The effects of dark matter on compact binary systems

Ebrahim Hassani a,1, Amin Rezaei Akbarieh b,2, Yousef Izadi c,3

1Faculty of Physics, University of Birjand, Birjand, Iran
2Faculty of Physics, University of Tabriz, Tabriz, Iran
3Department of Physics and Applied Physics, University of Massachusetts, Lowell, MA 01854, USA

Abstract As compact binary star systems move inside the halo of our Galaxies, they interact with dark matter particles. The interaction between dark matter particles and baryonic matter causes dark matter particles to lose some part of their kinetic energy. After dark matter particles have lost part of their kinetic energy, they gravitationally bound to stars and stars start to accrete dark matter particles from the halo. The accretion of dark matter particles inside compact binary systems increases the mass of the binary components and then, the total mass of the binary systems increases too. According to Kepler's third law, increased mass by this way can affect other physical parameters (e.g. semi-major axes and orbital periods) of these systems too. In this work, we estimated the period change of some known compact binary systems due to the accretion of dark matter particles into them. We investigated the effects of different dark matter particle candidates with masses in the range \(10^{-5} - 10^{15} \text{GeV} \cdot \text{c}^{-2}\) and dark matter density as high as the dark matter density near the Galactic central regions. Our overall result is that the estimated period change due to the accretion of dark matter particles into compact binary systems can be as high as the measured values for these systems.

1 Introduction

Rotation curves of galaxies reveal the non-uniform distribution of dark matter (DM) inside galaxies [1]. From this point, one can infer that all astronomical objects inside galaxies are immersed inside DM. Then, it is logical to suppose that, the presence of DM will affect the physics of every astronomical object, including stars, binary star systems, and stellar clusters, inside galaxies.

If DM particles will interact with baryonic matter through weak interaction, then it can affect the internal structure and the evolutionary courses of stars too. Or in other words, considering DM effects on the physics of stars causes stars to follow different evolutionary paths in comparison to the stellar standard evolutionary models. For the first time, Steigman used DM supposition on the physics of the sun to solve the solar neutrino problem [2]. Simulation of dwarf galaxies also supports the supposition that DM particles affects the physics of individual stars. In evolved dwarf galaxies the DM halo around the dwarf galaxies heated up by the stars inside them. Then, The more the dwarf galaxy evolves, the more the DM halo heats up by stars [3]. In addition, the effects of DM on stars can be used to solve the paradox of youth problem for stars that are located near the Galactic massive black hole [4]. In addition to normal stars, DM effects on other celestial bodies like the moon [5, 6], planets [7], neutron stars (NS) [8–11], white dwarf stars (WD) [12–15], black holes [16–18] and binary star systems [19] are investigated in the literature. By passing the time, stars absorb and gather DM particles from the halo of galaxies. In this way, the mass of the stars increases too. According to the definition, capture rate (CR) of DM particles by a round massive body (like Earth, Sun, neutron stars, etc.) is the number of DM particles that are gravitationally bound to that body by passing the time [20]. For the first time, Press and Spergel estimated the CR relation of weakly interacting massive particles (WIMP) particles that are accreting into the sun [21]. In the next step, Gould obtained a general relation for the capture rate of DM particles by other round bodies like planets and stars [20]. Kouvaris used Press and Spergel relation to derive CR relation for NSs [22]. Hurst et al used Gould relation to obtain CR relation for WDs [23].

As a compact binary system moves inside DM halo, it feels dynamical friction that is imposed by the DM halo. Induced
dynamical friction by the DM halo can alter the physical parameters (e.g. orbital period and semi-major axis) of these systems. Dynamical friction that is imposed by this way can be used to constrain parameters of different DM models [24]. In a series of studies, authors tried to estimate the period change of compact binary systems due to the dynamical friction that is imposed by DM [24–32]. As an example, Gabriel and Rueda compared the observed period change of some known compact binary systems with the estimated period change due to dynamical friction and also the estimated period change due to the gravitational wave emissions from these systems [25]. They conclude that in some parameter space of DM, the orbital decay due to dynamical friction can be comparable to the orbital decay due to the gravitational wave emission.

In addition to “dynamical friction” and “gravitational wave emission” the accretion of DM particles inside compact binary systems can be the source of period change in these systems. As a compact binary system moves inside the DM halo, each star of the system can capture DM particles from these systems. As a compact binary system can be the source of period change in these systems [25]. They conclude that in some parameter (e.g. $p^2 \propto 1/M$), the increased total mass of the system too. Then, and according to Kepler’s third law (i.e. $p^2 \propto 1/M$), the increased total mass of the system by this way causes the period of the system to decrease.

In Sec. (5) we estimated the period change of some known compact binary systems due to the accretion of DM particles inside them and then compared the results with the period change of these systems due to dynamical friction and gravitational wave emission (see table (1) for summary of our results). The rest of the paper is structured as follows. In Sec. (2) CR relations for white dwarfs and neutron stars are presented and explained. In Sec. (3) a relation for the CR by compact binary systems is obtained. Discussion about DM density distribution inside galaxies is presented in Sec. (4).

Finally, Sec. (5) is devoted to the results and conclusions.

## 2 Capture Rate by Compact Stars

CR of DM particles by Hydrogen atoms is different from the CR relation for elements heavier than Hydrogen atoms. This is because in Hydrogen atoms the role of the spin of the outermost electron is not insignificant and then must be taken into account in scattering cross section relations. CR by Hydrogen atoms is in the form [19]

$$C_{x, H} = \left[ \frac{4\sqrt{6} \pi \rho_x}{m_x v_x} \frac{1}{v_x} n_H(r) r^2 \right] \times \left[ \sigma_{x, SI} + \sigma_{x, SD} \right] \times \left[ \int_0^R n_H(r) r^2 dr \right] \times \left[ \int_0^\infty \exp\left( -\frac{3u^2}{2v_x^2} \right) \sinh\left( \frac{3uv_x}{v_x} \right) (v_x^2 - \frac{\mu_x^2 H}{\mu_H} u^2) \theta\left( v_x^2 - \frac{\mu_x^2 H}{\mu_H} u^2 \right) du \right], \quad (1)$$

and for elements heavier than Hydrogen it is in the form [19]

$$C_{x, i} = \left[ \frac{8\sqrt{6} \pi E_0}{m_x v_x} \frac{\mu_i^2 \sigma_{x, SI}}{\mu_i} \frac{1}{v_x} \exp\left( -\frac{3u^2}{2v_x^2} \right) \times \left[ \sigma_{x, SI} \Lambda_i^2 \left( \frac{m_x n_{n,i}}{m_x + m_{n,i}} \right)^2 \left( \frac{m_x + m_p}{m_x m_p} \right)^2 \right] \times \left[ \int_0^R n_i(r) r^2 dr \right] \times \left[ \int_0^\infty \exp\left( -\frac{3u^2}{2v_x^2} \right) \sinh\left( \frac{3uv_x}{v_x} \right) \times \left( \exp\left( -\frac{m_x u^2}{2E_0} \right) - \exp\left( -\frac{m_i u^2}{2E_0} \right) \right) \exp\left( -\frac{m_x v_x^2}{2E_0} \frac{\mu_i}{\mu_{x,i}} (1 - \frac{\mu_i}{\mu_{x,i}}) \right) du \right]. \quad (2)$$

In Eqs. (1) and (2), $\rho_x$ is the DM density that surrounds the star, $m_x$ is the mass of DM particles, $v_x$ is the dispersive velocity of DM particles, $v_x$ is the speed of star relative to the DM halo, $\sigma_{x, SI}$ is the spin-independent scattering cross-section, $\sigma_{x, SD}$ is the spin-dependent scattering cross-section, $n_H$ is the number density of Hydrogen atoms in different locations of stars, $n_i$ is the number density of heavier (i.e. heavier than Hydrogen atoms) elements in different locations of stars, $r$ is the distance from the center of the star, $m_p$ is the mass of protons, $m_i$ is the nuclear mass of the element $i$, $\Lambda_i$ is the atomic number of element $i$, $E_0 = 3h^2/(2m_n(0.91m_{1/3}^3+0.3)^2)$ is the characteristic coherence energy (for more details see Ref. [20]) and $\mu_i, \mu_{x,i}$ and $\mu_{x,i}$ are defined in the form: $\mu_i = m_x / m_{n,i}$ and $\mu_{x,i} = (\mu_i + 1)/2$.

Evolved stars, like white dwarfs and neutron stars, are consumed almost all of their initial Hydrogen content. Then, in compact stars the contribution of Hydrogen atoms in capturing DM particles are insignificant in comparison to the
heavier elements. For this reason we just used Eq. (2) to calculate the CR of DM particles by white dwarfs and neutron stars.

Eq. (2) is consisted of four different bracket. First to third brackets can be calculated analytically. We calculated fourth bracket using numerical integration. In 3rd bracket the amount of number density is supposed to be a constant value for both white dwarfs and neutron stars. The average number density of a typical white dwarf (e.g. sirius WD star with mass \( M_{\text{sirius}W} = 1.018 M_\odot \)) and radius \( R_{\text{radius}} = 0.0084 R_\odot \)) is about

\[
\tilde{n}_{WD} = \frac{N}{V} = \frac{M_{WD}}{(4/3)\pi R_{WD}^3} = 1.2 \times 10^{35} \text{ (Kg.m}^{-3}\text{).} \tag{3}
\]

In Eq. (2) we supposed white dwarf consisted of carbon atoms with atomic mass: \( m_c = 12u = 1.99 \times 10^{-26} \text{ (Kg)} \). Similar to Eq. (2), number density of a typical neutron star can be calculated

\[
\tilde{n}_{NS} = \frac{N}{V} = \frac{M_{NS}}{(4/3)\pi R_{WD}^3} = 3.46 \times 10^{48} \text{ (Kg.m}^{-3}\text{),} \tag{4}
\]

which \( m_n = 1.67 \times 10^{-27} \text{ (Kg)} \) is the mass of a neutron.

3 Capture rate by compact binary systems

According to the Kepler’s third law, square of the period in binary systems is proportional to the cube of the semi-major axis of the orbit \([35] \)

\[
P^2 = \frac{4\pi^2}{GM}a^3, \tag{5}
\]

in which \( M = M_1 + M_2 \). If we suppose that all binary systems that are located inside the galaxies are immersed inside the DM halos then, it is logical to suppose that the both components of the compact binary systems absorb and accrete DM particles. By this way, and by passing the time, the total mass of the binary systems will increase too. In the next, we will estimate how much the increased mass will affect the other parameters of the compact binary systems. Taking differential of the both sides of the Eq. (5) and after some simplifications we have

\[
\dot{P} = \frac{3}{2} \frac{\dot{a}}{a} M = \frac{3}{2} \dot{M}_1 + \frac{3}{2} \dot{M}_2, \tag{6}
\]

where \( \dot{P} = dp/dt, \dot{a} = da/dt, M = dM/dt, \dot{M}_1 = dM_1/dt \) and \( \dot{M}_2 = dM_2/dt, M_1 \) and \( M_2 \) signifies the mass variation of the binary components due to the accretion of DM particles inside them. To calculate \( \dot{M}_1 \) and \( \dot{M}_2 \) in Eq. (6) it is enough to multiply Eq. (1) and Eq. (2) to the mass of the DM particles \( m_x \) (i.e. \( \dot{M}_1 = CR \times m_x \) where \( M_1 \) is the mass of the primary compact star).

In table (1) we presented the estimation of \( M/M \) (which \( M = M_1 + M_2 \)) for some known compact binary systems.

4 Dark matter density profile

N-body simulations of galaxies reveals the non-uniform distribution of DM inside galaxies. These results are in agreement with observations (i.e. the rotation curves of galaxies). Navarro, Frenk and White (NFW) DM profile describes the radial distribution of DM density inside galaxies and is written in the form \([36, 37]\)

\[
\rho_{\text{NFW}}(r) = \frac{\rho_0}{r_s(1 + \frac{r}{r_s})^2}, \tag{7}
\]

where \( \rho_0 \) is the local DM density and \( r_s \) is the size of the DM halo \([38]\). Both \( \rho_0 \) and \( r_s \) vary from galaxy to galaxy. In the case of the Milky way galaxy these parameters are estimated to be about \( \rho_0 = 0.26 \text{ (GeV.cm}^{-3}\text{)} \) and \( r_s = 20 \text{ (Kpc)} \) \([38]\) and for the case of M31 galaxy (andromeda galaxy) these parameters estimated to be about \( \rho_0 = 0.42 \text{ (GeV.cm}^{-3}\text{)} \) and \( r_s = 16.4 \pm 1.5 \text{ (Kpc)} \) \([39]\).

In addition to the NFW DM density profile, Einasto, Moore and isothermal DM density profiles can be used to describe the distribution of DM inside galaxies. The functionality of these profiles are in the form \([38]\)

\[
\rho_{X,\text{isothermal}} = \begin{cases} \frac{\rho_0}{r_s(1 + \frac{r}{r_s})^2} \quad & r_s = 5 \text{ (Kpc),} \\ \rho_0 \exp \left[ -\frac{\alpha}{\alpha} \left( \frac{r^\alpha}{r_s^\alpha} \right) \right] \quad & \alpha = 0.17, r_s = 25 \text{ (Kpc),} \end{cases} \tag{8}
\]

\[
\rho_{X,\text{Einasto}} = \begin{cases} \rho_0 \left[ \frac{r_s}{r_s + (r/r_s)^\alpha} \right]^{1/2} \quad & \alpha = 0.17, r_s = 25 \text{ (Kpc),} \end{cases} \tag{9}
\]

\[
\rho_{X,\text{Moore}} = \begin{cases} \rho_0 \left( \frac{r_s}{r} \right)^{1.16} \left( \frac{r^2 + r_s^2}{r_s^2} \right)^{1.84} \quad & r_s = 30 \text{ (Kpc).} \end{cases} \tag{10}
\]

Fig. (4) depicts the 2D representation of the distribution of DM density according to the NFW, Einasto, Moore and isothermal DM density profiles and for central region of our galaxy. From Fig. (4) it is conceivable that DM density near the central regions of the galaxies is the highest and by moving toward the outer regions its value decreases. So, we can say that DM affects the physics of astronomical objects (especially compact binary systems, which is the subject of this study) in central regions of galaxies more than the objects in outer regions.

For distances far from the central black hole of the galaxy...
Table 1: Physical parameters of the compact binary systems that we used in this study. Columns include: Type: types of the components of the compact binary systems; Name: name of the systems; \( M_p \) and \( M_c \): mass of primary and companion stars; \( P \): orbital period of the systems; \( d \): distance from the Galactic center; \( \dot{P}_{\text{obs}} / P \): measured period change; \( \dot{P}_{\text{GW}} / P \) and \( \dot{P}_{\text{DF}} / P \): period change due to the gravitational wave emission and dynamical friction. All data are from Table 1 of the Ref. [25]. By comparing measured \( \dot{P}_{\text{obs}} / P \) values with the calculated \( M_{\text{CR}} / M \) values in Fig. (5), we infer that for some DM particle candidates (e.g. SuperWIMPs), measured \( \dot{P}_{\text{obs}} / P \) values can be as high as the \( M_{\text{CR}} / M \) values. So, capturing these DM candidates by compact binary systems can be considered as one of the reasons of period change in these systems.

| Type    | Name            | \( m_p \) [\( M_{\odot} \)] | \( m_c \) [\( M_{\odot} \)] | \( P \) [days] | \( d \) [kpc] | \( \dot{P}_{\text{obs}} / P \) \( \times \times 10^{-16} \) | \( \dot{P}_{\text{GW}} / P \) \( \times \times 10^{-16} \) | \( \dot{P}_{\text{DF}} / P \) \( \times \times 10^{-24} \) |
|---------|----------------|-----------------------------|-----------------------------|----------------|-------------|---------------------------------|---------------------------------|---------------------------------|
| NS-NS   | J0737-3039     | 1.3381(7)                   | 1.2489(7)                   | 0.104          | 1.15(22)    | -1.393                          | -1.38874                        | -1.168                          |
|         | B1534+12       | 1.3330(4)                   | 1.3455(4)                   | 0.421          | 0.7         | -0.052905                       | -0.037554                       | -6.7126                         |
|         | J1756-2251     | 1.312(17)                   | 1.258(17)                   | 0.321          | 2.5         | -0.0757                          | -0.0793                         | -0.009771                       |
|         | J1906+0746     | 1.323(11)                   | 1.290(11)                   | 0.166          | 5.4         | -0.3939                          | -0.363                          | -0.18512                        |
|         | B1913+16       | 1.4398(2)                   | 1.3886(2)                   | 0.325          | 9.9         | -0.8533                          | -0.856602                       | -0.2828                         |
| NS-WD   | J0348+0432     | 2.01(4)                     | 0.172(3)                    | 0.104          | 2.1(2)      | -0.3038                          | -0.2871                         | -0.04441                        |
|         | J1012+5307     | 1.64(22)                    | 0.162(2)                    | 0.60           | 0.836(80)   | -0.289                          | -0.0212                         | -0.06566                        |
|         | J1141-6545     | 1.27(1)                     | 1.02(1)                     | 0.20           | 3.7         | -0.2321                          | -0.2332                         | -0.2071                         |
|         | J1738+0333     | 1.46(6)                     | 0.181(7)                    | 0.354          | 1.47(10)    | -0.0084680                      | -0.009155                       | -0.0693                         |
| WD-WD   | WDJ0651+2844   | 0.26(4)                     | 0.50(4)                     | 0.008          | 1           | -140                            | -120                            | -0.02025                        |

Fig. 1: (color on-line) 2D illustration of the different DM density profiles that are discussed in the text. For distances far from the Galactic center (e.g. distances more than 1 kpc), the difference between different DM density profiles are less than one order-of-magnitude. For this reason, the NFW DM density profile selected for the rest of this study.

(e.g. farther than 1 kpc), the difference between different DM density profiles are less than one order-of-magnitude. For this reason, we selected NFW DM density profile during the rest of the study. To obtain the results of our calculation, we considered DM density around compact binary systems to be \( \rho_x = 10^2 (\text{GeV/cm}^3) \) which correspond to the distance about \( r \approx 1 \text{(kpc)} \approx 3000 \text{(ly)} \) from the central black hole of the galaxy.

5 Results and Discussions

We used Eqs. (2) and (6) to estimate the accretion of DM particles inside compact binary systems. In our calculations, stars with masses lower than \( 1.24 M_{\odot} \) considered to be white dwarfs and stars with masses higher than \( 1.24 M_{\odot} \) considered to be neutron stars. The masses of the DM particles considered be in the range \( 10^{-15} \sim 10^5 \text{(GeV/c}^2) \) corresponding to the different DM particle candidates that we used in our calculations (see horizontal axes of the Fig. (5) for the mass range of different DM particles candidates).
Supposing that $\dot{a}/a$ values are equal to $\dot{P}/P$ values, Eq. (6) after some arrangement can be written in the below form:

$$\frac{\dot{M}}{M} = 3\frac{\dot{a}}{a} - 2\frac{\dot{P}}{P} = \dot{\bar{P}} - \bar{P}.$$  \hspace{1cm} (11)

Which means $\dot{M}/M$ has a linear relation with $\dot{P}/P$. After estimating $\dot{M}/M$ values theoretically, we compared the results with the measured $\dot{P}/P$ values (in the rest of this section we will use $\dot{P}_{obs}/P$ notation instead of $\dot{P}/P$ for period changes of compact binary systems). The results of our calculations are presented in Fig. (5) and table (1). Our overall results are:

- According to the amounts in table (1) measured values of $\dot{P}/P$ are of the order of magnitude $10^{-16} - 10^{-13}$ (sec$^{-1}$) which almost are in the same order of magnitude of the estimated $\dot{P}^{GW}/P$ values. Then we can infer that gravitational wave emission from compact binary systems can be considered as one of the main reasons for period decay in these systems.

- In table (1), estimated values of $\dot{P}^{DF}/P$ are of the order of magnitude $10^{-24} - 10^{-27}$ (sec$^{-1}$) which are much less than the measured $\dot{P}^{obs}/P$ values. Then we infer that dynamical friction that is imposed by DM halo can not be the main reason for period change in compact binary systems.

- According to the estimated $\dot{M}/M$ values in Fig. (5), period change due to the accretion of DM particles is very model dependent. In this work we just used four DM particles candidates which are axions with mass in the range $10^{-15} - 10^{-12}$ (GeV c$^{-2}$), Neutrinos with mass in the range $10^{-12} - 10^{-10}$ (GeV c$^{-2}$), SuperWIMPs with mass in the range $10^{-6} - 10^{4}$ (GeV c$^{-2}$), and WIMPs with mass in the range $10^{-1} - 10^{5}$ (GeV c$^{-2}$). Though there are many other DM candidates in the literature (for instance WIMPzilla particles with mass in the range $10^{12} - 10^{15}$ (GeV c$^{-2}$), [40]), but for the needs of this study the use of the above-mentioned candidates are sufficient. It is seen from Fig. (5) that, low-mass DM candidates has the potential to change the period of compact binary systems more than the observed values (i.e. $\dot{P}^{obs}/P$ values in table (1)). This prediction is obviously unacceptable. But this does not mean that our results reject the acceptance of low-mass DM particle candidates as DM particles candidates. This is because there are many other DM related parameters (e.g. spin-dependent and spin-independent scattering cross-sections, velocity of stars relative to the DM halo, DM density, and etc.) that have the potential to change our results hugely.

- From Fig. (5) we infer that intermediate-mass DM candidates has the ability to change the period of compact binary systems as comparable as the observed values. But high-mass DM candidates can not change the period of compact binary systems as much as the observed values. And as mentioned above, because of lack of our knowledge about the exact physical nature of DM we can not speak with confident that which DM candidate can be the best source of period change in compact binary systems.

Our overall results from the above discussions is that, the accretion of DM particles inside compact binary systems can be considered as one of the main reasons of observed period change in compact binary systems. Our results prefer DM candidates with mass in the range $m_{\chi} \propto 10^{-1} - 10^{5}$ (GeV c$^{-2}$) as the best DM candidates for this observed period changes. To discuss more about the possible consequences of the accretion of DM candidates into compact binary systems, other physical parameters that affects the CR relation in Eq. (2) must be taken into account. This alone can be the subjects of our next studies in this research.

6 Data availability

No new data were generated or analysed in support of this research.

7 Acknowledgements

Special thanks are due to Prof. Joakim Edsjö from the University of Stockholm, Sweden, and Prof. Gianfranco Bertone from the University of Amsterdam, Netherland, and Marco Taoso from National Institute of Nuclear Physics (INFN) Turin, Italy for their helpful discussions during the research.

References

1. Y. Sofue and V. Rubin, “Rotation curves of spiral galaxies,” Annual Review of Astronomy and Astrophysics, vol. 39, pp. 137–174, sep 2001.

2. G. Steigman, H. Quintana, C. L. Sarazin, and J. Faulkner, “Dynamical interactions and astrophysical effects of stable heavy neutrinos,” The Astronomical Journal, vol. 83, p. 1050, sep 1978.

3. J. I. Read, M. G. Walker, and P. Steger, “Dark matter heats up in dwarf galaxies,” Monthly Notices of the Royal Astronomical Society, vol. 484, no. 1, pp. 1401–1420, 2019.

4. E. Hassani, R. Pashouhesh, and H. Ebadi, “The effect of dark matter on stars at the Galactic center: The paradox of youth problem,” International Journal of Modern Physics D, vol. 29, p. 2050052, jun 2020.
Fig. 2: Calculated mass change (which is equal to the period change according to the Eq. (11)) of different types of compact binary systems and for different DM particle candidates. sub-plots (a)-(d) are for WD-WD type, sub-plots (e)-(h) for WD-NS type and sub-plots (i)-(l) for NS-NS type compact binary systems. In all sub-plots horizontal axes are the mass range of different DM particle candidates and vertical axes are the mass change of the compact binary systems. Only SuperWIMP particles have the potential to change the period of the compact binary systems in the range of the observed period change values (see Table (1) for the observed period change values).

5. M. H. Chan and C. M. Lee, “Constraining the spin-independent elastic scattering cross section of dark matter using the Moon as a detection target and the background neutrino data,” Physical Review D, vol. 102, no. 2, p. 23024, 2020.

6. R. Garani and P. Tinyakov, “Constraints on dark matter from the Moon,” Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, vol. 804, p. 135403, may 2020.

7. D. Hooper and J. H. Steffen, “Dark matter and the habitability of planets,” Journal of Cosmology and Astroparticle Physics, vol. 2012, no. 7, p. 46, 2012.

8. N. F. Bell, G. Busoni, and S. Robles, “Heating up neutron stars with inelastic dark matter,” Journal of Cosmology and Astroparticle Physics, vol. 2018, no. 9, p. 18, 2018.

9. J. Kopp, R. Laha, T. Opferkuch, and W. Sheppard, “Cuckoo’s eggs in neutron stars: can LIGO hear chirps from the dark sector?,” Journal of High Energy Physics, vol. 2018, no. 11, p. 96, 2018.

10. M. Cermeño, M. A. Pérez-García, and R. A. Lineros, “Enhanced Neutrino Emissivities in Pseudoscalar-mediated Dark Matter Annihilation in Neutron Stars,” The Astrophysical Journal, vol. 863, no. 2, p. 157, 2018.

11. N. F. Bell, A. Melatos, and K. Petraki, “Realistic neutron star constraints on bosonic asymmetric dark matter,” Physical Review D - Particles, Fields, Gravitation and Cosmology, vol. 87, p. 123507, jun 2013.

12. B. Dasgupta, A. Gupta, and A. Ray, “Dark matter capture in celestial objects: improved treatment of multiple scattering and updated constraints from white dwarfs,” Journal of Cosmology and Astroparticle Physics, vol. 2019, pp. 018–018, aug 2019.

13. M. Cermeño and M. A. Pérez-García, “Gamma rays from dark mediators in white dwarfs,” Physical Review D, vol. 98, no. 6, p. 63002, 2018.
14. P. W. Graham, R. Janish, V. Narayan, S. Rajendran, and P. Riggins, “White dwarfs as dark matter detectors,” Physical Review D, vol. 98, no. 11, p. 115027, 2018.

15. P. Amaro-Seoane, J. Casanellas, R. Schödel, E. Davidson, and J. Cuadra, “Probing dark matter crests with white dwarfs and IMBHs,” Monthly Notices of the Royal Astronomical Society, vol. 459, no. 1, pp. 695–700, 2016.

16. S. McDermott, H. B. Yu, and K. M. Zurek, “Constraints on scalar asymmetric dark matter from black hole formation in neutron stars,” Physical Review D - Particles, Fields, Gravitation and Cosmology, vol. 85, p. 23519, Jan 2012.

17. H. Umeda, N. Yoshida, K. Nomoto, S. Tsuruta, M. Sasaki, and T. Okubo, “Early black hole formation by accretion of gas and dark matter,” Journal of Cosmology and Astroparticle Physics, vol. 2009, no. 8, p. 24, 2009.

18. K. M. Belotsky, A. E. Dmitriev, E. A. Esipova, V. A. Gani, A. V. Grobov, M. Y. Khlopov, A. A. Kirillov, S. G. Rubin, and I. V. Svadkovsky, “Signatures of primordial black hole dark matter,” Modern Physics Letters A, vol. 29, p. 1440005, Dec 2014.

19. E. Hassani, H. Ebadi, and R. Pazhouhesh, “Capture rate of weakly interacting massive particles (WIMPs) in binary star systems,” sep 2020.

20. A. Gould, “Resonant enhancements in weakly interacting massive particle capture by the earth,” The Astrophysical Journal, vol. 321, p. 571, Oct 1987.

21. W. H. Press and D. N. Spergel, “Capture by the sun to dark matter on the smallest scales,” Physical Review D, vol. 101, p. 063016, Mar 2020.

22. J. Yoo, J. Chanamé, and A. Gould, “The End of the MACHO Era: Limits on Halo Dark Matter from Stellar Halo Wide Binaries,” The Astrophysical Journal, vol. 601, pp. 311–318, Jan 2004.

23. H. E. Bond, G. H. Schaefer, R. L. Gilliland, J. B. Holberg, B. D. Mason, I. W. Lindenblad, M. Seitz-McLeese, W. D. Arnett, P. Demarque, F. Spada, P. A. Young, M. A. Barstow, M. R. Burleigh, and D. Gudehus, “The Sirius System And Its Astrophysical Puzzles: Hubble Space Telescope and Ground-based Astrometry,” The Astrophysical Journal, vol. 840, p. 70, May 2017.

24. J. B. Holberg, M. A. Barstow, F. C. Bruhweiler, A. M. Cruise, and A. J. Penny, “Sirius B: A New, More Accurate View,” The Astrophysical Journal, vol. 497, pp. 935–942, Apr 1998.

25. R. W. Hilditch, An Introduction to Close Binary Stars. Cambridge University Press, Mar 2001.

26. D. Merritt, A. W. Graham, B. Moore, J. Diemand, and B. Terzić, “Empirical Models for Dark Matter Halos. I. Nonparametric Construction of Density Profiles and Comparison with Parametric Models,” The Astronomical Journal, vol. 137, pp. 2685–2700, Jan 2004.

27. J. F. Navarro, C. S. Frenk, and S. D. M. White, “The Structure of Cold Dark Matter Halos,” The Astrophysical Journal, vol. 462, p. 563, May 1996.

28. V. Barger, Y. Gao, W. Y. Keung, D. Marfatia, and G. Shaughnessy, “Dark matter and pulsar signals for Fermi LAT, PAMELA, ATIC, HESS and WMAP data,” Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics, vol. 678, pp. 283–292, Jul 2009.

29. A. Tamm, E. Tempel, P. Tenjes, O. Tihhonova, and T. Tuvikene, “Stellar mass map and dark matter distribution in M 31,” Astronomy and Astrophysics, vol. 546, p. A4, Oct 2012.
40. M. Schumann, “Direct detection of WIMP dark matter: concepts and status,” *Journal of Physics G: Nuclear and Particle Physics*, vol. 46, p. 103003, oct 2019.