

Too massive neutron stars: The role of dark matter?

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ABSTRACT

The maximum mass of a neutron star is generally determined by the equation of state of the star material. In this study, we take into account dark matter particles, assumed to behave like fermions with a free parameter to account for the interaction strength among the particles, as a possible constituent of neutron stars. We find dark matter inside the star would soften the equation of state more strongly than that of hyperons, and reduce largely the maximum mass of the star. However, the neutron star maximum mass is sensitive to the particle mass of dark matter, and a very high neutron star mass larger than $2M_{\odot}$ could be achieved when the particle mass is small enough, being M_{\odot} the mass of the sun. Such kind of dark-matter-admixed neutron stars could explain the recent measurement of the Shapiro delay in the radio pulsar PSR J1614-2230, which yielded a neutron star mass of $1.97 \pm 0.04M_{\odot}$ that may be hardly reached when hyperons are considered only, as in the case of the microscopic Brueckner theory. Furthermore, in this particular case, we point out that the dark matter around a neutron star should also contribute to the mass measurement due to its pure gravitational effect. However, our numerical calculation illustrates that such contribution could be safely ignored because of the usual diluted dark matter environment assumed. We conclude that a very high mass measurement of about $2M_{\odot}$ requires a really stiff equation of state in neutron stars, and find a strong upper limit (≤ 0.64 GeV) for the particle mass of non-self-annihilating dark matter based on the present model.

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1. Introduction

Neutron star (NS), a new form of compact star with degenerate neutrons as predicted by Landau in 1932, is generally believed to have a maximum mass, beyond which the star will be unstable and collapse into a black hole. When considering a NS as free Fermi gas of neutrons, the balance between the star's gravitational self-attraction and neutron degeneracy pressure leads to the original Oppenheimer-Volkoff mass limit of approximately $0.7M_{\odot}$. Incorporating the strong interaction between neutrons will certainly increase this value because of the repulsive nature of the short-range core. However, when hyperons are included as another constituent of the star, a softer equation of state (EoS) will be obtained with a consequent reduction of the maximum NS mass. An exact prediction for the maximum mass is difficult due to the large uncertainty when extrapolating the EoS of dense matter from relatively low densities in nuclear experiments to very high densities in astrophysical objects. The final conclusion will depend on the composition of a NS and how we describe the interactions between its constituents.

The recent measurement [1] of the Shapiro delay in the radio pulsar PSR J1614-2230 yielded a mass of $1.97 \pm 0.04M_{\odot}$. Such a high NS mass measurement has raised great interests in the structure and composition of NSs, since it might rule out many predictions of non-nucleonic components (free quarks, mesons, hyperons) in NS interiors [2–4].

For example, a large NS maximum mass larger than $2M_{\odot}$ is obtained from nucleonic EoS from the microscopic Brueckner theory, but a rather low value below $1.4M_{\odot}$ is found for hyperon stars (HSs) in the same method [5,6], namely so-called hyperon puzzle. 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 hyperon-hyperon potentials should be minor as long as the hyperonic partial densities remain limited. However, there is still a possibility that if there is universal strong repulsion in all relevant channels the maximum mass may be significantly raised [7], so the including of an improved hyperon-nucleon and hyperon-hyperon potentials and hyperonic three-body forces is still appealing to settle this apparent contradiction, which badly needs further experimental data. In addition, the presence of a strongly-interacting quark matter, in the star's interior (i.e., hybrid star), is proposed to be a good candidate for troubleshooting this problem [8]. However, NS masses substantially above $2M_{\odot}$ seem to be out of reach even for

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hybrid stars using most of effective quark matter EoS (bag model [9], NJL model [10], color dielectric model [11]). A hybrid star with $2M_{\odot}$ is only allowed when using the Dyson–Schwinger approach for the description of quark matter [12].

Dark matter (DM), as another possible constituent in NS interior, has been taken into account and a new kind of compact star, i.e., DM-admixed NS, has been studied recently in several articles [13–21]. 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 [13]. Such quark star objects are at present very uncertain in theory and could easily accord with astrophysical measurements within the modification of model parameters [22,23]. Another generally considered DM candidate is the non-self-annihilating particle, such as the newly interesting mirror DM ([24] and references therein) or asymmetric DM ([25] 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. [14] studied the various structures of the DM-admixed NSs by solving the relativistic two-fluid formalism. Ciarcelli & Sandin [15] 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. More recently, Goldman [16] discussed the implications of asymmetric DM on NSs, and argued that a large mass will pose no problem for a mixed NS. They adapted scaled EoSs of nuclear matter for that of the dark baryons, and used two central energy densities for the solving of NS structure equations. In this study, 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_{χ} as in [26]. 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.

In addition, the non-self-annihilating DM, mirror DM or asymmetric DM, is generally believed to simply accumulate during the whole evolution series from the proton-star to the final compact state. As the heavy DM particles usually do not collapse with the ordinary matter, an extended halo around the star is formed [27,28], therefore there should exist an extra general-relativistic mass effect from the halo. This is particularly relevant for the mass measurement of PSR J1614-2230, because the inferred large NS mass is based on the large Shapiro delay and Keplerian orbital parameters of a binary system [1], and information on the size of the NS in the binary system is actually not clear. It may be possible that the inferred mass comprises the mass of the star and also the mass of a possible DM halo. It is in the present article that for the first time the mass contribution from the possible extended halo is taken into account. For that we should consider carefully the spatial scale of the related halo and the DM density around the position of the binary system (see the following section for details).

This paper is arranged as follows. The details of our theoretical model are presented in Section 2, followed by the numerical results. Conclusions and discussions are given in Section 3.

2. The model

DM particles, as the most abundant matter component in the universe, could accrete onto stars due to their kinetic energy loss

in the scattering process and also gravitationally trapped inside or around the star during the whole star evolution stage. DM particles being scattered inside the star would modify the local pressure–energy density relationship of the matter and hence change the theoretical prediction of the gravitational mass of the star. DM particles left behind the star could form an extended halo around the star, which is expected to increase the measured mass of the star. We will study in detail these two aspects in the following two subsections respectively.

2.1. DM-admixed NS model

The structure equations for compact stars, namely the Einstein field equations for hydrostatic equilibrium (i.e., the Tolman–Oppenheimer–Volkov (TOV) equations) are written as:

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

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

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 nuclear matter (corresponding to NSs) or hypernuclear matter (corresponding to HSS), 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 [29]. When performing the study of HSS, the very recent Nijmegen extended soft-core ESC08b hyperon–nucleon potentials [8] is included as well. The EoS can be computed straightforwardly after adding the contributions of the noninteracting leptons [8]. (ii) For the description of the NS/HS crust, we join the hadronic EoS with those by Negele and Vautherin [30] in the medium-density regime, and those by Feynman–Metropolis–Teller [31] and Baym–Pethick–Sutherland [32] for the outer crust.

The DM part may stabilize itself in a barotropic state in the same way as in the case of ordinary matter, but it is very difficult to determine what is the EoS of DM. We will take DM as Fermi gas with m_{χ} accounting for the energy scale of the interaction, and write the energy density and pressure of DM as those of a self-interacting Fermi gas as [26]:

$$\mathcal{E}_{\chi} = \frac{m_{\chi}^4}{\pi^2} \int_0^{k_F/m_{\chi}} x^2 \sqrt{1+x^2} dx + \left(\frac{1}{3\pi^2}\right)^2 \frac{k_F^6}{m_{\chi}^2}, \quad (3)$$

$$P_{\chi} = \frac{m_{\chi}^4}{3\pi^2} \int_0^{k_F/m_{\chi}} \frac{x^4}{\sqrt{1+x^2}} dx + \left(\frac{1}{3\pi^2}\right)^2 \frac{k_F^6}{m_{\chi}^2}, \quad (4)$$

where m_{χ} is the mass of DM particles, and the Fermi momentum k_F is related to the number density ρ by $k_F = (3\pi^2 \rho)^{1/3}$.

For weak interaction (WI) the scale m_{χ} can be interpreted as the expected masses of W or Z bosons generated by the Higgs field, which is ~ 300 GeV. For strongly interacting (SI) DM particles, m_{χ} is assumed to be ~ 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.

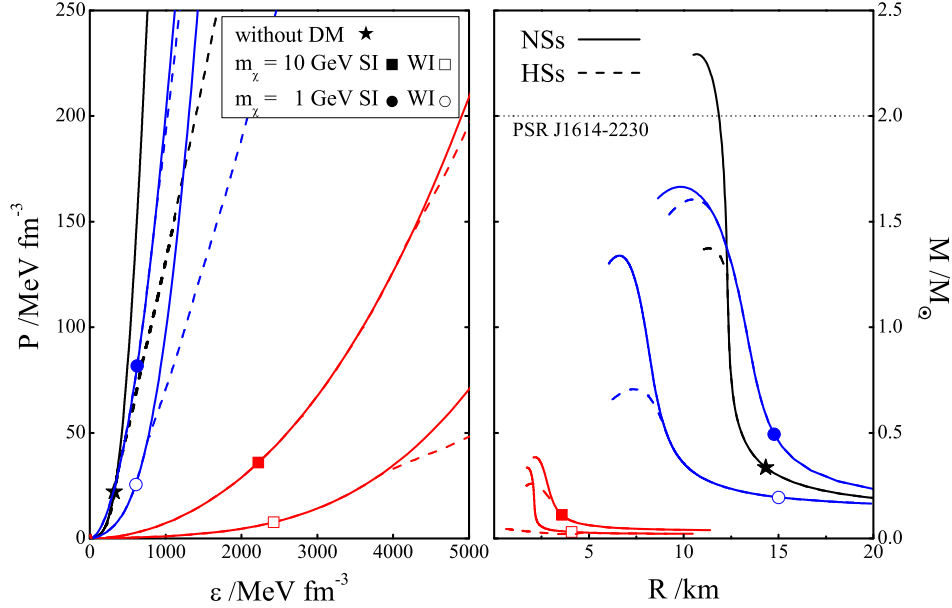


Fig. 1. Equations of state (left panel) and mass-radius relations (right panel) of the DM-admixed NSs (solid curves) and HSs (dashed curves) with a recently-determined DM particle mass $m_\chi = 10$ GeV for SI and WI DM, to be compared with the case without DM. The results with a modified DM particle mass with $m_\chi = 1$ GeV are also shown. The $\sim 2M_\odot$ limit of PSR J1614-2230 is indicated with a horizontal line.

As far as the pressure and energy density of NS and DM have been determined, we then start with a central mass density $\varepsilon(r=0)$, and integrate out until the surface density equals that of iron. This gives the stellar radius R and its enclosed mass $M = m(R)$. Each EoS is related to a NS equilibrium sequence with different central mass density, and there is a maximum value of central density (or central pressure) for each EoS, which corresponds to the maximum weight of the star sequence. The mass of the stars can not be larger than the maximum mass value because it will unavoidably collapse due to unbearable gravity. If a theoretical model predicts a maximum value of NS which is lower than the mass measurements of pulsars in the market, we say the model fails to explain the experiments and is ready to be improved or rejected.

Fig. 1 presents EoSs (left panel) and mass-radius relations (right panel) of the DM-admixed NSs (solid curves) and HSs (dashed curves) with a recently-determined DM particle mass $m_\chi = 10$ GeV [33] for SI and WI DM, to be compared with the case without DM. The mass of 10 GeV accounts for a consistent description about various recent direct detection experiments, with which the EoSs are substantially softened after the inclusion of DM contribution both in SI and WI cases. This leads to smaller maximum masses, as shown in the right panel. A maximum value of $2.29M_\odot$ ($1.37M_\odot$) when DM is not included is decreased to $0.39M_\odot$ ($0.26M_\odot$) in the SI case, and to $0.34M_\odot$ ($0.05M_\odot$) in the WI case for NSs (HSs), where the recent-observed $\sim 2M_\odot$ mass measurement is indicated with a dotted horizontal line. The softening of DM in this case is seen to be quite evident, even stronger than that of hyperons. However, current predictions of the DM particle mass span the range from keV as the sterile neutrino to around TeV as weakly interacting massive particles (usually shortened as WIMP). If we use a decreased mass of $m_\chi = 1$ GeV to redo the calculation, the evident softening effect of DM is somehow weakened as illustrated in the same figure, and a larger maximum masses are obtained, namely $1.67 M_\odot$ ($1.61 M_\odot$) in the SI case, and $1.34 M_\odot$ ($0.71 M_\odot$) in the WI case for NSs (HSs). This demonstrates an interesting sensitive dependency of the maximum mass on the DM particle mass m_χ , which needs further exploration.

In Table 1 we collect the calculated characteristics of the maximum mass configurations (maximum masses, corresponding radii

Table 1

Characteristics of the maximum mass configurations (maximum masses M , corresponding radii R and central number densities ρ_c) for different DM mass m_χ and composition.

m_χ (GeV)		SI			WI		
		$M(M_\odot)$	R (km)	ρ_c (fm ⁻³)	$M(M_\odot)$	R (km)	ρ_c (fm ⁻³)
0.01	NS	2.96	17.3	0.35	2.11	12.4	0.77
	HS	2.96	17.3	0.35	2.11	12.4	0.77
0.1	NS	2.88	16.8	0.36	2.06	11.7	0.82
	HS	2.88	16.8	0.36	2.06	11.7	0.82
1	NS	1.67	9.85	0.68	1.34	6.61	1.39
	HS	1.61	10.5	0.61	0.71	7.39	1.32
10	NS	0.39	2.16	2.61	0.34	1.74	4.12
	HS	0.26	1.99	3.62	0.05	0.65	40.9

and central number densities) with different DM mass m_χ and composition. Because of the conflict mentioned above between the HS theoretical model and the recent observed large mass, special attention is paid to the HS results, which are presented in Fig. 2 of the EoSs (left panel) and mass-radius relations (right panel) using DM mass m_χ ranging from 0.01 GeV to 10 GeV for SI (curves with symbol) and WI (curves without symbol) DM, to be compared with the case without DM. It is clear that the smaller the mass of DM, the larger the mass of the compact star could reach. If the newly measurement of $1.97 \pm 0.04 M_\odot$ is required for a HS, an upper limit on the DM mass around 0.64 GeV (0.16 GeV) are set for SI (WI) DM.

Our prediction on the upper limit of DM mass could be relaxed. For example, if a part of the measured $2M_\odot$ is deposited around the NS, e.g., $1.61M_\odot$, the upper limit of DM mass could be increased to as large as 10 GeV. This is the reason why we further consider the DM extended halo contribution.

2.2. DM halo around NS

To get the mass contribution of DM halo via gravitational capture, we first should calculate the spatial scale of the related halo

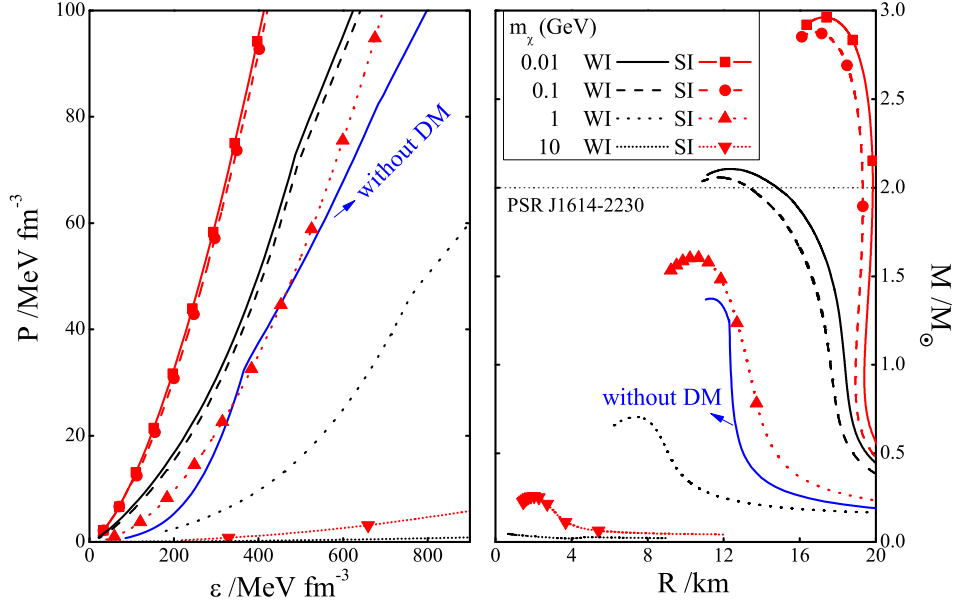


Fig. 2. Equations of state (left panel) and mass-radius relations (right panel) of the DM-mixed HSs with DM mass m_χ ranging from 0.01 GeV to 10 GeV for SI (curves with symbol) and WI (curves without symbol) DM, to be compared with the case without DM. The $\sim 2M_\odot$ limit of PSR J1614-2230 is indicated with a horizontal line.

and the DM density at the NS location. We estimate the size of the halo as big as that of the possible Roche lobe of the centered PSR J1614-2230, which is calculated using the following theoretical formula by Eggleton [34]:

$$R = \frac{0.49(M_1/M_2)^{2/3}}{0.6(M_1/M_2)^{2/3} + \ln[1 + (M_1/M_2)^{1/3}]} a, \quad (5)$$

where a is the major semi-axis of this binary system which is 3×10^{11} cm. M_1 is the gravitational mass of the NS, and M_2 is that of its companion star, a $0.5M_\odot$ white dwarf (WD) [1]. The gravitational mass of the NS is ready to change when incorporating the DM (as shown below), but the value of the WD, i.e., $0.5M_\odot$, is fixed since it is implied by the detected Shapiro delay of PSR J1614-2230 by the WD. A possible DM halo around the WD has no influence on this value, because the measurement is done for a complete period of the binary system.

The DM density in the extended halo around the NS is highly dependent on the local distribution of DM density which should be determined from the accreting history in the binary system. Here, for a simple calculation, we adopt the density value determined by our Galaxy density profile. We restrict our evaluation to several spherically symmetric Galactic DM profiles, and scale the profiles with a fixed value of 0.389 GeV/cm^3 at the solar position. As shown in Fig. 3, *Einasto* stands for the best-fitting Einasto density profile obtained from the results of the Aquarius simulation [35]. *ViaLactea* stands for a profile extrapolated from the via Lactea II simulation [35]. *NFW* stands for the prototypical Navarro-Frenk-White density profile [36]. The last *Burkert* profile is characterized by a very smooth central cusp [37,38]. From the celestial coordinates of PSR J1614-2230 (16 h 14 min right ascension and -22 degrees 30 min declination) and its distance from the sun (1.2 kpc) [1], we can calculate its distance from the galactic center, which is 7.44 kpc. Then the local DM densities ρ_χ can be evaluated corresponding to the four profiles above, namely 0.4868 GeV/cm^3 , 0.4832 GeV/cm^3 , 0.4771 GeV/cm^3 , 0.4472 GeV/cm^3 , respectively. Since they do not differ much, it is proper to take an average value of $\bar{\rho}_\chi = 0.474 \text{ GeV/cm}^3$ for the following calculation. Hence the contributed mass of gravitationally captured DM particles can be finally written as

$$M_\chi = \frac{4}{3} \pi R^3 \bar{\rho}_\chi, \quad (6)$$

where we have neglected the size of the star (~ 10 km) compared to its large Roche lobe ($\sim 10^6$ km), and have regarded the halo as an ideal spherical object. In this case, the extra mass measurement contribution from the above extended halo is around $10^{-24} M_\odot$, which could be safely ignored. However, the capture of DM may be further enhanced by the motion of the NSs in close binaries [39]. Our adopted value should be considered as the lower limit mass contribution. Even though, DM mass contribution from the extended halo alone is hard to account for the large mass measurement even the density could be increased by several orders in some exotic mechanism, such as some abnormal stellar merge events of DM stars, or abnormally efficient absorbing of DM.

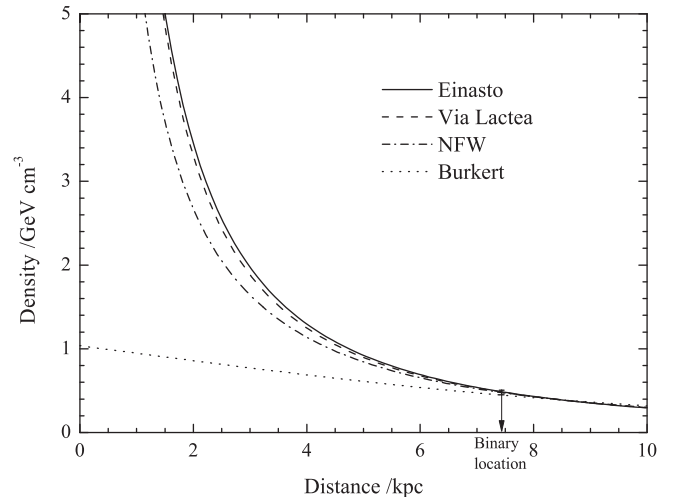


Fig. 3. Four models of the galactic DM density profiles employed in the paper. *Einasto* stands for the best-fitting Einasto density profile obtained from the results of the Aquarius simulation [35]. *ViaLactea* stands for a profile extrapolated from the via Lactea II simulation [35]. *NFW* stands for the prototypical Navarro-Frenk-White density profile [36]. *Burkert* stands for the Burkert profile [37,38]. The location of the binary system $r = 7.44$ kpc is indicated with an arrow.

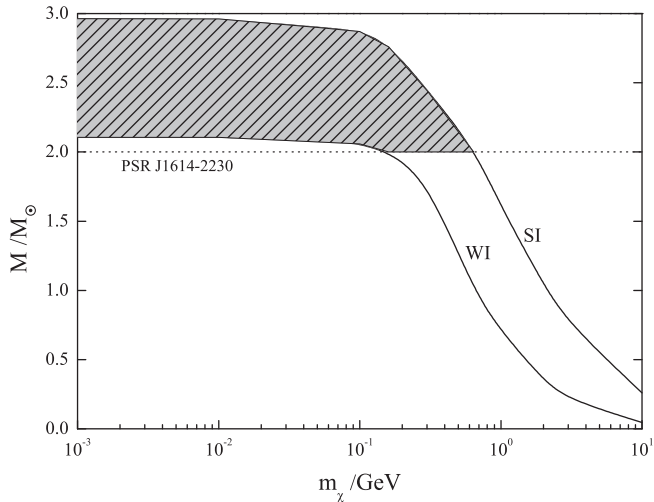


Fig. 4. Hs's maximum masses as a function of the particle mass of DM candidates m_χ . The upper line is for $m_\chi = 100$ MeV (SI case), and the lower line for $m_\chi = 300$ GeV (WI case). Again the $\sim 2M_\odot$ limit of PSR J1614-2230 is indicated with a horizontal line.

Finally we summarize in Fig. 4 with a shaded area the mass limit of DM particle m_χ based on our present model, assuming the observed PSR J1614-2230 is a HS. The $\sim 2M_\odot$ limit is again indicated with a horizontal line. The upper line corresponds to $m_\chi = 100$ MeV (SI case), and the lower line to $m_\chi = 300$ GeV (WI case). The dependence of the maximum mass on the DM particle mass is very sensitive when the mass is relatively large (above 0.1 GeV). For small mass value less than 0.01 GeV, the calculated mass-radius curves are very close to each other in our model, and almost fixed results are obtained for the maximum mass ($\sim 2.96M_\odot$) and corresponding radius (~ 17.3 km), as shown in Table 1. This is because that the $\mathcal{E}(P)$ relation of DM has a weaker dependence on the change of the particle mass m_χ based on the present Fermi-gas model (Eq. (4)) when the particle mass is small, as a result the maximum mass never exceeds $3M_\odot$ and comfortably lies below the usual constrain for NSs' mass. Moreover, as discussed before, this mass limit from the compact star can be referred as an upper limit for the mass of non-self-annihilating DM particles, namely, it should obey $m_\chi \leq 0.64$ GeV. More information on the interaction properties among DM particles will certainly further narrow this region.

3. Conclusion

In this paper, we present a consistent DM-admixed NS model to investigate the possible influence of DM on the NS mass measurement. We take DM as Fermi-gas with certain repulsive interaction among the DM particles and none-interaction between DM and ordinary matter as is generally assumed. The pressure (energy density) of DM particles scattered into the compact star could be regarded as an extra component to the total pressure (energy density) in the TOV equations. In this scenario, the DM ingredient is expected to soften the total EoS and result in a reduced maximum mass. However, the final results are sensitive to the adopted DM particle mass. The smaller the DM particle mass, the harder the EoS or the larger the maximum mass. The observed very massive NS requires a very stiff EoS and then sets a strong upper limit on the DM particle mass. In our numerical calculation, DM particle mass should be less than 0.64 GeV for SI DM and 0.16 GeV for WI DM. In order to relax such strong constraint, we further consider the possible extended DM halo contribution to the particular mass

measurement in [1]. However, due to the diluted DM environment, such kind of contribution could be safely ignored. Some exotic mechanism, such as abnormal stellar merge events of DM stars, or abnormally efficient absorbing of DM, may lead to an unusual dense DM halo and then relax the upper limit greatly. Generally, the EoS of the pulsar should be really stiff unless there is a very dense DM halo around the compact object. Very recently, such a high mass NS has been successfully explained as a hybrid star described by a very stiff nucleonic EoS [12] in the Brueckner theory, which is consistent with our findings. This conclusion would be meaningful for the research of microscopic physics. Since our present calculation is based on the ordinary NS structure equations, we can not provide the specific configuration of the DM-admixed NS. If one notice the quite small values of NS radii in Table 1 for large DM particle mass, they are more like DM-stars rather than NSs. More proper scheme should be applied to solve the two-fluid equations with a updated reasonable DM EoS, which is referred to a future work.

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