Reshuffled SIMP Dark matter

Shu-Yu Ho , Pyungwon Ko , & Chih-Ting Lu (Korea Institute for Advanced Study)

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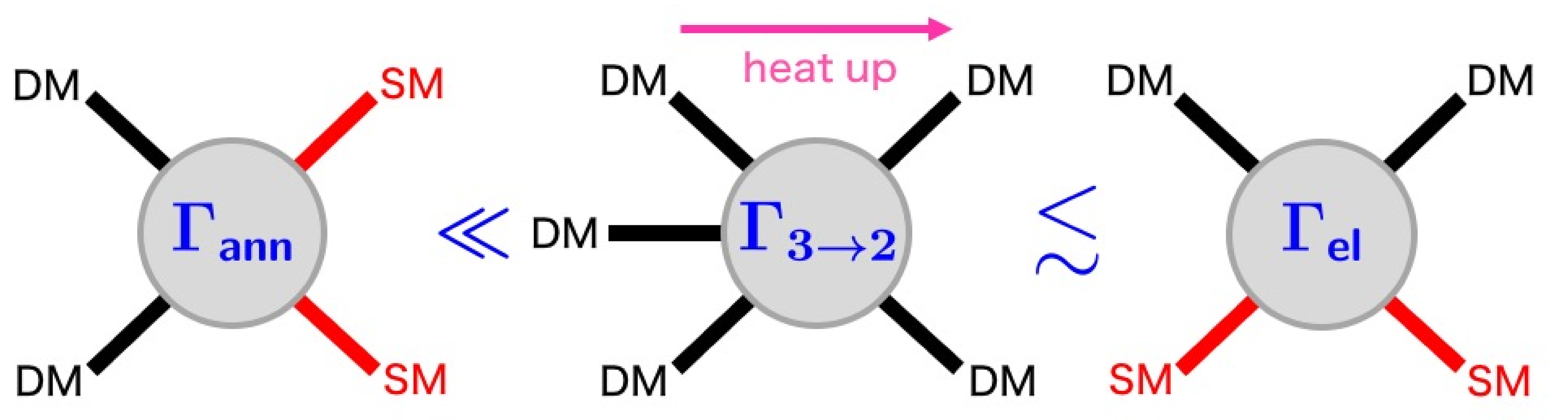
Abstract

We reanalyze the multi-component strongly interacting massive particle (mSIMP) scenario using an effective operator approach. As in the typical single-component SIMP case, the total relic abundance of mSIMP dark matter (DM) is determined by the coupling strengths of 3 to 2 processes achieved by a five-point effective operator. Interestingly, we find that there is an unavoidable 2 to 2 process induced by the corresponding five-point interaction in the dark sector, which would reshuffle the mass densities of SIMP DM after the chemical freeze-out (f.o.) of DM. We dub this DM scenario as reshuffled SIMP (rSIMP).

Strongly interacting massive particle (SIMP) DM

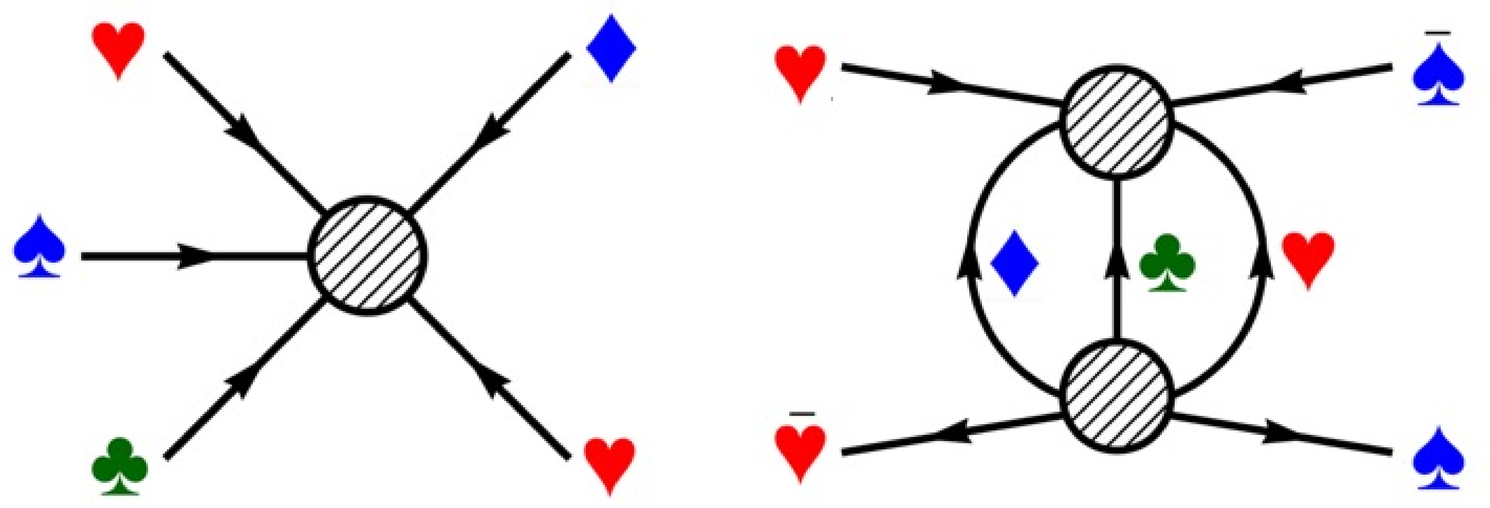


$\Gamma_{\rm ann} = n_{\rm DM}\langle\sigma_{\rm ann} v\rangle$ $\Gamma_{3\to2} = n_{\rm DM}^2\langle\sigma_{3\to2} v^2\rangle$ $\Gamma_{\rm el} = n_{\rm SM}\langle\sigma_{\rm el} v\rangle$

■ SIMP scenario : $\Gamma_{\rm el} \gtrsim \Gamma_{3\to2} \gg \Gamma_{\rm ann} > H_{\rm DM} \simeq \dfrac{m_{\rm DM}^2}{m_{\rm Pl}}$

■ $\langle\sigma v^2\rangle \equiv \dfrac{\alpha_{\rm eff}^3}{m_{\rm DM}^5} \xrightarrow{\text{fit DM relic}} \begin{array}{c}\alpha_{\rm eff} \simeq \mathcal{O}(1-10)\\ m_{\rm DM} \simeq \mathcal{O}(10-100)\ \text{MeV}\end{array}$

rSIMP scenario



number-changing process : deplete the DM yields

number-conserving process : redistribute/**reshuffle** the DM yields

■ $\dfrac{\Gamma_{3\to2}}{\Gamma_{2\to2}^{\text{2-loop}}} = \dfrac{n_{\rm DM}^2\langle\sigma v^2\rangle}{n_{\rm DM}\langle\sigma v\rangle} = \dfrac{n_{\rm DM}^2\alpha_{\rm eff}^3/m_{\rm DM}^5}{n_{\rm DM}\alpha_{\rm eff}^6/[(4\pi)^8 m_{\rm DM}^2]}$

$= \dfrac{(4\pi)^8}{\alpha_{\rm eff}^3}\dfrac{n_{\rm DM}}{m_{\rm DM}^3} \simeq \dfrac{1}{\alpha_{\rm eff}^3 x_{\rm f.o.}^3} \ll 1\,,\quad x_{\rm f.o.} = \dfrac{m_{\rm DM}}{T_{\rm f.o.}} \simeq 20$

■ rSIMP scenario : $\Gamma_{2\to2}^{\text{2-loop}} > \Gamma_{\rm el} \gtrsim \Gamma_{3\to2} \gg \Gamma_{\rm ann} > H_{\rm DM}$

Effective theory model

■ Three representative EFT models for the rSIMP scenario :

Model	Fields	$U(1)_{\rm D}$	Interaction
A	$(\heartsuit,\spadesuit)$	$(2,-3)$	$\mathcal{O}^{(5)}_{\heartsuit\spadesuit} = \dfrac{c}{3!2!\Lambda}\heartsuit^3\spadesuit^2$
B	$(\heartsuit,\diamondsuit)$	$(2,-3)$	$\mathcal{O}^{(6)}_{\heartsuit\diamondsuit} = \dfrac{c}{3!2!\Lambda^2}\heartsuit^3\overline{\diamondsuit^c}\diamondsuit$
C	$(\heartsuit,\clubsuit,\diamondsuit)$	$(1,-2,-5)$	$\mathcal{O}^{(6)}_{\heartsuit\clubsuit\diamondsuit} = \dfrac{c}{3!\Lambda^2}\heartsuit^3\bar{\clubsuit}\diamondsuit$

$\heartsuit\spadesuit$: Complex scalar $\diamondsuit\clubsuit$: Dirac fermion

Annihilation processes

Model	$n\to2$	Number-conserving/changing process
A	$2\to2$	$\heartsuit\bar\heartsuit\to\spadesuit\bar\spadesuit \quad \spadesuit\bar\spadesuit\to\heartsuit\bar\heartsuit$
	$3\to2$	$\heartsuit\heartsuit\heartsuit\to\bar\spadesuit\bar\spadesuit \quad \heartsuit\heartsuit\spadesuit\to\bar\heartsuit\bar\spadesuit \quad \heartsuit\spadesuit\spadesuit\to\bar\heartsuit\bar\heartsuit$
B	$2\to2$	$\heartsuit\bar\heartsuit\to\diamondsuit\bar\diamondsuit \quad \diamondsuit\bar\diamondsuit\to\heartsuit\bar\heartsuit$
	$3\to2$	$\heartsuit\heartsuit\heartsuit\to\bar\diamondsuit\bar\diamondsuit \quad \heartsuit\heartsuit\diamondsuit\to\bar\heartsuit\bar\diamondsuit \quad \heartsuit\diamondsuit\diamondsuit\to\bar\heartsuit\bar\heartsuit$
C	$2\to2$	$\heartsuit\bar\heartsuit\to\diamondsuit\bar\diamondsuit,\clubsuit\bar\clubsuit \quad \diamondsuit\bar\diamondsuit,\clubsuit\bar\clubsuit\to\heartsuit\bar\heartsuit \quad \diamondsuit\bar\diamondsuit\to\clubsuit\bar\clubsuit \quad \clubsuit\bar\clubsuit\to\diamondsuit\bar\diamondsuit$
	$3\to2$	$\heartsuit\heartsuit\heartsuit\to\bar\diamondsuit\clubsuit \quad \heartsuit\heartsuit\diamondsuit\to\bar\heartsuit\clubsuit \quad \heartsuit\heartsuit\bar\clubsuit\to\bar\heartsuit\diamondsuit \quad \heartsuit\diamondsuit\bar\clubsuit\to\bar\heartsuit\bar\heartsuit$

■ Model A & B : $3m_\heartsuit > 2m_{\spadesuit,\diamondsuit} > m_\heartsuit$

■ Model C : $3m_\heartsuit > m_\clubsuit + m_\diamondsuit > m_\heartsuit > |m_\clubsuit - m_\diamondsuit|$

DM-$e^\pm$ interactions

■ If the $U(1)_{\rm D}$ symmetry is gauged, it is natural to introduce vector-portal interactions between the dark sector and the SM sector after SSB as

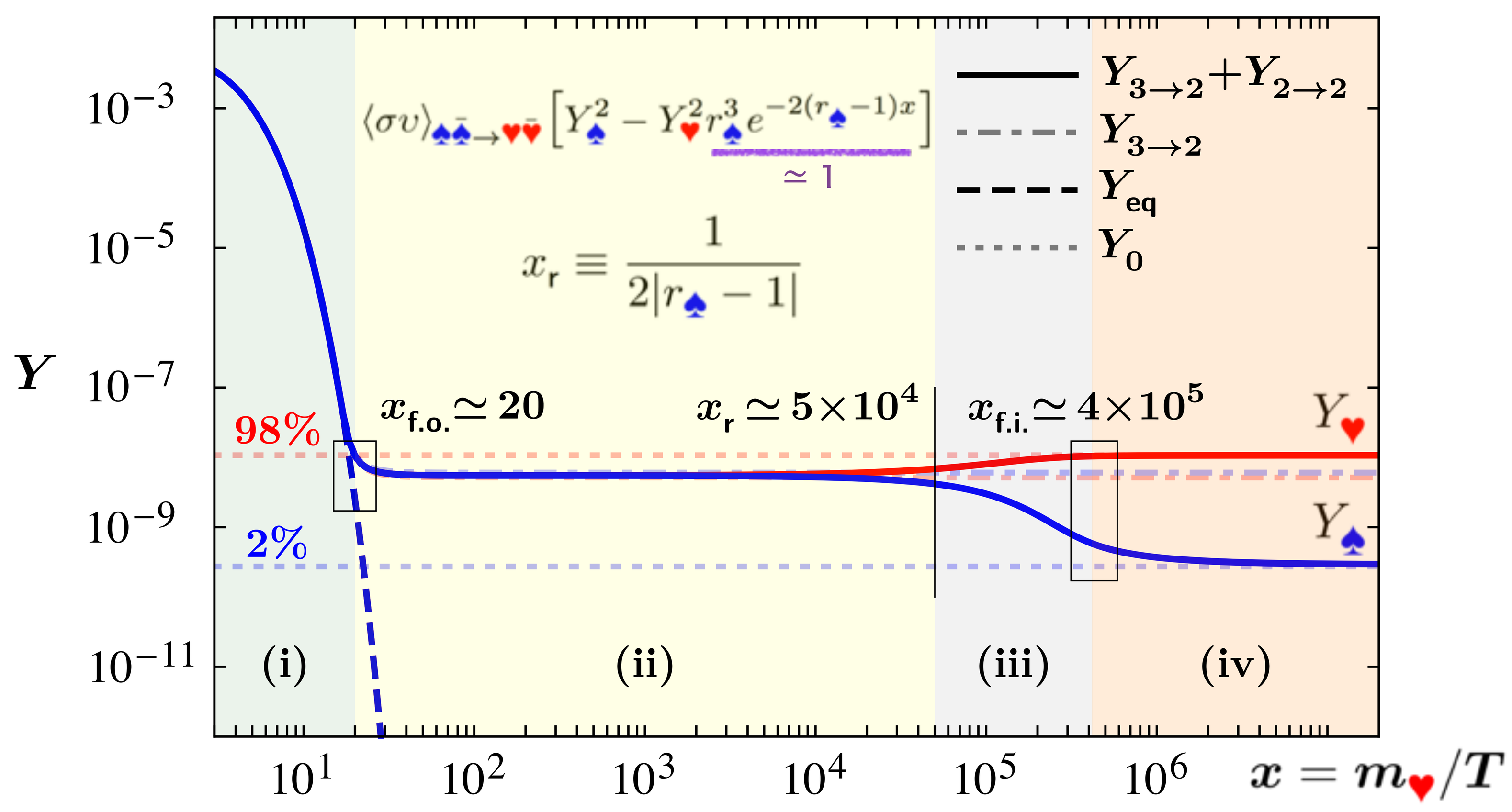
$$\mathcal{O}^{(6)}_{\phi e} = \frac{c_{\phi e}}{\Lambda_{Z'}^2}\left(i\phi^\dagger\overleftrightarrow{\partial_\mu}\phi\right)(\bar{e}\gamma^\mu e)\,,\quad \phi = \heartsuit,\spadesuit\,,$$

$$\mathcal{O}^{(6)}_{\psi e} = \frac{c_{\psi e}}{\Lambda_{Z'}^2}(\bar\psi\gamma_\mu\psi)(\bar{e}\gamma^\mu e)\,,\quad \psi = \clubsuit,\diamondsuit\,,$$

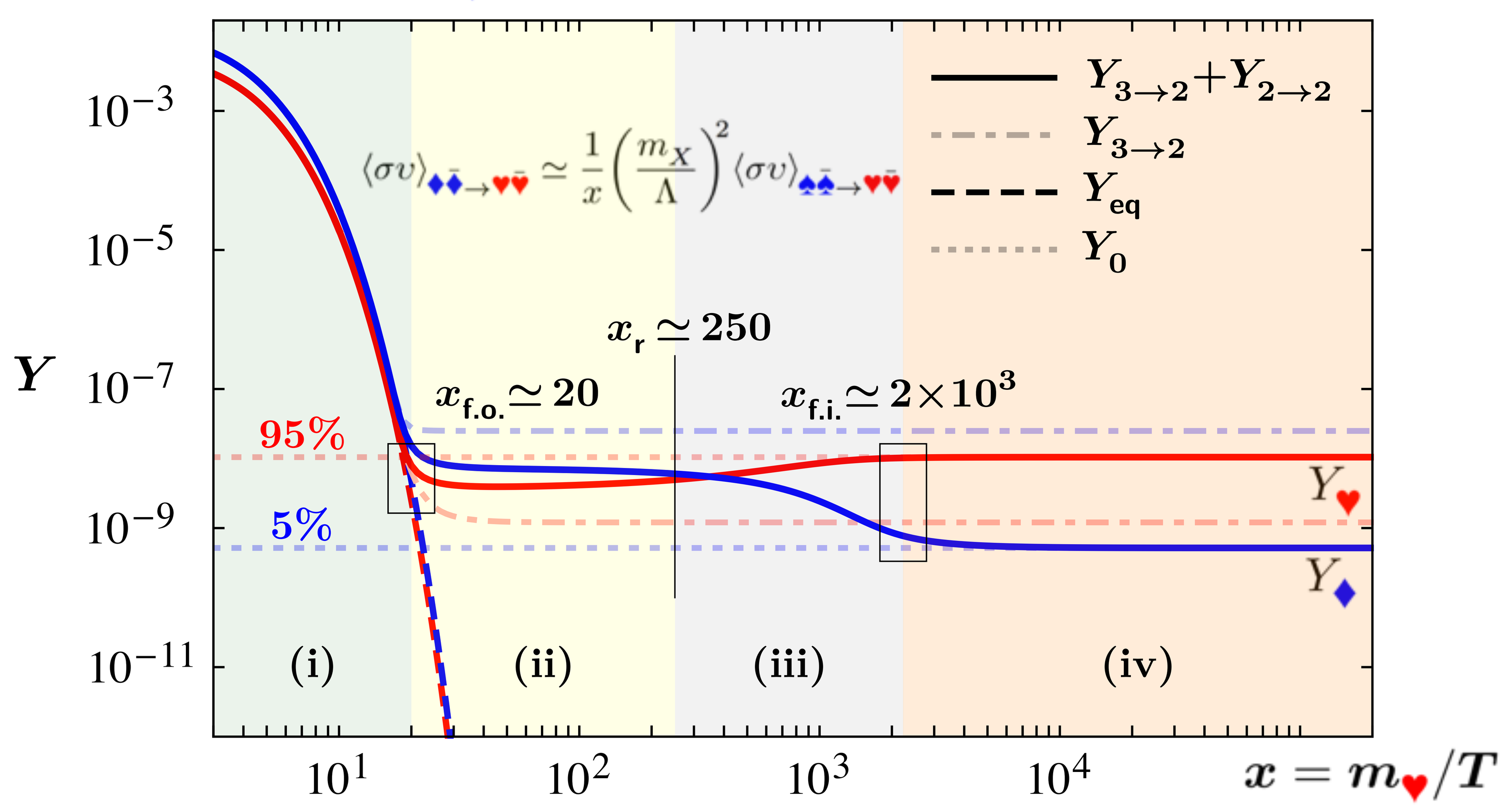
■ As we shall see below, the rSIMP masses are tens of MeV scale, we then focus on the DM and $e^\pm$ interactions.

Cosmological evolution of DM

$(m_\heartsuit, m_\spadesuit, \Lambda) = (20, 20.0002, 40)$ MeV, $c = 93$



$(m_\heartsuit, m_\diamondsuit, \Lambda) = (20, 20.04, 40)$ MeV, $c = 126$



Kinetic decoupling (k.d.) of DM

■ Momentum relaxation rate between DM and $e^\pm$: $\gamma_e(x)$

■ Kinetic equilibrium condition : $\gamma_e(x_{\rm f.o.}) \gtrsim H(x_{\rm f.o.})\,x_{\rm f.o.}^2$

■ Kinetic decoupling condition : $\gamma_e(x_{\rm k.d.}) \gtrsim 2H(x_{\rm k.d.})$

■ Kinetic temperature : $x_{\rm k.d.} \simeq x_{\rm f.o.}^{3/2}/\sqrt[4]{2} \simeq 75 < x_{\rm f.i.}$
$\Rightarrow \Gamma_{2\to2}^{\text{2-loop}} > \Gamma_{\rm el}$