Strange stars confronting with the observations: non-Newtonian gravity effects, or the existence of a dark-matter core

Shu-Hua Yang

Central China Normal University

Collaborators:

Chun-Mei Pi, Xiao-Ping Zheng, Fridolin Weber

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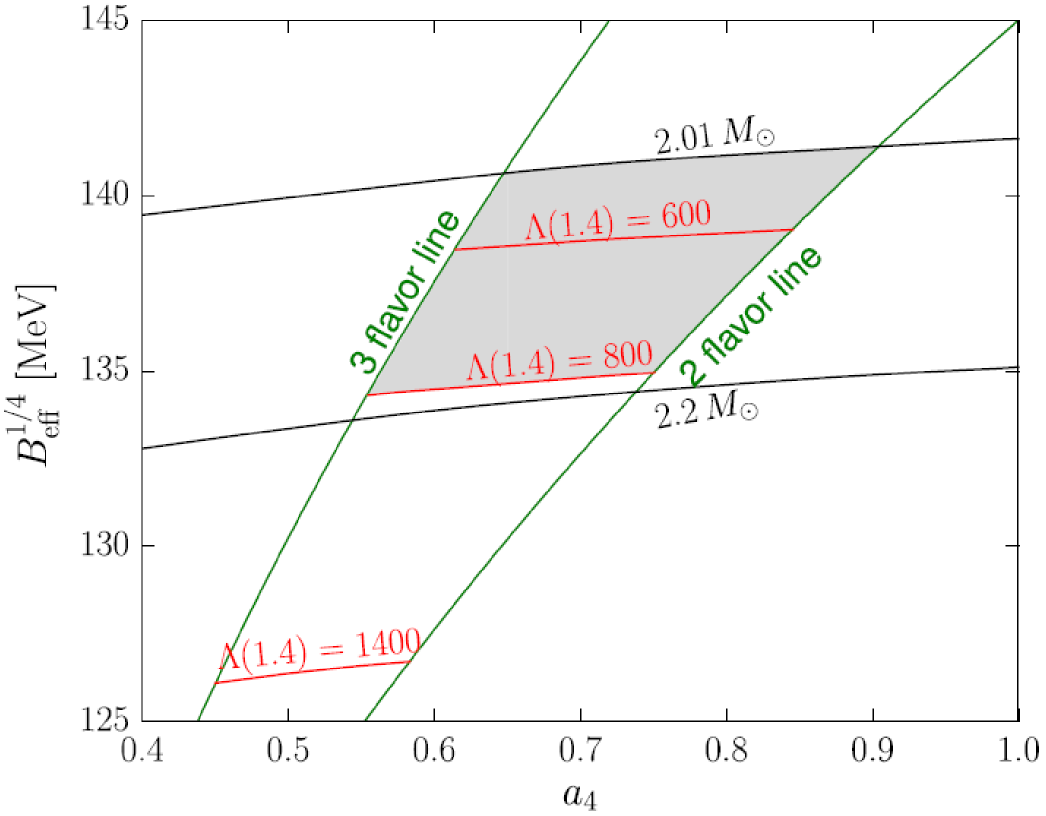
1. Introduction

- The EOS of compact stars is still in lively debate.
- Besides the conventional NS model, strange stars (SSs) are suggested as a possible nature of compact stars after it was conjectured that strange quark matter (SQM) consisting of up, down and strange quark could be the true ground state of strong interaction (Witten 1984).



$M_{max} \geq 2.01 M_\odot$

PSR J0348+0432

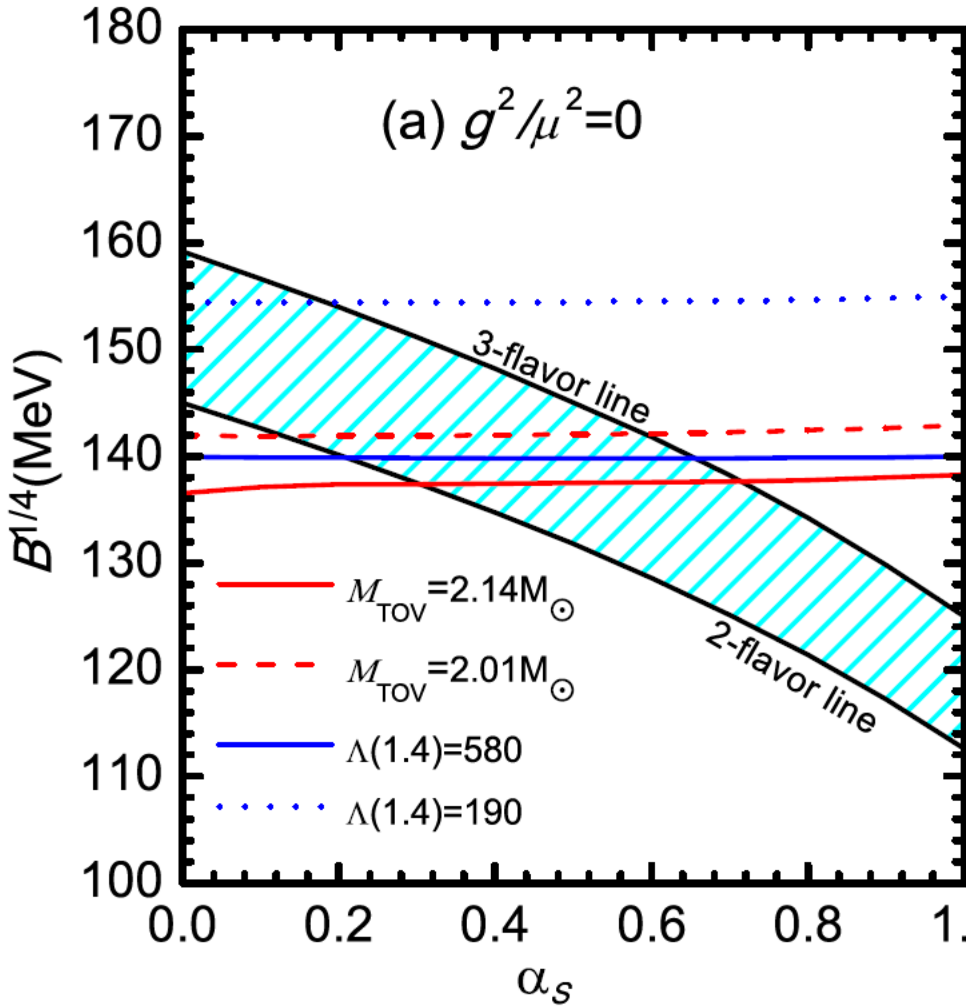
(Antoniadis et al. 2013)

$\Lambda(1.4) \leq 800$

GW170817

(Abbott et al. 2017)

Zhou et al. 2018, , Phys. Rev. D 97, 083015



$M_{\max} \geq 2.14\, M_\odot$

PSR J0740+6620

(Cromartie et al. 2020)

$\Lambda(1.4) \leq 580$

GW170817

(Abbott et al. 2018)

Yang et al., ApJ 902, 32 (2020)

- The existence of SSs seems to be ruled out by the observation of compact stars if the standard MIT bag model of SQM is used to compute the bulk properties of SSs.

- This is no longer the case,

  if alternative gravity (eg. non-Newtonian gravity) is considered,

  or if the SSs have a dark matter core (eg. mirror dark matter) .

2. Non-Newtonian gravity in strange stars

- 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.

- 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 super-symmetric extension of the standard model (Fayet 1980, 1981).

- Effects of non-Newtonian gravity on the properties of NSs and SSs have been studied (e.g., Krivoruchenko et al. 2009; Wen et al. 2009; Lu et al. 2017). The inclusion of non-Newtonian gravity leads to stiffer EOSs and higher maximum masses of compact stars.

Non-Newtonian gravity

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.,

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

where, α is the strength parameter

λ is the range of the Yukawa force

In the boson exchange picture, the Yukawa force is mediated by the exchange of bosons of mass μ

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

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

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.

The contribution of the Yukawa correction $V_Y(r)$ of Eq. (12) to the energy density of SQM is obtained by integrating over the quark density distributions $n_b(\vec{x}_1)$ and $n_b(\vec{x}_2)$ contained in a given volume V (Long et al. 2003; Krivoruchenko et al. 2009; Wen et al. 2009; Lu et al. 2017)

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

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

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

$$\epsilon = \epsilon_Q + \epsilon_Y.$$

$$p = p_Q + p_Y,$$

Standard MIT Bag Model

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

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

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

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

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

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

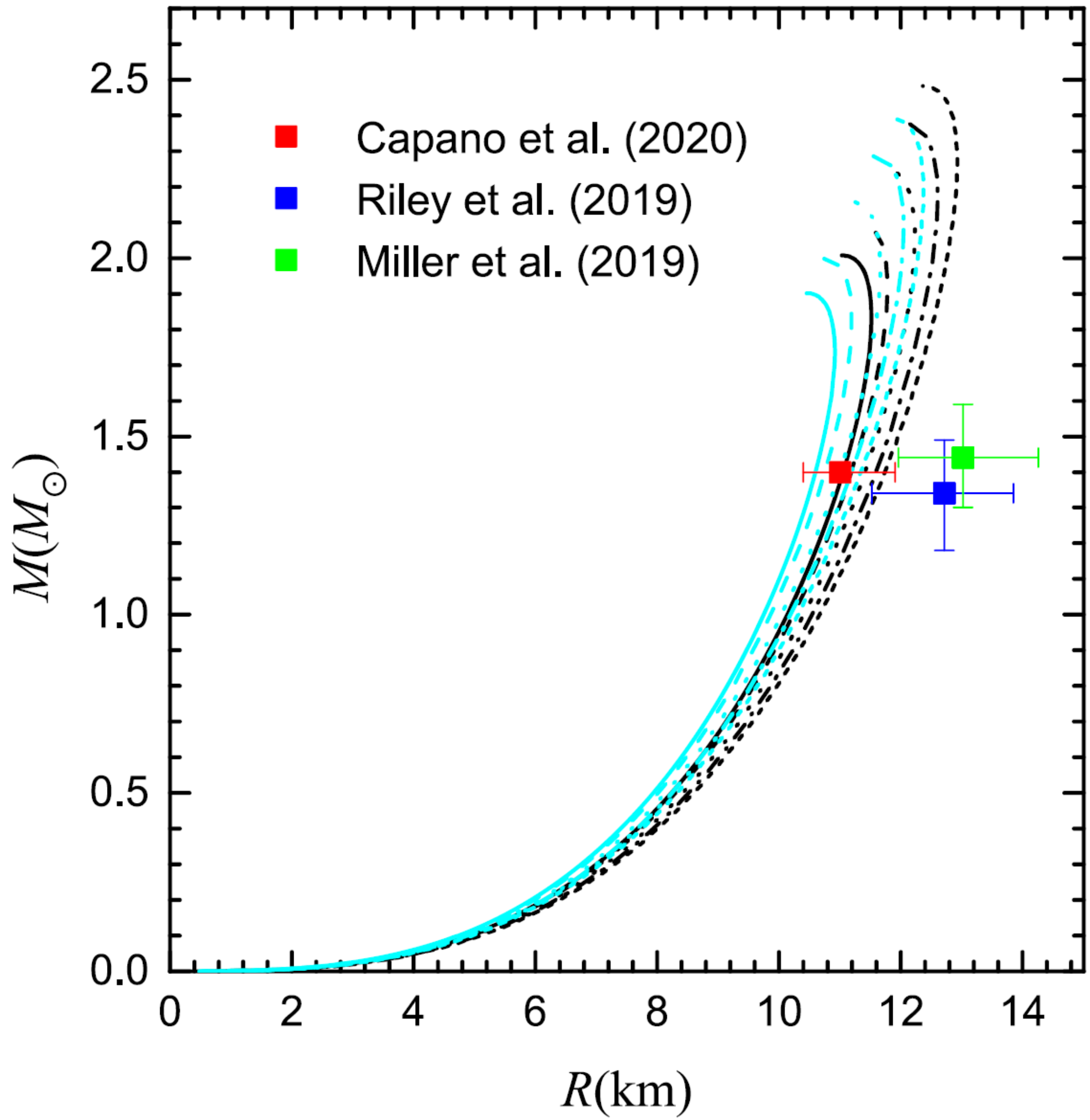


Figure 2. Mass–radius relation of strange stars. The black curves are for $B^{1/4} = 142$ MeV, $\alpha_S = 0.2$, and the cyan curves are for $B^{1/4} = 146$ MeV, $\alpha_S = 0$. The solid, dashed, dotted, dashed–dotted, and short-dashed lines are for $g^2/\mu^2 = 0, 1, 3, 5$, and 7 GeV^{-2}, respectively. The red data is $R_{1.4} = 11.0^{+0.9}_{-0.6}$ km,

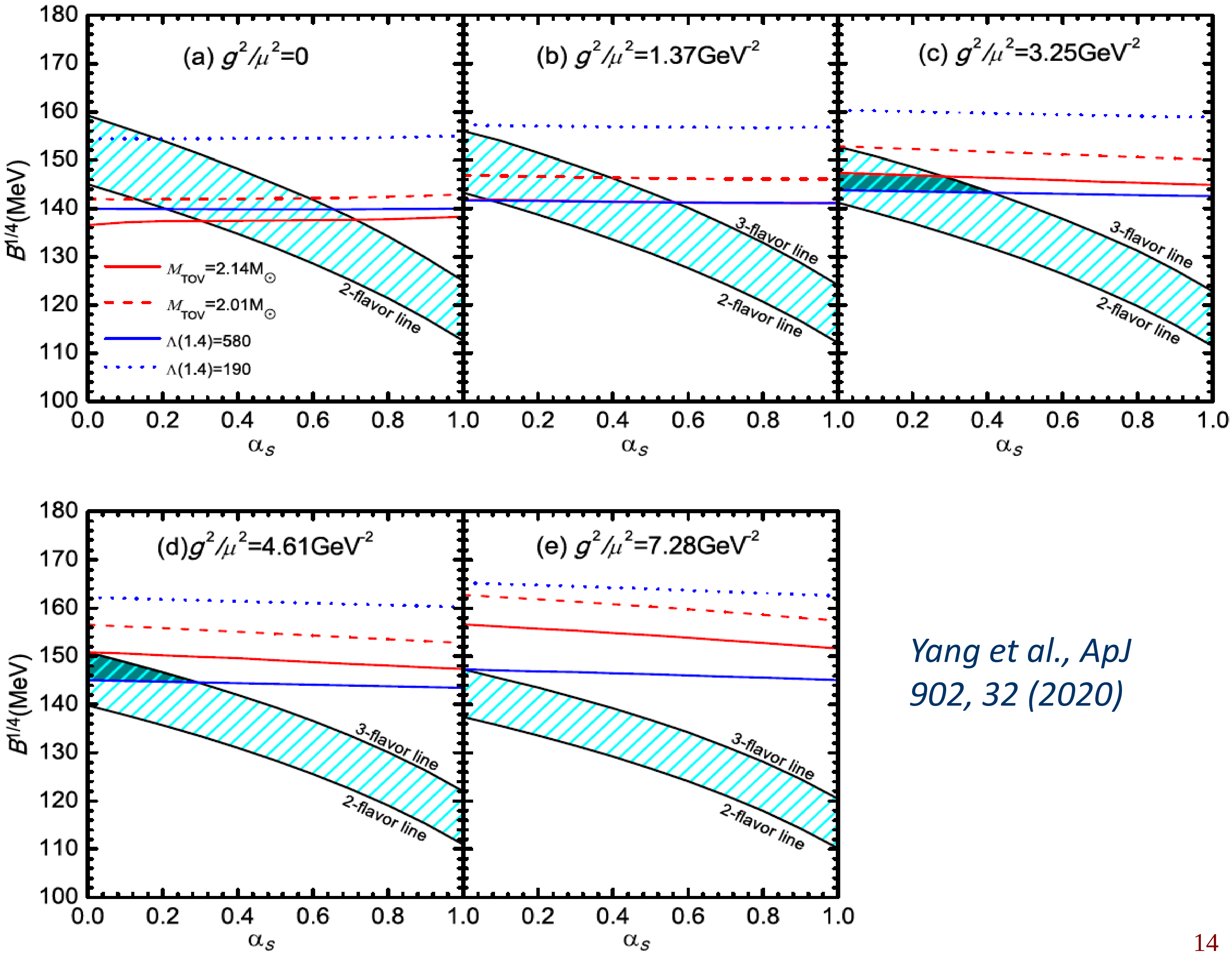
The allowed parameter space of the SQM model is investigated according to the following constraints：

1、For 3-flavor quark matter，$(\frac{E}{A})_{min} \leq 930$ MeV

2、For 2-flavor quark matter，$(\frac{E}{A})_{min} \geq 934$ MeV

3、PSR J0740+6620 $M_{\max} \geq 2.14 M_{\odot}$. *(Cromartie et al. 2020)*

4、GW170817 $\Lambda(1.4) \leq 580$ *(Abbott et al. 2018)*



Yang et al., ApJ 902, 32 (2020)

Results:

- For the standard MIT bag model, mass and tidal deformability observations would rule out the existence of SSs if non-Newtonian gravity effects are ignored.

- For a strange quark mass of m_s=95MeV, SSs can exist for $1.37\ \mathrm{GeV}^{-2} \leq g^2/\mu^2 \leq 7.28\ \mathrm{GeV}^{-2}$, limits on SQM model are $141.3\ \mathrm{MeV} \leq B^{1/4} \leq 150.9\ \mathrm{MeV}$ and $\alpha_S \leq 0.56$.

Density dependent quark mass model

The key feature of the QMDD model is the use of density dependent quark masses to express non-perturbative interaction effects.

Taking into account both the linear confinement and leading order interactions, the quark mass scaling is：

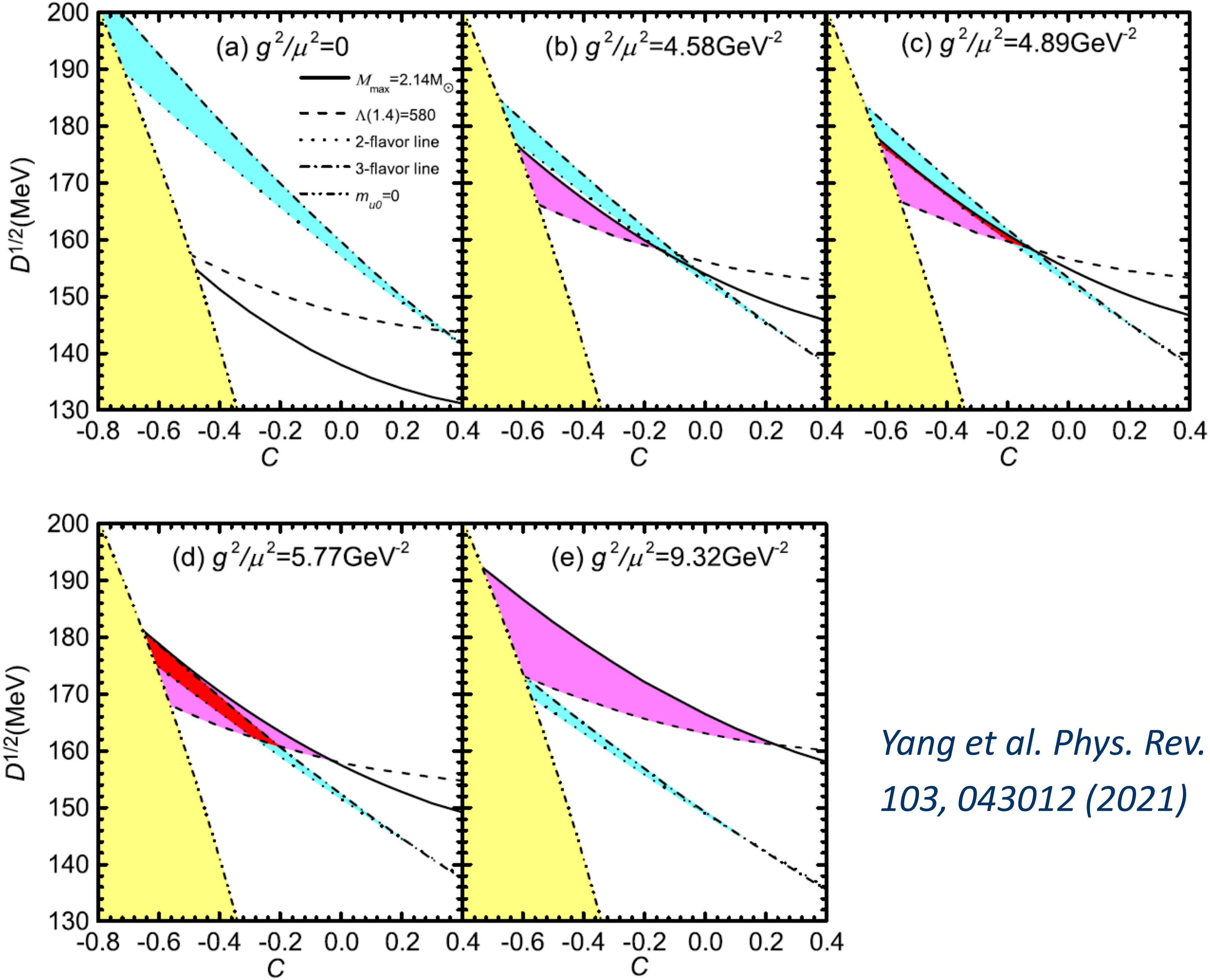
$$m_i = m_{i0} + m_I \equiv m_{i0} + \frac{D}{n_b^{1/3}} + C n_b^{1/3}.$$

Fully self-consistent thermodynamic treatment：

$$\epsilon_Q = \Omega_0 - \sum_i \mu_i^* \frac{\partial \Omega_0}{\partial \mu_i^*},$$

$$p_Q = -\Omega_0 + n_{\mathrm{b}} \frac{\partial m_{\mathrm{I}}}{\partial n_{\mathrm{b}}} \frac{\partial \Omega_0}{\partial m_{\mathrm{I}}}.$$

Xia et al, Phys. Rev. D 89, 105027 (2014)



Yang et al. Phys. Rev. D 103, 043012 (2021)

Results:

- For the QMDD model, mass, radius, and tidal deformability observations would rule out the existence of SSs if non-Newtonian gravity effects are ignored.

- For the current quark masses of m_{u0} =2.16 MeV, m_{d0} = 4.67 MeV, and m_{s0} = 93 MeV, SSs can exist for values of the non-Newtonian gravity parameter g^2/μ^2 in the range of 4.58 $\mathrm{GeV}^{-2} \leq g^2/\mu^2 \leq 9.32\ \mathrm{GeV}^{-2}$, and that the parameters D and C of the QMDD model are restricted to 158.3 MeV $\leq D^{1/2} \leq$ 181.2 MeV and $-0.65 \leq C \leq -0.12$.

3. Strange stars with a mirror-dark-matter core

Compact stars might contain a dark-matter core made of self-interacting dark matter.

Mirror dark matter is a stable and self-interacting dark matter candidate that emerges from the parity symmetric extension of the Standard Model of particles.

Neutron stars with a mirror-dark-matter core have been studied by Ciarcelluti and Sandin (2009,2011).

In the minimal parity-symmetric extension of the standard model, the two sectors are described by the same Lagrangians, but where ordinary particles have left-handed interactions, mirror particles have right-handed interactions. Thus, the microphysics of MDM is the same as that of ordinary matter.

SQM made of u, d and s quarks and e is supposed to be the true ground state of baryonic matter. As a result, Its mirror twin, the mirror SQM made of $u^{'}$ $d^{'}$ $s^{'}$ and $e^{'}$ is the true ground state of the mirror partner of baryonic matter.

We use the same EOS for SQM and MDM.

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

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

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

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

where,

$$\begin{aligned} \epsilon(r) &= \epsilon_Q(r) + \epsilon_D(r), \\ p(r) &= p_Q(r) + p_D(r), \end{aligned}$$

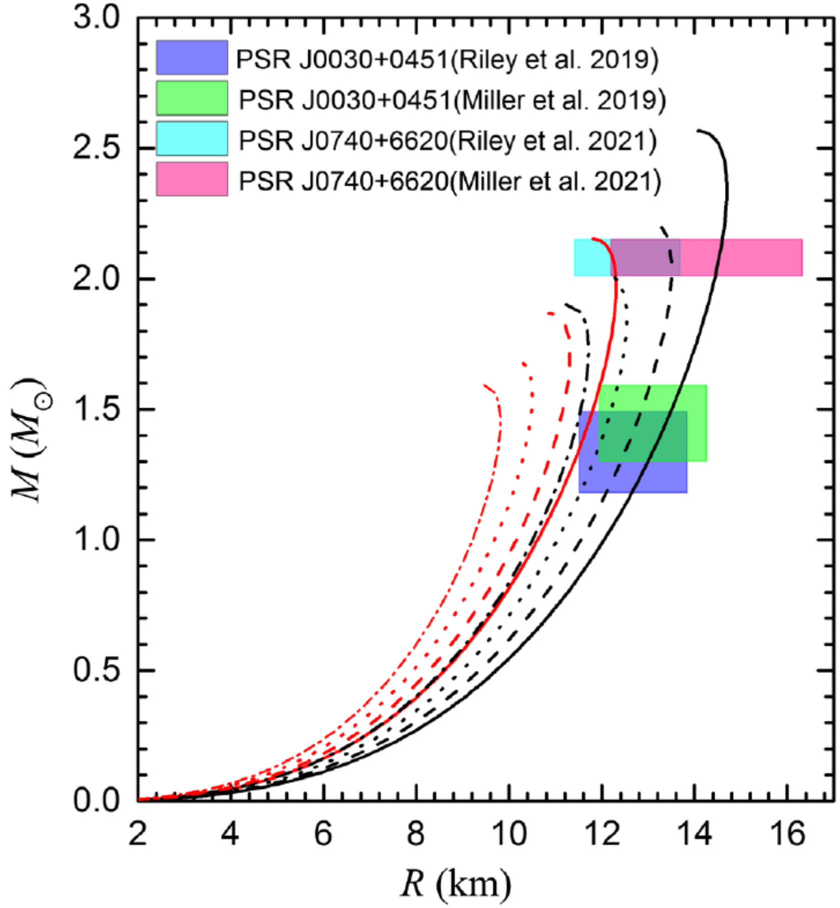


FIG. 3. The mass-radius relation of SSs for a strange quark mass of $m_s = 93$ MeV. The black lines are for $\alpha_S = 0.7$ and $B^{1/4} = 125.1$ MeV, and the red lines are for $\alpha_S = 0.7$ and $B^{1/4} = 137.3$ MeV. The solid, dashed, dotted, dash-dotted lines are for the mass fraction of MDM $f_D = 0$, 10%, 20%, and 30%,

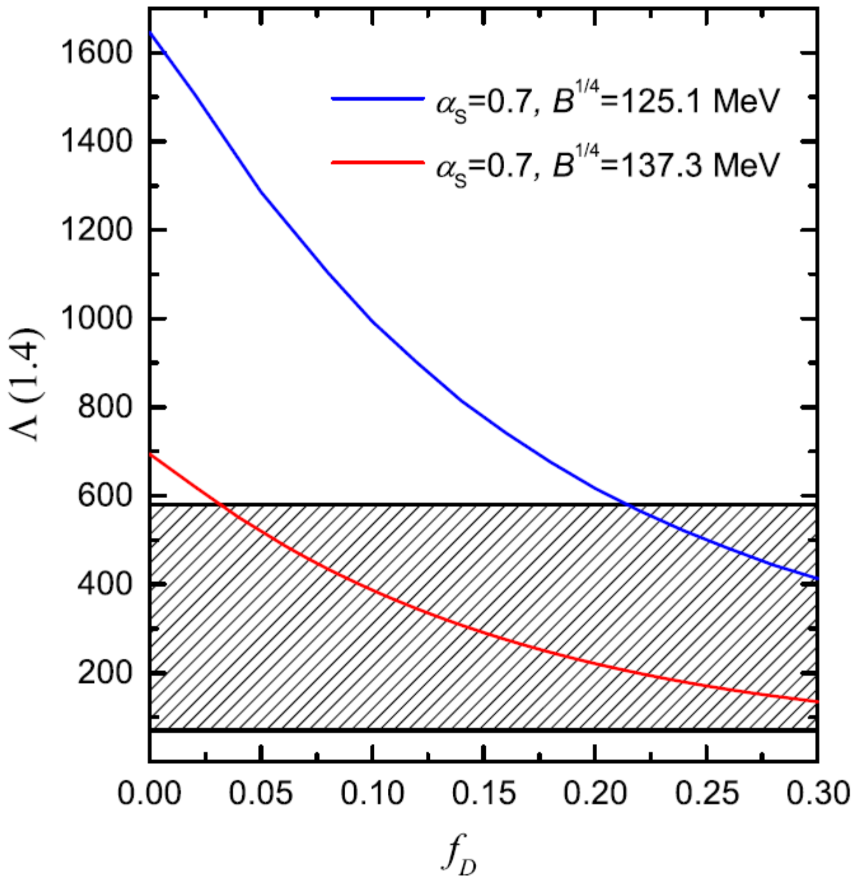
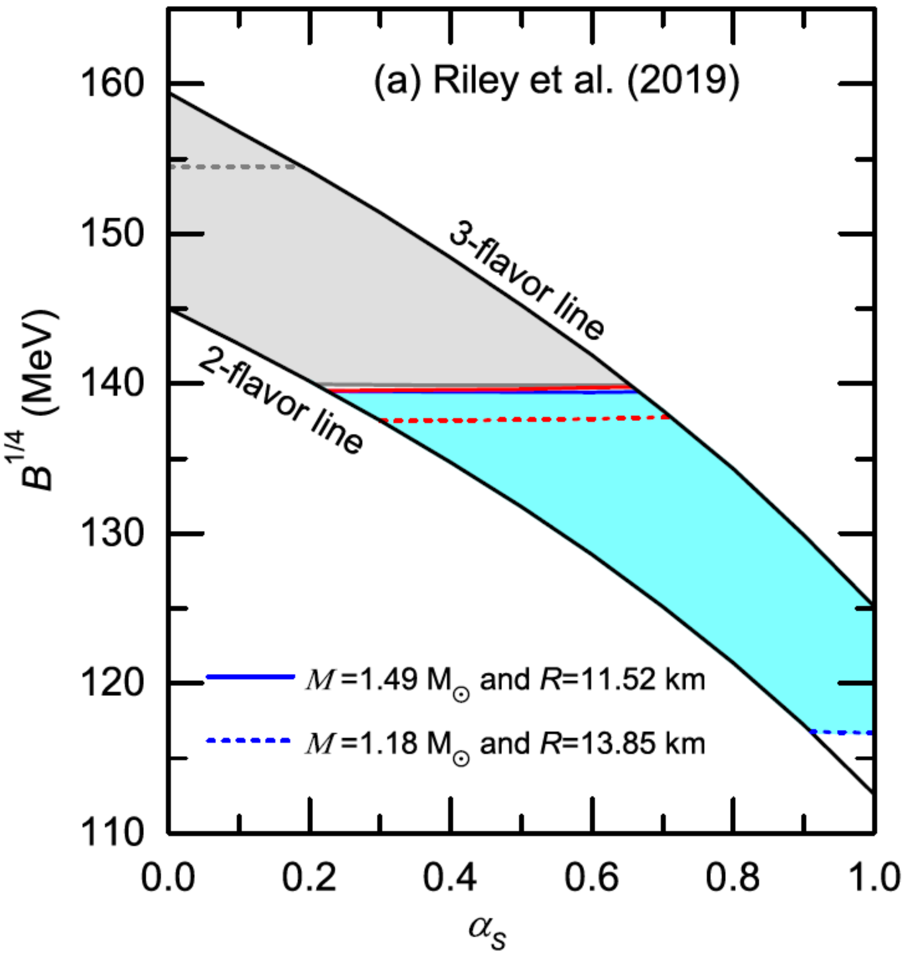
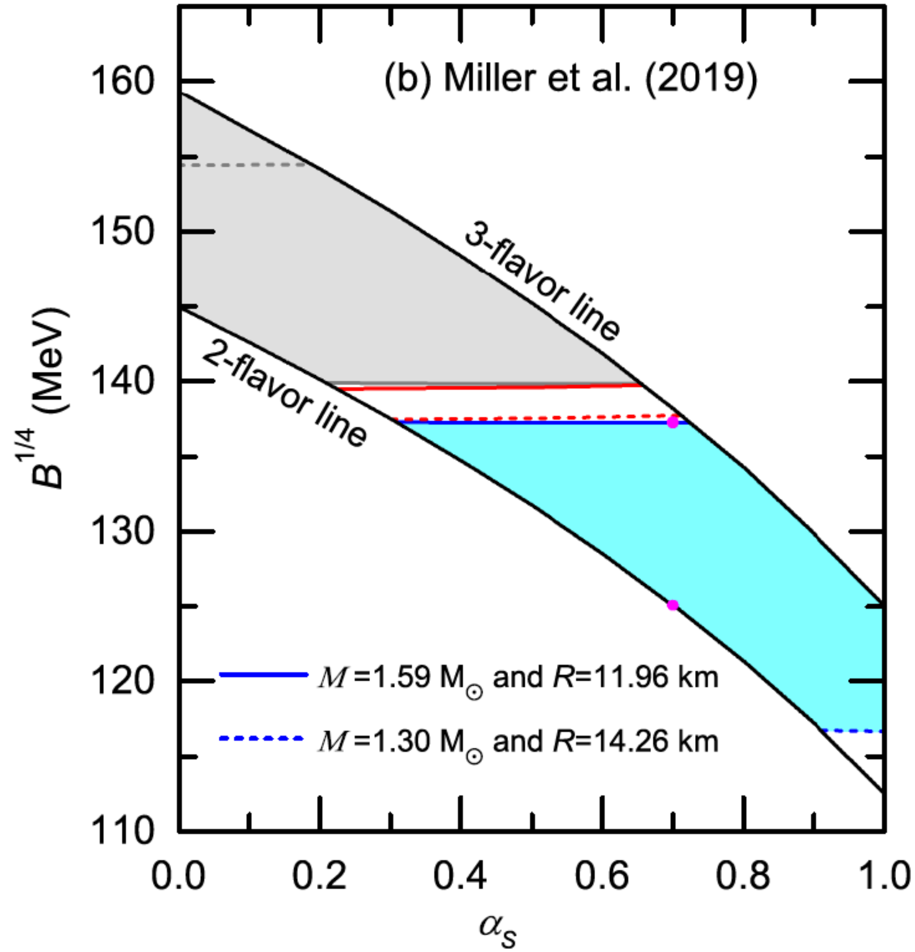


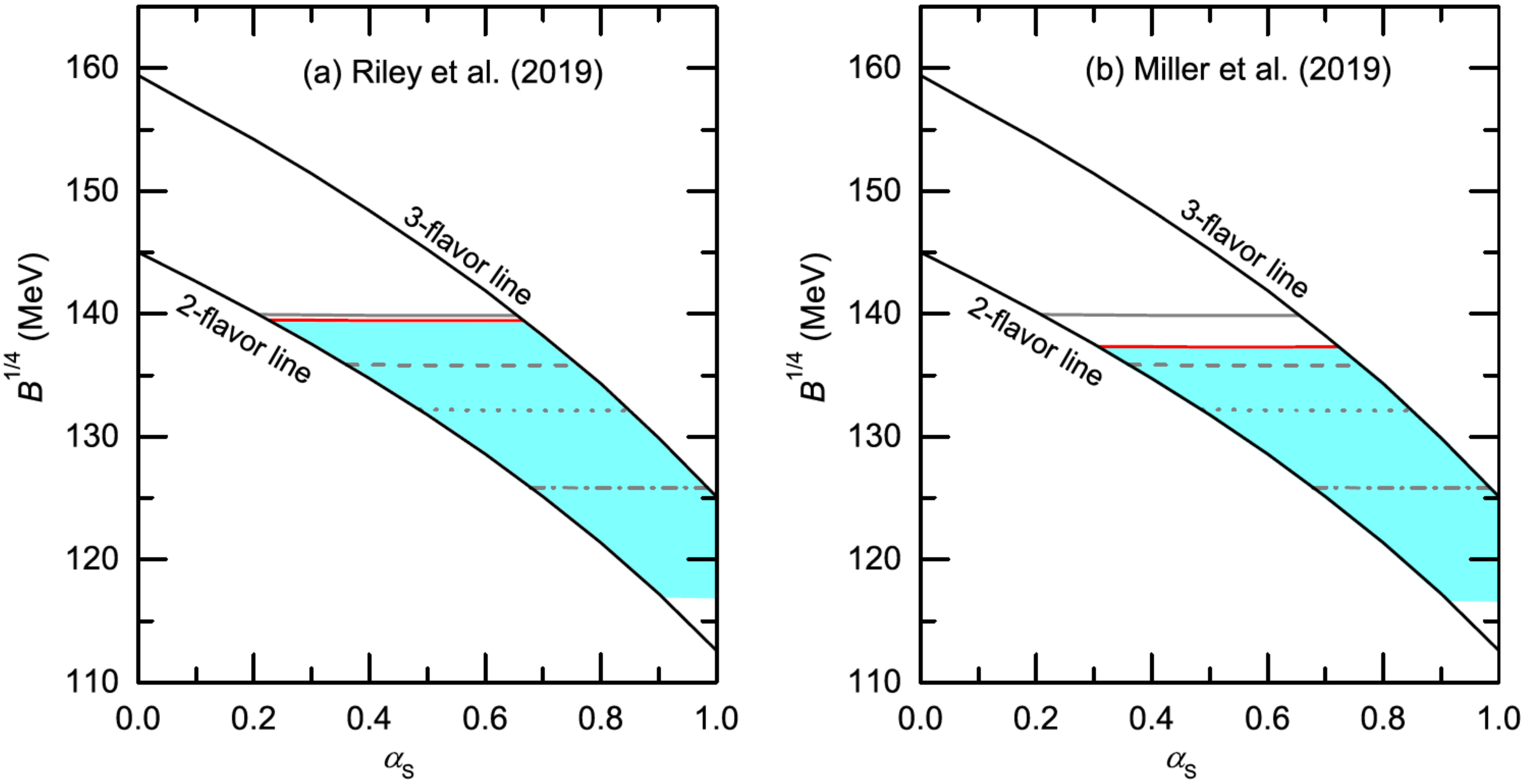
FIG. 4. Relation between the dimensionless tidal deformability of a 1.4 $M_\odot$ star [$\Lambda(1.4)$] and the mass fraction of MDM (f_D) for





SSs in standard MIT bag model without a dark matter core

Yang et al. Phys. Rev. D 104, 083016 (2021)



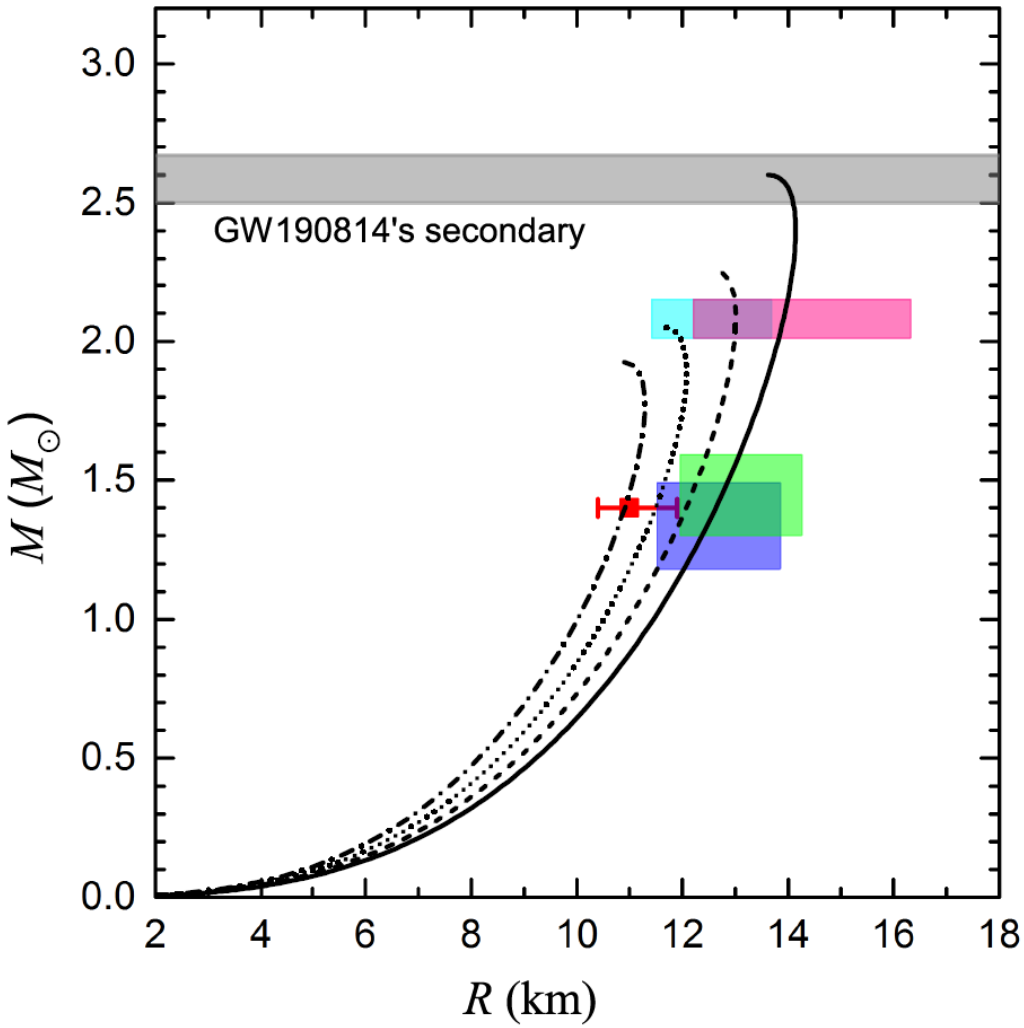
As the value of f_D (the mass fraction of MDM) increases, the parameter space regions which satisfy lambda(1.4) < 580 shift downward;
they begin to overlap with the cyan-shadowed areas for f_D= 0.5% for the analysis of NICER data for PSR J0030+0451 by Riley et al. and f_D= 3.1% for Miller et al..

Results:

We find that to explain the observations of GW170817, PSR J0740+6620 and PSR J0030+0451 simultaneously, strange stars in GW170817 should have a mirror-dark-matter core although it is unnecessary for PSR J0740+6620 and PSR J0030+0451 to contain one.

More generally, our study leads to the result that for the standard MIT bag model, the observations of compact stars mentioned above could serve as an evidence for the existence of a dark-matter core inside strange stars.

The color flavor-locked SSs and the 2.6 M_{sun} component in GW190814



Yang et al., Submitted to Phys. Rev. D

FIG. 2: The mass-radius relation of the CFL SSs for $a_4 = 0.6$, $B_{\rm eff}^{1/4} = 128.6$ MeV, and $\Delta = 100$ MeV. The solid, dashed, dotted, dash-dotted lines are for the mass fraction of MDM $f_D = 0$, 10%, 20%, and 30%, respectively.

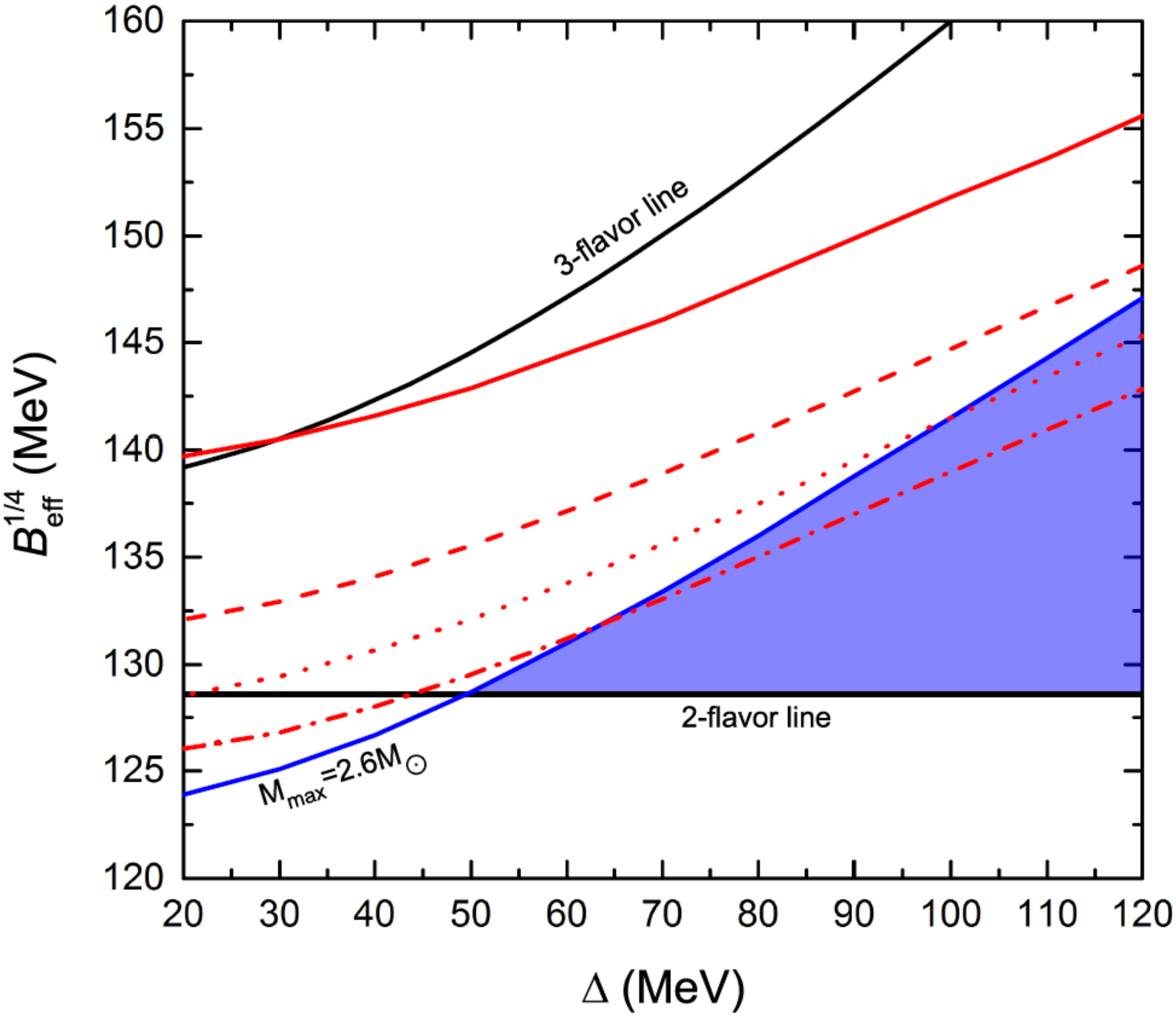


FIG. 5: Constraints on $B_{\rm eff}^{1/4}$ and Δ for the CFL SSs with $a_4 = 0.6$. The blue-shadowed area is the same as that in Fig. 4, which shows the parameter space which satisfies $M_{\rm max} \geq 2.6\,M_{\odot}$ for the CFL SSs without a MDM core ($f_D = 0$). The solid, dashed, dotted, dash-dotted red lines are for $\Lambda(1.4) = 580$ with $f_D = 0$, 10%, 15.4%, and 20%, respectively.

4. Summary

The tension between the theory of strange stars and the observations of compact stars

- **Alternative gravity (eg. non-Newtonian gravity)**

  Standard MIT bag model

  Density dependent quark mass model

- **SSs with a dark-matter core (eg. mirror dark matter)**

  Standard MIT bag model

Thanks !