Composite Dark Matter with Forbidden Annihilation

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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.

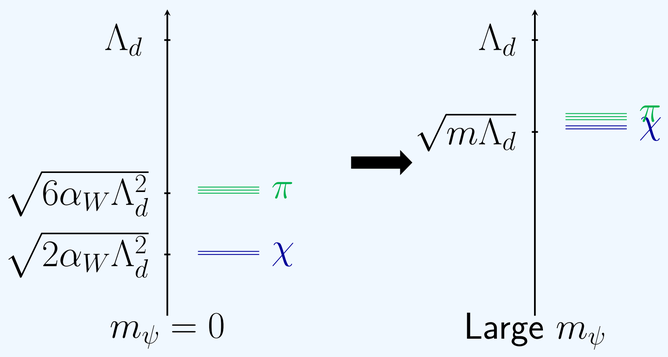
$$\Omega_{\rm DM}h^2 \sim 0.12\,\frac{2\times10^{-26}\ {\rm cm}^3/{\rm s}}{\langle\sigma v\rangle_{\rm ann}},\quad \langle\sigma v\rangle_{\rm ann}\sim\frac{\alpha_{\rm ann}^2}{m_{\rm DM}^2}.$$

- Indirect detection experiments have sensitivity to DM with $\mathcal{O}(1\text{–}100)$ TeV mass. [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.
  → **Composite DM Model**

Mass Spectrum [Abe, Sato, TY, JHEP 09(2024)]

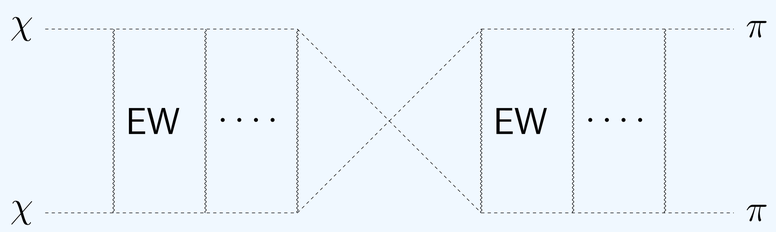
Sources of dark pion mass

- 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: $\Delta\equiv m_\pm-m_0\simeq\alpha_W m_W\sin^2\frac{\theta_W}{2}\simeq166$ MeV



Sommerfeld Effect

Heavy EW interacting DM → **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
→ **SE in final states** [Cui and Luo (2021)]

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: $SU(3)_L\times SU(3)_R\to SU(3)_V$ by $\langle\bar\psi\psi\rangle\sim v_d^3$ $\to SU(2)_W$ triplet χ (G-parity odd) and quintuplet π (G-parity even) dark pions
Chiral Lagrangian

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

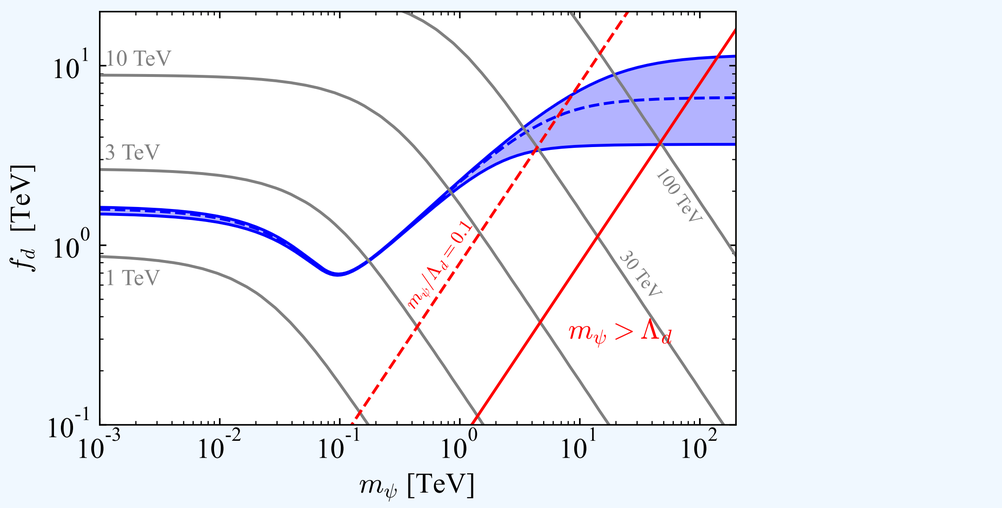
- χ is stable because of G-parity : $U\to U^T$
- π decays to EW gauge bosons via WZW term.

χ^0 is a DM candidate.

DM annihilation (Leading Order)

- $m_\psi=0$: $\chi\chi\to WW$ $\quad\langle\sigma v\rangle_{WW}\propto\frac{\alpha_W^2}{m_\chi^2}\Rightarrow m_\chi\sim1.8$ 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, **TY** (2024)]



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

Forbidden channels affect the relic abundance.

Enhanced Cross Section

Cross section of $\chi^0\chi^0\to\pi\pi$ at LO

$$\sigma(\chi^0\chi^0\to\pi\pi)v_{\rm rel}^{(\chi)}\simeq\frac{|\boldsymbol{p}_\pi|}{16\pi m_\pi^3}(\mathcal{A}\mathcal{A}^\dagger)_{11}\propto v_{\rm rel}^{(\pi)}$$

$$\mathcal{A}=\begin{pmatrix}\mathcal{M}(\chi^0\chi^0\to\pi^{++}\pi^{--}) & \mathcal{M}(\chi^0\chi^0\to\pi^+\pi^-) & \mathcal{M}(\chi^0\chi^0\to\pi^0\pi^0)\\ \mathcal{M}(\chi^+\chi^-\to\pi^{++}\pi^{--}) & \mathcal{M}(\chi^+\chi^-\to\pi^+\pi^-) & \mathcal{M}(\chi^+\chi^-\to\pi^0\pi^0)\end{pmatrix}$$

SE factors are obtained by solving Schroedinger eqns.

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

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

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

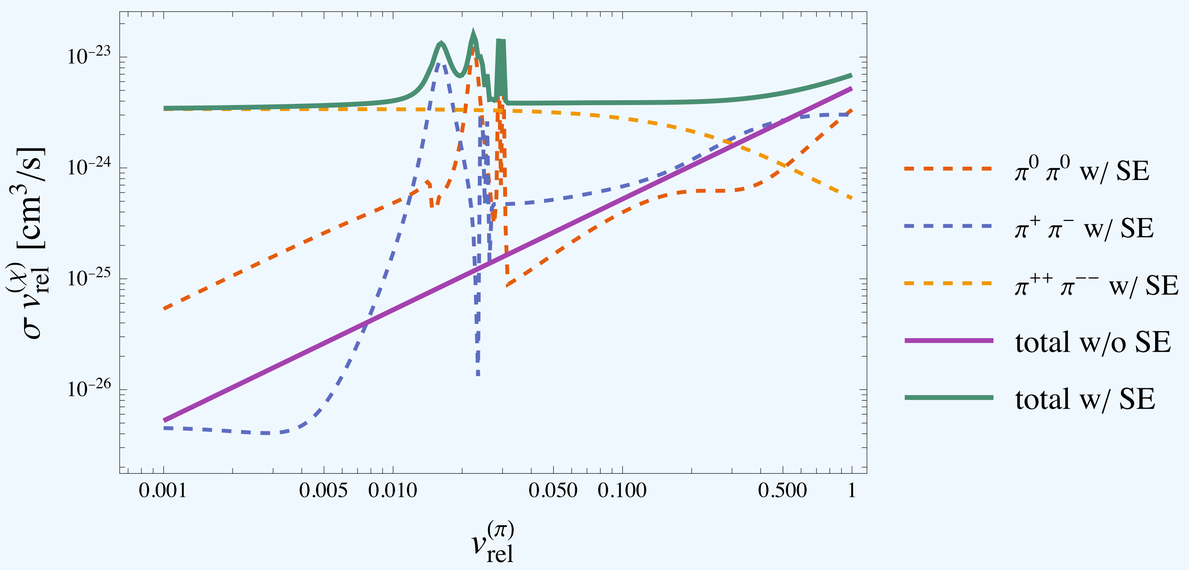
$$\mathbf{V}_\pi(r)\equiv\begin{pmatrix}-4A+8\Delta & -2B & 0\\ -2B & -A+2\Delta & -3\sqrt{2}B\\ 0 & -3\sqrt{2}B & 0\end{pmatrix},\quad\vec\psi_\pi(r)\equiv\begin{pmatrix}\psi_\pi^{\pm\pm}(\boldsymbol{r})\\ \psi_\pi^{\pm}(\boldsymbol{r})\\ \psi_\pi^{0}(\boldsymbol{r})\end{pmatrix}$$

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

Amplitude w/ SE : $\mathcal{A}_{\rm SE}=\vec\psi_\chi^\dagger(0)\mathcal{A}\vec\psi_\pi(0)$

Cross section w/ SE

$$\sigma_{\rm SE}(\chi^0\chi^0\to\pi\pi)v_{\rm rel}^{(\chi)}\simeq\frac{|\boldsymbol{p}_\pi|}{16\pi m_\pi^3}|\mathcal{A}_{\rm SE}|^2$$



DM mainly annihilate into $\pi^{++}\pi^{--}$ near threshold.

Future Work

- How does the decay of π affect the relic abundance?
- Comparison w/ the current constraints from indirect detection experiments