What a Direct Neutrino Mass Measurement Might Teach Us about the Dark Sector

Michael Klasen*

Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Straße 9, 48149 Münster, Germany

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Abstract—Searches for dark matter suggest that it couples to ordinary matter only very weakly and possibly only through the Higgs or other scalar bosons. On the other hand, neutrinos might not couple to the Higgs boson directly, but only through a loop of dark matter particles, which would naturally explain the small neutrino masses. We demonstrate that current experimental constraints on such a “scotogenic” scenario allow to make the linear dependence of the lightest neutrino mass on the dark sector-Higgs coupling explicit, so that a measurement by the KATRIN experiment would directly determine its value.

Keywords: dark sector, direct neutrino mass measurement, neutrino mass

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1. INTRODUCTION

The nature of dark matter (DM) and the absolute neutrino mass scale are two prominent research topics, which are currently under intense scrutiny. In particular, we now have observational evidence for DM ranging from galactic rotation curves to the large scale structure of the Universe and the cosmic microwave background (CMB), informing us that DM is cold and about five times more abundant than ordinary matter. Neither massive compact halo objects nor primordial black holes nor standard model (SM) neutrinos can explain a substantial fraction of DM. New heavy particles such as weakly interacting massive particles (WIMPs) remain the most promising candidates, since their relic density after freeze-out agrees with observations [1].

We also know now from solar, atmospheric and reactor observations that (at least two) SM neutrinos have non-zero masses with a minimal value for their sum of 0.06 eV for normal mass ordering, which rises to 0.2 eV for each neutrino in the quasi-degenerate regime [2]. This happens to be also the sensitivity upper limits on the sum of neutrino masses can be as strong as 0.12 eV [5].

Scotogenic models provide an intriguing connection between the two puzzles of the nature of DM and the smallness of neutrino masses. There, these neutrino masses are generated at one or more loops, and at least one heavy particle in the loop can be a DM candidate. A discrete $Z_2$ symmetry is usually employed to guarantee its stability and prevent a tree-level seesaw mechanism.

2. THE SCOTOGENIC MODEL

The simplest scotogenic (i.e., “created from DM”) model is very economical, as it adds to the left-handed SM lepton doublets $L_\alpha$ ($\alpha = 1, 2, 3$) only three generations of fermion singlets $N_i$ ($i = 1, 2, 3$) and an inert complex scalar doublet $(\eta^+, \eta^0)$, which does not develop a vacuum expectation value (VEV). The lightest neutral fermion is then a good DM candidate. Apart from kinetic terms, the Lagrangian of this model is given by [6]

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

with a scalar potential

$$V = m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} (\phi^\dagger \phi)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \lambda_3 (\phi^\dagger \phi) (\eta^\dagger \eta)$$

*E-mail: michael.klasen@uni-muenster.de

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The experimental information mentioned above constrains the eigenvalues of the Yukawa coupling matrices to be of similar size (Fig. 2). For large absolute neutrino masses, their differences and thus also those of the Yukawa couplings become naturally small, whereas they are of course substantial in the limit of small absolute neutrino masses (grey points). The upper limits on LFV processes (blue points) impose upper limits on the Yukawas, while the relic density (green points) imposes lower limits. Together, both constraints then lead to a narrow band of $|y_2/y_1| \sim 1$ (red points) for both normal ordering (NO, shown here), inverse ordering (IO) and all other combinations of Yukawa couplings (not shown).

The linear dependence of the absolute neutrino mass on the dark sector–Higgs boson coupling then becomes explicit (Fig. 3), since LFV and relic density constraints act again in opposite directions. A KATRIN measurement of the absolute neutrino mass would therefore directly translate into a measurement of

$$|\lambda_5| = \begin{cases} 
(3.08 \pm 0.05) \times 10^{-9} \text{ m}_{\nu_1}/\text{eV} & \text{(NO)} \\
(3.11 \pm 0.06) \times 10^{-9} \text{ m}_{\nu_1}/\text{eV} & \text{(IO)}.
\end{cases} \quad (4)
$$

Below, $m_{\nu_1} = 0.052$ eV, the heaviest neutrino mass dominates and

$$|\lambda_5| = \begin{cases}
(1.6 \pm 0.7) \times 10^{-10} & \text{(NO)} \\
(1.7 \pm 1.5) \times 10^{-10} & \text{(IO)}
\end{cases} \quad (5)
$$

becomes independent of $m_{\nu_1}$. The dark sector–Higgs boson coupling $\lambda_5$ can therefore be predicted (modulo an arbitrary sign), once the absolute neutrino mass scale is known.

With the ratio of $m_{\nu_1}/\lambda_5$ fixed, Eq. (3) can be inverted to yield an approximate dependence

$$|y_1| = \begin{cases}
(0.078 \pm 0.021) \sqrt{m_{N_1}/\text{GeV}} & \text{(NO)} \\
(0.081 \pm 0.012) \sqrt{m_{N_1}/\text{GeV}} & \text{(IO)}
\end{cases}
$$

of the lightest Yukawa coupling eigenvalue on the square root of the DM mass $m_{N_1}$ (Fig. 4). The only condition is that the DM mass is sufficiently smaller than those of the scalars (temperature scale) and much smaller than those of the other fermions, which is imposed by the experimental constraints. This implies that if the DM mass is known, we can predict its coupling to the SM charged leptons and neutrinos.

As LFV and relic density constraints are not only complementary to each other, but also to a direct neutrino mass measurement, the parameter space of

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**Fig. 1.** Neutrino mass generation in the scotogenic model.

\[ + \lambda_4 (\phi^\dagger \eta) (\eta^\dagger \phi) + \frac{\lambda_5}{2} \left[ (\phi^\dagger \eta)^2 + (\eta^\dagger \phi)^2 \right], \quad (2) \]

which breaks $SU(2)_L \times U(1)_Y \to U(1)_{em}$, when the SM Higgs $\phi$ obtains a VEV. Perturbativity imposes $|y_{1\alpha}|^2 < 4\pi$ and $|\lambda_{2,3,4,5}| < 4\pi$, and vacuum stability requires $\lambda_{1,2} > 0$, $\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$ and $\lambda_4 + \lambda_5 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$. Neutrino masses are then generated at one loop by the $3 \times 3$ Yukawa matrices $y_{1\alpha}$ through the diagram in Fig. 1.

A key observation is that the mass splitting of the real and imaginary components of $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$, $m_{\nu_R}^2 - m_{\nu_I}^2 = 2\lambda_5 (\phi^0)^2$, is naturally small, since $\lambda_5 = 0$ implies $L$ conservation and $m_{\nu_1} = 0$. In the limit $\lambda_5 \ll 1$, the neutrino mass matrix simplifies to

$$\langle m_{\nu}\rangle_{\alpha\beta} \approx 2 \lambda_5 \langle \phi^0 \rangle^2 \sum_{i=1}^{\frac{\eta_{1\beta} y_{1\alpha} m_{N_i}}{32 \pi^2 (m_{\nu_R,i}^2 - m_{\nu_I,i}^2)}} \left[ 1 + \frac{m_{N_i}^2}{m_{\nu_R,i}^2 - m_{\nu_I,i}^2} \log \left( \frac{m_{\nu_R,i}^2 - m_{\nu_I,i}^2}{m_{N_i}^2} \right) \right], \quad (3)$$

i.e., it is not only bilinear in $y$, but also linear in $\lambda_5$.

### 3. EXPERIMENTAL CONSTRAINTS

Our main new observations are that the observational constraints on the DM relic density, neutrino mass differences and mixing angles, lepton flavor violation (LFV) processes and new charged particle masses allow us to make the linear dependence of the lightest neutrino mass on the dark sector coupling $\lambda_5$ and the quadratic dependence on the eigenvalues of the Yukawa couplings $y$ explicit [7]. To this end, we impose the most recent measurements and limits from Planck [5], solar, atmospheric and reactor neutrinos [2], MEG [8], SINDRUM [9], and OPAL [10] on the parameter space of the scotogenic model, using the Casas–Ibarra parametrisation. Direct and indirect detection constraints are not relevant, as the fermion scatters off nuclei only at one loop. The lightest neutrino mass is scanned from 4 meV to 2 eV and $|\lambda_5|$ from $10^{-12}$ to $10^{-8}$.
fermion DM in the scotogenic model will be almost completely testable in the near future (Fig. 5). Here, only points satisfying the neutrino mass difference, mixing angle and the DM relic density constraints are shown. Currently the limit on $\mu \rightarrow e\gamma$ [8] is currently stronger than the one for $\mu \rightarrow 3e$ [9], but this might change soon [11, 12].

5. DISCUSSION AND OUTLOOK

The theoretical reason for our observations lies in the intimate topological connection of the neutrino mass diagram to the diagrams mediating LFV and, after cutting the internal fermion line, DM annihilation. These correlations are absent for scalar DM, which can also annihilate into weak gauge bosons. In
Fig. 4. Yukawa coupling of the lightest neutrino as a function of the DM mass. The ratio of the neutral scalar over the DM mass is given on the temperature scale.

Fig. 5. Branching ratios of viable scotogenic models for the LFV processes $\mu \rightarrow e\gamma$ (blue) and $\mu \rightarrow 3e$ (red points), their current (full) [8, 9] and future (dashed) [11, 12] experimental limits, and the current [4] and future [3] KATRIN limits (yellow lines) on the electron neutrino mass.

In this case, inelastic scattering in the Sun can provide stringent bounds [13]. If scalars and fermions are close in mass, coannihilations must be and have been considered [14].

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CONFLICT OF INTEREST

The authors declare that he has no conflicts of interest.

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