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Exploring dark sector parameters in light of neutron star temperatures

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The effect of dark-matter (DM) heating in the neutron star (NS) is an intriguing topic to study. In this talk we present such a study with DM as a spin-$1/2$ Dirac particle, χ, carrying U(1) dark charge. The U(1) gauge boson, V, interacts with Standard Model (SM) fermions through kinetic and mass mixings with photon and neutral Z bosons. These mixings enable the annihilation $\chi\bar{\chi} \to VV$ and the subsequent decay of V into a pair of SM fermions ($f\bar{f}$). This chain of processes is a new NS heating mechanism in addition to $\chi\bar{\chi} \to f\bar{f}$ and the kinetic heating induced by DM-baryon scattering. The new feature of our work also includes the axial-vector term in $\chi f\bar{f}$ vertex, which is non-negligible when particles scatter relativistically. We discuss constraints on dark sector parameters by NS temperatures and the prospect of measuring these temperatures by JWST.

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[*] Speaker

1. Introduction

It has been pointed out that the neutron star (NS) heating is an effective avenue for probing DM properties [1–13]. Here we consider a simple U(1) model for DM interaction,

$$\mathcal{L}_{\rm DM} = i\bar{\chi}\gamma^{\mu}(\partial_{\mu} - ig_d V_{\mu})\chi - m_{\chi}\bar{\chi}\chi \tag{1}$$

where DM χ is a Dirac fermion carrying $U(1)_X$ dark charge g_d, and V is the gauge boson. We consider symmetric dark matter [14] where χ and $\bar{\chi}$ are identical in numbers. The dark boson V is assumed to mix with SM photon and Z boson through kinetic [15–20] and mass mixing terms [21–23]. The introduction of kinetic and mass mixing terms leads to the following interaction between dark boson V and the standard model (SM) fermions

$$\mathcal{L}_{\rm DB-SM} = \left(\varepsilon_{\gamma} e J_{\mu}^{\rm EM} + \varepsilon_Z \frac{g_2}{\cos\theta_W} J_{\mu}^{\rm NC}\right) V^{\mu} \tag{2}$$

where g_2 is the $SU(2)_L$ coupling, $J_{\mu}^{\rm EM}$ and $J_{\mu}^{\rm NC}$ are SM electromagnetic and neutral currents, respectively, ε_{γ} and ε_Z are related to the above kinetic and mass mixing parameters. We note that Eqs. (1) and (2) describe DM self-interaction and its interaction with SM particles, which can be probed by measuring the temperatures of old neutron stars.

2. DM capture and NS temperature

DM can be gravitationally captured by NS when it loses an appreciable fraction of its energy due to scatterings with baryons and leptons inside the star. This process has been discussed in Refs. [24, 25] with neutrons, protons and leptons in NS as scattering targets. In NS, neutron dominates other particles in numbers, so that we only consider neutron contribution to the capture rate C_c in our analysis.

The DM number N_{χ} in the star satisfies the differential equation

$$\frac{dN_{\chi}}{dt} = C_c - C_a N_{\chi} N_{\bar{\chi}}, \tag{3}$$

while the number of $\bar{\chi}$ satisfies the similar equation with $N_{\chi} \leftrightarrow N_{\bar{\chi}}$. Here C_a is the DM annihilation rate. Both coefficients C_c and C_a are given in Refs. [6, 24, 25] and references therein. The exact solutions to Eq. (3) and its $\bar{\chi}$ counterpart are given by

$$N_{\chi} = N_{\bar{\chi}} = C_c \tau_{\rm eq} \tanh\left(\frac{t}{\tau_{\rm eq}}\right) \tag{4}$$

with $\tau_{\rm eq} = 1/\sqrt{C_c C_a}$ the equilibrium timescale. For $t \gg \tau_{\rm eq}$, one expects $dN_{\chi}/dt = 0$ and $N_{\chi}(t \gg \tau_{\rm eq}) = \sqrt{C_c/C_a}$ according to Eq. (3). This is in fact consistent with Eq. (4) in the limit $t \to \infty$ so that $\tanh(t/\tau_{\rm eq}) \to 1$. In the equilibrium stage, it is easy to see that $\Gamma_a \equiv C_a N_{\chi} N_{\bar{\chi}} = C_c$ by substituting $N_{\chi} = N_{\bar{\chi}} = \sqrt{C_c/C_a}$. In other words, the DM annihilation at this stage only depends on the capture rate. Numerically one can show that the equilibrium stage has already been reached for a Gyr old neutron star.

It is clear that the constant DM annihilation rate becomes the heat source for NS because most of the annihilation products could deposit their energies to NS. This effect modifies the evolution equation for NS interior temperature T_b into

$$\frac{dT_b}{dt} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_\chi}{c_V}, \tag{5}$$

where ϵ_ν is the neutrino emissivity, ϵ_γ the photon emissivity, ϵ_χ the DM emissivity that is responsible for the heating from DM annihilation and c_V the NS heat capacity [26]. We note that only the NS surface temperature T_s is measurable, which is related to T_b by $T_s \approx 8.7 \times 10^5\,\mathrm{K}\,(g_s/10^{14}\,\mathrm{cm\,s^{-1}})^{1/4}(T_b/10^8\,\mathrm{K})^{0.55}$ where $g_s = GM/R^2 \approx 1.85 \times 10^{14}\,\mathrm{cm\,s^{-2}}$ accounts for the redshift correction from the star's surface gravity [27]. It is also noted that T_b and T_s are essentially not distinguishable for $T_b < 3700\,\mathrm{K}$ [6].

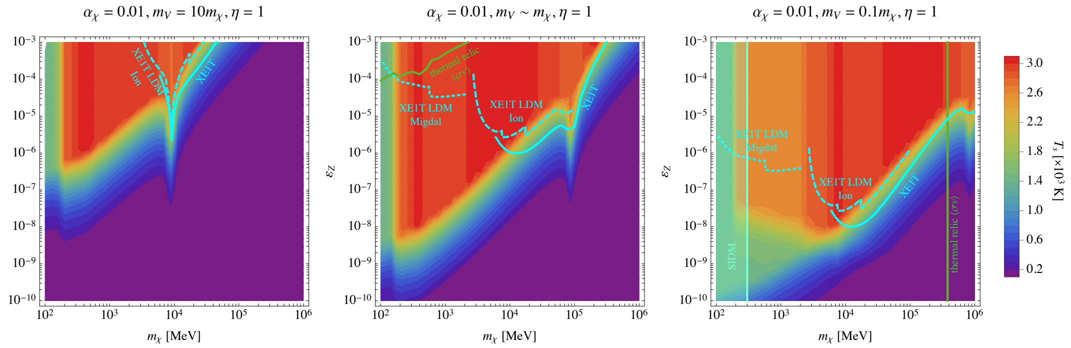

Figure 1: NS surface temperature T_s on the $m_\chi - \varepsilon_Z$ plane. The NS age is taken as 3 Gyrs, $\alpha_\chi = 0.01$ and $\eta \equiv \varepsilon_\gamma/\varepsilon_Z = 1$. From left to right, $m_V/m_\chi = 10$, 1, and 0.1 as benchmark cases. For comparisons, we show direct-detection constraints from XENON1T [28] and XENON LDM [29, 30], and SIDM constraints [31–35].

DM emissivity ϵ_χ is divided into two terms as follows:

$$\epsilon_\chi = \frac{\mathcal{E}_\chi + \mathcal{K}_\chi}{V}, \tag{6}$$

where V is the NS volume, $\mathcal{E}_\chi$ is the rate of energy injection by DM annihilation, while $\mathcal{K}_\chi$ is the loss of DM kinetic energies to the star through the capturing process.

3. Numerical results on NS temperatures

Here we present how NS surface temperature T_s is affected by the DM annihilation. If ϵ_χ is suppressed on the right hand side of Eq. (5), the standard cooling mechanism predicts $T_s \approx 100\,\mathrm{K}$ for a 3-Gyr-old NS. On the other hand, as ϵ_χ is competitive to $\epsilon_{\gamma,\nu}$, T_s could remain in a relatively higher value.

In Fig. 1, we present NS surface temperature T_s on the $m_\chi - \varepsilon_Z$ plane. We only show the case with $\varepsilon_\gamma = \varepsilon_Z$, and $\alpha_\chi \equiv g_d^2/4\pi = 0.01$. For the other cases, see Ref. [36]. The DM annihilation channels considered are $\chi\bar{\chi} \to VV$ and $\chi\bar{\chi} \to f\bar{f}$ whenever they are kinematically allowed. The

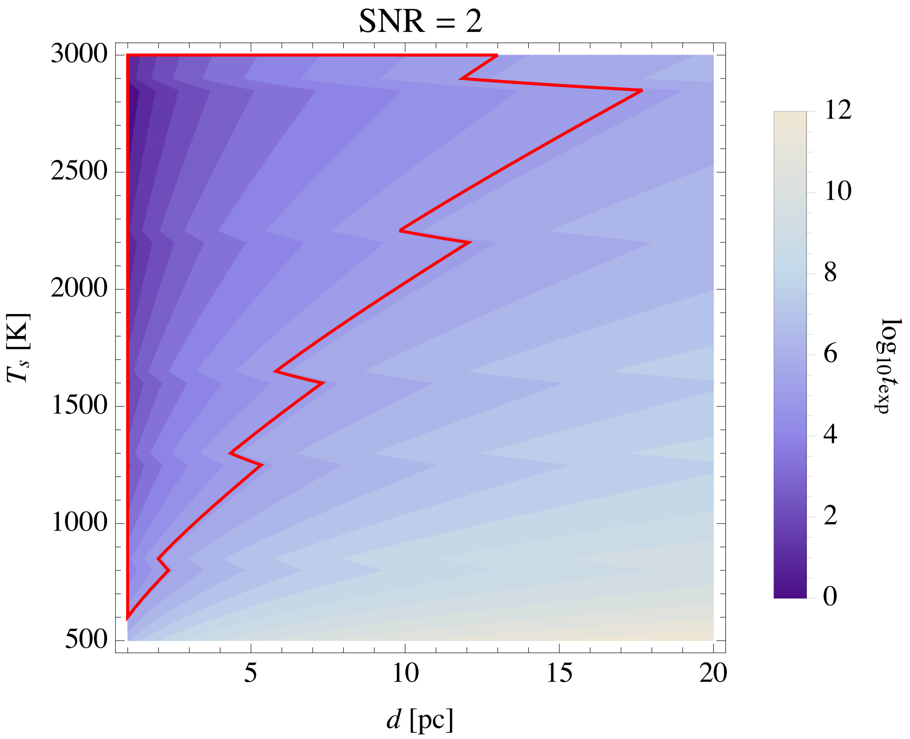

Figure 2: The exposure time $t_{\rm exp}$ for SNR = 2 in JWST. The region enclosed by the red line indicates $t_{\rm exp} \leq 10^5$ s.

final states of the latter channel directly deposit energies to NS, which can counteract the decline of NS temperature. The energy deposition of the first channel results from the decay of dark boson V. From left to right of Fig. 1, we present results with $m_V = 10\ m_\chi$, $m_V \sim m_\chi$, and $m_V = 0.1\ m_\chi$. For comparisons, we also show direct-detection constraints from XENON1T [28], XENON LDM [29, 30], and SIDM constraints [31–35]. It is interesting to observe that the constraints from NS temperature measurement complement those obtained by direct detections for $m_V = 10\ m_\chi$ and $m_V \sim m_\chi$. The complementariness is however weaker for $m_V = 0.1\ m_\chi$.

4. Prospect of detections by JWST

Since DM annihilation could significantly raise T_s, we discuss the possibility of measuring T_s by the James Webb Space Telescope (JWST) [37]. At the temperature T_s, the NS blackbody spectral flux density at frequency ν is given by [4]

$$f_\nu(\nu, T_s, d) = \frac{(k_B T_s)^3}{2\pi}\left(\frac{a^3}{e^a - 1}\right)\left(\frac{R_0\gamma}{d}\right)^2, \tag{7}$$

where R_0 is the NS radius, $\gamma \approx 1.35$ is the relativistic factor of DMs on the NS surface, d is the distance between the NS and the Earth, and $a = 2\pi\nu/k_B T_s$. The peak of f_ν occurs at $a \approx 3$ and the peak value is clearly proportional to T_s^3. Taking $T_s = 2000$ K and $d = 10$ pc as an example, we find that f_ν peaks at $\nu^{-1} = 2\,\mu$m with the peak value of 0.84 nJy. The signal-to-noise ratio (SNR) for

JWST-like telescope scales as $\sqrt{t_{\rm exp}}$ for a given ν where $t_{\rm exp}$ is the exposure time. The argument for such a scaling is given in [36].

We note that JWST covers 0.8 μm to 5.0 μm imaging sensitivity in its Near-Infrared Imager and Slitless Spectrograph (NIRISS) with multiple filters [38]. For example, F200W filter is centered at $\nu^{-1} = 2\,\mu$m and it can reach $f_\nu = 10$ nJy with SNR = 10 for $t_{\rm exp} = 10^4$ s. To reach the peak of f_ν for $T_s = 2000$ K, i.e., 0.84 nJy with SNR = 2, the required exposure time is 5.6×10^4 s. In Fig. 2, we plot $t_{\rm exp}$ for obtaining SNR = 2 over $d - T_s$ plane. The region enclosed by the red line represents $t_{\rm exp} < 10^5$ s. For NS that is located within 10 pc, JWST can achieve SNR = 2 with $t_{\rm exp} \leq 10^5$ s for $T_s \geq 1750$ K.

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