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GW170817 Constraints on Equations-of-states of a Neutron Star in the Presence of WIMP Dark Matter

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Neutron star (NS) properties are studied by considering dark matter inside its core. We have considered a moderately light neutralino as a dark matter candidate within the framework of the Next-to-Minimal Supersymmetric Standard Model (NMSSM), satisfying the results of the DAMA collaboration. In this work, it is assumed that neutralino interacts with the hadronic matter of NS through the Higgs boson. We have used the relativistic mean-field (RMF) model with IOPB-I, and NL3 parameter sets to study the equations-of-state (EoS) in the presence of dark matter. The predicted EoSs are used into the TOV equations to obtain the mass-radius of the NS. The calculated properties of NS are compared with the corresponding data of the GW170817 event.

KEYWORDS: Neutron star, WIMP dark matter, GW data . . .

1. Introduction

Dark matter (DM) is one of the most highlighted areas of interest among the physicists. Currently, several modern observations support and confirm the existence of DM on a wide range of scales. The nature and origin of DM remain unknown even though there are several proposed DM candidates [1] and DM searches going on [2–5]. Weakly Interacting Massive Particles (WIMPs) are reasonably the most popular DM candidates, which are thermal relics from the Big-Bang and satisfy the relic density of DM. The interaction of the neutralino (a Fermionic DM candidate) with nuclei through elastic [6] or inelastic scattering [7, 8] has been studied in various laboratories around the globe. The range of a spin-independent (SI) cross-section of elastic scattering of DM with nuclei and mass of DM particle from the recently discovered channelling effect on the threshold energy in DAMA are, respectively, given below as [9–11]

$$3 \times 10^{-41} cm^2 \lesssim \sigma_p^{SI} \lesssim 5 \times 10^{-39} cm^2 \tag{1}$$

$$3GeV \lesssim m_{DM} \lesssim 8GeV. \tag{2}$$

In Ref. [9], authors found a one-to-one relation between the SI direct detection rate and DM relic density if elastic scattering of WIMP on nuclei occurs dominantly through Higgs exchange. The SI direct detection cross section of elastic scattering of DM (χ) with nucleons (φ) is given by [9]

$$\sigma(\chi\varphi \to \chi\varphi) = \frac{y^2}{\pi} \frac{\mu_r^2}{v^2 M_h^4} f^2 m_N^2, \tag{3}$$

where $v = 246\,GeV$, m_N, M_h are the Higgs vacuum expectation value, the nucleon mass and the Higgs mass, respectively. $\mu_r = \frac{m_N m_{DM}}{m_N + m_{DM}}$ is the reduced mass of a nucleon-DM particle system. The variables y, fm_N/v are the Yukawa couplings for DM interaction with Higgs boson and the interaction of Higgs particle with the nucleons, respectively.

In this paper, we examine consequences of DM particle on the properties of NS, which have been discussed in the literature [12–20] with different assumptions. The mass-radius relation of NS can be affected in the presence of DM inside its core [21]. In the paper [12], the authors have reported that the presence of DM core inside an NS can modify the gravitational waves (GWs) signal from the BNS merger. The modified GWs signal may be given the additional peaks in the post-merger frequency spectrum. These additional peaks might be identified in future GW signal from BNS mergers and hence will be an indirect probe to DM.

The paper is organized as follows: The formalism is presented in Sec. 2. In Sec. 3, we present numerical results. Finally, we summarize and conclude our work in Sec. 4.

2. Formalism

In this work, we have considered the neutralino (χ), a lightest mass eigenstate of WIMP within NMSSM [22–24] as the Fermionic DM candidate. The interaction Lagrangian density of the neutralino with the baryonic matter (φ) of an NS through the Higgs exchange (h) is given by [25]

$$\mathcal{L} \quad = \quad \mathcal{L}_{had.} + \bar{\chi}\left[i\gamma^\mu\partial_\mu - M_\chi + yh\right]\chi + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{2}M_h^2 h^2 + f\frac{M_n}{v}\bar{\varphi}h\varphi, \qquad (4)$$

where $\mathcal{L}_{had.}$ is the Lagrangian density for pure hadronic matter, which is considered here within the RMF model [26] with IOPB-I [27] and NL3 [28] parameter sets. The M_χ, M_h, and M_n represent the masses for the DM, Higgs boson, and nucleon, respectively. In the mean field theory approximation, the higher order terms of the Higgs scalar potential (*i.e.*, h^3 and h^4) are negligible [21].

We have considered the central value of the Higgs-nucleon coupling $f = 0.3$ in agreement with [29]. The variables of DM-baryonic matter interaction Lagrangian are determined by assuming DM mass, and an SI DM-nucleon cross-section in the range as suggested by the DAMA results in [30,31]. We have taken a light Higgs boson with a mass $M_h = 40\,GeV$ in NMSSM, so that $y < 1$. The EoS is obtained by solving Eq. (4) by imposing $\beta-$ equilibrium conditions. EoSs are used in the TOV equations [32] to find the NS properties with DM particle inside it having the Fermi momentum as $k^f_{DM} = 0.06\,GeV$ [33].

3. Results and Discussion

The EoSs of NS with and without DM corresponding to IOPB-I [27] and NL3 [28] parameter sets are shown in Figure 1(a). The curves are labelled as shown in the figure. We compare the predicted EoSs with the posterior of GW170817, which are represented by the grey and yellow shaded regions corresponding to the 50% and 90% confidence levels [34]. The vertical lines (blue lines) represent the nuclear saturation density and twice its value. These densities are assumed to almost correlated with bulk macroscopic properties of NSs [38]. The presence of DM inside the core of an NS softens EoS. The IOPB-I EoSs with and without DM pass through the 90% and 50% credible limits of the observational band (posterior EoSs) at and around the nuclear saturation density ρ_{nucl} and at density larger than ρ_{nucl}, respectively. These EoSs become softer at further high density and do not satisfy GW170817 data. The NL3 EoSs meet the 90% as well as 50% confidence level of posterior EoSs only at large value of the energy density. The effects of the DM on the core EoSs are consistent with what was found in Refs. [21, 25]. However, EoS becomes stiffer when considering the DM haloes around NS [39], and hence an improvement in the structural properties. In the next paragraph, we present how these softer EoSs in the presence of DM affect the properties of an NS.

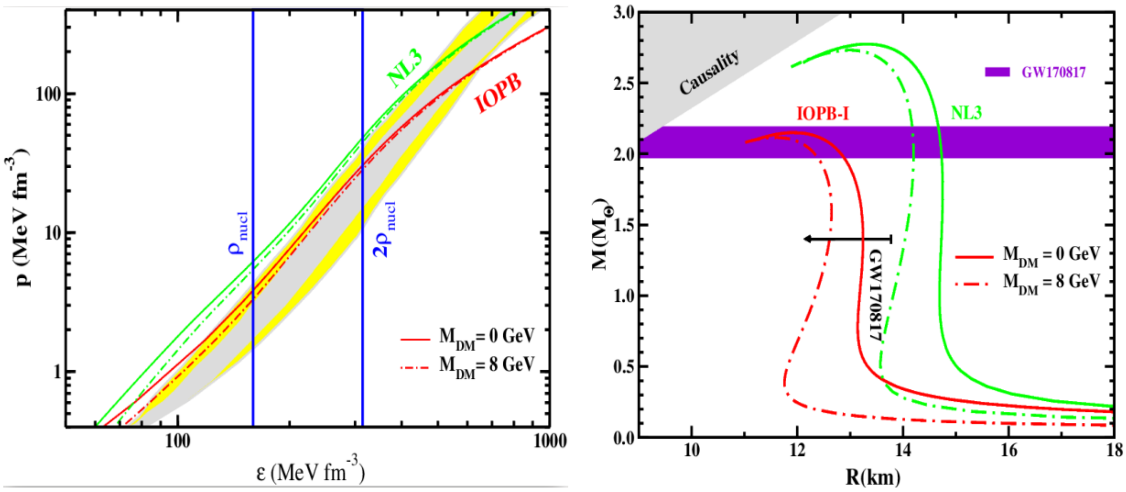

Fig. 1. (color online) (a) The EOSs of NS with (M_{DM} = 8 GeV) and without (M_{DM} = 0 GeV) DM corresponding to IOPB-I [27] and NL3 [28] parameter sets. The grey (yellow) shaded region correspond to the 50% (90%) posterior credible limit from the GW data [34]. (b) The mass-radius relation for an NS corresponding to the EOSs shown in the left panel. The grey shaded region shows the causality region [35]. The recent constraints on the mass [36] and radii [37] of an NS are also shown.

The mass-radius (MR) relations for NS, obtained using the EoS shown in the left panel, are presented in Figure 1(b). The violet band $2.01 \pm 0.04 \lesssim M(M_\odot) \lesssim 2.16 \pm 0.03$ represents the maximum mass range for a non-rotating NS constrained through (pulsars or) GW170817 data [36]. The precisely measured mass of PSR J0348+0432 with the value $(2.01 \pm 0.04) M_\odot$ [40] also satisfies this violet band. These results indicate that the theoretically predicted masses of NSs should reach the limit of $\sim 2.0\ M_\odot$. The black arrow in the figure describes the radius at the canonical mass of an NS [37] with the maximum value $R_{1.4} \leq 13.76$ km. The IOPB-I EoSs with and without DM satisfy the radius range (black arrow) at canonical mass constrained from GW170817 [37]. As expected, the MR curves of an NS go down in the presence of a DM. It is clear from the figure that the NL3 EoSs are ruled out by the GW170817 data due to their stiff nature. While the IOPB-I EoSs with and without DM predict the maximum mass of NS that satisfy the violet band. It is to be noted that on considering the large value of DM wave number, the EoSs for the NL3 set can be significantly reduced to satisfy the GW170817 mass range. It is clear from the figure that the effects of DM are more crucial for masses below the highest mass. In other words, the radius of an NS is reduced corresponding to fix masses of NS other than the maximum masses.

4. Summary and Conclusions

In summary, we have analyzed how DM inside NS core affects an EoS and consequently, the properties of NS. We have assumed that neutralinos, the lightest mass eigen state of WIMPs, are trapped uniformly in the NS core. The neutralinos interact with the baryonic matter of NS through the Higgs exchange. The neutralino and Higgs boson are considered within the NMSSM where the scattering cross-section of the DM particle with nuclei satisfies the DAMA results. The EoSs of NSs are generated using the RMF Lagrangian density with IOPB-I, and NL3 parameter sets. We have found that the presence of DM in NS soften an EoS, which results in lowering the values of NS observables such as mass-radius relation. The effects of DM are significant on the masses other than the maximum masses of NS.

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