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The Dark Matter Self-Interaction and Its Impact on the Critical Mass for Dark Matter Evaporations Inside the Sun

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Abstract

We study the capture, annihilation and evaporation of dark matter (DM) inside the Sun. It has been shown that the DM self-interaction can increase the DM number inside the Sun. We demonstrate that this enhancement becomes more significant in the regime of small DM mass, given a fixed DM self-interaction cross section. This leads to the enhancement of neutrino flux from DM annihilation. On the other hand, for DM mass as low as as a few GeVs, not only the DM-nuclei scatterings can cause the DM evaporation, DM self-interaction also provides non-negligible contributions to this effect. Consequently, the critical mass for DM evaporation (typically $3 \sim 4$ GeV without the DM self-interaction) can be slightly increased. We discuss the prospect of detecting DM self-interaction in IceCube-PINGU using the annihilation channels $\chi\chi \to \tau^+\tau^-, \nu\bar{\nu}$ as examples. The PINGU sensitivities to DM self-interaction cross section $\sigma_{\chi\chi}$ are estimated for track and cascade events.

Keywords: annihilation, critical mass, dark matter, evaporation, IceCube, PINGU, scattering, self-interaction

1. Introduction

In this talk, we present the general framework of DM capture, annihilation and evaporation in the Sun. The capture of galactic DM by the Sun through DM-nuclei collisions was first proposed and calculated in Refs. [1, 2, 3, 4]. It was then observed that the assumption of DM thermal distribution according to the average temperature of the Sun is a good approximation for capture and annihilation processes, but the correction to the evaporation mass can reach to 8% in the true distribution calculation [5]. The abundance of DM inside the Sun hence results from the balancing among DM capture, annihilation and evaporation processes.

In our study, we note that for both collisionless cold DM and warm DM there exists a so-called core/cusp problem [6] which addresses the discrepancy between the computational structure simulation and the actual observation [7, 8, 9]. DM self-interaction has been introduced to resolve this inconsistency [10]. Constraints on the ratio of DM self-interaction cross section to the DM mass, $0.1 < \sigma_{\chi\chi}/m_\chi < 1.0$ (cm^2/g), were obtained from observations of various galactic structures [11, 12, 13, 14]. We note that the authors in Ref. [15] used the IceCube data [16] to constrain the magnitude of $\sigma_{\chi\chi}$ for m_χ in the range of $O(10)$ GeV to $O(1)$ TeV (also see the study of high energy neutrino flux from DM annihilation within the Sun with the inclusion of DM self-interaction in Ref. [17]). In their work the evaporation effect can be neglected for the considered DM mass range. In this presentation we shall concentrate on the low mass region of $O(1)$ GeV DM mass since such a mass range has not been probed by the IceCube data mentioned above. Furthermore, this is also the mass range where the indirect search is crucial. In the case of spin-independent interaction, the sensitivity of DM direct search quickly turns poor for m_χ less than 10 GeV [18]. Therefore the IceCube-PINGU [19] detector with an 1 GeV threshold energy could be more sensitive than some of the direct detection experiments

for $m_\chi < 10$ GeV. For spin-dependent interaction, the IceCube-PINGU sensitivity has been estimated to be much better than constraints set by direct detection experiments [20].

2. DM accumulation in the Sun

The evolution of DM particles captured by the solar gravity is described by the following differential equation,

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2 \tag{1}$$

with N_χ the DM number in the Sun, and C_c the rate at which DM are captured by the Sun. One has [21]

$$C_c^{\rm SD} \simeq 3.35\times10^{24}\ {\rm s}^{-1}\left(\frac{\rho_0}{0.3\ {\rm GeV/cm}^3}\right)\left(\frac{270\ {\rm km/s}}{\bar{v}}\right)^3 \times\left(\frac{\rm GeV}{m_\chi}\right)^2\left(\frac{\sigma_{\rm H}^{\rm SD}}{10^{-6}\ {\rm pb}}\right) \tag{2}$$

for spin-dependent (SD) interaction;

$$C_c^{\rm SI} \simeq 1.24\times10^{24}\ {\rm s}^{-1}\left(\frac{\rho_0}{0.3\ {\rm GeV/cm}^3}\right) \times\left(\frac{270\ {\rm km/s}}{\bar{v}}\right)^3\left(\frac{\rm GeV}{m_\chi}\right)^2\left(\frac{2.6\sigma_{\rm H}^{\rm SI}+0.175\sigma_{\rm He}^{\rm SI}}{10^{-6}\ {\rm pb}}\right) \tag{3}$$

for spin-independent (SI) interaction. Here ρ_0 is the local DM density, $\bar{v}$ is the DM velocity dispersion and σ_A is DM-nuclei cross section for SD or SI interaction.

C_s is the rate at which DM are captured due to their scattering with DM that have already been trapped in the Sun [17],

$$C_s = \sqrt{\frac{3}{2}}n_\chi\sigma_{\chi\chi}v_{\rm esc}(R_\odot)\frac{v_{\rm esc}(R_\odot)}{\bar{v}}\left\langle\hat{\phi}_\chi\right\rangle\frac{{\rm erf}(\eta)}{\eta} \tag{4}$$

where $v_{\rm esc}(R_\odot)$ is the solar escape at the surface and $\eta^2 = 3(v_\odot/\bar{v})^2/2$ with $v_\odot$ the velocity of the Sun.

C_e is the the DM evaporation rate due to DM-nuclei interactions [22],

$$C_e \simeq \frac{8}{\pi^3}\sqrt{\frac{2m_\chi}{\pi T_\chi(\bar{r})}}\frac{v_{\rm esc}^2(0)}{\bar{r}^3}\times\exp\left(-\frac{m_\chi v_{\rm esc}^2(0)}{2T_\chi(\bar{r})}\right)\Sigma_{\rm evap}, \tag{5}$$

where $v_{\rm esc}(0)$ is the solar escape velocity at the core, T_χ is the DM temperature in the Sun, and $\bar{r}$ is average DM orbit radius. The quantity $\Sigma_{\rm evap}$ is the sum of the scattering cross section of all the nuclei within a radius $r_{95\%}$, where the solar temperature has dropped to 95% of the DM temperature.

C_a is the DM annihilation rate given by,

$$C_a \simeq \frac{\langle\sigma v\rangle V_2}{V_1^2}, \tag{6}$$

where

$$V_j \simeq 6.5\times10^{28}\ {\rm cm}^3\left(\frac{10\ {\rm GeV}}{jm_\chi}\right)^{3/2}. \tag{7}$$

C_{se} is the evaporation rate induced by the interaction between DM particles in the Sun given by [23],

$$C_{se} = \frac{\int_\odot \frac{dC_{se}}{dV}d^3r}{\left(\int_\odot n_\chi(r)d^3r\right)^2}, \tag{8}$$

where

$$\frac{dC_{se}}{dV} = \frac{4}{\sqrt{\pi}}\sqrt{\frac{m_\chi}{2T_\chi}}\frac{n_0^2\sigma_{\chi\chi}}{m_\chi}\exp\left[-\frac{2m_\chi\phi(r)}{T_\chi}\right] \times\exp\left[-\frac{E_{\rm esc}(r)}{T_\chi}\right]\tilde{K}(m_\chi) \tag{9}$$

and

$$n_\chi(r) = n_0\exp\left(-\frac{m_\chi\phi(r)}{T_\chi}\right). \tag{10}$$

Here n_0 is the DM number in the solar core, ϕ is the solar gravitational potential, $E_{\rm esc}(r)$ is the escape energy at radius r inside the Sun and $\tilde{K}(m_\chi)$ is defined in the appendix of Ref. [23]. All the coefficients $C_{c,a,e,s,se}$ are positive and time-independent.

With $N_\chi(0) = 0$ as the initial condition, the general solution to Eq. (1) is

$$N_\chi(t) = \frac{C_c\tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e)\tanh(t/\tau_A)/2}, \tag{11}$$

with

$$\tau_A = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}} \tag{12}$$

the time-scale for the DM number in the Sun to reach the equilibrium. If the equilibrium state is achieved, i.e., $\tanh(t/\tau_A) \sim 1$, one has

$$N_{\chi,{\rm eq}} = \sqrt{\frac{C_c}{C_a + C_{se}}}\left(\pm\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4}+1}\right), \tag{13}$$

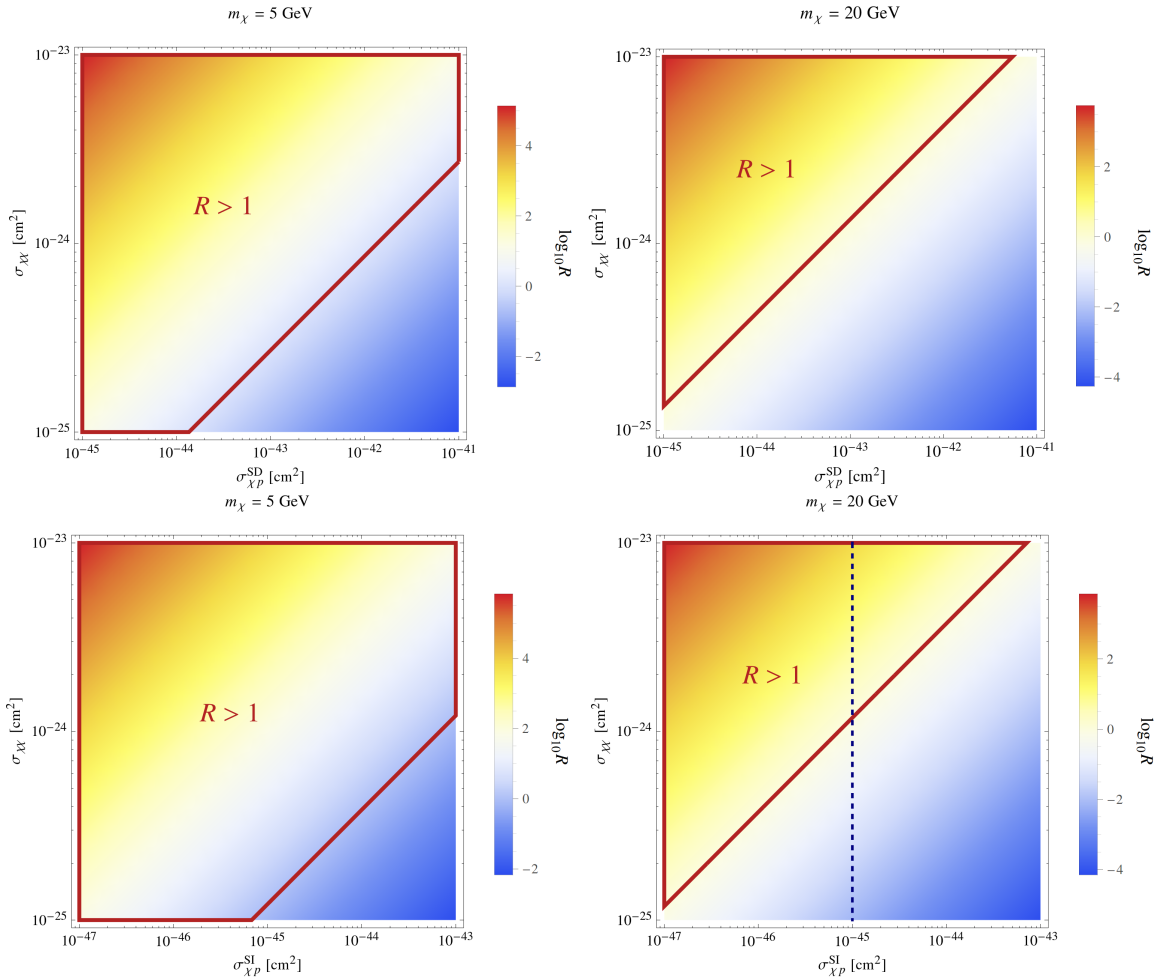

Figure 1: Ratio R over the $\sigma_{\chi p} - \sigma_{\chi\chi}$ plane. The upper panel is for SD interaction and the lower panel is for SI interaction. The red-circled region is for $R > 1$. The region to the right of the blue-dashed line is excluded by LUX.

where one takes the positive sign for $C_s > C_e$ and the negative sign for $C_e > C_s$. The dimensionless parameter R is defined as

$$R \equiv \frac{(C_s - C_e)^2}{C_c(C_a + C_{se})}. \tag{14}$$

This ratio determines whether the self-interaction is important ($R > 1$) or not ($R < 1$). The region for $R > 1$ is shown in Fig. 1. Note that the region for $R > 1$ shrinks when m_χ becomes heavier. It implies that the self-interaction is significant for lighter DM.

Thus, the DM total annihilation rate in the Sun's core is given by

$$\begin{aligned}\Gamma_A &= \frac{C_a}{2} N^2_{\chi,\mathrm{eq}} \\ &= \frac{1}{2}\frac{C_c C_a}{C_a + C_{se}} \left(\pm\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4} + 1} \right)^2 .\end{aligned} \tag{15}$$

Where the sign convention is identical to that Eq. (13). The result for Γ_A is shown in Fig. 2.

3. Probing DM self-interaction at IceCube-PINGU

To probe DM self-interaction for small m_χ, we consider DM annihilation channels, $\chi\chi \to \tau^+\tau^-$ and $\nu\bar{\nu}$, for producing neutrino final states to be detected by

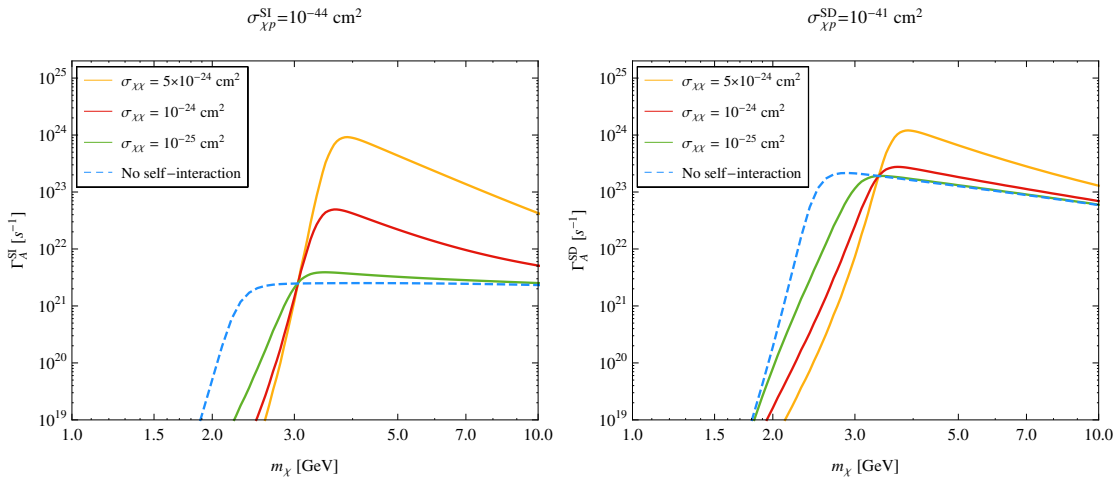

Figure 2: The annihilation rate Γ_A of the captured DM inside the Sun. The left panel assumes DM-nuclei scattering is dominated by SI interaction while the right panel assumes such scattering is dominated by SD interaction.

IceCube-PINGU [19]. The neutrino differential flux of flavor i, Φ_{ν_i}, from $\chi\chi \to f\bar{f}$ can be expressed as

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = P_{\nu_j\to\nu_i}(E_\nu)\frac{\Gamma_A}{4\pi R_\odot^2}\sum_f B_f\left(\frac{dN_{\nu_j}}{dE_{\nu_j}}\right)_f \qquad (16)$$

where $R_\odot$ is the distance between the neutrino source and the detector, $P_{\nu_j\to\nu_i}(E_\nu)$ is the neutrino oscillation probability during the propagation, B_f is the branching ratio corresponding to the channel $\chi\chi \to f\bar{f}$, dN_ν/dE_ν is the neutrino spectrum at the source, and Γ_A is the DM annihilation rate in the Sun. To compute dN_ν/dE_ν, we employed `WimpSim` [24] with a total of 50,000 Monte-Carlo generated events.

The neutrino event rate in the detector is given by

$$N_\nu = \int_{E_{\rm th}}^{m_\chi}\frac{d\Phi_\nu}{dE_\nu}A_\nu(E_\nu)dE_\nu d\Omega \qquad (17)$$

where $E_{\rm th}$ is the detector threshold energy, $d\Phi_\nu/dE_\nu$ is the neutrino flux from DM annihilation, A_ν is the detector effective area, and Ω is the solid angle. We study both muon track events and cascade events induced by neutrinos. The PINGU module will be implanted inside the IceCube in the near future [19] and can be used to probe neutrino energy down to $O(1)$ GeVs.

The atmospheric background event rate can also be calculated by Eq. (17) with $d\Phi_\nu/dE_\nu$ replaced by the atmospheric neutrino flux. Hence

$$N_{\rm atm} = \int_{E_{\rm th}}^{E_{\rm max}}\frac{d\Phi_\nu^{\rm atm}}{dE_\nu}A_\nu(E_\nu)dE_\nu d\Omega. \qquad (18)$$

In our calculation, the atmospheric neutrino flux $d\Phi_\nu^{\rm atm}/dE_\nu$ is taken from Refs. [25, 26]. We set $E_{\rm max} = m_\chi$ in order to compare with the DM signal.

The angular resolution for IceCube-PINGU detector at $E_\nu = 5$ GeV is roughly 10° [19]. Hence we consider neutrino events arriving from the solid angle range $\Delta\Omega = 2\pi(1-\cos\psi)$ surrounding the Sun with $\psi = 10°$. We present the IceCube-PINGU sensitivity to $\sigma_{\chi\chi}$ in the DM mass region 3 GeV $< m_\chi <$ 20 GeV for both SD and SI cases in Fig. 3. The sensitivities to $\sigma_{\chi\chi}$ are taken to be 2σ significance for 5 years of data taking. The shadow areas in the figures represent those parameter spaces disfavored by the Bullet Cluster and halo shape analyses. Below the black solid line, the DM self-interaction is too weak to resolve the core/cusp problem of the structure formation. Two benchmark values of thermal average cross section, $\langle\sigma v\rangle = 3\times10^{-26}$ cm^{3}s^{-1} and $\langle\sigma v\rangle = 3\times10^{-27}$ cm^{3}s^{-1} are used for our studies. We note that the latter value for $\langle\sigma v\rangle$ does not contradict with the relic density, since DM annihilation inside the Sun occurs much later than the period of freeze-out.

We take $\sigma_{\chi p}^{\rm SD} = 10^{-41}$ cm^2 for SD interaction, and take $\sigma_{\chi p}^{\rm SI} = 10^{-44}$ cm^2 for SI interaction. We stress that $\sigma_{\chi p}^{\rm SD} = 10^{-41}$ cm^2 is below the lowest value of IceCube bound $\sigma_{\chi p}^{\rm SD} \sim 10^{-40}$ cm^2 at $m_\chi \sim 300$ GeV [16]. For SI interaction, $\sigma_{\chi p}^{\rm SI} = 10^{-44}$ cm^2 is below the LUX bound for $m_\chi < 8$ GeV [27]. We find that cascade events provide better sensitivities to DM self-interaction than track events do in all cases. One can also see that the sensitivity to $\sigma_{\chi\chi}$ becomes better for smaller annihilation cross section $\langle\sigma v\rangle$ for a fixed $\sigma_{\chi p}$, as noted in earlier works [17, 15] which neglect both C_e and C_{se}. This is evident from Eq. (15) since R increases as C_a decreases. It is instructive to take the limit $R \gg 1$ such

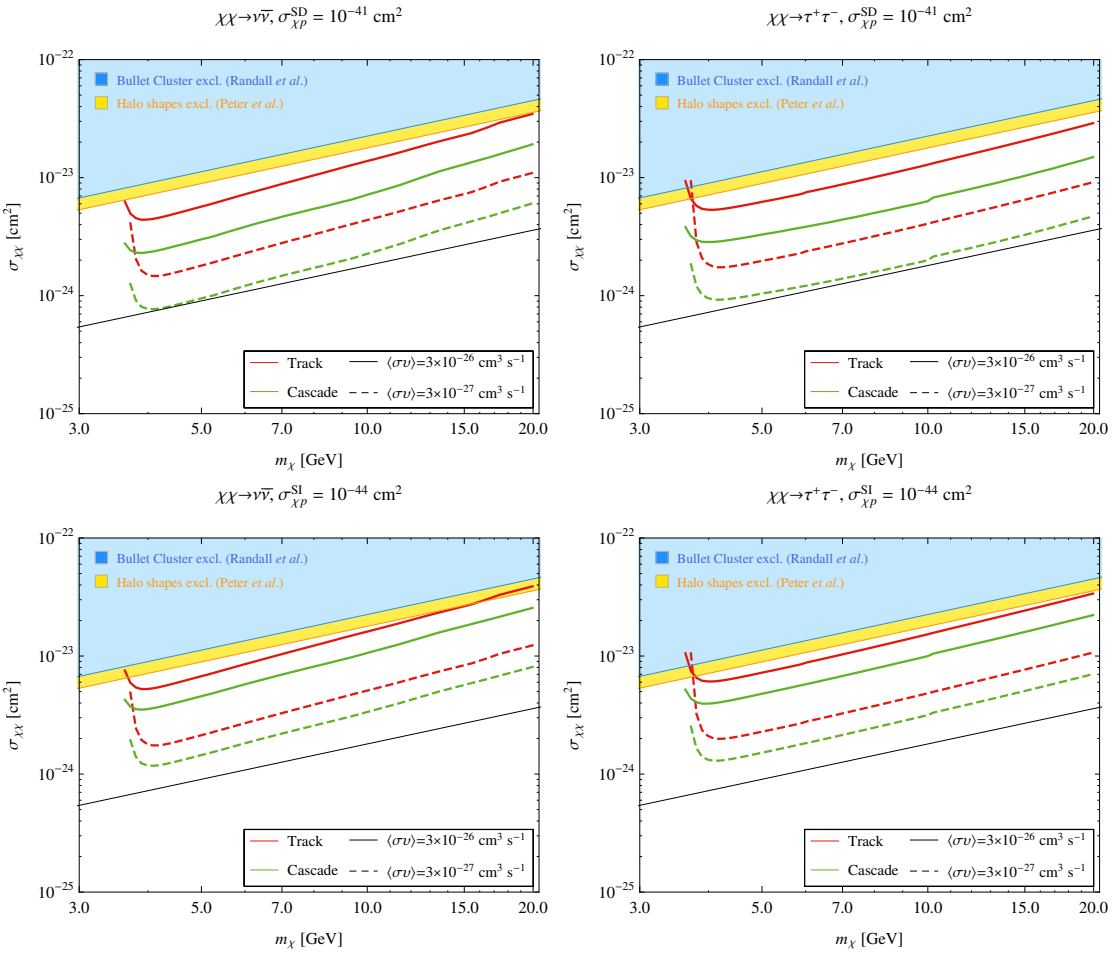

Figure 3: The IceCube-PINGU sensitivities to DM self-interaction cross section $\sigma_{\chi\chi}$ as a function of m_χ. The upper panel is the DM-nucleus interaction inside the Sun which is assumed to be dominated by SD interaction. The lower panel is assumed to be dominated by SI interaction.

that $\Gamma_A \to (C_c C_a)R/2(C_a + C_{se})$ for $C_s > C_e$. It is easily seen that Γ_A is inversely proportional to C_a (in the mass range that C_{se} is negligible) and is independent of C_c. In other words, only C_s and C_a determine the annihilation rate (we are in the region that C_e is suppressed as compared to C_s). We also see that the sensitivity to $\sigma_{\chi\chi}$ does become significantly worse as $m_\chi \to 4$ GeV. This is the critical m_χ below which the DM evaporations from the Sun is important.

4. Conclusion

We have presented the time evolution of DM number trapped inside the Sun with DM self-interaction considered. We focused on the low m_χ range which requires the consideration of evaporation effects due to both DM-nuclei and DM-DM scatterings. The parameter region for the trapped DM inside the Sun to reach the equilibrium state is presented. We also found that the inclusion of DM self-interaction can increase the number of trapped DM as well as raise the evaporation mass scale. The parameter space on $\sigma_{\chi\chi} - \sigma^{SD(SI)}_{\chi p}$ plane for significant enhancement on trapped DM number ($R > 1$) is identified. The parameter space for $R > 1$ becomes larger for smaller m_χ. For $C_s < C_e$, the condition $R > 1$ leads to the suppression of neutrino flux, since the first term on the right hand side of Eq. (15) is negative. We have proposed to study $\sigma_{\chi\chi}$ with the future IceCube-PINGU detector where the energy threshold can be lowered down to 1 GeV. We considered cascade and track events resulting from neutrino flux induced by DM annihilation channels $\chi\chi \to \nu\bar{\nu}$ and $\chi\chi \to \tau^+\tau^-$ inside the Sun. We found that cascade events always provide better sensitivity to $\sigma_{\chi\chi}$. The sensitivity to $\sigma_{\chi\chi}$ is also

improved with a smaller DM annihilation cross section $\langle\sigma v\rangle$.

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