A THEORY FOR SCOTOGENIC DARK MATTER STABILISED BY RESIDUAL GAUGE SYMMETRY

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International Conference on Neutrinos and Dark Matter (NDM-2020)
Hurghada, Egypt - January 2020

in collaboration with Oleg Popov, Rahul Srivastava and José W. F. Valle.

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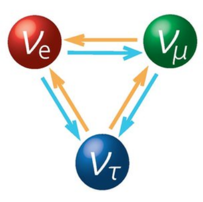
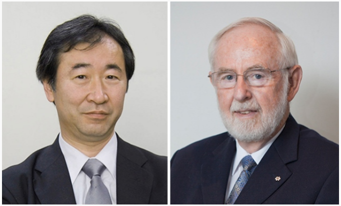
NEUTRINO MASSES

Neutrino masses

- Neutrino oscillations (2015 Nobel Prize)





- Δm_{21}^2, Δm_{31}^2

[1]S. Weinberg (1979)

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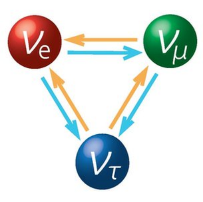
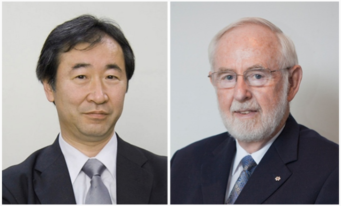
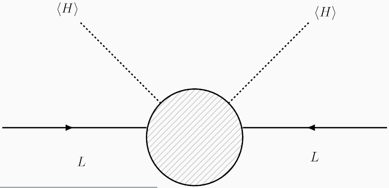




- Δm^2_{21}, Δm^2_{31}
- Only LH neutrinos in the SM $\Rightarrow \frac{1}{\Lambda_{NP}} L_L L_L H H$[1]
- The D5WO breaks L (or $B-L$) by 2 units $\Rightarrow$ neutrinos are Majorana.



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  - new physics at lower scale $\Rightarrow$ richer pheno.
- Symmetries are usually needed to forbid tree-level masses.
- Could we use the same symmetries to help us with yet another important issue such as that of **Dark Matter**?

- **Scotogenic model:**[2]
  - SM field content + an inert doublet (η) and fermion singlets (N).
  - *ad hoc* Z_2 symmetry, under which only the BSM fields are odd.
- Z_2 forbids tree-level masses and stabilises the lightest Z_2-odd field (DM).

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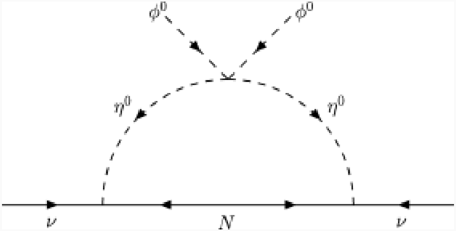

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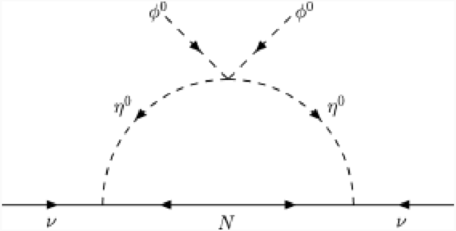

- Could the DM-stabilising & tree-level-mass-forbidding symmetry arise naturally from the gauge structure?
- That's what we investigate in the context of 3-3-1 models...

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3-3-1 MODELS

SM		3-3-1[3]
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$\Rightarrow$	$SU(3)_c \otimes SU(3)_L \otimes U(1)_X$
$Q = T_3 + Y$	$\Rightarrow$	$Q = T_3 - \frac{1}{\sqrt{3}} T_8 + XI$

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- LH fermions are distributed in an economical fashion:

$$L_{aL} = (\nu_{aL} \;\; e_{aL})^T \sim \mathbf{2} \quad \Rightarrow \quad l_{aL} = (\nu_{aL} \;\; e_{aL} \;\; N_{aL})^T \sim \mathbf{3}$$

$$Q_{aL} = (u_{aL} \;\; d_{aL})^T \sim \mathbf{2} \quad \Rightarrow \quad q_{iL} = (d_{iL} \;\; -u_{iL} \;\; D_{iL})^T \sim \mathbf{3}^*$$

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- Anomaly cancellation & asymptotic freedom: # generations =# colours = 3
- The minimal scalar sector contains

$$\eta, \chi \equiv \begin{pmatrix} \eta_1^0 \\ \eta_2^- \\ \eta_3^0 \end{pmatrix}, \begin{pmatrix} \chi_1^0 \\ \chi_2^- \\ \chi_3^0 \end{pmatrix}; \rho \equiv \begin{pmatrix} \rho_1^+ \\ \rho_2^0 \\ \rho_3^+ \end{pmatrix}, \; \langle \eta_1^0 \rangle^2 + \langle \rho_2^0 \rangle^2 = v_{EW}^2 \text{ and } \langle \chi_3^0 \rangle \propto w \quad (1)$$

- Symmetry breaking happens in two stages:

$$\mathrm{SU(3)_c \otimes SU(3)_L \otimes U(1)_X} \xrightarrow{w} \mathrm{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y} \xrightarrow{v_{EW}} \mathrm{SU(3)_c \otimes U(1)_Q} \quad (2)$$

[3] M. Singer, J. W. F. Valle, J. Schechter (1980)

- Gauged $B - L$ symmetry can be realised by also introducing $U(1)_N$ (3-3-1-1[4])

$$B - L = \beta' T_8 + N \, . \tag{3}$$

- As in the SM case, anomalies cancel out when adding *e.g.* $\nu_{aR} \sim (-1, -1, -1)$ or $(-4, -4, 5)$.

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$$\sigma \equiv v_\sigma + S_\sigma + iA_\sigma \sim (\mathbf{1}, \mathbf{1}, 0, 2) \, . \tag{4}$$

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- In the following, we show that:
  - M_P ensures the stability of the lightest M_P-odd particle $\rightarrow$ DM.
  - M_P forbids tree-level neutrino masses $\rightarrow$ scotogenic masses.

[4] P. V. Dong, T. D. Tham, H. T. Hung (2013)

scoto-3-3-1-1 model

- The leptons and scalars in our model are[5]

Field	$SU(3)_L$	$U(1)_X$	$U(1)_N$	$B-L$	Q	$M_P=(-1)^{3(B-L)+2s}$
l_{aL}	**3**	$-\frac{1}{3}$	$-\frac{2}{3}$	$(-1,-1,0)^T$	$(0,-1,0)^T$	$(++-)^T$
e_{aR}	**1**	-1	-1	-1	-1	$+$
ν_{iR}	**1**	0	-4	-4	0	$-$
ν_{3R}	**1**	0	5	5	0	$+$
N_{aR}	**1**	0	0	0	0	$-$
η	**3**	$-\frac{1}{3}$	$\frac{1}{3}$	$(0,0,1)^T$	$(0,-1,0)^T$	$(++-)^T$
ρ	**3**	$\frac{2}{3}$	$\frac{1}{3}$	$(0,0,1)^T$	$(1,0,1)^T$	$(++-)^T$
χ	**3**	$-\frac{1}{3}$	$-\frac{2}{3}$	$(-1,-1,0)^T$	$(0,-1,0)^T$	$(--+)^T$
σ	**1**	0	2	2	0	$+$
ζ	**3**	$\frac{2}{3}$	$\frac{7}{3}$	$(2,2,3)^T$	$(1,0,1)^T$	$(+,+,-)^T$
ξ	**3**	$\frac{2}{3}$	$\frac{4}{3}$	$(1,1,2)^T$	$(1,0,1)^T$	$(-,-,+)^T$

[5] **JL**, O. Popov, R. Srivastava, J. W. F. Valle (2019); ArXiv: 1909.06386

- The Yukawa sector is then

$$-\mathcal{L}_{lep} = y^{e}_{ab}\,\overline{l_{aL}}\,\rho\,e_{bR} + h_{ab}\epsilon_{kmn}\,(\overline{l_{aL}})_k\,(l_{bL})^c_m\,\xi^*_n + y^N_{ab}\,\overline{l_{aL}}\,\chi N_{bR} + \frac{(m_N)_{ab}}{2}\,\overline{(N_{aR})^c}\,N_{bR} + h.c.$$

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- Charged lepton masses $\propto y^e\langle\rho^0_2\rangle$.
- M_P conservation $\Rightarrow \langle\chi^0_1\rangle, \langle\xi^0_2\rangle = 0 \Rightarrow$ massless neutrinos at tree-level.

Scotogenic neutrino mass

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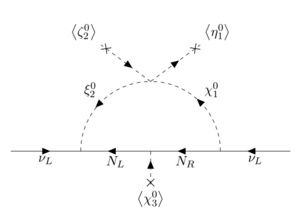
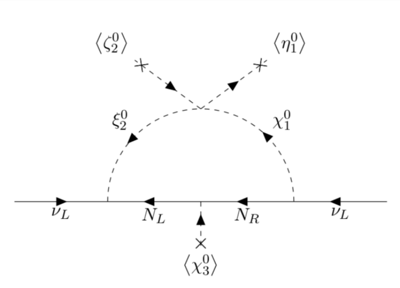


.

- The loop closes due to $\lambda_1(\chi^\dagger\eta)(\zeta^\dagger\xi)$ in the potential.
- Internal fields are M_P-odd:
  - the lightest is stable (DM)
  - (real) scalar or fermion



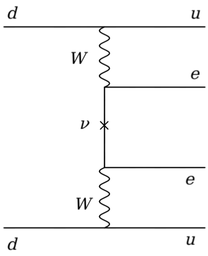
.

$$m_\nu^{ab} = \frac{c_1}{8\pi^2} h^{*ac} s_N c_N \left\{ m_{N_1} \left[s_{S_2} c_{S_2} \left(Z\left(\frac{m_{S_1}^2}{m_{N_1}^2}\right) - Z\left(\frac{m_{S_2}^2}{m_{N_1}^2}\right)\right) - s_{A_2} c_{A_2} \left(Z\left(\frac{m_{A_1}^2}{m_{N_1}^2}\right) - Z\left(\frac{m_{A_2}^2}{m_{N_1}^2}\right)\right)\right] \right. \tag{6}$$
$$\left. - m_{N_2} \left[s_{S_2} c_{S_2} \left(Z\left(\frac{m_{S_1}^2}{m_{N_2}^2}\right) - Z\left(\frac{m_{S_2}^2}{m_{N_2}^2}\right)\right) - s_{A_2} c_{A_2} \left(Z\left(\frac{m_{A_1}^2}{m_{N_2}^2}\right) - Z\left(\frac{m_{A_2}^2}{m_{N_2}^2}\right)\right)\right] \right\}_{cd} y^{N*db} + \{a \leftrightarrow b\} ,$$

with $Z(x) = \frac{x}{1-x} \ln x$.

- The anti-symmetric nature of h_{ab} $\Rightarrow$ $\det m_\nu = 0 \Rightarrow 1$ neutrino is massless.

- The Majorana nature of neutrinos, as predicted by our model, can be undoubtedly established if $0\nu\beta\beta$ decay is ever observed.



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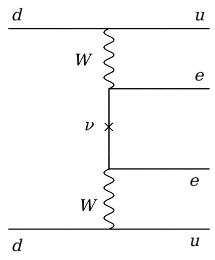

- Our model allows for other tree-level contributions, *e.g.* scalar-mediated.
- The standard contribution is, however, the dominant one.

- It depends on the effective Majorana mass

$$\langle m_{\beta\beta}\rangle = |\cos(\theta_{12})^2\cos(\theta_{13})^2 m_1 + \sin(\theta_{12})^2\cos(\theta_{13})^2 m_2 e^{2i\phi_{12}} + \sin(\theta_{13})^2 m_3 e^{2i\phi_{13}}| \quad (7)$$

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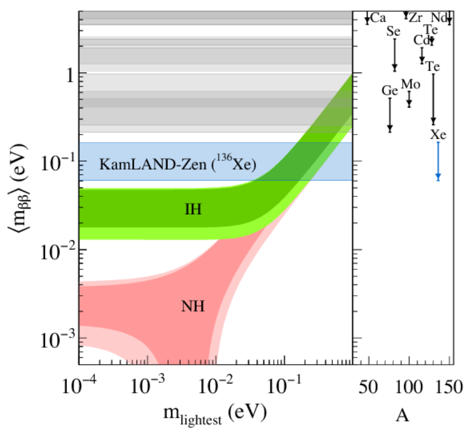
- For three massive active neutrinos



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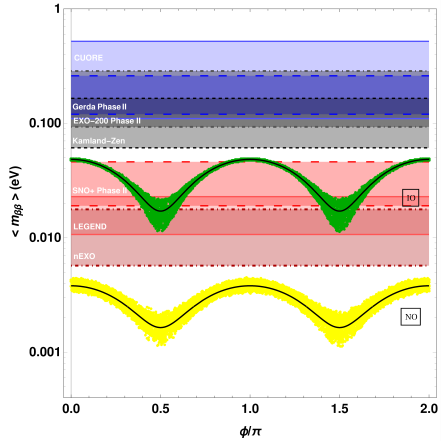
[6] KamLAND-Zen Collaboration (2016)

- In our case, however, one neutrino is massless.
- This gives a lower bound for the $0\nu\beta\beta$ decay rate.
- $\langle m_{\beta\beta}\rangle = |\cos(\theta_{12})^2\cos(\theta_{13})^2 m_1 + \sin(\theta_{12})^2\cos(\theta_{13})^2 m_2 e^{2i\phi_{12}} + \sin(\theta_{13})^2 m_3 e^{2i\phi_{13}}|$



CONCLUSIONS

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- Neutrino masses can be generated through many mechanisms, all of which require BSM physics.
- Radiative mechanisms are appealing
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  - new physics at lower scales
- In general, symmetries are required to forbid tree-level.
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- In general, symmetries are required to forbid tree-level.
- The same symmetries can be used to stabilise DM candidates.
- Here we have proposed a $SU(3)_c \otimes SU(3)_L \otimes U(1)_X \otimes U(1)_N$ SM extension.
- $B - L$ symmetry is gauged and dictates neutrino masses and DM stability through a residual matter-parity symmetry.
- The stable WIMP DM candidate can either be a scalar or a fermion.
- Neutrino masses are radiative and mediated by DM (**Scotogenic**).
- The gauge structure naturally predicts a massless neutrino.
- Thus, there exists an unavoidable lower bound for the $0\nu\beta\beta$ decay rate.

- Thank you!