The dark matter self-interaction and its impact on the critical mass for dark matter evaporations inside the Sun

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Outline

1. Motivations of self-interaction (SI) dark matter (DM) & evaporation
2. Schematic view of SIDM
3. Modification to DM evolution equation
4. When would self-interaction effect be significant?
5. The behavior of $N_\chi$ and its effect to the annihilation rate
6. Implication to DM indirect searches
7. Summary
Motivations

1 **Indirect search’s perspective:**
   - IceCube-PINGU can probe $1 \text{ GeV} \leq E_\nu \leq 10 \text{ GeV}$ in the future,
   - This range is favored by some DM direct search,
   - DM evaporation can not be ignored,
   - SIDM can enhance the annihilation rate,
   - As well as lower the evaporation mass, $m_{ev}$.

2 **Astrophysical perspective:**
   - SIDM can alleviate the core/cusp problem.

3 **Theoretical perspective:**
   - Asymmetric DM model also favors in this mass range.
**Schematic view of SIDM**

\[ \chi p \text{ scattering}^1 \]
\[ \sigma_{\chi p} \gtrsim 10^{-43} \text{ cm}^2 \]

\[ \chi \chi \text{ annihilation}^2 \]
\[ \Omega\chi \approx \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{A\nu} \rangle} \]

\[ \chi \chi \text{ self-interaction}^3 \]
\[ \frac{\sigma_{\chi\chi}}{m_\chi} \lt 1.7 \times 10^{-24} \text{ cm}^3 \text{ GeV}^{-1} \]

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Schematic view of SIDM

**Before**

- $v^\chi > v_{esc}$
- DM in the halo

**After**

- $v'^\chi < v_{esc}$
- DM captured by the Sun
Schematic view of SIDM

Situations after DM-DM scattering:
- both captured,
- one captured, the other escaped,
- both eject.

The possibilities of last two is extremely small comparing to the first in the Sun.

The self-interaction rate, $C_s$, is proportional to

$$C_s \propto n_\chi \sigma_{\chi \chi} F(\bar{\nu}_\chi, \nu_\odot, \text{esc})$$

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4 The detail mathematical argument contains these three possibilities has been discussed by Zentner in Phys. Rev. D 80, 063501 (2009).
The DM evolution equation

The evolution equation of DM in the Sun with self-interaction, $C_s$, and evaporation, $C_e$:

$$ \frac{dN}{dt} = C_c + C_s N - C_e N - C_a N^2. $$

The differential equation is a Riccati equation and can be solved analytically. The kinematic coefficients:

- $C_c$: for capture,
- $C_e$: for evaporation,
- $C_a$: for annihilation.

All have been well-investigated in recent studies\textsuperscript{5}.

The solution to the evolution equation thus gives:

\[ N(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e) \tanh(t/\tau_A)/2} \]

where \( \tau_A \) is the time-scale to reach equilibrium and

\[ \tau_A = \frac{1}{\sqrt{C_c C_a + (C_s - C_e)^2/4}}. \]

Assuming \( \tanh(t/\tau_A) \sim 1 \):

\[ N_{eq} = \frac{C_s - C_e}{2C_a} + \sqrt{\frac{(C_s - C_e)^2}{4C_a^2}} + \frac{C_c}{C_a}. \]
The DM evolution equation

Absence of $C_s^6$:

\[ N(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} + C_e \tanh(t/\tau_A)/2}, \quad N_{\text{eq}} = -\frac{C_e}{2C_a} + \sqrt{\frac{C_e^2}{4C_a^2} + \frac{C_c}{C_a}} \]

Absence of both $C_s$ and $C_e^7$:

\[ N(t) = \sqrt{\frac{C_c}{C_a}} \tanh(\sqrt{C_cC_a} t), \quad N_{\text{eq}} = \sqrt{\frac{C_c}{C_a}}. \]

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When would SI or evap. becomes crucial?

Making some arrangement of the DM number in the Sun,

\[ N_{eq} = \sqrt{\frac{C_c}{C_a}} \left( \sqrt{\frac{(C_s - C_e)^2}{4C_c C_a}} + \sqrt{\frac{(C_s - C_e)^2}{4C_c C_a}} + 1 \right) \]

and we define the parameter, \( R_{se} \):

\[ R_{se} \equiv \frac{(C_s - C_e)^2}{C_c C_a} \]

Hence we have

\[ \begin{cases} R_{se} > 1, & \text{SI or evap. is important;} \\ R_{se} < 1, & \text{SI or evap. becomes irrelavant,} \end{cases} \]

for convenience.
$R_{se}$ over $(\sigma_{\chi p}, \sigma_{\chi\chi})$-plane

The SI is significant when $m_\chi$ becomes lighter, $\mathcal{O}(1)$ GeV.
The equilibrium state, \( \tanh(t/\tau_A) \sim 1 \)

The equilibrium time-scale

\[
\tau_A = \frac{1}{\sqrt{C_c C_a + (C_s - C_e)^2/4}},
\]

thus, the equilibrium state means

\[
\tanh(t/\tau_A) \sim 1.
\]

\( \tau_A \) is much more shorten comparing to \( C_s = C_e = 0 \).
The equilibrium state, $\tanh(t/\tau_A) \sim 1$

- $\sigma_{\chi p}$: smaller than the LUX bound$^8$,
- $\sigma_{\chi\chi}$: not violating Bullet cluster constraint$^9$ $\sigma_{\chi\chi}/m_\chi < 1.7 \times 10^{-24}$ cm$^2$ GeV$^{-1}$.

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tanh($t/\tau_A$) over ($\sigma_{\chi p}, \sigma_{\chi \chi}$)-plane
Effect of self-interaction and evaporation to DM

Behavior of $N_\chi$

If self-interaction exists, it will also delay the happening of evaporation. We are able to probe smaller $m_\chi$.

\[ \sigma_{\chi p} = 10^{-44} \text{ cm}^2 \]

\[ \sigma_{\chi \chi} = 10^{-24} \text{ cm}^2 \]

\[ \sigma_{\chi \chi} = 10^{-25} \text{ cm}^2 \]

No self–interaction

\[ N_\chi \]

\[ m_\chi \text{ [GeV]} \]
Enhancement to the annihilation rate

The DM annihilation rate gives: \( \Gamma_A \propto C_a N^2_\chi \).

\[ \sigma_{\chi p} = 10^{-44} \text{ cm}^2 \]

\[ m_\chi [\text{GeV}] \]

\[ \Gamma_A [\text{s}^{-1}] \]
Indirect search: IceCube-PINGU

The Precision IceCube Next Generation Upgrade: PINGU\(^\text{10}\)

\(^{10}\)Aartsen et al., arXiv:1401.2046 (2014).
Neutrinos from DM annihilation in the Sun

The differential neutrino flux from DM annihilation in the Sun is given by

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_A(m_\chi, \sigma_{\chi p}, \sigma_{\chi\chi})}{4\pi R^2} P_{\nu_i \rightarrow \nu_j}(R, E_\nu) \sum_f B_f \left( \frac{dN_\nu}{dE_\nu} \right)_f$$

where:

- $dN_\nu/dE_\nu$: $\nu$-spectrum at the source, taking care by WimpSim\textsuperscript{11},
- $B_f$: branching ratio,
- $P_{\nu_i \rightarrow \nu_j}$: $\nu$-oscillation effect through the propagation,
- $\Gamma_A$: the annihilation rate,
- $R$: propagation distance, 1 A.U.

\textsuperscript{11}Blennow et al., JCAP 01, 21 (2008).
Atmospheric background

The major atmospheric backgrounds\textsuperscript{12} are $\nu_e$ and $\nu_\mu$. During the night, atmospheric $\nu$-oscillation in matter via the propagation is also taking into consideration.

Event rate

The event rate of DM signals/ATM backgrounds is given by

\[ N_\nu = \int \frac{d\Phi_\nu}{dE_\nu d\Omega} A^\text{eff}_\nu(E_\nu) dE_\nu d\Omega \]

where \( A^\text{eff}_\nu(E_\nu) \) is the detector contained effective area and can be estimated by the detector effective volume, \( V^\text{eff}(E_\nu) \), through:

\[ A^\text{eff}_\nu(E_\nu) \propto V^\text{eff}(E_\nu)[n_p\sigma_{\nu p}(E_\nu) + n_n\sigma_{\nu n}(E_\nu)] \]

with:

- \( \sigma_{\nu p/n} \): \( \nu \)-proton/neutron cross section,
- \( n_{p/n} \): neutron/proton number density.
Constraints on $\sigma_{\chi\chi}$
1. The general DM evolution equation with SI & evap. effects is solvable.
2. In the low $m_\chi$ region, $\mathcal{O}(1)$ GeV, SI or evap. is important.
3. The existence of SI effect lowers the evaporation mass and allow us to probe smaller $m_\chi$.
4. SI and evap. effects also shorten the equilibrium time-scale.
5. It is testable via indirect searches such as IceCube-PINGU/JUNO.