Physics of the Dark Universe 28 (2020) 100484

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

On the change of old neutron star masses with galactocentric distance

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ARTICLE INFO

Article history:
Received 14 November 2019
Received in revised form 23 January 2020
Accepted 27 January 2020

Keywords:
Neutron stars
Dark matter
Galaxy centre

ABSTRACT

We show that the pulsar mass depends on the environment, and that it decreases going towards the centre of the Milky Way. This is due to two combined effects, the capture and accumulation of self-interacting, non-annihilating dark matter by pulsars, and the increase of the dark matter density going towards the galactic centre. We show that mass decrease depends both on the density profile of dark matter, steeper profiles producing a faster and larger decrease of the pulsar mass, and on the strength of self-interaction. Once future observations will provide the pulsar mass in a dark matter rich environment, close to the galactic centre, the present result will be able to put constraints on the characteristics of our Galaxy halo dark matter profile, on the nature of dark matter, namely on its annihilating or non-annihilating nature, on its strength of self-interaction, and on the particle mass.

1. Introduction

Dark matter (DM) is a key ingredient for models that try to explain cosmological structure formation without modifying gravity. Although the gravitational effects of DM are well documented [1,2], direct detection of particles for this dominant matter component continues to elude proofs: in accelerators or in nuclear recoil experiments [3–13], indirect WIMP annihilation searches [14], in DM stars [15,16] or in some other indirect quests as illustrated in Refs. [17–24].

In this context, different testing avenues of possible DM effects are welcome, such as in pulsars, i.e. rotating neutron stars (NSs), which provide the advantage of extreme densities and can accrete DM, thus straining the saturated neutron gas. The amount of DM acquired by a NS follows the Tolman–Oppenheimer–Volkoff (TOV) equation [25,26], as in e.g. [27]. Moreover, the effect of DM on NSs can directly lead to bounds for the masses of the different DM candidates [28,29]. For example, a recently discovered class of radio transients, such as fast radio bursts [30–33], can be caused by the collapsing NSs with accreted enough DM near GC [34].

Self-annihilating DM can also produce characteristic effects on NS [35–41]. In particular, WIMPs annihilation in DM cores should produce temperature and luminosity changes, through heat, of old stars [35–37,39]. However, those changes are difficult to detect [35,42].

Apart from WIMPs, DM could be made of asymmetric dark matter (ADM). In that case, the origin of the present DM abundance is similar to visible matter [43].[2] As ADM does not annihilate, its collapse and thermalization can give rise to extremely compact objects and to changes in the mass–radius ($M-R$) relation. The comparison of the $M-R$ relations coming from usual NSs and from NSs containing DM could yield constraints on DM and on the NS equation of state (EoS) [44]. Moreover, above a

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[2] Mirror matter is a peculiar case of ADM.

https://doi.org/10.1016/j.dark.2020.100484
2212-6864/© 2020 Published by Elsevier B.V.

critical value of accumulated DM [45], DM could become self-gravitating, form a mini black-hole, and constrain the DM particle cross section and mass [36].

Several authors realized in the last years that admixing DM with NS matter, coupled only through gravity, has similar results as the presence of exotic matter [42], allowing to explain very compact NSs [46], or very massive pulsars ($2M_\odot$, e.g., PSR J1614-2230 with $M = 1.97 \pm 0.04 M_\odot$ [47] and PSR J0348+0432 of $M = 2.01 \pm 0.04 M_\odot$ [48]) larger than the typical observed pulsars.[3]

Non-annihilating DM, among other results [27,56–60], yields the counterintuitive property of getting smaller and less massive NSs, the more DM they accrete [27,42]. Studies have been performed on NSs admixed with mirror DM [42], degenerate DM [61], and ADM [62], finding that increasing the ratio of DM to normal matter yields NSs with smaller radii and masses. In Ref. [27] NSs and White Dwarfs (WDs) matter admixed with 100 GeV ADM were studied, finding that planets-like objects could form. Those results were extended in [63] to particle masses in the range 1–500 GeV.

In this paper, based on the results obtained in our previous work [63], we propose a testable galactic probe for DM existence in the form of the evolution of the pulsar mass towards the galactic centre (GC). According to the discussion above, NSs in increasingly DM rich environments should accrete more DM and thus display a characteristic mass decrease, the closer they are to the galactic centre. We use NSs because (1) the very large baryon density inside NSs makes an interaction between baryons and DM following DM capture most likely; (2) the NSs strong gravitational force makes DM particles escape very unlikely, after they interact and lose energy. This mass evolution is easier to test than other probes such as NS temperature time evolution with DM accretion, as discussed previously.

In Section 2 we discuss our model for DM accretion in NS. In Section 3 we discuss, using simulations and observations, how to get a realistic dark matter halo, while in Section 4 we compare the predicted change of NS mass, moving towards the GC, with observations. In Section 5 we discuss the use of pulsars in the GC, before to present our conclusions in Section 6.

2. Accumulation of dark matter in compact objects

The equilibrium of ADM admixed onto a NS was studied in several papers, including [27,63], by means of the TOV equation for visible (or ordinary) matter (OM) and ADM, minimally coupled to gravity [63]. Among other results, it was shown that the compact object (CO) mass decreases as the accumulated DM increases. Solving TOV equation only tells how much DM (as well as OM) a CO can contain, which is $\simeq 10^{-5} M_\odot$ for a particle mass of 200 GeV [63]. However, the process to provide that amount of DM to a given CO remains to be determined. The acquisition of DM onto a NS can be divided into three phases, i.e. (1) the collapse of the protostar; (2) the star evolution until supernova explosion; (3) the NS phase.

To our knowledge, there is only one simulation that estimates the DM accretion onto a NS [64], to construct a model that builds up the DM external to the NS. Analytical studies provided an estimate of the accreted DM by NSs, making some simplifications, such as neglecting the DM capture during the pre-NS phase [35,45], or considering progenitor phase capture comparable to the NS phase [37]. Focusing on the NS phase, several authors decomposed this phase in further stages [35,37,39,64–67]: (1) DM capture in NS coming from DM-nucleon scattering; (2) DM orbit decrease due to DM-neutron scattering; (3) DM-DM interaction in NS.

The phase 2 can lead to a Bose–Einstein condensate or a black hole (BH) formation [45,66]. Disregarding this phase, we can obtain the DM particle number evolution by

$$\frac{dN_{\rm dm}}{dt} = C_{\rm c} + C_{\rm s} N_{\rm dm}, \tag{1}$$

as determined in Eq. (3.8) of Ref. [66], where $C_{\rm c}$ is the DM-nucleon capture rate, and $C_{\rm s}$ is the DM self-interaction capture rate (see [66]). $C_{\rm c}$ is given in Ref. [65], assuming a Maxwellian DM distribution, and taking into account general relativistic corrections: (see [35,37,65,66]).

As shown by Ref. [45], in the framework of a spherically symmetric accretion scenario for a typical NS of mass $1.4 M_\odot$ and R = 10 km, the total accreted mass is

$$M_{\rm acc} = 1.3 \times 10^{43} \left(\frac{\rho_{\rm dm}}{0.3\ {\rm GeV/cm^3}} \right) \left(\frac{\rm t}{\rm Gyr} \right) f\ \ {\rm GeV}, \tag{2}$$

where $\rho_{\rm dm}$ is the local DM density, t is the accretion time of DM by the NS and f gives the NS particle fraction undergoing scatterings while in the NS, that is set $f = 1$ for scattering cross section $\sigma_{\rm dm} > 10^{-45}$ cm^2, or $f = 0.45\, \sigma_{\rm dm}/\sigma_{\rm crit}$, with $\sigma_{\rm crit} \simeq 6 \times 10^{-46}$ cm^2, for a homogeneous NS (see [35] for a detailed calculation).[4] From XENON1T [68], $\sigma_{\rm dm}$ for a particle mass of some hundreds of GeV is $\simeq 10^{-45}$ cm^2, leading to $f \simeq 1$. Note that Eq. (2) is an underestimation of a factor $\simeq$ 10, since the accretion during the NS progenitor phase, of the same order as in the NS phase [37] (factor of 2), and the accretion coming from DM self-interaction [66] are not taken into account, and finally because in this paper, we will use NSs having mass $2M_\odot$.[5] The time t changes from pulsar to pulsar. Pulsars can be very young (e.g., CRAB pulsar), very old, $>10^{10}$ yrs (PSR J1518+4904, PSR J1829+2456) [69], $\simeq$2 Gyr (PSR J1811-1736) [69], or present intermediate ages, e.g. some 10^8 yrs (PSR B1534+12 , PSR J0737-3039, PSR J1756-2251, etc.) [69,70]. In our calculation, we used $t = 10$ Gyr.[6] We chose this value because the number of old neutron stars (10^9, 10^{10} yrs) increases going towards the galactic centre [71–73] with a maximum around 3 kpc (note that the majority of pulsars are located at $r > 3$ kpc – ATNF catalogue). It is highly probable that the trend continues going towards the galactic centre.

Moreover, NSs and Supernovae numbers increase going towards the galactic centre [74,75], inducing a larger probability to find older objects close to the GC. These are other obvious incentives to eagerly wait for new observations finding objects closer to the GC.

We obtain DM accretion $\simeq 10^{-11} {\rm M}_\odot$ for a typical NS in the solar neighbourhood , which is in agreement with the capture rates of Refs [45,66,67,76] and the results from [65], but below the estimates from the DM accumulated using TOV. A better agreement between the accreted DM mass and the accumulated DM mass coming from TOV is obtained for NSs located in Superdense DM clumps, Ultra Compact mini-haloes [77], and close to the GC. We recall that another approach to DM accretion is proposed by [78].

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[3] Recall that General Relativity (GR) gives an upper limit to NSs mass of $3.2 M_\odot$ [49] using an extreme causal equation of state, although in Ref. [50] a more conservative limit of $4.7 M_\odot$ is found. Gravitational waves (GW) observations accompanied by a short gamma-ray burst, assumed to be originated from a black hole centre engine, lead to an upper mass limit of $\lesssim 2.2 M_\odot$ for NSs [51,52]. However, should the short gamma-ray burst be originated instead from a magnetar centre engine, the $2.2 M_\odot$ mass could become a lower limit. Note that the present heaviest pulsar PSR J0740+6620 reaches $2.14 M_\odot$ [53,54]. The theoretical lower limit to NSs mass is 0.1 $M_\odot$ but lepton-rich proto neutron stars are unbound below about 1 $M_\odot$ [55].

[4] Note that in usually inhomogenehous NS, f will be larger than the proposed estimate [35].

[5] Then Eq. (2) must also multiplied by a factor 2.05.

[6] In what follows we discuss the effect of a change in total accretion time t.

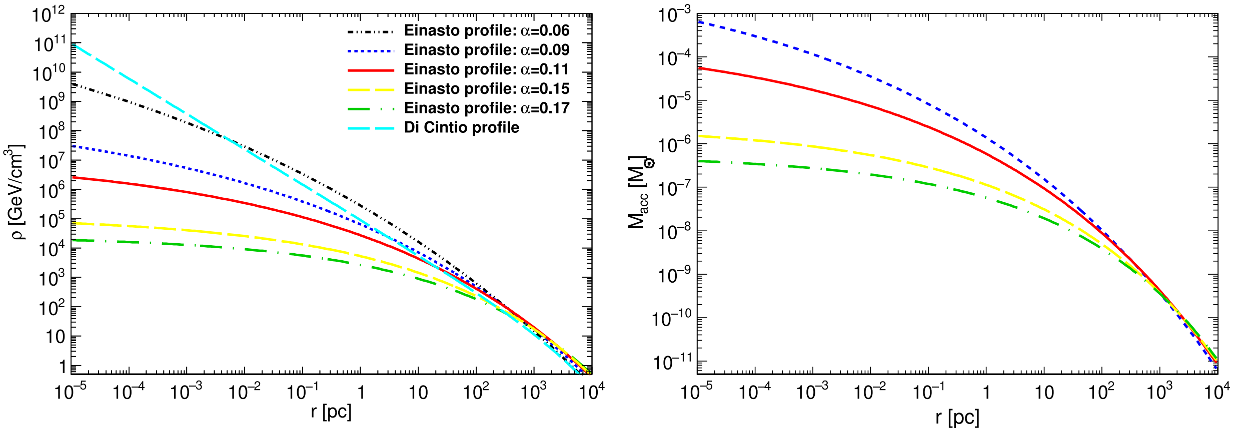

Fig. 1. (Left panel) Einasto profile for $\alpha = 0.06, 0.09, 0.11, 0.15, 0.17$ (black dot dot dashed, blue dotted, red solid, yellow long dashed, and green dot dashed lines, respectively). The cyan dashed line is the Di Cintio profile [79] (labelled DC14 in the text). (Right panel) The accreted mass according to Kouvaris formula (Eq. (2)). In this plot we do not consider the accreted mass corresponding to the Di Cinto profile, nor to the Einasto profile with $\alpha = 0.06$, in order to be conservative in our calculations.

3. Dark matter in the Milky Way

The nature of the Milky Way (MW) density profile is not known from observations [80,81], with some simulations predicting cuspy profiles [82], while some more recent ones finding a flattening towards the GC [83,84]. Consequently, the determination of the DM environment in which NSs are embedded in MW, and the estimation of DM accreted by them, poses problem. In this paper, we use the Einasto profile, as it yields a good description of recent simulations [83]. Note that such profile, obtained in DM-only simulations, does not consider baryon effects. Moreover, as COs accrete DM according to their environment, locally dense environments lead to larger DM content, which gives rise to smaller mass COs.

In the left panel of Fig. 1, the Einasto DM density profile is plotted for different values of the parameters (see the figure caption for details),

$$\rho = \rho_{-2} \mathrm{e}^{-2\frac{1}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha}-1\right]}, \tag{3}$$

where α gives the degree of cuspiness of the profile, and r_{-2} indicates the distance at fixed slope $\frac{d\ln\rho}{d\ln r} = -2$, where the density reaches ρ_{-2}.

In order to fix the three free parameters of the Einasto profile, there are two possibilities: (1) simulations; (2) MW observations. Concerning simulations, the value of α lies in the range $0.12 < \alpha < 0.22$ [85], while more recently Ref. [86,87] found $\alpha \simeq 0.15$ for a halo having the mass of the MW, in agreement with other DM-only simulations (no baryons account) and MW observations. However, baryons affect the density profile by (1) steepening it with adiabatic contraction [88–91]; (2) flattening it with supernovae feedback or similar effects [79,92–94], such as dynamical friction [93,95].

Process (1) dominates MW-type galaxies and, as a consequence, DM-only simulations need a correction as in Ref. [96], that was later confirmed by hydro-dynamical simulations [79], which showed that the inner slope of the density profile is steepened as $\frac{d\ln\rho}{d\ln r}\big|_{r\to 0} \simeq -1.2$ [90]. This result translates into a reduction of the inner slope from $\alpha = 0.15$, given in DM-only simulations [86,87], to $\alpha = 0.11$ [97], which we choose as our fiducial value. Due to adiabatic contraction, the concentration parameter changes from values $\simeq 8.5$ of DM-only simulations [98,99] to a value two times larger, $18-20$ [79], in agreement with observations of the MW [80,100,101], producing a reduction of r_{-2}. For a halo having a virial mass $M_{\rm vir}$, and virial radius $r_{\rm vir}$, $r_{-2} = r_{\rm vir}/c$. Then, taking into account baryons effects, for MW-like mass halo, $r_{-2} \simeq 10$ kpc, in agreement with SPH simulations [79], and 2 times smaller than N-body only simulations (e.g. [86]). In the following, we use as fiducial value 15 kpc. In order to get the normalization, i.e. the third parameter ρ_{-2}, we use Eq. (3) with the previous given values of α, and r_{-2}, and assuming that the local density, $\rho(R_\odot)$, being $R_\odot$ the distance Sun-GC, has the value estimated by [102], $\rho(R_\odot) = 0.420^{+0.019}_{-0.021}$, using their value of $R_\odot$. The Einasto model with those parameters, and all the quantities related to it, is plotted in red (solid line). In the paper, we will also consider a range of parameterization differing from the fiducial case.

As previously reported, observations, within the limits of their uncertainties, allow to constraint the Einasto profile. For a given α, mass constraints, e.g. $M(60\,{\rm kpc}) = (4 \pm 0.7) \times 10^{11} M_\odot$ [103,104], together with, e.g., the [102] local density $\rho_\odot$, allows to fix the density profile parameters [97].[7] γ-rays observations [104] have also been used to constrain the Einasto profile parameters, together with mass modelling [105,106] obtaining constraints in agreement with those of [85], and with our fiducial case: $0.10 < \alpha < 0.22$, $8 < r_{-2} < 30$ kpc.

The right panel of Fig. 1 shows the corresponding DM accreted using the formula given in Eq. (2) from Ref. [45]. The blue dotted, red solid, yellow long dashed, and green dot dashed lines correspond to $\alpha = 0.09, 0.11, 0.15, 0.17$. This means, that while a NS located at the Sun neighbourhood will accrete $\simeq 10^{-11} \mathrm{M}_\odot$, one located at $10^{-5}(0.1)$ pc will accrete $6.5 \times 10^{-4} (3.4 \times 10^{-6}) \mathrm{M}_\odot$, in the case $\alpha = 0.09$.

4. Mass change of neutron stars

Once the accreted DM mass, $M_{\rm acc}$, as a function of the distance to the GC is determined from the right panel of Fig. 1, we can determine the corresponding mass change of the NS. In order to do so, we use Fig. 10 of our previous work [63], where the maximum mass of NSs was obtained as a function of the DM mass inside the NS, $M_{\rm DM}$, for the DM weakly interacting case, $y = 0.1$.[8] Moreover, we obtained similar plots for larger values

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[7] ($\simeq$10 kpc, $\rho_{-2} \simeq 0.3$ GeV/cm^3, 0.11).

[8] The interaction strength is expressed in terms of the ratio of the DM fermion mass m_f, and scale of interaction m_I, $y = m_f/m_I$. This can be converted to usual units: one can estimate the cross section of DM self-interaction, taking the mass of the DM particle m_f in units of GeV, as

$$\sigma = \frac{1}{4\pi}\frac{m_f^2}{m_I^4} = \frac{y^4}{m_f^2} 3.2 \times 10^{-27} \mathrm{cm}^2$$

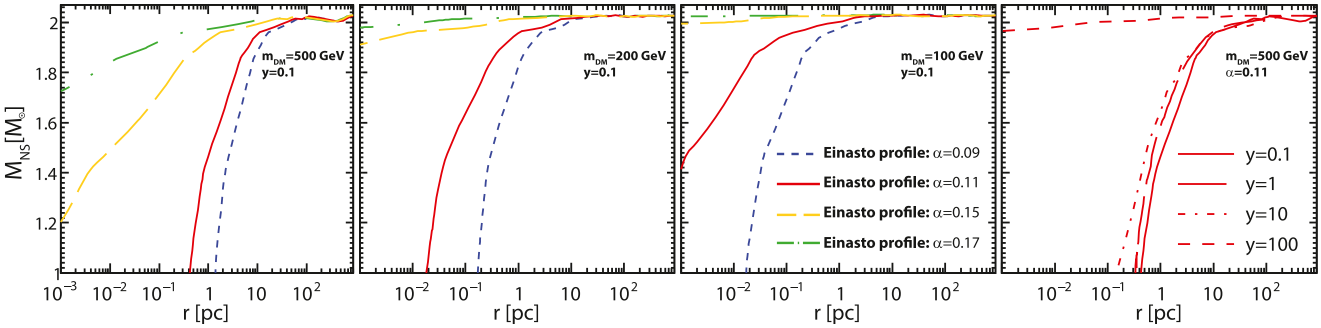

Fig. 2. The changes of the NS mass from DM accumulation as a function of the NS distance to GC, for a particle mass $M = 500$ (leftmost), 200 (centre left) and 100 (centre right) GeV, with $y = 0.1$ and $\alpha = 0.09, 0.11, 0.15, 0.17$ (blue dotted, red solid, yellow long dashed , and green dot dashed). The rightmost panel shows the role of the interaction strength for particle mass $M = 500$ GeV, $\alpha = 0.11$, and $y = 0.1, 1, 10, 100$ (solid, long dashed, dash dotted, and long dashed dotted lines).

of the interaction parameter y, $y = 1, 10, 100$. Since M_{DM} must be equal to the accreted mass M_{acc}, we find a relation between the total mass of the NS, M_{NS} (M_T in the notation of [63]) and the distance from the GC. The result is plotted in Fig. 2. Its leftmost panel displays the change in mass of a NS moving towards the MW halo centre (colour and line coding as in Fig. 1), for a particle mass, $M = 500$ GeV, and $y = 0.1$. Our reference model ($\alpha = 0.11$, red solid line) shows a NS mass change from 2 to 1 $M_\odot$ at 0.4 pc,[9] while in the case $\alpha = 0.09$ (blue dotted line) the same change is observed at 1.35 pc. The other two cases show a slower mass change. The yellow long dashed line ($\alpha = 0.15$), and the green dot dashed line ($\alpha = 0.17$) show that the mass reduces from 2 to 1.2 $M_\odot$, and from 2 to 1.7 $M_\odot$, at 10^{-3} pc, respectively. The next two panels show how the mass changes with decreasing the DM particle mass ($M = 200$ GeV, centre left, 100 GeV, centre right). Finally the rightmost plot shows the effect of the interaction strength for our reference profile ($\alpha = 0.11$), and from right to left, in the cases $y = 0.1, 1, 10, 100$. Strongest interaction ($y = 100$) produces very small mass changes, while the weaker the interaction, the larger the change is.

All the above results are obtained with the conservative assumption of using a density profile from DM-only simulations, shallower than in recent hydrodynamic simulations [79].

As the right panel of Fig. 1 shows, we excluded from the analysis the $\alpha = 0.06$ Einasto profile, and even the DC14 profile [79], a realistic profile calculated with hydro-dynamical simulations, to remain conservative. In the same line, a recent paper appearing after our results were publicized [107], using the steeper NFW profile, that entails a central density 600 times higher than our conservative profile, is reporting a DM to total mass fraction of order 1% for NSs at a distance around the centre of the order of kpc, while our model predicts at 1kpc a fraction of 7.4×10^{-4}%, neglecting possible spikes due to the BH. For precision's sake, most probably, the best description of the density profile close to the galactic centre is DC14 ([79] and references therein), since it describes very well, and shows very good agreement with, the profile of observed galaxies. This would induce the central density of a factor 3×10^4 larger than what we have plotted. Such conjecture is reinforced, as several papers are agreeing on the fact that the density close to the galactic centre is of the order of, or even much larger (10^4 times larger) than, that indicated by DC14 (i.e. [39,108,109]). Furthermore, Ref. [110] expect DM density spikes in the GC, whereas Lacroix [111] does not exclude a spike with radius smaller than a few tens of parsecs for cuspy outer halos. Recently, [112] examined the spikes and gave several references discussing their existence (e.g. [113,114]).

Although we made the choice of a more conservative density profile, we note that the orbital dynamics of PSR B1257+12 [115], together with the accretion predictions [108] allows much larger DM accumulation in NS than in our present work: up to 10% of a NS mass, in agreement with DC14 [116]. Moreover, complex astrophysical phenomena are occurring on sub-parsec scale near the GC, such as DM particles gravitational scattering by stars and capture in the supermassive BH, together with highly enhanced central density from the supermassive BH formation [108,109]. Thus, more accurate density profiles can be introduced [39,108].

5. Mass determination of neutron stars close to the galactic centre

At this stage, the remaining question is whether the mass change of NSs can be determined by observations. Despite the hundreds, or up to thousands, pulsars theoretically expected in the GC [117–119], only six have been detected in the Galaxy inner 30′ [120–123]. In particular, the J1745-2900 [120–123], a transient magnetar, is located 0.1 pc from the GC. This "missing pulsars" problem can be understood by hyper-strong interstellar scattering [124], more complex scattering models, stellar population synthesis arguments, or pulsar emission suppression mechanisms [125].

Estimates for SKA (Square Kilometre Array) [126] advocate detection of a $L_{1000} \simeq 0.7$ mJy kpc^2 5-ms MSP (millisecond pulsar) at the GC with a ratio signal/noise of $S/N = 10$ and spectral index $\alpha = -1$. A few pulsar-black hole binaries are also estimated [126] in the inner parsec, while [119] propose a conservative upper limit $\simeq 200$, albeit [127] predicts that up to 52 canonical pulsars could be observed, and 10000 MSPs, by SKA and Next Generation Very Large Array (ngVLA) surveys [128,129]. In addition , the factor of 10 improvement in sensitivity at high frequencies promised by the ngVLA [128] will be an unprecedented probe of General Relativity and black hole physics, making dramatic improvements on the detection of pulsars close to the GC. These promises are already in motion with the Event Horizon Telescope (EHT) [130] whose team recently released the first image of the M87 black hole.

After a pulsar is detected, the mass needs to be determined. Mass measurements can be obtained in different ways [131, 132], and recently, an interesting new technique was added to the several already known, based on pulsar glitch data to constrain superfluid and nuclear EoS models [133]. The upcoming SKA [134], Athena [135,136], NICER [137] and eXTP [138] observatories are expected to offer precise measurements of the masses, together with radii, pinning down the composition of NS.

$$\rightarrow \sigma/m_f = \frac{y^4}{m_f^3} 1.8 \times 10^{-3} \mathrm{cm}^2/\mathrm{g} \qquad (4)$$

[9] Note that reducing the accumulation time, t, shifts the curves inward, i.e. towards smaller radii, by a same factor.

6. Conclusions

We have shown that the NS mass should reflect the changes of the DM environment in the MW (Fig. 2). This is done taking into account the DM accretion of NSs (see [63] for details), as it changes because of the increase of DM content [45] when we move towards the GC [104]. This allows us to propose that the evolution of the pulsar masses towards the GC of the MW can be a probe of the existence of DM. In fact, the decrease of the NS mass for NSs located closer and closer to the GC would put constraints on the characteristics of the Galaxy halo dark matter profile, on the dark matter particle mass, and on the self-interaction strength. Such changes are expected to be observed in the near future in telescopes such as ngVLA, SKA, Athena, NICER or eXTP [128,134–138].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

M.D. work was supported by the Polish National Science Centre (NCN) grant 2016/23/B/ST2/00692. MLeD acknowledges the financial support by Lanzhou University starting fund and the Fundamental Research Funds for the Central Universities, China (Grant No. lzujbky-2019-25). L.T. acknowledges support from the FPA2016-81114-P Grant from Ministerio de Ciencia, Innovacion y Universidades, Spain, Heisenberg Programme of the Deutsche Forschungsgemeinschaft, Germany under the Project Nr. 383452331 and PHAROS COST Action CA16214.

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