On the evolution process of two-component dark matter in the Sun

Yen-Hsun Lin

Department of Physics, National Cheng Kung University, Taiwan

JHEP **1804**, 074 (2018)

Introduction

We introduce dark matter (DM) evolution process in the Sun under a two-component DM (2DM) scenario. Both DM species χ and ξ with masses heavier than 1 GeV are considered. In this picture, both species could be captured by the Sun through DM-nucleus scattering and DM self-scatterings, e.g. $\chi\chi$ and $\xi\xi$ collisions. In addition, the *heterogeneous self-scattering* due to χ and ξ collision is essentially possible in any 2DM models. This new introduced scattering naturally weaves the evolution processes of the two DM species that was assumed to evolve independently. Moreover, the heterogeneous self-scattering enhances the number of DM being captured in the Sun mutually. This effect significantly exists in a broad range of DM mass spectrum. We have studied this phenomena and its implication for the solar-captured DM annihilation rate. It would be crucial to the DM indirect detection when the two masses are close. General formalism of the 2DM evolution in the Sun as well as its kinematics are studied.

Formalism

1DM Case

For only one DM specie χ, the evolution of DM number N_χ in the Sun can be characterized by the following differential equation

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

where the terms $C_{c,s,a,e,se}$ describe the solar capture, DM self-capture, annihilation, evaporation and DM self-evaporation rates. In the absence of evaporations, a general solution to Eq. (1) can be obtained by

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

where $\tau = 1/\sqrt{C_c C_a + C_s^2/4}$ is the equilibrium timescale. When $t \gg \tau$, $dN_\chi/dt = 0$.

2DM Case

Once the second DM specie ξ is included, additional evolution equation should be added. In this scenario, the self-interactions are not only due to $\chi\chi$ and $\xi\xi$ scatterings as well as $\chi\xi$ scattering. Thus, the evolution process is determined by

$$\frac{dN_\chi}{dt} = C_c^\chi + (C_s^\chi - C_e^\chi)N_\chi + (C_s^{\chi\to\xi} - C_{se}^{\chi\to\xi}N_\chi)N_\xi - (C_a^\chi + C_{se}^\chi)N_\chi^2, \tag{3}$$

$$\frac{dN_\xi}{dt} = C_c^\xi + (C_s^\xi - C_e^\xi)N_\xi + (C_s^{\xi\to\chi} - C_{se}^{\xi\to\chi}N_\xi)N_\chi - (C_a^\xi + C_{se}^\xi)N_\xi^2, \tag{4}$$

where N_χ and N_ξ determine the χ and ξ evolutions in the Sun respectively. The coefficients $C^{\chi(\xi)\to\xi(\chi)}$ are added to describe the scattering rates induced by heterogeneous self-interaction from χ and ξ interaction. It is this heterogeneous self-interaction that weaves Eqs. (3) and (4) together. They are mutually dependent and cannot be treated separately.

Numerical Analysis

Notation Convention

Assuming the relic abundances are $\Omega_\chi h^2$ and $\Omega_\xi h^2$ respectively and $\Omega_{\rm DM}h^2 = \Omega_\chi h^2 + \Omega_\xi h^2$ is the total DM relic abundance. If the annihilation is dominated by *s*-wave process at freeze-out epoch, we have the relic abundance is inversely proportional to the annihilation cross section. Thus,

$$\Omega_{\rm DM}h^2 = \Omega_\chi h^2 + \Omega_\xi h^2 \propto \frac{1+r_\rho}{\langle\sigma_\chi v\rangle_0} \equiv \frac{1}{\langle\sigma_{\rm eff} v\rangle_0} \tag{5}$$

where $r_\rho = \Omega_\chi/\Omega_\xi$ and $\langle\sigma_{\rm eff}v\rangle_0 = 3\times10^{-26}$ cm^3 s^{-1} the *effective* annihilation cross section. Suppose the local DM density $\rho \propto \Omega h^2$, then we have $r_\rho = \rho_\chi/\rho_\xi$ as well. Therefore,

$$0.3\,{\rm GeV\,cm^{-3}} = \rho_\chi + \rho_\xi = \rho_\chi(1+r_\rho) \tag{6}$$

and the local number density $n_\alpha = \rho_\alpha/m_\alpha$ where $\alpha = \chi, \xi$.

Number of DM in the Sun

Suppose $r_\rho = 1$ and $m_\chi \gg m_\xi$, we have $n \ll n_\xi$ thus χ affects ξ little. Thus, in the equilibrium stage where $dN_\chi/dt = 0$ we can drop $C_s^{\xi\to\chi}N_\chi^{\rm eq}$ in Eq. (4). Under this condition, simple expressions for

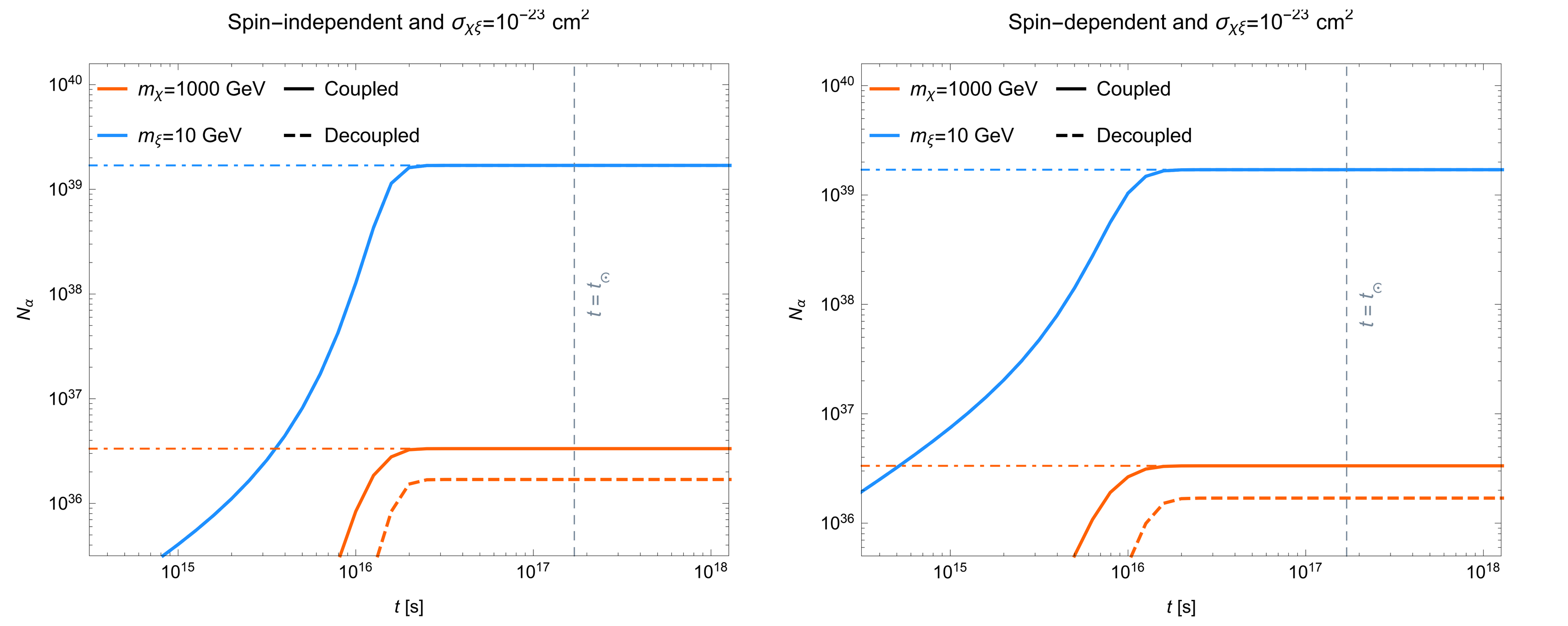

Figure 1. Evolution of DM number $N_{\chi,\xi}$ in the Sun with $r_\rho = 1$. We consider $m_\chi = 1000$ GeV and $m_\xi = 10$ GeV. Thus ξ is subject to a large correction from χ. Spin-independent and dependent cases are both shown.

DM number can be obtained

$$N_\chi^{\rm eq} = \frac{C_s^\chi}{C_a^\chi}\left(\frac{1}{2} + \sqrt{\frac{1}{4} + R_\chi}\right) \tag{7}$$

$$N_\xi^{\rm eq} = \frac{C_s^\xi}{C_a^\xi}\left(\frac{1}{2} + \sqrt{\frac{1}{4} + R_\xi}\right) \tag{8}$$

where

$$R_\chi = \frac{C_a^\chi(C_c^\chi + C_s^{\chi\to\xi}N_\xi^{\rm eq})}{(C_s^\chi)^2} \quad \text{and} \quad R_\xi = \frac{C_a^\xi C_c^\xi}{(C_s^\xi)^2} \tag{9}$$

is the correction factor due to heterogeneous self-interaction. The numerical results for $N^{\rm eq}$ are plotted in Figure 1.

Implication for DM Indirect Search

When an appreciated amount of DM particles accumulate in the solar core, the total annihilation rate as a result of these particles is given by

$$\Gamma_\alpha = \frac{1}{2}C_a^\alpha N_\alpha^2 \tag{10}$$

for a given DM specie α. If both N_α are in equilibrium stage, then from Eqs. (7) and (8) we can easily obtain

$$\Gamma_\chi^{\rm eq} = \frac{1}{2}\frac{(C_s^\chi)^2}{C_a^\chi}\left(\frac{1}{2} + \sqrt{\frac{1}{4} + R_\chi}\right)^2 \tag{11}$$

$$\Gamma_\xi^{\rm eq} = \frac{1}{2}\frac{(C_s^\xi)^2}{C_a^\xi}\left(\frac{1}{2} + \sqrt{\frac{1}{4} + R_\xi}\right)^2 \tag{12}$$

where $R_{\chi,\xi}$ are given in Eq. (9). The above equations assume ξ dominates the DM population over χ. Counter case is vice versa.

The numerical results for total annihilation rate with $r_\rho = 1$ are plotted in Figure 2. We only show the spin-independent case. The spin-dependent case is similar. On the left panel of Figure 2, we fixed $m_\xi = 10$ GeV and Γ_ξ is indicated by the blue line. When $m_\chi > m_\xi$ it is true that $n_\chi < n_\xi$.

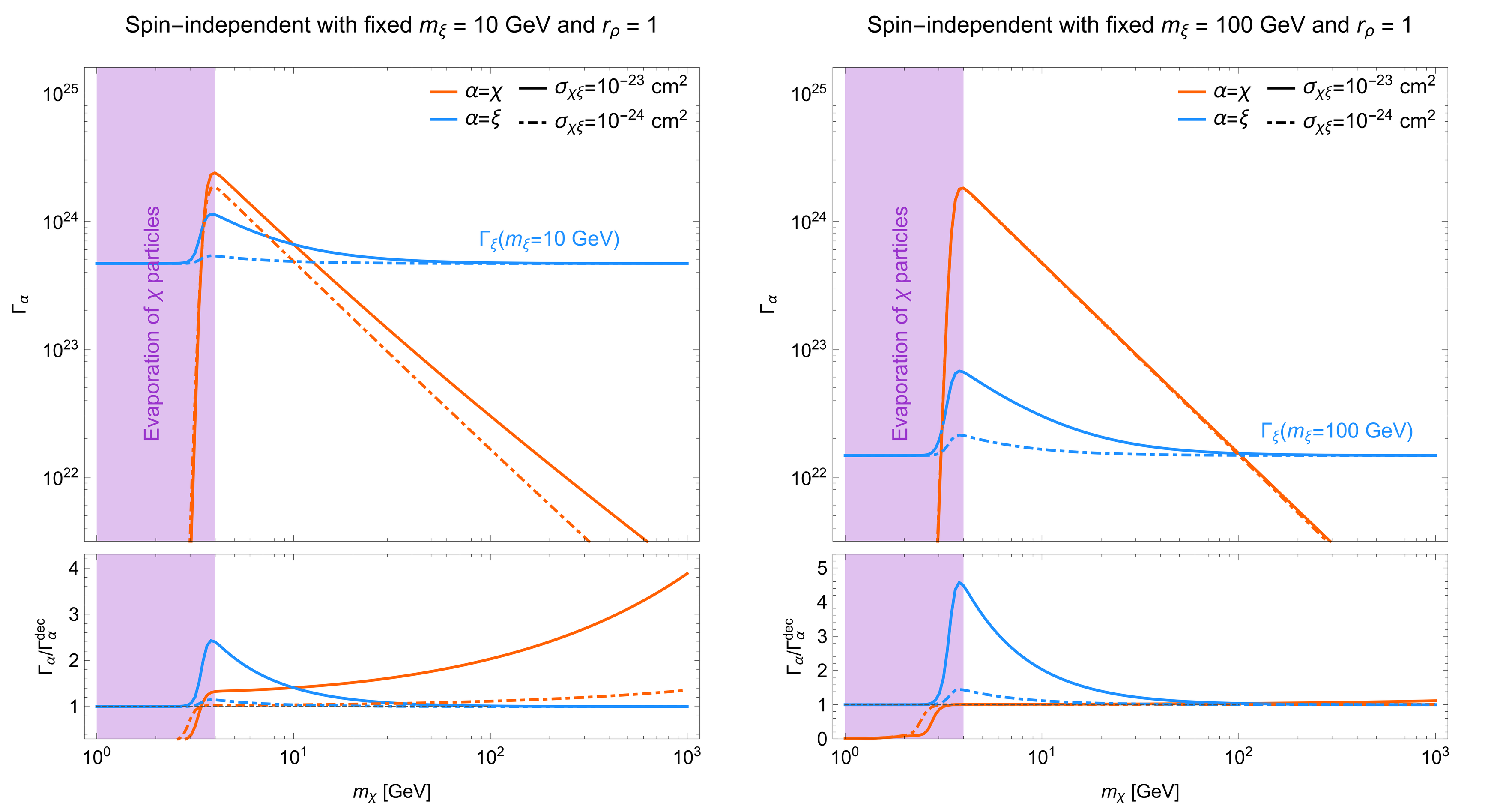

Figure 2. Total annihilation rate Γ_α with fixed m_ξ = 10 GeV (left) and 100 GeV (right). Orange and blue lines are for χ and ξ particles respectively. Solid line indicates $\sigma_{\chi\xi}$ = 10^{-23} cm^2 and dot-dashed $\sigma_{\chi\xi}$ = 10^{-24} cm^2. Γ_α with smaller n_α is subject to a larger correction from the other specie.

Hence ξ is the dominant specie in the Sun and Γ_ξ can be considered as independent of χ particles. But Γ_χ is usually subject to a correction from ξ when $m_\chi > m_\xi$. However, when m_χ is close to m_ξ, both numbers $N_{\chi,\xi}$ are nearly equivalent. Mutual influence is strong in this region. Not only Γ_χ is enhanced by ξ particles, as well as Γ_ξ is increased by χ particles in the Sun. The ratio of correction is shown in the lower panel. A quick drop of Γ_χ when $m_\chi \lesssim 4$ GeV is due to the evaporation effect.

Summary

The heterogeneous self-interaction is a natural consequence of any 2DM or *n*DM models. This effect will eventually reflect in the DM annihilation rates. Potentially, if the DM annihilates to the SM particles in the final state, such signal could be detected in the terrestrial detectors. Therefore, the strength of the heterogeneous self-interaction could be probed. Moreover, any sign of such interaction could be considered as a possible existence of DM beyond one-component.

References

1. A. Gould, *Astrophys. J.* **321**, 560 (1987)
2. A. Gould, *Astrophys. J.* **321**, 571 (1987)
3. D. N. Spergel and P. J. Steinhardt, *Phys. Rev. Lett.* **84**, 3760 (2000)
4. A. R. Zentner, *Phys. Rev. D* **80**, 063501 (2009)
5. J. Herrero-Garcia, A. Scaffidi, M. White and A. G. Williams, *JCAP* **1711**, 021 (2017)

✉ yenhsun@phys.ncku.edu.tw