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Probing dark matter self-interaction in the Sun with IceCube-PINGU

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The halo dark matter (DM) can be gravitationally captured by the Sun. For self-interacting DM (SIDM), we show that the number of DM trapped inside the Sun remains unsuppressed even if the DM-nucleon cross section is negligible. We consider a SIDM model where U(1) gauge symmetry is introduced to account for the DM self-interaction. Such a model naturally leads to isospin violation for DM-nucleon interaction, although isospin symmetry is still allowed as a special case. We show that the indirect detection of DM-induced neutrinos from the Sun can probe those SIDM parameter ranges not yet reachable by direct detections. Those parameter ranges are either the region with a very small dark matter mass (less than a few GeV) or the region opened up due to isospin violations.

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1. Introduction

In this paper, the general framework of dark matter (DM denoting χ) capture, annihilation and evaperation inside the Sun via DM-nuclei scattering ($\sigma_{\chi p}$) and DM-DM scattering ($\sigma_{\chi\chi}$) is presented. We take that both the galactic DM and the nuclei inside the Sun follow the thermal distributions. If DM collides with nuclei in the Sun it can be captured by the Sun when its final velocity is smaller than the escape velocity from the Sun. Alternatively, DM trapped inside the Sun will be kicked out if its final velocity after the scattering with the nuclei is larger than the escape velocity. The inclusion of DM self-interaction also have effects on the capture and evaporation of DM inside the Sun. The existence of self-interacting DM (SIDM) [1] was proposed to solve the cusp/core [2], missing satellites [3], and too-big-to-fail [4] problems those are the inconsistencies between the N-body collisionless DM simulation and astrophysical observations on small scale structures. Constraints on the ratio of SIDM cross section to the DM mass, $0.1 < \sigma_{\chi\chi}/m_\chi < 1.0$ (cm^2/g), were obtained from various observations. We found that the total DM trapped in the Sun can be increased if DM self-interaction is included [5]. This implies a considerable excess cosmic rays come from the annihilation of DM in the direction of the Sun. We show the allowed parameter space of $\sigma_{\chi\chi}$ can be tested by measuring such DM indirect signals. For illustrative purpose, we only consider neutrino flux produced by DM annihilating into leptons such as $\chi\chi \to \tau^+\tau^-$ and $\chi\chi \to \nu\bar{\nu}$. The final-state neutrinos can be detected by the IceCube-PINGU. In the case of suppressed $\sigma_{\chi p}$, we find the total DM number to be accumlated is only slightly less than the scenario of unsuppressed $\sigma_{\chi p}$ [6]. It means that $\sigma_{\chi\chi}$ plays an important role in trapped DM in the Sun. Therefore, we have a significant DM indirect signal even if the direct detection of $\sigma_{\chi p}$ is not very promising. We use this feature to show the complementary probe of SIDM between direct and indirect detections.

2. Dark matter accumulation in the Sun

The general DM evolution equation in the Sun is given by

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2 \tag{2.1}$$

with N_χ the DM number in the Sun, C_c the rate at which DM are captured by the Sun [7, 8],

$$C_c^{\mathrm{SI}} \simeq 1.24\times 10^{24}\ \mathrm{s}^{-1}\left(\frac{\rho_0}{0.3\ \mathrm{GeV/cm}^3}\right)\left(\frac{270\ \mathrm{km/s}}{\bar{v}}\right)^3\left(\frac{\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{2.6\sigma_{\mathrm{H}}^{\mathrm{SI}}+0.175\sigma_{\mathrm{He}}^{\mathrm{SI}}}{10^{-6}\ \mathrm{pb}}\right) \tag{2.2}$$

Here $\sigma_{\mathrm{H}}^{\mathrm{SI}}$ and $\sigma_{\mathrm{He}}^{\mathrm{SI}}$ are SI DM-hydrogen and -helium cross sections respectively. We note that C_c can be categorized by the type of interactions between DM particles and nucleons. In this proceeding we only mention the results of spin-independent interaction. For the spin-dependent interaction discussion, we encourage readers to our published papers [5, 6]. C_s is the rate at which DM are captured due to their scattering with DM that have already been trapped in the Sun [9],

$$C_s = \sqrt{\frac{3}{2}}n_\chi \sigma_{\chi\chi} v_{\mathrm{esc}}(R_\odot)\frac{v_{\mathrm{esc}}(R_\odot)}{\bar{v}}\left\langle \widehat{\phi}_\chi \right\rangle \frac{\mathrm{erf}(\eta)}{\eta}, \tag{2.3}$$

where $\left\langle \widehat{\phi}_\chi \right\rangle \simeq 5.1$ [10] is a dimensionless average solar potential experienced by the captured DM within the Sun. C_e is the the DM evaporation rate due to DM-nuclei interactions,

$$C_e \simeq \frac{8}{\pi^3}\sqrt{\frac{2m_\chi}{\pi T_\chi(\bar{r})}}\frac{v^2_{\rm esc}(0)}{\bar{r}^3}\exp\left(-\frac{m_\chi v^2_{\rm esc}(0)}{2T_\chi(\bar{r})}\right)\Sigma_{\rm evap}, \tag{2.4}$$

where $v_{\rm esc}(0)$ is the escape velocity from the core of the Sun, T_χ is the DM temperature in the Sun, and $\bar{r}$ is average DM orbit radius which is the mean DM distance from the solar center. The quantity $\Sigma_{\rm evap}$ is the sum of the scattering cross sections 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 [11],

$$C_a \simeq \frac{\langle \sigma v\rangle V_2}{V_1^2}, \tag{2.5}$$

where

$$V_j \simeq 6.5\times 10^{28}\ \mathrm{cm}^3\left(\frac{10\ \mathrm{GeV}}{jm_\chi}\right)^{3/2} \tag{2.6}$$

is the DM effective volume inside the Sun and $\langle \sigma v\rangle$ is the relative velocity averaged annihilation cross section. And C_{se} is the evaporation rate induced by the interaction between DM particles in the Sun,

$$C_{se} = \frac{\int_\odot \frac{dC_{se}}{dV}d^3r}{\left(\int_\odot n_\chi(r)d^3r\right)^2}, \tag{2.7}$$

where

$$\frac{dC_{se}}{dV} = \frac{4}{\sqrt{\pi}}\sqrt{\frac{m_\chi}{2T_\chi}}\frac{n_0^2\sigma_{\chi\chi}}{m_\chi}\exp\left[-\frac{2m_\chi\phi(r)}{T_\chi}\right]\exp\left[-\frac{E_{\rm esc}(r)}{T_\chi}\right]\tilde{K}(m_\chi) \tag{2.8}$$

and

$$n_\chi(r) = n_0\exp\left(-\frac{m_\chi\phi(r)}{T_\chi}\right) \tag{2.9}$$

The coefficients $C_{a,c,e,s,se}$ are taken to be positive and *time-independent*.

3. Testability of SIDM at IceCube-PINGU

A large parameter space that can be reached the steady DM number in the Sun for the relevant $\sigma_{\chi p}$ and $\sigma_{\chi\chi}$ [5]. Here we concentrate on the probe of SIDM. We consider DM annihilation channels, $\chi\chi\to\tau^+\tau^-$ and $\nu\bar{\nu}$, for producing neutrino final states to be detected by IceCube-PINGU [12]. The neutrino differential flux of flavor i, Φ_{ν_i}, from $\chi\chi\to f\bar{f}$ can be expressed as

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = P_{\nu_j\to\nu_i}(E_\nu)\frac{\Gamma_A}{4\pi R_\odot^2}\sum_f B_f\left(\frac{dN_{\nu_j}}{dE_{\nu_j}}\right)_f \tag{3.1}$$

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. The neutrino event rate in the detector is given by

$$N_\nu = \int_{E_{\rm th}}^{m_\chi} \frac{d\Phi_\nu}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega \tag{3.2}$$

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 atmospheric background event rate can also be calculated by Eq. (3.2) with $d\Phi_\nu/dE_\nu$ replaced by the atmospheric neutrino flux. The angular resolution for IceCube-PINGU detector at $E_\nu = 5$ GeV is roughly 10° [12]. Hence we consider neutrino events arriving from the solid angle range $\Delta\Omega = 2\pi(1-\cos\psi)$ surrounding the Sun with $\psi = 10^\circ$. We present the IceCube-PINGU sensitivity to $\sigma_{\chi\chi}$ in the DM mass region 3 GeV $< m_\chi <$ 20 GeV for SI cases in Fig. 1. 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. One can see that a large parameter space is covered by the IceCube-PINGU sensitivities.

4. Direct and indirect complementary detection of SIDM - A case of dark U(1) model

We then apply a simple hidden $U(1)$ gauge symmetry and ϕ_μ is the corresponding gauge boson that mediate dark force among DM. The relevant effective Lagragian can be written as

$$L_{{\rm mixing},U(1)} = \frac{\varepsilon_\gamma}{2}\phi_{\mu\nu}F^{\mu\nu} + \varepsilon_Z m_Z^2 \phi_\mu Z^\mu, \tag{4.1}$$

where the parameters ε_γ and ε_Z are originated from kinetic and mass mixings between ϕ^μ and photon and Z boson. The SI cross section between DM and any nucleus with mass number A and proton number Z is then given by

$$\sigma_{\chi A} \approx \frac{16\pi\alpha_\chi\alpha_{\rm em}}{m_\phi^4}[\varepsilon_p Z + \varepsilon_n(A-Z)]^2\mu_{\chi A}^2, \tag{4.2}$$

with $\alpha_{\rm em}$ the fine structure constant, $\mu_{\chi A} \equiv m_\chi m_A/(m_\chi + m_A)$ the reduced mass for DM-nucleus system and $\alpha_\chi \equiv e_D^2/(4\pi)$ is the fine structure constant in the hidden $U(1)$ sector. The effective ϕ_μ-nucleon couplings, ε_p and ε_n, can be expressed in terms of ε_γ and ε_Z such that [13]

$$\begin{aligned} \varepsilon_p &= \varepsilon_\gamma + \frac{\varepsilon_Z}{4s_W c_W}(1-4s_W^2) \approx \varepsilon_\gamma + 0.05\varepsilon_Z \,, \\ \varepsilon_n &= -\frac{\varepsilon_Z}{4s_W c_W} \approx -0.6\varepsilon_Z \,. \end{aligned} \tag{4.3}$$

Therefore, isospin violation is generally introduced in the hidden $U(1)$ model since the ratio $\varepsilon_n/\varepsilon_p$ can be any number [14]. Let us define $\varepsilon_n/\varepsilon_p \equiv \eta$, with $\eta = 1$ for isospin symmetric case and

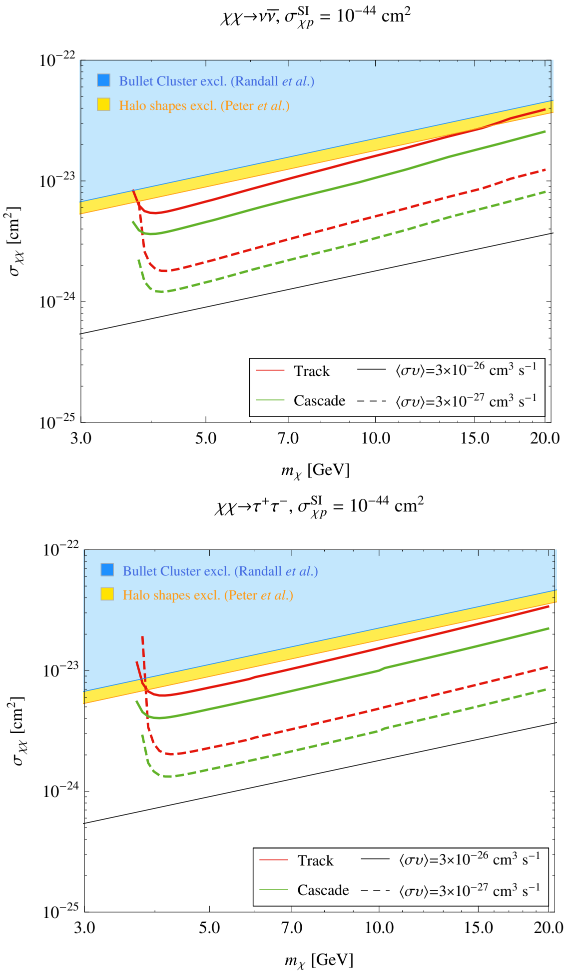

Figure 1: The IceCube-PINGU sensitivities to DM self-interaction cross section $\sigma_{\chi\chi}$ as a function of m_χ. The DM-nucleus interaction inside the Sun is assumed to be dominated by SI interaction.

$\eta = -0.7$ for the maximized isospin violation with respect to Xe element. And $\varepsilon_\gamma = 10^{-9}$ stands for the DM-nuclei cross section that is within the next generation direct detection region while $\varepsilon_\gamma = 10^{-10}$ represents the case of DM-nuclei cross section which is suppressed. The evolution behaviors of N_χ with different m_χ and η for $m_\phi = 30$ MeV are shown in Fig. 2. One can see that the total trapped DM numbers are slightly less for the suppressed $\sigma_{\chi p}$ case but still provide enough indirect signals. Although one should notice that the accumulation time is also longer for the small $\sigma_{\chi p}$ scenario. Neutrino signals arise from the decays of ϕ which is produced by DM annihilation, $\chi\bar{\chi} \to \phi\phi \to 4\nu$. For the hidden $U(1)$ gauge model we consider in this paper, the branching ratio for $\phi \to \nu\bar{\nu} \approx 75\%, 39\%, 48\%$ and 67% for $\eta = 1, -0.3, -0.5$ and -0.7, respectively. The lifetime of ϕ is constrained by Big Bang Nucleosynthesis (BBN), $\tau_\phi \lesssim \mathcal{O}(1)$ s, in order to produce extra degrees of freedom. Considering a 30 MeV ϕ with 5 GeV energy (corresponding to $m_\chi = 10$ GeV), the decay time of ϕ would be less than 170 s. One can easily estimated that, for a ϕ with 170 s of decay time, it travels for roughly 5×10^7 km before its decay into electron-position or neutrino pair. The decay point is already outside the Sun but not yet reaching to the Earth. Given the distance

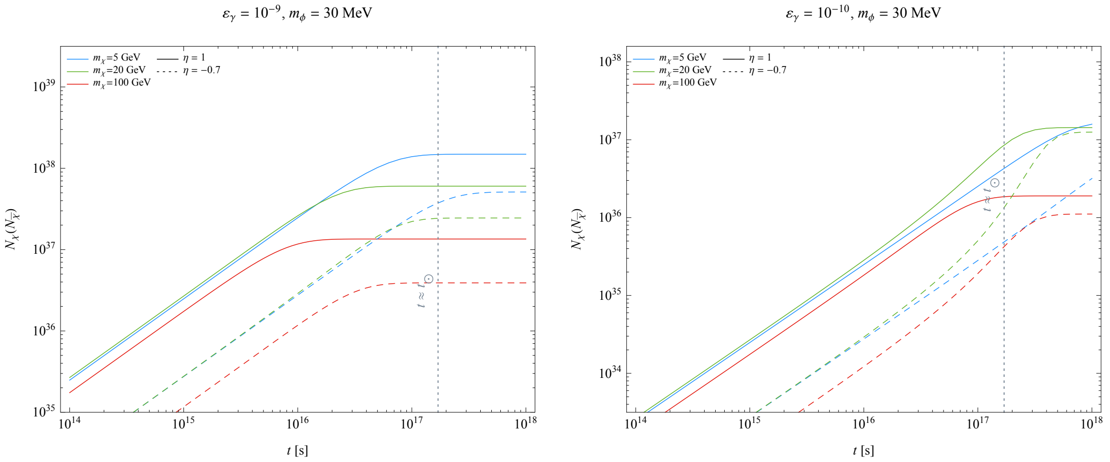

Figure 2: The $N_\chi(N_{\bar\chi})$ for $\varepsilon_\gamma = 10^{-9}$ and 10^{-10} for $m_\phi = 30\,\mathrm{MeV}$. Solid lines are for isospin symmetric case and dashed lines are for isospin violated case. Blue, green and red curves are for $m_\chi = 5\,\mathrm{GeV}$, $20\,\mathrm{GeV}$ and $100\,\mathrm{GeV}$, respectively. The solar age ($t_\odot$) is indicated by the gray dashed line.

between the Sun and the Earth at 1.5×10^8 km, those ϕ with 30 MeV of mass and moving toward the Earth shall decay between Sun and Earth provided E_ϕ is less than 150 GeV. Hence the neutrino flux will be observed by the terrestrial detector. Using similar calculation for the expective neutrino signals and atmospheric background estimation we present the IceCube-PINGU sensitivities to m_ϕ with different values of η in colored solid lines in Fig. 3. Regions above these lines are beyond the reach of the detector within a 2σ detection significance in 5 years. The left panel is for cascade events and the right one is for track events. Furthermore, each sensitivity curve terminates at the evaporation mass scale below which the DM signature from the Sun is suppressed. BBN excludes $m_\phi < 20$ MeV for $\varepsilon_\gamma = 10^{-10}$, while it exludes $m_\phi < 0.3$ MeV for $\varepsilon_\gamma = 10^{-9}$. For simplicity, we only present results for $\varepsilon_\gamma = 10^{-9}$ here. The orange band is SIDM allowed region. The colored shaded regions are exluded by LUX for differnet η values. The gray dashed lines indicate the relation between α_χ and m_χ required by the thermal relic density. density. It is of interest to compare results with different η values. It is seen that the sensitivity curve with $\eta = 1$ differs significantly from those with other η values. However, sensitivity curevs with $-0.3 \leq \eta \leq -0.7$ do not differ much from one another. Compare left and right panels of Fig. 3, one can see that cascade events can probe a larger part of $m_\chi - m_\phi$ parameter space. We notice that the IceCube-PINGU sensitivity with LUX constraint is significantly weaken by isospin violation. As one can see that the LUX excluded region shrinks as η decreases from 1 to -0.7. On ther other hand, the indirect DM signature from the Sun is less affected by η. Hence the complementarity of two searches becomes more apparent when $\sigma_{\chi p}$ is subject to more severe isospin violation suppression.

5. Summary

In summary, we have studied the time evolution of DM number trapped inside the Sun with SIDM considered. We found that the inclusion of SIDM can increase the number of trapped DM and shorten the accumulation time. Most of the SIDM parameter space which is allowed by the

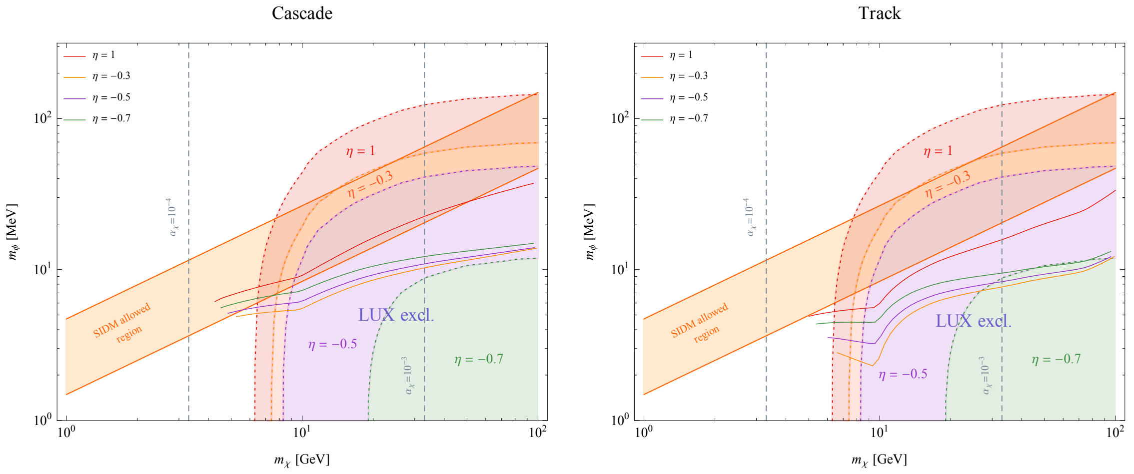

Figure 3: The IceCube-PINGU sensitivities to m_ϕ for different values of η. The left panel is for track events and the right panel is for cascade events. The sensitivity curves and LUX excluded regions correspond to $\varepsilon_\gamma = 10^{-9}$. The results corresponding to $\varepsilon_\gamma = 10^{-10}$ are not shown since BBN constraint rules out most of the m_ϕ parameter space plotted here.

astrophysical observations can be probed by IceCube-PINGU if DM annihilate into neutrino final states via the channels $\chi\chi \to \nu\bar{\nu}(\tau^+\tau^-)$. We further demonstrate that DM accumulation in the Sun is dominated by SIDM when $\sigma_{\chi p}$ is highly suppressed. In this case, the total number of captured DM is not significantly reduced such that the strength of indirect signal is insensitive to $\sigma_{\chi p}$.

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