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Phenomenological study of neutrinoless double beta decay and sterile dark matter in extended left right symmetric model

In this chapter, we have studied a flavor symmetry-based extended left-right symmetric model(LRSM) with a dominant type-II seesaw mechanism and have explored the associated neutrino phenomenology. The particle content of the model includes usual quarks and, leptons along with additional sterile fermion per generation in the fermion sector while the scalar content contains Higgs doublets and scalar bidoublet. Realization of this extension of LRSM has been done by using $A_4 \times Z_4$ discrete symmetries. In this work, we have included the study of new physics contributions to the NDBD process within the framework along with sterile neutrino dark matter(DM) phenomenology.

3.1 Introduction

Standard Model(SM) is the most economical and successful model of particle physics, But it fails to explain various phenomena like lepton flavor violation, small neutrino mass, baryon asymmetry of the universe, dark matter, etc. One of the main drawbacks of the SM is that it explains the parity violation of weak interaction adhocly by assuming that transformation of the right-handed counterpart of the particles to be transformed as singlet under SU_2 gauge group. Because of this, there has to be some framework where parity violation can be explained naturally. Left right symmetric model is one such framework where both right-handed and left-handed particles are treated on equal footing and it is the most economical way to restore parity came a long way in explaining neutrino mass, lepton number violation, dark matter, baryon asymmetry of the universe thereby gaining popularity. LRSM [78–82] is a very simple extension of the standard model gauge group where parity restoration is obtained at a high energy scale and the fermions are assigned to the gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which can be tested in present-day experiments. The usual type-I [57, 59–62] and type-II [63–65, 58, 66, 67] seesaw arises naturally in LRSM. Several other problems like parity violation of weak interaction, massless neutrinos, CP problems, hierarchy problems, etc can also be addressed in the framework of LRSM. The seesaw scale is identified as the breaking of the $SU(2)_R$ symmetry. In this model, the electric charge generator is given by, $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$, where T_{3L} and T_{3R} are the generators of $SU(2)_L$ and $SU(2)_R$ and B-L being the baryon minus lepton number charge operator. The mass of neutrino can be explained in extended LRSM with canonical seesaw, inverse seesaw, linear seesaw, extended seesaw, etc. In this work LRSM is extended with a neutral fermions per generation, which is known as extended seesaw. Within this extended seesaw type-II dominance is considered for phenomenological analysis. With this extra singlet fermion, the mass matrix in type-II dominance can be given as-

$$\mathcal{M} = \begin{pmatrix} M_L & 0 & M_D \\ 0 & 0 & M \\ M_D^T & M^T & M_R \end{pmatrix} \tag{3.1}$$

Where light neutrino mass is $m_\nu = v_L f_L$. A natural type-II seesaw dominance allows large light-heavy neutrino mixing thus leading to many new physics contributions to neutrinoless double beta decay along with constraints on light neutrino mass. In one of the recent works [167] extended LRSM is studied in details considering linear seesaw to show the phenomenological importance in different LFV processes and unitarity violation etc using flavor symmetry.

In this work, we have used $A_4 \times Z_4$ discrete symmetries to realize the extended seesaw with type-II dominance. We aim to study here the extension of LRSM which offers the advantage of studying neutrino mass, new physics contribution to the NDBD process, and DM phenomenology within one framework. A_4 is the discrete group of even permutations of four objects and is the smallest non-Abelian group containing triplet irreducible representations. More importantly, flavor symmetry has been used within the framework of LRSM in very few works [168–170, 147]. In some other important literature extended LRSM is also discussed considering different dominant seesaw [171–175]. We extensively discussed different leading-order contributions to the NDBD process and, DM phenomenology in the considered framework. Discrete symmetry will constrain different mass matrices arising from the framework considered and which will lead to phenomenological implications.

This chapter is structured as follows. In section 3.2, we briefly discuss the left-right symmetric model with extended seesaw with type-II dominance. The flavor symmetric model considering type-II dominance is discussed in section 3.3. We also discuss the different new physics contributions to the amplitude of the decay process in section 3.4. In section 3.5, we discuss light sterile neutrino as a probable dark matter candidate. We present our numerical analysis and results in section 3.6 and then in Section 3.7, we conclude by giving a brief overview of our work.

3.2 LRSM with extended seesaw with type-II dominance:

In this work, LRSM is extended with a neutral sterile fermion per generation along with quarks and leptons. Scalar sector of this extension consist of Higgs bidoublet Φ, two scalar triplets Δ_L, Δ_R and two doublets H_L,H_R. The B-L charge of Higgs bidoublet, scalar triplets, and doublets are 0,2 and -1 respectively. This kind of extension of LRSM is known as the extended LR model and the naturally arising seesaw from it is called the extended seesaw mechanism which is well explained in literature such as [176, 171]. It is quite well known that type-II dominance in such a scenario allows large left-right mixing which leads to interesting phenomenology. The Quarks(Q) and leptons(l) (LH and RH) that transform in the L-R symmetric gauge group are given by,

$$Q_L = \begin{bmatrix} u' \\ d' \end{bmatrix}_L, Q_R = \begin{bmatrix} u' \\ d' \end{bmatrix}_R, l_L = \begin{bmatrix} \nu_l \\ l \end{bmatrix}_L, l_R = \begin{bmatrix} \nu_l \\ l \end{bmatrix}_R. \tag{3.2}$$

where the Quarks are assigned with quantum numbers $(3,2,1,1/3)$ and $(3,1,2,1/3)$ and leptons with $(1,2,1,-1)$ and $(1,1,2,-1)$ respectively under $\mathrm{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$. The sterile fermion transformation under the relevant Gauge group is given as $S_L(1,1,1,0)$ The scalar sector in this extension of LRSM consists of a bi-doublet with quantum number $\Phi(1,2,2,0)$, the $SU(2)_{L,R}$ triplets, $\Delta_L(1,3,1,2)$, $\Delta_R(1,1,3,2)$ and two $SU(2)_{L,R}$ doublets, $H_L(1,2,1,-1)$, $H_R(1,1,2,-1)$.

A natural type-II dominance in such a case can be realized with the following Yukawa interaction-

$$-\mathcal{L}_\mathcal{Y} = \bar{l_L}[Y_1\Phi + Y_2\tilde{\Phi}]l_R + f[\bar{l_L}^c l_L\Delta_L + \bar{l_R}^c l_R\Delta_R] + F(\bar{l_R})H_R S_L^c + h.c \tag{3.3}$$

In terms of mass matrices, we can write Eq(3.3) as-

$$-\mathcal{L}_{\mathcal{Y}} \supset M_D \bar{\nu_L} N_R + M_L \bar{\nu_L}^c \nu_L + M_R \bar{\nu_R}^c \nu_R + M \bar{N_R} S_L + h.c \tag{3.4}$$

where, $M_D = Y < \Phi >$ is the Dirac neutrino mass matrix which measures the light and heavy neutrino mixing and Y stands for Yukawa coupling, $M_R = f < \Delta_R >= f v_R$ ($M_L = f < \Delta_L >= f v_L$) is the Majorana mass term for heavy(Light) neutrinos and f is the Majorana left-right symmetric coupling along with v_R, v_L corresponding to the vacuum expectation values(VEV) of scalar triplets, finally $M = F < H_R >$ stands for heavy neutrino-sterile mixing matrix. We have assumed the induced VEV of $< H_L >$ to be zero. Now in flavor basis, the complete 9×9 mass matrix for neutral fermions can be represented as-

$$\mathcal{M} = \begin{pmatrix} M_L & 0 & M_D \\ 0 & 0 & M \\ M_D^T & M^T & M_R \end{pmatrix} \tag{3.5}$$

One can use the standard seesaw mechanism to integrate out the heaviest neutrino, Using Mass ordering $M_R > M > M_D \gg M_L$ one can obtain-

$$\mathcal{M}' = \begin{pmatrix} M_L - M_D M_R^{-1} M_D^T & -M_D M_R^{-1} M_D^T \\ M M_R^{-1} M_D^T & M M_R^{-1} M^T \end{pmatrix} \tag{3.6}$$

In the Eq(3.6) which is the intermediate block diagonalized mass matrix, it is seen that the (2,2) element is larger than the entries in the limit $M_R > M > M_D \gg M_L$. So using the same procedure we can integrate out sterile neutrino mass matrix. Now we can write down light neutrino mass matrix as-

$$\begin{aligned} m_\nu &= [M_L - M_D M_R^{-1} M_D^T] - (-M_D M_R^{-1} M_D^T)(M M_R^{-1} M_D^T)(M M_R^{-1} M^T) \\ &= [M_L - M_D M_R^{-1} M_D^T] - M_D M_R^{-1} M_D^T \\ &= M_L = m_\nu^{II} \end{aligned} \tag{3.7}$$

After complete block diagonalization which is extensively discussed in various works of literature, we can write t left-handed neutrino, heavy right-handed neutrino, and sterile neutrino mass matrices as-

$$\begin{aligned} m_\nu &= M_L \\ M_R &= \frac{v_R}{v_L} M_L \\ M_S &= -M M_R^{-1} M^T \end{aligned} \tag{3.8}$$

Again these mass matrices can be diagonalized by using respective 3×3 unitary matrices as follows-

$$\begin{aligned} m_\nu^{diag} &= U_\nu^\dagger m_\nu U_\nu^* = diag(m_1, m_2, m_3) \\ M_N^{diag} &= U_N^\dagger M_N U_N^* = diag(M_{N_1}, M_{N_2}, M_{N_3}) \\ M_S^{diag} &= U_S^\dagger M_S U_S^* = diag(M_{S_1}, M_{S_2}, M_{S_3}) \end{aligned} \tag{3.9}$$

Complete block diagonalization results-

$$\begin{aligned} \mathcal{M}_{diag} &= V_{9\times9}^\dagger \mathcal{M} V_{9\times9}^* \\ &= (\mathcal{W}.\mathcal{U})^\dagger \mathcal{M} (\mathcal{W}.\mathcal{U}) \\ &= diag(m_1.m_2, m_{3,} M_{S_1}, M_{S_2}, M_{S_3}, M_{N_1}, M_{N_2}, M_{N_3}) \end{aligned} \tag{3.10}$$

where, $\mathcal{W}$ is the bock diagonalized mixing matrix and $\mathcal{U}$ is the unitary mixing matrix. Thus the complete 9×9 unitary mixing matrix can be written as-

$$V = \mathcal{W}.\mathcal{U} = \begin{pmatrix} U_\nu & M_D M^{-1} U_S & M_D M_R^{-1} U_N \\ (M_D M^{-1})^\dagger U_\nu & U_S & M M_R^{-1} U_N \\ \mathcal{O} & (M M_R^{-1})^\dagger U_S & U_N \end{pmatrix} \tag{3.11}$$

3.3 Flavor symmetric realization of extended LRSM with type-II dominance:

In this section, we have realized the extended LRSM considering type-II dominance case using $A_4 \times Z_4$ flavor symmetry. Type-II dominance in extended LRSM allows for large left-right mixing. A_4 is a discrete group of even permutations of four objects. It has three inequivalent one-dimensional representations 1, $1'$ and$1''$ an irreducible three-dimensional representation 3.

The particle content and their respective charge assignments of the model are given in Table(3.1). One can get a diagonal charged lepton mass matrix and the Dirac neutrino mass matrix by considering a suitable flavon with proper charge assignments. Now, as we are interested in type-II dominant case within extended LRSM, we have already discussed in the section(3.2) that mass matrices of light neutrino, heavy neutrino, and sterile neutrino are independent of Dirac neutrino mass matrix (not mixing) allow us to assume flavor independent structure of Dirac neutrino mass matrix. This is well motivated for the reason that we can assume that this kind of extension originates from $SO(10)$ GUT (grand unified theory) with a proper choice of intermediate symmetry such as Pati-Salaam symmetry. In this scenario, the charged lepton mass matrix and Dirac neutrino mass matrix can be treated on equal footing and taken to be equivalent to up type quark mass matrix. The main objective of this work is to constrain the mass matrix of light neutrino, heavy neutrino, and sterile neutrino with $A_4 \times Z_4$ flavor symmetry to study the impact of these constrained mass matrices on mixing where Dirac neutrino mass matrix plays a crucial role. The light neutrino mass formula is governed by a type-II seesaw mechanism, $m_\nu^{II} = M_L$ while type-I seesaw contribution $m_\nu^I = -M_D M_R^{-1} M_D^T$ is exactly canceled out in the complete diagonalization method. Since the light neutrino mass formula is independent of the Dirac neutrino mass matrix, any value of M_D is allowed consistent with GUT mass fitting without any fine-tuning of the Yukawa couplings. Further, we have studied their impact on neutrinoless double beta decay contributions and active sterile mixing with dark matter phenomenology.

Field	l_L	l_R	S_L	Φ	Δ_L	Δ_R	H_L	H_R	χ_ν	ε'	ρ
$SU(2)_L$	2	1	1	3	3	1	2	1	1	1	1
$SU(2)_R$	1	2	1	1	1	3	1	2	1	1	1
$U(1)_{B-L}$	-1	-1	0	2	2	2	-1	-1	0	0	0
A_4	3	3	3	1	1	1	3	1	3	1	1
Z_4	-1	$-i$	$-i$	1	1	1	$-i$	i	1	1	i

Table 3.1 Fields and their respective transformations under the symmetry group of the model.

Now, the effective Lagrangian can be written as-

$$\mathcal{L} \supset \frac{1}{\Lambda}(\bar{l}_R(f_R^0\varepsilon' + f_R^\nu\chi^\nu)\Delta_R l_R + \bar{l}_L(f_L^0\varepsilon' + f_L^\nu\chi^\nu)\Delta_L l_L + F\bar{l_R}H_R\rho S_L^c + h.c) \tag{3.12}$$

Where Λ is the cut-off scale. The role of the flavon ε' is to break the $\mu-\tau$ symmetry of light and heavy neutrino mass matrices. In our work, we take the flavon alignment to be, $<\chi^\nu>\sim(1,1,1), <\rho>\sim v$.

The light neutrino mass matrix can be computed from-

$$M_L = v_L f_L \tag{3.13}$$

Where f_L is the Majorana Yukawa coupling. Now, the light neutrino mass matrix can be written as-

$$M_L = \frac{v_L f_L^0}{\Lambda}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} + \frac{v_L f_L^\nu}{\Lambda}\begin{pmatrix} 2\chi_1^\nu & -\chi_3^\nu & -\chi_2^\nu \\ -\chi_3^\nu & 2\chi_2^\nu & -\chi_1^\nu \\ -\chi_2^\nu & -\chi_1^\nu & 2\chi_3^\nu \end{pmatrix} \tag{3.14}$$

Using the chosen flavon alignment we will get the heavy neutrino mass matrix of the form given below-

$$M_L = a_L \begin{pmatrix} 2z & -z & 1-z \\ -z & 1+2z & -z \\ 1-z & -z & 2z \end{pmatrix} \tag{3.15}$$

Where $a_L = \frac{v_L f_L^0}{\Lambda}$ and $z = \frac{f_L^\nu}{f_L^0}$. Because of the left-right symmetry, we can take $f_R = f_L$ and similarly we will get the Majora neutrino mass matrix of form using (3.8)

$$M_R = a_R \begin{pmatrix} 2z & -z & 1-z \\ -z & 1+2z & -z \\ 1-z & -z & 2z \end{pmatrix} \tag{3.16}$$

Where $a_R = \frac{v_R f_R^0}{\Lambda}$ and $z = \frac{f_R^\nu}{f_R^0}$. So we can say that the model parameter $z = \frac{f_R^\nu}{f_R^0} = \frac{f_L^\nu}{f_L^0}$.

Now the sterile mass matrix is given by-

$$M = m_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \tag{3.17}$$

where m_0 is the free parameter of the model containing v which is the VEV of ρ and cut-off scale. We want to work on a basis where the sterile neutrino mass matrix is diagonal. To get the diagonal sterile neutrino mass matrix we change the basis by a unitary rotation given by-

$$U = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \tag{3.18}$$

After using this rotation one can get a diagonal sterile neutrino mass term as-

$$M = m_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3.19}$$

At this basis, the light neutrino mass matrix is given as-

$$M_L = a_L \begin{pmatrix} 1-z & -z & 2z \\ -z & 1+2z & -z \\ 2z & -z & 1-z \end{pmatrix} \tag{3.20}$$

and the Majorana neutrino mass matrix-

$$M_R = a_R \begin{pmatrix} 1-z & -z & 2z \\ -z & 1+2z & -z \\ 2z & -z & 1-z \end{pmatrix} \tag{3.21}$$

Using (3.8),(3.21) and (3.19) we can have the sterile neutrino mass matrix as-

$$M_S = \frac{m_0^2}{(9z^2-1)a_R} \begin{pmatrix} 2z+3z^2 & -z+3z^2 & -1-z+3z^2 \\ -z+3z^2 & -1+2z+3z^2 & -z+3z^2 \\ -1-z+3z^2 & -z+3z^2 & 2z+3z^2 \end{pmatrix} \tag{3.22}$$

3.4 Neutrinoless Double beta deacy in extended LRSM:

Neutrinoless double beta decay has been studied extensively within the framework of LRSM inin many works of literature [152–157, 163, 159]. In this section, we will discuss different new physics contributions to the neutrinoless double beta decay process in extended LRSM scenario. In our framework, the light neutrino mass arises from the extended type-II dominant seesaw mechanism. The type-II seesaw dominance not only provides mass relation between light and heavy neutrinos but also allows large Dirac neutrino mass and thereby giving large light-heavy neutrino mixing. This light-heavy neutrino mixing plays an important role in giving sizable contributions to neutrinoless double beta decay. In this kind of scenario mass of the right-handed boson (W_R) is kept very high scale, so the contribution to the NDBD process due to purely right-handed current is suppressed as the contribution from purely right-handed current is proportional to $\frac{1}{M_{W_R}^4}$. Similarly, λ and η diagram gets suppressed because of the same argument [171].

The charge current interaction for leptons and quarks which mainly governs the NDBD process is given as follows,

$$\mathcal{L}^{q}_{cc} = \frac{g_L}{\sqrt{2}}\bar{d}\gamma^{\mu}P_L W^{-}_{L\mu} + \frac{g_R}{\sqrt{2}}\bar{d}\gamma^{\mu}P_R W^{-}_{R\mu} + h.c \tag{3.23}$$

$$\mathcal{L}^{lep}_{cc} = \frac{g_L}{\sqrt{2}}\sum_{\alpha=e,\mu,\tau}\bar{l_\alpha}\gamma^{\mu}P_L\nu_\alpha W^{-}_{L\mu} + \frac{g_R}{\sqrt{2}}\sum_{\alpha=e,\mu,\tau}\bar{l_\alpha}\gamma^{\mu}P_R\nu_\alpha W^{-}_{R\mu} + h.c. \tag{3.24}$$

Mass eigenstates of neutral lepton are related to light neutrino flavor states (e,μ,τ) as-

$$\nu_\alpha = U_{\alpha_i}\nu_i + Z_{\alpha_i}N_j + Y_{\alpha_i}S_k \tag{3.25}$$

Where, U_{α_i}, Z_{α_j} and, Y_{α_k} are the mixing matrices of light neutrino, heavy neutrino and sterile neutrino.

The leading order contribution which contributes to the NDBD process arises from purely left-handed current due to the exchange light neutrino(ν), heavy right-handed neutrino (N_R) and, sterile neutrino (S_L).The Feynmann amplitude of these contributions is proportional to-

$$\mathcal{A}^{LL}_{\nu} \propto G_F^2\sum_{i=1,2,3}\frac{U^2_{ei}}{p^2} \tag{3.26}$$

$$\mathcal{A}^{LL}_{N} \propto G_F^2\sum_{j=1,2,3}\left(-\frac{Z^2_{ej}}{M_{N_j}}\right) \tag{3.27}$$

$$\mathcal{A}^{LL}_{S} \propto G_F^2\sum_{k=1,2,3}\left(-\frac{Y^2_{ek}}{M_{S_k}}\right) \tag{3.28}$$

Where G_F is the Fermi constant. The corresponding effective Majorana mass parameters, which are basically the measure of lepton number violation are given as-

$$|m^{\nu}_{ee}| = \sum_{i=1,2,3} U^2_{ei}m_{\nu i}, \tag{3.29}$$

$$|m_{ee}^N| = < p^2 > \sum_{j=1,2,3} \frac{Z_{ej}^2}{M_{Nj}} \tag{3.30}$$

$$|m_{ee}^S| = < p^2 > \sum_{k=1,2,3} \frac{Y_{ek}^2}{M_{Sk}} \tag{3.31}$$

where $< p^2 >$ is the virtual neutrino momentum of the order nuclear Fermi scale.

3.5 Light sterile neutrino in extended LRSM :

The extended left-right symmetric model discussed above can lead to a sterile neutrino of mass at the eV-GeV range depending on the parameter m_0. Thus it is possible to achieve a sterile neutrino in the keV range within the framework which is considered as a viable dark matter candidate in the present scenario. The sterile neutrino can be produced from active-sterile oscillation by Dodelson-Widrow (DW) mechanism [131]. One can obtain the mass as well as the mixing of the extra sterile neutrino with the active neutrinos using (3.11). It is evident from the expressions that both are functions of p and one can obtain the desired mass range of sterile neutrino by fine-tuning m_0.

There are many cosmological and astrophysical constraints on sterile neutrino dark matter [28, 132–134]. Sterile neutrinos can be produced from Standard model plasma through their mixing with active neutrinos in the early universe. Since sterile neutrinos are fermionic dark matter candidate, lower bounds exist on its mass known as Tremaine-Gunn bound. Again, the upper limit on mass can be obtained from X-ray constraints. Direct and indirect detection of dark matter also impose significant bounds on sterile neutrino which can be seen in [135–138].

Any stable neutrino state with a non-vanishing mixing to the active neutrinos will be produced through active-sterile neutrino conversion. Thus the abundance is generated through the mixing between sterile and active neutrinos. The mechanism of non-resonant production of sterile neutrinos is known as Dodelson-Widrow (DW) mechanism. The resulting relic abundance can be expressed as:

$$\Omega_{DM}h^2 = 1.1\times 10^7 \sum C_\alpha(m_s)|\varepsilon_{\alpha s}|^2\left(\frac{m_s}{keV}\right)^2, \alpha = e,\mu,\tau \tag{3.32}$$

where $sin^2 2\theta = 4\sum|\varepsilon_{\alpha s}|^2$ with $|\varepsilon_{\alpha s}|$is the active-sterile leptonic mixing matrix element and m_s represents the mass of the lightest sterile fermion.

The lightest sterile neutrino present in the model is not completely stable and can decay into an active neutrino through their mixing. The radiative decay of sterile neutrino induced at one loop level result in photon producing monochromatic X-rays. Thus there exist X-ray bounds on the sterile neutrino dark matter. In LRSM, along with the bounds on bound on the mixing angle, x-ray bound leads to some constraints on the properties of the bosonic sector of the theory because of the mixing of the right WR gauge bosons W_R with the SM W_L [177]. However, in our model, the mixing can be neglected. The total decay width of the process $N \longrightarrow \gamma\nu$ in presence of gauge boson mixing can be written as [177],

$$\Gamma_{N\longrightarrow\gamma\nu} = \frac{G_F^2\alpha m_s^3}{64\pi^4}\sum\left|4m_{l\alpha}(V_R)_{\alpha 1}.\zeta - \frac{3}{2}\theta_{\alpha 1}m_s\right|^2 \tag{3.33}$$

Since in our model, gauge boson mixing is negligible i.e $\zeta = 0$, the expression for decay width will be

$$\Gamma_{N\longrightarrow\gamma\nu} = \frac{9G_F^2\alpha m_s^5}{1024\pi^4}sin^2 2\theta, \alpha = e,\mu,\tau \tag{3.34}$$

The nonobservation of X-ray lines from clusters provides upper limits to the active-sterile mixing angle as well as the sterile neutrino mass. We have implemented the bounds from X-ray in our analysis. An important constraint on sterile neutrino dark matter is Ly-α bound. This bound provides stronger bounds on the velocity distribution of the DM particles from the effect of their free streaming on the large scale structure formation. This constraint can be converted into a bound for the mass of the DM particle which can be seen in [132]. The constraint is strongly model dependent and the bounds are governed by the production mechanism of the DM candidate. In this work, We have adopted the bounds considering $XQ-100$ Ly-α data [137].

As seen from the above equations, the decay rate and as well as the relic abundance depend on the mixing and mass of the DM candidate. Hence, the same set of model parameters which are supposed to produce correct neutrino phenomenology can also be used to evaluate the relic abundance and the decay rate of the sterile neutrino.

3.6 Numerical results and analysis:

In this section, we will study different new physics contributions to the NDBD process in this particular framework. Here, we are interested to study different new physics contribution to the NDBD process as mentioned earlier. As the purely right-handed contribution gets suppressed and the dominant contribution comes from a purely left-handed current. We have taken the Dirac neutrino mass matrix as a input parameter for analysis. In our framework, we are assuming that TeV scale LRSM is originating from $SO(10)$ GUT or its sub-group Pati-Salam symmetry. In this limit, we can take the charged lepton mass matrix and the Dirac neutrino mass matrix on equal footing which is equivalent to up type quark mass matrix. The Dirac neutrino mass matrix is given as-

$$M_D = V_{CKM} M_U V_{CKM}^T = \begin{pmatrix} 0.067-0.004i & 0.302-0.022i & 0.550-0.530i \\ 0.302-0.022i & 1.480 & 6.534-0.001i \\ 0.550-0.530i & 6.534-0.001i & 159.72 \end{pmatrix} GeV \quad (3.35)$$

The V_{CKM} and up type mass matrix is given as:

$$V_{CKM} = \begin{pmatrix} 0.97427 & 0.22534 & 0.00351-0.0033i \\ -0.2252+0.0001i & 0.97344 & 0.0412 \\ 0.00876-0.0032i & -0.0404-0.0007i & 0.99912 \end{pmatrix} GeV \quad (3.36)$$

$$M_U = diag(2.3MeV, 1.275GeV, 173.210GeV) \quad (3.37)$$

The sterile and right-handed neutrino mixing is coming from the model and it is a diagonal one given in (3.19). Which is-

$$M = m_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3.38}$$

The parameter m_o is chosen to be free and we assume two different values, 50 GeV and 150 GeV for numerical analysis for numerical analysis. The complete diagonalization of the mixing matrix gives extended LRSM with additional singlet fermion as discussed earlier and detailed analysis is given in [176]. The mass of the light neutrino, heavy neutrino, and sterile neutrino in terms of oscillation parameters can be written as:

$$m_\nu = M_L = U_{PMNS} m_\nu^{diag} U_{PMNS}^T \tag{3.39}$$

$$M_N = M_R = \frac{v_R}{v_L} U_{PMNS} m_\nu^{diag} U_{PMNS}^T \tag{3.40}$$

$$M_S = -m_o^2 \frac{v_L}{v_R} U_{PMNS}^* (m_\nu^{diag})^{-1} U_{PMNS}^\dagger \tag{3.41}$$

U_{PMNS} is the diagonalizing matrix of the light neutrino mass matrix, m_ν such that,

$$m_\nu = U_{PMNS} M_\nu^{(diag)} U_{PMNS}^T \tag{3.42}$$

where, $M_\nu^{(diag)} = diag(m_1, m_2, m_3)$ and,

$$\mathrm{U_{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{U_{Maj}} \tag{3.43}$$

is the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix and $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and δ is the leptonic Dirac CP phase. The diagonal matrix $\mathrm{U_{Maj}} = \mathrm{diag}(1, \mathrm{e}^{\mathrm{i}\alpha}, \mathrm{e}^{\mathrm{i}(\beta+\delta)})$ contains the Majorana CP phases α, β.

The diagonal mass matrix of the light neutrinos can be written as,

$$M_\nu^{(diag)} = \mathrm{diag}(m_1, \sqrt{m_1^2+\Delta m_{21}^2}, \sqrt{m_1^2+\Delta m_{31}^2}) \tag{3.44}$$

for normal hierarchy and

$$M_\nu^{(diag)} = \mathrm{diag}(\sqrt{m_3^2+\Delta m_{23}^2-\Delta m_{21}^2}, \sqrt{m_3^2+\Delta m_{23}^2}, m_3) \tag{3.45}$$

for inverted hierarchy.

In this work, light neutrino mass directly comes from type-II dominance. Here we want to see the different contributions to the NDBD process. First of all, we will see the case of the exchange of light neutrinos. The dimensionless parameter which is relevant to the lepton number violating process in this process is given by,

$$\eta_\nu = \frac{1}{m_e}\sum_{i=1}^{3} U_{ei}^2 m_i = \frac{m_{ee}^\nu}{m_e} \tag{3.46}$$

where m_e is the mass of electron. And the effective mass parameter is given as

$$|m_{ee}^\nu| = \sum_{i=1,2,3} U_{ei}^2 m_{\nu i}, \tag{3.47}$$

$$m_\nu^{eff} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta} \tag{3.48}$$

with $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ are respective oscillation angle and α and β are the Majorana phase.

Now, we consider the nonstandard contribution to the NDBD process due to purely left-handed current because of the exchange of right-handed neutrino. This results in dimensionless parameters which can be given as-

$$\eta_N = -m_P \sum_{j=1}^{3} \frac{Z_{ej}^2}{M_i j} \tag{3.49}$$

where m_p is the mass of proton. And the effective Majorana mass parameter is-

$$|m_{ee}^N| = < p^2 > \sum_{j=1,2,3} \frac{Z_{ej}^2}{M_{Nj}} \tag{3.50}$$

where $< P^2 > = | m_e m_p \mathcal{M}_N / \mathcal{M}_\nu |$ is the virtual neutrino momentum.

Now for sterile neutrino contribution, the dimensionless parameter arising from the exchange of sterile neutrino can be given as-

$$\eta_S = -m_P \sum_{k=1}^{3} \frac{Y_{ek}^2}{M_{S_k}} \tag{3.51}$$

Effective Majorana mass parameter is -

$$|m_{ee}^S| = < p^2 > \sum_{k=1,2,3} \frac{Y_{ek}^2}{M_{S_k}} \tag{3.52}$$

Now the combined contribution of all the processes discussed above can be written as-

$$| m_{ee}^{tot} | = \sum_{i=1,2,3} U_{ei}^2 m_{\nu i} + < p^2 > \sum_{j=1,2,3} \frac{Z_{ej}^2}{M_{Nj}} + < p^2 > \sum_{k=1,2,3} \frac{Y_{ek}^2}{M_{S_k}} \tag{3.53}$$

Oscillation parameters	3σ(NO)	3σ(IO)
$\frac{\Delta m_{21}^2}{10^{-5} eV^2}$	6.82 - 8.04	6.82 - 8.04
$\frac{\Delta m_{31}^2}{10^{-3} eV^2}$	2.431 - 2.60	2.31-2.51
$sin^2\theta_{12}$	0.269 - 0.343	0.269 - 0.343
$sin^2\theta_{23}$	0.407 - 0.612	0.411 - 0.621
$sin^2\theta_{13}$	0.02034 - 0.02430	0.02053 - 0.02436
$\frac{\delta}{\pi}$	0.87 - 1.94	1.12- 1.94

Table 3.2 Latest global fit neutrino oscillation data for both mass ordering in 3-σ range [36]

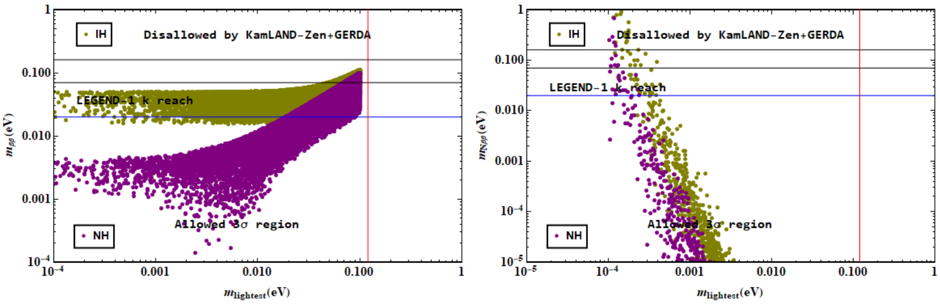

Fig. 3.1 Light neutrino contribution to neutrinoless double beta decay process(left) and nonstandard contribution due to exchange of heavy neutrino(right) considering both NH and IH case. The band of black and the blue solid horizontal line represents the KamLAND-Zen bound on the effective mass and Legend-1k reach. The red solid vertical line represents the Planck bound on the sum of the absolute neutrino mass respectively.

Using these values we solve for the parameters of the model. From these, we have evaluated the corresponding mixing matrices which are denoted as U_{ei}, Z_{ej}, and Y_{ek}. Then we calculated the effective mass for both cases. During our calculations, the effective mass assumes different values depending on whether the neutrino mass states follow the normal hierarchy (NH) or inverted hierarchy (IH). The standard neutrino contribution to the NDBD process as a function of light neutrino mass is shown on the left side of Fig 3.1. It is seen from the figure that the light neutrino contribution to neutrinoless double beta decay (NDBD) can saturate the bound imposed by KamLAND-ZEN and GERDA. We have also incorporated the future sensitivity of experiments like Legend-1k in our analysis. We have seen that for NH the contribution is well within the upper bound provided by mentioned experiments. In the case of IH, the contribution is well within the bound provided by KamLAND-ZEN and GERDA but some points are above the upper bound of future sensitivity of Legend-1k reach. The right-handed neutrino contribution to the NDBD process is depicted on the right side of Fig 3.1. From this figure we see that the lightest neutrino mass for the NH case is between the order of 10^{-2} to 10^{-3} eV and for the IH can it is below 10^{-2} eV with effective mass ranging from 10^{-5} to 1 eV. For sterile contribution we have already mentioned that we will estimate this for two empirical values of m_o, 50 GeV and 150 GeV.

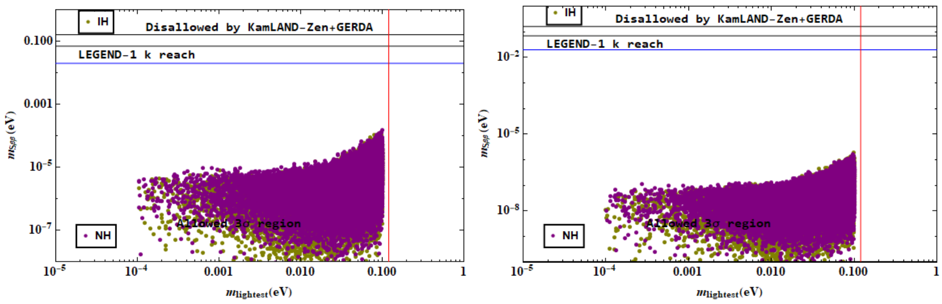

Fig. 3.2 Sterile neutrino contribution to neutrinoless double beta decay process for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right) considering both NH and IH case. The band of black and the blue solid horizontal line represents the KamLAND-Zen bound on the effective mass and Legend-1k reach. The red solid vertical line represents the Planck bound on the sum of the absolute neutrino mass respectively.

Effective mass parameter due to the exchange of sterile neutrino considering $m_o = 50$ GeV as a function of lightest neutrino mass is shown on the left side of Fig 3.2. It is seen that the lightest neutrino mass ranging from 10^{-4} to 10^{-1} eV gives an effective mass ranging from 10^{-4} to 10^{-8} eV for both NH and IH cases which is well within the experimental limit. Again for $m_o = 150$ GeV, the plot of the effective mass parameter with the lightest neutrino mass for sterile contribution is shown on the right side of Fig3.2. In this case lightest neutrino mass ranging from 10^{-4} to 10^{-1} eV gives effective mass ranging from 10^{-6} to 10^{-10} eV for both NH and IH cases. So it can be inferred that on increasing the value of the mass parameter of sterile neutrino the contribution from sterile neutrino to the NDBD process becomes smaller. The total contribution to the NDBD process considering standard, right-handed neutrino and sterile neutrino for the cases $m_o = 50$ GeV and $m_o = 150$GeV with respect to the lightest neutrino mass is shown on the left and right side of Fig3.3 respectively. From these plots, it can be said that there is not much difference in total contribution due to the change in the value of m_o. For both cases, the total effective mass ranges from 10^{-4} to

10^{-1} eV for both NH and IH which is well within the bound provided by KamLAND-ZEN and GERDA. But specifically for NH in both cases many of the data points are slightly above the future sensitivity of Legend -1k reach.

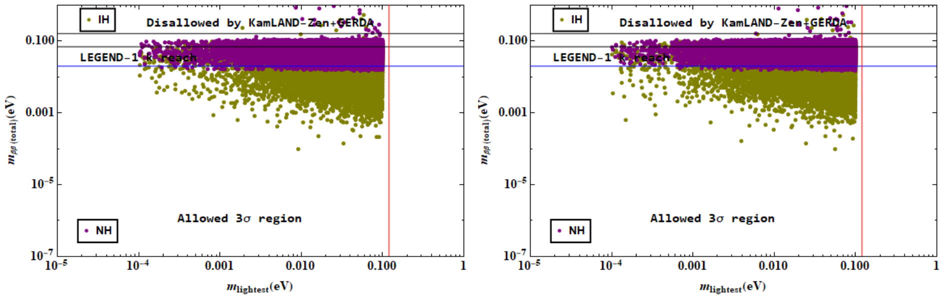

Fig. 3.3 Total contribution to neutrinoless double beta decay process for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right) considering both NH and IH case. The band of black and the blue solid horizontal line represents the KamLAND-Zen bound on the effective mass and Legend-1k reach. The red solid vertical line represents the Planck bound on the sum of the absolute neutrino mass respectively.

We also study sterile neutrino dark matter phenomenology in the framework. The same set of the evaluated model parameters is used to calculate the mass and mixing of the sterile neutrinos present in the model. We have considered the lightest sterile neutrino as a potential dark matter candidate. We have obtained the relic abundance and the decay of the dark matter particle using Eq. 3.32 and Eq. 4.46 respectively. As mentioned above, we perform the dark matter study using two different values of the parameter m_0 i.e. 50 GeV and 150 GeV. The obtained results are shown from fig 3.4 to fig 3.9.

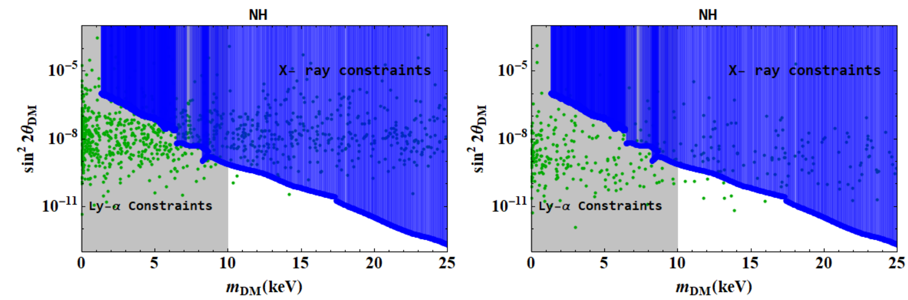

Fig. 3.4 Mass mixing parameter space for the DM candidate for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for NH. The cosmological bounds from Ly-α and X-rays have been implemented.

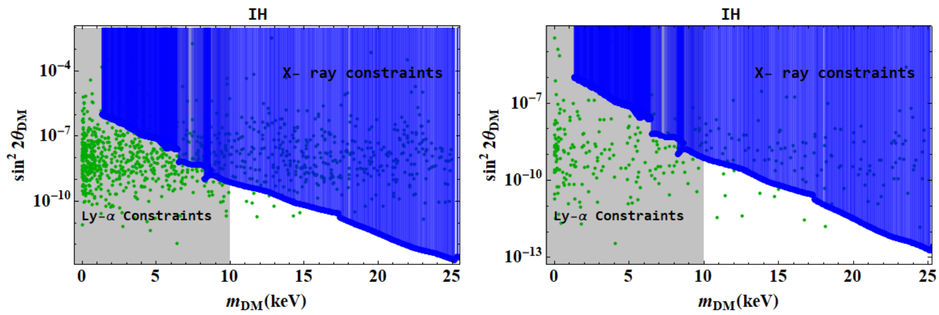

Fig. 3.5 Mass mixing parameter space for the DM candidate for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for IH. The cosmological bounds from Ly-α and X-rays have been implemented.

Fig 3.4 and 3.5 depict the mass mixing parameter of the sterile neutrino dark matter. After implementing the current cosmological bounds, the allowed parameter space lies within $10-25$ keV for both cases in NH. In the case of IH, the allowed parameter space is $10-24$ keV for $m_o = 50$ keV. It has been observed that the value of m_o has no significant effects on the mass and mixing limit. However, one can obtain more allowed data points for $m_o = 150$ GeV as can be seen from these figures.

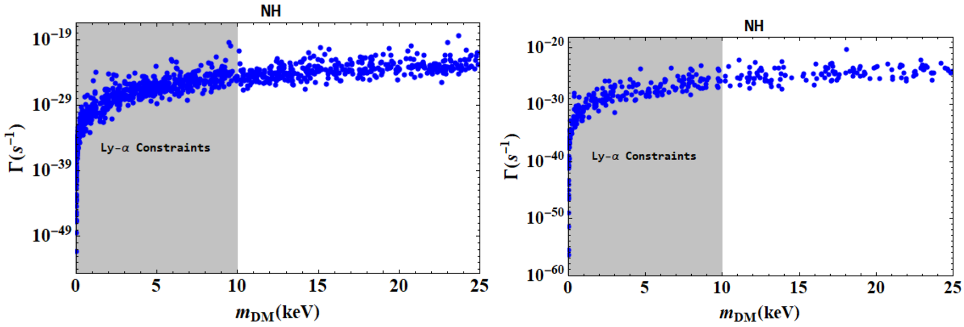

Fig. 3.6 Decay rate of the DM candidate for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for NH. The cosmological bounds from Ly-α and X-rays have been implemented.

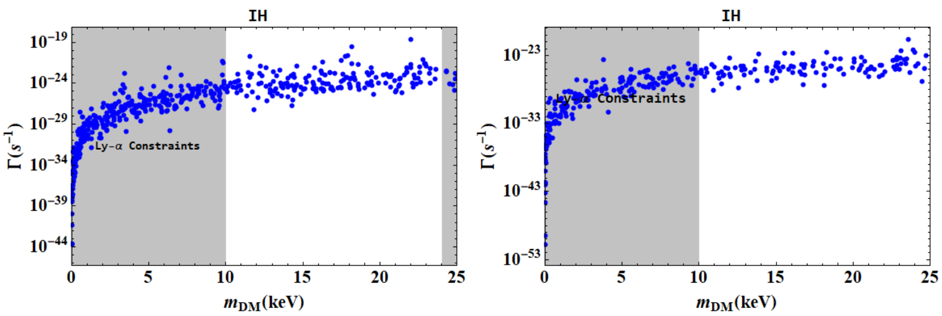

Fig. 3.7 Decay rate of the DM candidate for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for IH. The cosmological bounds from Ly-α and X-rays have been implemented.

The decay rate of the DM candidate is shown in the above figures fig 3.6 and fig 3.7 for NH and IH respectively. For $m_o = 50$ GeV, the decay rate for the allowed mass range is around 10^{-26} s^{-1} and that in case of $m_o = 150$ GeV is around 10^{-26} s^{-1} in case of NH. However, the decay rates are slightly larger in case the of IH for both values of m_o.

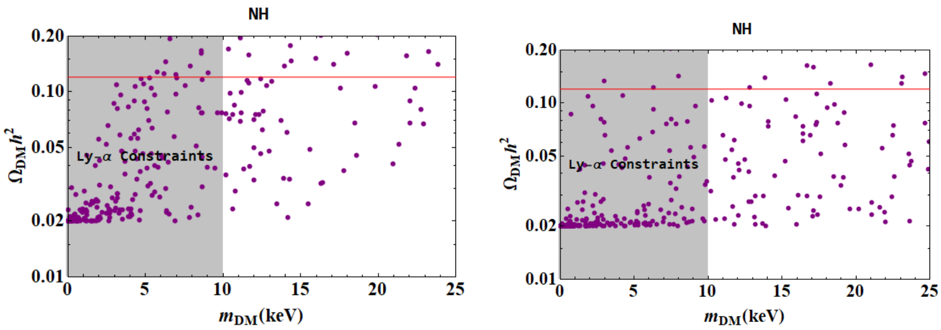

Fig. 3.8 Sterile neutrino contribution to the total DM abundance for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for IH. The cosmological bounds from Ly-α and X-rays have been implemented.

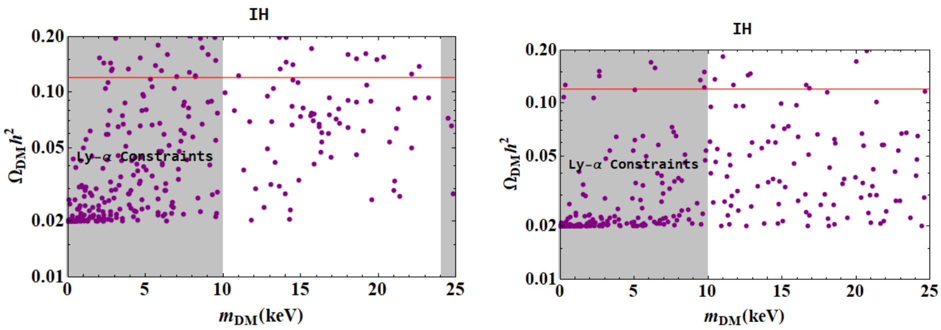

Fig. 3.9 Sterile neutrino contribution to the total DM abundance for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for IH. The cosmological bounds from Ly-α and X-rays have been implemented.

Fig 3.8 and fig 3.9 show the relic abundance of the proposed DM candidate. The sterile neutrino DM can contribute to 17 % to almost 100 % of the total DM relic abundance in all the cases.

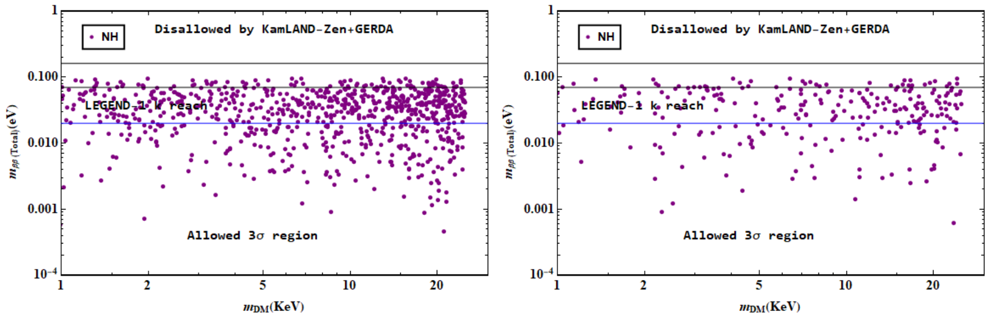

Fig. 3.10 Correlation between DM mass and effective mass for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for NH.

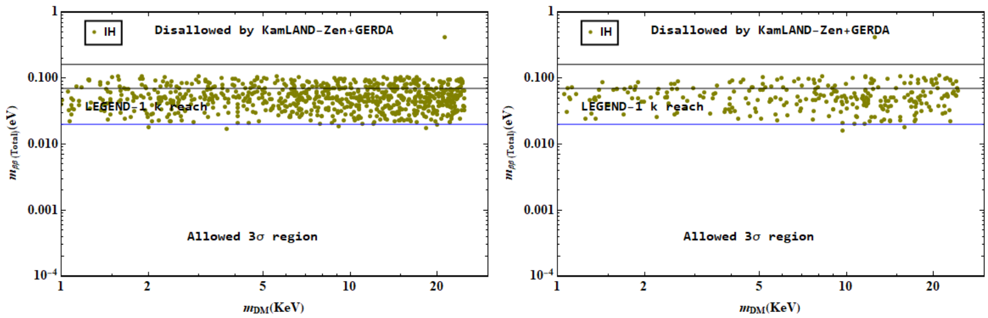

Fig. 3.11 Correlation between DM mass and effective mass for $m_o = 50$ GeV (left) and $m_o = 150$ GeV(right)for IH.

Fig 3.10 and fig 3.11 represent the correlation of the dark matter property with the active neutrino phenomenology. It has been observed that for the allowed mass range of the DM i.e. for (10-25) keV, the effective mass range lies well within the experimental limit in all the cases. Thus the model can propose a viable DM candidate along with rich neutrino phenomenology.

3.7 Summary

In this work, we extend the generic left-right symmetric model with an extra singlet fermion per generation. We have realized this extension with A_4 and Z_4 flavor symmetry considering the type-II dominance case. Because of the extension, there will be new physics contributions to the NDBD process and type-II dominance will constrain some of the contributions. We have computed all the mass matrices of light neutrino, heavy neutrino, and sterile neutrino using flavor symmetry which will constrain the model. Type-II dominance gives rise to large left-right mixing which is discussed in detail in our work. By estimating the contribution coming from light neutrinos, heavy neutrinos, and sterile neutrinos, it is seen that all the contributions coming from these exchanges are well within the experimental bound. The singlet fermion in the keV range can be a viable DM candidate in the model. We have extensively studied the sterile neutrino dark matter phenomenology. It has been found that the allowed mass range lies within $10-25$ keV in this model. We have found that the DM candidate can provide a significant contribution to the total relic abundance. The implications of the model on low energy processes as well as the baryon asymmetry of the Universe can also be addressed which we leave for our future study.