

# NEUTRON STAR AS A DARK MATTER DETECTOR

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# INTRODUCTION

At the moment, astrophysical observations are known that indicate the existence of a dark matter in our Universe. These include the study of galaxy rotation curves [1], gravitational lensing[2], and the structure of the Bullet galaxy cluster [3]. Currently, various experiments are being carried out to search for latent particles. Experiments can be divided into direct and indirect. Direct detection can occur in underground experiments such as CDMS, which in principle can detect recoil energies from collisions between Weakly Interacting Massive Particles (WIMP) and nuclei, or in atmospheric experiments, such as XQC, where strongly interacting particles can collide with a detector. Indirect detection can occur with gamma rays and neutrino telescopes, where the presence of WIMPs can be detected indirectly by observing WIMP annihilation products. In particular, given that WIMPs can annihilate, and since they can be trapped within the Earth or the Sun, such annihilations will produce jets of particles, and in particular neutrinos, emanating directly from the center of the Earth or Sun, which could possibly be detected with using neutrino telescopes [4].

In this paper, we consider the possibility of indirect detection from the annihilation of trapped WIMPs inside a neutron star. Neutron stars have a high density and at the same time the surface of neutron stars has a low temperature. When WIMPs annihilate inside a star, a huge amount of energy is released, which heats the star. As we will show, once the rate of accretion of dark matter particles balances the rate of annihilation, the amount of energy released does not depend on the temperature of the star, and therefore, at later times, WIMP annihilation can maintain a constant temperature of the star.

# 1. WIMP'S ACCRETION RATE ONTO THE NEUTRON STAR

The accretion of dark matter particles onto the Earth and the Sun is not a new topic. Press and Spergel were the first to study in [4] the rate of capture of WIMPs into the Earth and the Sun. The rate of accretion onto a neutron star was also estimated by Goldman and Nusinov [5], who were the first to study the effect of WIMPs on neutron stars. In this section, we calculate the WIMP accretion rate onto a neutron star. We assume that the population of WIMPs has a Maxwell-Boltzmann velocity distribution

$$p(v)dv = n_0 \left( \frac{3}{2\pi\bar{v}^2} \right)^{3/2} 4\pi v^2 \exp \left( \frac{-3v^2}{2\bar{v}^2} \right) dv \quad (1.1)$$

where  $\bar{v}$  is the average WIMP velocity in our galaxy, and  $n_0$  is the WIMP density in the vicinity of the neutron star. A stream of WIMPs that cross a spherical surface of radius  $R$  with a speed between  $v$  and  $v + dv$  and an angle relative to the normal between  $\theta$  and  $\theta + d\theta$ , and

$$dF = n_0 \left( \frac{3}{2\pi\bar{v}^2} \right)^{3/2} \pi v^3 \exp \left( \frac{-3v^2}{2\bar{v}^2} \right) d(\cos \theta^2) dv \quad (1.2)$$

Let us express the flux in terms of the WIMP energy  $E = (1/2)v^2$  and the angular momentum  $J = vR \sin \theta$ . The total accretion rate is [11]

$$d\mathcal{F} = 4\pi R^2 dF = \left( \frac{3}{2\pi\bar{v}^2} \right)^{3/2} \exp \left( \frac{-3v^2}{2\bar{v}^2} \right) 4\pi dE dJ^2 \quad (1.3)$$

The actual WIMP capture rate by the star can be calculated in two steps. The first is to determine how much of the phase space for  $E$  and  $J$  can give orbits for WIMPs that intersect with a neutron star. In the second step, we must determine how much of the particles that cross the star lose enough energy to

be trapped inside the star. Here we will already give the final equation for the rate of accretion of dark matter onto a neutron star from the article [\[6\]](#)

$$\mathcal{F} = \frac{3.042 \times 10^{25}}{m_\chi(\text{GeV})} \times A \times f \quad (1.4)$$

where  $A$  is a constant parametrizing the local density of dark matter in the vicinity of a neutron star,  $f$  is the fraction of particles undergoing one or more scatterings inside the star.

## 2. ANNIHILATION RATE

Once a WIMP undergoes one scattering within a star, it loses enough energy on average to become gravitationally bound to the star. Even if there is enough kinetic energy to force it to leave the star, it will be forced to return and probably dissipate again, losing even more energy. The Wimp can repeat this process several times until its kinetic energy is reduced to the thermal velocity within the star. If the WIMP is a Majorana neutrino, then it can co-annihilate with another. The annihilation depends on the cross section and also on the density of WIMPs inside the star. The elastic cross section is determined

$$\sigma_{\chi} = \frac{2G_F^2}{\pi} \mu^2 I_s, \quad (2.1)$$

where  $\mu$  is the reduced mass of the WIMP-nucleus system,  $I_s$  is the form factor depending on the nuclei. The annihilation cross section of two Majorana neutrinos is given by

$$\sigma_A = \frac{G_F^2 m_{\chi}^2}{3\pi} \beta^2, \quad (2.2)$$

where  $\beta$  is the WIMP velocity in the center of mass system. Once the WIMP is thermalized in the star,  $\langle \beta^2 \rangle = 3T/(2m_{\chi})$  ( $T$  is the temperature inside the star).

The WIMP annihilation rate in a star is given by

$$\Gamma_A = \langle \sigma_{\chi} v \rangle \int n^2 dV, \quad (2.3)$$

где  $\langle \sigma_{\chi} v \rangle$  - is the thermally averaged annihilation cross section times the velocity and  $n$  is the WIMP density inside the neutron star. We assume that the density inside the star is constant. In this case, the number of WIMPs inside

the star is determined by

$$\frac{dN}{dt} = \mathcal{F} - C_A N^2 \quad (2.4)$$

Constant  $C_A = \langle \sigma_\chi v \rangle / V$ , where  $V$  - star volume. The accretion rate  $\mathcal{F}$  was obtained in the previous section. Solution of the previous equation

$$N(t) = \sqrt{\frac{\mathcal{F}}{C_A}} \tanh\left(\frac{t}{\tau}\right) \quad (2.5)$$

Time scale  $\tau = \frac{1}{\sqrt{\mathcal{F}C_A}}$ . The energy released as a result of annihilation is equal to

$$E = C_A N^2 m_\chi = \mathcal{F} \tanh^2(t/\tau) m_\chi \quad (2.6)$$

The amount of energy released depends on the time scale  $\tau$ . If  $\tau$  is large compared to the age of known neutron stars, the hyperbolic tangent is suppressed and the effect of dark matter on the star's temperature is negligible.

### 3. COOLING AND HEATING THE NEUTRON STAR

Let us consider the effect of WIMP annihilation on the temperature of a neutron star. During the annihilation of WIMPs, a large amount of energy is released, which is mainly carried by quarks, photons, and leptons. These particles will heat up the star, since they cannot leave it. The energy carried by neutrinos is extremely small compared to the energy carried by quarks, leptons and photons. Therefore, we can assume that all the energy from annihilation goes to heat the star. We also believe that the energy released during annihilation and the emissivity of this process does not depend on temperature. As long as an equilibrium is reached between accretion and annihilation, the released energy over time remains unchanged.

Let us assume that the released energy from WIMP annihilation is equal to  $E = \mathcal{F}m_\chi$ . The emissivity is

$$\epsilon_{dm} = \frac{E}{4\pi R^3/3} = \frac{3\mathcal{F}m_\chi}{4\pi R^3} \quad (3.1)$$

It is also necessary to take into account the processes that contribute to the cooling of the neutron star. During the first million years, the star will cool down due to the emission of neutrinos. The emissivity of this process is

$$\epsilon_\nu = (1.2 \times 10^4 \text{ erg cm}^{-3} \text{ s}^{-1}) \left( \frac{n}{n_0} \right)^{2/3} \left( \frac{T}{10^7 \text{ K}} \right)^8 \quad (3.2)$$

where  $n$  is the baryon density of the star. After the first million years, and approximately as soon as the temperature of the star falls below  $10^8$  K, the dominant cooling mechanism is no longer neutrino radiation, but photon radiation from the surface of the star. The rate of heat loss from the surface of the



star is

$$L_\gamma = 4\pi R^2 \sigma T_{surface}^4 \quad (3.3)$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $T_{surface}$  is the surface temperature of the star. The surface temperature of a star is well approximated by the expression [7]

$$T_{surface} = (0.87 \times 10^6 K) \left( \frac{g_s}{10^{14} \text{cm/s}^2} \right)^{1/4} \left( \frac{T}{10^8 \text{K}} \right)^{0.55} \quad (3.4)$$

where  $T$  is the internal temperature of the star and  $g_s = GM/R^2$  is the surface gravity. The heat loss rate  $L_\gamma$  can now be expressed in terms of the internal temperature as

$$L_\gamma = 4\pi R^2 \sigma (0.87 \times 10^6 K)^4 \left( \frac{g_s}{10^{14} \text{cm/s}^2} \right) \left( \frac{T}{10^8 \text{K}} \right)^{2.2} \quad (3.5)$$

If we divide  $L_\gamma$  by the volume of the star, we can get the "effective" photon emissivity, measured in energy over volume and time

$$\epsilon_\gamma = \frac{L_\gamma}{(4/3)\pi R^3} = 1.8 \times 10^{14} \left( \frac{T}{10^8 \text{K}} \right)^{2.2} \text{erg cm}^{-3} \text{s}^{-1} \quad (3.6)$$

where we used  $g_s = 1.85 \times 10^{14} \text{cm/s}^2$ . To be able to derive temperature as a function of time, we need to know the heat capacity of the star. For a gas of noninteracting fermions, the heat capacity is given by the expression [8]

$$c_V = \frac{k_B^2 T}{3\hbar^3 c} \sum_i p_F^i \sqrt{m_i^2 c^2 + (p_F^i)^2} \quad (3.7)$$

where the sum runs over the different species. In the case we investigate, namely the one of noninteracting nuclear matter,  $i$  runs over  $n$ ,  $p$ ,  $e$  and the

Fermi momenta for neutral matter in weak equilibrium are

$$p_F^n = (340 \text{ MeV}) \left( \frac{n}{n_0} \right)^{1/3} \quad (3.8)$$

$$p_F^p = p_F^e = (60 \text{ MeV}) \left( \frac{n}{n_0} \right)^{2/3} \quad (3.9)$$

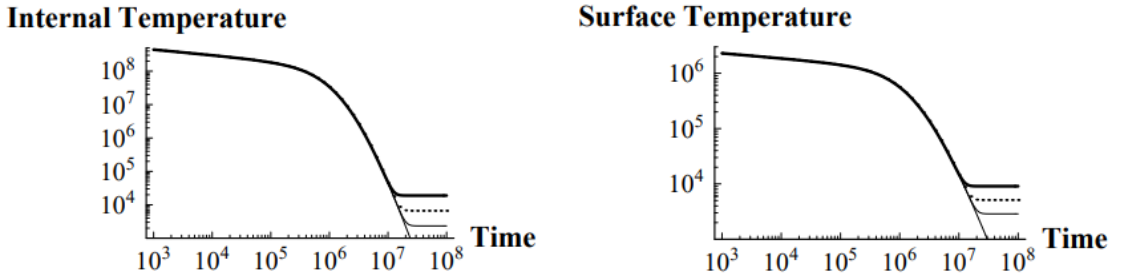


Рисунок 3.1 — Left Panel: The internal temperature of a neutron star (in Kelvin) with  $M = 1.4M_\odot$  and  $R = 10$  km as a function of time (in years). The solid line that crosses the time axis corresponds to the case where the effect of dark matter annihilation is neglected. The thin solid line corresponds to a local dark matter density for the star of  $0.3 \text{ GeV/cm}^3$ . The dashed and the thick solid lines correspond to local densities of 3 and  $30 \text{ GeV/cm}^3$  respectively. Right Panel: As in the left panel for the surface temperature of the neutron star.

The cooling of a star is dictated by the differential equation

$$\frac{dT}{dt} = \frac{-L_\nu - L_\gamma + L_{dm}}{V c_V} = \frac{V(-\epsilon_\nu - \epsilon_\gamma + \epsilon_{dm})}{V c_V} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_{dm}}{c_V} \quad (3.10)$$

We neglected the contribution of WIMPs to the specific heat capacity, since they make up an insignificant fraction of the star's mass. We solved equation (4.10) numerically by setting the initial temperature of the star to  $10^{10}$  K at a very early time. On fig. 1, we plotted the internal and surface temperatures of a star as a function of time on a logarithmic scale. We plotted the temperature for 3 different cases, which correspond to different local dark matter densities in the vicinity of the star. We chose the local dark matter densities to be  $0.3 \text{ GeV/cm}^3$ , which are 10 and 100 times higher. For comparison, we also plotted

the cooling curve for the same star without taking into account the effect of dark matter annihilation. As can be seen from the figures, the annihilation of dark matter does not affect the temperature of the star up to  $t = 10$  Myr. Between  $10^3$  and  $10^6$  years, the star cools due to the emission of neutrinos, and after about 1 million years, due to the emission of photons from the surface of the star. This means that inevitably, when the temperature of the star drops enough, the power of dark matter annihilation that heats the star will equal the power of emission of photons, and as a result, the temperature will remain unchanged depending on time. This happens at about  $t = 10$  million years and at surface temperatures between 3,000 and 10,000 K (depending on the local density of dark matter and the mass and radius of the star).

## 4. CONCLUSIONS

In this work, the effect of WIMP annihilation on the temperature of a neutron star was considered. For a typical neutron star, WIMP annihilation was found to equalize the star's temperature around  $\sim 10^4\text{K}$  at  $t = 10$  million years. Alternatively, instead of trying to detect neutron stars at such a low temperature, it may be more efficient to study pulsars already detected by their non-thermal emission and limit their thermal emission by setting an upper bound on their temperature [9].

# BIBLIOGRAPHY

1. *Rubin V. C., Ford Jr. W. K., Thonnard N.* Extended rotation curves of high-luminosity spiral galaxies. IV. Systematic dynamical properties, Sa through Sc // *Astrophys. J. Lett.* — 1978. — Vol. 225. — P. L107–L111.
2. Gravitational lens magnification and the mass of abell 1689 / A. N. Taylor [et al.] // *Astrophys. J.* — 1998. — Vol. 501. — P. 539. — arXiv: [astro-ph/9801158](#).
3. Direct constraints on the dark matter self-interaction cross-section from the merging galaxy cluster 1E0657-56 / M. Markevitch [et al.] // *Astrophys. J.* — 2004. — Vol. 606. — P. 819–824. — arXiv: [astro-ph/0309303](#).
4. *Press W. H., Spergel D. N.* Capture by the sun of a galactic population of weakly interacting, massive particles //. — 1985. — Vol. 296. — P. 679–684.
5. *Goldman I., Nussinov S.* Weakly Interacting Massive Particles and Neutron Stars // *Phys. Rev. D.* — 1989. — Vol. 40. — P. 3221–3230.
6. *Kouvaris C.* WIMP Annihilation and Cooling of Neutron Stars // *Phys. Rev. D.* — 2008. — Vol. 77. — P. 023006. — arXiv: [0708.2362 \[astro-ph\]](#).
7. Stellar Superfluids / D. Page [et al.]. — 2013. — arXiv: [1302.6626 \[astro-ph.HE\]](#).
8. *Teukolsky S., Shapiro S.* Black holes, white dwarfs, and neutron stars : the physics of compact objects. — Wiley, 1983. — ISBN 9780471873167.
9. *Camargo D. A., Queiroz F. S., Sturani R.* Detecting Dark Matter with Neutron Star Spectroscopy // *JCAP.* — 2019. — Vol. 09. — P. 051. — arXiv: [1901.05474 \[hep-ph\]](#).