Singlet-Doublet Majorana Dark Matter and Neutrino Mass in a Type-I Seesaw Scenario

Manoranjan Dutta[1*], Subhaditya Bhattacharya[2†], Purusottam Ghosh[3‡], Narendra Sahu[4*]

[1]ph18resch11007@iith.ac.in, [2]subhab@iitg.ac.in, [3]purusottamghosh@hri.res.in, [4]nshau@phy.iith.ac.in

[*]Indian Institute of Technology Hyderabad, Telangana-502285, India. [†]Indian Institute of Technology Guwahati, North Guwahati, Assam-781039, India. [‡]Harish-Chandra Research Institute, HBNI, Jhunsi, Allahabad - 211 019, India

Abstract

A minimal extension of the Standard Model (SM) by a vector-like fermion doublet and three right handed (RH) singlet neutrinos is proposed in order to explain dark matter and tiny neutrino mass simultaneously. The DM arises as a mixture of the neutral component of the fermion doublet and one of the RH neutrinos, both assumed to be odd under an imposed $\mathcal{Z}_2$ symmetry. Being Majorana in nature, the DM escapes from Z-mediated direct search constraints to mark a significant difference from singlet-doublet Dirac DM. The other two $\mathcal{Z}_2$ even heavy RH neutrinos give rise masses and mixing of light neutrinos via Type-I Seesaw mechanism. Relic density and direct search allowed parameter space for the model is investigated through detailed numerical scan.

Model for Singlet-Doublet Majorana Dark Matter

The model addressed here, contains

- A vector-like fermion doublet $\Psi = \begin{pmatrix}\psi^0 \\ \psi^-\end{pmatrix}$
- Three right handed neutrinos (N_{R_i}), i=1,2,3.

Fields→	Ψ	N_{R_1}	N_{R_2}	N_{R_3}
$SU(2)$	2	1	1	1
$U(1)_Y$	-1	0	0	0
$\mathcal{Z}_2$	-1	-1	+1	+1

Table: Particle content and their charge assignments under $SU(2)$, $U(1)_Y$ and $\mathcal{Z}_2$ groups.

The Lagrangian of the model reads as,

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{\Psi}\left(i\gamma^\mu D_\mu - M\right)\Psi + \overline{N_{R_i}} i\gamma^\mu \partial_\mu N_{R_i} - \left(\frac{1}{2}M_{R_i}\overline{N_{R_i}}\left(N_{R_i}\right)^c + h.c\right) + \mathcal{L}_{yuk}. \tag{1}$$

where,

$$-\mathcal{L}_{yuk} = \left[\frac{Y_1}{\sqrt{2}}\overline{\Psi}\tilde{H}\left(N_{R_1} + (N_{R_1})^c\right) + h.c\right] + \left(Y_{j\alpha}\overline{N_{R_j}}\tilde{H}^\dagger L_\alpha + h.c.\right). \tag{2}$$

After EWSB,

$$-\mathcal{L}_{mass} = M\overline{\psi^0_L}\psi^0_R + \frac{1}{2}M_{R_1}\overline{N}_{R_1}(N_{R_1})^c + \frac{m_D}{\sqrt{2}}\left(\overline{\psi^0_L}N_{R_1} + \overline{\psi^0_R}(N_{R_1})^c\right) + h.c. \tag{3}$$

The mass matrix in the basis $((\psi^0_R)^c, \psi^0_L, (N_{R_1})^c)^T$,

$$\mathcal{M} = \begin{pmatrix} 0 & M & \frac{m_D}{\sqrt{2}} \\ M & 0 & \frac{m_D}{\sqrt{2}} \\ \frac{m_D}{\sqrt{2}} & \frac{m_D}{\sqrt{2}} & M_{R_1} \end{pmatrix}. \tag{4}$$

$\mathcal{M}$ can be diagonalised by $\mathcal{U}.\mathcal{M}.\mathcal{U}^T = \mathcal{M}_{Diag.}$, where,

$$\mathcal{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\pi/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\cos\theta & \sin\theta \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{\sqrt{2}}\sin\theta & -\frac{1}{\sqrt{2}}\sin\theta & \cos\theta \end{pmatrix}. \tag{5}$$

After diagonalization, In the small mixing limit ($\theta \to 0$), we get three Majorana states with masses:

$$m_{\chi_1} \approx M + \frac{m_D^2}{M - M_{R_1}},\ m_{\chi_2} = M,\ m_{\chi_3} \approx M_{R_1} - \frac{m_D^2}{M - M_{R_1}}\ , \tag{6}$$

where we have assumed $m_D << M, M_{R_1}$. Hence it is clear that $m_{\chi_1} > m_{\chi_2} > m_{\chi_3}$ and χ_3 becomes the stable DM candidate.
Majorana DM $\to$ No diagonal Z-mediated interaction.

Dark Parameters : $\{\ m_{\chi_3}, \Delta M = (m_{\chi_1} - m_{\chi_3}) \approx (m_{\chi_2} - m_{\chi_3}),\ \sin\theta\ \}$.

Relic Density as a function of DM mass

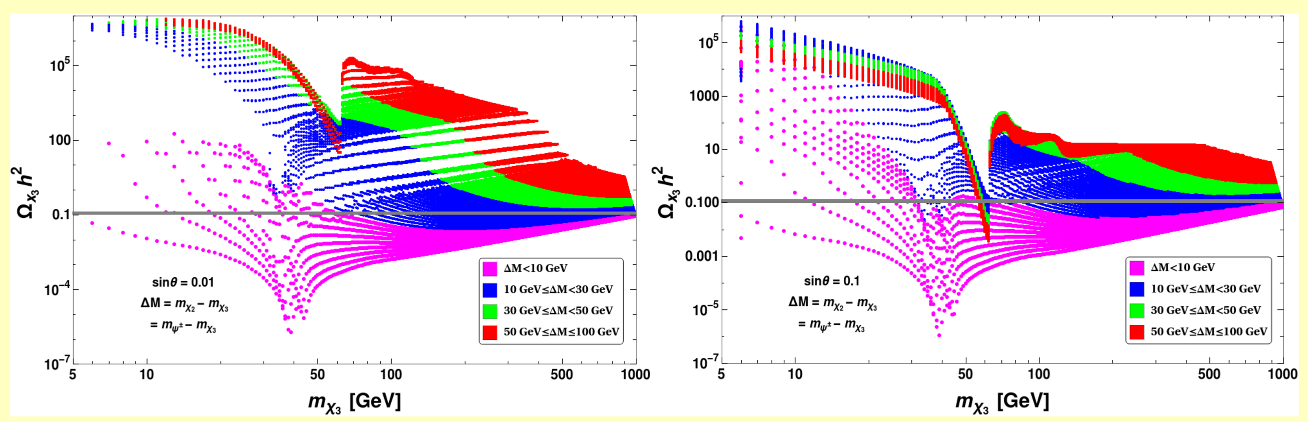

Figure: Variation of relic density with DM mass and ΔM.

- At small ΔM, relic is contributed mostly from co-annihilations mediated by off-diagonal Z mediation and $W^\pm$ mediation.
- With increase in ΔM, co-annihilation decreases gradually and annihilation takes over.
- At a particular ΔM, the annihilation mediated by Higgs increases with increase in singlet-doublet mixing $\sin\theta$ as $Y_1(\propto \Delta M \sin 2\theta$.)

Relic density allowed parameter space in the $\Delta M - m_{\chi_3}$ plane

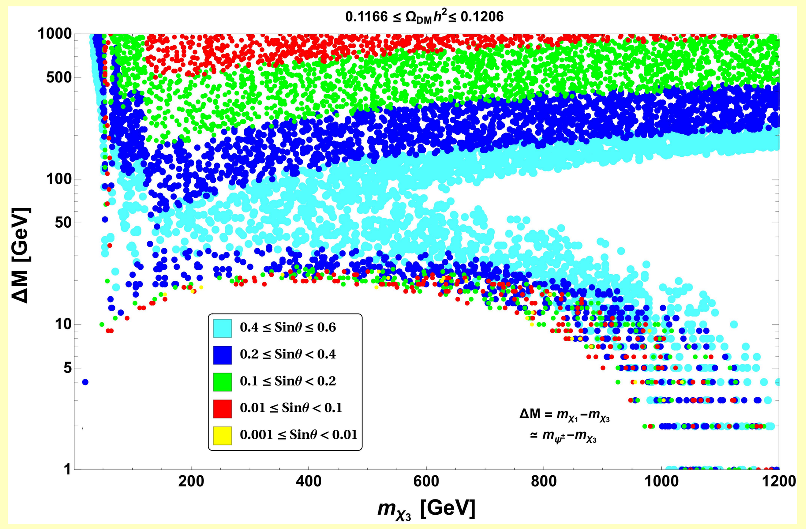

Figure: Relic density allowed (from PLANCK) parameter space in the $\Delta M - m_{\chi_3}$ plane.

- Bifurcation around $\Delta M \sim 50$ GeV separating the figure into two regions.
- In the bottom half, with higher DM mass, annihilation decreases, so one needs to be more relied on co-annihilations to get the correct relic, requiring ΔM to decrease.
- In the top half, co-annihilation contribution can be neglected, relic is dominantly decided by annihilations proportional to $Y_1 \propto \Delta M \sin 2\theta$, so for ΔM, $\sin\theta$ should decrease and vice-versa.

Direct Detection of Singlet-Doublet Majorana Dark Matter

- Direct detection of DM is possible through DM particle scattering off detector nuclei via Higgs mediation. Since DM is of Majorana nature, Z-mediated direct search is absent making the model well distinguished from singlet-doublet Dirac DM, which has been studied earlier.
- Direct search cross section being proportional to $\Delta M \sin^2 2\theta$, smaller $\sin\theta$s survives the cut.
- However, larger $\sin\theta$s with appropriately smaller ΔM also survives the cut.

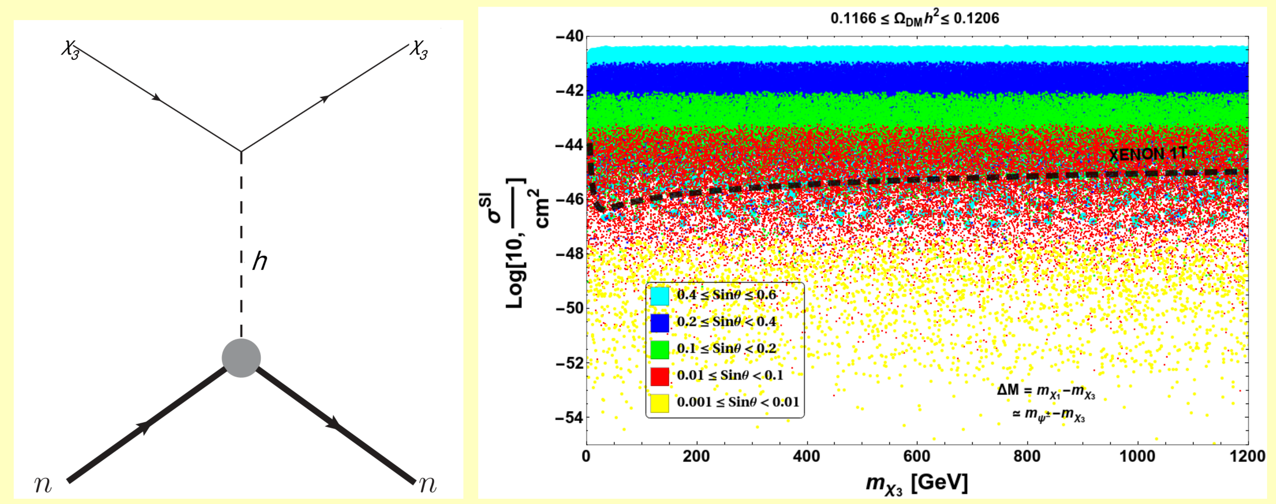

Figure: Left: Feynman diagram for direct detection, Right: Direct detection cross section for the DM (χ_3) confronted with bounds from XENON1T experiment.

Relic and direct search allowed parameter space in ΔM vs m_{χ_3} Plane

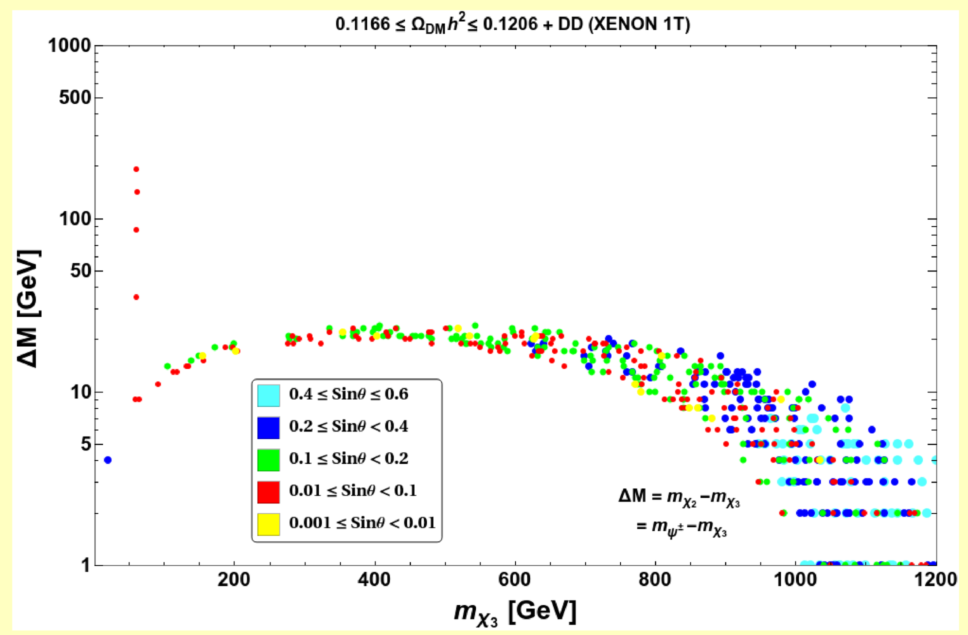

Figure: Relic and direct search allowed parameter space in ΔM vs m_{χ_3} Plane

- Direct search constraint crucially tames down the relic density allowed parameter space.
- Large $\sin\theta$ (upto ~ 0.6) is allowed for the model at hand in contrast to the singlet-doublet Dirac DM where maximum $\sin\theta \sim 0.05$.)
- $\sin\theta$ is correlated to both DM mass and ΔM.
- Large $\sin\theta$ values are allowed only for large DM mass because direct search cross-section being proportional to $\Delta M \sin^2 2\theta$, for large $\sin\theta$, ΔM should be small in order to be allowed by direct search bound; however small ΔM leads to more co-annihilations making the relic under-abundant, so one has to go towards the higher mass so that the decrease in annihilation compensates the increase in co-annihilation, giving correct relic.

Neutrino mass

A tiny neutrino mass is generated via Type I seesaw from parts of Eqn.1,

$$-\mathcal{L}^{\nu}_{mass} \supset \left(Y_{j\alpha}\overline{N_{R_j}}\tilde{H}^\dagger L_\alpha + h.c.\right) + \left(\frac{1}{2}M_{R_j}\overline{N}_{R_j}(N_{R_j})^c + h.c.\right). \tag{7}$$

where $\alpha = e, \mu, \tau$ and $j = 2, 3$.
In the basis where the the heavy Majorana mass matrix that takes part in seesaw is diagonal *i.e.*, $M_R = \mathbf{Diag}(0, M_{R_2}, M_{R_3})$, the light neutrino mass matrix obtained through Type-I seesaw is given by $m_\nu = -m_D M_R^{-1} m_D^T$.
M_R is constrained from processes like $\mu \to e\gamma$ using Ibarra-Casas paramtrization.

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