

# Dark matter annihilation and local warming in the core of a neutron star

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In this contribution we propose that the possible existence of a component of self-annihilating dark matter in the universe may result in a local inner core warming of medium-age neutron stars on a time-scale of  $\sim 10^2$  yr. The energy released from annihilation of a massive ( $m_\chi \gtrsim$  TeV) dark matter particle in the central regions of the star could be capable of injecting an extra neutrino/photon component allowing a positive emissivity, opposed to the usual negative values for the standard cooling processes. As a result, an enhanced early warming era in the neutron star coolig scenario may result.

In the  $\Lambda$ CDM paradigm, current indications from recent Planck data [1] show that the current total matter content of the Universe is roughly 27%, more precisely Planck data yield (at 68% CL) a physical baryonic content  $\Omega_b h^2 = 0.02207 \pm 0.00033$  and a physical dark matter (DM) content of  $\Omega_c h^2 = 0.1196 \pm 0.0031$ . DM, being about five times more abundant than baryonic matter, has not yet been thoroughly taken into account in our current understanding of microscopic processes occurring inside stars. Namely, for neutron stars (NSs), the physical description of the interior has mostly been attempted only taking into account ordinary standard model species. Even if a tiny fraction, it remains to be determined at what extent the DM component may play a role and, consequently, trigger observable effects that could have been missidentified entangled in the, already complex, description of these objects.

Provided DM could be a Majorana particle, the emission of radiation in the final states from self-annihilation could be used as indirect evidence of its existence as we will argue. Although we should keep in mind that there is not yet consensus on basic DM properties such as bosonic or fermionic nature or, as mentioned, whether it is a Majorana or Dirac particle. To try to shed light on these aspects there is an international multi-messenger effort involving collider, direct or indirect searches where DM signals may be detected. Typically, globular clusters or the galactic center seem regions where a vast amount of this type of matter is expected. Some partial hints of an extra photon component coming from the galactic center have already arised [2]. The actual interaction strength in this dark sector is not clearly determined so far

and candidates in the weak sector (WIMPs) seem favoured in light of cosmological arguments. Regarding fundamental properties such as the mass of the DM candidate, favoured values in the range  $m_\chi \sim \mathcal{O}(10 \text{ GeV}/c^2 - 10 \text{ TeV}/c^2)$  are under current scrutiny.

In our galaxy a DM density distribution can be described under the form of a power-law density profile as already pointed out in the seminal work of [3]. Assuming this prior, the possibility of gravitational accretion of the dark component into massive compact stars comes naturally. In particular, the very dense environments of planets and stars seem capable to resonantly capture DM [4].

More in detail, in a NS with radius  $R$  and baryonic number  $N_B$  the large opacity of its internal dense core to incoming WIMPs seems capable to stabilize an inner distribution of these, given a scattering cross-section with nucleons around the value of the geometrical cross-section  $\sigma_{\text{geom}} \simeq 2.4 \times 10^{-45} \text{ cm}^2 \left(\frac{1.4M_\odot}{M}\right) \left(\frac{R}{11.5 \text{ km}}\right)^2$ . For possibly larger cross-sections than this and in order to preserve unitarity, the NS opacity saturates providing no enhancement of DM capture. On the other hand, for cross-sections smaller than the geometrical value there is a fundamental limit given by the escape velocity of the NS, that on the Newtonian approximation is  $v_{\text{esc}} \simeq 0.6c \sqrt{2G \left(\frac{M}{1.4M_\odot}\right) \left(\frac{11.5 \text{ km}}{R}\right)}$ . In this case, the NS gravitational potential well could bound the WIMPs kinematically although to form an inner thermalized distribution they must further interact with a nucleus/nucleon with mass  $M'$  losing an energy fraction  $\frac{\Delta E_k}{E_k} \lesssim \frac{4M'm_\chi}{(M'+m_\chi)^2}$  of the incoming kinetic energy  $E_k$  every time.

The internal thermalized DM distribution can be parametrized by a particle number density  $n_\chi(r, T) = n_{0,\chi} e^{-\left(\frac{r}{r_{\text{th}}}\right)^2}$  where  $r_{\text{th}}$  is the thermal radius and  $n_{0,\chi}$  is the central value normalized to the DM population number inside the star of radius  $R$  [5] at a given time in a local environment density similar to our solar system value of about  $\rho_\chi \simeq 0.3 \text{ GeV}/\text{cm}^3$ .

The population at a given time inside the NS,  $N_\chi(t)$ , is obtained from the solution of an ordinary differential equation  $\dot{N}_\chi = C_\chi - C_a N_\chi^2$  including competing processes by means of a capture rate  $C_\chi$  and an annihilation rate  $C_a$  yielding [4]

$$N_\chi(t) = \sqrt{\frac{C_\chi}{C_a}} \coth \left[ \frac{(t - t_{\text{col}})}{\tau} + \coth^{-1} \left( \sqrt{\frac{C_a}{C_\chi}} N_\chi(t_{\text{col}}) \right) \right], \quad (1)$$

with  $\tau^{-1} = \sqrt{C_\chi C_a}$  the relaxation time to achieve equilibrium and  $N_\chi(t_{\text{col}})$  is the number of DM particles inside the progenitor core at the time of the collapse (NS birth). This population is essentially inherited from the progenitor star in its lifetime.

The energetics of the dynamical microscopic processes must include the heating and cooling possibilities. First, considering the specific emissivity (energy released per unit volume and unit time) in the photon and neutrino channels arising from the annihilation channels it could be written as

$$\varepsilon_\chi(r, T) \simeq n_\chi^2(r, T) m_\chi \langle \sigma_a v \rangle \sum_{i=\nu, \gamma} f_i, \quad (2)$$

with  $\langle \sigma_a v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$  the velocity averaged annihilation cross-section and  $f_i \simeq \int \frac{E}{m_\chi} \frac{dN_i}{dE} dE$  the energy fraction from the spectrum  $\frac{dN_i}{dE}$ . We must note that the quantity  $f = f_\nu + f_\gamma$  is a positive number, *injecting* net energy into the system.

In the typical scenarios for NS cooling [6] standard-model (anti)neutrinos and photons are in charge of cooling efficiently the system. From observations, effective external temperatures

can be measured for a dozen isolated NSs [7]. In the so-called direct URCA process a very efficient neutrino cooling mode is triggered if the proton fraction in the core is large enough, in excess of (9 – 11)%. Since this requires large central densities it is uncertain whether this mode is switched on. However, if the existence of a spectator neutron is allowed, reactions  $p + e + n \rightarrow n + n + \nu_e$ ,  $n + n \rightarrow p + n + e + \bar{\nu}_e$  under the so-called modified URCA (MURCA) process can proceed. Its emissivity is given by

$$\varepsilon_\nu^{MURCA} \simeq -8.55 \times 10^{21} \left( \frac{T}{10^9 \text{ K}} \right)^8 \text{ erg s}^{-1} \text{ cm}^{-3}, \quad (3)$$

where the minus sign means that they are cooling modes, effectively removing energy from the system. In addition to this mode and at late times ( $\gtrsim 10^5$  yr) the standard photon mode overtakes the cooling as a black-body emitter with a luminosity  $L_\gamma \simeq 4\pi R^2 \sigma_{SB} T_e^4$  and  $T_e \simeq T^{0.5+\alpha}$ ,  $\alpha \simeq 0.1$  is the effective temperature with  $T_e \simeq 0.87 \times 10^6 (T/10^8 \text{ K})^{0.55}$ . This yields  $\varepsilon_\gamma \simeq -L_\gamma / \frac{4}{3}\pi R^3$  [6].

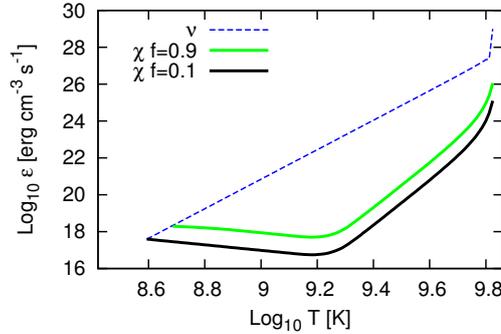


Figure 1: Emissivities in the inner NS core as a function of internal temperature for  $m_\chi = 10$  TeV. Dashed line is the MURCA neutrino process while the solid green and black lines denote the effect of a DM energy deposit of  $f = 0.9, 0.1$  respectively.

If we now consider the dynamical heat-energy flow the equations for the luminosity  $L$  and local temperature  $T$  (including redshift factors  $e^\Phi$  in a curved static spacetime) read [8]

$$\frac{1}{4\pi r^2} \sqrt{1 - \frac{r_s}{r}} \frac{\partial}{\partial r} (e^{2\Phi} L) = -\varepsilon - \frac{C_v}{e^\Phi} \frac{\partial T}{\partial t}, \quad \frac{L}{4\pi r^2} = \kappa \sqrt{1 - \frac{r_s}{r}} e^{-\Phi} \frac{\partial}{\partial r} (T e^\Phi), \quad (4)$$

where  $\varepsilon = \sum_{j=\nu,\gamma} \varepsilon_j$  is the contribution of the emissivities,  $r_s = 2GM$  is the Schwarzschild radius,  $C_v$  is the heat capacity per unit volume and  $\kappa$  is the thermal conductivity.  $C_v$  is the sum of the contribution of partial heat capacities from particle constituents (we take protons, neutrons, electrons)  $C_v = \sum_{i=p,n,e} C_{v,i}$ . For a degenerate core with fermions we have (per unit volume)

$C_{v,i} = N_i(0) \frac{\pi^2}{3} k_B^2 T$  and  $N_i(0) = \frac{m_i^* c^2 p_{F,i}}{\pi^2}$  is the density of states for a degenerate quantum system, being  $p_{F,i}$  the  $i$ th-Fermi momentum and  $m_{p,n}^* < m_n$  the in-medium nucleon mass, that can be reduced with respect to vacuum values due to many-body effects [9]. Consistently, we

take  $m_e^* = m_e$ . Let us note that in the Newtonian limit (the one we are going to analyze in this contribution) the solution is obtained from solving in the isothermally flat limit. This is a consequence of the large thermal conductivity in the system. Relativistic corrections to time and distance scales are set to unity. Then the equation simplifies to

$$C_v \frac{dT}{dt} = -|\varepsilon_\nu| - |\varepsilon_\gamma| + \varepsilon_\chi. \quad (5)$$

In Fig.(1) we show the emissivities in the NS inner core as a function of internal temperature  $T$ . We suppose neutrinos, photons and DM particles in a flat, Newtonian space. We assume an initial temperature of  $T \simeq 1$  MeV. We depict with a dashed line the MURCA neutrino process while the solid green and black lines denote the effect of an energy deposit of  $f = 0.9, 0.1$ , respectively. We can see that at a  $T \simeq 10^{8.6-8.7}$  K the emissivities are comparable. This  $T$  drop corresponds to  $\sim 10^2$  yr assuming a central core density of 3.5 times that of nuclear saturation density for a 10 TeV particle. Let us remind here that we have supposed that the core is isothermal at very early times. Standard approaches show that isothermality in the core takes about  $\Delta t \simeq 10$  yr to be achieved, however this correction should not change much the results obtained here. In a previous work [10] it was determined that the possible effect on the cooling pattern in a NS was a flattening of the temperature of the star around  $\sim 10^4$  K at times larger than  $\sim 10^7$  yrs, making this a challenging experimental confirmation, especially if looking towards central galactic locations where DM fraction may be enhanced. We find here that, for existing models of DM candidates with masses in the  $\gtrsim$ TeV range this is, in principle, a viable measurement that could test the proposed mechanism. This is subject of ongoing work and results will appear elsewhere. As a final remark let us mention that we have supposed that the fate of the NS is to remain as a nucleon-matter object, but if, however, a nucleation massive event is triggered, further consequences may result. This has been partially explored in [11][12][13]. M. A. P. G. would like to thank useful conversations with J. Pons and C. Kouvaris and the kind hospitality of IAP where part of this work was developed and the Spanish MICINN MULTIDARK, FIS2012-30926 projects.

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