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Reheating neutron stars with the annihilation of self-interacting dark matter

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Abstract and Results

Compact stellar objects such as neutron stars (NS) are ideal places for capturing dark matter (DM) particles. We study the effect of self-interacting DM (SIDM) captured by nearby NS that can reheat it to an appreciated surface temperature through absorbing the energy released due to DM annihilation. When DM-nucleon cross section $\sigma_{\chi n}$ is small enough, DM self-interaction will take over the capture process and make the number of captured DM particles increased as well as the DM annihilation rate. The corresponding NS surface temperature resulted from DM self-interaction is about hundreds of Kelvin and is potentially detectable by the future infrared telescopes. Such observations could act as the complementary probe on DM properties to the current DM direct searches.

Introduction

A compact stellar object such as neutron star (NS) is a perfect place to capture DM par- ticles even when DM-nucleon cross section $\sigma_{\chi n}$ is way smaller than the current direct search limits. Due to strong gravitational field, NS is sensitive to a broad spectrum of DM mass from 10 keV to PeV, sometimes it can be even extended to higher mass region. Unlike the Sun, it loses its sensitivity to DM when m_χ 5 GeV as a consequence of evaporation. Besides the DM-nucleon interaction, inconsistencies in the small-scale structure between the observations and the N - body simulations may imply the existence of self-interacting DM (SIDM).

$$3\,\mathrm{cm}^2\,\mathrm{g}^{-1} \leq \sigma_{\chi\chi}/m_\chi \leq 6\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

Cooling of Neutron Star :

An old NS having age greater than billions of years could become a cold star after pro- cessing several cooling mechanism by emitting photons and neutrinos.

photon emission

Stefan-Boltzmann's law that is defined as the NS surface temperature T_{sur} where $L = 4\pi R^2 \sigma T^4_{sur}$

$$\epsilon_\gamma = \frac{L_\gamma}{(4/3)\pi R^3} \approx \begin{cases} 2.71\times 10^{-17}\,\mathrm{GeV}^4\,\mathrm{yr}^{-1}\left(\frac{T_{\rm int}}{10^8\,\mathrm{K}}\right)^{2.2} & T_{\rm int} \gtrsim 3700\,\mathrm{K}, \\ 2.56\times 10^{-9}\,\mathrm{GeV}^4\,\mathrm{yr}^{-1}\left(\frac{T_{\rm int}}{10^8\,\mathrm{K}}\right)^{4} & T_{\rm int} \lesssim 3700\,\mathrm{K}, \end{cases}$$

$$T_{\rm sur} = 0.87\times 10^6\,\mathrm{K}\left(\frac{g_s}{10^{14}\,\mathrm{cm\,s^{-2}}}\right)^{1/4}\left(\frac{T_{\rm int}}{10^8\,\mathrm{K}}\right)^{0.55}$$

$g_s = GM/R^2 = 1.85\times 10^{14}\,\mathrm{cm\,s^{-2}}$ is the surface gravity

neutrino emission

$$\epsilon_\nu \approx 1.81\times 10^{-27}\,\mathrm{GeV}^4\,\mathrm{yr}^{-1}\left(\frac{n}{n_0}\right)^{2/3}\left(\frac{T_{\rm int}}{10^7\,\mathrm{K}}\right)^{8}$$

$n \simeq 3.3\times 10^{38}\,\mathrm{cm}^{-3}$ is the NS baryon number density and $n_0 \simeq 0.17\,\mathrm{fm}^{-3}$ the baryon density for the nuclear matter and $n_0 \simeq 0.17\,\mathrm{fm}^{-3}$the baryon density for the nuclear matter. It is therefore $n/n_0 \simeq 2.3$.

Heating of Neutron Star by Dark Matter:

NS heating comes from the contributions of DM annihilation and dark kinetic heating.

Dark kinetic heating : the halo DM particles constantly bombard NS can deposit their kinetic energy to the star.

$$\mathcal{K}_\chi = C_c E_s$$

$E_s = m_\chi(\gamma - 1)$ is the DM kinetic energy deposited in NS and $\gamma \simeq 1.35$

DM annihilation :

$$\mathcal{E}_\chi = 2m_\chi \Gamma_A = m_\chi C_a N_\chi^2 f_\chi$$

The NS interior temperature T_{int} can be described by the following differential equation

$$\frac{dT_{\rm int}}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}$$

The purple shaded area is where standard NS cooling overwhelms the DM heating. The corresponding T_{sur} is about 120 K. DM-nucleon interaction and DM self-interaction are responsible for the heating on T_{sur} above and below the purple shaded region in the middle of this figure respectively. The constraints on $\sigma_{\chi n}$ from different DM direct searches such as DARWIN, LUX and XENON1T are shown in the plot as well. The NS surface temperature T_{sur} induced by DM self-interaction roughly ranges from 120 K to 700 K. The corresponding blackbody peak wavelength is infrared and could be detected by the forthcoming telescopes such as JWST, TMT and E-ELT. The corresponding observations on T_{sur} could act as the complementary probe to DM direct searches in the future.

Dark Matter Capture by Neutron Star:

$$\frac{dN_\chi}{dt} = C_c + C_s N_\chi - C_a N_\chi^2$$

capture rate due to DM scattering with target neutrons in NS

$$C_c = \sqrt{\frac{6}{\pi}}\frac{\rho_0}{m_\chi}\frac{v_{\rm esc}(r)}{\bar{v}^2}\frac{\bar{v}}{1-2GM/R}\xi N_n \sigma^{\rm eff}_{\chi n}\left(1-\frac{1-e^{-B^2}}{B^2}\right)$$

DM self-capture

$$C_s = \sqrt{\frac{3}{2}}\frac{\rho_0}{m_\chi}v_{\rm esc}(R)\frac{v_{\rm esc}(R)}{\bar{v}}\langle\hat{\phi}_\chi\rangle\frac{\mathrm{erf}(\eta)}{\eta}\frac{1}{1-2GM/R}\sigma_{\chi\chi}$$

The sum of individual $\sigma_{\chi\chi}$ never surpasses the geometric area over the DM particles are thermally distributed in the NS. The geometric area is characterized by the thermal radius r_{th}

$$r_{\rm th} = \sqrt{\frac{9T_\chi}{4\pi G\rho_n m_\chi}} \approx 24\,\mathrm{cm}\left(\frac{T_\chi}{10^5\,\mathrm{K}}\cdot\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{1/2}$$

T_χ is the DM temperature

geometric limit : $N_\chi\sigma_{\chi\chi}$ must not larger than πr_{th}^2

more and more DM particles accumulate in the NS, the chance of DM annihilation

$$C_a \approx \frac{\langle\sigma v\rangle}{4\pi R^3/3}$$, the total annihilation rate is $$\Gamma_A = \frac{1}{2}C_a N_\chi^2(t)$$

$$N_\chi(t) = \frac{C_c \tanh(t/\tau)}{\tau^{-1} - C_s\tanh(t/\tau)/2}$$

where $\tau = 1/\sqrt{C_c C_a + C_s^2/4}$ is the equilibrium timescale.

$$N_\chi(t \gg \tau) \equiv N_{\chi,\rm eq} = \sqrt{\frac{C_c}{C_a}}\left(\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4}+1}\right) \qquad R \equiv \frac{C_s^2}{C_c C_a}\begin{cases} \gg 1, & C_s\text{-dominant} \\ \ll 1, & C_c\text{-dominant} \end{cases}$$

$$N^{R\ll 1}_{\chi,\rm eq} = \sqrt{\frac{C_c}{C_a}} \quad \text{and} \quad N^{R\gg 1}_{\chi,\rm eq} = \frac{C_s}{C_a}.$$

That means, either the capture is dominated by C_c or C_s that could accumulate the same amount of DM particles in NS.

Numerical Results :