COMPLEMENTARY TEST OF DARK MATTER SELF-INTEACTION BY INDIRECT AND DIRECT DARK MATTER DETECTIONS

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Based upon work done with Chian-Shu Chen and Yen-Hsun Lin, JCAP01 (2016) 013, arXiv: 1508.05263 [hep-ph]
OUTLINE:

➤ Motivation: why self-interacting dark matter (SIDM)? what are the interesting consequences of SIDM?

➤ Symmetric dark U(1) model—a realization of SIDM and ensure *indirect signature* from dark matter (DM) annihilation

➤ DM signature from the Sun—*indirect search*

➤ Constraint from LUX (*direct search*) and small search window in dark U(1) parameter space by IceCube-PINGU

➤ Summary
MOTIVATIONS

- The Sun is a good target for detecting dark matter (DM) signal through observing neutrinos—*indirect search*. DM density in the Sun is expected to be larger than the average DM density in the solar density.

- The possibility of detecting the above neutrinos correlates with DM direct detection, which so far gives bound on $\sigma_{\chi A}$.

- There is a possibility of breaking the above correlation: the combination of suppressed $\sigma_{\chi A}$ and large $\sigma_{\chi \chi} \Rightarrow$ significant neutrino flux can still be expected from the Sun.

- The above is self-interaction dominant scenario. Can such a scenario be realized in a SIDM model?
Evolution Equation

\[ \frac{dN_X}{dt} = C_c - C_e N_X - C_a N_X^2 \]

C_c : Capture, C_e : evaporation, C_a : annihilation

The evaporation term is important only when DM mass is less than 4 GeV.

DARK MATTER CAPTURE, EVAPORATION AND ANNIHILATION IN THE SUN

Capture is due to the scattering between halo DM and the nuclei in the Sun

\[
C_c^{\text{SD}} \simeq 3.35 \times 10^{24} \text{ s}^{-1} \left( \frac{\rho_0}{0.3 \text{ GeV/cm}^3} \right) \left( \frac{270 \text{ km/s}}{\bar{v}} \right)^3 \left( \frac{\text{GeV}}{m_\chi} \right)^2 \left( \frac{\sigma_H^{\text{SD}}}{10^{-6} \text{ pb}} \right)
\]

\[
C_c^{\text{SI}} \simeq 1.24 \times 10^{24} \text{ s}^{-1} \left( \frac{\rho_0}{0.3 \text{ GeV/cm}^3} \right) \left( \frac{270 \text{ km/s}}{\bar{v}} \right)^3 \left( \frac{\text{GeV}}{m_\chi} \right)^2 \left( \frac{2.6\sigma_H^{\text{SI}} + 0.175\sigma_H^{\text{He}}}{10^{-6} \text{ pb}} \right)
\]

\[
C_a \simeq \frac{\langle \sigma_v \rangle V_2}{V_1^2}, \quad \text{with} \quad V_j \simeq 6.5 \times 10^{28} \text{ cm}^3 \left( \frac{10 \text{ GeV}}{jm_\chi} \right)^{3/2}
\]

Take \(m_\chi=10 \text{ GeV}, \langle \sigma_v \rangle =3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}\), then \(C_a =1.6 \times 10^{-55} \text{ s}^{-1}\)

For SD interaction, \(\tau_A =4.5 \times 10^8 \text{ years}\), while the age of the Sun is roughly \(3 \times 10^9 \text{ years}\). Equilibrium has been reached!
The consequence of equilibrium

\[ N_\chi(t) = C_c \tau_A \tanh(t / \tau_A) \]

\[ \tau_A = \frac{1}{\sqrt{C_c C_a}} \]

At the present day, \[ N_\chi = \frac{C_c}{\sqrt{C_c C_a}} \]

The number of neutrinos produced per unit time is proportional to

\[ C_a N_\chi^2 \]

It turns out the number of neutrinos produced only depends on \( C_c \)

\( C_c \) is proportional to \( \sigma_\chi A \)

Smaller cross section leads to smaller neutrino flux
DM self interaction

- Self-interaction proposed to resolve small-scale structure problem in the universe.
  
  D. N. Spergel and P. J. Steinhardt, PRL 84, 3760 (2000)

- Observations on various galactic structures place the constraint $0.1 < \sigma_{\chi\chi}/m_\chi < 1.0 \ (cm^2/g)$

  \[ \sigma_{\chi\chi} = 1.78 \times 10^{-23} \ cm^2 \ \text{for} \ m_\chi = 10 \ GeV \]

S. W. Randall, M. Markevitch, D. Clowe, A. H. Gonzalez and M. Bradac, Astrophys. J. 679, 1173 (2008);
DM capture by self-interaction: the scattering

Zentner, Phys. Rev. D80, 063501 (2009)

$$C_s = \sqrt{\frac{3}{2}} n_\chi \sigma_{\chi\chi} v_{\text{esc}}(R_\odot) \frac{v_{\text{esc}}(R_\odot)}{\bar{u}} \left\langle \phi_\chi \right\rangle \frac{\text{erf}(\eta)}{\eta}$$

$n_\chi$ : DM number density in the halo
Dark matter evolution with self-interaction

- Modified evolution equation:

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

- The equilibrium time scale is shorter:

\[
\tau = \frac{1}{\sqrt{C_c C_a + C_s^2/4}} \quad C_a \propto <\sigma v>
\]

- \(C_s \propto n_\chi \sigma_{\chi\chi}; \quad \Phi_\nu \propto C_a N_\chi^2 \propto \frac{C_s^2}{C_a} \quad \text{(for } C_s^2 \gg 4C_c C_a\text{)}\)

Probing self interaction!
The presence of self-interaction shifts the evaporation mass scale higher. The annihilation increases with DM self-interaction cross section.
SYMMETRIC DARK U(1) MODEL

\[ \mathcal{L}_{\text{DM vector}} = e D \bar{\chi} \gamma^\mu \chi \phi_\mu \]

DM as Dirac fermion

\[ \mathcal{L}_{\text{mixing, U(1)}} = \frac{\varepsilon_\gamma}{2} \phi_{\mu\nu} F^{\mu\nu} + \varepsilon_Z m_Z^2 \phi_{\mu} Z^\mu \]

\[ \phi - \gamma \text{ mixing and} \]
\[ \phi - Z \text{ mixing} \]

The mediator couples to nucleons through mixings with photon and Z boson

\[ \mathcal{L}_{\text{mixing/vector}} = \left( \varepsilon_\gamma e J_{\text{em}}^\mu + \varepsilon_Z g_2 e_Z J_{\text{NC}}^\mu \right) \phi_\mu \]

\[ J_{\text{em}}^\mu = \sum_f Q_f \bar{f} \gamma^\mu f \]

\[ J_{\text{NC}}^\mu = \sum_f \bar{f} \gamma^\mu \left[ I_{3f} \left( \frac{1 - \gamma_5}{2} \right) - Q_f s_W^2 \right] f \]
**SYMMETRIC DARK U(1) MODEL**

*DM-nucleon coupling*

- Independent parameters: \( \alpha_\chi, m_\chi, m_\phi, \varepsilon_\gamma, \eta \)

\[
\sigma^{\text{SI}}_{\chi \phi} \approx 1.5 \times 10^{-24} \text{ cm}^2 \varepsilon_\gamma^2 \left( \frac{\alpha_\chi}{0.01} \right) \left( \frac{m_\phi}{30 \text{ MeV}} \right)^{-4}
\]

*DM-nucleus scattering cross section*

\[
\sigma_{\chi A} \approx \frac{16\pi\alpha_\chi\alpha_{\text{em}}}{m_\phi^4} \left[ \varepsilon_p Z + \varepsilon_n (A - Z) \right]^2 \mu_{\chi A}^2
\]

\[
\varepsilon_p = \varepsilon_\gamma + \frac{\varepsilon_Z}{4s_Wc_W} (1 - 4s_W^2) \approx \varepsilon_\gamma + 0.05\varepsilon_Z,
\]

\[
\varepsilon_n = -\frac{\varepsilon_Z}{4s_Wc_W} \approx -0.6\varepsilon_Z.
\]

*reduced mass*

One has isospin violation in general, i.e.,

\[
\eta \equiv \frac{\varepsilon_n}{\varepsilon_p} \neq 1
\]

Related to DM capture by the Sun
DM self-interaction

vanishes in the non-relativistic limit

Dominant contribution

\[ \sigma_{\chi \bar{\chi}} = 4\pi \alpha_\chi^2 \frac{m_\chi^2}{m_\phi^4} \]

For very small mediator mass, the momentum transfer \((p-p')^2\) will dominate \(m_\phi^2\). Careful treatment is needed.
Thermal relic constraint
\[ \chi \bar{\chi} \rightarrow \phi \phi \]

\[ < \sigma v > = 6 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \quad \text{Dirac fermion} \]

then \[ \alpha_\chi \approx 3.3 \times 10^{-5} (m_\chi / \text{GeV}) \]

Independent parameters:
\[ \varepsilon_\gamma, \eta, m_\chi, m_\phi \]
SYMMETRIC DARK U(1) MODEL

BBN constraint

To generate large self-interaction cross section $\sigma_{\chi \bar{\chi}}$, the mediator mass should be small. For $m_\phi < 100 \, \text{MeV}$, the main decay modes of $\phi$ are: $\phi \rightarrow e^+e^-$, and $\phi \rightarrow \nu\bar{\nu}$. The decay time of the former should be less than 1s. Hence $\varepsilon_\gamma \geq 5 \times 10^{-11} \sqrt{10 \, \text{MeV}/m_\phi}$. Upper bound comes from electron anomalous magnetic moment, beam dump experiments and supernova cooling.

T. Lin, H.-B. Yu and K. Zurek,

The allowed range for $\varepsilon_\gamma$

$\varepsilon_\gamma \geq 5 \times 10^{-11} \sqrt{10 \text{ MeV}/m_\phi}$.

T. Lin, H.-B. Yu and K. Zurek,

We take $\varepsilon_\gamma = 10^{-9}$, and $10^{-10}$ for analysis

Independent parameters:
$\varepsilon_\gamma$, $\eta$, $m_\chi$, $m_\phi$

Constrained
LUX set stringent constraints on the parameter space for isospin symmetric case. Small window is left for indirect search.
DARK MATTER SIGNATURE FROM THE SUN

**DM evolution equation in the Sun**

\[
\frac{dN_\chi}{dt} = C_c - C_e N_\chi + C_s N_\bar{\chi} - (C_a + C_{se}) N_\chi N_\bar{\chi},
\]

\[
\frac{dN_\bar{\chi}}{dt} = C_c - C_e N_\bar{\chi} + C_s N_\chi - (C_a + C_{se}) N_\bar{\chi} N_\chi,
\]

evaporation by the scattering of \( \bar{\chi} \) and \( \chi \).

**Symmetric DM:** \( N_\chi = N_\bar{\chi} \)

\[\Rightarrow \quad \frac{dN_\chi}{dt} = C_c - C_e N_\chi + C_s N_\chi - (C_a + C_{se}) N_\chi^2\]

This has been derived and solved in

C.-S. Chen, F.-F. Lee, GLL, Y.-H. Lin, JCAP 10

(2014), 049
DARK MATTER SIGNATURE FROM THE SUN

\[ C_c \propto \left( \frac{\rho_\chi}{0.15 \text{ GeV/cm}^3} \right) \left( \frac{\text{GeV}}{m_\chi} \right) \left( \frac{270 \text{ km/s}}{v_\chi} \right) \sum_A F_A(m_\chi, \eta) \sigma^0_{\chi A} \frac{m_\phi^4}{(m_\phi^2 + q_A^2)^2}, \]

\[ C_s(q^2) \propto \left( \frac{\rho_\chi}{0.15 \text{ GeV/cm}^3} \right) \left( \frac{\text{GeV}}{m_\chi} \right) \left( \frac{270 \text{ km/s}}{v_\chi} \right) \frac{\sigma^0_{\chi \chi} \operatorname{erf}(\eta)}{\eta} \frac{m_\phi^4}{(m_\phi^2 + q^2)^2}, \]

No such problem for annihilation \( \chi \bar{\chi} \rightarrow \phi \phi \)
DARK MATTER SIGNATURE FROM THE SUN

DM accumulation in the Sun

$\sigma_{\chi p}(\varepsilon_{\gamma})$ still plays an essential role
DARK MATTER SIGNATURE FROM THE SUN

The effect of self-interaction on the number of trapped DMs

Self-interaction does not completely take over
NEUTRINO FLUX ARRIVING AT THE EARTH

Distance between Sun and Earth

Branching fraction for specific annihilation channel

\[
\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Gamma_A}{4\pi R_{\odot}^2} P_{\nu_j \rightarrow i}(E_{\nu}) \sum_f B_f \left( \frac{dN_{\nu_j}}{dE_{\nu_j}} \right)_f
\]

Energy distribution per annihilation

\[\chi \bar{\chi} \rightarrow \phi \bar{\phi}, \phi \rightarrow \nu \bar{\nu}\]

Note that the mediator can also decay to electron-position pair

The branching ratio for decaying to neutrinos is determined by

\[
\frac{\epsilon_Z}{\epsilon_\gamma} = -\frac{\eta}{\eta + 12}
\]

\[
\mathcal{L}_{\text{mixing/vector}} = \left( \epsilon_\gamma e J^\mu_{\text{em}} + \epsilon_Z \frac{g_2}{c_W} J^\mu_{\text{NC}} \right) \phi_\mu
\]

\[
J^\mu_{\text{em}} = \sum_f Q_f \bar{f} \gamma^\mu f
\]

\[
J^\mu_{\text{NC}} = \sum_f \bar{f} \gamma^\mu \left[ I_{3f} \left( \frac{1 - \gamma_5}{2} \right) - Q_f s_{W}^2 \right] f
\]

\[
N_\nu = \int_{E_{th}}^{m_X} \frac{d\Phi_\nu}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega
\]

\[
N_{\text{atm}} = \int_{E_{th}}^{E_{\text{max}}} \frac{d\Phi_{\nu_{\text{atm}}}}{dE_\nu} A_\nu(E_\nu) dE_\nu d\Omega
\]

- Consider neutrino events from the solid angle range $\Delta \Omega = 2\pi (1 - \cos \psi)$ surrounding the Sun
- Take $\psi = 10^\circ$ to match PINGU angular resolution
- Take the threshold energy to be 1 GeV
LUX constraints rules out almost all the parameter spaces except the tiny window. This window is in the region of negligible self-interaction.
ICECUBE-PINGU 5-YEAR SENSITIVITY (2σ) WITH TRACK EVENTS

\[ \varepsilon_\gamma = 10^{-9} \]

The tiny window not reached by LUX is in the self-interaction relevant region for some values of \( \eta \).
SUMMARY

➤ We have studied the signature of DM self-interaction in a dark U(1) model with a light vector mediator which connects DM with standard model particles.

➤ We find that DM-nucleon cross section and DM self-interaction cross section are closely related to each other by the model parameters. DM self-interaction enhances the DM annihilation rate in the Sun significantly but not overwhelmingly.

➤ In such a model, we find that the chance of detecting DM signature from the Sun is still correlated to the result of direct search.

➤ It is of high interest to explore some other models in which the above scenario does not hold.