PROCEEDINGS OF SCIENCE

# Absolute neutrino mass as the missing link to the dark sector

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With the KATRIN experiment, the determination of the absolute neutrino mass scale down to cosmologically favored values has come into reach. We show that this measurement provides the missing link between the Standard Model and the dark sector in scotogenic models, where the suppression of the neutrino masses is economically explained by their only indirect coupling to the Higgs field. We determine the linear relation between the electron neutrino mass and the scalar coupling $\lambda_5$ associated with the dark neutral scalar mass splitting to be $\lambda_5 = 3.1 \times 10^{-9}\ m_{\nu_e}/\mathrm{eV}$.

*41st International Conference on High Energy physics - ICHEP2022*
*6-13 July, 2022*
*Bologna, Italy*

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PoS(ICHEP2022)553

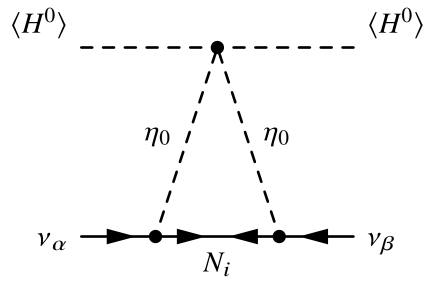


**Figure 1:** One loop diagram which generates neutrino masses in the scotogenic model.

## 1. Introduction

The nature of Dark Matter (DM) remains an open question in particle physics even though dark matter is five times more abundant than ordinary matter. The observation of neutrino oscillations implies that these particles do have masses. The reason why neutrino masses are small is still a mystery. The KATRIN experiment aims to determine the absolute neutrino mass scale and has recently set the limit of 0.8 eV [1] with a sensitivity goal of 0.2 eV [2].

The scotogenic model combines both of these questions by explaining neutrino masses with loop corrections where a weakly interacting massive particle (WIMP) runs in the loop which naturally yields small neutrino masses [3]. The corresponding one loop diagram is shown in Fig. 1. Our work [4] investigates how the connection between DM and neutrinos can be used to constrain the phenomenologically important parameter $\lambda_5$.

## 2. The scotogenic model

In the scotogenic model the Standard Model (SM) in extended by a scalar doublet $\eta$ and three generations of fermion singlets (right handed neutrinos) $N_i$. Both these new fields are odd under a $Z_2$ symmetry while the SM fields have even charge [3]. The terms in the Lagrangian involving the new fields are given by

$$\mathcal{L}_N = -\frac{m_{N_i}}{2} N_i N_i + y_{i\alpha}(\eta^\dagger L_\alpha) N_i + \text{h.c.} - V, \tag{1}$$

with

$$\begin{aligned} V =& m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger \eta\right)^2 + \lambda_3\left(H^\dagger H\right)\left(\eta^\dagger \eta\right) \\ &+ \lambda_4\left(H^\dagger \eta\right)\left(\eta^\dagger H\right) + \frac{\lambda_5}{2}\left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right]. \end{aligned} \tag{2}$$

where $H$ is the SM Higgs doublet and $L_\alpha$ is the SM lepton doublet. All fermion field are given as Weyl spinors. After Electroweak Symmetry Breaking (EWSB), the masses of the physical charged and neutral scalars are

$$\begin{aligned} m_{\eta^+}^2 &= m_\eta^2 + \lambda_3 \langle H^0 \rangle^2, \\ m_R^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5)\, \langle H^0 \rangle^2, \\ m_I^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5)\, \langle H^0 \rangle^2. \end{aligned} \tag{3}$$

Note how the real and imaginary components of the neutral field have a mass splitting governed by $\lambda_5$.

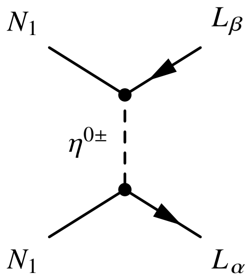


**Figure 2:** Main annihilation channel for fermion DM.

Majorana neutrino masses are generated at one loop by the loop given in Fig. 1. This loop can be evaluated giving the following expression for the neutrino mass matrix:

$$
\begin{aligned}
(M_\nu)_{\alpha\beta} &= \sum_{i=1}^{3} \frac{y_{i\alpha} y_{i\beta} m_{N_i}}{32\pi^2} \left[ \frac{m_R^2}{m_R^2 - m_{N_i}^2} \log\left(\frac{m_R^2}{m_{N_i}^2}\right) - (R \to I) \right] \\
&\approx 2\lambda_5 \langle H^0 \rangle^2 \sum_{i=1}^{3} \frac{y_{i\alpha} y_{i\beta} m_{N_i}}{32\pi^2 (m_{R,I}^2 - m_{N_i}^2)} \left[ 1 + \frac{m_{N_i}^2}{m_{R,I}^2 - m_{N_i}^2} \ln\left(\frac{m_{N_i}^2}{m_{R,I}^2}\right) \right]
\end{aligned}
\tag{4}
$$

In the second line we approximated the formula for small $\lambda_5$. Note how the neutrino masses are zero for vanishing $\lambda_5$. As Majorana neutrino masses violate lepton number, $\lambda_5$ is naturally small.

A useful trick in order to find models with the correct neutrino parameters is to use the Casas-Ibarra parameterization [5] and invert the neutrino mass formula. We find

$$
y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U_{\text{PMNS}}^\dagger \tag{5}
$$

with

$$
\Lambda_i = 2\lambda_5 \langle H^0 \rangle \frac{m_{N_i}}{32\pi^2 (m_{R,I}^2 - m_{N_i}^2)} \left[ 1 + \frac{m_{N_i}^2}{m_{R,I}^2 - m_{N_i}^2} \ln\left(\frac{m_{N_i}^2}{m_{R,I}^2}\right) \right] \tag{6}
$$

where $\hat{m}_\mu$ is the diagonal neutrino mass matrix and $U_{\text{PMNS}}$ is the PMNS matrix. Thus the Yukawa couplings are not free parameters but can be calculated from the other parameters. The Yukawa couplings have a profound impact on the phenomenology as they are the only portal for fermions interacting with the dark sector. The connection to the neutrino masses is given in Eq. (4). Further for fermion DM the main annihilation channel is given by the diagram in Fig. 2. All occurring vertices are Yukawa couplings.

An important constraint on radiative seesaw models is lepton flavor violation (LFV). At one loop there are lepton flavor violating decays of charged leptons. We give some diagrams in Fig. 3. LFV in the scotogenic model has been studied in more detail in Refs. [6, 7]. The most important constraint tends to be on the branching ratio $\text{BR}(\mu \to e\gamma)$. It is worth noticing that these processes are also governed by the Yukawa couplings.

## 3. Numerical calculation

We perform a random scan over the parameter space of the scotogenic model restricting ourselves to fermion DM. The Higgs parameters $m_H^2$ and $\lambda_1$ are fixed to the SM values while we fix $\lambda_2 = 0.5$ as it only induces self interactions and has only a small impact on the phenomenology. We

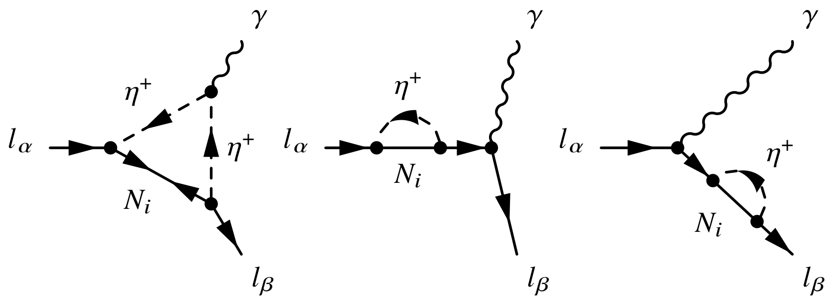

**Figure 3:** Some diagrams leading to LFV in the scotogenic model.

sample the mass parameter $m_\eta, m_{N_i}$ in the range from 100 GeV to 10 TeV and the scalar couplings $\lambda_{3,4}$ in the range $[-4\pi, 4\pi]$ while imposing the vacuum stability conditions

$$\begin{aligned} &\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}, \\ &\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}. \end{aligned} \tag{7}$$

Further we have $10^{-12} < |\lambda_5| < 10^{-8}$ and we impose the perturbativity limit on the Yukawa couplings $|y_{i\alpha}|^2 < 4\pi$. The neutrino parameters are varied in the $3\sigma$ ranges of the measured values [8]. We use SPheno 4.0.3 [9, 10] to calculate the particle masses and LFV branching ratios and micrOMEGAs 5.0.8 [11] to obtain the DM relic density. We constrain the LFV observables with the current limits

$$\begin{aligned} \mathrm{BR}(\mu \to e\gamma) &< 4.2 \cdot 10^{-13} \ [12], \\ \mathrm{BR}(\mu \to 3e) &< 1.0 \cdot 10^{-12} \ [13], \\ \mathrm{CR}(\mu - e, \mathrm{Ti}) &< 4.3 \cdot 10^{-12} \ [14]. \end{aligned} \tag{8}$$

and the relic density with $\Omega h^2 = 0.12 \pm 0.02$ where we allow a theoretical uncertainty [15]. Finally we exclude all points where coannihilation plays a significant role.

## 4. Results

We show the results of the parameter scan in Fig. 4. In the regime where the absolute neutrino mass is larger than the mass differences, the neutrino masses are almost degenerate. In this regime, the Casas Ibarra formula can be approximated $y \propto \sqrt{\frac{m_\nu}{\lambda_5}} f(m_N, m_\eta)$ for some function $f$ depending only on the masses. In Fig. 4 we see that constraining the relic density, forces $\frac{y}{f(m_N, m_\eta)}$ constant which allows us to fit a linear relation between $\lambda_5$ and $m_\nu$. We fit for both normal and inverted hierarchy giving the result

$$|\lambda_5| = \begin{cases} (3.08 \pm 0.05) \cdot 10^{-9} \, m_{\nu_1}/\mathrm{eV} & \text{(NH)} \\ (3.11 \pm 0.06) \cdot 10^{-9} \, m_{\nu_1}/\mathrm{eV} & \text{(IH)} \end{cases} \tag{9}$$

In the hierarchical scenario the mass differences dominate over the absolute neutrino mass and different values of $\lambda_5$ yield the correct relic density. However LFV constraints exclude large $y$ and therefore small $\lambda_5$. Therefore the allowed values of $\lambda_5$ are independent of the absolute neutrino mass and given by

$$|\lambda_5| = \begin{cases} (1.6 \pm 0.7) \cdot 10^{-10} & \text{(NH)} \\ (1.7 \pm 1.5) \cdot 10^{-10} & \text{(IH)} \end{cases} \tag{10}$$

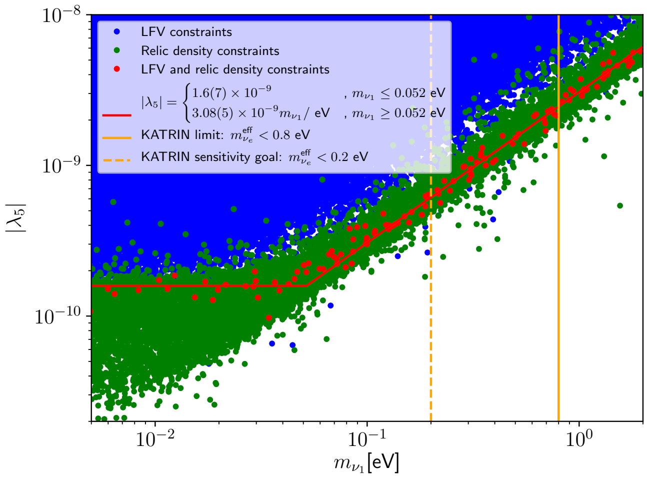


**Figure 4:** The results of the parameter scan on the absolute neutrino mass-$\lambda_5$ plane for normal hierarchy.

## 5. Conclusion

We investigate fermion DM in the scotogenic model and show that the intrinsic connections of neutrino masses and DM yields some relations between the absolute neutrino mass probed by KATRIN and the parameter $\lambda_5$. This parameter has a big impact on the phenomenology as the Yukawa couplings are fixed by the Casas-Ibarra parameterization. In the regime where the neutrino masses are degenerate, the relic density forces a linear relation between the absolute neutrino mass and $\lambda_5$. In the hierarchical scenario, the relic density combined with LFV constraints force $\lambda_5$ to a constant value. We have checked that our results are valid for both normal as well as inverted hierarchy.

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