Radiative neutrino masses.

Antonio Enrique Cárcamo Hernández

Departamento de Física, Universidad Técnica Federico Santa María
Centro Científico-Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile
Millennium Institute for Subatomic Physics at the High-Energy Frontier, SAPHIR, Chile

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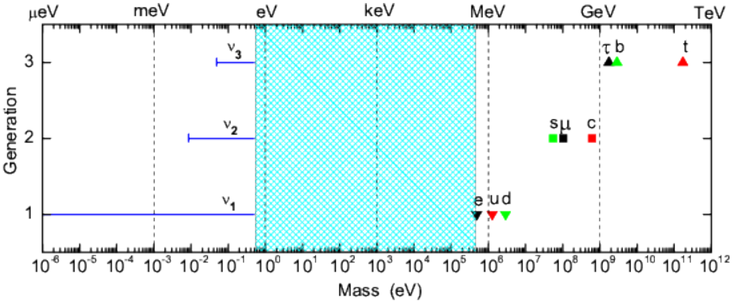
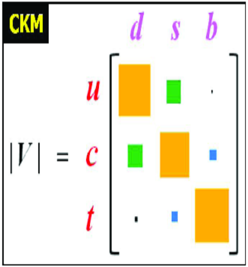
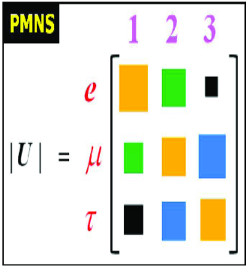
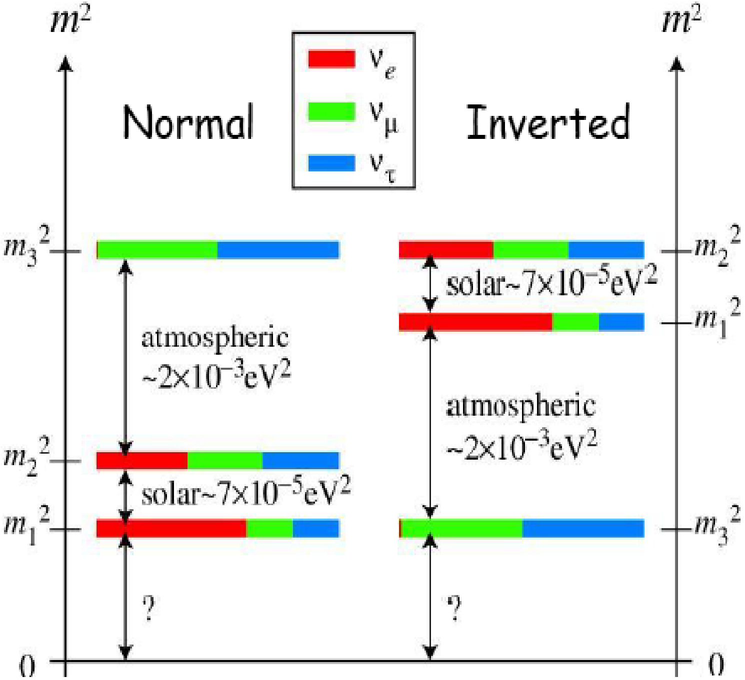
Based on: AECH, C. Hati, S. Kovalenko, J. W. F. Valle and C. A. Vaquera-Araujo, JHEP **03**, 034 (2022)
A. Abada, N. Bernal, AECH, S. Kovalenko, T. B. de Melo and T. Toma, arXiv:2212.06852.

Introduction



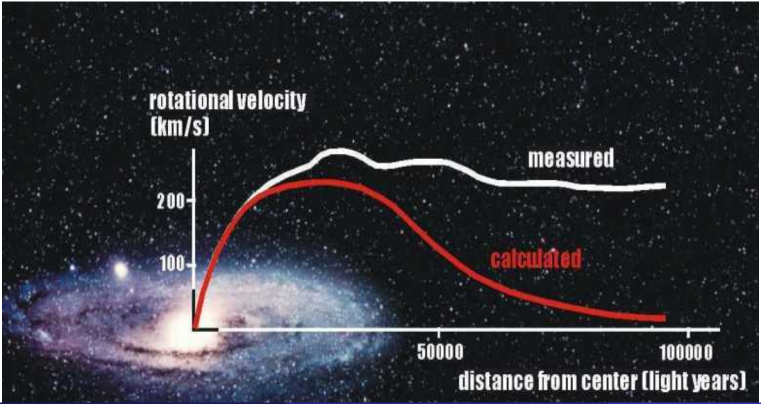




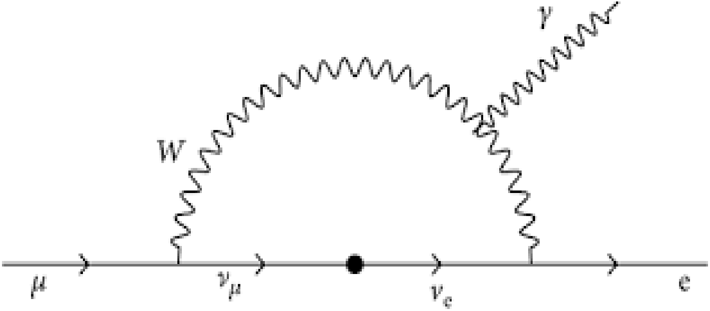


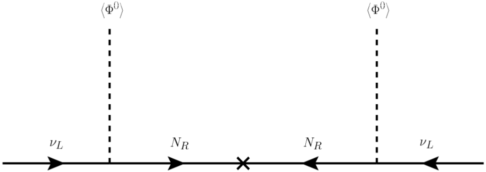
m^2
m^2
ν_e
ν_μ
ν_τ
Normal
Inverted
$m_3{}^2$
$m_2{}^2$
$m_1{}^2$
atmospheric
~2×10^{-3}eV^2
solar~7×10^{-5}eV^2
?
0
$m_2{}^2$
$m_1{}^2$
$m_3{}^2$
solar~7×10^{-5}eV^2
atmospheric
~2×10^{-3}eV^2
?
0


known universe.
observable matter
< 5%
dark energy
~68%
dark matter
~27%
Source: NASA


rotational velocity
(km/s)
measured
200
100
calculated
50000
100000
distance from center (light years)

$$Br_{SM}\left(\mu \to e\gamma\right) \sim \mathcal{O}\left(10^{-54}\right), \; Br_{exp}\left(\mu \to e\gamma\right) < 4.2 \times 10^{-13}$$





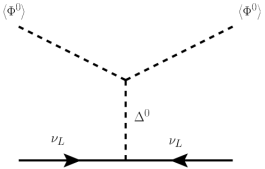
Type I seesaw

$LHN \quad \mathbf{2}\otimes\mathbf{2}\otimes\mathbf{1}$

Minkowski 1977, Gellman, Ramond, Slansky 1980

Glashow, Yanagida 1979, Mohapatra, Senjanovic 1980

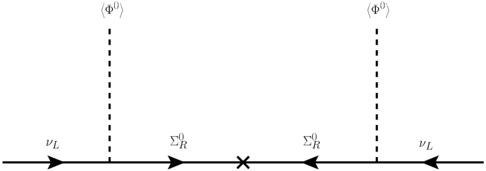
Lazarides Shafi Weterrich 1981, Schechter-Valle 1980 and 1982



Type II seesaw

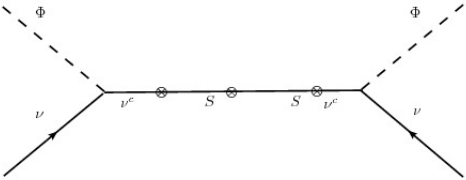
$L\Delta L \quad \mathbf{2}\otimes\mathbf{3}\otimes\mathbf{2}$

Schechter-Valle 1980 and 1982



Type III seesaw

$LH\Sigma \quad \mathbf{2}\otimes\mathbf{2}\otimes\mathbf{3}$



Inverse seesaw

$$-\mathcal{L}_{mass}^{(\nu)} = \frac{1}{2}\left(\overline{\nu_L^C} \quad \overline{N}_R \quad \overline{S}_R \right) \mathbf{M}_\nu \begin{pmatrix} \nu_L \\ N_R^C \\ S_R^C \end{pmatrix} + H.c$$

$$\mathbf{M}_\nu = \begin{pmatrix} 0_{3\times 3} & \mathbf{M}_1 & \mathbf{M_L} \\ \mathbf{M}_1^T & 0_{3\times 3} & \mathbf{M}_2 \\ \mathbf{M_L}^T & \mathbf{M}_2^T & \mu \end{pmatrix}$$

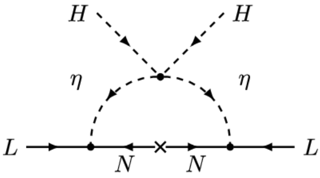
$$\mathbf{M_L} = 0_{3\times 3}$$

$$Q_{\nu_L}^{U(1)_L} = Q_{S_R}^{U(1)_L} = -Q_{N_R}^{U(1)_L} = 1$$

$$\widetilde{\mathbf{M}}_\nu = \mathbf{M}_1 \left(\mathbf{M}_2^T\right)^{-1} \mu \mathbf{M}_2^{-1} \mathbf{M}_1^T$$

$$\mathbf{M}_\nu^{(1)} = -\frac{1}{2}\left(\mathbf{M}_2 + \mathbf{M}_2^T\right) + \frac{1}{2}\mu$$

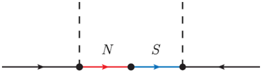
$$\mathbf{M}_\nu^{(2)} = \frac{1}{2}\left(\mathbf{M}_2 + \mathbf{M}_2^T\right) + \frac{1}{2}\mu$$



One loop Ma radiative seesaw model

η and N are odd under a preserved Z_2

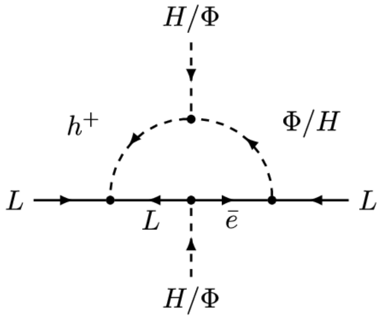
$$L\widetilde{\eta}N, \frac{\lambda_5}{2}\left(H^\dagger \cdot \eta\right)^2 + h.c$$



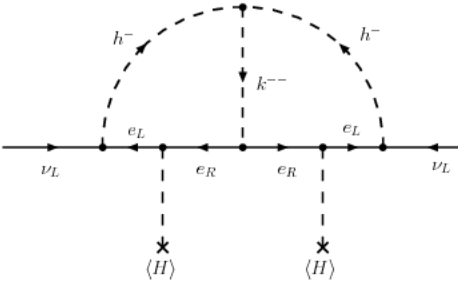
Linear seesaw:

$$\mu = 0_{3\times 3}$$

$$\widetilde{\mathbf{M}}_\nu = -\mathbf{M}_L \mathbf{M}_2^{-1} \mathbf{M}_1^T - \mathbf{M}_1 \left(\mathbf{M}_2^T\right)^{-1} \mathbf{M}_L^T$$

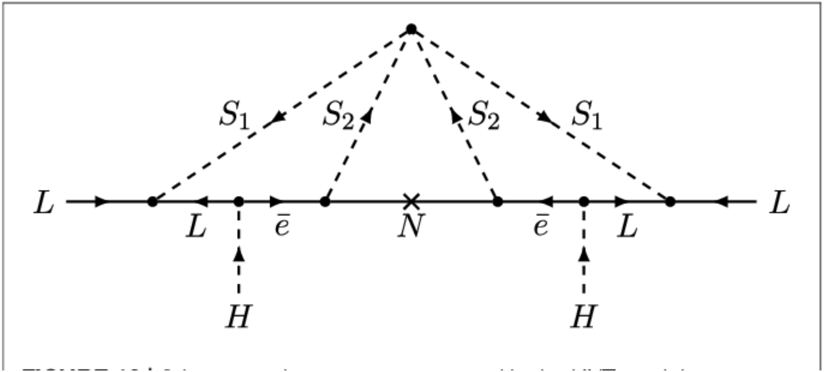


Zee model

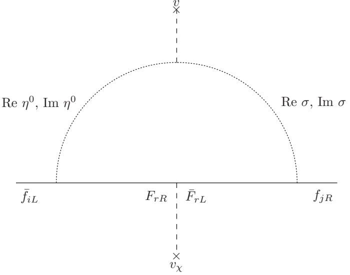


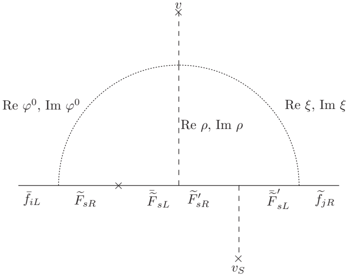
Zee Babu model

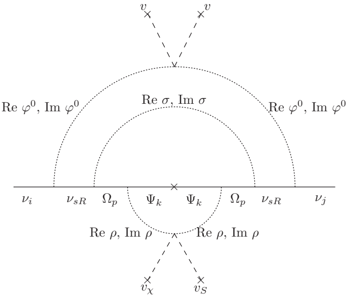
Field	Spin	G_{SM}	Z_2
S_1	0	$(1, 1, -1)$	$+$
S_2	0	$(1, 1, -1)$	$-$
N	$\frac{1}{2}$	$(1, 1, 0)$	$-$



KNT model







$$m_\nu \sim l^3 y^6 \lambda \frac{v^2}{M},$$

$$y \sim 0.3, \lambda \sim 0.1$$

$$M \sim \mathcal{O}\left(13\right) \; TeV$$

$$m_\nu \sim \mathcal{O}\left(0.1\right) \; eV$$

AECH, S. Kovalenko, M. Maniatis and I. Schmidt, "Fermion mass hierarchy and $g-2$ anomalies in an extended 3HDM Model," JHEP **10** (2021), 036

Scotogenic neutrino masses with GCU

Field	$\mathrm{SU}(3)_c$	$\mathrm{SU}(3)_L$	$\mathrm{U}(1)_X$	$\mathrm{U}(1)_N$	Q	$M_P = (-1)^{3(B-L)+2s}$
q_{iL}	$\mathbf{3}$	$\overline{\mathbf{3}}$	0	0	$(-\frac{1}{3}, \frac{2}{3}, -\frac{1}{3})^T$	$(++-)^T$
q_{3L}	$\mathbf{3}$	$\mathbf{3}$	$\frac{1}{3}$	$\frac{2}{3}$	$(\frac{2}{3}, -\frac{1}{3}, \frac{2}{3})^T$	$(++-)^T$
u_{aR}	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	$+$
d_{aR}	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$+$
U_{3R}	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{4}{3}$	$\frac{2}{3}$	$-$
D_{iR}	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$-$
l_{aL}	$\mathbf{1}$	$\mathbf{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$(0, -1, 0)^T$	$(++-)^T$
e_{aR}	$\mathbf{1}$	$\mathbf{1}$	-1	-1	-1	$+$
ν_{iR}	$\mathbf{1}$	$\mathbf{1}$	0	-4	0	$-$
ν_{3R}	$\mathbf{1}$	$\mathbf{1}$	0	5	0	$+$
Ω_{aL}	$\mathbf{1}$	$\mathbf{8}$	0	0	$\begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$	$\begin{pmatrix} - & - & + \\ - & - & + \\ + & + & - \end{pmatrix}$
η	$\mathbf{1}$	$\mathbf{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$(0, -1, 0)^T$	$(++-)^T$
ρ	$\mathbf{1}$	$\mathbf{3}$	$\frac{2}{3}$	$\frac{1}{3}$	$(1, 0, 1)^T$	$(++-)^T$
χ	$\mathbf{1}$	$\mathbf{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$(0, -1, 0)^T$	$(--+)^T$
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	2	0	$+$
σ	$\mathbf{1}$	$\mathbf{1}$	0	1	0	$-$

Table: 3311 model field content ($a = 1, 2, 3$ and $i = 1, 2$ are family indices).

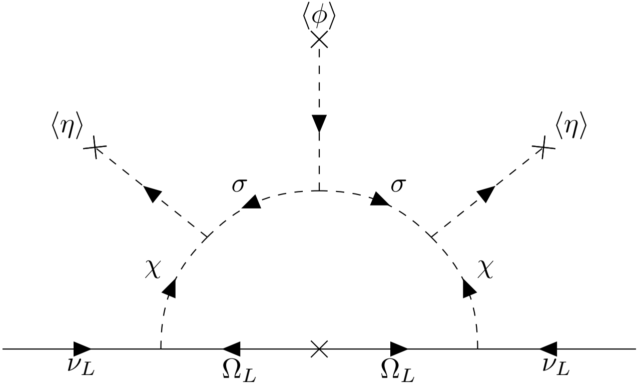


Figure: Feynman-loop diagram contributing to the light active Majorana neutrino mass matrix.

In the limit where the trilinear scalar interactions $\phi^{\dagger}\sigma^{2}$ and $(\eta^{\dagger}\chi)\sigma$ are absent, the model Lagrangian has an accidental $U(1)$ symmetry under which ϕ and σ have the same charge whereas the remaining fields are neutral under this symmetry.

$$Q = T_3 - \frac{T_8}{\sqrt{3}} + X, \qquad B - L = -\frac{2}{\sqrt{3}} T_8 + N, \tag{1}$$

$$q_{iL} = \begin{pmatrix} d_i \\ -u_i \\ D_i \end{pmatrix}_L \qquad q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ U_3 \end{pmatrix}_L \qquad l_{aL} = \begin{pmatrix} \nu_a \\ e_a \\ N_a \end{pmatrix}_L , \tag{2}$$

The gauged $B - L$ symmetry is spontaneously broken leaving a discrete remnant symmetry $M_P = (-1)^{3(B-L)+2s}$.

$$\begin{aligned} \langle \eta \rangle &= \frac{1}{\sqrt{2}} (v_1, 0, 0)^T, \quad \langle \rho \rangle = \frac{1}{\sqrt{2}} (0, v_2, 0)^T, \quad \langle \chi \rangle = (0, 0, w)^T, \\ \langle \phi \rangle &= \frac{1}{\sqrt{2}} \Lambda, \quad \langle \sigma \rangle = 0. \end{aligned} \tag{3}$$

We assume $w, \Lambda, \gg v_1, v_2$, such that the SSB pattern of the model is

$$\begin{gathered} SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)_N \\ \downarrow w, \Lambda \\ SU(3)_C \times SU(2)_L \times U(1)_Y \times M_P \\ \downarrow v_1, v_2 \\ SU(3)_C \times U(1)_Q \times M_P . \end{gathered} \tag{4}$$

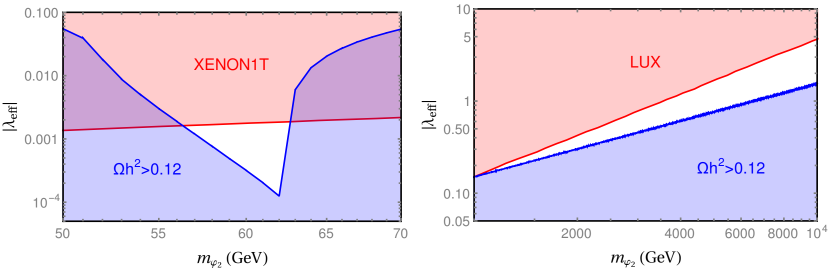


Figure: Viable mass regions where the field φ_2 of the simplified model described in the text behaves as a dark matter candidate. The red regions correspond to the current direct detection limits The blue regions represent values of the effective coupling $\lambda_{\rm eff}$ where the corresponding relic density is incompatible with the Planck measurement.

For the case of fermionic DM candidate, one has:

$$< \sigma v > \approx \left(\frac{\alpha}{150\,\text{GeV}}\right)^2 \left(\frac{M_\Omega}{3\,\text{TeV}}\right)^2 \approx \left(\frac{M_\Omega}{3\,\text{TeV}}\right)^2 \text{pb}, \qquad (5)$$

$$\Omega_{DM} h^2 = \frac{0.1\,\text{pb}}{< \sigma v >}, \qquad (6)$$

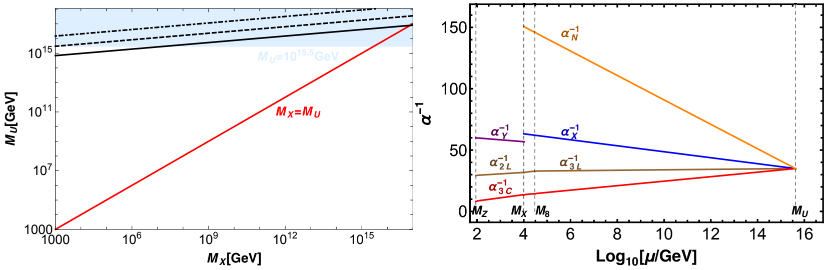


Figure: Left) Unification scale M_U as a function of the 3-3-1-1 symmetry breaking scale M_X, for three benchmark choices $M_8 = M_X$ (solid curve), $M_8 = 3M_X$ (dashed curve) and $M_8 = 10M_X$ (dot-dashed curve). (Right) An example of $\mathrm{SU}(3)_c \times \mathrm{SU}(3)_L \times \mathrm{U}(1)_X \times \mathrm{U}(1)_N$ unification for a phenomenologically accessible 3-3-1-1 symmetry breaking scale $M_X = 10$ TeV and $M_8 = 3M_X = 30$ TeV.

Scotogenic three-loop neutrino mass model

Field	q_{iL}	u_{iR}	d_{iR}	ℓ_{iL}	ℓ_{iR}	N_{R_k}	ϕ	η	φ	ρ	ζ	σ
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
$U(1)'$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-3	-3	0	0	3	3	-1	0	$\frac{1}{2}$
$\mathbb{Z}_2$	1	1	1	1	1	-1	1	-1	-1	-1	-1	1

Table: Particle charge assignments under the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)' \otimes \mathbb{Z}_2$ symmetry. Here $i = 1, 2, 3$ and $k = 1, 2$.

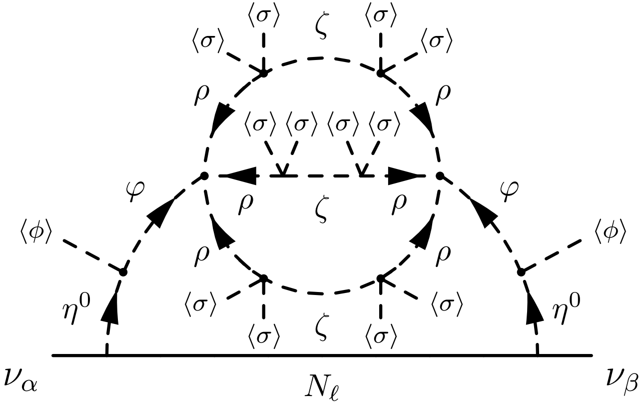


Figure: Scotogenic loop for light active neutrino masses where $\ell = 1, 2$ and $\alpha, \beta = e, \mu, \tau$. The scalar quartic coupling $\left(\phi^{\dagger}\eta\right)^{2}$ arises at two-loop level.

In the limit where the trilinear scalar interaction $A\left[(\eta^{\dagger}\phi)\varphi + \mathrm{H.c.}\right]$ is absent, the model Lagrangian has an accidental $U(1)_X$ symmetry under which the inert $SU(2)_L$ scalar doublet η has charge -1 and the charges of the left and right leptonic fields are equal to 1, while the remaining fields are neutral.

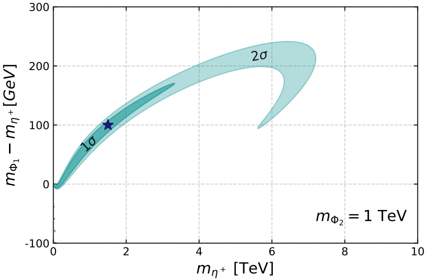


Figure: The 1-σ and 2-σ regions in the $m_{\Phi_1} - m_{\eta^+}$ versus m_{η^+} plane allowed by the fit of the oblique S, T and U parameters including the CDF measurement of the W mass. In the left (right) panel the mass of the neutral scalar Φ_2 is $m_{\Phi_2} = 1$ TeV ($m_{\Phi_2} = 2$ TeV). In both cases, the mixing angle is fixed at $\theta_\Phi = 0.2$.

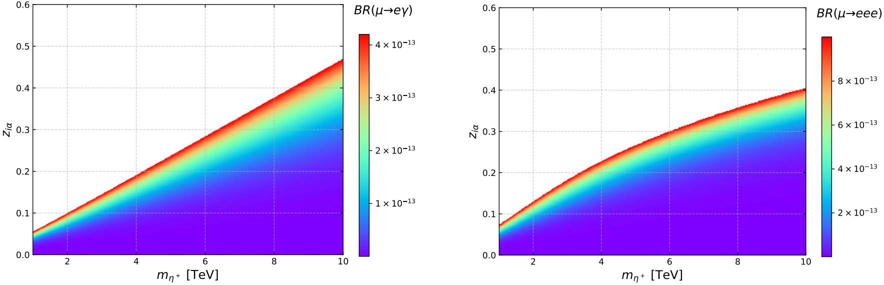
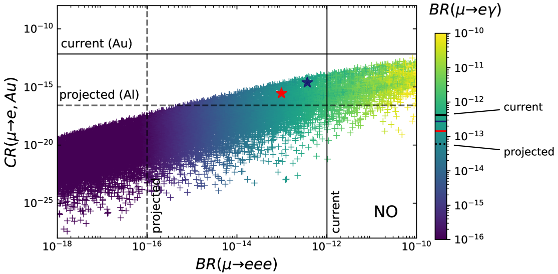
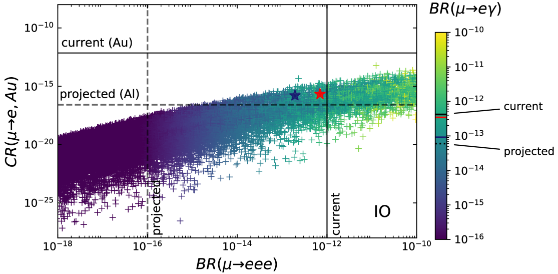


Figure: Parameter space in the $m_{\eta^+} - z_{i\alpha}$ plane consistent with the charged lepton flavor violation limits. The colored regions are allowed by the current constraints.


current (Au)
projected (Al)
projected
current
NO
$BR(\mu\to e\gamma)$
current
projected
$CR(\mu\to e, Au)$
$BR(\mu\to eee)$


current (Au)
projected (Al)
projected
current
IO
$BR(\mu\to e\gamma)$
current
projected
$CR(\mu\to e, Au)$
$BR(\mu\to eee)$

Conclusions

- Dark matter stability can arise from a residual matter-parity symmetry.
- Leptonic $SU(3)_L$ octets allow GCU and one loop scotogenic neutrino generation. DM can also be accounted for.
- Tiny active neutrino masses can be generated at three loop level within a minimal extended IDM.
- The minimal extended IDM acommodates oblique parameter constraints, W mass anomaly and leads to CLFV processes within the reach of the future experimental sensitivity.

Acknowledgements

Thank you very much to all of you for the attention.

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Extra Slides

$$\begin{pmatrix} \eta^0 \\ \varphi \end{pmatrix} = \begin{pmatrix} \cos\theta_\Phi & \sin\theta_\Phi \\ -\sin\theta_\Phi & \cos\theta_\Phi \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}, \tag{7}$$

$$\begin{pmatrix} \rho_R \\ \zeta_R \end{pmatrix} = \begin{pmatrix} \cos\theta_\Xi & \sin\theta_\Xi \\ -\sin\theta_\Xi & \cos\theta_\Xi \end{pmatrix} \begin{pmatrix} \Xi_1 \\ \Xi_2 \end{pmatrix}, \tag{8}$$

$$\begin{pmatrix} \rho_I \\ \zeta_I \end{pmatrix} = \begin{pmatrix} \cos\theta'_\Xi & \sin\theta'_\Xi \\ -\sin\theta'_\Xi & \cos\theta'_\Xi \end{pmatrix} \begin{pmatrix} \Xi_3 \\ \Xi_4 \end{pmatrix}. \tag{9}$$

Parameters	Scanned ranges
θ_R	$[0, 2\pi]$
λ_{14}	$[0.01, 1]$
m_{N_R}, m_{η^+}, $m_{\Phi_{1,2}}$, $m_{\Xi_{1,2,3,4}}$	$[500, 10000]$ GeV

Table: Scanned parameter ranges.

θ_Φ	0.2		0.2	
θ_Ξ	0.3		0.3	
θ'_Ξ	0.1		0.1	
m_{η^+} [GeV]	1500		1700	
m_{Φ_1} [GeV]	1600		1765	
m_{Φ_2} [GeV]	1000		2000	
m_{N_R} [GeV]	8954.5	4246.9	5040.0	3450.7
m_{Ξ_1} [GeV]	8130.4	2925.0	8244.0	3282.9
m_{Ξ_2} [GeV]	1452.5	4748.5	2431.6	1815.4
m_{Ξ_3} [GeV]	8932.4	2763.1	6392.1	3637.6
m_{Ξ_4} [GeV]	7127.2	9336.4	1296.0	1458.4
λ_{14}	0.729	0.726	0.363	0.504
y_η^{e1}	0.124	0.346	-0.009	0.639
y_η^{e2}	-0.253	0.389	0.154	0.152
$y_\eta^{\mu 1}$	0.746	0.220	-0.313	0.031
$y_\eta^{\mu 2}$	-0.307	-0.272	0.312	-0.440
$y_\eta^{\tau 1}$	0.705	-0.335	-0.400	-0.183
$y_\eta^{\tau 2}$	0.207	0.225	0.043	0.475
$\text{BR}(\mu \to e\gamma)$	2.730×10^{-13}	9.170×10^{-14}	1.428×10^{-13}	3.452×10^{-13}
$\text{BR}(\mu \to eee)$	3.686×10^{-13}	1.933×10^{-13}	9.799×10^{-14}	6.997×10^{-13}
$\text{BR}(\mu - e, Au)$	2.392×10^{-15}	1.599×10^{-16}	2.816×10^{-16}	2.122×10^{-16}
m_{ee} [meV]	3.67	48.36	3.67	48.36