Higgs Portal Dark Matter and Neutrino Mass Generation in a Z_4 Scotogenic Model

Noel Jonathan Jobu [1] Kenji Nishiwaki [1]

[1]Shiv Nadar Institution of Eminence, Delhi NCR, India

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Osaka University

SHIV NADAR
INSTITUTION OF EMINENCE DEEMED TO BE UNIVERSITY
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Motivation

- Dark matter and neutrino mass are two of the most compelling hints of physics beyond the Standard Model.
- Radiative models like the Scotogenic framework link neutrino mass generation with dark matter in a testable way.

Model

	Z_4	$SU(2)_L$	$U(1)_Y$	Spin
η_A	i	2	1	0
η_B	$-i$	2	1	0
N_{A_i}	i	1	0	1/2
N_{B_i}	$-i$	1	0	1/2
S	-1	1	0	0

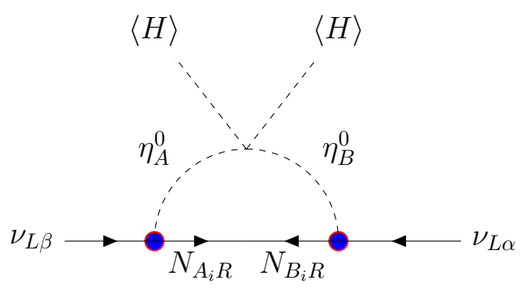
All Standard Model fields take +1 of the Z_4 parity. The SM Higgs H and the new singlet scalar S mix via a mass term.

Parameter	Particle mixing	Particle type
θ_{N_i}	$N_{A_i} \leftrightarrow N_{B_i}$	Majorana fermion (i=1,2,3.)
θ_R	$\eta^0_{R_A} \leftrightarrow \eta^0_{R_B}$	Real scalar
θ_I	$\eta^0_{I_A} \leftrightarrow \eta^0_{I_B}$	Imaginary scalar
θ_{CS}	$\eta^+_A \leftrightarrow \eta^+_B$	Charged scalar
α	$S \leftrightarrow H$	Real singlet scalar

- The one-loop neutrino mass $\mathcal{M}^{\nu}_{\alpha\beta}$ arises from the mass splitting between the real and imaginary parts of the neutral scalars, which is induced by the coupling λ_5 through the term:

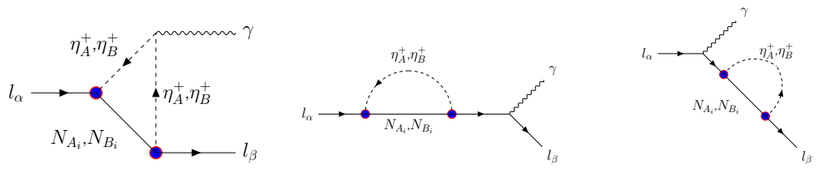
$$\frac{1}{2}\left[\lambda_5 \left(H^\dagger \eta_A\right)\left(H^\dagger \eta_B\right) + \text{h.c.}\right]$$

- The scalar contributions from the real and imaginary components enter with opposite sign, leading to divergence cancellation in the Scotogenic model. When their masses are equal, the total contribution cancels out, resulting in a vanishing neutrino mass.
- The singlet VEV breaks the Z_4 symmetry to a residual Z_2, which stabilizes the lightest Majorana fermion as the DM candidate.



Lepton Flavor Violation (LFV)

$(\mu \to e + \gamma\,, \tau \to \mu + \gamma\,, \tau \to e + \gamma)$



- $\mu \to e + \gamma$ imposes the strongest constraints on the lepton portal Yukawa couplings (●).
- These bounds are sensitive to the mass differences between the charged scalar and right-handed neutrinos within the loop.

Electroweak Precision Tests (Oblique Parameters)

We constrain the mass splittings between charged and neutral components of the inert scalar via the T parameter.

$$T = 0.01 \pm 0.12$$

Vacuum stability

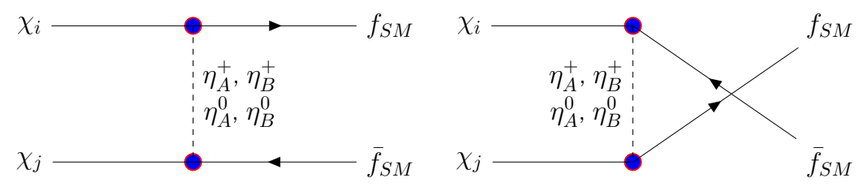
- We ensure bonded from below condition by requiring that the quartic part of the potential $\mathcal{V}^{(4)} > 0$ as the fields $\phi_i \to \infty$ via the use of the Sylvester criterion.
- For a stable vacuum minima, we impose positivity of the Hessian matrix via the Sylvester criterion.

$$(H)_{ij} = \left.\frac{\partial^2 \mathcal{V}}{\partial\phi_i \partial\phi_j}\right|_{\phi_i=\langle\phi_i\rangle,\phi_j=\langle\phi_j\rangle} \geq 0$$

Dark Matter Relic

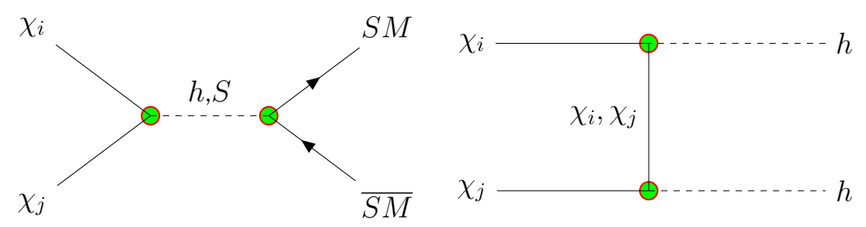
We consider WIMP thermal freeze-out scenario with co-annihilation of nearly degenerate partner particles to produce the correct relic. The DM candidate is a Majorana fermion N_{B_3} and its co-annihilating partner is N_{A_3}.

Lepton Portal



- Yukawa couplings (●) are not free parameters; they are determined by the Casas-Ibarra parametrization.
- $i = 1, 2$ and $j = 1, 2$ where χ_1 is the DM candidate and χ_2 is its co-annihilating partner.

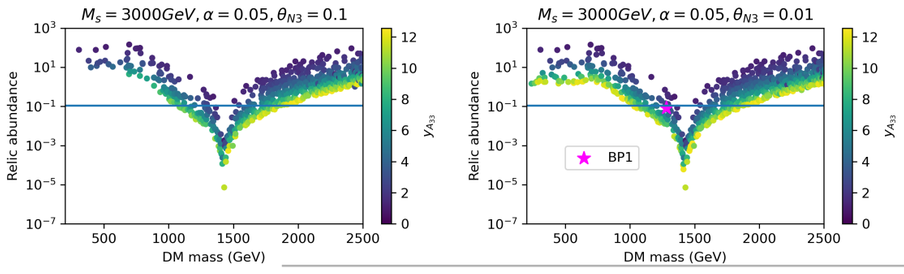
Higgs Portal



- Yukawa couplings (●) and Higgs–singlet mixing angle α are free parameters controlling interaction strength, subject to direct detection constraints.
- The correct relic abundance is achieved in the Higgs portal-dominated regime by setting $y_{B_{33}} = 0$, suppressing singlet–DM coupling lowering direct detection signals. Relic density is satisfied via the $y_{A_{33}}$ coupling to N_{A_3}.

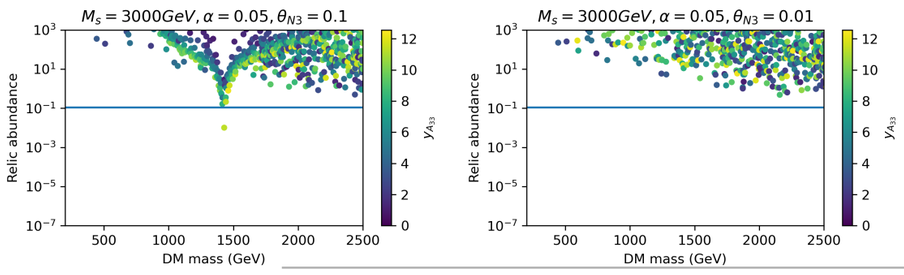
Results

All points in the DM mass vs relic abundance plots satisfy constraints from lepton flavor violation, electroweak precision observables, and direct detection bounds.
(**Preliminary**)



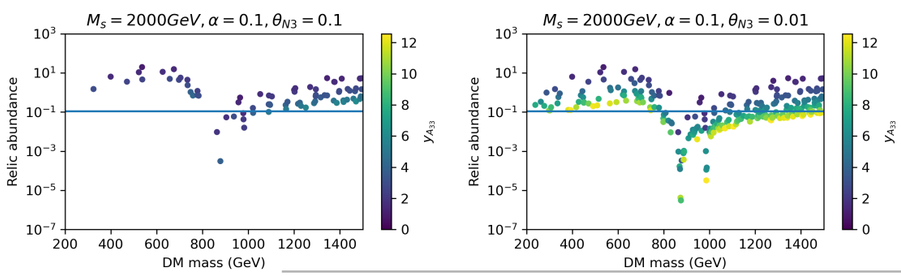
- Higgs portal dominates around resonant region BP1; color code is magnitude of Higgs portal Yukawa coupling
- Smaller $\theta_{N_3} = 0.01$ (Right figure) allows larger Yukawa coupling while still avoiding direct detection.

(**Preliminary**)

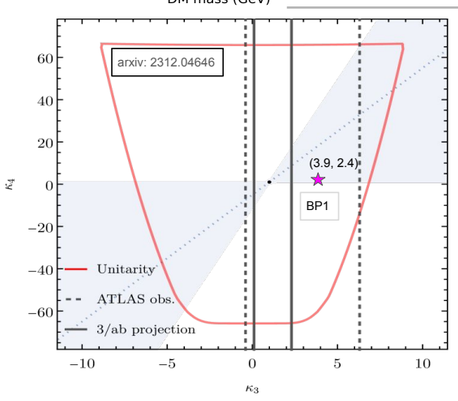


- Without co-annihilation, only resonant region can produce required DM relic (Left figure).
- Lower $\theta_{N_3} = 0.01$ increases the overall relic abundance (Right figure).

(**Preliminary**)



- Low singlet mass region ($m_S = 2000$ GeV) is hard to satisfy DM direct detection bounds.
- For non-resonant region, Yukawa must be high to satisfy relic.



- Parameters κ_3, κ_4 quantify deviations in the trilinear and quartic Higgs self-couplings, defined as $\kappa_l = g_l / g_l^{SM}$ where $l = 3, 4$.
- Collider data imposes strong bounds on κ_3 while unitarity constraints limit κ_4; our model remains consistent with both.
- These bounds translate directly into constraints on the Higgs–singlet mixing angle and the mass of the singlet scalar.
  BP1: $(\kappa_3,\ \kappa_4) = (3.9, 2.4) \to M_S = 3000$ GeV, $\alpha = 0.05$

Summary

- Neutrino masses are generated radiatively at one loop, with mass splitting between real and imaginary components controlled by the coupling λ_5.
- Co-annihilation with a nearly degenerate RHN and annihilation via Lepton and Higgs portals achieves the correct relic abundance.
- Our model predicts testable deviations in Higgs self-couplings κ_3 and κ_4, constrained by collider and unitarity bounds.
- The Higgs portal in our model provides a testable signature for the dark sector and neutrino mass generation, and the singlet scalar may also serve as a viable candidate for inflation in future work.

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nj702@snu.edu.in