Asymmetric dark matter semi-annihilation into long-lived particles

Based on 2412.01470

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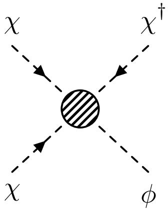
Introduction - semi-annihilating dark matter



$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\frac{1}{2}[n_\chi^2 - n_\chi n_\chi^{\mathrm{eq}}]\langle \sigma v \rangle_{\chi\chi\to\chi^\dagger\phi} \tag{1}$$

[D'Eramo, Thaler, '10]

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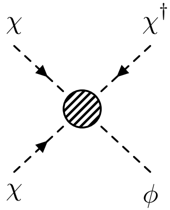

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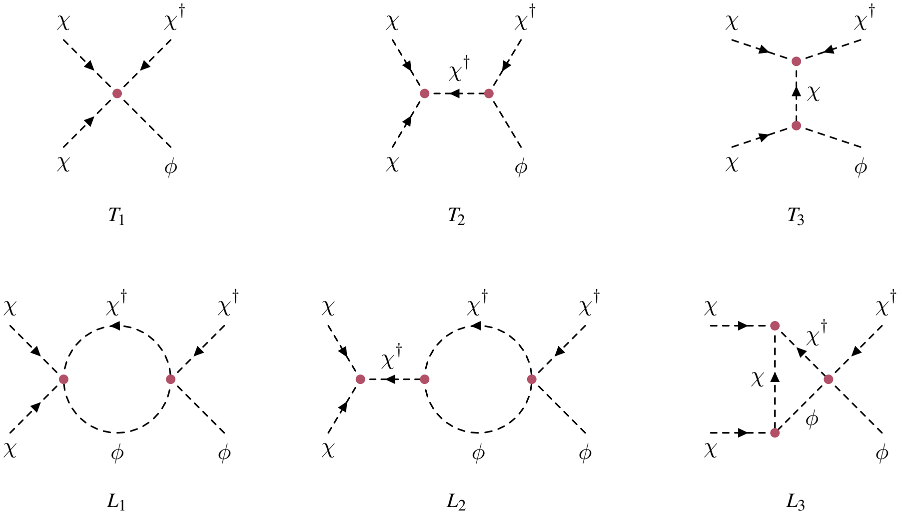
[D'Eramo, Thaler, '10]

Asymmetric semi-annihilation in A. Ghosh, D Ghosh, Mukhopadhyay '20

$$\mathcal{L} \supset \frac{\mu}{3!}\chi^3 + \frac{\lambda}{3!}\phi\chi^3 + \mathrm{H.c.} + \frac{\lambda_1}{4}|\chi|^4 + \frac{\lambda_2}{2}\phi^2|\chi|^2 + \mu_1\phi|\chi|^2 + \frac{\mu_2}{3!}\phi^3 + \frac{\lambda_3}{4!}\phi^4. \tag{2}$$

Dark matter asymmetry via semi-annihilations



[A. Ghosh, D Ghosh, Mukhopadhyay '20]

CP asymmetry and unitarity relations

$$SS^\dagger = S^\dagger S = 1 \quad \rightarrow \quad S^\dagger = 1 - \mathrm{i}T^\dagger = (1 + \mathrm{i}T)^{-1} \tag{3}$$

$$|T_{fi}|^2 = -\mathrm{i}T^\dagger_{if}\mathrm{i}T_{fi} = -\mathrm{i}T_{if}\mathrm{i}T_{fi} + \sum_n \mathrm{i}T_{in}\mathrm{i}T_{nf}\mathrm{i}T_{fi} - \ldots \tag{4}$$

[Coster, Stapp '70; Bourjaily, Hannesdottir, *et al.* '21; Hannesdottir, Mizera '22; Blažek, Maták '21a]

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[Coster, Stapp '70; Bourjaily, Hannesdottir, *et al.* '21; Hannesdottir, Mizera '22; Blažek, Maták '21a]

$$\begin{aligned}\Delta|T_{fi}|^2 = &\sum_n (\mathrm{i}T_{in}\mathrm{i}T_{nf}\mathrm{i}T_{fi} - \mathrm{i}T_{if}\mathrm{i}T_{fn}\mathrm{i}T_{ni}) \\ &- \sum_{n,m} (\mathrm{i}T_{in}\mathrm{i}T_{nm}\mathrm{i}T_{mf}\mathrm{i}T_{fi} - \mathrm{i}T_{if}\mathrm{i}T_{fm}\mathrm{i}T_{mn}\mathrm{i}T_{ni}) \\ &+ \ldots\end{aligned} \tag{5}$$

[Blažek, Maták '21a]

$$\sum_f \Delta|T_{fi}|^2 = 0 \tag{6}$$

[Dolgov '79; Kolb, Wolfram '80;

Asymmetric semi-annihilations - scalar model

Additional ϕ_2 field enables non-vanishing asymmetry

$$\mathcal{L} \supset -\frac{\lambda_1}{6}\chi^3\phi_1 - \frac{\lambda_2}{6}\chi^3\phi_2 + \text{H.c.} - \lambda_{12}|\chi|^2\phi_1\phi_2 - \frac{\lambda_3}{2}|\chi|^2\phi_3^2. \tag{7}$$

- Strong annihilation into visible sector represented by ϕ_3 field
- Long-lived ϕ_1, ϕ_2 particles

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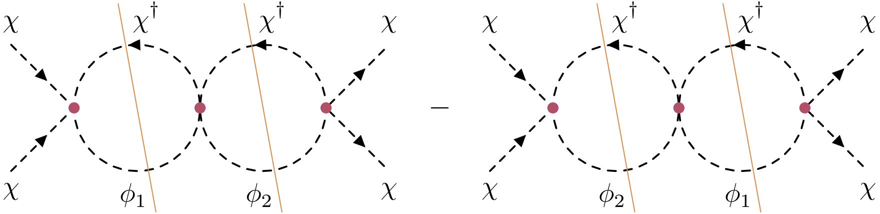
Asymmetric semi-annihilations from



Asymmetric semi-annihilations - scalar model

Boltzmann equations for the asymmetry

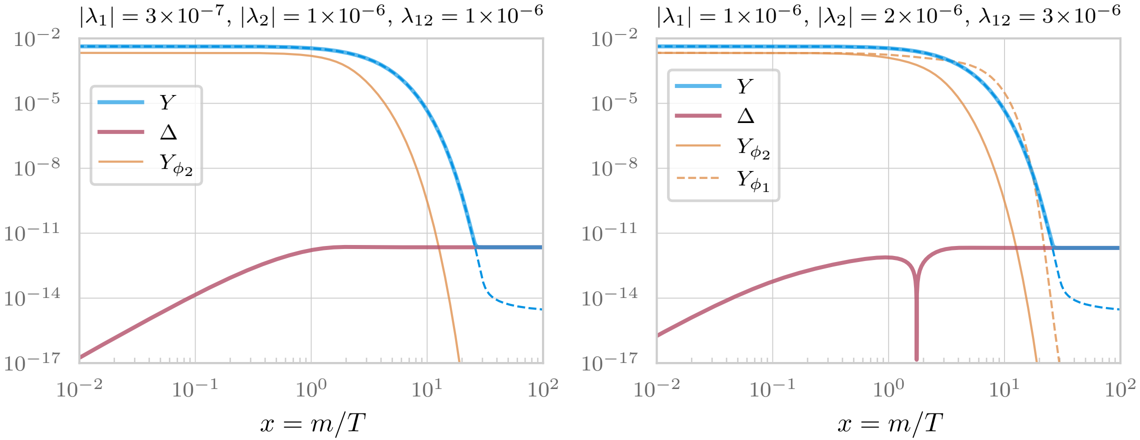
$$\left(\frac{\mathrm{d}\Delta}{\mathrm{d}x}\right)_{\mathrm{source}} = -\frac{3}{8}\frac{s}{Hx}Y_0^{\mathrm{eq}}Y\left(\frac{Y_{\phi_1}}{Y_{\phi_1}^{\mathrm{eq}}} - \frac{Y_{\phi_2}}{Y_{\phi_2}^{\mathrm{eq}}}\right)\Delta\langle\sigma v\rangle_{\chi\chi\to\chi^\dagger\phi_1} \tag{8}$$

$$\left(\frac{\mathrm{d}\Delta}{\mathrm{d}x}\right)_{\mathrm{washout}} = -\frac{3}{2}\frac{s}{Hx}Y_0^{\mathrm{eq}}\Delta\sum_{i=1,2}\left(\frac{Y}{Y_0^{\mathrm{eq}}} + \frac{1}{2}\frac{Y_{\phi_i}}{Y_{\phi_i}^{\mathrm{eq}}}\right)\langle\sigma v\rangle_{\chi\chi\to\chi^\dagger\phi_i} \tag{9}$$

$$Y = Y_\chi + Y_{\bar{\chi}} = \frac{n_\chi + n_{\bar{\chi}}}{s} \quad \text{and similarly for } \phi_1 \text{ and } \phi_2 \tag{10}$$

$$\frac{Y_{\phi_1}}{Y_{\phi_1}^{\mathrm{eq}}} = \frac{Y_{\phi_2}}{Y_{\phi_2}^{\mathrm{eq}}} \;\Rightarrow\; \text{no asymmetry} \tag{11}$$

Asymmetric semi-annihilations - scalar model



(a) (b)

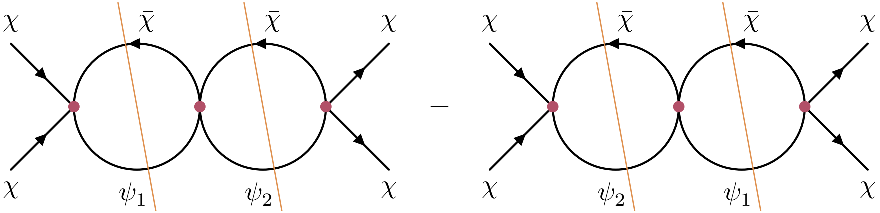
$m = 200$ GeV, $m_{\phi_2} = 400$ GeV, $m_{\phi_1} = 0$ (left), $m_{\phi_1} = 260$ GeV (right)

Asymmetric semi-annihilations - fermionic model

Effective dimension-6 operators

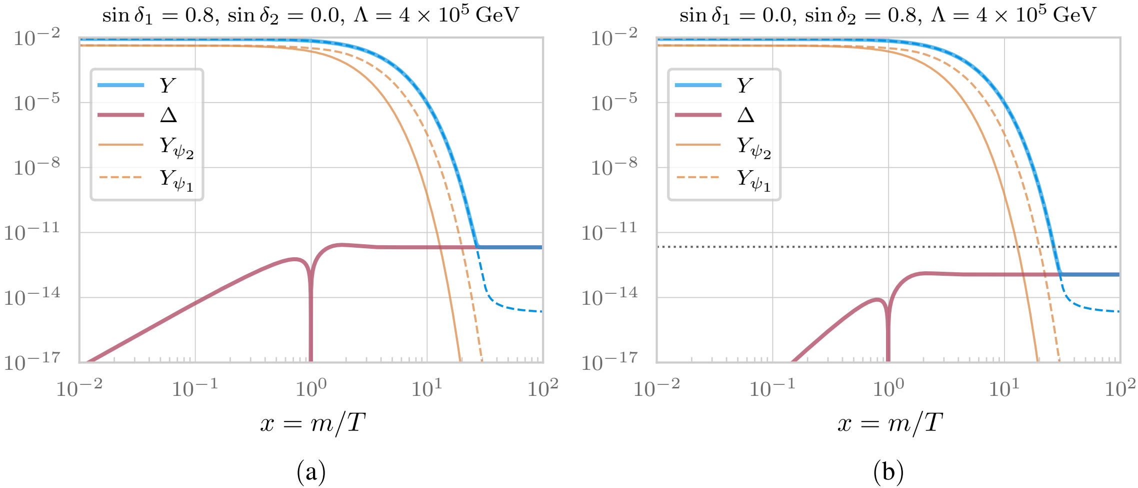
$$\mathcal{L} \supset -\frac{\kappa_1}{6\Lambda^2}(\bar{\chi}^c P_R \chi)(\bar{\chi}^c P_L \psi_1) - \frac{\kappa_2}{6\Lambda^2}(\bar{\chi}^c P_R \chi)(\bar{\chi}^c P_L \psi_2) - \frac{\kappa_{12}}{2\Lambda^2}(\bar{\chi}^c P_L \psi_1)^\dagger(\bar{\chi}^c P_L \psi_2) + \text{H.c.}$$

Asymmetric semi-annihilations from



$\sin\delta_1 = \text{Im}[\kappa_1^*\kappa_{12}^*\kappa_2]/|\kappa_1^*\kappa_{12}^*\kappa_2|$ $\qquad$ $\sin\delta_2 = \text{Im}[\kappa_1^*\kappa_{12}\kappa_2]/|\kappa_1^*\kappa_{12}\kappa_2|$

Asymmetric semi-annihilations - fermionic model



$$|\kappa_1| = |\kappa_2| = |\kappa_{12}| = 1$$

Summary

- Even feeble asymmetric semi-annihilation can have substantial effect on dark matter relic density

- Semi-annihilations into long-lived particles $\rightarrow$ dark matter totally asymmetric after freeze-out

[Blažek, Maták, Zaujec, '24]

Summary

- Even feeble asymmetric semi-annihilation can have substantial effect on dark matter relic density
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[Blažek, Maták, Zaujec, '24]

Thank you!