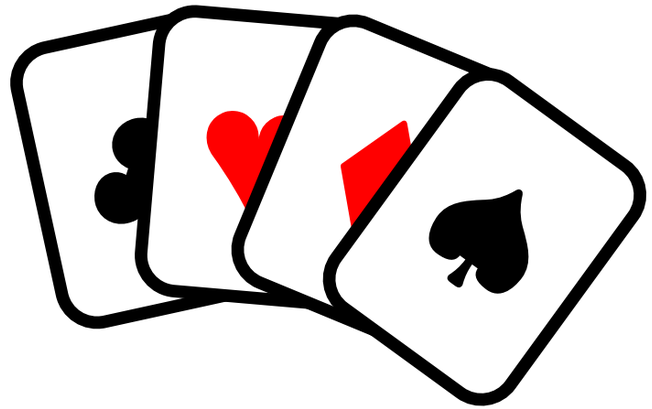
KOREA INSTITUTE FOR ADVANCED STUDY



Reshuffled SIMP Dark Matter

Shu-Yu Ho

In collaboration with Pyungwon Ko & Chih-Ting Lu (KIAS)

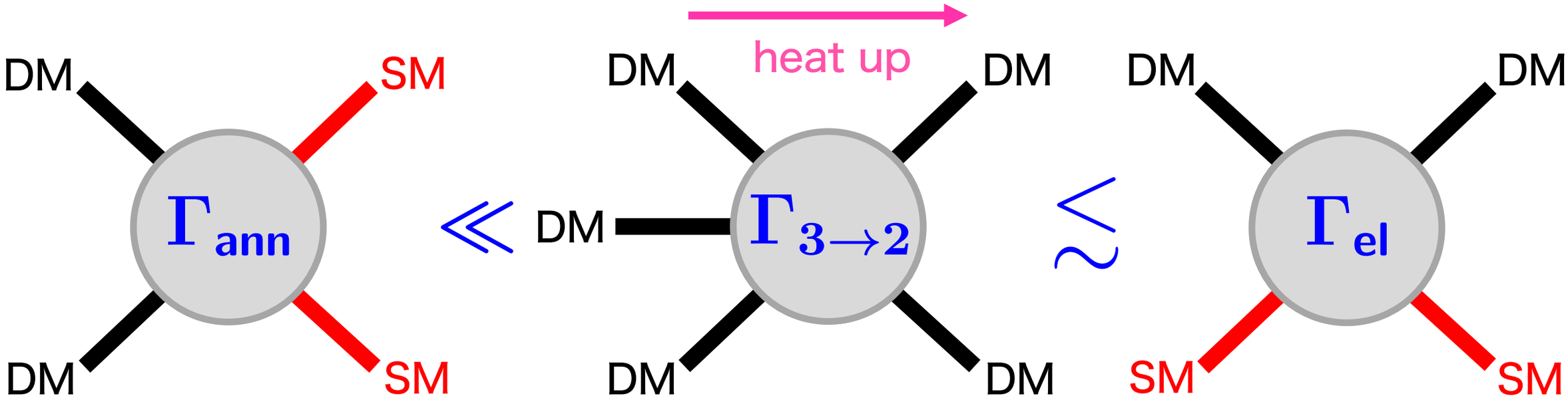
arXiv : 2107.04375

08/02/2021

Asia-Pacific Workshop on Particle Physics and Cosmology 2021

I. Introduction

Strongly interacting massive particles (SIMP)



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

SIMP scenario :

$$\Gamma_{el} \gtrsim \Gamma_{3\to2} \gg \Gamma_{ann} > H_{DM}$$

$$\langle\sigma_{3\to2}v^2\rangle \equiv \frac{\alpha_{eff}^3}{m_{DM}^5}$$

$$\alpha_{ann} \simeq 0$$

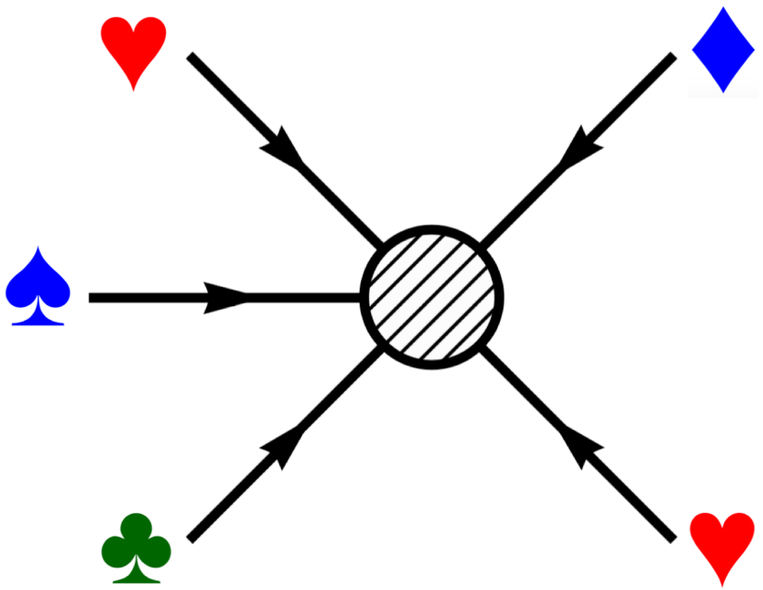
$$\alpha_{eff} \simeq 1 - 10$$

(strong scale)

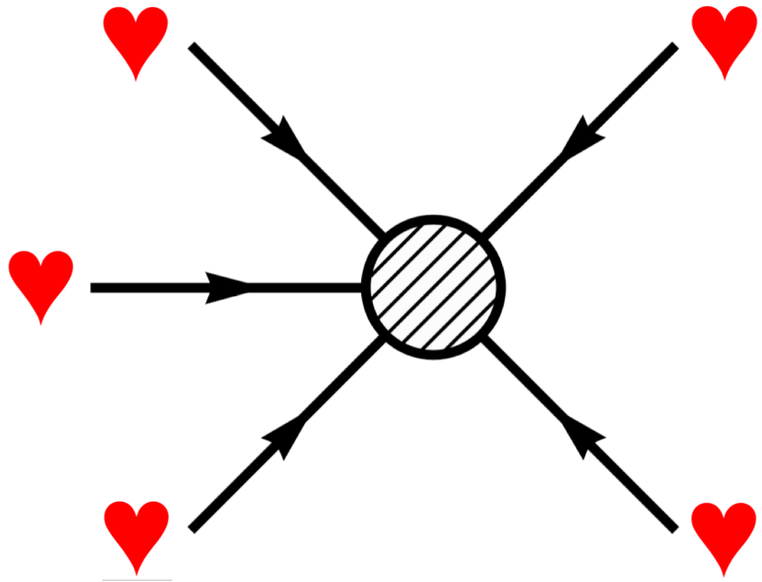
$$m_{DM} \sim 100\,\mathrm{MeV}$$

Y. Hochberg, E. Kuflik, T. Volansky & J.G. Wacker (2014)

Multi-component SIMP scenario



multi-component SIMP

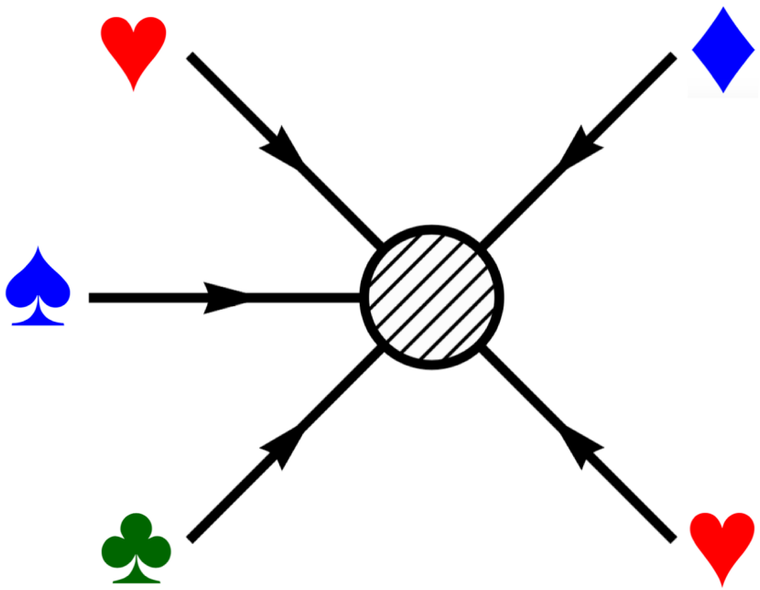


single-component SIMP

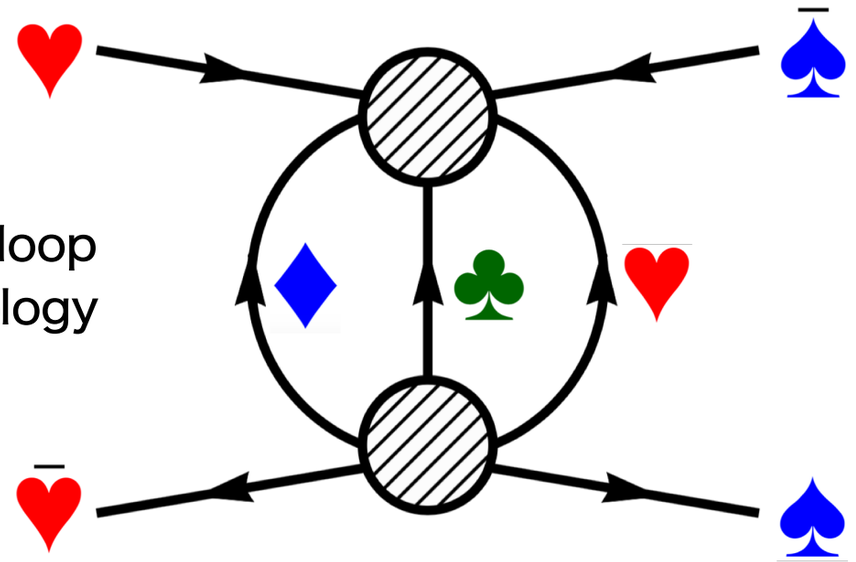
What is the difference between single-component SIMP scenario & multi-component SIMP scenario?

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario

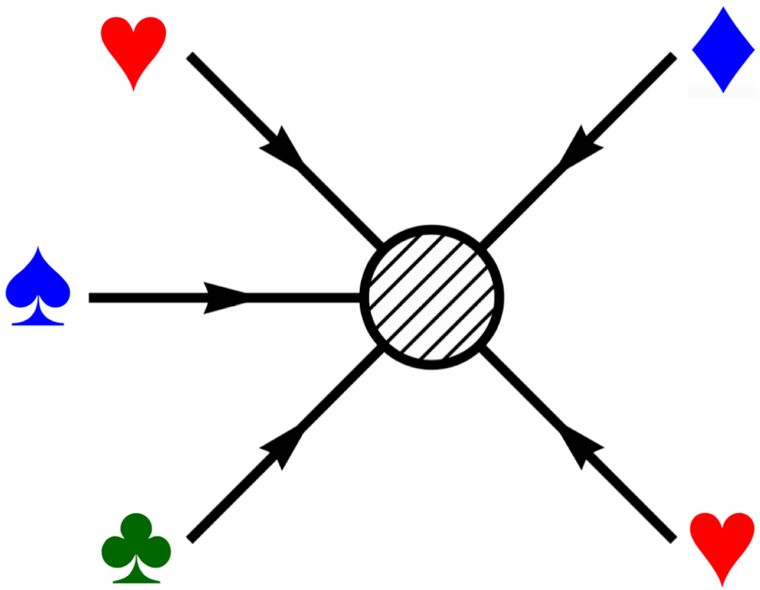


multi-component SIMP

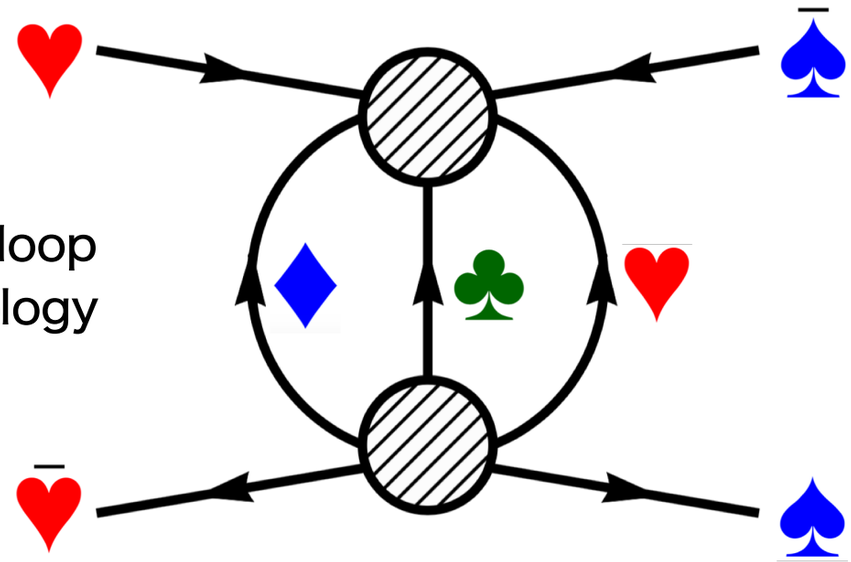


Poker notation : ♠ (spade) ♥ (heart) ♦ (diamond) ♣ (club)

Multi-component SIMP scenario



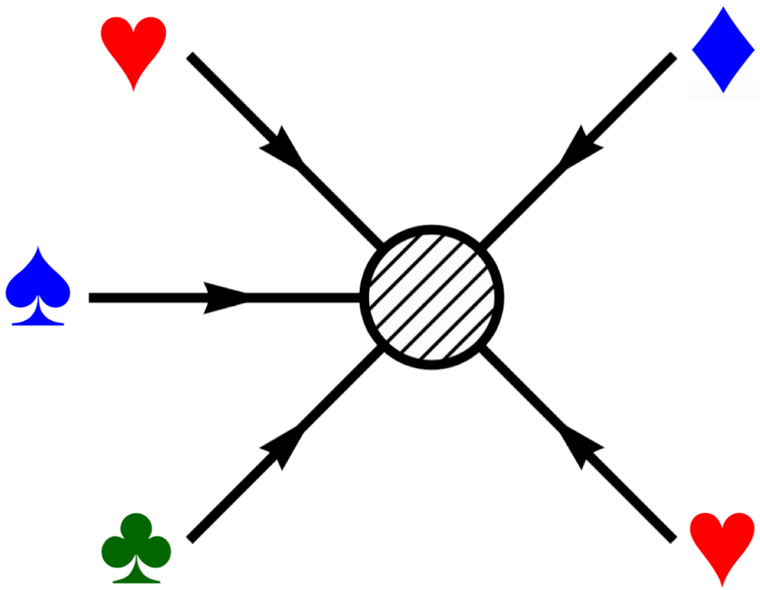
multi-component SIMP



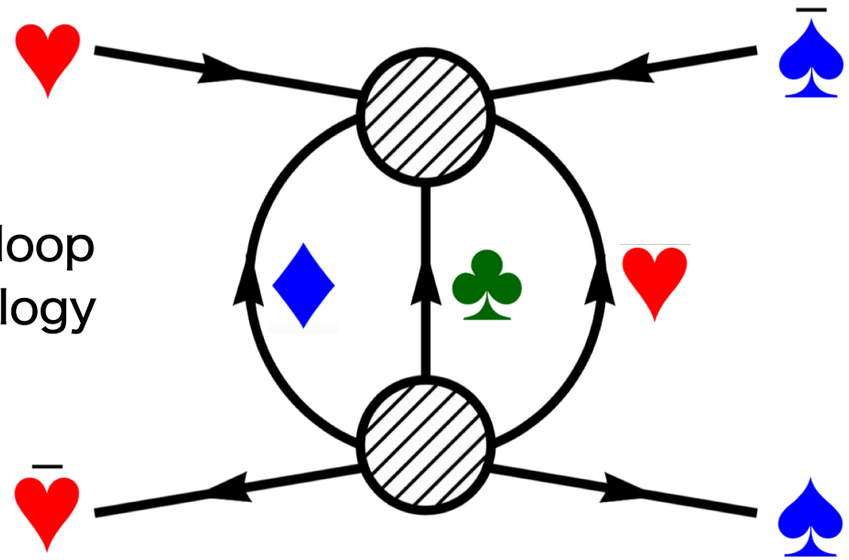
$$\Gamma_{3\to 2} \gtrless ? \quad \Gamma^{\text{2-loop}}_{2\to 2}$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



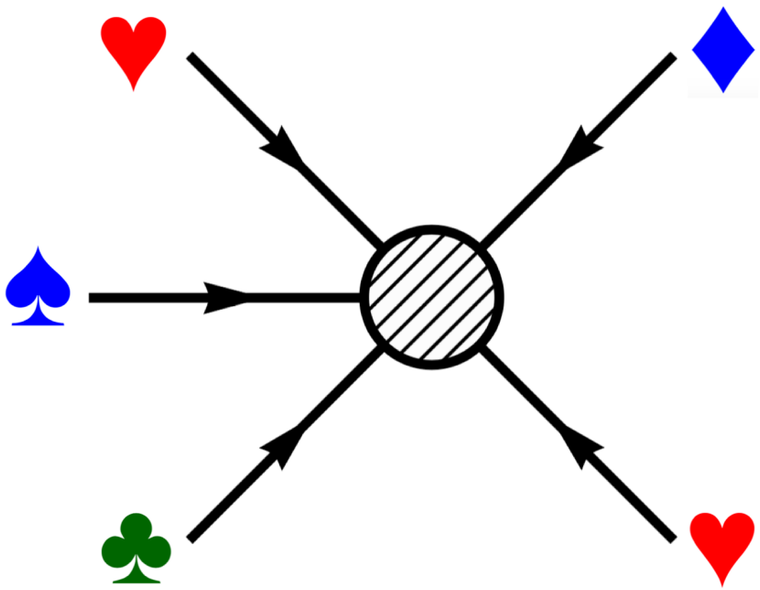
multi-component SIMP



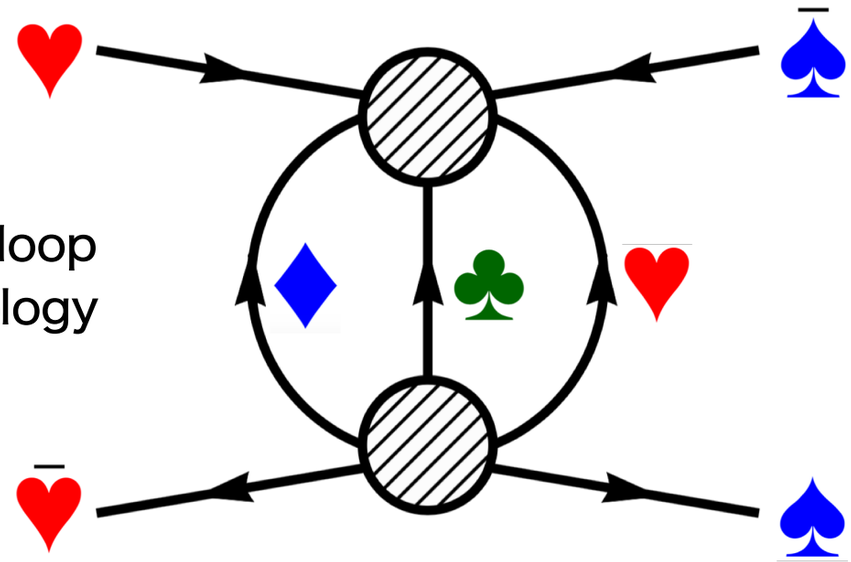
$$\left.\frac{\Gamma_{3\to 2}}{\Gamma^{\text{2-loop}}_{2\to 2}}\right|_{T=T_f} = \left.\text{——————————}\right|_{T=T_f}$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



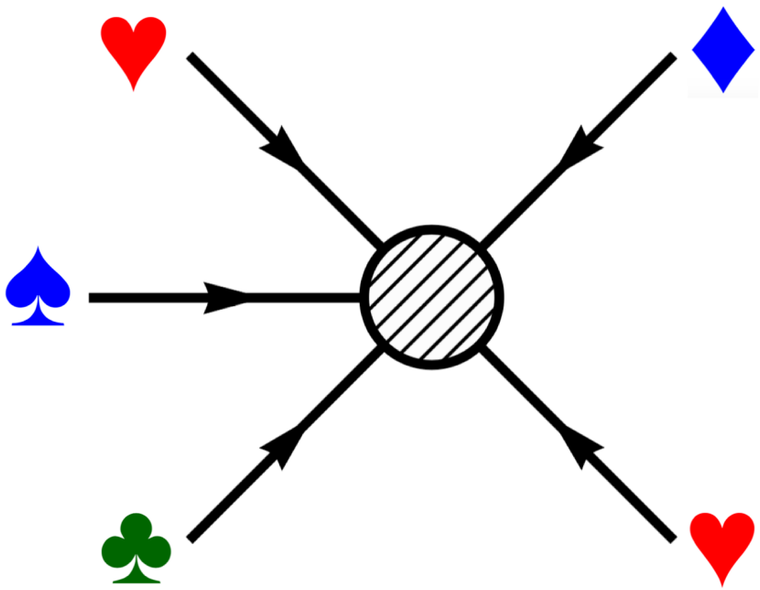
multi-component SIMP



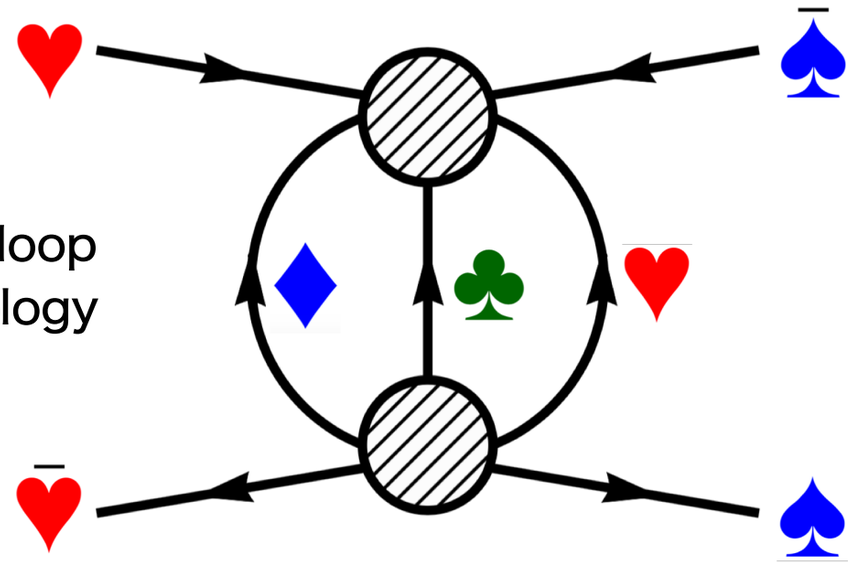
$$\left.\frac{\Gamma_{3\to2}}{\Gamma^{\text{2-loop}}_{2\to2}}\right|_{T=T_f} = \left.\frac{n^2_{\text{DM}}\langle\sigma_{3\to2}v^2\rangle}{n_{\text{DM}}\langle\sigma^{\text{2-loop}}_{2\to2}v\rangle}\right|_{T=T_f}$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



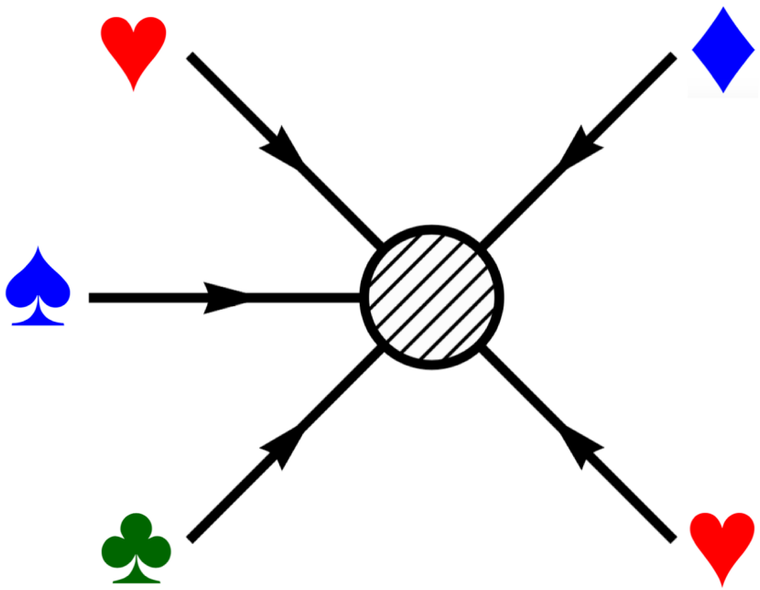
multi-component SIMP



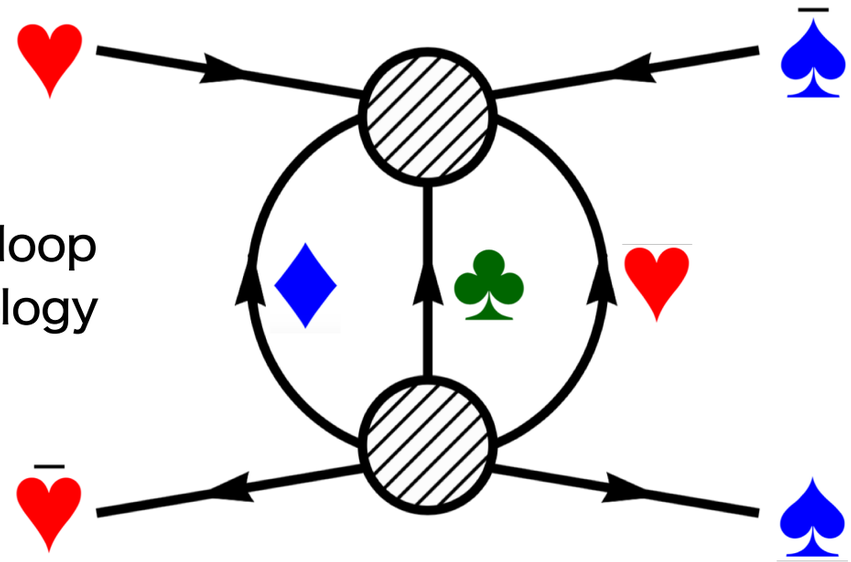
$$\left.\frac{\Gamma_{3\to 2}}{\Gamma^{\text{2-loop}}_{2\to 2}}\right|_{T=T_f} = \left.\frac{n^2_{\text{DM}}\alpha^3_{\text{eff}}/m^5_{\text{DM}}}{n_{\text{DM}}\alpha^6_{\text{eff}}/\left[(4\pi)^8 m^2_{\text{DM}}\right]}\right|_{T=T_f}$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



multi-component SIMP

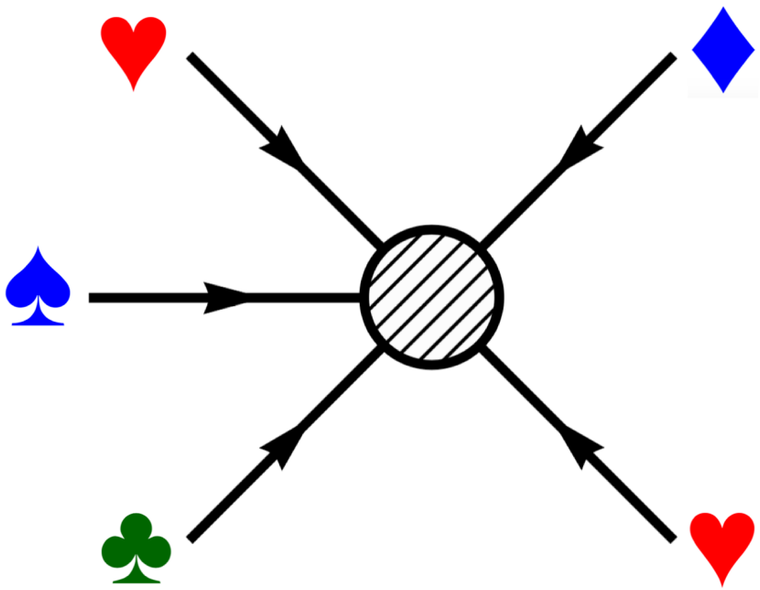


two-loop
topology

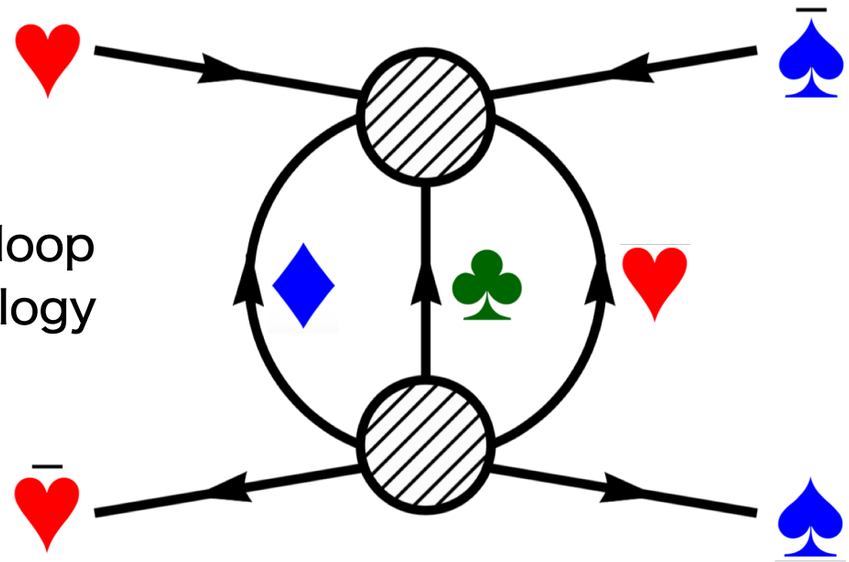
$$\left.\frac{\Gamma_{3\to 2}}{\Gamma^{\text{2-loop}}_{2\to 2}}\right|_{T=T_f} = \frac{(4\pi)^8}{\alpha_{\text{eff}}^3}\frac{n_{\text{DM}}(T_f)}{m_{\text{DM}}^3}$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



multi-component SIMP



two-loop topology

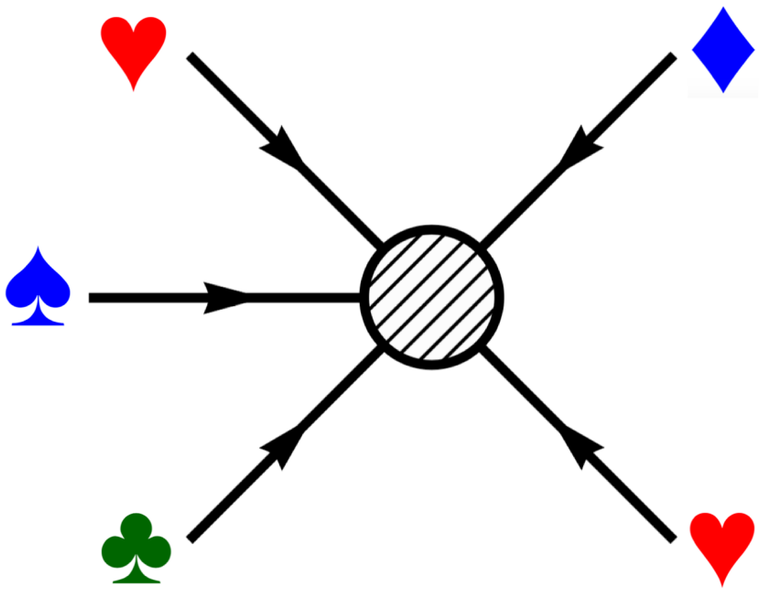
$$\left.\frac{\Gamma_{3\to2}}{\Gamma^{\text{2-loop}}_{2\to2}}\right|_{T=T_f} = \frac{(4\pi)^8}{\alpha_{\text{eff}}^3}\frac{n_{\text{DM}}(T_f)}{m_{\text{DM}}^3}$$

$$n_{\text{DM}}(T_f) \simeq \left(\frac{z_f}{2\pi}\right)^{3/2} e^{-z_f} T_f^3 \sim 10^{-8} T_f^3$$

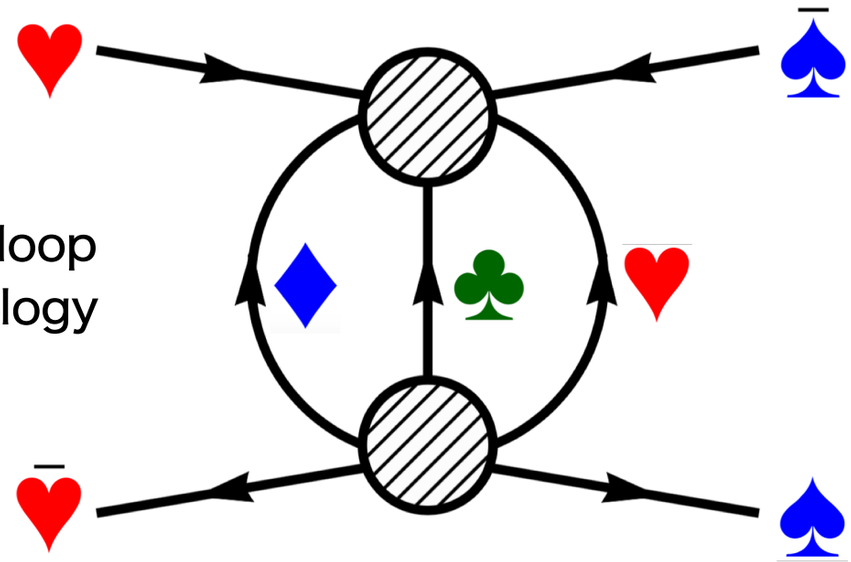
$$z_f \equiv \frac{m_{\text{DM}}}{T_f} \simeq 20$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Multi-component SIMP scenario



multi-component SIMP

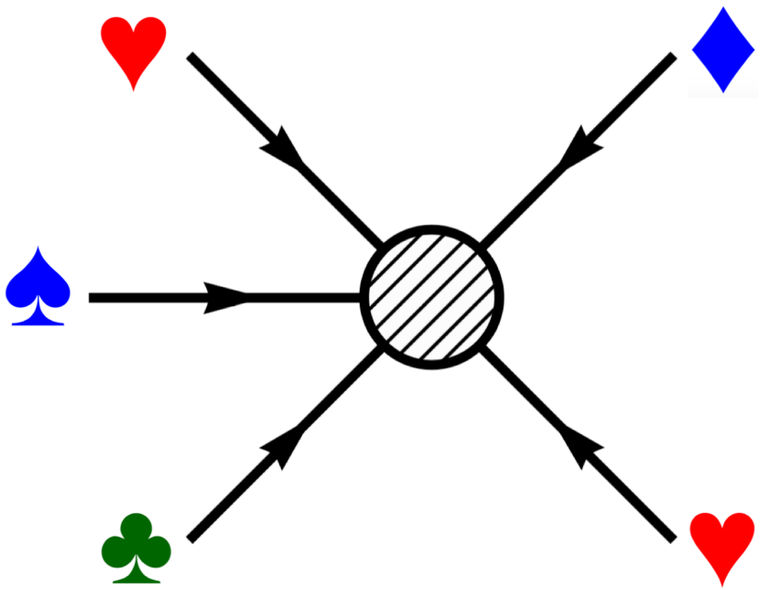


two-loop
topology

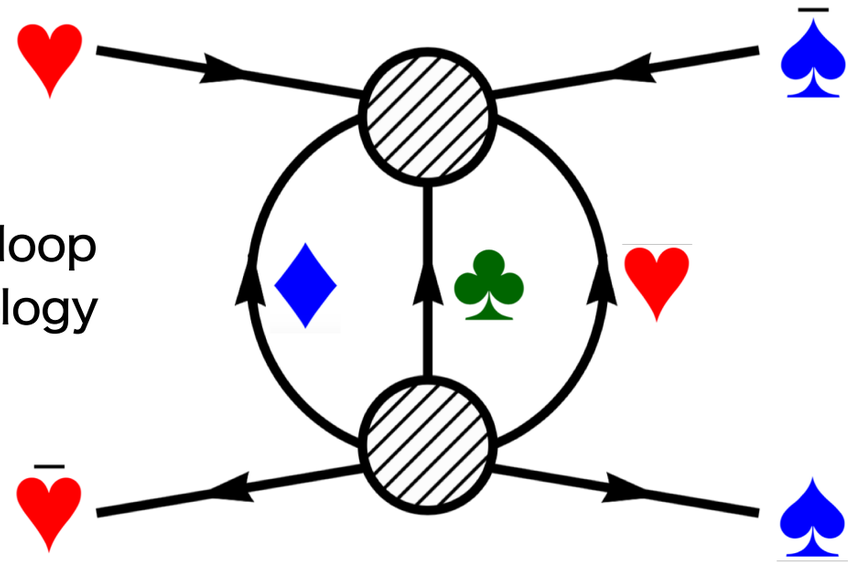
$$\left.\frac{\Gamma_{3\to 2}}{\Gamma^{\text{2-loop}}_{2\to 2}}\right|_{T=T_f} = \frac{(4\pi)^8}{\alpha_{\text{eff}}^3}\frac{n_{\text{DM}}(T_f)}{m_{\text{DM}}^3} \simeq \frac{1}{\alpha_{\text{eff}}^3 z_f^3} \ll 1 \qquad z_f \equiv \frac{m_{\text{DM}}}{T_f} \simeq 20$$

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

Reshuffled SIMP (rSIMP)



number-changing process
: deplete the DM yields



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

rSIMP scenario : $\Gamma^{\text{2-loop}}_{2\to 2} > \Gamma_{\text{el}} \gtrsim \Gamma_{3\to 2} \gg \Gamma_{\text{ann}} > H_{\text{DM}}$

will be explained later

Poker notation : ♠(spade) ♥(heart) ♦(diamond) ♣(club)

II. Effective operator

EFT Model

Three representative EFT models for the rSIMP scenario.

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

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

Annihilation process

♥♠ : S ♣♦ : F

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

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

Model	$n \to 2$	Number-conserving/changing process
A $\heartsuit^3\spadesuit^2$	$2 \to 2$	$\heartsuit\bar{\heartsuit} \to \spadesuit\bar{\spadesuit}$ $\spadesuit\bar{\spadesuit} \to \heartsuit\bar{\heartsuit}$ Two pair
	$3 \to 2$	$\heartsuit\heartsuit\heartsuit \to \bar{\spadesuit}\bar{\spadesuit}$ $\heartsuit\heartsuit\spadesuit \to \bar{\heartsuit}\bar{\spadesuit}$ $\heartsuit\spadesuit\spadesuit \to \bar{\heartsuit}\bar{\heartsuit}$ Full house
B $\heartsuit^3\overline{\diamondsuit^c}\diamondsuit$	$2 \to 2$	$\heartsuit\bar{\heartsuit} \to \diamondsuit\bar{\diamondsuit}$ $\diamondsuit\bar{\diamondsuit} \to \heartsuit\bar{\heartsuit}$
	$3 \to 2$	$\heartsuit\heartsuit\heartsuit \to \bar{\diamondsuit}\bar{\diamondsuit}$ $\heartsuit\heartsuit\diamondsuit \to \bar{\heartsuit}\bar{\diamondsuit}$ $\heartsuit\diamondsuit\diamondsuit \to \bar{\heartsuit}\bar{\heartsuit}$
C $\heartsuit^3\overline{\clubsuit}\diamondsuit$	$2 \to 2$	$\heartsuit\bar{\heartsuit} \to \diamondsuit\bar{\diamondsuit}, \clubsuit\bar{\clubsuit}$ $\diamondsuit\bar{\diamondsuit}, \clubsuit\bar{\clubsuit} \to \heartsuit\bar{\heartsuit}$ $\diamondsuit\bar{\diamondsuit} \to \clubsuit\bar{\clubsuit}$ $\clubsuit\bar{\clubsuit} \to \diamondsuit\bar{\diamondsuit}$
	$3 \to 2$	$\heartsuit\heartsuit\heartsuit \to \bar{\diamondsuit}\bar{\clubsuit}$ $\heartsuit\heartsuit\diamondsuit \to \bar{\heartsuit}\bar{\clubsuit}$ $\heartsuit\heartsuit\bar{\clubsuit} \to \bar{\heartsuit}\bar{\diamondsuit}$ $\heartsuit\diamondsuit\bar{\clubsuit} \to \bar{\heartsuit}\bar{\heartsuit}$ Three of a kind

DM-SM interaction

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

$$\overleftrightarrow{\partial_\mu} \equiv \overrightarrow{\partial_\mu} - \overleftarrow{\partial_\mu}$$

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

B. V. Lehmann & S. Profumo (2020)

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

Since the SIMP mass is tens of MeV scale, we then focus on the DM and $e^\pm$ interactions.

III. Cosmological evolution

Model A : $\heartsuit^3\spadesuit^2$

$\heartsuit\spadesuit$: s

The Boltzmann equations of comoving number yields $Y_\heartsuit$, $Y_\spadesuit$

$$\frac{dY_\heartsuit}{dx} = -\frac{s^2}{Hx}\left\{ 3\langle\sigma v^2\rangle_{\heartsuit\heartsuit\heartsuit\to\bar\spadesuit\bar\spadesuit}\left[Y_\heartsuit^3 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^3}{(Y_\spadesuit^{\rm eq})^2}\right] + \langle\sigma v^2\rangle_{\heartsuit\heartsuit\spadesuit\to\bar\heartsuit\bar\spadesuit}\left(Y_\heartsuit^2 Y_\spadesuit - Y_\heartsuit Y_\spadesuit Y_\heartsuit^{\rm eq}\right) - \langle\sigma v^2\rangle_{\heartsuit\spadesuit\spadesuit\to\bar\heartsuit\bar\heartsuit}\left[Y_\heartsuit Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{Y_\heartsuit^{\rm eq}}\right]\right\} - \frac{s}{Hx}\left\{\langle\sigma v\rangle_{\heartsuit\bar\heartsuit\to\spadesuit\bar\spadesuit}\left[Y_\heartsuit^2 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^2}{(Y_\spadesuit^{\rm eq})^2}\right] - \langle\sigma v\rangle_{\spadesuit\bar\spadesuit\to\heartsuit\bar\heartsuit}\left[Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{(Y_\heartsuit^{\rm eq})^2}\right]\right\}$$

$$\frac{dY_\spadesuit}{dx} = -\frac{s^2}{Hx}\left\{ 2\langle\sigma v^2\rangle_{\heartsuit\spadesuit\spadesuit\to\bar\heartsuit\bar\heartsuit}\left[Y_\heartsuit Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{Y_\heartsuit^{\rm eq}}\right] - 2\langle\sigma v^2\rangle_{\heartsuit\heartsuit\heartsuit\to\bar\spadesuit\bar\spadesuit}\left[Y_\heartsuit^3 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^3}{(Y_\spadesuit^{\rm eq})^2}\right]\right\} - \frac{s}{Hx}\left\{\langle\sigma v\rangle_{\spadesuit\bar\spadesuit\to\heartsuit\bar\heartsuit}\left[Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{(Y_\heartsuit^{\rm eq})^2}\right] - \langle\sigma v\rangle_{\heartsuit\bar\heartsuit\to\spadesuit\bar\spadesuit}\left[Y_\heartsuit^2 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^2}{(Y_\spadesuit^{\rm eq})^2}\right]\right\}$$

s : entropy density H : Hubble parameter

$$x \equiv \frac{m_\heartsuit}{T} \qquad Y_j^{\rm eq} = \frac{45\sqrt{2}}{8\pi^{7/2}}\frac{g_j}{g_{\star s}(x)}(r_j x)^{3/2}e^{-r_j x} \qquad r_j \equiv \frac{m_j}{m_\heartsuit}$$

Model A : $\heartsuit^3\spadesuit^2$

$\heartsuit\spadesuit$: S

The Boltzmann equations of comoving number yields $Y_\heartsuit$, $Y_\spadesuit$

$$\frac{dY_\heartsuit}{dx} = -\frac{s^2}{Hx}\Bigg\{ 3\langle\sigma v^2\rangle_{\heartsuit\heartsuit\heartsuit\to\bar\spadesuit\bar\spadesuit}\left[Y_\heartsuit^3 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^3}{(Y_\spadesuit^{\rm eq})^2}\right] + \langle\sigma v^2\rangle_{\heartsuit\heartsuit\spadesuit\to\bar\heartsuit\bar\spadesuit}\left(Y_\heartsuit^2 Y_\spadesuit - Y_\heartsuit Y_\spadesuit Y_\heartsuit^{\rm eq}\right) - \langle\sigma v^2\rangle_{\heartsuit\spadesuit\spadesuit\to\bar\heartsuit\bar\heartsuit}\left[Y_\heartsuit Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{Y_\heartsuit^{\rm eq}}\right]\Bigg\}$$

$$-\frac{s}{Hx}\Bigg\{ \langle\sigma v\rangle_{\heartsuit\bar\heartsuit\to\spadesuit\bar\spadesuit}\left[Y_\heartsuit^2 - Y_\spadesuit^2\frac{(Y_\heartsuit^{\rm eq})^2}{(Y_\spadesuit^{\rm eq})^2}\right] - \langle\sigma v\rangle_{\spadesuit\bar\spadesuit\to\heartsuit\bar\heartsuit}\left[Y_\spadesuit^2 - Y_\heartsuit^2\frac{(Y_\spadesuit^{\rm eq})^2}{(Y_\heartsuit^{\rm eq})^2}\right]\Bigg\}$$

two-loop function (sunset diagram)

$$\mathcal{I}(t) \approx 1 + \frac{1}{2t^2}\left[4 - 3\ln t^2 - \frac{3}{2}(\ln t^2)^2\right]$$

J. F. Yang, J. Zhou & C. Wu (2003)

$$\langle\sigma v^2\rangle_{\heartsuit\heartsuit\heartsuit\to\bar\spadesuit\bar\spadesuit} = \frac{c^2(m_\heartsuit/\Lambda)^2}{2304\pi m_\heartsuit^5}\sqrt{9-4r_\spadesuit^2}$$

$$\langle\sigma v^2\rangle_{\heartsuit\heartsuit\spadesuit\to\bar\heartsuit\bar\spadesuit} = \frac{\sqrt{3}c^2(m_\heartsuit/\Lambda)^2}{128\pi m_\heartsuit^5}\frac{\sqrt{4r_\spadesuit^2+8r_\spadesuit+3}}{r_\spadesuit(r_\spadesuit+2)^2}$$

$$\langle\sigma v^2\rangle_{\heartsuit\spadesuit\spadesuit\to\bar\heartsuit\bar\heartsuit} = \frac{c^2(m_\heartsuit/\Lambda)^2}{256\pi m_\heartsuit^5}\frac{\sqrt{4r_\spadesuit^2+4r_\spadesuit-3}}{r_\spadesuit^2(2r_\spadesuit+1)}$$

$$\langle\sigma v\rangle_{\heartsuit\bar\heartsuit\to\spadesuit\bar\spadesuit} = \frac{c^4}{32\pi(4\pi)^8 m_\heartsuit^2}\mathcal{I}^2\left(\frac{\Lambda}{m_\heartsuit}\right)\sqrt{1-r_\spadesuit^2}$$

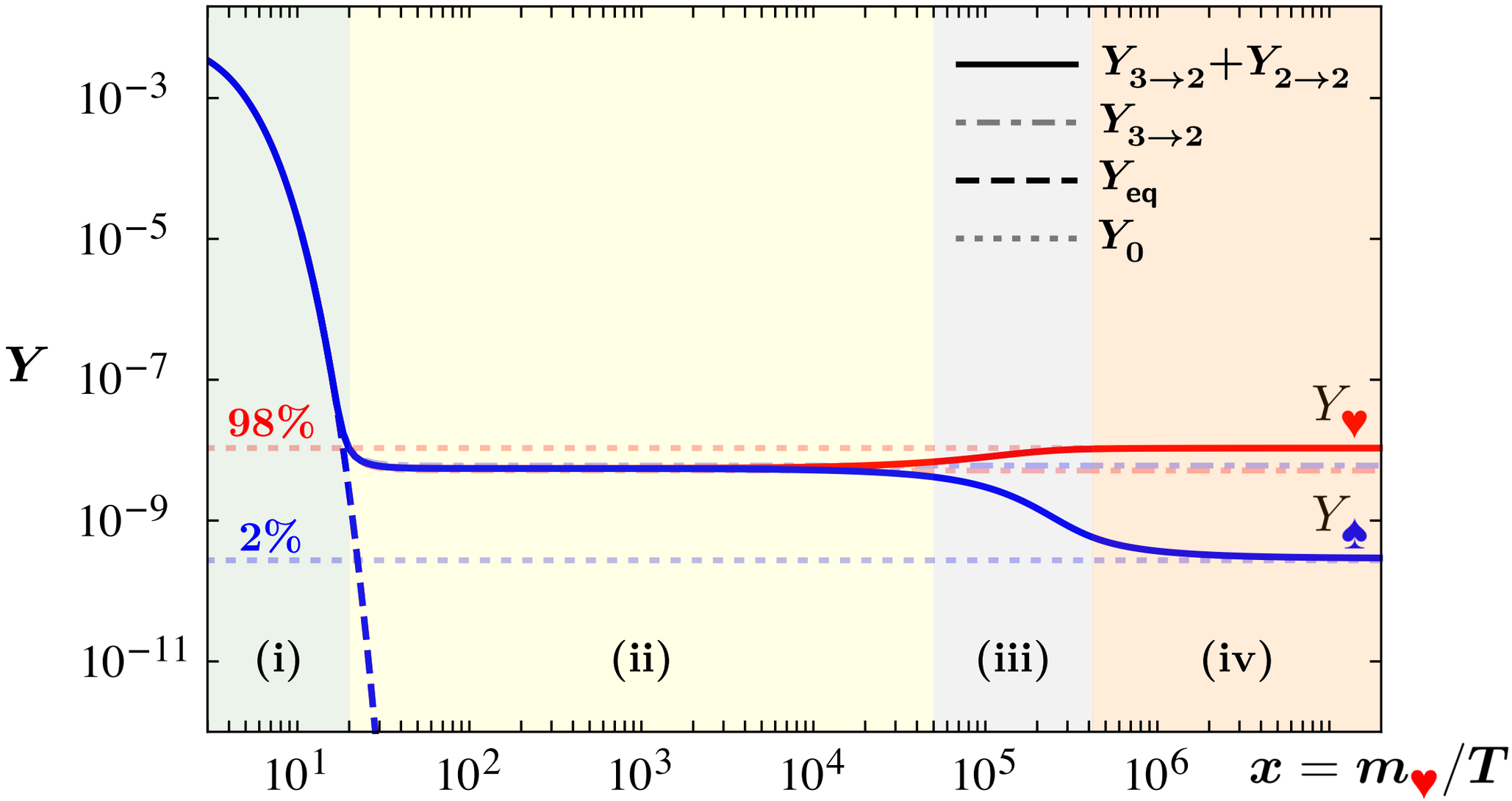
$$\langle\sigma v\rangle_{\spadesuit\bar\spadesuit\to\heartsuit\bar\heartsuit} = \frac{c^4}{32\pi(4\pi)^8 m_\heartsuit^2}\mathcal{I}^2\left(\frac{\Lambda}{m_\heartsuit}\right)\frac{\sqrt{r_\spadesuit^2-1}}{r_\spadesuit^3}$$

$$\Lambda \gtrsim m_{\heartsuit,\spadesuit}$$

Model A : ♥^{3}♠^{2}

♥♠ : S

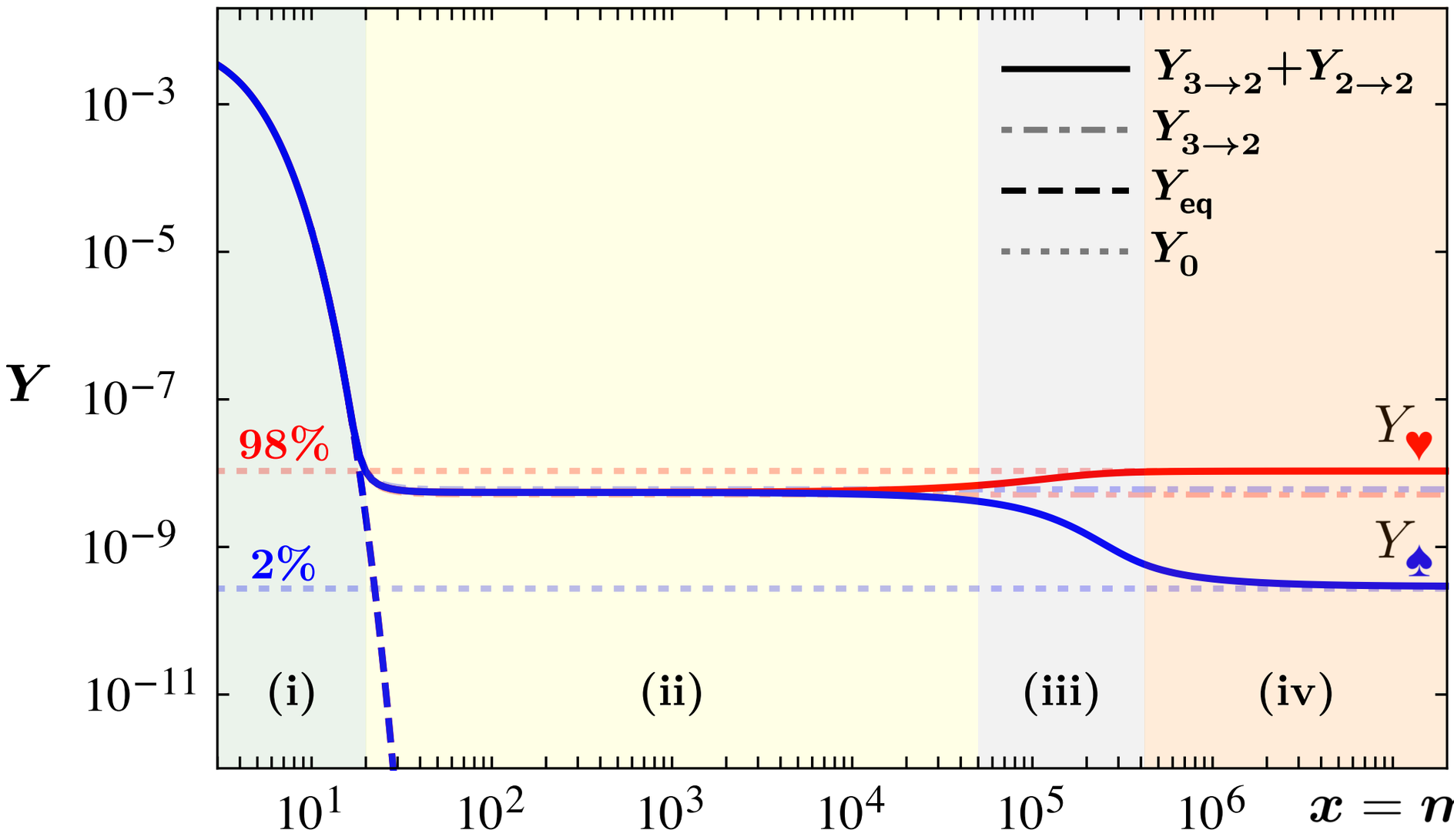
$(m_{\heartsuit}, m_{\spadesuit}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



Model A : ♥^{3}♠^{2}

♥♠ : S

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$

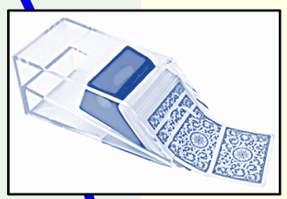


(i)
chemical
equilibrium
$\Gamma_{3\to2} \gg H$

Model A : ♥^{3}♠^{2}

♥♠ : S

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



chemical freeze-out

$\Gamma_{3\to 2} \simeq H$

$Y_{3\to 2}+Y_{2\to 2}$

$Y_{3\to 2}$

Y_{eq}

Y_0

Y

10^{-3}

10^{-5}

10^{-7}

10^{-9}

10^{-11}

98%

2%

$x_{\mathrm{f.o.}} \simeq 20$

$Y_{♥}$

$Y_{♠}$

(i) (ii) (iii) (iv)

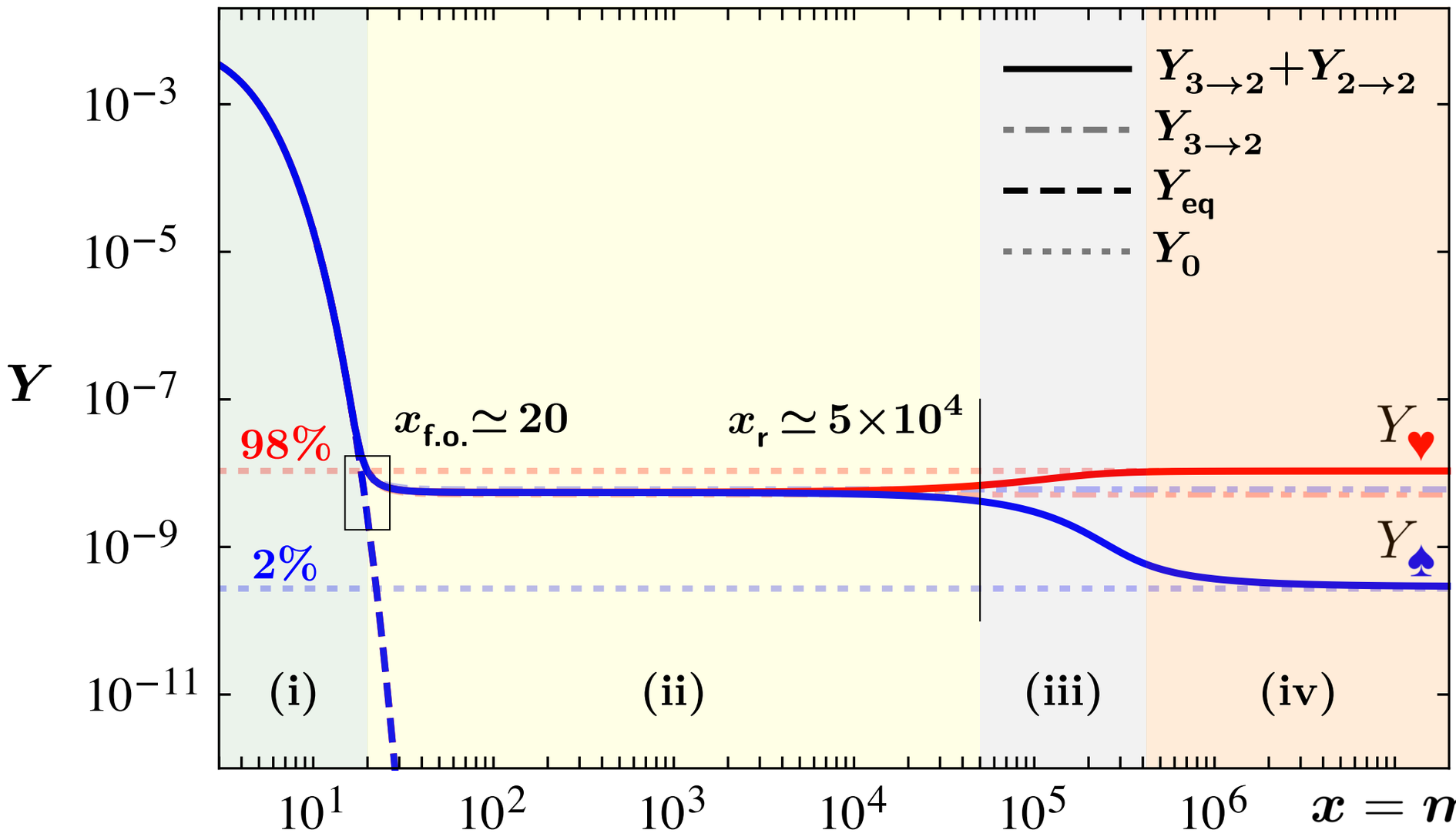
10^1 10^2 10^3 10^4 10^5 10^6 $x = m_{♥}/T$

(i)
chemical
equilibrium

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



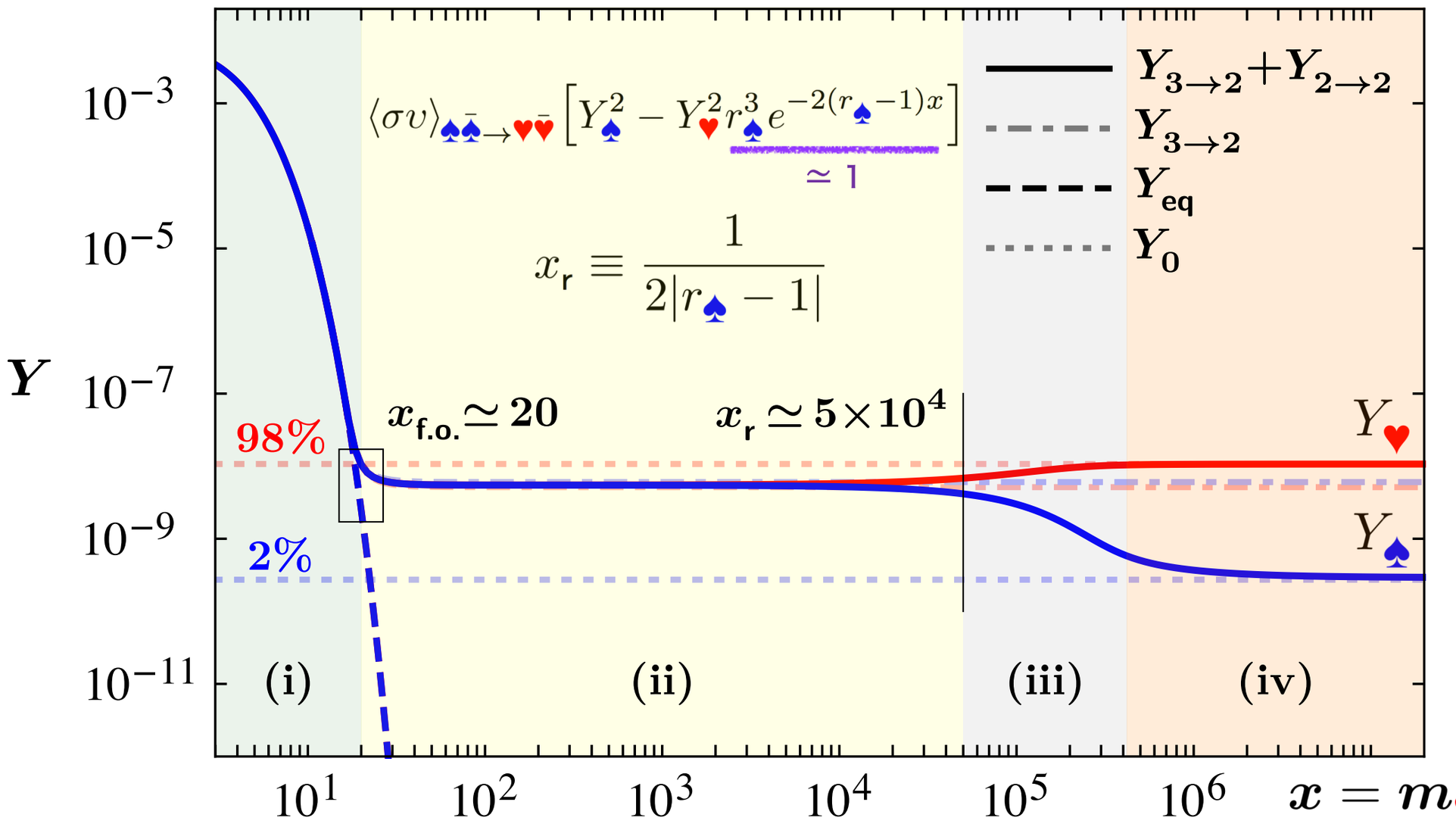
(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



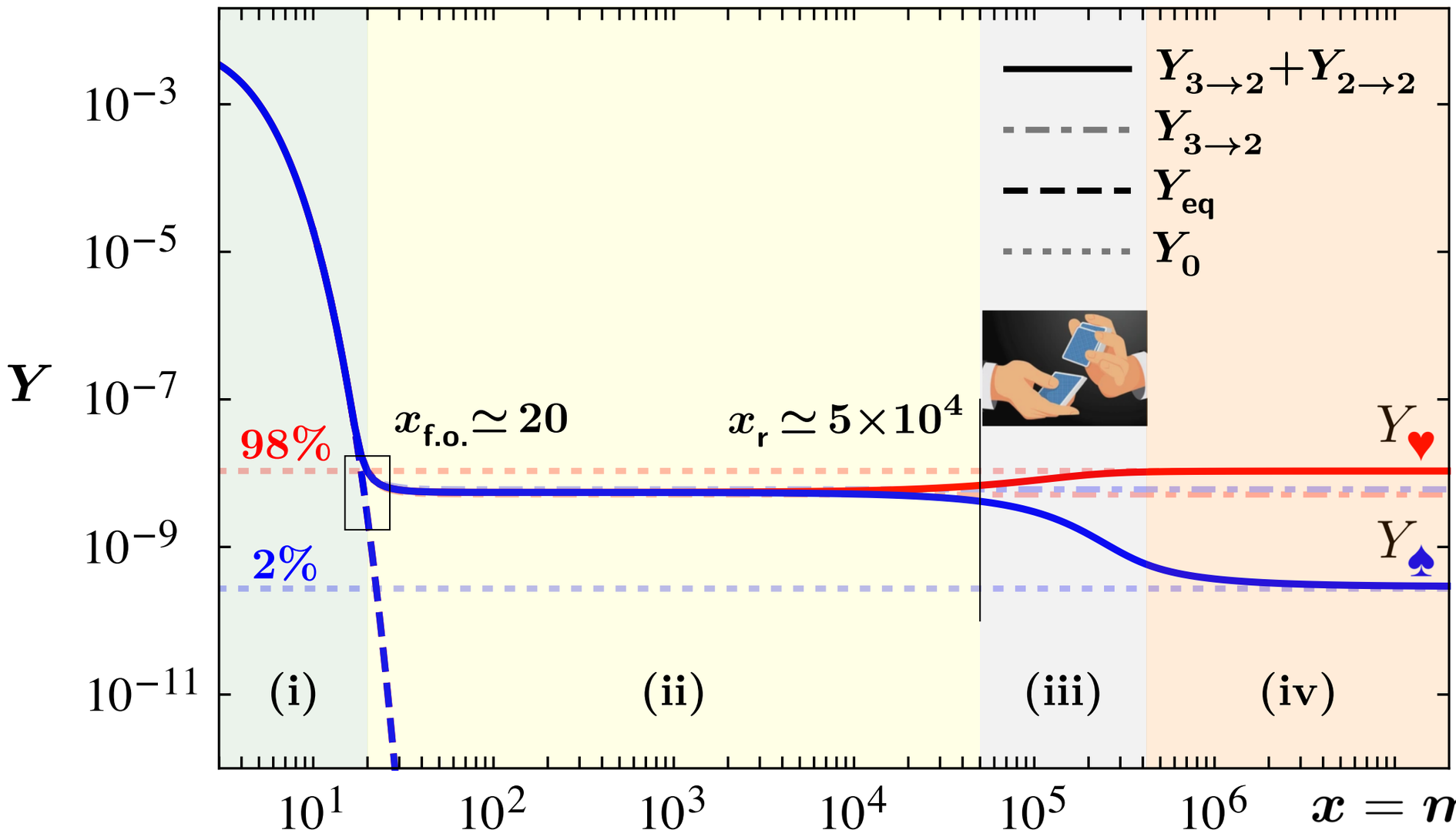
(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



(i) chemical equilibrium

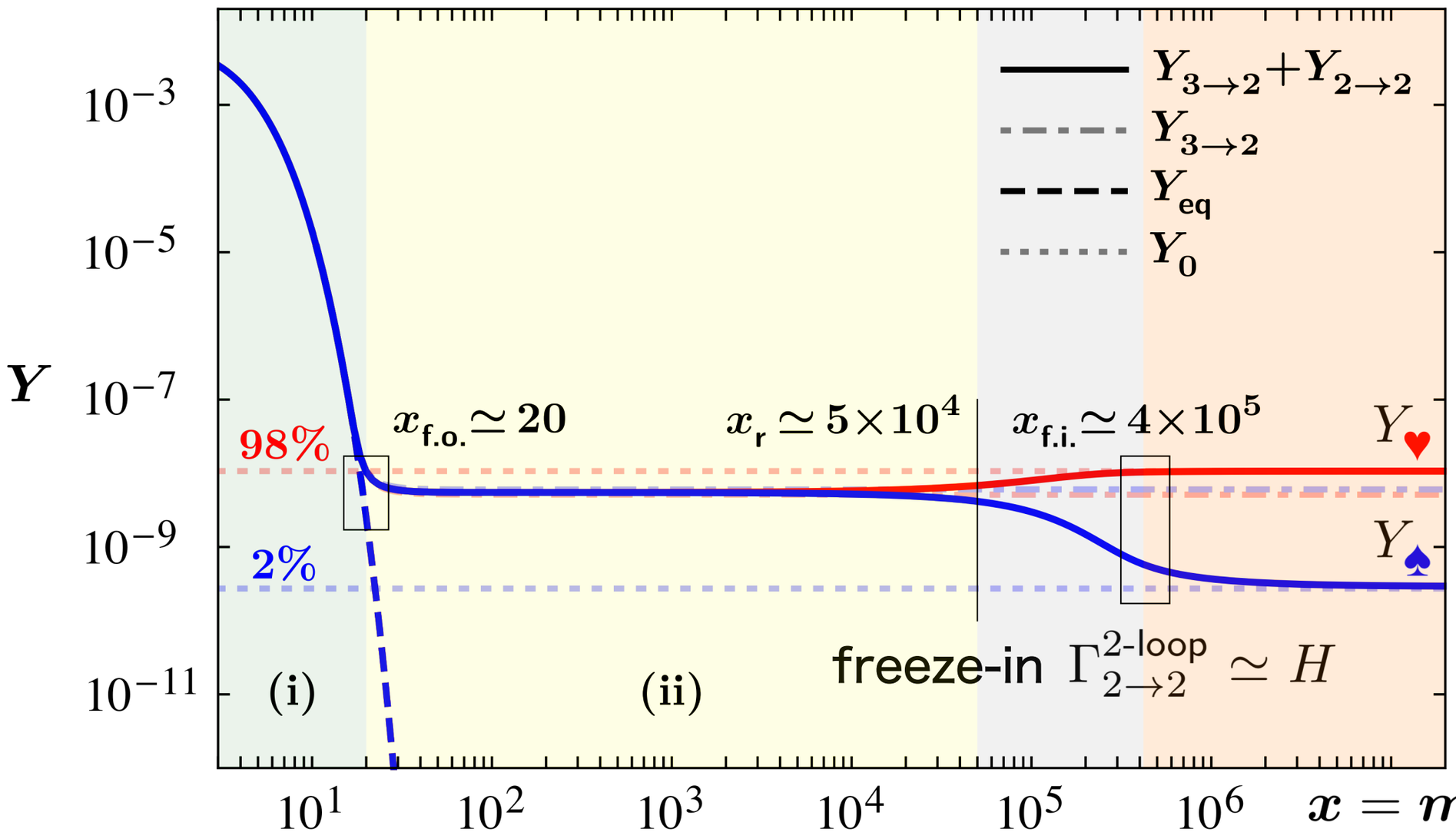
(ii) $2 \to 2$ hibernation

(iii) reshuffled period

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



(i) chemical equilibrium

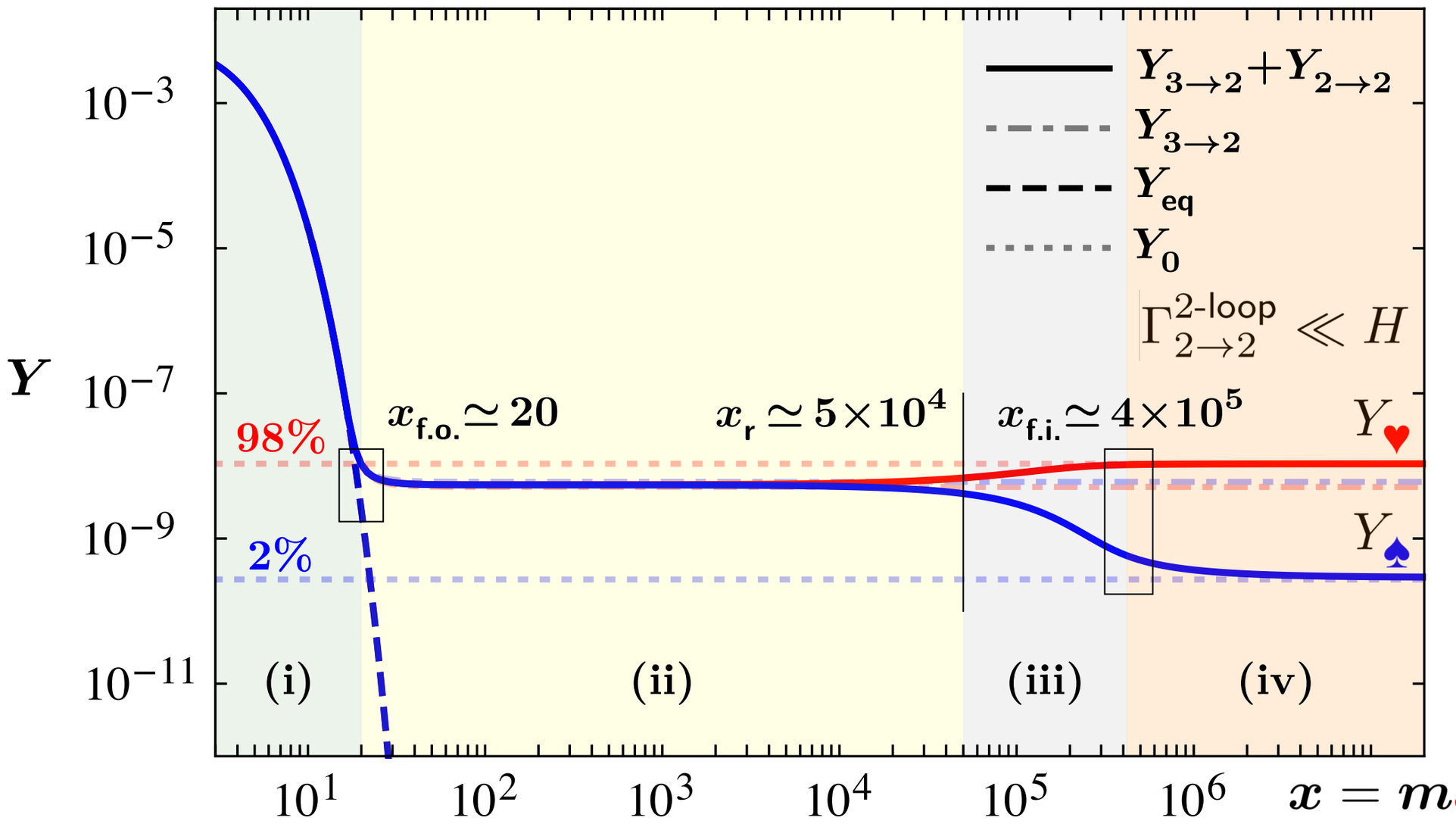
(ii) $2 \to 2$ hibernation

(iii) reshuffled period

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 20.0002, 40)\,\mathrm{MeV},\ c = 93$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

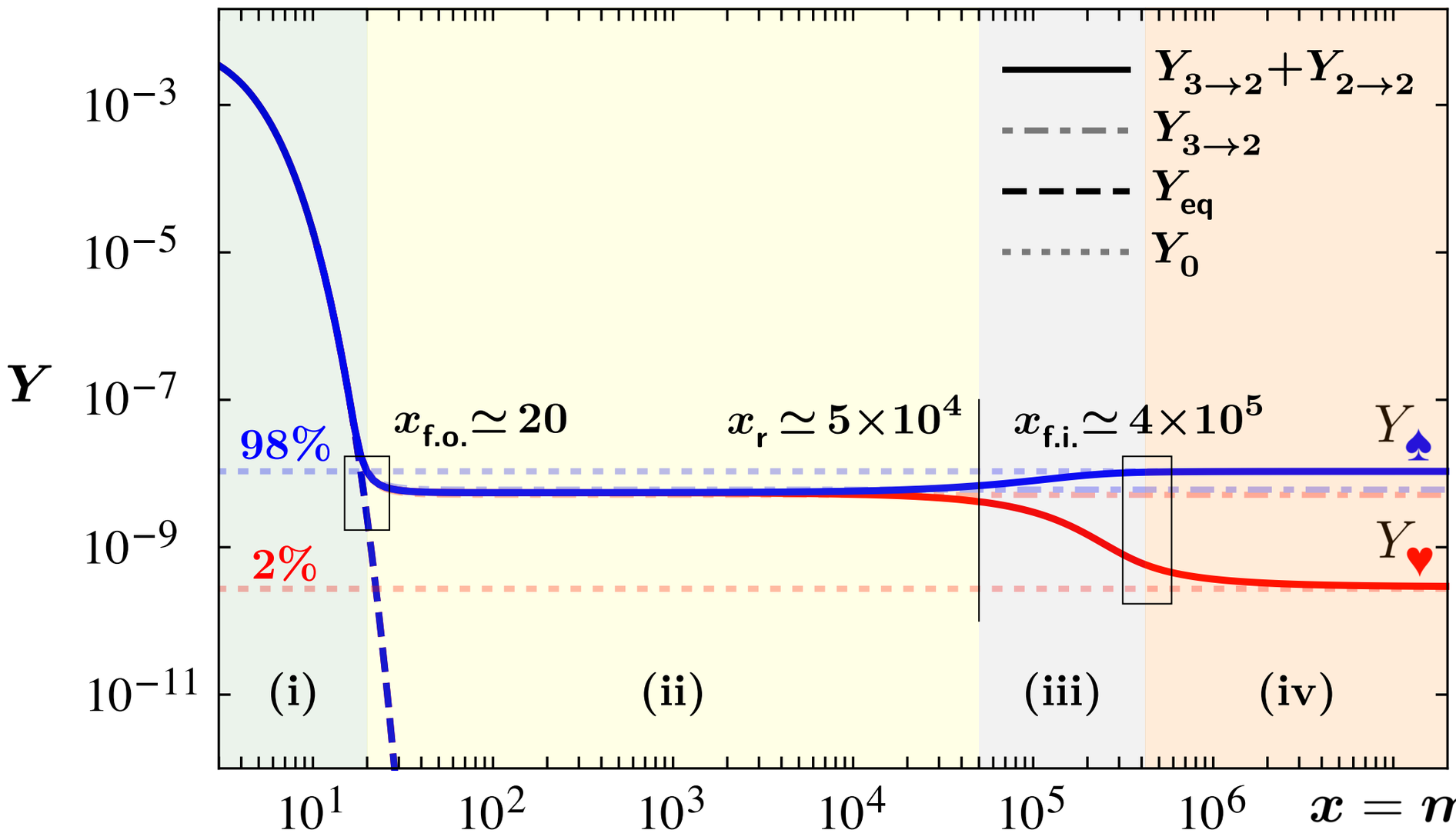
(iii) reshuffled period

(iv) frozen

Model A : ♥^{3}♠^{2}

♥♠ : s

$(m_{♥}, m_{♠}, \Lambda) = (20, 19.9998, 40)\,\mathrm{MeV}, c = 93$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

(iii) reshuffled period

(iv) frozen

Model B : ♥^{3} $\overline{♦^c}$ ♦

♥ : S ♦ : F

The 3 to 2 annihilation cross-sections w/ degenerate masses

$$\langle\sigma v^2\rangle_{♥♥♥\to\bar{♦}\bar{♦}} = \frac{\sqrt{5}c^2(m_♥/\Lambda)^4}{4608\pi m_♥^5}\left(5+\frac{18}{x}+\frac{12}{x^2}\right)$$

SO(9) inv. form

$\eta \equiv \frac{1}{2}(v_1^2+v_2^2+v_3^2)$

S. M. Choi, H. M. Lee & M. S. Seo (2017)

$$\langle\sigma v^2\rangle_{♥♥♦\to\bar{♥}\bar{♦}} = \frac{\sqrt{5}c^2(m_♥/\Lambda)^4}{768\pi m_♥^5}\left(5+\frac{6}{x}+\frac{4}{x^2}\right)$$

$$\langle\sigma v^2\rangle_{♥♦♦\to\bar{♥}\bar{♥}} = \frac{\sqrt{5}c^2(m_♥/\Lambda)^4}{768\pi m_♥^5}\left(\frac{3}{x}+\frac{2}{x^2}\right)$$

The 2 to 2 annihilation cross-sections

p-wave dominate

$$\langle\sigma v\rangle_{♥\bar{♥}\to♦\bar{♦}} = \frac{c^4(m_♥/\Lambda)^4}{16\pi(4\pi)^8 m_♥^2}\mathcal{I}^2\left(\frac{\Lambda}{m_♥}\right)\sqrt{1-r_♦^2}\times\left[1-r_♦^2+\frac{3}{4x}(5r_♦^2-2)\right]$$

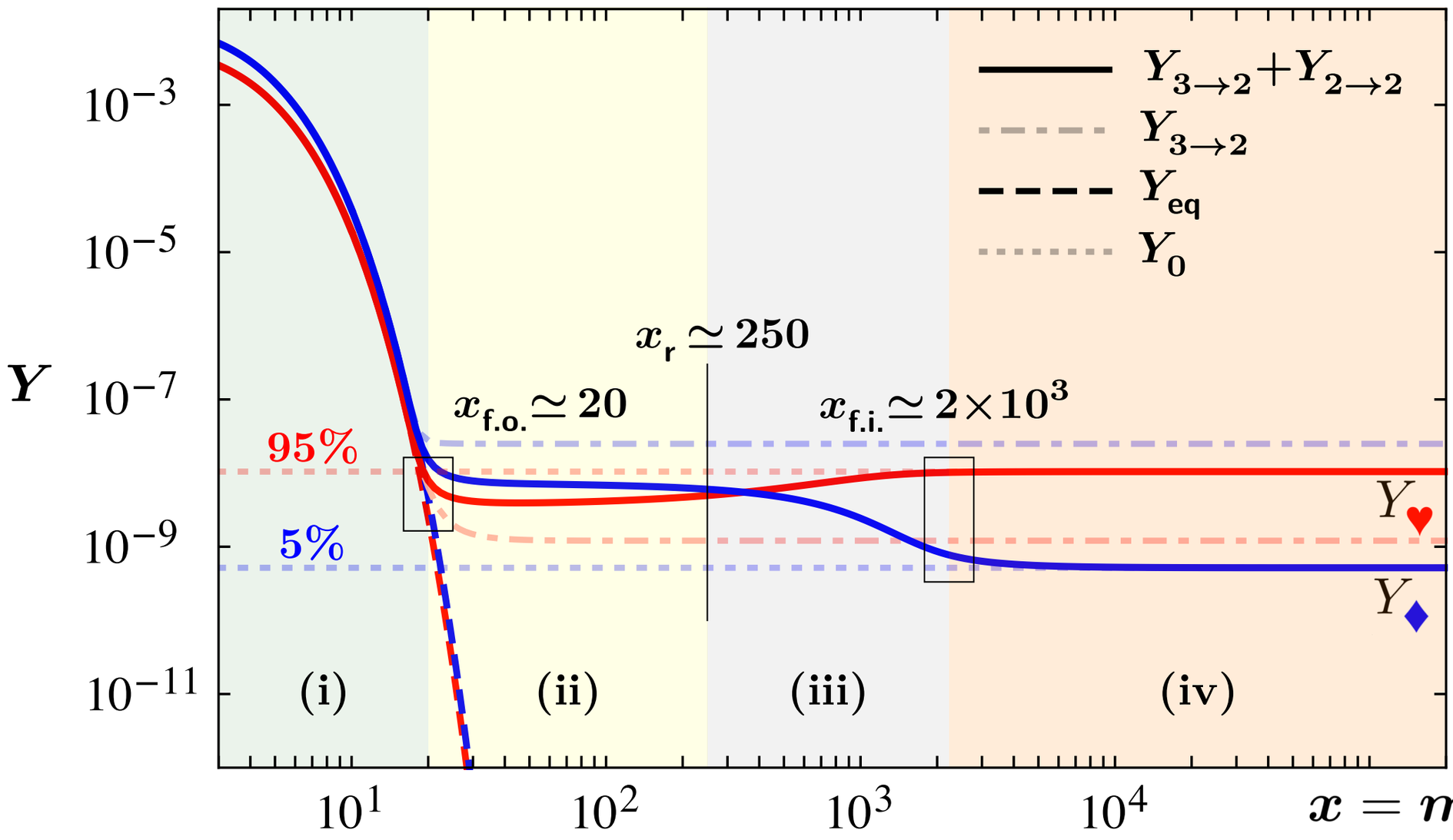
$$\langle\sigma v\rangle_{♦\bar{♦}\to♥\bar{♥}} = \frac{3c^4(m_♥/\Lambda)^4}{32\pi(4\pi)^8 x m_♥^2}\mathcal{I}^2\left(\frac{\Lambda}{m_♥}\right)\frac{\sqrt{r_♦^2-1}}{r_♦}$$

fermion-number-violating Feynman rules A. Denner, et al. 92'

Model B : ♥$^3\overline{♦^c}$♦

♥ : S ♦ : F

$(m_{♥}, m_{♦}, \Lambda) = (20, 20.04, 40)\,\mathrm{MeV}, c = 126$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

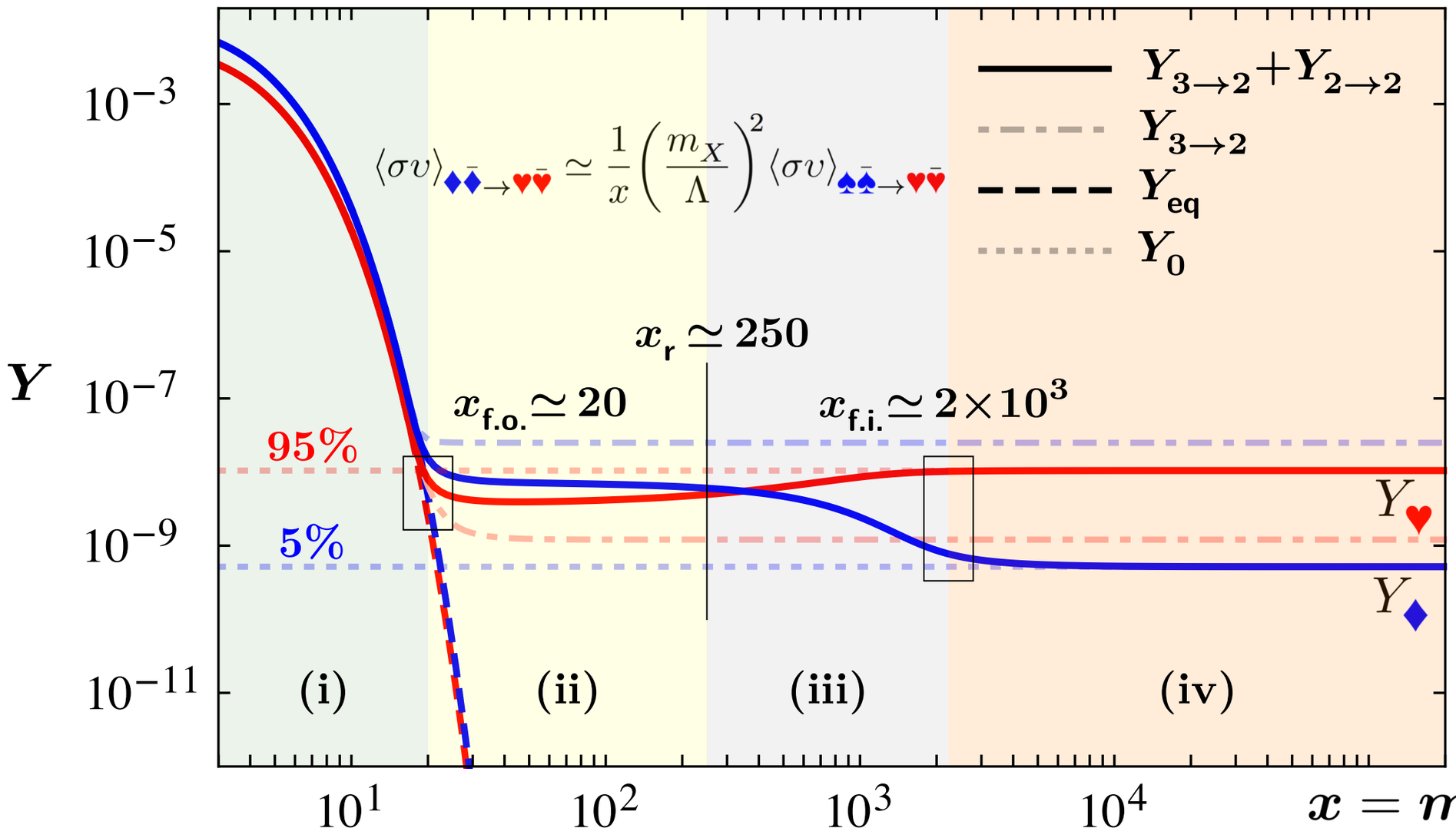
(iii) reshuffled period

(iv) frozen

Model B : ♥^{3} $\overline{♦^c}$ ♦

♥♠ : S ♦ : F

$(m_{♥}, m_{♦}, \Lambda) = (20, 20.04, 40)\,\mathrm{MeV}, c = 126$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

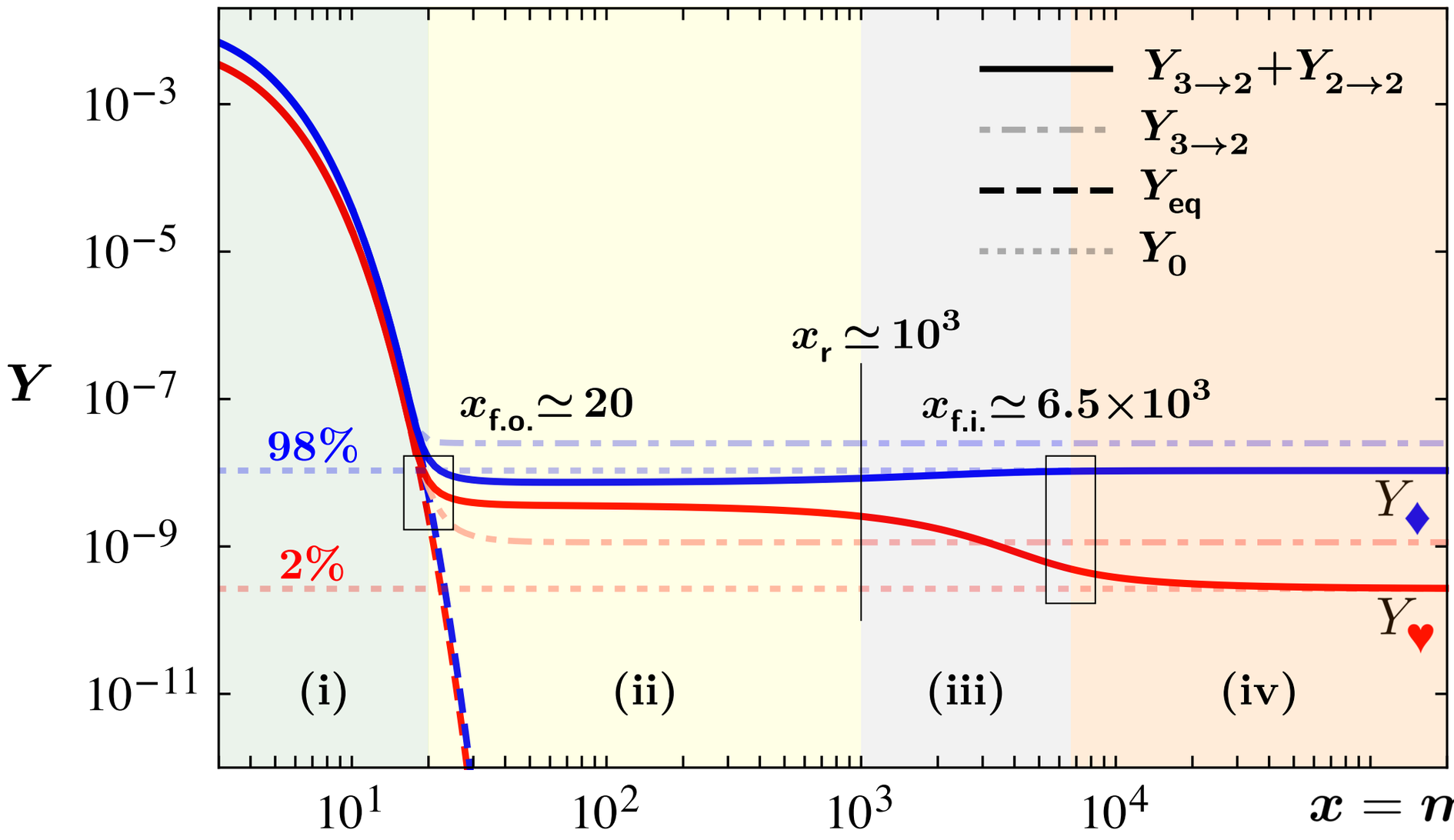
(iii) reshuffled period

(iv) frozen

Model B : ♥^{3} $\overline{♦^c}$ ♦

♥ : S ♦ : F

$(m_{♥}, m_{♦}, \Lambda) = (20, 19.99, 40)\,\mathrm{MeV}, c = 131$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

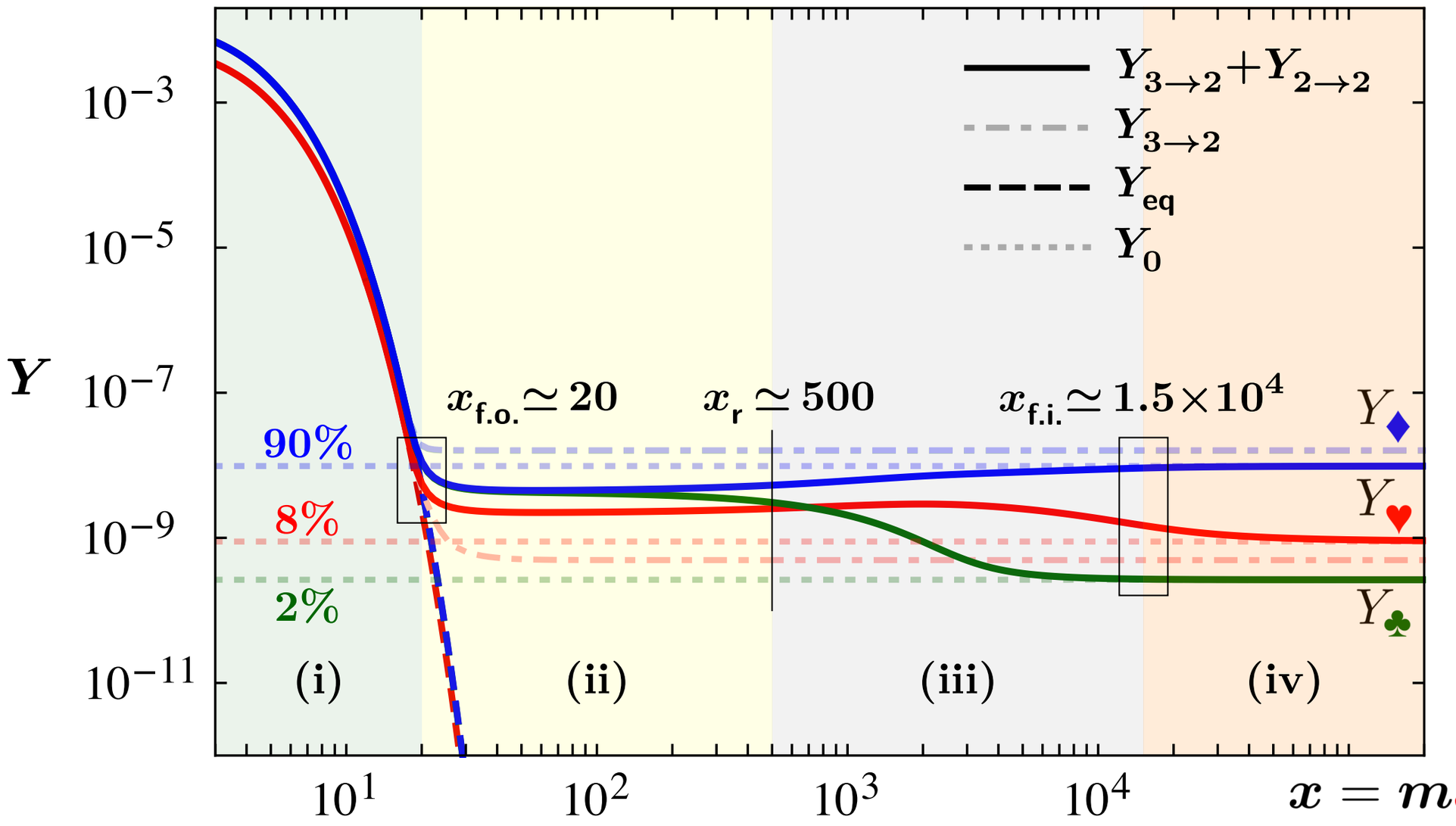
(iii) reshuffled period

(iv) frozen

Model C : ♥$^3\overline{♣}$♦

♥ : S ♣♦ : F

$(m_{♥}, m_{♣}, m_{♦}, \Lambda) = (20, 20.02, 19.998, 40)\,\mathrm{MeV}, c = 209$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

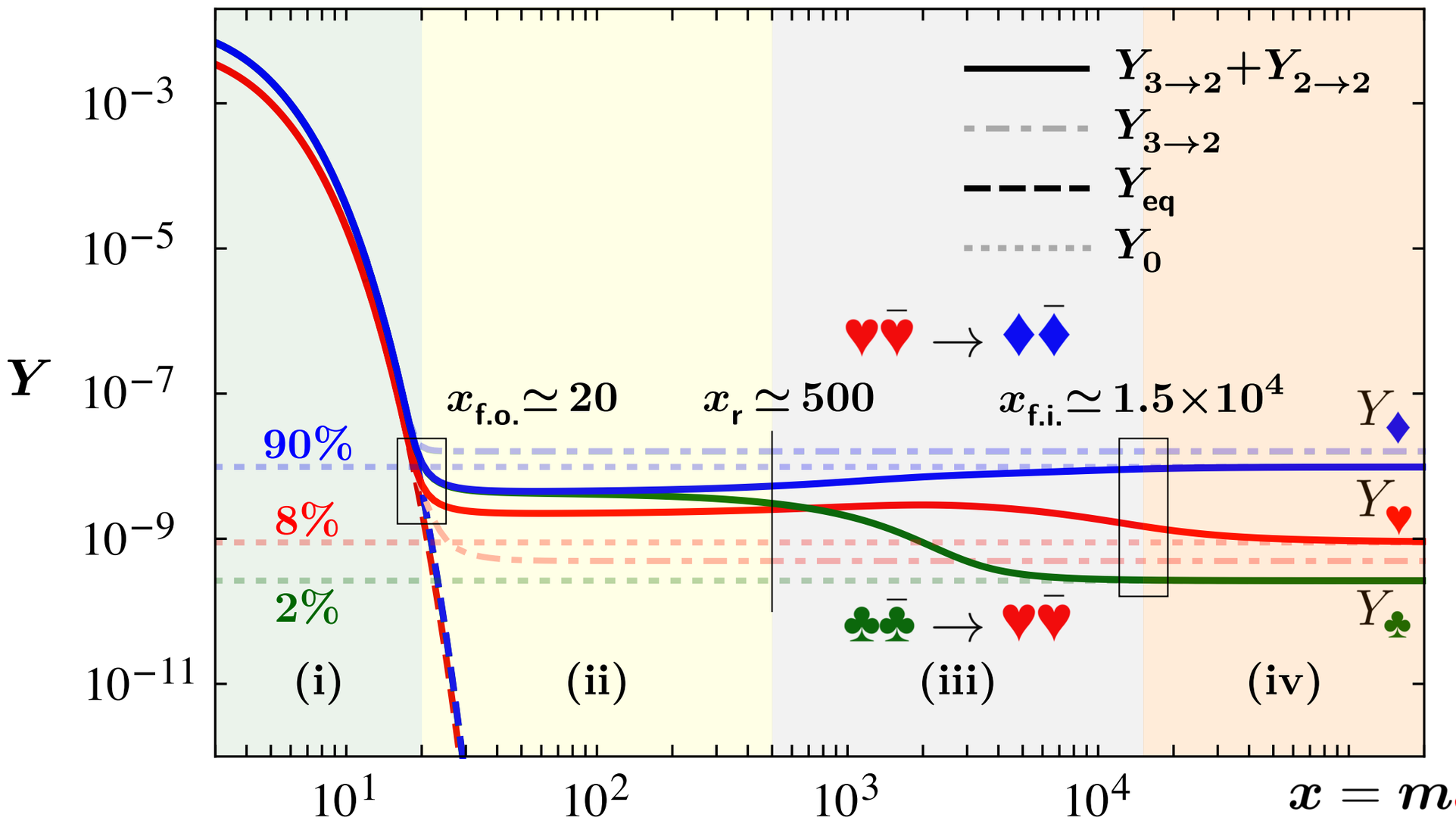
(iii) reshuffled period

(iv) frozen

Model C : ♥$^3\overline{♣}$♦

♥ : S ♣♦ : F

$(m_{♥}, m_{♣}, m_{♦}, \Lambda) = (20, 20.02, 19.998, 40)\,\mathrm{MeV}, c = 209$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

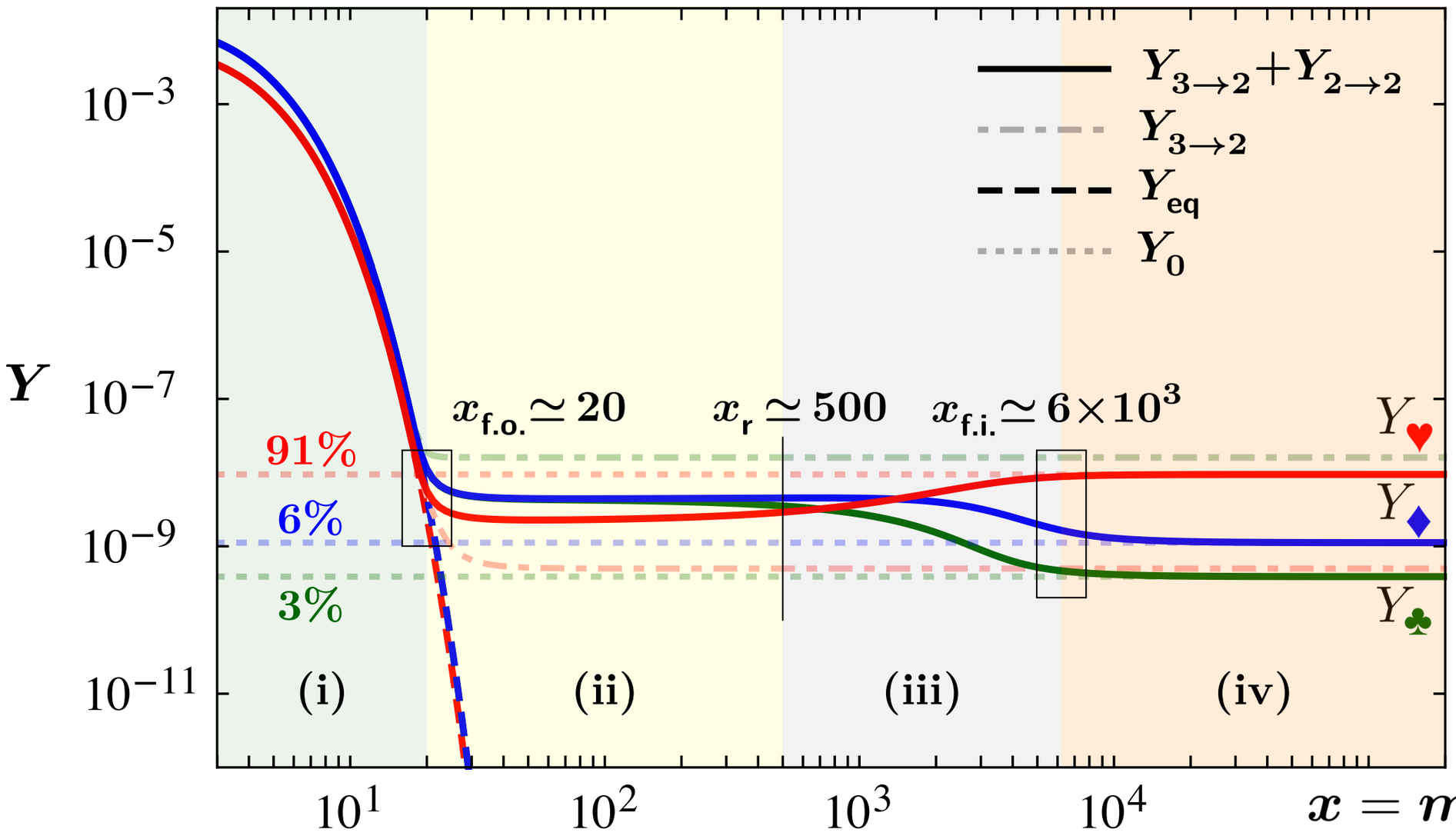
(iii) reshuffled period

(iv) frozen

Model C : ♥$^3\overline{♣}$♦

♥ : S ♣♦ : F

$(m_{♥}, m_{♣}, m_{♦}, \Lambda) = (20, 20.02, 20.01, 40)\,\mathrm{MeV}, c = 207$



(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

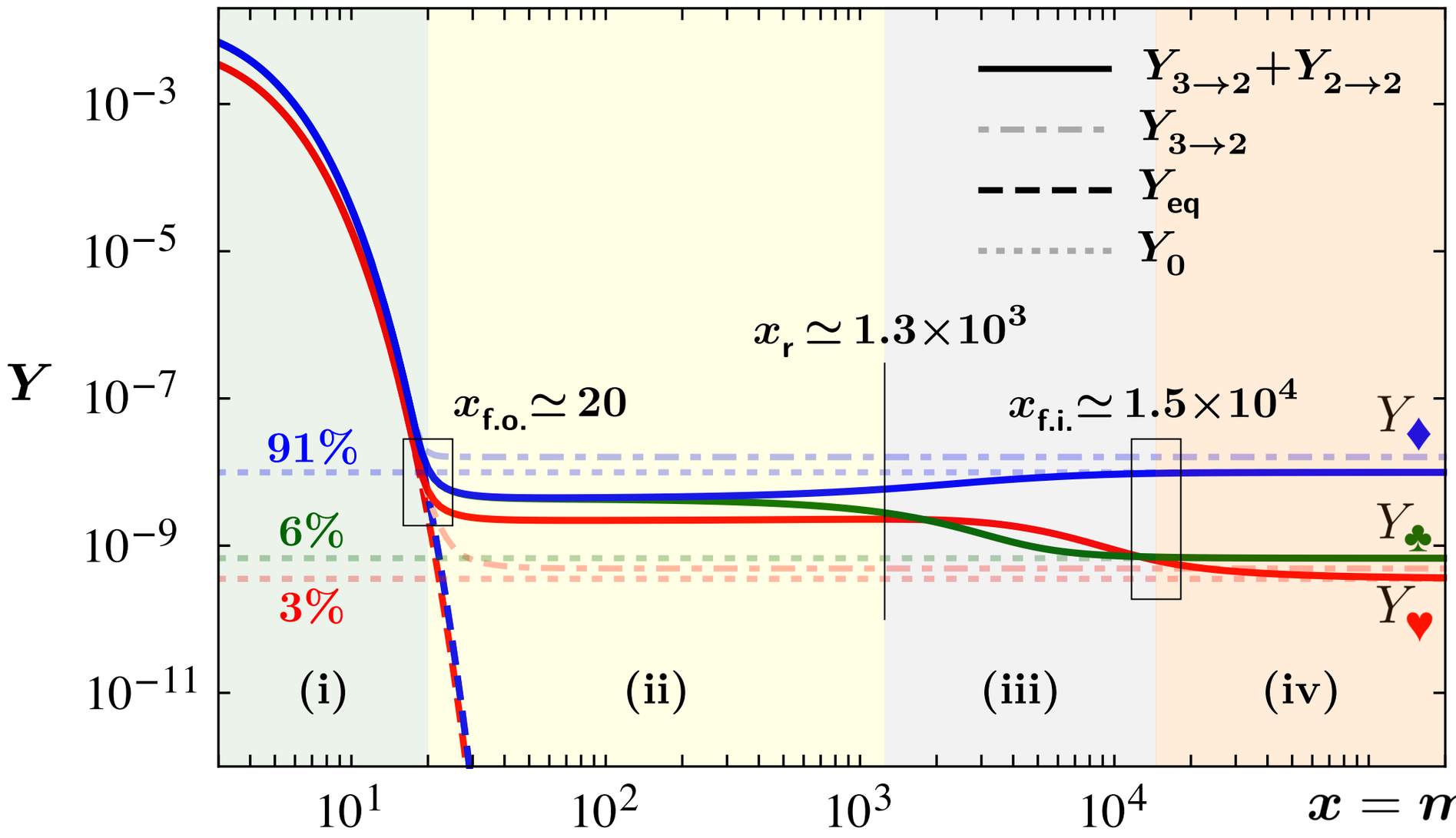
(iii) reshuffled period

(iv) frozen

Model C : ♥^{3}♣♦

♥ : S ♣♦ : F

$(m_{♥}, m_{♣}, m_{♦}, \Lambda) = (20, 20.008, 19.996, 40)\,\mathrm{MeV},\ c = 210$



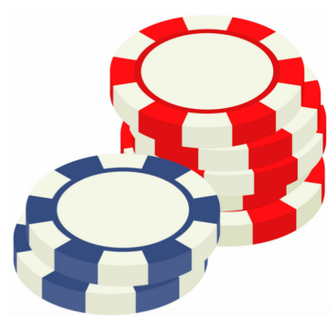
(i) chemical equilibrium

(ii) $2 \to 2$ hibernation

(iii) reshuffled period

(iv) frozen

IV. Constraints



Relic abundance of DM

♥♠ : S ♣♦ : F

The total relic density of rSIMP DM in terms of the comoving number yields is given by

$$Y_j^0 = Y_j(x \to \infty)$$

$$\Omega_{\text{SIMP}} h^2 \simeq 5.49 \times 10^5 \left(\frac{m_{\heartsuit}}{\text{MeV}}\right) \sum_{j=\text{SIMP}} Y_j^0 r_j$$

S. Bhattacharya, *et al.* (2020)

Benchmark points for the rSIMP models

	$(m_{\heartsuit}, m_{\spadesuit}, \Lambda)/\text{MeV}$	c	$(\Omega_{\heartsuit}, \Omega_{\spadesuit})/\Omega_{\text{DM}}$
Model A	$(15, 15.0003, 45)$	90	$(98.7, 1.3)\%$
	$(20, 19.9998, 40)$	93	$(2.5, 97.5)\%$
	$(25, 25.0002, 50)$	133	$(98.5, 1.5)\,\%$

	$(m_{\heartsuit}, m_{\diamondsuit}, \Lambda)/\text{MeV}$	c	$(\Omega_{\heartsuit}, \Omega_{\diamondsuit})/\Omega_{\text{DM}}$
Model B	$(15, 15.03, 45)$	182	$(94.7, 5.3)\%$
	$(20, 19.99, 40)$	131	$(2.4, 97.6)\%$
	$(25, 25.05, 50)$	180	$(97.4, 2.6)\%$

	$(m_{\heartsuit}, m_{\clubsuit}, m_{\diamondsuit}, \Lambda)/\text{MeV}$	c	$(\Omega_{\heartsuit}, \Omega_{\clubsuit}, \Omega_{\diamondsuit})/\Omega_{\text{DM}}$
Model C	$(15, 15.03, 14.998, 30)$	132	$(10.3, 1.9, 87.8)\%$
	$(20, 20.04, 20.02, 40)$	204	$(94.5, 1.3, 4.2)\%$
	$(25, 24.999, 24.998, 50)$	300	$(4.8, 37.7, 57.5)\,\%$

$$\Omega_{\text{DM}} h^2 = 0.12$$

Planck 2018

Effective number of neutrinos in CMB

♥ : S

Assuming the SIMP DM mainly couple to $e^{\pm}$, the effective number of neutrino species during CMB era is estimated as

C. Boehm, M. J. Dolan & C. McCabe (2013)

$$N_{\mathrm{eff}}(T_{\mathrm{CMB}}) = \left[1 + \frac{4}{11}\sum_{j=\mathrm{SIMP}} g_{\star s}^{\mathrm{DM}}(r_j m_{\heartsuit}, T_{\nu \mathrm{d}})\right]^{-4/3} N_{\mathrm{eff}}^{\mathrm{SM}}(T_{\mathrm{CMB}})$$

neutrino decoupling temperature

effective # of neutrinos at the CMB temperature

mass dependence entropy d.o.f of DM

$N_{\mathrm{eff}}^{\mathrm{SM}}(T_{\mathrm{CMB}}) = 3.044$

J. J. Bennett, *et al.* (2021)

Lower bound for the rSIMP mass

$$N_{\mathrm{eff}} = 2.99^{+0.34}_{-0.33}\ (95\%\ \mathrm{C.L.}) \longrightarrow m_{\heartsuit} \gtrsim (9.4, 10.6, 12.2)\,\mathrm{MeV}$$

Planck 2018

A B C

Kinetic equilibrium

♥ : S

In the SIMP scenario, the DM particles should keep kinetic equilibrium with SM particles until the f.o. temperature

kinetic equilibrium condition

$$\gamma(z_f) \gtrsim H(z_f) z_f^2$$

momentum relaxation rate

S. M. Choi, *et al.* (2019)

$$\gamma_e(x) = \frac{31\pi^3}{189\,x^6} \frac{m_{\heartsuit}^5}{\Lambda_{Z'}^4} \sum_{j=\mathrm{SIMP}} c_{je}^2$$

P. Gondolo, *et al.* (2012)

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

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

Kinetic equilibrium

♥ : S

In the SIMP scenario, the DM particles should keep kinetic equilibrium with SM particles until the f.o. temperature

kinetic equilibrium condition

$$\gamma(z_f) \gtrsim H(z_f) z_f^2$$

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$$\gamma_e(x) = \frac{31\pi^3}{189\, x^6} \frac{m_{\heartsuit}^5}{\Lambda_{Z'}^4} \sum_{j=\mathrm{SIMP}} c_{je}^2$$

P. Gondolo, *et al.* (2012)

$$\sum_{j=\mathrm{SIMP}} c_{je}^2 \gtrsim 10^{-9} \left(\frac{\Lambda_{Z'}}{200\,\mathrm{MeV}} \right)^4 \left(\frac{m_{\heartsuit}}{20\,\mathrm{MeV}} \right)^{-3}$$

Kinetic equilibrium

♥ : SIMP

In the SIMP scenario, the DM particles should keep kinetic equilibrium with SM particles until the f.o. temperature

kinetic decoupling condition

$$\gamma(x_{\text{k.d.}}) \simeq 2H(x_{\text{k.d.}}) \qquad \gamma_e(x) = \frac{31\pi^3}{189\,x^6}\frac{m_{\heartsuit}^5}{\Lambda_{Z'}^4}\sum_{j=\text{SIMP}} c_{je}^2$$

$$\rightarrow \quad x_{\text{k.d.}} \simeq 75 \ll x_{\text{f.i.}}$$

P. Gondolo, *et al.* (2012)

$$\rightarrow \quad \Gamma_{2\to 2}^{\text{2-loop}} > \Gamma_{\text{el}}$$

$$\sum_{j=\text{SIMP}} c_{je}^2 \gtrsim 10^{-9}\left(\frac{\Lambda_{Z'}}{200\,\text{MeV}}\right)^4\left(\frac{m_{\heartsuit}}{20\,\text{MeV}}\right)^{-3}$$

Unitarity bound

♥ : S

The thermally-averaged 3 to 2 annihilation cross-sections can be bounded from above by partial-wave unitarity.

$$\langle \sigma v^2 \rangle \leqslant \frac{48\sqrt{3}\pi^2 x^2}{m_{\heartsuit}^5} \frac{g_4 g_5}{g_1 g_2 g_3}$$

M. H. Namjoo, T. R. Slatyer & C. L. Wu (2019)

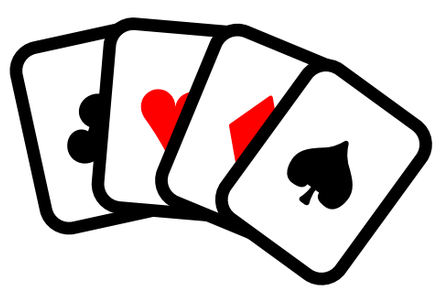
1,2,3 → 4,5

Model A : $c\,(m_X/\Lambda) \lesssim 1.3 \times 10^4$

Model B & C : $c\,(m_X/\Lambda)^2 \lesssim 8 \times 10^3$

Our benchmark points in these three models are justified.

V. Summary



Summary

We propose a new thermally-produced multi-component DM scenario called rSIMP with the following condition

$$\Gamma^{\text{2-loop}}_{2\to 2} > \Gamma_{\text{el}} \gtrsim \Gamma_{3\to 2} \gg \Gamma_{\text{ann}} > H_{\text{DM}}$$

We have studied the rSIMP scenario by the EFT approach.

In the rSIMP scenario, there is an inevitable two-loop induced 2 to 2 process which would redistribute the DM yields after the chemical freeze-out.

The rSIMP masses must be degenerate and $\mathcal{O}(20\,\text{MeV})$ to contribute non-negligible densities to the DM abundance.