An ultraviolet completion for the Scotogenic model

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Work in collaboration with

Pablo Escribano

[arXiv:2107.10265]

NuCo 2021

Colombia

There are MANY Majorana neutrino mass models...

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

There are MANY Majorana neutrino mass models...

Review: [Cai, Herrero-García, Schmidt, AV, Volkas, 2017]

See talk by Antonio Cárcamo

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

Loop suppression

Dark matter candidate

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

Outline

Introduction

Finished already!

The Scotogenic model

A quick review of the well-known Scotogenic model

An UV completion for the Scotogenic model

An UV extension that addresses some of its drawbacks and leads to new pheno

The Scotogenic model

Also known as...

The inert doublet model

The radiative seesaw

Ma's model

The Scotogenic model

[Ma, 2006]

σκότος

skotos = darkness

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

Inert (or dark) doublet

Dark Matter!

$$\mathcal{L}_N = \overline{N_i} \not{\partial} N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

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

The Scotogenic model

[Ma, 2006]

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

Inert scalar sector: $\eta^\pm$ $\quad \eta^0 = (\eta_R + i \eta_I)/\sqrt{2}$

$$\begin{aligned} m_{\eta^+}^2 &= m_\eta^2 + \lambda_3 \langle H^0 \rangle^2 \\ m_R^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5)\,\langle H^0 \rangle^2 \\ m_I^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5)\,\langle H^0 \rangle^2 \end{aligned} \quad \Longrightarrow \quad \mathrm{m}_R^2 - m_I^2 = 2\,\lambda_5\,\langle H^0 \rangle^2$$

Radiative neutrino masses

[Ma, 2006]

Tree-level:

Forbidden by the $\mathbb{Z}_2$ symmetry

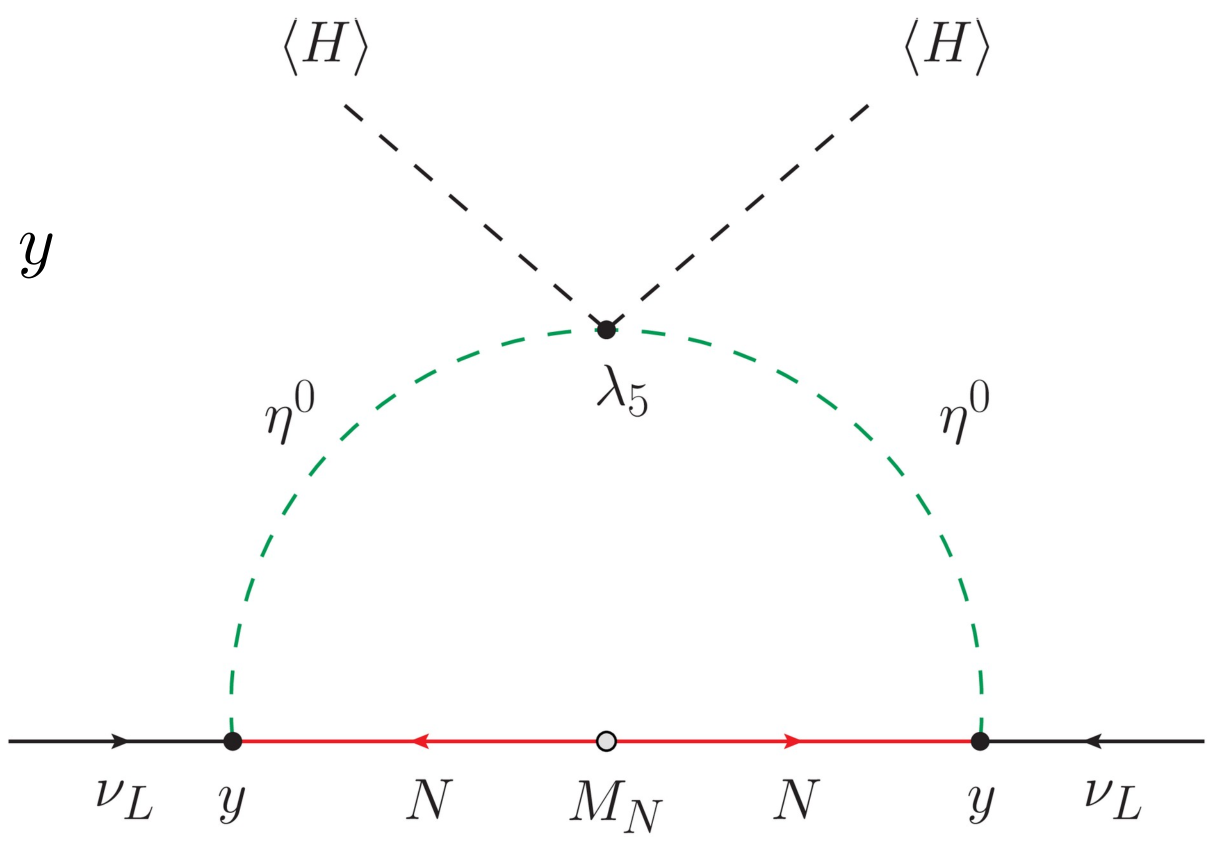
Radiative generation of neutrino masses

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

Dark particles in the loop

[Other variations in Restrepo, Zapata, Yaguna, 2013]

1-loop neutrino masses



Radiative neutrino masses

[Ma, 2006]

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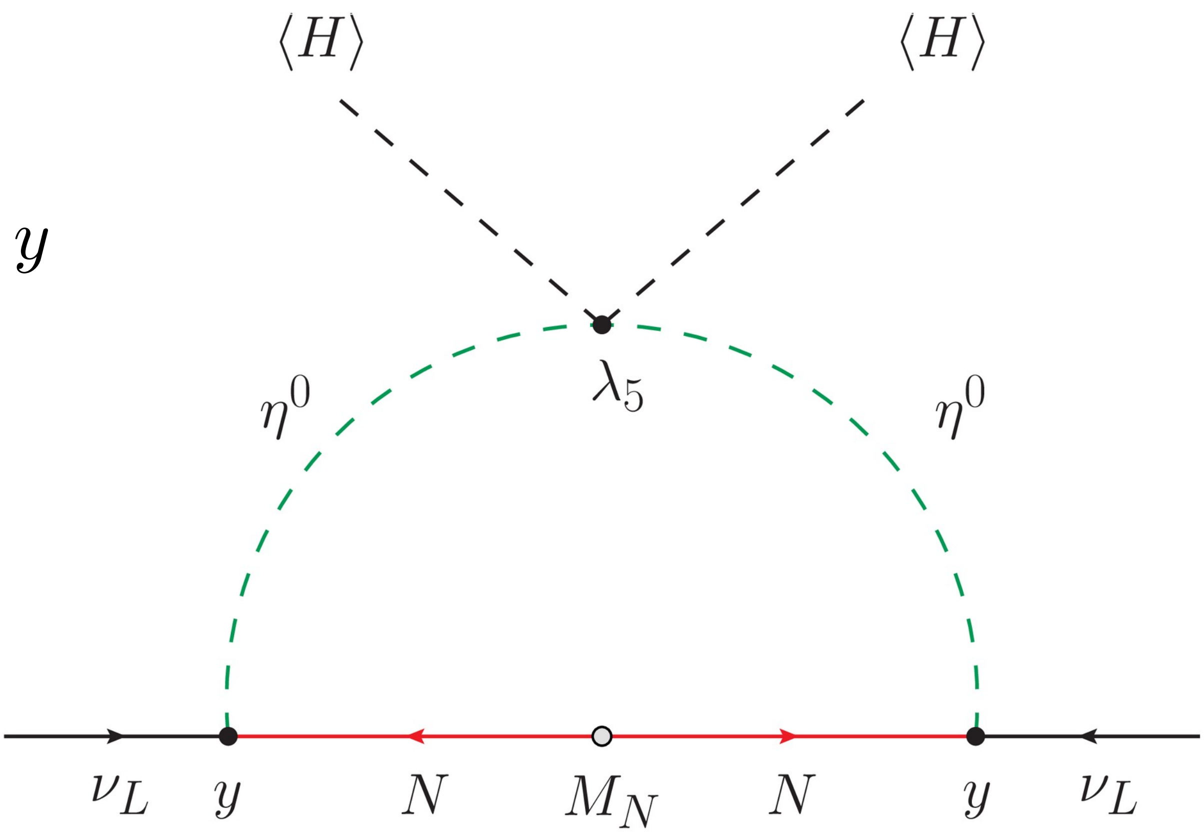


Dark matter

The lightest particle charged under $\mathbb{Z}_2$ is stable: dark matter candidate

Fermion Dark Matter: N_1

- It can only be produced via Yukawa interactions
- Potential problems with lepton flavor violation: is it compatible with the current bounds?

Scalar Dark Matter: the lightest neutral η scalar, η_R or η_I

- It also has gauge interactions
- Not correlated to lepton flavor violation

Drawbacks

There is no explanation for the smallness of the λ_5 parameter

Although it's natural ['t Hooft, 1980]

The $\mathbb{Z}_2$ Scotogenic parity is an *ad-hoc* symmetry

These issues can be simultaneously addressed in ultraviolet completions of the Scotogenic model

Chuck Norris fact of the day

Chuck Norris can divide by zero.

An UV completion for the Scotogenic model

Work in collaboration with **Pablo Escribano**

[arXiv:2107.10265]

Ultraviolet theory

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	$-\frac{1}{2}$
NEW! → Δ	1	1	3	1	-1
NEW! → S	1	1	1	0	1

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

Scalar triplet

$$S$$

Scalar singlet

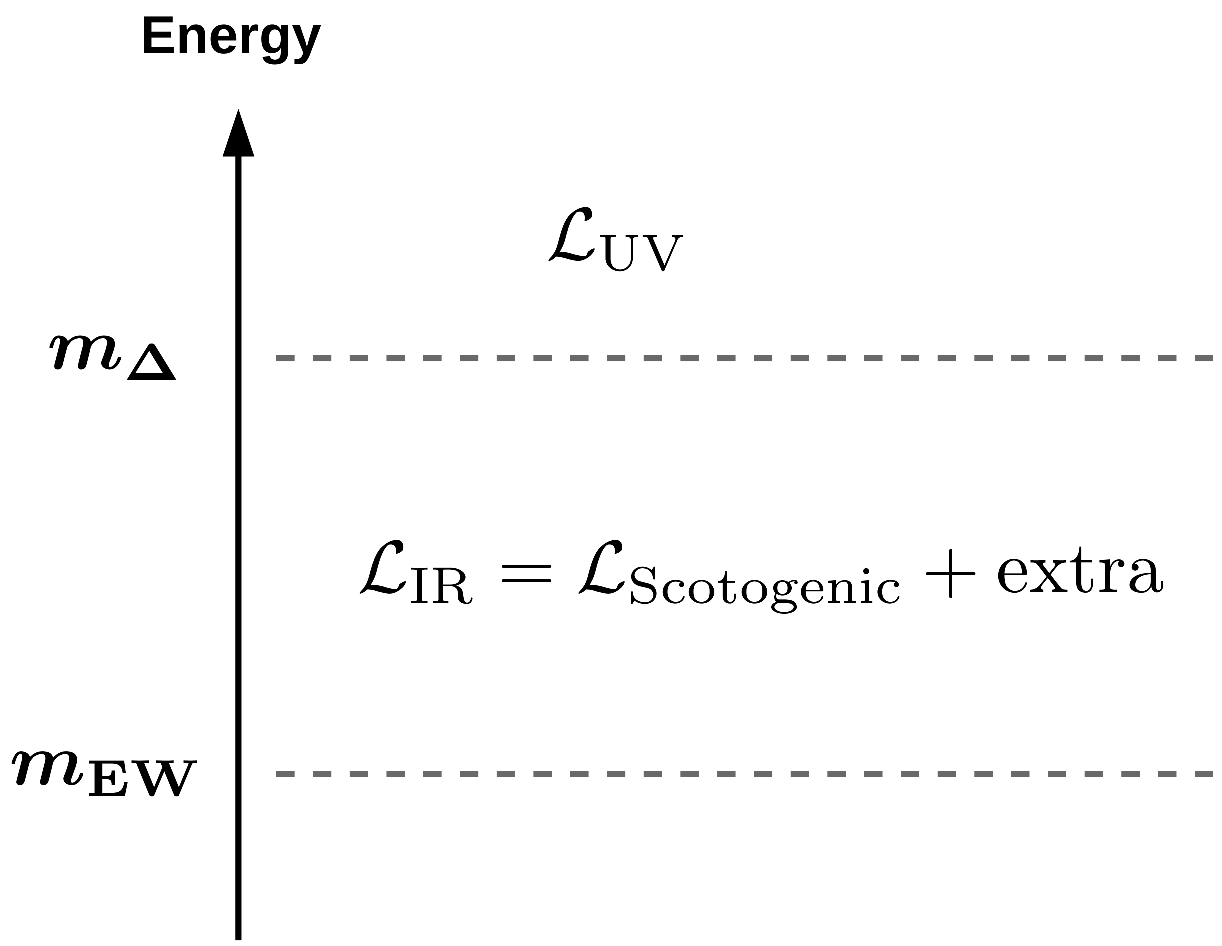
Ultraviolet theory

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

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

Other terms are forbidden by lepton number

Low-energy theory



Assumption

$m_\Delta \gg$ other mass scales

Strategy

Integrate out Δ and keep contributions up to dimension 6

$$\mathcal{O}\left(\frac{1}{m_\Delta^2}\right)$$

Low-energy theory

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

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

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$$\langle H^0\rangle = \frac{v_H}{\sqrt{2}} \qquad \langle S\rangle = \frac{v_S}{\sqrt{2}}$$

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

Symmetry breaking

[Ma, 2015]
[Centelles Chuliá et al, 2019]

Low-energy theory

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

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

Automatically small
λ_5 coupling

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Automatically small
λ_5 coupling

$\mathbb{Z}_2$-even scalars

$$H^0 = \frac{1}{\sqrt{2}} \left(v_H + \phi + i\, A \right) \qquad S = \frac{1}{\sqrt{2}} \left(v_S + \rho + i\, J \right)$$

$\mathbb{Z}_2$-even scalars

$$H^0 = \frac{1}{\sqrt{2}} \left(v_H + \phi + i\, A \right) \qquad S = \frac{1}{\sqrt{2}} \left(v_S + \rho + i\, J \right)$$

CP-even scalars

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

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

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

Higgs-like boson @ LHC

Mixing angle

$$\tan(2\alpha) \approx 2\, \frac{\lambda_3^S}{\lambda_S}\, \frac{v_H}{v_S}$$

$\mathbb{Z}_2$-even scalars

$$H^0 = \frac{1}{\sqrt{2}}\left(v_H + \phi + i\, A\right) \qquad\qquad S = \frac{1}{\sqrt{2}}\left(v_S + \rho + i\, J\right)$$

CP-odd scalars

A : would-be Goldstone absorbed by the Z

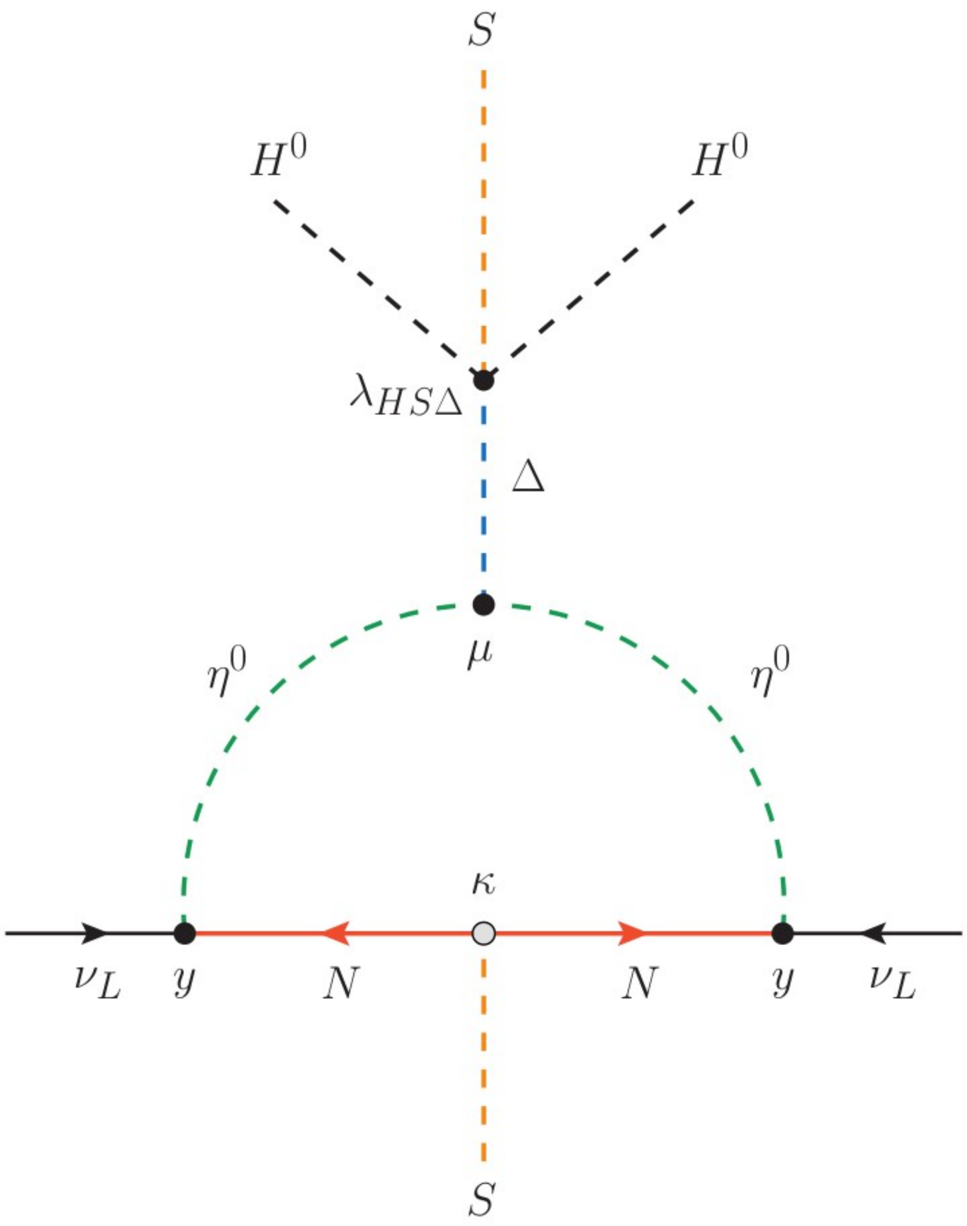
J : massless Goldstone boson, **the majoron**

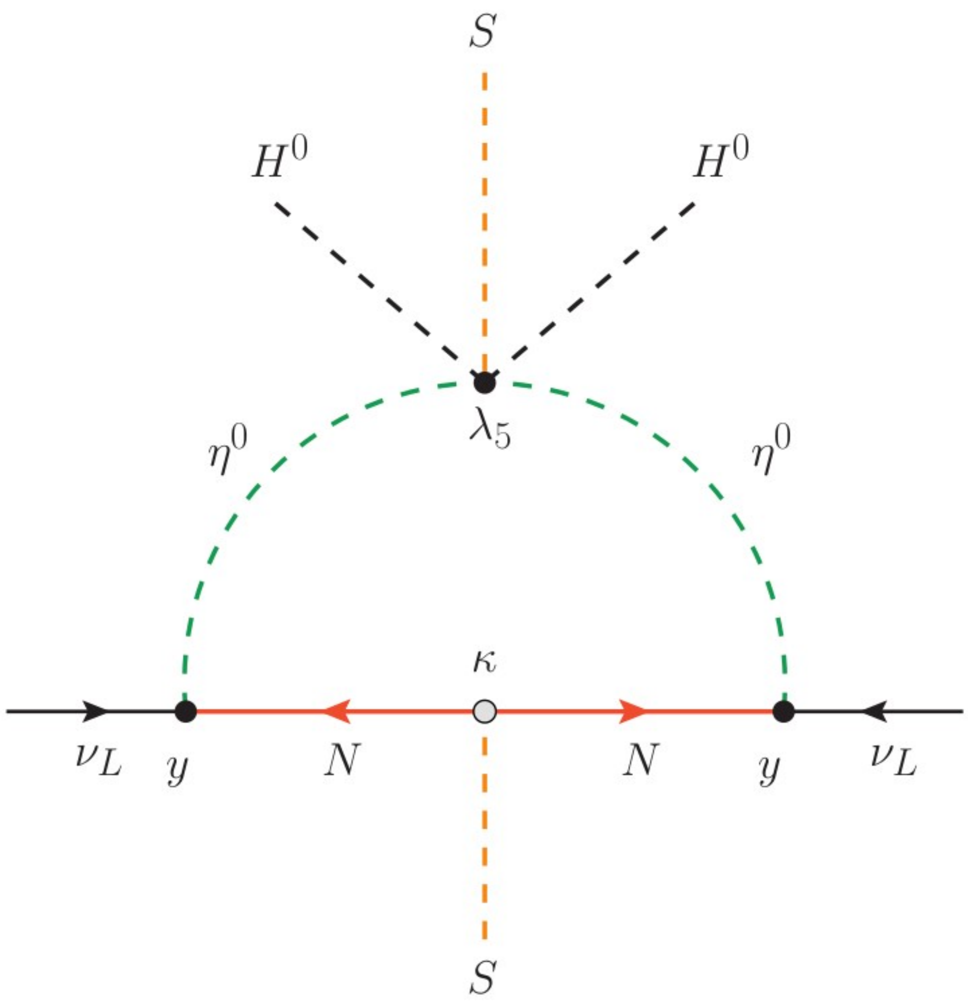
Singlet state

Must have suppressed couplings to matter

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

Neutrino masses

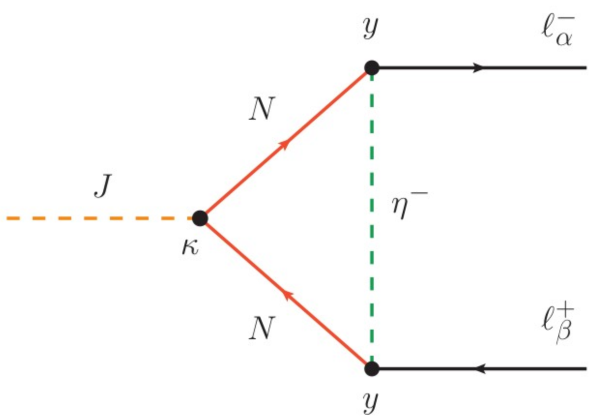


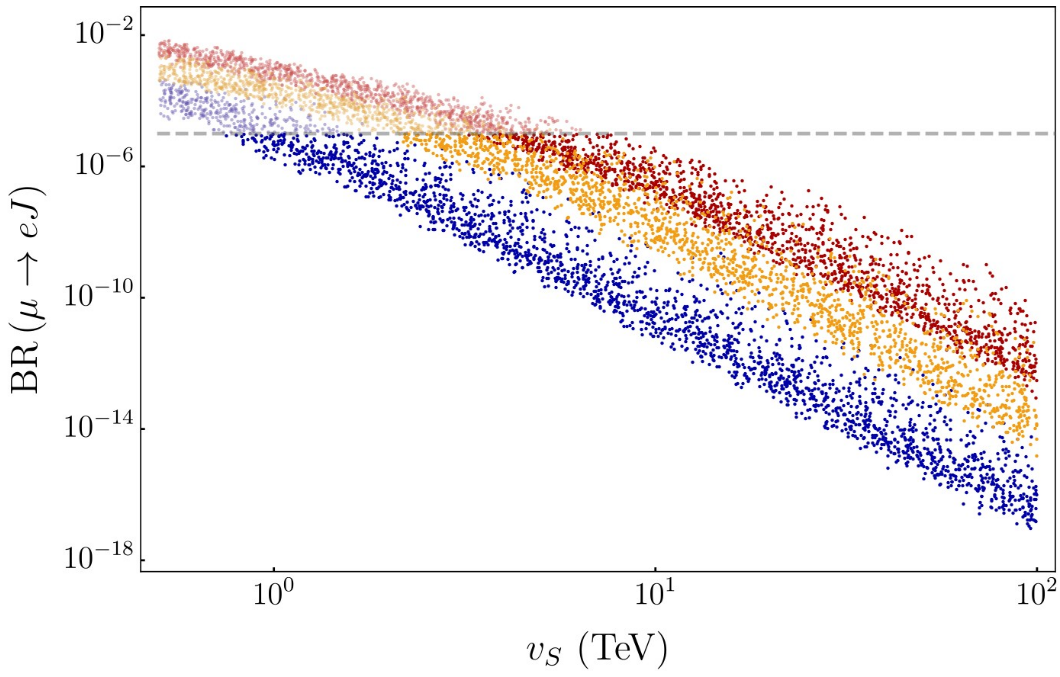


Phenomenology

Majoron couplings to charged leptons

1-loop coupling





$$\mathcal{L}_{J\ell\ell} = \frac{i\,J}{32\,\pi^2\,v_S}\,\overline{\ell}\left(M_\ell\,y^\dagger\,\Gamma\,y\,P_L - y^\dagger\,\Gamma\,y\,M_\ell\,P_R\right)\ell$$

$$\Gamma_{mn} = \frac{M_{N_n}^2}{\left(M_{N_n}^2 - m_{\eta^+}^2\right)^3}\left(M_{N_n}^4 - m_{\eta^+}^4 + 2\,M_{N_n}^2\,m_{\eta^+}^2\,\log\frac{m_{\eta^+}^2}{M_{N_n}^2}\right)\delta_{mn}$$

Sizable rates for low lepton number breaking scales

Phenomenology

Collider signatures

Invisible Higgs decay : $h \to J\,J$

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

$$\Longrightarrow \lambda_3^S \lesssim 10^{-2}$$

Dark matter

New production mechanisms
(particulary relevant for fermion DM)

$$N_1\,N_1 \longleftrightarrow \mathrm{SM}\,\mathrm{SM}$$

$$N_1\,N_1 \longleftrightarrow J\,J$$

Mediated by the new scalars

[Bonilla et al, 2020]

Final discussion

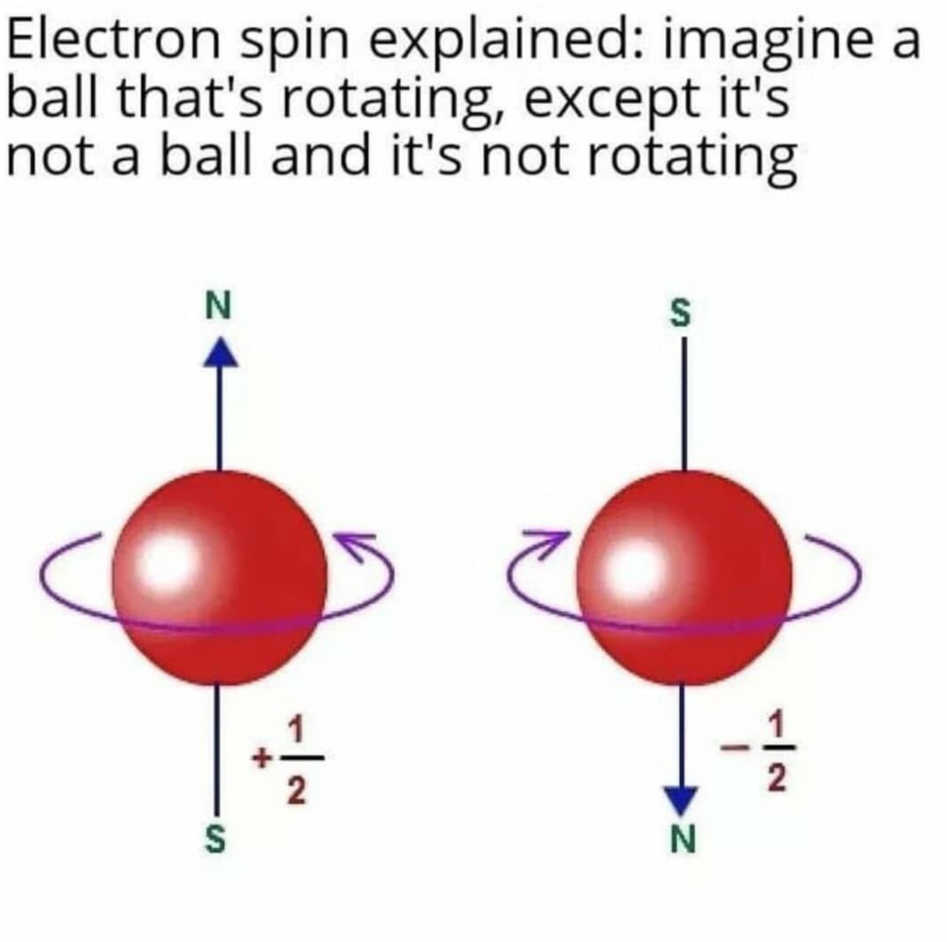
Final discussion

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

An ultraviolet completion for the Scotogenic model:

- Automatically small λ_5 coupling due to large scale suppression
- $\mathbb{Z}_2$ parity from spontaneous lepton number breaking
- Additional degrees of freedom at low energies: massive scalar + massless majoron
- Novel phenomenological predictions: lepton flavor violation (with majorons), Higgs physics and dark matter

Thanks for your attention!



Backup slides

A philosophical moment

Occam's razor:

The simplest explanation is the correct one

Occam's laser:

The most awesome explanation is the correct one

Occam's hammer:

My explanation is the correct one

All credit goes to
Alberto Aparici