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Can neutron stars constrain dark matter?

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Because of their strong gravitational field, neutron stars capture weakly interacting dark matter particles (WIMPs) more efficiently compared to other stars, including the white dwarfs. Once captured, the WIMPs sink to the neutron star center and annihilate, heating the star. We find that this heat could lead to detectable effects on the surface temperature of old neutron stars, especially those in dark-matter-rich regions such as the Galactic center or cores of globular clusters. The capture and annihilation is fully efficient even for WIMP-to-nucleon cross sections (elastic or inelastic) as low as $\sim 10^{-45}$ cm^2, and for the annihilation cross sections as small as $\sim 10^{-57}$ cm^2. Thus, detection of a sufficiently cold neutron star in a dark-matter-rich environment would exclude a wide range of dark matter candidates, including those with extremely small cross sections.

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I. INTRODUCTION

Since the initial discovery of the "missing mass" problem by Zwicky in the 1930s, a lot of theoretical, experimental, and observational effort has been put into unveiling the mystery of dark matter. A number of possibilities have been proposed, including modifications of the gravitational theory, hidden sector(s), primordial black holes and other massive objects, and new dark matter particles.

An attractive solution of the dark matter problem within the context of particle physics can be provided by a class of models with weakly interacting massive particles (WIMP). The standard model does not have a WIMP with the required characteristics, which means that WIMPs are probably related to physics beyond the standard model. There are several dark matter propositions according to what extension of the standard model one selects: supersymmetry [1,2], hidden sectors [3,4], technicolor [5–8], etc.

All currently existing evidence in favor of dark matter (as, for example, WMAP [9]) is of gravitational origin. In order to distinguish between the dark matter models, a direct (nongravitational) detection of dark matter particles is required. The most important parameters that determine the perspectives of the direct detection are the cross section σ_N of the dark matter-to-nucleon interaction, and the dark matter self-annihilation cross section σ_A, or the decay rate in models with decaying dark matter. Underground direct search experiments such as CDMS [10] and Xenon [11] have put tight constraints on the spin-independent and spin-dependent cross sections of WIMPs scattering off nuclei targets at the level of $\sigma_N \lesssim 10^{-43}$ cm^2. Interestingly, the DAMA Collaboration [12] claims the observation of an annual modulated signal with high statistical significance. A possible reconciliation of all the underground search experiments points to the existence of dark matter with excited states, in which case WIMPs can interact also inelastically [13,14], or to less mainstream scenarios as in [15,16].

In the past 20 years, there have been several attempts to constrain the properties of WIMPs by looking at signatures related to the accretion and/or annihilation of WIMPs inside stars. This includes the capture of WIMPs in the Earth and the Sun [17–19], the self-annihilation of WIMPs that can lead to an observable neutrino spectrum [20,21], the effect of dark matter in the evolution of low-mass stars [22,23], and the study of the WIMP accretion and/or annihilation inside compact stars such as neutron stars [24–26] and white dwarfs [27,28].

Compact objects and, in particular, neutron stars constitute a potentially promising way of constraining dark matter models. First, the high baryonic density in compact stars increases the probability of WIMP scattering within the star and eventually the gravitational trapping. This is crucial in view of the tiny value of σ_N. It should be noted that in the models with the inelastic dark matter interactions, the elastic and inelastic cross sections of the WIMP scattering inside the star are of the same order, because the WIMP velocity is much higher than the asymptotic value of 220 km/s, and its kinetic energy is therefore much larger than the splitting between the WIMP excited and ground states. Second, at the late stages of their evolution, neutron stars can be rather cold objects due to the lack of possible burning or heating mechanisms, and therefore heating by annihilation of the dark matter could produce an observable effect.

Close cousins of the neutron stars are the white dwarfs, the second most compact objects. They are easier to observe due to their larger surface area. However, they are lighter and less dense than neutron stars. For an efficient capture, a dark matter particle has to collide at least once per star crossing. For a neutron star, this requires the cross section to satisfy $\sigma_N \gtrsim 10^{-45}$ cm^2, while for a solar mass

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white dwarf of radius 5000 km one should have $\sigma_N \gtrsim 10^{-39}$ cm^2. As a result, neutron stars can probe much smaller values of the WIMP-to-nucleon cross section.

In this paper we consider constraints on the dark matter parameters that may arise from the neutron star cooling. This question has been addressed previously [25]. Here we concentrate specifically on the effect of the dark-matter-rich environments such as the Galactic center or cores of the globular clusters, and on the role of the neutron star progenitor.

In Sec. II we review the accretion and annihilation rates of dark matter WIMPs relevant for neutron stars. In Sec. III we study how the accretion of dark matter on the progenitor of a neutron star can affect the accretion and annihilation rates of WIMPs in a neutron star emerging after the collapse of its progenitor. In Sec. IV, we present lower bounds for the surface temperature of a neutron star as a function of its position in the galaxy, and in Sec. V we derive similar limits for neutron stars in globular clusters. We conclude in Sec. VI.

II. ACCRETION AND ANNIHILATION OF DARK MATTER INSIDE A NEUTRON STAR

The accretion rate of the dark matter WIMPs onto a neutron star, having taken into account relativistic effects [25], is

$$F = \frac{8}{3}\pi^2 \frac{\rho_{\rm dm}}{m}\left(\frac{3}{2\pi v^2}\right)^{3/2} \frac{GMR}{1-\frac{2GM}{R}} v^2 (1 - e^{-3E_0/v^2}) f, \quad (1)$$

where $\rho_{\rm dm}$ is the dark matter density at the neutron star location, m is the mass of the WIMP, M and R are the mass and the radius of the neutron star, respectively, v is the average velocity of WIMPs asymptotically far from the star, and E_0 is the typical WIMP energy loss at a single collision inside the star. The energy E_0 defines the maximum energy of WIMPs that can be trapped gravitationally after a single collision. The factor f (in the case of neutron stars) equals one for both elastic and inelastic cross sections if the latter is larger than $\sim 10^{-45}$ cm^2, and equals $f = \sigma_N/(10^{-45}\ {\rm cm}^2)$ for $\sigma_N < 10^{-45}$ cm^2. This factor describes inefficiency of dark matter trapping in case the probability of collision during a single passage through the star is less than one. In general, the fraction f for the particles that undergo one or more scatterings while inside the star is defined as [17]

$$f = \left\langle 1 - \exp\left[-\int \frac{\sigma_N \rho}{m_n} dl\right]\right\rangle \simeq \left\langle \int \frac{\sigma_N \rho}{m_n} dl \right\rangle, \quad (2)$$

where ρ is the density of the star. The average is taken over all different WIMP trajectories, and the last approximation holds if the elastic cross section between WIMP-nucleus σ_N is smaller than $\sigma_{\rm crit} = m_n R^2/M \simeq 10^{-45}$ cm^2 (for a neutron star). Although the fraction f depends on the density profile of the star, the mass of the scatterer m_n, and the WIMP-scatterer cross section, it becomes roughly proportional to $\sigma_N/\sigma_{\rm crit}$ so long as $\sigma \ll \sigma_{\rm crit}$, and upon having made the assumption of uniform density.

For a typical neutron star of mass $M = 1.4 M_\odot$ and radius $R = 10$ km, the rate of accretion is

$$F = 1.25 \times 10^{24}\ {\rm s}^{-1}\left(\frac{\rho_{\rm dm}}{{\rm GeV/cm}^3}\right)\left(\frac{100\ {\rm GeV}}{m}\right) f, \quad (3)$$

where we have used $v = 220$ km/s.

We are interested in dark matter candidates that can self-annihilate. In that case the number of dark matter particles inside the star $N(t)$, as a function of time, is governed by

$$\frac{dN(t)}{dt} = F - C_A N(t)^2, \quad (4)$$

where $C_A = \langle \sigma_A v \rangle / V$ is the thermally averaged annihilation cross section over the effective volume within which the annihilation takes place. The solution of this equation is

$$N(t) = \sqrt{\frac{F}{C_A}} {\rm Tanh}\frac{t+c}{\tau}, \quad (5)$$

where c is a constant determined by the initial condition, and

$$\tau = 1/\sqrt{FC_A}.$$

The power released inside the star due to the annihilation of dark matter is

$$W(t) = Fm{\rm Tanh}^2 \frac{t+c}{\tau}. \quad (6)$$

Ignoring the initial constant c, the Tanh saturates to one for times larger than τ, and the released power is simply $W = Fm$. Thus, at times larger than τ, the heating power due to dark matter annihilations can be written as

$$W_h = Fm\chi,$$

where χ represents the fraction of energy that goes into heat. If the annihilation products are rich in neutrinos, a substantial part of the annihilation energy might escape as neutrinos fly out of the star. The coefficient χ depends on the particular dark matter candidate and its self-annihilation channels. For example, dark matter candidates that decay predominantly to a pair W^+-W^- might have $\chi \simeq 0.7$ since 30% of W decay to neutrinos. For simplicity purposes from now on we assume that $\chi = 1$ (all annihilation energy is deposited locally), keeping in mind that our results are also valid for $\chi < 1$ as long as we rescale the local dark matter density by $1/\chi$ in order to compensate in energy. We should also emphasize that the limits we impose here are complementary to constraints coming from neutrino flux limits from WIMP annihilation in the Sun, in the sense that the latter are stricter for larger values of $1-\chi$.

The WIMP particles trapped in the neutron star further collide with the neutrons and eventually come to thermal equilibrium with the star. Pauli blocking plays an important role in this process. Initially, the WIMP velocity is large, so that the energy transferred to neutrons exceeds the Fermi energy and all neutrons participate in the scattering. Once the WIMP velocity drops and the transfer energy becomes smaller than the Fermi energy, only a fraction of neutrons close to the Fermi surface remains available for collisions. With the account of the blocking, the time necessary for a WIMP to cool down to a temperature T is estimated as follows:

$$t_{\rm th} = 0.2\ {\rm yr}\left(\frac{m}{\rm TeV}\right)^2\left(\frac{\sigma}{10^{-43}\ {\rm cm}^2}\right)^{-1}\left(\frac{T}{10^5\ {\rm K}}\right)^{-1}.$$

This estimate is in agreement with Ref. [24]. For the cross sections of order of the present experimental limit, $t_{\rm th}$ is a very short time compared to a typical age of neutron stars (of order several Myr) that we consider here. For a typical WIMP of 1 TeV, the thermalization cannot be achieved in 1 Myr if the cross section is smaller than 10^{-51} cm^2. This bound might be even lower considering that thermalization might have been achieved at higher temperatures at a slightly earlier time than 10^6 years.

If the thermalization condition is satisfied, the WIMPs follow a Boltzmann distribution in velocities and distance from the center of the star, with almost all of the dark matter concentrated within the thermal radius

$$r_{\rm th} = \left(\frac{9T}{8\pi G\rho_c m}\right)^{1/2} \simeq 22\ {\rm cm}\left(\frac{T}{10^5\ {\rm K}}\right)^{1/2}\left(\frac{100\ {\rm GeV}}{m}\right)^{1/2}, \tag{7}$$

where ρ_c is the density of the neutron star. If the thermalization condition is not satisfied, the WIMPs occupy a larger volume up to the total volume of the neutron star.

Let us now review the basics of neutron star cooling. We will assume here the usual picture of a neutron star, ignoring exotic possibilities such as quark matter cores, color superconducting matter [29], and other effects that can alter the cooling of a typical star [30]. In the standard picture, the neutron star cools through a modified Urca process the first million years, and later through thermal photon emission from its surface. As it was pointed out in [25], heating from dark matter annihilation can compete with the photon emission once the temperature of the star drops at later times. This happens when the power released in dark matter annihilations, Eq. (6), equals the thermal energy loss rate, $L_\gamma = 4\pi R^2\sigma T^4$, where σ is the Stefan-Boltzmann constant, R is the radius of the neutron star, and T is the surface temperature of the star. For a given local dark matter density, the photon emission and heating due to dark matter annihilation equilibrate at a surface temperature

$$\frac{T}{10^5\ {\rm K}} = 0.04\left(\frac{\rho_{\rm dm}}{{\rm GeV/cm^3}}\right)^{1/4}. \tag{8}$$

Once the equilibrium is reached, the temperature does not drop further but remains constant [25].

The time needed to reach the equilibrium stage is determined by the longest of the two time scales: the time of cooling of the neutron star to sufficiently low temperature and the time scale τ entering Eq. (6). The neutron star cooling takes at least 1 Myr [25], while the value of τ is estimated as follows:

$$\tau = 3.4\times 10^{-5}\ {\rm yr}\left(\frac{100}{m}\right)^{1/4}\left(\frac{{\rm GeV/cm^3}}{\rho_{\rm dm}}\right)^{1/2} \times\left(\frac{10^{-36}\ {\rm cm}^2}{\langle\sigma v\rangle}\right)^{1/2}\left(\frac{T}{10^5\ {\rm K}}\right)^{3/4} f^{-1/2}, \tag{9}$$

where $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section.

In dark matter models where WIMPs are produced thermally, the annihilation cross section is of the order of 10^{-36} cm^2. Since we are interested in times larger than a million years, we see that for a typical thermal relic WIMP, τ is by many orders of magnitude smaller than the neutron star cooling time, and therefore Eq. (8) becomes applicable as soon as the neutron star temperature drops to a sufficiently small value.

In models with nonthermal dark matter production, the annihilation cross section is essentially a free parameter. In Fig. 1 we plotted the minimum annihilation cross section required to reach equilibrium between the dark matter accretion and annihilation in 1 Myr, as a function of the local dark matter density for two distinct values of the WIMP mass. The equilibrium neutron star temperature is taken to be 10^5 K. As it can be seen from the plot, the minimum annihilation cross section ranges from 10^{-61} to 10^{-57} cm^2. Therefore, the constraints on the dark matter related to the dark matter annihilation in neutron stars are valid even for nonthermally produced WIMPs with an extremely small annihilation cross section. As we argue later, the accumulation of dark matter in the neutron star progenitor extends the range of applicability of the equilibrium equations to even lower annihilation cross sections.

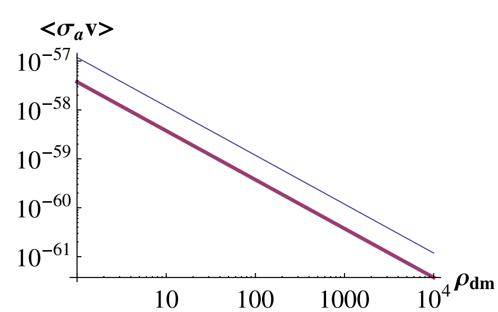

FIG. 1 (color online). The minimum annihilation cross section (in cm^2) as a function of the local dark matter density (in GeV/cm^3) for a dark matter WIMP of 100 GeV (thin line) and 1 TeV (thick line), in order the characteristic time scale for equilibrium between accretion and annihilation of WIMPs τ to be 1×10^6 years (having assumed a temperature of 10^5 K).

To conclude this section, let us comment on the WIMP accretion in white dwarfs, another compact object where the dark matter annihilation may lead to observable effects [28]. White dwarfs have typical radii 2 orders of magnitude larger than neutron stars, which makes their observation easier. However, being less dense, white dwarfs lose significantly in the accretion rate. The efficient capture of WIMPs in white dwarfs (i.e., at least one collision per star crossing) requires a cross section larger than $\sim 10^{-39}$ cm^2, while the corresponding number for a neutron star is $\sim 10^{-45}$ cm^2. This is an important difference, in view of the existing experimental limits. One might try to improve the situation by assuming that the scattering of WIMPs off the whole nuclei of matter constituting the white dwarf is coherent. In the case of carbon nuclei, this would increase the probability of scattering by a factor of 12. However, taking into account the acceleration of the WIMPs due to the gravitational field of the white dwarf, a typical WIMP of 100 GeV or heavier has a de Broglie wavelength much smaller than the radius of the carbon nucleus. Since the loss of coherence is exponential [31], the enhancement factor practically disappears. In addition, in case of Majorana fermions, WIMPs can only have spin-dependent interactions with nuclei, so the interaction with the whole ^{12}C nucleus is zero.

III. THE EFFECT OF A NEUTRON STAR PROGENITOR

Neutron stars are occasionally formed when a supermassive star collapses gravitationally after having burned all of its fuel. The collapse is followed by a supernova explosion (type II), and a protoneutron star is formed evolving eventually to a neutron star. In this section we investigate what is the effect of the presence of the massive star on the accretion and annihilation rates derived in the previous section. In principle, the existence of a supermassive star can change the local dark matter density by accretion, and therefore once the neutron star is formed, it might accrete with a different rate because of the differ ent dark matter density. However, we will see that this effect could have observational consequences only in scenarios where WIMPs have extremely small annihilation cross sections.

We start by considering a typical massive star of 15 solar masses. In the first stage the star burns hydrogen for about 11×10^6 years. It is followed by the helium burning stage which lasts for about 2×10^6 years, then by the carbon stage for 2000 years, and then by neon, oxygen, and silicon stages before the star explodes [32]. The last stages are very short and have no significant effect on the accretion of the dark matter. In fact, even the carbon stage can be neglected as the amount of dark matter accreted at this stage is at least 1 order of magnitude smaller than during the first two stages.

We estimate the amount of dark matter accumulated in the progenitor star at the hydrogen and helium stages by means of Eq. (1), where the relativistic effects can be neglected and the fraction f representing the probability of a collision during single star crossing is now much smaller than 1. The total amount of the dark matter accumulated during the star lifetime is

$$N_0 = 5 \times 10^{37}\left(\frac{\rho_{\rm dm}}{\rm GeV/cm^3}\right)\left(\frac{100\ \rm GeV}{m}\right)\left(\frac{\sigma_N}{10^{-43}\ \rm cm^2}\right). \tag{10}$$

Here, as before, $\rho_{\rm dm}$ is the dark matter density at the star location. The helium state dominates the accretion, unless the cross section is spin dependent, in which case only the hydrogen stage contributes. The total amount of the accumulated dark matter is then reduced by roughly a factor of 5.

A remark is in order. From Eq. (3) we find that the total amount of WIMPs accreted by a neutron star in the characteristic time of 1 Myr is 4×10^{37}, which is comparable to the total amount of WIMPs accumulated by the neutron star progenitor. Thus, the effect of the progenitor cannot be neglected *a priori* and has to be investigated in more detail.

One may be surprised that two quite different objects—the neutron star progenitor and the neutron star itself—accrete dark matter with comparable efficiency. This numerical coincidence is a result of two competing effects that roughly compensate each other. Larger mass and radius of a progenitor lead to more dark matter particles crossing the star. However, smaller matter density makes the probability of capture after a single crossing small.

Now we turn to the question of how fast the WIMPs can be thermalized inside the massive star. The thermalization determines the space distribution of WIMPs at the moment of the neutron star formation. We estimated the thermalization time as the time it takes a WIMP to lose kinetic energy down to the temperature of the star core. At the hydrogen stage, the WIMPs of $m = 100$ GeV have enough time to thermalize, while the WIMPs of $m = 1$ TeV do not. At the helium and subsequent stages, the thermalization is achieved for the whole range of masses from 100 GeV to 1 TeV.

Once thermalized, the WIMPs follow the Boltzmann distribution in velocities and distances from the center of the star, with most of them concentrated within the thermal radius (7), where now T is the core temperature and ρ_c is the mass density at the corresponding stage. Therefore, at the end of the star's life, most of WIMPs will reside within the thermal radius of the last, silicon stage, with $T = 3.34 \times 10^9$ K and $r_{\rm th} = 2 \times 10^7$ cm. We also found that no significant amount of accumulated dark matter annihilates during the lifetime of the massive star for self-annihilation cross sections of the order of 10^{-36} cm^2 or smaller.

Since the probability of WIMP scattering off a nucleon during single star crossing is much smaller than 1 even at the silicone stage, the supernova explosion will have no direct impact on the WIMP distribution after the explo sion. Therefore the newly born neutron star will find itself inside a dense dark matter cloud with a total amount of dark matter given by Eq. (10) and the temperature and radius characteristic of the dark matter distribution at the silicone stage.

When the neutron star is formed, it starts accreting the surrounding dark matter, both from the cloud accumulated by the neutron star progenitor and from the background dark matter distribution. Since the dark matter is essentially noninteracting, these processes are independent. The amount of WIMPS in the cloud, N_c, is governed by the equation

$$\frac{dN_c}{dt} = -F = -1.25 \times 10^{26}\ \mathrm{s}^{-1}\left(\frac{\mathrm{cm}^3}{V}\right) f \times N_c, \quad (11)$$

where F is the rate given by Eq. (3). The dark matter density in the cloud drops exponentially with the characteristic time scale

$$\tau_{\mathrm{acc}} = 2 \times 10^{-4}\ \mathrm{s}\left(\frac{m}{100\ \mathrm{GeV}}\right)^{-3/2}.$$

Here we have assumed a spin-independent cross section and the volume of the cloud that corresponds to the thermal dark matter distribution at the silicone stage. The constant f is set to 1. However, even for a spin-dependent cross section, for which the dark matter cloud is much larger as it corresponds to the hydrogen stage, the time scale τ_{acc} is of the order of a year. In either case, independently of the initial value, the WIMP density in the cloud drops down to the background density in a very short time; i.e., all of the dark matter in the cloud gets accreted by the neutron star fast.

Whether the accumulated dark matter produces an observable effect depends on the annihilation cross section. From Eq. (9) we see that for annihilation cross sections typical of thermal relic models, the characteristic time scale for reaching the equilibrium between accretion and annihilation is very small. This means that very shortly after the neutron star's birth, the dark matter accumulated by the neutron star progenitor will be burned out. At the initial stages of the neutron star cooling, this extra energy release is negligible in the total energy balance determined by the modified Urca processes.

However, for nonthermal WIMP candidates with a very small cross section, the time scale for reaching the equilibrium between accretion and annihilation τ could be of the order of a million years. In this case the dark matter accumulated by the neutron star progenitor might have an observable effect as it speeds up the transition to the equilibrium regime. In Fig. 2 we plotted the power produced by WIMP burning as a function of the time. We assumed a very small annihilation cross section $\sigma_A = 10^{-60}$ cm^2 and the background dark matter density

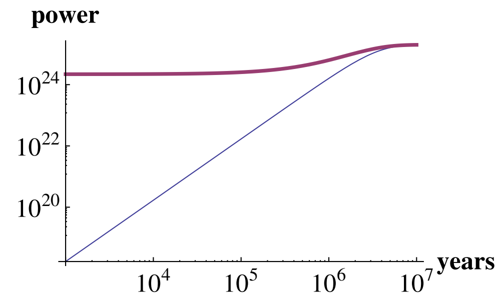

FIG. 2 (color online). Power due to WIMP burning in erg/sec as a function of time. The thick line assumes the preexistence of a massive star, where in the thin one, the neutron star starts accreting at $t = 0$. We assumed an annihilation cross section of 10^{-60} cm^2 and $\rho_{\mathrm{dm}} = 100\ \mathrm{GeV/cm}^3$.

$\rho_{\mathrm{dm}} = 100\ \mathrm{GeV/cm}^3$ (see Secs. IV and V). The difference is large at small times, and decreases with time until both curves converge to the same value. At 1 Myr, the increase in the power due to the accumulated dark matter is given by a factor of 4, corresponding to a temperature increase by a factor of $\sqrt{2}$. Interestingly, in this particular scenario the temperature continues to increase up to a neutron star age of about 10^7 yr.

Finally, consider the effect of the neutron star kick velocities. In principle, a kick given to a neutron star at collapse could move it outside of the dark matter cloud accreted by the neutron star progenitor. This would happen if in the rest frame of the neutron star, the kinetic energy of an average WIMP after the kick is larger than its potential energy. Assuming that the accreted dark matter is concentrated within the thermal radius of the silicon stage (roughly 5000 km), it would take a kick of at least 8000 km/s in order for the WIMPs to escape from the gravitational well of the neutron star. Since usually kicks are of the order of 1000 km/s or less, this effect cannot change our conclusions.

IV. NEUTRON STARS CLOSE TO THE GALACTIC CENTER

Equation (8) gives the surface temperature of a neutron star that can be sustained at later ages by burning dark matter. Obviously, the effect is more pronounced in places where the local dark matter density is high, such as the Galactic center. The dark matter halo profile of the Milky Way is the subject of intense research. Several simulations have been performed in order to obtain the profile that describes rotation curves best. We will consider three different profiles. The first one is the standard Navarro-Frenk-White (NFW)

$$\rho_{\mathrm{NFW}} = \frac{\rho_s}{\frac{r}{r_s}(1 + \frac{r}{r_s})^2}, \quad (12)$$

where $\rho_s = 0.26\ \mathrm{GeV/cm}^3$, and $r_s = 20$ kpc [33]. The second is the Einasto profile

$$\rho_{\rm Ein} = \rho_s \exp\left[-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right], \qquad (13)$$

where $\rho_s = 0.06\ \mathrm{GeV/cm^3}$, $\alpha = 0.17$, and $r_s = 20$ kpc [34]. The third profile is the Burkert

$$\rho_{\rm Bur} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}, \qquad (14)$$

where $\rho_s = 3.15\ \mathrm{GeV/cm^3}$, and $r_s = 5$ kpc [35]. All the profiles are normalized to a local dark matter density at the Earth location of $0.3\ \mathrm{GeV/cm^3}$.

In Fig. 3, we plotted the surface temperature of a neutron star that can be maintained by burning accreted dark matter WIMPs for the three aforementioned dark matter halo profiles. As expected, the Burkert profile gives the smallest surface temperature almost regardless of the distance to the Galactic center. There is no spike in the Burkert profile, and the local dark matter density increases by only 1 order of magnitude when going from the location of the Earth to the Galactic center, making the neutron star surface temperature (that scales as the local dark matter density to the power 1/4) too small (around 5000 K) to be detected with the current observational capabilities. The Einasto profile, which is considered the best fit to the data, gives a temperature slightly over 3×10^4 K, varying slowly as a function of the distance to the Galactic center. For example, the surface temperature changes only by a factor of 5 as one goes from the inner 1 kpc down to the inner 10^{-4} pc of the galaxy. The NFW profile gives the most pronounced effect, which is due to the spike in the Galactic center. The surface temperature rises faster (compared to the other profiles), reaching a value of 3×10^5 K at 10^{-4} pc from the Galactic center.

The curves of Fig. 3 should be considered as lower bounds for the surface temperature of the neutron star: for a given dark matter halo profile, the curves represent the coldest temperature the neutron star can reach if it burns dark matter. The observation of a neutron star with a lower temperature would mean that dark matter WIMPs with an elastic cross section as low as 10^{-45} cm^3 (or even lower, see below) and an annihilation cross section as small as $10^{-57} - 10^{-61}$ cm^2 depending on the mass of the WIMP, and the local dark matter density, are excluded. The observation of the neutron star with a surface temperature higher than the predicted curves is consistent with the existence of dark matter WIMPs with the above characteristics. However, a mere existence of such a neutron star is not conclusive for the existence of these WIMPs. A neutron star can have a larger temperature because it might still be young, for example, at the stage where it still cools through neutrino emission via Urca process, or even if equilibrium between photon emission and WIMP burning has not yet been reached. In addition, nonisolated neutron stars can maintain a relatively high temperature due to accretion of ordinary matter from a binary companion star. In that case a conclusive answer would require the observation of an isolated neutron star and an accurate knowledge of its age.

As we already have mentioned, for an elastic (or inelastic) cross section larger than 10^{-45} cm^2, the mean free path of the WIMP is smaller than the radius of the neutron star, ensuring that the WIMP will collide at least once every time it passes through the star. However, one can always trade the cross section for the local dark matter density. In Fig. 4, we present the asymptotic surface temperature of a typical star in the inner 10^{-4} pc of the galaxy as a function of the elastic (or inelastic) cross section of the WIMP with the neutron, for the NFW and Einasto profiles. As it can be seen from the figure, even for a cross section as low as 10^{-50} cm^2, an old neutron star at 10^{-4} pc from the Galactic center may maintain a surface temperature of 2×10^4 K (using the NFW profile).

If WIMPs are fermions, the Pauli blocking may prevent them from collapsing into the black hole. The amount of dark matter needed to overcome the Pauli blocking can be estimated by requiring that the gravitational potential energy of a WIMP is larger than its Fermi energy,

$$\frac{GNm^2}{r} > k_F, \qquad (15)$$

where N is the total number of WIMPs and $k_F = (3\pi^2 N/(4\pi r^3/3))^{1/3}$ is the WIMP Fermi momentum.

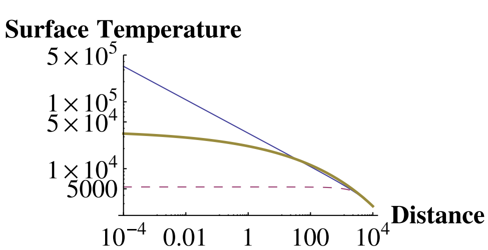

FIG. 3 (color online). The surface temperature of a typical old neutron star in units of K as a function of the distance of the star from the Galactic center in pc, with the dark matter annihilation taken into account. The three curves correspond to three different dark matter profiles: NFW (thin solid line), Einasto (thick solid line), and Burkert (dashed line).

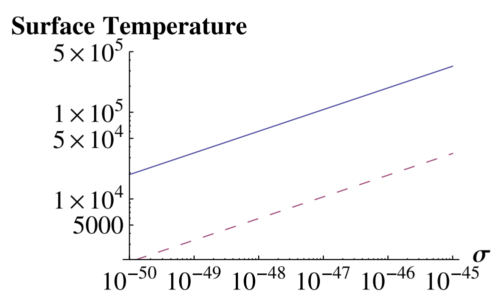

FIG. 4 (color online). The surface temperature of an old typical neutron star located at 10^{-4} pc in units of K as a function of the elastic (or inelastic) cross section (in cm^2) for the NFW (solid line) and the Einasto (dashed line) profiles.

Taking into account corrections due to the nonzero mass of the WIMPs and assuming that no annihilations occur during the accretion, the number of WIMPs required for a gravitational collapse is 10^{51} (10^{48}) particles for a WIMP mass of 100 GeV (1 TeV). With an accretion rate of Eq. (3), even for an extremely high dark matter density $\rho_{\rm dm} = 10^{10}\ {\rm GeV/cm^3}$ it would take 2.5×10^9 yr (2.5×10^7 yr) in order for the WIMPs to collapse gravitationally. If the dark matter density is smaller than $10^7\ {\rm GeV/cm^3}$, the required number of WIMPs cannot be accreted during the whole lifetime of the universe. We should emphasize that this is a conservative estimate, since we completely neglected the annihilation during accretion. Therefore, the black hole formation by dark matter inside neutron stars should not be of any concern in case of fermionic dark matter except maybe in the very center of the galaxy.

Despite the fact that the center of the galaxy is a dark-matter-rich environment where the effect of the dark matter annihilation on the temperature of a neutron star is enhanced, it is a place where observations of neutron stars are quite a difficult task. The center of the galaxy is opaque in the UV and optical band, making the observations hard [36]. For this reason, other places with potentially high local dark matter density, such as globular clusters, should also be studied.

V. NEUTRON STARS IN GLOBULAR CLUSTERS

Another potentially dark-matter-rich environment is centers of globular clusters. Globular clusters are dense spherical collections of stars orbiting the Galactic core. A typical globular cluster, such as $M4$, has a baryonic mass of 10^5 solar masses and a core radius of 0.5 pc. Although globular clusters are baryon-dominated systems, the dark matter density in their cores may exceed the average halo density by several orders of magnitude.

To put constraints on the dark matter properties, we are interested in old neutron stars with temperatures of order 10^5 K or below. An observation of an isolated neutron star with a temperature higher than predicted by the cooling models may point, in the absence of other heating sources, toward a WIMP-powered heating mechanism.

Although there are several globular clusters observed, we shall focus on $M4$ (we will comment on the other clusters in the end of this section). As an upper bound, we adopt an estimate of the dark matter density in the core of $M4$ obtained in Ref. [27], where a NFW dark matter density profile of Eq. (12) was used with $\rho_s = 24\ {\rm GeV/cm^3}$ and $r_s = 171$ pc [27]. Apart from the parameters of the dark matter density profile, the WIMPs in $M4$ have a much smaller velocity dispersion compared to that of the galaxy. We use a value of $v = 20$ km/s [37], which is an order of magnitude smaller than that for the galaxy. By inspection of Eq. (3), we see that for a typical neutron star, the accretion rate scales as inverse of the velocity, and therefore reduction of the velocity by an order of magnitude implies an increase of the accretion rate by the same factor.

In Fig. 5 we present the surface temperature of an old neutron star powered by the burning of dark matter for a NFW profile with the parameters of the $M4$ globular cluster, as a function of the distance from the center of the cluster. At 0.1 pc, the temperature is expected to be 10^5 K, while at the edge of the core (0.5 pc) the temperature should be 7×10^4 K.

Two comments are in order. First, the NFW profile used in the above estimate does not include the effects of the tidal stripping and the baryonic contraction. With these effects taken into account, the core dark matter density in $M4$ is somewhat smaller. For example, close to the edge of the core the difference is by about a factor of 3 [28], which corresponds to only a 30% decrease in the value of the surface temperature since the latter scales as the dark matter density to the power 1/4.

Second, although we considered $M4$ as an example, several globular clusters have been observed that may contain such neutron stars. In principle, the analysis should be redone for every particular candidate. However, we should emphasize that $M4$ is a typical globular cluster, and we do not expect to have dramatic changes in our predictions. For example, 47 Tuc is another globular with a mass larger than $M4$. The core dark matter density might be higher in 47 Tuc, but this would barely make a difference due to the slow dependence of temperature on the dark matter density.

Although white dwarfs are easier to spot in globular clusters, the neutron stars might be more appropriate for probing smaller annihilation and elastic (inelastic) cross sections. Pulsars have already been detected in globular clusters. A characteristic example is the pulsar PSR B1620-26 found in the outskirts of the core of $M4$. It is a part of a triple bound system with a planet and a white dwarf. Since the age of $M4$ is of the order of a billion years, the neutron star is expected to be old enough to exhibit the effect of dark matter burning. In this case its temperature should be 7×10^4 K (without baryonic contraction) or 5.3×10^4 K (with baryonic contraction). However, the neutron star might still be accreting matter from the companion white dwarf, in which case its temperature may be

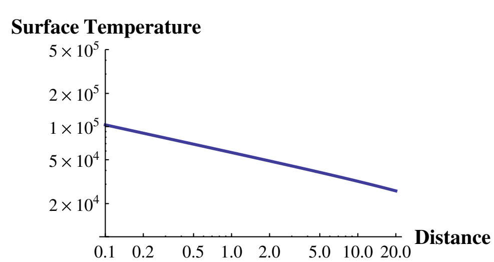

FIG. 5 (color online). The surface temperature of a typical old neutron star in units of K as a function of the distance in pc for a NFW profile of the globular cluster $M4$.

higher than this prediction. Observation of the temperature lower than $\sim 5 \times 10^4$ K would be inconsistent with the existence of WIMP with the properties described above.

Another example is the source *X*7 of the 47 Tuc globular cluster, which has low variability and seems to be a non-accreting neutron star, with a spectrum that fits a neutron star with a hydrogen atmosphere and an effective temperature as low as 89 eV [38]. This is a temperature of the order of 10^6 K, an order of magnitude higher than predicted by the dark matter burning mechanism. In the absence of the precise knowledge of the neutron star age, this is consistent with the dark matter WIMPs scenario. We should also mention that a detailed comparison requires a more thorough investigation since there is no direct equivalence between the hydrogen atmosphere spectrum and the black-body one. In general, isolated neutron stars (or neutron stars that have low variability and therefore no accretion from companion stars) in globular clusters constitute ideal candidates for observing the effects of the WIMP burning.

VI. DISCUSSION

In this paper we examined the effect of WIMP annihilation on the temperature of a neutron star. We estimated the surface temperatures of old neutron stars according to their location in the galaxy or in a globular cluster. We also investigated the effect of a neutron star progenitor on the accretion of WIMPs onto the neutron star. We found that, although a considerable number of WIMPs is accumulated by the progenitor during the evolution preceding the formation of a neutron star, the effect of this accumulation is observable only in cases where the annihilation cross section is extremely small.

We argued that observations of neutron stars with low (of order 10^5 K or lower) surface temperature will put constraints on a large set of dark matter candidates. Because of their high density, the neutron stars accrete the dark matter at a significant rate even when the WIMP-to-nucleon cross section (elastic or inelastic) is as low as 10^{-45} cm^2, which is 2 orders of magnitude lower than the current experimental limit. Even for lower values of the cross section, the effects of WIMP accretion and annihilation may be observable in neutron stars that are situated in dark-matter-rich environments such as the Galactic center and cores of globular clusters. Thus, the neutron stars can probe much smaller WIMP cross sections than less dense objects such as, e.g., white dwarfs.

The WIMP constraints that we presented are valid even if the WIMPs have a very small annihilation cross section as low as 10^{-57} cm^2 (or even lower for large local dark matter densities). This means that our constraints hold also for a variety of WIMP candidates that are produced non-thermally, for which the annihilation cross section is, in general, a free parameter.

Prospective candidates to test the WIMP-burning heating mechanism are isolated neutron stars that are old but appear warmer than predicted by the cooling models. Care should be taken to exclude the conventional heating mechanisms that may be operational at late stages of neutron star evolution, such as those powered by the accretion of ordinary matter or relaxation of the neutron star magnetic field [39,40]. There is a couple of examples of potential candidates. One of them is J0437-4715, a few billion years old neutron star with a roughly 10^5 K temperature [41]. Although this temperature can be sustained by WIMP burning, it would require a substantial local dark matter density, which is unlikely as J0437-4715 is only 140 pc from the Earth. Unless there is a peak in the dark matter density at the position of J0437-4715, WIMP burning cannot explain this temperature. A similar candidate is J0108-1431 at 130 pc from Earth, with a temperature $\sim 9 \times 10^4$ K [42]. As in the case of J0437-4715, this temperature is still higher than what the dark matter burning can provide, assuming the dark matter density at the location of J0108-1431 is the same as around the Earth. Candidates like those above, with smaller temperatures or in rich dark matter regions such as globular clusters, might make it possible to constrain a large class of dark matter WIMP scenarios.

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