Lepton number violating processes and dark matter in models with a type I+II seesaw mechanism

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QUARKS
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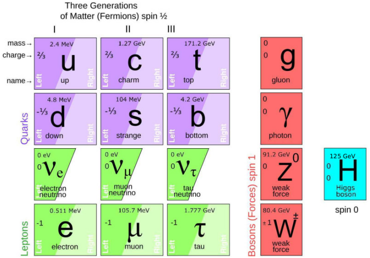
SM cannot solve

- the problem of neutrino masses
- the DM problem
- the problem of baryon asymmetry in the Universe (BAU)
- ...



M. Shaposhnikov, J. Phys. Conf. Ser. 408 (2013)

SM extentions of leptonic sector

- restore the symmetry between right- and left-handed $SU(2)$ groups
- explain the smallness of m_ν by seesaw mechanism and neutrino oscillations
- introduce the DM candidate – sterile neutrino with keV mass

$\Delta N_{\rm eff} < 0.23$ Planck 1807.06209

$\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM}$ $(N_{\rm eff}^{\rm SM}{=}3.044)$

$\Omega_{\rm DM} h^2 \simeq 0.12$ Planck 1807.06209

$\tau_{\rm DM} > \tau_U \simeq 10^{17}$ s

$|\xi_e^{\rm BBN}| \equiv \frac{|\mu_e|}{T_\nu} < 0.027$ BBN 2405.06509

Minimal left-right symmetric model

Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	New particles
$L_{iL} = \begin{pmatrix} \nu_i' \\ l_i' \end{pmatrix}_L$	1	2	1	–1	
$L_{iR} = \begin{pmatrix} \nu_i' \\ l_i' \end{pmatrix}_R$	1	1	2	–1	N_1 – DM N_2, N_3
$Q_{iL[R]} = \begin{pmatrix} u_i' \\ d_i' \end{pmatrix}_{L[R]}$	3	2 [1]	1 [2]	1/3	
$W_L = \{W_L^+, W_L^-, W_L^3\}$	1	3	1	0	W_2
$W_R = \{W_R^+, W_R^-, W_R^3\}$	1	1	3	0	Z_2
B	1	1	1	0	
$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$	1	2	2	0	H_{125} H_1^0, H_2^0, H_3^0
$\Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	1	3	1	2	A_1^0, A_2^0 $H_1^\pm, H_2^\pm$
$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}$	1	1	3	2	$H_1^{\pm\pm}, H_2^{\pm\pm}$

No evidence of new particles is observed, however there are some experimental **hints** (see below)

1. The initial LR symmetry is spontaneously broken

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle\Delta_R\rangle} SU(2)_L \times U(1)_Y, \tag{1}$$

$$\langle\Delta_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \tag{2}$$

2. The bidoublet and the left-handed triplet acquire VEVs as a result of spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \xrightarrow{\langle\phi\rangle,\langle\Delta_L\rangle} U(1)_Q, \tag{3}$$

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \qquad \langle\Delta_L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix} \tag{4}$$

where $\sqrt{k_1^2 + k_2^2} \equiv k_+ = 246$ GeV,

$$v_L = \frac{1}{v_R}\frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)} \simeq 0 \qquad \text{VEV seesaw} \tag{5}$$

$$v_L \ll k_+ \ll v_R \tag{6}$$

Seesaw type I+II mechanism in the neutrino sector

$$\mathcal{L} \supset (\overline{\nu_L} \;\; \overline{\nu_R^c}) M_\nu \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \qquad \text{where} \qquad M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \tag{7}$$

$$M_D = \frac{h_L k_1 + \tilde{h}_L k_2}{\sqrt{2}}, \qquad M_L = \sqrt{2} h_M v_L, \qquad M_R = \sqrt{2} h_M v_R, \tag{8}$$

$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix}, \qquad \begin{aligned} \nu_L &= U_{\rm PMNS} P_L \nu + \Theta P_L N, \\ \nu_R &= -\theta^T U_\nu^* P_R \nu + U_N P_R N, \end{aligned} \tag{9}$$

where

$$\mathcal{U} = W \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix}, \quad W \simeq \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix}, \quad \theta \ll I, \qquad \begin{aligned} U_{\rm PMNS} &\simeq (1 - 1/2\theta\theta^\dagger) U_\nu, \\ \Theta &\simeq \theta U_N^* \end{aligned}$$

$$m_\nu \simeq -M_D M_R^{-1} M_D^T + M_L \qquad \text{seesaw type I+type II} \tag{10}$$

An active-sterile mixing matrix Θ can be parametrized as $(\Omega\Omega^T = I)$

$$\Theta = i U_{\rm PMNS} \sqrt{\tilde{m}}\, \Omega \sqrt{\hat{M}}\, U_N^\dagger \qquad \text{Casas-Ibarra-like parametrization} \tag{11}$$

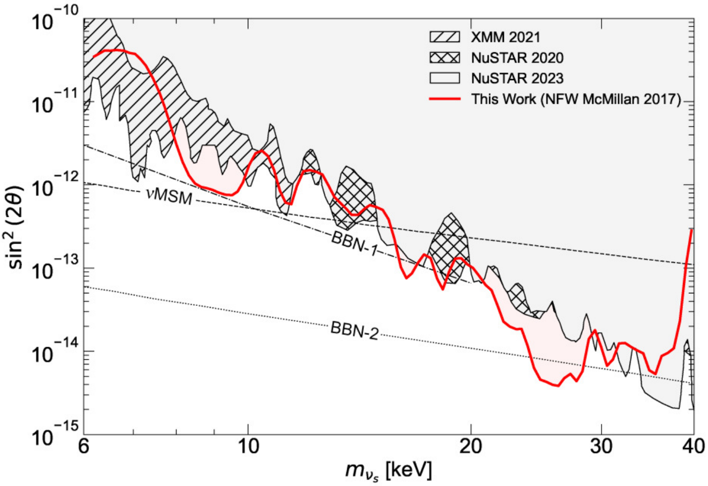
$$\text{where} \quad \tilde{m} = \hat{m} - U_{\rm PMNS}^\dagger M_L U_{\rm PMNS}^*, \qquad \text{or}^* \quad \tilde{m} = \hat{m} - \frac{v_L}{v_R} U_{\rm PMNS}^\dagger \hat{M} U_{\rm PMNS}^* \tag{12}$$

* in the approximation $\mathcal{O}(\theta^2) \ll 1$, $\hat{m} \ll \hat{M}$, $U_N = I$ Dubinin et al., 2506.04035 [hep-ph]

In general, Ω can be paramerized as (ω can be complex, $\xi = \pm 1$) $X_\omega \equiv e^{\mathrm{Im}\omega}$

$$\Omega_{\mathrm{NH}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \multicolumn{2}{c}{\Omega_{2\times 2}} \\ 0 & & \end{pmatrix}, \quad \Omega_{\mathrm{IH}} = \begin{pmatrix} 0 & \multicolumn{2}{c}{\Omega_{2\times 2}} \\ 0 & & \\ 1 & 0 & 0 \end{pmatrix}, \quad \Omega_{2\times 2} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

Mixing: $|\Theta_{\alpha I}|^2 \equiv U^2_{\alpha I}$, $U^2_{\mathrm{DM}} = U^2_1$ $U^2_I = \sum_\alpha U^2_{\alpha I}$, $U^2_\alpha = \sum_I U^2_{\alpha I}$



Model-independent DM bounds

Krivonos et al, 2405.17861 [hep-ph]

Collider physics: $v_R \gtrsim \mathcal{O}(\text{TeV})$

Precise measurements of the n decay Serebrov et al, Phys. Rev. D 112 (2025) 115012

$$M_{W_2} = 304^{+24}_{-20}\ \text{GeV}, \qquad \xi = -0.039 \pm 0.014$$

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix}, \quad \tan 2\xi = -\frac{2k_1 k_2}{v_R^2}, \quad \sqrt{k_1^2 + k_2^2} \equiv k_+ = 246\ \text{GeV}$$

Tree-level masses of gauge bosons

$$M^2_{W_{1,2}} = \frac{g^2}{4}\left(k_+^2 + v_R^2 \mp v_R^2 \sqrt{1 + \tan^2 2\xi}\right) \;\rightarrow\; v_R \simeq 624\ \text{GeV}, \quad k_2 \simeq 40 \div 64\ \text{GeV}$$

$$M^2_{Z_{1,2}} = \frac{1}{4}\left([g^2 k_+^2 + 2v_R^2(g^2 + g'^2)] \mp \sqrt{[g^2 k_+^2 + 2v_R^2(g^2 + g'^2)]^2 - 4g^2(g^2 + 2g'^2)\, k_+^2 v_R^2}\right)$$

$\rightarrow M_{Z_2} \simeq 495$ GeV, $\qquad M_{N_i} \lesssim v_R$,

$M^{\text{tree}}_{\texttt{Higgses}} < v_R$ (but unambiguity of the choice of Higgs couplings)

$$\begin{pmatrix} W_L^3 \\ W_R^3 \\ B \end{pmatrix} \simeq \begin{pmatrix} 0.88 & -0.02 & 0.47 \\ -0.23 & 0.85 & 0.47 \\ -0.41 & -0.53 & 0.74 \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix}$$

For the case $V^l_{L,R} = I,\ U_N = I,\ \theta\theta^\dagger \ll I,\ g_L = g_R = g \qquad (U = U_{\mathrm{PMNS}})$

$$\mathcal{L}^{\nu}_{NC} = \frac{1}{2}\sum_{X=Z_1,Z_2} \overline{\nu}\gamma^\mu X_\mu \left[(U^\dagger U)a^L_X P_L + (U^T\Theta^*)(\Theta^T U^*)a^R_X P_R\right]\nu \qquad \rightarrow \text{ small } Z_2$$

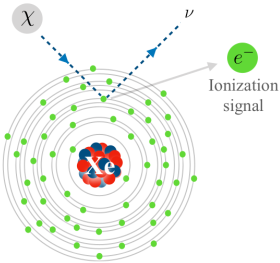
$$\mathcal{L}^{N}_{NC} = \frac{1}{2}\sum_{X=Z_1,Z_2} \overline{N}\gamma^\mu X_\mu \left[(\Theta^\dagger\Theta)a^L_X P_L + a^R_X P_R\right] N$$

$$+ \left(\overline{\nu}\gamma^\mu X_\mu \left[(U^\dagger\Theta)a^L_X P_L - (U^T\Theta^*)a^R_X P_R\right] N + \text{h.c.}\right)$$

$$\mathcal{L}^{\nu}_{CC} = \frac{g}{\sqrt{2}}\sum_{X=W_1,W_2} \bar{l}\gamma^\mu X^-_\mu \left[U\, a^L_X P_L + (\Theta^T U^*)a^R_X P_R\right]\nu + \text{h.c.} \qquad \rightarrow \text{ tiny } W_2$$

$$\mathcal{L}^{N}_{CC} = \frac{g}{\sqrt{2}}\sum_{X=W_1,W_2} \bar{l}\gamma^\mu X^-_\mu (\Theta a^L_X P_L - a^R_X P_R)N + \text{h.c.} \qquad \rightarrow \textbf{ SIZABLE } W_2$$

$$a^L_{Z_{1,2}} \simeq \{0.75,\ 0.21\},\ a^R_{Z_{1,2}} \simeq \{0.02,\ 0.79\},\ a^L_{W_{1,2}} \simeq \{1,\ -0.02\},\ -a^R_{W_{1,2}} \simeq \{0.02,\ 1\}$$



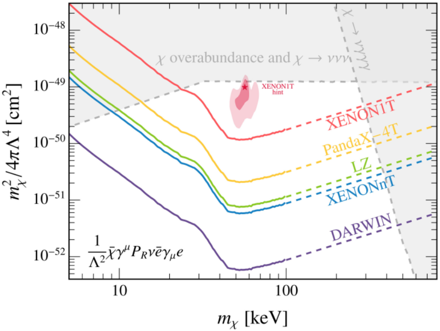
XENON1T

search on fermionic DM-electron absorption

$$\chi + A \quad \rightarrow \quad \nu + A^+ + e^-$$
$$\chi + e^- \quad \rightarrow \quad \nu + e^-$$

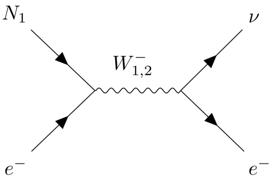
The best fit

$$m_\chi = 56.5 \text{ keV}, \qquad \sigma_e = 10^{-49} \text{ cm}^2$$



Dror et al., 2011.01940 [hep-ph]

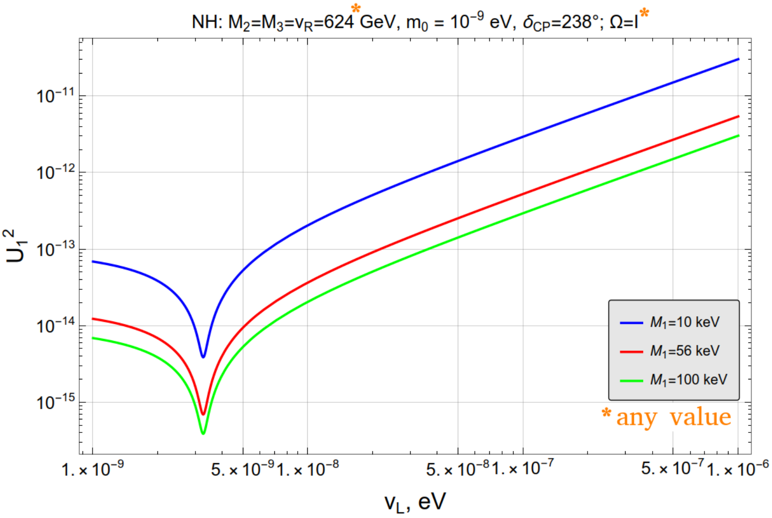
In our case



$$\sigma_e \equiv \frac{m_{N_1}^2}{4\pi\Lambda^4} \simeq 5 \cdot 10^{-49} \text{ cm}^2$$

where Λ is a ratio of a mediator mass to its coupling

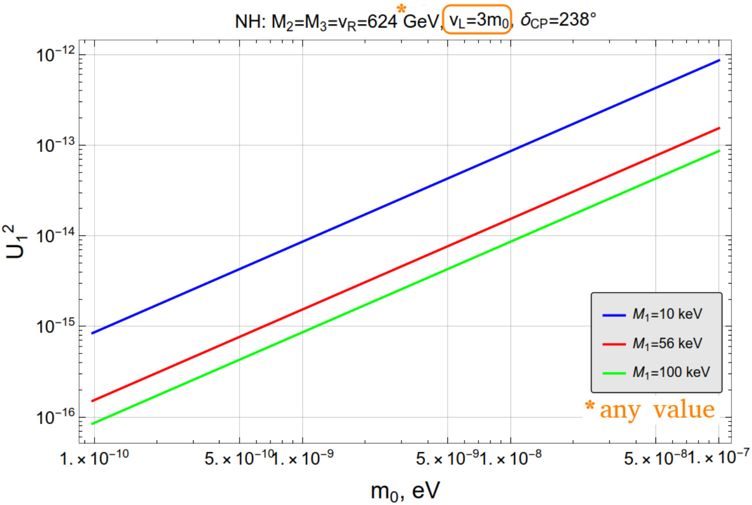
Numerical estimations of the DM mixing



– U_1^2 does not depend on Ω and is insensitive to v_R

– U_1^2 can be reduced by 1 order of magnitude by

i) using $v_L \simeq 3m_0$, ii) increasing M_1 by 1 order of magnitude



– IH: $U_1^2 \approx 10^{-6} \div 10^{-7}$, therefore, the IH must be excluded

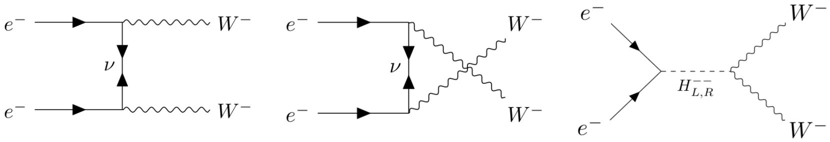
– U_1^2 is very sensitive to m_0:

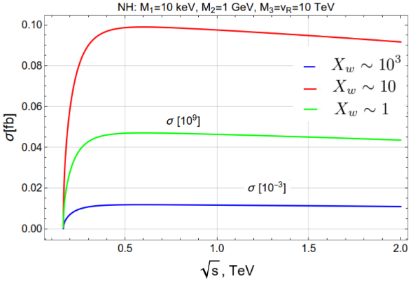
i) $m_0 \simeq 10^{-9}$ eV – the masses $M_1 = 5 \div 25$ keV are allowed;

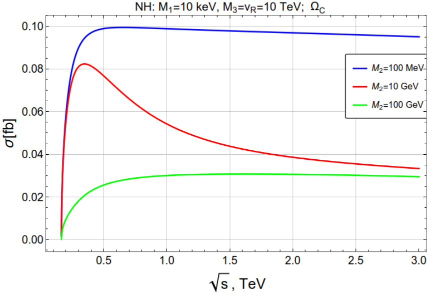
ii) $m_0 < 10^{-9}$ eV – all masses M_1 are possible

Inverse neutrinoless double beta decay

$$e^- e^- \to W^- W^-$$







Our calculations are based on analytical formulas in Asaka, Tsuyuk, 1508.04937 [hep-ph]

(that are not appropriate for low v_R)

We consider the MLRM with the lightest HNL as DM

- The masses of observed neutrinos are generated by the seesaw mechanism of types I and (possibly) II
- The mass hierarchy between the ligtest standard neutrino ($0 < m_0 \leq 10^{-5}$) and two others neutrinos **can** be explained using different types of seesaw mechanism (in this case m_0 is generated by v_L)
- The mixing dependence on v_L, $U^2(v_L)$, is sizable if at least one of the HNLs has a mass of the order of v_R

- Manifest left-right symmetric models (not necessarily the MLRM) predict sizable interactions of HNLs with the gauge boson W_2
- Assuming that $M_{W_2} \approx 300$ GeV with a tiny mixing angle (a hint from precision measurements of n-decay), the LR scale is about 600 GeV with all masses of new particles at or below v_R-scale. (The discussion of possible rich phenomenology is far beyond the scope of this talk)
- Under the assumption above, the XENON1T hint can be explained at tree level

- Under the assumption that N_1 is DM, the recent observational data (XMM 2021, νSTAR 2020, 2023) exclude the possibility of an IH for active neutrinos

- DM mixing U_1^2 is very sensitive to m_0:
  i) $m_0 \simeq 10^{-9}$ eV – only $M_1 \simeq 5 \div 25$ keV are allowed;
  ii) $m_0 < 10^{-9}$ eV – all masses M_1 are possible

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THANK YOU FOR YOUR ATTENTION