Sommerfeld Effect in Composite Dark Matter

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Motivation

- Thermal freeze-out scenario is one of the most attractive scenarios for the production of Dark Matter (DM) in the early Universe.

$$\Omega_{\rm DM}h^2 \sim 0.12\frac{2\times 10^{-26}\,{\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}}, \quad \langle\sigma v\rangle_{\rm ann} \sim \frac{\alpha_{\rm ann}^2}{m_{\rm DM}^2}.$$

- Indirect detection sensitive to DM with $\mathcal{O}(1\text{–}100)$ TeV mass [e.g. MAGIC Collaboration (2023), H.E.S.S. Collaboration (2018)]
- $\alpha_{\rm ann} \sim \mathcal{O}(1)$ matches the relic abundance for $m_{\rm DM} \gtrsim \mathcal{O}(10)$ TeV.
- DM model with QCD-like gauge theory is a natural choice.
  $\to$ **Composite DM Model**

Composite DM Model

3-flavors of vector-like fermions ψ (dark quark), $\bar\psi$ (anti-dark quark) and the $SU(N_c)$ gauge interaction. [Bai and Hill (2010), Antipin, Redi, Strumia and Vigiani (2015)]

	$SU(N_c)$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
ψ	N_c	**1**	**3**	0
$\bar\psi$	$\bar N_c$	**1**	**3**	0

Chiral symmetry breaking: $SU(3)_L \times SU(3)_R \to SU(3)_V \supset SU(2)_W$ $\to SU(2)_W$ triplet χ (G-parity odd) and quintuplet π (G-parity even) dark pions

Chiral Lagrangian

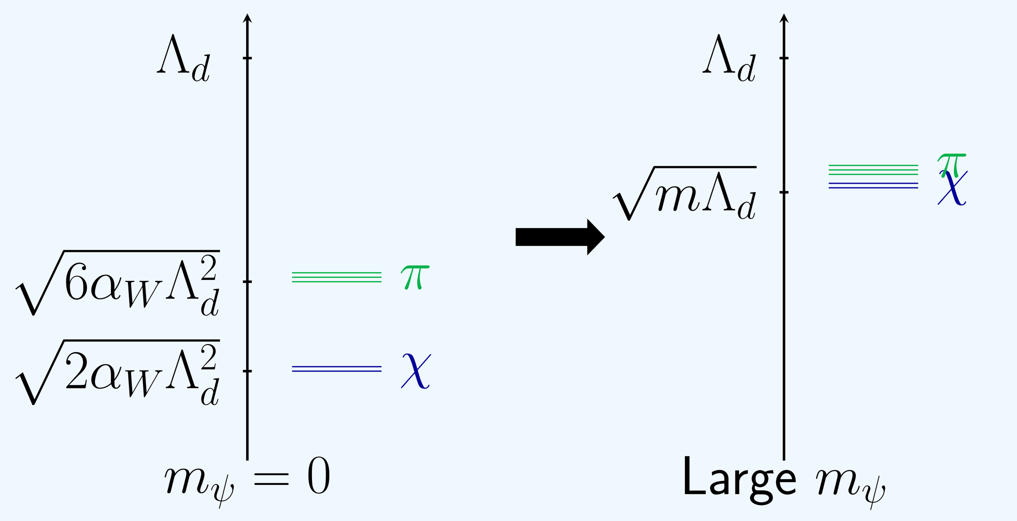
$$\mathcal{L} = \frac{f_d^2}{4}{\rm Tr}\left[D_\mu U D^\mu U^\dagger\right] + v_d^3\,{\rm Tr}[MU + {\rm h.c.}] + \mathcal{L}_{\rm WZW}$$

- χ is stable because of G-parity : $U \to U^T$
- π decays to EW gauge bosons via WZW term.

Previous Work [Abe, Sato and TY, JHEP 09(2024)]

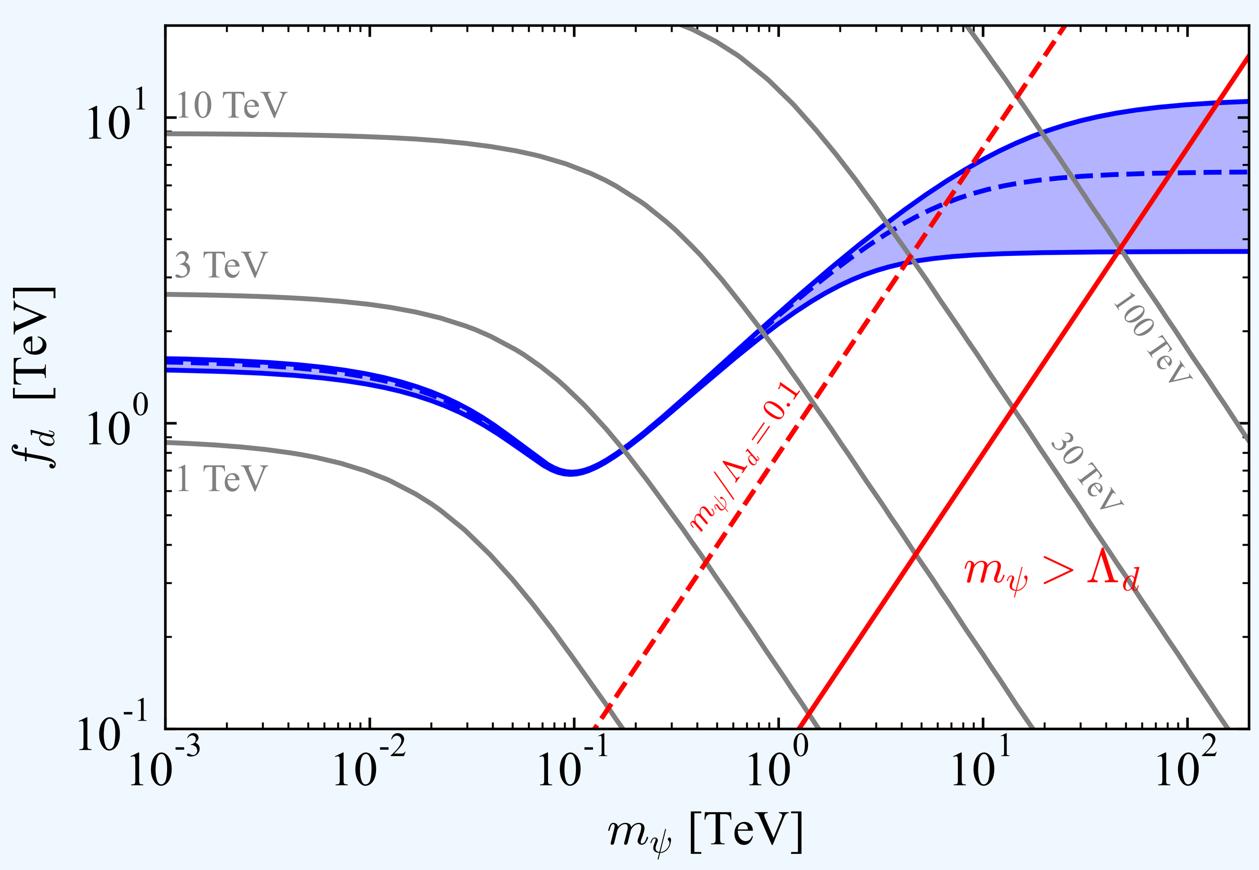
Sources of dark pion mass

- Dark quark mass: $m_\Pi^2 \sim m_\psi \Lambda_d$
- $SU(2)_W$ radiative correction: $\delta m_R^2 \sim C^2(R)\alpha_W \Lambda_d^2$
- EW symmetry breaking: $\Delta \equiv m_Q - m_0 \sim Q^2\alpha_W m_W \sin^2\frac{\theta_W}{2} \sim \mathcal{O}(100)$ MeV



DM annihilation (Leading Order)

- $m_\psi = 0$: $\chi\chi \to WW$ $\quad \langle\sigma v\rangle_{WW} \propto \frac{\alpha_W^2}{m_\chi^2} \Rightarrow m_\chi \sim 1.8$ TeV.
- Large m_ψ: $\chi\chi \to \pi\pi$ $\quad \langle\sigma v\rangle_{\pi\pi} \propto \frac{m_\chi^2}{f_d^4}\exp\left(-\frac{m_\pi - m_\chi}{T}\right) \Rightarrow m_\chi \sim \mathcal{O}(1\text{–}10)$ TeV
  Forbidden channels [Abe, Sato and **TY** (2024)]

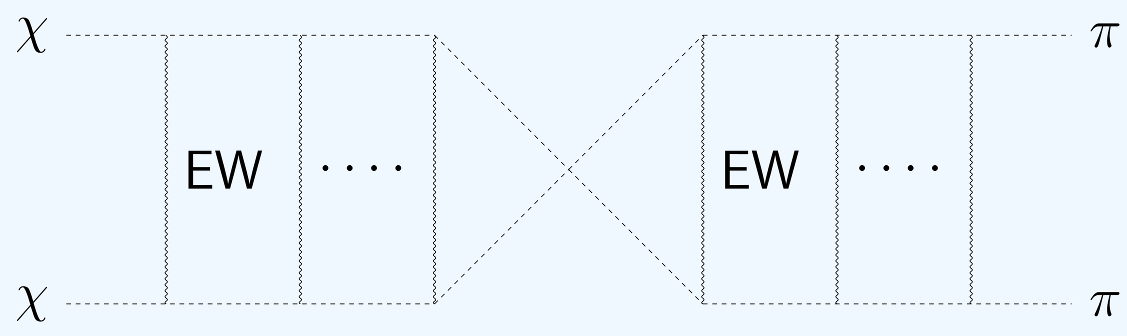


Glay contour indicates DM mass m_χ. Chiral Lagrangian is valid for $m_\psi \lesssim \Lambda_d$.

Forbidden channels can determine the DM abundance.

Sommerfeld Effect

Heavy EW interacting DM $\to$ **Sommerfeld effect** (SE) must be taken into account. [Hisano, Matsumoto, Nojiri and Saito (2005)]



EW interactions also affect final two-body states in forbidden channels
$\to$ **SE in final states** [Cui and Luo (2021)]

Toy Model

We consider $\chi\chi \to \pi\pi$ via interaction terms w/o derivative:

$$\mathcal{L}_{\rm int} = \frac{4mv_d^3}{3f_d^4}\left(\frac{1}{2}(\chi^0)^2 + \chi^+\chi^-\right)\left(\frac{1}{2}(\pi^0)^2 + \pi^+\pi^- + \pi^{++}\pi^{--}\right)$$

Mixing of two-body states by EW interactions

- $\chi^0\chi^0 \leftrightarrow \chi^+\chi^-$
- $\pi^0\pi^0 \leftrightarrow \pi^+\pi^- \leftrightarrow \pi^{++}\pi^{--}$

SE factor $\leftarrow$ solving Schroedinger eqns.

$$\left[-\frac{1}{2\mu_\chi}\frac{d^2}{dr^2} + \mathbf{V}_\chi(r) - \frac{p_\chi^2}{2\mu_\chi}\right]\vec\psi_\chi(r) = 0,$$

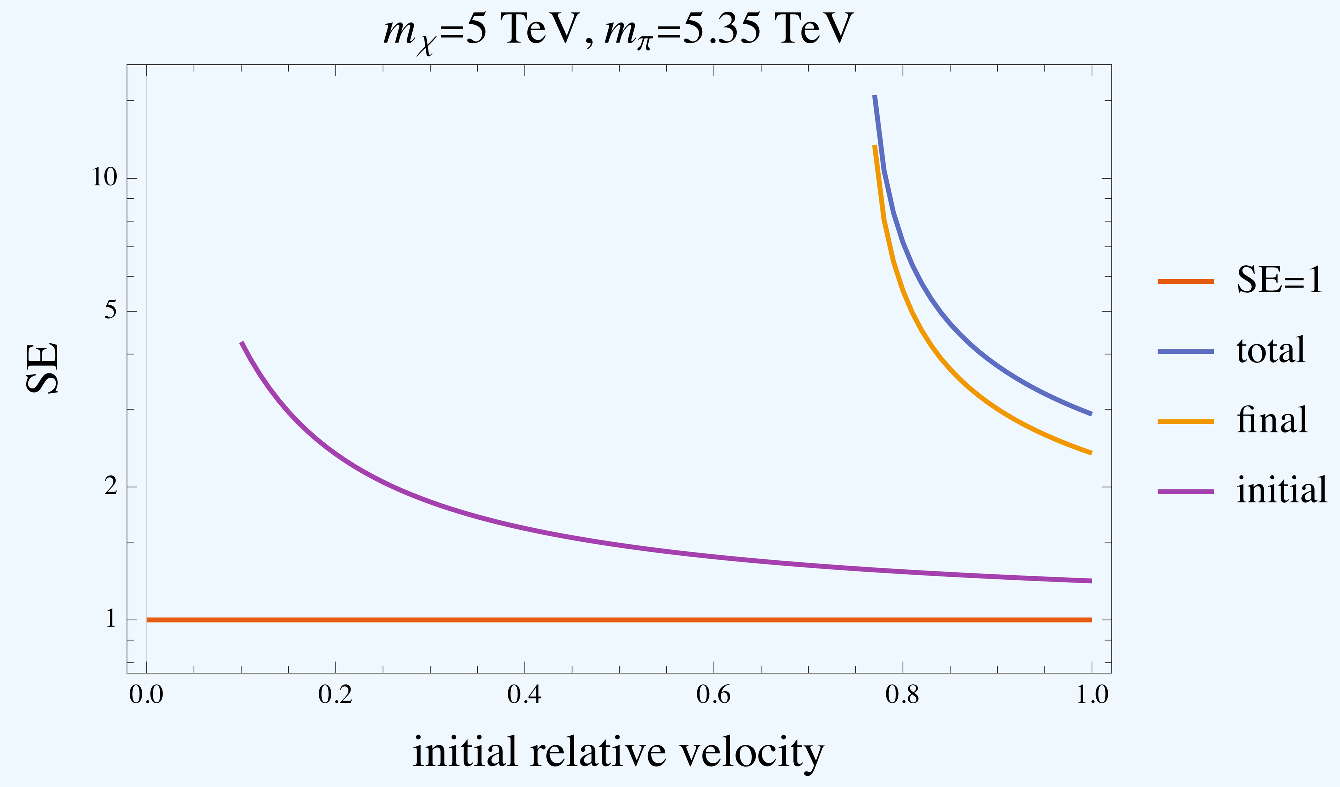
$$\mathbf{V}_\chi(r) \equiv \begin{pmatrix} 0 & -\sqrt{2}B \\ -\sqrt{2}B & -A+2\Delta\end{pmatrix}, \quad \vec\psi_\chi(r) \equiv \begin{pmatrix}\psi_\chi^{00}(r) \\ \psi_\chi^{\pm}(r)\end{pmatrix},$$

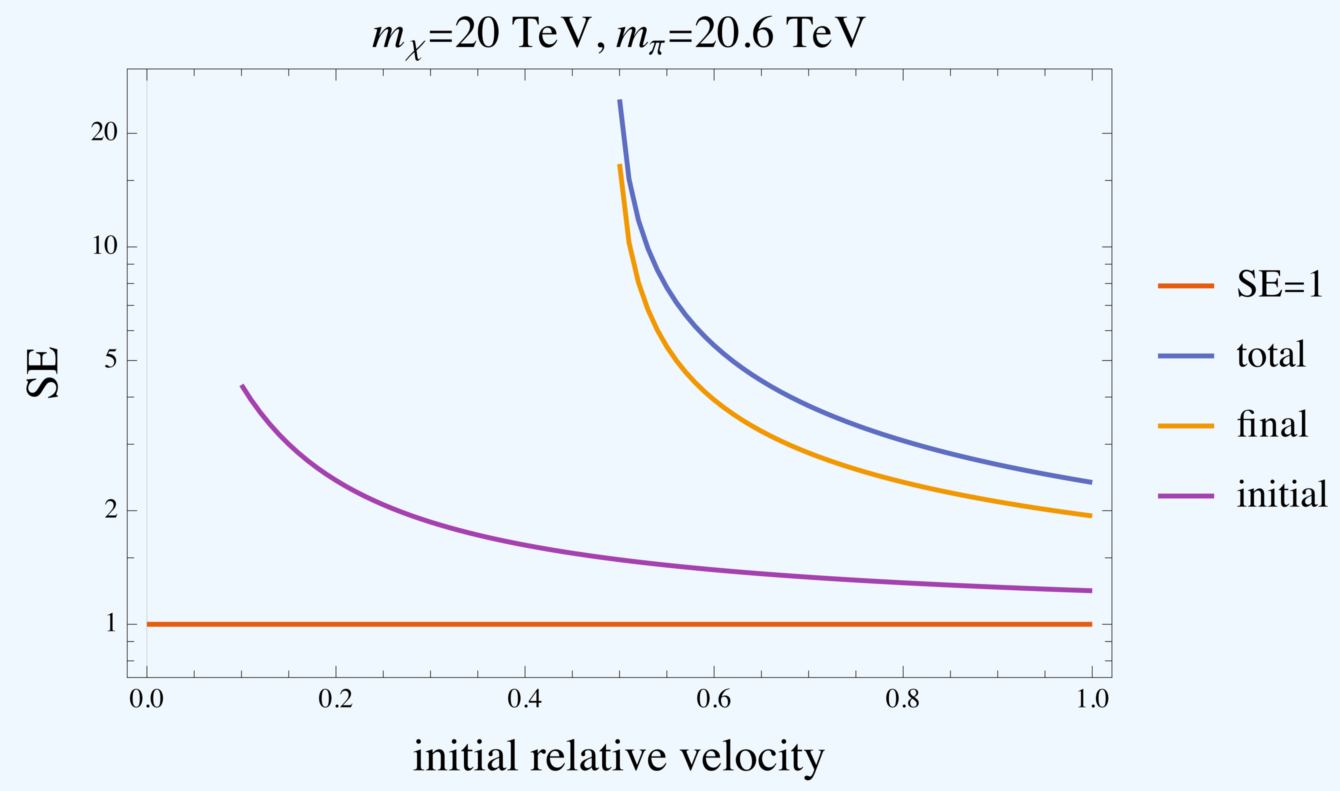
$$\left[-\frac{1}{2\mu_\pi}\frac{d^2}{dr^2} + \mathbf{V}_\pi(r) - \frac{p_\pi^2}{2\mu_\pi}\right]\vec\psi_\pi(r) = 0,$$

$$\mathbf{V}_\pi(r) \equiv \begin{pmatrix} -4A+8\Delta & -2B & 0 \\ -2B & -A+2\Delta & -3\sqrt{2}B \\ 0 & -3\sqrt{2}B & 0\end{pmatrix}, \quad \vec\psi_\pi(r) \equiv \begin{pmatrix}\psi_\pi^{\pm\pm}(r) \\ \psi_\pi^{\pm}(r) \\ \psi_\pi^{0}(r)\end{pmatrix}$$

$$A \equiv \frac{\alpha}{r} + \frac{\alpha_W c_W^2}{r}e^{-m_Z r}, \quad B \equiv \frac{\alpha_W}{r}e^{-m_W r}$$

Amplitude w/ SE factor : $\mathcal{M} \sim \vec\psi_\chi^\dagger(0)\mathcal{M}_{\rm LO}\vec\psi_\pi(0)$





Final state SE dominantly contributes to the total SE factor.

Future Work

- Adding interaction terms w/ derivative.
- Comparing w/ the current constraints from indirect detection experiments.