Inert Doublet-Triplet Model with Two Dark Matter Candidates

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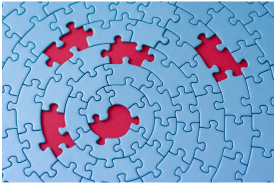
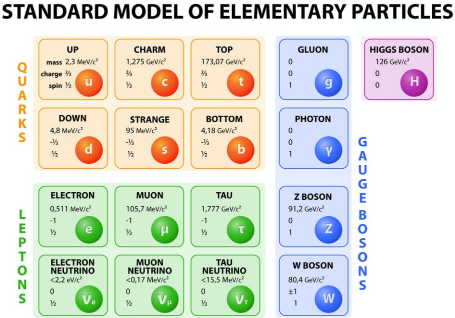
In spite of the Standard Model success to accurately explain most particle phenomena, there is a list of non solved problems that can't be explained within the SM context:

- Neutrino masses origin.
- Baryon asymmetry of the universe.
- Dark Matter existence.
- Gravitational interaction.



There are missing pieces that we are still trying to find!



Motivation

- Neutrino mass generation through Seesaw I + Seesaw II mechanisms.
- Improve dark matter relic abundance in the Scotogenic model (Ernest Ma, 2006) by adding a second scalar candidate.
- It is possible to study leptogenesis resulting from the out of equilibrium decay of heavy particles.
- It is convenient to study different phenomena BSM within the same model.

Figure: Vera Rubin studied the rotation curves of spiral galaxies.

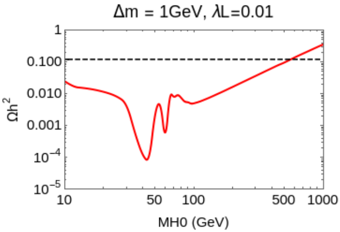


Figure: Relic density for the Scotogenic model as a function of DM mass.

The Model

We consider an Standard Model extension by adding an $SU(2)_L$ inert scalar doublet Φ_2, a hypercharless inert scalar triplet T and a scalar triplet Δ with $Y = 1$. Additionaly, we extend the fermion sector with three fermion singlets N_i, which represent the right handed neutrinos. A discrete $Z_2 \times Z_2'$ symmetry is introduce to guarantee the stability of the two dark matter candidates.

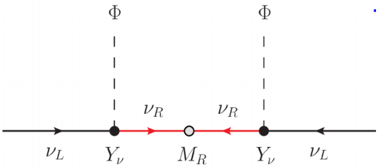
Particle	SU(3)	SU(2)	U(1)	Z_2	Z_2'
N_i	1	1	0	-1	1
Δ	1	3	1	1	1
T	1	3	0	1	-1
Φ_2	1	2	1/2	-1	1

All SM particles are trivially charged under $Z_2 \times Z_2'$ symmetry.

Model with two DM candidates: Physical Review D 105, 115010 (2022)
N. Chakrabarty, R. Roshan, A. Sil

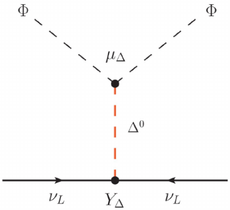
Neutrino mass generation

$$\mathscr{L}_{new} = \frac{1}{2} M_{N\alpha} \bar{N_\alpha}^c N_\alpha + Y_\alpha \bar{\ell}_{L\alpha} \tilde{\Phi}_2 N_\alpha + Y_{\Delta\alpha\beta} \ell^T_{L\alpha} C i\tau_2 \Delta \ell_{L\beta} + h.c. \quad (1)$$



Seesaw Type I

$$m_\nu \sim Y_\nu \frac{\langle \Phi \rangle^2}{M_R^2}$$



Seesaw Type II

$$m_\nu \sim Y_\Delta \mu \frac{\langle \Phi \rangle^2}{M_\Delta^2}$$

Majorana neutrinos ⇒ lepton number violation.

Scalar potential

The most general scalar potential invariant under $Z_2 \times Z_2'$ is:

$$
\begin{aligned}
V = & \mu_1^2 \Phi_1^\dagger \Phi_1 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 \\
& + \frac{1}{2} \lambda_5 \left((\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right) + \mu_\Delta^2 \Delta^\dagger \Delta + \lambda_\Delta (\Delta^\dagger \Delta)^2 + \lambda_6 \Phi_1^\dagger \Phi_1 \Delta^\dagger \Delta \\
& + \lambda_7 \Phi_2^\dagger \Phi_2 \Delta^\dagger \Delta + \mu_{\Phi_1 \Delta} \left(\Phi_1^\dagger \Delta \tilde{\Phi}_1 + h.c. \right) + \mu_{\Phi_2 \Delta} \left(\Phi_2^\dagger \Delta \tilde{\Phi}_2 + h.c. \right) \\
& + \mu_T^2 T^\dagger T + \lambda_T (T^\dagger T)^2 + \lambda_{\Phi_1 T} \Phi_1^\dagger \Phi_1 T^\dagger T + \lambda_{\Phi_2 T} \Phi_2^\dagger \Phi_2 T^\dagger T.
\end{aligned}
\tag{2}
$$

Where $\tilde{\Phi}_i = i\tau_2 \Phi_i^*$ is the doublet charge conjugate and τ_2 the second of Pauli matrices.

Relevant parameters: $\lambda_L = (\lambda_3 + \lambda_4 + \lambda_5)/2$, $\lambda_{\Phi_1 T}, \lambda_{\Phi_2 T}$ y Δm

Electroweak Symmetry Breaking EWSB

After electroweak symmetry breaking, the neutral component of Φ_1 acquires a vacuum expectation value (VEV) v. Φ_2 y T are inert scalars, therefore do not obtain a VEV.

$$\langle \Phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \tag{3}$$

$$\langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{4}$$

$$\langle \Delta \rangle_0 = \begin{pmatrix} 0 \\ 0 \\ v_T \end{pmatrix} \tag{5}$$

$$\langle T \rangle_0 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} . \tag{6}$$

Where $v = 246$ GeV.

Masses of the physical scalars.

After EWSB the masses of the physical scalars are:

$$m^2_{H_1^\pm} = \mu_1^2 + \lambda_1 v^2 + \lambda_6 v_T^2$$

$$m^2_{H_2^\pm} = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 + \lambda_7 v_T^2$$

$$m^2_{\Delta^\pm} = \mu_\Delta^2 + \frac{1}{2}\lambda_6 v^2 + 2\lambda_\Delta v_T^2$$

$$m^2_{T^\pm} = \mu_t^2 + \frac{1}{2}\lambda_{\Phi_1 T} v^2$$

$$m^2_{H_1^0} = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right) v^2 + \mu_{\Phi_2\Delta} v_T + \lambda_7 v_T^2$$

$$m^2_{H_{2,3}^0} = \frac{1}{2}\left(a + b \pm \sqrt{(a-b)^2 + 4c^2}\right)$$

$$m^2_{T^0} = \mu_t^2 + \frac{1}{2}\lambda_{\Phi_1 T} v^2$$

$$m^2_{A_1^0} = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right) v^2 - \mu_{\Phi_2\Delta} v_T + \lambda_7 v_T^2$$

Masses of the physical scalars.

$$m^2_{A^0_{2,3}} = \frac{1}{2}\left(d + f \pm \sqrt{(d-f)^2 + 4g^2}\right)$$

$$m^2_{A^0_4} = \mu_t^2 + \frac{1}{2}\lambda_{\Phi_1 T} v^2$$

$$m^2_{\Delta^{\pm\pm}} = 2\mu_\Delta^2 + \lambda_6 v^2 + 4\lambda_\Delta v_T^2$$

Where: $a = 2\lambda_1 v^2$, $b = 2\mu_\Delta^2 + \lambda_6 v^2 + 12\lambda_\Delta v_T^2$, $c = \mu_{\Phi_1\Delta} v$, $d = -2\mu_{\Phi_1\Delta} v_T$, $f = 2\mu_\Delta^2 + \lambda_6 v^2 + 12\lambda_\Delta v_T^2$ and $g = \mu_{\Phi_1\Delta} v$.

The Seesaw type II contribution to the neutrino mass generation is:

$$m_\nu = 2 Y_\Delta v_T,$$

with a choice $v_T \sim 1 eV$, the matrix Y_Δ must be adjusted to produce the neutrino mass scale.

The dark matter candidates are the lightest particles charged under Z_2 and Z_2', therefore H_0 and T_0 are our DM candidates.

Perturbativity, positivity and unitarity constraints

To ensure the scalar potential remains bounded from below we impose the positivy conditions:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_\Delta > 0, \quad \lambda_T > 0.$$

$$\lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \lambda_6 + \sqrt{\lambda_1 \lambda_4} > 0 \tag{7}$$

$$\lambda_7 + \sqrt{\lambda_2 \lambda_\Delta} > 0, \quad \lambda_{\Phi_1 T} + \sqrt{\lambda_1 \lambda_T} > 0 \quad \lambda_{\Phi_2 T} + \sqrt{\lambda_2 \lambda_T} > 0$$

We also have the unitarity constraints:

$$|\lambda_3 \pm \lambda_4| \leq 8\pi, \quad |\lambda_3 \pm \lambda_5| \leq 8\pi, \quad |\lambda_3 + 2\lambda_4 \pm \lambda_5| \leq 8\pi$$

$$|\lambda_T| \leq 24\pi, \quad |\lambda_\Delta| \leq 24\pi, \quad |\lambda_{\Phi_2 T}| \leq 8\pi, \quad |\lambda_{\Phi_1 T}| \leq 8\pi \tag{8}$$

$$\left| \lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2} \right| \leq 8\pi, \quad \left| \lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_5^2} \right| \leq 8\pi.$$

Results: Dark matter relic density

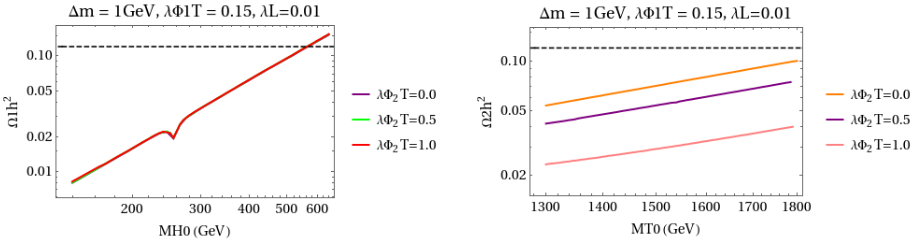


Figura 1: Dark matter density for H^0 and T^0, where $MT^0 > MH^0$, $\Delta m = MH^{\pm} - MH^0 = 1GeV$ and $\lambda_L = 0.01$. Dashed line shows the Planck limit for the total relic density: $\Omega_{DM}h^2 = 0.120 \pm 0.001$. To compute the dark matter density we use computer tools such as SARAH and MicrOmegas.

$$\Omega h^2_{Total} = \Omega h^2_{H^0} + \Omega h^2_{T^0}$$

Direct detection experimental limits

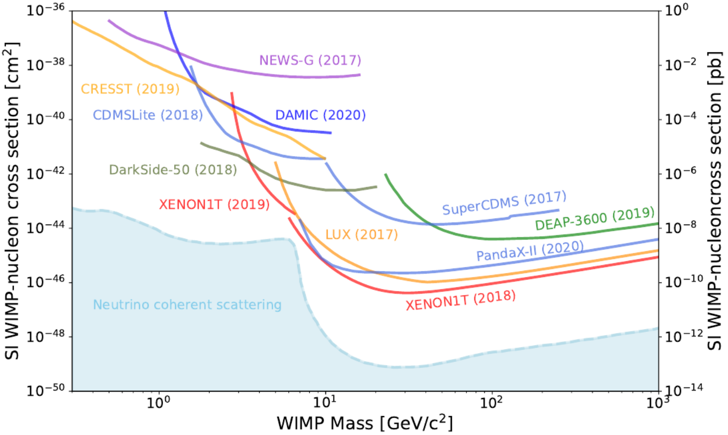
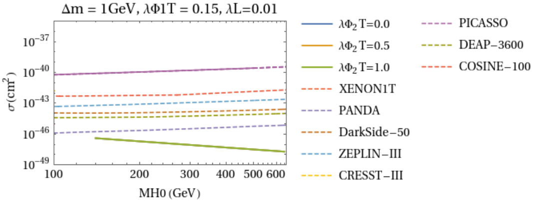
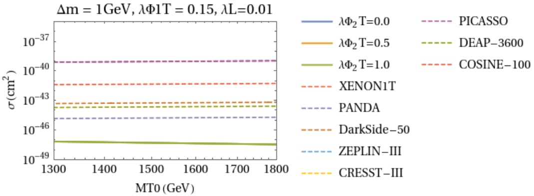


Figure: Upper limits for the spin independent DM-nucleon cross section. Credit: Prog. Theor. Exp. Phys. 2022, 083C01 (2022).

Results: Spin Independent cross section





Figures show the spin independent DM-nucleons scattering cross sections for H^0 and T^0 respectively. The different dashed lines represent the upper limits from direct detection experiments.

Points allowed by relic density

Table II shows sample points allowed by theoretical constraints and total relic density. Points are also allowed by direct detection experiments limits.

$MH0$	$MT0$	$\Omega_{H_0} h^2$	$\Omega_{T_0} h^2$	Ωh^2	$\sigma_{H^0}(pb)$	$\sigma_{T^0}(pb)$
430	1510	0.0733	0.0377	0.111	1.811×10^{-12}	2.075×10^{-12}
450	1490	0.0799	0.0369	0.117	1.655×10^{-12}	2.134×10^{-12}
460	1480	0.0832	0.0366	0.120	1.520×10^{-12}	2.194×10^{-12}

Constraints on the electroweak parameters S, T and U have been considered:

$$S = -0.01 \pm 0.07$$
$$T = 0.04 \pm 0.06$$
$$U = 0.01 \pm 0.11$$

Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

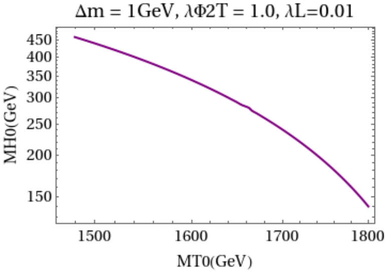
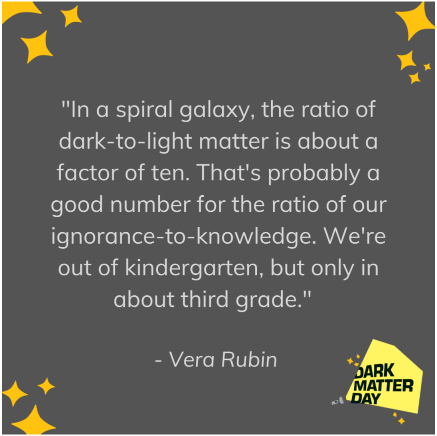


Figure: Figure shows points allowed by total relic density limit observed by Planck in the $MH0 - MT0$ plane.

Conclusions

- Relic density for each candidate is underabundant, but considering the contribution of both candidates to the total relic abundance allows to recover some desert regions.
- The mass splitting is very important, a very large $\Delta m \sim 100 GeV$ between the components of the scalar triplet makes de relic density very small.
- For an appropriate choice of the relevant parameters, we obtain the observed relic abundance and the DM-nucleon cross section within experimental limits.
- Different phenomena beyond the SM can be explained within a single model by proposing the appropiate SM extensions.
- In addition to dark matter phenomenology, we aim to study baryogenesis via leptogenesis of the out of equilibrium decay of heavy neutrinos and the active scalar triplet.



Thank you for your attention!