A dark clue to seesaw and leptogenesis in a pseudo-Dirac singlet doublet scenario with (non)standard cosmology

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Singlet doublet dark matter

- Standard model extended with a vector fermion doublet Ψ and a vector fermion singlet χ having odd charges under a imposed Z_2.

$$\mathcal{L} \subset Y\Psi\tilde{H}\chi + m_\Psi\overline{\Psi}\Psi + m_\chi\overline{\chi}\chi \tag{1}$$

$$\mathcal{M}_D = \begin{pmatrix} M_\Psi & M_D \\ M_D & M_\chi \end{pmatrix}, \tag{2}$$

where we define $M_D = \frac{Yv}{\sqrt{2}}$

- Diagonalising the mass matrix yields two neutral Dirac eigenstates (ξ_1, ξ_2) with mass eigenvalues

$$M_{\xi_1} \approx M_\chi - \frac{M_D^2}{M_\Psi - M_\chi} \tag{3}$$

$$M_{\xi_2} \approx M_\Psi + \frac{M_D^2}{M_\Psi - M_\chi} \tag{4}$$

- Therefore, the lightest state is ξ_1, which we identify as our DM candidate.
- The DM stability is achieved by the unbroken $\mathcal{Z}_2$ symmetry.
- The mixing between two flavor states, *i.e.* neutral part of the doublet (ψ^0) and the singlet field (χ) is parameterised by θ as

$$\sin 2\theta \simeq \frac{2Yv}{\Delta M}, \tag{5}$$

  where $\Delta M = M_{\xi_2} - M_{\xi_1} \approx M_\Psi - M_\chi$ in the small Y limit. In small mixing case, ξ_1 can be identified with the singlet χ.
- The DM phenomenology is mainly controlled by the following independent parameters.

$$\{M_\Psi,\ M_\chi,\ \theta\}. \tag{6}$$

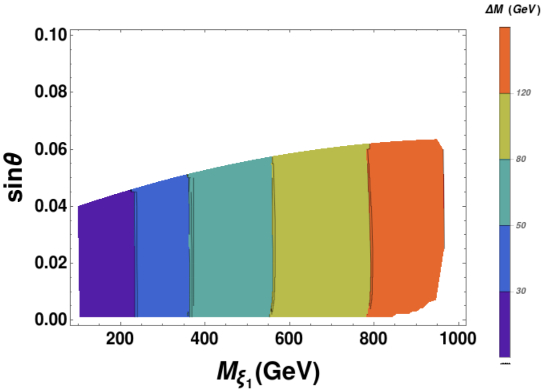


Figure: Region of parameter space allowed from both the relic density and direct detection bounds are shown in a plane of dark matter mass M_{ξ_1} and mixing angle $\sin\theta$. Different colors are for different values of mass gap $\Delta M = (M_{\xi_2} - M_{\xi_1})$ allowed here. In this scenario, upper limit in $\sin\theta$ is strongly constrained from direct detection bounds which gradually relaxed with higher dark matter mass and thus a lower cross section.

Motivation

- Is there any way out to evade the strong limit on the mixing angle? It is found that a small bare Majorana mass term for the the singlet fermion brings in a pseudo-Dirac dark matter capable of evading the strong spin-independent direct detection bound by suppressing the dark matter annihilation processes mediated by the neutral current.
- We ask that whether presence of the same mass term can yield light neutrino masses radiatively satisfying observed oscillation data.
- Leptogenesis could be a bonus!

The Model

BSM and SM Fields	$SU(3)_C$	$\times SU(2)_L$	$\times U(1)_Y \equiv \mathcal{G}$	$U(1)_L$	$\mathcal{Z}_2$
$\Psi_{L,R}$	1	2	$-\frac{1}{2}$	0	$-$
$\chi_{L,R}$	1	1	0	0	$-$
$\phi_i \ (i=1,2,3)$	1	1	0	0	$-$
$\ell_L \equiv \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$	1	2	$-\frac{1}{2}$	1	$+$
$H \equiv \begin{pmatrix} w^+ \\ \frac{1}{\sqrt{2}}(v+h+iz) \end{pmatrix}$	1	2	$\frac{1}{2}$	0	$+$

Table: Fields and their quantum numbers under the SM gauge symmetry, lepton number and additional $\mathcal{Z}_2$.

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_Y, \tag{7}$$

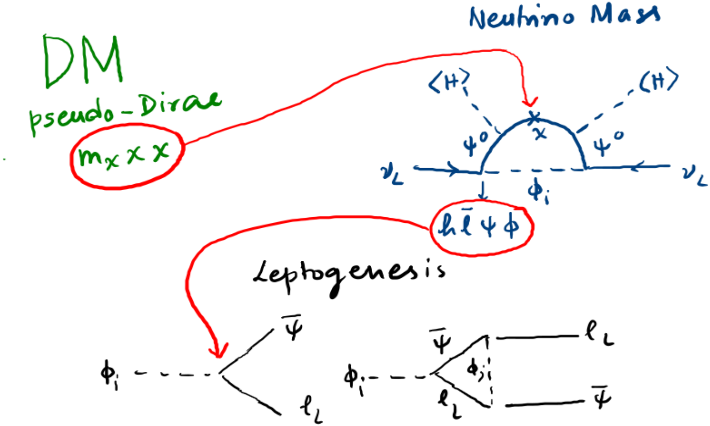
where,

$$\mathcal{L}_f = i\bar{\Psi}\gamma_\mu D^\mu \Psi + i\bar{\chi}\gamma_\mu \partial^\mu \chi - M_\Psi \bar{\Psi}\Psi - M_\chi \bar{\chi}\chi - \frac{m_{\chi_L}}{2}\overline{\chi^c}P_L\chi - h.c. - \frac{m_{\chi_R}}{2}\overline{\chi^c}P_R\chi - h.c., \tag{8}$$

and

$$\mathcal{L}_Y = Y_1\bar{\Psi}_L\tilde{H}\chi_R + Y_2\bar{\Psi}_R\tilde{H}\chi_L + h_{\alpha i}\bar{\ell}_{L_\alpha}\Psi_R\phi_i + h.c.. \tag{9}$$

Assumptions: $Y_1 = Y_2$, $m_{\chi_L} = m_{\chi_R} \ll M_\chi$



We study these in non-cosmological background.

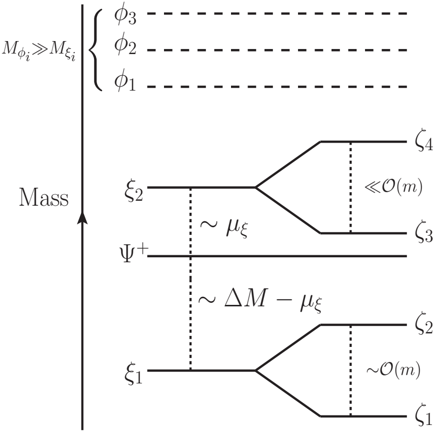


Figure: Mass spectrum of the dark sector, showing the lightest pseudo-Dirac mode as the dark matter and other heavy BSM fermions and scalars. The mass of the charged fermion is M_Ψ and it lies somewhere in between ξ_1 and ξ_2. The mass ordering is subject to change depending on the numerical values of m, ΔM and $\sin\theta$.

Hubble parameter:

$$H(T) \approx \frac{2\sqrt{2}\pi^{3/2}\bar{g}_*^{1/2}}{3\sqrt{10}} \frac{T^2}{M_{\rm Pl}} \left(\frac{T}{T_r}\right)^{n/2}, \quad (\text{with} \quad T \gg T_r), \tag{10}$$

$$= H_R(T) \left(\frac{T}{T_r}\right)^{n/2}, \tag{11}$$

where $H_R(T) \sim 1.66\ \bar{g}_*^{1/2} \frac{T^2}{M_{\rm Pl}}$, the Hubble rate for radiation dominated Universe.

The relevant set of parameters which participate in the DM phenomenology in presence of the modified cosmology are the following :

$$\Big\{\Delta M,\ \sin\theta,\ T_r,\ n\Big\}, \tag{12}$$

for a certain DM mass.

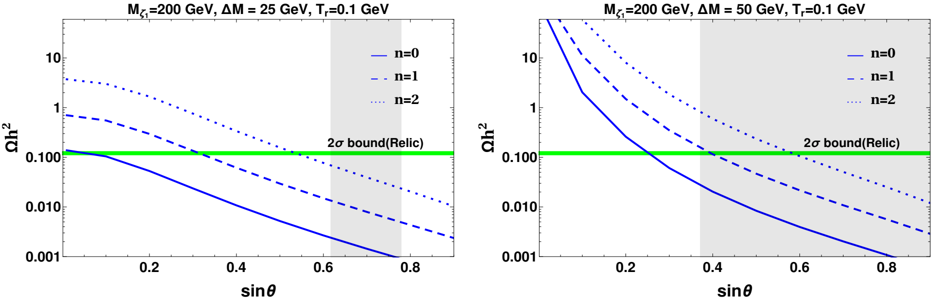


Figure: Relic abundance of the DM as a function of the mixing angle between the singlet and doublet is shown considering both standard (solid line) and non-standard (dashed and dotted lines) thermal history of the Universe, for $M_{\zeta_1} = 200$ GeV with (left) $\Delta M = 25$ GeV and (right) $\Delta M = 50$ GeV. The disfavored region from the spin independent direct detection constraints are denoted by respective shaded region. Here we have considered $T_r = 0.1$ GeV.

Relic satisfied benchmark points

BP	n	T_r (GeV)	M_{ζ_1} (GeV)	ΔM (GeV)	$\sin\theta$	Ωh^2	$\mathrm{Log}_{10}\left[\frac{\sigma^{\rm SI}}{\rm cm^2}\right]$
I	2	0.1	200	25	0.53	0.12	-46.71
II	2	0.1	1000	90	0.325	0.12	-46.8

Table: Two sets of relic and SI direct search satisfied points. We took $m_{\chi_L} = m_{\chi_R} = 1$ GeV.

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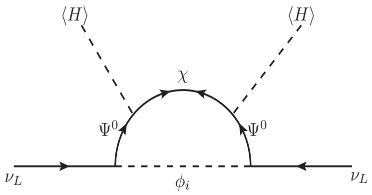
This model renders a mechanism which explains the radiative generation of light neutrino mass. The relevant one loop process is shown below which establishes the fact that the presence of the heavy scalars are essential in order to make the Majorana light neutrinos massive.



The light neutrino mass matrix can be expressed as

$$m_{\nu_{\alpha\beta}} = h^T_{i\alpha} \Lambda_{ii} h_{\beta i}, \tag{13}$$

where, $\Lambda_{ii} = \Lambda^L_{ii} + \Lambda^R_{ii}$. where Λ^L_{ii} and Λ^R_{ii} include the contribution from m_{χ_L} and m_{χ_R} respectively. We use CI parametrisation

$$h^T = D_{\sqrt{\Lambda^{-1}}} \, \mathcal{R} \, D_{\sqrt{m_\nu^{\rm diag}}} \, U^\dagger, \tag{14}$$

where,

$$\mathcal{R} = O \; e^{iA}$$

is a complex orthogonal matrix.

The exponential of the anti-symmetric matrix A can be simplified to

$$e^{iA} = 1 - \frac{\cosh r - 1}{r^2} A^2 + i \frac{\sinh r}{r} A \tag{15}$$

with $r = \sqrt{a^2 + b^2 + c^2}$ and

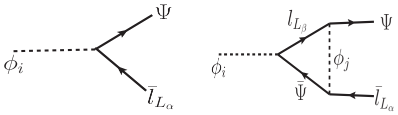
$$A = \begin{pmatrix} 0 & a & b \\ -a & 0 & c \\ -b & -c & 0 \end{pmatrix} \tag{16}$$

For our purpose, we consider O as an identity matrix and also for simplicity of the anti-symmetric matrix A we have chosen the equality $a = b = c \equiv a$.

BP	Λ_{11} (eV)	Λ_{22} (eV)	Λ_{33} (eV)	a	$h_{\alpha i} \times 10^4$
I	9.94×10^7	1.02×10^8	1.04×10^8	2.9	$\begin{pmatrix} -10.08 - 3.17i & 4.02 - 7.94i & -0.31 - 6.58i \\ -1.54 - 10.38i & 8.92\,0.26i & 5.71 - 3.1i \\ 1.05 - 6.88i & 5.65 + 1.81i & 4.13 - 0.83i \end{pmatrix}$
II	5.54×10^7	5.69×10^7	5.83×10^6	2.7	$\begin{pmatrix} -9.55 - 3.0i & 3.97 - 7.5i & -0.29 - 6.22i \\ -1.46 - 9.84i & 8.44 + 0.24i & 5.39 - 2.91i \\ 0.96 - 6.53i & 5.36 + 1.69i & 3.86 - 0.75i \end{pmatrix}$

Table: Numerical estimation of the two Yukawa coupling matrices which are obtained for the sets of benchmark points (BP) tabulated in Table 2. Reference scalar masses are considered as $M_{\phi_i} = \{10^7, 10^{7.1}, 10^{7.2}\}$ GeV.

Leptogenesis



The total lepton asymmetry receives contributions from superposition of tree level and vertex diagram.

$$\epsilon^i_{\text{vertex}} = \frac{1}{4\pi} \sum_{j \neq i} \frac{\text{Im}\left[(h^\dagger h)_{ij} h_{\alpha j} h^*_{\alpha i}\right]}{(h^\dagger h)_{ii}} x_{ij} \log\left(\frac{x_{ij}}{x_{ij}+1}\right) \tag{17}$$

The evolutions of number densities of ϕ and $B - L$ asymmetry can be obtained by solving the following set of coupled Boltzmann's equations (BEQs)

$$\frac{dN_{\phi_i}}{dz} = -D_i(N_{\phi_i} - N^{eq}_{\phi_i}), \quad \text{with} \quad i = 1,2,3 \tag{18}$$

$$\frac{dN_{B-L}}{dz} = -\sum_{i=1}^{3} \epsilon_i D_i(N_{\phi_i} - N^{eq}_{\phi_i}) - \sum_{i=1}^{3} W_i N_{B-L}, \tag{19}$$

with $z = M_{\phi_1}/T$ when the decaying scalar is the ϕ_1.

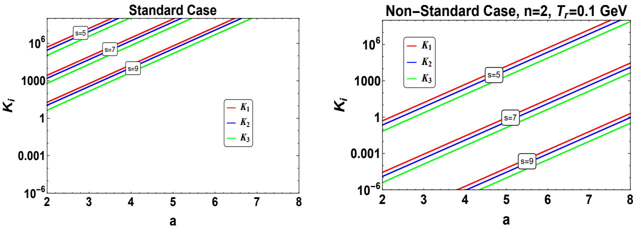


Figure: Washout factors as a function of a for (left) standard and (right) non-standard case. We consider here $M_{\phi_i} = \{10^s, 10^{s+0.1}, 10^{s+0.2}\}$ GeV with $s = \{7, 8, 9\}$ for the benchmark point I in Table 2.

BP	a	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3\rvert$	$\eta_B(n=1)$	$\eta_B(n=2)$
I	2.9	3.01×10^{-9}	2.21×10^{-8}	1.95×10^{-8}	5.07×10^{-13}	3.71×10^{-10}
II	2.7	2.68×10^{-9}	1.98×10^{-8}	1.7×10^{-8}	5.69×10^{-13}	3.28×10^{-10}

Table: Estimating baryon asymmetry considering compressed mass hierarchy with $M_{\phi_i} = \{10^7, 10^{7.1}, 10^{7.2}\}$ GeV for the two benchmark points in Table 2.

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Conclusion

- We provide a dark matter origin of neutrino mass and leptogenesis.
- A fast expansion prior to to BBN is prefered to have weak washout and obtain observed order of baryon asymmetry with weaker Yukawa coupling.
- Studying flavored leptogenesis could be interesting.