Annual meeting of the DPyC-SMF:

Ultraviolet extensions of the Scotogenic model.

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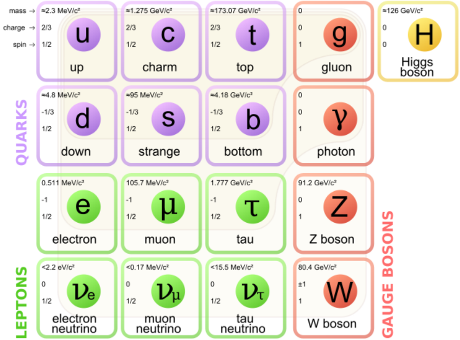
Outline

- Introduction to the Scotogenic model.
- UV extensions.
- Model II(1,2).
- Phenomenology of the UV extensions.
- Summary.



- Gauge theory $SU(3)_c \times SU(2)_L \times U(1)_Y$

  ⇒ Accidental symmetries: lepton number...

  ⇒ Massless neutrinos.

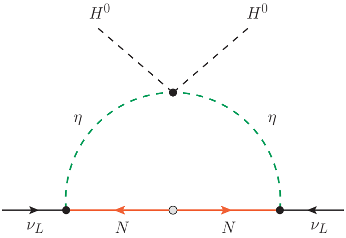
- Open questions (neutrino sector):

  ⇒ What is the origin of neutrino masses?

  ⇒ Are neutrinos Dirac or Majorana fermions?

The Scotogenic model is an extension to the standard model where three generations of right-handed fermions (N) and a scalar doublet are added: • EM, Phys. Rev. D **73**, 077301 (2006)

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
ℓ_L	**1**	**2**	-1/2	+
e_R	**1**	**1**	-1	+
N	**1**	**1**	0	−
H	**1**	**2**	1/2	+
η	**1**	**2**	1/2	−



Where the yukawa sector of the lagrangian can be written as:

$$\mathcal{L}_Y = y\,\overline{N}\,\widetilde{\eta}^\dagger\,\ell_L + \frac{1}{2} M_N\,\overline{N}^c N + \text{h.c.}\,, \tag{1}$$

and the scalar potential

$$\begin{aligned}\mathcal{V}_{UV} = m_H^2 H^\dagger H + \frac{\lambda_1}{2}(H^\dagger H)^2 + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 \\ + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \left[\frac{\lambda_5}{2}(H^\dagger \eta)^2 + \text{h.c.}\right]\,.\end{aligned} \tag{2}$$

After the Spontaneous Symmetry Breaking (SSB) using

$$\langle H^0 \rangle = \frac{v_H}{\sqrt{2}}\,, \quad \langle \eta^0 \rangle = 0\,. \tag{3}$$

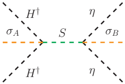
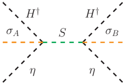
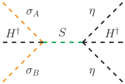
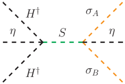
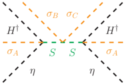
we obtain the mass at one loop level for ν_L such that

$$(m_\nu)_{\alpha\beta} = \frac{\lambda_5\, v_H^2}{32\pi^2} \sum_n \frac{y_{n\alpha}\, y_{n\beta}}{M_{N_n}} \left[\frac{M_{N_n}^2}{m_0^2 - M_{N_n}^2} + \frac{M_{N_n}^4}{\left(m_0^2 - M_{N_n}^2\right)^2} \log \frac{M_{N_n}^2}{m_0^2} \right], \tag{4}$$

where $m_0^2 = m_\eta^2 + (\lambda_3 + \lambda_4)\, v_H^2/2$ and M_{N_n} are the diagonal elements of the M_N matrix. Two of the main "problems" of this formulation are:

- Dark $\mathbb{Z}_2$ discrete symmetry is introduced ad-hoc to the model in order to forbid the interaction $\bar{N} H^\dagger \ell_L$ within the model.
- $\lambda_5 \sim 10^{-5} \ll 1$. In order to recover the smallness of neutrinos masses.

Ultraviolet extensions to the Scotogenic model.

Top.	Diagram	Required operators
I		$(\sigma_A H^\dagger S \tilde{H})$,$(\sigma_B \tilde{\eta}^\dagger S^\dagger \eta)$
II		$(\sigma_A H^\dagger S \eta)$,$(\sigma_B H^\dagger S^\dagger \eta)$
III		$(\sigma_A \sigma_B H^\dagger S)$,$(H^\dagger \eta S^\dagger \eta)$
IV		$(H^\dagger S H^\dagger \eta)$,$(\sigma_A \sigma_B S^\dagger \eta)$
V		$(\sigma_A H^\dagger S \eta)$,$((S^\dagger)^2 \sigma_B \sigma_C)$

λ_5 operator in the UV theory.

- DPS, PE and AV, **arXiv:2301.05249**.

(A) $\mathrm{U(1)_L} \xrightarrow{\langle\sigma\rangle} \mathbb{Z}_2$

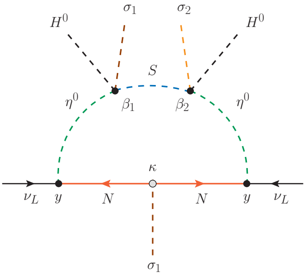
(B) Have an effective $(H^\dagger\eta)^2$ after the decoupling of an scalar S and the SSB. Leaving a natural suppressed λ_5 parameter.

$$\mathcal{O}_{\lambda_5} = (H^\dagger\eta)^2\sigma_A\sigma_B\,, \quad (5)$$

$$\mathcal{O}_{\lambda_5} = (H^\dagger\eta)^2\sigma_A^2\sigma_B\sigma_C\,, \quad (6)$$

We have the operator $\sigma_1 \bar{N}^c N$ within all the models.

We obtain 50 different models of this kind. One example of them II(1,2):



$$q_N = \frac{1}{2}\,,\; q_\eta = -\frac{1}{2}\,,\; q_S = \frac{3}{2}\,,\; q_{\sigma_1} = -1\,,\; q_{\sigma_2} = 2\,. \tag{7}$$

$$\boxed{\frac{\lambda_5}{2} = -\frac{v_{\sigma_1} v_{\sigma_2} \beta_1 \beta_2}{2 m_S^2} \ll 1}$$

$$\begin{aligned}
\mathcal{V}_{\rm UV} &= m_H^2 H^\dagger H + m_S^2 S^* S + m_{\sigma_i}^2 \sigma_i^* \sigma_i + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 \\
&+ \frac{\lambda_S}{2}(S^* S)^2 + \frac{\lambda_{\sigma_i}}{2}(\sigma_i^* \sigma_i)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_3^S (H^\dagger H)(S^* S) \\
&+ \lambda_3^{\sigma_i}(H^\dagger H)(\sigma_i^* \sigma_i) + \lambda_3^{\eta S}(\eta^\dagger \eta)(S^* S) + \lambda_3^{\eta \sigma_i}(\eta^\dagger \eta)(\sigma_i^* \sigma_i) \\
&+ \lambda_3^{\sigma\sigma}(\sigma_1^* \sigma_1)(\sigma_2^* \sigma_2) + \lambda_3^{\sigma_i S}(\sigma_i^* \sigma_i)(S^* S) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) \\
&+ \left[\beta_1(\sigma_1 H^\dagger S \eta) + \beta_2(\sigma_2 H^\dagger S^\dagger \eta) + \frac{\mu}{\sqrt{2}}(\sigma_2 \sigma_1 \sigma_1) + \lambda_0 (S S \sigma_1 \sigma_2^*) + \text{h.c.}\right]\,,
\end{aligned} \tag{8}$$

Once S is integrated out, we obtain

$$\begin{aligned}\mathcal{V}_{\rm IR} &= m_H^2(H^\dagger H) + m_\eta^2(\eta^\dagger\eta) + m_{\sigma_i}^2(\sigma_i^*\sigma_i) + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 + \frac{\lambda_{\sigma_i}}{2}(\sigma_i^*\sigma_i)^2 \\ &+ \lambda_3(H^\dagger H)(\eta^\dagger\eta) + \lambda_3^{\sigma_i}(H^\dagger H)(\sigma_i^*\sigma_i) + \lambda_3^{\eta\sigma_i}(\eta^\dagger\eta)(\sigma_i^*\sigma_i) + \lambda_3^{\sigma\sigma}(\sigma_1^*\sigma_1)(\sigma_2^*\sigma_2) \\ &+ \left[\lambda_4 - \frac{|\beta_i|^2}{m_S^2}(\sigma_i^*\sigma_i)\right](H^\dagger\eta)(\eta^\dagger H) \\ &+ \left[\frac{\mu}{\sqrt{2}}(\sigma_2\sigma_1\sigma_1) - \frac{\beta_1\beta_2}{m_S^2}\sigma_1\sigma_2(H^\dagger\eta)^2 + \text{h.c.}\right] + \mathcal{O}\left(\frac{1}{m_S^4}\right).\end{aligned} \tag{9}$$

After the decomposition

$$H^0 = \frac{1}{\sqrt{2}}(v_H + \phi + i\,A)\,, \quad \sigma_i = \frac{1}{\sqrt{2}}(v_{\sigma_i} + \rho_i + i\,J_i)\,, \tag{10}$$

The non-trivial tadpole equation are

$$\left.\frac{d\mathcal{V}_{\rm IR}}{dH^0}\right|_{\langle H^0,\sigma_i\rangle=\{\frac{v_H}{\sqrt{2}},\frac{v_{\sigma_i}}{\sqrt{2}}\}} = \frac{v_H}{\sqrt{2}}\left(m_H^2 + \lambda_1\frac{v_H^2}{2} + \lambda_3^{\sigma_1}\frac{v_{\sigma_1}^2}{2} + \lambda_3^{\sigma_2}\frac{v_{\sigma_2}^2}{2}\right) = 0, \tag{11}$$

$$\left.\frac{d\mathcal{V}_{\rm IR}}{d\sigma_1}\right|_{\langle H^0,\sigma_i\rangle=\{\frac{v_H}{\sqrt{2}},\frac{v_{\sigma_i}}{\sqrt{2}}\}} = \frac{v_{\sigma_1}}{\sqrt{2}}\left(m_{\sigma_1}^2 + \mu\,v_{\sigma_2} + \lambda_3^{\sigma_1}\frac{v_H^2}{2} + \lambda_{\sigma_1}\frac{v_{\sigma_1}^2}{2} + \lambda_3^{\sigma\sigma}\frac{v_{\sigma_2}^2}{2}\right) = 0, \tag{12}$$

$$\left.\frac{d\mathcal{V}_{\rm IR}}{d\sigma_2}\right|_{\langle H^0,\sigma_i\rangle=\{\frac{v_H}{\sqrt{2}},\frac{v_{\sigma_i}}{\sqrt{2}}\}} = \frac{v_{\sigma_2}}{\sqrt{2}}\left(m_{\sigma_2}^2 + \mu\frac{v_{\sigma_1}^2}{2v_{\sigma_2}} + \lambda_3^{\sigma_2}\frac{v_H^2}{2} + \lambda_{\sigma_2}\frac{v_{\sigma_2}^2}{2} + \lambda_3^{\sigma\sigma}\frac{v_{\sigma_1}^2}{2}\right) = 0. \tag{13}$$

Taking our attention in the η fields

$$\eta^0 = \frac{1}{\sqrt{2}}(\eta_R + i\,\eta_I)\,. \tag{14}$$

The mass of the charged η^+ and the neutral $\eta_{R,I}$ fields are given by

$$m^2_{\eta^+} = m^2_\eta + \frac{v_H^2}{2}\lambda_3^{\rm eff}\,, \tag{15}$$

$$m^2_{\eta_R} = m^2_\eta + \frac{v_H^2}{2}\left(\lambda_3^{\rm eff} + \lambda_4^{\rm eff} - \frac{\beta_1\beta_2 v_{\sigma_1} v_{\sigma_2}}{m_S^2}\right)\,, \tag{16}$$

$$m^2_{\eta_I} = m^2_\eta + \frac{v_H^2}{2}\left(\lambda_3^{\rm eff} + \lambda_4^{\rm eff} + \frac{\beta_1\beta_2 v_{\sigma_1} v_{\sigma_2}}{m_S^2}\right)\,, \tag{17}$$

where we defined

$$\lambda_3^{\rm eff} \equiv \lambda_3 + \lambda_3^{\eta\sigma_1}\frac{v_{\sigma_1}^2}{v_H^2} + \lambda_3^{\eta\sigma_2}\frac{v_{\sigma_2}^2}{v_H^2} \tag{18}$$

$$\lambda_4^{\rm eff} \equiv \lambda_4 - \frac{\beta_1^2 v_{\sigma_1}^2}{2m_S^2} - \frac{\beta_2^2 v_{\sigma_2}^2}{2m_S^2}\,. \tag{19}$$

For the CP-even fields we get

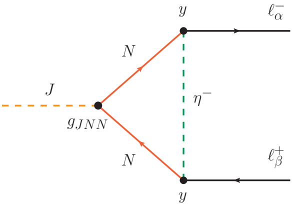
$$\mathcal{M}_R^2 = \begin{pmatrix} \lambda_1 v_H^2 & \lambda_3^{\sigma_1} v_H v_{\sigma_1} & \lambda_3^{\sigma_2} v_H v_{\sigma_2} \\ \lambda_3^{\sigma_1} v_H v_{\sigma_1} & \lambda_{\sigma_1} v_{\sigma_1}^2 & v_{\sigma_1}(\mu + \lambda_3^{\sigma\sigma} v_{\sigma_2}) \\ \lambda_3^{\sigma_2} v_H v_{\sigma_2} & v_{\sigma_1}(\mu + \lambda_3^{\sigma\sigma} v_{\sigma_2}) & \lambda_2 v_{\sigma_2}^2 - \frac{\mu v_{\sigma_1}^2}{2 v_{\sigma_2}} \end{pmatrix}$$

On the other hand, for the CP-odd scalars

$$\mathcal{M}_I^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -2\mu v_{\sigma_2} & -\mu v_{\sigma_1} \\ 0 & -\mu v_{\sigma_1} & -\frac{\mu v_{\sigma_1}^2}{2 v_{\sigma_2}} \end{pmatrix}, \qquad \widehat{\mathcal{M}_I^2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{\mu(v_{\sigma_1}^2 + 4 v_{\sigma_2}^2)}{2 v_{\sigma_2}} \end{pmatrix},$$

where the mixing $J_1 - J_2$ is

$$\tan(2\theta) = \frac{2\,(\mathcal{M}_I^2)_{23}}{(\mathcal{M}_I^2)_{22} - (\mathcal{M}_I^2)_{33}} = \frac{4 v_{\sigma_1} v_{\sigma_2}}{4 v_{\sigma_2}^2 - v_{\sigma_1}^2}\,. \tag{20}$$

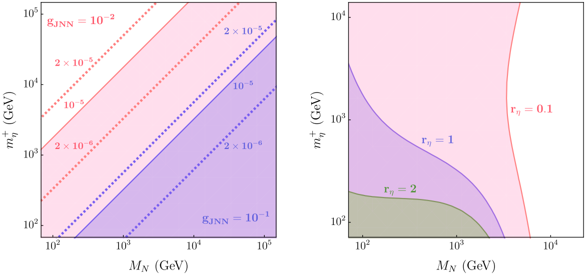


$$\mathcal{L}_{\ell\ell J} = J\,\bar{\ell}_\beta \left(S_L^{\beta\alpha}\, P_L + S_R^{\beta\alpha}\, P_R \right) \ell_\alpha + \text{h.c.}\,. \qquad (21)$$

with

$$g_{JNN} = \begin{cases} i\,\frac{\kappa}{\sqrt{2}} & \text{in models with one } \sigma \text{ singlet} \\ i\,\frac{\kappa}{\sqrt{2}}\cos\theta & \text{in models with two } \sigma \text{ singlets} \end{cases}$$

$$S_{L,R} \propto g_{JNN} \frac{M_N^2 - m_{\eta^+}^2 + m_{\eta^+}^2 \log\left(\frac{m_{\eta^+}^2}{M_N^2}\right)}{M_N^2 - m_{\eta^+}^2 + M_N^2 \log\left(\frac{m_{\eta^+}^2}{M_N^2}\right)}\,. \qquad (22)$$



Contours of $\mathrm{BR}(\mu \to eJ)$ in the $\left(M_N, m_{\eta^+}\right)$ plane. The colored regions correspond to the regions allowed by the current experimental bound on the branching ratio. On the left, g_{JNN} has been fixed to 10^{-1} (blue) and to 10^{-2} (pink), while $r_\eta = 1$ has been used. On the right, the coupling g_{JNN} was not fixed and three different values of the r_η ratio have been considered, 0.1 (pink), 1 (blue) and 2 (green).

$$\mathrm{BR}(\mu \to eJ) = \frac{m_\mu}{32\,\pi\,\Gamma_\mu}\left(|S_L^{e\mu}|^2 + |S_R^{e\mu}|^2\right) , \tag{23}$$

- We provided the condition for $U(1)_L$ charges must satisfy in order to recover the Scotogenic model in each of the 50 models.
- This UV extensions enrich the phenomenology of the Scotogenic model.
- We studied the effective coupling at one-loop level between the majoron and two charged leptons. Using experimental bounds for the transition $\mu \to eJ$ we set the allowed region in the new physic parameter space (m_η, m_N).
- Illustrated the possibility of having $\mathbb{Z}_2$ dark parity as an accidental symmetry after the SSB, obtaining 19 different models.

Thank you!