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Review

Confronting Strange Stars with Compact-Star Observations and New Physics

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Abstract: Strange stars ought to exist in the universe according to the strange quark matter hypothesis, which states that matter made of roughly equal numbers of up, down, and strange quarks could be the true ground state of baryonic matter rather than ordinary atomic nuclei. Theoretical models of strange quark matter, such as the standard MIT bag model, the density-dependent quark mass model, or the quasi-particle model, however, appear to be unable to reproduce some of the properties (masses, radii, and tidal deformabilities) of recently observed compact stars. This is different if alternative gravity theory (e.g., non-Newtonian gravity) or dark matter (e.g., mirror dark matter) are considered, which resolve these issues. The possible existence of strange stars could thus provide a clue to new physics, as discussed in this review.

Keywords: alternative gravity; strange stars; dark matter; equation of state; tidal deformability

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1. Introduction

The equation of state (EOS) of the dense matter in compact stars (neutron stars, strange stars) is still a mystery today [1]. The observations of the global properties of compact stars, such as masses and radii, have the potential to unravel this mystery [2,3]. In the past few years, tight constraints on the EOS of dense matter were obtained from the tidal deformability derived from the LIGO/Virgo observation of the binary neutron star merger GW170817 and the precise measurements of the mass and radius of compact stars with NICER (Neutron star Interior Composition Explorer) [4–13].

Aside from neutron stars (NSs), strange stars (SSs) could also exist in the universe [14–19], being made of strange quark matter (SQM) consisting of up, down, and strange quarks. This is a consequence of the hypothesis proposed by Itoh [20], Bodmer [21], Witten [22], and Terazawa [23,24] which states that SQM could be the true ground state of baryonic matter rather than conventional atomic nuclei. The galaxy is likely to be contaminated by strange quark nuggets if SQM is the true ground state, and NSs could be converted to SSs by these strange quark nuggets [18,25,26]. Therefore, many compact stars (neutron stars) could actually be SSs [19].

Many researchers have attempted to identify SSs through observations of compact stars (see [19,27] and references therein). For example, Di Clemente et al. [28] and Horvath et al. [29] suggest that the central compact object within the supernova remnant HESS J1731-347 could be an SS rather than an NS because of its small mass (a mass of the order or smaller than one solar mass) [30]. This is because the analysis of various types of supernova explosions indicates that it is not possible to produce an NS with a mass smaller than about 1.17 $M_\odot$ [31], but it is possible to produce an SS with a small mass. In fact, the mass and radius observations of compact stars have long been used to identify SSs, and some SS candidates have been reported, such as compact stars in the X-ray sources SAX J1808.4-3658 [32], 4U 1728-34 [33], RX J1856.5-3754 [34,35], and 4U 1746-37 [36], as well as the radio pulsar PSR B0943+10 [37].

Besides the possible absolute stability of SQM and the existence of SSs (which is the case for this review), there are other possibilities that have been widely investigated:

- If SQM is not the true ground state of baryonic matter but is only a metastable state, hybrid stars (NSs consisting of an SQM core or a hadron–quark mixed phase) might exist (e.g., [38–40]).
- There is the possibility that metastable hadronic stars could coexist with SSs, which is called the two-families scenario (e.g., [41–45]).
- Compact stars (neutron stars) might be strangeon stars made of strangeons (coined by combining the words "strange" and "nucleon") (e.g., [46–48]).
- Instead of SSs, up–down quark stars might exist because quark matter made of up and down quarks could be more stable than ordinary nuclear matter and SQM in some models (e.g., [49–52]).

The parameters of the SQM model could be constrained by the observations of compact stars [53–63]. For the MIT bag model, Weissenborn et al. [53] found that the parameters of the model could be constrained if one demands that the maximum mass of SSs must be greater than the mass of PSR J1614-2230 ($1.97 \pm 0.04\, M_\odot$ [64]). The parameters of the model were further constrained by Zhou et al. [56] using both the mass of PSR J0348+0432 ($2.01 \pm 0.04\, M_\odot$ [65]) and the tidal deformability of GW170817 [66]. It was found that SSs could exist in certain ranges of the values of the parameters of the SQM model. However, $\Lambda(1.4) \leq 800$ [66] [$\Lambda(1.4)$ is the dimensionless tidal deformability for a $1.4\, M_\odot$ star] was used in this paper, which was updated to $\Lambda(1.4) = 190^{+390}_{-120}$ [we will use $\Lambda(1.4) \leq 580$ in this review] [67]. Moreover, the largest observed mass of pulsars was updated to $2.14^{+0.10}_{-0.09}\, M_\odot$ (PSR J0740+6620) in 2020 [68]. With these new data, Yang et al. [57] found that the existence of SSs seems can be ruled out if the standard MIT bag model of SQM is used. Note that the above conclusion remains correct [58] although the mass of PSR J0740+6620 was updated to $2.08 \pm 0.07\, M_\odot$ [69]. In addition to the standard MIT bag model, SSs are ruled out by the observations of compact stars for the density-dependent quark mass model [59] and the quasi-particle model [60].

However, Yang et al. [57] found that SSs cannot be ruled out if non-Newtonian gravity effects are considered.[1] Moreover, aside from the non-Newtonian gravity effects, Yang et al. [58] found that the observations of compact stars could be satisfied if a mirror-dark-matter (MDM) core exists in some SSs.

Non-Newtonian gravity is one of the alternative theories of gravity beyond general relativity (GR). MDM is one of the possible candidates of dark matter (DM) theory, which is beyond the standard model (SM) of particles. Both the alternative theory of gravity and DM constitute the new physics that is being vividly discussed today.

Compact stars (NSs or SSs) are dense objects with strong gravity. Although GR agrees well with the experiments in the solar system, it is not fully tested in the strong-field domain [6,70]. Thus, compact stars are ideal places to test gravity theories. The properties of compact stars in the framework of the alternative theory of gravity have been studied extensively (e.g., [71–104]). For recent reviews, see [6,105,106].

The nature of DM is still unknown today. If DM is self-interacting (but has a negligible annihilation rate) [107–109], compact stars might contain a DM core (or a DM halo), which will impact the global properties of the stars. Additionally, the observations of compact stars might help us to reveal the nature of DM. The properties of compact stars with a DM core (or a DM halo) have been widely studied (e.g., [110–143]), and recent reviews can be seen in the introductory part of [125].

This review is organized as follows: In Section 2, we briefly review the EOS of SQM employed in this paper (i.e., the standard MIT bag model). In Section 3, we study the structure and the dimensionless tidal deformability of SSs without the consideration of the new physics and show that in this case, SSs can be ruled out via the observations of compact stars. Then, SSs with the non-Newtonian gravity effects are outlined in Section 4, and SSs with an MDM core are discussed in Section 5. Finally, the conclusions are given in Section 6.

2. EOS of SQM

In this review, we use the standard MIT bag model for SQM [14–16,19]. The mass of u and d quarks is taken to be zero, while the mass of s quarks is nonzero (both $m_s = 93$ MeV and $m_s = 95$ MeV are considered in this review [144].[2] The first-order perturbative corrections in α_S (the strong interaction coupling constant) are considered.

The thermodynamic potentials for each species of the quarks and the electrons are given by [16,57,58]

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

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

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

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

where $f \equiv \ln[(\mu_s + \sqrt{\mu_s^2 - m_s^2})/m_s]$, σ is a renormalization constant which is of the order of the chemical potential of s quarks. In this review, we take $\sigma = 300$ MeV.

The energy density and the pressure are given by

$$\epsilon_Q = \sum_{i=u,d,s,e} (\Omega_i + \mu_i n_i) + B, \tag{5}$$

$$p_Q = -\sum_{i=u,d,s,e} \Omega_i - B, \tag{6}$$

where B is the bag constant, μ_i $(i = u, d, s, e)$ are the chemical potentials, and n_i are the number densities as follows:

$$n_i = -\frac{\partial \Omega_i}{\partial \mu_i}. \tag{7}$$

To calculate ϵ_Q and p_Q, the condition of the chemical equilibrium

$$\mu_d = \mu_s = \mu_u + \mu_e, \tag{8}$$

and electric charge neutrality condition

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0, \tag{9}$$

should be employed.

3. SSs without the Consideration of the New Physics

3.1. The Global Properties of SSs

In the following review, geometrized units $G = c = 1$ are used.

The structure of SSs can be calculated by solving the Tolman–Oppenheimer–Volkoff (TOV) equations (which are for static stars and are derived in the framework of GR) [145,146]:

$$\frac{dp(r)}{dr} = -\frac{[m(r) + 4\pi r^3 p(r)][\epsilon(r) + p(r)]}{r[r - 2m(r)]}, \tag{10}$$

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

For a given EOS and for a given pressure at the center of the star, these equations can be solved using the following boundary conditions: $p(R) = 0$, $m(0) = 0$.

The definition of the dimensionless tidal deformability is $\Lambda \equiv \lambda/M^5$, where λ is the tidal deformability parameter.[3] Considering that $\lambda = \frac{2}{3}k_2R^5$ (k_2 is the dimensionless tidal Love number and R is the radius) [147–150], we can obtain

$$\Lambda = \frac{2}{3}k_2\beta^{-5}, \tag{12}$$

where β ($\equiv M/R$) is the compactness of the star.

One can calculate the tidal Love number k_2 using the following expression [3]:

$$k_2 = \frac{8}{5}\frac{\beta^5 z}{F}, \tag{13}$$

where

$$z = (1 - 2\beta)^2[2 - y_R + 2\beta(y_R - 1)], \tag{14}$$

$$\begin{aligned} F \;=\; & 6\beta(2 - y_R) + 6\beta^2(5y_R - 8) + 4\beta^3(13 - 11y_R) \\ & +4\beta^4(3y_R - 2) + 8\beta^5(1 + y_R) + 3z\ln(1 - 2\beta). \end{aligned} \tag{15}$$

Note that in Equations (14) and (15), y_R is not equal to the value of $y(r)$ at the surface of the star $[y(R)]$. In fact, $y_R = y(R) - 4\pi R^3\epsilon_s/M$, because the energy density ϵ_s is nonzero inside the surface of SSs [151]. The quantity $y(r)$ satisfies

$$\frac{dy(r)}{dr} = -\frac{y(r)^2}{r} - \frac{y(r) - 6}{r - 2m(r)} - rQ(r), \tag{16}$$

where

$$\begin{aligned} Q(r) \;=\; & 4\pi\frac{[5 - y(r)]\epsilon(r) + [9 + y(r)]p(r) + \frac{\epsilon(r)+p(r)}{\partial p(r)/\partial\epsilon(r)}}{1 - 2m(r)/r} \\ & -4\left[\frac{m(r) + 4\pi r^3 p(r)}{r[r - 2m(r)]}\right]^2. \end{aligned} \tag{17}$$

One can solve Equation (16) together with the TOV equations for a given EOS, and the boundary condition is $y(0) = 2$.

The mass–radius relation of SSs is shown in Figure 1, which is calculated by solving the TOV equations using the standard MIT bag model. All the parameter sets of [$B^{1/4}$(MeV), α_S] can satisfy both the “2-flavor line” and “3-flavor line” constraints (see Figure 2). From Figure 1, we find that for the fixed value of α_S, both the maximum mass of SSs and the radius of a $1.4M_\odot$ SS increase significantly with the decreasing of $B^{1/4}$. Meanwhile, for the fixed value of $B^{1/4}$, these properties change slightly for different values of α_S (see the green line and the black dashed line in Figure 1).

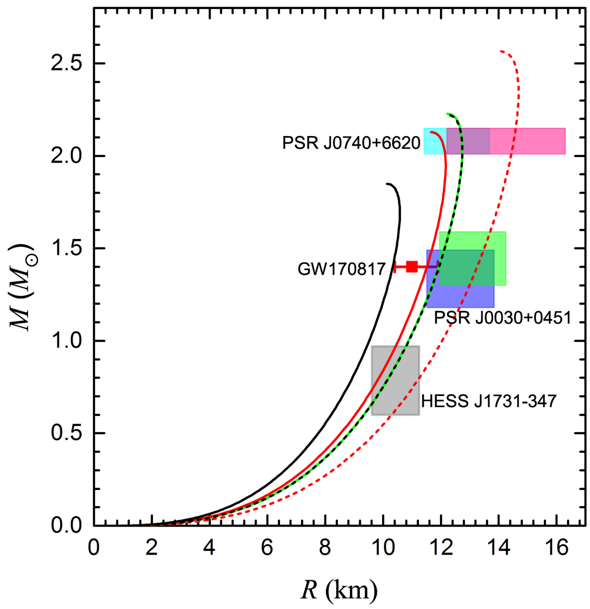

Figure 1. The mass–radius relation of SSs for $m_s = 93$ MeV. The black lines are for $\alpha_S = 0.4$ (the solid one is for $B^{1/4} = 148.4$ MeV, and the dashed one is for $B^{1/4} = 134.8$ MeV), the red lines are for $\alpha_S = 0.7$ (the solid one is for $B^{1/4} = 138.1$ MeV, and the dashed one is for $B^{1/4} = 125.1$ MeV), and the green line is for the data set ($\alpha_S = 0.7$, $B^{1/4} = 134.8$ MeV). The red data point corresponds to the radius of a 1.4 $M_\odot$ compact star obtained from the observations of GW170817 [152]. The blue and green regions correspond to the mass and radius of PSR J0030+0451 obtained from NICER data, which are given by Riley et al. [153] and Miller et al. [154], respectively. The cyan and pink regions are for PSR J0740+6620, where the mass is from [69], and the radius is obtained from the NICER and XMM-Newton data by Riley et al. [155] and Miller et al. [156], respectively. The gray region corresponds to the central compact object within the supernova remnant HESS J1731-347 [30].

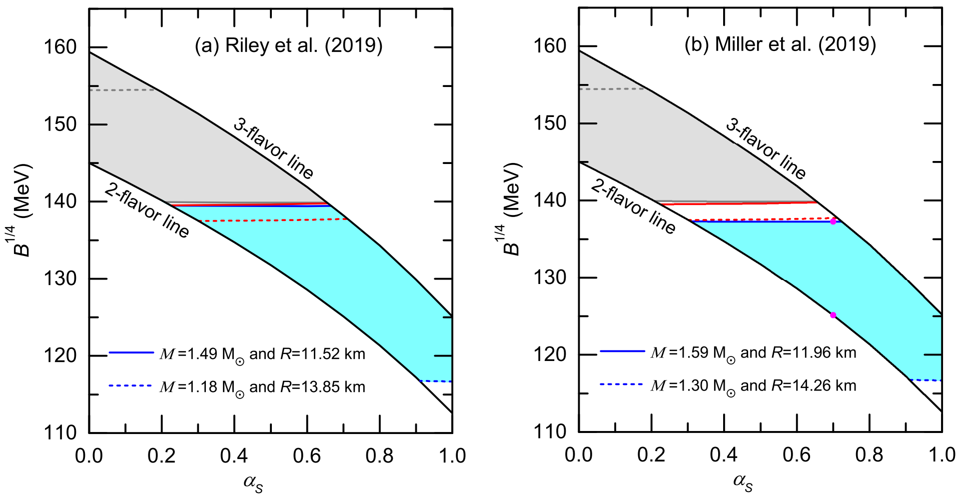

Figure 2. Constraints on the parameters of the standard MIT model for $m_s = 93$ MeV. The gray solid and dashed lines are for $\Lambda(1.4) = 580$ and $\Lambda(1.4) = 190$, respectively. The red solid and dashed lines are for $M_{\max} = 2.08\, M_\odot$ and $M_{\max} = 2.14\, M_\odot$, respectively. The magenta dots in (**b**) correspond to (125.1, 0.7) and (137.3, 0.7), which will be used later in Figures 8 and 9. Image from [58]. Data from Riley et al. [153] and Miller et al. [154].

As shown in Figure 1, the red solid line, the green line, and the black dashed line can comply with all the observed data. However, this result turns out to be not true as we will show later in Section 3.2. The reason for this is that the data of GW170817 shown in this figure is from [152], which is not based on the study of SSs or the standard MIT bag model.

3.2. Parameter Space of SQM

The allowed parameter space of the standard MIT model can be calculated with the following constraints [53–62,157]:

First, pure SSs can exist only if SQM is the true ground state of baryonic matter, which means that the energy per baryon of SQM must be smaller than that of ^{56}Fe ($E/A \sim$ 930 MeV). It is common to compare the energy per baryon of SQM to ^{56}Fe although the latter is only the third lowest after ^{62}Ni and ^{58}Fe. The parameter regions that satisfy this constraint are the areas below the 3-flavor line in Figure 2.

The second constraint follows that the energy per baryon of the nonstrange quark matter (quark matter made of u and d quarks) in bulk must be larger than 934 MeV (the additional 4 MeV comes from the correction of the surface effects [14,18,53,56]). This constraint ensures that atomic nuclei do not dissolve into their constituent quarks. The parameter regions that satisfy this constraint are the areas above the 2-flavor line in Figure 2. Here, a small value of the surface tension [σ = (70 MeV)^3] is employed [14]. However, the exact surface tension value is still uncertain, and it could be much larger [158–164]. Therefore, the critical value of 934 MeV could be smaller, and the 2-flavor line in Figure 2 will shift downward, leading to a larger allowed parameter region.

The two constraints mentioned above must be fulfilled, as we discuss other constraints in the following sections. In other words, we are only interested in the areas between the 3-flavor line and the 2-flavor line.

The third constraint is $\Lambda(1.4) \leq 580$ [$\Lambda(1.4)$ is the dimensionless tidal deformability of a 1.4 $M_\odot$ star], which follows from the observation of GW170817 [$\Lambda(1.4) = 190^{+390}_{-120}$] [67]. This constraint leads to the gray-shadowed areas in Figure 2.

The fourth constraint is $M_{\rm max} \geq 2.08\,M_\odot$, where $M_{\rm max}$ is the maximum mass of SSs derived from the TOV equations, and 2.08 $M_\odot$ is the mass of PSR J0740+6620 [69].[4] The parameter regions that satisfy this constraint are the areas below the red solid lines in Figure 2. Since the mass of PSR J0740+6620 was first reported to be $2.14^{+0.10}_{-0.09}\,M_\odot$ [68], we also use $M_{\rm max} \geq 2.14\,M_\odot$ in Section 4.2 following our previous papers [57,59,62]. The red dashed lines for $M_{\rm max} = 2.14\,M_\odot$ are also shown in Figure 2. As can be seen from Figure 2, both for $M_{\rm max} \geq 2.08\,M_\odot$ and $M_{\rm max} \geq 2.14\,M_\odot$, one can reach the same conclusion that SSs can be ruled out due to the observations of PSR J0740+6620 and GW170817.

The last constraint is from the observed mass and radius of PSR J0030+0451. Two independent data are derived from the NICER observations, namely, $M = 1.34^{+0.15}_{-0.16}\,M_\odot$ and $R_{\rm eq} = 12.71^{+1.14}_{-1.19}$ km by Riley et al. [153], and $M = 1.44^{+0.15}_{-0.14}\,M_\odot$ and $R_{\rm eq} = 13.02^{+1.24}_{-1.06}$ km by Miller et al. [154]. These data have been translated into the $B^{1/4}$–α_S space and are shown in Figure 2 (see the blue lines). The cyan-shadowed areas in Figure 2 correspond to the parameter space allowed by this constraint.

In fact, as can be seen from Figure 2, the cyan-shadowed areas can satisfy not only the constraint from the observation of PSR J0030+0451 but also the constraint from the observation of PSR J0740+6620. We find that the cyan-shadowed area and the gray-shadowed area (remember that the gray-shadowed area corresponds to the parameter space allowed by the tidal deformability of GW170817) do not overlap, which means that for the standard MIT bag model, SSs can be ruled out via the observations concerning compact stars.

Here, we want to stress that, in addition to the standard MIT bag model, SSs can be ruled out by the observations of compact stars for the density-dependent quark mass model [59] and the quasi-particle model [60] if one does not consider alternative theories of gravity or the existence of a DM core in the stars.

4. SSs in the Framework of Non-Newtonian Gravity

The inverse-square law of gravity is expected to be modified because of the geometrical effect of the extra space–time dimensions predicted by string theory, which tries to unify gravity with the other three fundamental forces [167–169]. Non-Newtonian gravity also arises due the exchange of weakly interacting bosons in the super-symmetric extension of

SM [170,171]. Many efforts have been made to constrain the deviations from Newton's gravity; see [172] for reviews.

The effects of non-Newtonian gravity on the properties of compact stars have been widely investigated [57,59,62,71,72,173–179]. The inclusion of non-Newtonian gravity leads to stiffer EOSs, which can support higher maximum masses of compact stars. Thus, some soft EOS of dense nuclear matter cannot be ruled out by the observed massive pulsars under non-Newtonian gravity effects [72].

4.1. EOS of SQM in the Framework of Non-Newtonian Gravity

The deviation from the inverse-square law of gravity is often characterized by a Yukawa potential [180].[5] Considering the non-Newtonian gravity effects, the potential energy describing the interaction between the two objects with masses m_1 and m_2 is

$$V(r) = -\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right) = V_N(r) + V_Y(r), \tag{18}$$

where $V_N(r)$ is the Newtonian potential, $V_Y(r)$ is the Yukawa correction, G is the gravitational constant, α is the dimensionless strength parameter of the Yukawa force, and λ is the length scale of the Yukawa force.

In the boson exchange picture, the range of the Yukawa force is

$$\lambda = \frac{1}{\mu}, \tag{19}$$

where μ is the mass of the bosons exchanged between m_1 and m_2. Meanwhile, the strength parameter is

$$\alpha = \pm\frac{g^2}{4\pi G m_b^2}, \tag{20}$$

where the $\pm$ sign refers to scalar/vector bosons.[6]

As will be shown later in Section 4.2, SSs can exist for 1.37 GeV^{-2} $\leq g^2/\mu^2 \leq$ 7.28 GeV^{-2}. This theoretical region is compared with the constraints from terrestrial experiments in Figure 3. One can see that the theoretical region is allowed by many experiments.

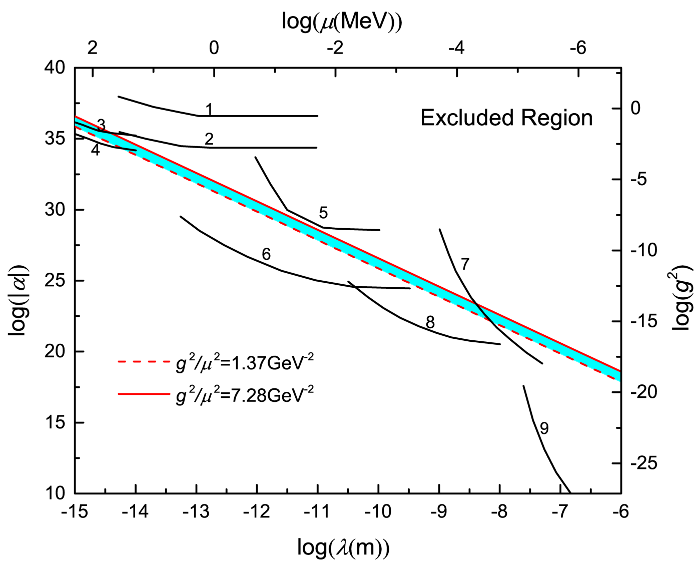

Figure 3. Theoretical bounds on g^2/μ^2 in comparison with constraints on the strength parameter $|\alpha|$ and the range of the Yukawa force λ from different experiments: curves 1 and 2 are from [181]; 3 and 4 are from [182]; 5 and 6 are from [183]; and 7, 8, 9 are from [184–186], respectively. The image is from [57].

A neutral weakly coupled spin-1 gauge U-boson is suggested to be a candidate for the exchanged boson. This U-boson is proposed in the super-symmetric extension of SM [170,171], and many terrestrial experiments have been conducted to search for it [187]. It has also been found that this U-boson can help to explain the 511 keV γ-ray observation from the galactic bulge [188–190].

The extra energy density results from the Yukawa correction $V_Y(r)$ of Equation (18) is [57,178,191]

$$\epsilon_Y = \frac{1}{2V}\int 3n_b(\vec{x}_1)\frac{g^2}{4\pi}\frac{e^{-\mu r}}{r}3n_b(\vec{x}_2)d\vec{x}_1 d\vec{x}_2 = \frac{9}{2}\frac{g^2}{\mu^2}n_b^2, \tag{21}$$

where $n_b(\vec{x}_1)$ and $n_b(\vec{x}_2)$ are the densities, $r = |\vec{x}_1 - \vec{x}_2|$, and V is the normalization volume. The prefactor of three appears before $n_b(\vec{x}_1)$ and $n_b(\vec{x}_2)$ because the baryon number of quarks is $1/3$. The extra pressure resulting from the Yukawa correction is

$$p_Y = n_b^2 \frac{d}{dn_b}\left(\frac{\epsilon_Y}{n_b}\right). \tag{22}$$

Assuming that the boson mass is independent of the density, one can obtain the following:

$$p_Y = \epsilon_Y = \frac{9}{2}\frac{g^2}{\mu^2}n_b^2. \tag{23}$$

Thus, the total energy density and pressure of SQM are

$$\epsilon = \epsilon_Q + \epsilon_Y, \tag{24}$$

$$p = p_Q + p_Y, \tag{25}$$

where ϵ_Q and p_Q are given by Equations (5) and (6), respectively.

When we employ the EOS of SQM described by $p(\epsilon)$, the Yukawa correction is considered as a part of the matter system in GR:

$$T^{\alpha\beta} = [\epsilon + p(\epsilon)]u^\alpha u^\beta + p(\epsilon)g^{\alpha\beta}. \tag{26}$$

As a result, the effects of non-Newtonian gravity on compact stars can be studied by solving the TOV equations [71,72,192].

4.2. The Allowed Parameter Space of SQM in the Framework of Non-Newtonian Gravity

Considering the non-Newtonian gravity effects, the mass–radius relation of SSs is shown in Figure 4. Both parameter sets of [$B^{1/4}$(MeV), α_S] used in Figure 4 can satisfy the “2-flavor line” and “3-flavor line” constraint as will be shown in Figure 5. One can find that the inclusion of the non-Newtonian gravity leads to a larger maximum mass of SSs.

By imposing the first four constraints presented in Section 3.2 (i.e., the last constraint from the observation of PSR J0030+0451 is not considered here), the allowed parameter space of the standard MIT model is restricted to the dark cyan-shadowed regions shown in Figure 5c,d, which correspond to $g^2/\mu^2 = 3.25$ GeV^{-2} and 4.61 GeV^{-2}, respectively.

As can be seen from Figure 5a, the constraints $M_{\rm max} \geq 2.14\,M_\odot$ and $\Lambda(1.4) \leq 580$ cannot be satisfied simultaneously for the case of $g^2/\mu^2 = 0$. However, the gap between the $M_{\rm max} = 2.14\,M_\odot$ line and the $\Lambda(1.4) = 580$ line becomes smaller as the value of g^2/μ^2 increases, and finally these two lines almost completely overlap with each other when g^2/μ^2 is as large as 1.37 GeV^{-2} [see Figure 5b], which indicates that all four constraints can be satisfied. The allowed parameter space continues to exist as the value of g^2/μ^2 increases until it vanishes for $g^2/\mu^2 > 7.28$ GeV^{-2}[see Figure 5e], where the “2-flavor line” and “3-flavor line” constraint cannot be satisfied simultaneously. Therefore, we have the conclusion that SSs can exist for 1.37 GeV$^{-2} \leq g^2/\mu^2 \leq 7.28$ GeV^{-2}.

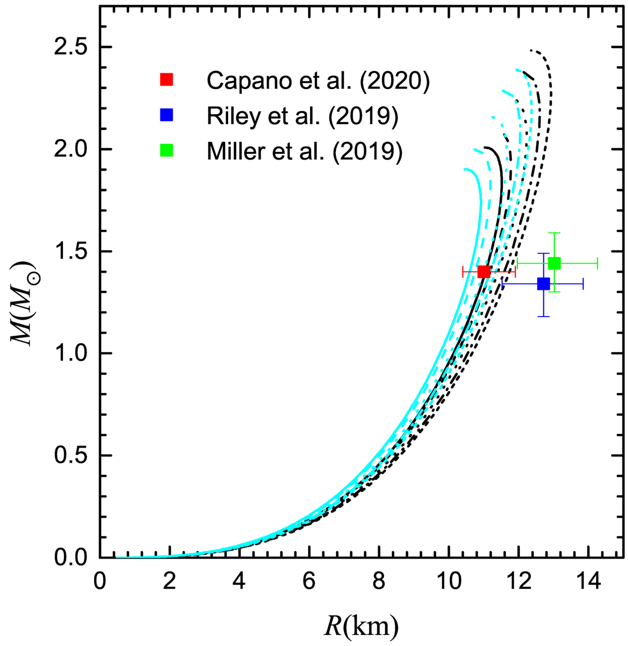

Figure 4. The mass–radius relation of SSs for $m_s = 95$ MeV. The black and cyan lines are for parameter sets of [$B^{1/4}$(MeV), α_S] with (142, 0.2) and (146, 0), respectively. For each color, the lines are for $g^2/\mu^2 = 0, 1, 3, 5$, and 7 GeV^{-2} from left to right. The observational data are the same as those shown in Figure 1 for GW171807 and PSR J0030+0451. The image is from [57]. Data from Capano et al. [152], Riley et al. [153] and Miller et al. [154].

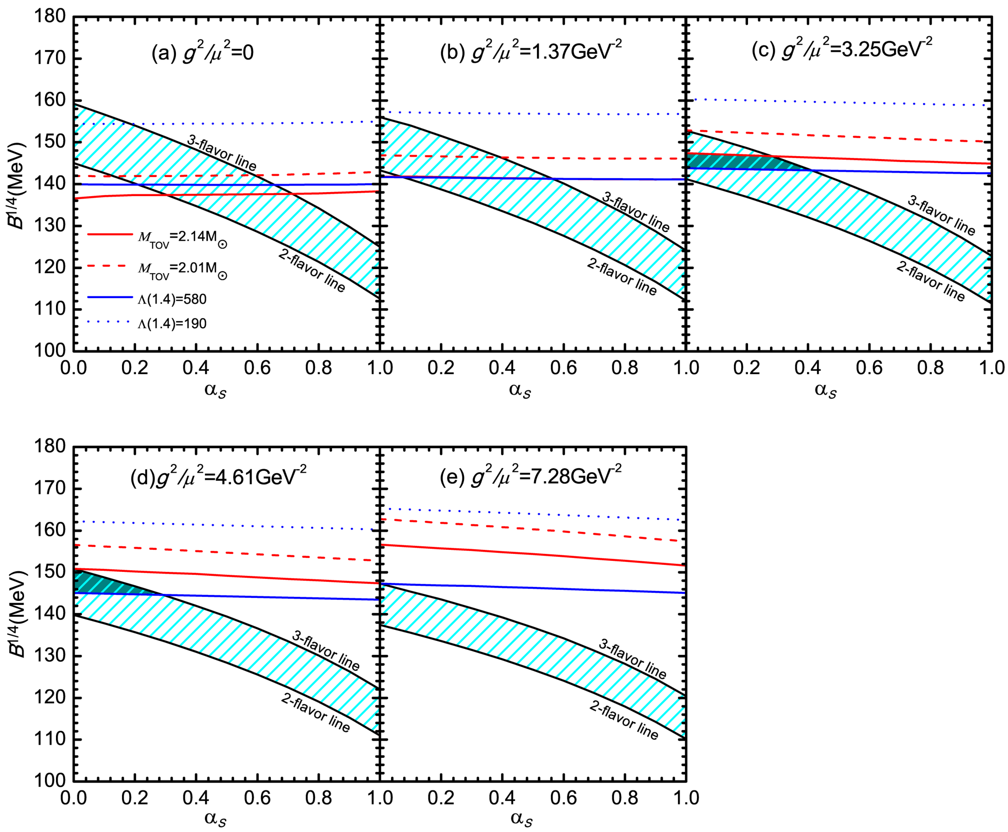

Figure 5. Constraints on the parameters of the standard MIT model for $m_s = 95$ MeV and different values of g^2/μ^2. The image is from [57].

Moreover, one can find that for the existence of SSs, $B^{1/4}$ must be larger than 141.3 MeV, and α_S must be smaller than 0.56 [see Figure 5b, where the $M_{\rm max} = 2.14\,M_\odot$ line (the $\Lambda(1.4) = 580$ line) meets the 3-flavor line at the point (141.3, 0.56)], while the upper limit of $B^{1/4}$ is 150.9 MeV [see Figure 5d, where the $M_{\rm max} = 2.14\,M_\odot$ line cuts across the 3-flavor line at the point (150.9, 0)] [57].

We also find that the largest allowed maximum mass of SSs is 2.37 $M_\odot$, corresponding to the parameter set $g^2/\mu^2 = 7.28$ GeV^{-2}, $\alpha_S = 0$ and $B^{1/4} = 147.3$ MeV. Thus, the GW190814's secondary component with mass $2.59^{+0.08}_{-0.09}\,M_\odot$ [193] could not be a static SS even considering the non-Newtonian effect. However, it could be a rotating SS [194].

Now, we consider all the five constraints presented in Section 3.2. From Figures 6 and 7, one sees that the gap between the blue solid line and the gray solid line is almost unchanged as the value of g^2/μ^2 increases. As a result, the dark cyan-shadowed regions and the cyan-shadowed regions cannot overlap for all the choices of the value of g^2/μ^2, which means that for the standard MIT model, SSs are ruled out by the observations of compact stars even if the effects of non-Newtonian gravity are considered.

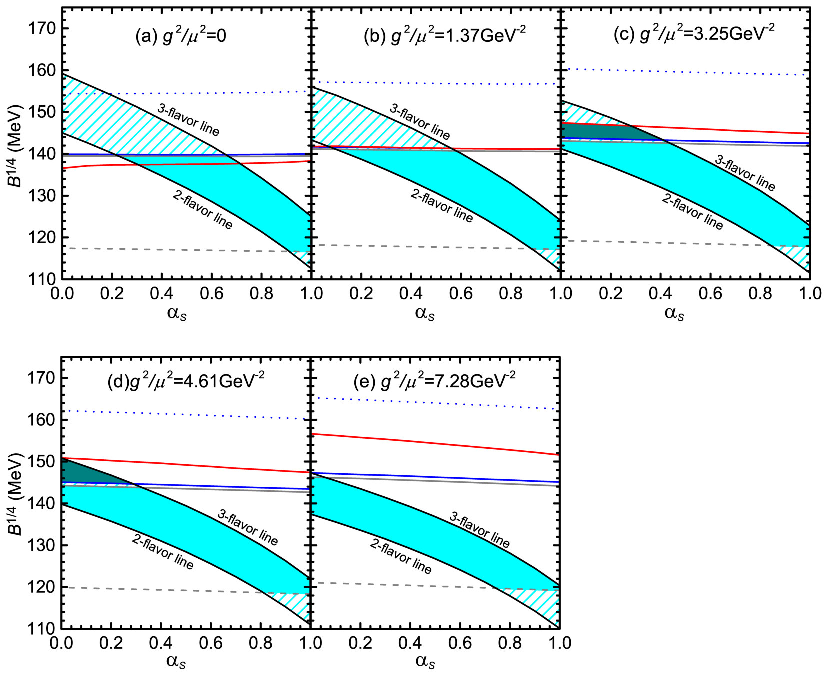

Figure 6. Constraints on the parameters of the standard MIT model for $m_s = 95$ MeV. The red and blue lines are the same as those in Figure 5 except that the dashed red line is not shown in this figure. The dark cyan-shadowed regions are also the same as those in Figure 5, which are restricted by the first four constraints presented in Section 3.2. The last constraint (i.e., the constraint from the observation of PSR J0030+0451) leads to the cyan-shaded region. This figure is for the case of Riley et al. [153], where the gray solid and dashed lines are for the [$M\,(M_\odot)$, $R\,$(km)] sets (1.49, 11.52) and (1.18, 13.85), respectively. The image is from [62].

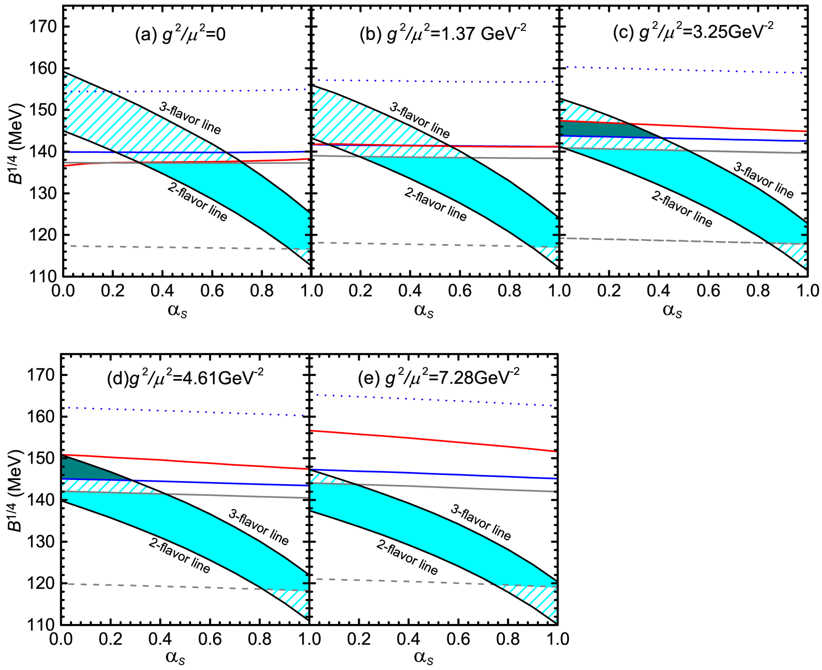

Figure 7. The same as Figure 6, but for the case of Miller et al. [154], where the gray solid and dashed lines are for the [M ($M_\odot$), R (km)] sets (1.59, 11.96) and (1.30, 14.26), respectively. The image is from [62].

5. SSs with a Mirror-Dark-Matter Core

As a consequence of the parity symmetric extension of SM of particles, mirror dark matter (MDM) is regarded as a type of DM candidate [195]. The idea of MDM was first realized by Lee and Yang in 1956 when the weak interaction was found to violate parity [196]. These authors suggested that the existence of a set of unknown particles could restore the symmetry. There are many reviews about MDM [197–201].

The properties of MDM-admixed compact stars have been widely investigated [58,110,111,121–124,136]. It was found that the existence of an MDM core in compact stars leads to a softer EOS and that the mass and radius observations of compact stars might serve as a signature for the existence of an MDM core in NSs [111].

5.1. EOS of MDM

In the minimal parity-symmetric extension of SM [110,111,195,202], the ordinary matter and MDM are described by the same lagrangians, and the only difference between them is that ordinary particles have left-handed interactions while mirror particles have right-handed interactions. Therefore, the microphysics of MDM and ordinary matter are exactly the same, which means that they have the same EOS. In this review, MDM is the mirror strange quark matter made of mirror up (u'), mirror down (d'), and mirror strange (s') quarks and mirror electrons (e'), which has the same EOS as that of SQM.

MDM and ordinary matter could interact directly. For example, photon–mirror photon kinetic mixing has been studied, and its strength is of order 10^{-9} [123,201]. This interaction is too weak to have an apparent effect on the structure of compact stars [110]. The interactions between quarks and mirror quarks have not been studied thus far. Meanwhile, it is reasonable to suppose that these interactions are weak and their effects on the structure of SSs could be ignored.[7]

5.2. The Properties of SSs with an MDM Core

For SSs with an MDM core, although the SQM and MDM components do not interact directly, they can interact with each other through the gravitational interaction. Thus, a two-fluid formalism is employed to study the properties of SSs with an MDM core.

The TOV equations in the two-fluid formalism are given by (e.g., [110,111,123,128])

$$\frac{dm(r)}{dr} = 4\pi\epsilon(r)r^2, \tag{27}$$

$$\frac{dp_Q(r)}{dr} = -\frac{[m(r)+4\pi r^3 p(r)][\epsilon_Q(r)+p_Q(r)]}{r[r-2m(r)]}, \tag{28}$$

$$\frac{dp_M(r)}{dr} = -\frac{[m(r)+4\pi r^3 p(r)][\epsilon_M(r)+p_M(r)]}{r[r-2m(r)]}, \tag{29}$$

with

$$\epsilon(r) = \epsilon_Q(r)+\epsilon_M(r), \tag{30}$$

$$p(r) = p_Q(r)+p_M(r), \tag{31}$$

where the subscript Q and M are for SQM and MDM, respectively.

In the two-fluid formalism, the dimensionless tidal deformability (Λ) can be calculated in similar fashion to that described in Section 3.1, except that Equation (17) should be changed into (e.g., [123,128])

$$Q(r) = \frac{4\pi r}{r-2m(r)}\left[[5-y(r)]\epsilon(r)+[9+y(r)]p(r)+\frac{\epsilon_Q(r)+p_Q(r)}{\partial p_Q(r)/\partial\epsilon_Q(r)}+\frac{\epsilon_M(r)+p_M(r)}{\partial p_M(r)/\partial\epsilon_M(r)}\right] -4\left[\frac{m(r)+4\pi r^3 p(r)}{r[r-2m(r)]}\right]^2. \tag{32}$$

To obtain $y(r)$, Equation (16) should be calculated together with Equations (27)–(29) for a given SQM and MDM pressure at the center of the star under the following boundary conditions: $y(0)=2$, $m(0)=0$, $p_Q(R)=0$, and $p_M(R_M)=0$ (R is the radius of SSs, and R_M is the radius of the MDM core).

Besides the energy density jump at the surface of SS, another energy density jump ϵ_{sM} exists at the surface of the MDM core. As a result, an additional term $-4\pi R_M^3\epsilon_{sM}/M(R_M)$ should be added to $y(R_M)$.

Obviously, the properties of SSs with an MDM core change with the mass fraction of MDM (f_M), where $f_M \equiv M_M/M$ (M is the total mass of the star, and M_M is the mass of the MDM core).

Figure 8 shows the mass–radius relation of SSs for different values of f_M. Two sets of SQM parameters [$B^{1/4}$(MeV), α_S] [(125.1, 0.7) and (137.3, 0.7)] are chosen, which are shown by the magenta dots in Figure 2b. From Figure 8, one sees that for fixed values of $B^{1/4}$ and α_S, the maximum mass of SSs decreases as the value of f_M increases. In other words, the existence of an MDM core leads to a softer EOS.

Figure 9 shows the relation between $\Lambda(1.4)$ and f_M. One can see that for a given value of f_M, the value of $\Lambda(1.4)$ increases with the decrease of $B^{1/4}$. It also can be seen from Figure 9 that $\Lambda(1.4)$ decreases as the value of f_M increases. For both parameter sets considered in Figure 9, SSs cannot agree with the observation of GW170817 if f_M is not large enough. The critical values of f_M are 3.1% and 21.4% for $B^{1/4} = 137.3$ MeV and 125.1 MeV, respectively.

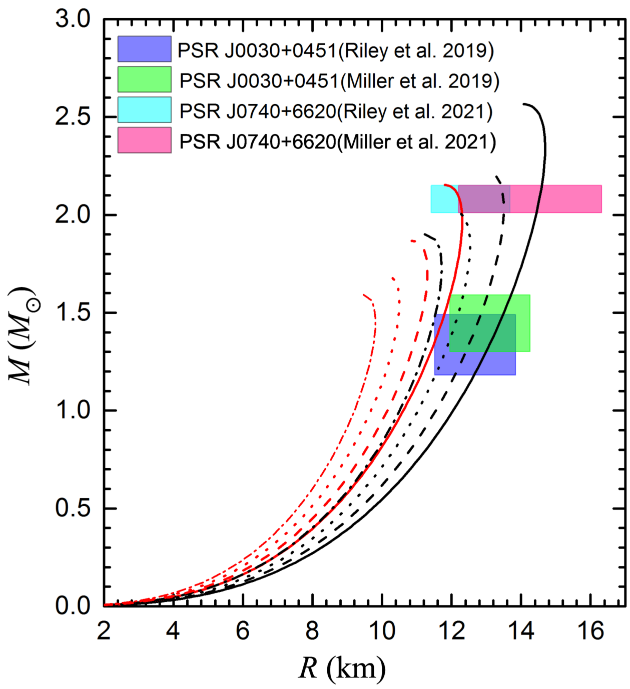

Figure 8. The mass–radius relation of SSs for $m_s = 93$ MeV and $\alpha_S = 0.7$. The black and red lines are for $B^{1/4} = 125.1$ MeV and 137.3 MeV, respectively. For each color, the lines are for $f_M = 0$, 10%, 20%, and 30% from right to left. The observational data are the same as those shown in Figure 1 for PSR J0030+0451 and PSR J0740+6620. The image is from [58]. Data from Riley et al. [153,155] and Miller et al. [154,156].

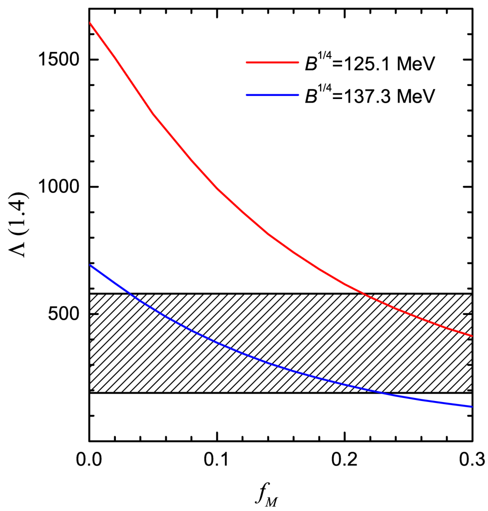

Figure 9. Relation between $\Lambda(1.4)$ and f_M for $m_s = 93$ MeV. The shaded region corresponds to the observation of GW170817 [$70 < \Lambda(1.4) < 580$]. The image is from Ref. [58].

5.3. The Allowed Parameter Space of SQM for SSs with an MDM Core

The allowed parameter space of the standard MIT model is investigated by imposing all the five constraints presented in Section 3.2, and the result is shown in Figure 10. Note that the cyan-shadowed areas in Figure 10 are for the case of SSs without an MDM core, which could fulfill the constraints from the observations of PSR J0740+6620 and PSR J0030+0451 (see Section 3.2). From Figure 10, one sees that the parameter space area which satisfies the tidal deformability observation of GW170817 (the area above the $\Lambda(1.4) = 580$ line) shifts downward as the value of f_M increases and that area begins to overlap with the cyan-shadowed area for $f_M = 0.5\%$ for the case of Riley et al. [153] (Figure 10a) and $f_M = 3.1\%$ for the case of Miller et al. [154] (Figure 10b).

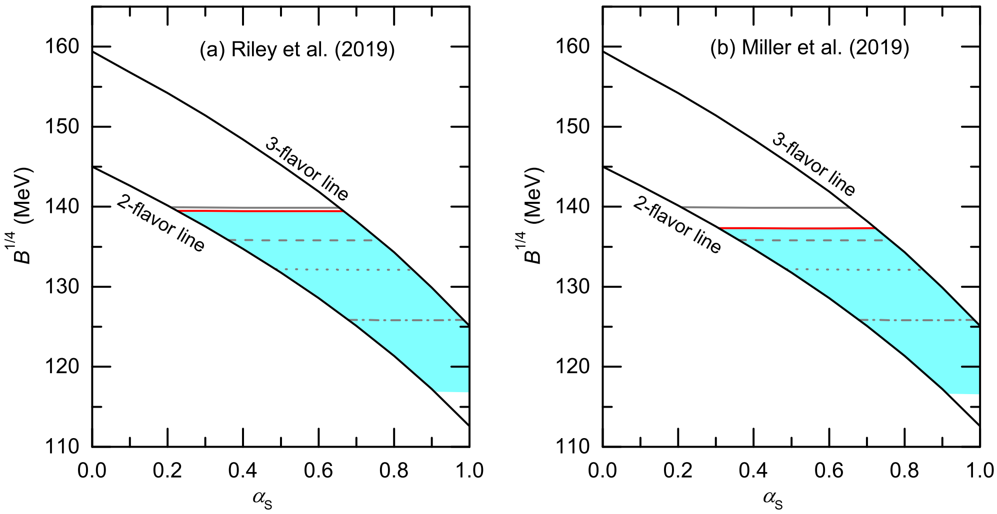

Figure 10. Constraints on the parameters of the standard MIT model for $m_s = 93$ MeV. The cyan-shadowed areas are the same as those in Figure 2. The gray lines are for $\Lambda(1.4) = 580$ with $f_M = 0$, 5%, 10%, and 20% from top to bottom. The red lines also correspond to $\Lambda(1.4) = 580$, which are for $f_M = 0.5\%$ in (**a**) and for $f_M = 3.1\%$ in (**b**). The image is from [58]. Data from Riley et al. [153] and Miller et al. [154].

Thus, we have the conclusion that assuming PSR J0740+6620 and PSR J0030+0451 do not have an MDM core, all the observations of compact stars could be satisfied if SSs in GW170817 have a large enough MDM core ($f_M > 0.5\%$ for Riley et al. [153] and $f_M > 3.1\%$ for Miller et al. [154]). However, PSR J0740+6620 or PSR J0030+0451 might also have an MDM core. In that case, one can easily deduce that SSs in GW170817 should have a larger MDM core in order to satisfy all the observations of compact stars.

6. Conclusions

In this review, it is shown that for the standard MIT bag model, SSs are ruled out by the observations from GW170817 and PSR J0740+6620 (and PSR J0030+0451). In fact, SSs are also ruled out for the density-dependent quark mass model [59] and the quasi-particle model [60]. However, the tension between the theory of SSs and the observations of compact stars could be resolved if alternative gravity (i.e., non-Newtonian gravity) or dark matter (i.e., mirror dark matter) is considered.

We find that the non-Newtonian gravity effects of SSs could help to relieve the tension between the observations of the tidal deformability of GW170817 and the mass of PSR J0740+6620. However, if the constraints from the mass and radius of PSR J0030+0451 are added, the existence of SSs is still ruled out even if the effects of non-Newtonian gravity are considered. However, the possibility of the existence of SSs should be investigated under the framework of other alternative gravity theories [6,105,106].

In the scenario of SSs with an MDM core, it is found that to explain all the observations of compact stars, an MDM core should exist in the SSs of GW170817. Moreover, although this result is derived for the case of MDM, it is qualitatively valid for other kinds of DM that could exist inside SSs. As a result, one arrives at the conclusion that for the standard MIT bag model, the current observations of compact stars could serve as evidence for the existence of a DM core inside SSs.

One obvious difference between the non-Newtonian scenario and the MDM scenario is that the equilibrium sequence of SSs with non-Newtonian gravity effects is a single line, while the equilibrium sequence of SSs with an MDM core is nonunique and is a fan-shaped region as shown in Figure 11. Since the value of f_M for each SS is different (which depends on its evolutionary history) [111], SSs could be located everywhere on that region. Given further mass and radius observations of compact stars in the near future, one will be able to distinguish between these two scenarios.

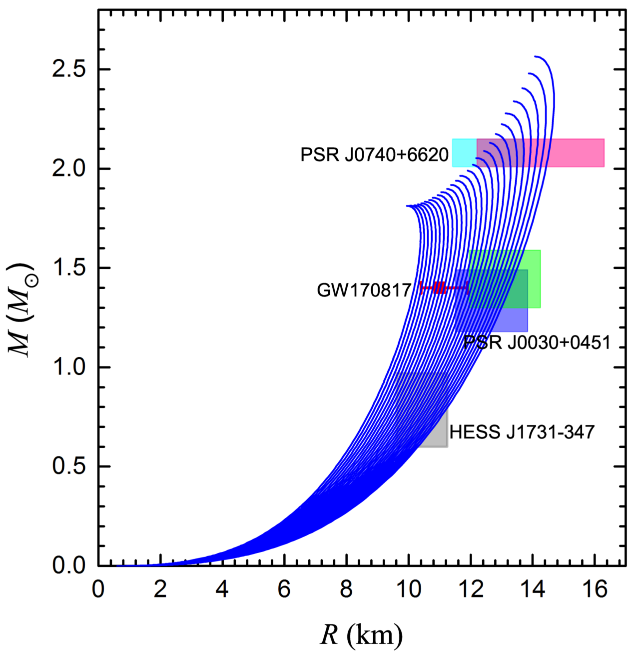

Figure 11. The mass–radius relation of SSs for $m_s = 93$ MeV $\alpha_S = 0.7$ and $B^{1/4} = 125.1$ MeV. The rightmost line is for SSs without an MDM core (i.e., $f_M = 0$). Other lines are for SSs with different f_M, namely, from $f_M = 2\%$ to 50% with step 2% (From right to left. For $f_M = 50\%$, the MDM core has the same radius as that of the SS with an ordinary SQM). The observational data are the same as those shown in Figure 1.

From the aspect of the study of SQM, this review is limited to the standard MIT bag model, the density-dependent quark mass model [61,208–212], and the quasi-particle model [213–217]. However, similar investigations should be carried out in the future that are based on other phenomenological SQM models such as the Nambu–Jona–Lasinio (NJL) model [218–222], the perturbative QCD approach [223–225], and the models considering isospin interaction [226–229]. Moreover, SQM is supposed to be in a color superconducting state [230–235], and the quarks might pair in different patterns such as CFL (color-flavor locked phase) [236–238] and 2SC (two-flavor superconducting) [230,231]. Therefore, similar investigations should also be carried out for color superconducting SQM. Note that recently SSs made of CFL SQM were employed to explain the large mass of the GW190814's secondary component ($2.59^{+0.08}_{-0.09}\,M_\odot$) [44,239–241].

In summary, alternative gravity theory and DM could play a significant role in the study of SSs and the possibility of the existence of SSs could provide a clue to new physics. More observations of compact stars are expected in the near future using the gravitational wave detectors aLIGO, aVirgo, Kagra, the Einstein Telescope (ET), and the Cosmic Explorer (CE); the X-ray missions eXTP and STROBE-X; and the radio observatory SKA. With these new data, we might finally confirm (or rule out) the existence of SSs (In this review, we mainly discuss SSs by considering the bulk properties of compact stars such as the mass, radius, and tidal deformability. However, the study of SSs is far beyond these issues. For example, some special phenomena associated with compact stars might also help to reveal their nature. In fact, the neutrinos emitted during the combustion of an NS into an SS could be possibly directly detected [242]. Some explosions, especially fast radio bursts, may point to the existence of SSs [243], and it has also been suggested identify strange quark objects may be identified via a search for close-in exoplanets around pulsars [244]). This would provide useful information concerning the gravity theory or the properties of DM.

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Abbreviations

The following abbreviations are used in this review:

DM	dark matter
EOS	equation of state
eXTP	enhanced X-ray timing and polarimetry mission
GR	general relativity
LIGO	llaser interferometer gravitational wave observatory
MDM	mirror dark matter
MIT	Massachusetts Institute of Technology
NICER	Neutron star Interior Composition Explorer
NS	neutron star
SM	standard Model
SQM	strange quark matter
SS	strange star
STROBE-X	Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays
SKA	Square Kilometre Array observatory
TOV	Tolman–Oppenheimer–Volkoff
Virgo	Virgo interferometer

Notes

1 For the standard MIT model, this is true considering the constraints from the observations of PSR J0740+6620 and GW170817, which are mentioned in the previous paragraph. However, if the observation data of PSR J0030+0451 are also considered, SSs will be ruled out even if we consider the effects of non-Newtonian gravity [62]. The details can be seen in Section 4.2 of this review.

2 For the choice of the value of m_s, we simply follow the early papers related to this review. The results are similar whether we choose $m_s = 93$ MeV or $m_s = 95$ MeV. In fact, the results will not be changed qualitatively even if we choose $m_s = 150$ MeV, as shown in [57,58].

3 λ symbolizes the tidal deformability parameter here. It also symbolizes the length scale of non-Newtonian gravity conventionally in Equations (18) and (19).

4 a new massive compact star with a mass of $2.35 \pm 0.17\, M_{\odot}$ was reported recently (PSR J0952-0607) [165]. It is one of the fastest-spinning pulsars with a spin period of 1.41 ms, and the rotation effects on the mass and radius cannot be ignored for this star [166].

5 in the weak-field limit, a Yukawa term also appears in alternative theories of gravity such as f(R), the nonsymmetric gravitational theory, and modified gravity [6].

[6] Scalar bosons lead to a softer EOS of dense matter, while vector bosons make the EOS stiffer [71]. In the following section of this review, we will focus on vector bosons. This is necessary because a stiff EOS is needed to explain the large mass of PSR J0740+6620, with g being the boson–baryon coupling constant and m_b being the baryon mass.

[7] In the study of neutron–mirror neutron $(n - n')$ mixing [203–207], it was found that a mirror-matter core could develop in ordinary NSs through the process of $n - n'$ conversion [122]. However, since SQM is self-bound, the transformation to mirror matter is suppressed [122].

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