

Constraints from compact star observations on non-Newtonian gravity in strange stars based on a density dependent quark mass model

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Using a density dependent quark mass (QMDD) model for strange quark matter, we investigate the effects of non-Newtonian gravity on the properties of strange stars and constrain the parameters of the QMDD model by employing the mass of PSR J0740 + 6620 and the tidal deformability of GW170817. We find that for the QMDD model these mass and tidal deformability observations would rule out the existence of strange stars if non-Newtonian gravity effects are ignored. For the current quark masses of $m_u = 2.16$ MeV, $m_d = 4.67$ MeV, and $m_s = 93$ MeV, we find that a strange star can exist for values of the non-Newtonian gravity parameter g^2/μ^2 in the range of $4.58 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 9.32 \text{ GeV}^{-2}$, and that the parameters D and C of the QMDD model are restricted to $158.3 \text{ MeV} \leq D^{1/2} \leq 181.2 \text{ MeV}$ and $-0.65 \leq C \leq -0.12$. It is found that the largest possible maximum mass of a strange star obtained with the QMDD model is $2.42 M_\odot$ and that the secondary component of GW190814 with a mass of $2.59^{+0.08}_{-0.09} M_\odot$ could not be a static strange star. We also find that for the mass and radius of PSR J0030 + 0451 given by Riley *et al.* through the analysis of observational data of NICER, there exists a very tiny allowed parameter space for which strange stars computed for the QMDD model agree with the observations of PSR J0740 + 6620, GW170817 and PSR J0030 + 0451 simultaneously. However, for the mass and radius given by Miller *et al.*, no such parameter space exist.

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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 [5–10].

Effects of non-Newtonian gravity on the properties of neutron stars and SSs have been studied extensively [e.g., [11–19]]. The conventional inverse-square-law of gravity is expected to be violated in the efforts of trying to unify gravity with the other three fundamental forces, namely, the electromagnetic, weak and strong interactions [20–22]. Non-Newtonian gravity arise due to either the geometrical effect of the extra space-time dimensions predicted by string theory and/or the exchange of weakly interacting bosons, such as a neutral very weakly coupled spin-1 gauge

U-boson proposed in the supersymmetric extension of the standard model [23,24]. Although the existence of non-Newtonian gravity is not confirmed yet, constraints on the upper limits of the deviations from Newton's gravity have been set experimentally (see [25] and references therein).

For the standard MIT bag model, Yang *et al.* [19] found that if non-Newtonian gravity effects are ignored, the existence of SSs is ruled out by the mass of PSR J0740 + 6620 ($2.14^{+0.10}_{-0.09} M_\odot$ for a 68.3% credibility interval; $2.14^{+0.20}_{-0.18} M_\odot$ for a 95.4% credibility interval) [26] and the dimensionless tidal deformability of a $1.4 M_\odot$ star of GW170817 ($\Lambda(1.4) = 190^{+390}_{-120}$) [27,28]. However, if non-Newtonian gravity effects are considered, Yang *et al.* [19] found that SSs can exist for certain ranges of the values of the non-Newtonian gravity parameter g^2/μ^2 , and the bag constant B and the strong interaction coupling constant α_s of the SQM model. For example, for a strange quark mass of $m_s = 95$ MeV, SSs can exist for $1.37 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 7.28 \text{ GeV}^{-2}$, and limits on parameters of the SQM model are $141.3 \text{ MeV} \leq B^{1/4} \leq 150.9 \text{ MeV}$ and $\alpha_s \leq 0.56$.

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Recently, the density dependent quark mass (QMDD) model was revisited in detail by Backes *et al.* [29] without the inclusion of the non-Newtonian effects. Similar to the results given by Yang *et al.* [19], they found that the observations of GW170817 and the mass of PSR J0740 + 6620 cannot be satisfied simultaneously for SSs with the QMDD model. These authors did not use the constraints of the dimensionless tidal deformability of a $1.4 M_\odot$ star from GW170817 directly. Instead, they employed the radius of a $1.4 M_\odot$ star, which is $R_{1.4} = 11.0_{-0.6}^{+0.9}$ km, derived from the observations of GW170817 by Capano *et al.* [30].

In this paper, we will investigate the effects of non-Newtonian gravity on the properties of SSs and constrain the parameter space of the QMDD model using the tidal deformability of GW170817 and the mass of PSR J0740 + 6620. Moreover, constraints from the mass and radius of PSR J0030 + 0451 derived from NICER observations [31,32] are investigated too.

This paper is organized as follows. In Sec. II, we briefly review the QMDD model and the equation of state (EOS) of SQM including the non-Newtonian gravity effects. In Sec. III, numerical results and discussions are presented. Finally, a brief summary of our results is given in Sec. IV.

II. EOS OF SQM INCLUDING THE NON-NEWTONIAN GRAVITY EFFECTS

Before discussing the effects of non-Newtonian gravity on the EOS of SQM, we briefly review the phenomenological model for the EOS employed in this paper, namely the QMDD model.

The key feature of the QMDD model is the use of density dependent quark masses to express nonperturbative interaction effects [33,34]. The first few QMDD studies of the EOS of SQM were thermodynamically inconsistent [e.g., [35–38]]. However a fully self-consistent thermodynamic treatment of the QMDD model has been established in the years that followed [e.g., [39–41]]. Furthermore, while the original quark mass scaling formalism barely accounted for the confinement interaction [e.g., [33,42]], an improved quark mass scaling taking into account both the linear confinement and leading order interactions has been introduced by Xia *et al.* [41].

Taking into account both the linear confinement and leading order interactions, the quark mass scaling is given by [41]

$$m_i = m_{i0} + m_I \equiv m_{i0} + \frac{D}{n_b^{1/3}} + C n_b^{1/3}. \quad (1)$$

Here m_I is a density dependent term that includes the quark interaction effects introduced through the adjustable parameters C and D , m_{i0} is the current mass of quark flavor i with $m_{u0} = 2.16$ MeV, $m_{d0} = 4.67$ MeV, and $m_{s0} = 93$ MeV [43], and n_b is the baryonic density,

$$n_b = \frac{1}{3} \sum_i n_i, \quad (2)$$

where the number density of each quark species n_i is given by Eq. (6).

The equation of state (EOS) of SQM with the above density dependent quark masses is to be determined subject to the following fully consistent thermodynamic conditions [41]. At zero temperature, the thermodynamic potential of free unpaired particles is given by

$$\Omega_0 = - \sum_i \frac{g}{24\pi^2} \left[\mu_i^* \nu_i \left(\nu_i^2 - \frac{3}{2} m_i^2 \right) + \frac{3}{2} m_i^4 \ln \frac{\mu_i^* + \nu_i}{m_i} \right], \quad (3)$$

where $g = 6$ is the degeneracy of quarks, μ_i^* is the effective chemical potential of quark flavor i , and it is related to the chemical potential μ_i through the following equation:

$$\mu_i = \mu_i^* + \frac{1}{3} \frac{\partial m_I}{\partial n_b} \frac{\partial \Omega_0}{\partial m_I}. \quad (4)$$

The quantity ν_i denotes the Fermi momentum of a quark of type i ,

$$\nu_i = \sqrt{\mu_i^{*2} - m_i^2}, \quad (5)$$

and the corresponding particle number densities are given by

$$n_i = \frac{g}{6\pi^2} (\mu_i^{*2} - m_i^2)^{3/2} = \frac{g \nu_i^3}{6\pi^2}. \quad (6)$$

The energy density without the effects of the non-Newtonian gravity is given by

$$\epsilon_Q = \Omega_0 - \sum_i \mu_i^* \frac{\partial \Omega_0}{\partial \mu_i^*}, \quad (7)$$

and the pressure is obtained from

$$p_Q = -\Omega_0 + \sum_{i,j} \frac{\partial \Omega_0}{\partial m_j} n_i \frac{\partial m_j}{\partial n_i}, \quad (8)$$

which can be written in the more convenient form,

$$p_Q = -\Omega_0 + n_b \frac{\partial m_I}{\partial n_b} \frac{\partial \Omega_0}{\partial m_I}. \quad (9)$$

In addition, chemical equilibrium is maintained by the weak-interaction of SQM, which leads for the chemical potentials to the following conditions:

$$\mu_d = \mu_s, \quad (10)$$

$$\mu_s = \mu_u + \mu_e. \quad (11)$$

The electric charge neutrality condition is given by

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0. \quad (12)$$

Non-Newtonian gravity is often characterized effectively by adding a Yukawa term to the normal gravitational potential [44].¹ The Yukawa-type non-Newtonian gravity between the two objects with masses m_1 and m_2 is [20–22]

$$V(r) = -\frac{G_\infty m_1 m_2}{r} (1 + \alpha e^{-r/\lambda}) = V_N(r) + V_Y(r), \quad (13)$$

where $V_Y(r)$ is the Yukawa correction to the Newtonian potential $V_N(r)$. The quantity $G_\infty = 6.6710 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$ is the universal gravitational constant, α is the dimensionless coupling constant of the Yukawa force, and λ is the range of the Yukawa force mediated by the exchange of bosons of mass μ (given in natural units) among m_1 and m_2 ,

$$\lambda = \frac{1}{\mu}. \quad (14)$$

In this picture, the Yukawa term is the static limit of an interaction mediated by virtual bosons. The strength parameter in Eq. (13) is given by

$$\alpha = \pm \frac{g^2}{4\pi G_\infty m_b^2}, \quad (15)$$

where the $\pm$ sign refers to scalar (upper sign) or vector (lower sign) bosons, g is the boson-baryon coupling constant, and m_b is the baryon mass.

Krivoruchenko *et al.* [11] suggested that a neutral very weakly coupled spin-1 gauge U-boson proposed in the supersymmetric extension of the standard model is a favorite candidate for the exchanged boson [23,24]. This light and weakly interacting U-boson has been used to explain the 511 keV γ -ray observation from the Galactic bulge [46–48], and various experiments in terrestrial laboratories have been proposed to search for this boson [49]. Since the new bosons contribute to the EOS of dense matter in terms of g^2/μ^2 [50], which can be large even when both the coupling constant g and the mass μ of the light and weakly interacting bosons are small, the structure of

compact stars may be greatly influenced by the non-Newtonian gravity effects.

It has been shown by Krivoruchenko *et al.* [11] that an increase of g (a decrease of μ) of scalar bosons has a negative contribution to pressure, which makes the EOS of dense matter softer and reduces the maximum mass of a compact star. By contrast, an increase of g (a decrease of μ) of vector bosons makes the EOS of dense matter stiffer and increases the maximum mass of a compact star. In the following, we will only study the case of vector bosons since a stiff EOS of SQM is needed to accommodate the tidal deformability of GW170817 and the mass of PSR J0740 + 6620.

The contribution of the Yukawa correction $V_Y(r)$ of Eq. (13) to the energy density of SQM is obtained by integrating over the quark densities $n_b(\vec{x}_1)$ and $n_b(\vec{x}_2)$ inside a given volume V [11,12,17,51],

$$\epsilon_Y = \frac{1}{2V} \int 3n_b(\vec{x}_1) \frac{g^2 e^{-\mu r}}{4\pi r} 3n_b(\vec{x}_2) d\vec{x}_1 d\vec{x}_2, \quad (16)$$

where $r = |\vec{x}_1 - \vec{x}_2|$. The prefactors of 3 in front of the quark densities are required since the baryon number of quarks is $1/3$. Equation (16) can be evaluated further since the quark densities $n_b(\vec{x}_1) = n_b(\vec{x}_2) \equiv n_b$ are essentially independent of position [7–10]. Moving n_b outside of the integral then leads for the energy density of SQM inside of $V = 4\pi R^3/3$ (for simplicity taken to be spherical²) to [17,19]

$$\epsilon_Y = \frac{9}{2} g^2 n_b^2 \int_0^R r e^{-\mu r} dr. \quad (17)$$

Upon carrying out the integration over the spherical volume one arrives at

$$\epsilon_Y = \frac{9}{2} \frac{g^2 n_b^2}{\mu^2} [1 - (1 + \mu R) e^{-\mu R}]. \quad (18)$$

Because the system we are considering is in principle very large, we may take $R \rightarrow \infty$ in Eq. (18) to arrive at

$$\epsilon_Y = \frac{9}{2} \frac{g^2}{\mu^2} n_b^2. \quad (19)$$

This analysis shows that the additional contribution to the energy density from the Yukawa correction, V_Y , is simply determined (aside from some constants) by the number of quarks per volume. The total energy density of SQM is obtained by adding ϵ_Y to the standard expression for the energy density of SQM given by Eq. (7), leading to

¹An extra Yukawa term also naturally arises in the weak-field limit of some modified theories of gravity, e.g., $f(R)$ gravity, the nonsymmetric gravitational theory, and modified gravity. See [45], and references therein.

²The actual geometry of the volume is unimportant since we are only interested in the local modification of the energy [Eq. (19)] caused by the Yukawa term.

$$\epsilon = \epsilon_Q + \epsilon_Y. \quad (20)$$

Correspondingly, the extra pressure due to the Yukawa correction is

$$p_Y = n_b^2 \frac{d}{dn_b} \left(\frac{\epsilon_Y}{n_b} \right) = \frac{9}{2} \frac{g^2 n_b^2}{\mu^2} \left(1 - \frac{2n_b}{\mu} \frac{\partial \mu}{\partial n_b} \right). \quad (21)$$

Assuming a constant boson mass (independent of the density) [11,12,17], one obtains

$$p_Y = \epsilon_Y = \frac{9}{2} \frac{g^2}{\mu^2} n_b^2. \quad (22)$$

The total pressure including the non-Newtonian gravity (Yukawa) term then reads

$$p = p_Q + p_Y, \quad (23)$$

where p_Q is given by Eq. (9).

III. RESULTS AND DISCUSSIONS

For a given SQM EOS, the structure of strange stars and their tidal deformability is calculated from the Tolman-Oppenheimer-Volkoff equation, as described in Refs. [52–57].

The mass-radius relations of SSs for different non-Newtonian gravity parameters are shown in Fig. 1. We choose $D^{1/2} = 161.3$ MeV, $C = -0.23$ because for this set of parameter, the observations of PSR J0740 + 6620, GW170817 and PSR J0030 + 0451 (only for mass and radius data given by Riley *et al.* [31]) can be satisfied simultaneously when the non-Newtonian gravity parameter $g^2/\mu^2 = 5.77$, as will be shown in Fig. 3. The dash-dotted line for $g^2/\mu^2 = 9.32$ satisfies the constraints on PSR J0030 + 0451 set by NICER data and the radius data derived by Capano *et al.* [30]. The corresponding set of parameter $D^{1/2} = 161.3$ MeV, $C = -0.23$, and $g^2/\mu^2 = 9.32$ is ruled out by the constraints employed by this paper later, which can be seen in Fig. 2(e).

We investigate the allowed parameter space of QMDD model according to the following five constraints [e.g., [19,29,58–62]]:

First, as pointed out by Backes *et al.* [29], the quark masses could become negative at high densities and a negative mass has no physical meaning, resulting in a regime where the model is not valid. Following Backes *et al.* [29], we present the invalid $D^{1/2}$ – C parameter regions in Fig. 2 (namely, the yellow-shaded regions), which are separated with other areas by requiring $m_{u0} = 0$ at $n = 1.5 \text{ fm}^{-3}$ (around 10 times the nuclear saturation density). These yellow-shaded regions are ruled out because for the parameters located in these regions, m_{u0} becomes negative

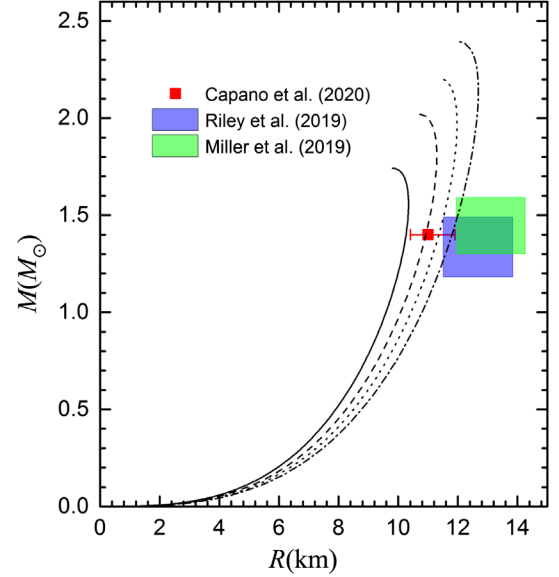


FIG. 1. The mass-radius relation of SSs with $D^{1/2} = 161.3$ MeV, $C = -0.23$. The solid, dashed, dotted, dash-dotted lines are for $g^2/\mu^2 = 0.0, 3.0, 5.77$, and 9.32 GeV^{-2} , respectively. The red data are $R_{1.4} = 11.0^{+0.9}_{-0.6} \text{ km}$, which is the radius of $1.4 M_\odot$ constrained by the observations of GW170817 [30]. The blue and green regions show the mass and radius estimates of PSR J0030 + 0451 derived from NICER data by Riley *et al.* [31] ($R = 12.71^{+1.14}_{-1.19} \text{ km}$, $M = 1.34^{+0.15}_{-0.16} M_\odot$) and Miller *et al.* [32] ($R = 13.02^{+1.24}_{-1.06} \text{ km}$, $M = 1.44^{+0.15}_{-0.14} M_\odot$).

on densities lower than $n = 1.5 \text{ fm}^{-3}$, which may happen in the cores of the massive SSs.

Second, 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 ($E/A \sim 930 \text{ MeV}$) [3].³ This constraint results in the 3-flavor lines (the dash-dotted lines) shown in Fig. 2.

Here we want to stress that atomic nuclei do not transition to (lumps of) SQM, and neither the EOS of ordinary nuclear matter nor NN scattering data are impacted by the possible absolute stability of SQM. The reason is that the creation of SQM requires a significant fraction of strange quarks to be present. Conversion of an ^{56}Fe nucleus, for instance, into SQM requires a very high-order weak interaction to simultaneously change dozens of u and d quarks into s quarks. The probability of this happening is astronomically small. For lower baryon numbers, the conversion requires a lower-order weak interaction, but finite-size effects and the positive

³It is common practice to compare the energy of SQM to ^{56}Fe . The energy per baryon of ^{56}Fe , however, is only the third lowest after ^{62}Ni and ^{58}Fe .

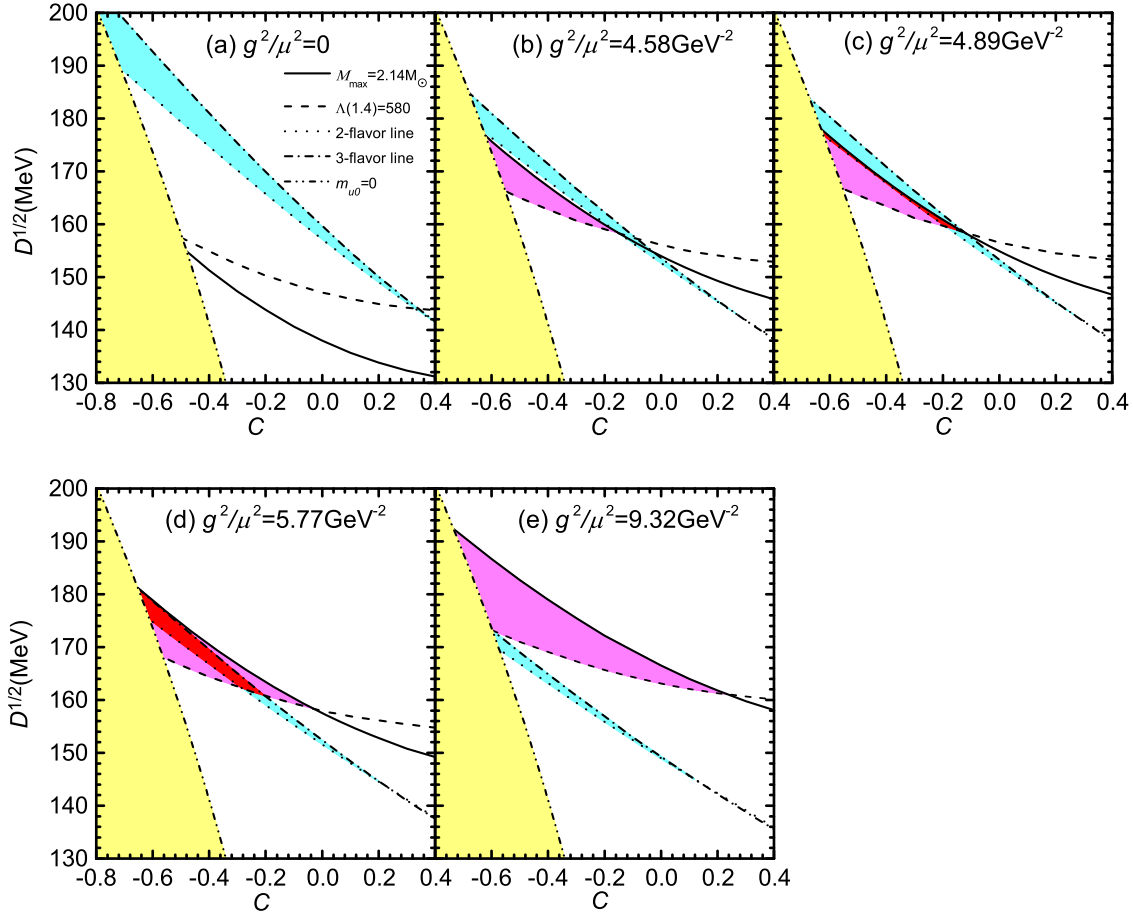


FIG. 2. Constraints on $D^{1/2}$ and C for $g^2/\mu^2 = 0$ (a), $g^2/\mu^2 = 4.58 \text{ GeV}^{-2}$ (b), $g^2/\mu^2 = 4.89 \text{ GeV}^{-2}$ (c), $g^2/\mu^2 = 5.77 \text{ GeV}^{-2}$ (d), and $g^2/\mu^2 = 9.32 \text{ GeV}^{-2}$ (e), respectively. The red-shadowed regions in panels (c) and (d) indicate the allowed parameter spaces. (See text for details.)

electrostatic potential of SQM destabilize small lumps of SQM so that they become unstable even if SQM is stable in bulk.

The third constraint is given by assuming that nonstrange quark matter (i.e., two-flavor quark matter made of 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 [5,9,59,62]. By imposing $E/A \geq 934 \text{ MeV}$ on nonstrange quark matter, one ensures that atomic nuclei do not dissolve into their constituent quarks. This leads to the 2-flavor lines (dotted lines) in Fig. 2. The cyan-shaded areas between the 3-flavor lines (the dash-dotted lines) and the 2-flavor lines (dotted lines) in Fig. 2 show the allowed $D^{1/2}$ – C parameter regions where the second and the third constraints described just above are fulfilled.

The fourth constraint is that the maximum mass of SSs must be greater than the mass of PSR J0740 + 6620, $M_{\text{max}} \geq 2.14 M_{\odot}$. By employing this constraint, the allowed parameter space is limited to the region below the solid lines in Fig. 2.

The last constraint follows from $\Lambda(1.4) \leq 580$, where $\Lambda(1.4)$ is the dimensionless tidal deformability of a $1.4 M_{\odot}$

star. The parameter space satisfies this constraint corresponds to the region above the dashed lines in Fig. 2. The magenta-shaded areas between the solid lines and the dashed lines in Fig. 2 show the allowed $D^{1/2}$ – C parameter regions where both constraints from the mass PSR J0740 + 6620 and the tidal deformability of GW170817 are fulfilled.

By imposing all the five constraints discussed above, the allowed $D^{1/2}$ – C parameter space of QMDD model is restricted to the red-shadowed regions shown in Figs. 2(c) and 2(d), which are obtained for non-Newtonian gravity parameter values of $g^2/\mu^2 = 4.89 \text{ GeV}^{-2}$, and $g^2/\mu^2 = 5.77 \text{ GeV}^{-2}$, respectively. An overlapping region where all the five constraints are simultaneously satisfied does not exist for all other cases shown in Fig. 2, panels (a), (b), (e), which correspond to $g^2/\mu^2 = 0$, $g^2/\mu^2 = 4.58 \text{ GeV}^{-2}$, and $g^2/\mu^2 = 9.32 \text{ GeV}^{-2}$, respectively.

From Fig. 2(a), one sees that for the case of $g^2/\mu^2 = 0$, the five constraints mentioned above cannot be satisfied simultaneously. This situation continues as the value of g^2/μ^2 becomes bigger until it is as large as 4.58 GeV^{-2} , in which case the $M_{\text{max}} = 2.14 M_{\odot}$ line, the $\Lambda(1.4) = 580$ line and the 2-flavor line intersect at the point $(158.3, -0.15)$

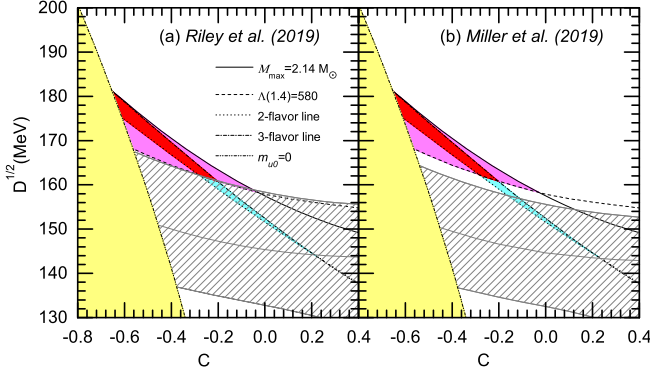


FIG. 3. Constraints on $D^{1/2}$ and C for $g^2/\mu^2 = 5.77 \text{ GeV}^{-2}$. The gray-shaded regions in panels (a) and (b) indicate the parameter spaces restricted by the mass and radius of PSR J0030 + 0451 derived from the NICER observation by Riley *et al.* [31] and Miller *et al.* [32], respectively.

[see Fig. 2(b)]. The allowed parameter space vanished entirely for $g^2/\mu^2 > 9.32 \text{ GeV}^{-2}$, as shown in Fig. 2(e).

Let us focus on Fig. 2, panels (b), (c) and (d) once again. In Fig. 2(b), the $M_{\text{max}} = 2.14 M_{\odot}$ line, the $\Lambda(1.4) = 580$ line and the 2-flavor line intersect at the point (158.3, -0.15), which means that the lower limit of $D^{1/2}$ is 158.3 MeV. In Fig. 2(c), the $M_{\text{max}} = 2.14 M_{\odot}$ line, the $\Lambda(1.4) = 580$ line and the 3-flavor line intersect at the point (158.5, -0.12), which means that the upper limit of C is -0.12. Whereas, in Fig. 2(d), the $M_{\text{max}} = 2.14 M_{\odot}$ line, the 3-flavor line and the $m_{u0} = 0$ line intersect at the point (181.2, -0.65), which suggests that the upper limit of $D^{1/2}$ is 181.2 MeV and the lower limit of C is -0.65.

In addition, one can see from Fig. 2(e) that the largest allowed maximum mass for our SQM model that can satisfy all the above five constraints simultaneously is reached at $D^{1/2} = 173.1 \text{ MeV}$, $C = -0.60$ and $g^2/\mu^2 = 9.32 \text{ GeV}^{-2}$, which is $2.42 M_{\odot}$.

Recently, the NICER observations of the isolated pulsar PSR J0030 + 0451 produced two independent measurements of the pulsar's mass and equatorial radius: $M = 1.34^{+0.15}_{-0.16} M_{\odot}$ and $R_{\text{eq}} = 12.71^{+1.14}_{-1.19} \text{ km}$ [31], and $M = 1.44^{+0.15}_{-0.14} M_{\odot}$ and $R_{\text{eq}} = 13.02^{+1.24}_{-1.06} \text{ km}$ [32]. In Fig. 3, these data on the M - R plane are translated into the $D^{1/2}$ - C space (namely, the gray-shaded regions) for the case of $g^2/\mu^2 = 5.77 \text{ GeV}^{-2}$. The gray lines in Fig. 3(a) are for $(M(M_{\odot}), R(\text{km}))$ sets (1.49, 11.52), (1.34, 12.71), and (1.18, 13.85) from top to bottom, and these parameter sets correspond to the data given by Riley *et al.* [31]. The gray lines in Fig. 3(b) are for (1.59, 11.96), (1.44, 13.02), and (1.30, 14.26) from top to bottom, and these parameter sets come from the data given by Miller *et al.* [32].

We can see from Fig. 3(a) that the allowed parameter space constrained by the mass and radius of PSR J0030 + 0451 given by Riley *et al.* [31] (the gray-shaded region) marginally overlaps with the allowed region (the

red-shaded region) restricted by the five constraints mentioned earlier. However, for the observational data given by Miller *et al.* [32] in Fig. 3(b), no such overlapping region exist. This means that there exists a very tiny allowed parameter space for which our SQM model agrees with the observations related to PSR J0740 + 6620, GW170817 and PSR J0030 + 0451 simultaneously if one employs the mass and radius given by Riley *et al.* [31]. On the other hand, if the data from Miller *et al.* [32] are employed, these observations cannot be explained simultaneously. Although we only show the case of $g^2/\mu^2 = 5.77 \text{ GeV}^{-2}$ in Fig. 3, we have checked some other cases between $4.58 \text{ GeV}^{-2} < g^2/\mu^2 < 9.32 \text{ GeV}^{-2}$ and find that one always arrives at the above conclusion.

IV. SUMMARY

In this paper, we have investigated the effects of non-Newtonian gravity on the properties of SSs and constraint the parameter space of the QMDD model using astrophysical observations related to PSR J0740 + 6620 and GW170817. Similarly to the results presented in Ref. [19], we found that

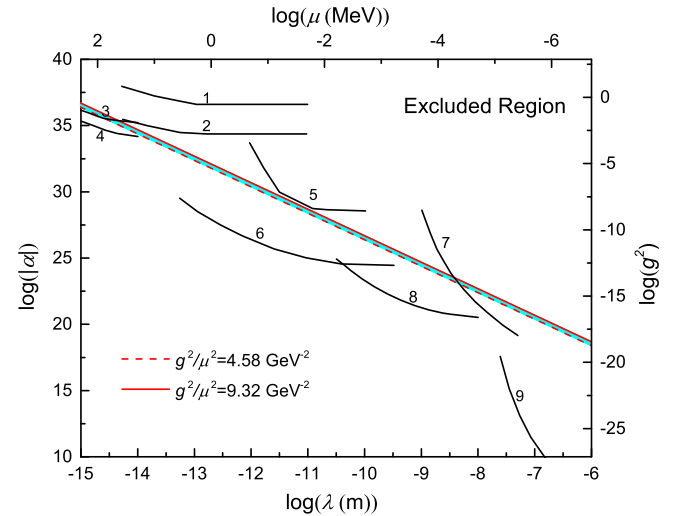


FIG. 4. Upper bounds on the strength parameter $|\alpha|$ respectively the boson-nucleon coupling constant g as a function of the range of the Yukawa force μ (bottom) and the mass of hypothetical bosons (top), set by different experiments as used in Ref. [19]: curves 1 and 2 refer to constraints from np scattering of scalar and vector bosons, respectively [63]; 3 and 4 are constraints extracted from charge radii and binding energies of atomic nuclei, respectively [64]; 5 was established from the spectroscopy of antiprotonic He atoms and 6 from neutron total cross section scattering of ^{208}Pb nuclei [65]; 7 is from an experiment measuring the Casimir force between a Au-coated microsphere and a silicon carbide plate [66]; 8 is obtained by measuring the angular distribution of 5 Å neutrons scattered off of an atomic xenon gas [67]; 9 shows the constraints from the force measurements between a test mass and rotating source masses of gold and silicon [68]. The cyan-shaded strip corresponds to $4.58 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 9.32 \text{ GeV}^{-2}$.

these observations cannot be explained by the SQM model employed in this paper if the non-Newtonian gravity effects are not included. In other words, the existence of SSs is ruled out in this case.

Considering the non-Newtonian gravity effects, for the current quark mass $m_{u0} = 2.16$ MeV, $m_{d0} = 4.67$ MeV, and $m_{s0} = 93$ MeV [43], an allowed parameter space of $D^{1/2}$ and C exists only when $4.58 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 9.32 \text{ GeV}^{-2}$, and the parameters of the QMDD model are restricted to $158.3 \text{ MeV} \leq D^{1/2} \leq 181.2 \text{ MeV}$ and $-0.65 \leq C \leq -0.12$. As shown in Fig. 4, theoretical bounds on g^2/μ^2 of $4.58 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 9.32 \text{ GeV}^{-2}$ for which QSs are found to exist (indicated by the cyan-colored strip in the figure) is excluded by some experiments (curves labeled 4, 6, 8, 9) but allowed by others (curves labeled 1, 2, 5 and parts of curves 3 and 7).

We also find that the largest allowed maximum mass of SSs for the QMDD model is $2.42 M_{\odot}$, corresponding to the parameter set $D^{1/2} = 173.1 \text{ MeV}$, $C = -0.60$ and $g^2/\mu^2 = 9.32 \text{ GeV}^{-2}$. Therefore, even considering the non-Newtonian effect, the GW190814's secondary component with mass $2.59^{+0.08}_{-0.09} M_{\odot}$ [69] could not be a static SS. However, it could be a rigid or differentially rotating SS [70].

Moreover, by translating the mass and radius of PSR J0030 + 0451 observed by NICER into the $D^{1/2}$ - C space, we find that for the analysis by Riley *et al.* [31], there exists a very tiny allowed parameter space for which SSs constructed with the QMDD model agree with the observations related to PSR J0740 + 6620, GW170817 and PSR J0030 + 0451 simultaneously; but for the analysis by Miller *et al.* [32], these observations cannot be explained simultaneously.

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