An ultraviolet completion for the Scotogenic model

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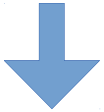
1. Introduction

The Standard Model (SM)
is an incomplete theory and therefore must be extended

- Experimental observation of neutrino flavor oscillations

- Nature of the dark matter of the universe



Many models have been proposed but one appealing possibility are radiative models

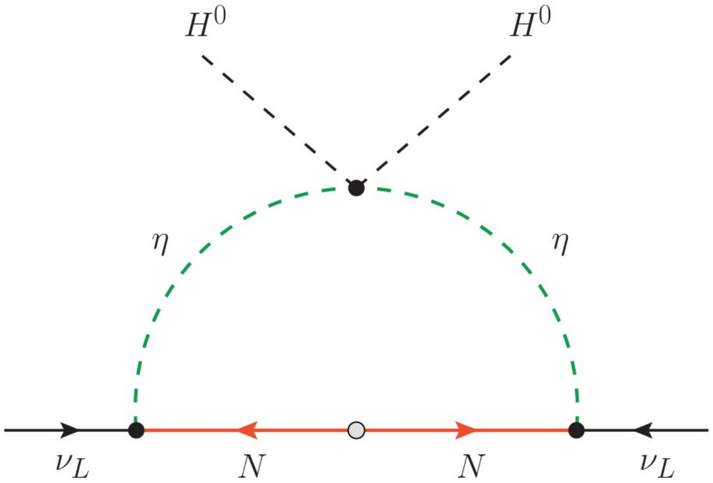
One of the most popular radiative models proposed to generate neutrino masses is the **Scotogenic model**.

[Ma, hep-ph/0601225]

Scotogenic model = SM + 3 singlet fermions + 1 scalar doublet + a dark $\mathbb{Z}_2$ parity

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
N	3	**1**	0	$-$
η	1	**2**	$1/2$	$-$

- It induces neutrino masses at the 1-loop level
- It obtains a weakly-interacting DM candidate



Yukawa and Majorana mass terms

$$\mathcal{L}_N = -\frac{M_{N_i}}{2}\overline{N_i^c}N_i + y_{i\alpha}\eta\overline{N_i}\ell_\alpha + \text{ h.c.}$$

Scalar potential

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger\eta + \frac{\lambda_1}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(H^\dagger H\right)\left(\eta^\dagger\eta\right)$$
$$+ \lambda_4\left(H^\dagger\eta\right)\left(\eta^\dagger H\right) + \frac{\lambda_5}{2}\left[\left(H^\dagger\eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

1. Introduction: Scalar sector

Scalar sector

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(H^\dagger H\right) \left(\eta^\dagger \eta\right)$$
$$+ \lambda_4 \left(H^\dagger \eta\right) \left(\eta^\dagger H\right) + \frac{\lambda_5}{2} \left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

- Vacuum configuration: $\langle H^0 \rangle = \frac{v}{\sqrt{2}} \quad , \quad \langle \eta^0 \rangle = 0$

⇨ The electroweak symmetry gets broken in the standard way.

⇨ The $\mathbb{Z}_2$ symmetry remains unbroken and the stability of the lightest $\mathbb{Z}_2$-charged particle is guaranteed.

- If all the scalar potential parameters are real, CP is conserved in the scalar sector.

⇨ The real and imaginary components of the neutral scalar doublet do not mix

$$\eta^0 = \frac{1}{\sqrt{2}} \left(\eta_R + i\, \eta_I\right)$$

1. Introduction: Scotogenic states' masses

Scalar masses

$$m^2_{\eta^+} = m^2_\eta + \lambda_3 \frac{v^2}{2}$$

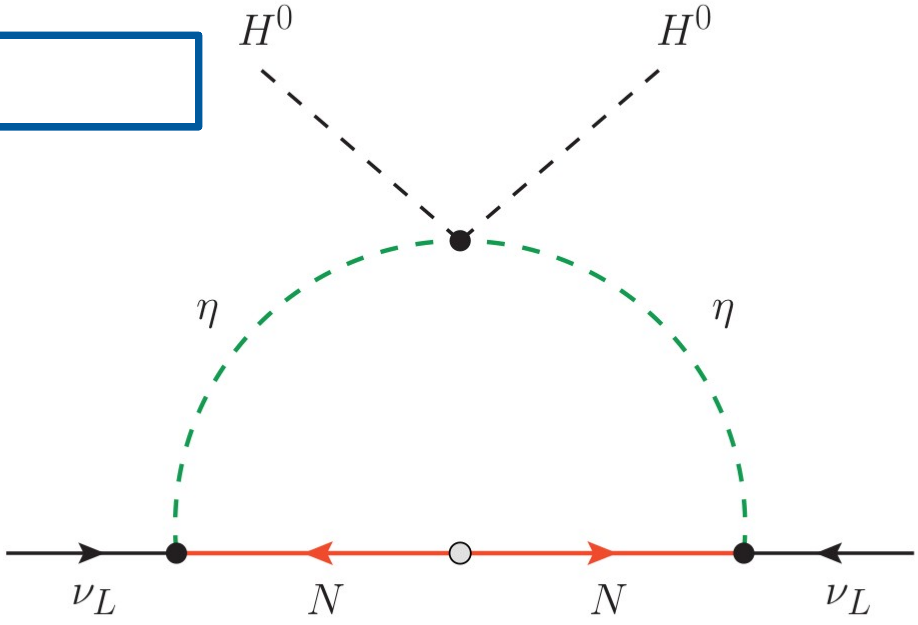
$$\eta^0 = \frac{1}{\sqrt{2}} (\eta_R + i\,\eta_I) \Rightarrow$$

$$m^2_R = m^2_\eta + (\lambda_3 + \lambda_4 + \lambda_5)\, \frac{v^2}{2}$$

$$m^2_I = m^2_\eta + (\lambda_3 + \lambda_4 - \lambda_5)\, \frac{v^2}{2}$$

Neutrino masses

The neutrino masses are forbidden at tree-level thanks to the Z_2 symmetry



$$m_\nu = \frac{\lambda_5 v^2}{32\pi^2} y^T M_R^{-1} f_{\text{loop}}\, y$$

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

1. Introduction: Open questions

⇨ There is no explanation for the smallness of the λ_5 parameter, although it's natural in the sense of 't Hooft. ['t Hooft, 1980]

⇨ The $\mathbb{Z}_2$ symmetry present in the model is *ad-hoc*.

This work:

We consider an ultraviolet completion of the Scotogenic model that provides a natural explanation for the smallness of the λ_5 parameter. Here the $\mathbb{Z}_2$ parity emerges at low energies from the breaking of a global U(1) symmetry.

2. The UV completion: particle content

Lepton and scalar particle content of the model and their representations under the gauge and global symmetries:

Field	Generations	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
ℓ_L	3	1	2	-1/2	1
e_R	3	1	1	-1	1
N	3	1	1	0	$\frac{1}{2}$
H	1	1	2	1/2	0
η	1	1	2	1/2	$-\frac{1}{2}$
Δ	1	1	3	1	-1
S	1	1	1	0	1

The old Scotogenic model (ℓ_L, e_R, N, H, η)

NEW (Δ, S)

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \Rightarrow \textbf{Scalar triplet}$$

$$S \Rightarrow \textbf{Scalar singlet}$$

2. The UV completion: the Lagrangian

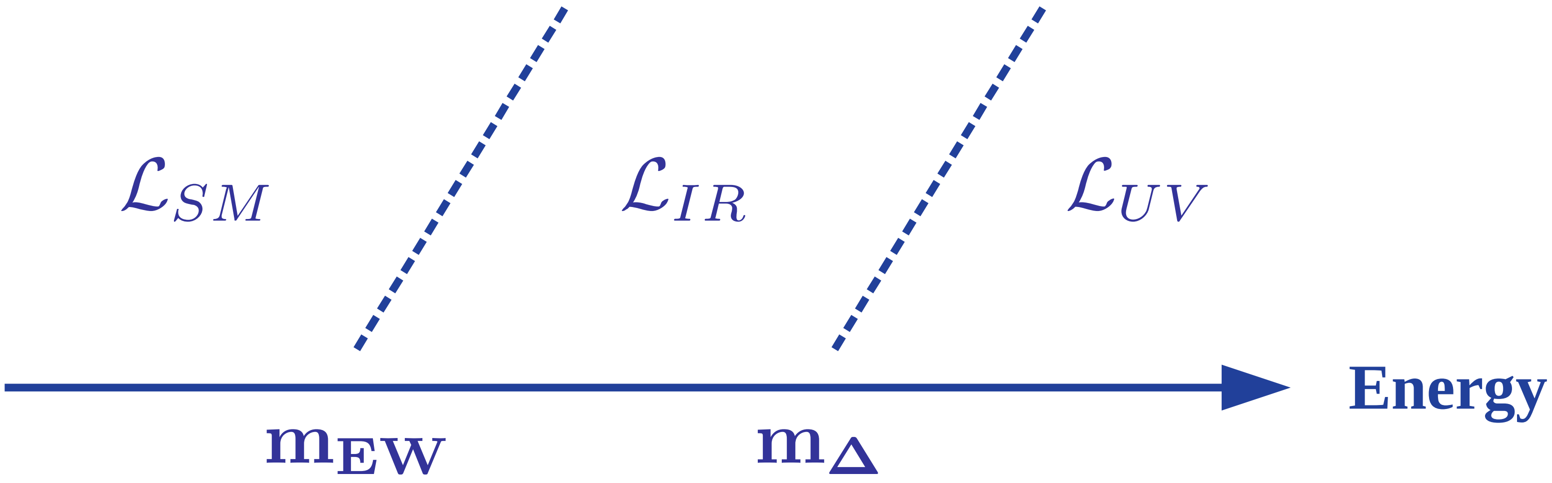
Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + y\, \overline{N} \eta\, i\sigma_2\, \ell_L + \kappa\, S^* \overline{N^c} N + \text{ h.c. } - \mathcal{V}_{\text{UV}}$$

Scalar potential

$$\begin{aligned}
\mathcal{V}_{\text{UV}} = & \; m_H^2 H^\dagger H + m_S^2 S^* S + m_\eta^2 \eta^\dagger \eta + m_\Delta^2 \,\text{Tr}\left(\Delta^\dagger \Delta\right) \\
& + \frac{1}{2}\lambda_1 \left(H^\dagger H\right)^2 + \frac{1}{2}\lambda_S \left(S^* S\right)^2 + \frac{1}{2}\lambda_2 \left(\eta^\dagger \eta\right)^2 \\
& + \frac{1}{2}\lambda_{\Delta 1}\, \text{Tr}\left(\Delta^\dagger \Delta\right)^2 + \frac{1}{2}\lambda_{\Delta 2} \left(\text{Tr}\, \Delta^\dagger \Delta\right)^2 + \lambda_3^S \left(H^\dagger H\right)\left(S^* S\right) \\
& + \lambda_3 \left(H^\dagger H\right)\left(\eta^\dagger \eta\right) + \lambda_3^\Delta \left(H^\dagger H\right) \text{Tr}\left(\Delta^\dagger \Delta\right) + \lambda_3^{\eta S} \left(\eta^\dagger \eta\right)\left(S^* S\right) \\
& + \lambda_3^{\eta\Delta} \left(\eta^\dagger \eta\right) \text{Tr}\left(\Delta^\dagger \Delta\right) + \lambda_3^{S\Delta} \left(S^* S\right) \text{Tr}\left(\Delta^\dagger \Delta\right) \\
& + \lambda_4 \left(H^\dagger \eta\right)\left(\eta^\dagger H\right) + \lambda_4^\Delta \left(H^\dagger \Delta^\dagger \Delta H\right) + \lambda_4^{\eta\Delta} \left(\eta^\dagger \Delta^\dagger \Delta \eta\right) \\
& + \left[\lambda_{HS\Delta} S \left(H^\dagger \Delta i\sigma_2 H^*\right) + \mu \left(\eta^\dagger \Delta i\sigma_2 \eta^*\right) + \text{ h.c. } \right]
\end{aligned}$$

2. The UV completion: the strategy



- We assume that the mass of the triplet scalar is much larger than any other mass scale in the model
- Then, we integrate out the triplet Δ and we keep operators up to dimension 6

$$\mathcal{L}_{IR} = \mathcal{L}_{\text{Scotogenic}} + extra + \mathcal{O}\left(\frac{1}{m_{\Delta}^3}\right)$$

2. The UV completion: the low-energy Lagrangian

Lagrangian

$$\mathcal{L}_{\rm IR} = \mathcal{L}_{\rm SM} + y\,\overline{N}\eta\, i\sigma_2\,\ell_L + \kappa\, S^*\,\overline{N^c}N + \text{ h.c. } - \mathcal{V}_{\rm IR}$$

Scalar potential

$$\begin{aligned}\mathcal{V}_{\rm IR} = {} & m_H^2 H^\dagger H + m_S^2 S^* S + m_\eta^2 \eta^\dagger \eta + \left(H^\dagger H\right)^2 \left[\frac{\lambda_1}{2} - \frac{|\lambda_{HS\Delta}|^2}{m_\Delta^2}\left(S^* S\right)\right] + \frac{\lambda_S}{2}\left(S^* S\right)^2 \\ & + \left(\eta^\dagger \eta\right)^2 \left(\frac{\lambda_2}{2} - \frac{|\mu|^2}{m_\Delta^2}\right) + \lambda_3^S \left(H^\dagger H\right)\left(S^* S\right) + \lambda_3 \left(H^\dagger H\right)\left(\eta^\dagger \eta\right) + \lambda_3^{\eta S}\left(\eta^\dagger \eta\right)\left(S^* S\right) \\ & + \lambda_4 \left(H^\dagger \eta\right)\left(\eta^\dagger H\right) - \left[\frac{\lambda_{HS\Delta}\mu^*}{m_\Delta^2} S\left(H^\dagger \eta\right)^2 + \text{ h.c. }\right] + \mathcal{O}\left(\frac{1}{m_\Delta^4}\right).\end{aligned}$$

2. The UV completion: the low-energy Lagrangian

Lagrangian

$$\mathcal{L}_{\rm IR} = \mathcal{L}_{\rm SM} + y\,\overline{N}\eta\, i\sigma_2\,\ell_L + \kappa\, S^* \overline{N^c} N + \text{ h.c. } - \mathcal{V}_{\rm IR}$$

Scalar potential

$$\mathcal{V}_{\rm IR} = m_H^2 H^\dagger H + m_S^2 S^* S + m_\eta^2 \eta^\dagger \eta + \left(H^\dagger H\right)^2 \left[\frac{\lambda_1}{2} - \frac{|\lambda_{HS\Delta}|^2}{m_\Delta^2}\left(S^* S\right)\right] + \frac{\lambda_S}{2}\left(S^* S\right)^2$$
$$+ \left(\eta^\dagger \eta\right)^2 \left(\frac{\lambda_2}{2} - \frac{|\mu|^2}{m_\Delta^2}\right) + \lambda_3^S \left(H^\dagger H\right)\left(S^* S\right) + \lambda_3 \left(H^\dagger H\right)\left(\eta^\dagger \eta\right) + \lambda_3^{\eta S}\left(\eta^\dagger \eta\right)\left(S^* S\right)$$
$$+ \lambda_4 \left(H^\dagger \eta\right)\left(\eta^\dagger H\right) - \left[\frac{\lambda_{HS\Delta}\mu^*}{m_\Delta^2} S \left(H^\dagger \eta\right)^2 + \text{ h.c. }\right] + \mathcal{O}\left(\frac{1}{m_\Delta^4}\right).$$

Neutral fields:

$$H^0 = \frac{1}{\sqrt{2}}\left(v_H + \phi + iA\right)$$
$$S = \frac{1}{\sqrt{2}}\left(v_S + \rho + iJ\right)$$

$$\mathrm{U(1)_L} \xrightarrow{v_S} \mathbb{Z}_2$$

2. The UV completion: the low-energy Lagrangian

Lagrangian

$$\mathcal{L}_{\rm IR} = \mathcal{L}_{\rm SM} + y\, \overline{N} \eta\, i\sigma_2\, \ell_L + \kappa\, S^* \overline{N^c} N + \text{ h.c. } - \mathcal{V}_{\rm IR}$$

Scalar potential

$$\mathcal{V}_{\rm IR} = m_H^2 H^\dagger H + m_S^2 S^* S + m_\eta^2 \eta^\dagger \eta + \left(H^\dagger H\right)^2 \left[\frac{\lambda_1}{2} - \frac{|\lambda_{HS\Delta}|^2}{m_\Delta^2} \left(S^* S\right)\right] + \frac{\lambda_S}{2} \left(S^* S\right)^2$$
$$+ \left(\eta^\dagger \eta\right)^2 \left(\frac{\lambda_2}{2} - \frac{|\mu|^2}{m_\Delta^2}\right) + \lambda_3^S \left(H^\dagger H\right)\left(S^* S\right) + \lambda_3 \left(H^\dagger H\right)\left(\eta^\dagger \eta\right) + \lambda_3^{\eta S} \left(\eta^\dagger \eta\right)\left(S^* S\right)$$
$$+ \lambda_4 \left(H^\dagger \eta\right)\left(\eta^\dagger H\right) - \left[\frac{\lambda_{HS\Delta} \mu^*}{m_\Delta^2} S \left(H^\dagger \eta\right)^2 + \text{ h.c. }\right] + \mathcal{O}\left(\frac{1}{m_\Delta^4}\right).$$

$$H^0 = \frac{1}{\sqrt{2}} \left(v_H + \phi + i A\right)$$

$$S = \frac{1}{\sqrt{2}} \left(v_S + \rho + i J\right)$$

$$\frac{\lambda_5}{2} \equiv - \frac{\lambda_{HS\Delta} \mu^* v_S}{\sqrt{2} m_\Delta^2} \ll 1$$

2. The UV completion: Z_2 -even scalars

CP-even

$$H^0 = \frac{1}{\sqrt{2}}(v_H + \phi + iA) \qquad S = \frac{1}{\sqrt{2}}(v_S + \rho + iJ)$$

Mass matrix

$$\mathcal{M}_R^2 = \begin{pmatrix} v_H^2\left(\lambda_1 - \frac{v_S^2|\lambda_{HS\Delta}|^2}{m_\Delta^2}\right) & v_H v_S\left(\lambda_3^S - \frac{v_H^2|\lambda_{HS\Delta}|^2}{m_\Delta^2}\right) \\ v_H v_S\left(\lambda_3^S - \frac{v_H^2|\lambda_{HS\Delta}|^2}{m_\Delta^2}\right) & v_S^2 \lambda_S \end{pmatrix}$$

Diagonalization

$$V_R^T \mathcal{M}_R^2 V_R = \mathrm{diag}\left(m_h^2, m_\Phi^2\right)$$

Mixing angle

$$\tan(2\alpha) = \frac{2\left(\mathcal{M}_R^2\right)_{12}}{\left(\mathcal{M}_R^2\right)_{11} - \left(\mathcal{M}_R^2\right)_{22}} \approx 2\frac{\lambda_3^S}{\lambda_S}\frac{v_H}{v_S}$$

$v_H \ll v_S$

The lightest of the resulting two mass eigenstates is to be identified with the Higgs-like state h

$m_h \approx 125\,\mathrm{GeV}$

2. The UV completion: Z_2 -even scalars

CP-odd

$$H^0 = \frac{1}{\sqrt{2}}(v_H + \phi + iA) \qquad S = \frac{1}{\sqrt{2}}(v_S + \rho + iJ)$$

Mass matrix

$$\mathcal{M}_I^2 = \begin{pmatrix} m_H^2 + \frac{v_H^2}{2}\lambda_1 + \frac{v_S^2}{2}\lambda_3^S - \frac{v_H^2 v_S^2 |\lambda_{HS\Delta}|^2}{2m_\Delta^2} & 0 \\ 0 & m_S^2 + \frac{v_S^2}{2}\lambda_S + \frac{v_H^2}{2}\lambda_3^S - \frac{v_H^4 |\lambda_{HS\Delta}|^2}{4m_\Delta^2} \end{pmatrix}$$

⇨ A is the would-be Goldstone boson that becomes the longitudinal component of the Z boson.

⇨ J is the majoron, a massless Goldstone boson associated to the spontaneous breaking of lepton number.

⇨ The low-energy theory is the Scotogenic model with additional scalar fields

2. The UV completion: Z_2 -odd states

Scalars

$$\eta^0 = \frac{1}{\sqrt{2}} \left(\eta_R + i\,\eta_I\right)$$

$$m_{\eta_R}^2 = m_\eta^2 + \lambda_3^S \frac{v_S^2}{2} + \left(\lambda_3 + \lambda_4 - \frac{2\lambda_{HS\Delta}\mu v_S}{\sqrt{2}m_\Delta^2}\right)\frac{v_H^2}{2}$$

$$m_{\eta_I}^2 = m_\eta^2 + \lambda_3^S \frac{v_S^2}{2} + \left(\lambda_3 + \lambda_4 + \frac{2\lambda_{HS\Delta}\mu v_S}{\sqrt{2}m_\Delta^2}\right)\frac{v_H^2}{2}$$

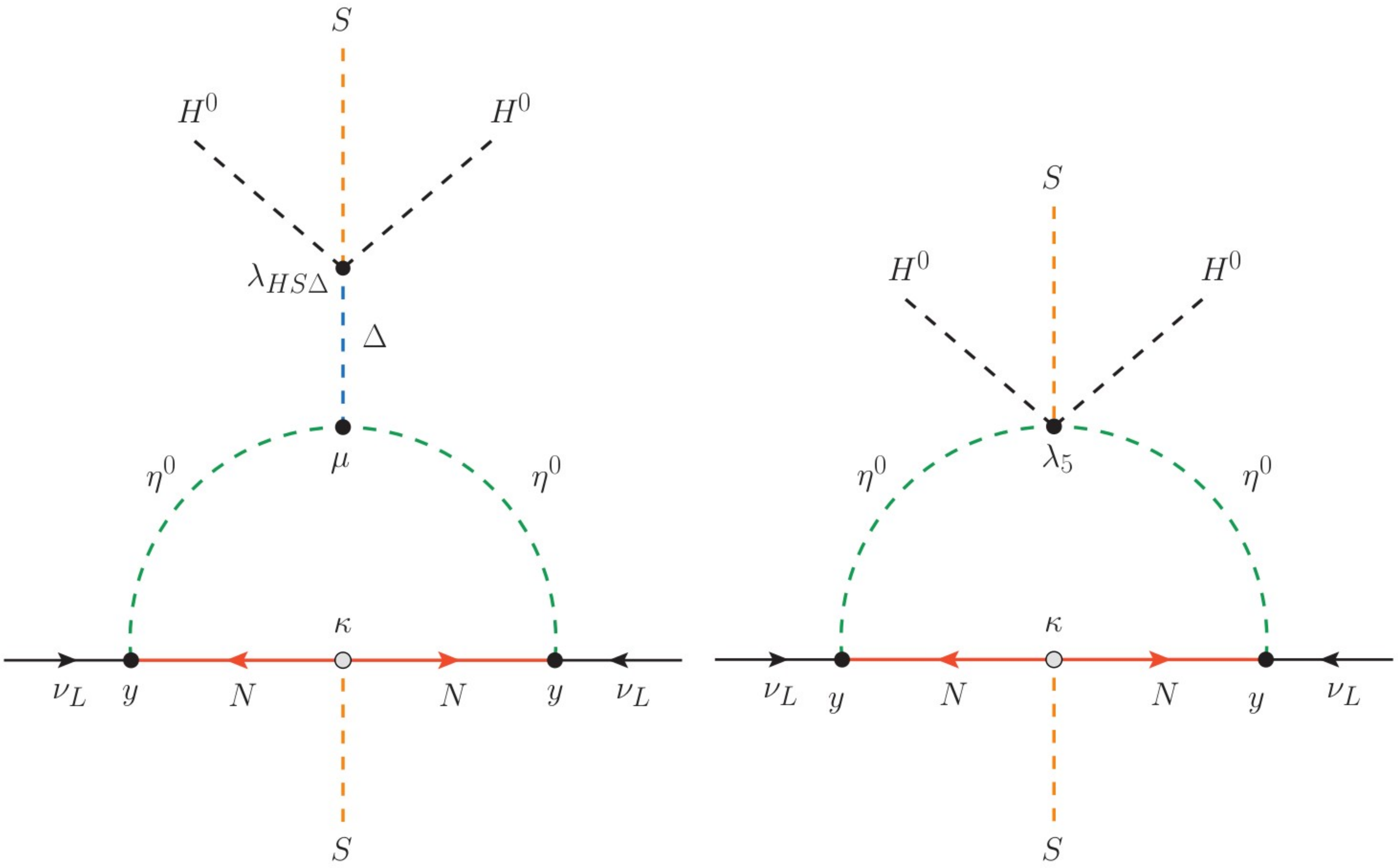
$$m_{\eta^+}^2 = m_\eta^2 + \lambda_3 \frac{v_H^2}{2} + \lambda_3^{\eta S} \frac{v_S^2}{2}$$

$$m_{\eta_R}^2 - m_{\eta_I}^2 = -\frac{4\lambda_{HS\Delta}\mu v_S}{\sqrt{2}m_\Delta^2}\frac{v_H^2}{2} \equiv \lambda_5 v_H^2$$

Fermions

Majorana mass term: $\dfrac{M_N}{2}\overline{N}^c N \;\Rightarrow\; M_N = \sqrt{2}\kappa v_S$

2. The UV completion: neutrino masses



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

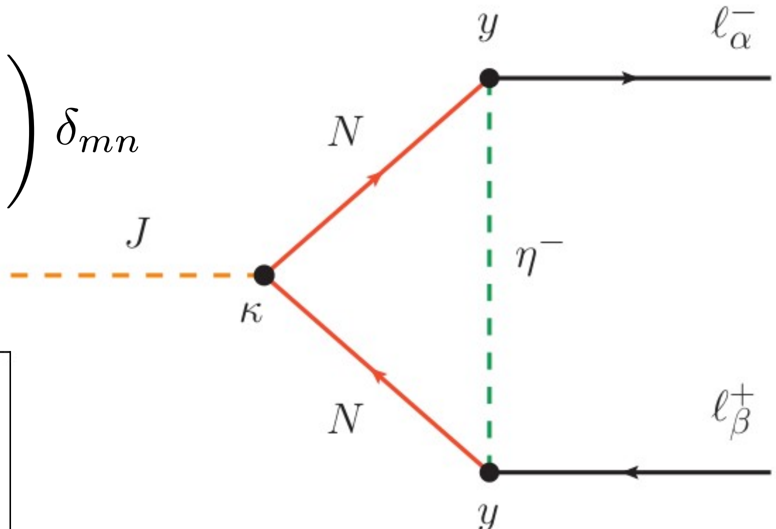
$$m_0^2 = m_\eta^2 + \lambda_3^S \, v_S^2/2 + (\lambda_3 + \lambda_4) \, v_H^2/2$$

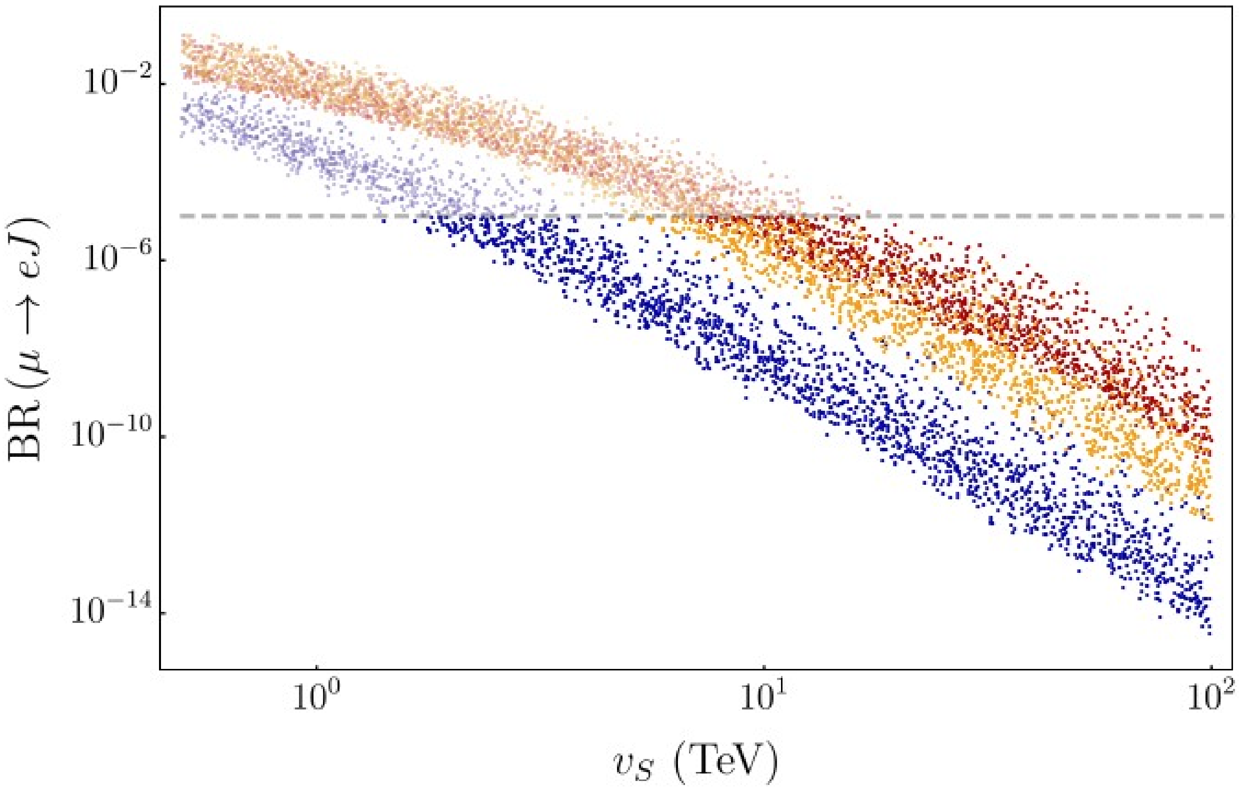
2. The UV completion: phenomenology

Majoron couplings to charged leptons

$$\mathcal{L}_{J\ell\ell} = -\frac{iJ}{16\pi^2 v_S}\bar{\ell}\left(M_\ell y^\dagger \Gamma y P_L - y^\dagger \Gamma y M_\ell P_R\right)\ell$$

$$\Gamma_{mn} = \frac{M_{N_n}^2}{\left(M_{N_n}^2 - m_{\eta^+}^2\right)^2}\left(M_{N_n}^2 - m_{\eta^+}^2 + m_{\eta^+}^2 \log\frac{m_{\eta^+}^2}{M_{N_n}^2}\right)\delta_{mn}$$





TWIST collaboration limit

$$\mathrm{BR}(\mu \to eJ) < 10^{-5}$$

[Bayes *et al.*, hep-ex/1409.0638]

Near future limits

$$\mathrm{BR}(\mu \to eJ) < 7.3 \times 10^{-8}$$

[Perrevoort, PhD thesis]

2. The UV completion: phenomenology

Collider signatures

Interaction Lagrangian of the CP-even scalar *h* to a pair of majorons: $\mathcal{L}_{hJJ} = \frac{1}{2} g_{hJJ}\, h\, J^2$

$$g_{hJJ} = v_S \lambda_S \sin\alpha + \left(\lambda_3^S - \frac{v_H^2 \left|\lambda_{HS\Delta}\right|^2}{m_\Delta^2} \right) v_H \cos\alpha$$

Experimental constraint

$$\mathrm{BR}(h \to JJ) < 0.11 \text{ at } 95\% \text{ C.L.}$$

⇒ $\lambda_3^S \lesssim 10^{-2}$

[ATLAS Collaboration, hep-ex/1904.05105]

Dark matter

The new scalars can alter the DM phenomenology substantially. In the case of fermion DM, the annihilation channels

$$N_1 N_1 \to \text{ SM SM } , \; N_1 N_1 \to JJ$$

may reduce the tuning normally required in the original Scotogenic model with fermion DM.

[Vicente, Yaguna, hep-ph/1412.2545]

3. Summary and discussion

- The Scotogenic model is a very economical scenario for neutrino masses that includes a dark matter candidate

- However, an ultraviolet completion for the model may offer interesting possibilities:

  - A natural explanation for the smallness of the λ_5 parameter due to large scale suppression.

  - The $\mathbb{Z}_2$ symmetry is obtained from spontaneous lepton number breaking.

  - Additional particles at low energies. In our case, a massive scalar and a massless Goldstone boson, the majoron.

  - The new states and interactions can have a remarkable impact on the phenomenology of the model.

Thanks for your attention!