Absolute neutrino mass as the missing link to the dark sector

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Introduction

Dark Matter (DM):

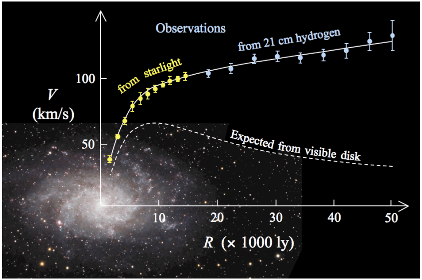
- Evidence from many different length scales
- Five times more abundant than ordinary matter
- Cold (warm?) and (only?) gravitationally interacting
- Weakly interacting massive particles (WIMPs): "miracle"

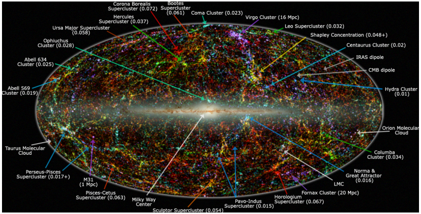
Neutrinos:

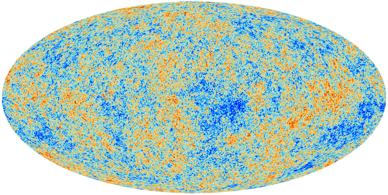
- (At least two) Standard Model (SM) neutrinos have $m_{\nu_i} \neq 0$
- Neither cold nor more than small fraction (0.5–1.6%) of Ω_c

Observational evidence for dark matter

MK, M. Pohl, G. Sigl, Prog. Nucl. Part. Phys. 85 (2015) 1







Neutrino masses and mixings

Atmospheric and solar neutrino oscillations: [PDG 2021]

- $\sin^2(\theta_{12}) = 0.307 \pm 0.013$
- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
- $\sin^2(\theta_{23}) = 0.546 \pm 0.021$ (NO) [Favored by T2K and NOνA]
- $\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}$ eV^2 (NO)
- $\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$
- $\delta = 1.36^{+0.20}_{-0.16}\ \pi$ rad [MINOS, T2K and NOνA]

Absolute neutrino mass scale:

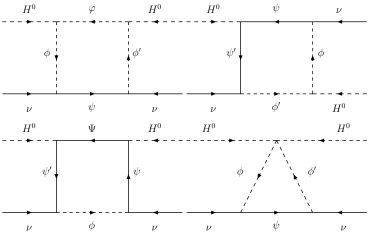
- Minimal allowed value: $\sum_i m_{\nu_i} > 0.06$ eV
- Quasi-degenerate regime: $m_{\nu_i} > 0.2$ eV [KATRIN sensitivity goal]
- Current upper limit: $m_{\nu_i} < 1.1$ eV [KATRIN Coll., PRL 123 (2019) 221802]
- Cosmology limit: $\sum_i m_{\nu_i} < 0.12$ eV [Planck Coll., AA 641 (2020) A6 and C4(E)]

An intriguing connection: Linking DM to neutrinos

"Scotogenic" (= created from dark matter) models:

- Radiative seesaw: Mass generation at one (or more) loop(s)
- At least one particle in the loop can be DM

Classification of one-loop realizations: [D. Restrepo et al., JHEP 1311 (2013) 011]



Properties:

- Up to 4 new fields, odd under Z_2 ($\rightarrow$ no tree, DM stability)
- Singlets of $SU(3)_C$, singlets/doublets/triplets of $SU(2)_L$

The scotogenic model (1)

E. Ma, Phys. Rev. D 73 (2006) 077301 [hep-ph/0601225]

Left-handed SM lepton doublets: L_α $(\alpha = 1, 2, 3)$

New dark (Z_2-odd) particle content:

- (Inert) complex Higgs doublet (η^+, η^0) with $\langle \eta^0 \rangle = 0$ (Z_2)
- 3 generations of fermion singlets (sterile neutrinos, N_i)

DM candidate: Lightest neutral fermion N_i (or scalar)

Lagrangian (apart from kinetic terms):

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

Neutrino masses generated at 1 loop by 3×3 Yukawa matrices $y_{i\alpha}$
Perturbativity: $|y_{i\alpha}|^2 < 4\pi$

The scotogenic model (2)

E. Ma, Phys. Rev. D 73 (2006) 077301 [hep-ph/0601225]

Complex SM Higgs doublet: (ϕ^+, ϕ^0) with $\langle \phi^0 \rangle = 246 \text{ GeV}/\sqrt{2}$

Scalar potential ($\sim$ 2HDM, breaking $SU(2)_L \times U(1)_Y \to U(1)_{\rm em.}$):

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

Vacuum stability:

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$$

Perturbativity: $|\lambda_{2,3,4,5}| < 4\pi$

Parameters:

- m_ϕ, λ_1 fixed by $\langle \phi^0 \rangle$, $m_h^2 = 2\lambda_1 \langle \phi^0 \rangle^2 = -2m_\phi^2 = (125 \text{ GeV})^2$
- Since $\langle \eta^0 \rangle = 0$, λ_2 induces only self-interactions and decouples

The scotogenic model (3)

E. Ma, Phys. Rev. D 73 (2006) 077301 [hep-ph/0601225]

Scalar masses:

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

where $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ and

$$m_R^2 - m_I^2 = 2\lambda_5 \langle \phi^0 \rangle^2$$

is naturally small ($\lambda_5 = 0$ implies L conservation and $m_{\nu_i} = 0$).

[J. Kubo, E. Ma, D. Suematsu, PLB 642 (2006) 18]

We scan over $|\lambda_5| \in [10^{-12}; 10^{-8}]$. [A. Vicente, C. Yaguna, JHEP 02 (2015) 144]

Experimental constraints (1)

LEP limit on charged particle masses: [OPAL Coll., PLB 572 (2003) 8]

- For $\lambda_3 < 1$, implies lower limit on $m_\eta \in [0.1; 10]$ TeV
- m_η then dominates over $\langle \phi^0 \rangle$
- $\lambda_{3,4}$ then subdominant and $m_{\eta^\pm} \simeq m_{R,I}$

We use the same mass range for m_{N_i} (but lightest $m_{N_i} < m_{R,I}$).

SM neutrino mass matrix: $(m_\nu)_{\alpha\beta} = (y^T \Lambda y)_{\alpha\beta}$ with

$$\Lambda_i = \frac{m_{N_i}}{32\pi^2}\left[\frac{m_R^2}{m_R^2 - m_{N_i}^2}\log\left(\frac{m_R^2}{m_{N_i}^2}\right) - (R \to I)\right].$$

Diagonalized by the PMNS matrix U with

$$U^T\, m_\nu\, U = \hat{m}_\nu \equiv \mathrm{diag}(m_1, m_2, m_3).$$

Then, for a given set of masses in Λ_i, the Yukawa couplings

$$y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U^\dagger$$

are constrained up to rotation matrix R. [J. Casas, A. Ibarra, NPB 618 (2001) 171]

Experimental constraints (2)

Lepton flavor violation:

$$\begin{aligned} \mathrm{BR}(\mu \to e\gamma) &< 4.2 \cdot 10^{-13} \text{ [MEG]} && (2 \cdot 10^{-15} \text{ [MEG]}) \\ \mathrm{BR}(\mu \to 3e) &< 1.0 \cdot 10^{-12} \text{ [SINDRUM]} && (10^{-16} \text{ [Mu3e]}) \\ \mathrm{CR}(\mu - e, \mathrm{Ti}) &< 4.3 \cdot 10^{-12} \text{ [SINDRUM II]} && (10^{-18} \text{ [PRIME]}) \end{aligned} \quad (1)$$

- Depend on m_{η^+}, m_{N_i}, $y_{i\alpha}$ through form factors, box diagrams
- Calculated with SPheno 4.0.3 [W. Porod, F. Staub, CPC 183 (2012) 2458]

Relic density:

- Standard freeze-out, N_i annihilate to SM leptons L_α via $y_{i\alpha,i\beta}$
- $\Omega h^2 = 0.12 \pm 0.02$ (theor.) [Planck Coll., AA 641 (2020) A6 and C4(E)]
- Calculated with micrOMEGAs 5.0.8 [G. Belanger et al., CPC 231 (2018) 173]

Direct detection:

- Occurs only at one loop
- Currently beyond experimental reach

Numerical results

Full numerical scan over the parameter space:

- 4 masses: m_{N_i}, m_η
- 3 couplings: $\lambda_{3,4,5}$
- 3 rotation angles: θ_i
- $m_{\nu_{1,3}} \in [4 \times 10^{-3}; 2]$ eV (NO, IO)

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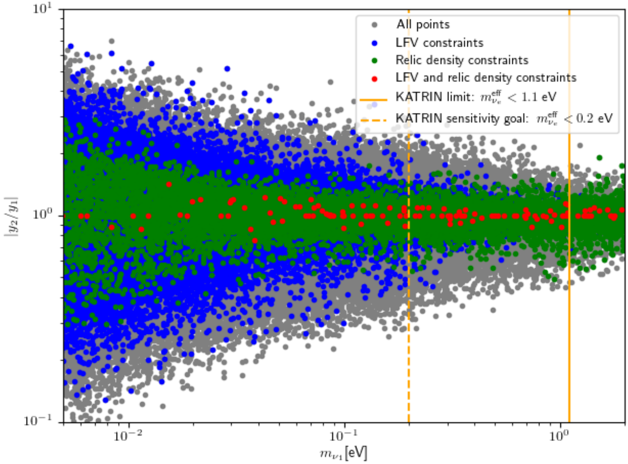
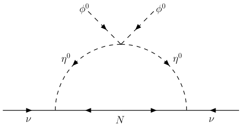
Ratios of Yukawa coupling eigenvalues



Large/small variation for small/large m_{ν_1} $\rightarrow$ Rotation angles unimportant.
$l_\alpha \rightarrow l_\beta\gamma, 3l_\beta$ impose upper limits on $y_{\alpha,\beta}$ $\rightarrow$ Ratios further constrained.
Relic density requires sizable $y_{\alpha,\beta}$ $\rightarrow$ $|y_\beta/y_\alpha| \sim 1$ for all m_{ν_1} (NO and IO)

Neutrino mass matrix and dark sector–Higgs coupling



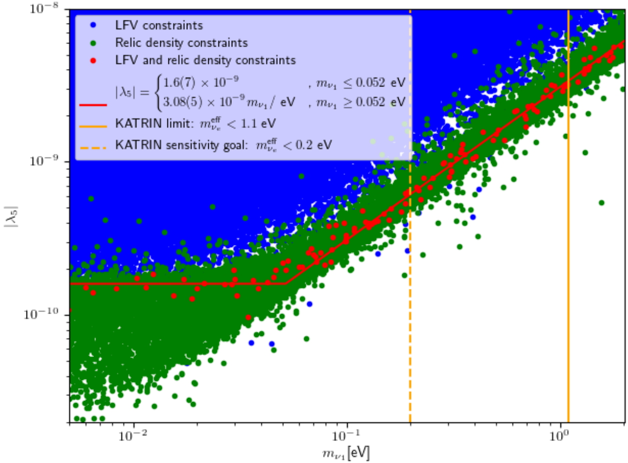
When $\lambda_5 \ll 1$ and $m_R^2 \approx m_I^2$, neutrino mass matrix simplifies to

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

i.e. it is not only bilinear in y, but also linear in λ_5.

Above constraints allow us to make this explicit for the eigenvalue.

Absolute neutrino mass and dark sector–Higgs coupling (1)



Lepton flavor violation requires small Yukawa couplings $\rightarrow$ Large λ_5.
Relic density requires large Yukawa couplings $\rightarrow$ Small λ_5.
Overlap region is indeed linear in lightest neutrino mass eigenvalue m_{ν_1}.

Absolute neutrino mass and dark sector–Higgs coupling (2)

Degenerate/KATRIN regime:

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

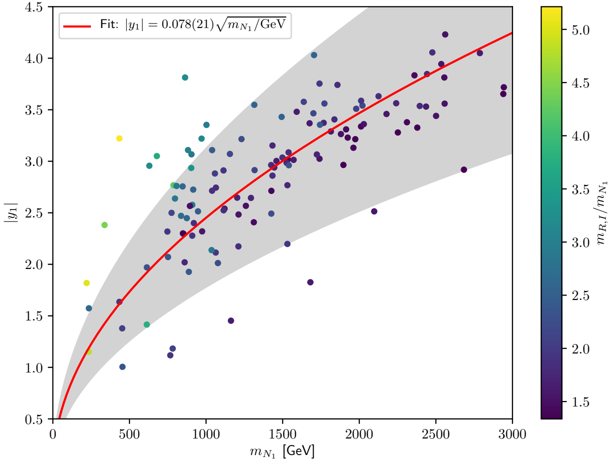
Below $m_{\nu_1} = 0.052$ eV, heaviest neutrino mass dominates and

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

becomes independent of m_{ν_1}. Sign of λ_5 is arbitrary.

The dark sector–Higgs boson coupling λ_5 can therefore be predicted, once the absolute neutrino mass scale is known.

Yukawa coupling of the lightest neutrino (1)



Square root fit (red curve, grey shaded area) at 90% C.L.

Temperature scale: Ratio of neutral scalar over DM mass.

Yukawa coupling of the lightest neutrino (2)

Reminder:

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

With $m_{\nu_1}/|\lambda_5|$ fixed, Yukawas are correlated with DM/scalar mass.

Relic density constrains $m_{R,I}/m_{N_1} \sim 1.5$.

Leading term in the neutrino mass matrix is then $\propto |y_1|^2/m_{N_1}$.

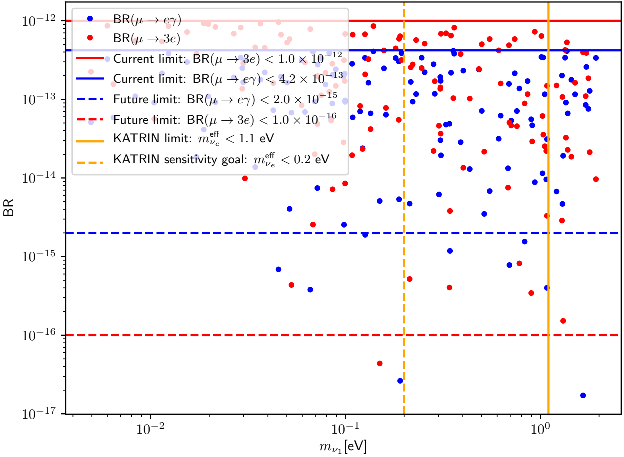
Other dark fermions $N_{2,3}$ are significantly heavier.

Fit result:

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

If DM mass is known, we can predict its coupling to SM leptons.

Complementarity of KATRIN and LFV experiments



Current (full) and future (dashed) experimental limits.

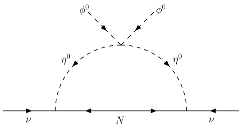
$\mu \to e\gamma$ stronger than $\mu \to 3e$, but this might change soon.

Fermion DM space can be almost completely tested.

Summary (1)

Conclusions:

- Scotogenic model is simplest radiative seesaw model with DM
- Fermion DM parameter space now severely constrained
- KATRIN measurement of m_{ν_1} would directly predict λ_5
- Together with LFV would test complete parameter space
- Measurement of m_{N_1} would predict coupling to SM leptons



Reasons:

- Constraints inherent in neutrino mass one-loop diagram
- Topologically similar to penguin diagram mediating LFV
- Also similar to DM annihilation, when cut on fermion line

Summary (2)

Caveats:

- Correlations absent for scalar DM, when cut on scalar lines
- Scalar doublets can also annihilate into weak gauge bosons
- New constraints from inelastic scattering in the Sun

  [T. de Boer, MK et al., JCAP 08 (2021) 038]
- Coannihilations studied elsewhere [MK, D. Restrepo et al., JCAP 04 (2013) 044]

Outlook:

- Observations generalize to other scotogenic models
- Examples: Fermion triplet, singlet-doublet scalars
- When LFV is weaker, must also consider collider constraints