Neutron stars as dark matter probes

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We examine whether the accretion of dark matter onto neutron stars could ever have any visible external effects. Captured dark matter which subsequently annihilates will heat the neutron stars, although it seems the effect will be too small to heat close neutron stars at an observable rate while those at the galactic center are obscured by dust. Nonannihilating dark matter would accumulate at the center of the neutron star. In a very dense region of dark matter such as that which may be found at the center of the galaxy, a neutron star might accrete enough to cause it to collapse within a period of time less than the age of the Universe. We calculate what value of the stable dark matter-nucleon cross section would cause this to occur for a large range of masses.

I. INTRODUCTION

Observations of the kinematics of self gravitating objects such as galaxies and clusters of galaxies consistently send us the same message—if we are to believe in Einstein's theory of gravity on these scales, then there appears to be an invisible quantity of dark matter in each of these objects which weighs more than the matter we can observe. Cosmological observations add weight to this hypothesis and tells us that this invisible matter cannot consist of baryons, rather it must be a new kind of matter which interacts with the rest of the standard model rather feebly—dark matter [1].

The exact coupling and mass of this dark matter is not known but has been constrained. One hypothesis is that the dark matter annihilates with itself and interacts with the rest of the standard model via the weak interaction. This weakly interacting massive particle (WIMP) scenario has gained favor because such particles would fall out of equilibrium with the rest of the plasma at such a temperature that their relic abundance today would be approximately correct to explain the astronomical observations.

Such a scenario also predicts a direct detection signal due to the recoil of atoms which are hit by dark matter particles, recoils which are being searched for at several purpose built experiments (e.g. [2–4]). We also expect to see signals from the self-annihilation of WIMP dark matter in regions of the galaxy where the density is large, although there are many uncertainties with regards to the magnitude of this signal. Neither of these signals has yet been detected although international efforts to find such signals are intensifying to coincide with the opening of the LHC which also may create WIMP dark matter particles.

Since we only understand the thermal history of the Universe back to the start of nucleosynthesis, we cannot say with any surety whether or not the WIMP scenario

makes sense. Furthermore there are many other scenarios of dark matter which involve much more massive particles or particles which cannot annihilate with themselves [5,6]. There is roughly 5–7 times the amount of dark matter in the Universe by mass relative to baryonic matter. This ratio is rather close to 1, a mystery which is only solved within the WIMP framework by a happy coincidence. The closeness of these numbers has led some researchers to suggest that, like baryons, dark matter also possesses a conserved charge and there is an asymmetry in this charge in the Universe. If the two asymmetries are related then one would require the dark matter mass to be approximately 5–7 times the mass of a nucleon. This intriguing possibility would be consistent with the controversial DAMA experiment [7] and the slight hint of anomalous noise in the cogent experiment [8]. Such a dark matter candidate could also have interesting implications for solar physics [9].

Since any constraints on the nature of the mass and cross section of dark matter particles are interesting, in this paper we will consider both of these paradigms and see whether or not it is possible to obtain any new constraints from a new angle—namely by considering the capture of dark matter by neutron stars.

The accretion of dark matter onto stellar objects has been considered by various groups looking at both stars [10–14] and compact objects [15–17]. In particular, the structure and the ultimate fate of neutron stars which accrete nonannihilating dark matter has been discussed before [18–20].

Our aim is to consider the accretion of dark matter onto neutron stars in greater detail in order to examine whether or not it would ever be possible to either observe the heating of a neutron star due to dark matter annihilation within the object, or the collapse of a neutron star which accretes nonannihilating dark matter.

In the next section we will outline our estimate for the accretion rate of dark matter onto a neutron star. Then we will explain which densities we will be assuming for dark matter in the Milky Way. We will then go on to work out

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how hot we can expect a neutron star to get simply due to the accretion of dark matter and compare this with observations.

Finally we will look at whether it is at all sensible to imagine a situation where the accretion of nonannihilating dark matter onto a neutron star would give rise to its subsequent collapse before concluding.

II. CAPTURE RATE OF DARK MATTER ONTO NEUTRON STARS

In this section we will calculate the rate at which dark matter (DM) particles will accrete onto neutron stars. This reintroduction of the formalism is essentially the same as the existing literature. Where our analysis differs to previous studies is the inclusion of general relativity (GR) effects in the calculation of the escape velocity. The total capture rate depends on the density of target nuclei and the escape velocity, quantities which both vary throughout the star.

A. Basic equations

The expression which needs to be calculated is the following [21]:

$$C = 4\pi \int_0^{R_\star} r^2 \frac{dC(r)}{dV} dr, \tag{1}$$

where the capture rate for a given radius is given by

$$\frac{dC(r)}{dV} = \left(\frac{6}{\pi}\right)^{1/2} \sigma_0 A_n^4 \frac{\rho_\star}{M_n} \frac{\rho_\chi}{m_\chi} \frac{v^2(r)}{\bar{v}^2} \frac{\bar{v}}{2\eta A^2}$$
$$\times \left\{ \left(A_+ A_- - \frac{1}{2}\right)[\chi(-\eta, \eta) - \chi(A_-, A_+)] \right.$$
$$\left. + \frac{1}{2} A_+ e^{-A_-^2} - \frac{1}{2} A_- e^{-A_+^2} - \eta e^{-\eta^2} \right\} \tag{2}$$

and the various functions within this expression are

$$A^2 = \frac{3v^2(r)\mu}{2\bar{v}^2\mu_-^2}, \qquad A_\pm = A \pm \eta, \qquad \eta = \sqrt{\frac{3v_\star^2}{2\bar{v}^2}},$$

$$\chi(a, b) = \int_a^b e^{-y^2} dy = \frac{\sqrt{\pi}}{2}[\text{erf}(b) - \text{erf}(a)],$$

$$\mu = m_\chi/M_n, \qquad \mu_- = (\mu - 1)/2.$$

In the above, m_χ is the mass of the DM particle, ρ_χ is the ambient DM mass density, A_n is the atomic number of the neutron star nuclei, M_n is the nucleus mass, $\bar{v}$ is the DM velocity dispersion, $v_\star$ is the star's velocity with respect to the zero point of the DM velocity distribution and $v(r)$ is the escape velocity at a given radius r inside the neutron star (see below); subscript $\star$ refers to the neutron star quantities.

The velocity dispersion $\bar{v}$ is chosen as being constant throughout the galaxy. This is a rather simplistic approximation, especially at small galactic radii where the pres-

ence of the central supermassive black hole (SMBH) should cause the velocity dispersion to increase dramatically. The consequences of this will be discussed in Sec. IV D.

For neutron stars it is important to note that there is a maximum effective cross section—the sum of all the cross sections of all the nuclei in the object cannot exceed the total surface area of the star since this is obviously an absolute upper limit on the total cross-section of the object. Because of this, cross sections in excess of $\sigma_0^{\text{max}} = 2 \times 10^{-45}$ cm^2 will not increase the probability of capture. We will take this into account in what follows.

B. Inelastic dark matter

One of the ideas which has become a popular explanation of the DAMA results is the idea of inelastic dark matter where dark matter is some kind of composite, excitable state which can undergo inelastic collisions by some of the collision energy in a given encounter going into knocking the particle into an excited state [22]. This means that there is a minimum and a maximum energy exchange which can take place for a given initial velocity dark matter particle scattering off a particular nucleon [23]. In particular it makes the energy exchange required for capture to be less since not all of that energy goes back into elastically back-scattering the impinging dark matter particle up to an escaping orbit. Constraints on the capture of dark matter onto white dwarves become particularly interesting in such scenarios [17].

In some sense, what we have written below will include the effects of inelastic dark matter since the motivation for such models comes from trying to explain data from experiments like DAMA so that the effective cross section needs to be relatively large $\sim 10^{-41}$ cm^2. For such large cross sections, as we have explained above, the neutron star will become opaque for cross sections above about $\sigma_0^{\text{max}} = 2 \times 10^{-45}$ cm^2. The details of the inelastic scattering will not be important since any kind of energy exchange once these particles have been accelerated by gravity as they fall to the surface of the neutron star will dwarf the kind of resonance energies associated with inelastic dark matter models invoked to explain the anomalous direct detection experiments. For this reason, the following conclusions should be read as to include the case of inelastic dark matter.

C. Neutron star escape velocity

The quantities in this Eq. (2) have various origins—$\bar{v}$ and ρ_χ depend upon the distribution of dark matter in the galaxy and we will discuss them later. The calculation of the escape velocity is more complicated—in a normal star we can simply use Newtonian gravity but if we were to apply the same simple equations to a neutron star we would obtain superluminal escape velocities suggesting the star is unstable. This is of course due to the fact that neutron stars

are relativistic objects and we need to take into account GR effects to calculate the escape velocity properly.

The space-time geometry inside a static, spherical fluid star is

$$ds^2 = -e^{2\Phi}dt^2 + \left(1 - \frac{2M(r)}{r}\right)^{-1}dr^2 + r^2 d\Omega^2, \quad (3)$$

where $M(r) = 4\pi \int_0^r \rho(r')r'^2 dr'$ and Φ is determined by solutions of

$$\frac{d\Phi}{dr} = \frac{GM(r)/c^2 + 4\pi Gr^3 P(r)/c^4}{r\left[r - 2\frac{GM(r)}{c^2}\right]}, \quad (4)$$

where P is the pressure inside the star. Following the usual Lagrange method of calculating the escape velocity we find that

$$v_{esc}^2 = \frac{1}{(1 - \frac{2GM(r)}{rc^2})(\frac{d\tau}{dr})^2 + \frac{1}{c^2}} = c^2(1 - e^{2\Phi}). \quad (5)$$

What remains is to obtain the density and pressure as a function of radius so that we are able to solve Eqs. (2) and (5). This is done using the Oppenheimer-Volkoff equations, which are the GR versions of the equations of stellar structure.

$$\frac{dP}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]$$
$$\times \left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}, \quad (6)$$

$$\frac{dM}{dr} = 4\pi r^2 \rho(r). \quad (7)$$

We integrate these equations outwards for different central pressures. The initial condition for $\Phi(r = 0)$ is chosen so that its value at the surface of the star matches its solution at large radii $\Phi(r > R_{NS}) = \frac{1}{2}\ln(1 - 2GM/rc^2)$. We then vary the central pressure in order to find the maximal mass one can obtain in the given conditions. As an equation of state (EOS) for the neutron star matter, we consider the unified model developed by Pandharipande and Ravenhall [24] which is based on the Friedman-Pandharipande-Skyrme (FPS) EOS. We then simply pick a typical solution which gives a profile apparently shared by the majority of neutron stars [25]: $M_{NS} = 1.44 M_\odot$, $R_{NS} = 10.6$ km, $\rho_{NS}^{central} = 1.4 \times 10^{18}$ kg/m^3.

Once the structure of the neutron star including the escape velocity has been obtained in this way we are half way to being able to calculate the capture rate by integrating Eq. (2). In principle this is not a full calculation because while we are calculating the escape velocity as a function of radius in a way which makes sense, we are not then looking at the effect that curved geodesics will have on the capture rate. Nevertheless, we believe that the capture rate calculated with the machinery presented here will be ac-

curate within a factor of a few. This is an appropriate level of accuracy for this work.

We also need to make some assumption about the expected density of dark matter in the galaxy, which is what we shall turn to now.

III. GALACTIC DENSITY OF DARK MATTER

There are various possible methods of obtaining a realistic profile for the density of dark matter in the galaxy. First, we choose to use the Einasto profile

$$\rho(r) = \rho_{-2}e^{-(2/\alpha)[(r/r_{-2})^\alpha - 1]}, \quad (8)$$

where ρ_{-2} is the DM density at galactic radius r_{-2} where the logarithmic gradient $d\ln\rho/d\ln r = -2$ and α is a parameter describing the degree of curvature of the profile. We choose this profile because it describes well DM halos of various sizes which appear in N-body simulations [26].

Several recent studies have estimated the local density of dark matter in some detail [27–29]. We do not go to such lengths and adopt a simpler method, simply ensuring that the enclosed mass at the location of the sun $M_{MW}(R_\odot) = \int_0^{R_\odot} 4\pi r^2 \rho(r)dr$ yields the correct Keplerian velocity $v_{kepl.}(R_\odot) = (GM_{MW}(R)/R_\odot)^{1/2} = 220$ km s^{-1}, where $R_\odot$ is the galactic radius of the Sun. Although it neglects baryons, this gives a reasonable density in line with other methods and gives us a density of 0.3–0.5 GeV cm^{-3} of dark matter at the solar radius. One then obtains a 1-parameter set of solutions in α with the corresponding values of r_{-2}, which lie between 10 and 30 kpc (see Fig. 1). Note that N-body simulations typically yield values of $\alpha \sim 0.15$–0.19 for Milky Way size halos [30]. We will allow a bit more freedom to adopt steeper profiles since we have not explicitly taken into account the effect of baryonic contraction in this work [31,32].
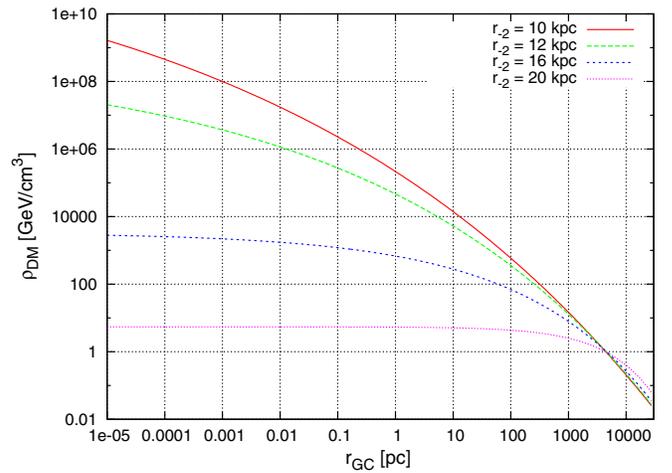

FIG. 1 (color online). Einasto DM density profiles for four different sets of parameters: $(r_{-2}, \alpha) = (10$ kpc, 0.06), (12 kpc, 0.09), (16 kpc, 0.19), and (20 kpc, 0.53).

We will assume that the velocity dispersion of dark matter is 200 km s^{-1}. Sometimes it will be smaller and sometimes larger than this depending on the detailed dynamics of the dark matter halo and this is a poorly understood subject [33], we will attempt to model the effect of varying velocity dispersion in Section IV D.

IV. ANNIHILATING DARK MATTER AND ITS CONSEQUENCES

Now we have the neutron star density and escape velocity profiles and models for the density of dark matter in the Milky Way, we can calculate how much dark matter will be captured using Eq. (2). The result as a function of radius for the four different density profiles can be seen in Fig. 2.

A. Annihilation of dark matter and injection of energy

We next need to analyze what happens to dark matter once it has been captured. In order to do this, we base our calculations on Kouvaris' work [16], adapting the formulae to our situation when necessary. For most cases of interest where the scattering cross-sections are not microscopically small, one can show that the captured WIMPs will thermalise relatively quickly, forming a roughly Maxwell-Boltzmann distribution in velocity and distance around the center of the neutron star. If the particle we consider is an ordinary WIMP which can annihilate with itself it will do so at a rate determined by the self-annihilation cross section and the density of dark matter in the star. Following Kouvaris' argument, we assume that in most interesting situations (where the self-annihilation cross section corresponds to that required for a good relic abundance), the annihilation rate reaches the accretion rate (Fig. 2) within around 10×10^6 years, which is also approximately the
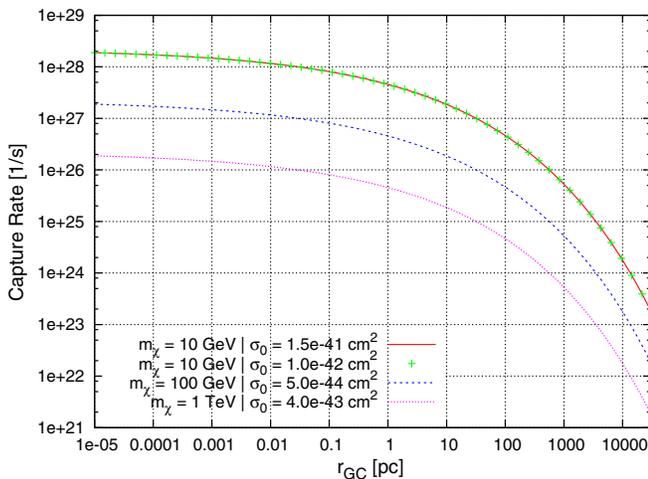

FIG. 2 (color online). Dark matter accretion rates vs galactic radius for four different configurations of dark matter (cf. legend in figure) and with $(r_{-2}, \alpha) = (16$ kpc, $0.19)$. The merging of the two first cases is due to the fact that we take into account the limiting geometrical cross section of the neutron star surface.

time where the DM annihilation begins to affect the temperature of the neutron star.

B. Cooling of the neutron star

While some energy will be lost to neutrinos, the energy generated by the annihilation of most dark matter candidates is carried in the main by leptons, quarks and photons. We therefore neglect that part lost to neutrinos and assume that all the annihilation mass energy goes into heating the neutron star.

Since all the dominant cooling processes involved in this situation scale with some positive power of the temperature except for the WIMP annihilation emissivity, the latter will dominate at some point in the life of the star.

The cooling of the neutron star is given by the following differential equation:

$$\frac{dT}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_{DM}}{c_V}, \qquad (9)$$

where c_V is the heat capacity of the star. ϵ_{DM} is the emissivity (released energy per volume per time) produced by the annihilation of the DM when the latter saturates and is given by $\epsilon_{DM} = 3Cm_\chi/4\pi R^3$. ϵ_ν is the emissivity due to the modified Urca process, which makes the neutron star lose energy through neutrino emission by converting protons and electrons to neutrons and vice versa, and is given by [34]

$$\epsilon_\nu = (1.2 \times 10^3 \text{ J m}^{-3} \text{ s}^{-1})\left(\frac{n}{n_0}\right)^{2/3}\left(\frac{T}{10^7 \text{ K}}\right)^8 \qquad (10)$$

(where n is the baryon density in the star and $n_0 = 0.17$ fm^{-3} the baryon density in nuclear matter). Finally, ϵ_γ accounts for the effective emissivity in photons measured in energy over volume and time and is given by

$$\epsilon_\gamma = \frac{L_\gamma}{(4/3)\pi R^3} \simeq 1.56 \times 10^{13}\left(\frac{T}{10^8 \text{ K}}\right)^{2.2} \text{ J m}^{-3} \text{ s}^{-1}, \qquad (11)$$

where L_γ simply is the rate of heat loss from the surface of the neutron star: $L_\gamma = 4\pi R^2 \sigma T_{surface}^4$ (with σ the Stefan-Boltzmann constant).

C. Change in outward appearance

The DM heats the neutron star at a constant rate which will dominate any other thermal process at late times. Note that, since when the DM particles annihilate their equilibrium density corresponds to a negligible fraction of the total mass, we have neglected the contribution of the WIMPs to the specific heat.

In order to determine the thermal evolution of the star through its internal and surface temperatures, we solve numerically the differential equation (9). As the temperature at interesting times (i.e. beyond 10^6 years when the

star starts to cool down) is reasonably insensitive to the initial conditions, we arbitrarily set $T(t=0) = 10^9$ K.

The surface temperature is related to the internal temperature by the following approximation [35]:

$$T_{\text{surface}} = (0.87 \times 10^6 \text{ K})\left(\frac{g_s}{10^{12} \text{ m/s}^2}\right)^{1/4}\left(\frac{T}{10^8 \text{ K}}\right)^{0.55},$$

where $g_s = GM_{\text{NS}}/R_{\text{NS}}^2$ is the surface gravity on the neutron star.

D. Results for annihilating dark matter—How hot do neutron stars get?

Changing the position of the neutron star in the galaxy changes the accretion rate of dark matter which in turn changes the temperature of the neutron star due to internal dark matter annihilation.

Since we are working with a 1-parameter set of density profiles (see Sec. III), our predictions will be model-dependent. However, knowing the discrepancy between the different DM density distributions gives us a relatively good picture of the whole space of possibilities and since many relations involved in the process are linearly related to the density parameter, the reader can scale our results up or down as required.

For every pair of parameters (r_{-2}, α) defining an Einasto profile which matches our given constraints, we define the properties $(m_{\text{DM}}, \sigma_0)$ of the DM particle we want to probe; we then calculate the capture rate for our standard neutron star and we finally apply the temperature gradient given by Eq. (9) in order to find the final internal and surface temperatures. In Fig. 3, we present an example of our results, with $m_\chi = 10$ GeV and $\sigma_0 = 1.5 \times 10^{-41}$ cm^2.

As previously mentioned in Sec. II, we decided to use a constant velocity dispersion in our simulations for the sake of clarity. Near the galactic center, however, the velocity dispersion increases significantly due to the presence of the central SMBH (Fig. 4). The results shown here are deduced from the static radial Jeans equation

$$\frac{1}{\rho}\frac{\partial}{\partial r}(\rho\sigma_R^2) + 2\frac{\beta\sigma_R^2}{r} = -\frac{GM(r)}{r^2},$$

using $\sigma^2 = 2\sigma_T^2 + \sigma_R^2$ as the three dimensional velocity dispersion and σ_R and σ_T as the one dimensional velocity dispersions in the radial and tangential directions (assuming a spherically symmetric DM distribution so that $\sigma_\theta = \sigma_\phi = \sigma_T$); $\beta = 1 - \sigma_T^2/\sigma_R^2$ is the anisotropy parameter. We use the relationship $\beta = -0.31 - 0.295\gamma$ which comes from a rough fit to the regular line in the $\beta - \gamma$ plane found in figure 11 of the paper [36]. $M(r)$ is given by the sum $M(r) = M_{\text{Baryons}}(r) + M_{\text{DM}}(r)$, where the latter is simply integrated from the DM density profile and the former is obtained by considering standard baryonic density distributions in our galaxy. We assume the presence of a SMBH of mass $3.7 \times 10^6 M_\odot$ and total masses at a
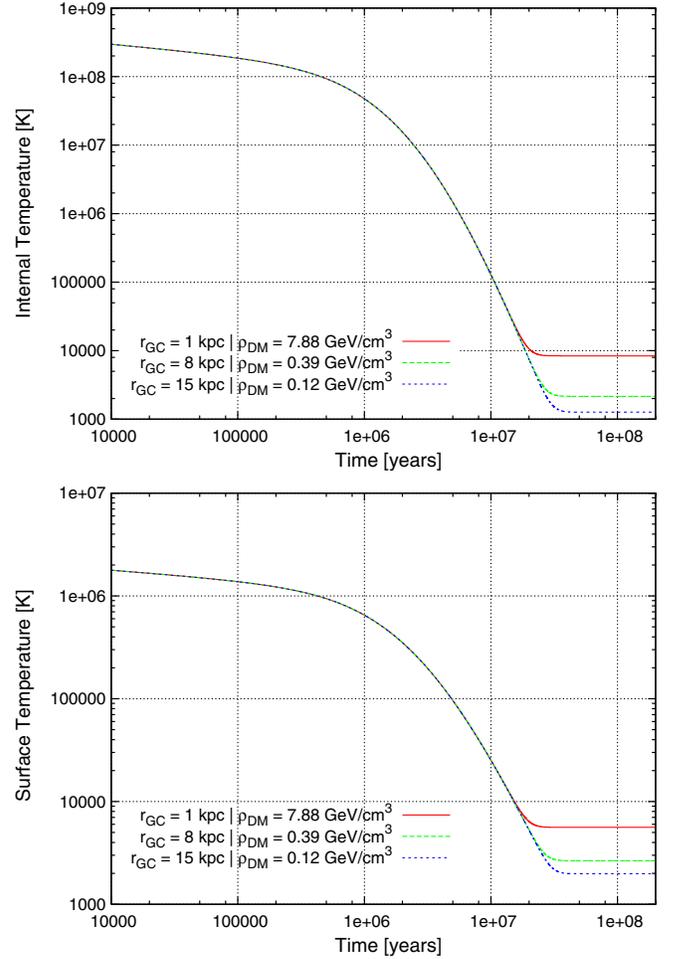

FIG. 3 (color online). Evolution of the internal (above) and surface temperatures of a $1.44 M_\odot$ neutron star situated at various galactic radii. In the present case, $m_\chi = 10$ GeV, $\sigma_0 = 1.5 \times 10^{-41}$ cm^2 and $(r_{-2}, \alpha) = (16 \text{ kpc}, 0.19)$.
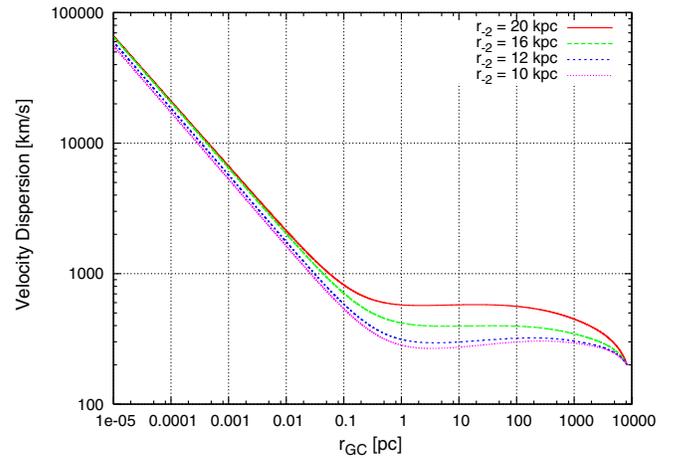

FIG. 4 (color online). Velocity dispersions with respect to the galactic radius for the four different Einasto DM density profiles considered in the present article.

galactic radius of 30 kpc for the bulge and the disk of respectively $1.3 \times 10^{10} M_\odot$ and $6.5 \times 10^{10} M_\odot$.

The capture rate depends in a non trivial way on this quantity, basically decreasing for larger values of the velocity dispersion. The emissivity due to DM annihilation will follow the same general trend, leading to lower final surface temperatures of the neutron star (Fig. 5).

We would like to point out however that this is not the only possible way of calculating the velocity dispersion of dark matter. In particular, it has been noted in N-body simulations that the pseudophase space density $\rho/\sigma^3 \propto r^{-1.875}$ [37] which is very close to the value obtained in spherical infall calculations [38]. If we assume this relation is true, then the velocity dispersion falls towards the center of the galaxy, even in the presence of baryonic contraction. However, we shall present temperature results for the velocity dispersion which is calculated using the Jeans equation so as to be conservative.

Using the method described before, we calculate the final temperatures of our neutron star at different galactic radii, starting with $r_{GC} = 10^{-5}$ pc and going outwards through the halo up to a radius of 50 kpc. For every DM density profile and for every type of DM particle, we get a specific curve. As we said, however, the relation between the various sets of solutions is rather straightforward, since the temperature gradient varies as: $dT/dt \propto C m_\chi$. Note that the results obtained so far do not depend much on m_χ since $C \propto 1/m_\chi$. For nonrelativistic accretion the dependence on the mass might be more pronounced since the kinematics of individual collisions would depend on the ratio between the nucleon mass and the dark matter particle. For the case of neutron stars however any such depen-

dency will be suppressed since the kinetic energy of the dark matter particle will be much larger and any small recoil in the neutron star will result in the particle being captured.

In the most favorable cases in terms of DM properties and distribution, the highest surface temperatures one can possibly obtain lie around 10^6 K near the galactic center (Fig. 6).

E. Density profiles with central spikes

In all our calculations so far we have been considering straightforward Einasto profiles without taking too much care about the complex astrophysical phenomena occurring near the galactic center on a subparsec scale. The formation of a super massive black hole is thought to enhance the density in this central region [39] and this combined with effects such as self-annihilation, gravitational scattering of DM particles by stars and capture in the supermassive black hole must be included if one wishes to obtain a more realistic picture of this central region.

It is interesting to evaluate the possible consequences of considering much higher DM densities at small radii. To do so, we take as a benchmark the density profiles presented in [40] and we extract a few values in order to determine the evolution of the surface temperature (Fig. 7). One can observe that, in the most extreme situations, the neutron star manages to keep its surface temperature well above 10^6 K at late times if it is situated at less than one thousandth of a parsec from the central black hole. Since there have been a large number of compact objects observed by the Chandra X-ray telescope in this central region [41], this might prove interesting in the future.
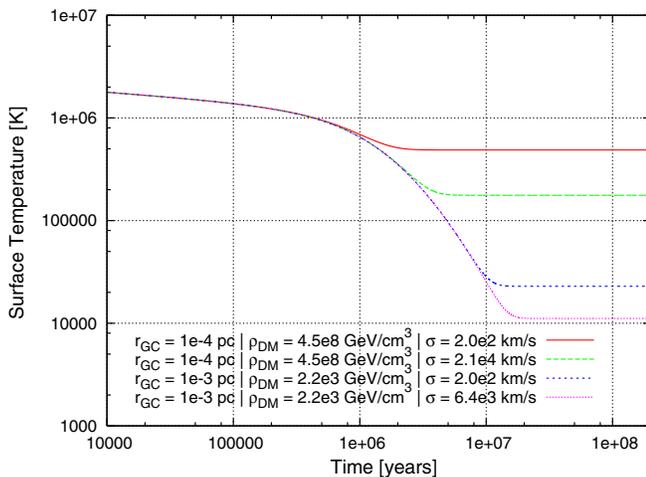

FIG. 5 (color online). Evolution of the surface temperature of a $1.44 M_\odot$ neutron star situated at two different galactic radii. The plot is for dark matter with a mass $m_\chi = 10$ GeV and a scattering cross section of $\sigma_0 = 1.5 \times 10^{-41}$ cm^2. We compare here the approximate constant velocity dispersion ($\sigma \equiv \bar{v} = 200$ km/s) with the effective velocity dispersion deduced from the static radial Jeans equation.
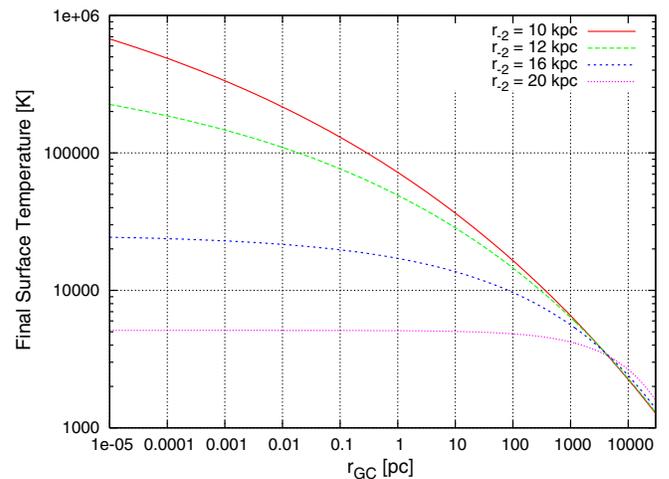

FIG. 6 (color online). Final surface temperature of the neutron star (at late times) for different DM density distributions, with $m_\chi = 10$ GeV and $\sigma_0 = 1.5 \times 10^{-41}$ cm^2.
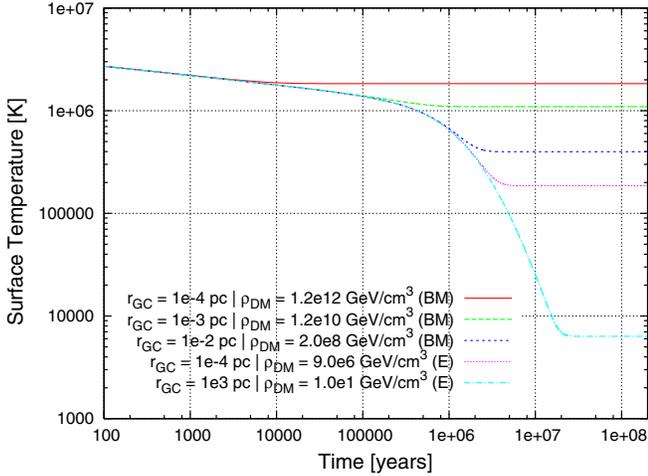
FIG. 7 (color online). Evolution of the surface temperature of a 1.44 $M_\odot$ neutron star situated at various galactic radii (cf. legend in figure). The plot is for dark matter with a mass $m_\chi = 10$ GeV and a scattering cross section of $\sigma_0 = 1.5 \times 10^{-41}$ cm^2. The DM densities are deduced from two models: profiles obtained by Bertone and Merritt in [40] (BM) and Einasto profiles (E).

F. Observational situation

It is a challenge for astronomers to observe the thermal emission from neutron stars due to their very small surface area and luminosity. Rather than attempting to provide a complete review of this complicated subject we will mention a couple of examples of relatively cool neutron stars which have been observed.

Pulsar PSR J0108-1431 is a nearby pulsar located between 100 and 200 pc from the Solar System. The spin down age suggests that this object is older than 10^8 yr so that its surface will have had a long time to cool. Indeed, observations suggest that the surface temperature is a very low $T_{\text{eff}} < 9 \times 10^4$ K if the distance is 200 pc or $T_{\text{eff}} < 5 \times 10^4$ K if the pulsar is located at a distance of 130 pc [42]. Comparison with Fig. 3 shows that even this very low temperature is too high to betray underlying heating by dark matter, probably by around an order of magnitude.

Pulsar PSR J0437-4715 is a much older object with a spin down age of nearly 5 Gyr, yet its surface temperature is slightly higher than that of J0108-1431 [42]. It seems to be challenging to explain this relatively high surface temperature (for its age) and it has been suggested that the explanation may lie in internal heating [43]. Unfortunately, it does not seem that this internal heating comes from dark matter since in order for this to be the case we would require a density of dark matter much larger than what is expected in this region of the galaxy (PSR J0437-4715 lies only about 130 pc from the Solar System). Also, if we were to explain the temperature of this object using dark matter, we would also expect a similar temperature for PSR J0108-1431.

If it were possible to extend observations in the future to lower temperatures and we were able to find a neutron star with a temperature $\sim 10^4$ K then the situation would become much more interesting. A temperature of 10^4 K is about as low as could be possible for the very oldest neutron stars which exist. If such a low temperature neutron star was observed this would tell us that any combination of dark matter density and cross section which predicts a temperature higher than this at the solar radius in the galaxy is ruled out.

As we have shown, we can expect higher temperatures for neutron stars which lie at the center of the galaxy because of the larger accretion rates in that region. It is however difficult to see into the center of the galaxy, in fact the very center is obscured by dust [44] and as we move upwards in frequency through the electromagnetic spectrum, we find the center of the galaxy becomes invisible in the infrared, only to return into view in the X-ray part of the spectrum. Since this rules out the possibility of viewing objects with temperatures less than many millions of degrees, the observational situation becomes more complicated (not to mention the 3 orders of magnitude drop in luminosity relative to local neutron stars simply due to distance). We may be able to see a very hot neutron star lying at the galactic center, but it would be necessary to find some reliable way of dating the object to a relatively high precision in order to establish that this heating is anomalous and caused by dark matter.

From these considerations, it is clear that the conclusion largely depends on the assumptions made about the DM distribution in the Milky Way. Nevertheless, there is a small hope that the most extreme configurations might be tested through observations.

Therefore, our chances of using neutron stars as dark matter probes through the method described above are nonzero but limited. There exists however an alternative way of benefiting from the high accretion power of these very dense objects if we assume that DM particles do not coannihilate with each other.

V. NONANNIHILATING DARK MATTER

In the case of nonannihilating DM particles, there would be no heating of the neutron star due to annihilation—the neutron star would simply accrete DM in its core. If the amount of dark matter in the core were to increase without limit, there would be various possible outcomes. In the case of fermionic dark matter and in the absence of any pressure due to the exchange of gauge bosons, the density would increase until Fermi statistics starts to play a role. When this occurs, the dark matter core would develop the equation of state of nonrelativistic degenerate fermionic matter, $P \propto \rho^{5/3}$. In order to calculate the effect of such a degenerate dark matter core upon the neutron star, the correct thing to do would be to simultaneously solve the Oppenheimer-Volkoff equation for the two stars colocated on top of each other and therefore both contributing to the gravitational field relevant for the solution. We have ob-

tained such solutions, and have confirmed that when there is a large mass contribution due to a degenerate dark matter core existing in the star, the normal mass-radius and indeed maximum mass of the neutron star that can be obtained varies.

In practice however, the amount of dark matter which needs to be added to the core of the neutron star for this to happen is typically far in excess of the Chandrasekhar mass (M_{Ch}) corresponding to the degenerate dark matter star for all but the lightest dark matter candidates. At this critical point, the degeneracy pressure of dark matter would become relativistic and the degenerate dark matter core would become unstable. Gravitational collapse of the dark matter core would occur, creating a black hole at the center of the neutron star, resulting in the neutron matter also becoming unstable.

The black hole thus created would swallow the neutron star entirely. This is particularly intriguing possibility not simply for its inherent drama but also because it could in principle provide an additional explanation of the unexplained gamma ray bursts observed in the Universe other than the coalescence of a neutron star with another compact object. It would therefore be interesting if enough dark matter could be accreted for reasonable values of the relevant parameters—namely the density of dark matter in the places where neutron stars reside, the mass of the dark matter and its cross section for scattering off nuclei.

Fixing the accretion time available for the neutron star to capture DM particles, one can determine, for a given m_χ, the cross-section needed to accrete a mass equivalent to $M_{Ch}(m_\chi)$ which is the amount of accreted dark matter required to instigate the collapse of the neutron star. This procedure allows us to pick out regions on the $\sigma_0 - m_\chi$ plane where this could occur (Fig. 8). We assume that the Chandrasekhar limit is of the order of $M_{Ch} \approx M_{Pl}^3/m_\chi^2$ and we consider three accretion times: 10^6, 10^8, and 10^{10} years, corresponding roughly to 0.01%, 1%, and 100% of the age of the Universe, respectively. We also consider two different densities 10^{11} and 10^5 GeV cm^{-3}. The higher density 10^{11} GeV cm^{-3} is the rather extreme limit of the predictions of Bertone and Merritt for nonannihilating dark matter in a central spike. Since we consider the limiting effective cross section given by the geometrical cross section of the neutron star ($\sigma_0^{max} = 2 \times 10^{-45}$ cm^2), there exists a minimum value for the DM particle mass below which the fixed accretion time is too short for the star to accrete M_{Ch}. The corresponding limiting σ_0 is shown on the graph by the upper cutoff at high cross sections. It is possible to see that in the most extreme case, namely, a neutron star immersed in a density of 10^{11} GeV cm^{-3} for 10^{10} years do we obtain results which are approaching the region of interest for direct detection experiments.

The cross sections required become much smaller for higher dark matter masses since much fewer of these
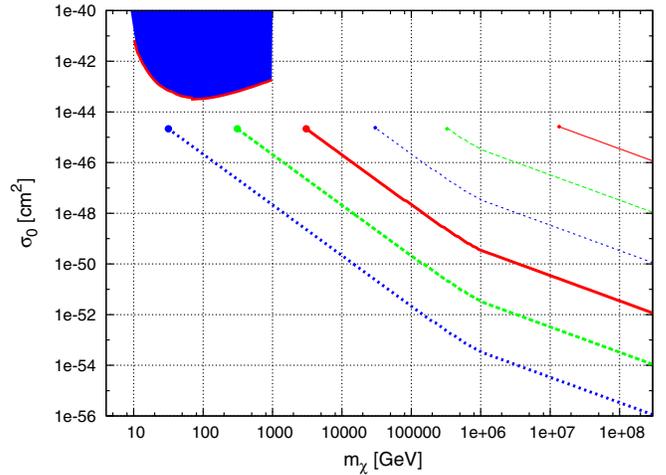

FIG. 8 (color online). Neutron stars immersed for long enough in a high enough density of nonannihilating dark matter will eventually accumulate the amount of DM particles which correspond to the Chandrasekhar limit M_{Ch} and collapse. The red solid lines here correspond to the cross section σ_0 and mass m_χ required to cause collapse after 10^6 years. The green longer dashed lines correspond to 10^8 years and the blue shorter dashed lines correspond to 10^{10} years. The thicker the line the higher the density—we plot two lines for each duration of time corresponding to 10^{11} and 10^5 GeV cm^{-3}. The upper right region of each line is excluded since the conditions in this region would give rise to a black hole. The curved line corresponds to the latest data from the CDMS experiment (assuming a velocity dispersion $\bar{v} = 230$ km/s and $\rho_{DM} = 0.3$ GeV/cm^3) to place the results in context. The change in the slope of the lines around 10^6 GeV is explained in the text.

particles need to be accreted to reach their correspondingly smaller Chandrasekhar mass limit. The change in the slope of the line at high masses can be understood in the following way—the typical energy exchanged in a recoil of a dark matter particle with a nucleon goes like $m_{nuc}v^2$ for $m_\chi \gg m_{nuc}$. When a 10^3 GeV mass dark matter particle travelling at 200 km s^{-1} falls onto a neutron star its velocity increases to close to the speed of light and the energy exchanged in this collision is much larger than the total kinetic energy the particle had at infinity. Such a particle will lose so much energy in the kick it will almost certainly be captured by the neutron star [45]. For a much more massive particle this is no longer true and it will have a lower probability of being captured due to a single scatter, hence the different slope at higher energies.

VI. CONCLUSIONS

In this work we have investigated whether or not it would ever be possible to use the accretion of dark matter onto neutron stars in order to understand the properties of dark matter better.

We first looked at the effects of annihilating dark matter on the temperature of the neutron stars. As can be seen in

Fig. 6, the highest final surface temperatures which could be caused by the heating of neutron stars with dark matter lie around 5×10^5 K even in the most optimistic circumstances (at $r_{GC} = 10^{-4}$ pc, for $m_\chi = 10$ GeV, $\sigma_0 = 1.5 \times 10^{-41}$ cm^2 and using $r_{-2} = 10$ kpc). If we consider a pessimistic variable velocity dispersion calculated using Jeans equation and rising towards the center of the galaxy, the final temperature drops to 1.8×10^5 K. Given the surface area of the neutron stars, these values would produce luminosities in the vicinity of $10^{-2} L_\odot$ (respectively $2 \times 10^{-4} L_\odot$ with variable velocity dispersion) with a peak wavelength at about 6 nm (16 nm), corresponding to a frequency of ~ 50 PHz (18 PHz). These sources would thus radiate mainly in the range between extreme ultraviolet (UV) and soft X-rays. Given the important absorption due to dust between us and the center of our galaxy and the presence of other luminous X-ray sources in this region, we believe that the objects in question would prove rather tricky to detect.

Perhaps more interesting are the constraints on nonannihilating dark matter which come from the fact that if enough of such dark matter were to accumulate onto a neutron star it would form a degenerate star at the center. If this internal star were to get too large, it might reach its own Chandrasekhar mass, which is smaller than that of the neutron star since the dark matter mass is greater than the nucleon mass in most models. In the event of the mass of dark matter in the star reaching the Chandrasekhar mass of

the star, the dark matter would lead to the collapse of the neutron star which collected it. Such an event might happen for the kind of values of dark matter mass and cross section currently being probed by direct detection experiments but only in regions of extremely high density. On the other hand, for higher mass dark matter particles, required cross sections are much smaller, since a much smaller mass of dark matter would need to be accumulated in order for collapse to occur.

The idea that the accretion of stable dark matter could be responsible for the collapse of neutron stars is very exciting, in this paper we have quantified how likely that is. For low mass dark matter particles, it seems extremely unlikely, since we would need DM densities of the order of 10^{11} GeV/cm^3 in order to put significant constraints on the $\sigma_0 - m_\chi$ plane.

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