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Constraining decaying dark matter with neutron stars

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ABSTRACT

The amount of decaying dark matter, accumulated in the central regions in neutron stars together with the energy deposition rate from decays, may set a limit on the neutron star survival rate against transitions to more compact objects provided nuclear matter is not the ultimate stable state of matter and that dark matter indeed is unstable. More generally, this limit sets constraints on the dark matter particle decay time, τ_χ. We find that in the range of uncertainties intrinsic to such a scenario, masses $(m_\chi/\text{TeV}) \gtrsim 9\times10^{-4}$ or $(m_\chi/\text{TeV}) \gtrsim 5\times10^{-2}$ and lifetimes $\tau_\chi \lesssim 10^{55}$ s and $\tau_\chi \lesssim 10^{53}$ s can be excluded in the bosonic or fermionic decay cases, respectively, in an optimistic estimate, while more conservatively, it decreases τ_χ by a factor $\gtrsim 10^{20}$. We discuss the validity under which these results may improve with other current constraints.

Disentangling the nature of dark matter (DM) is one of the greatest current challenges in physics. Whether this is realized through a stable or a decaying particle remains unknown to date. There is a vast literature with many well-motivated particle physics models containing unstable, long-lived DM particle candidates, see e.g. [1] for a review. Possible DM decay timescales, τ_χ, are constrained by cosmic microwave background (CMB) anisotropies, Fermi LAT limits on galaxy clusters and galactic γ-ray diffuse emission, antiprotons and the observed excess in the cosmic electron/positron flux [2,3]. It is usually assumed that the decay daughter particles are (nearly) massless although a more generic situation with arbitrary non-zero masses, m_D, may also occur [4–6]. The spread of the current bounds on the DM lifetime τ_χ or, equivalently, on the DM decay rate $\Gamma_\chi = 1/\tau_\chi$ is large. For example, PAMELA [7] and Fermi LAT [8] data can be interpreted in a scenario where a decaying χ-particle has a lifetime $\tau_{e^+e^-} \sim 10^{26}$ s for DM masses $m_\chi \gtrsim 300$ GeV and well into the TeV range [9] (we use $c = 1$). Such lifetimes may appear in the context of supersymmetric grand unification theories through dimension 6 operators [10] with $\tau_{\text{GUT}} \sim 10^{27}\ \text{s}\left(\frac{\text{TeV}}{m_\chi}\right)^5\left(\frac{M_{\text{GUT}}}{2\times10^{16}\ \text{GeV}}\right)^4$. On the other hand, CMB data provide a constraint $\Gamma_\chi^{-1} \gtrsim 30$ Gyr for massless daughter particles while for sufficiently heavy ones, $m_D \lesssim m_\chi$, decay times remain unrestricted [5].

Here we consider a scenario where weakly interacting scalar bosonic or fermionic metastable DM is gravitationally accreted onto neutron stars (NSs), and possibly first onto the progenitor stars. In brief, NSs are astrophysical objects believed to have a central core, which constitutes the bulk of the star and where mass densities are supranuclear, i.e. in excess of $\rho_0 \simeq 2.4\times10^{14}$ g/cm^3. Although there is a rich phenomenology on the possible internal core composition, for the sake of simplicity, we conservatively consider it here to be composed of nucleon (n) fluid, with mass densities $\rho_n \sim (1-10)\rho_0$. Under these conditions, NSs are efficient DM accretors. They can effectively capture an incoming weakly interacting χ-particle passing through the star since its mean free path is much smaller than the typical NS radius. Explicitly, $\lambda_\chi \simeq \frac{1}{\sigma_{\chi n} n_n}$ where $\sigma_{\chi n}$ is the χ-nucleon elastic scattering cross-section that we will use in the S-wave approximation and $n_n = \rho_n/m_n$ is the nucleon particle density, with m_n the nucleon mass.

Compilation of the latest results in direct detection searches [11] allows analysis to set limits at a level of $\sigma_{\chi n} \simeq 10^{-44}$ cm^2 in the $m_\chi \sim (10\text{–}10^4)$ GeV range. For the sake of discussion in this work, we will consider this $\sigma_{\chi n}$ value as representative for a DM particle candidate having in mind that current experimental efforts can potentially provide more stringent lower values. In the same fashion, assuming an average NS with typical radius $R \simeq 12$ km

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and mass $M \simeq 1.5 M_\odot$ each DM particle will scatter inside a number of times given by

$$R/\lambda_\chi \simeq 6.1 \left(\frac{R}{12\ \mathrm{km}}\right)\left(\frac{\sigma_{\chi n}}{10^{-44}\ \mathrm{cm}^2}\right)\left(\frac{\rho_n}{3\rho_0}\right). \quad (1)$$

However, accretion of DM will proceed not only during the NS lifetime, but also in the previous late stages of the progenitor star where the dense nuclear ash central core allows the build-up of a χ-distribution, $n_\chi(r)$, over time. In previous works we have considered the effect of a self-annihilating DM particle on the internal NS dynamics [12–15] but here we will focus on the possibility that the only process depleting DM is decay.

The picture is thus similar to proton decay searches such as those performed by Super Kamiokande [16] consisting of a 50 kton water detector looking for proton decay channels $p \to e^+\pi_0, \bar{\nu}K^+$. This volume involves $\sim 10^{33}$ protons and is thus sensitive to $\tau_p \sim 10^{33\text{-}34}$ yr as showed by analysis of data [17]. By analogy, we consider the NS core as a tank of DM that builds up in time starting as early as the progenitor star phase. The numbers of captured particles will depend on the size, mass and composition of the progenitor star (as well as on the NS phase) once the DM-ordinary matter scattering cross-section is fixed.

The DM accretion process onto NSs has been previously estimated, see for example [18,19], by means of the capture rate, C_χ, given an equation of state for regular standard-model matter in the interior of the NS at a given galactic location and with a corresponding ambient DM density. Taking as reference a local value for DM density $\rho^{ambient}_{\chi,0} \simeq 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$, it is approximated by

$$C_\chi \simeq \frac{3\times 10^{22}}{f\left(\frac{M}{R}\right)}\left(\frac{M}{1.5M_\odot}\right)\left(\frac{R}{10\ \mathrm{km}}\right)\left(\frac{1\ \mathrm{TeV}}{m_\chi}\right)\left(\frac{\rho^{ambient}_\chi}{0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\ \mathrm{s}^{-1}, \quad (2)$$

with $f\left(\frac{M}{R}\right) = 1 - 0.4\left(\frac{M}{1.5M_\odot}\right)\left(\frac{10\ \mathrm{km}}{R}\right)$ a redshift correction factor. Following [20] we do not consider a reduction of the DM-n cross-section since we use current experimental sensitivity $\sigma_{\chi n} \simeq 10^{-44}$ cm^2, well above the geometrical cross-section. It is important to note that this dependence sets a limit on the intrinsic capability of NSs to accumulate a critical amount of DM and possibly serve as a test-bench for DM properties.

In the NS, the DM particle number, N_χ, can be obtained solving the differential equation $\frac{dN_\chi}{dt} = C_\chi - \Gamma N_\chi$, considering competing processes, capture and decay, the latter treated via a generic decay rate Γ. The DM population at time t is thus

$$N_\chi(t) = \frac{C_\chi}{\Gamma} + \left(N_\chi(t_{\mathrm{col}}) - \frac{C_\chi}{\Gamma}\right)e^{-\Gamma(t-t_{\mathrm{col}})},\ \ t > t_{\mathrm{col}}. \quad (3)$$

This solution takes into account the possibility of an existing DM distribution in the progenitor star before the time of the collapse, t_{col}, that produced the supernova explosion. Depending on the χ-mass and thermodynamical conditions inside the star, it may be possible to thermally stabilize a DM internal distribution. For the $\sigma_{\chi n}, m_\chi$ range values discussed so far this is indeed the case.

The DM particle density takes the form $n_\chi(r,T) = \frac{\rho_\chi}{m_\chi} = n_{0,\chi} e^{-\frac{m_\chi}{k_B T}\Phi(r)}$, with $n_{0,\chi}$ the central value. $\Phi(r) = \int_0^r \frac{GM(r')dr'}{r'^2}$ is the gravitational potential. Assuming a constant baryonic density in the core $M(r) = \int_0^r \rho_n 4\pi r'^2 dr'$, we finally obtain

$$n_\chi(r,T) = n_{0,\chi} e^{-(r/r_{\mathrm{th}})^2}, \quad (4)$$

with a thermal radius $r_{\mathrm{th}} = \sqrt{\frac{3k_B T}{2\pi G\rho_n m_\chi}}$.

In order to asses the importance of the progenitor DM capture efficiency and thus the $N_\chi(t_{\mathrm{col}})$ value, let us consider a $15M_\odot$ progenitor star and its composition through the burning ages [21]. After the He-burning stage for $t_{\mathrm{He}\to\mathrm{CO}} \simeq 2\times 10^6$ yr, a CO mass $\sim 2.4M_\odot$ sits in the core with a radius $R \sim 10^8$ cm. The gravitationally-captured DM population is $C_\chi^{\mathrm{He}\to\mathrm{CO}} t_{\mathrm{He}\to\mathrm{CO}} \simeq 3.35\times 10^{39}\left(\frac{1\ \mathrm{TeV}}{m_\chi}\right)\left(\frac{\rho^{ambient}_\chi}{0.3\ \mathrm{GeV/cm}^3}\right)$. Coherence effects may play a role for slowly moving, low m_χ incoming DM particles when their associated de Broglie wavelength is comparable to the nuclear size, and in this case one should include a multiplicative factor to account for nucleus (N) instead of nucleon scatterings, i.e. $\sigma_{\chi N} \simeq A^2\left(\frac{\mu}{m_n}\right)^2 \sigma_{\chi n}$ where A is the baryonic number and μ the reduced mass for the $\chi - N$ system. Since the later burning stages proceed rapidly, the He → CO stage gives the main contribution to the DM capture in the progenitor.

As the fusion reactions happen at higher densities and temperatures, the DM thermal radius contracts. In this way, for example, for $m_\chi = 1$ TeV in the He → CO, $r_{\mathrm{th}} \simeq 470$ km, while for Si → FeNi, $r_{\mathrm{th}} \simeq 70$ km. The thermalization time $t_{\mathrm{th}}^{-1} = \left(\frac{3k_B T}{m_\chi}\right)^{1/2} \sigma_{\chi N} \frac{n_N m_\chi m_N}{(m_\chi + m_N)^2}$, where $n_N = \frac{\rho_N}{m_N}$, for both cases is small compared to the dynamical burning timescales $t_{\mathrm{th}}/t_{\mathrm{He}\to\mathrm{CO}} \simeq 10^{-5}$, $t_{\mathrm{th}}/t_{\mathrm{Si}\to\mathrm{FeNi}} \simeq 10^{-7}$. However during the core collapse, the dynamical timescale involved is $\Delta t_{\mathrm{dyn\,col}} \simeq \sqrt{\frac{3}{8\pi\bar{\rho}G}} \simeq 10^{-3}$ s where $\bar{\rho}$ is an average matter density. Assuming a proto-NS (PNS) forms with $T \simeq 10$ MeV, central density $n_n = 5n_0$ and a neutron-rich fraction $Y_{\mathrm{neut}} \sim 0.9$, $n_{\mathrm{neut}} = Y_{\mathrm{neut}} 5n_0 \simeq \frac{p^3_{\mathrm{F,neut}}}{3\pi^2}$, thermalization time in this phase takes longer to be achieved [22] $t_{\mathrm{th}} = \left(\frac{2m_\chi^2}{9m_n k_B T}\frac{p_{\mathrm{F,neut}}}{m_n}\frac{1}{n_n\sigma_{\chi n}}\right) \simeq 10^{-2}$ s.

The core collapse may thus affect the DM population inside the star since those DM particles remaining outside the PNS may effectively not be considered to play a role in the NS phase. The number of DM particles in the star interior, $r < R_*$, is written as $N_\chi = \int_0^{R_*} n_{0,\chi} e^{-(r/r_{\mathrm{th}})^2} dV$ and it is a dynamical quantity since r_{th} is temperature (time)-dependent. As long as $R_* \gg r_{\mathrm{th}}$, we obtain $N_\chi = n_{0,\chi}(\pi r_{\mathrm{th}})^3$. The retained fraction is

$$f_\chi = N_\chi^{-1} \int_0^{R_{\mathrm{PNS}}} n_{0,\chi} e^{-(r/r_{\mathrm{th}})^2} dV, \quad (5)$$

so that for $R_{\mathrm{PNS}} \simeq 10$ km, $f_\chi \simeq 2\times 10^{-3}$. The retained DM population in the PNS after the collapse is thus $N_\chi = N_\chi(t_{\mathrm{col}}) f_\chi \simeq 6.7\times 10^{36}\left(\frac{f_\chi}{2\times 10^{-3}}\right)\left(\frac{1\ \mathrm{TeV}}{m_\chi}\right)$. Let us note that the central DM density in the newly formed PNS $n_{0,\chi} \simeq 3\times 10^{23}$ cm^{-3} is much smaller than that in the baryonic medium $\sim 10^{38}$ cm^{-3}.

At this point one should check that the DM content does not exceed the fundamental Chandrasekar limiting mass for the star to survive. If this was the case, it may lead to gravitational collapse of the star (see [23,24]). Therefore, for fermionic DM, we expect $N_\chi(t) < N_{\mathrm{Ch}}$, where $N_{\mathrm{Ch}} \sim (M_{\mathrm{Pl}}/m_\chi)^3 \sim 1.8\times 10^{54}(1\ \mathrm{TeV}/m_\chi)^3$ with M_{Pl} the Planck mass, and for the bosonic case $N_{\mathrm{Ch}} \sim (\mathrm{M_{Pl}}/\mathrm{m}_\chi)^2 \sim 1.5\times 10^{32}(1\ \mathrm{TeV}/\mathrm{m}_\chi)^2$. In case a Bose–Einstein condensate is considered [25] $N_{\mathrm{BEC}} \simeq 10^{36}(T/10^5\ \mathrm{K})^5$ and the condition is $N_\chi(t) < N_{\mathrm{Ch}} + N_{\mathrm{BEC}}$. As described, in the fermionic case, DM remains at all times below the limiting mass, but this may not be the case in the cooling path of the PNS if a Bose–Einstein condensate is formed for a DM particle in the ∼ TeV mass range. The scenario described here may be indeed at the border of the collapse case, however we will restrict our discussion to the