Max-Planck-Insitut für Kernphysik

Absolute neutrino mass as the missing link to the dark sector

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Scotogenic model

- Open questions in the SM
  - Dark matter
  - Neutrino masses
- Model proposed by E. Ma (2006) (*scotos*: Greek for darkness)
- Dark matter generates neutrino masses
- Two viable dark matter candidates (fermion singlet & scalar doublet)

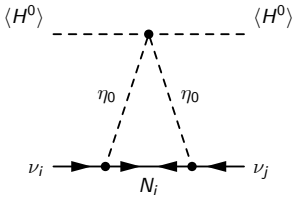

Figure: Neutrino loop in the scotogenic model

Field	Generation	Spin	$U(1)_Y \times SU(2)_L \times SU(3)_c$	$\mathbb{Z}_2$
η	1	0	$(\frac{1}{2}, 2, 1)$	-1
N	3	$\frac{1}{2}$	(0,1,1)	-1
SM particles	-	-	-	$+1$

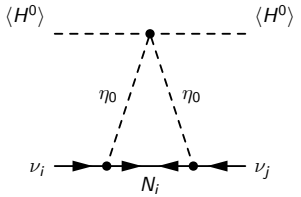

Figure: Neutrino loop

- Part of the Lagrangian

$$\mathcal{L} \supset y_{i\alpha}(\eta^\dagger l_\alpha) N_i + \text{h.c.}$$

$$- \lambda_3 (H^\dagger H)(\eta^\dagger \eta) - \lambda_4 (H^\dagger \eta)(\eta^\dagger H) - \frac{\lambda_5}{2}\left[(H^\dagger \eta)^2 + \text{h.c.}\right]$$

- Neutrino loop can be evaluated

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

- Majorana Neutrino masses violate Lepton number
  $\Rightarrow$ λ_5 naturally small ('t Hooft)

Yukawa couplings

- Casas-Ibarra
  - Invert Neutrino mass formula $y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U^\dagger_{\text{PMNS}}$

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

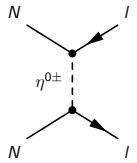

Figure: Main annihilation channel

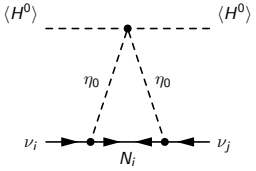

Figure: Neutrino loop in the scotogenic model

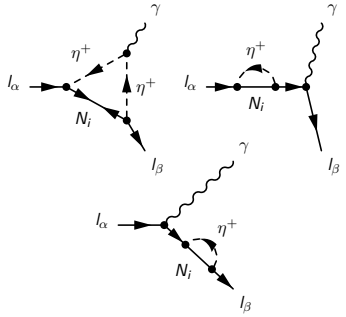

Figure: Diagrams leading to LFV.

Numerical calculation

- Random scan of the parameter space for fermion dark matter
- Casas-Ibarra
  - Invert Neutrino mass formula $y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U^\dagger_{\text{PMNS}}$

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

  - Use Neutrino parameter as input to calculate Yukawa couplings
- SPheno 4.0.3[1]
  - Particle masses
  - Lepton Flavor Violation (LFV) branching ratio
- micrOMEGAs 5.0.8[2]
  - Dark matter relic density
  - Exclude coannihilation

[1] Werner Porod (2003); W. Porod and Staub (2012)
[2] Bélanger et al. (2018)

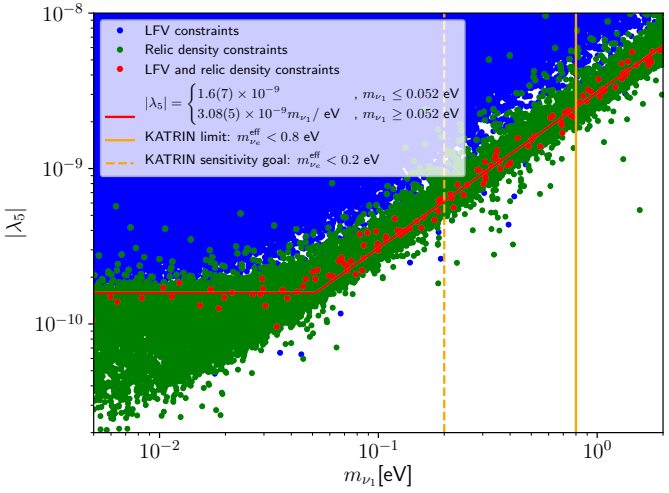

Figure: Normal hierarchy

Degenerate scenario

- Casas Ibarra

$$y \propto \sqrt{\frac{m_\nu}{\lambda_5}} f(m_N, m_\eta)$$

- Relic density

$$\Omega h^2 = 0.12 \pm 0.02$$

$$\Rightarrow \frac{y}{f(m_N, m_\eta)} = \text{const}$$

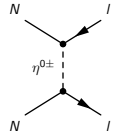

Figure: Main annihilation channel

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

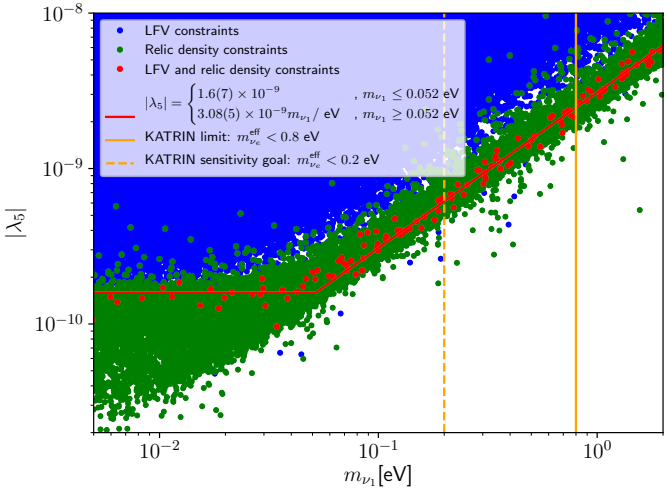

Figure: Normal hierarchy

Hierarchical scenario

- LFV constraints exclude large y i.e. small λ_5

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

Conclusion

- Scotogenic model
  - Scalar doublet and fermion singlet dark matter
  - Neutrino masses at one loop
- Dark matter und Neutrino masses intrisically connected
- Relic density constraint yields a relation between m_ν and λ_5

Thank you for your attention

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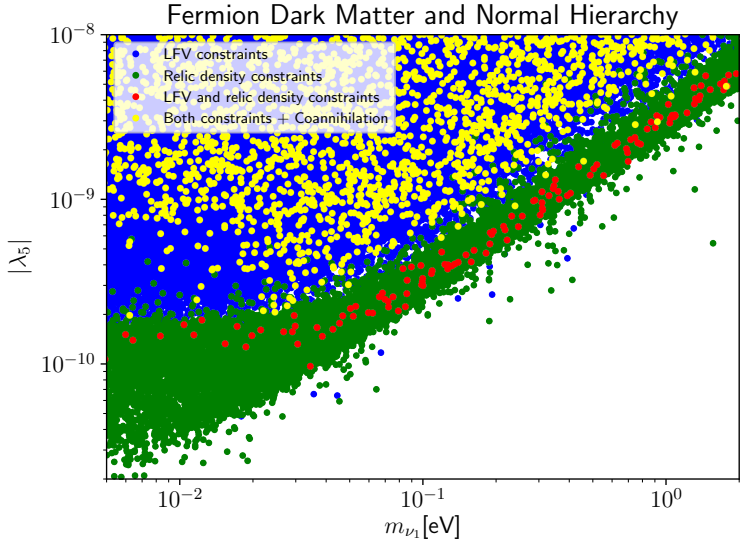
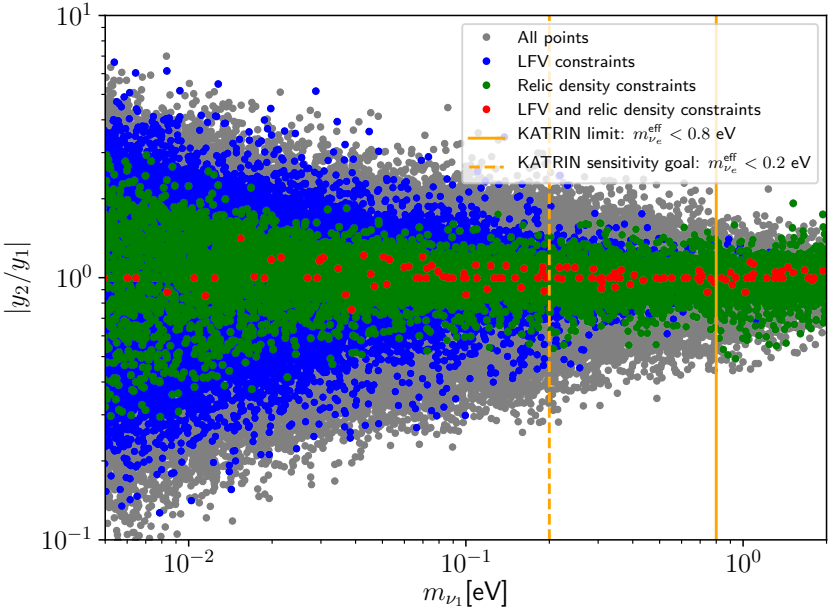
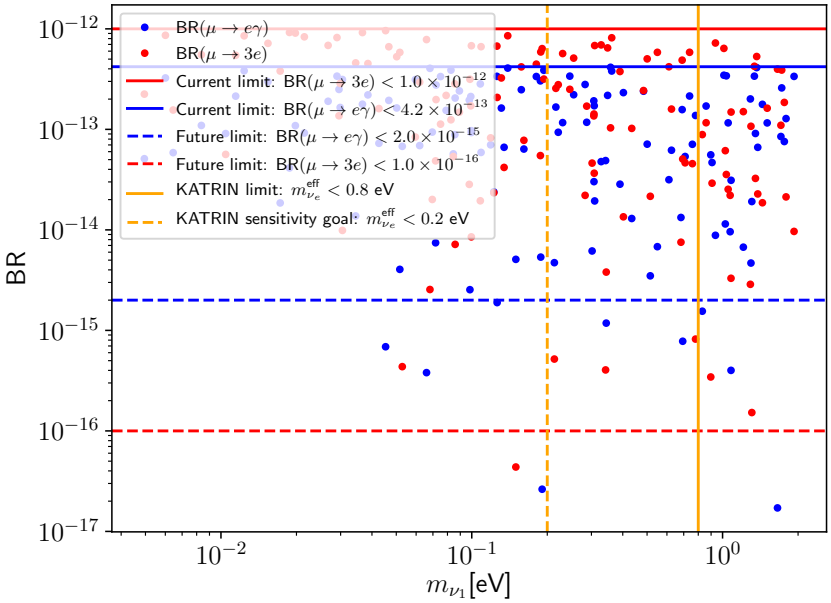
Any Questions?

Backup slides

Coannihilations




All points
LFV constraints
Relic density constraints
LFV and relic density constraints
KATRIN limit: $m^{\text{eff}}_{\nu_e} < 0.8$ eV
KATRIN sensitivity goal: $m^{\text{eff}}_{\nu_e} < 0.2$ eV
$|y_2/y_1|$
m_{ν_1}[eV]
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0


BR($\mu \to e\gamma$)
BR($\mu \to 3e$)
Current limit: BR($\mu \to 3e$) $< 1.0 \times 10^{-12}$
Current limit: BR($\mu \to e\gamma$) $< 4.2 \times 10^{-13}$
Future limit: BR($\mu \to e\gamma$) $< 2.0 \times 10^{-15}$
Future limit: BR($\mu \to 3e$) $< 1.0 \times 10^{-16}$
KATRIN limit: $m^{\text{eff}}_{\nu_e} < 0.8$ eV
KATRIN sensitivity goal: $m^{\text{eff}}_{\nu_e} < 0.2$ eV
BR
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-2}
10^{-1}
10^{0}
m_{ν_1}[eV]