Neutron stars: new constraints on asymmetric dark matter

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We study an impact of asymmetric dark matter on properties of the neutron stars and their ability to reach the two solar masses limit, which allows us to present a new upper constraint on the mass of dark matter particle. Our analysis is based on the observational fact of existence of three pulsars reaching this limit and on the theoretically predicted reduction of the neutron star maximal mass caused by accumulation of dark matter in its interior. Using modern data on spatial distribution of baryon and dark matter in the Milky Way we argue that particles of dark matter can not be heavier than 5 GeV. We also demonstrate that light dark matter particles with masses below 0.2 GeV can create an extended halo around the neutron star leading not to decrease, but to increase of its visible gravitational mass. Furthermore, we predict that high precision measurements of the neutron stars maximal mass near the Galactic center, will put a stringent constraint on the mass of the dark matter particle. This last result is particularly important to prepare ongoing, and future radio and X-ray surveys.

INTRODUCTION

Despite strong observational evidences of dark matter (DM) existence [1], at present, its fundamental nature remains a mystery, which is the reason why there exist so many DM candidates. Among the most promising ones are WIMPs, axions [2] and sterile neutrinos [3]. Unfortunately, until now, terrestrial experiments on nuclear recoil of DM [4], and direct searches of the DM annihilation [5] have not yet found a suitable candidate.

Because of it, the astrophysical probes of the DM properties are of high interest. Compact astrophysical objects, such as neutron stars (NSs) are especially attractive in this context, since they can accumulate a sizable amount of DM in the stellar interior [6–9]. At the same time, depending on its nature, DM can affect the properties of NSs in quite different ways. For instance, an accretion of self-annihilating DM to a NS will increase its luminosity and effective temperature [10].

A challenging new way to study DM is to consider that the DM particles are similar to those of baryon matter (BM). Likewise, this new particle carries a conserved charge, and, as a consequence, causes an absence of symmetry between such particles and antiparticles [11, 12]. Hence, due to the absence of anti-particles, no self-annihilation can occur, and as such, this process produces no heat. Such type of DM is usually called asymmetric dark matter (ADM). There is a large number of articles that have explored ADM in different astrophysical contexts. Examples are the studies of ADM in the Sun [13–16] and other stars [17, 18]. This DM type is the subject of our study in this letter.

Several robust observational results strongly support the existence of DM [19]. For instance, in Ref. [20] is reported that in Galaxy, about 70% of its total mass is DM. Therefore, if ADM exists, in principle, its fraction inside the NSs can be significant. In the absence of repulsive self-interactions, the gravitational collapse of ADM can lead to the formation of a mini black hole inside the NS; this imposes a powerful constraint on the properties of DM [21]. If, however, ADM is constituted by fermions or bosons with self-repulsion, then it can resist gravitational collapse and form stable configurations inside the NSs [22].

The main consequence resulting from the presence of DM inside the NSs is the reduction of the stellar mass (see [23] and references therein). This measurable effect provides an opportunity to infer the DM properties from the mass-radius relation for NSs. [24] has shown that the mass of pulsars admixed with DM depends on its distance from the Galaxy center. Presently, however, this approach is limited, since it requires reliable observational data on many compact objects. At the same time, a significant reduction of the NS mass caused by the presence of DM, can make the two solar mass limit unattainable and shift the maximal apparent mass to lower values. Thus, observational fact of the existence of three NSs that have the largest known masses (i.e., PSR J0348+0432, PSR J0740+6620, PSR J1614-2230) [25–27], enables us to formulate a strict constraint on the maximum mass of an ADM particle, which is the primary goal of this study.
DARK MATTER ADMIXED NEUTRON STARS

The current experimental bounds for the DM direct detection imposes the DM-BM interaction cross-section \( \sigma_D \sim 10^{-45} \text{ cm}^2 \) \cite{28} to be many orders of magnitude lower than a typical nuclear one \( \sigma_N \sim 10^{-24} \text{ cm}^2 \). Conveniently, we neglect the interaction between baryons and DM particles in the rest of the article. Accordingly, we assume that the BM and DM are coupled only through gravity, and their energy-momentum tensors are conserved separately. Hence, the system of equations

\[
\frac{dp_j}{dr} = -\frac{(\epsilon_j + p_j)(M + 4\pi r^3 \rho)}{r^2 (1 - 2M/r)} \quad (1)
\]

describes the relativistic hydrostatic equilibrium of a NS with DM. Hereafter subscript index \( j = B \) and \( j = D \) stands for BM and DM, respectively; \( p_j \) and \( \epsilon_j \) correspond to the pressure and energy density of the \( j \) component, \( r \) is the distance from the centre of the star, and \( p(r) = p_B(r) + p_D(r) \). The gravitational mass \( M \) is the sum of masses of both components, i.e., \( M(r) = M_B(r) + M_D(r) \), where

\[
M_j(r) = 4\pi \int_0^r \epsilon_j(r') r'^2 dr'. \quad (2)
\]

The system of Eqs. \( 1 \) along with a definition of \( M \) is a generalization of the Tolman-Oppenheimer-Volkov equation (TOV) \cite{29,30}, recovered in the absence of the DM, when \( p_D = 0 \) and \( \epsilon_D = 0 \). We compute the radial density profiles of the BM and DM from Eqs. \( 1 \) and \( 2 \), by imposing two conditions at the centre of the star and two boundary conditions. The first set corresponds to the central densities of BM and DM. The second set assumes that each of the matter components is dynamically equilibrated with the surrounding vacuum at its boundary, which means that their pressures are equal to zero. Thus, the radii of the BM and DM spheres \( R_B \) and \( R_D \) are defined by the condition

\[
p_j(R_j) = 0. \quad (3)
\]

The DM component is not accessible by direct observations. Hence, it is natural to identify the NS radius \( R \) with \( R_B \), i.e. \( R = R_B \). The total gravitational mass, and the fraction of DM inside the NS are defined as

\[
M_T = M_B(R_B) + M_D(R_D), \quad (4)
\]

\[
f_X = \frac{M_D(R_D)}{M_T}, \quad (5)
\]

respectively. It is clear that variation of central densities of BM and DM allows us to obtain different values of \( M_T \) and \( R \) at given \( f_X \).

**BM equation of state**

The reliable modelling of the DM distribution inside NSs requires all the effects of BM to be taken under control. For this purpose we use the recently developed realistic EoS with induced surface tension (IST EoS hereafter) \cite{31,32}, which accounts for the short-range repulsion between baryons, and their long-range attraction of the mean field type. This EoS is consistent with nuclear and hadron matter experimental data, i.e. the nuclear matter ground state properties \cite{31}, the proton flow data \cite{32}, constraints on the hadron hard-core radii obtained in the heavy-ion collisions \cite{34,35}. Furthermore, recently, the IST EoS was successfully applied to modelling of purely baryon-lepton NSs \cite{32}. In this work, we stay with a parametrization of the present EoS found in Ref. \cite{36}.

Partial derivatives of \( p_B \) with respect to chemical potentials of neutrons \( \mu_n \), protons \( \mu_p \) and electrons \( \mu_e \) give the number densities of corresponding particles, i.e. \( n_n, n_p \) and \( n_e \). Note that the baryonic charge density is \( n_B = n_n + n_p \). Conditions of electric neutrality \( n_p = n_e \) and equilibrium concerning \( \beta \)-decay \( \mu_n = \mu_p + \mu_e \) exclude \( \mu_p \) and \( \mu_e \) from the list of independent variables. Thus, \( p_B \) is a function of \( n_B \) only, which coincides with the chemical potential associated with the baryonic charge \( \mu_B \), i.e. \( \mu_n = \mu_B \). The energy density of BM is defined through the well known thermodynamic identity as

\[
\epsilon_B = \sum_{i=n,p,e} \mu_i n_i - p_B = \mu_B n_B - p_B. \quad (6)
\]

**DM equation of state**

Here we consider the DM component as a relativistic Fermi gas of noninteracting particles with the spin one-half. The corresponding EoS has been exhaustively described in the literature, for instance in Ref. \cite{37}. The energy density of DM is obtained from the thermodynamic identity

\[
\epsilon_D = \mu_D n_D - p_D, \quad (7)
\]

where \( \mu_D \) and \( n_D = \partial p_D/\partial \mu_D \) are chemical potential and particle number density of DM. Typically, its repulsive self-interaction is accounted for by the term \( n_D^2/m_1^2 \) in pressure, where \( m_1 \) is an interaction scale. We neglect this term, since, for example, at \( m_1 = m_\chi \) it does not exceed 15% of \( p_D \) even in the NS centre, where \( n_D \) reaches the highest value.

**GRAVITATIONAL INFLUENCE OF DM CONDENSATE**

Once we solved a two-component system of Eqs. \( 1 \) with the appropriate boundary conditions, we can anal-
Fig. 1: Total gravitational mass $M_T$ of the DM admixed NS vs. its visible radius $R$ calculated for $m_\chi = 0.1$ GeV (upper panel) and 1 GeV (lower panel) for the different fractions of DM $f_\chi$. The straight dashed line corresponds to $M = 2 M_\odot$.

The influence of the DM on the total gravitational mass of a NS and its visible radius. Fig. 1 shows the mass-radius relation of the DM admixed NS for two values of $m_\chi$ and different fractions $f_\chi$. We found that light DM particles can not sizably reduce the maximal mass of NS $M_{max}$. Moreover, we note that $m_\chi = 0.1$ GeV yields $M_{max} > 2 M_\odot$ for any $f_\chi$. However, for heavy DM particles the situation changes completely. As it is seen from the lower panel of Fig. 1, DM with $m_\chi = 1$ GeV strongly influences the mass-radius relation of NSs. For example, for $f_\chi = 3.3\%$ (red dotted curve) $M_{max}$ equals to $2 M_\odot$, while further increase of the DM fraction leads to decrease of $M_{max}$ below $2 M_\odot$ (green dashed curve). For larger values of $m_\chi$, the reduction of $M_{max}$ is even more dramatic. Such a sensitivity of the NSs mass to the presence of DM is related to its distribution in the stellar interior.

Fig. 2 shows the radial profiles of the energy density of BM and DM inside a NS. In the case of light DM particles (with $m_\chi = 0.1$ GeV) these profiles are rather gradual at all fractions $f_\chi$. Besides that, the typical values of $\epsilon_D$ are significantly smaller than $\epsilon_B$, while $R_D$ is large. In particular, $R_D = 9.4$ km for $f_\chi = 0.3\%$, $R_D = 21.2$ km for $f_\chi = 1.0\%$ and $R_D = 135.2$ km for $f_\chi = 3.0\%$. Note, that these large values of $R_D$ relate to the existence of dilute and extended halos of DM around a baryon core of NS. As a consequence, at small $m_\chi$ DM does not form a compact structure inside the NS able to significantly reduce its total mass. This explains qualitatively why the presence of light DM particles inside a NS is consistent with $M_T \geq 2 M_\odot$. The situation is completely different in the case of heavy DM particles. The lower panel of Fig. 2 demonstrates that the energy density profile of DM with $m_\chi = 10$ GeV is very steep. Indeed, $\epsilon_D$ drops from its maximal value, being four orders of magnitude above $\epsilon_B$, to almost zero within only about $R_D = 0.1$ km. Such a high value of $\epsilon_D$ in combination with small $R_D$ leads to a very compact core of DM. The corresponding compactness $2M_D(R_D)/R_D$ can reach values up to 0.4, while total compactness is even slightly larger. It follows from Eq. (1) that in this case the derivatives $dp_B/dr$ and $dp_D/dr$ become large by an absolute value. Hence, $\epsilon_B$ and $\epsilon_D$ rapidly decrease at $r \sim R_D$, which is seen on the lower panel of Fig. 2.

At $r > R_D$ the impact of the DM core weakens and profile of the BM energy density becomes gradual again. At the same time, the values of $\epsilon_D$ in the regions of the star with $r \sim 0.1 - 9$ km are considerably smaller than without DM. This leads to a significant reduction of the total mass of NS. Thus, we conclude that heavy DM particles tend to create very compact core, which even despite small fraction $f_\chi$, reduces the total mass of NS, and does not allow it to reach the two solar masses limit. It is also worth noting that for large $m_\chi$, the energy density profiles inside NS are very sensitive to the fraction of DM. For example, at $m_\chi = 10$ GeV a relative increase of $f_\chi$ by 7.6\% (from 0.299\% to 0.322\%) leads to about 40\% reduction of $\epsilon_B$ and, consequently, to a drastic decrease of the NS maximal mass from $2.07 M_\odot$ to $1.88 M_\odot$.

Thus, we conclude that light DM particles do not modify the mass-radius relation significantly, while heavier DM particles lead to a substantial reduction of the NS maximal mass.

Fig. 3 shows $M_{max}$ as a function of $f_\chi$ for several values of $m_\chi$. As shown, for $m_\chi = 0.1$ GeV (solid red curve), the most significant reduction of the NS maximal mass is achieved at $f_\chi \simeq 1.3\%$ with $M_{max} = 2.07 M_\odot$. We notice that the existence of an extended DM halo in-
creases the NS maximal mass at larger fractions $f_\chi$. At the same time, for $m_\chi = 1.0$ GeV (green dotted curve) $M_{\text{max}}$ monotonously decreases with the grows of $f_\chi$, and gets smaller than $2M_\odot$ already at $f_\chi = 0.312\%$. For $m_\chi = 0.174$ GeV the lowest value of $M_{\text{max}}$ is $2M_\odot$. Therefore, within the present model, DM particles with $m_\chi \leq 0.174$ GeV are consistent with the $2M_\odot$ constraint for any $f_\chi$, while for heavier DM particles the NS mass can reach $2M_\odot$ only if $f_\chi$ is limited from above.
CONSTRaining Mass of the Dark Matter particles

Below for each value of $m_\chi$ we find a critical fraction of DM $f_\chi^*$, which yields to $M_{\text{max}} = 2 M_\odot$. Fig. 4 shows how this quantity (black curve) varies with $m_\chi$. Any point above this curve corresponds to the unphysical region with $M_{\text{max}} < 2 M_\odot$, and, consequently, is inconsistent with the two solar mass observational limit [25–27]. All the points below this curve agree with the observational condition $M_{\text{max}} > 2 M_\odot$. Note, that for $5 \text{ GeV} < m_\chi < 1 \text{ TeV}$, the critical fraction of DM is well fitted by the power law: $f_\chi^* \sim m_\chi^{-1.92}$. The found dependence of $f_\chi^*$ on $m_\chi$ allows us to constrain the DM particle mass.

For this we assume that the DM fraction inside the NS is not lower than the one in the stellar surrounding, which depends only on the distance from the Galaxy centre $d$. We denote this quantity $f_\chi^*$, and compute it by using the Navarro-Frenk-White spatial mass distribution of DM in the Milky Way [38]:

$$\rho_\chi(d) = \rho_\odot \frac{d_c}{d} \left(1 + \frac{d}{d_c}\right)^{-2}. \quad (8)$$

We adopt the characteristic density $\rho_\odot = 5.22 \pm 0.46 \times 10^7 M_\odot \text{pc}^{-3}$ and characteristic length $d_c = 8.1 \pm 0.7 \text{ kpc}$ determined in Ref. [39] directly from the observational data analysis. In particular, we are interested in the local fraction of DM $f_\chi^*$ in regions near the heaviest known pulsars, specifically, PSR J0348+0432 with $M = 2.01 \pm 0.04 M_\odot$ [24], PSR J0740+6620 with $M = 2.17^{+0.11}_{-0.10} M_\odot$ [26] and PSR J1614-2230 with $M = 1.97^{+0.04}_{-0.04} M_\odot$ [27]. Their distances to the Galaxy centre are 9.9 kpc, 8.6 kpc and 7.0 kpc, respectively. Moreover, these pulsars are not located in the Galaxy bulge (with a size $d_b \simeq 1.9 \text{ kpc}$) [40]. Therefore, with high accuracy, we can consider only the contribution of the stellar disc to the BM density profile:

$$\rho_B(d) = \rho_{d_\odot} e^{-d/d_{d_\odot}}. \quad (9)$$

Here $\rho_{d_\odot} = 15.0 M_\odot \text{pc}^{-3}$ and $d_{d_\odot} = 3.0 \text{ kpc}$ [40].

We estimate the local fraction of DM in the Milky Way as the ratio of DM mass density to the total mass density of DM and BM. Thus, using Eqs. (8) and (9), we find the upper estimates for fraction $f_\chi^*$, which are 1.6 $\pm$ 0.4 % near PSR J0348+0432, 1.35 $\pm$ 0.35 % near PSR J0740+6620 and 1.2 $\pm$ 0.3 % near PSR J1614-2230. In Fig. 4 these values are depicted as red, green and blue lines. Their intersections with the black curve define the maximal value of $m_\chi$, which is consistent with the existence of the corresponding pulsar. Therefore, we can conclude that existence of two solar mass NSs in the Milky Way excludes DM heavier than about 5 GeV.

The number of pulsars and magnetars in the most central part of the Galaxy within 70 pc from its center is likely to be high [41]. The upcoming observational missions are expected to measure masses of NSs in that region with high precision. Future surveys, probably, will significantly replenish a collection of already known six pulsars in the central region, including a transient magnetar J1745-2900. Among other specific measurements these searches will provide a more accurate information about the mass of NSs, the ones close to the Galactic center are especially under big interest. The following astronomical projects are very promising in this context: radio telescopes – the Karoo Array Telescope (MeerKAT) [42], the Square Kilometer Array (SKA) [43], the Next Generation Very Large Array (ngVLA) [44], space telescopes – the Neutron Star Interior Composition Explorer Mission (NICER) [45], the Advanced Telescope for High Energy Astrophysics (ATHENA) [46], the enhanced X-ray Timing and Polarimetry mission (eXTP) [47], and the Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X) [48].

Summary and Conclusions

Using the observational fact of the existence of the three heaviest known NSs (i.e., PSR J0348+0432, PSR J0740+6620, PSR J1614-2230) with the masses exceeding the two solar ones, we present a novel upper constraint on the mass of DM particles. Our analysis is based on the ability of NSs to accumulate a sizeable amount of ADM, which can significantly reduce the mass of the host NS. Therefore, by using recent results on the distribution of DM and BM in Milky Way, we argue that particles of ADM can not be more massive than 5 GeV. We also demonstrate that DM lighter than 0.2 GeV can create an extended halo around the NS leading not to decrease but to increase of the NS total (gravitational) mass. These results are under big interest for the forthcoming and ongoing projects, which are planned to increase the total number of observed compact objects by a factor $\sim 10$ and to provide a better determination of their masses and radii [42–44].

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Planck Collab., P. A. R. Ade et al., A&A, 594, A13 (2016).
[2] L. J. Rosenberg, K. A. van Bibber, Phys. Rep. 325, 1 (2000).
[3] S. Dodelson, L. M. Widrow, Phys. Rev. D 72, 17 (1994).
[4] F. Mayet, A. M. Green, J. B. R. Battat, Phys. Rep. 627, 1 (2016).
[5] J. Conrad, arXiv:1411.1925 (2014).
[6] C. Kouvaris, P. Tinyakov, Phys. Rev. D 82, 063531 (2010).
[7] B. Bertoni, A. E. Nelson, S. Reddy, Phys. Rev. D 88, 123505 (2013).
[8] G. Narain, J. Schaffner-Bielich, I. N. Mishustin, Phys. Rev. D 74, 063003 (2006).
[9] G. Panotopoulos, I. Lopes, Phys. Rev. D 96, 023002 (2017).
[10] M. Á. Pérez-García, J. Silk, Phys. Lett. B 711, 6 (2012).
[11] J. L. Feng, M. Kaplinghat, H. Tu, H.-B. Yu, J. of Cosm. and Astropart. Phys. 07, 004 (2009).
[12] I. Lopes, K. Kadota, J. Silk, Astrophys. J. Lett. 780, L15 (2014).
[13] I. Lopes, J. Silk, Astrophys. J. 757, 130 (2012).
[14] A. C. Vincent, P. Scott, A. Serenelli, Phys. Rev. Lett. 114, 081302 (2015).
[15] A. C. Vincent, P. Scott, A. Serenelli, J. Cosm. Astrop. Phys. 11, 007 (2016).
[16] K. Murase, I. M. Shoemaker, Phys. Rev. D 94, 063512 (2016).
[17] A. Martins, I. Lopes, J. Casanellas, Phys. Rev. D 95, 023507 (2017).
[18] J. Lopes, I. Lopes, Astrophys. J. 879, 50 (2019).
[19] B.-L. Young, Front. Phys. 12, 121201 2017.
[20] L. Posti, A. Helmi, A&A, 621, A56 2019.
[21] C. Kouvaris, Phys. Rev. Lett. 108, 191301 (2012).
[22] N. F. Bell, A. Melatos, K. Petraki, Phys. Rev. D 87, 123507 (2013).
[23] M. Deliyskiewicz et al., Phys. Rev. D 99, 063015 (2019).
[24] A. Del Popolo et al., arXiv:1904.13060 (2019).
[25] J. Antoniadis et al., Science, 340, 448 (2013).
[26] H. T. Cromartie et al., arXiv:1904.06750 (2019).
[27] P. B. Demorest, T. Pennucci, S. M. Ransom, Nature 467, 1081 (2010).
[28] T. Marrodán Undagoitia, L. Rauch, J. Phys. G 43, 013001 (2016).
[29] R. C. Tolman, Phys. Rev. 55, 364 (1939).
[30] J. R. Oppenheimer, G. M. Volkoff, Phys. Rev. 55, 374 (1939).
[31] V. V. Sagun et al., Nucl. Phys. A 924, 24 (2014).
[32] V. V. Sagun, I. Lopes, A. I. Ivanytskyi, Astrophys. J. 871, 157 (2019).
[33] A. I. Ivanytskyi et al., Phys. Rev. C 97, 064905 (2018).
[34] V. V. Sagun et al., Eur. Phys. J. A 54, 100 (2018).
[35] V. V. Sagun et al., Eur. Phys. J. Web of Conf. 137, 09007 (2017).
[36] V. V. Sagun, G. Panotopoulos, I. Lopes, submitted to Phys. Rev. D (2019).
[37] A. Nelson, S. Reddy, D. Zhou, arXiv:1803.03266 (2018).
[38] J. F. Navarro, C. S. Frenk, S. D. M. White, Astrophys. J. 462, 563 (1996).
[39] H.-N. Lin, X. Li, Mon. Not. Roy. Astron. Soc. 487, 5679 (2019).
[40] Y. Sofue, Publ. Astron. Soc. Jap. 65, 118 (2013).
[41] G. C. Bower et al., ASP Conf. Ser. 517, 793 (2018).
[42] M. Bailes et al., arXiv:1803.07421 (2018).
[43] A. Watts et al., Proc. Sci., 043 (2015).
[44] E. J. Murphy (and the ngVLA science and technical community), Proc. Int. Astro. Un. 336, 426 (2018).
[45] A. Watts, Am. Inst. Phys. Conf. Proc. 2127, 020008 (2019).
[46] R. Cassano et al., arXiv:1807.09080 (2018).
[47] J. J. M. in’t Zand, E. Bozzo, J. Qu et al., Sci. Ch. Phys., Mech. & Astron. 62, 29506 (2019).