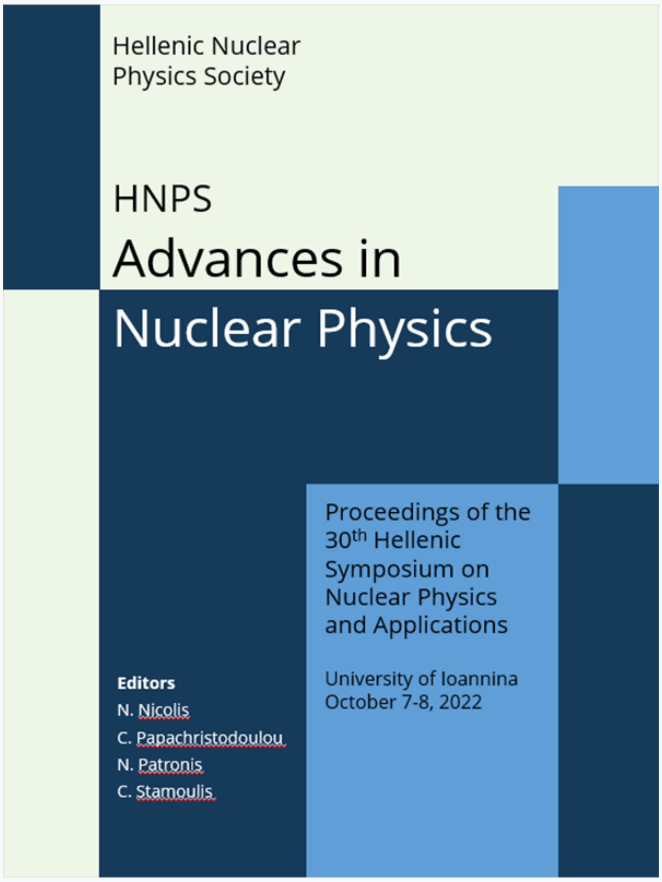
HNPS Advances in Nuclear Physics

Vol 29 (2023)

HNPS2022



The Effects of Dark Matter upon Neutron Stars' Properties

Michael Vikiaris

doi: [10.12681/hnpsanp.5081](https://doi.org/10.12681/hnpsanp.5081) doi: 10.12681/hnpsanp.5081

The Effects of Dark Matter upon Neutron Stars' Properties

M. Vikiaris[1] and Ch. Moustakidis[2]

Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

Abstract The nature of dark matter 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 see its gravitational effects. Galaxies and clusters of galaxies are most likely to contain dark matter that is trapped to their Gravitational Field. This leads us to the natural conclusion that compact objects might contain dark matter too. Among the compact objects of galaxies (of our Universe), neutron stars may be considered as natural laboratories where theories can be tested, and observational data can be received. Thus, many models of dark matter have been produced to check the existence of dark matter in those stars. Since we know for sure the varying parameters of Neutron Stars (Radii, Mass, Tidal Polarizability Parameter etc.), by inserting dark matter to our equations we can see the differences we obtain in the aforementioned parameters. In this study, we chose to work with two theoretical models concerning the trapping of dark matter in the gravitational field of a neutron star. Star's gravitational field is able to trap dark matter, but the latter extends well beyond the star's radius, creating a dark halo around the neutron star. By studying the various parameters of the star, we can obtain crucial information about the whole structure, the properties and even the nature of dark matter.

Keywords Neutron Stars, Dark Matter, Equation of State, Dark Matter Halo, Two Fluid Model

INTRODUCTION

Neutron Stars (NS) are objects that provide us with natural laboratories to investigate the equation of state of super dense nuclear matter, as well as to test the predictions of the General Relativity. These compact objects have been studied, over the years, to a great extent [1-2].

The bulk properties of NS are very sensitive on the Equation of State (EoS) of nuclear matter concerning both its low and high density part. During the last years, very rich information has been gained by the detection of gravitational waves (GW) that are emitted from binary systems which followed by their merger [3-5]. In particular, the details (frequency and amplitude) of the observed GW are sensitive on the tidal deformability Λ which characterizes the structure of the NS and is related to how amenable an NS is to diverge from its spherical form. Since the tidal deformability is sensitive also on the internal structure of the NS and also on its bulk properties including mass and radius, we expect that the accurate measurement of Λ may provide useful information on the equation of state.

Neutron Stars containing ordinary hadronic or even more quark matter have been studied a lot and their properties are constrained with satisfactory accuracy. However, the universe is governed by an unknown type of matter, the Dark Matter (DM) [6-8]. In particular, Dark Matter does not or at least very weakly interact with the ordinary matter. However, because it has mass, it interacts gravitationally and consequently we can observe, under some certain assumptions, its gravitational effects. Since this kind of matter is mostly gathered in Galaxies and Cluster of Galaxies, we think that a strong gravitational field is required to trap it.

In recent years there has been extensive research into the trapping of dark matter in the strong gravitational field of neutron stars [9-26]. This study has mainly focused on how trapped dark matter affects the basic properties of NSs and how this can be inferred from measurements of tidal deformability from observations of mergers of binary neutron star systems.

[1] M. Vikiaris: mvikiari@auth.gr
[2] Ch. Moustakidis: moustaki@auth.gr

The motivation of the present work is to extend the recent study concerning the trapped dark matter in the interior of NS. In particular, we investigate the possibility to gain useful information and constraints of some possible DM candidates. We focus mainly on the case of fermionic dark matter where the mass of the DM particles and the self-interactions are treated as a free parameter. Moreover, using two different models concerning the structure of the NS and DM admixture, we predict the properties of this new compact object including mass, radius and mainly the tidal deformability. The results are compared with recent astrophysical observations. Obviously, the present study does not relate with the terrestrial experiments concerning DM (see for example the recent references [27-29]). In any case, useful constraints can be inferred by comparing the present theoretical study with those originated from recent observations.

More precisely, we employ for comparison a) the two fluid model (hereafter TF model) (where ordinary matter and dark matter are not interacting with each other), as well as b) the model introduced by Nelson, Reddy and Zhou [17] (hereafter NRZ model), based on the invariance of the chemical potential in the interior and exterior of the mixed compact object. We mainly focus on the creation of a halo around neutron stars, consisting of dark matter particles. We expect that this halo affects appreciably the tidal deformability and may be revealed by the future observations.

THEORETICAL MODELS

I) NRZ model

Firstly, we describe below the NRZ model. In this approach, we first require the chemical potential to be constant in the presence of a neutron star's gravitational field

$$\mu_\chi = \widetilde{\mu_\chi}\sqrt{g_{tt}(r)} = const, \tag{1}$$

where $\widetilde{\mu_\chi}$ is DM chemical potential in local Lorentz frame. If one neglects the back reaction of DM on the NS structure, a specification of $\widetilde{\mu_\chi}$(r = 0) uniquely determines the distribution of DM inside the NS. The number density of DM n_χ is obtained by noting that $\widetilde{\mu_\chi}(r)$= $(\partial\varepsilon_\chi/\partial n_\chi)$, where ε_χ is the DM energy density. Then we define the energy density of the dark matter particle

$$\varepsilon_\chi = \varepsilon_{kin} + m_\chi n_\chi + \frac{g_\chi^2}{2m_\varphi^2} n_\chi^2. \tag{2}$$

In Eq. (2) $\varepsilon_{kin} = \frac{1}{\pi^2}\int_0^{k_{Fx}} k^2\left(k^2 + m_\chi^2 - m_\chi\right)dk$ is the kinetic energy of the dark particle and $k_{Fx} = \left(3\pi^2 n_\chi\right)^{\frac{1}{3}}$. Also, g_χ/m_φ is the coupling constant that we use in this model (1/z in the Two fluid model since z = m_φ/g_χ). The pressure of DM is given by the thermodynamic equation

$$p_\chi = -\varepsilon_\chi + \widetilde{\mu_\chi} n_\chi. \tag{3}$$

The calculations are performed using an iteration process until there is a convergence. In particular, we first solve the Tolman-Oppenheimer-Volkoff (TOV) equations [30] (see below the TF model) for an NS with ordinary matter where we obtain g_{tt} and we calculate the DM density profile in the local density approximation. Then, we update the EoS with the energy density and pressure contributions, and then, at the point where we have reached the "surface" of the neutron star, we solve the TOV equations again using the updated Dark Matter EoS. The structure we create is shown schematically Fig. 1. Practically, we have the creation of a NS that serves as the "core" of the larger dark structure which has a radius as big as the dark halo.

Figure 1. *Visualization of the dark matter halo model. The "core" of the dark structure is the neutron star. The radius of the dark structure is the dark matter halo radius.*

II) Two Fluid Model

For the TF model, we used the same EoS for the dark matter, but this time we solved the TOV equations for the two fluids simultaneously, that is

$$\frac{dp_{om}}{dr} = -(p_{om} + \varepsilon_{om})\frac{dv}{dr} \tag{4}$$

$$\frac{dm_{om}}{dr} = 4\pi r^2 \varepsilon_{om} \tag{5}$$

$$\frac{dp_{dm}}{dr} = -(p_{dm} + \varepsilon_{dm})\frac{dv}{dr} \tag{6}$$

$$\frac{dm_{dm}}{dr} = 4\pi r^2 \varepsilon_{dm} \tag{7}$$

$$\frac{dv}{dr} = \frac{(m_{om}+m_{dm})+4\pi r^3(p_{om}+p_{dm})}{r\left(r-2(m_{om}+m_{dm})\right)}. \tag{8}$$

The indices "om" and "dm" stand for ordinary and dark matter, respectively. We solve the above systems of the TOV equations including the corresponding differential equation for the second love number k_2 and also the tidal deformability which is defined as $\Lambda = \frac{64}{3}k_2\left(\frac{R}{R_s}\right)^5$ with R_s being the Schwarzschild Radius, equal to $2GM/c^2$.

RESULTS AND DISCUSSION

The dependence of pressure as a function of the distance that we receive as a result using the NRZ model, is illustrated in Fig. 2. We get the formation of a dark halo that exceeds the radius of the star and reaches almost 85 km. This is the radius of the halo for the current parametrization.

Moreover, in Fig. 3, using also the NPZ model, we display the effects of the self-interaction on Λ as a function of the total dark mater mass Mx. The tidal deformability is sensitive not only on the interaction, but also on the contribution of the dark matter mass and receives huge values and inconsistent with observations for large values of Mx.

Now, using the TF model, we create Fig. 4 which provides an image of a NS where DM is trapped inside it and drops to zero faster than the neutron matter as a subject of initial condition and the parametrization of dark mater properties. In addition, we can further constrain the mass of the DM particle on the lower values. The work we conducted focused mainly on testing various DM particle masses in a certain range with the fraction of DM pressure being constant. By searching computationally, the tidal Λ of a NS, we can determine whether the structure we created is feasible in Nature or not, depending on whether the result we get agrees with the observational data that we have so far.

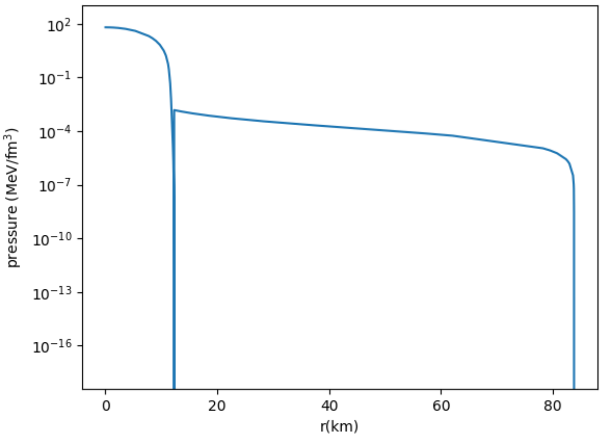


Figure 2. *Pressure-radius figure that demonstrates the creation of dark matter halo using the NRZ model. This model depicts that dark matter exists in the gravitational field of NS. This is why the total pressure starts from 10^2 MeV/fm^3, technically drops to 0 at around 12-13 km indicating the radius of the NS. However, outside the NS, the pressure has a non-negative value and drops slowly until a certain point. This point is the radius of the dark halo.*

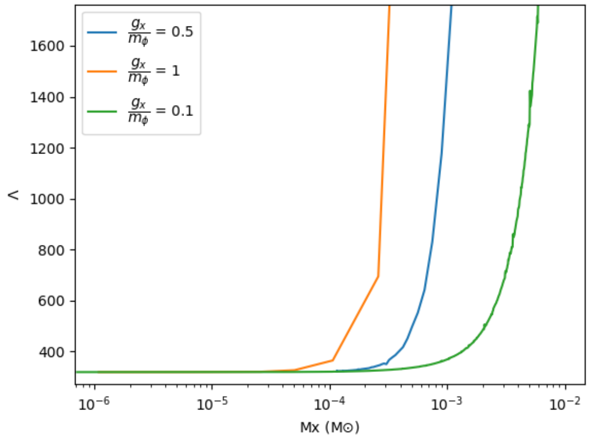


Figure 3. *Λ-Mx diagram that depicts the dependency of Λ on the Dark Matter mass. The tidal polarizability parameter (Λ) is a parameter that can be observed with the help of gravitational waves. Thus, since the dark halo affects the radius and mass that are used in the equations of Λ, it is important to understand the behavior of the curves that we receive by changing the initial conditions.*

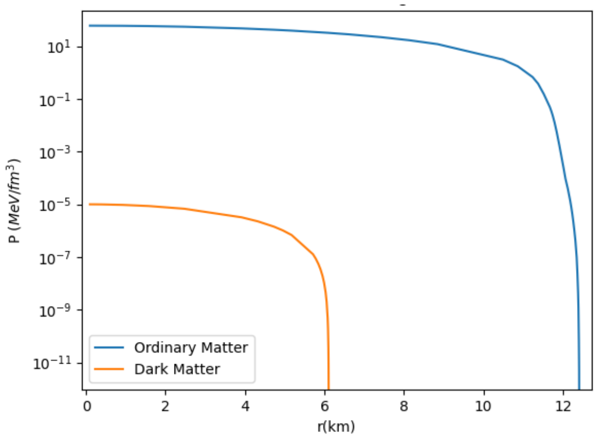


Figure 4. *Pressure-radius figure using the TF model. For some initial conditions, dark matter drops to zero faster than ordinary neutron star matter. In some are other cases the ordinary neutron star matter drops to zero faster, leading to the formation of a dark halo around the star. The case depicted here falls to the first category, but adds very little mass to the structure so there is no way of detecting DM through Λ.*

In particular, in Fig. 5, we provide the constraints on dark mater properties. We mainly focus on the behavior of the Λ parameter since this is the key parameter that we receive from observational data. Obviously, the lower mass DM particles fail to be consistent with observational data. A possible explanation is that the DM particle is so light, the repulsive interaction that we used (the 1/z) drives the halo radius to huge values. Consequently, the mass that this DM halo contains, with this Radius ($\Lambda \sim (R/M)^5$) drives the values of Λ outside of the range of observational data.

Similar conclusions are drawn from Fig. 6 and 7, where possible constraints on the strength of self-interaction are in order. In any case, a suitable interplay between particle mass and interaction leads to the prediction of the observational data. Work in this direction is in progress.

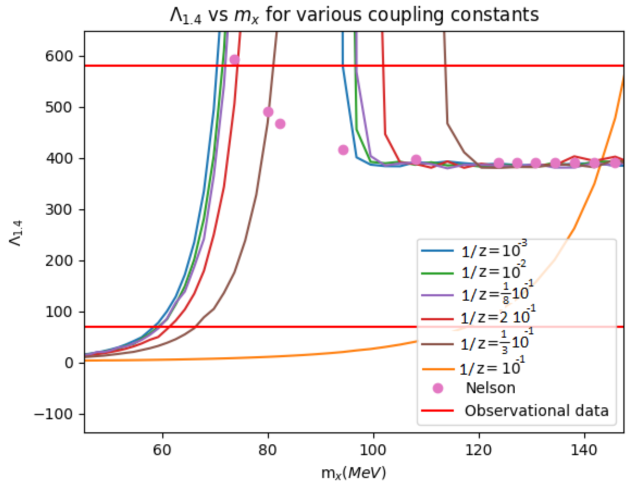


Figure 5. *Tidal polarizability of a NS of 1.4 solar masses ($\Lambda_{1.4}$) versus DM particle mass (m_χ). This graph depicts the behavior of the Λ parameter of a neutron star that contains dark matter and forms a dark matter halo. We mostly care about the halo, since the new halo radius and the mass that is added to the structure gives changes to this parameter. We see that for the lower mass candidates, this parameter falls outside the observational range of data, while for higher mass DM particles do not form a dark halo.*

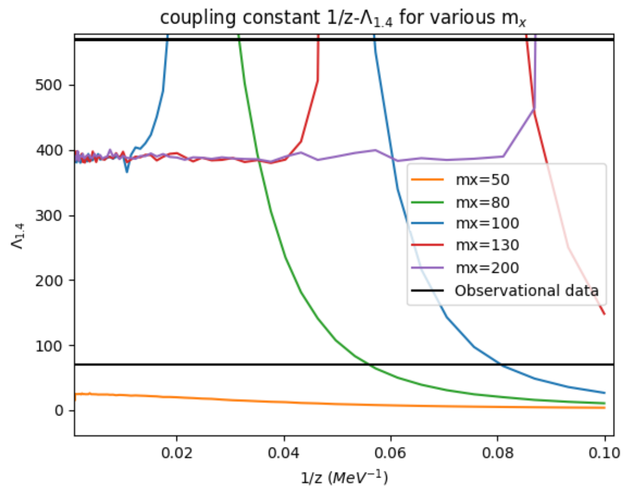


Figure 6. *Tidal polarizability of a NS of 1.4 solar masses ($\Lambda_{1.4}$) versus coupling constant (1/z). This figure depicts the behavior of the Λ parameter for a neutron star of 1.4 Solar Masses as we change the coupling constant 1/z. This constant refers to the interaction between the DM particles. Here we used a repulsive interaction. The smaller the coupling constant, the more compacted DM can be, thus we get lower Radii for the dark halo. As 1/z receives higher values, the radius of the dark halo becomes enormous and drives Λ outside the range of observational data.*

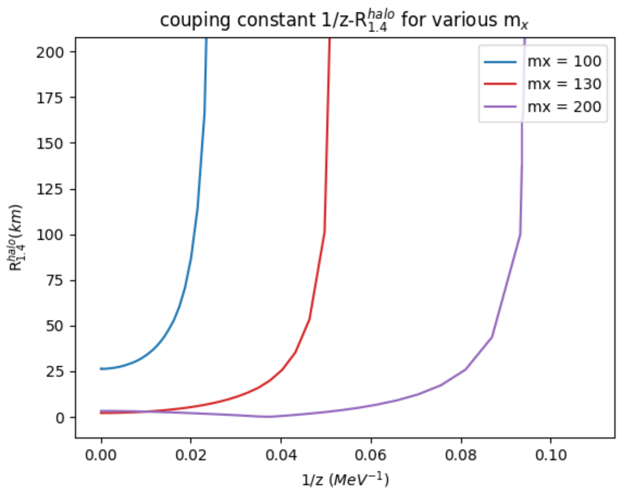


Figure 7. *Dark halo radius of a NS of 1.4 solar masses ($R_{1.4}^{halo}$) versus the coupling constant (1/z). This figure shows that for lower DM particle masses and for increasing coupling constant, the radius of the dark halo gets very big numbers, driving the Λ parameter outside the observational data range. In this figure we can also note that 3 instead of 5 different masses for the DM particle mass are visible, because for lower masses the radius of the halo starts at 250 km.*

CONCLUSIONS

In the present work, as an additional study of recent similar investigations, we concentrated on the properties of exotic compact objects consisting of dark matter and neutron star matter, in the framework of the TF, as well as the NRZ model. According to our main hypothesis, the dark matter particles are fermions with a mass in the range of few MeV up to few to 1 GeV, while self-interaction with a coupling constant that varied in a large interval was also considered. We focus mainly on the creation of dark matter halo around the neutron star and calculate the bulk properties of this exotic object, including the distribution of the two fluids, the mass and radius and mainly the tidal deformability. We compare the results with recent observation constraints of the tidal deformability. We found that the predictions of all the aforementioned properties are very sensitive on the parametrization of the dark matter particles.

More importantly, we found that constraints on the mass and interaction of DM are possible by comparison with observed range of tidal deformability. In particular, low mass of DM particles favors both a huge halo and extremely large mass and radius of the compact objects far from the observations. On the other hand, large DM mass close to 1 GeV favors very limited or even non-existent halo. In any case, useful insight can be gained from the comparison of the theoretical prediction with observation, while the possible constraints on the parametrization of the dark matter is possible. It is worth to mention here that additional future observation of the tidal deformability may offer even more stringent constraints.

From the theoretical point of view, the consideration of other particles, for example bosons as DM candidates, will be of interest and this project is under current study. Concluding, the neutron star, due to the strong gravitational field, offers the possibility to investigate and check theoretical predictions of the nature and properties of dark matter. In this case, an additional tool enters the quiver for studying not only the kind but also the properties of dark matter. Future, more elaborated observations will definitely shed light on this issue.

References

[1] N. K. Glendenning, Compact Stars—Nuclear Physics, Particle Physics and General Relativity, Springer, New York (1997)

[2] P. Haensel, A. Y. Potekhin, and D. G. Yakovlev, Neutron Stars 1: Equation of State and Structure, Springer-Verlag, New York (2007)
[3] B. P. Abbott et al., Phys. Rev. Lett. 119, 161101 (2017)
[4] B. P. Abbott et al., Phys. Rev. Lett. 121, 161101 (2018)
[5] B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)
[6] Snowmass 2013 Cosmic Frontier Working Groups 1–4 collaboration, Dark matter in the coming decade: complementary paths to discovery and beyond, Phys. Dark Univ. 7-8, 16 (2015)
[7] D.N. Spergel and P.J. Steinhardt, Phys. Rev. Lett. 84, 3760 (2000)
[8] A. Loeb and N. Weiner, Phys. Rev. Lett. 106, 171302 (2011)
[9] D.E. Kaplan, M.A. Luty and K.M. Zurek, Phys. Rev. D 79, 115016 (2009)
[10] S.M. Boucenna and S. Morisi, Front. Phys. 1, 33 (2014)
[11] K.M. Zurek, Phys. Rep. 537, 91 (2014)
[12] C. Kouvaris and P. Tinyakov, Phys. Rev. D 82, 063531 (2010)
[13] S.C. Leung, M.C. Chu and L.M. Lin, Phys. Rev. D 84, 107301 (2011)
[14] C. Kouvaris and N.G. Nielsen, Phys. Rev. D 92, 063526 (2015)
[15] B. Bertoni, A.E. Nelson and S. Reddy, Phys. Rev. D 88, 123505 (2013)
[16] I. Goldman and S. Nussinov, Phys. Rev. D 40, 3221 (1989)
[17] A. E. Nelson, S. Reddy, and D. Zhou, J. Cosmol. Astropart. Phys. 07, 12 (2019)
[18] J. Ellis, A. Hektor, G. Hütsi, et al., Phys. Lett. B 781, 607 (2018)
[19] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, Phys. Rev. D 79, 015014 (2009)
[20] J. F. Navarro, "The structure of cold dark matter halos", in Symposium-international astronomical union, Cambridge University Press, vol. 171, pp. 255–258 (1996)
[21] Sandin and P. Ciarcelluti, Astropart. Phys. 32, 278 (2009)
[22] R. Ciancarella et al., Phys. Dark Universe 32, 100796 (2021)
[23] G. Panotopoulos and I. Lopes, Phys. Rev. D 96, 083004 (2017)
[24] J. Ellis et al., Phys. Rev. D 97, 123007 (2018)
[25] H. C. Das, A. Kumar, B. Kumar, et al., Mon. Notices Royal Astron. Soc. 495, 4893 (2020)
[26] C. Kouvaris and P. Tinyakov, Phys. Rev. D 82, 063531 (2010)
[27] L.S. Ahn S et al., Phys. Rev. Lett. 124, 101802 (2020)
[28] O. Kwon et al., Phys. Rev. Lett. 126, 191802 (2021)
[29] K.Y. Andrew et al., Phys. Rev. Lett. 130, 071002 (2023)
[30] J. Lattimer and M. Prakash, Astrophys. J. 550, 426 (2001)