Non-Newtonian Gravity in Strange Quark Stars and Constraints from the Observations of PSR J0740+6620 and GW170817

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Received 2019 September 24; revised 2020 August 20; accepted 2020 August 25; published 2020 October 8

Abstract

We investigate the effects of non-Newtonian gravity on the properties of strange quark stars (SQs) and constrain the parameters of the standard MIT bag model used to describe strange quark matter (SQM) by employing the mass of PSR J0740+6620 and the tidal deformability of GW170817. We find that, for the standard MIT bag model, these mass and tidal deformability observations would rule out the existence of QSs if non-Newtonian gravity effects are ignored. For a strange quark mass of \( m_s = 95 \) MeV, we find that QSs can exist for values of the non-Newtonian gravity parameter \( g^2/\mu^2 \) in the range of 1.37 GeV\(^{-2} \leq g^2/\mu^2 \leq 7.28 \) GeV\(^{-2} \) and limits on the bag constant and the strong interaction coupling constant of the SQM model given by 141.3 MeV \( \leq B^{1/4} \leq 150.9 \) MeV and \( \alpha_S \leq 0.56 \). For a strange quark mass of \( m_s = 150 \) MeV, QSs can exist for 1.88 GeV\(^{-2} \leq g^2/\mu^2 \leq 6.27 \) GeV\(^{-2} \) and limits on the parameters of the SQM model given by 139.7 MeV \( \leq B^{1/4} \leq 147.3 \) MeV and \( \alpha_S \leq 0.49 \).

1. Introduction

The gravitational-wave event GW170817 (Abbott et al. 2017a) and its associated electromagnetic counterpart (Abbott et al. 2017b) have placed constraints on the neutron star matter equation of state (EOS; see reviews, e.g., Baiotti 2019; Li et al. 2019; Orsaria et al. 2019; Raithel 2019). Among these studies, several works have checked whether the observations from GW170817 are compatible with QSs, in which the matter consists of deconfined up (u), down (d), and strange (s) quarks and electrons (Lai et al. 2018, 2019; Zhou et al. 2018).

Zhou et al. (2018) found that the tidal deformability of GW170817, together with the mass of PSR J0348+0432 (2.01 \( \pm 0.04 \) M_\odot) ( Antoniadis et al. 2013), can restrict the parameter space of the SQM model, but cannot rule out the possible existence of QSs. However, the dimensionless tidal deformability for a 1.4 M_\odot star (\( \Lambda(1.4) \)) employed by these authors is \( \Lambda(1.4) \leq 800 \) (Abbott et al. 2017a), which has been improved to \( \Lambda(1.4) = 190.3^{+300}_{-120} \) (\( \Lambda(1.4) \leq 580 \) will be used in this paper) (Abbott et al. 2018). Moreover, the millisecond pulsar J0740+6620 with a mass of \( 1.41^{+0.10}_{-0.09} \) M_\odot (68.3% credibility interval; 2.14^{+0.20}_{-0.18} \) M_\odot for a 95.4% credibility interval) was reported recently (Cromartie et al. 2020), which sets a new record for the maximum mass of neutron stars (NSs). In this paper, we show that the existence of QSs seems to be ruled out by these new data (see panel (a) in Figures 3 and 4) if the standard MIT bag model of SQM is used to compute the bulk properties of SQs.

This is no longer the case, however, if non-Newtonian gravity is considered, as will be shown in this paper. Effects of non-Newtonian gravity on the properties of NSs and QSs have been studied (e.g., Krivoruchenko et al. 2009; Wen et al. 2009; Sulaksono et al. 2011; Lin et al. 2014; Lu et al. 2017), and it was found that the inclusion of non-Newtonian gravity leads to stiffer EOSs and higher maximum masses of compact stars. Hence, within the framework of non-Newtonian gravity, the observed massive pulsars do not rule out a rather soft behavior of the EOS of dense nuclear matter (Wen et al. 2009).

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 (Fischbach & Talmadge 1999; Adelberger et al. 2003, 2009). Non-Newtonian gravity arises due to either the geometrical effect of the extra spacetime 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 (Fayet 1980, 1981). Non-Newtonian gravity is often characterized effectively by adding a Yukawa term to the normal gravitational potential (Fujii 1971). Constraints on the deviations from Newton’s gravity have been set experimentally, see Murata & Tanaka (2015) and references therein. (Besides, an 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 (Lin et al. 2014; Li et al. 2019).

In this paper, we will study the effects of non-Newtonian gravity on the properties of QSs and constrain the parameter space of the SQM model using the updated tidal deformability of GW170817 and the recently reported mass of PSR J0740+6620. This paper is organized as follows: In Section 2, we briefly review the theoretical framework of the EOS of strange quark matter including the non-Newtonian gravity effects and the calculations of the structure and tidal deformability of strange stars. In Section 3, numerical results and discussions are presented. Finally, a summary is given in Section 4.
2. Theoretical Framework

2.1. EOS of Strange Quark Matter Including the Non-Newtonian Gravity Effects

Before discussing the effects of non-Newtonian gravity on the EOS of SQM (Farhi & Jaffe 1984; Alcock et al. 1986; Haensel et al. 1986; Alcock & Olinto 1988; Madsen 1999), we briefly review the phenomenological model for the EOS employed in this paper, namely, the standard bag model (Farhi & Jaffe 1984; Alcock et al. 1986; Haensel et al. 1986; Weber 2005). 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 $\alpha_s$ are taken into account.

The thermodynamic potential for the $u$, $d$, and $s$ quarks, and for the electrons are given by (Alcock et al. 1986; Pi et al. 2015)

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

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

$$\Omega_s = -\frac{1}{4\pi^2} \left\{ \mu_s \sqrt{\mu_s^2 - m_s^2} \left( \mu_s^2 - \frac{5}{2} m_s^2 \right) + \frac{3}{2} m_s^4 f(u_s, m_s) - \frac{2\alpha_s}{\pi} \left[ 3(\mu_s \sqrt{\mu_s^2 - m_s^2} - m_s^2 f(u_s, m_s))^2 - 2(\mu_s^2 - m_s^2)^2 - 3m_s^4 \ln\frac{m_s}{\mu_s} + 6 \ln\frac{\sigma}{\mu_s}(\mu_s \sqrt{\mu_s^2 - m_s^2} - m_s^2 f(u_s, m_s)) \right] \right\}.$$  

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

where $f(u_s, m_s) \equiv \ln(\mu_s + \sqrt{\mu_s^2 - m_s^2})/m_s$. The quantity $\sigma (=300\text{MeV})$ is a renormalization constant whose value is of the order of the chemical potential of strange quarks, $\mu_s$. Values of $m_s = 95\text{MeV}$ and $m_e = 150\text{MeV}$ have been considered for the strange quark mass in our calculations (Olive & Particle Data Group 2014; Tanabashi et al. 2018).

The number density of each quark species is given by

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

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

$$\mu_u = \mu_s,$$

$$\mu_s = \mu_u + \mu_e.$$  

The electric charge neutrality condition is given by

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

The total baryon number density follows from

$$n_b = \frac{1}{3}(n_u + n_s + n_d).$$

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

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

and the corresponding pressure is obtained from

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

where $B$ denotes the bag constant.

According to Fujii (1971), non-Newtonian gravity can be described by adding a Yukawa-like term to the conventional gravitational potential between two objects with masses $m_1$ and $m_2$, i.e.,

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

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

$$\lambda = \frac{1}{\mu}.$$  

In this picture, the Yukawa term is the static limit of an interaction mediated by virtual bosons. The strength parameter in Equation (12) is given by

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

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.

Shown in Figure 1 are the parameter spaces log $g^2/\mu$ and log $[\alpha^2]-\log \lambda$ associated with the abovementioned hypothetical bosons. Constraints on the parameter spaces set by several recent experiments are indicated. The theoretical bounds on $g^2/\mu^2$ of $1.37 \text{GeV}^{-2} \leq g^2/\mu^2 \leq 7.28 \text{GeV}^{-2}$, for which QSs are found to exist (see Section 3) are shown by the cyan-colored strip in this figure. As can be seen, the theoretical region is excluded by some experiments (curves labeled 6, 8, and 9) but allowed by others (curves labeled 1, 2, 3, and 5 as well as parts of curves 4 and 7).

Instead of the Yukawa-type non-Newtonian gravity, power-law modifications to conventional potential have also been considered in other contexts (Fischbach et al. 2001), in which case the total potential is written in the form

$$V(r) = -\frac{G_{\infty} m_1 m_2}{r^{1 + \alpha_N}}$$

Here $\alpha_N$ is a dimensionless constant and $r_0$ corresponds to a new length scale associated with a non-Newtonian process. For example, terms with $N = 2$ and $N = 3$ may be generated by the simultaneous exchange of two massless scalar particles or
two massless pseudoscalar particles, respectively. (See Adelberger et al. 2003 for details.)

Following Krivoruchenko et al. (2009), the Yukawa-type non-Newtonian gravity is used in this paper. Krivoruchenko et al. (2009) suggested that a neutral very weakly coupled spin-1 gauge U-boson proposed in the super-symmetric extension of the standard model is a favorite candidate of the exchanged boson. This light and weakly interacting U-boson has been used to explain the 511 keV Čerenkov observation from the galactic bulge (Jean et al. 2003; Boehm et al. 2004a, 2004b), and various experiments in terrestrial laboratories have been proposed to search for this boson (Yong & Li 2003; Alcock & Olinto 1988; Madsen 1999; Weber 2005). Moving \( n_b \) outside of the integral then leads for the energy of SQM contained inside of \( V = 4 \pi R^3 / 3 \) (for simplicity taken to be spherical) to (Lu et al. 2017)

\[
\epsilon_Y = \frac{9}{2} g^2 n_b^2 \int_0^R r e^{-\mu r} dr. \tag{17}
\]

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

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

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

\[
\epsilon_Y = \frac{9}{2} \frac{g^2}{\mu^2} n_b^2. \tag{19}
\]

This analysis shows that the additional contribution to the energy density from the Yukawa correction, \( \epsilon_Y \), is simply determined (aside from some constants) by the number of quarks per volume. The total energy density of SQM is obtained by adding \( \epsilon_Y \) to the standard expression for the energy density of SQM given by Equation (10), leading to

\[
\epsilon = \epsilon_Q + \epsilon_Y. \tag{20}
\]

Correspondingly, the extra pressure due to the Yukawa correction is

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

Assuming a constant boson mass independent of the density (Krivoruchenko et al. 2009; Wen et al. 2009; Lu et al. 2017), one obtains

\[
p_Y = \epsilon_Y = \frac{9}{2} \frac{g^2}{\mu^2} n_b^2. \tag{22}
\]

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

\[
p = p_Q + p_Y, \tag{23}
\]

where \( p_Q \) is given by Equation (11).

In summary, the full EOS of SQM accounting for the Yukawa correction is given by \( p(\epsilon) \). This quantity constitutes,
via the energy-momentum tensor
\[ T^{ab} = (\epsilon + p(\epsilon))u^a u^b + p(\epsilon)g^{ab}, \]  
the source term of Einstein’s field equation. The effects of the Yukawa correction term on compact stellar objects can thus be explored as usual by solving the Tolman–Oppenheimer–Volkoff (TOV) equation (Oppenheimer & Volkoff 1939; Tolman 1939; Krivoruchenko et al. 2009; Wen et al. 2009; Lin et al. 2014) with \( p(\epsilon) \) (the matter equation) serving as an input quantity (Fujii 1988).

2.2. Strange Quark Star Structure and Tidal Deformability

In the following, we use geometrized units \( G = c = 1 \) and define the compactness \( \beta \), which is given by \( \beta \equiv M/R \).

The dimensionless tidal deformability is defined as \( \Lambda \equiv \lambda/M^3 \), where \( \lambda \) denotes the tidal deformability parameter,\(^5\) which can be expressed in terms of the dimensionless tidal Love number \( k_2 \) as \( \lambda = 2 k_2 R^3 \) (Flanagan & Hinderer 2008; Hinderer 2008; Damour & Nagar 2009; Hinderer et al. 2010). Thus, one has
\[
\Lambda = \frac{2}{3} k_2 \beta^{-5}.
\]

The tidal Love number \( k_2 \) can be calculated using the expression (e.g., Lattimer & Prakash 2016; Wei et al. 2019, 2020)
\[
k_2 = \frac{8}{5} \beta^2 z,
\]
with
\[
z \equiv (1 + 2 \beta^2)[2 - y_R + 2 \beta(y_R - 1)]
\]
and
\[
F \equiv 6 \beta(2 - y_R) + 6 \beta^2(5 y_R - 8) + 4 \beta^3(13 - 11 y_R)
+ 4 \beta^4(3 y_R - 2) + 8 \beta^5(1 + y_R) + 3 \beta(1 - 2 \beta).
\]

In Equations (27) and (28), \( y_R \equiv y(R)/4 \pi R^3 c_s/M \), 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 of a nonzero energy density \( c_s \) just inside the surface of QSs (Postnikov et al. 2010). The quantity \( y(r) \) satisfies the differential equation
\[
\frac{dy(r)}{dr} = -\frac{y(r)^2}{r} - \frac{y(r) - 6}{r - 2 m(r)} - r Q(r),
\]
with
\[
Q(r) \equiv 4 \pi \left[ 5 - y(r) \right] \epsilon(r) + [9 + y(r)] p(r) + [\epsilon(r) + p(r)]/c_s^2 - \frac{m(r) + 4 \pi r^3 p(r)}{r (r - 2 m(r))}.
\]

\(^5\) The symbol \( \lambda \) is also used in Equations (12) and (13), where it denotes the length scale of non-Newtonian gravity. It symbolizes the tidal deformability parameter conventionally only in this paragraph.

Figure 2. Mass-radius relation of strange stars. The black curves are for \( B^{1/4} = 142 \) MeV, \( \alpha_s = 0.2 \), and the cyan curves are for \( B^{1/4} = 146 \) MeV, \( \alpha_s = 0 \). The solid, dashed, dotted, dashed–dotted, and short-dashed lines are for \( g^2/\mu^2 = 0, 1, 3, 5, \) and \( 7 \) GeV\(^{-2} \), respectively. The red data is \( R_{1.4} = 11.0_{-0.5}^{+0.6} \) km, which is the radius of 1.4 \( M_\odot \), constrained by the observations of GW170817 (Capano et al. 2020). The blue and green data show the mass and radius estimates of PSR J0030+0451 derived from NICER data by Riley et al. (2019) \((R = 12.71_{-0.14}^{+0.14} \) km, \( M = 1.34_{-0.18}^{+0.15} M_\odot \)) and Miller et al. (2019) \((R = 13.02_{-0.14}^{+0.15} \) km, \( M = 1.44_{-0.15}^{+0.15} M_\odot \)).

3. Results and Discussions

By solving the TOV equations, the mass–radius relation of strange stars for different non-Newtonian gravity parameters is shown in Figure 2. We choose two sets of parameters, namely, \( B^{1/4} = 142 \) MeV, \( \alpha_s = 0.2 \), and \( B^{1/4} = 146 \) MeV, \( \alpha_s = 0 \), since they can satisfy both the “2-flavor line” and “3-flavor line” constraints, which will be shown later in Figure 3. One can see that the maximum mass of strange stars becomes larger with the inclusion of the Yukawa (non-Newtonian gravity) term. We also find that the radius of a 1.4 \( M_\odot \) QS is consistent with the results derived from GW170817, but PSR J0030+0451 will not be a QS.

We calculate the allowed parameter space of the SQM model according to the following constraints (e.g., Schaab et al. 1997; Weissenborn et al. 2011; Pi et al. 2015; Zhou et al. 2018): First, the existence of QSs 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, \( ^{56}\text{Fe} \) \((E/A \sim 930 \) MeV\) (Witten 1984),

\[
\frac{dp(r)}{dr} = -\frac{m(r) + 4 \pi r^3 p(r)}{r (r - 2 m(r))} \left[ \epsilon(r) + p(r) \right],
\]
\[
\frac{dm(r)}{dr} = 4 \pi \epsilon(r) r^2,
\]
This constraint results in the three-flavor line shown in Figures 3 and 4.

The second constraint is given by assuming that non-strange quark matter (i.e., two-flavor quark matter made of only $u$ and $d$ quarks) in bulk has an energy per baryon higher than that of $^{56}$Fe, plus a 4 MeV correction coming from surface effects (Farhi & Jaffe 1984; Madsen 1999; Weissenborn et al. 2011; Zhou et al. 2018). By imposing $E/A \geq 934$ MeV on non-strange quark matter, one ensures that atomic nuclei do not dissolve into their constituent quarks. This leads to the 2-flavor lines in Figures 3 and 4. The shaded areas between the three-flavor lines and the two-flavor lines in Figures 3 and 4 show the (allowed) $B^{1/4} - \alpha_g$ parameter regions where both constraints on the energy per baryon described just above are fulfilled.

The third constraint is that the maximum mass of QSs must be greater than the mass of PSR J0740+6620, $M_{\text{max}} \geq M_{\odot}$. By employing this constraint, the allowed parameter space is limited to the region below the red solid lines in Figures 3 and 4. The red dashed lines in Figures 3 and 4 correspond to a stellar mass of 2.01 $M_{\odot}$, and are shown for comparison.

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 that satisfies this constraint corresponds to the region above the blue solid lines in Figures 3 and 4. The blue dotted lines shown in these figures correspond to a tidal deformability of $\Lambda(1.4) = 190$.

By imposing all four constraints mentioned above, the allowed $B^{1/4} - \alpha_g$ parameter space of the SQM model considered in this paper is restricted to the dark cyan-shadowed regions shown in Figures 3(c), (d), and (e), which are obtained for non-Newtonian gravity parameter values of $g^2/\mu^2 = 3.25$ GeV$^{-2}$, $g^2/\mu^2 = 4.61$ GeV$^{-2}$, $g^2/\mu^2 = 3.06$ GeV$^{-2}$, and $g^2/\mu^2 = 4.35$ GeV$^{-2}$, respectively. For all other cases studied in our paper, an overlapping region where all four constraints are simultaneously satisfied does not exist. This is selectively shown in Figures 3(a), (b), and (e) which correspond to $g^2/\mu^2 = 0$, $g^2/\mu^2 = 1.37$ GeV$^{-2}$, and $g^2/\mu^2 = 7.28$ GeV$^{-2}$, respectively. Figures 4(a), (b), and (e) illustrate the situation for a strange quark mass of 150 MeV. Here, the corresponding non-Newtonian gravity parameter values are $g^2/\mu^2 = 0$, $g^2/\mu^2 = 1.88$ GeV$^{-2}$, and $g^2/\mu^2 = 6.27$ GeV$^{-2}$, respectively.

From Figures 3(a) and 4(a), one sees that for the case of $g^2/\mu^2 = 0$, the constraints $M_{\text{max}} \geq 2.14 M_{\odot}$ and $\Lambda(1.4) \leq 580$ cannot be satisfied simultaneously. This situation continues as the value of $g^2/\mu^2$ becomes bigger until it is as large as 1.37 GeV$^{-2}$ for a strange quark mass of $m_s = 95$ MeV (1.88 GeV$^{-2}$ for $m_s = 150$ MeV), in which case the $M_{\text{max}} = 2.14 M_{\odot}$ lines almost completely coincide with the $\Lambda(1.4) = 580$ lines (see Figures 3(b) and 4(b)).

Depending on the value of the strange quark mass, the allowed parameter space vanished entirely for $g^2/\mu^2 > 7.28$ GeV$^{-2}$ or $g^2/\mu^2 > 6.27$ GeV$^{-2}$, as shown in Figures 3(e) and 4(e).
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It is necessary to focus on Figures 3(b) and (d) (Figures 4(b) and (d)) once again. In Figure 3(b) (Figure 4(b)), the $M_{\text{max}} = 2.14 M_\odot$ line and the $\Lambda(1.4) = 580$ line almost completely overlap. These two lines cut across the “three-flavor line” at the point where the bag constant has a value of $B^{1/4} = 141.3$ MeV ($B^{1/4} = 139.7$ MeV) and the strong coupling constant has a value of $\alpha_s = 0.56$ ($\alpha_s = 0.49$). Therefore, one can draw the conclusion that by considering the four constraints discussed in this paper, the lower limit of $B^{1/4}$ is 141.3 MeV (139.7 MeV), and the upper limit of $\alpha_s$ is 0.56 (0.49). On the other hand, in Figure 3(d) (Figure 4(d)), the $M_{\text{max}} = 2.14 M_\odot$ line meets the “three-flavor line” and the longitudinal coordinate axis at $B^{1/4} = 150.9$ MeV ($B^{1/4} = 147.3$ MeV), which suggests that the upper limit of $B^{1/4}$ is 150.9 MeV (147.3 MeV).

4. Summary

In this paper, we have investigated the effects of non-Newtonian gravity on the properties of QSs and constrained the parameter space of the SQM model using observations related to PSR J0740+6620 and GW170817. It is found that these observations cannot be explained by the SQM model studied in this paper if non-Newtonian gravity effects are not included. In other words, the existence of QSs would be ruled out in this case. Considering the non-Newtonian gravity effects, regions in the $B^{1/4}$-$\alpha_s$ parameter space have been established for which SQM exists (i.e., is absolutely stable) and the EOS associated with such matter leads to properties of compact stars that are in agreement with observation. The constraints on the bag constant and the strong coupling constant depend on the mass of the strange quark. For a strange quark mass of $m_s = 95$ MeV, $141.3$ MeV $\leq B^{1/4} \leq 150.9$ MeV, and $\alpha_s \leq 0.56$. While, for a strange quark mass of $m_s = 150$ MeV, $139.7$ MeV $\leq B^{1/4} \leq 147.3$ MeV, and $\alpha_s \leq 0.49$.

Moreover, as shown in Figure 1, the ranges of the non-Newtonian gravity parameter ($1.37 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 7.28 \text{ GeV}^{-2}$ for $m_s = 95$ MeV, and $1.88 \text{ GeV}^{-2} \leq g^2/\mu^2 \leq 6.27 \text{ GeV}^{-2}$ for $m_s = 150$ MeV) agree well with the constraints set by some, but not all, experiments.

As shown in this paper, the possible existence of (absolutely stable) QSs is impacted by non-Newtonian gravity. The existence of QSs, therefore, may constrain the non-Newtonian gravity parameter $g^2/\mu^2$. And for a given value of $g^2/\mu^2$, the allowed parameter space of SQM ($B^{1/4}$ and $\alpha_s$) can be fixed. Our results are intimately related to the maximum mass of neutron stars, their radii, and the upper limit of the tidal deformability of neutron stars. In light of the rapidly increasing data on the properties of such objects provided by NICER and gravitational-wave interferometers, this connection should definitely be explored further. The conclusions drawn in this investigation are based on the standard MIT bag model of SQM. It would be interesting to carry out a similar investigation that is based on other SQM models such as the quasi-particle model (for a brief review, see Xu et al. 2015).
Finally, we mention that the existence of QSs can (and should) also be investigated in the framework of other, alternative theories of gravity (e.g., Li et al. 2019).

We are especially indebted to the anonymous referee for useful suggestions that helped us to improve the paper. This work is supported by the Fundamental Research Funds for the Central Universities (grant No. CCNU19QN063) and the Scientific Research Program of the National Natural Science Foundation of China (NSFC, grant Nos. 11447012 and 11773011). F.W. is supported through the U.S. National Science Foundation under Grants PHY-1714068 and PHY-2012152.

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