Neutrinos and Dark Matter

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Outline

BSM physics and Neutrino Mass

Neutrinos in the SM

In the SM neutrinos are massless

- Minimal field content: No right-handed neutrinos (SM Singlets)
- Only renormalizable interactions
- Accidental Lepton number L conservation.

Neutrino solar problem

- Deficit of solar neutrinos reaching the earth (only detected approx. $1/3$ of the expected)
- Solution: Neutrinos Oscillate
- $\Rightarrow$ Neutrinos are Massive

Neutrino Oscillations

Two Inequivalent bases: Mass vs Flavor

$$\nu_\ell = U_{\ell j}\nu_j, \qquad \ell = e, \mu, \tau, \qquad j = 1, 2, 3, \ldots$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & e^{i\frac{\phi_3}{2}} \end{pmatrix}$$

with $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E}) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$.

Current Status: De Salas et al. 2006.11237 [hep-ph]

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21} [10^{-5}$eV$^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert [10^{-3}eV^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert [10^{-3}eV^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

Two possible scenarios:

- Normal Ordering: $m_1 < m_2 < m_3$
- Inverted Ordering: $m_3 < m_1 < m_2$

Two possible choices for the neutrino nature:

- Dirac: $m\overline{\nu}_L \nu_R + \mathrm{h.c.}$
- Majorana: $\frac{m}{2}\overline{\nu}_L \nu_L^c + \mathrm{h.c.}$

Neutrino Mass Generation Mechanisms

Neutrinos in the SM

Field	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$
Q_{iL}	**3**	**2**	$1/6$
u_{iR}	**3**	**1**	$2/3$
d_{iR}	**3**	**1**	$-1/3$
L_{iL}	**1**	**2**	$-1/2$
e_{iR}	**1**	**1**	-1
H	**1**	**2**	$1/2$

$$Q_{iL} = \begin{pmatrix} u \\ d \end{pmatrix}_{iL}, \quad L_{iL} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{iL}, \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad i = 1, 2, 3.$$

$D = 5$ Weinberg Operator

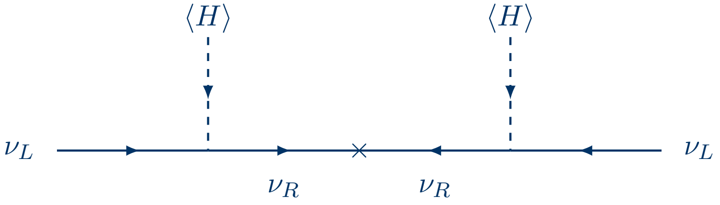
$$\mathcal{L} \supset -\frac{y^\nu}{\Lambda}(\overline{L}_L \widetilde{H})(\widetilde{H}^T L_L^c) + \text{h.c.} \to -\frac{m_\nu}{2}\overline{\nu}_L \nu_L^c + \text{h.c.}$$

- Simplest option and unique for $D = 5$
- No new fields needed beyond the SM content
- Majorana neutrino
- Effective theory: Non renormalizable

Seesaw (type I) Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Mohapatra, Senjanovic, Schechter, Valle

SM + ν_{iR}: two new mass terms

$$\mathcal{L} \supset -y^{\nu} \overline{L}_L \widetilde{H} \nu_R - \frac{M}{2} \overline{\nu}_R \nu_R^c + \text{h.c.} \to -\frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$



- Majorana Neutrinos
- If $M \gg m$, naturally light active neutrinos: $m_{\text{light}} \sim -mM^{-1}m^T$, and heavy molstly right-handed states $m_{\text{heavy}} \sim M$

Scotogenic model (Ma, 0601225[hep-ph])

Two BSM ingredients:

- Inert scalar isodoublet $\eta \sim (\mathbf{1}, \mathbf{2}, 1/2)$
- Singlet fermions $S_{iR} \sim (\mathbf{1}, \mathbf{1}, 0)$

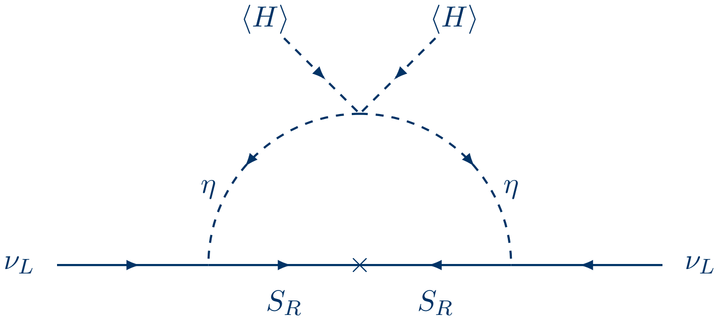
Extra global symmetry $\mathbb{Z}_2$: $\eta \to -\eta$, $S_R \to -S_R$.

Relevant terms

$$\mathcal{L} \supset -h\overline{L}_L\widetilde{\eta}S_R - \frac{M}{2}\overline{S}_R S_R^c + \text{h.c.} \qquad V(H,\eta) \supset \frac{\lambda_5}{2}(H^\dagger \eta)^2 + \text{h.c.}$$

- No tree level neutrino mass term

Radiative mechanism



$$m_{ij}^{\text{light}} = \sum_k \frac{h_{ik}h_{jk}m_{S_k}}{32\pi^2}\left[\frac{m_R^2}{m_R^2 - m_{S_k}^2}\log\left(\frac{m_R^2}{m_{S_k}^2}\right) - \frac{m_I^2}{m_I^2 - m_{S_k}^2}\log\left(\frac{m_I^2}{m_{S_k}^2}\right)\right].$$

Scotogenic model features

- Majorana neutrinos
- Naturally small masses through loop suppression
- Low scale mediators
- WIMP Dark Matter candidate: lightest electrically neutral $\mathbb{Z}_2$-odd state
- Ad hoc stabilizing global symmetry $\mathbb{Z}_2$.

New Ideas on Neutrino Masses and DM candidates

- $B - L$ Scotogenic Dirac Neutrinos
- $3 - 3 - 1 - 1$ Models
- Extra-dimensional Models

$B - L$ Scotogenic Dirac Neutrinos

J. Leite, América Morales, J.W.F. Valle, CAV-A 2003.02950 [hep-ph]

- Extended Gauge Symmetry $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$
- Unbroken $B - L$ symmetry stabilizing DM
- Dirac Neutrinos
- Massive Z' by Stueckelberg mecanism

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	$\mathbb{Z}_2$
ν_{iR}	1	1	0	–1	–
S_{iL}	1	1	0	2n	+
S_{iR}	1	1	0	2n	+
η	1	2	1/2	2n+1	+
σ	1	1	0	2n+1	–

- $n(\neq 0) \in \mathbb{Z}$
- $U(1)_{B-L}$ promoted to gauge symmetry through the inclusion of three left-handed neutrinos with $B - L = -1$
- Auxiliary discrete $\mathbb{Z}_2$ that forbids tree level Dirac masses is softly broken by the trilinear term in the scalar potential $\frac{\mu_3}{\sqrt{2}}(\eta^\dagger H\sigma + h.c.)$.

Stueckelberg Mechanism

$$\mathcal{L}_{\rm kin}^{\rm St} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2}(M_{Z'} Z'^{\mu} - \partial^{\mu} A)^2,$$

is invariant under the $U(1)_{B-L}$ gauge transformations

$$Z'^{\mu} \to Z'^{\mu} + \partial^{\mu}\Lambda,$$
$$A \to A + M_{Z'}\Lambda,$$

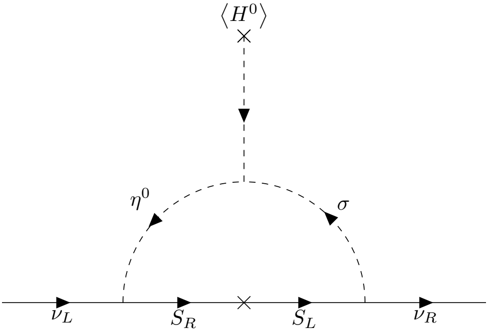
where A is a scalar Stueckelberg compensator and $Z'^{\mu\nu} = \partial^{\mu} Z'^{\nu} - \partial^{\nu} Z'^{\mu}$. Upon gauge-fixing

$$\mathcal{L}_{\rm fg}^{\rm St} = -\frac{1}{2\xi}(\partial_{\mu} Z'^{\mu} + M_{Z'}\xi A)^2,$$

the Z' boson acquires mass $M_{Z'}$ and the compensator A decouples:

$$\mathcal{L}_{\rm kin}^{\rm St} + \mathcal{L}_{\rm fg}^{\rm St} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'^{\mu} Z'_{\mu} - \frac{1}{2\xi}(\partial_{\mu} Z'^{\mu})^2 + \frac{1}{2}\partial^{\mu} A \partial_{\mu} A - \frac{1}{2} M_{Z'}^2 \xi A^2.$$

Neutrino masses



$$(m_\nu)_{ij} = \frac{\sin(2\theta)}{32\pi^2} \sum_k y^\nu_{ik} h_{kj} m_{S_k} \left[\frac{m^2_{\varphi_1}}{m^2_{\varphi_1} - m^2_{S_k}} \ln \frac{m^2_{\varphi_1}}{m^2_{S_k}} - \frac{m^2_{\varphi_2}}{m^2_{\varphi_2} - m^2_{S_k}} \ln \frac{m^2_{\varphi_2}}{m^2_{S_k}} \right].$$

$3-3-1-1$ Models

S.K. Kang, O. Popov, R. Srivastava, J.W.F. Valle, CAV-A 1902.05966 [hep-ph]

- Extended Gauge Symmetry $SU(3)_c \times SU(3)_W \times U(1)_X \times U(1)_N$
- First scotogenic model in this framework
- Majorana neutrinos
- DM stabilized by Matter Parity in a non-supersymmetric context

$3-3-1$ Models

Gauge symmetry

$$SU(3)_c \otimes SU(3)_W \otimes U(1)_X$$

One additional diagonal generator

$$T_8 = \frac{\lambda_8}{2} = \frac{1}{2\sqrt{3}}\mathrm{diag}(1,1,-2)$$

$\Rightarrow$ Different models based on Hypercharge embedding

$$Y = \beta T_8 + X$$

Basic Fields (arbitrary β)

$$\psi_{aL} \equiv \begin{pmatrix} \nu_{aL} \\ \ell_{aL} \\ k_{aL} \end{pmatrix} \sim \mathbf{3}, \quad Q_{3L} \equiv \begin{pmatrix} u_{3L} \\ d_{3L} \\ j_{3L} \end{pmatrix} \sim \mathbf{3}, \quad Q_{\alpha L} \equiv \begin{pmatrix} d_{\alpha L} \\ -u_{\alpha L} \\ j_{\alpha L} \end{pmatrix} \sim \overline{\mathbf{3}},$$
$$\nu_{aR},\ \ell_{aR},\ k_{aR},\ u_{aR},\ d_{aR},\ j_{aR} \sim \mathbf{1}, \qquad a = 1, 2, 3, \qquad \alpha = 1, 2.$$

- Left handed leptons go into triplets of $SU(3)_L$
- Two families of left-handed quarks go into anti-triplets
- To cancel gauge anomalies, the third family of left handed quarks transform as a triplet.
- One can exchange triplets for anti-triplets and visceversa to obtain an almost equivalent model.

Original SVS (Singer-Valle-Schechter) model

Field	331 rep	Components	Lepton number ?
ψ_{aL}	$\left(\mathbf{1},\mathbf{3},-\frac{1}{3}\right)$	$\left(\left(\nu_{aL},\ell_{aL}\right),\nu^c_{aR}\right)^T$	$\left(1,1,-1\right)^T$
ℓ_{aR}	$\left(\mathbf{1},\mathbf{1},-1\right)$	ℓ_{aR}	1
$Q_{\alpha L}$	$\left(\mathbf{3},\overline{\mathbf{3}},0\right)$	$\left(\left(d_\alpha,-u_\alpha\right),D_\alpha\right)^T$	$\left(0,0,2\right)^T$
Q_{3L}	$\left(\mathbf{3},\mathbf{3},\frac{1}{3}\right)$	$\left(\left(t_L,b_L\right),U_{3L}\right)^T$	$\left(0,0,-2\right)^T$
$u_{aR}\,,U_{3R}$	$\left(\mathbf{3},\mathbf{1},\frac{2}{3}\right)$	$u_{aR}\,,U_{3R}$	0
$d_{aR}\,,D_{\alpha R}$	$\left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$	$d_{aR}\,,D_{\alpha R}$	0
ϕ_1	$\left(\mathbf{1},\mathbf{3},\frac{2}{3}\right)$	$\left(\left(\phi_1^+,\phi_1^0\right),\widetilde{\phi}_1^+\right)^T$	$\left(0,0,-2\right)^T$
$\phi_{i=2,3}$	$\left(\mathbf{1},\mathbf{3},-\frac{1}{3}\right)$	$\left(\left(\phi_i^0,\phi_i^-\right),\widetilde{\phi}_i^0\right)^T$	$\left(0,0,-2\right)^T$

VEV alignment

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ u \\ 0 \end{pmatrix}, \quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u' \\ 0 \\ 0 \end{pmatrix}, \quad \langle\phi_3\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ w \end{pmatrix}$$

SSB pattern

- $w \gg u, u'$:

$$\begin{array}{c} SU(3)_c \otimes SU(3)_L \otimes U(1)_X \\ \downarrow w \\ SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \\ \downarrow u, u' \\ SU(3)_c \otimes U(1)_Q \end{array}$$

- This minimal SVS model is not viable, as it cannot accommodate the current neutrino oscillation data (Fonseca, Hirsch, 2017).
- Here L is a combination of T_8 and a global $U(1)$ symmetry generated by $\mathcal{L}$ (Tully, Joshi 2001):

$$L = \frac{2}{\sqrt{3}} T_8 + \mathcal{L}, \qquad \text{(SVS)}.$$

  Is it this symmetry consistent?

There is a class of models based on 3-3-1 where Lepton number is consistently defined: Those with gauged $\mathcal{L}$ (Dong,Tham,Huong, 2013), known as 3-3-1-1 models.

Scotogenic 3311(Kang, Popov, Srivastava, Valle, V-A, 2019)

Field	SU(3)$_c$	SU(3)$_L$	U(1)$_X$	U(1)$_N$	$M_P = (-1)^{3(B-L)+2s}$
q_{iL}	**3**	$\bar{\mathbf{3}}$	0	0	$(++-)^T$
q_{3L}	**3**	**3**	$1/3$	$2/3$	$(++-)^T$
u_{aR}	**3**	**1**	$2/3$	$1/3$	$+$
d_{aR}	**3**	**1**	$-1/3$	$1/3$	$+$
U_{3R}	**3**	**1**	$2/3$	$4/3$	$-$
D_{iR}	**3**	**1**	$-1/3$	$-2/3$	$-$
l_{aL}	**1**	**3**	$-1/3$	$-2/3$	$(++-)^T$
e_{aR}	**1**	**1**	-1	-1	$+$
ν_{iR}	**1**	**1**	0	-4	$-$
ν_{3R}	**1**	**1**	0	5	$+$
$F_{aL,R}$	**1**	**3**	$-1/3$	$-1/3$	$(--+)$

Field	SU(3)$_c$	SU(3)$_L$	U(1)$_X$	U(1)$_N$	$M_P = (-1)^{3(B-L)+2s}$
η	**1**	**3**	$-1/3$	$1/3$	$(++-)^T$
ρ	**1**	**3**	$2/3$	$1/3$	$(++-)^T$
χ	**1**	**3**	$-1/3$	$-2/3$	$(--+)^T$
ϕ	**1**	**1**	0	2	$+$
S	**1**	**1**	0	$2/3$	$+$
σ	**1**	**1**	0	$1/3$	$-$
Ω	**1**	**6**	$2/3$	$2/3$	$\begin{pmatrix} + & + & - \\ + & + & - \\ - & - & + \end{pmatrix}$

Yukawa Interactions

$$\mathcal{L}^{\text{Yuk}} \supset \bar{l}^{i}_{aL} Y_e^{ab} e_{bR} \rho_i + \overline{F}^{i}_{aR} Y_1^{ab} l_{ibL} \sigma + \overline{F}_{aL} m_F^{ab} F_{bR} + F_{iaL,R} Y_{2L,R}^{ab} F_{jbL,R} \Omega^{ij} + \text{h.c.},$$

VEV alignment

$$\langle \eta \rangle = \frac{1}{\sqrt{2}}(v_1, 0, 0)^T, \quad \langle \rho \rangle = \frac{1}{\sqrt{2}}(0, v_2, 0)^T, \quad \langle \chi \rangle = (0, 0, w)^T, \quad \langle \phi \rangle = \frac{1}{\sqrt{2}}\Lambda,$$

$$\langle S \rangle = v_s, \quad \langle \sigma \rangle = 0, \quad \langle \Omega \rangle = \begin{pmatrix} w_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & w_2 \end{pmatrix}.$$

Spontaneous symmetry breaking pattern

$$
\begin{gathered}
SU(3)_C \times SU(3)_L \times U(1)_X \times U(1)_N \\
\downarrow w, \Lambda, w_2, v_s \\
SU(3)_C \times SU(2)_L \times U(1)_Y \times M_P \\
\downarrow v_1, v_2, w_1 \\
SU(3)_C \times U(1)_Q \times M_P \,.
\end{gathered}
$$

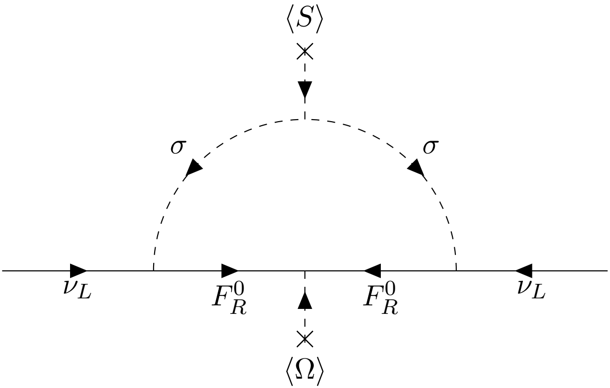
- $\phi \sim (\mathbf{1}, \mathbf{1}, 0, 2)$ breaks spontaneously $B - L$ by two units.
- After SSB a remnant discrete symmetry is preserved

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

Matter-parity without invoking supersymmetry!

Neutrino mass relevant terms

$$\mathcal{L}_{\mathsf{m}_\nu} = \overline{F}^{i}_{aR} Y_1^{ab} l_{ibL} \sigma + F_{iaR} Y_{2R}^{ab} F_{jbR} \Omega^{ij} + \mu_2 \sigma^2 S^* + \text{h.c.}$$

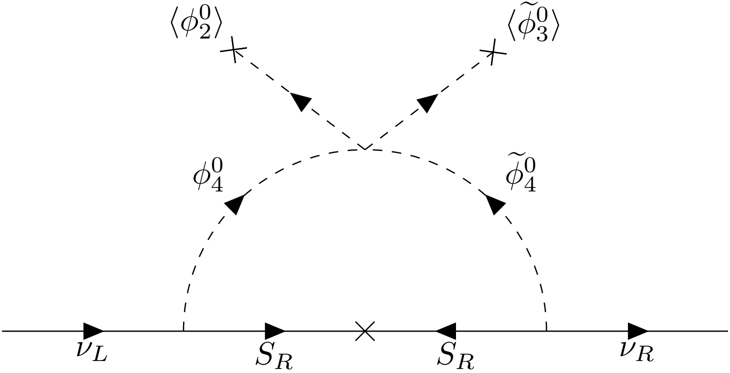


J. Leite, América Morales, J.W.F. Valle, CAV-A 2005.03600 [hep-ph]

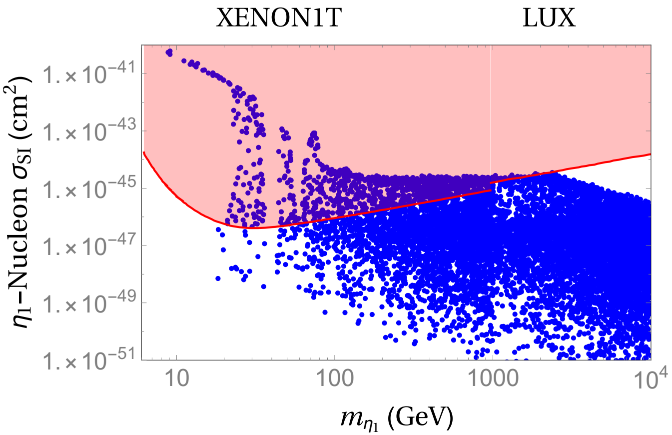
- $3-3-1-1$ version of our previous $B-L$ extension
- Gauge $B-L$ preserved after EWSB stabilizes WIMP DM
- Dirac Neutrinos
- Rich DM phenomenology.

Field	3-3-1-1 rep	Components	$B-L$	$\mathrm{U}(1)_{\mathrm{PQ}}$
$Q_{\alpha L}$	$\left(\mathbf{3},\mathbf{3},0,-\frac{1}{3}\right)$	$((u_{\alpha L},d_{\alpha L}),D_{\alpha L})^T$	$\left(\frac{1}{3},\frac{1}{3},-\frac{5}{3}\right)^T$	1
Q_{3L}	$\left(\mathbf{3},\mathbf{3}^*,\frac{1}{3},1\right)$	$((b_L,-t_L),U_{3L})^T$	$\left(\frac{1}{3},\frac{1}{3},\frac{7}{3}\right)^T$	1
u_{aR}	$\left(\mathbf{3},\mathbf{1},\frac{2}{3},\frac{1}{3}\right)$	u_{aR}	$\frac{1}{3}$	4
U_{3R}	$\left(\mathbf{3},\mathbf{1},\frac{2}{3},\frac{7}{3}\right)$	U_{3R}	$\frac{7}{3}$	4
d_{aR}	$\left(\mathbf{3},\mathbf{1},-\frac{1}{3},\frac{1}{3}\right)$	d_{aR}	$\frac{1}{3}$	-2
$D_{\alpha R}$	$\left(\mathbf{3},\mathbf{1},-\frac{1}{3},-\frac{5}{3}\right)$	$D_{\alpha R}$	$-\frac{5}{3}$	-2
ψ_{aL}	$\left(\mathbf{1},\mathbf{3}^*,-\frac{1}{3},-\frac{1}{3}\right)$	$((e_{aL},-\nu_{aL}),\nu^c_{aR})^T$	$(-1,-1,+1)^T$	-3
e_{aR}	$(\mathbf{1},\mathbf{1},-1,-1)$	e_{aR}	-1	-6
S_{aR}	$(\mathbf{1},\mathbf{1},0,0)$	S_{aR}	0	0
Φ_1	$\left(\mathbf{1},\mathbf{3}^*,\frac{2}{3},\frac{2}{3}\right)$	$\left(\left(\phi_1^0,-\phi_1^+\right),\widetilde{\phi}_1^+\right)^T$	$(0,0,2)^T$	3
Φ_2	$\left(\mathbf{1},\mathbf{3}^*,-\frac{1}{3},\frac{2}{3}\right)$	$\left(\left(\phi_2^-,-\phi_2^0\right),\widetilde{\phi}_2^0\right)^T$	$(0,0,2)^T$	-3
Φ_3	$\left(\mathbf{1},\mathbf{3}^*,-\frac{1}{3},-\frac{4}{3}\right)$	$\left(\left(\phi_3^-,-\phi_3^0\right),\widetilde{\phi}_3^0\right)^T$	$(-2,-2,0)^T$	-3
Φ_4	$\left(\mathbf{1},\mathbf{3}^*,-\frac{1}{3},-\frac{1}{3}\right)$	$\left(\left(\phi_4^-,-\phi_4^0\right),\widetilde{\phi}_4^0\right)^T$	$(-1,-1,1)^T$	-3

Neutrino Mass



Wimp Dark matter

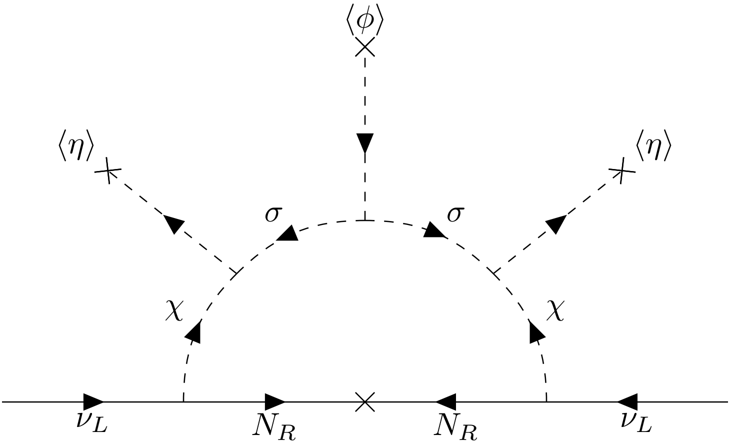


A.E. Cárcamo Hernández, J.W.F. Valle, CAV-A 2006.06009 [hep-ph]

- Minimal $3-3-1-1$ scotogenic model
- Majorana Neutrinos
- DM stabilized by Matter Parity

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

Neutrino Mass

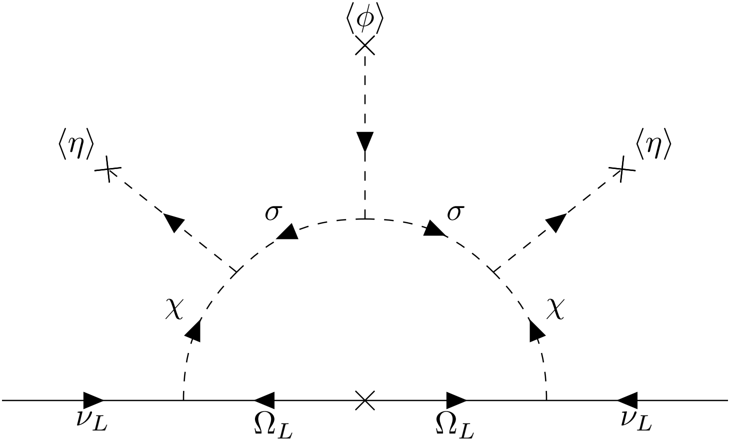


A.E. Cárcamo Hernández, C. Hati, S. Kovalenko, J.W.F. Valle, CAV-A
2109.05029 [hep-ph]

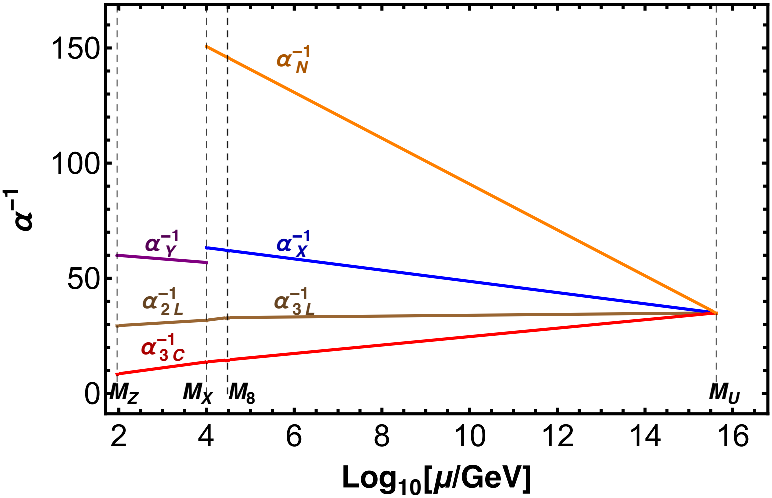
- Scotogenic $3-3-1-1$ with octets
- Majorana neutrinos
- DM stabilized by Matter Parity
- Gauge coupling unification

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

Neutrino Mass



Gauge Coupling Unification

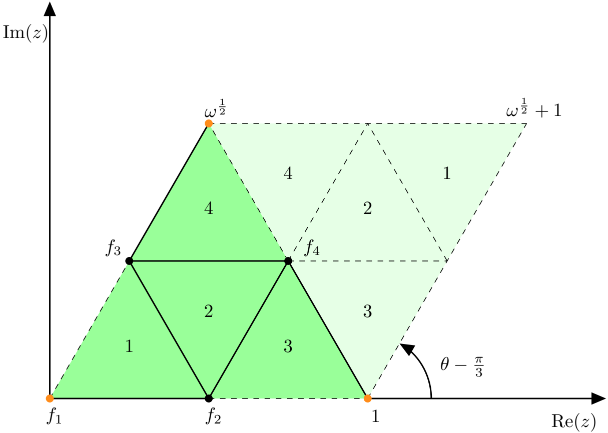


Extra-dimensional Models

F. de Anda, I. Antoniadis, J.W.F. Valle, CAV-A 2007.10402 [hep-ph]

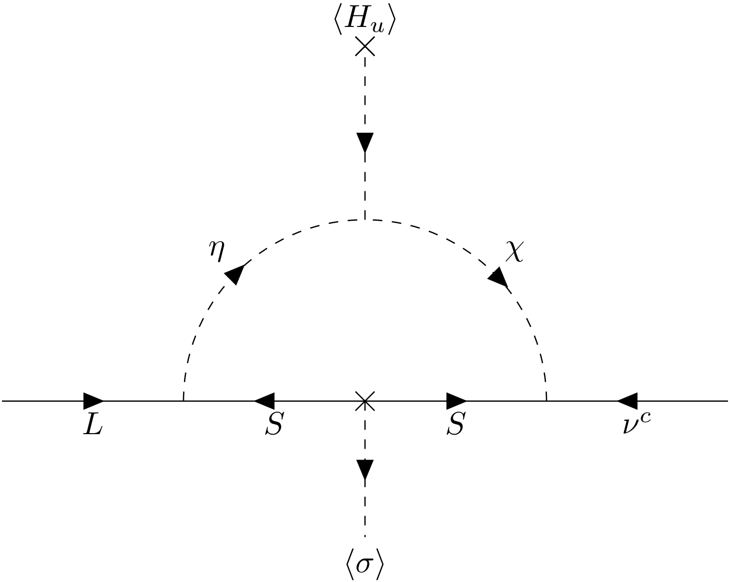
- Orbifolded $6D$ model with remnant A_4 flavor symmetry
- Dirac Neutrinos
- Realistic model for quark and lepton masses and mixings.

$\mathbb{M}^6 \to \mathbb{M}^4 \times (\mathbb{T}^2/\mathbb{Z}_2)$ orbifold compactification



Field	$SU(3)$	$SU(2)$	$U(1)$	A_4	$\mathbb{Z}_3$	$\mathbb{Z}_2$	Localization
L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	ω^2	1	Brane
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\mathbf{3}$	ω	1	Brane
e^c	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{3}$	ω	1	Brane
Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{3}$	ω^2	1	Brane
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{3}$	ω^2	1	Brane
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	1	1	Bulk
T^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{1}$	ω	1	Brane
T	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$\mathbf{1}$	ω^2	1	Brane
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{3}$	ω^2	1	Brane
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	1	1	Brane
σ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	ω	1	Brane
S	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	ω	-1	Brane
η	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	1	-1	Brane
χ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	ω^2	-1	Brane

Neutrino Mass



Prediction: Golden Relation

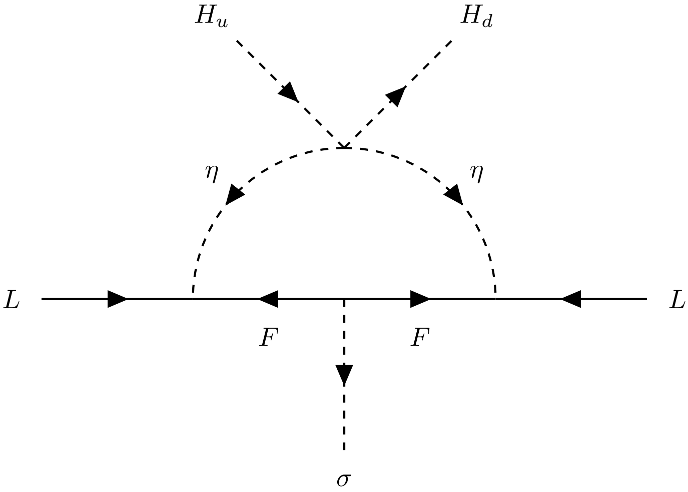
$$\frac{m_\tau}{\sqrt{m_\mu m_e}} \approx \frac{m_b}{\sqrt{m_s m_d}}.$$

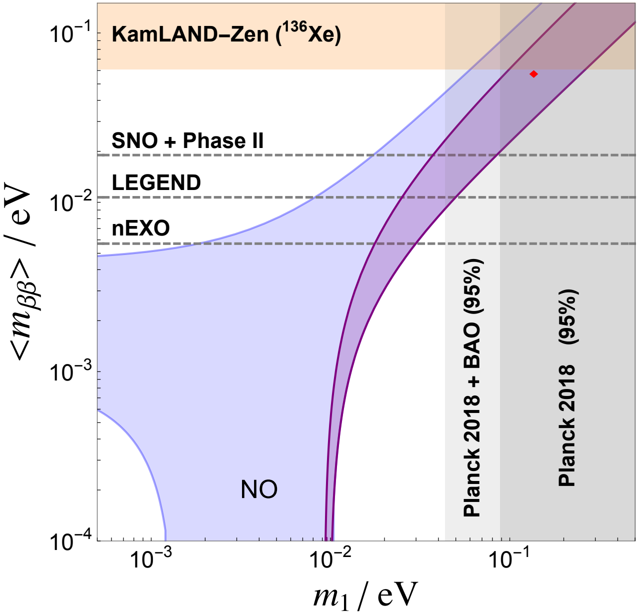
F. de Anda, O. Medina, J.W.F. Valle, CAV-A 2110.06810 [hep-ph]

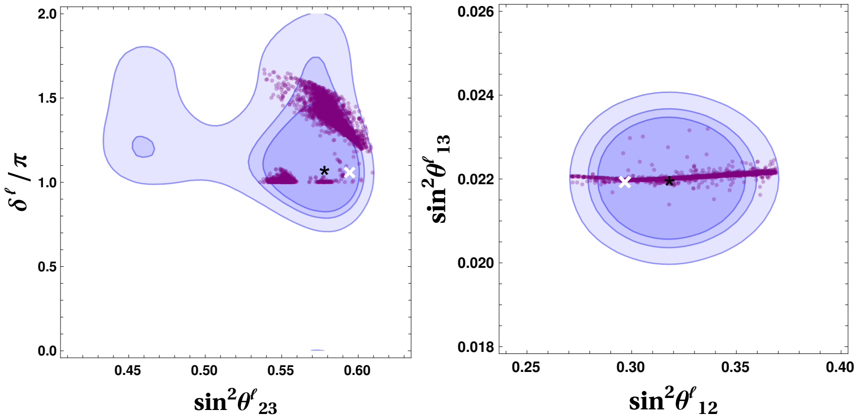
- Orbifolded $6D$ model with remnant A_4 flavor symmetry
- Majorana neutrinos
- Predictive model for quark and lepton masses and mixings $\chi^2 = 1.96$.

Field	$\mathrm{SU}(3)_\mathrm{C}$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_\mathrm{Y}$	$\mathbb{Z}_4$	A_4	Location
L	$\mathbf{1}$	$\mathbf{2}$	-1	1	$\mathbf{3}$	Brane
d^c	$\mathbf{3}$	$\mathbf{1}$	$2/3$	1	$\mathbf{3}$	Brane
e^c	$\mathbf{1}$	$\mathbf{1}$	2	1	$\mathbf{3}$	Brane
Q	$\mathbf{3}$	$\mathbf{2}$	$1/3$	1	$\mathbf{3}$	Brane
$u^c_{1,2,3}$	$\mathbf{3}$	$\mathbf{1}$	$-4/3$	-1	$\mathbf{1}'', \mathbf{1}', \mathbf{1}$	Bulk
F	$\mathbf{1}$	$\mathbf{1}$	0	i	$\mathbf{3}$	Brane
H_u	$\mathbf{1}$	$\mathbf{2}$	1	-1	$\mathbf{3}$	Brane
H_d	$\mathbf{1}$	$\mathbf{2}$	-1	1	$\mathbf{3}$	Brane
η	$\mathbf{1}$	$\mathbf{2}$	1	$-i$	$\mathbf{1}$	Brane
σ	$\mathbf{1}$	$\mathbf{1}$	0	-1	$\mathbf{3}$	Bulk

Neutrino Mass



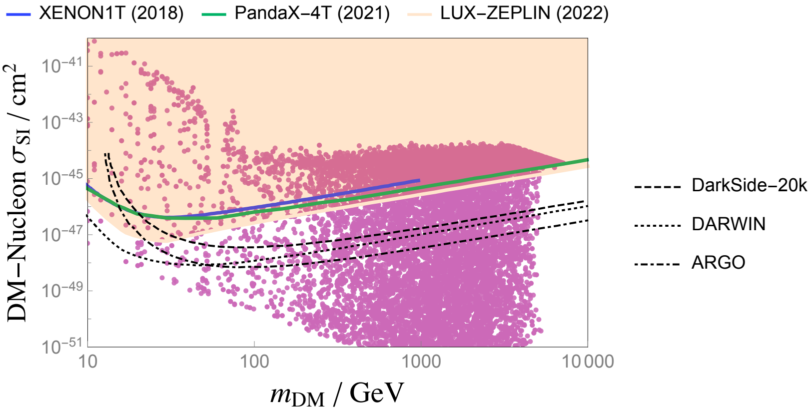

KamLAND–Zen (^{136}Xe)
SNO + Phase II
LEGEND
nEXO
NO
Planck 2018 + BAO (95%)
Planck 2018 (95%)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$<m_{\beta\beta}>$ / eV
m_1 / eV


2.0
1.5
1.0
0.5
0.0
0.45
0.50
0.55
0.60
δ^ℓ/π
$\sin^2\theta^\ell_{23}$
0.026
0.024
0.022
0.020
0.018
0.25
0.30
0.35
0.40
$\sin^2\theta^\ell_{13}$
$\sin^2\theta^\ell_{12}$

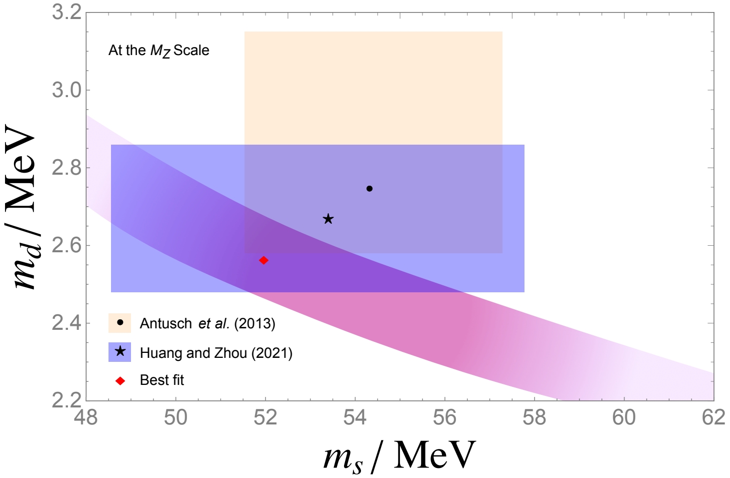
F. de Anda, O. Medina, J.W.F. Valle, CAV-A 2212.09174 [hep-ph]

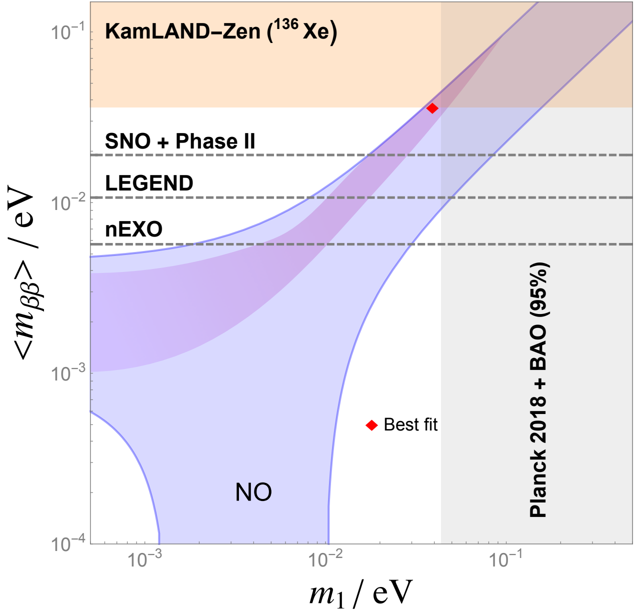
- Orbifolded $6D$ model with remnant A_4 flavor symmetry
- Majorana neutrinos with Low Scale See Saw
- WIMP Dark matter identified with first Kaluza-Klein excitation of scalar that drives family symmetry breaking and neutrino mass mechanism.
- Predictive model for quark and lepton masses and mixings $\chi^2 = 1.05$.

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	A_4	$\mathbb{Z}_2$	$\mathbb{Z}_3$	Localization
L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	1	1	Brane
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\mathbf{3}$	1	1	Brane
e^c	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{3}$	1	1	Brane
Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{3}$	1	1	Brane
$u^c_{1,2,3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{1}'', \mathbf{1}', \mathbf{1}$	-1	1	Bulk
ν^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	-1	ω	Brane
S	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	-1	ω^2	Brane
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{3}$	-1	1	Brane
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{3}$	1	1	Brane
H_ν	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{3}$	-1	ω^2	Brane
σ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	1	ω^2	Bulk



XENON1T (2018)
PandaX−4T (2021)
LUX−ZEPLIN (2022)
DM−Nucleon σ_{SI} / cm^2
10^{-41}
10^{-43}
10^{-45}
10^{-47}
10^{-49}
10^{-51}
10
100
1000
10 000
m_{DM} / GeV
DarkSide−20k
DARWIN
ARGO


At the M_Z Scale
3.2
3.0
2.8
2.6
2.4
2.2
48
50
52
54
56
58
60
62
m_d / MeV
m_s / MeV
Antusch *et al.* (2013)
Huang and Zhou (2021)
Best fit


KamLAND–Zen (136 Xe)
SNO + Phase II
LEGEND
nEXO
Best fit
NO
Planck 2018 + BAO (95%)
$<m_{\beta\beta}>$ / eV
m_1 / eV
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Conclusions

- Scotogenic scenarios for neutrino mass generation and WIMP DM emerge naturally in Gauge extensions of the SM and Extra-dimensional field theories, both for Majorana and Dirac Neutrinos
- DM Stability can be related to a robust Gauge symmetry or a discrete remnant symmetry after SSB.
- Wimp KKDM introduced by the neutrino mass generation mechanism in extra dimensions.

Thanks