Vector-fermion dark matter
- preliminary results -

Bohdan GRZADKOWSKI
University of Warsaw

- Multi-component generic dark matter
- Vector-fermion two-component dark matter
- Summary

◇ A. Ahmed, M. Duch, BG and M. Iglicki, "Multi-Component Dark Matter: dark vector boson and dark Majorana fermion(s)", in progress
◇ M. Duch, BG, M. McGarrie, "A stable Higgs portal with vector dark matter", JHEP 1509 (2015) 162
◇ S. Bhattacharya, A. Drozd, BG, J. Wudka, "Two-Component Dark Matter", JHEP 1310 (2013) 158
◇ A. Drozd, BG, J. Wudka, "Multi-Scalar-Singlet Extension of the Standard Model - the Case for Dark Matter and an Invisible Higgs Boson", JHEP 1204 (2012) 006

Multi-component generic dark matter

Motivations:

- Naturality
- No satisfactory single-component model

- Two separate dark sectors, χ_i and $\tilde{\chi}_i$, common dark sector $\tilde{\phi}$ and SM ϕ
- Stabilizing symmetry: $\mathbb{Z}_2 \times \mathbb{Z}_2'$

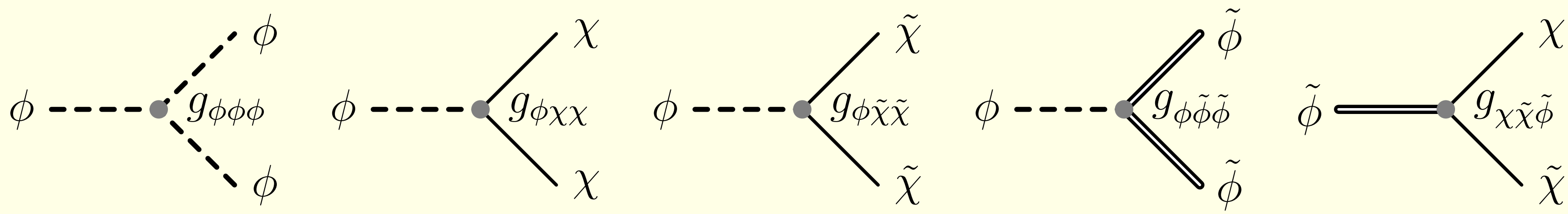
$A(\mathbb{Z}_2, \mathbb{Z}_2')$	$\chi_0(-,+)$	$\chi_1(-,+)$	$\tilde{\phi}(-,-)$
$\tilde{A}(\mathbb{Z}_2, \mathbb{Z}_2')$	$\tilde{\chi}_0(+,-)$	$\tilde{\chi}_1(+,-)$	

$\phi(+,+)$ - SM

We limit our-self to a model that contains three odd particle $\chi, \tilde{\chi}$ and $\tilde{\phi}$:

$A(\mathbb{Z}_2, \mathbb{Z}'_2)$	$\chi(-,+)$	$\tilde{\phi}(-,-)$
$\tilde{A}(\mathbb{Z}_2, \mathbb{Z}'_2)$	$\tilde{\chi}(+,-)$	

$\phi(+,+)$ - SM



$$\chi\chi(\tilde{\chi}\tilde{\chi}, \tilde{\phi}\tilde{\phi}) \leftrightarrow \phi\phi' \qquad \textit{Annihilation}$$

$$\chi\chi \leftrightarrow \tilde{\chi}\tilde{\chi}, \tilde{\phi}\tilde{\phi} \leftrightarrow \chi\chi(\tilde{\chi}\tilde{\chi}) \qquad \textit{Conversion}$$

$$\tilde{\phi}\phi \leftrightarrow \chi\tilde{\chi}, \chi\phi \leftrightarrow \tilde{\chi}\tilde{\phi}\tilde{\chi}\phi \leftrightarrow \chi\tilde{\phi}, \qquad \textit{Semi-annihilation}$$

$$\tilde{\phi} \leftrightarrow \chi\tilde{\chi} \qquad \textit{Semi-decay}$$

where ϕ, ϕ' belong to the visible sector.

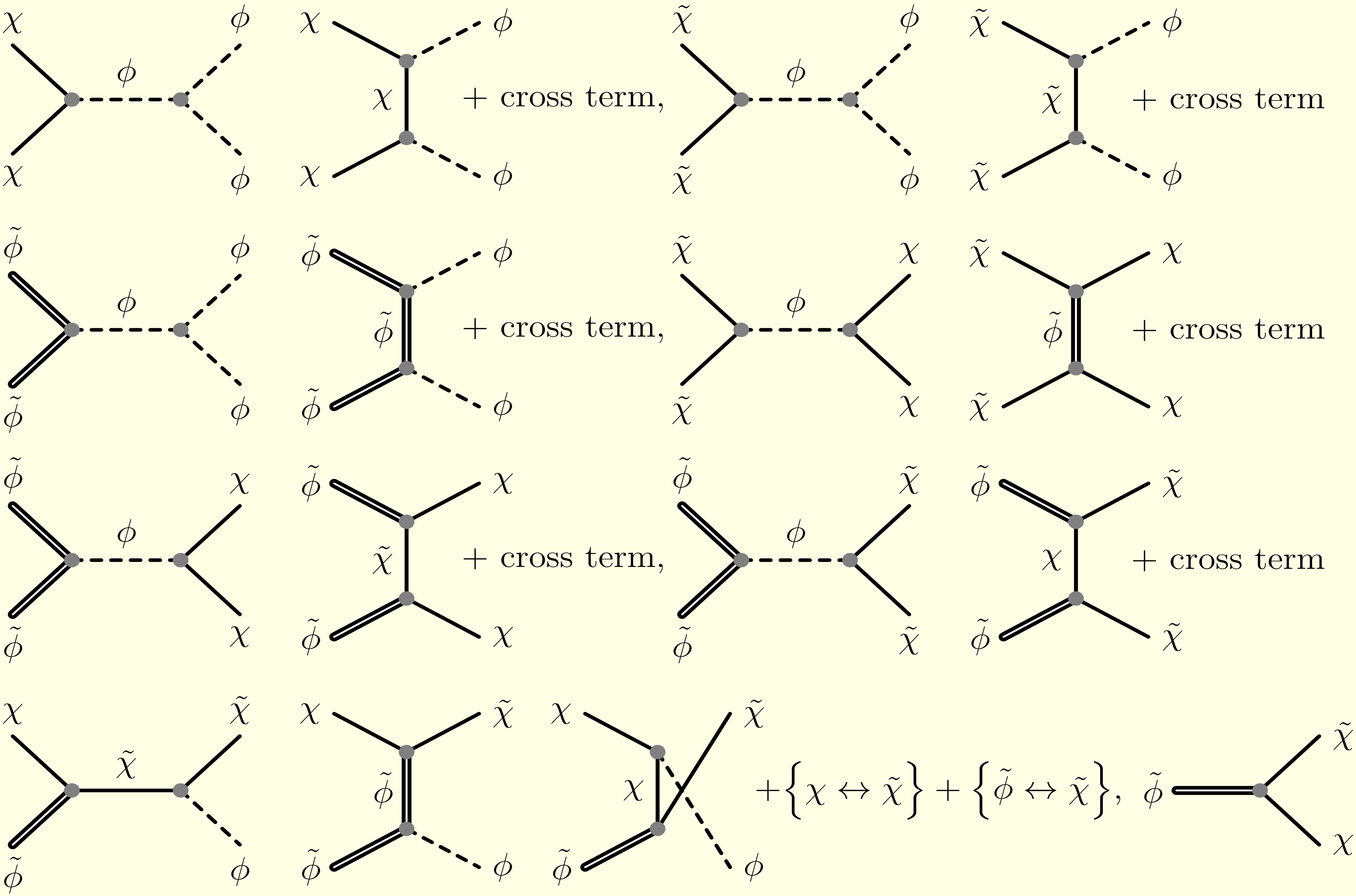


Figure 1: The Feynman diagrams of annihilation, conversion, semi-annihilation, and decay.

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma^{\chi\chi\phi\phi'} v_{\text{Møl}} \rangle \left(n_\chi^2 - \bar{n}_\chi^2\right) - \langle \sigma^{\chi\chi\tilde{\chi}\tilde{\chi}} v_{\text{Møl}} \rangle \left(n_\chi^2 - n_{\tilde{\chi}}^2 \frac{\bar{n}_\chi^2}{\bar{n}_{\tilde{\chi}}^2}\right)$$

$$- \left[\langle \sigma^{\chi\tilde{\phi}\tilde{\chi}\phi} v_{\text{Møl}} \rangle \left(n_\chi n_{\tilde{\phi}} - \bar{n}_\chi \bar{n}_{\tilde{\phi}} \frac{n_{\tilde{\chi}}}{\bar{n}_{\tilde{\chi}}}\right) + \{\chi \leftrightarrow \tilde{\chi}\} + \{\tilde{\phi} \leftrightarrow \tilde{\chi}\}\right]$$

$$+ \Gamma_{\tilde{\phi}\to\chi\tilde{\chi}} \left(n_{\tilde{\phi}} - \bar{n}_{\tilde{\phi}} \frac{n_\chi}{\bar{n}_\chi} \frac{n_{\tilde{\chi}}}{\bar{n}_{\tilde{\chi}}}\right),$$

$$\frac{dn_{\tilde{\chi}}}{dt} = -3Hn_{\tilde{\chi}} - \langle \sigma^{\tilde{\chi}\tilde{\chi}\phi\phi'} v_{\text{Møl}} \rangle \left(n_{\tilde{\chi}}^2 - \bar{n}_{\tilde{\chi}}^2\right) + \langle \sigma^{\chi\chi\tilde{\chi}\tilde{\chi}} v_{\text{Møl}} \rangle \left(n_\chi^2 - n_{\tilde{\chi}}^2 \frac{\bar{n}_\chi^2}{\bar{n}_{\tilde{\chi}}^2}\right)$$

$$- \left[\langle \sigma^{\tilde{\chi}\tilde{\phi}\chi\phi} v_{\text{Møl}} \rangle \left(n_{\tilde{\chi}} n_{\tilde{\phi}} - \bar{n}_{\tilde{\chi}} \bar{n}_{\tilde{\phi}} \frac{n_\chi}{\bar{n}_\chi}\right) + \{\chi \leftrightarrow \tilde{\chi}\} + \{\tilde{\phi} \leftrightarrow \tilde{\chi}\}\right]$$

$$+ \Gamma_{\tilde{\phi}\to\chi\tilde{\chi}} \left(n_{\tilde{\phi}} - \bar{n}_{\tilde{\phi}} \frac{n_\chi}{\bar{n}_\chi} \frac{n_{\tilde{\chi}}}{\bar{n}_{\tilde{\chi}}}\right),$$

$$
\begin{aligned}
\frac{dn_{\tilde{\phi}}}{dt} &= -3Hn_{\tilde{\phi}} - \langle \sigma^{\tilde{\phi}\tilde{\phi}\phi\phi'} v_{\text{Møl}} \rangle \left(n_{\tilde{\chi}}^2 - \bar{n}_{\tilde{\chi}}^2 \right) \\
&- \langle \sigma^{\tilde{\phi}\tilde{\phi}\chi\chi} v_{\text{Møl}} \rangle \left(n_{\tilde{\phi}}^2 - n_{\chi}^2 \frac{\bar{n}_{\tilde{\phi}}^2}{\bar{n}_{\chi}^2} \right) - \langle \sigma^{\tilde{\phi}\tilde{\phi}\tilde{\chi}\tilde{\chi}} v_{\text{Møl}} \rangle \left(n_{\tilde{\phi}}^2 - n_{\tilde{\chi}}^2 \frac{\bar{n}_{\tilde{\phi}}^2}{\bar{n}_{\tilde{\chi}}^2} \right) \\
&- \left[\langle \sigma^{\tilde{\chi}\tilde{\phi}\chi\phi} v_{\text{Møl}} \rangle \left(n_{\tilde{\chi}} n_{\tilde{\phi}} - \bar{n}_{\tilde{\chi}} \bar{n}_{\tilde{\phi}} \frac{n_{\chi}}{\bar{n}_{\chi}} \right) + \{ \chi \leftrightarrow \tilde{\chi} \} + \{ \tilde{\phi} \leftrightarrow \tilde{\chi} \} \right] \\
&- \Gamma_{\tilde{\phi} \to \chi\tilde{\chi}} \left(n_{\tilde{\phi}} - \bar{n}_{\tilde{\phi}} \frac{n_{\chi}}{\bar{n}_{\chi}} \frac{n_{\tilde{\chi}}}{\bar{n}_{\tilde{\chi}}} \right) .
\end{aligned}
$$

I: $m_{\tilde{\phi}} > m_{\tilde{\chi}} + m_{\chi},$

II: $m_{\tilde{\chi}} > m_{\chi} + m_{\tilde{\phi}},$

III: $m_{\chi} > m_{\tilde{\chi}} + m_{\tilde{\phi}}.$

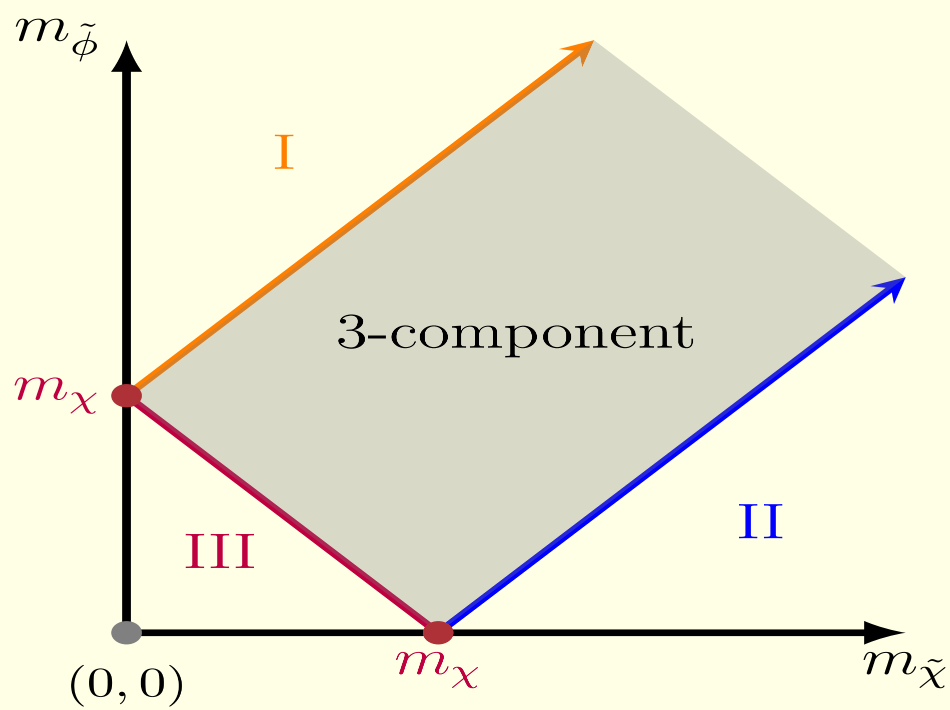
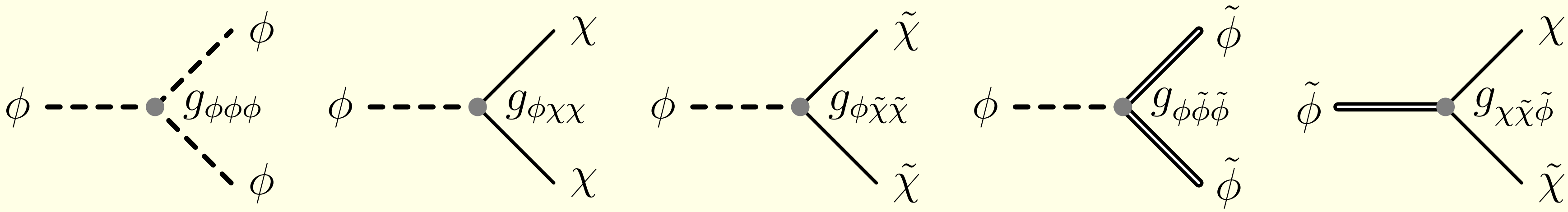


Figure 2: 2- and 3-component dark matter scenarios, we consider m_{χ} to be fixed, the gray region represent parameter space where the all three dark sector particles are stable, whereas the regions I, II and III represent the 2-component scenarios with $\tilde{\phi}, \tilde{\chi}$ and χ are unstable, respectively.



$$\alpha \equiv \frac{g_{\phi\phi\phi}}{g_{\mathsf{SM}}} = \frac{g_{\phi\chi\chi}}{g_{\mathsf{SM}}} = \frac{g_{\phi\tilde{\chi}\tilde{\chi}}}{g_{\mathsf{SM}}}, \quad \beta \equiv \frac{g_{\phi\tilde{\phi}\tilde{\phi}}}{g_{\mathsf{SM}}}, \quad \xi \equiv \frac{g_{\chi\tilde{\chi}\tilde{\phi}}}{g_{\mathsf{SM}}}.$$

- All the thermally averaged cross sections of the order of the electroweak scale, i.e.

$$\langle \sigma^{abcd} v_{\mathsf{Møl}} \rangle \approx \frac{G_F^2}{2\pi} m^2 f^2(\alpha, \beta, \xi) \sim \sigma_0 f_{abcd}^2(\alpha, \beta, \xi),$$

where $\sigma_0 \equiv \frac{G_F^2}{2\pi} m^2 \sim 10^{-11}$ GeV^{-2} and m is the mass of dark matter candidate which is order electroweak scale ~ 100 GeV. $f_{abcd}(\alpha, \beta, \xi)$ is a dimensionless function which parametrizes the couplings of each annihilation diagrams in terms of α, β and ξ.

- We parameterize all the thermally average cross sections $\langle \sigma^{abcd} v_{\text{Møl}} \rangle$ in terms of $f_{abcd}(\alpha, \beta, \xi)$:

$$\begin{aligned} f_{\chi\chi\phi\phi'} \sim f_{\tilde{\chi}\tilde{\chi}\phi\phi'} &\propto \alpha^2, \\ f_{\tilde{\phi}\tilde{\phi}\phi\phi'} &\propto (\alpha + \beta)\beta, \\ f_{\chi\tilde{\phi}\tilde{\chi}\phi} \sim f_{\tilde{\chi}\tilde{\phi}\chi\phi} \sim f_{\chi\tilde{\chi}\tilde{\phi}\phi} &\propto (\alpha + \beta)\xi, \\ f_{\chi\phi\tilde{\chi}\tilde{\phi}} \sim f_{\tilde{\chi}\phi\chi\tilde{\phi}} \sim f_{\tilde{\phi}\phi\chi\tilde{\chi}} &\propto (\alpha + \beta)\xi, \\ f_{\chi\chi\tilde{\chi}\tilde{\chi}} \sim f_{\tilde{\chi}\tilde{\chi}\chi\chi} &\propto (\alpha^2 + \xi^2), \\ f_{\tilde{\phi}\tilde{\phi}\chi\chi} \sim f_{\tilde{\phi}\tilde{\phi}\tilde{\chi}\tilde{\chi}} &\propto (\alpha\beta + \xi^2). \end{aligned}$$

- Decay width of the $\tilde{\phi}$ is approximately $\Gamma_{\tilde{\phi}\to\chi\tilde{\chi}} \sim \xi^2 \times \mathcal{O}(1)$ GeV when the decay processes are kinematically allowed otherwise it is zero.

- SM is in thermal equilibrium, so $Y_\phi \sim \bar{Y}_\phi$.

Case-I: $m_{\tilde{\phi}} \gtrsim m_{\tilde{\chi}} + m_{\chi}$

BMP-I: $m_{\tilde{\phi}} = 300$ GeV, $m_{\tilde{\chi}} = 150$ GeV and $m_{\chi} = 100$ GeV

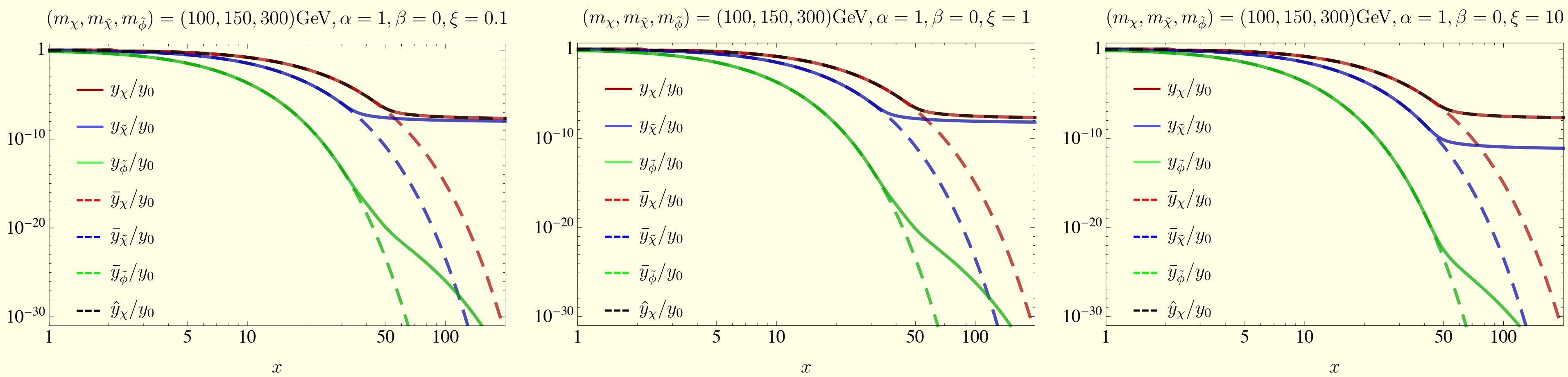


Figure 3: The left, middle and right plots are for the values of parameter $\xi = 0.1, 1$ and 10, respectively. The values of other parameters are kept fixed $\alpha = 1$ and $\beta = 0$. Hereafter x is defined as $x \equiv m_{\tilde{\phi}}/T$.

- In this 2CDM scenario it is interesting to observe the decoupling of the $\tilde{\phi}$ from the thermal bath. Note that we consider $\beta \equiv g_{\phi\tilde{\phi}\tilde{\phi}}/g_{\text{SM}} = 0$ and hence there is no direct annihilation of the $\tilde{\phi}\tilde{\phi}$ to SM fields. The only way the $\tilde{\phi}$ disappears into the SM states, is through the scattering processes $\chi\phi \leftrightarrow \tilde{\phi}\tilde{\chi}$ and $\tilde{\chi}\phi \leftrightarrow \tilde{\phi}\chi$. Therefore when any of the two remaining states χ or $\tilde{\chi}$ decouples from the equilibrium, then the $\tilde{\phi}$ also decouples.

Case-II: $m_{\tilde{\chi}} \gtrsim m_\chi + m_{\tilde{\phi}}$

BMP-II: $m_{\tilde{\phi}} = 125$ GeV, $m_{\tilde{\chi}} = 250$ GeV and $m_\chi = 100$ GeV

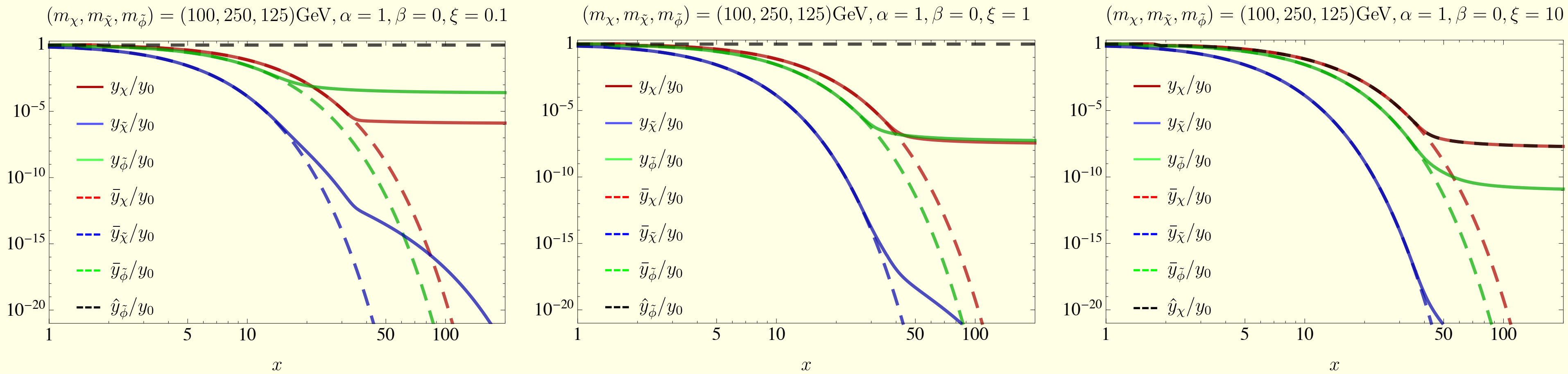


Figure 4: The left, middle and right plots are for the values of parameter $\xi = 0.1, 1$ and 10, respectively. The values of other parameters are kept fixed $\alpha = 1$ and $\beta = 0$.

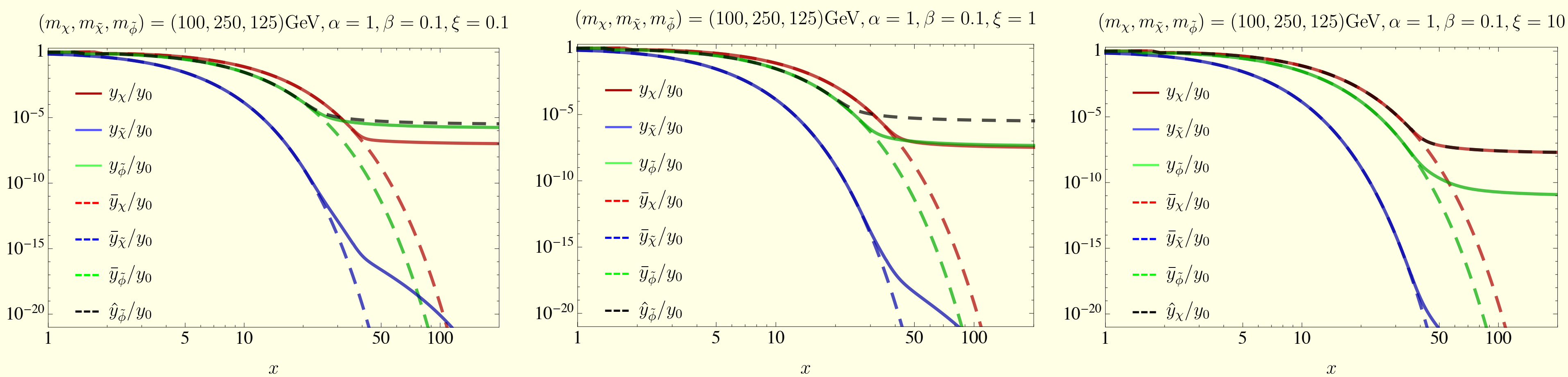


Figure 5: As above, but with $\beta = 0.1$.

Case-III: $m_\chi \gtrsim m_{\tilde{\chi}} + m_{\tilde{\phi}}$

BMP-III: $m_{\tilde{\phi}} = 25$ GeV, $m_{\tilde{\chi}} = 50$ GeV and $m_\chi = 100$ GeV

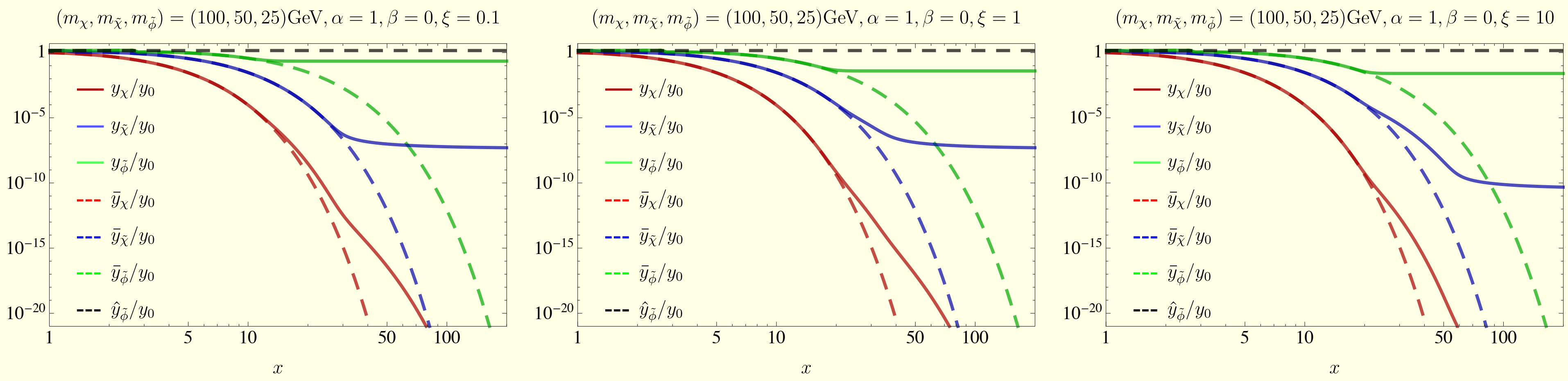


Figure 6: The left, middle and right plots are for the values of parameter $\xi = 0.1, 1$ and 10, respectively. The values of other parameters are kept fixed $\alpha = 1$ and $\beta = 0$.

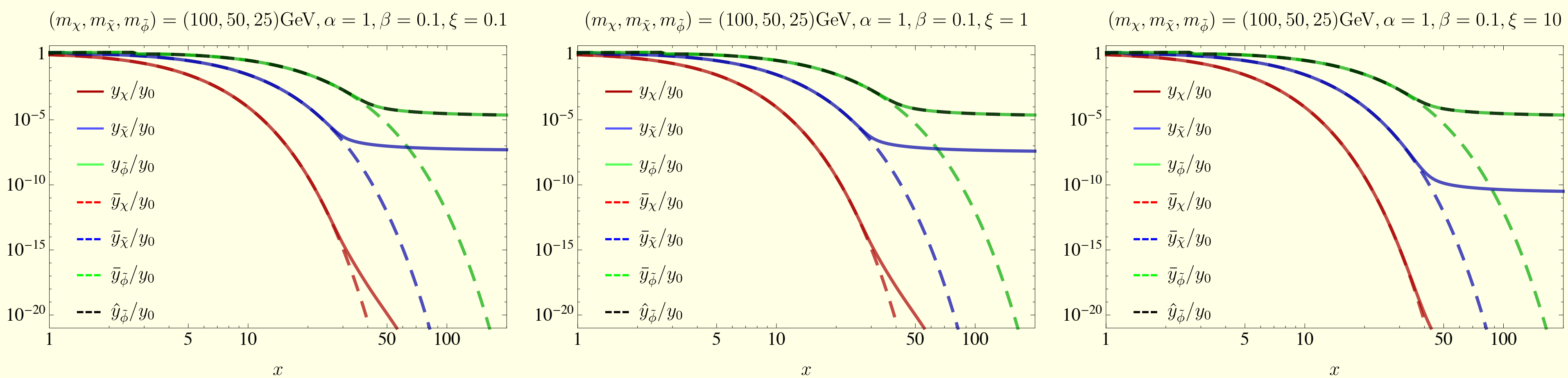


Figure 7: As above, but with $\beta = 0.1$.

Three-component dark matter scenario

BMP-IV: $m_{\tilde{\phi}} = 50$ GeV, $m_{\tilde{\chi}} = 75$ GeV and $m_{\chi} = 100$ GeV

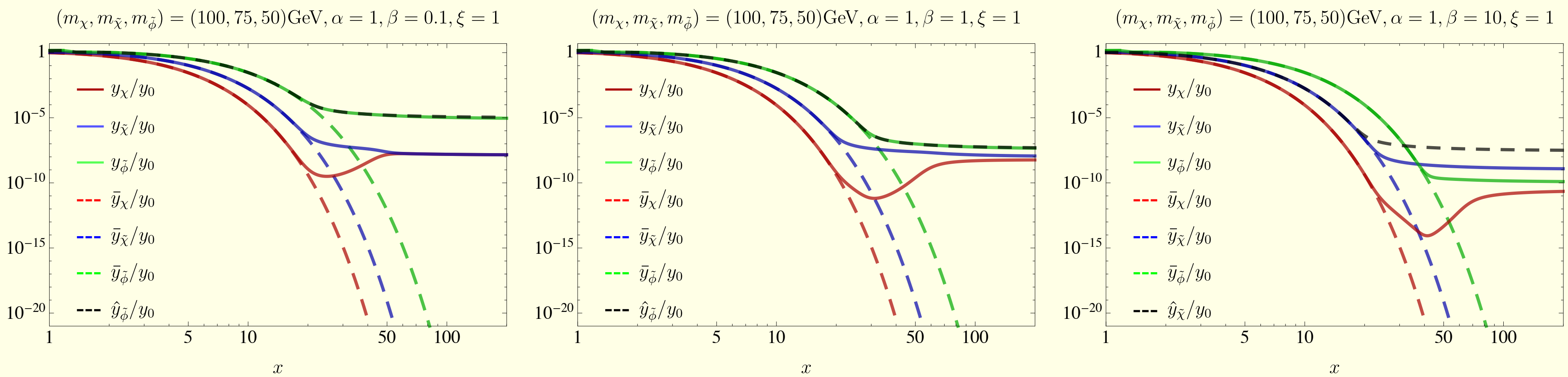


Figure 8: The left, middle and right plots are for the values of parameter $\beta = 0.1, 1$ and 10, respectively. The values of other parameters are kept fixed $\alpha = 1$ and $\xi = 1$.

Three-component dark matter scenario

BMP-V: $m_{\tilde{\phi}} = 50$ GeV, $m_{\tilde{\chi}} = 50$ GeV and $m_{\chi} = 100$ GeV

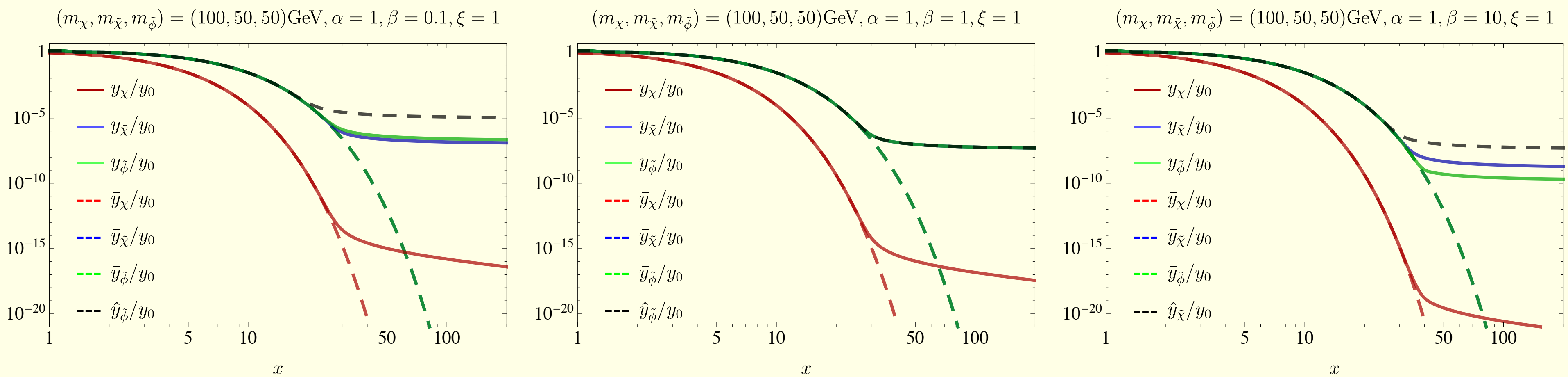


Figure 9: The left, middle and right plots are for the values of parameter $\beta = 0.1, 1$ and 10, respectively. The values of other parameters are kept fixed $\alpha = 1$ and $\xi = 1$.

Vector-fermion two-component dark matter

$$\mathcal{G}_{SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \quad \mathcal{G}_{DS} \equiv U(1)_X$$

$$S = (\mathbf{1}, \mathbf{1}, 0, 2), \quad \chi = (\mathbf{1}, \mathbf{1}, 0, 1).$$

SM fields are neutral under the dark-sector gauge group $\mathcal{G}_{DS}$.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \mathcal{L}_{int},$$

where $\mathcal{L}_{SM}$ is the SM Lagrangian, $\mathcal{L}_{DS}$ is the dark-sector Lagrangian,

$$\mathcal{L}_{DS} = -\frac{1}{4}\mathcal{F}^X_{\mu\nu}\mathcal{F}^{\mu\nu}_X + \left(\mathcal{D}_\mu S\right)^* \mathcal{D}^\mu S + \mu_S^2 |S|^2 - \lambda_S |S|^4$$
$$+ \bar{\chi}\left(i\not{D} - m_D\right)\chi - \frac{1}{\sqrt{2}}\left(y S^* \chi^{\mathsf{T}} \mathcal{C} \chi + \text{H.c.}\right),$$

and $\mathcal{L}_{int}$ is the interaction Lagrangian between the SM and the dark-sector,

$$\mathcal{L}_{int} = -\kappa |S|^2 |H|^2.$$

Charge conjugation symmetry $\mathcal{C}$:

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

where γ_2 is the gamma matrix. It is instructive to write the scalar potential for our model,

$$V(H,S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|H|^2|S|^2.$$

T. Hambye, JHEP 0901 (2009) 028,
M. Duch, BG, M. McGarrie, JHEP 1509 (2015) 162,
S. Weinberg, Phys. Rev. Lett. 110, 24, (2013) 241301

Tree-level positivity or stability of scalar potential implies the following constraints:

$$\lambda_H > 0, \quad \lambda_S > 0, \quad \kappa > -2\sqrt{\lambda_H\lambda_S}$$

Minimization conditions for the scalar potential:

$$\big(2\lambda_H v^2 - 2\mu_H^2 + \kappa v_x^2\big)v = 0, \quad \big(2\lambda_S v_x^2 - 2\mu_S^2 + \kappa v^2\big)v_x = 0,$$

where $\langle H^\intercal \rangle \equiv (0, v/\sqrt{2})$ and $\langle S \rangle \equiv v_x/\sqrt{2}$ are the vevs of respective fields. we require $\kappa^2 > 4\lambda_H\lambda_S$ and the values of vevs are:

$$v^2 = \frac{4\lambda_S\mu_H^2 - 2\kappa\mu_S^2}{4\lambda_H\lambda_S - \kappa^2}, \quad v_x^2 = \frac{4\lambda_H\mu_S^2 - 2\kappa\mu_H^2}{4\lambda_H\lambda_S - \kappa^2}.$$

We expand the Higgs doublet and the singlet around their vevs as follow:

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\pi^+ \\ v + h + i\pi^0 \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}\big(v_x + \phi + i\sigma\big),$$

where $\pi^{0,\pm}$ and σ are the Goldstone modes and they will be gauged away in the unitary gauge to give masses to $Z, W^\pm$ and X.

The mass squared matrix for the scalar fluctuations (h, ϕ)

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & \kappa v v_x \\ \kappa v v_x & 2\lambda_S v_x^2 \end{pmatrix}.$$

$\mathcal{M}^2$ can be diagonalized by the orthogonal rotational matrix $\mathcal{R}$, such that,

$$\mathcal{M}^2_{\text{diag}} \equiv \mathcal{R}^{-1}\mathcal{M}^2\mathcal{R} = \begin{pmatrix} m^2_{h_1} & 0 \\ 0 & m^2_{h_2} \end{pmatrix}, \quad \text{where} \quad \mathcal{R} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix},$$

where (h_1, h_2) are the two Higgs physical states in the mass eigen bases with masses $(m^2_{h_1}, m^2_{h_2})$, defined in terms of (h, ϕ)

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathcal{R}^{-1} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

$$\sin 2\alpha = \frac{\text{sign}(\lambda_{SM} - \lambda_H)\, 2\mathcal{M}_{12}^2}{\sqrt{(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2)^2 + 4(\mathcal{M}_{12}^2)^2}}, \quad \cos 2\alpha = \cdots .$$

There are 5 real parameters in the potential: μ_H, μ_S, λ_H, λ_S and κ. Adopting the minimization conditions μ_H, μ_S could be replaced by v and v_x. The SM vev is fixed at $v = 246.22$ GeV. Using the condition $M_{h_1} = 125.7$ GeV, v_x^2 could be eliminated in terms of $v^2, \lambda_H, \kappa, \lambda_S, \lambda_{SM} = M_{h_1}^2/(2v^2)$:

$$v_x^2 = v^2 \frac{4\lambda_{SM}(\lambda_H - \lambda_{SM})}{4\lambda_S(\lambda_H - \lambda_{SM}) - \kappa^2}$$

Eventually there are 4 independent parameters:

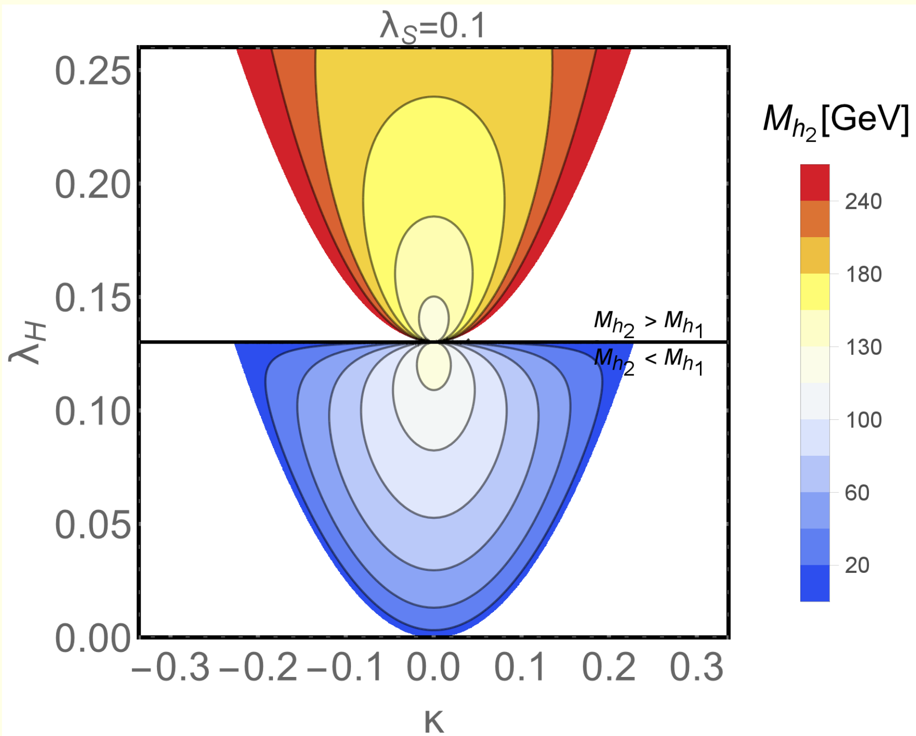
$$(\lambda_H, \kappa, \lambda_S, g_x),$$

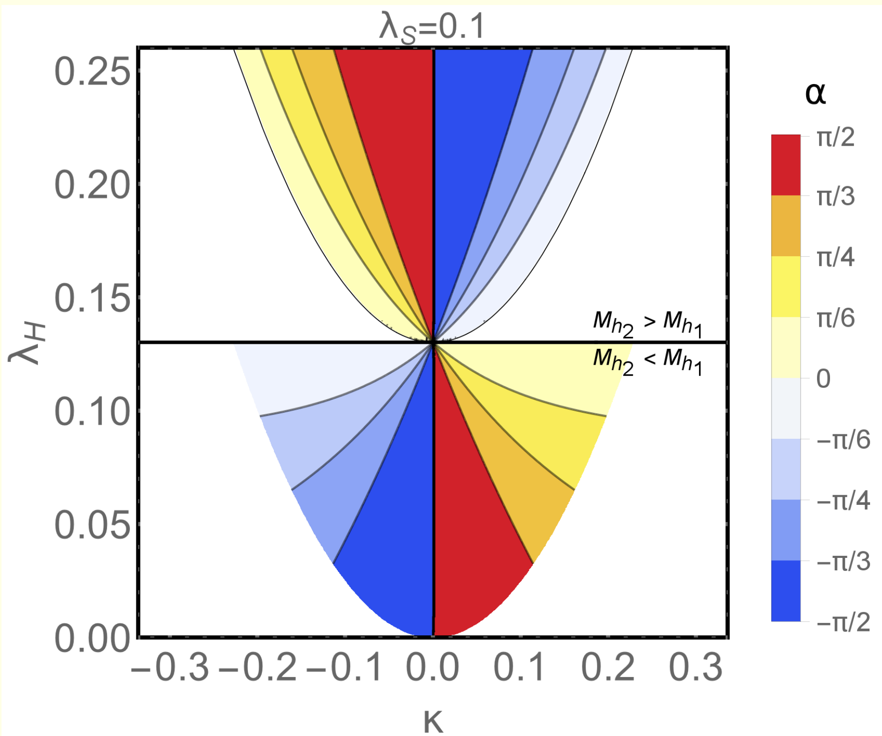
where g_x is the $U(1)_X$ coupling constant.

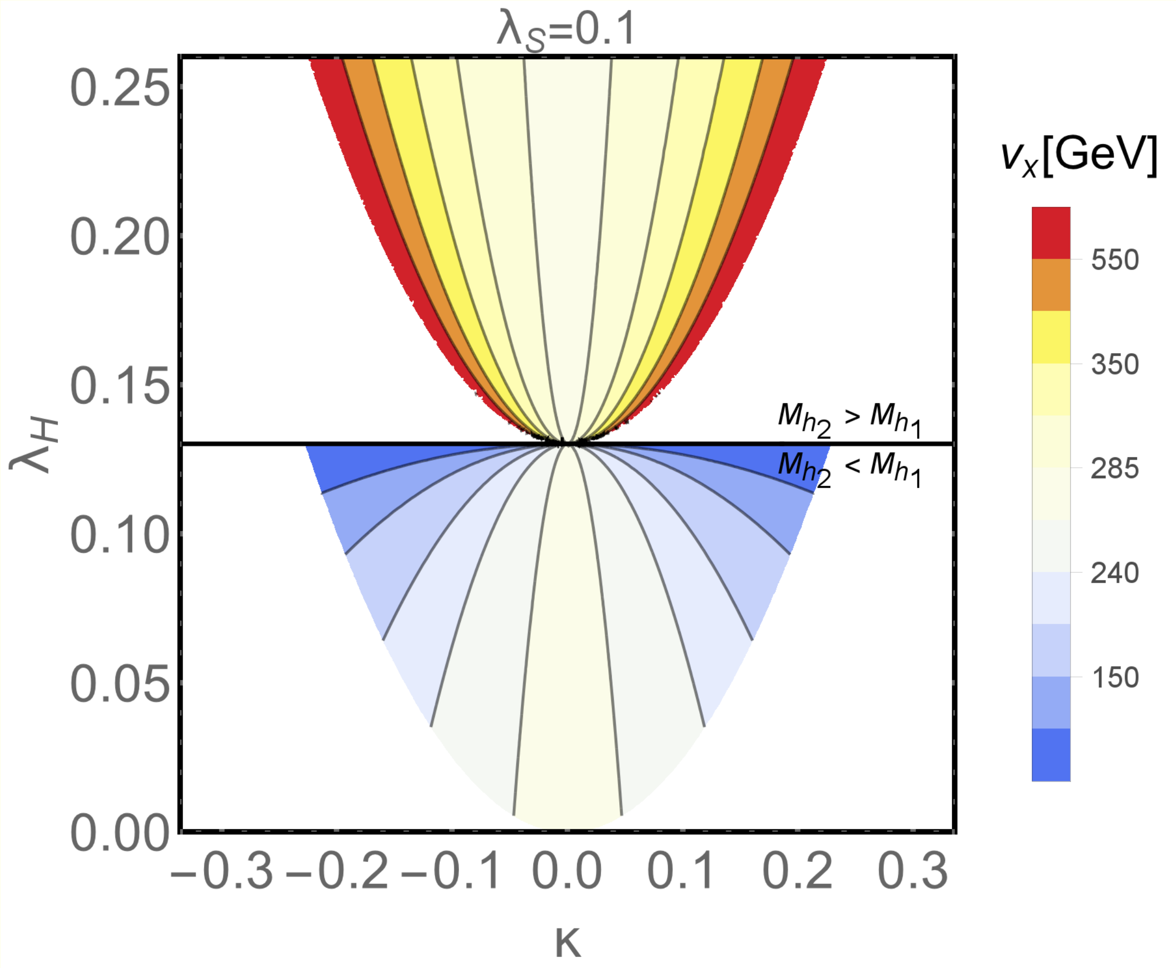
- Bottom part of the plot ($\lambda_H < \lambda_{SM} = M_{h_1}^2/(2v^2) = 0.13$): the heavier Higgs is the currently observed one.

- Upper part ($\lambda_H > \lambda_{SM}$) the lighter state is the observed one.

- White regions in the upper and lower parts are disallowed by the positivity conditions for v_x^2 and $M_{h_2}^2$, respectively.







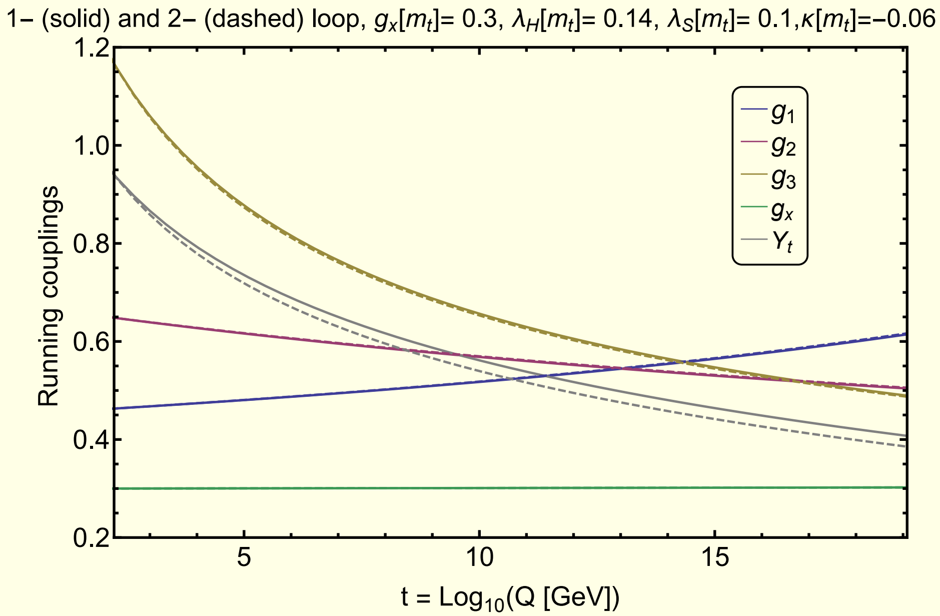
Contour plots for the vacuum expectation value of the extra scalar $v_x \equiv \sqrt{2}\langle S\rangle$.

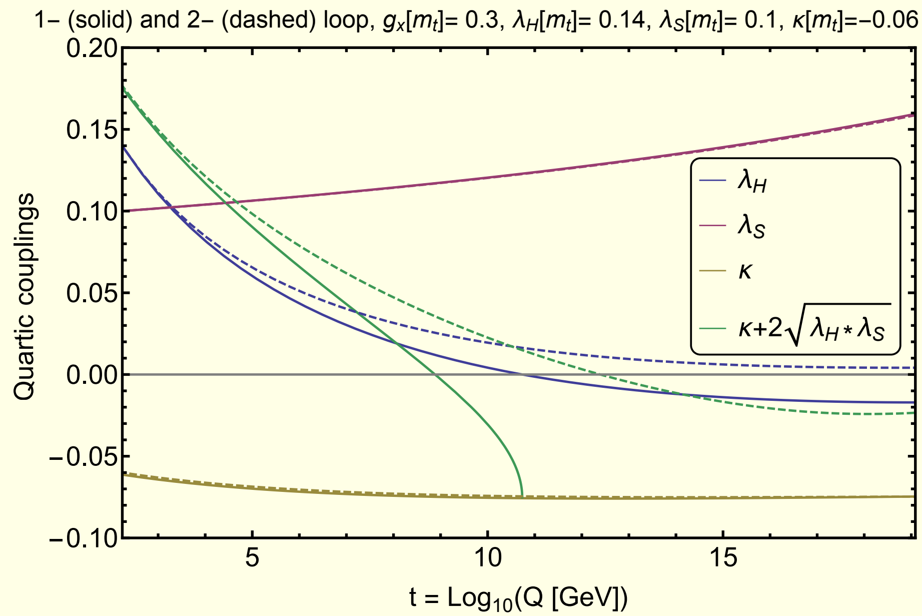
Vacuum stability

$$V = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

2-loop running of parameters adopted

$$\lambda_H(Q) > 0, \quad \lambda_S(Q) > 0, \quad \kappa(Q) + 2\sqrt{\lambda_H(Q)\lambda_S(Q)} > 0$$





The mass of the Higgs boson is known experimentally therefore within *the SM* the initial condition for running of $\lambda_H(Q)$ is fixed

$$\lambda_H(m_t) = M_{h_1}^2/(2v^2) = \lambda_{SM} = 0.13$$

For VDM this is not necessarily the case:

$$M_{h_1}^2 = \lambda_H v^2 + \lambda_S v_x^2 \pm \sqrt{\lambda_S^2 v_x^4 - 2\lambda_H \lambda_S v^2 v_x^2 + \lambda_H^2 v^4 + \kappa^2 v^2 v_x^4}.$$

VDM:

- Larger initial values of λ_H such that $\lambda_H(m_t) > \lambda_{SM}$ are allowed delaying the instability (by shifting up the scale at which $\lambda_H(Q) < 0$).
- Even if the initial λ_H is smaller than its SM value, $\lambda_H(m_t) < \lambda_{SM}$, still there is a chance to lift the instability scale if appropriate initial value of the portal coupling $\kappa(m_t)$ is chosen.

$$\beta_{\lambda_H}^{(1)} = \beta_{\lambda_H}^{SM\ (1)} + \kappa^2$$

After the SSB the dark fermionic sector Lagrangian can be rewritten as,

$$\mathcal{L}_F = \frac{i}{2}\left(\bar{\chi}\gamma^\mu\partial_\mu\chi + \bar{\chi^c}\gamma^\mu\partial_\mu\chi^c\right) - \frac{m_D}{2}\left(\bar{\chi}\chi + \bar{\chi^c}\chi^c\right) - \frac{yv_x}{2}\left(\bar{\chi}^c\chi + \bar{\chi}\chi^c\right)$$
$$- \frac{g_X}{2}\left(\bar{\chi}\gamma^\mu\chi - \bar{\chi^c}\gamma^\mu\chi^c\right)X_\mu - \frac{y}{2}\left(\bar{\chi}^c\chi + \bar{\chi}\chi^c\right)\phi.$$

Mass eigenstates

$$\psi_+ \equiv \frac{1}{\sqrt{2}}\left(\chi + \chi^c\right), \qquad \psi_- \equiv \frac{1}{i\sqrt{2}}\left(\chi - \chi^c\right),$$

with $m_\pm = m_D \pm yv_x$.
In the new bases we can rewrite the above dark fermionic Lagrangian as,

$$\mathcal{L}_F = \frac{i}{2}\left(\bar{\psi}_+\gamma^\mu\partial_\mu\psi_+ + \bar{\psi}_-\gamma^\mu\partial_\mu\psi_-\right) - \frac{1}{2}m_+\bar{\psi}_+\psi_+ - \frac{1}{2}m_-\bar{\psi}_-\psi_-$$
$$- \frac{i}{2}g_X\left(\bar{\psi}_+\gamma^\mu\psi_- + \bar{\psi}_-\gamma^\mu\psi_+\right)X_\mu - \frac{y}{2}\left(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-\right)\phi.$$

The dark fermionic mass eigenstates $\psi_\pm$ are Majorana fermions and the mass difference between the two Majorana states ($\psi_\pm$) is defined as,

$$\Delta m_\psi \equiv m_+ - m_- = 2yv_x$$

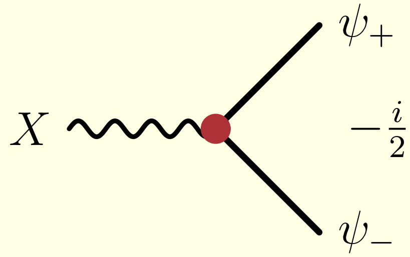
Note that the above Lagrangian has a discrete symmetry $Z_2 \times Z_2'$, under which the SM fields are even whereas the dark sector fields transform as follows

Symmetry	X_μ	ψ_+	ψ_-	ϕ
Z_2	$-$	$+$	$-$	$+$
Z_2'	$-$	$-$	$+$	$+$

Table 1: Discrete symmetries: $Z_2 \times Z_2'$

$A(\mathbb{Z}_2, \mathbb{Z}_2')$	$\chi(-,+)$	$\tilde{\phi}(-,-)$
$\tilde{A}(\mathbb{Z}_2, \mathbb{Z}_2')$	$\tilde{\chi}(+,-)$	

$\phi(+,+)$ - SM



$-\frac{i}{2} g_X \left(\bar{\psi}_+ \gamma^\mu \psi_- + \bar{\psi}_- \gamma^\mu \psi_+\right) X_\mu$

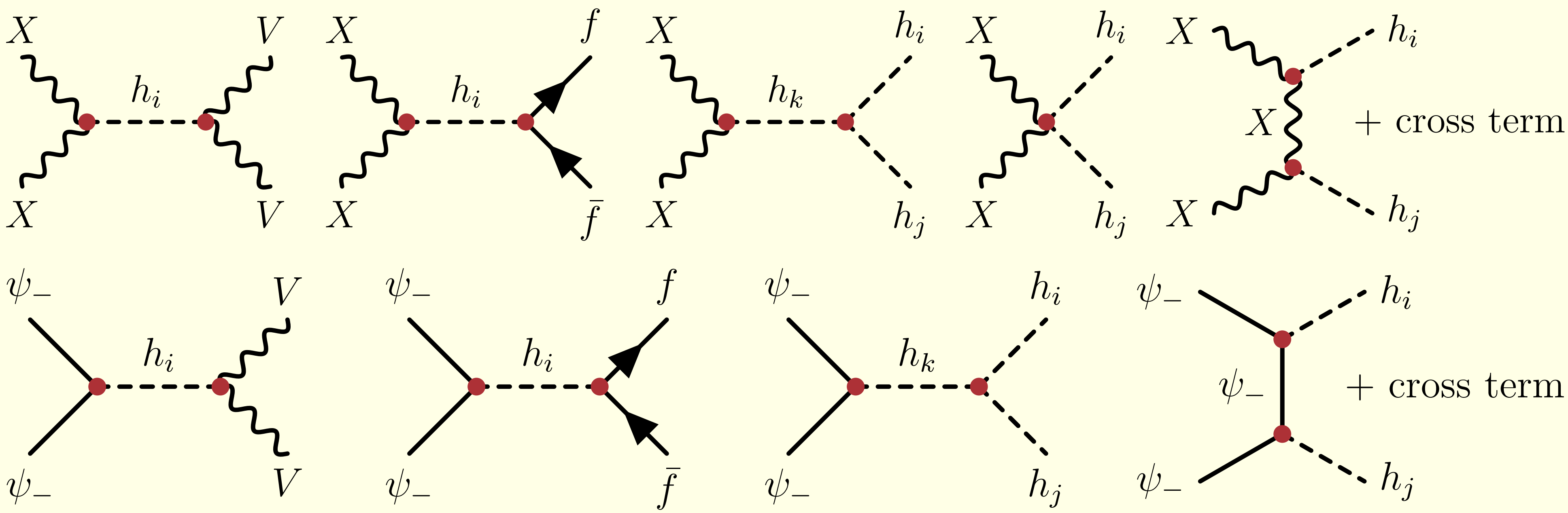


Figure 10: The vector dark matter X_μ and Majorana fermion dark matter $\psi_\pm$ annihilation diagrams. Above V and $(\bar{f})f$ denote the SM vector bosons ($W^\pm$ and Z) and the SM (anti)fermions (quarks and leptons).

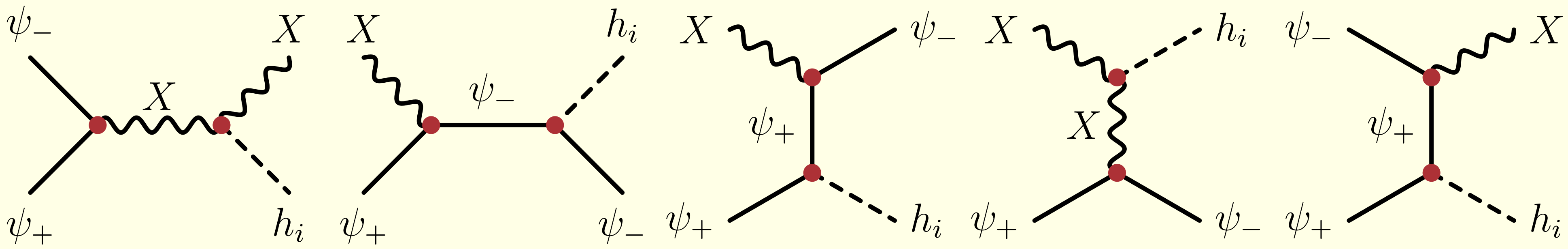


Figure 11: Semi-annihilation diagrams for the dark particles.

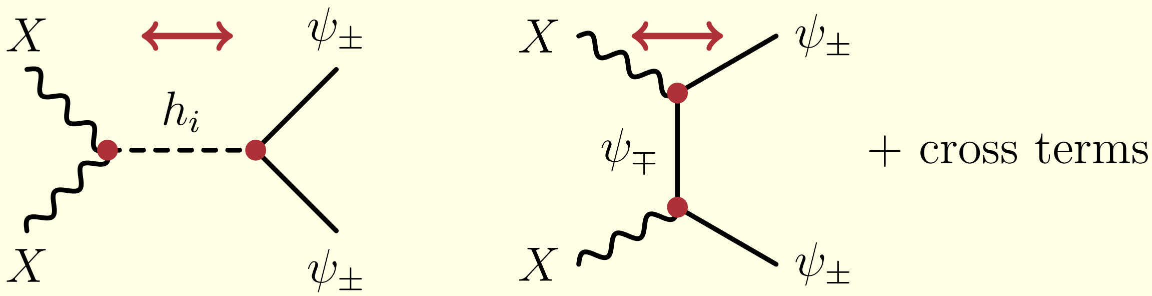


Figure 12: Dark matter conversion processes.

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

$$- \langle\sigma^{X\psi_-\psi_+h_i}_{v_{\text{Møl}}}\rangle\left(n_X n_{\psi_-} - \bar{n}_X\bar{n}_{\psi_-}\frac{n_{\psi_+}}{\bar{n}_{\psi_+}}\right) - \langle\sigma^{Xh_i\psi_+\psi_-}_{v_{\text{Møl}}}\rangle\bar{n}_{h_i}\left(n_X - \bar{n}_X\frac{n_{\psi_+}n_{\psi_-}}{\bar{n}_{\psi_+}\bar{n}_{\psi_-}}\right)$$

$$- \langle\sigma^{XX\psi_+\psi_+}_{v_{\text{Møl}}}\rangle\left(n_X^2 - \bar{n}_X^2\frac{n_{\psi_+}^2}{\bar{n}_{\psi_+}^2}\right) - \langle\sigma^{XX\psi_-\psi_-}_{v_{\text{Møl}}}\rangle\left(n_X^2 - \bar{n}_X^2\frac{n_{\psi_-}^2}{\bar{n}_{\psi_-}^2}\right)$$

$$+ \Gamma_{\psi_+\to X\psi_-}\left(n_{\psi_+} - \bar{n}_{\psi_+}\frac{n_X}{\bar{n}_X}\frac{n_{\psi_-}}{\bar{n}_{\psi_-}}\right),$$

$$
\begin{aligned}
\frac{dn_{\psi_-}}{dt} &= -3Hn_{\psi_-} - \langle \sigma^{\psi_-\psi_-\phi\phi'}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_-} - \bar{n}^2_{\psi_-} \right) - \langle \sigma^{\psi_-\psi_+ X h_i}_{v_{\text{Møl}}} \rangle \left(n_{\psi_-} n_{\psi_+} - \bar{n}_{\psi_-} \bar{n}_{\psi_+} \frac{n_X}{\bar{n}_X} \right) \\
&- \langle \sigma^{X\psi_-\psi_+ h_i}_{v_{\text{Møl}}} \rangle \left(n_X n_{\psi_-} - \bar{n}_X \bar{n}_{\psi_-} \frac{n_{\psi_+}}{\bar{n}_{\psi_+}} \right) - \langle \sigma^{\psi_- h_i X \psi_+}_{v_{\text{Møl}}} \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^{\psi_-\psi_- XX}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_-} - \bar{n}^2_{\psi_-} \frac{n^2_X}{\bar{n}^2_X} \right) - \langle \sigma^{\psi_-\psi_-\psi_+\psi_+}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_-} - \bar{n}^2_{\psi_-} \frac{n^2_{\psi_+}}{\bar{n}^2_{\psi_+}} \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} &= -3Hn_{\psi_+} - \langle \sigma^{\psi_+\psi_+\phi\phi'}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_+} - \bar{n}^2_{\psi_+} \right) - \langle \sigma^{\psi_+\psi_- X h_i}_{v_{\text{Møl}}} \rangle \left(n_{\psi_+} n_{\psi_-} - \bar{n}_{\psi_+} \bar{n}_{\psi_-} \frac{n_X}{\bar{n}_X} \right) \\
&- \langle \sigma^{X\psi_+\psi_- h_i}_{v_{\text{Møl}}} \rangle \left(n_X n_{\psi_+} - \bar{n}_X \bar{n}_{\psi_+} \frac{n_{\psi_-}}{\bar{n}_{\psi_-}} \right) - \langle \sigma^{\psi_+ h_i X \psi_-}_{v_{\text{Møl}}} \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^{\psi_+\psi_+ XX}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_+} - \bar{n}^2_{\psi_+} \frac{n^2_X}{\bar{n}^2_X} \right) - \langle \sigma^{\psi_+\psi_+\psi_-\psi_-}_{v_{\text{Møl}}} \rangle \left(n^2_{\psi_+} - \bar{n}^2_{\psi_+} \frac{n^2_{\psi_-}}{\bar{n}^2_{\psi_-}} \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),
\end{aligned}
$$

Input parameters and strategies

- potential: 5 $(\mu_H, \mu_S, \lambda_H, \lambda_S, \kappa)$, vector DM: 1 (g_x), fermionic DM: 2 (m_D, y),
- $v = 246$ GeV and $M_{h_1} = 125$ GeV,
- we adopt: $\kappa, \sin\alpha, m_X, g_x, m_\pm$, then $M_{h_2}, \mu_H, \mu_S, \lambda_H, \lambda_S$ and m_D, y are calculable.

$$m_X = g_x v_x \quad m_\pm = m_D \pm y v_x$$

Strategies:

A: $y \ll 1$ $(m_+ \simeq m_-)$ $\Longrightarrow$ slow $\psi_\pm\psi_\pm$ annihilation (so $\psi_\pm$ dominate the DM abundance) $\Longrightarrow$ $Y_{\psi_\pm}$ controlled by semi-annihilation which is sensitive to g_x and to the whole dark sector. To have semi-annihilation controlled exclusively by g_x one should assume $m_+ + m_- > m_X + M_{h_2}$ and small mixing $\sin\alpha \sim 0.1$. Strong dependance on g_x is expected. It would be a three-component DM.

B: $y \gg 1$ and $\sin\alpha \sim 0.1$ with $m_X < M_{h_2}$ $\Longrightarrow$ fast $\psi_\pm\psi_\pm$ annihilation and X may dominate the DM abundance $\Longrightarrow$ n_X controlled by semi-annihilation which is sensitive to g_x and to the whole dark sector. In addition $m_+ + m_- < m_X + M_{h_2}$ to allow for disappearance of X in the semi-annihilation.

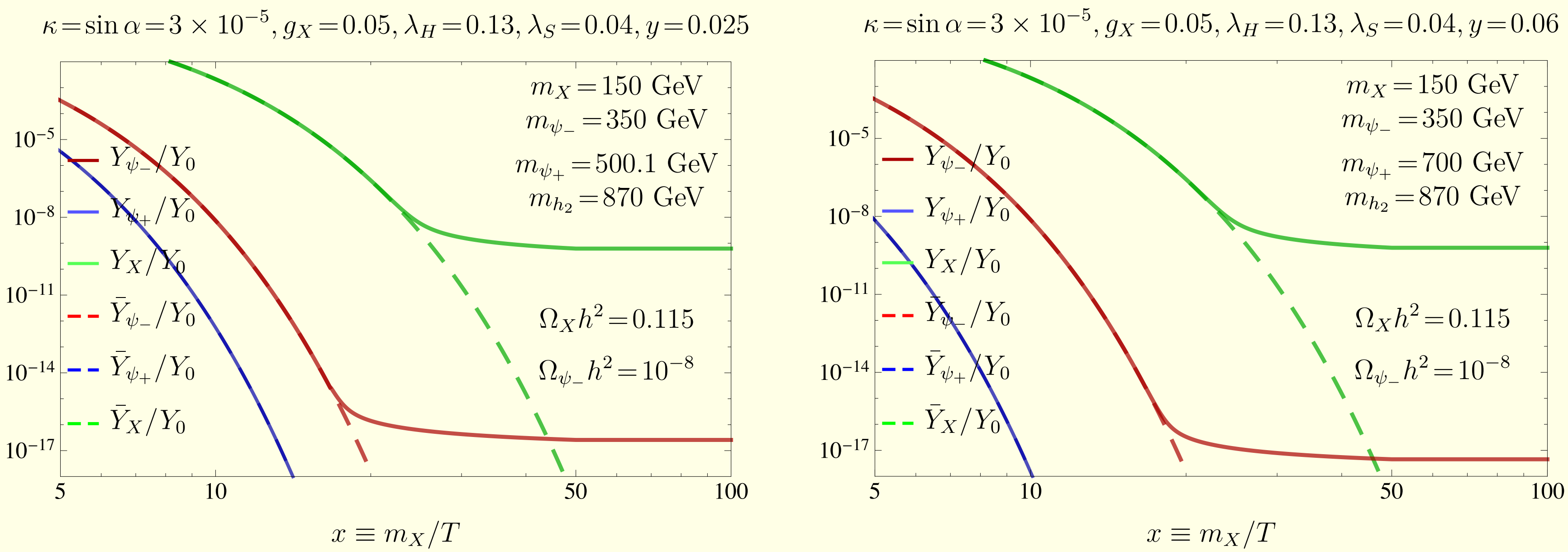


Figure 13: Evolution of dark sector yields: small $g_x \implies X$ domination, suppressed sensitivity to $y \ll 1$.

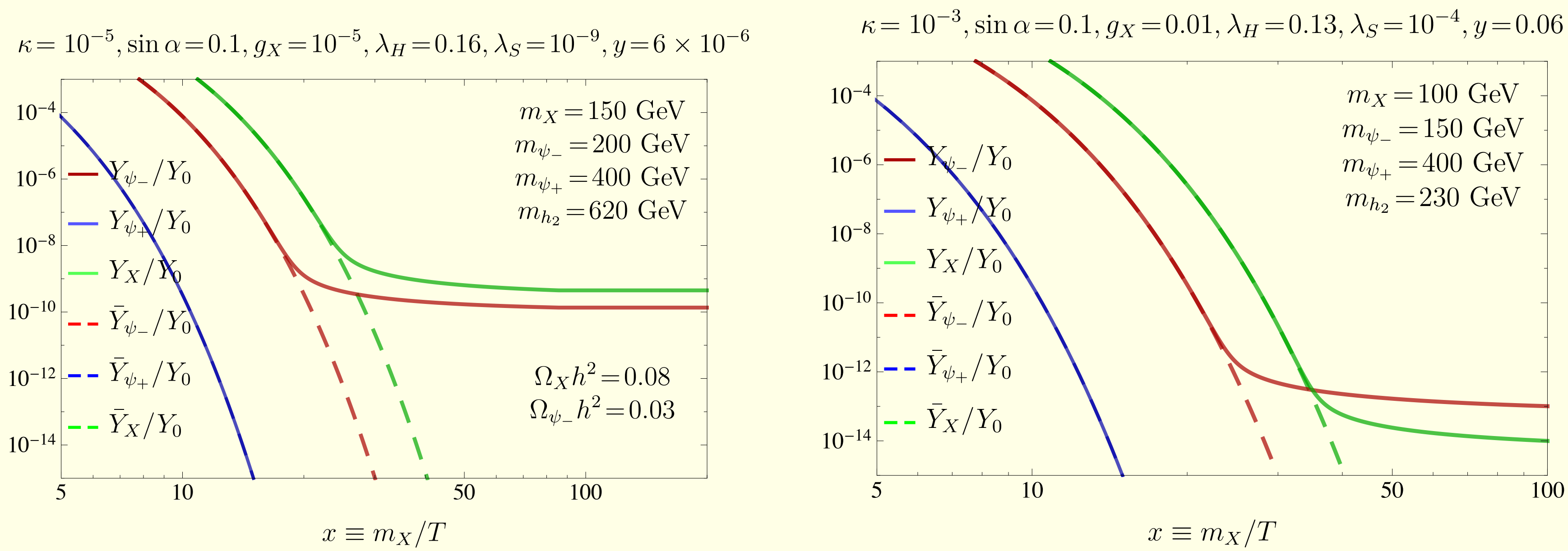


Figure 14: Evolution of dark sector yields, shows a possibility of crossing.

Two-component dark matter scenario

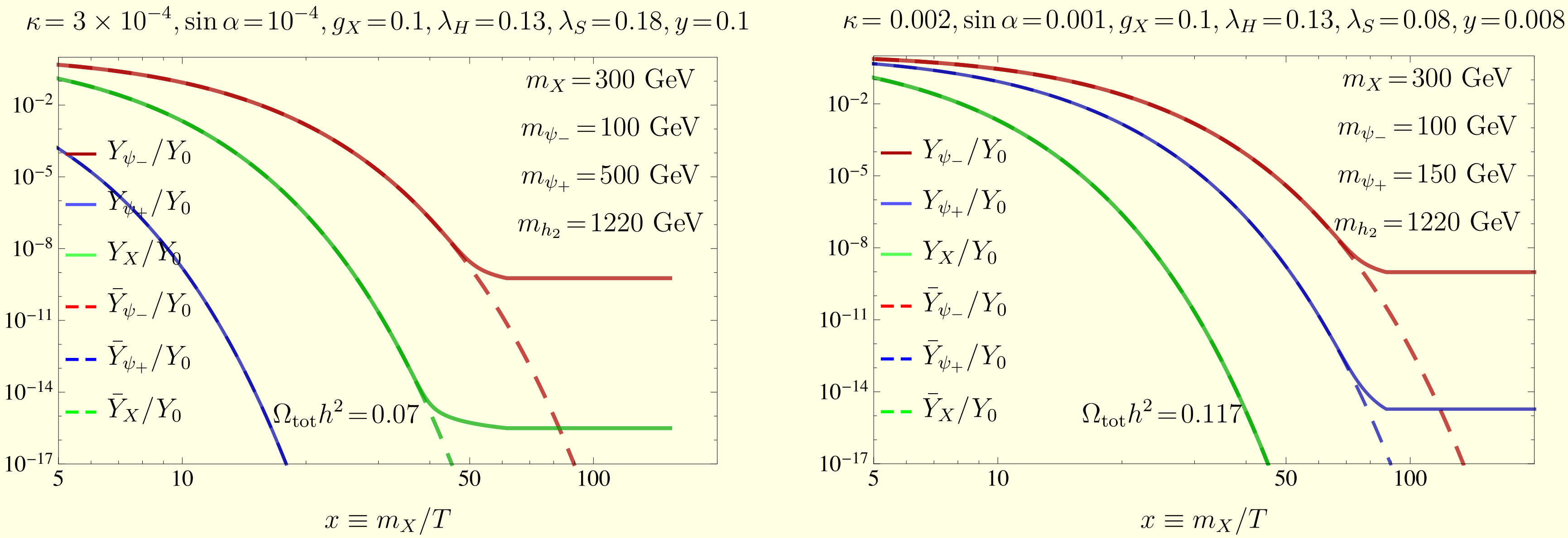


Figure 15: Evolution of dark sector yields, shows y-dependence/independence.

Three-component dark matter scenario.

Strategies:

A: $y \ll 1$ $(m_+ \simeq m_-)$ $\Longrightarrow$ slow $\psi_\pm\psi_\pm$ annihilation (so $\psi_\pm$ dominate the DM abundance) $\Longrightarrow$ $Y_{\psi_\pm}$ controlled by semi-annihilation which is sensitive to g_x and to the whole dark sector. To have semi-annihilation controlled exclusively by g_x one should assume $m_+ + m_- > m_X + M_{h_2}$ and small mixing $\sin\alpha \sim 0.1$. Strong dependance on g_x is expected. It would be a three-component DM.

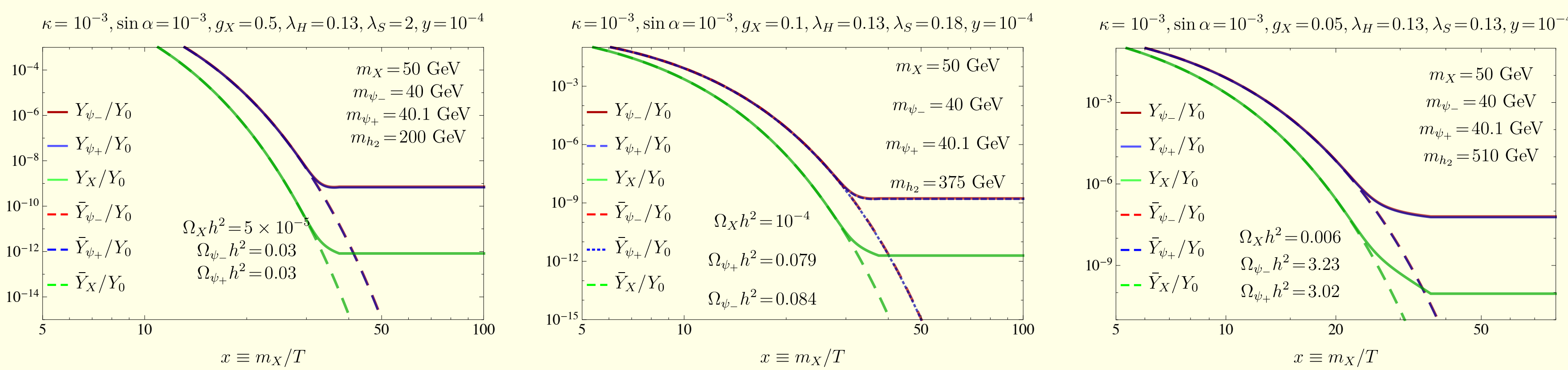


Figure 16: Evolution of dark sector yields, here $m_+ + m_- < m_X + M_{h_2}$.

Three-component dark matter scenario

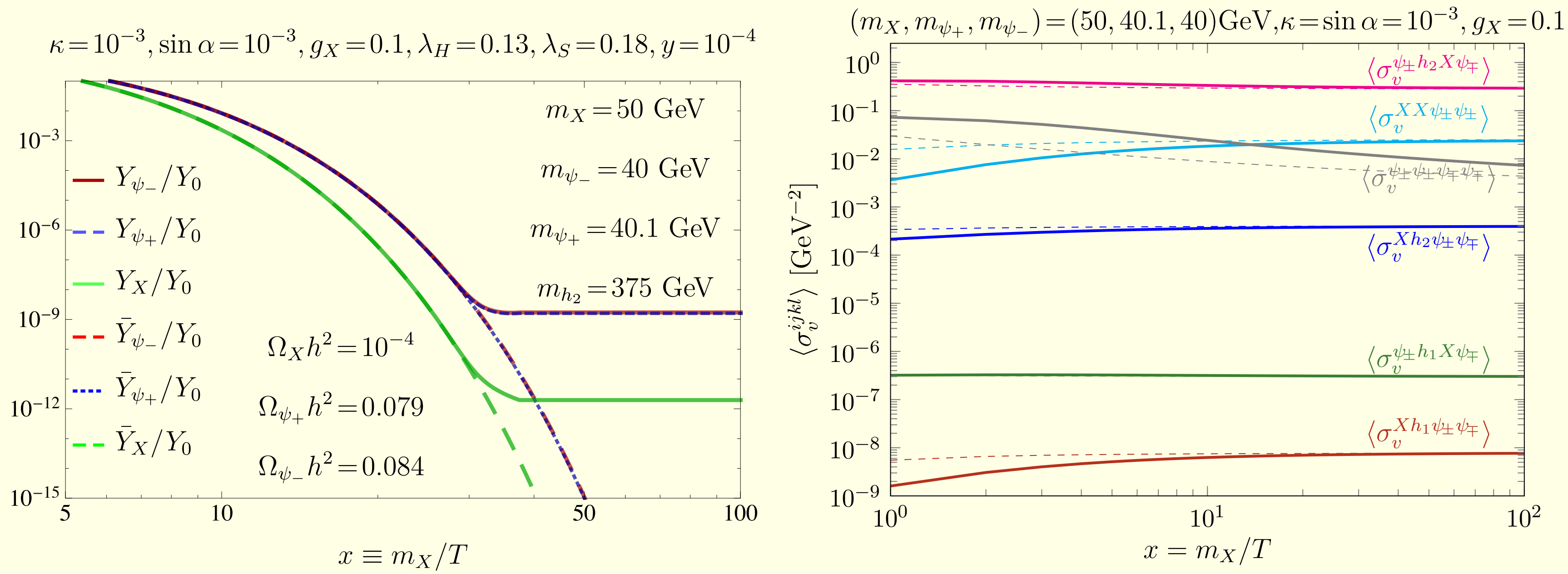


Figure 17: Evolution of dark sector yields and corresponding thermaly averaged cross sections.

Summary

- Two-sector dark matter generic scenario based on the stabilizing $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry was considered.

- Sensitivity of the leading component to the presence of the other dark elements was determined and discussed.

- The vector-fermion model based on extra $U(1)$ symmetry was introduced and the set of three Boltzmann equations for the system was discussed. Its numerical solutions were presented. Cross-sections were generated by CalcHEP while the Boltzmann equations were solved adopting a dedicated code.

- The project is still in progress.