Presence of bosonic dark matter in admixed neutron stars

Author: Georgina Xifra Goya
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Àngels Ramos Gómez

Abstract: We study how the presence of bosonic self-interacting dark matter influences the properties of admixed neutron stars. We only consider the gravitational interaction between baryonic and dark matter. We also explore different possibilities for the unknown mass, m_χ, and self-coupling, λ, of the dark matter component, as well as different ratios of the central energy densities of dark and baryonic matter, $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c}$. Two scenarios are found: for $m_\chi = 400$ MeV, the dark matter is contained in the core of the star, which decreases its mass and radius with increasing dark matter fraction, whereas an extended halo of dark matter is formed for $m_\chi = 100$ MeV. The tidal deformability obtained from the gravitational waves of a binary neutron star merger favors the dark matter core scenario and puts severe constraints on the self-coupling value.

I. INTRODUCTION

Nowadays, there is an increasing interest in knowing the nature of dark matter (DM). Many experiments to detect DM particles and study their interaction with nuclei and atoms have been conducted to no avail. Neutron stars (NSs) are compact objects that can capture a considerable amount of DM, thus providing a perfect scenario to learn about possible sources of DM [1].

Recent observations of NSs, such as X-ray timing made by the NICER mission, provided a simultaneous measurement of the mass and radius of neutron stars [2–5], putting stringent constraints on the theoretical models of the nuclear equation-of-state (EoS). The detection of gravitational waves (GW) by the Advanced LIGO and Virgo interferometers, opened up new opportunities to learn about the properties of the dense compact systems [6]. GW signals provide information on the tidal deformability, a relevant observable to consider for constraining the EoS of NSs, as it is responsive to deformation effects induced by the merging of NSs in a binary system, as has been demonstrated from the analysis of the GW170817 event [7].

Neutron stars are mainly composed of neutrons and a lower proportion of protons and electrons. Because of the higher densities at the core of the NSs, nucleons have a high chemical potential favoring their conversion into other particles. There has been a great deal of research done in that regard, as for instance the conversion of nucleons into hyperons and Δ particles in the inner cores [8]. Another possibility is the coexistence of strongly correlated hadronic matter in the NS core and deconfined quark matter at the high densities of the core center, where interactions between quarks are low [6]. GW measurements have also led to emerging models with baryonic matter (BM) and DM in admixed NSs [9].

Similar to BM, DM can be composed of bosonic and fermionic particles. The stability of a self-gravitating system formed by DM fermions without self-interaction can exist due to Fermi pressure, compensating for the gravitational contraction. In the case of DM bosons, this contraction can be counterbalanced with either the principle of uncertainty or the possible self-interaction between them [1].

This project aims to explore the hypothesis of the existence of NSs where BM is admixed with bosonic DM, considering only the gravitational interaction between BM and DM. We will discuss the effect on the NS mass, its visible and gravitational radius and tidal deformability, and will extract some conclusions.

II. FORMALISM

A. Equations of state for BM and DM

Consider a neutron star as an infinite and homogeneous system of neutrons, protons and electrons. The matter in the star obeys the requirement of charge neutrality, meaning the same number of protons as electrons, and conservation of the baryon number. We can find the NS matter composition by imposing β-stability, which is the equilibrium against the weak interaction processes. When densities are close to the nuclear saturation density, $n_0 = 0.16$ fm^{-3}, the conversion of electrons into muons is possible as the chemical potential of the electron reaches the value of the muon mass. More conversions could happen due to weak interactions, but they will not be considered in this work.

We will use a simple parametrization of the energy per baryon of asymmetric nuclear matter at zero temperature from [10]:

$$e = e_0 u \frac{u-2-\delta}{1+\delta u} + S_0 u^\gamma \left(1-2x_p\right)^2 , \qquad (1)$$

where $e_0 = -15.6 \pm 0.2$ MeV is the binding energy per nucleon for symmetric nuclear matter at saturation density, $u = n/n_0$ is the fraction of baryon density to nuclear saturation density, $x_p = n_p/n$ is the proton fraction and S_0 the so-called symmetry energy at saturation. The fitting parameters are δ, S_0 and γ and the best values, tested against a microscopic evaluation of the EoS of nuclear matter, are $\delta = 0.2$, $S_0 = 32$ MeV and $\gamma = 0.6$ [10]. The pressure is obtained from the thermodynamic relation $p = n^2 \partial e/\partial n$, including the leptonic contributions. We note that this EoS will not produce NS maximum masses of $\sim 2\ M_\odot$ as would be required by some observations. However, we have opted by this simple analytic expression since it is easy to apply and the conclusions of this present work remain valid.

Regarding the DM component, we will only consider the bosonic self-interacting case, subject to the self-interacting potential $V(\phi) = \frac{\lambda}{4}|\phi^2|$, where λ is a coupling constant [1]. We will consider the existence of DM at zero temperature forming a perfect Bose-Einstein Condensate. Bosonic DM particles obey a scalar field that is driven by the Klein-Gordon equation.

With these assumptions, an analytical EoS for self-interacting bosonic DM is obtained in a locally flat space-time without anisotropies. It gives pressure, p, depending on energy density, ϵ, as

$$p = \frac{m_\chi^4}{9\lambda}\left(\sqrt{1+\frac{3\lambda}{m_\chi^4}\epsilon} - 1\right)^2, \tag{2}$$

where m_χ is the DM particle mass.

We will consider that the neutron star is composed by a mixture of two perfect fluids, BM and self-interacting DM, that only interact with each other by gravity. We will use the equations for relativistic hydrostatic equilibrium called the Tolman–Oppenheimer–Volkoff equations (TOV), extended to the two-fluid scenario,

$$\frac{dp_\mathrm{B}}{dr} = -\left(p_\mathrm{B} + \epsilon_\mathrm{B}\right)\frac{d\Phi}{dr}, \tag{3}$$

$$\frac{dM_\mathrm{B}}{dr} = 4\pi\epsilon_\mathrm{B} r^2, \tag{4}$$

$$\frac{dp_\mathrm{D}}{dr} = -\left(p_\mathrm{D} + \epsilon_\mathrm{D}\right)\frac{d\Phi}{dr}, \tag{5}$$

$$\frac{dM_\mathrm{D}}{dr} = 4\pi\epsilon_\mathrm{D} r^2, \tag{6}$$

$$\frac{d\Phi}{dr} = \frac{(M_\mathrm{B}+M_\mathrm{D}) + 4\pi r^3\left(p_\mathrm{B}+p_\mathrm{D}\right)}{r\left(r - 2\left(M_\mathrm{B}+M_\mathrm{D}\right)\right)}, \tag{7}$$

which form a set of coupled differential equations. The subscript $_B(_D)$ refers to BM (DM). The total pressure is $p = p_B + p_D$ and the total energy density, $\epsilon = \epsilon_\mathrm{B} + \epsilon_\mathrm{D}$.

These equations have been solved numerically following a finite-differences method. Regarding the initial conditions, we must assume a central pressure for the BM and DM components and impose a vanishing mass at the center of the star, $M_B(r\sim 0) = M_D(r \sim 0) \simeq 0$. For the boundary conditions, we require that the star's outermost radius is the one where both p_B and p_D vanish.

Once the TOV equations are solved, one obtains R_D, R_B, M_D, M_B and the dark matter fraction, $F_\chi = M_\mathrm{D}/M_\mathrm{B}$. It is relevant to differentiate between two possible scenarios. Firstly, the case where the DM is inside the NS ($R_D \leq R_B$) and, secondly, the case corresponding to the formation of a DM halo around the baryonic NS ($R_B < R_D$). Nonetheless, the visible radius is always R_B, but the outermost radius, the gravitational one, depends on the previously mentioned scenarios.

B. Tidal deformability

We can define the dimensionless tidal deformability as

$$\Lambda = \frac{\lambda_t}{M^5} = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5, \tag{8}$$

where k_2 is the Love number, which is given by

$$\begin{aligned} k_2 =& \frac{8C^5}{5}(1-2C)^2[2+2C(y-1)-y] \\ &\times\{2C[6-3y+3C(5y-8)] \\ &+4C^3[13-11y+C(3y-2) \\ &+2C^2(1+y)] + 3(1-2C)^2[2-y \\ &+2C(y-1)]\ln(1-2C)\}^{-1}, \end{aligned} \tag{9}$$

where $C = M/R$ is the compactness of the star and y is related to the quadrupolar metric function [1]. It is obtained solving

$$\begin{aligned} ry'(r) + y(r)^2 + y(r)e^{\lambda(r)}\{1 + 4\pi r^2\big[p(r) \\ -\epsilon(r)\big]\} + r^2 Q(r) = 0, \end{aligned} \tag{10}$$

and evaluating the solution at the star's surface $y(R)$, with the initial condition $y(0) = 2$ [1]. It is important to consider that the tidal deformability depends on the gravitational mass. Thus, the star's surface is the one corresponding to the outermost, or gravitational, radius that will not coincide with the visible radius for stars with a DM halo.

To solve the previous differential equation, we need the parameter $Q(r)$:

$$\begin{aligned} Q(r) = 4\pi e^{\lambda(r)}\left[5\epsilon(r) + 9p(r) + \sum_i \frac{\epsilon_i(r)+p_i(r)}{dp_i/d\epsilon_i}\right] \\ -6\frac{e^{\lambda(r)}}{r^2} - \left(d\nu(r)/dr\right)^2, \end{aligned} \tag{11}$$

where

$$\begin{aligned} e^{\lambda(r)} &= \left[1 - \frac{2M(r)}{r}\right]^{-1}, \\ \frac{d\nu(r)}{dr} \equiv \frac{2\ d\Phi(r)}{dr} &= \frac{2}{r}\left[\frac{M(r)+4\pi p(r) r^3}{r - 2M(r)}\right]. \end{aligned} \tag{12}$$

The differential Eq. (10), with the information provided by Eqs. (11) and (12), is solved numerically and permits obtaining the tidal deformability from Eqs. (8) and (9). Be aware that p, ϵ and $M(r)$ imply the sum over BM and DM components.

III. RESULTS

We will consider two possible scenarios corresponding to a DM core and a DM halo. We will discuss the total mass of the NSs as a function of their outermost radius and the tidal deformability as a function of the total mass of the NSs for two DM particle masses, $m_\chi = 400$ MeV and $m_\chi = 100$ MeV, and for different values of the coupling constant, λ.

A. DM core and DM halo scenarios

The initial conditions fixed in our model for each NS are the central baryonic energy density, $\epsilon_\mathrm{B}^\mathrm{c}$, obtained from the baryonic EoS of the NS, Eq. (1), as $\epsilon_\mathrm{B}^\mathrm{c} = n^c e$ and the corresponding baryonic pressure, p_B^c. Note that the free-Fermi gas contribution of the leptons have also been added to ϵ_B and p_B. The chosen values of the initial conditions for the results presented in this section, are the ones corresponding to a baryonic NS with $M = 1.4\ M_\odot$, namely: $\epsilon_\mathrm{B}^\mathrm{c} = 610$ MeV/fm^3 and $p_B^\mathrm{c} = 96$ MeV/fm^3.

We have represented the energy density as a function of the distance to the center of the star for the BM and DM contributions separately, for two different possible DM particle masses. The results for $m_\chi = 400$ MeV, which

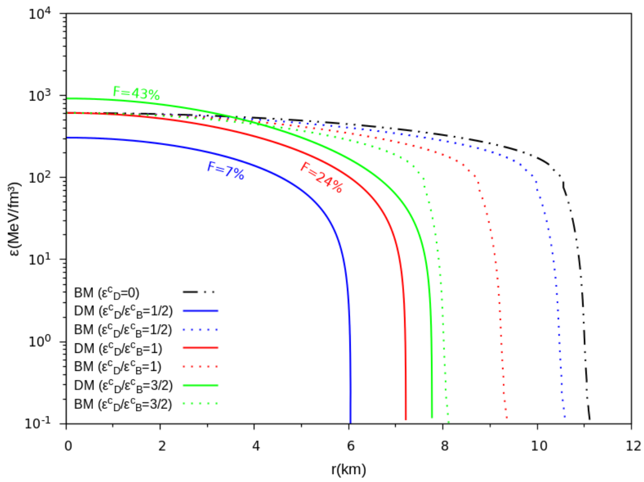

FIG. 1: Energy density as a function of the distance to the center of the star, for $m_\chi = 400$ MeV and $\lambda = \pi$. Results are presented for different ratios $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$ between DM and BM. The final DM fraction is also given. Dashed lines represent BM and solid lines DM.

corresponds to the first possible scenario, are shown in Fig. 1 for different ratios, $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c} = 0, 1/2, 1, 3/2$, which produce increasing values of dark matter fraction, F_χ. In all the chosen cases, we observe that the DM component (solid lines) remains inside the star, concentrated in the core, with a radius of $R_D \lesssim 8$ km. Higher values of the ratio $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$ increase the DM core, while the total radius of the NS, determined by the baryonic matter contribution (dashed lines), decreases, making the NS more compact.

The results for $m_\chi = 100$ MeV are shown in Fig. 2. In this case, the selected ratios, $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c} = 0, 0.020, 0.023, 0.026$ must be much smaller than for $m_\chi = 400$ MeV, in order to avoid DM fractions, F_χ, above 90%. This is not covered in this work because it would imply having NSs almost made of only DM. We observe that

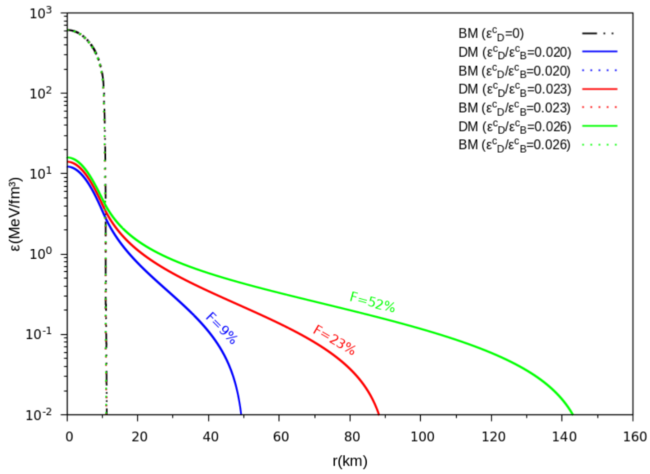

FIG. 2: Energy density as a function of the distance to the star center for $m_\chi = 100$ MeV and $\lambda = \pi$. Results are presented for different ratios $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$ between DM and BM. The final DM fraction is also given. Dashed lines represent BM and solid lines DM.

the DM component is vastly extended compared to BM, an effect that is similar for all three chosen ratios, $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$. This case corresponds to the second scenario, where we have a NS core of BM, similar for all the three ratios, and a DM halo surrounding it and extending over large distances. Like before, the larger the $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$ ratio is, the larger the radius of the DM region, in this case, the DM halo.

B. Mass-radius relation for different stars

In this section we represent the total mass of the NSs as a function of the outermost radius for both scenarios.

In the case of $m_\chi = 400$ MeV, displayed in Fig. 3, we can see that, as the ratio $\epsilon_\mathrm{D}^\mathrm{c}/\epsilon_\mathrm{B}^\mathrm{c}$ increases, for a fixed total mass, the NSs become more compact since the value of the outermost radius reduces. To illustrate this effect with some numerical values, we focus on two different NS masses, $M = 1.4\ M_\odot$ and the maximum mass for each ratio, and extract the corresponding DM fraction and radius. The results are displayed in Table I.

Considering all the cases, we can see that the maximum mass and its radius decrease as the presence of DM increases. The reduction in size with increasing DM component is also seen for the star of mass $M = 1.4\ M_\odot$.

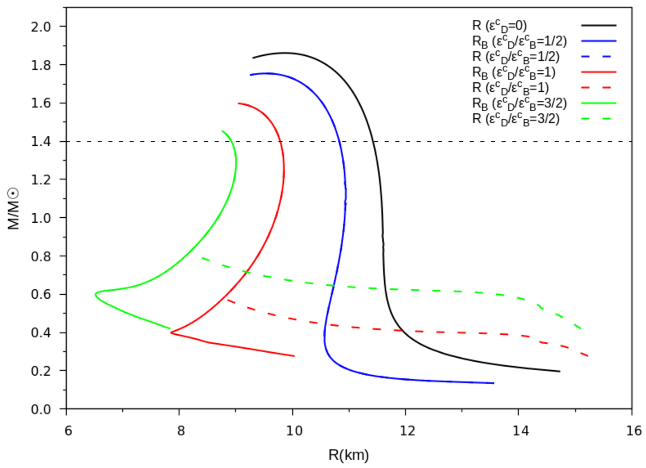

FIG. 3: Total NS mass as a function of the visible radius, R_B (solid lines) for $m_\chi = 400$ MeV. Dashed lines represent the NS mass as a function of the outermost radius, which coincides with R_B for the highest mass values.

TABLE I: Values of the maximum mass and its corresponding DM fraction and radius of admixed NSs for different ratios $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c}$, in the case of $m_\chi = 400$ MeV. The DM fraction and radius for a NS with $M = 1.4\ M_\odot$ have also been included.

$\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c}$	$M_{\rm max}\ (M_\odot)$	$F_{\rm max}(\%)$	$R_{\rm max}$(km)	$F_{1.4}(\%)$	$R_{1.4}$(km)
0	1.84	0	9.30	0	11.42
1/2	1.75	4	9.25	6	10.83
1	1.60	11	9.04	16	9.80
3/2	1.45	18	8.76	21	8.92

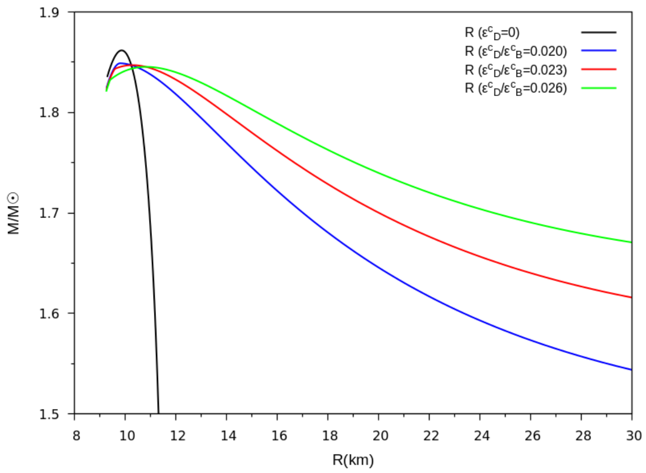

FIG. 4: Total NS mass as a function of the outermost radius, which is R_D for $m_\chi = 100$ MeV. The x-axis is truncated, as the DM halo extends to about 150 km.

However, from Fig. 3, we can observe that some NSs with lower masses have a DM halo even for $m_\chi = 400$ MeV, which correspond to the dashed lines in the figure.

For the $m_\chi = 100$ MeV case, displayed in Fig. 4, we can see that the maximum mass for different fractions is very similar. On the contrary, their corresponding radius, which is determined by the DM component in this case, increases with the DM fraction. We observe that, even at the lowest $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c}$ ratio considered, the minimum mass achieved is never below 1.5 $M_\odot$, which is a rather unrealistic situation.

C. Tidal deformability

We have considered the same two scenarios to study the behavior of the tidal deformability, Λ, as a function of the NS mass. We have also varied the coupling constant, namely $\lambda = \pi/2, \pi, 2\pi$, to explore other possible combinations compatible with the experimental constraints for $M = 1.4\ M_\odot$, $\Lambda_{1.4M_\odot} = 190^{+390}_{-120}$ obtained from the GW170817 event [7]. These constraints are indicated by the double-headed arrow in Fig. 5 and 6, corresponding to $m_\chi = 400$ MeV and $m_\chi = 100$ MeV, respectively.

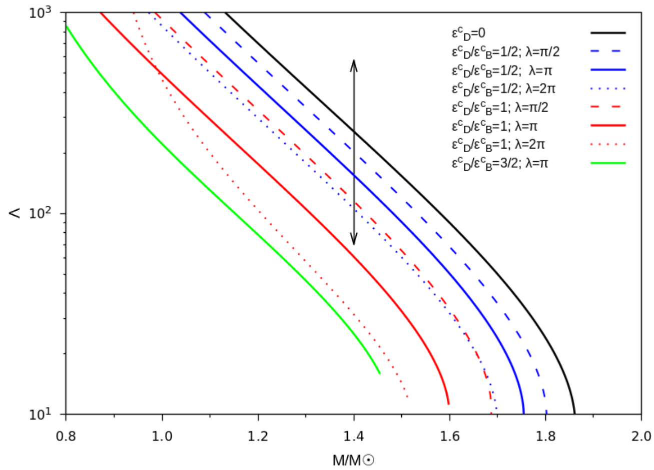

FIG. 5: Tidal deformability as a function of the total mass for different admixed NSs with DM, in the case of $m_\chi = 400$ MeV. The dashed lines correspond to the variation of the coupling constant, λ, for each $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c}$, and the solid lines are the ratios with $\lambda = \pi$.

It is expected that the presence of DM in NSs strongly influences the value of the tidal deformability because it has a high impact on the value of the gravitational radius. Therefore, measurements of Λ could provide the radius of the admixed NSs and the fraction of DM present.

In the case of $m_\chi = 400$ MeV, the accepted values of the tidal deformability for $M = 1.4\ M_\odot$ are compatible with all the coupling constants employed when $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c} = 1/2$, whereas only the value $\lambda = \pi/2$ would be possible for the ratio $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c} = 1$. Values of λ for $\epsilon_{\rm D}^{\rm c}/\epsilon_{\rm B}^{\rm c} = 3/2$ have not been included because none of them fit in the valid range of Λ. For a fixed NS mass, we observe that the tidal deformability decreases with increasing proportion of DM, in line with the size reduction observed in the previous section.

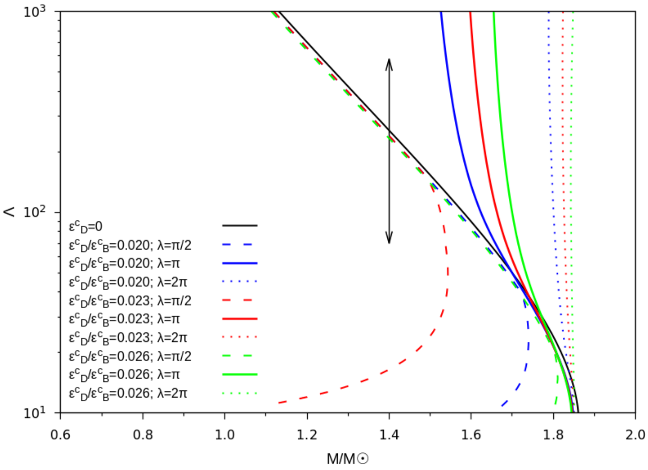

FIG. 6: Tidal deformability as a function of the total mass for different admixed NSs with DM, in the case of $m_\chi = 100$ MeV. The dashed lines correspond to the variation of the coupling constant, λ, for each $\epsilon^c_D/\epsilon^c_B$, and the solid lines are the ratios with $\lambda = \pi$.

For the $m_\chi = 100$ MeV case represented in Fig. 6, we cannot even obtain a NS mass of $M = 1.4\ M_\odot$ for any of the ratios $\epsilon^c_D/\epsilon^c_B$ explored taking $\lambda = \pi$. Decreasing the coupling constant, λ, it is possible to achieve $M = 1.4\ M_\odot$, as seen by the dashed lines in Fig. 6. For a given NS mass, we can observe that the tidal deformability increases very strongly with the presence of DM, an effect that is tied to the substantial increase of the gravitational radius.

IV. CONCLUSIONS

In this work, we have studied the influence of bosonic dark matter in neutron stars regarding two possible scenarios: a DM core and a DM halo obtained with DM particles of mass $m_\chi = 400$ MeV and $m_\chi = 100$ MeV, respectively.

For the DM core case, we have obtained that, as the DM fraction increases, the resulting NSs have a larger DM core but a lower BM radius, making them to be more compact. We have also seen that some NSs with lower masses have a DM halo even for $m_\chi = 400$ MeV.

For the DM halo case, we have obtained BM cores with similar visible radiuses despite the variation of the energy density ratio $\epsilon^c_D/\epsilon^c_B$. In contrast, the DM halo is vastly extended, making the DM component of the NS more dilute. We also observed that the NS mass range obtained in this scenario is rather unrealistic.

Furthermore, we have confirmed the compatibility of both scenarios with the experimental tidal deformability constraints, for some energy density ratios, $\epsilon^c_D/\epsilon^c_B$, and selected coupling constants, λ. In consequence, we can determine that the existence of admixed DM stars is permitted.

To conclude, we confirmed that the influence of dark matter on neutron stars is significant and could have an impact on the interpretation of experimental measurements of neutron stars. For instance, baryonic models whose maximum mass is greater than 2 $M_\odot$ may be discarded by the presence of a significant fraction of dark matter in the core. Moreover, previously rejected baryonic models with tidal deformability slightly above the upper limit, $\Lambda > 580$, may be accepted.

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