Solar Investigation of Multicomponent Dark Matter

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Introduction

1. **Evidences for existence of Dark Matter**
   - Rotation curves of spiral galaxies
   - Gravitional lensing effects
   - Cosmic Microwave Background (CMB) anisotropy, PLANCK/WMAP

2. **Types of Dark Matter**
   - **WIMPs** : Based on thermal freeze-out of DM candidate upon annihilation into visible sector.
   - **FIMPs** : Based on non thermal freeze-in production from decay or annihilation of unstable or metastable particles.
   - **SIMPs** : Based on number changing self annihilation (4$\rightarrow$ 2 or 3 $\rightarrow$2 processes).
   - **Other candidates** : Sterile neutrinos, ALPs etc.

Why not multi-component?

Motivation

- **Characteristics of multi-component Dark Matter (MCDM)**
- **Relic density :** $\Omega_{\rm DM}{\rm h}^2 = \sum_i \Omega_i {\rm h}^2$

Assumption: The contribution of each DM component to the local density is same as their contribution to the relic density.

- **Coupled Boltzmann equations** : Annihilations into visible and dark sector. Boltzmann equations changes depending on the nature of dark matter (WIMP, FIMP, SIMP etc.).
- **Direct and Indirect detection of MCDM** : Indirect detection prospects in Sun?

9 Neutrino signal from the Sun and the Earth

This module does not work yet in case of 2DM

Belanger G., Boudjema F., Pukhov A., micrOMEGAs : a code for the calculation of Dark Matter properties in generic models of particle interaction

WIMP and Sun

Evolution of DM number abundance inside Sun Phys. Rept. 267, 195 (1996)

$$\frac{dN}{dt} = C_c - C_a N^2. \quad (1)$$

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

$$\sigma_i^{\mathrm{SI}} = A^2 \left(\frac{m_A}{m_p}\right)^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A}\right)^2 \sigma_{\chi p}^{\mathrm{SI}}. \quad (3)$$

$$C_c \simeq 3.35 \times 10^{24}\ \mathrm{s}^{-1} \left(\frac{\rho_0}{0.3\ \mathrm{GeV/cm}^3}\right) \left(\frac{270\ \mathrm{km/s}}{\bar{v}}\right)^3 \left(\frac{\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{\sigma_{\mathrm{H}}^{\mathrm{SD}}}{10^{-6}\ \mathrm{pb}}\right). \quad (4)$$

$$\sigma_i^{\rm SD} = A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A} \right)^2 \frac{4(J_i+1)}{3J_i} \left| \langle S_{p,i} \rangle + \langle S_{n,i} \rangle \right|^2 \sigma_{\chi p}^{\rm SD} \tag{5}$$

The annihilation rate coefficient of dark matter

$$C_a \simeq \frac{\langle \sigma v \rangle \, V_2}{V_1^2}, \quad V_j \simeq 6.5 \times 10^{28} \, \rm cm^3 \left(\frac{10 \, GeV}{j m_\chi} \right)^{3/2} . \tag{6}$$

Thermal WIMP annihilation : $\langle \sigma v \rangle \simeq 2.2 \times 10^{-26}$ cm^3 s^{-1}. PRD 86, 023506 (2012)
$\Gamma_{\rm ann} = \frac{C_a}{2} N(t_S)^2$, $t_S = 4.6 \times 10^9$ yr; $\Gamma_{\rm ann} = C_c/2$ in equilibrium.

DM number abundance inside the Sun

$$N(t) = \sqrt{\frac{C_c}{C_a}} \tanh \left(\frac{t}{\tau_{\rm EQ}} \right); \;\; N_{EQ} = \sqrt{\frac{C_c}{C_a}}; \;\; \tau_{\rm EQ}^{-1} \equiv \sqrt{C_c C_a} \tag{7}$$

DM annihilation flux

$$\Phi = \frac{\Gamma_{\rm ann}}{4\pi D^2}, \;\; D \simeq 1.5 \times 10^8 {\rm km}, \;\; \Gamma_{\rm ann} = \frac{C_a}{2} N(t_S)^2. \tag{8}$$

Differential neutrino flux from Sun at earth PPPC 4 DMν: JCAP 03, 053 (2014)

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \Phi \left(\frac{dN_{\nu_i}}{dE_{\nu_i}} \right)_x , \tag{9}$$

The muon flux PRD 79, 015010 (2009); PRD 84, 031301 (2011)

$$\begin{aligned} \Phi_\mu &= \int_{E_\mu^{\rm th}}^{m_\chi} dE_\mu \int_{E_\mu}^{m_\chi} dE_{\nu_\mu} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \times \\ & \left[\frac{\rho}{m_p} \frac{d\sigma_\nu}{dE_\mu} (E_\mu, E_{\nu_\mu}) R_\mu (E_\mu, E_\mu^{\rm th}) \right] + (\nu \to \bar{\nu}) , \end{aligned} \tag{10}$$

Neutrino (anti neutrino) scattering cross-section

$$\frac{d\sigma_\nu^{(p,n)}(E_\mu, E_{\nu_\mu})}{dE_\mu} = \frac{2}{\pi} G_F^2 m_p \left(a_\nu^{(p,n)} + b_\nu^{(p,n)} \frac{E_\mu^2}{E_{\nu_\mu}^2} \right) , \tag{11}$$

neutrinos $a_\nu^{(p,n)} = 0.15,\ 0.25,\ b_\nu^{(p,n)} = 0.04,\ 0.06$
antineutrinos $a_{\bar{\nu}}^{(p,n)} = b_\nu^{(n,p)},\ b_{\bar{\nu}}^{(p,n)} = a_\nu^{(n,p)}$.

$$R_\mu(E_\mu, E_\mu^{\rm th}) = \frac{1}{\beta\rho} \log\left(\frac{\alpha + \beta E_\mu}{\alpha + \beta E_\mu^{\rm th}}\right) , \quad (12)$$

$\alpha = 2.3 \times 10^{-3}\,{\rm cm}^2{\rm g}^{-1}{\rm GeV}^{-1},\ \beta = 4.4 \times 10^{-6}\,{\rm cm}^2{\rm g}^{-1}.$

DM with fractional abundance but annihilates into SM particles only

$$\frac{dN}{dt} = fC_{\rm c} - \frac{C_a}{f} N^2 , \quad (13)$$

$\sigma_i' = f\sigma_i$ and $\langle\sigma v\rangle' = \dfrac{\langle\sigma v\rangle}{f}$.

$N(t) = f\sqrt{\dfrac{C_c}{C_a}} \tanh\left(\dfrac{t}{\tau_{\rm EQ}}\right),\ \tau_{\rm EQ}' \equiv \dfrac{1}{\sqrt{fC_{\rm c}\frac{C_a}{f}}} = \tau_{\rm EQ},\ \Phi' = \dfrac{C_a}{2f} N^2 = f\Phi.$

Differential neutrino flux at earth

$$\frac{d\Phi_{\nu_i}'}{dE_{\nu_i}} = \Phi'\left(\frac{dN_{\nu_i}}{dE_{\nu_i}}\right)_x = f\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} . \quad (14)$$

Modified muon flux $\Phi_\mu' = f\Phi_\mu$.

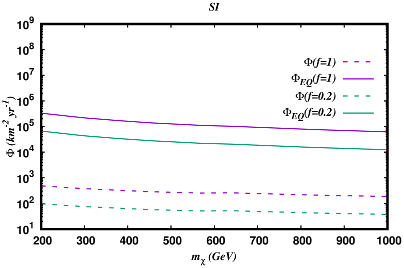

Figure: *Left panel: Dark matter annihilation flux inside Sun for SI scattering of dark matter at $t = t_S$ (dashed lines) and at equilibrium $t = \tau_{\rm EQ} > t_S$ (solid lines). Right panel: Dark matter annihilation flux inside Sun for SD scattering of dark matter at $t = t_S > \tau_{\rm EQ}$ in equilibrium. Both figures are plotted for $f = 1$ and $f = 0.2$.*

Multiple WIMPs and Sun

DM candidates $\chi_1,\ \chi_2$ inside Sun with no mutual interaction

$$\frac{dN_1}{dt} = fC_{1c} - \frac{C_{1a}}{f} N_1^2 \,,$$
$$\frac{dN_2}{dt} = (1-f)C_{2c} - \frac{C_{2a}}{(1-f)} N_2^2 \,, \qquad (15)$$

$C_{kc} \propto \sigma_{\chi_k p}$ and $C_{ka} = \langle \sigma v \rangle\ V_{2a}/V_{1a}^2$; $k = 1, 2$.
In presence of internal conversion ($\chi_1\chi_1 \to \chi_2\chi_2$)

$$\frac{dN_1'}{dt} = fC_{1c}' - C_{1a}' N_1'^2 - C_{12}' N_1'^2 \,,$$
$$\frac{dN_2'}{dt} = (1-f)C_{2c}' - C_{2a}' N_2'^2 + \gamma C_{12}' N_1'^2 \,, \qquad (16)$$

$$C_{ka}' = \langle \sigma v \rangle_{kk} \frac{V_{2k}}{V_{1k}^2} \,, \qquad C_{12}' = \langle \sigma v \rangle_{11\to 22} \left[\frac{V_2}{V_1^2} \right]_{m=m_1} \,. \qquad (17)$$

$C_{kc}' = C_{kc}$, γ: absorption coefficient

$$N_1'(t) = \sqrt{\frac{fC_{1c}'}{C_{1a}' + C_{12}'}} \tanh\left(\frac{t}{\tau_{1\mathrm{EQ}}'}\right) ,$$
$$\tau_{1\mathrm{EQ}}' = \frac{1}{\sqrt{fC_{1c}'(C_{1a}' + C_{12}')}}, \tag{18}$$

Condition: $\gamma C_{12}' N_1'^2 >> (1-f)C_{2c}'$

$$N_2'(t) \simeq \sqrt{\frac{\gamma C_{12}'}{C_{2a}'}} \sqrt{\frac{fC_{1c}'}{C_{1a}' + C_{12}'}} \tanh\left(\frac{t}{\tau_{2\mathrm{EQ}}'}\right) ,$$
$$\tau_{2\mathrm{EQ}}' \simeq \frac{1}{\sqrt{\gamma C_{2a}' C_{12}'}} \sqrt{\frac{C_{1a}' + C_{12}'}{fC_{1c}'}} . \tag{19}$$

Aoki et.al. PRD 86, 076015 (2012); PRD 90, 076011 (2014)
Berger et. al. JCAP 02, 005 (2015)

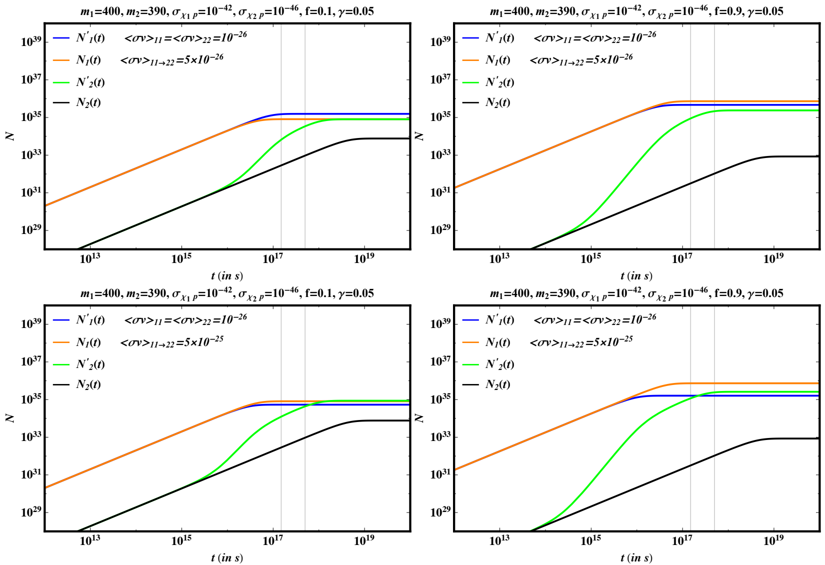

Figure: Dark matter masses m_k are in GeV, $\sigma_{\chi_k p}$ in cm^2 and annihilation cross-sections $\langle \sigma v \rangle_{kk}$ and $\langle \sigma v \rangle_{11\to 22}$ are in cm^3 s^{-1} unit.

In absence of internal conversion

$$\Phi_k = \frac{\Gamma^k_{\rm ann}}{4\pi D^2}\,, k = 1, 2, \tag{20}$$

where annihilation rates of dark matter $\chi_{1,2}$ are expressed as

$$\Gamma^1_{\rm ann} = \frac{C_{1a}}{2f} N_1^2(t_S)\,, \qquad \Gamma^2_{\rm ann} = \frac{C_{2a}}{2(1-f)} N_2^2(t_S)\,, \tag{21}$$

Differential neutrino flux

$$\frac{d\Phi^k_{\nu_i}}{dE_{\nu_i}} = \Phi_k \left(\frac{dN^k_{\nu_i}}{dE_{\nu_i}}\right)_x \; ; k = 1, 2 \tag{22}$$

$$\begin{aligned} \Phi^k_\mu \quad &= \quad \int_{E^{\rm th}_\mu}^{m_k} dE_\mu \int_{E_\mu}^{m_k} dE_{\nu_\mu} \frac{d\Phi^k_{\nu_\mu}}{dE_{\nu_\mu}} \\ &\times \left[\frac{\rho}{m_p}\frac{d\sigma_\nu}{dE_\mu}(E_\mu, E_{\nu_\mu}) R_\mu(E_\mu, E^{\rm th}_\mu)\right] + (\nu \to \bar{\nu})\,. \end{aligned} \tag{23}$$

In presence of $\chi_1\chi_1 \to \chi_2\chi_2$ transfer

$$\Phi'_k = \frac{\Gamma'^k_{\rm ann}}{4\pi D^2}\,, \quad \Gamma'^k_{\rm ann} = \frac{C'_{ka}}{2} N'^2_k(t_S)\; k = 1,2 \tag{24}$$

$$\Phi'^k_\mu = \int_{E_\mu^{\rm th}}^{m_k} dE_\mu \int_{E_\mu}^{m_k} dE_{\nu_\mu} \frac{d\Phi'^k_{\nu_\mu}}{dE_{\nu_\mu}} \times \left[\frac{\rho}{m_p}\frac{d\sigma_\nu}{dE_\mu}(E_\mu, E_{\nu_\mu})R_\mu(E_\mu, E_\mu^{\rm th})\right] + (\nu \to \bar{\nu})\,, \tag{25}$$

Efficiency factor: $\xi_k = \dfrac{\Phi'_k}{\Phi_k}$, $\dfrac{d\Phi'^k_{\nu_i}}{dE_{\nu_i}} = \xi_k \dfrac{d\Phi^k_{\nu_i}}{dE_{\nu_i}}$; $k = 1, 2$.
This implies $\Phi'^k_\mu = \xi_k \Phi^k_\mu$.

$\xi = \xi(\gamma, f,\ m_k,\ \sigma_{\chi_k p},\ \langle\sigma v\rangle_{kk}\,, \langle\sigma v\rangle_{11\to 22})$

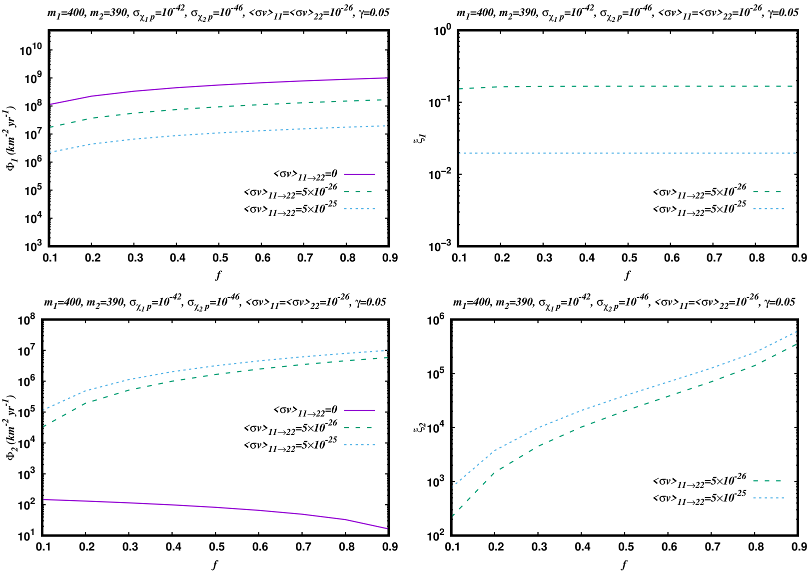

Figure: Variation of Φ_k and ξ_k with f.

$$\xi_1 = \frac{C'_{1a}}{C'_{1a} + C'_{12}} = \frac{\langle \sigma v \rangle_{11}}{\langle \sigma v \rangle_{11} + \langle \sigma v \rangle_{11 \to 22}}$$

$$\xi_2 = \gamma \frac{f}{1-f} (1 - \xi_1) \frac{C_{1c}}{C_{2c}} \frac{\tanh^2\left(\frac{t_s}{\tau'_{2\mathrm{EQ}}}\right)}{\tanh^2\left(\frac{t_s}{\tau_{2\mathrm{EQ}}}\right)}$$

Feasible model:

$\chi_1, \ \chi_2$ DM with axial vector interaction $\chi_k \gamma_\mu \gamma_5 \chi_k; \ k = 1, 2$, charged under two different Z_2 symmetry.

Spin dependent interaction with SM sector fermion via vector boson : $\chi_k \gamma^\mu \gamma_5 \chi_k \bar{f}_{\mathrm{SM}} \gamma_\mu \gamma_5 f_{\mathrm{SM}}$.

Velocity suppressed Spin independent interaction : $\chi_k \gamma^\mu \gamma_5 \chi_k \bar{f}_{\mathrm{SM}} \gamma_\mu f_{\mathrm{SM}}$.

Summary

- Dark matter with spin-independent interaction fails to reach equilibrium DM number abundance but Spin- dependent DM reaches equilibrium inside Sun.
- For partial contribution with fractional DM abundance, dark matter annihilation flux will be scaled by the fraction of total DM relic abundance $\Phi' = f\Phi$ if conversion between two dark matter candidate is absent. Corresponding neutrino flux and muon flux generated at the detector are also found to be suppressed by factor f. Interestingly, it is found that the time to reach steady state is independent of the value f.
- For multi-particle dark matter inside Sun, late time annihilation of χ_1 into χ_2 having suffucient annihilation cross-section $\langle \sigma v \rangle_{11 \to 22}$, modifies dark matter number abundance and corresponding DM annihilation flux considerably. Internal conversion also changes the equilibration time of dark matter candidate.
- The efficiency factor $\xi_k;\ k = 1, 2$ determines the scale of enhancement or suppression of DM annihilation flux. Corresponding muon flux for the dark matter candidate will also get boosted or suppressed by the factor ξ_k.