figure 4 shows the relation between the dimensionless tidal deformability of a 1.4 $M_\odot$ star [$\Lambda(1.4)$] and the mass fraction of MDM (f_D) for $m_s = 93$ MeV. One can easily find that $\Lambda(1.4)$ is bigger for a smaller value of $B^{1/4}$ for a given value of f_D. One can also find that $\Lambda(1.4)$ decreases with the increasing of the value of f_D for a given set of SQM parameters [$B^{1/4}$(MeV), α_S]. For the case of SSs without a MDM core (i.e., $f_D = 0$), the tidal deformability observation of GW170817 cannot be satisfied for both parameter sets of SQM, (125.1, 0.7) and (137.3, 0.7). However, the tidal deformability observation of GW170817 can be satisfied if the value of f_D is larger than certain values, specifically, 3.1% for the case of (137.3, 0.7), and 21.4% for the case of (125.1, 0.7).

Figures 5 and 6 show the constraints to the parameters of the EOS of SQM for $m_s = 93$ and $m_s = 150$ MeV, respectively. We want to stress that the cyan-shadowed areas in Fig. 5 (Fig. 6) are the same as these in Fig. 1 (Fig. 2), which are for the case of SSs without a MDM core ($f_D = 0$) and satisfy both $M_{\max} \geq 2.08\ M_\odot$ and the observational data of NICER for PSR J0030 + 0451. However, the lines for $\Lambda(1.4) = 580$ with various values of the mass fraction of MDM (f_D) are presented in Figs. 5 and 6. Remember that the regions above the $\Lambda(1.4) = 580$ lines satisfy $\Lambda(1.4) < 580$, which means that they agree with the tidal deformability observation of GW170817. One can see from Figs. 5 and 6 that as the value of f_D increases, the parameter space regions which satisfy $\Lambda(1.4) < 580$ shift downward. As can be seen from Fig. 5, for a strange quark mass of $m_s = 93$ MeV, the parameter space regions which satisfy $\Lambda(1.4) < 580$ begin to overlap with the cyan-shadowed areas for the value of $f_D = 0.5\%$ for the analysis of NICER data for PSR J0030 + 0451 by Riley *et al.* [17] [Fig. 5(a)], and $f_D = 3.1\%$ for Miller *et al.* [18] [Fig. 5(b)]. Thus, for a strange quark mass of $m_s = 93$ MeV, assuming PSR J0740 + 6620 and PSR J0030 + 0451 are SSs without a MDM core, there exists allowed parameter space for which SSs agree with the observations of PSR J0740 + 6620, PSR J0030 + 0451 and GW170817 simultaneously in the case that SSs in GW170817 have a MDM core with $f_D > 0.5\%$ (for the case of Riley *et al.* [17], and $f_D > 3.1\%$ for the case of Miller *et al.* [18]). Similarly, as can be seen from Fig. 6, for a strange quark mass of $m_s = 150$ MeV, assuming PSR J0740 + 6620 and PSR J0030 + 0451 are SSs without a MDM core, there exists allowed parameter space for which SSs agree with the observations of PSR J0740 + 6620, PSR J0030 + 0451 and GW170817 simultaneously in the case that SSs in GW170817 have a MDM core with $f_D > 1.3\%$ (for the case of Riley *et al.*, and $f_D > 3.0\%$ for the case of Miller *et al.*).

V. SUMMARY

In this paper, we study the structure and the tidal deformability of SSs with a MDM core and explain the observations of GW170817, PSR J0740 + 6620, and PSR J0030 + 0451 simultaneously. Our explanation is based on the notion (which was first realized by Ciarcelluti and Sandin [42]) that the mass fraction of MDM (f_D) of each SS could be different and it depends on the individual history. We show that all the above observations could be explained simultaneously if one assumes that PSR J0740 + 6620 and PSR J0030 + 0451 are SSs without a MDM core, while SSs in GW170817 have a MDM core with $f_D > 0.5\%$ (for the case of Riley *et al.* [17], and $f_D > 3.1\%$ for the case of Miller *et al.* [18]) for a strange quark mass of $m_s = 93$ MeV. However, for a strange quark mass of

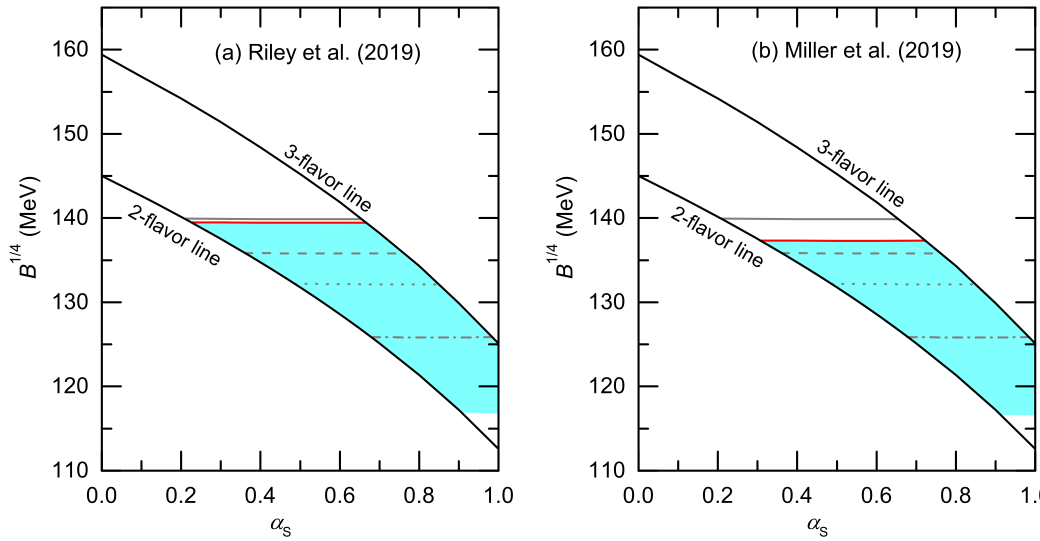

FIG. 5. Constraints on $B^{1/4}$ and α_S for a strange quark mass of $m_s = 93$ MeV. Similar to Fig. 1, the cyan-shadowed areas indicate the parameter space which satisfies both $M_{\max} \geq 2.08\ M_\odot$ and the observational data of NICER for PSR J0030 + 0451 [(a) for the analysis by Riley *et al.* [17] and (b) for Miller *et al.* [18]] for SSs without a MDM core (i.e., $f_D = 0$). The gray lines and the red lines are for $\Lambda(1.4) = 580$ with various values of the mass fraction of MDM (f_D). More specifically, the solid, dashed, dotted, dash-dotted gray lines are for $\Lambda(1.4) = 580$ with $f_D = 0$, 5%, 10%, and 20%, respectively. The red lines are for $\Lambda(1.4) = 580$ with $f_D = 0.5\%$ in (a), and with $f_D = 3.1\%$ in (b).

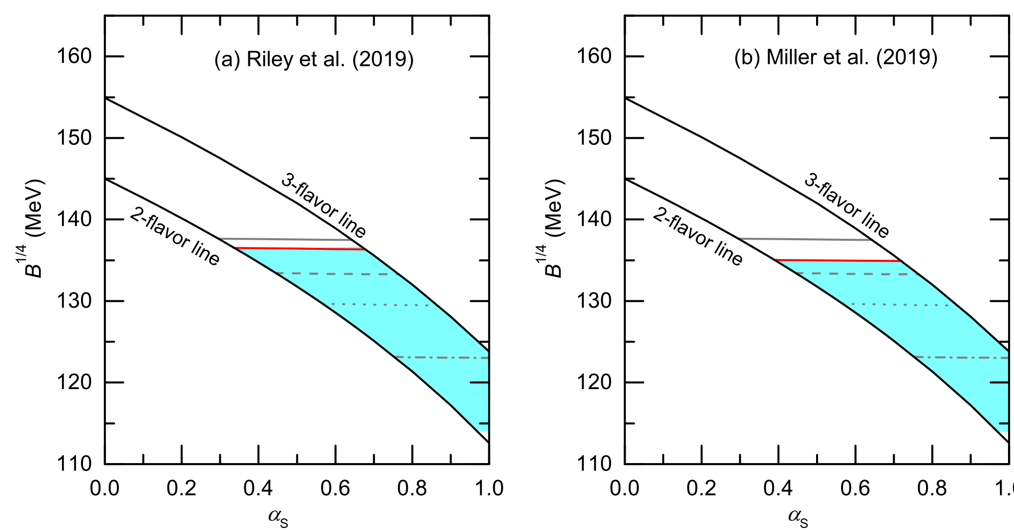

FIG. 6. Constraints on $B^{1/4}$ and α_S for a strange quark mass of $m_s = 150$ MeV. Similar to Fig. 2, the cyan-shadowed areas indicate the parameter space which satisfies both $M_{\max} \geq 2.08\ M_\odot$ and the observational data of NICER for PSR J0030 + 0451 for SSs without a MDM core (i.e., $f_D = 0$). The gray lines and the red lines are for $\Lambda(1.4) = 580$ with various values of the mass fraction of MDM (f_D). More specifically, the solid, dashed, dotted, dash-dotted gray lines are for $\Lambda(1.4) = 580$ with $f_D = 0$, 5%, 10%, and 20%, respectively. The red lines are for $\Lambda(1.4) = 580$ with $f_D = 1.3\%$ in (a), and with $f_D = 3.0\%$ in (b).

$m_s = 150$ MeV, SSs in GW170817 should have a MDM core with $f_D > 1.3\%$ (for the case of Riley *et al.*, and $f_D > 3.0\%$ for the case of Miller *et al.*). In fact, it is easy to deduce that in order to fulfill all these observations, it is not necessary to assume that PSR J0740 + 6620 and PSR J0030 + 0451 are SSs without a MDM core. PSR J0740 + 6620 and PSR J0030 + 0451 could be SSs with a MDM core, but SSs in GW170817 should have a larger MDM core than them in this case. As a conclusion, to explain all of the observations, SSs in GW170817 should have a MDM core.

There are many possible ways that a MDM core could be formed in SSs. We mention that the composition of the MDM core is the mirror strange quark matter consisting of mirror up (u'), mirror down (d') and mirror strange (s') quarks and mirror electrons (e'). First, if a strange star is formed during a Quark Nova [73] and if there are mirror dark matters in the progenitor star, a mirror strange quark matter core could be formed. Second, neutron stars could have a mirror-dark-matter core, which either originates from the progenitor star, or from the accretion during the evolution process [36,41]. If SQM is the true ground state, the galaxy is likely to be contaminated by strange quark nuggets which could convert neutron stars into SSs [9,10]. Similarly, mirror strange quark nuggets could convert the mirror-dark-matter core into mirror strange quark matter. Third, if the density distribution of dark matter is highly nonhomogeneous, a strange star could acquire a mirror strange quark matter core if it mergers with a compact astrophysical objects with stellar sizes made of mirror dark matter [42].

Finally, as pointed out by Ciarcelluti and Sandin [42], although our results are calculated for MDM, they are qualitatively valid for other kinds of dark matter that could form stable cores inside SSs. Therefore, our study leads to the result that for the standard MIT bag model, the observations of GW170817, PSR J0740 + 6620 and PSR J0030 + 0451 could serve as evidence for the existence of a dark-matter core inside SSs.

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[1] N. Itoh, Prog. Theor. Phys. **44**, 291 (1970).
[2] A. R. Bodmer, Phys. Rev. D **4**, 1601 (1971).
[3] E. Witten, Phys. Rev. D **30**, 272 (1984).
[4] H. Terazawa, J. Phys. Soc. Jpn., **58**, 3555 (1989); **58**, 4388 (1989); **59**, 1199 (1990).
[5] E. Farhi and R. L. Jaffe, Phys. Rev. D **30**, 2379 (1984).
[6] C. Alcock, E. Farhi, and A. Olinto, Astrophys. J. **310**, 261 (1986).
[7] P. Haensel, J. L. Zdunik, and R. Schaefer, Astron. Astrophys. **160**, 121 (1986), http://articles.adsabs.harvard.edu/pdf/1986A%26A...160..121H.
[8] C. Alcock and A. V. Olinto, Annu. Rev. Nucl. Part. Sci. **38**, 161 (1988).
[9] J. Madsen, Lect. Notes Phys. **516**, 162 (1999).
[10] F. Weber, Prog. Part. Nucl. Phys. **54**, 193 (2005).
[11] S.-H. Yang, C.-M. Pi, X.-P. Zheng, and F. Weber, Phys. Rev. D **103**, 043012 (2021).
[12] S.-H. Yang, C.-M. Pi, X.-P. Zheng, and F. Weber, Astrophys. J. **902**, 32 (2020).
[13] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Phys. Rev. Lett. **119**, 161101 (2017).
[14] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Phys. Rev. Lett. **121**, 161101 (2018).
[15] H. T. Cromartie *et al.*, Nat. Astron. **4**, 72 (2020).
[16] E. Fonseca *et al.*, Astrophys. J. Lett. **915**, L12 (2021).
[17] T. E. Riley *et al.*, Astrophys. J. Lett. **887**, L21 (2019).
[18] M. C. Miller *et al.*, Astrophys. J. Lett. **887**, L24 (2019).
[19] D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. **84**, 3760 (2000).
[20] S. Tulin and H.-B. Yu, Phys. Rep. **730**, 1 (2018).
[21] G. Bertone and T. M. P. Tait, Nature (London) **562**, 51 (2018).
[22] S.-C. Leung, M.-C. Chu, and L.-M. Lin, Phys. Rev. D **84**, 107301 (2011).
[23] A. Li, F. Huang, and R.-X. Xu, Astropart. Phys. **37**, 70 (2012).
[24] X. Y. Li, F. Y. Wang, and K. S. Cheng, J. Cosmol. Astropart. Phys. 10 (2012) 031.
[25] Q.-F. Xiang, W.-Z. Jiang, D.-R. Zhang, and R.-Y. Yang, Phys. Rev. C **89**, 025803 (2014).
[26] S. Mukhopadhyay, D. Atta, K. Imam, D. N. Basu, and C. Samanta, Eur. Phys. J. C **77**, 440 (2017).
[27] J. Ellis, G. Hutsi, K. Kannike, L. Marzola, M. Raidal, and V. Vaskonen, Phys. Rev. D **97**, 123007 (2018).
[28] J. Ellis, A. Hektor, G. Hutsi, K. Kannike, L. Marzola, M. Raidal, and V. Vaskonen, Phys. Lett. B **781**, 607 (2018).
[29] Z. Rezaei, Astropart. Phys. **101**, 1 (2018).
[30] X. D. Wang, B. Qi, G. L. Yang, N. B. Zhang, and S. Y. Wang, Int. J. Mod. Phys. D **28**, 1950148 (2019).
[31] M. Deliyergiyev, A. DelPopolo, L. Tolos, M. LeDelliou, X. Lee, and F. Burgio, Phys. Rev. D **99**, 063015 (2019).
[32] M. Bezares, D. Vigano, and C. Palenzuela, Phys. Rev. D **100**, 044049 (2019).
[33] O. Ivanytskyi, V. Sagun, and I. Lopes, Phys. Rev. D **102**, 063028 (2020).
[34] A. Bauswein, G. Guo, J.-H. Lien, Y.-H. Lin, and M.-R. Wu, arXiv:2012.11908.
[35] A. Das, T. Malik, and A. C. Nayak, arXiv:2011.01318.
[36] R. Ciancarella, F. Pannarale, A. Addazi, and A. Marciano, Phys. Dark Universe **32**, 100796 (2021).
[37] B. Kain, Phys. Rev. D **103**, 043009 (2021).
[38] Z. Berezhiani, R. Biondi, M. Mannarelli, and F. Tonelli, arXiv:2012.15233.
[39] P. Mukhopadhyay and J. Schaffner-Bielich, Phys. Rev. D **93**, 083009 (2016).
[40] G. Panotopoulos and I. Lopes, Phys. Rev. D **96**, 023002 (2017).
[41] F. Sandin and P. Ciarcelluti, Astropart. Phys. **32**, 278 (2009).
[42] P. Ciarcelluti and F. Sandin, Phys. Lett. B **695**, 19 (2011).
[43] F.Özel, Nature (London) **441**, 1115 (2006).
[44] T. E. Riley *et al.*, Astrophys. J. Lett. **918**, L27 (2021).
[45] M. C. Miller *et al.*, Astrophys. J. Lett. **918**, L28 (2021).
[46] P. A. Zyla *et al.* (Particle Data Group Collaboration), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).

[47] R. Foot, H. Lew, and R. R. Volkas, Phys. Lett. B **272**, 67 (1991).
[48] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[49] I. Y. Kobzarev, L. B. Okun, and I. Y. Pomeranchuk, Sov. J. Nucl. Phys. **3**, 837 (1966), https://inspirehep.net/literature/1351288.
[50] S. I. Blinnikov and M. Y. Khlopov, Sov. J. Nucl. Phys. **36**, 472 (1982), https://inspirehep.net/literature/177194.
[51] S. I. Blinnikov and M. Y. Khlopov, Sov. Astron. **27**, 371 (1983), http://articles.adsabs.harvard.edu/pdf/1983SvA....27..371B.
[52] E. W. Kolb, D. Seckel, and M. S. Turner, Nature (London) **314**, 415 (1985).
[53] M. Y. Khlopov, G. M. Beskin, N. G. Bochkarev, L. A. Pustilnik, and S. A. Pustilnik, Sov. Astron. **35**, 21 (1991), http://articles.adsabs.harvard.edu/pdf/1991SvA....35...21K.
[54] R. Foot, Int. J. Mod. Phys. D **13**, 2161 (2004).
[55] Z. Berezhiani, Int. J. Mod. Phys. A **19**, 3775 (2004).
[56] Z. Berezhiani, in *From Fields to Strings: Circumnavigating Theoretical Physics*, edited by M. Shifman *et al.* (World Scientific, Singapore, 2005), p. 2147.
[57] L. B. Okun, Phys. Usp. **50**, 380 (2007).
[58] P. Ciarcelluti, Int. J. Mod. Phys. D **19**, 2151 (2010).
[59] R. Foot, Int. J. Mod. Phys. A **29**, 1430013 (2014).
[60] M. Pavsic, Int. J. Theor. Phys. **9**, 229 (1974).
[61] Z. Berezhiani and L. Bento, Phys. Rev. Lett. **96**, 081801 (2006).
[62] Z. Berezhiani, Eur. Phys. J. C **64**, 421 (2009).
[63] T. Hinderer, Astrophys. J. **677**, 1216 (2008).
[64] E. E. Flanagan and T. Hinderer, Phys. Rev. D **77**, 021502(R) (2008).
[65] T. Damour and A. Nagar, Phys. Rev. D **80**, 084035 (2009).
[66] T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D **81**, 123016 (2010).
[67] J. M. Lattimer and M. Prakash, Phys. Rep. **621**, 127 (2016).
[68] S. Postnikov, M. Prakash, and J. M. Lattimer, Phys. Rev. D **82**, 024016 (2010).
[69] C. Schaab, B. Hermann, F. Weber, and M. K. Weigel, J. Phys. G **23**, 2029 (1997).
[70] S. Weissenborn, I. Sagert, G. Pagliara, M. Hempel, and J. Schaffner-Bielich, Astrophys. J. Lett. **740**, L14 (2011).
[71] C.-M. Pi, S.-H. Yang, and X.-P. Zheng, Res. Astron. Astrophys. **15**, 871 (2015).
[72] E.-P. Zhou, X. Zhou, and A. Li, Phys. Rev. D **97**, 083015 (2018).
[73] D. Leahy and R. Ouyed, Mon. Not. R. Astron. Soc. **387**, 1193 (2008).