Dark matter and lepton flavor phenomenology in a scotogenic model

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Overview

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Open questions of the Standard Model

The Standard Model has open questions :

- gravity
- hierarchy problem
- matter anti-matter asymmetry
- dark matter
- neutrino masses
- ...

Introduction to the scotogenic model

$$\textit{scotogenic} \;=\; \underbrace{\textit{scoto}}_{\text{dark}} + \underbrace{\textit{genic}}_{\text{generate}}$$

The first scotogenic model was developed by Ma [arXiv:0601225].
SM is extended by 3 majorana fermions + 1 scalar field.
The scotogenic models are classified in Restrepo, Yaguna, Zapata [arXiv:1308.3655]

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Details of the T1-2A model

Esch, Klasen, Yaguna [arXiv:1804.0338]

The SM is extended by :

Fermions

- a singlet F
- a Dirac doublet Ψ

$$\Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix}$$

$$\Psi_2 = \begin{pmatrix} -\left(\Psi_2^-\right)^\dagger \\ \left(\Psi_2^0\right)^\dagger \end{pmatrix}$$

and Scalars

- a singlet S
- a doublet Φ

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(\phi^0 + iA^0\right) \end{pmatrix}$$

Details of the T1-2A model

	Ψ_1	Ψ_2	F	Φ	S
$SU(2)_L$	2	2	1	2	1
$U(1)_Y$	-1	1	0	1	0
$\mathbb{Z}_2$	-1	-1	-1	-1	-1

Table: Additional field content of the model T1-2A.

The new particles are odd under a $\mathbb{Z}_2$ symmetry whereas the particles from the SM are even.
The lightest particle will be stable and will provide a DM candidate.

The scalar sector after EWSB

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left[v + h^0 + iG^0\right] \end{pmatrix}, \quad S, \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left[\phi^0 + iA^0\right] \end{pmatrix} \quad (1)$$

$$\mathcal{M}_\phi^2 = \begin{pmatrix} \mu_S^2 + \frac{1}{2}v^2\lambda_S & vT \\ vT & \mu_\Phi^2 + \frac{1}{2}v^2\left[\lambda_\Phi + \lambda'_\Phi + \lambda''_\Phi\right] \end{pmatrix} \quad (2)$$

Diagonalization according to

$$\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} = U_\phi \begin{pmatrix} S \\ \phi^0 \end{pmatrix} \quad (3)$$

The fermion sector after EWSB

$$F\,, \qquad \Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix}, \qquad \Psi_2 = \begin{pmatrix} -\left(\Psi_2^-\right)^\dagger \\ \left(\Psi_2^0\right)^\dagger \end{pmatrix} \tag{4}$$

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_F & \frac{v}{\sqrt{2}}y_1 & \frac{v}{\sqrt{2}}y_2 \\ \frac{v}{\sqrt{2}}y_1 & 0 & M_\Psi \\ \frac{v}{\sqrt{2}}y_2 & M_\Psi & 0 \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix} = U_\chi \begin{pmatrix} F \\ \Psi_1^0 \\ (\Psi_2^0)^\dagger \end{pmatrix} \tag{6}$$

The masses are the eigenvalues of the mass matrix $\mathcal{M}_{\chi^0}$.

Particle content in the mass basis

To summarize, the particle content in their physical states are :

fermion content

- three neutral particles : $\chi_1^0\,,\chi_2^0\,,\chi_3^0$,
- a charged fermion : $\chi^{\pm}$.

scalar content

- two neutral scalar and one neutral pseudo-scalar : $\phi_1^0\,,\phi_2^0\,,A^0$,
- a charged scalar $\phi^{\pm}$.

Three candidates for dark matter : $\chi_1^0\,,\phi_1^0\,,A^0$.

Interaction terms and neutrino masses

$$L_i \;=\; \begin{pmatrix} \nu_i \\ e_i^- \end{pmatrix} \tag{7}$$

Interaction terms

$$-\mathcal{L} \;\supset\; g_\Psi^i \Psi_2 L_i S + g_F^i \Phi L_i F + g_R^i L^c_{\mathrm{Ri}} \Phi^\dagger \Psi_1 \tag{8}$$

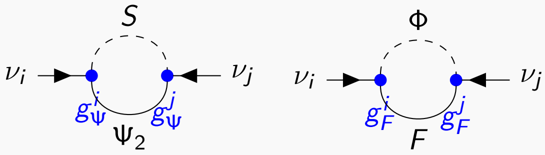
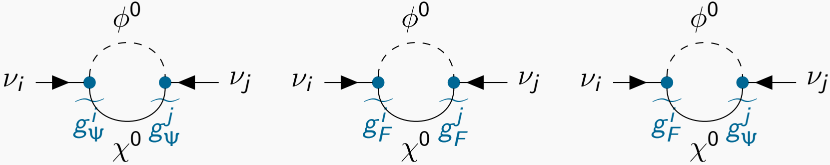
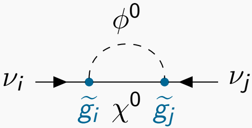


Figure: Generation of neutrino masses at the one-loop level in the model T1-2A. The diagrams show the contributions in the interaction basis.

Computation of the neutrino masses

$$-\mathcal{L} \supset g_\Psi^i \Psi_2 L_i S + g_F^i \Phi L_i F + g_R^i L^c_{\mathrm{Ri}} \Phi^\dagger \Psi_1$$





$$\equiv \overline{\nu_j^c}\; \underbrace{\tilde{g}_j \frac{M_{\chi^0}}{16\pi^2} \mathrm{B}_0(0, M^2_{\chi^0}, M^2_{\phi^0}) \tilde{g}_i}_{(\mathcal{M}_\nu)_{ij}}\; \nu_i \qquad (9)$$

$$\mathcal{M}_\nu = \mathcal{G}^t M_L \mathcal{G} \qquad (10)$$

Computation of the neutrino masses

$$M_\nu = \begin{pmatrix} g_\Psi^1 & g_F^1 & 0 \\ g_\Psi^2 & g_F^2 & 0 \\ g_\Psi^3 & g_F^3 & 0 \end{pmatrix} \begin{pmatrix} M_{11} & M_{12} & 0 \\ M_{21} & M_{22} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_F^1 & g_F^2 & g_F^3 \\ 0 & 0 & 0 \end{pmatrix} \quad (11)$$

Parameter	Interval in [GeV]
Δm_{12}^2	$[7.0; 7.84] \cdot 10^{-23}$
m_{ν_2}	$[8.367; 8.854] \cdot 10^{-12}$
Δm_{13}^2	$[2.47; 2.57] \cdot 10^{-21}$
m_{ν_3}	$[4.96; 5.07] \cdot 10^{-11}$

Parameter	Interval in degrees
θ_{12}	$[31.90; 34.98]$
θ_{13}	$[8.33; 8.81]$
θ_{23}	$[46.8; 51.6]$
δ_{CP}	$[143; 251]$

Neutrino masses and mixing parameters extracted from global fits of experimental neutrino data NuFit2020.

The intervals are restrictive $\rightarrow$ difficult from random couplings to obtain the experimental values

Casas Ibarra parametrization

[hep-ph/0103065]

From this equation :

$$\mathcal{M}_\nu = \mathcal{G}^t M_L \mathcal{G}$$

we can isolate the $\mathcal{G}$ matrix :

Casas Ibarra parametrization

$$\mathcal{G} = \underbrace{\mathrm{U_L}\, \mathrm{D_M^{-1/2}}}\, \mathrm{R}\, \underbrace{\mathrm{D}_\nu^{1/2}\, \mathrm{V^*_{PMNS}}} \tag{12}$$

D_ν is the diagonal matrix which contains the neutrino masses. Thanks to this parametrization, the couplings g_Ψ and g_F are a function of the neutrino masses.

The numerical strategy

The numerical strategy

- *SARAH* [arXiv:1309.7223]
- *SPheno* [arXiv:1104.1573]
- *micrOMEGAS* [arXiv:1801.0350]
- We used a Markov Chain Monte Carlo (MCMC) technique to efficiently scan the parameter space

Constraints

Observable	Interval
m_H	125.1 ± 3.0 GeV
$\mathrm{BR}(\mu^- \to e^- \gamma)$	$< 4.2 \cdot 10^{-13}$
$\mathrm{BR}(\tau^- \to e^- \gamma)$	$< 3.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \gamma)$	$< 4.4 \cdot 10^{-8}$
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	$< 1.0 \cdot 10^{-12}$
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	$< 2.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^+ e^- e^-)$	$< 1.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	$< 2.1 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-)$	$< 1.7 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	$< 2.7 \cdot 10^{-8}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Ti})$	$< 4.3 \cdot 10^{-12}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Pb})$	$< 4.6 \cdot 10^{-11}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Au})$	$< 7.0 \cdot 10^{-13}$

$\mathrm{BR}(Z^0 \to e^\pm \mu^\mp)$	$< 7.5 \cdot 10^{-7}$
$\mathrm{BR}(Z^0 \to e^\pm \tau^\mp)$	$< 9.8 \cdot 10^{-6}$
$\mathrm{BR}(Z^0 \to \mu^\pm \tau^\mp)$	$< 1.2 \cdot 10^{-5}$
$\mathrm{BR}(\tau^- \to e^- \pi^0)$	$< 8.0 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \pi^0)$	$< 1.1 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to e^- \eta)$	$< 9.3 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to e^- \eta')$	$< 1.6 \cdot 10^{-7}$
$\mathrm{BR}(\tau^- \to \mu^- \eta)$	$< 6.5 \cdot 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^- \eta')$	$< 1.3 \cdot 10^{-7}$
$\Omega_{\mathrm{CDM}} h^2$	0.1198 ± 0.0042
Direct detection	XENON1T

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Results on dark matter

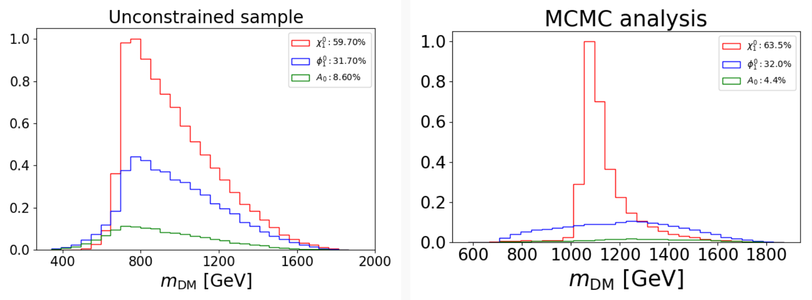


Figure: Histogram of the dark matter mass in a scan without constraints (left), and in the MCMC scan (right).

Dark matter nature

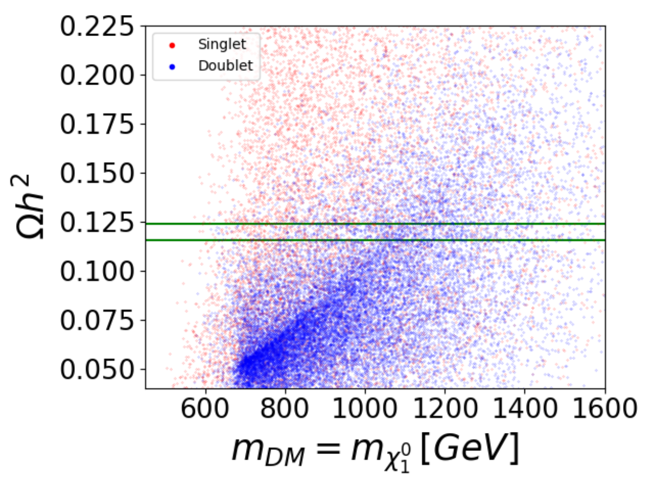


Figure: The points are from a scan without constraints, and they were selected in order to have a fermionic DM.

Dark matter nature

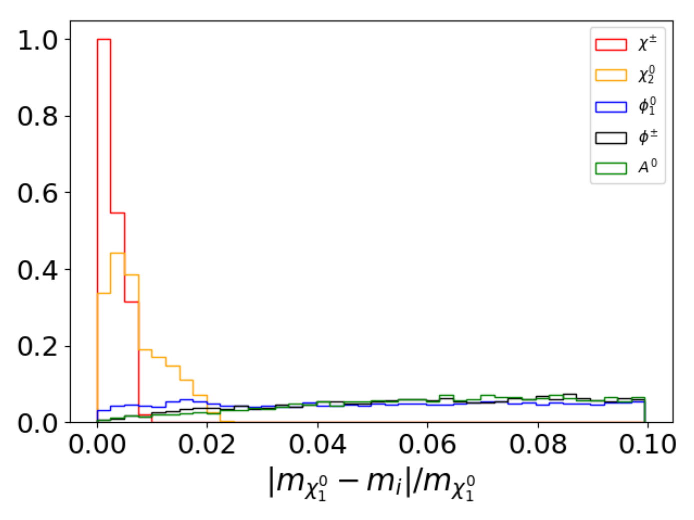


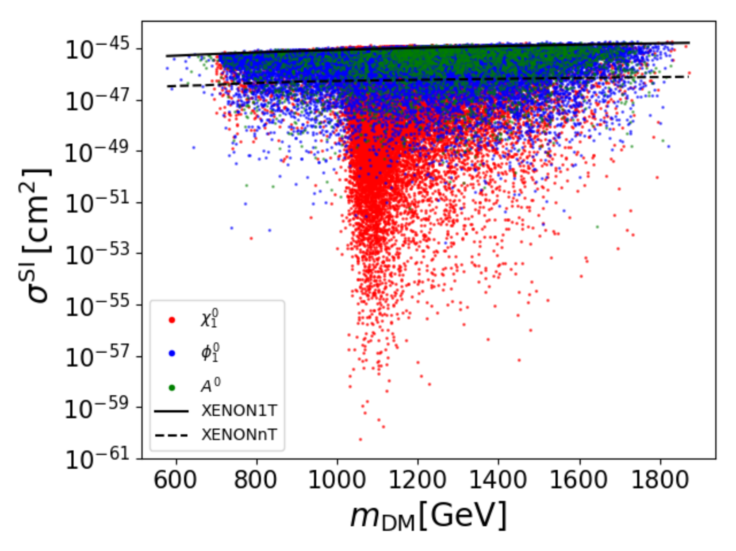
Figure: Coannihilation processes in the case of a fermionic DM.

Dark matter nature

The most important coannihilation processes for a fermionic DM χ_1^0 :

- $\chi_1^0\,\chi_2^0 \;\rightarrow\; \tau\,\bar{\tau}$
- $\chi_1^0\,\chi^{\pm} \;\rightarrow\; d_i\,\bar{u}_i$
- $\chi^{\pm}\,\chi^{\mp} \;\rightarrow\; \tau\,\bar{\tau}$

Direct Detection



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Summary

- The SM was extended by two scalars (doublet and singlet) and two fermions (doublet and singlet).
- The T1-2A model provides two-non-zero neutrino masses and a viable candidate for DM. The DM can be scalar, pseudo-scalar or fermionic.
- This model emphasizes a fermionic DM with a mass between 1TeV and 1.2TeV.
- The model survives to the projection of the XENONnT limit.

Thank you

Thank you for your attention !

Back up MCMC

$$\mathcal{L}_n \equiv \mathcal{L}(\vec{\theta}_n, \vec{O}) = \prod_i \mathcal{L}_i(\vec{\theta}_n, O_i)\,. \tag{13}$$

$$\ln \mathcal{L}_i(\vec{\theta}_n, O_i) = \frac{O_i(\vec{\theta}_n) - O_i^{\rm exp}}{2\sigma_i^2}\,, \tag{14}$$

$$p = \mathcal{L}^{n+1}/\mathcal{L}^n\,. \tag{15}$$

Back up Casas Ibarra parametrization

$$\mathrm{M}_{11} = \sum_{k,n} f_{kn} (U_F^\dagger)^2_{3k} (U_S^\dagger)^2_{1n} \,, \tag{16}$$

$$\mathrm{M}_{12} = \frac{1}{\sqrt{2}} \sum_{k,n} f_{kn} (U_F^\dagger)_{1k} (U_F^\dagger)_{3k} (U_S^\dagger)_{1n} (U_S^\dagger)_{2n} \,, \tag{17}$$

$$\mathrm{M}_{22} = \frac{1}{2} \sum_{k,n} f_{kn} (U_F^\dagger)^2_{1k} \left[(U_S^\dagger)^2_{2n} - \left(U_S^\dagger\right)^2_{3n} \right] , \tag{18}$$

$$f_{kn} = \frac{1}{16\pi^2} \frac{M_{\chi_k^0}}{M^2_{\Phi_n^0} - M^2_{\chi_k^0}} \left[M^2_{\chi_k^0} \log\left(\frac{M^2_{\chi_k^0}}{\mu^2} \right) - M^2_{\Phi_n^0} \log\left(\frac{M^2_{\Phi_n^0}}{\mu^2} \right) \right] . \tag{19}$$

Back up Setup of the g couplings

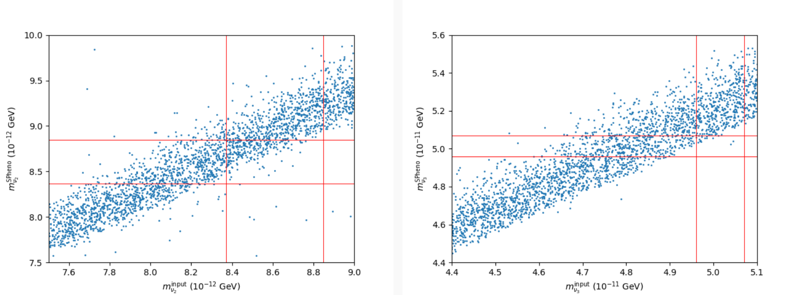


Figure: Impact of one-loop corrections to scalar and fermion masses on the neutrino masses.

The leading order masses are the ones entering in the Casas Ibarra parametrization. The NLO masses are the ones given by *SPheno*.

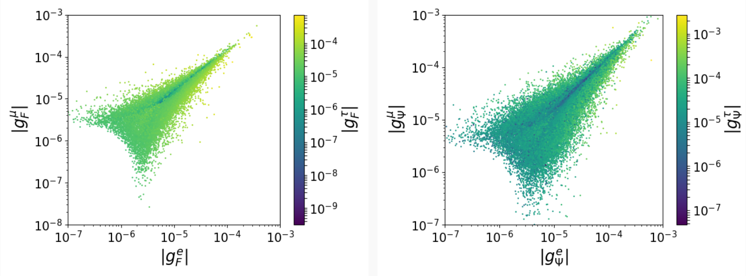
The scalar sector after EWSB

Leading order masses :

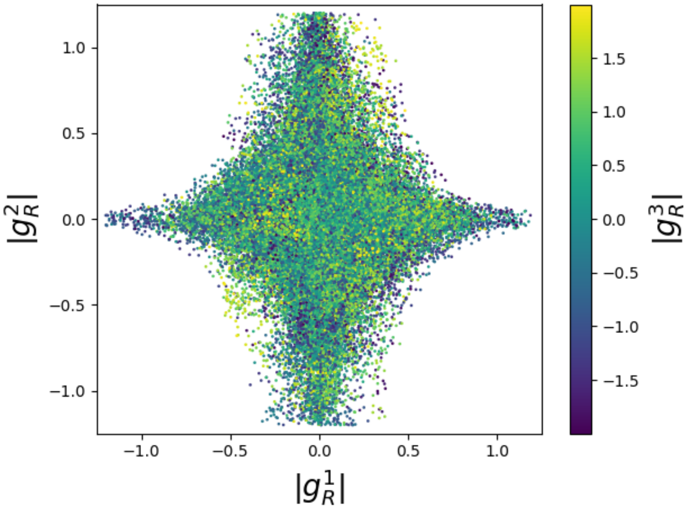
$$
\begin{aligned}
m^2_{\phi^0_{1,2}} &= \frac{1}{2}\Bigg[\mu_S^2 + \mu_\Phi^2 + \frac{1}{2}v^2\big(\lambda_S + \lambda_L\big) \\
&\qquad \mp \sqrt{\Big[\mu_S^2 - \mu_\Phi^2 + \frac{1}{2}v^2\big(\lambda_S - \lambda_L\big)\Big]^2 + 4v^2T^2}\,\Bigg],
\end{aligned} \tag{20}
$$

$$
\begin{aligned}
m^2_{A^0} &= \mu_\Phi^2 + \frac{1}{2}v^2\Big[\lambda_\Phi + \lambda'_\Phi - \lambda''_\Phi\Big], \\
m^2_{\phi^\pm} &= \mu_\Phi^2 + \frac{1}{2}v^2\lambda_\Phi\,.
\end{aligned} \tag{21}
$$

Couplings



Couplings



Relic density