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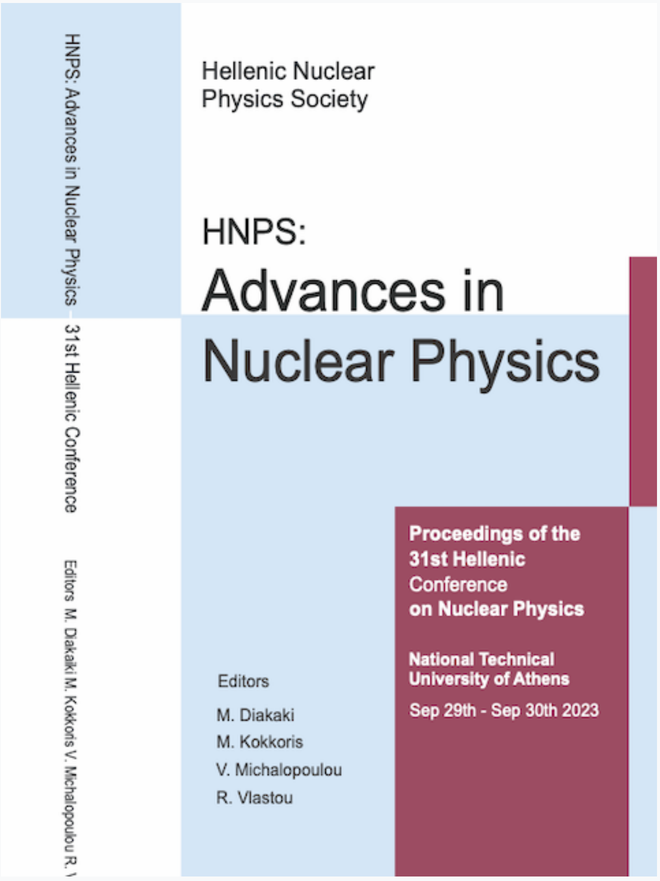

Supramassive dark objects with neutron star origin

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Supramassive dark objects with neutron star origin

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Abstract Till today, the nature of dark matter remains elusive despite all our efforts. This missing matter of the universe has not been observed by the existing dark matter direct-detection experiments, but we can infer its gravitational effects. Galaxies and clusters of galaxies are most likely to contain dark matter trapped to their gravitational field. This leads us to the natural assumption that compact objects might contain dark matter 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 dark matter have proposed its presence in those stars. By employing the two fluid model, we discovered a stable area in the M-R diagram of a celestial formation consisting of neutron and dark matter 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 that of our sun. To elucidate, this entity resembles an enormous celestial body of dark matter, 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 dark matter and even more on its basic properties.

Keywords Neutron Star, Dark Matter, Two Fluid Model, Supermassive Object

INTRODUCTION

It is well-known that among the compact objects found in galaxies, neutron stars are considered as natural laboratories, where theories can be tested, and observational data can be gathered [1]. If possible for dark matter (DM) to clump sufficiently with nuclear matter in neutron stars, then this mixing could influence the measurable properties of neutron stars. Thus, many models of DM have proposed its presence in those stars [2-5]. This suggests that neutron stars could act as laboratories for indirectly measuring DM properties. 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 Ref. [6]. Also many other possibilities of how celestial bodies like neutron stars can accumulate DM and interact with neutron matter - nucleons are investigated in previous studies [7-8].

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. Properties such as the mass and radius of the neutron star can be determined by solving the multi-fluid Tolman-Oppenheimer-Volkoff (TOV) equations [9].

Applying the two fluid model in our study, we came to a surprising possibility of a stable area in the M-R diagram of a celestial formation consisting of neutron and DM that is substantial in size and vast in dimensions (for a detailed analysis see Ref.[10]). This formation spans hundreds of kilometers in diameter and possesses a mass equivalent to 100 or more times that of our sun. 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 DM particles $m_\chi < 1$~GeV or very strong self-interaction strength. The lower the m_χ

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or/and the stronger the interaction the higher the M_{max} and R_{max}. But before we claim something like this in our study, several crucial questions that need convincing answers arise: a) How stable are these objects [11], b) which 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) does the crucial assumption of our investigation, that the fermions are stable on the time scale 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) remain valid or in other words, does the assumption that the fermions constituting the new compact object are conserved, hold [12] e) when and how the possible supramassive compact objects, made of exotic fermions, could 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. Then perhaps we could talk about the formation of certain hybrid objects in which exotic fermion stars could be surrounded by halos of regular matter.

Answering most of the aforementioned questions, forms a large part of our research on the subject, especially the stability issue. In addition, the motivation in 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 as a first effort towards the extension and generalization of the work done in Refs [12-13]. The main goal is to find stable compact configurations of supramassive objects. In Refs. [12-13] the efforts are focused on compact stars consisting of one kind of fermions (or bosons) with arbitrary masses and interaction strengths. The present study considers a two fluid model consisting of neutron star matter and a DM fluid composed of either fermions or bosons.

We investigate the possibility to gain useful information and constraints of some possible DM candidates as well. Using a two-fluid model for neutron stars 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 our findings are rigorously guided from the stability conditions that these new objects must obey.

THE THEORETICAL 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, interact 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 (TOV) equations (two for each fluid) simultaneously. These four equations are defined below

$$\frac{dP_{NS}}{dr} = -\frac{GE_{NS}(r)M(r)}{c^2r^2}\left(1+\frac{P_{NS}(r)}{E_{NS}(r)}\right)\left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}$$
$$\frac{dM_{NS}(r)}{dr} = \frac{4\pi r^2}{c^2}E_{NS}(r)$$
$$\frac{dP_{DM}}{dr} = -\frac{GE_{DM}(r)M(r)}{c^2r^2}\left(1+\frac{P_{DM}(r)}{E_{DM}(r)}\right)\left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}$$
$$\frac{dM_{DM}(r)}{dr} = \frac{4\pi r^2}{c^2}E_{DM}(r)$$

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

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For fermionic dark matter we used the following equation of state [12]:

$$E_{DM}(n_x) = \frac{(m_x c^2)^4}{(hc)^3 8\pi^2}\left[x\sqrt{1+x^2}(1+2x^2) - \ln\left(x+\sqrt{1+x^2}\right)\right] + \frac{y^2}{2}(hc)^3 n_x^2 \ ,$$

where $y = \frac{g_x}{m_\varphi c^2}$ is the strength of the interaction. The pressure by definition is:

$$P_{DM}(n_x) = n_x \frac{dE_{dm}(n_x)}{n_x} - E_{DM}(n_x) \ ,$$

which gives:

$$P_{DM}(n_x) = \frac{(m_x c^2)^4}{(hc)^3 8\pi^2}\left[x + \sqrt{1+x^2}\left(\frac{2x^2}{3} - 1\right) + \ln\left(x+\sqrt{1+x^2}\right)\right] + \frac{y^2}{2}(hc)^3 n_x^2$$

For the bosonic equation of state we used the following [5,11]:

$$E_{DM}(n_x) = m_x c^2 n_x + \frac{u^2}{2}(hc)^3 n_x^2 \ ,$$

$$P_{DM}(n_x) = \frac{u^2}{2}(hc)^3 n_x^2$$

where u is the corresponding interaction strength.

To measure the total pressure and energy density of the two fluid model we use reference [14] to calculate:

$$E(n_b, n_x) = E_{NS}(n_b) + E_{DM}(n_x) \ ,$$

$$P(n_b, n_x) = P_{NS}(n_b) + P_{DM}(n_x)$$

For the stability part, which is very important and crucial for this research, the main path to follow is to perturbate the static solution by solving the Sturm-Liouville eigenvalue equation which yields eigenfrequencies ω_n, being real numbers. Then, you have to search for negative values of the eigenfrequencies. The negative value means an exponential growth in the system, leading to the collapse of the star.

We searched for stability by analyzing the behavior of baryonic and dark matter particles while maintaining a fixed total mass of the compact object M_{TOT}. In particular we extremize the number of dark matter and baryonic matter particles N_x and N_b for a fixed mass and we obtain a pair of central pressures P_c^{NS}, P_c^{DM} which serve as the coordinates for the critical curve. It all comes down to solving this system and finding the corresponding pressures that obey it:

$$\left(\frac{dN_b}{dP_c^{NS}}\right)_{M=const} = \left(\frac{dN_x}{dP_c^{NS}}\right)_{M=const} = 0$$

$$\left(\frac{dN_b}{dP_c^{DM}}\right)_{M=const} = \left(\frac{dN_x}{dP_c^{DM}}\right)_{M=const} = 0$$

The corresponding number of particles is given by the following expression:

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

The configurations with particles positioned to the left of the point where the maximum and minimum of N_b and N_x merge are deemed stable, while those situated to the right are considered unstable. In fact it is sufficient to simply study the dependence of the number of particles N_b or N_x from the central pressure of one of the fluids (P_c^{DM} or P_c^{NS}) to identify the stability-instability critical points.

RESULTS AND DISCUSSION

Actually, there is an infinite number of possible configuration of the Dark Matter-Neutron Star m_x, the strength of the self-interaction and the fraction $f = \frac{P^c_{DM}}{P^c_{NS}}$ of the central densities. Basically, all of them are unconstrained. In the present study we focus on a few stable configurations which prove and confirm our hypothesis for the existence of supramassive dark objects, with neutron star origin, in the universe.

It is proper to clarify here that, by supramassive compact objects, we mean those whose compactness $C = \frac{GM}{Rc^2}$ is in the neutron star region, i.e. [0.15-0.25] or at least greater than the value 0.1 but less than the maximum upper limit $C_{max} = \frac{4}{9}$ where the objects collapse to a black hole. 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 noteworthy that the majority of 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 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 ten to even hundred 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 time scales, or by the density distribution of DM in the universe. Besides, compact DM objects with large masses and corresponding radii have already been studied (for a systematic review see references [12,13]). 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 computationally a difficult and time-consuming task. Since we are primarily interested in proving the stability of these objects, we chose 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, the interaction and the fraction f.

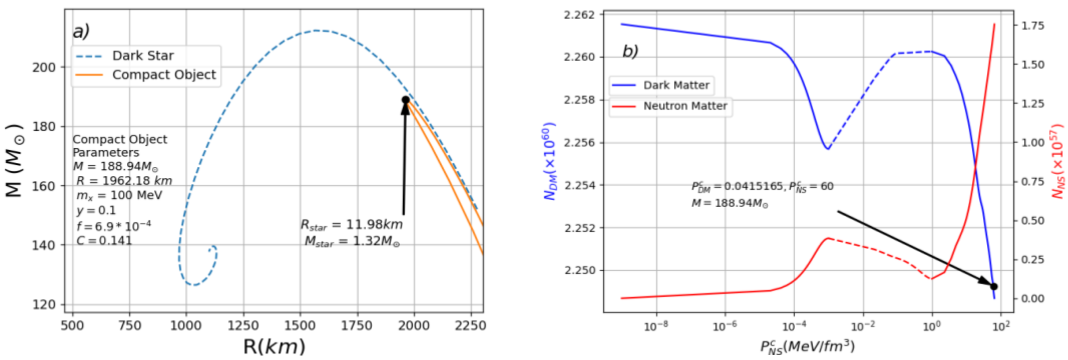

Figure 1. *(a) The M-R dependence for the case of pure fermionic DM (dashed line) DMNS object (solid line) of a heavy particle with mass m_x = 100 MeV, interaction y = 0.1 and fraction f = 6.9x10^-4. The arrow indicate the specific case where M = 188.94$M_\odot$ and R = 1962.18 km (correspond to a neutron star with mass M = 1.32$M_\odot$ and radius R = 11.98 km in the center). (b) The dependence of the number of dark matter and neutron matter particles N_{DM}, N_{NS} for the fixed mass M = 188.94$M_\odot$ as a function of the central value of the NS pressure P^c_{NS}. Since the configuration belong to the stability curve we conclude stability of this specific compact star case.*

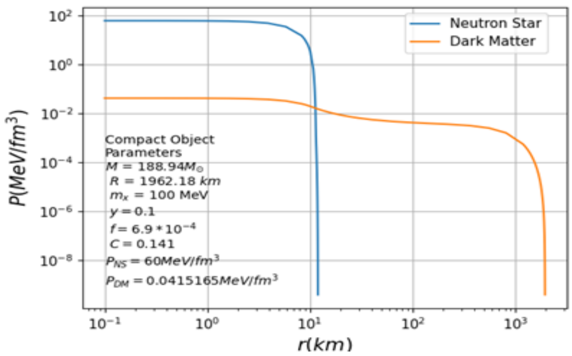

***Figure 2**. The pressure of DM and neutron star matter as a function of the distance r for a specific configuration of a dark matter particle of mass 100 MeV and an interaction of 0.1*

In Fig. 1(a), we display the M-R dependence for the case of pure fermionic DM object and DM-neutron star mixture object (indicated as compact object) for m_x=100 MeV, y=0.1 and fraction f=6.9x10^{-4}. Obviously there is an infinite number of possible configurations but we focus on the indicated case M=188.94M_o and R=1962.18 km with a neutron star M=1.32M_o and R=11.98 km in the center. This is an object with compactness C=0.141. In Fig. 1(b), we confirm the stability of this object, with the help of P_{NS}^c-$N_{DM,NS}$ diagram. The object, which indicated with the arrow, belongs to the second stable branch of the N_{DM} (or N_{NS}) number.

Moreover, in Fig. 2 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. 1(a).

In Fig. 3(a), we investigate the case of a heavier DM particle with mass m_x =1500 MeV. We select the indicated case M=29.905M_o and R=606.56 km with a neutron star M=1.41 M_o and R=11.99 km in the center. Again, in Fig. 3(b), we confirm the stability of this object.

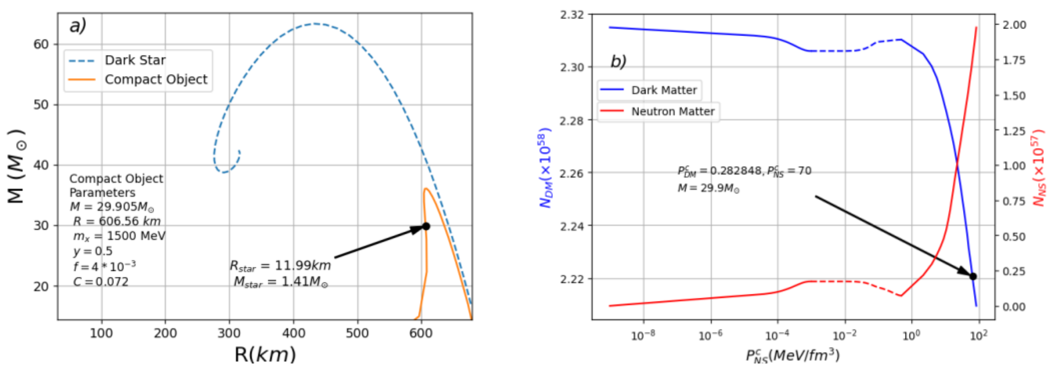

Figure 3. *(a) The same as Fig. 2 but for a particle with mass m_x=1500 MeV, y = 0.5, f =* $2.8 \times 10^{-5}4*^{10\text{-}3ct}$ *object of M = 29.9$M_{\odot}$, R = 606.56 km (the neutron star in the core is M = 1.41$M_{\odot}$ and R = 11.99 km). (b) Same as Fig. 2 but for the corresponding dark object of (a). Since the configuration belong to the stability curve we conclude stability of this specific compact star case.*

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

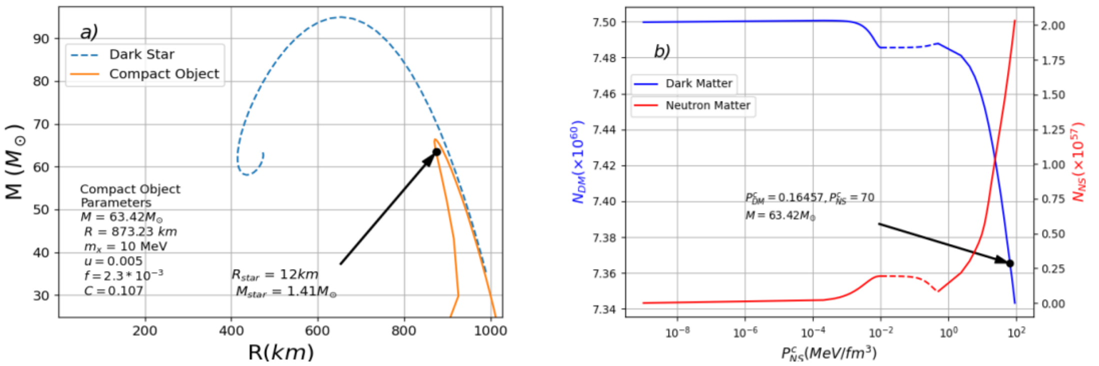

Figure 4. *(a) Same as Fig.2 but now using the bosonic eos. This is for a particle of m=10 MeV, u=0.005, f=2.3×10*$^{-3}$*and a compact object of M=63.42M*$_\odot$*, R=873.2 3km (the neutron star in the core is M=1.41M*$_\odot$ *and R=12 km). (b) Same as Fig. 2 but for the corresponding dark object of (a). Since the configuration belong to the stability curve we conclude stability of this specific compact star case*

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

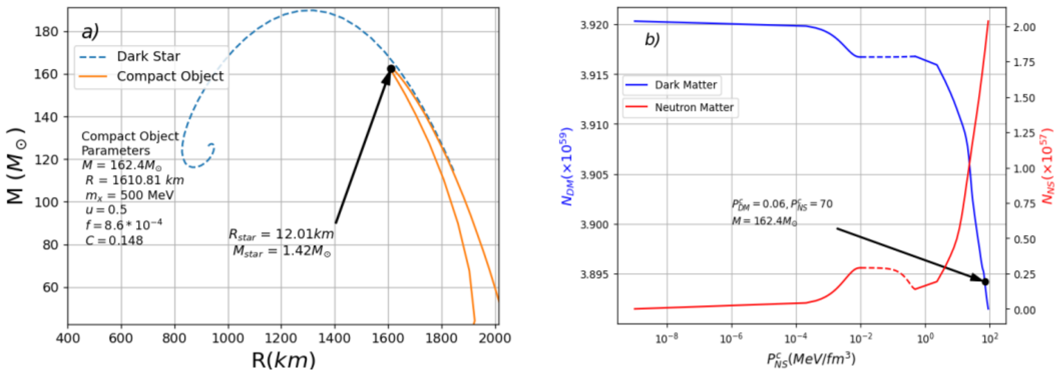

Figure 5. *(a) Same as Fig.4 using the bosonic eos. This is for a particle of m=500 MeV , u=0.5, f=8.6×10*$^{-4}$ *and a compact object of M=162.4M*$_\odot$*, R=1610.81 km (the neutron star in the core is M=1.42M*$_\odot$ *and R=12.01 km). (b) Same as Fig. 2 but for the corresponding dark object of (a). Since the configuration belong to the stability curve we conclude stability of this specific compact star case.*

In general, the *a)* figures contain the M-R diagram for the compact objects and, for comparison, for the pure dark star. Furthermore, one can see the configuration we work with where we check its stability and the corresponding neutron star that exists in the core of the compact object. One can clearly see that even an ordinary neutron star can be in fact the core of a bigger, heavier object made of dark matter that is not visible to us, except for its gravitational effects. Also, it is worthwhile to note that in the orange line of the compact object, configurations can be stable according to the two-fluid model even from the left side of the peak, something that with the one-fluid stability would be unstable. This is a strong indicator that the stability of these objects should be thoroughly examined using the two-fluid stability.

What is also of importance while checking the figures is to understand that these objects are heavily dependent on the dark matter parameters. Heavier dark matter particle mass leads to smaller configurations, while lighter particles result in bigger configurations. This happens because the heavier the particle is, the more matter gets concentrated towards the center of the object. Also, we should not forget to mention the significance of the interaction between dark matter particles. If the interaction is strong, the configuration mass and radius is bigger. This can also be seen in the equations of state for the two types of dark matter. If the interaction is weak, then the object's dimensions depend heavily on the dark matter particle mass.

The *b)* figures depict the N_x and $N_b - P_{NS}^c$ dependance that showcase the stability of these objects. From a physics point of view, this is logical because by slowly adding baryonic matter to a dark star and requesting that the total mass is constant, the dark particles must decrease while baryons increase, indicating the stable region. If dark particles increase and baryons decrease, it means that this is an unstable region. Also, we should note that if someone used the one-fluid stability criterion, some configurations that are stable with the two-fluid stability, would have been ruled out leading us to wrong conclusions.

CONCLUSIONS

We investigated possible supramassive dark objects stable configurations, with neutron star origin. We used EoS of self-interactive 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 there is an infinite number of these configurations (we have selected a few of them to present), which are also stable against perturbations. This implies 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.

We worked with dark matter parameters and conditions that create supramassive objects in the universe and we studied their stability. In our case, what makes our approach different from the rest of the literature is that we examine the extreme cases where dark matter is dominant and quickly takes over in the mass of the compact object. This is all done on the condition that there is not any kind of interaction between dark and baryonic matter. Also, our approach to the stability of these objects differs from the rest of the literature because we used the two-fluid model criterion, which differs from the one-fluid model criterion and showcased the importance to do that.

In the present work we do not indent to answer on the question "how these objects are created". There are few speculations related to this question. A relevant discussion is provided in Ref. [15]. 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 of having dark compact object originated from DM perturbations growing from primordial over-densities. Finally, another possibility is copious production and capture of DM in the core-collapse supernova of neutron stars progenitor [4]. In any case, there is no any strong theoretical prediction which argues strongly against the creation of these supramassive DM objects. Other studies [7] also suggest that, without assuming any priors on DM parameters, the detection of gravitational waves from non-annihilating heavy dark matter with weaker interactions might be achievable. This prospect could potentially span the entire parameter space providing potential explanations for missing pulsars, and going well below the neutrino floor.

The last proposition brings us to the most critical question, as far as the objects are concerned, of how they can be located. The most powerful tool in this case is the gravitational lensing which 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-KARGA collaboration) which include two cases: a) merger between two dark compact objects or b) merger between one of them and another compact object including pure neutron star or black hole. The signal of the corresponding gravitational waves will transfer useful information for the structure of these objects [17]. A future study is to employ the classical method, that is to consider small radial perturbations of the equilibrium configuration by solving the Sturm-Liouville eigenvalue equation, in order to check the stability of various configurations. Moreover, the interesting possibility that some of recent measurement's of very massive neutron stars [18] (a problem directly related with the black hole-neutron stars mass gap) can be explained by the dark matter capture, is under investigation and the results will be reported in a future work.

Acknowledgments

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