Vector-fermion dark matter

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based on:
A. Ahmed, M. Duch, B. Grządkowski, MI
„*Multi-Component Dark Matter: the vector and fermion case*" – in progress

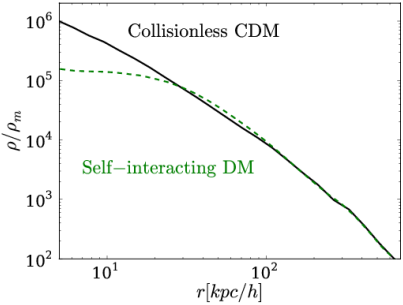
Matter to the Deepest
Podlesice, 3–8 September 2017

Why multicomponent dark matter?

- Single-component WIMP's – perfect in large scales
- Galactical scales problems – possible solution: 2 component DM ($m_1 \ll m_2$)
  - core-cusp problem

◇ simulations ⇒ cuspy decreasing of DM density with radius

◇ observations ⇒ flat distribution in the core



  - too-big-to-fail problem: bigger satellite galaxies around the Milky Way and other big galaxies predicted by simulations
- Why only one component? (vs. **17** particles of SM)

Vector-fermion model

- Gauge group: $\mathcal{G} = \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{Standard Model gauge group}} \times U(1)_X$.
- SM not charged under $U(1)_X$
- New fields: S – complex scalar , χ – Dirac fermion, X_μ – $U(1)_X$ gauge boson
- Charges:

$$S : (1, 1, 0, 1), \qquad \chi : (1, 1, 0, 1/2)$$

The Lagrangian

- $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{\text{portal}}$
- The dark sector Lagrangian

$$\mathcal{L}_{\text{DM}} = -\frac{1}{2}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} + (\mathcal{D}_\mu S)^* \mathcal{D}^\mu S + \mu_S^2 |S|^2 - \lambda_S |S|^4$$
$$+ \bar{\chi}(i\not{D} - m_D)\chi - \frac{1}{\sqrt{2}}(y_X S^* \chi^T \mathcal{C}\chi + h.c.)$$
$$D_\mu \equiv \partial_\mu + i g_x q_x X_\mu$$

- $\mathcal{L}$ invariant under $\mathcal{C}$ symmetry:

$$X_\mu \xrightarrow{\mathcal{C}} -X_\mu, \quad S \xrightarrow{\mathcal{C}} S^*, \quad \chi \xrightarrow{\mathcal{C}} \chi^{\mathcal{C}} = -i\gamma_2\chi^*$$

$\mathbb{Z}_2$ symmetry $\Rightarrow$ no $U(1)_Y$-$U(1)_X$ mixing $\Rightarrow$ no X_μ decay into SM

$\cancel{B^{\mu\nu}\mathcal{F}_{\mu\nu}}$

- The Higgs portal Lagrangian – the only DM-SM interaction

$$\mathcal{L}_{\text{portal}} = -\kappa |S|^2 |H|^2$$

Higgs particles mixing

$$V(H,S) = \underbrace{-\mu_H^2|H|^2 + \lambda_H|H|^4}_{\text{SM}} \underbrace{-\mu_S^2|S|^2 + \lambda_S|S|^4}_{\text{DM}} + \underbrace{\kappa|H|^2|S|^2}_{\text{portal}}$$

- Spontaneous symmetry breaking

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \qquad H = \langle H \rangle + \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\pi^+ \\ h + i\pi^0 \end{pmatrix}$$

$$\langle S \rangle = \frac{v_x}{\sqrt{2}}, \qquad S = \langle S \rangle + \frac{\phi + i\sigma}{\sqrt{2}}$$

- π^+, π^0, σ – the Goldstone bosons
- h and ϕ mix to mass eigenstates h_1 and h_2:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathcal{R}^{-1} \begin{pmatrix} h \\ \phi \end{pmatrix}, \qquad \text{where } \mathcal{R} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$$

- h_1 considered to be the known Higgs particle, $m_{h_1} = 125$ GeV

Majorana fermion states

$$\boxed{\mathcal{L}_{DF} = \bar{\chi}(i\not{D} - m_D)\chi - \frac{1}{\sqrt{2}}(y_X S^* \chi^T \mathcal{C}\chi + h.c.)}$$

- After SSB we diagonalize $\mathcal{L}_{DF}$ with mass eigenstates $\psi_\pm$:

$$\psi_+ = \frac{\chi + \chi^{\mathcal{C}}}{\sqrt{2}}, \qquad m_+ = m_D + y_x v_x$$

$$\psi_- = \frac{\chi - \chi^{\mathcal{C}}}{i\sqrt{2}}, \qquad m_- = m_D - y_x v_x$$

Feynman rules

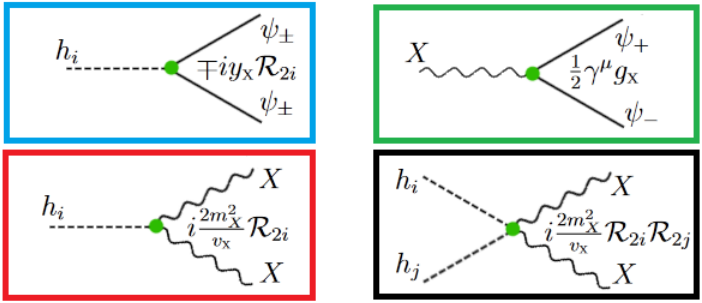
- Interaction Lagrangian of the dark sector:

$$\mathcal{L}_{\text{int}} = -\frac{y_x}{2}(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-)\phi - \frac{i}{4}g_x(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+)X_\mu$$
$$+ v_x g_x^2 X^\mu X_\mu \phi + \frac{g_x^2}{2}X^\mu X_\mu \phi^2,$$

$$\mathcal{R} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$$

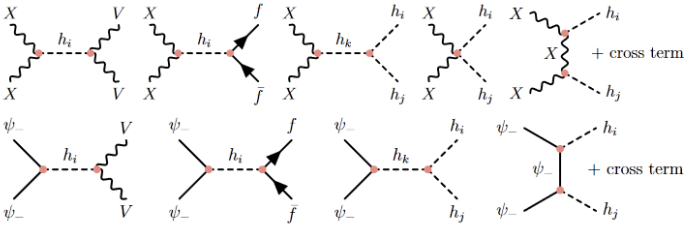
the only decay possibility

$m_- < m_+ \Rightarrow \psi_-$ <u>always</u> stable

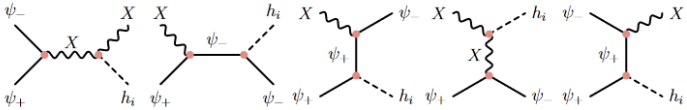


2-2 processes

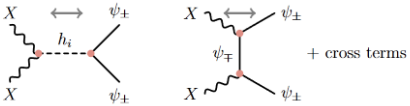
ANNIHILATIONS (2DM —> 2SM)



SEMI-ANNIHILATIONS (2DM —> SM + DM)



CONVERSIONS (2DM —> 2DM)



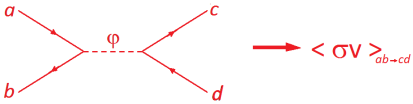
The Boltzmann equation for DM – the general form

the model

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{int}$$

$$\Downarrow$$

interactions



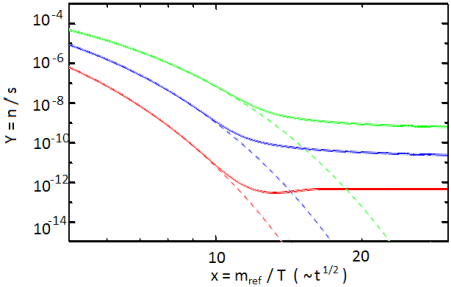
$$\Downarrow$$

Boltzmann equation

$$\frac{dn_a}{dt} + 3Hn_a = -\sum_{bcd} < \sigma v >_{ab\to cd} \left(n_a n_b - \frac{\bar{n}_a \bar{n}_b}{\bar{n}_c \bar{n}_d} n_c n_d \right) + \text{decays}$$

$$\Downarrow$$

DM density time dependence



The Boltzmann equations for our model

$$
\begin{aligned}
\frac{dn_X}{dt} =& -3Hn_X - \langle \sigma_v^{XX\phi\phi'} \rangle \left(n_X^2 - \bar{n}_X^2 \right) - \langle \sigma_v^{X\psi_+\psi_- h_i} \rangle \left(n_X n_{\psi_+} - \bar{n}_X \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \right) \\
& - \langle \sigma_v^{X\psi_-\psi_+ h_i} \rangle \left(n_X n_{\psi_-} - \bar{n}_X \bar{n}_{\psi_-} \frac{n_{\psi_+}}{\bar{n}_{\psi_+}} \right) - \langle \sigma_v^{Xh_i\psi_+\psi_-} \rangle \bar{n}_{h_i} \left(n_X - \bar{n}_X \frac{n_{\psi_+} n_{\psi_-}}{\bar{n}_{\psi_+} \bar{n}_{\psi_-}} \right) \\
& - \langle \sigma_v^{XX\psi_+\psi_+} \rangle \left(n_X^2 - \bar{n}_X^2 \frac{n_{\psi_+}^2}{\bar{n}_{\psi_+}^2} \right) - \langle \sigma_v^{XX\psi_-\psi_-} \rangle \left(n_X^2 - \bar{n}_X^2 \frac{n_{\psi_-}^2}{\bar{n}_{\psi_-}^2} \right) \\
& + \Gamma_{\psi_+ \to X\psi_-} \left(n_{\psi_+} - \bar{n}_{\psi_+} \frac{n_X}{\bar{n}_X} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \right) \\
\frac{dn_{\psi_-}}{dt} =& -3Hn_{\psi_-} - \langle \sigma_v^{\psi_-\psi_-\phi\phi'} \rangle \left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2 \right) - \langle \sigma_v^{\psi_-\psi_+ Xh_i} \rangle \left(n_{\psi_-} n_{\psi_+} - \bar{n}_{\psi_-} \bar{n}_{\psi_+} \frac{n_X}{\bar{n}_X} \right) \\
& - \langle \sigma_v^{X\psi_-\psi_+ h_i} \rangle \left(n_X n_{\psi_-} - \bar{n}_X \bar{n}_{\psi_-} \frac{n_{\psi_+}}{\bar{n}_{\psi_+}} \right) - \langle \sigma_v^{\psi_- h_i X\psi_+} \rangle \bar{n}_{h_i} \left(n_{\psi_-} - \bar{n}_{\psi_-} \frac{n_{\psi_+}}{\bar{n}_{\psi_+}} \frac{n_X}{\bar{n}_X} \right) \\
& - \langle \sigma_v^{\psi_-\psi_- XX} \rangle \left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2 \frac{n_X^2}{\bar{n}_X^2} \right) - \langle \sigma_v^{\psi_-\psi_-\psi_+\psi_+} \rangle \left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2 \frac{n_{\psi_+}^2}{\bar{n}_{\psi_+}^2} \right) \\
& + \Gamma_{\psi_+ \to X\psi_-} \left(n_{\psi_+} - \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \frac{n_X}{\bar{n}_X} \right) \\
\frac{dn_{\psi_+}}{dt} =& [\psi_- \leftrightarrow \psi_+] - \Gamma_{\psi_+ \to X\psi_-} \left(n_{\psi_+} - \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \frac{n_X}{\bar{n}_X} \right)
\end{aligned}
$$

Solving the Boltzmann equations

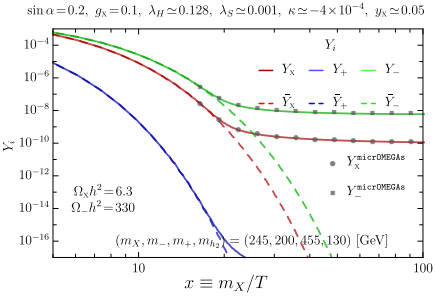
- Experimental constraints $\rightarrow$ relic density $\Omega_{\rm DM} h^2 \approx 0.12$
- Convenient variables: $Y \equiv \frac{n}{s}$, $x = \frac{m_{\rm ref}}{T}$ $\Rightarrow$ BEq.: $\frac{dY_i}{dx} = \frac{m_{\rm ref}}{m_i}\frac{dn_i}{dt} + 3Hn$

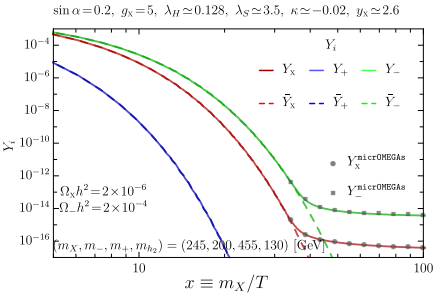
$$\Omega_i h^2 = \frac{h^2 s_0}{\rho_{\rm cr}} m_i Y_i^\infty = 2.742 \times 10^8 \left(\frac{m_i}{\rm GeV}\right) Y_i^\infty$$

- The BEq. solved by `micrOMEGAs` and a dedicated c++ code
  - `micrOMEGAs` dedicated to 1 or 2 component DM
  - our model – 2 or 3 components
- Free parameters: $g_x,\ \sin\alpha,\ m_X,\ m_+,\ m_-,\ m_{h_2}$.

The results – 2 component DM

- Bigger g_X $\Rightarrow$ stronger DM-SM interactions $\Rightarrow$ smaller abundance
- Good agreement with `micrOMEGAs`





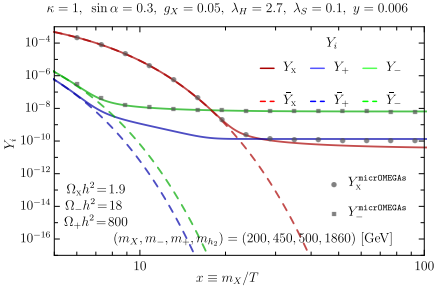
$$\langle \sigma v \rangle = a_0 + a_1 x^{-1} + a_2 x^{-2} + \ldots$$

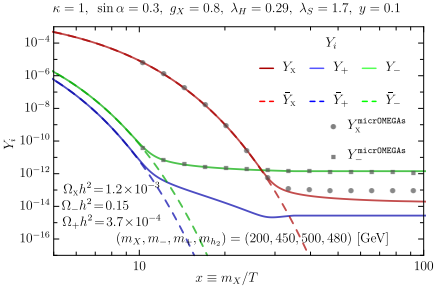
process	a_N	a_{N+1}	N
$XX \to$ SM	$1.2 \cdot 10^{-2}$	$-3.5 \cdot 10^{-2}$	0
$\psi_+\psi_+ \to$ SM	$2.7 \cdot 10^{-4}$	$-8.2 \cdot 10^{-4}$	1
$\psi_-\psi_- \to$ SM	$7.8 \cdot 10^{-3}$	$-6.2 \cdot 10^{-2}$	1
$\Psi_+\Psi_+ \to XX$	$6.9 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	0
$XX \to \Psi_-\Psi_-$	$6.4 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	0
$\Psi_+, \Psi_+ \to \Psi_-\Psi_-$	$3.8 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	0
$\Psi_+\Psi_- \to Xh_1$	$4.5 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$	0
$\Psi_+\Psi_- \to Xh_2$	$1.1 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	0
$\Psi_+ h_1 \to X\Psi_-$	$2.3 \cdot 10^{-4}$	$4.2 \cdot 10^{-3}$	0
$\Psi_+ h_2 \to X\Psi_-$	$5.6 \cdot 10^{-3}$	$9.4 \cdot 10^{-2}$	0
$X\Psi_+ \to \Psi_- h_1$	$2.8 \cdot 10^{-4}$	$-3.1 \cdot 10^{-4}$	0
$X\Psi_+ \to \Psi_- h_2$	$6.7 \cdot 10^{-3}$	$-7.6 \cdot 10^{-3}$	0
$\Psi_+ \to X\Psi_-$	$1 \cdot 10^{-3}$		

process	a_N	a_{N+1}	N
$XX \to$ SM	$7.68 \cdot 10^{4}$	$-2.18 \cdot 10^{5}$	0
$\psi_+\psi_+ \to$ SM	$1.69 \cdot 10^{3}$	$-5.19 \cdot 10^{3}$	1
$\psi_-\psi_- \to$ SM	$4.88 \cdot 10^{4}$	$-3.86 \cdot 10^{5}$	1
$\Psi_+\Psi_+ \to XX$	$4.29 \cdot 10^{3}$	$9.93 \cdot 10^{3}$	0
$XX \to \Psi_-\Psi_-$	$4 \cdot 10^{2}$	$1.03 \cdot 10^{3}$	0
$\Psi_+, \Psi_+ \to \Psi_-\Psi_-$	$2.39 \cdot 10^{4}$	$1.25 \cdot 10^{4}$	0
$\Psi_+\Psi_- \to Xh_1$	$2.8 \cdot 10^{1}$	$1.11 \cdot 10^{2}$	0
$\Psi_+\Psi_- \to Xh_2$	$6.67 \cdot 10^{2}$	$2.76 \cdot 10^{3}$	0
$\Psi_+ h_1 \to X\Psi_-$	$1.42 \cdot 10^{3}$	$2.61 \cdot 10^{4}$	0
$\Psi_+ h_2 \to X\Psi_-$	$3.51 \cdot 10^{4}$	$5.88 \cdot 10^{5}$	0
$X\Psi_+ \to \Psi_- h_1$	$1.75 \cdot 10^{3}$	$-1.95 \cdot 10^{3}$	0
$X\Psi_+ \to \Psi_- h_2$	$4.19 \cdot 10^{4}$	$-4.87 \cdot 10^{4}$	0
$\Psi_+ \to X\Psi_-$	$2.59 \cdot 10^{0}$		

The results – 3 component DM

- Disagreement with `micrOMEGAs`





$$\langle \sigma v \rangle = a_0 + a_1 x^{-1} + a_2 x^{-2} + \ldots$$

process	a_N	a_{N+1}	N
$XX \to \mathrm{SM}$	$4 \cdot 10^{-2}$	$-1.9 \cdot 10^{-2}$	0
$\psi_+\psi_+ \to \mathrm{SM}$	$9.6 \cdot 10^{-4}$	$-3.1 \cdot 10^{-4}$	1
$\psi_-\psi_- \to \mathrm{SM}$	$9.9 \cdot 10^{-4}$	$-1.1 \cdot 10^{-4}$	1
$\Psi_+\Psi_+ \to XX$	$1 \cdot 10^{-5}$	$1.7 \cdot 10^{-5}$	0
$\Psi_-\Psi_- \to XX$	$1.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$	0
$\Psi_-\Psi_- \to \Psi_+\Psi_+$	$2.3 \cdot 10^{-4}$	$5.6 \cdot 10^{-4}$	0
$\Psi_+\Psi_- \to Xh_1$	$1.6 \cdot 10^{-6}$	$-2.6 \cdot 10^{-6}$	0
$Xh_2 \to \Psi_+\Psi_-$	$6.1 \cdot 10^{-7}$	$6.9 \cdot 10^{-5}$	0
$X\Psi_- \to \Psi_+ h_1$	$7.1 \cdot 10^{-6}$	$1.1 \cdot 10^{-4}$	0
$\Psi_+ h_2 \to X\Psi_-$	$1.6 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$	0
$X\Psi_+ \to \Psi_- h_1$	$4.7 \cdot 10^{-7}$	$1.1 \cdot 10^{-4}$	0
$\Psi_- h_2 \to X\Psi_+$	$9.5 \cdot 10^{-4}$	$-9.7 \cdot 10^{-5}$	0

process	a_N	a_{N+1}	N
$XX \to \mathrm{SM}$	$7.82 \cdot 10^{0}$	$-2.54 \cdot 10^{0}$	0
$\psi_+\psi_+ \to \mathrm{SM}$	$1.8 \cdot 10^{-1}$	$-1.1 \cdot 10^{-1}$	1
$\psi_-\psi_- \to \mathrm{SM}$	$1.7 \cdot 10^{-1}$	$-7 \cdot 10^{-2}$	1
$\Psi_+\Psi_+ \to XX$	$6.8 \cdot 10^{-1}$	$1.03 \cdot 10^{0}$	0
$\Psi_-\Psi_- \to XX$	$9 \cdot 10^{-1}$	$6.8 \cdot 10^{-1}$	0
$\Psi_-\Psi_- \to \Psi_+\Psi_+$	$1.52 \cdot 10^{1}$	$3.66 \cdot 10^{1}$	0
$\Psi_+\Psi_- \to Xh_1$	$1 \cdot 10^{-1}$	$-1.7 \cdot 10^{-1}$	0
$Xh_2 \to \Psi_+\Psi_-$	$4 \cdot 10^{-2}$	$4.52 \cdot 10^{0}$	0
$X\Psi_- \to \Psi_+ h_1$	$4.7 \cdot 10^{-1}$	$7.13 \cdot 10^{0}$	0
$\Psi_+ h_2 \to X\Psi_-$	$1.05 \cdot 10^{0}$	$7.55 \cdot 10^{0}$	0
$X\Psi_+ \to \Psi_- h_1$	$3.1 \cdot 10^{-2}$	$7.31 \cdot 10^{0}$	0
$\Psi_- h_2 \to X\Psi_+$	$6.2 \cdot 10^{1}$	$-5.84 \cdot 10^{0}$	0

Summary

- The simple $U(1)$ extension of the Standard Model gauge group
- New fields: a scalar S, a Dirac fermion χ and a gauge boson X_μ
- After SSB: two Majorana fermions $\psi_\pm$, a gauge boson X_μ and a second Higgs particle h_2
- Convenient framework to analyze various multicomponent (2 or 3) DM scenarios
- Developement of the general multicompDM Boltzmann equation solving tool
- Parameter space scans are performed (problem: time)
- Work still in progress...

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THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

Other parameters expressed in terms of the free ones

free parameters:

$$g_x,\ \sin\alpha,\ m_X,\ m_+,\ m_-,\ m_{h_2}$$

other parameters:

$$v_x = \frac{m_X}{g_x} \qquad \kappa = \frac{(m_1^2 - m_2^2)\sin(2\alpha) g_x}{2 v v_x}$$

$$\lambda_H = \frac{m_1^2 \cos^2\alpha + m_2^2 \sin^2\alpha}{2v^2} \qquad \lambda_S = \frac{m_1^2 \sin^2\alpha + m_2^2 \cos^2\alpha}{2v_x^2}$$

$$y_x = \frac{m_+ - m_-}{2v_x} \qquad m_D = \frac{m_+ + m_-}{2}$$

Symmetries of the Lagrangian

$$\mathcal{L}_{\text{int}} = -\frac{y_x}{2}(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-)\phi - \frac{i}{4}g_x(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+)X_\mu$$
$$+ v_x g_x^2 X^\mu X_\mu \phi + \frac{g_x^2}{2}X^\mu X_\mu \phi^2$$

Symmetry	X_μ	ψ_+	ψ_-	ϕ
$\mathbb{Z}_2$	$-$	$+$	$-$	$+$
$\mathbb{Z}_2'$	$-$	$-$	$+$	$+$
$\mathbb{Z}_2''$	$+$	$-$	$-$	$+$

- The lightest odd particle stable
- No DM→SM decays

2 component DM scan

- Bigger $g_x \Rightarrow$ stronger DM-SM interactions $\Rightarrow$ smaller abundance
- Bigger mass $\Rightarrow$ smaller $\bar{Y} \sim \left(\frac{m}{T}\right)^{3/2} e^{-\frac{m}{T}} \Rightarrow$ smaller abundance
- s-channel resonance effect when $m_{h_2} \approx 2m_-$