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Dark matter effect on the mass measurement of neutron stars

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1 Introduction

The recent measurement of the Shapiro delay in the radio pulsar PSR J1614-2230 yielded a mass of 1.97 $\pm$ 0.04 $M_\odot$ [1]. Such a high neutron star (NS) mass might rule out many predictions of non-nucleonic components (free quarks, mesons, hyperons) in NS interiors, since they usually reduce the theoretical maximum mass of the star [2, 3, 4, 5, 6, 7, 8, 9, 10]. For example, a large NS maximum mass larger than 2 $M_\odot$ is obtained from nucleonic equation of state (EoS) from the microscopic Brueckner theory, but a rather low value below 1.4 $M_\odot$ is found for hyperon stars (HSs) in the same method [2, 3]. Although the present calculation did not include three-body hyperon interaction due to the complete lack of experimental and theoretical information, it seems difficult to imagine that these could strongly increase the maximum mass, since the importance of the hyperon interactions should be minor as long as the hyperonic partial densities remain limited. However, if there is a universal strong repulsion in all relevant channels the maximum mass may be significantly raised [11], so the including of the hyperonic three-body interaction, together with an improved hyperon-nucleon and hyperon-hyperon potentials, is still appealing to settle this apparent contradiction. In addition, the presence of a strongly-interacting quark matter in the star's interior, i.e., a hybrid star model, is proposed to be a good candidate for troubleshooting this problem [12], However, NS masses substantially above 2 $M_\odot$ seem to be out of reach even for hybrid stars using most of effective quark matter EoS (Eg. bag model [13], Nambu-Jona-Lasinio model [14], color dielectric model [15]). A hybrid star with 2 $M_\odot$ is only allowed for the description of quark matter in the Dyson-Schwinger approach [16], or possible in the latest version of the Polyakov-Nambu-Jona-Lasinio model [17].

Very recently, dark matter (DM), as another possible constituent in NS interior, has been taken into account and a new type of compact star, i.e., DM-admixed

NS, has been studied in several articles [18, 19, 20, 21, 22, 23, 24, 25, 26]. The general effect induced by DM inside NS is complicated due to the lack of information about the particle nature of DM. DM could annihilate, such as the most favored candidate, neutralino, which may lead to sizable energy deposit and then enhance the thermal conductivity or trigger the deconfinement phase transition in the core of NS for the emergency of a quark star, as illustrated by Perez-Garcia et al. in [18]. Such quark star objects are at present very uncertain in theory and could easily accord with astrophysical measurements within the modification of model parameters [27, 28]. Another generally considered DM candidate is the non-self-annihilating particle, such as the newly interesting mirror DM ([29] and references therein) or asymmetric DM ([30] and references therein). When they accumulate in NSs, the resulting maximum mass is then rather sensitive to the EoS model of DM. Assuming that the DM component is governed by an ideal Fermi gas, Leung et al. [19] studied the various structures of the DM-admixed NSs by solving the relativistic two-fluid formalism. Ciarcelluti & Sandin [20] approximated the EoS of mirror matter with that of ordinary nuclear matter, varied the relative size of the DM core, and explained all astrophysical mass measurements based on one nuclear matter EoS.

In this paper, we will consider non-self-annihilating DM particles as fermions, and the repulsive interaction strength among the DM particles is assumed to be a free parameter $m_{\mathcal{I}}$ as in [31]. Different to previous DM-admixed NS models, we take the total pressure (energy) density as the simple sum of the DM pressure(energy) and NS pressure (energy), the general dependence of the mass limit on DM particle mass and the interaction strength is then presented based on the present model. Furthermore, in the particular case of PSR J1614-2230, we notice that the DM around the star should also contribute to its mass measurement due to the pure gravitational effect. However, our numerically calculation illustrates that such contribution could be safely ignored because of the usual diluted DM environment assumed.

The paper is arranged as follows. The details of our theoretical model are presented in §2, followed by the numerical results. A short summary is given in §3.

2 The model

We begin with the treatment of the DM particles scattered inside the star. They would modify the local pressure-energy density relationship of the matter and hence change the theoretical prediction of the gravitational mass of the star. The structure equations for compact stars, the Tolman-Oppenheimer-Volkov equations are written as:

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\mathcal{E}(r)}{r^2}\frac{\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{m(r)}\right]}{1-\frac{2Gm(r)}{r}}, \tag{1}$$

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

being G the gravitational constant. P and $\mathcal{E}$ denote the pressure and energy density. The EoS of the star, relating P and $\mathcal{E}$, is needed to solve the above set of equations. In our DM-admixed NS model, $P = P_N + P_\chi, \mathcal{E} = \mathcal{E}_N + \mathcal{E}_\chi$, with the subscript $N(\chi)$ representing NS matter (DM).

The EoS of the ordinary NS matter is handled in the following way: (i) We treat the interior of the stars as β-equilibrium hypernuclear matter, with certain amount of leptons to maintain charge neutrality. The hadronic energy density we use in the article is based on the microscopic parameter-free Brueckner-Hartree-Fock nuclear many-body approach, employing the latest derivation of nucleon-nucleon microscopic three-body force [32], supplemented by the very recent Nijmegen extended soft-core ESC08b hyperon-nucleon potentials [12]. The EoS can be computed straightforwardly after adding the contributions of the noninteracting leptons [12]. (ii) For the description of the NS crust, we join the hadronic EoS with those by Negele and Vautherin [33] in the medium-density regime, and those by Feynman-Metropolis-Teller [34] and Baym-Pethick-Sutherland [35] for the outer crust.

The EoS of DM is modeled to be that of a self-interacting Fermi gas with one parameter $m_\mathcal{I}$ accounting for the energy scale of the interaction [31]. For weak interaction (WI) the scale $m_\mathcal{I}$ can be interpreted as the expected masses of W or Z bosons generated by the Higgs field, which is $\sim$ 300 GeV. For strongly interacting (SI) DM particles, $m_\mathcal{I}$ is assumed to be $\sim$ 100 MeV, according to the gauge theory of the strong interactions. This is a wide enough range of energy scale, and we hope the calculation would cover most of the promising DM candidates.

Then we consider the mass contribution of DM halo via gravitational capture. We first estimate the size of the halo R as big as that of the possible Roche lobe [36] of the centered PSR J1614-2230, namely $R = 0.49(M_1/M_2)^{2/3}\ a/\{0.6(M_1/M_2)^{2/3} + ln[1 + (M_1/M_2)^{1/3}]\}$, with a being the major semi-axis of this binary system, namely 3×10^{11} cm. $M_1(M_2)$ is the gravitational mass of the NS (the companion star). The local DM density is estimated from several spherically symmetric Galactic DM profiles [37, 38, 39, 40], and we take an average value of $\overline{\rho_\chi} = 0.474$ GeV/cm^3. Thus the contributed mass of gravitationally captured DM particles can be obtained from $M_\chi = \frac{4}{3}\pi R^3 \overline{\rho_\chi}$. Here the size of the star ($\sim$ 10 km) has been neglected compared to its large Roche lobe ($\sim 10^6$ km), and the halo has been regarded as an ideal spherical object.

Finally our calculated result is present in Fig. 1 with a shallowed area indicating the mass limit of DM particle m_χ, assuming the observed PSR J1614-2230 is a HS. The $\sim 2\ M_\odot$ limit is indicated with a horizontal line. The upper line corresponds to $m_\mathcal{I} = 100$ MeV (SI case), and the lower line to $m_\mathcal{I} = 300$ GeV (WI case). Specially we mention that the extra mass measurement contribution from the extended halo is only around $10^{-24}\ M_\odot$, which could be safely ignored for the analysis of Shapiro delay. This mass limit from the compact star can be referred as an upper limit for the

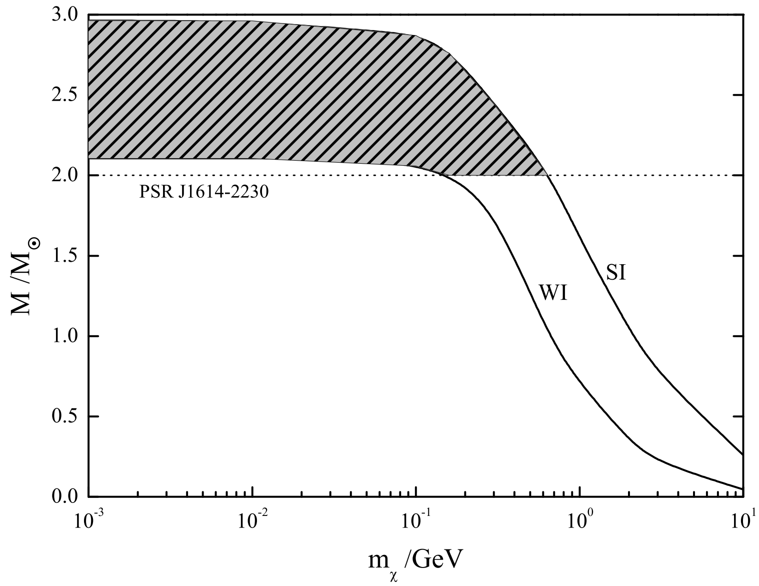

Figure 1: HSs' maximum masses as a function of the particle mass of DM candidates m_χ. The upper line is for $m_{\mathcal{I}} = 100$ MeV (SI case), and the lower line for $m_{\mathcal{I}} = 300$ GeV (WI case). Again the $\sim 2\ M_\odot$ limit of PSR J1614-2230 is indicated with a horizontal line. Taken from Ref. [41].

mass of non-self-annihilating DM particles, namely, it should obey $m_\chi < 0.64$ GeV for SI DM and < 0.16 GeV for WI DM.

3 Summary

In this article, we consider DM as another possible constituent in HSs' interior, to solve the recent hyperon puzzle provoked by the recent 2-solar-mass NS measurement. We take DM as self-interacting Fermi gas with certain repulsive interaction among the DM particles and non-interaction between DM and ordinary matter as is generally assumed. We find that the star maximum mass is sensitive to the particle mass of DM, and a high enough star mass larger than 2 $M_\odot$ could be achieved when the particle mass is small enough. In this particular model, a strong upper limit 0.64 GeV for DM mass is obtained in SI DM and 0.16 GeV for DM mass in WI DM. In order to relax such strong constraint, we further consider the possible extended DM halo contribution to the particular mass measurement. However, due to the diluted DM environment, such kind of contribution could be safely ignored.

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