Emergence of dark symmetry as well as neutrino mass scales from A_4 flavor symmetry

(arXiv:2406.00188)

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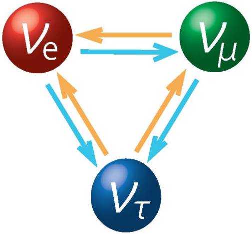
Introduction: Massive Neutrino !!

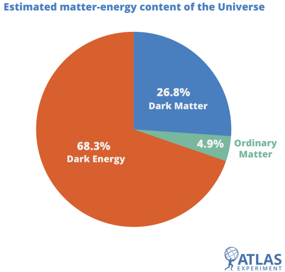
- ✐ Neutrinos are massless in the Standard Model.
- ➡ Neutrino Oscillation $\Longrightarrow$ Neutrinos are massive.
- ➡ Neutrinos tiny mass and mixing are long standing puzzle $\Longrightarrow$ “Leptonic flavor puzzle”.



Non-abelian groups "Flavor symmetries" provide a deeper understanding of this puzzle. $(S_3, A_4, S_4, A_5, \Delta(27), etc.)$
Ma and Rajasekaran, hep-ph/0106291 Babu, Ma, and Valle, hep-ph/0206292
Altarelli and Feruglio, hep-ph/0512103

The Dark Matter ??

- ✐ Discrepancy between observed galaxy rotation curves and the theoretical prediction.
- ➡ The Planck satellite data tells that there is ∼ **26.8** % dark matter (DM).
  Aghanim et al., 10.1051/0004-6361/201833910



The absence of a cosmological DM particle in the SM raises another significant concern.

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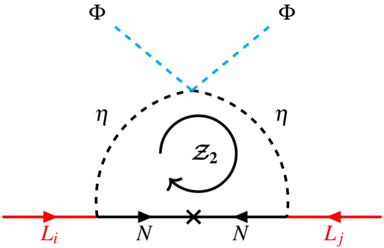
BSM

The Scotogenic Model

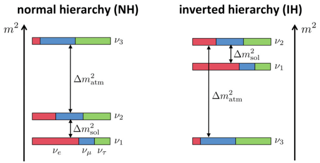
- There are various theoretical models to generate the neutrino mass and explain the DM stability.
- The Scotogenic model proposed by Ma is minimal extension of SM which provides a possible connection between neutrino mass generation and DM stability.
  Ma, hep-ph/0601225

- Two BSM particles scalar η and fermion N are introduced.
- The Z_2 symmetry on top of SM symmetry $\implies$ DM stability.



Neutrino Oscillations: Two mass scales

- ✐ From the neutrino oscillations we infer neutrinos are massive but no information about mass ordering: Normal or Inverted.
- ➡ Till now we only know that there are two mass scales: atmospheric and solar.



The typical neutrino mass models or scotogenic models fail to provide an understanding of these two different mass scales.

Recently, scoto-seesaw mass mechanism has been proposed which explains the two different mass scales observed in neutrino oscillation data while preserving the outcomes of the scotogenic model.

Rojas, Srivastava, and Valle, 10.1016/j.physletb.2018.12.014

A Unified Model ??

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- ➡ Hence, even the most simple and elegant BSM models require the addition of at least a new dark as well as a flavor symmetry, along with the expansion of the BSM particle content, to account for DM and to explain neutrino mass and flavor structure !!

We develop a simple framework with minimal particle content, that can explain the DM stability, neutrino mass generation, and flavor structure of the lepton sector along with the two mass scales of neutrino oscillation experiments using only a single flavor symmetry.

Our Proposal

✌ **We have employed a A_4 flavor symmetry on top of SM symmetry.**

Fields	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	$A_4 \to Z_2$
L_i	(1, 2, -1)	$(1, 1', 1'') \to (+, +, +)$
e_{R_i}	(1, 1, -2)	$(1, 1', 1'') \to (+, +, +)$
Φ	(1, 2, 1)	$1 \to +$
η	(1, 2, 1)	$3 \to (+, -, -)$
N	(1, 1, 0)	$3 \to (+, -, -)$

- The particle content of our model is similar to the scotogenic.
- The BSM particles, scalar η and fermion N are triplet under A_4 while all the SM particles are singlets of A_4.
- We have utilized the fact that Z_2 is a subgroup of A_4 which can serve as a dark symmetry.

Yukawa Lagrangian and Scalar Potential

$$
\begin{aligned}
-\mathcal{L}_y = & \, y_{11}(\overline{L_1})_1\phi(e_{1R})_1 + y_{22}(\overline{L_2})_{1''}\phi(e_{2R})_{1'} + y_{33}(\overline{L_3})_{1'}\phi(e_{2R})_{1''} \\
& + y_1(\overline{L_1})_1(\eta N)_1 + y_2(\overline{L_2})_{1''}(\eta N)_{1'} + y_3(\overline{L_3})_{1'}(\eta N)_{1''} \\
& + M(\overline{N^c}N)_1 + h.c. \, ,
\end{aligned}
$$

$$
\begin{aligned}
V = & \, \mu_\eta^2\eta^\dagger\eta + \mu_\phi^2\phi^\dagger\phi + \lambda_1[\phi^\dagger\phi]_1^2 + \lambda_2[\eta^\dagger\eta]_1^2 + \lambda_3[\eta^\dagger\eta]_{1'}[\eta^\dagger\eta]_{1''} + \lambda_4[\eta^\dagger\eta^\dagger]_{1'}[\eta\eta]_{1''} \\
& + \lambda_{4'}[\eta^\dagger\eta^\dagger]_{1''}[\eta\eta]_{1'} + \lambda_5[\eta^\dagger\eta^\dagger]_1[\eta\eta]_1 + \lambda_6\left([\eta^\dagger\eta]_{3_1}[\eta^\dagger\eta]_{3_1} + h.c.\right) + \lambda_7[\eta^\dagger\eta]_{3_1}[\eta^\dagger\eta]_{3_2} \\
& + \lambda_8[\eta^\dagger\eta^\dagger]_{3_1}[\eta\eta]_{3_2} + \lambda_9[\eta^\dagger\eta]_1[\phi^\dagger\phi] + \lambda_{10}[\eta^\dagger\phi]_{3_1}[\phi^\dagger\eta]_{3_1} + \lambda_{11}\left([\eta^\dagger\eta^\dagger]_1\phi\phi + h.c.\right) \\
& + \lambda_{12}\left([\eta^\dagger\eta^\dagger]_{3_1}[\eta\phi]_{3_1} + h.c.\right) + \lambda_{13}\left([\eta^\dagger\eta^\dagger]_{3_2}[\eta\phi]]_{3_1} + h.c.\right) + \lambda_{14}\left([\eta^\dagger\eta]_{3_1}\eta^\dagger\phi + h.c.\right) \\
& + \lambda_{15}\left([\eta^\dagger\eta]_{3_2}\eta^\dagger\phi + h.c.\right) \, .
\end{aligned}
$$

Scalar Mass Spectrum

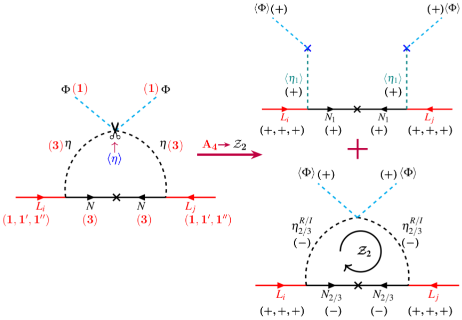
$$
\begin{aligned}
m^2_{H_1,H_2} &= \lambda_1 v_1^2 + \Lambda v_2^2 \mp \sqrt{(\lambda_1 v_1^2 + \Lambda v_2^2)^2 + v_1^2 v_2^2(\alpha^2 - 4\Lambda\lambda_1)}\,, \\
m_A^2 &= -2\lambda_{11}\left(v_1^2 + v_2^2\right), \quad m_G^2 = 0\,, \\
m^2_{H^\pm} &= -(\lambda_{10} + 2\lambda_{11})\left(v_1^2 + v_2^2\right)/2, \quad m^2_{G^\pm} = 0\,, \\
m^2_{\eta_2^R} &= (\kappa_1 v_2^2 - 3\zeta v_1 v_2)/2, \quad m^2_{\eta_2^I} = (\kappa_2 v_2^2 - 4\lambda_{11} v_1^2 - \zeta v_1 v_2)/2\,, \\
m^2_{\eta_3^R} &= m^2_{\eta_2^R} + 3\zeta v_1 v_2, \quad m^2_{\eta_3^I} = m^2_{\eta_2^I} + \zeta v_1 v_2\,, \\
m^2_{\eta_2^\pm} &= (\kappa_3 v_2^2 - (\lambda_{10} + 2\lambda_{11}) v_1^2 - \zeta v_1 v_2)/2, \quad m^2_{\eta_3^\pm} = m^2_{\eta_2^\pm} + \zeta v_1 v_2\,.
\end{aligned}
$$

λ's have perturbativity limit, $\lambda \leq \sqrt{4\pi}$.
It implies scalar masses in this model, $m_S \sim 600$ GeV so as DM mass.

$$
\begin{aligned}
\Lambda &= \lambda_2 + \lambda_3 + 2\lambda_4 + \lambda_5\,, \\
\kappa_1 &= (-3\lambda_3 - 6\lambda_4 + 2\lambda_6 + \lambda_7 + \lambda_8)\,, \\
\kappa_2 &= (-3\lambda_3 - 2\lambda_4 - 4\lambda_5 - 2\lambda_6 + \lambda_7 + \lambda_8)\,, \\
\kappa_3 &= (-3\lambda_3 - 4\lambda_4 - 2\lambda_5 + \lambda_8)\,, \\
\alpha &= \lambda_9 + \lambda_{10} + 2\lambda_{11}, \\
\zeta &= \lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15}\,.
\end{aligned}
$$

$A_4 \to Z_2$ Breaking

- The A_4 symmetry is broken to residual Z_2 symmetry by the VEV of η.
- All the SM particles behave even under Z_2. Since they are singlets of A_4.
- The BSM particles being triplets of A_4 can have odd charges under Z_2 symmetry.



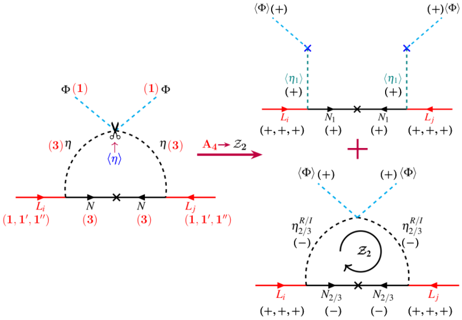
The VEV alignment $\langle\eta\rangle = (v_2, 0, 0)^T$ leads to the $A_4 \to Z_2$ breaking. The triplet components have the following transformation under the residual symmetry

$$
\begin{aligned}
N_1 &\to +N_1\,, & \eta_1 &\to +\eta_1\,,\\
N_{2,3} &\to -N_{2,3}\,, & \eta_{2,3} &\to -\eta_{2,3}\,.
\end{aligned}
$$

Neutrino Mass Generation

Once the η develops VEV the loop breaks into two pieces as shown: tree level seesaw and scoto loop.

- Neutrino mass is generated from this hybrid mass mechanism known as scoto-seesaw mass mechanism.



Neutrino Mass Matrix

At the tree level the seesaw contribution is given by

$$m_D = \begin{pmatrix} y_1 v_2 & 0 & 0 \\ y_2 v_2 & 0 & 0 \\ y_3 v_2 & 0 & 0 \end{pmatrix}, \ \mathcal{M} = \begin{pmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & M \end{pmatrix} \quad \Rightarrow \quad m_\nu^{(1)} = -\frac{1}{M} \begin{pmatrix} y_1^2 v_2^2 & y_1 y_2 v_2^2 & y_1 y_3 v_2^2 \\ * & y_2^2 v_2^2 & y_2 y_3 v_2^2 \\ * & * & y_3^2 v_2^2 \end{pmatrix}$$

- Rank of matrix $m_\nu^{(1)}$ is 1 $\Rightarrow$ **only one neutrino is massive at tree level.**
- Remaining two neutrinos masses can be generated at one loop level given by $m_\nu^{(2)}$

$$m_\nu^{(2)} = \begin{pmatrix} y_1^2 d_1 & y_1 y_2 d_2 & y_1 y_3 d_3 \\ * & y_2^2 d_3 & y_2 y_3 d_1 \\ * & * & y_3^2 d_2 \end{pmatrix}$$

Neutrino Mass Matrix

Combining the tree level and loop level mass matrices the final form of neutrino mass matrix is given by

$$m_\nu^{(TOT)} = \begin{pmatrix} A & C & \tilde{C}^* \\ C & B & D \\ \tilde{C}^* & D & \tilde{B}^* \end{pmatrix}$$

➡ The neutrino mass matrix $m_\nu^{(TOT)}$ features the generalized $\mu - \tau$ reflection symmetry.

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$$m_\nu^{(TOT)} = \begin{pmatrix} A & C & \tilde{C}^* \\ C & B & D \\ \tilde{C}^* & D & \tilde{B}^* \end{pmatrix} \qquad \boxed{M_\nu^{(\mu-\tau)} = \begin{pmatrix} A & C & C^* \\ C & B & D \\ C^* & D & B^* \end{pmatrix}}$$

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Cont...

$$A = y_1^2 \left(d_1 - \frac{v_2^2}{2M} \right), \qquad D = y_2 y_3 \left(d_1 - \frac{v_2^2}{2M} \right),$$
$$B = y_2^2 \left(d_3 - \frac{v_2^2}{2M} \right), \qquad \tilde{B} = y_3^2 \left(d_2 - \frac{v_2^2}{2M} \right),$$
$$C = y_1 y_2 \left(d_2 - \frac{v_2^2}{2M} \right), \quad \tilde{C} = y_1 y_3 \left(d_3 - \frac{v_2^2}{2M} \right).$$

$$d_1 = c_1 + c_2 + c_3, \quad d_2 = c_1 + \omega c_2 + \omega^2 c_3, \quad d_3 = c_1 + \omega^2 c_2 + \omega c_3.$$

In the $y_2 = y_3$ limit it produce the exact $\mu - \tau$ reflection symmetry which predicts, $\theta_{23} = 45^\circ$ and $\delta_{\rm CP} = \pm\pi/2$.

Nu Sector: Generalized $\mu - \tau$ reflection symmetry

- Our model aligns with normal ordering of neutrino masses.
- The generalized $\mu - \tau$ reflection symmetry shown by blue and green color.
- The octant of the mixing angle θ_{23}

$$y_2 \leq y_3 \implies \theta_{23} \leq 45^\circ$$
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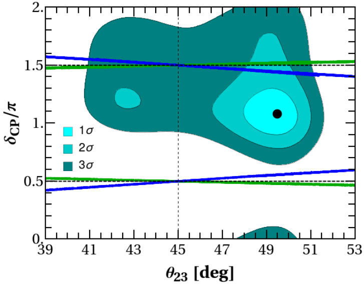
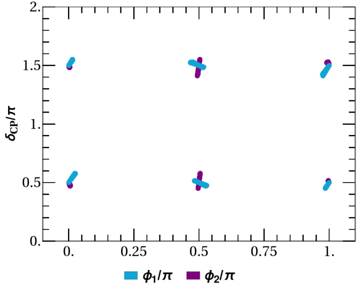
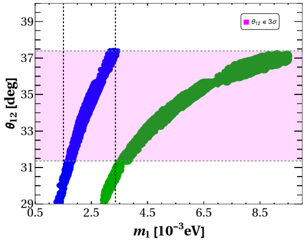
- Majorana phases are also correlated in our model with the Dirac CP phase.

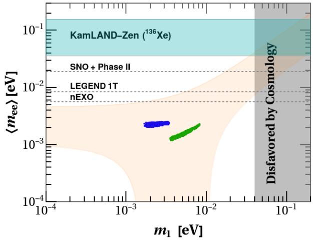




Nu sector: Lightest Neutrino Mass and $0\nu ee$ Decay

- The m_1 has a lower limit in our model while concerning the mixing angle θ_{12} values in its 3σ value.
- The $0\nu ee$ decay is a robust way of searching for lepton number violation and Majorana nature of neutrinos.
- This narrow region of $\langle m_{ee} \rangle$ is due to the constraint value of neutrino masses and the Majorana phases.

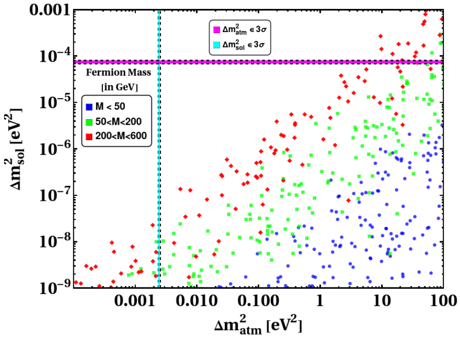




$$|m_{ee}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{2i\phi_{12}} m_2 + s_{13}^2 e^{2i\phi_{13}} m_3|$$

Dark Sector: Fermionic DM ×

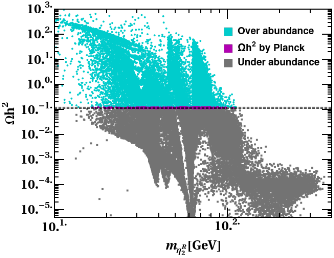
- In our analysis we have found that the fermionic DM case is not allowed if we consider the 3σ allowed ranges for the two mass squared differences of the neutrino oscillations.

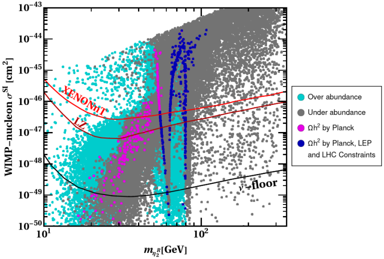


➡ Here, we can infer that both the mass squared differences observed in neutrino oscillations can not be fit together.

Dark Sector: Scalar DM ✓

The model prediction for scalar DM





- The magenta points which lie below the LZ line are allowed points and the range is from 20 GeV to 80 GeV.
- Imposing the collider constraints from LEP and LHC will further constraint this allowed mass region of DM candidate in $55\,\text{GeV} \leq m_{\eta_2^R} \leq 80\,\text{GeV}$.

Final Remarks

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✌ **In summary, our explicit model is highly predictive with its predictions testable in various neutrino sectors as well as dark matter experiments.**

Thank you for your attention !!

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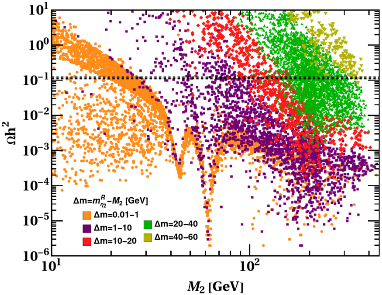
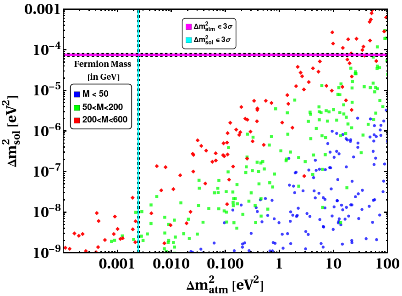
Back Up (Fermionic DM)





Back Up (Loop Mass)

$$(\mathcal{M}_\nu)_{ij} = \frac{Y_{ik}Y_{jk}}{32\pi^2}M_k\left[\frac{(m^R_{\eta_l})^2}{(m^R_{\eta_l})^2 - M_k^2}\ln\left(\frac{m^R_{\eta_l}}{M_k}\right)^2 - \frac{(m^I_{\eta_l})^2}{(m^I_{\eta_l})^2 - M_k^2}\ln\left(\frac{m^I_{\eta_l}}{M_k}\right)^2\right] .$$

Because of A_4 symmetry in our model, we have $l = k$. We express the mass matrix as

$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} Y_{ik}Y_{jk}c_k ,$$

where, Y_{ik} and Y_{jk} are Yukawa couplings at one-loop level, and

$$c_k = \frac{M_k}{32\pi^2}\left[\frac{(m^R_{\eta_k})^2}{(m^R_{\eta_k})^2 - M_k^2}\ln\left(\frac{m^R_{\eta_k}}{M_k}\right)^2 - \frac{(m^I_{\eta_k})^2}{(m^I_{\eta_k})^2 - M_k^2}\ln\left(\frac{m^I_{\eta_k}}{M_k}\right)^2\right] .$$

$$d_1 = c_1 + c_2 + c_3, \quad d_2 = c_1 + \omega c_2 + \omega^2 c_3, \quad d_3 = c_1 + \omega^2 c_2 + \omega c_3.$$

$$A = y_1^2\left(d_1 - \frac{v_2^2}{2M}\right), \qquad D = y_2 y_3\left(d_1 - \frac{v_2^2}{2M}\right),$$

$$B = y_2^2\left(d_3 - \frac{v_2^2}{2M}\right), \qquad \tilde{B} = y_3^2\left(d_2 - \frac{v_2^2}{2M}\right),$$

$$C = y_1 y_2\left(d_2 - \frac{v_2^2}{2M}\right), \quad \tilde{C} = y_1 y_3\left(d_3 - \frac{v_2^2}{2M}\right).$$

Back Up (A_4 generators and Z_2 subgroup)

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} ; \quad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} ;$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} a_1 \\ -a_2 \\ -a_3 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \\ 0 \end{pmatrix}$$