Coannihilation and scotogenic fermionic dark matter

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- **Singlet-like fermionic DM** is more rich in phenomenology.

Valle, Rojas, Hirsch, Vicente, Restrepo, De Romari, ...
1307.8134, 1603.05685, 1605.01915, 1612.06569, 1907.11938, 1910.08422 ...

Singlet-Triplet Model

Particle Content:

	Standard Model			New Scalars		New Fermions	
	L	e^c	Φ	Ω	η	Σ	F
Multiplicity	3	3	1	1	1	1	1
$U(1)_Y$	$-1/2$	1	$1/2$	0	$1/2$	0	0
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{1}$
$\mathcal{Z}_2$	$+$	$+$	$+$	$+$	$-$	$-$	$-$

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Yukawa:

$$\mathcal{L} = Y^{\alpha\beta}\bar{L}_\alpha \Phi e_\beta + \boxed{Y_F^\alpha \bar{L}_\alpha \tilde{\eta} F^c + Y_\Sigma^\alpha \bar{L}_\alpha \Sigma^c \tilde{\eta}} + \boxed{Y_\Omega Tr[\bar{\Sigma}\Omega]F^c} + \boxed{\frac{M_\Sigma}{2} Tr[\bar{\Sigma}\Sigma^c] + \frac{M_F}{2}\bar{F}F^c} + \text{h.c.}$$

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Scalar Potential:

$$\mathcal{V} = \boxed{-\mu_\phi^2 (\Phi^\dagger \Phi) + \mu_\eta^2 (\eta^\dagger \eta) - \frac{1}{2}\mu_\Omega^2 \,\mathrm{Tr}\,(\Omega^\dagger \Omega)} + \boxed{\mu_\Omega^\phi (\Phi^\dagger \Omega \Phi) + \mu_\Omega^\eta (\eta^\dagger \Omega \eta)}$$

$$+ \boxed{\frac{1}{2}\lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \frac{1}{2}\lambda_5 \left[(\Phi^\dagger \eta)^2 + (\eta^\dagger \Phi)^2\right]}$$

$$+ \boxed{\frac{1}{2}\lambda_\Omega^\phi (\Phi^\dagger \Phi)\,\mathrm{Tr}\,(\Omega^\dagger \Omega) + \frac{1}{4}\lambda_\Omega^\Omega [\mathrm{Tr}\,(\Omega^\dagger \Omega)]^2 + \frac{1}{2}\lambda_\Omega^\eta (\eta^\dagger \eta)\,\mathrm{Tr}\,(\Omega^\dagger \Omega)}$$

Scalar sector

Fields:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\phi^+ \\ v_\phi + \phi^0 + i\,G^0 \end{pmatrix}, \quad \Omega = \begin{pmatrix} \frac{v_\Omega}{\sqrt{2}} + \frac{\Omega^0}{\sqrt{2}} & \Omega^+ \\ \Omega^- & -\frac{v_\Omega}{\sqrt{2}} - \frac{\Omega^0}{\sqrt{2}} \end{pmatrix}, \quad \eta = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\eta^+ \\ \eta_R^0 + i\,\eta_I^0 \end{pmatrix}$$

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Neutral scalars:

$$\{\phi^0, \Omega^0\} \longrightarrow \{h, H\} : \quad \mathcal{M}_0^2 = \begin{pmatrix} \lambda_1 v_\phi^2 & \lambda_\Omega^\phi v_\Omega v_\phi - \frac{1}{\sqrt{2}}\,\mu_\Omega^\phi\,v_\phi \\ \lambda_\Omega^\phi v_\Omega v_\phi - \frac{1}{\sqrt{2}}\,\mu_\Omega^\phi\,v_\phi & 2\lambda_\Omega^\Omega v_\Omega^2 + \frac{1}{2\sqrt{2}}\,\mu_\Omega^\phi\,\frac{v_\phi^2}{v_\Omega} \end{pmatrix}$$

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Charged scalars:

$$\{\phi^\pm, \Omega^\pm\} \to \{G^\pm, H^\pm\} : \quad \mathcal{M}_\pm^2 = \sqrt{2}\,\mu_\Omega^\phi \begin{pmatrix} v_\Omega & \frac{1}{2}\,v_\phi \\ \frac{1}{2}\,v_\phi & \frac{1}{4}\,\frac{v_\phi^2}{v_\Omega}\end{pmatrix} + g^2\,\xi_{W^\pm}\begin{pmatrix}\frac{1}{4}\,v_\phi^2 & -\frac{1}{2}\,v_\phi v_\Omega \\ -\frac{1}{2}\,v_\phi v_\Omega & v_\Omega^2\end{pmatrix}$$

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$$m_{\eta_R^0}^2 = \mu_\eta^2 + \frac{1}{2}\lambda_\Omega^\eta v_\Omega^2 - \frac{1}{\sqrt{2}}\mu_\Omega^\eta\, v_\Omega + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)\, v_\phi^2$$

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$$\lim \lambda_5 \to 0 \implies m_{\eta_R^0} = m_{\eta_I^0}$$

Fermion mixing & Neutrino mass

Fermion mixing:

$$\{F, \Sigma^0\} \to \{\chi_1^0, \chi_2^0\} : \quad \mathcal{M}_\chi = \begin{pmatrix} M_F & Y_\Omega v_\Omega \\ Y_\Omega v_\Omega & M_\Sigma \end{pmatrix} \implies V \cdot \mathcal{M}_\chi \cdot V^T = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0})$$

$$\tan(2\theta) = \frac{2\, Y_\Omega\, v_\Omega}{M_\Sigma - M_F}$$

$$m_{\chi_{1,2}^0} = \frac{1}{2}\left[(M_\Sigma + M_F) \mp \sqrt{(M_\Sigma - M_F)^2 + 4 Y_\Omega^2\, v_\Omega^2}\right]$$

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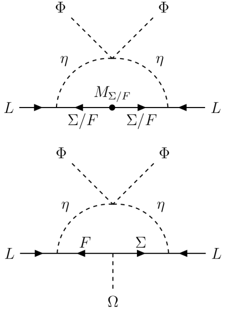
Neutrino mass:



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Neutrino mass:

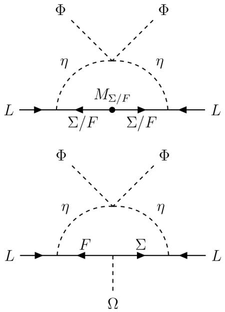
Neutrino mass matrix: $\boldsymbol{\mathcal{M}_\nu = Y_\nu \cdot \mathcal{F} \cdot Y_\nu^T}$

$$Y_\nu = \begin{pmatrix} Y_F^1 & Y_\Sigma^1/\sqrt{2} \\ Y_F^2 & Y_\Sigma^2/\sqrt{2} \\ Y_F^3 & Y_\Sigma^3/\sqrt{2} \end{pmatrix} \cdot V^T(\theta), \qquad \mathcal{F} = \begin{pmatrix} \frac{\mathcal{I}_1}{32\pi^2} & 0 \\ 0 & \frac{\mathcal{I}_2}{32\pi^2} \end{pmatrix},$$

$$\mathcal{I}_j = m_{\chi_j^0}\left[\frac{\ln\left(m^2_{\chi_j^0}/m^2_{\eta_R^0}\right)}{\left(m^2_{\chi_j^0}/m^2_{\eta_R^0}\right) - 1} - \frac{\ln\left(m^2_{\chi_j^0}/m^2_{\eta_I^0}\right)}{\left(m^2_{\chi_j^0}/m^2_{\eta_I^0}\right) - 1}\right]$$

$$\boldsymbol{Y_\nu = U \cdot (\widetilde{\mathcal{M}}_\nu)^{1/2} \cdot \rho \cdot (\mathcal{F})^{-1/2}} \quad \text{with} \quad U^\dagger \mathcal{M}_\nu U^* = \widetilde{\mathcal{M}}_\nu,$$

$$\rho^{\mathrm{NO}} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix} \quad \text{and} \quad \rho^{\mathrm{IO}} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \\ 0 & 0 \end{pmatrix}.$$



$\boldsymbol{\lim \lambda_5 \to 0 \implies \mathcal{I}_j \propto \lambda_5\, m_{\chi_j^0}}$ $\longrightarrow$ Smaller λ_5 and $m_{\chi_j^0} \implies$ bigger $Y_{F,\Sigma}$

Constraints

Bounded below: $i)\ \lambda_1 \geq 0, \quad ii)\ \lambda_2 \geq 0, \quad iii)\ \lambda_\Omega^\Omega \geq 0, \quad iv)\ \lambda_3 + \sqrt{\lambda_1 \lambda_2} \geq 0,$

$v)\ \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} \geq 0, \quad vi)\ \lambda_\Omega^\phi + \sqrt{2\lambda_1\lambda_\Omega^\Omega} \geq 0, \quad vii)\ \lambda_\Omega^\eta + \sqrt{2\lambda_2\lambda_\Omega^\Omega} \geq 0,$

$$viii)\ \sqrt{2\lambda_1\lambda_2\lambda_\Omega^\Omega} + \lambda_3\sqrt{2\lambda_\Omega^\Omega} + \lambda_\Omega^\phi\sqrt{\lambda_2} + \lambda_\Omega^\eta\sqrt{\lambda_1} + \sqrt{\left(\lambda_3 + \sqrt{\lambda_1\lambda_2}\right)\left(\lambda_\Omega^\phi + \sqrt{2\lambda_1\lambda_\Omega^\Omega}\right)\left(\lambda_\Omega^\eta + \sqrt{2\lambda_2\lambda_\Omega^\Omega}\right)} \geq 0$$

[Merle et al. 1603.05685, Kannike 1205.3781]

Perturbativity: $\lambda_i \leq 4\pi$ and $Y_j \leq \sqrt{4\pi}$

$\mathcal{Z}_2$ symmetry: $\mu_\Omega^\eta \lesssim \mathcal{O}(1\ \text{TeV})$ [Merle et al. 1603.05685]

EWPO: $S = -0.02 \pm 0.10, \quad T = 0.03 \pm 0.12, \quad U = 0.01 \pm 0.11$ [PDG]

$\rho_{exp} = 1.00038 \pm 0.00020 \longrightarrow \rho = 1 + (4\, v_\Omega^2/v_\phi^2) \implies v_\Omega \lesssim 4\ \text{GeV}\ (3\sigma)$

Neutrino oscillation:

$\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}, \quad \sin^2\theta_{23} = 0.537^{+0.016}_{-0.020}, \quad \sin^2\theta_{13} = 0.0022^{+0.00062}_{-0.00063},$

$\Delta m_{21}^2 = 7.42^{+0.20}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2, \quad$ ´$\mathrm{m}_{31}^2 = 2.517^{+0.026}_{-0.028} \times 10^{-3}\ \mathrm{eV}^2, \quad \delta_{\mathrm{CP}} = 197^\circ{}^{+27^\circ}_{-24^\circ}$

[de Salas et al. 2006.11237]

Constraints

Direct searches: $m_H > 150$ GeV [LEP & LHC], $M_\Sigma >$100 GeV (from Σ^+) [LEP],

$m_{\eta^+} > 70$ GeV [OPAL, hep-ph/0703056].

Though there exist some bounds on $\eta^0_{R,I}$ [0810.3924] from netralino search at LEP, they are not very constraining.

Bounds from LEP and LHC on charged scalar and neutral leptons are not directly applicable to H^+ and $\chi^0_{1,2}$.

LHC searches on slepton decaying to massless neutralino might put some bound on m_{H^+}. So, we choose $m_{H^+} > 400$ GeV (conservatively).

Decay width: $\mathcal{B}(h \to inv) < 13\%$, $\delta\Gamma_Z < 5$ MeV (2σ), $\delta\Gamma_W < 90$ MeV (2σ) [PDG]

cLFV: $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG], $\mathcal{B}(\mu \to 3e) < 1.0 \times 10^{-12}$ [SINDRUM]

$\mathcal{C}(\mu, Au \to e, Au) < 7.0 \times 10^{-13}$ [SINDRUMII]

DM Constraints

Relic density: $\Omega h^2 = 0.120 \pm 0.001$ [Planck]

DM direct detection (Strongest):

0.1 GeV - 4 GeV: **DarkSide-50** [2302.01830]

4 GeV - 10 GeV: **XENON1T ^{8}B** [2012.02846] and **PandaX-4T ^{8}B** [2207.04883]

10 GeV - 10 TeV: **LZ** [2207.03764]

XENON1T [1805.12562], **XENONnT** [2303.14729], **PandaX-4T** [2107.13438] .

Coherent neutrino-nucleon scattering → **Neutrino floor** [Billard et al. 2104.07634]

Parameters

Parameters from Lagrangian:

Complex Yukawa couplings	Real Yukawa couplings	Scalar mass terms and trilinear couplings	Scalar quartic couplings	Fermionic masses
$Y_F^1,\ Y_F^2,\ Y_F^3,$ $Y_\Sigma^1,\ Y_\Sigma^2,\ Y_\Sigma^3$	Y_Ω	$\mu_\phi,\ \mu_\eta,\ \mu_\Omega,\ \mu_\Omega^\phi,\ \mu_\Omega^\eta$	$\lambda_1,\ \lambda_2\ \lambda_3,\ \lambda_4,\ \lambda_5,$ $\lambda_\Omega^\phi,\ \lambda_\Omega^\eta,\ \lambda_\Omega^\Omega$	$M_F,\ M_\Sigma$

Define: $\Delta m_{\Sigma F} = M_\Sigma - M_F,\quad \Delta m_{\eta^+ F} = m_{\eta^+} - M_F$ and $\Delta m^2_{\eta_I^0 \eta^+} = m^2_{\eta_I^0} - m^2_{\eta^+}$

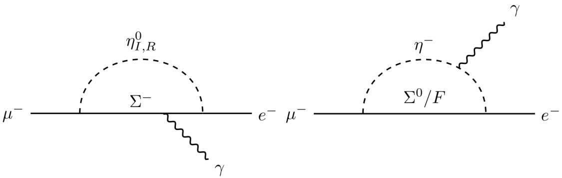
After Reduction:

There remain 16 independent parameters (No Majorana phase).

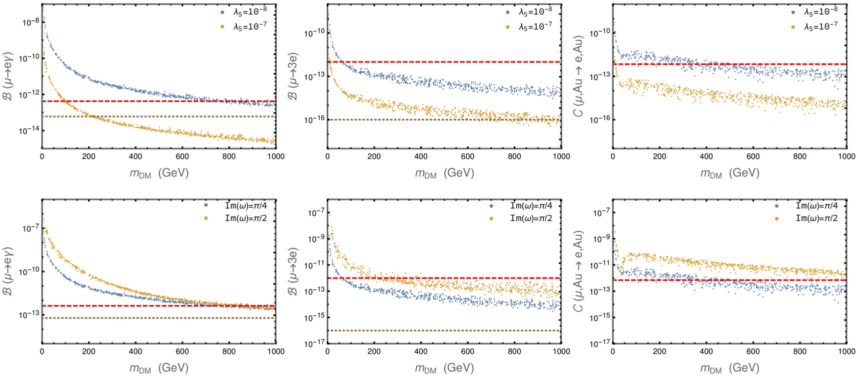
BP0:

M_F (GeV)	$\Delta m_{\Sigma F}$ (GeV)	$\Delta m_{\eta^+ F}$ (GeV)	$\Delta m^2_{\eta_I^0 \eta^+}$ (GeV^2)	μ_Ω^η (GeV)	v_Ω (GeV)	Y_Ω	Re(ω)	Im(ω)	λ_1	λ_2	λ_3	λ_5	λ_Ω^ϕ	λ_Ω^Ω	λ_Ω^η
[1, 1000]	200	500	1000	400	4.0	2.0	$\pi/4$	$\pi/4$	0.2626	0.5	0.5	10^{-8}	0.5	0.5	0.5

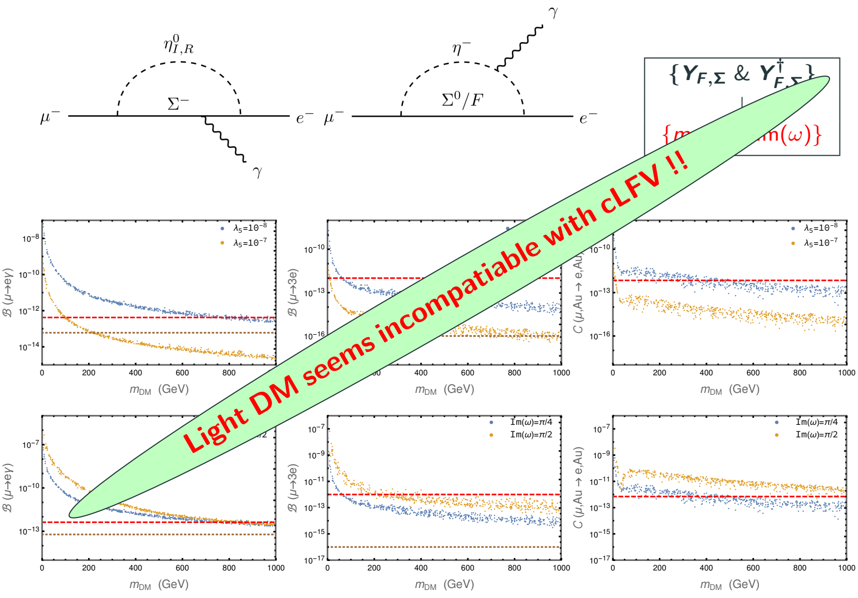
More on cLFV



$$\{\boldsymbol{Y_{F,\Sigma}}\ \&\ \boldsymbol{Y^\dagger_{F,\Sigma}}\}$$
$$\downarrow$$
$$\{m_{\chi_1^0}, \lambda_5, \mathrm{Im}(\omega)\}$$

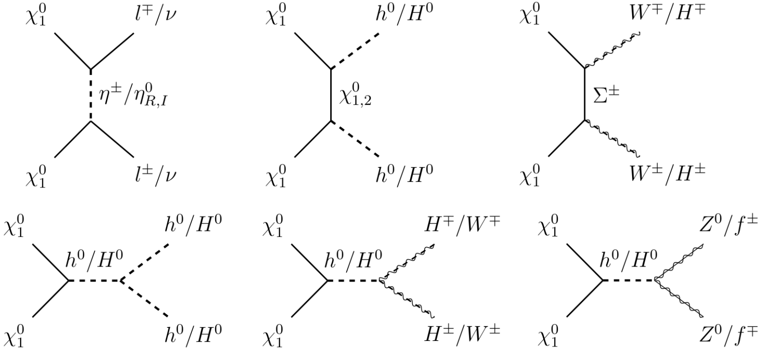


More on cLFV


η⁰_I,R
Σ⁻
μ⁻
e⁻
γ
η⁻
Σ⁰/F
{Y_F,Σ & Y†_F,Σ}
Light DM seems incompatiable with cLFV !!
λ5=10⁻⁸
λ5=10⁻⁷
Im(ω)=π/4
Im(ω)=π/2
B (μ→eγ)
B (μ→3e)
C (μ,Au → e,Au)
m_DM (GeV)

DM annihilation (No coannihilation)

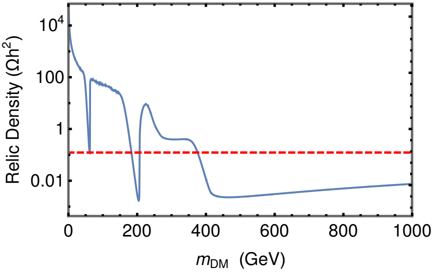
Processes:



Dependencies:

Scalar mixing and m_{H^0}: $\{\lambda_1, \lambda_\Omega^\phi, v_\Omega\}$
Fermion mixing: $\{v_\Omega, Y_\Omega, \Delta m_{\Sigma F}\}$
Couplings of SM and $\mathcal{Z}_2$-odd leptons through η: $Y_{F,\Sigma} \longrightarrow \{\lambda_5, \text{Im}(\omega), M_F\}$
Masses of $\mathcal{Z}_2$-odd particles: $\{M_F,\ \Delta m_{\Sigma F}(\text{slightly}),\ \Delta m_{\eta^+ F}(\text{slightly})\}$

Relic vs m_{DM} (BP0)

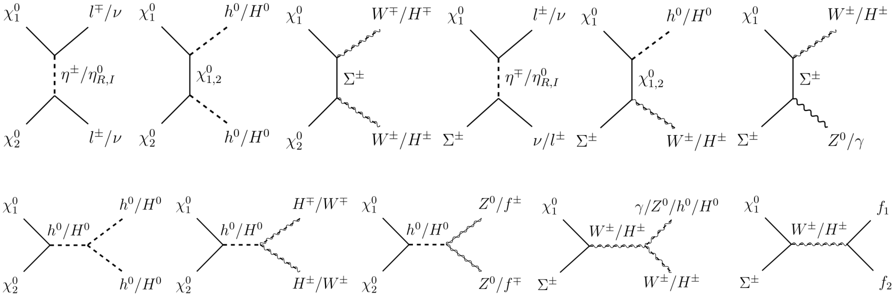


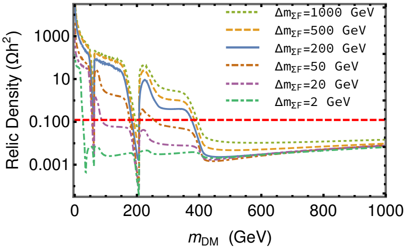
- **1st dip** at $m_{DM} = 62.5$ GeV $(m_h/2)$: $\chi_1^0\chi_1^0 \to h^0 \to SM\ SM$
- **2nd dip** at $m_{DM} = 200$ GeV $(m_H/2)$: $\chi_1^0\chi_1^0 \to H^0 \to SM\ SM$
- **3rd dip** near $m_{DM} = 250$ GeV $\{(m_{W^\pm} + m_{H^\pm})/2,\ (m_{h^0} + m_{H^0})/2\}$:

  Opening of $\chi_1^0\chi_1^0 \to W^\pm H^\mp$ and $\chi_1^0\chi_1^0 \to h^0 H^0$
- **4th dip** near $m_{DM} = 400$ GeV $(m_{H^0},\ m_{H^\pm})$:

  Opening of $\chi_1^0\chi_1^0 \to H^0 H^0$ and $\chi_1^0\chi_1^0 \to H^+ H^-$

Fermion-fermion coannihilation

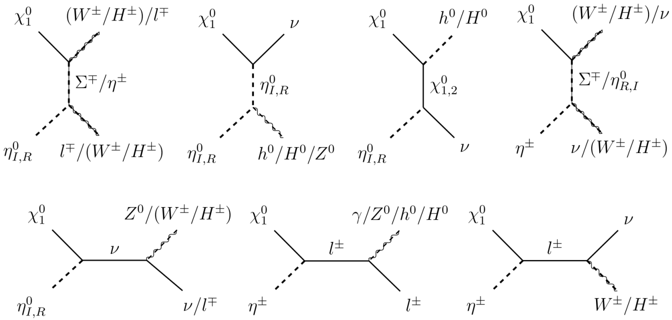


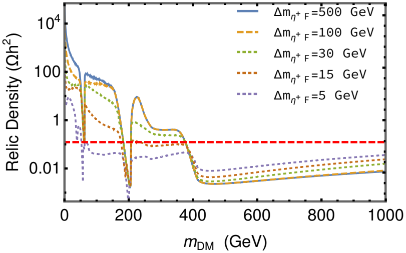


$$\langle \sigma_c v \rangle \propto \sum_{i,j} \sigma_{ij} e^{-\frac{m_i - m_{\rm DM}}{T}} e^{-\frac{m_j - m_{\rm DM}}{T}}$$

$$\to e^{-(m_{\chi_2} - m_{\chi_1})/T}.$$

Fermion-scalar coannihilation

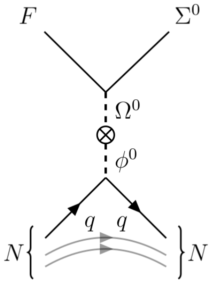




$$\langle \sigma_c v \rangle \propto \sum_{i,j} \sigma_{ij} e^{-\frac{m_i - m_{\rm DM}}{T}} e^{-\frac{m_j - m_{\rm DM}}{T}}$$

$$\to e^{-(m_\eta - m_{\chi_1})/T}.$$

Direct detection



$$\sigma^{\rm SI}_{\rm DM-N} \approx \frac{\mu_{\rm red}^2}{\pi}\left[\frac{Y_\Omega f_N m_N}{2v}\sin 2\theta\,\sin 2\beta\left(\frac{1}{m_{h^0}^2}-\frac{1}{m_{H^0}^2}\right)\right]^2$$

m_N: Nucleon mass

f_N: Nucleon form factor ≈ 0.3

$\mu_{\rm red}$: Reduced mass $= (m_{\chi_1^0}\, m_N)/(m_{\chi_1^0} + m_N)$

θ: Fermion mixing angle $\longrightarrow \tan(2\theta) = \frac{2\,Y_\Omega\, v_\Omega}{M_\Sigma - M_F}$

β: Scalar mixing angle $\longrightarrow \tan 2\beta = \frac{4 v_\Omega v_\phi(\mu^\phi_\Omega - \sqrt{2}\lambda^\Omega_\phi v_\Omega)}{4\sqrt{2}\lambda^\Omega_\Omega v_\Omega^3 - 2\sqrt{2}\lambda_1 v_\Omega v_\phi^2 + \mu^\phi_\Omega v_\phi^2}$

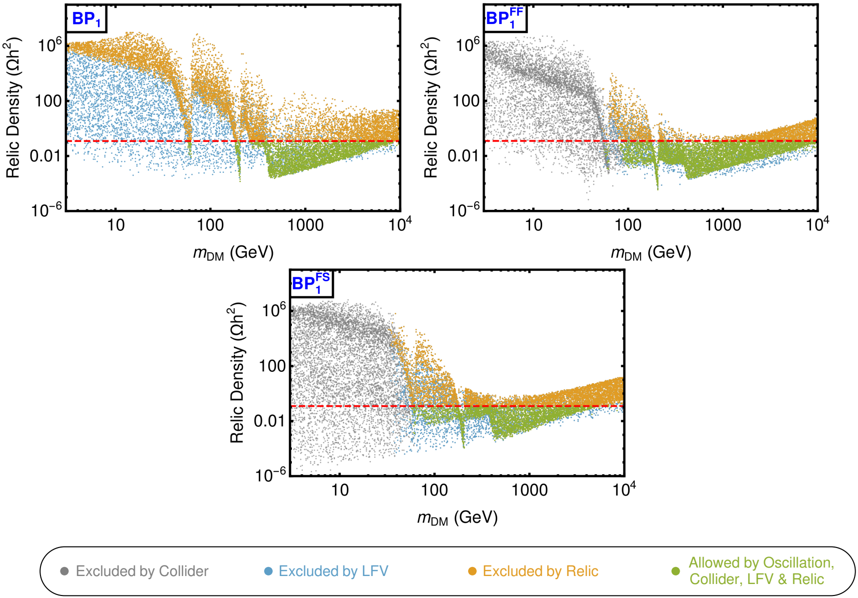
Dependencies: $\sigma^{\rm SI}_{\rm DM-N} \longrightarrow \{\lambda_1, \lambda^\phi_\Omega, v_\Omega, Y_\Omega, \Delta m_{\Sigma F}\}$ (but not on $m_{\chi_1^0}$)

Cases	v_Ω (GeV)	M_F (GeV)	$\Delta m_{\Sigma F}$ (GeV)	$\Delta m_{\eta^+ F}$ (GeV)	$\Delta m^2_{\eta_I^0 \eta^+}$ (GeV^2)	μ_Ω^η (GeV)	Y_Ω	Re(ω)	Im(ω)	λ_1	λ_2	λ_3	λ_5	λ_Ω^ϕ	λ_Ω^Ω	λ_Ω^η
Scenario-I																
BP_1			[100, 500]	[100, 500]	1000											
BP_1^{FF}	4.0	[3, 10000]	[1, 50]	[100, 500]	1000	400	[0.1, 3.5]	$[-\pi, \pi]$	$[-2\pi, 2\pi]$	0.2626	0.5	0.5	$[10^{-9}, 0.5]$	0.5	0.5	0.5
BP_1^{FS}			[100, 500]	[1, 30]	[1, 1000]											
Scenario-II																
BP_2			[100, 500]	[100, 500]	1000											
BP_2^{FF}	1.5	[3, 10000]	[1, 50]	[100, 500]	1000	400	[0.1, 3.5]	$[-\pi, \pi]$	$[-2\pi, 2\pi]$	0.2626	0.5	0.5	$[10^{-9}, 0.5]$	0.5	0.5	0.5
BP_2^{FS}			[100, 500]	[1, 30]	[1, 1000]											

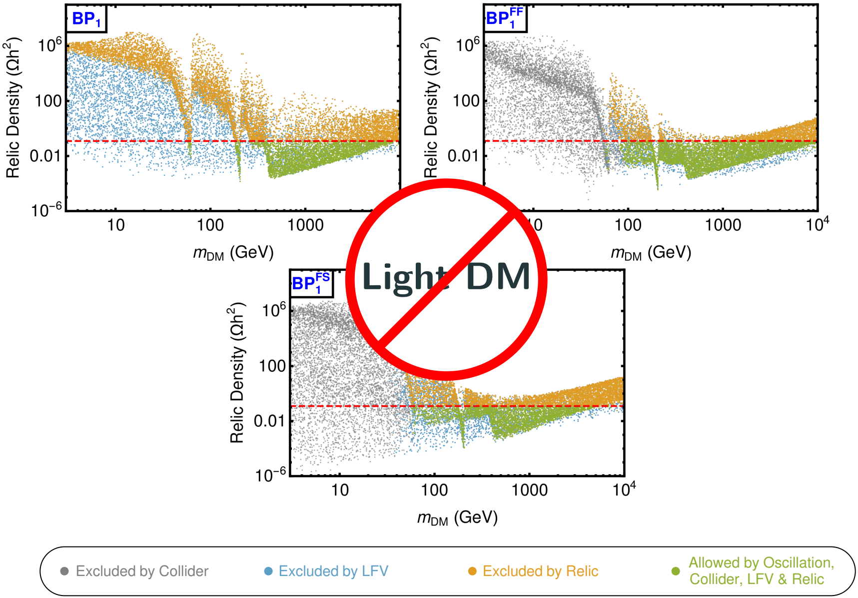
No Superscript: No coannihilation
Superscript FF: Fermion-fermion coannihilation
Superscript FS: Fermion-Scalar coannihilation

$m_{H^0} = \{400 \text{ GeV (Scenario-I)}, 1100 \text{ GeV (Scenario-II)}\}$

Scanning: Relic

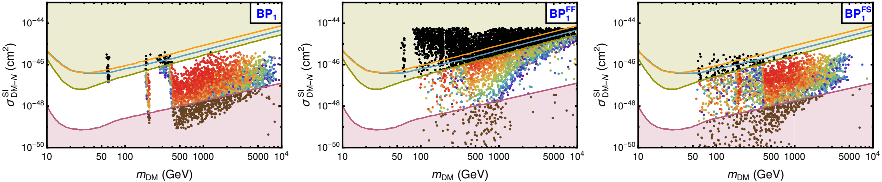


Scanning: Relic

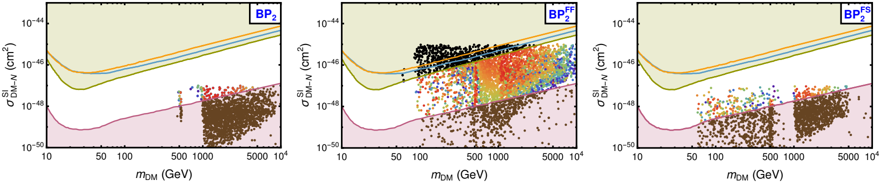


Scanning: Direct detection

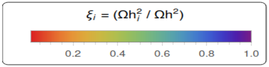
Scenario-I (High v_Ω)



Scenario-II (Low v_Ω)



No Coannihilation | **Fermion-Fermion Coannihilation** | **Fermion-Scalar Coannihilation**



Summary

✍ This model cannot accommodate light fermionic dark matter (both singlet-like and triplet-like) below 62.5 GeV.

✍ Without any coannihilation feasible parameter-space can be obtained only for $m_{DM} > m_H$ (apart from discrete resonance at $m_{DM} = m_H/2$)

✍ Fermion-fermion coannihilation provides feasible parameter-space for $m_{DM} > 100$ GeV whereas fermion-scalar coannihilation does the same job from $m_{DM} >$62.5 GeV.

✍ While fermion-scalar coannihilation is the most promising scenario for higher values of v_Ω, fermion-fermion coannihilation is the most promising case for lower values of v_Ω.