STRANGE QUARK STARS AS A PROBE OF DARK MATTER

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Abstract

We demonstrate that the observation of old strange quark stars (SQSs) can set important limits on the scattering cross-sections $\sigma_q$ between light quarks and non-interacting scalar dark matter (DM). By analyzing a set of 1403 solitary pulsar-like compact stars in the Milky Way, we find that the old solitary pulsar PSR J1801-0857D can set the most stringent upper limits on $\sigma_q$ or the cross-sections $\sigma_p$ between DM and protons. By converting $\sigma_p$ into $\sigma_q$ based on effective operator analyses, we show that the resulting $\sigma_q$ limit, by assuming PSR J1801-0857D is an SQS, is comparable with that of the current direct detection experiments in terrestrial labs but weaker by several orders of magnitude than that obtained by assuming PSR J1801-0857D is a neutron star (NS), which requires an extremely small $\sigma_q$ far beyond the limits of direct detection experiments. Our findings imply that old pulsars are more likely to be identified as SQSs than as NSs in future terrestrial experiments observing scalar DM.

Key words: dark matter – stars: neutron

1. INTRODUCTION

The observation of pulsar-like old compact stars can provide constraints on dark matter (DM). Accreted onto the star by strong gravity, DM can accumulate efficiently inside the star via scattering with the star matter and eventually may collapse into a star-killing black hole (BH). In order to prevent the destruction of the star, the interactions between DM and the star matter must be extremely weak. After the pioneering work by Goldman and Nussinov (Goldman & Nussinov 1989) on this subject, much work has been devoted to constraining the properties of DM based on the observation of old compact stars (Bertone & Fairbairn 2008; de Lavallaz & Fairbairn 2010; Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012; Bramante et al. 2013, 2014; Bramante & Linden 2014; Zheng et al. 2015). In these studies it is generally assumed that the host compact stars are neutron stars (NSs), and thus numerous constraints on DM-nucleon interactions have been obtained. In particular, if the self-interactions of bosonic DM (which is preferred in many theories beyond the standard model) can be ignored, the formation of a Bose–Einstein condensate (BEC) state could further facilitate the occurrence of DM collapsing into a BH; the resulting limits on the DM-nucleon interactions would far exceed the limits of terrestrial experiments (Bernabei et al. 2008; Aprile et al. 2012, 2015; Agnese et al. 2013, 2014; Akerib et al. 2014; Billard et al. 2014). This leads to the conclusion that, if old compact stars are NSs, then bosonic DM cannot be detected directly.

However, the composition of pulsar-like compact stars remains unclear and continues to be a challenging subject in contemporary science (Xu 2003; Lattimer & Prakash 2004; Alford et al. 2007; Weber et al. 2009). Aside from conventional NSs, another important category comprises strange quark stars (SQSs) (Itoh 1979; Alford et al. 2007; Weber et al. 2009), which are made purely of deconfined $u$, $d$, and $s$ quark matter (with some leptons); i.e., strange quark matter (SQM) that might be the true ground state of QCD matter and is absolutely stable according to the Bodmer–Witten–Terazawa hypothesis (Witten 1984; Weber et al. 2009). Many investigations have been undertaken in order to distinguish SQSs from NSs: e.g., SQSs have a much larger dissipation rate of radial vibrations (Wang & Lu 1984) and higher bulk viscosity (Haensel et al. 1989); the spin rate of SQSs can be much closer to the Kepler limit than that of NSs (Madsen 1992); SQSs may cool more rapidly than NSs within the first 30 years (Schaab et al. 1997); the gravity-mode (g-mode) eigenfrequencies in SQSs are much lower than those in NSs (Fu et al. 2008); and so on. In the present work, we show that SQSs could be good indicators of the interactions between light quarks and DM, and that the observation of scalar bosonic DM in future terrestrial experiments will likely indicate that old pulsars are SQSs rather than NSs.

This paper is organized as follows. We first briefly introduce the methods of calculating the accretion mass of DM by a compact star in Section 2. Then the compact star models are described in Section 3. In Section 4, we present the results and discussions. Finally, the conclusions are given in Section 5.

2. ACCRETION OF DM

Following our recent work (Zheng et al. 2015), we adopt a spherically symmetric accretion scenario to calculate the capture rate of DM by a structured compact star. The total mass of DM captured by a star during the time period of $t$ can be obtained as

$$M_t = 4.07 \times 10^{40} \text{GeV} \frac{M_S R_S}{1 - 2.964 \frac{M_S}{R_S}} \left(\frac{m_q n_q}{0.3 \text{ GeV cm}^{-3}}\right) \times \left(\frac{v_0}{220 \text{ km s}^{-1}}\right)^{-1} \left(\frac{t}{\text{ Gyr}}\right) f,$$

where $M_S$ (in units of solar mass $M_{\odot}$) and $R_S$ (in units of km) are the star’s mass and radius, respectively; $m_q$ ($n_q$) is the mass (number density) of DM particles that are assumed to follow a Maxwell–Boltzmann distribution with the mode speed of $v_0$; and $f$ is the fraction of DM particles that undergo at least one...
collision inside the star, which can be expressed as

$$f = \left(1 - e^{-\sum \sigma_i(r) n_i(r) \int d\lambda}\right),$$

(2)

with \(\sigma_i\) denoting the scattering cross-section between DM and star constituent particle \(i\) in free space, and \(\xi_i(r)\) indicating the medium corrections due to the Pauli blocking effect and Fermi motion. The integration in the exponent is taken over the arc length along the trajectory \((l)\) of DM crossing through the star, and the summation is for various constituent particles of the star. Finally, all of the possible trajectories of DM inside the compact star are averaged (denoted by the angle brackets) in Equation (2). The DM-lepton interactions play minor roles and are neglected in the calculations.

Shortly after being captured by a compact star, the DM may become thermalized with the star matter and gather at the host star’s center, which has a radius of about several meters, within a typical time period of \(t_{\text{th}} \sim 0.2\) year \(\left(\frac{m_\chi}{10^{-2} \text{ GeV}}\right)^{1/2} \left(\frac{T_s}{10^{8} \text{ K}}\right)^{-3}\), where \(T_s\) is the central temperature of the star and \(T_s = 10^8\) K (McDermott et al. 2012; Bertoni et al. 2013; Bramante et al. 2013; Zheng et al. 2015). Particularly for bosonic DM, the BEC state, confined by the star’s gravitational field, can be formed when the number of accumulated DM particles exceeds a critical value of \(N_{\text{BEC}} \approx 2 \times 10^{15}(T_c/T_s)^3\). The DM particles exceeding \(N_{\text{BEC}}\) will fall into the ground state and gather within a tiny sphere with a radius \(r_{\text{BEC}} \sim 1.4 M_\chi^{1/2} \mu \text{m}\), where \(M_\chi\) is in units of GeV. The DM in the BEC phase will quickly become self-gravitating and form a boson star inside of the host star.

As long as the boson star mass exceeds its Chandrasekhar limit, i.e., \(M_\beta > M_\text{chan} + m_\chi N_{\text{BEC}}\), it collapses into a BH. For non-interacting bosonic DM, we have \(M_\text{chan} = (2/\pi) M_\text{pl}^2/m_\chi\), with the Planck mass \(M_\text{pl} = 1.22 \times 10^{19}\) GeV. The newly born BH might grow and eventually swallow the host star if it accretes the star matter faster than its evaporation through Hawking radiation (see, e.g., Equation (47) in Zheng et al. 2015)). Specifically, we adopt a spherically symmetric Bondi accretion scenario (Shapiro & Teukolsky 1983) to calculate the accretion rate of star matter, and the BH is assumed to evaporate through the Hawking radiation of photons. The stable growth of BH mass \(M_\text{BH}\) is guaranteed by the condition \(\frac{dM_\text{BH}}{dt} \bigg|_{t=0} > 0\). As a result, the observation of old compact stars implies that either \(M_\beta < M_\text{chan} + m_\chi N_{\text{BEC}}\) or \(\frac{dM_\text{BH}}{dt} \bigg|_{t=0} < 0\) must be satisfied to prevent the destruction of these stars. This means that the interactions between DM and star matter cannot be too strong so as to prevent the BH formation or stable growth of BH mass, which would put limits on the scattering cross-sections between DM and compact star matter.

### 3. COMPACT STAR MODELS

In the present work, SQSs are assumed to be static and consist of neutrino-free SQM in \(\beta\)-equilibrium with electric charge neutrality. The equation of state (EOS) of SQM is taken from the MIT bag model (Chodos et al. 1974) with two light flavors, i.e., the \(u\) and \(d\) quarks, and one massive flavor, corresponding to the \(s\) quark. We further consider corrections in the thermodynamic potential due to perturbation theory to first order in \(\alpha_s\) in the \(\overline{\text{MS}}\) scheme (Fraga & Romatschke 2005; Kurkela et al. 2010; Xu et al. 2015). We select the QCD scale parameter \(\Lambda_{\overline{\text{MS}}}\) and the invariant mass parameter \(m_0\) to be 146.2 MeV and 279.9 MeV, respectively, according to Table I in (Xu et al. 2015). Then the QCD coupling and the \(s\) quark mass are determined by the running renormalization subtraction point \(\Lambda\) given by

$$\Lambda = \frac{2}{3}(\mu_u + \mu_d + \mu_s),$$

(3)

where \(\mu_q\) \((q = u, d, s)\) denotes the chemical potential of each flavor. The bag constant is \(B^1/4 = 135.0\) MeV, in order to yield a value of 873.6 MeV, for the binding energy per baryon for cold SQM in equilibrium, versus a value of 954.7 MeV, for two-flavor \(u - d\) quark matter in equilibrium; thus, the absolutely stable condition is satisfied. The SQS structure is then obtained by solving the Tolman–Oppenheimer–Volkoff equations. Shown in Figure 1 is the radial density distribution of each quark flavor for a typical SQS with mass \(M_s = 1.4 M_\odot\), and the SQS radius is obtained as \(R_s = 11.47\) km. Based on Figure 1, the \(f\) in Equation (2) can then be evaluated. We note that using the MIT bag model without perturbation corrections for the quark interactions (Fu et al. 2008) does not change our conclusions.

For NSs, we adopt the conventional NS model in which the NS is assumed to consist of \(\beta\)-stable and electrically neutral \(npe\mu\) matter, and the EOS is taken from the Skyrme–Hartree–Fock approach using the MSL1 interaction (Zhang & Chen 2013). Details can be found in (Zheng et al. 2015). The thermalization and BEC formation of DM in the interior of compact stars depend significantly on the star’s internal temperature \(T_s\), which is largely uncertain in observations. For NSs, following our previous work (Zheng et al. 2015), the \(T_s\) can be estimated from the relatively well-studied NS surface temperature \(T_s\), based on the study of the thermal structure of the insulating envelope presented by Gudmundsson et al. (1982). In particular, Gudmundsson et al. (1982) found that the temperature \(T_s\) measured at the inner boundary of the envelope (with density \(\rho \sim 10^{10} \text{ g cm}^{-3}\)) can be related to the surface temperature \(T_s\) as

$$T_s = 1.288 \times 10^8 \text{ K} \left(\frac{10^{14} \text{ cm s}^{-2}}{g_s} \frac{T_s}{(10^8 \text{ K})^{4.0455}}\right)^{0.455}.$$  

(4)
where $g_s$ is the surface gravity. Since old compact stars are already isothermal in their interiors, the $T_c$ can be assumed to be equal to $T_p$.

Instead of having a bare surface with a steep density drop over a few fm, SQSs may be wrapped up either in a tiny crust consisting of “normal” matter, i.e., ions and electrons, with a maximum density below the neutron drip density (Alcock et al. 1986), or in a heterogeneous (solid) crust made of strange nuggets and electrons (Jaikumar et al. 2006). The former crust is supported by strong electric fields near the surface and has properties similar to the thermal envelope in Gudmundsson’s model. Thus, it plays the role of an insulating layer and in this case we assume the same relationship between $T_c$ and $T_s$ as shown in Equation (4), which leads to an estimate of $T_c/T_s \approx 15.1 \times (T_s/T_0)^{0.52}$, based on the QSS structure shown in Figure 1. By assuming $T_c \sim T_s$, our estimate is nicely consistent with the previous assumption presented by Blaschke et al. (2000) and Horvath et al. (1991), who use $T_c/T_s = 20$ in their work. For the heterogeneous crust within the strange nuggets model, Jaikumar et al. (2006) found a relatively large crust with a radial extent $\Delta R \approx 40$ m and a maximum density up to $\rho \sim 10^{13}$ g cm$^{-3}$. The opacity of the nugget matter has two origins, one due to the scattering of electrons off of nuggets, and the other due to scattering among different electrons. Since the nugget phase resembles the mixed phase of nuclei and electrons in the crust of normal NSs (Page et al. 2004; Jaikumar et al. 2006), we can also apply Equation (4) to estimate $T_c$ from $T_s$. It should be noted that a crust consisting of strange nuggets may exist only if the surface tension between the zero-pressure surface and the vacuum satisfies the condition $\sigma < \sigma_{\text{crit}}$ (Jaikumar et al. 2006). For the MIT bag model in this work, we have $\sigma \approx 4.1$ MeV · fm$^{-2}$ and $\sigma_{\text{crit}} \approx 135$ MeV · fm$^{-2}$, implying that a crust of mixed phase is indeed favored in our model. The above discussions suggest that Equation (4) provides a reasonable approach to estimate $T_c$ from $T_s$ for both NSs and SQSs.

Furthermore, for solitary compact stars older than several million years, the $T_c$ is estimated to be lower than $10^5$ K (Yakovlev & Pethick 2004; Negreiros et al. 2012). In the present work, we assume a fixed $T_c = 10^5$ K for both NSs and SQSs. Since the DM particles accumulated in old compact stars (e.g., those older than $10^9$ yr) essentially come from the accretion process at the late stage of thermal evolution, when the $T_c$ is lower than $10^5$ K, the resulting constraints in the present work are thus expected to be conservative, as a lower $T_c$ will lead to stronger constraints.

### 4. LIMITS ON $\sigma_p$ AND $\sigma_q$

Since numerous pulsar-like compact stars in various states have been observed in the Milky Way, the resulting constraints from different stars on DM-quark (proton) spin-independent (SI) scattering cross-sections $\sigma_p (\sigma_q)$ should vary from one star to another. Therefore, we scanned all of the available solitary compact objects and identified the one leading to the most stringent limits. Particularly, we focused only on the isolated pulsar systems in order to avoid the additional complexity due to the evolution history of pulsars in a binary (or more complex) system. Moreover, pulsars less than 1 million years old are ignored since they will have had little time to accrete enough DM, and they have a relatively higher temperature than older pulsars. There is little information regarding the masses and radii of the solitary pulsars, so we assume that all of them have a fiducial mass of $1.4 M_\odot$, with the radii calculated from the NS or SQS models. From Equation (1), for compact stars with the same structure, the variation of the constraints from different compact stars is mainly due to the term $w_s(r) = \rho_s(r) \cdot t$. Here the living age $t$ is taken as the pulsar’s spin-down age. The DM mass density $\rho_s(r) = m_s n_s(r)$ depends on the halo model, for which we adopt here the spherically symmetric generalized Navarro–Frenk–White (NFW) profile (Navarro et al. 1996) and Einasto profile (Merritt et al. 2006), i.e.,

$$
\rho_s(r) = \begin{cases} 
\tilde{\rho}_s \left[ \left( \frac{\ln(1+\frac{r}{c}) - \ln(1+\frac{\tilde{\rho}_s}{\tilde{\rho}_i})}{\ln(1+\frac{\rho_s}{c}) - \ln(1+\frac{\tilde{\rho}_s}{\tilde{\rho}_i})} \right)^{-\alpha} \right] & \text{(NFW)}, \\
\tilde{\rho}_s \left[ \left( \frac{\exp \left( -\frac{r}{\rho_s} \right) - \exp \left( -\frac{\tilde{\rho}_s}{\rho_s} \right) \right)} {\left( \exp \left( -\frac{\rho_s}{\rho_s} \right) - \exp \left( -\frac{\tilde{\rho}_s}{\rho_s} \right) \right)} \right] & \text{(Einasto)},
\end{cases}
$$

where $r_s$ is the scale radius, $\tilde{\rho}_s$ is the scale density, and $\alpha$ is the inner slope for the NFW profile and a shape parameter for the Einasto profile. We take $\alpha = 0.17$ for NFW (Einasto) based on the results of $N$-body simulations (Navarro et al. 2010) and $r_s = 20$ kpc (Iocco et al. 2011). The $\tilde{\rho}_i$ is then obtained by fitting the solar system DM density $\rho_0 = 0.4$ GeV cm$^{-3}$. We scanned all of the available 1403 solitary pulsars recorded in the ATNF Pulsar Catalog (Manchester et al. 2005) and found the one maximizing $w_s(r)$ to be PSR J1801-0857D, a solitary pulsar with an age of 9.71 Gyr and distance of 3.06 kpc from the galactic center. The corresponding $w_s(r)$ is 16.0 (19.1) GeV · Gyr · cm$^{-3}$ for NFW (Einasto), indicating small model dependence on the halo profiles for our results. It should be emphasized that, within the present framework, PSR J1801-0857D can set the strongest constraints on DM-quark and DM-proton-scattering cross-sections among all 1403 pulsars. All of the results in the following are calculated using the parameters of PSR J1801-0857D.

Now we can directly constrain $\sigma_p (\sigma_q)$ from the existence of PSR J1801-0857D by assuming it is a SQS (NS). Furthermore, one can convert the limits on $\sigma_p$ obtained from the SQS assumption to those on $\sigma_q$, and then compare them to the constraints obtained from the NS assumption, as well as the results released by various direct detection experiments. Based on general operator analyses for scalar DM, the effective operators describing the DM-quark interactions that can generate DM-nucleon SI scattering are limited to the following two classes (Gao et al. 2013):

$$
a_q \phi \phi \bar{q}q, \quad b_q \phi \phi \bar{q} \gamma \mu \gamma_{\nu} q.
$$

The above first and second operators lead to the scalar and vector DM-quark interactions, respectively, with $a_q$ and $b_q$ being the coupling coefficients. The corresponding effective operators describing the DM-nucleon interactions are $f^q_N \phi \phi \bar{N} N$ and $f^q_N \phi \phi \bar{\gamma} \gamma \mu \gamma_{\nu} \bar{N} N$, respectively, where $N$ denotes protons ($p$) or neutrons ($n$), and $f_N$ is related to $a_q$ and $b_q$ by

$$
f^q_N = \frac{1}{2 m_q} \sum_q \tilde{B}^q_{\tilde{N}} a_q, \quad f^q_N = \sum_q \tilde{B}^q_{\tilde{N}} b_q,
$$

with the dimensionless quantities (Gao et al. 2013)

$$
B^q_{\tilde{N}} = 9.3, \quad B^p_{\tilde{N}} = 6.5, \quad B^q_{\bar{N}} = 5.1, \quad B^p_{\bar{N}} = 7.1 \quad \text{and} \quad B^{p,n} = 1.2 \text{ for scalar interaction, and} \quad B^q_p = 2, \quad B^q_n = 1, \quad B^p_p = 1, \quad B^p_n = 2
$$
$B^{2s,2n}_{2s,2n} = 0$ for vector interaction. Equation (7) does not include the contributions of sea quarks and gluons to $f_{2s}$, which can be effectively encoded in an additional free coefficient (Cirigliano et al. 2014) and will be discussed later. Then the DM-proton-scattering cross-section, for both scalar and vector interactions, takes the form $\sigma_{p} = (\mu_{p}/|v|)^{2} f^{2}_{p}$, while the DM-quark scattering cross-sections are given by $\sigma_{q}^{s} = (1/4\pi)(\mu_{q}^{2} a_{q}^{2}/m_{q}^{2})$ for scalar interaction and $\sigma_{q}^{v} = \mu_{q}^{2} b_{q}^{2}/\pi$ for vector interaction. Here $\mu_{p}$ ($\mu_{q}$) is the DM-proton (DM-quark) reduced mass. In the present work, the current masses of various quark flavors are taken as $m_{u} = 2.3$ MeV, $m_{c} = 4.8$ MeV and $m_{s} = 95$ MeV. Thus, one can derive limits on $\sigma_{q}^{s}$ from those on $\sigma_{q}^{v}$ with a specific type of DM-quark interaction.

Shown in Figure 2 are the limits on $\sigma_{q}^{s}$ versus $m_{q}$, assuming that DM only interacts with the first family of quarks for two cases of the so-called isospin-violating DM (Feng et al. 2011) with $f_{u}/f_{p}$ = 1 and $-0.7$. Note that the cut-off mass around several TeV in Figure 2 implies that PSR J1801-0857D fails to put constraints on heavier DM, since for them Hawking radiation will always overwhelm the BH accretion and so the BH cannot grow stably. In addition, $B^{2s}_{2s}$ and $B^{2n}_{2n}$ are different for scalar and vector interactions, so the limits show an interaction dependence, with a stronger limit for the scalar interaction. On the other hand, the limits with NFW and Einasto only display a very small difference, as expected. As shown in Figure 2, PSR J1801-0857D can put extremely strong limits on $\sigma_{q}^{s}$, especially for light DM, on the order of $10^{-22}$ cm$^2$. Since similar results on $\sigma_{q}^{v}$ can be obtained via the relationship $\sigma_{q}^{v}/\sigma_{q}^{s} = (\mu_{d}/\mu_{u})^{2} g_{du}$, where $g_{du} = a_{d}/a_{u} (b_{d}/b_{u})$ for scalar (vector) interaction is related to the isospin-violating factor $g_{2u} = f_{u}/f_{p}$ by $g_{2u} = (g_{2u} B^{2u}_{2u} - B^{2p}_{2u})(B^{2u}_{2u} - g_{2u} B^{2n}_{2u})$, our present results are potentially useful for constraining various model parameters for DM-quark interactions (Gao et al. 2013).

We then move to the $m_{\chi} - \sigma_{p}$ plane. Figure 3 shows the constraints on $\sigma_{p}$ either obtained directly from the NS assumption or derived from the $\sigma_{q}$ from the SQS assumption, as shown in Figure 2. It is very interesting to see that, for both cases of $f_{u}/f_{p}$ = 1 and $-0.7$, the limits on $\sigma_{p}$ derived from $\sigma_{q}$ are shifted upward dramatically compared to those on $\sigma_{q}$, and become significantly larger than the limits given by NS. This is due to the fact that the $\sigma_{p}$ converted from the $\sigma_{q}$ is enlarged by a factor of $(\mu_{p}/|v|)^{2} (B^{2u}_{2u} + g_{2u} B^{2n}_{2u})^{2}$, with an amplitude of about $10^{6}$--$10^{7}$, and thus the limits on $\sigma_{p}$ set by the SQS assumption are significantly weakened compared to those set by the NS assumption. For comparison, the current limits and regions on $\sigma_{p}$ reported by various direct detection experiments are also shown in Figure 3, including the regions from the DAMA-Libra (Bernabei et al. 2008) and CDMS-II Si (Agnese et al. 2013), XENON100 (Aprile et al. 2012), and LUX (Akerib et al. 2014), and SuperCDMS(Si) (Agnese et al. 2014); the future experiment XENON1T (Aprile et al. 2015) and the “neutrino discovery limit” (Billard et al. 2014) are also included for comparison.

Figure 3 shows that, for both cases with $f_{u}/f_{p}$ = 1 and $-0.7$, the NS assumption provides the most stringent constraints. In particular, even for the isospin-invariant case that $f_{u}/f_{p} = 1$, they are beyond the sensitivity of the future experiments XENON1T up to $m_{\chi} \sim 400$ GeV. However, the constraints set by the SQS assumption with scalar interaction become compatible with the CDMS-Si contour for $f_{u} = f_{p}$, and the relatively more stringent constraints from vector interaction are still weaker than those of the current xenon-based experiments. Moreover, for the isospin-violating case with $f_{u}/f_{p} = -0.7$ (i.e., the so-called xenophobic DM), while the tension among various direct detection experiments is largelyameliorated due to the destructive interference of DM scattering with protons and neutrons inside the target nuclei, all of the currently favored DM regions are excluded from the SQS assumption, even by the softest limits. But it is interesting to see that future experiment XENON1T, even in the xenophobic case, is expected to have higher sensitivity than the limits set by the SQS assumption for massive DM. This means that if future experiments observe scalar DM signals within the mass region $\sim O(10)$ GeV, then the old compact objects are more likely to be identified as SQSs rather than NSs. On the other hand, if no positive signals are observed by XENON1T, then the old compact stars still provide important constraints on models that predict scalar DM with mass lighter than $\sim O(10)$ GeV.
Therefore, direct detection experiments for DM provide a novel way to probe the nature of pulsars. Finally, we discuss the effects of scalar and heavy quarks (gluon) by showing in Figure 4 the so-called degradation factor (Feng et al. 2013), which measures the suppression or amplification effects on the $\sigma_p$ constraints and is defined as

$$D(g_{su}, \lambda_{\theta}) = \frac{\sigma_p(0, 0)}{\sigma_p(g_{su}, \lambda_{\theta})},$$

with $g_{gu} = a_g/a_u$ and $\lambda_{\theta}$ being the rescaled heavy quark (gluonic) coupling defined in Cirigliano et al. (2014). Noting that the isospin-violating effect is very small for large $g_{su}$ or $\lambda_{\theta}$, Figure 4 only shows the results with $f_{p,n}/f_p = 1$. It is interesting to see $D(g_{su}, 0) > 1$ for all $g_{su}$, which demonstrates how including scalar constraints can significantly increase the sensitivity of the $\sigma_p$ constraints set by a SQS for both scalar and vector DM-pulsar interactions. On the other hand, for the heavy quark (gluon) effects with vector interaction, the sea quarks and gluons do not contribute to $f_{p,n}$ due to the conservation of vector current; consequently, Figure 4 only shows the degradation factor for scalar interaction. One can see that the heavy quark (gluon) effects can either increase or decrease the sensitivity, depending on the specific value of $\lambda_{\theta}$. To further constrain $g_{su}$ and $\lambda_{\theta}$, other independent constraints are necessary, e.g., from the collider experiments (Goodman et al. 2010).

5. CONCLUSIONS
For scalar DM with ignorable self-interactions, we have shown that the old SQSs can directly place important constraints on DM-quark scattering cross-sections $\sigma_q$, which can be further converted into the constraints on DM-proton-scattering cross-sections $\sigma_p$ based on effective operator analyses. By analyzing a set of 1403 solitary pulsar-like compact stars in the Milky Way, we have found that the old pulsar PSR J1801-0857D can put the most stringent constraints on $\sigma_q$ and $\sigma_p$. Furthermore, we have demonstrated that while the limits on $\sigma_q$ obtained by assuming PSR J1801-0857D is an NS essentially rule out the possibility of detecting scalar DM in terrestrial labs through direct detection experiments, the extracted limits from assuming PSR J1801-0857D is an SQS are significantly weakened to be comparable with the terrestrial direct detection experiments. Our results have indicated that DM direct detection experiments provide a novel way to probe the nature of old pulsar-like compact stars, and that old pulsars are more likely to be identified as SQSs rather than NSs if scalar DM can be observed by future direct detection experiments, e.g., XENON1T.

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