Supramassive dark objects with neutron star origin

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Until today, the nature of dark matter (DM) remains elusive despite all our efforts. This missing matter of the Universe has not been observed by the already operating DM direct-detection experiments, but we can infer its gravitational effects. Galaxies and clusters of galaxies are most likely to contain DM trapped to their gravitational field. This leads us to the natural assumption that compact objects might contain DM too. Among the compact objects exist in galaxies, neutron stars are considered as natural laboratories, where theories can be tested, and observational data can be received. Thus, many models of DM have proposed its presence in those stars. In particular, in the present study we focus on two types of dark matter particles, namely, fermions and bosons with a mass range of [0.01–1.5] GeV and self-interaction strength in the range $[10^{-4}–10^{-1}]$ MeV^{-1}. By employing the two-fluid model, we discovered a stable area in the mass-radius diagram of a celestial formation consisting of neutron star matter and DM that is substantial in size. This formation spans hundreds of kilometers in diameter and possesses a mass equivalent to 100 or more times the solar mass. To elucidate, this entity resembles an enormous celestial body of DM, with a neutron star at its core. This implies that a supramassive stellar compact entity can exist without encountering any issues of stability and without undergoing a collapse into a black hole. In any case, the present theoretical prediction can, if combined with corresponding observations, shed light on the existence of DM and even more on its basic properties.

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I. INTRODUCTION

The mystery concerning the nature of dark matter (DM) is still today one of the most challenging subjects in astrophysics and cosmology in general. Two scenarios exist today, either DM is self-annihilating and through this procedure the temperature gradient could be produced, or it is not self-annihilating and then the DM could cluster in blobs. But what is the possibility of having non-self-annihilating DM captured and existing inside astrophysical compact objects?

We know that, among the compact objects existing in galaxies, neutron stars are considered as natural laboratories, where theories can be tested and observational data can be received [1–3]. If it is possible that DM could clump in a sufficient amount with nuclear matter in neutron stars, this mixing could influence the neutron stars' measurable properties (for a recent review, see Ref. [4] and references therein). Thus, many models of DM have proposed its presence in those stars either by studying how they accumulate in stars, how they affect their structure and basic properties, or in more recent studies, how DM can be detected by measurements of tidal polarization in a binary system during the merger process [5–50]. This suggests the exciting possibility that neutron stars could act as laboratories for indirectly measuring DM properties. However, in the above works the study is limited to the case of the accretion of a small percentage of the DM so that its mass is also a small percentage of the total mass of the star. Another important question is how DM could become mixed with ordinary matter in a neutron star. One well studied possibility is through capture as described in Refs. [5–13], as well as many other possibilities of how celestial bodies like neutron stars can accumulate DM and interact with neutron matter—nucleons investigated in previous studies [51–54]. Relevant discussions about the nature, the self-interaction of DM, and dark objects are presented in Refs. [55–68].

It is very useful to treat the mixing between nuclear matter and DM as a two-fluid system, in which the first fluid describes the nuclear matter through an equation of state (EOS) for a neutron star without DM and the second fluid describes the DM. The properties such as the mass and radius of the neutron star can be determined by solving the multifluid Tolman-Oppenheimer-Volkov (TOV) equations [69–71].

Until today, no results were found from DM direct-detection experiments [72–74] and thus have placed strict constraints on the DM to the nucleons' coupling strength. From the perspective of the TOV equations, this is generally taken to mean that the coupling strength its negligibly small and that DM admixed neutron stars are two-fluid systems in which the only interfluid interactions are gravitational [27,50]. Applying the two-fluid model in our study, we came to a surprising possibility of a stable area in the mass-radius (M-R) diagram of a celestial formation consisting of neutron matter and DM that is substantial in size and vast in dimensions. This formation spans hundreds of kilometers in diameter and possesses a mass equivalent to 100 or more times the solar mass. To elucidate, this entity resembles an enormous celestial body of DM, with a neutron star at its core.

This possibility implies that a supramassive stellar compact entity can exist without encountering any issues of stability and without undergoing a collapse into a black hole. It seems that the existence of such objects may demand mass of the DM particle $m_\chi < 1$ GeV or very strong self-interaction strength. The lower is m_χ or/and stronger is the interaction, the higher is the $M_{\rm max}$ and $R_{\rm max}$. However, before we claim something like this in our study, several crucial questions that require convinced answers arise:

(a) How stable are these objects [75]? (b) What is their compactness? (c) Is there a consistency with the values of central pressure of the neutron star that do not exceed the accepted limits of the nuclear EOS? (d) Is the crucial assumption valid for our investigation, that the fermions are stable on the timescale comparable with the lifetime of the Universe ($\tau \geq H_0^{-1} \approx 14$ Gyr, where H_0 is the value of the Hubble constant), or in other words, holds the assumption that the fermions constituting the new compact object are conserved [65]? (e) When and how could the possible supramassive compact objects, made of exotic fermions, be formed? One could speculate that this happened after the inflation era. Large objects could serve as primary seeds clumping nuclear matter after the radiation decoupling era. Perhaps could be possible the formation of some hybrid objects where the exotic fermionic stars might be surrounded by the halo of ordinary matter.

Answering most of the aforementioned questions forms a large part of our research on the subject, especially the stability issue. Also, in addition, the motivation behind our present work is to extend the recent study concerning the trapped DM in the interior of neutron stars and far beyond it. It can be considered that the present study is a first effort toward the extension and generalization of the study done in the papers [65,66], but the main goal is to find stable compact configurations of supramassive objects. In the aforementioned paper, the study focused on compact stars consisting of one kind of fermion (or boson) with arbitrary masses and interaction strengths. The present study includes a similar study by considering a two-fluid model: the one consisting of neutron star matter and the other a DM fluid consisting of fermions or bosons. In general, the calculation of the DM-EOS is a very difficult task due to the great uncertainty that exists in the knowledge about it and mainly concerns the mass and the interaction but also its concentration in the Universe. Thus, only with some assumptions can one proceed with some predictions.

In the present study, we focus on the case of repulsive self-interaction between DM particles (whether fermions or bosons) based on known existing interactions. The repulsive interaction is fundamental to the stability of these objects, especially in the case of bosonic DM. The stronger the repulsive interaction, the greater the proportion of DM that can accumulate in these hybrid objects. It is fundamental for the stability of supramassive objects which is the object of study of this work. There are some justifications for strong repulsive interaction, such as some discrepancies at scales smaller than galaxy clusters could be addressed by a more complicated DM sector including large self-interactions (see Ref. [64] and references therein). Moreover, some recent work suggests that a strong velocity dependence in the interaction, such as would be the case if DM exchanges a light boson, provides the best fit to a range of galactic structures (for a relevant discussion see Ref. [64] and references therein).

We investigate the possibility to gain useful information and constraints of some possible DM candidates as well. Using a two-fluid model for a neutron star admixture with DM particles, we focus both on fermionic and bosonic DM, where their mass and the self-interaction are treated as free parameters. Using this approach, we predict the properties of this new compact object including mass and radius. All of our findings are rigorously guided from the stability conditions of which these new objects must obey.

The paper is organized as follows: In Sec. II, we briefly describe the two-fluid model used, accompanied with subsections dedicated to self-interacting DM equations of state, for fermionic and bosonic DM particles. In Sec. III, we discuss the important topic of stability and, in Sec. IV, we display and discuss the results of the present study. In Sec. V, we finalize our investigation with the concluding remarks.

II. TWO-FLUID MODEL

In the present work, we study compacts objects made by (a) non-self-annihilating DM particles admixed with (b) neutron star matter (including mainly neutrons and a small fraction of protons and electrons). We consider also that the total matter, described by these two fluids, interacts with each other only gravitationally. In order to predict the bulk properties of the objects consisting of the aforementioned two fluids, one has to solve the coupled Tolman-Oppenheimer-Volkov equations (two for each fluid) simultaneously. These four equations are defined below [69,70]:

$$\frac{dP_{\rm NS}(r)}{dr} = -\frac{G\mathcal{E}_{\rm NS}(r)M(r)}{c^2r^2}\left(1+\frac{P_{\rm NS}(r)}{\mathcal{E}_{\rm NS}(r)}\right) \times \left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}, \quad (1)$$

$$\frac{dM_{\rm NS}(r)}{dr} = \frac{4\pi r^2}{c^2}\mathcal{E}_{\rm NS}(r), \quad (2)$$

$$\frac{dP_{\rm DM}(r)}{dr} = -\frac{G\mathcal{E}_{\rm DM}(r)M(r)}{c^2r^2}\left(1+\frac{P_{\rm DM}(r)}{\mathcal{E}_{\rm DM}(r)}\right) \times\left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}, \quad (3)$$

$$\frac{dM_{\rm DM}(r)}{dr} = \frac{4\pi r^2}{c^2}\mathcal{E}_{\rm DM}(r), \quad (4)$$

where also $M(r) = M_{\rm NS}(r) + M_{\rm DM}(r)$ and $P(r) = P_{\rm NS}(r) + P_{\rm DM}(r)$ (the subscripts NS and DM stand for the neutron star and dark matter, respectively).

III. NEUTRON STAR MATTER AND DARK MATTER EQUATIONS OF STATE

In the present work, in order to describe the neutron star matter, we use the equation of state derived by Akmal *et al.* [76], in particular, the model A18 + UIX. This is an EOS with microscopic origin and its predictions are in very good agreement with both the measured maximum masses (see PSR J1614 − 2230 [77], PSR J0348 + 0432 [78], PSR J0740 + 6620 [79], and PSR J0952 − 0607 [80] pulsar observations for the possible maximum mass) and some astrophysical constraints for radii (see the GW170817 event [81]). It is worth to notice here that the present study mainly focuses on the EOS of DM and its properties. Nevertheless, the use of a realistic EOS for neutron stars provides a guarantee for the reliability of our results.

Now, concerning the DM particles, we consider that they are relativistic fermions, which interact with each other through a repulsive force. In particular, we consider Yukawa-type interaction on the form [64]

$$V(r) = \frac{g_\chi^2(\hbar c)}{4\pi r}\exp\left[-\frac{m_\phi c^2}{\hbar c}r\right], \quad (5)$$

where g_χ is the coupling constant and m_ϕ is the mediator mass. It is worth to mention that, in the majority of the similar studies, the DM is considered as a noninteracting gas of fermions. However, as we will see in the present study, the role of interaction is decisive for the creation and stability of supramassive objects. The contribution on the energy density of the self-interaction is given by

$$\mathcal{E}_{SI}(n_\chi) = \frac{y^2}{2}(\hbar c)^3 n_\chi^2, \quad (6)$$

where $y = g_\chi/m_\phi c^2$ (in units MeV^{-1}). In this case, the total energy density of the DM particles is given by [65]

$$\mathcal{E}_{\rm DM}(n_\chi) = \frac{(m_\chi c^2)^4}{(\hbar c)^3 8\pi^2}\left[x\sqrt{1+x^2}(1+2x^2) - \ln\left(x+\sqrt{1+x^2}\right)\right] + \frac{y^2}{2}(\hbar c)^3 n_\chi^2. \quad (7)$$

The corresponding pressure is calculated straightforwardly by using the definition

$$P_{\rm DM}(n_\chi) = n_\chi\frac{d\mathcal{E}_{\rm DM}(n_\chi)}{dn_\chi} - \mathcal{E}_{\rm DM}(n_\chi) \quad (8)$$

and is given by

$$P_{\rm DM}(n_\chi) = \frac{(m_\chi c^2)^4}{(\hbar c)^3 8\pi^2}\left[x\sqrt{1+x^2}(2x^2/3-1) + \ln\left(x+\sqrt{1+x^2}\right)\right] + \frac{y^2}{2}(\hbar c)^3 n_\chi^2, \quad (9)$$

where m_χ is the particle mass and

$$x = \frac{(\hbar c)(3\pi^2 n_\chi)^{1/3}}{m_\chi c^2}.$$

The total energy density and pressure of the two-fluid mixing, considering that the contribution of neutron star matter is defined as $\mathcal{E}_{\rm NS}(n_b)$ and $P_{\rm NS}(n_b)$, where both are functions of the baryon density n_b (for more details see Ref. [76]), are given simply by the following sums:

$$\mathcal{E}(n_b, n_\chi) = \mathcal{E}_{\rm NS}(n_b) + \mathcal{E}_{\rm DM}(n_\chi), \quad (10)$$

$$P(n_b, n_\chi) = P_{\rm NS}(n_b) + P_{\rm DM}(n_\chi). \quad (11)$$

With the aim of enriching the possible DM candidates, we will also consider the case where it consists of bosonic particles. We use in this case the EOS provided in Ref. [66] and used recently in Ref. [38], where the energy density and pressure are given, respectively, by

$$\mathcal{E}_{\rm DM}(n_\chi) = m_\chi c^2 n_\chi + \frac{u^2}{2}(\hbar c)^3 n_\chi^2,$$
$$P_{\rm DM}(n_\chi) = \frac{u^2}{2}(\hbar c)^3 n_\chi^2, \quad (12)$$

where the quantity $u = g_\chi/m_\phi c^2$ (in units MeV^{-1}) defines the strength of the interaction in analogy with the case of fermions. It is worth emphasizing here that, as it was found first in Ref. [82], the structure of the boson stars (mass and radius), even for low values of the self-interaction, can differ radically compared to the case of noninteracting matter. Then, by suitable choice of the interaction, the masses of the corresponding boson stars could be comparable to the Chandrasekhar mass of fermion stars. These boson stars could arise during the gravitational condensation of bosonic DM in the early Universe [82].

IV. STABILITY

The most usual method to study the stability is to consider small radial perturbations of the equilibrium configuration by solving the Sturm-Liouville eigenvalue equation, which yields eigenfrequencies ω_n [1]. The eigenfrequencies of the different modes form a discrete hierarchy $\omega_n^2 < \omega_{n+1}^2$ $n = 0, 1, 2\ldots$, with ω_n^2 being real numbers [83]. A negative value of ω_n^2 leads to an exponential growth of the radial perturbation and collapse of the star. Only when all eigenfrequencies are positive will the star be stable [84] (see also the relevant discussion in Ref. [83]). A relevant study of pulsation equations for compact stars made up of an arbitrary number of perfect fluids has been developed recently in Ref. [85].

In the present work, we employ the method developed by Henriques *et al.*, which was used for the study of boson-fermion stars [86–88]. This method has been elaborated and extended through the years for similar studies [75,89–91]. According to this method, the stability analysis is carried out by examining the behavior of baryons and DM particles, yet fixing the total mass M values. In particular, the stability curve is formed with the pair of central values of pressures $\{P_c^{\rm NS}, P_c^{\rm DM}\}$ exactly at the point where the number of particles reached the minimum and maximum values. These critical curves identify the transition from linear stable and unstable with respect to perturbations that conserve the mass and the particle number, hence fulfill the following conditions [89]:

$$\left(\frac{\partial N_b}{\partial P_c^{\rm NS}}\right)_{\rm M=const} = \left(\frac{\partial N_\chi}{\partial P_c^{\rm NS}}\right)_{\rm M=const} = 0,$$
$$\left(\frac{\partial N_b}{\partial P_c^{\rm DM}}\right)_{\rm M=const} = \left(\frac{\partial N_\chi}{\partial P_c^{\rm DM}}\right)_{\rm M=const} = 0, \qquad (13)$$

where N_b and N_χ are the numbers of baryons and DM particles, respectively. These numbers are given by the expression [27]

$$N_i = 4\pi \int_0^{R_i} n_i(r) \frac{r^2 dr}{\sqrt{1 - 2GM(r)/rc^2}}, \qquad i = b, \chi, \qquad (14)$$

where R_i is the radius of the corresponding fluid. Now, the stability analysis can be summarized as follows [89]: Sequences of stable equilibrium configurations that start from a purely DM star have the feature that the number of DM particles N_χ first decreases (as a function of the central pressures $P_c^{\rm DM}$ or $P_c^{\rm NS}$) down to the critical point and the number of baryons N_b increases. In general, equilibrium sequences can consist of continuous regions of stability and instability. In this case, therefore, we can have more than one branch of stability.

V. RESULTS AND DISCUSSION

What should be emphasized first is the basic difference between finding the stability of the two-fluid model and that of the one-fluid model. Thus, while in the one-fluid model, the finding of stability is limited to a curve on an M-R diagram, in the two-fluid model the curve has essentially been replaced by a surface on a corresponding diagram. This is due to the use of three independent parameters, that is, the DM mass m_χ, the strength of the self-interaction, and the fraction $f = P_{\rm DM}^c / P_{\rm NS}^c$ of the central densities. Basically, all of them are unconstrained. In the present study, we focus on a few stable configurations that prove and confirm our hypothesis for the existence of supramassive dark objects in the Universe, with neutron star origin.

It is proper to clarify here that, by supramassive compact objects, we mean those whose compactness $C = GM/Rc^2$ is comparable to those of neutron stars, i.e., $C \in [0.05\text{–}0.30]$. In any case, the effects of the general relativity are important and moreover the curvature of spacetime in the neighborhood of these objects is noticeable. This has the consequence that they can be perceived in this way.

It is worthwhile to notice that the majority of the relevant studies dedicated to the specific cases, where the hybrid objects consist mainly of hadronic matter and a small fraction of DM, lead to configurations with mass similar to neutron stars, but with the DM halo extended even to a few tens of kilometers.

To be more specific, in the present study, we investigated the possibility of very massive hybrid objects with masses ranging from tens to even hundreds of solar masses and radii also for tens to even thousands of kilometers. In principle, there is no *ad hoc* limitation to these configurations except for the stability condition. Some additional constraints can be introduced by the absorption rate of DM (in particular of the DM particle-neutron scattering cross section), in a neutron star and the associated timescales, or by the density distribution of DM in the Universe. Additionally, compact DM objects with large masses and corresponding radii have already been studied (for a systematic review, see Refs. [65,66]). The motivation of the present work is to study the corresponding supramassive compact objects, where a neutron star sits at their center triggering the accretion of DM in and around it.

In general, as already pointed out, calculating the stability of these objects is a computationally difficult and time-consuming problem. Since we are initially interested in proving the stability of these objects, we will choose some special cases whose stability we will confirm. A more systematic and extensive study may determine the stable range (concerning the mass and radius) of such objects as a function of the mass, interaction, and DM contribution to the central pressure.

Now, since the DM contributes a larger fraction on the total mass, some useful approximation, concerning the total number of fermions in the case of the maximum mass configurations, can be inferred by applying the analytical solution of the TOV equations, that is, the Tolman VII solution [92]. According to this solution, the energy density varies in the interior of the star according to the rule $\mathcal{E}(r) \sim (1 - (r/R)^2)$. In this case the binding energy $BE/c^2 = N_\chi m_x - M$ is given by [93]

$$\frac{BE}{Mc^2} = f(C), \qquad f(C) = \frac{11}{21}C + \frac{7187}{18018}C^2 + \cdots, \tag{15}$$

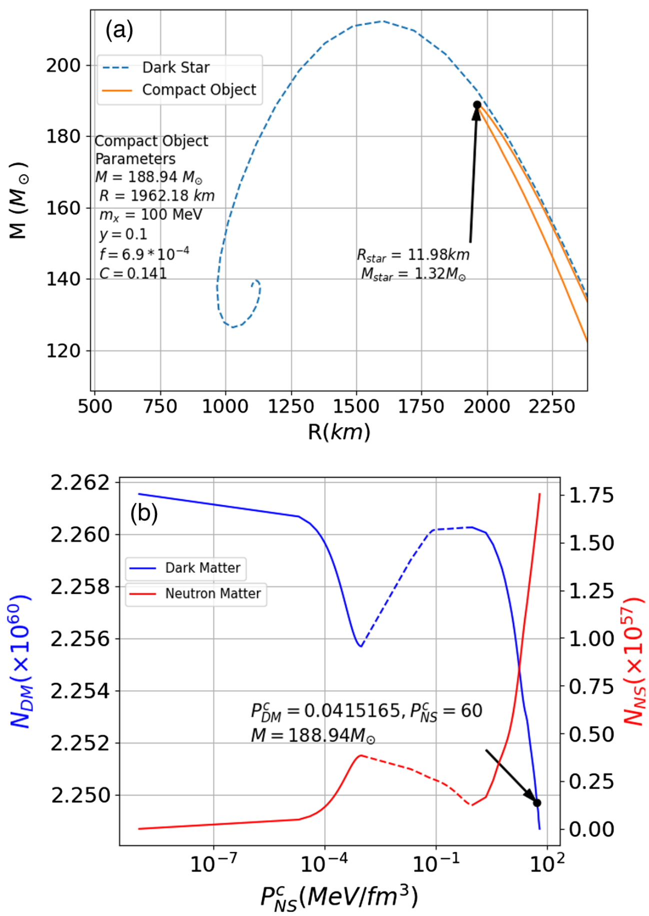

FIG. 1. (a) The M-R dependence for the case of pure fermionic DM (dashed line) and compact object (solid line) of DM fermion with mass $m_\chi = 100$ MeV [the rest properties, that is, the interaction strength y (in MeV^{-1}), the fraction f, and the compactness C also displayed in the figure). The arrow indicates the specific case of a compact object with $M = 188.94 M_\odot$ and $R = 1962.18$ km (corresponding to a neutron star with mass $M = 1.32 M_\odot$ and radius $R = 11.98$ km in the center). (b) The dependence of the number of DM particles $N_{\rm DM}$ and baryons $N_{\rm NS}$ on the pressure $P^c_{\rm NS}$ for equilibrium configurations of equal mass $M = 188.94 M_\odot$. The solid lines indicate the stable branches, while the dashed lines are the unstable ones. The arrow corresponds to the specific stable configuration, which is indicated also by an arrow in (a).

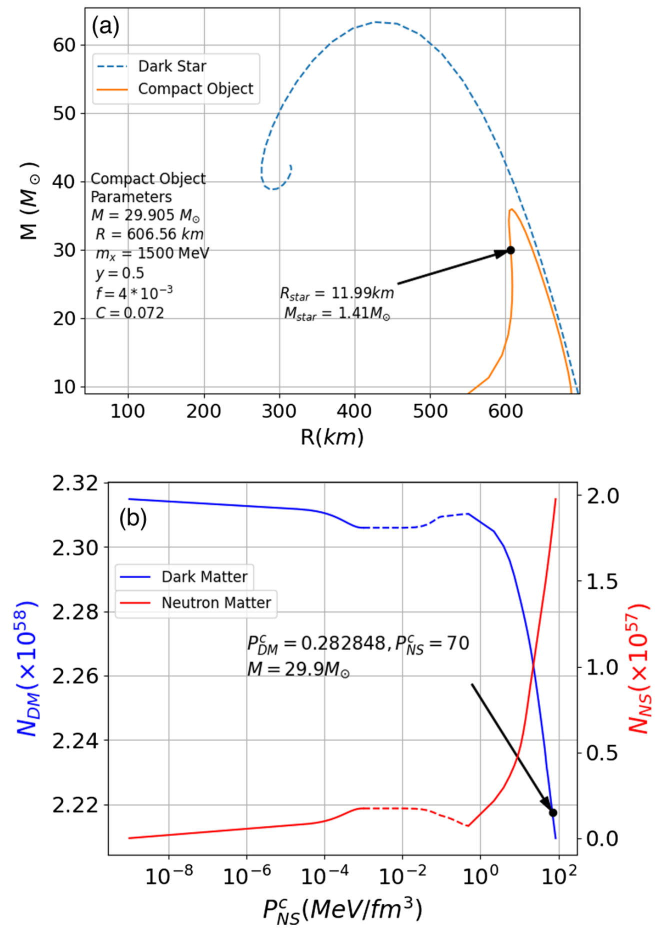

FIG. 2. (a) The same as in Fig. 1(a) for a DM fermion with mass $m_\chi = 1500$ MeV. We indicate the specific case $M = 29.905 M_\odot$ and $R = 606.56$ km, which include a neutron star in the center with mass $M = 1.41 M_\odot$ and $R = 11.99$ km. (b) The same as in Fig. 1(b).

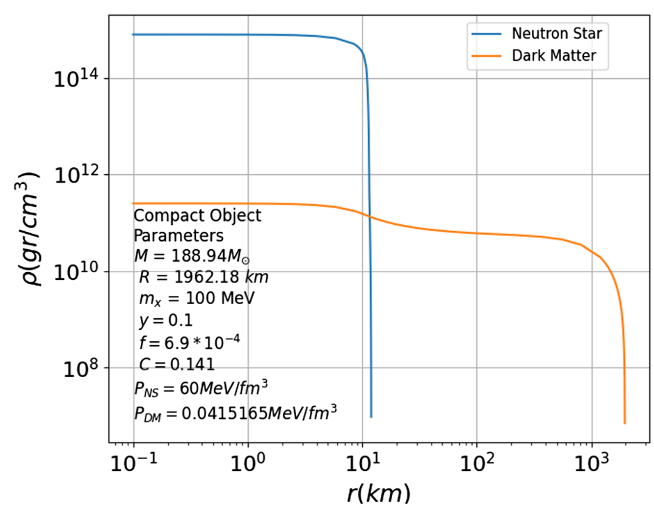

FIG. 3. The density of DM and neutron star matter as a function of the distance r for the specific configuration denoted in Fig. 1(a).

where $f(C)$ is a function of the compactness of the star $C = GM/Rc^2$. After some algebra, we get the following approximation for the critical number of fermions that corresponds to the stability limit,

$$N_\chi^{\rm cr} = 1.144 \times 10^{51}(0.627 + 0.27\tilde{y})(1 + f(C_{\rm cr})) \times \left(\frac{100\ {\rm GeV}}{m_\chi}\right)^3, \quad (16)$$

where $C_{\rm cr} = GM_{\rm max}/R_{\rm min}c^2$ (for a relevant discussion, see also Ref. [62]). The values $M_{\rm max}$ and $R_{\rm min}$ are taken from Ref. [65], where

$$M_{\rm max} = (0.384 + 0.165\tilde{y}) \times \left(\frac{\rm GeV}{m_\chi}\right)^2 \times 1.632 M_\odot, \quad (17)$$

$$R_{\rm min} = (3.367 + 0.797\tilde{y}) \times \left(\frac{\rm GeV}{m_\chi}\right)^2 \times 2.410\ ({\rm km}), \quad (18)$$

where $\tilde{y}$ is a dimensionless quantity, related to the interaction that runs in the range $10^{-2} - 10^3$ [65] and related to the parameter y according to $\tilde{y} = (m_\chi c^2/\sqrt{2})y$.

The expression (16) is similar to that found in Ref. [25] (using a Newtonian approach), where

$$N_\chi^{\rm cr} \simeq 1.8 \times 10^{51}\left(\frac{100\ {\rm GeV}}{m_\chi}\right)^3. \quad (19)$$

When the number of DM particles, concentrated in a neutron star, exceeds the Chandrasekhar limit, the compact object collapses into a black hole [25]. It is concluded then that the observations of old neutron stars can be used as a laboratory to constrain the DM-neutron scattering cross section [25].

In Fig. 1(a), we display the M-R dependence for the case of a pure fermionic DM object and DM-neutron star mixture object (indicated as compact object) for $m_\chi = 100$ MeV, $y = 0.1$ (in MeV^{-1}), and fraction $f = 6.9 \times 10^{-4}$.

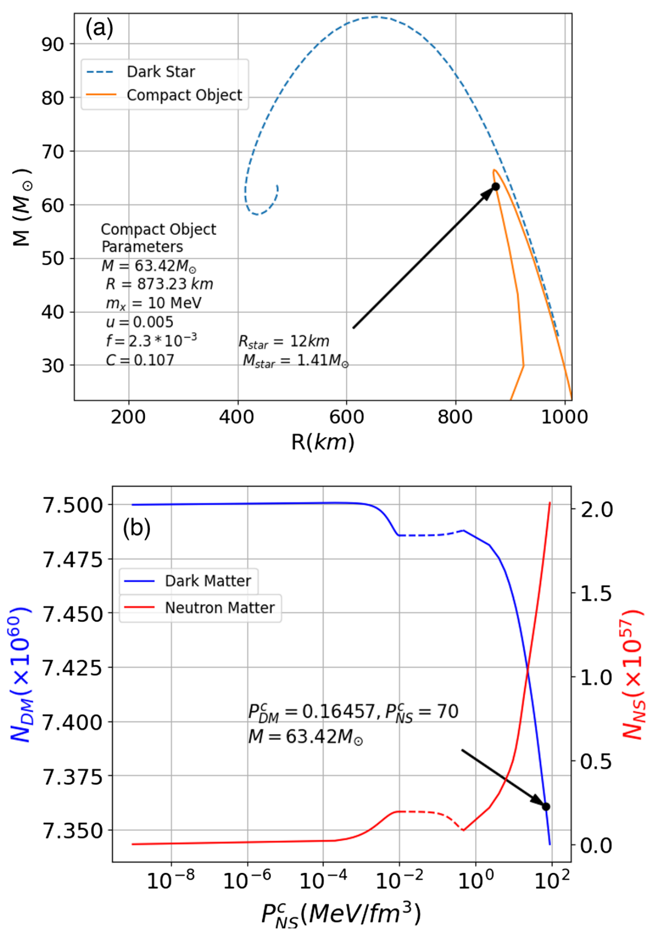

FIG. 4. (a) The M-R dependence for the case of pure bosonic DM (dashed line) and compact object (solid line) of a DM boson with mass $m_\chi = 10$ MeV. The arrow indicates the specific case where $M = 63.42 M_\odot$ and $R = 873.23$ km (corresponding to a neutron star with mass $M = 1.41 M_\odot$ and radius $R = 12$ km). (b) The same as in Fig. 1(b).

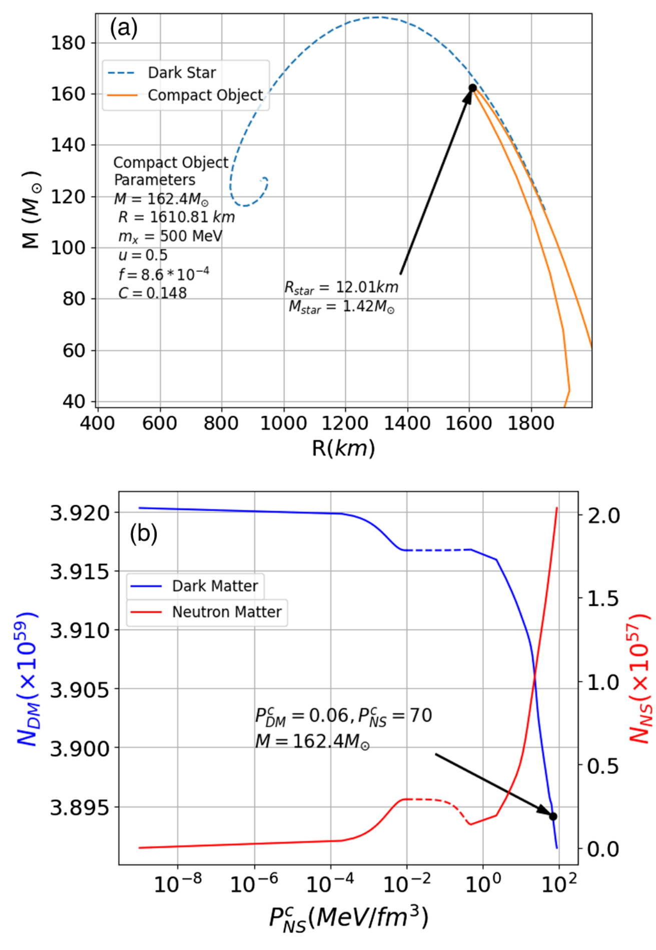

FIG. 5. (a) The same as in Fig. 4(a) for a DM boson with mass $m_\chi = 500$ MeV. We indicate the specific case where $M = 162.4 M_\odot$ and $R = 1610.81$ km (corresponding to a neutron star with mass $M = 1.42 M_\odot$ and radius $R = 12.01$ km). (b) The same as in Fig. 1(b).

Obviously there is an infinite number of possible configurations, but we focus on the indicated case $M = 188.94M_{\odot}$ and $R = 1962.18$ km with a neutron star $M = 1.32M_{\odot}$ and $R = 11.98$ km in the center. This object, with compactness $C = 0.141$, is indicated with an arrow. In Fig. 1(b), we confirm the stability of this object, with the help of the $P^c_{\rm NS} - N_{\rm DM,NS}$ diagram. The object, which is indicated also with the arrow, belongs to the second stable branch of the $P^c_{\rm NS} - N_{\rm DM,NS}$ diagram.

In Fig. 2(a), we investigate the case of a heavier DM particle with mass $m_{\chi} = 1500$ MeV. We select the indicated case $M = 29.905M_{\odot}$ and $R = 606.56$ km with a neutron star $M = 1.41M_{\odot}$ and $R = 11.99$ km in the center. Again, in Fig. 2(b), we confirm the stability of this object.

Moreover, in Fig. 3 we display the dependence of the pressure (which corresponds to neutron star matter and DM) on the radius r for the specific configuration denoted in Fig. 2(a).

In Fig. 4(a), we consider the case of a bosonic DM particle with mass $m_{\chi} = 10$ MeV. We select the specific configuration that corresponds to total mass $M = 63.42M_{\odot}$, $R = 873.23$ km (with a neutron star with mass $M = 1.41M_{\odot}$ and radius $R = 12$ km). This compact object is stable, as one can see in Fig. 4(b).

In Fig. 5(a) we select the case of a DM boson with mass $m_{\chi} = 500$ MeV. We select the configuration where $M = 162.4M_{\odot}$, $R = 160.81$ km (with a neutron star with mass $M = 1.42M_{\odot}$ and radius $R = 12.01$ km). This object is stable as confirmed in Fig. 5(b).

In the previous cases we focused on the case of supramassive objects. However, the case of a compact object in the region of the mass gap between neutron stars and black holes is also of great interest in astrophysics (for a recent discussion, see Ref. [94]). According to the findings of the present paper, there may be a stable configuration of objects with mixing of DM with neutron stars in this region. To be more specific, we display in Fig. 6(a) the M-R dependence for the case of a pure fermionic DM object and DM-neutron star mixture object (indicated as compact object) for $m_{\chi} = 100$ MeV, $y = 0.0001$, and fraction

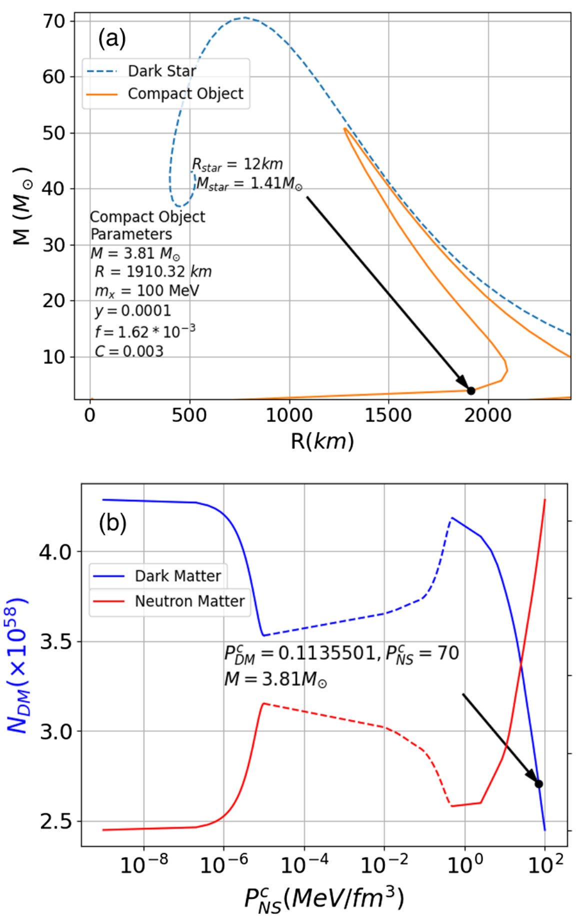

FIG. 6. (a) The same as in Fig. 1 (for a DM fermion with mass $m_{\chi} = 100$ MeV). We indicate the specific case $M = 3.81M_{\odot}$ and $R = 1910.32$ km, which includes a neutron star in the center with mass $M = 1.41M_{\odot}$ and $R = 12$ km. (b) The same as in Fig. 1(b).

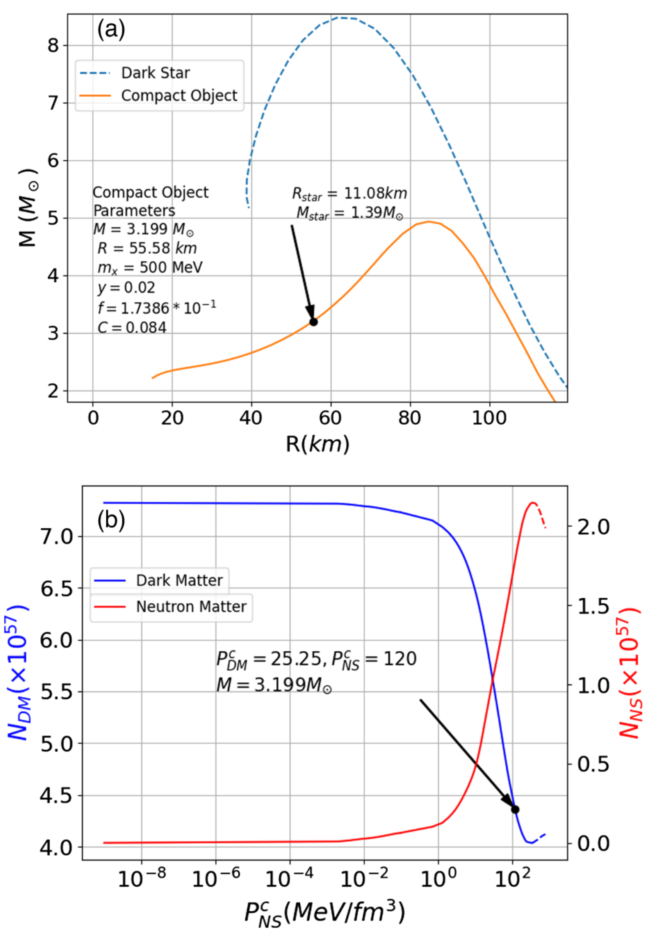

FIG. 7. (a) The same as in Fig. 1(a) for a DM fermion with mass $m_{\chi} = 500$ MeV. We indicate the specific case $M = 3.199M_{\odot}$ and $R = 55.58$ km, which includes a neutron star in the center with mass $M = 1.39M_{\odot}$ and $R = 11.08$ km. (b) The same as in Fig. 1(b).

$f = 1.6 \times 10^{-3}$. We focus on the indicated case $M = 3.81 M_{\odot}$ and $R = 1910.32$ km with a neutron star $M = 1.41 M_{\odot}$ and $R = 12$ km in the center. This is an object with compactness $C = 0.003$. In Fig. 6(b), we confirm the stability of this object, with the help of the $P^c_{\mathrm{NS}} - N_{\mathrm{DM,NS}}$ diagram.

Finally, in Fig. 7(a), we investigate the case of a heavier DM particle with mass $m_\chi = 500$ MeV. We select the indicated case $M = 3.199 M_{\odot}$ and $R = 55.58$ km with a neutron star $M = 1.39 M_{\odot}$ and $R = 11.08$ km in the center. Again, in Fig. 7(b), we confirm the stability of this object.

From the above study, it is clear that the existence of objects in the mass-gap region can be justified if one takes into account a suitable combination of DM parameters. These objects may resemble neutron stars but have a different structure and composition.

VI. CONCLUDING REMARKS

We investigated possible supramassive dark objects, stable configurations with neutron star origin. We used the EOS of self-interacting fermions and bosons and one of the most reliable EOS for the neutron star matter. Unlike other similar studies, we did not focus on the cases of neutron stars surrounded by a DM halo of a few kilometers and of low relative mass contribution of the DM. We found that the number of these configurations is unlimited (we just select few of them to present), which are also stable against perturbations. This means that they may exist in the Universe. An extension of this study is to include interactions between DM particles and baryons. This is an interesting perspective to be studied in future work.

In the present work, we do not intend to answer the question of how these objects are created. There are few speculations related to this question. A relevant discussion is provided in Ref. [83], for example, the accretion mechanism of DM into neutron stars as by the primordial formation of DM clumps surrounded by ordinary matter. Another possibility is having a dark compact object originating from DM perturbations growing from primordial overdensities. Finally, another possibility is copious production and capture of DM in the core-collapse supernova of a neutron star progenitor [27]. In any case, there is not any strong theoretical prediction that argues strongly against the creation of these supramassive DM objects. Some other works [52] also suggest that it could be possible, without assuming any priors on DM parameters, to have gravitational wave detection of nonannihilating heavy DM. This detection will cover the entire parameter space that explains the missing pulsars and go well below the neutrino floor.

The last proposition brings us to the most critical question: how we could locate them (as far as the objects are concerned). The most powerful tool in this case is the gravitational lensing that is based on space-time distortion which is caused by these objects. Another possibility is to detect a possible merger event, by the well-known detectors (LIGO-Virgo-KAGRA Collaboration), which includes two cases: (a) merger between two dark compact objects or (b) merger between one of them and another compact object including a pure neutron star or black hole. The signal of the corresponding gravitational waves will transfer useful information for the structure of these objects [95]. Another possible scenario to detect these objects, which was proposed in Ref. [89], could be that of a dark star in the second branch that accreted a low amount of neutron star matter and that lost part of the bosonic matter due to accretion onto a second more compact object, which led the star to the first unstable branch and triggered the dispersion mechanism [89].

In Ref. [68] the authors present in a systematic way the creation of giant dark stars in a baryonic mass environment. In particular, they claim that, since the dark stars reside in a large reservoir of baryons, the baryons can start to accrete onto the dark stars. The evolution of dark stars starts from their inception at $1 M_{\odot}$ and, as they accumulated mass from environment, grow to become supermassive stars, possibly as large as $10^7 M_{\odot}$ [68]. Finally, as pointed out in Ref. [4] (for more details see also references therein), exotic compact objects with near-Schwarzschild compactness may exist and constitute DM, e.g., some classes of boson stars, Q-balls, nontopological solitons, and ultracompact minihalos.

Moreover, in the present work we explored the interesting possibility that some of recent measurements of very massive neutron stars [96–98] and stars in the region of black hole–neutron stars mass gap can be attributed to the capture of DM by neutron stars. In any case, further theoretical studies and precise astrophysical observations will help to shed light on this open issue.

The presented study was the first attempt of investigating supramassive compacts objects with neutron star origin, guided by the stability criterion. We intend to extend our investigation focusing on the mass-gap region and to perform a categorization of our studies.

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