Dynamical Scoto-seesaw Mechanism in Gauged B-L model

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- This talk is based on our work:
  - Title: **Dynamical Scoto Seesaw Mechanism in a gauged** $\mathrm{B-L}$ **symmetry**
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Background: Neutrino Physics

- Experiments establish the SM to be the complete theory: Higgs boson is found.
- Still there are issues not addressed in the SM:
  - **Smallness of the neutrino mass**
    New physics is required in order to account for the existence of neutrino masses McDonald,Kajita
  - **Pattern of Neutrino Oscillation: Texture of neutrino mass and mixing**
    The global best fit neutrino oscillation related constraints obtained from the neutrino oscillation experiments with $\pm 1\sigma$:

$$\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}, \sin^2\theta_{23} = 0.537^{+0.016}_{-0.020}, \sin^2\theta_{13} = 0.0022^{+0.00062}_{-0.00063},$$
$$\Delta m^2_{21} = 7.42^{+0.20}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2, \Delta\mathrm{m}^2_{31} = 2.517^{+0.026}_{-0.028} \times 10^{-3}\ \mathrm{eV}^2,$$
$$\delta_{\mathrm{CP}} = 197^{\circ}{}^{+27^{\circ}}_{-24^{\circ}} \qquad .$$

  - **Dark matter candidate**
    weakly interacting massive particle (WIMP) dark matter candidates constitute a paradigm for explaining cold dark matter.
  - Gauge and fermion mass hieararchy problem, not enough CP violation etc

Neutrino Mass generation: Seesaw and Scotogenic

• Neutrino Mass generation Mechanism: Seesaw Mechanism

- Type-I Seesaw
- Type-II Seesaw
- Inverse Seesaw Valle, 1982

• Scotogenic means neutrino mass generation through loops: alternative to Seesaw mechanism.

• A particularly interesting possibility is provided by the so-called scotogenic approach in which WIMP dark matter mediates neutrino mass generation.
Ma 2013, Hirsch 2016

• In the simplest schemes, all neutrino masses arise at the one-loop level, with a common overall scale, modulated only by Yukawa couplings.

• Rather than invoking these paradigms separately, here we suggest a dynamical mechanism to realize naturally the scoto-seesaw scenario. Rojas, Mandal

We plan to do this in a model with gauged $U(1)_{\mathrm{B-L}}$

Earlier Attempts with $U(1)_{\mathrm{B-L}}$

- For the $U(1)_{B-L}$ symmetry to be gauged, it has to be anomaly free. Simplest gauged version cancels the anomalies: adds three lepton singlets $\nu_{iR} \sim -1$.
- A ν_{iR}-mediated (type-I) seesaw mechanism can be realized: Majorana mass generation possible, breaks $B - L$ by two units.
- In standard construction the seesaw-mediating ν_{iR} carry identical charges: all neutrino masses become proportional to a single energy scale, unable to address the observed hierarchy in $\Delta m^2_{sol}/\Delta m^2_{atm}$.
- An alternative anomaly-free $U(1)_{B-L}$ proposal: three neutral fermions with $B - L$ charges

$$(f_{1R}, f_{2R}, N_R) \sim (-4, -4, 5)$$

Montero '07, Ma '14

- Two sets of Leptons with different charges → Two types of interactions → Two different neutrino mass generation mechanism...

Modified gauged $U(1)_{\mathrm{B-L}}$

• Even after spontaneous breaking of $U(1)$ through the VEVs a residual symmetry emerges:

$$M_P = (-1)^{3(B-L)+2s}.$$

• 3 right handed neutrinos are introduced. Leptons along with leptonic dark sector fields with their symmetry transformation properties ($i = 1, 2, 3$ and $a = 1, 2$):

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to M_P$
Leptons	L_{iL}	$(2, -1/2)$	$-1 \to +1$
	e_{iR}	$(1, -1)$	$-1 \to +1$
	N_R	$(1, 0)$	$5 \to +1$
Dark fermion	f_{aR}	$(1, 0)$	$-4 \to -1$

• Fermionic part of the Lagrangian:

$$-\mathcal{L}_Y = Y^H_{ij}\overline{L}_{iL}He_{jR} + Y^\Phi_i\overline{L}_{iL}\tilde{\Phi}N_R + Y^\eta_{ia}\overline{L}_{iL}\tilde{\eta}f_{aR} + \frac{Y^N}{2}\varphi_1^*\overline{(N_R)^c}N_R + \frac{Y^f_a}{2}\varphi_2\overline{(f_{aR})^c}f_{aR} + h.c..$$

Extended Scalar sector

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to M_P$
Scalars	H	$(2, 1/2)$	$0 \to +1$
	Φ	$(2, 1/2)$	$6 \to +1$
	φ_1	$(1, 0)$	$10 \to +1$
	φ_2	$(1, 0)$	$8 \to +1$
	φ_3	$(1, 0)$	$2 \to +1$
Dark Scalars	η	$(2, 1/2)$	$-3 \to -1$
	σ	$(1, 0)$	$9 \to -1$

• For convenience, the most general renormalisable scalar potential is separated in two parts $V = V_1 + V_2$, where

$$V_1 = \sum_{i=1}^{3} \left[\mu_{\mathcal{D}_i}^2 \mathcal{D}_i^\dagger \mathcal{D}_i + \lambda_{\mathcal{D}_i} (\mathcal{D}_i^\dagger \mathcal{D}_i)^2 \right] + \sum_{i,j}^{i<j} \left[\lambda_{\mathcal{D}_i\mathcal{D}_j} (\mathcal{D}_i^\dagger \mathcal{D}_i)(\mathcal{D}_j^\dagger \mathcal{D}_j) + \lambda'_{\mathcal{D}_i\mathcal{D}_j} (\mathcal{D}_i^\dagger \mathcal{D}_j)(\mathcal{D}_j^\dagger \mathcal{D}_i) \right] \quad (1)$$

$$+ \sum_{k=1}^{4} \left[\mu_{\mathcal{S}_k}^2 S_k^\dagger \mathcal{S}_k + \lambda_{\mathcal{S}_k} (\mathcal{S}_k^\dagger \mathcal{S}_k)^2 \right] + \sum_{k,l}^{k<l} \lambda_{\mathcal{S}_k\mathcal{S}_l} (\mathcal{S}_k^\dagger \mathcal{S}_k)(\mathcal{S}_l^\dagger \mathcal{S}_l) + \sum_{i,k} \lambda_{\mathcal{D}_i\mathcal{S}_k} (\mathcal{D}_i^\dagger \mathcal{D}_i)(\mathcal{S}_k^\dagger \mathcal{S}_k)$$

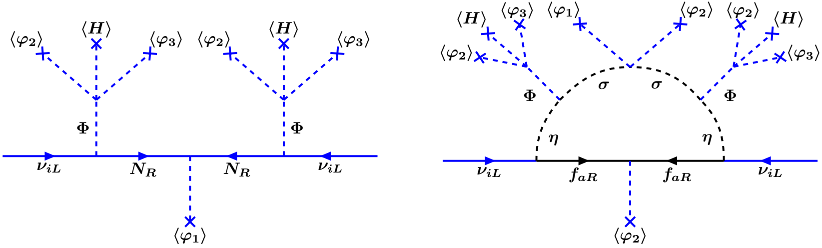
$$-V_2 = \frac{\mu_1}{\sqrt{2}} \Phi^\dagger \eta \sigma + \frac{\mu_2}{\sqrt{2}} \varphi_1^* \varphi_2 \varphi_3 + \lambda_1 \, \varphi_1 \varphi_2 \sigma^{*\,2} + \lambda_2 \Phi^\dagger H \varphi_2 \varphi_3^* + \text{h.c.}\,. \quad (2)$$

Scoto-Seesaw Framework

• With μ_Φ much larger than the other mass scales in the model, the tadpole equation leads to induced VEV

$$v_\Phi \simeq \frac{\lambda_2 v_H v_{\varphi_2} v_{\varphi_3}}{2\mu_\Phi^2} \equiv v_H \epsilon \ll v_H.$$

• Seesaw and scotogenic contributions to neutrino masses:



• The M_P even fields complete the seesaw contribution, whereas the dark sector (M_P-odd) fields complete the scotogenic diagram.

Neutrino Seesaw Scale

- Neutrino Mass Matrix

  • The tree-level contribution, in the basis $(\nu_{iL}, (N_R)^c)$, leads to the following mass matrix

$$M^{\nu,N} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & Y_1^\Phi v_\Phi \\ 0 & 0 & 0 & Y_2^\Phi v_\Phi \\ 0 & 0 & 0 & Y_3^\Phi v_\Phi \\ Y_1^\Phi v_\Phi & Y_2^\Phi v_\Phi & Y_3^\Phi v_\Phi & Y^N v_{\varphi_1} \end{pmatrix}$$

- Solar Neutrino Mass scale

  • Matrix is diagonalized and limiting case is taken: $v_{\varphi_i} \gg v_H \gg v_\Phi$.

  • Here $m_N \simeq v_{\varphi_1} Y^N/\sqrt{2}$ is the mass of N_R with $v_\Phi = v_H \epsilon$ being the small induced VEV.

  • The light neutrino mass matrix has only one non-vanishing eigenvalue

$$\sim -\frac{v_\Phi^2}{m_N} \sum_i (Y_i^\Phi)^2$$

.

Neutrino Scotogenic Scale

• Other two neutrinos get their masses through one loop scotogenic mechanism, with contributions,

$$M_{ij}^{\nu(\mathrm{SC})} = \sum_{c=1}^{2} Y_{ic}^{\eta}\mathcal{M}_c\, Y_{jc}^{\eta}, \qquad \text{with}$$

$$\mathcal{M}_c = \frac{m_{f_c}}{16\pi^2}\Big[\frac{\cos^2\theta_s m_{s_1}^2}{m_{s_1}^2 - m_{f_c}^2}\ln\frac{m_{s_1}^2}{m_{f_c}^2} - \frac{\cos^2\theta_a m_{a_1}^2}{m_{a_1}^2 - m_{f_c}^2}\ln\frac{m_{a_1}^2}{m_{f_c}^2}$$
$$+ \frac{\sin^2\theta_s m_{s_2}^2}{m_{s_2}^2 - m_{f_c}^2}\ln\frac{m_{s_2}^2}{m_{f_c}^2} - \frac{\sin^2\theta_a m_{a_2}^2}{m_{a_2}^2 - m_{f_c}^2}\ln\frac{m_{a_2}^2}{m_{f_c}^2}\Big],$$

where $m_{f_c} = v_{\varphi_2} Y_c^f/\sqrt{2}$ are the dark fermion masses.

• With either $\lambda_1 \to 0$ or $\mu_1 \to 0$, the loop-generated masses vanish.

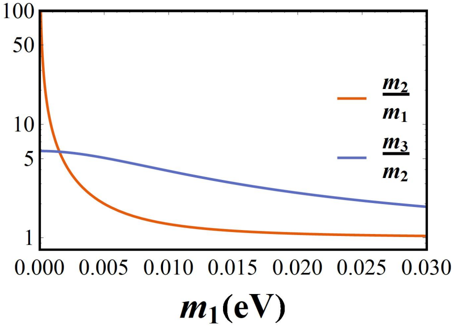
• With $\lambda_1 \to 0$, $m_{s_i} \to m_{a_i}$, with $\cos^2\theta_s \to \cos^2\theta_a$ and $\sin^2\theta_s \to \sin^2\theta_a$, leading to a cancellation between the first and the second, as well as the third and the fourth terms.

• With $\mu_1 \to 0$, $\theta_s, \theta_a \to 0$ so that only the first and the second terms survive; eventually to cancel out as $m_{s_1} \to m_{a_1}$, in this limit.

Neutrino Mass hierarchy: Explained

• Yukawa couplings controlling the cLFV processes are also involved in neutrino mass amd mixing: input benchmarks are chosen satisfying neutrino oscillation data.

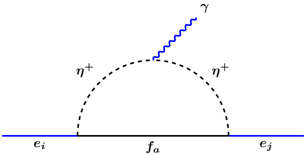
• Neutrino mass hierarchies plotted with varying the lightest neutrino mass, m_1, for normal ordering.

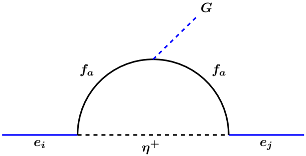


• For the lightest neutrino mass, m_1, the upper limit comes from: a. taking the bound on the sum of the neutrino masses from cosmology: $\Sigma_i m_i < 0.12$ eV coupled with b. the normal ordering assumption.

Charged Lepton Flavor Violation

- Leading contributions to the charged lepton flavour violating (cLFV) decays $e_i \to e_j\gamma$ and $e_i \to e_j G$ ($\mu \to e\gamma/\mu \to eG$)

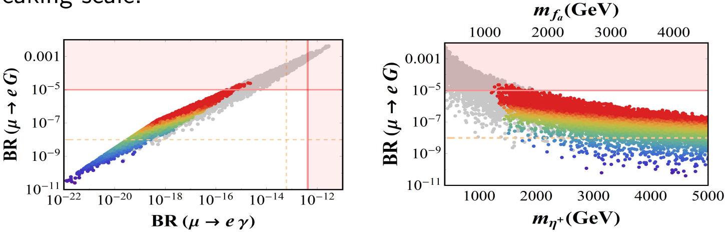




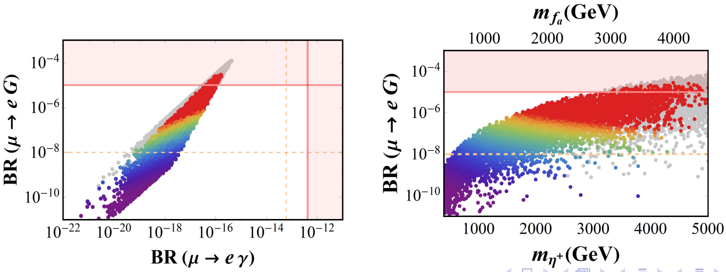
- Experimental cLFV Constraints:
  - $\mu \to e\gamma$: MEG-2 puts strongest constraint on the LFV process $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$. 1510.04284
    Future sensitivity from MEG-2: $\mathrm{BR}(\mu \to e\gamma) < 6 \times 10^{-14}$.
  - $\mu \to eG$: $\mathrm{BR}(\mu \to eG) \lesssim 10^{-5}$ from TWIST experiment.
    $\mathrm{BR}(\mu \to eG) \lesssim 10^{-8}$ from COMET experiment.
  - Other LFV decays like $\tau(\mu) \to 3e$, $\mu \to e$ conversion are possible, but with weaker bounds.

LFV Constraints

- Case-I: the induced VEV v_Φ varies with varying $v_\varphi \equiv v_{\varphi_{1,2,3}}$, which is the $B-L$-breaking scale.



- In case-II, v_Φ is kept constant while the symmetry breaking scale v_φ varies.

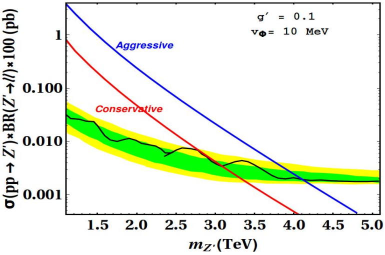


Collider Outlook

• Here both the N and Z' can be in the TeV-scale: better collider prospect than standard scoto-seesaw mechanism with either very heavy N or tiny doublet-singlet $\nu - N$ mixing.

• Presence of the Z': a Drell-Yan pair-production portal for the heavy neutrino (moreover with an enhanced gauge charge here: 5) which decays into potentially verifiable signals.

• In our model, we have many decay modes of $Z' \to S_i A_j$ and $Z' \to S_i Z$, where S_i and A_j are the CP-even and CP-odd scalars,



Dark Matter Prospects

- **Scalar Dark Matter:**

  • The neutral components of the singlet S_σ, A_σ and doublet S_η, A_η mix so as to produce the CP-even (s_1, s_2) and CP-odd (a_1, a_2) DM candidates, respectively.

  • Compared to simplest scoto-seesaw, there are other s-channel resonant and t-channel contributions to scalar DM annihilation here, which can enhance the annihilation cross section, reducing the relic.

- **Fermionic Dark Matter**

  • These dark fermions f_a have a new Z' portal to annihilate which is a contrast to the simplest non-gauged scoto-seesaw model.

  • In contrast to simplest scoto-seesaw, there is a singlet φ_2 here provides mass to the dark Majorana fermions f_a, and can act as a portal of DM annihilation, creating a resonant dip in the relic density.

Summary

• We have proposed a scheme where the scoto-seesaw mechanism has a dynamical origin, associated to a gauged $B - L$ symmetry.

• "Dark" states mediate solar neutrino mass generation radiatively, while the atmospheric scale arises *a la seesaw*;

• Indeed the origin of the solar scale is *scotogenic*, its radiative nature explaining the solar-to-atmospheric scale ratio.

• Dark matter stability follows from the residual matter parity that survives the breaking of $B - L$ gauge symmetry: Rich dark matter phenomenology.

• Apart from the possibility of being tested at colliders, see Fig. **??**, our scoto-seesaw model with gauged $B - L$ has sizeable charged lepton flavour violating phenomena.

Thank You