Vector-fermion dark matter

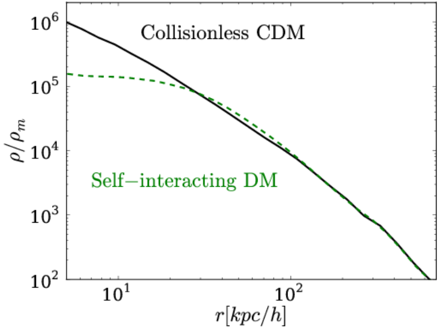
Michał Iglicki
University of Warsaw

based on:
A. Ahmed, M. Duch, B. Grządkowski, MI
Multi-Component Dark Matter: the vector and fermion case (1710.01853)

StringPheno18
Warsaw, 2-6 July 2018

Why multicomponent dark matter?

- Mono-component WIMP's – perfect in large scales, but severe constraints (ID, DD)
- Galactical scales problems – possible solution: strongly sef-interacting two-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 / missing satellites problem
    where are the predicted satellite galaxies of Milky Way?
- 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 $U(1)_X$, DM not charged under $\mathcal{G}_{\text{SM}}$
- New fields: complex scalar $S_{(q_X=1)}$, Dirac fermion $\chi_{(q_X=1/2)}$, $U(1)_X$ gauge boson X_μ
- The Lagrangian $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{\text{portal}}$

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

$$\mathcal{L}_{\text{portal}} = -\kappa|S|^2|H|^2 \qquad D_\mu \equiv \partial_\mu + ig_X q_X X_\mu$$

- $\mathcal{L}_{DM}$ invariant under dark charge symmetry:

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

$\Rightarrow$ no X_μ decay into SM

Mass eigenstates

Higgs sector

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

- Spontaneous symmetry breaking

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

- h and ϕ mix to mass eigenstates h_1 (SM Higgs particle) and h_2:

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

Fermionic sector

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

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

$$\psi_+ = \left(\chi + \chi^c\right)/\sqrt{2}, \qquad m_+ = m_D + y_X v_x$$

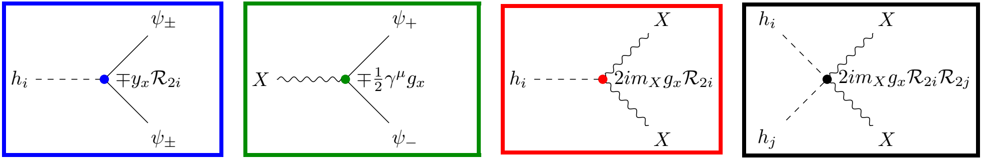
$$\psi_- = \left(\chi - \chi^c\right)/\left(i\sqrt{2}\right), \qquad m_- = m_D - y_X v_x$$

Feynman rules

- Interaction Lagrangian of the dark sector:

$$\mathcal{L}_{int} = -\frac{y_X}{2}(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-)\phi - \frac{i}{4}g_X(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+)X_\mu$$

$$+ v_x g_X^2 X^\mu X_\mu \phi + \frac{g_X^2}{2} X^\mu X_\mu \phi^2 \qquad \phi = \sin\alpha \; h_1 + \cos\alpha \; h_2$$



the only dark decay vertex

$m_- < m_+ \Rightarrow \psi_-$ always stable

$h_i = h_1$ or h_2

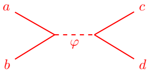
$$\mathcal{R} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$$

the model

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

$$\Downarrow$$

interactions



$$\longrightarrow \quad \langle \sigma v \rangle_{ab\to cd}$$

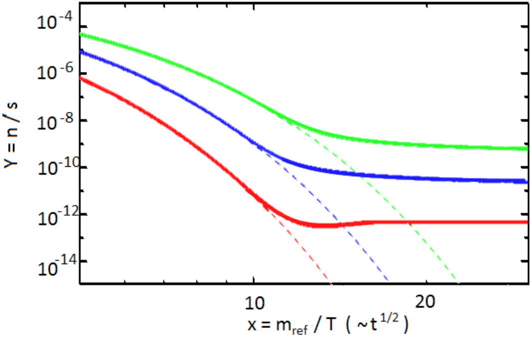
$$\Downarrow$$

Boltzmann equation

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

$$\Downarrow$$

DM density time dependence



$$\bar{n} \sim \left(\frac{m}{T}\right)^{3/2} e^{-m/T}$$

The Boltzmann equations for our model

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

$$\frac{dn_{\psi_-}}{dt} = -3Hn_{\psi_-} - \langle\sigma_v^{\psi_-\psi_-\phi\phi'}\rangle\left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2\right) - \langle\sigma_v^{\psi_-\psi_+Xh_i}\rangle\left(n_{\psi_-}n_{\psi_+} - \bar{n}_{\psi_-}\bar{n}_{\psi_+}\frac{n_X}{\bar{n}_X}\right)$$
$$- \langle\sigma_v^{X\psi_-\psi_+h_i}\rangle\left(n_X n_{\psi_-} - \bar{n}_X\bar{n}_{\psi_-}\frac{n_{\psi_+}}{\bar{n}_{\psi_+}}\right) - \langle\sigma_v^{\psi_-h_iX\psi_+}\rangle\bar{n}_{h_i}\left(n_{\psi_-} - \bar{n}_{\psi_-}\frac{n_{\psi_+}}{\bar{n}_{\psi_+}}\frac{n_X}{\bar{n}_X}\right)$$
$$- \langle\sigma_v^{\psi_-\psi_-XX}\rangle\left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2\frac{n_X^2}{\bar{n}_X^2}\right) - \langle\sigma_v^{\psi_-\psi_-\psi_+\psi_+}\rangle\left(n_{\psi_-}^2 - \bar{n}_{\psi_-}^2\frac{n_{\psi_+}^2}{\bar{n}_{\psi_+}^2}\right)$$
$$+\Gamma_{\psi_+\to X\psi_-}\left(n_{\psi_+} - \bar{n}_{\psi_+}\frac{n_{\psi_-}}{\bar{n}_{\psi_-}}\frac{n_X}{\bar{n}_X}\right)$$

$$\frac{dn_{\psi_+}}{dt} = [\psi_- \leftrightarrow \psi_+] - \Gamma_{\psi_+\to X\psi_-}\left(n_{\psi_+} - \bar{n}_{\psi_+}\frac{n_{\psi_-}}{\bar{n}_{\psi_-}}\frac{n_X}{\bar{n}_X}\right)$$

Strongly self-interacting DM

- SIDM – solution to the small-scale problems if

$$0.1\frac{\text{cm}^2}{\text{g}} < \frac{\sigma_T}{m_X} < 1\frac{\text{cm}^2}{\text{g}}$$

- Limiting mono-component cases:
  - Vector dark matter

    Duch, Grządkowski, Huang, 1710.00320

$$\Delta m \ll m_X \;\Rightarrow\; y_X = \frac{\Delta m}{2m_X} \ll g_X \qquad \Rightarrow \text{ fermions decouple from the SM}$$

$$m_+ + m_- > m_X + m_i \qquad \Rightarrow \text{ vector is stable}$$

SIDM possible via freeze-in mechanism ibid.

  - Fermion dark matter

    Baek, Ko, Park, 1112.1847

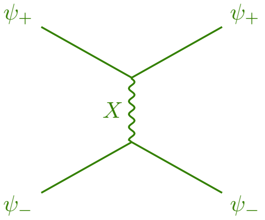
$$\Delta m \gg m_X \;\Rightarrow\; y_X \gg g_X \qquad \Rightarrow \text{ vector decouple from the SM}$$

$$m_+ > m_X \gg m_- \qquad \Rightarrow \psi_- \text{ dominates}$$

SIDM possible after introducing a light mediator Duerr, Schmidt-Hoberg,Wild, 1804.10385

Strongly self-interacting DM

- Light mediator: h_2 (severe ID constraints) or X_μ



requirements

- similar abundance of ψ_+ and ψ_-
  $\Rightarrow \; m_- \gg \Delta m$
- high self-interaction Xsec
  $\Rightarrow \; m_- \gg m_X$
- X_μ decouples from SM much later than $\psi_\pm$ ($y_X \gg g_X$)
  $\Rightarrow \; m_X \gg \Delta m$

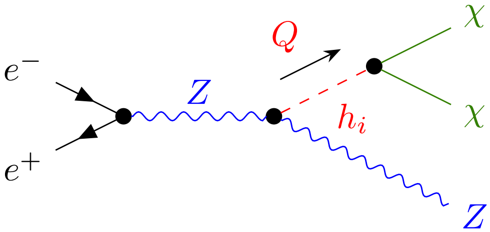
} automatical satisfaction of ID and DD constraints

- Parameters for large fermionic self-interaction

m_- [MeV]	m_X [MeV]	m_2 [MeV]	g_X	$\frac{\sigma_T}{m}$ $\left[\frac{\text{cm}^2}{\text{g}}\right]$
$2 \cdot 10^3$	2.5	2	0.0595	0.7
$5 \cdot 10^3$	4	3	0.0842	1.05
$10 \cdot 10^3$	7	5	0.114	0.75

$\Delta m = 1$ keV $\qquad g_X$ set by Ωh^2 constraint

Disentangling different cases in colliders



$$Q^2 = s - 2E_Z\sqrt{s} + m_Z^2$$

$$\chi = X_\mu,\ \psi_\pm$$

The differential cross-section:

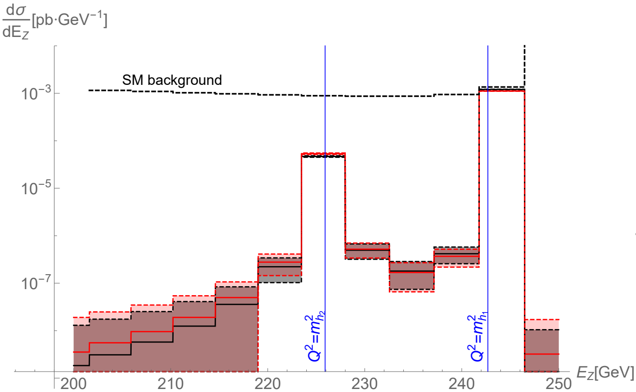
$$\frac{d\sigma}{dE_Z}(E_Z) = \frac{g_v^2 + g_a^2}{12\cdot(2\pi)^3}\sqrt{E_Z^2 - m_Z^2}\left(2m_Z^2 + E_Z^2\right)\left(\frac{g^2}{\cos\theta_W^2}\frac{1}{s - m_Z^2}\right)^2 \times$$

$$\times\ \frac{(\sin 2\alpha)^2\cdot\sqrt{1 - 4\frac{m_{DM}^2}{Q^2}}\cdot(m_1^2 - m_2^2)^2\cdot Q^4}{\left[(Q^2 - m_1^2)^2 + (m_1\Gamma_1)^2\right]\left[(Q^2 - m_2^2)^2 + (m_2\Gamma_2)^2\right]} \times \begin{cases} 2\left(\frac{y_X}{m_\pm}\right)^2\left[\frac{m_\pm^2}{Q^2} - 4\left(\frac{m_\pm^2}{Q^2}\right)^2\right] & \text{(FDM)} \\ \left(\frac{g_X}{m_X}\right)^2\left[1 - 4\frac{m_X^2}{Q^2} + 12\left(\frac{m_X^2}{Q^2}\right)^2\right] & \text{(VDM)} \end{cases}$$

In **theory** a substantial difference!

similar discussion in
- Ko, Yokoya, 1603.04737
- Kamon, Ko, Li, 1705.02149

Disentangling different cases in colliders – predicted shape of ILC data



— fermion DM — vector DM

dashed area – predicted statistical error

parameters of the collider

$$\int \mathscr{L}\, dt = 3500 \text{ fb}^{-1}, \ \sqrt{s} = 500 \text{ GeV}$$

input

$$m_{\text{DM}} = 50 \text{ GeV}, \ m_{h_2} = 180 \text{ GeV}$$
$$g_X = 0.12, \ y_X = 0.3, \ \Delta m = 250 \text{ GeV}$$

output

$$\Gamma_{h_1} = 48 \text{ keV} \quad \Gamma_{h_2} = 400 \text{ keV}$$
$$\text{BR}_{(h_1 \to \text{fer})} = 10.1\% \quad \text{BR}_{(h_2 \to \text{fer})} = 45.9\%$$
$$\text{BR}_{(h_1 \to \text{vec})} = 9.33\% \quad \text{BR}_{(h_2 \to \text{vec})} = 52.6\%$$

In **practice** the difference very hard to see!

Summary

- The simple $U(1)$ extension of the Standard Model gauge group
- DM candidates: two Majorana fermions $\psi_{\pm}$, a gauge boson X_μ mediated by Higgs portal (additional h_2 introduced)
- Convenient framework to analyze various mono- and multi- (2- or 3-) component DM scenarios
- Limiting 1-component cases: VDM, FDM
- SIDM case
- Discovery in colliders possible...
- ...but spin not easy to determine

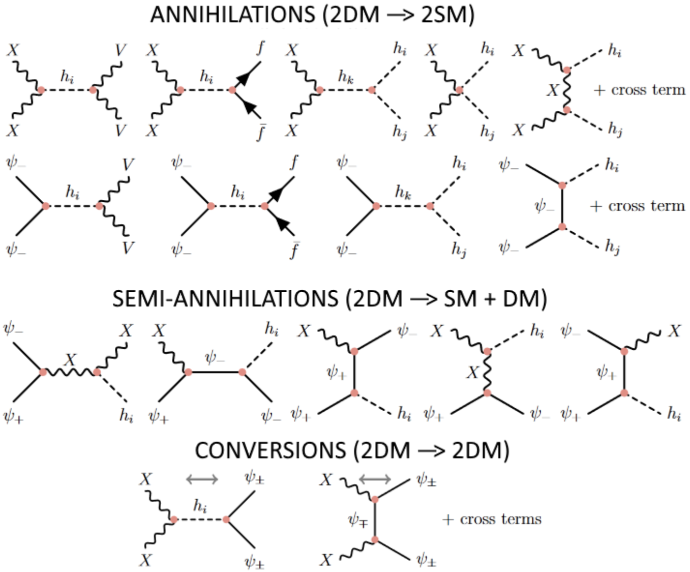
Summary

- The simple $U(1)$ extension of the Standard Model gauge group
- DM candidates: two Majorana fermions $\psi_\pm$, a gauge boson X_μ mediated by Higgs portal (additional h_2 introduced)
- Convenient framework to analyze various mono- and multi- (2- or 3-) component DM scenarios
- Limiting 1-component cases: VDM, FDM
- SIDM case
- Discovery in colliders possible. . .
- . . . but spin not easy to determine

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

2-2 processes



Solving the Boltzmann equations

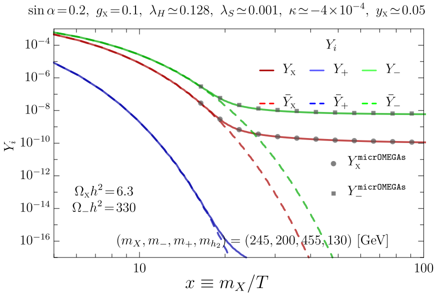
- Experimental constraints $\to$ relic density $\Omega_{\rm DM} h^2 \approx 0.12$
- Convenient variables: $Y \equiv \frac{n}{s}$, $x = \frac{m_{\rm ref}}{T}$ $\Rightarrow$ BEq.: $\frac{dY_i}{dx} = \frac{m_{\rm ref}}{m_i}\frac{dn_i}{dt} + 3Hn$

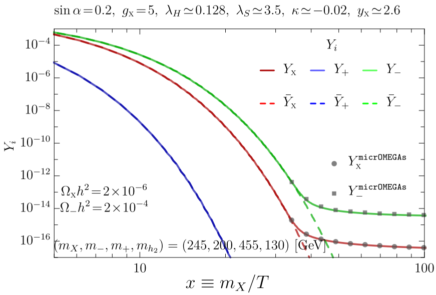
$$\Omega_i h^2 = \frac{h^2 s_0}{\rho_{\rm cr}} m_i Y_i^\infty = 2.742 \times 10^8 \left(\frac{m_i}{\rm GeV}\right) Y_i^\infty$$

- 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`





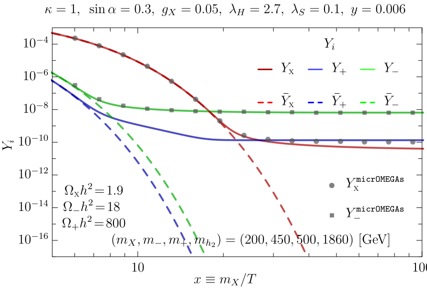
$$\langle \sigma v \rangle = a_0 + a_1 x^{-1} + a_2 x^{-2} + \dots$$

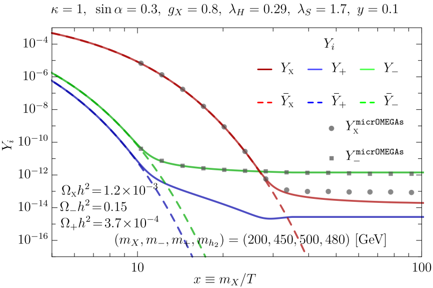
process	a_N	a_{N+1}	N
$XX \to$ SM	$1.2\cdot 10^{-2}$	$-3.5\cdot 10^{-2}$	0
$\psi_+\psi_+ \to$ SM	$2.7\cdot 10^{-4}$	$-8.2\cdot 10^{-4}$	1
$\psi_-\psi_- \to$ SM	$7.8\cdot 10^{-3}$	$-6.2\cdot 10^{-2}$	1
$\Psi_+\Psi_+ \to XX$	$6.9\cdot 10^{-4}$	$1.6\cdot 10^{-3}$	0
$XX \to \Psi_-\Psi_-$	$6.4\cdot 10^{-5}$	$1.6\cdot 10^{-4}$	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

- Third component is influential!
- 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
$XX \to$ SM	$4\cdot10^{-2}$	$-1.9\cdot10^{-2}$	0
$\psi_+\psi_+ \to$ SM	$9.6\cdot10^{-4}$	$-3.1\cdot10^{-4}$	1
$\psi_-\psi_- \to$ SM	$9.9\cdot10^{-4}$	$-1.1\cdot10^{-4}$	1
$\Psi_+\Psi_+ \to XX$	$1\cdot10^{-5}$	$1.7\cdot10^{-5}$	0
$\Psi_-\Psi_- \to XX$	$1.4\cdot10^{-5}$	$1.2\cdot10^{-5}$	0
$\Psi_-\Psi_- \to \Psi_+\Psi_+$	$2.3\cdot10^{-4}$	$5.6\cdot10^{-4}$	0
$\Psi_+\Psi_- \to Xh_1$	$1.6\cdot10^{-6}$	$-2.6\cdot10^{-6}$	0
$Xh_2 \to \Psi_+\Psi_-$	$6.1\cdot10^{-7}$	$6.9\cdot10^{-5}$	0
$X\Psi_- \to \Psi_+h_1$	$7.1\cdot10^{-6}$	$1.1\cdot10^{-4}$	0
$\Psi_+h_2 \to X\Psi_-$	$1.6\cdot10^{-5}$	$1.2\cdot10^{-4}$	0
$X\Psi_+ \to \Psi_-h_1$	$4.7\cdot10^{-7}$	$1.1\cdot10^{-4}$	0
$\Psi_-h_2 \to X\Psi_+$	$9.5\cdot10^{-4}$	$-9.7\cdot10^{-5}$	0

process	a_N	a_{N+1}	N
$XX \to$ SM	$7.82\cdot10^{0}$	$-2.54\cdot10^{0}$	0
$\psi_+\psi_+ \to$ SM	$1.8\cdot10^{-1}$	$-1.1\cdot10^{-1}$	1
$\psi_-\psi_- \to$ SM	$1.7\cdot10^{-1}$	$-7\cdot10^{-2}$	1
$\Psi_+\Psi_+ \to XX$	$6.8\cdot10^{-1}$	$1.03\cdot10^{0}$	0
$\Psi_-\Psi_- \to XX$	$9\cdot10^{-1}$	$6.8\cdot10^{-1}$	0
$\Psi_-\Psi_- \to \Psi_+\Psi_+$	$1.52\cdot10^{1}$	$3.66\cdot10^{1}$	0
$\Psi_+\Psi_- \to Xh_1$	$1\cdot10^{-1}$	$-1.7\cdot10^{-1}$	0
$Xh_2 \to \Psi_+\Psi_-$	$4\cdot10^{-2}$	$4.52\cdot10^{0}$	0
$X\Psi_- \to \Psi_+h_1$	$4.7\cdot10^{-1}$	$7.13\cdot10^{0}$	0
$\Psi_+h_2 \to X\Psi_-$	$1.05\cdot10^{0}$	$7.55\cdot10^{0}$	0
$X\Psi_+ \to \Psi_-h_1$	$3.1\cdot10^{-2}$	$7.31\cdot10^{0}$	0
$\Psi_-h_2 \to X\Psi_+$	$6.2\cdot10^{1}$	$-5.84\cdot10^{0}$	0

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$\rightarrow$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 $m_{h_2} \approx 2m_-$