An ultraviolet completion for the Scotogenic model

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In collaboration with

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7th IBS-ICTP-MultiDark Workshop

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

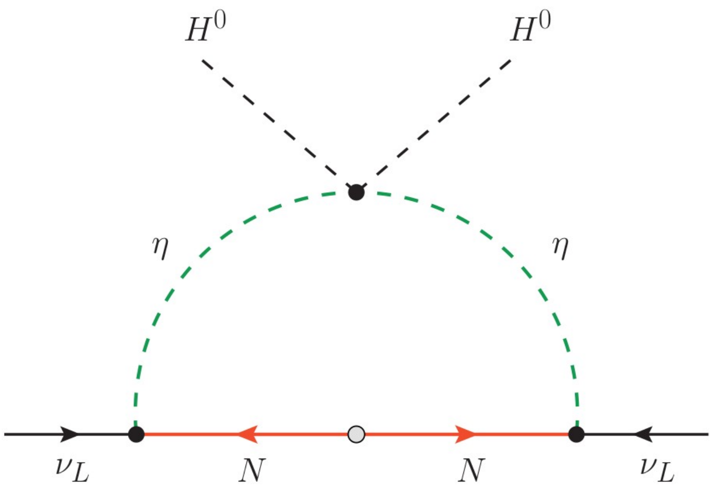
One of the most popular radiative models proposed to generate neutrino masses is the **Scotogenic model**.

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

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

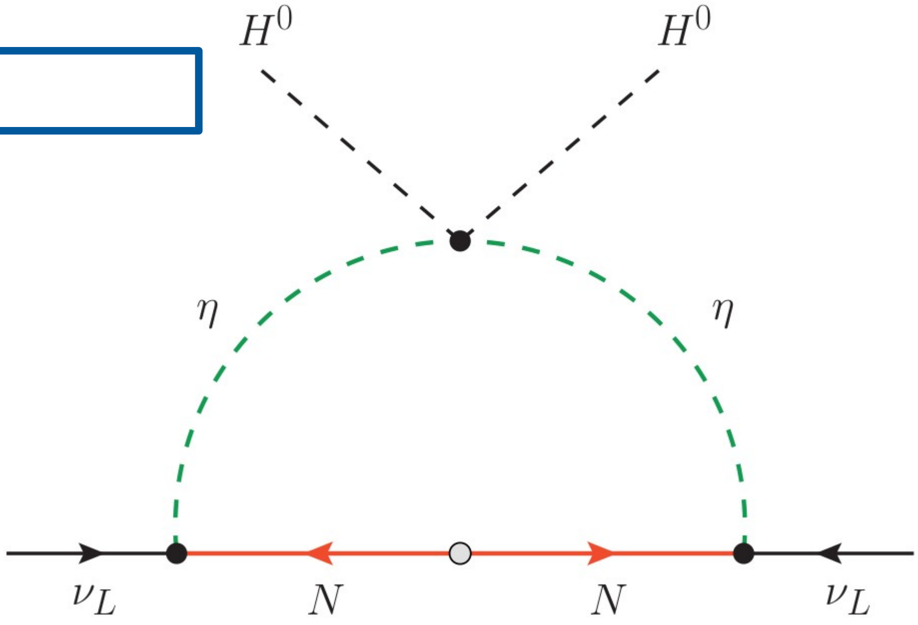
$$\eta^0 = \frac{1}{\sqrt{2}} \left(\eta_R + i\, \eta_I \right) \Rightarrow$$

$$m_R^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5) \frac{v^2}{2}$$

$$m_I^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5) \frac{v^2}{2}$$

Neutrino masses

The neutrino masses are forbidden at tree-level thanks to the $\mathbb{Z}_2$ symmetry



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

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

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	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
The old Scotogenic model	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
	S	1	1	1	0	1

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

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

2. The UV completion: the Lagrangian

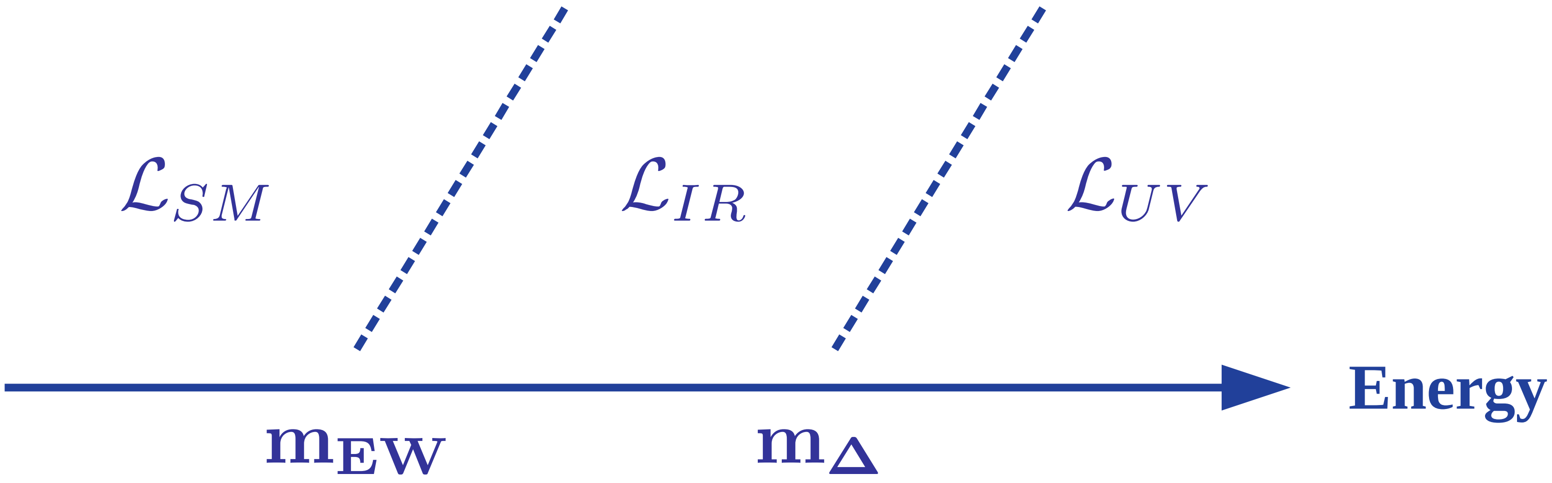
Lagrangian

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

Scalar potential

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

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

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

Scalar potential

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

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

$$\mathcal{V}_{\rm IR} = m_H^2 H^\dagger H + m_S^2 S^* S + m_\eta^2 \eta^\dagger \eta + \left(H^\dagger H\right)^2 \left[\frac{\lambda_1}{2} - \frac{|\lambda_{HS\Delta}|^2}{m_\Delta^2}\left(S^* S\right)\right] + \frac{\lambda_S}{2}\left(S^* S\right)^2$$

$$+ \left(\eta^\dagger \eta\right)^2 \left(\frac{\lambda_2}{2} - \frac{|\mu|^2}{m_\Delta^2}\right) + \lambda_3^S \left(H^\dagger H\right)\left(S^* S\right) + \lambda_3 \left(H^\dagger H\right)\left(\eta^\dagger \eta\right) + \lambda_3^{\eta S}\left(\eta^\dagger \eta\right)\left(S^* S\right)$$

$$+ \lambda_4 \left(H^\dagger \eta\right)\left(\eta^\dagger H\right) - \left[\frac{\lambda_{HS\Delta}\mu^*}{m_\Delta^2} S \left(H^\dagger \eta\right)^2 + \text{ h.c. }\right] + \mathcal{O}\left(\frac{1}{m_\Delta^4}\right).$$

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

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

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

2. The UV completion: Z_2 -even scalars

CP-even

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

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

$$V_R^T \mathcal{M}_R^2 V_R = \mathrm{diag}\left(m_{h_1}^2, m_{h_2}^2\right)$$

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

2. The UV completion: Z_2 -even scalars

CP-odd

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

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

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

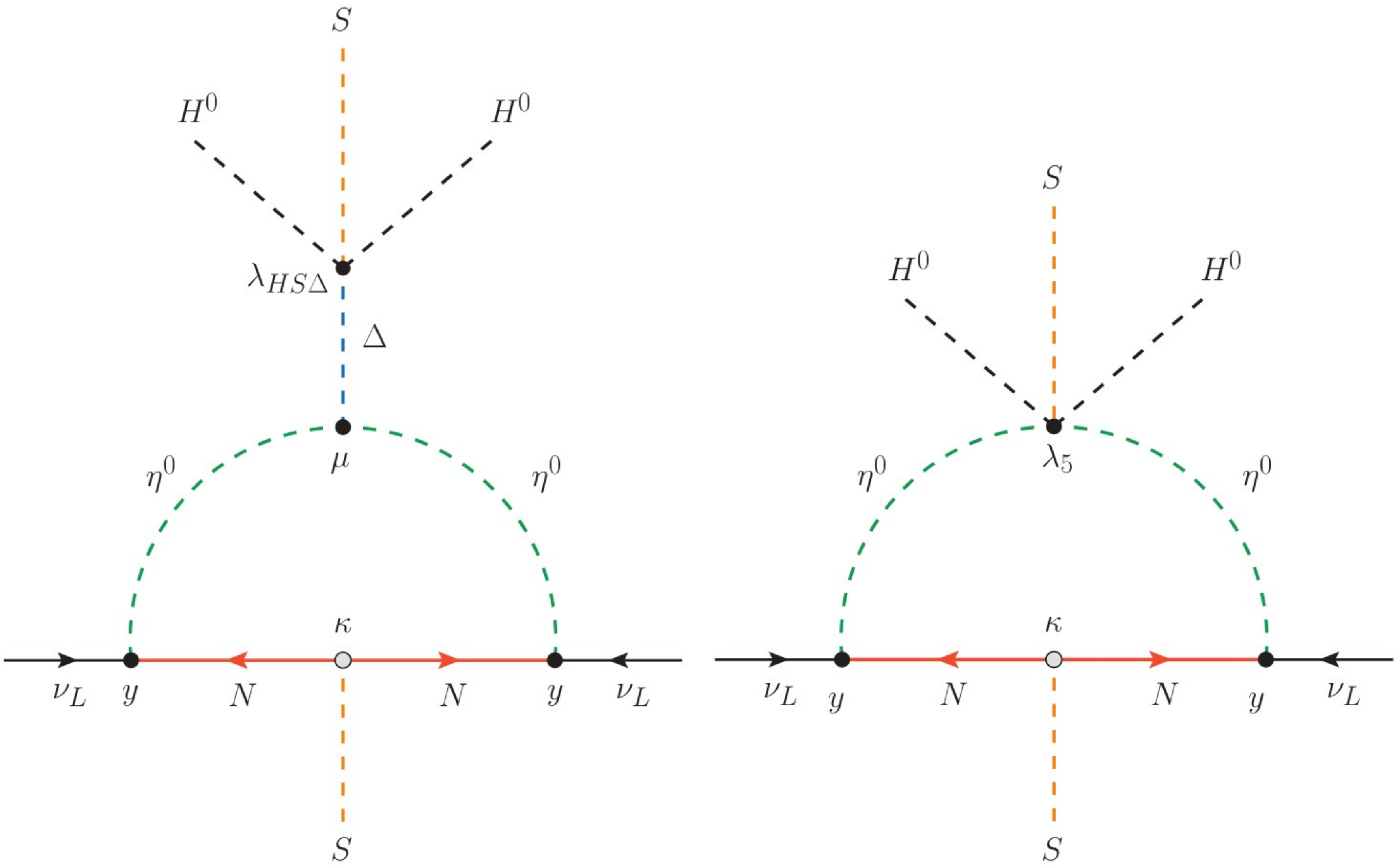
$$m^2_{\eta_R} = m^2_\eta + \lambda_3^{\eta S}\frac{v_S^2}{2} + \left(\lambda_3 + \lambda_4 - \frac{2\lambda_{HS\Delta}\mu v_S}{\sqrt{2}m^2_\Delta}\right)\frac{v_H^2}{2}$$
$$m^2_{\eta_I} = m^2_\eta + \lambda_3^{\eta S}\frac{v_S^2}{2} + \left(\lambda_3 + \lambda_4 + \frac{2\lambda_{HS\Delta}\mu v_S}{\sqrt{2}m^2_\Delta}\right)\frac{v_H^2}{2}$$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

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

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



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

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

- The lightest $\mathbb{Z}_2$ charged state is stable and can be a good DM candidate.

Two possibilities:

- **Fermion** dark matter: singlet N
- **Scalar** dark matter: doublet η_a

TOM GAULD for NEW SCIENTIST

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

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

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

Vicente, Yaguna 1412.2545

In the following, we will concentrate on the fermion DM

Dark matter in the Scotogenic model with spontaneous lepton number violation

Valentina De Romeri, Jacopo Nava, Miguel Puerta, Avelino Vicente
IFIC – CSIC / U. Valencia

[2210.07706]

3. Dark matter: Constraints

Several experimental and theoretical constraints have to be considered in the numerical analysis

Boundedness from below

$$\widetilde{\lambda}_1, \widetilde{\lambda}_2, \lambda_S \geq 0$$

$$\lambda_3 \geq -2\sqrt{\widetilde{\lambda}_1 \widetilde{\lambda}_2}$$

$$\lambda_3^S \geq -2\sqrt{\widetilde{\lambda}_1 \lambda_S}$$

$$\lambda_3^{\eta S} \geq -2\sqrt{\widetilde{\lambda}_2 \lambda_S}$$

$$\lambda_3 + \lambda_4 - |\lambda_5| \geq -2\sqrt{\widetilde{\lambda}_1 \widetilde{\lambda}_2}$$

$$\widetilde{\lambda}_1 \equiv \lambda_1 - \frac{v_S^2 \, |\lambda_{HS\Delta}|^2}{m_\Delta^2}$$

$$\widetilde{\lambda}_2 \equiv \lambda_2 - \frac{2\,|\mu|^2}{m_\Delta^2}$$

Neutrino masses

Casas, Ibarra hep-ph/0103065

$$y = \sqrt{\Lambda}^{-1} R \sqrt{\widehat{m}_\nu} U^\dagger$$

$$\Lambda_n = \frac{\lambda_5 v_H^2}{32\,\pi^2\, M_{N_n}} \left[\frac{M_{N_n}^2}{m_0^2 - M_{N_n}^2} + \frac{M_{N_n}^4}{\left(m_0^2 - M_{N_n}^2\right)^2} \log \frac{M_{N_n}^2}{m_0^2} \right]$$

$$U^T m_\nu U = \widehat{m}_\nu = \mathrm{diag}\,(m_1, m_2, m_3)$$

de Salas et al 2006.11237

3. Dark matter: Constraints

Higgs production and invisible decay

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

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

ATLAS Collaboration 1904.05105

⇒ $\lambda_3^S \lesssim 10^{-2}$

The Higgs can also decay invisibly into two singlet fermions if $m_{N_1} \leq m_h/2$

⇒ The Higgs production channels are suppressed with respect to the SM by the cosine of the mixing angle in the CP-even scalar sector

$$c_\alpha^2 \, \mathrm{BR}(h \to \text{ invisible }) < 0.19 \quad \text{at 95 \% C.L.}$$

3. Dark matter: Constraints

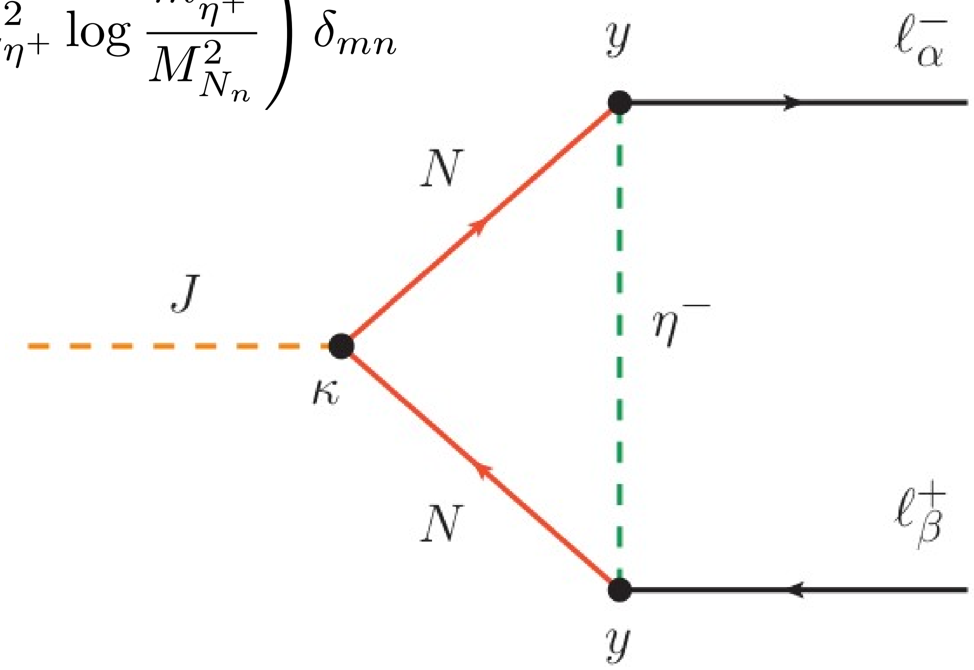
Majoron diagonal couplings to charged leptons

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

$S^{\beta\beta} = S_L^{\beta\beta} + S_R^{\beta\beta *}$

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

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



Bound from white dwarfs:

$$\text{Im}\, S^{ee} < 2.1 \times 10^{-13}$$

Calibbi, Redigolo, Ziegler, Zupan 2006.04795

Bound from the supernova SN1987A:

$$\text{Im}\, S^{\mu\mu} < 2.1 \times 10^{-9}$$

Croon, Elor, Leane, McDermott 2006.13942

⇨ Large couplings to electrons or muons are excluded since they would lead to an abundant production of majorons in dense astrophysical media and an efficient cooling mechanism

Lepton flavor violation

- $\ell_\alpha \to \ell_\beta \gamma$

Theses turn out to be the most constraining observables in most neutrino mass models

$$\text{MEG: BR}\,(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

MEG Collaboration 1605.05081

- $\ell_\alpha \to \ell_\beta \ell_\gamma \ell_\gamma\,, \quad \text{with } \beta = \gamma \text{ and } \beta \neq \gamma$

Analytical expressions in Abada *et al.* 1408.0138

The majoron mediated contributions are derived in Escribano, Vicente 2008.01099

- $\ell_\alpha \to \ell_\beta J$

$$\text{TRIUMPH: } |S^{e\mu}|^2 < 5.3 \times 10^{-11}$$

Jodidio *et al.* Phys.Rev.D 34

Hirsch, Vicente, Meyer, Porod 0902.0525

- $\mu - e$ conversion in nuclei

Analytical expressions in Abada *et al.* 1408.0138

3. Dark matter: Numerical results

As mentioned before, they concentrate on the fermion DM: N_1

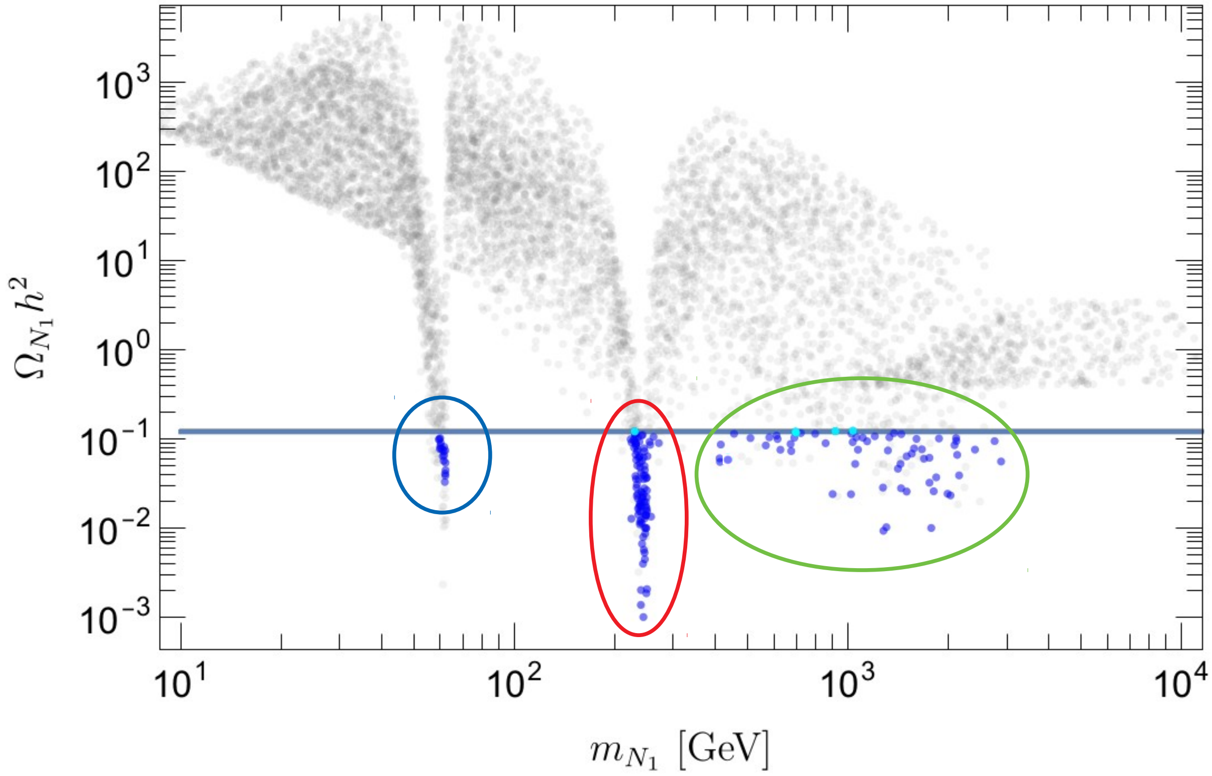
$$\lambda_{2,3,4,S} \in \left[10^{-6}, 1\right]$$
$$\lambda_5 \in \left[10^{-8}, 1\right]$$
$$m_{h_2} \in [20, 2000]\text{GeV}$$
$$\kappa_{11} \in [0.01, 1]$$
$$m_\eta^2 \in \left[10^5, 10^7\right] \text{GeV}^2 \text{ (or fixed)}$$
$$v_\sigma \in [0.5, 10]\text{TeV}$$

- λ_1 is fixed by the condition of requiring $m_{h_1} = m_h \approx 125\,\text{GeV}$
- In order to have N_1 as the DM candidate, we require $m_{N_1} < m_{N_{2,3}}$, $m_{\eta_{R,I}}$
- Regarding neutrino oscillation parameters, normal hierarchy for the neutrino spectrum was chosen and the best-fit values for the parameters were taken from the global fit. de Salas et al 2006.11237

  The angles of the orthogonal matrix R are assumed to be real and taken randomly

3. Dark matter: Relic abundance of N_1

Relic abundance of N_1 as a function of m_{N_1}



Grey points: overabundant DM, excluded by any constraint or where the spin-indendent N1-nucleon elastic scattering cross section is excluded by the data from LUX-ZEPLIN

Cyan points: solutions that reproduce the observed cold DM relic density measured form Planck data

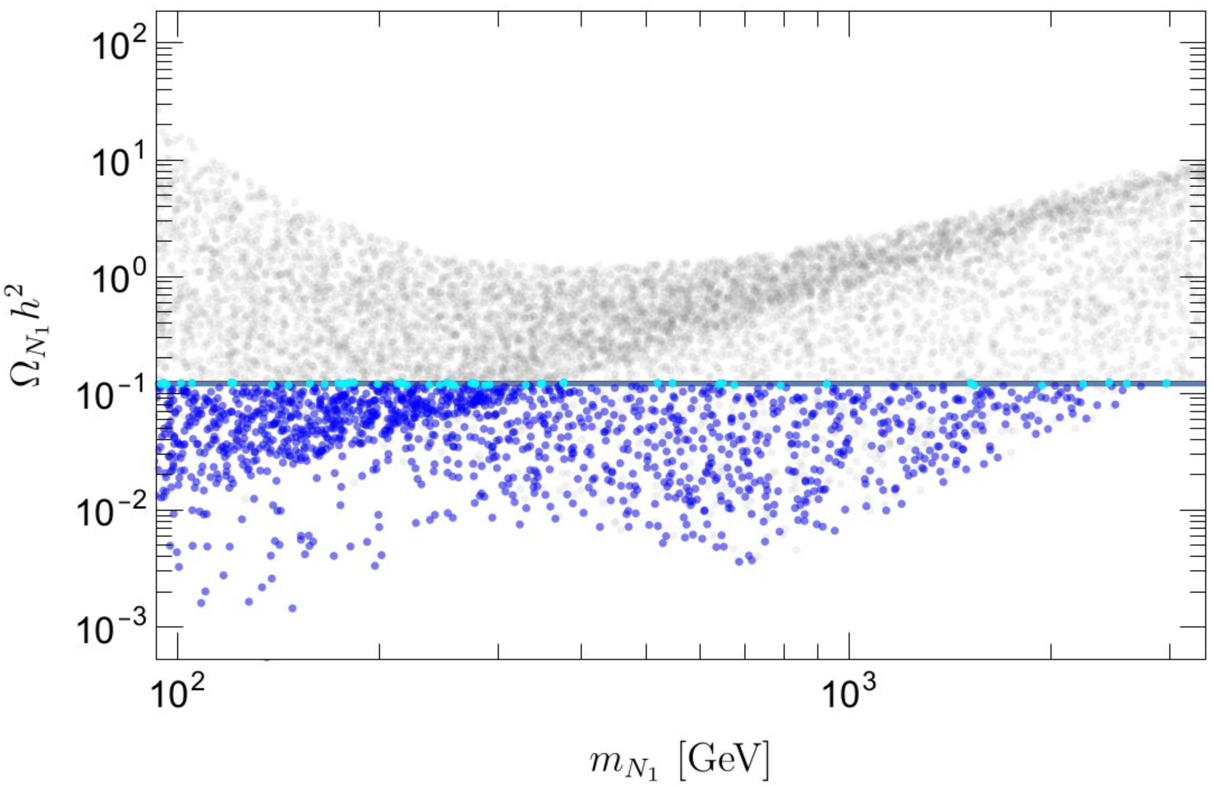
Blue points: underabundant DM

- m_{h_2} is fixed to 500 GeV to highlight the s-channel annihilation of N_1 via h_2
- Most of the solutions lead to overabundant DM, except for points in these regions:

  i) A resonant region where $m_{N_1} = m_h/2$
  ii) A second resonant region where $m_{N_1} = m_{h_2}/2$
  iii) A region of coannihilations at higher m_{N_1}

3. Dark matter: Relic abundance of N_1

Relic abundance of N_1 as a function of m_{N_1} in the coannihilation region



In the following:

$\Delta = m_{\eta_R} - m_{N_1} \in [0, 20]$ GeV

⇨ Coannihilations with $\eta_{R,I}$ and $\eta^{\pm}$ are very relevant

⇨ If coannihilations are relevant, more viable solutions can be found

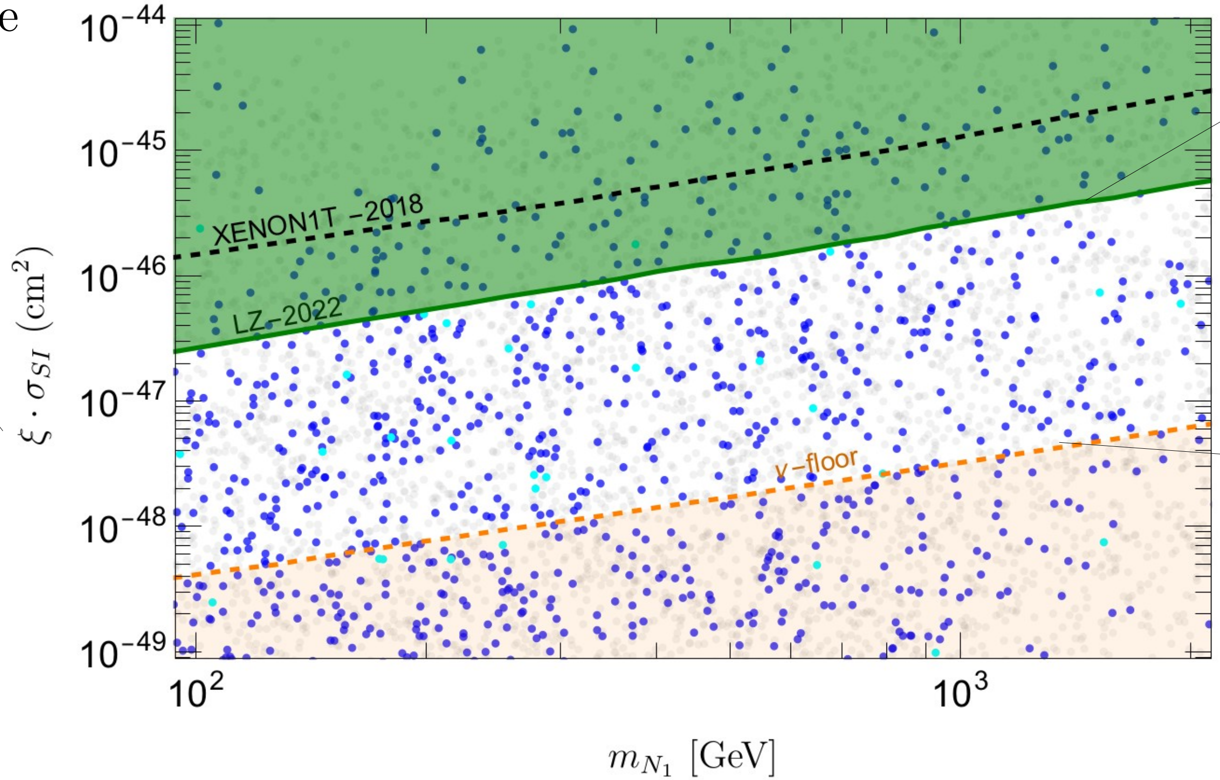
3. Dark matter: N_1 direct detection

Spin-independent N_1-nucleon elastic scattering cross section as a function of m_{N_1}

LZ Collaboration 2207.03764

Relative abundance

$$\xi = \frac{\Omega_{N_1}}{\Omega_{\mathrm{DM,\ Planck}}}$$



LUX-ZEPLIN experiment

ν-floor

Billard *et al.* 1307.5458

- Coannihilation region in order to maximize the number of viable solutions
- The neutrino floor should not be taken as a hard limit, as it can be overcome with different techniques and it has strong dependencies on the target material and a series of uncertainties

For more details: 2109.03247, 2109.03116, 2203.08084

3. Dark matter: N_1 indirect detection

- Gamma rays and charged cosmic rays are among the most suitable messengers to probe DM via indirect detection

- Regarding the DM annihilation into gamma rays:

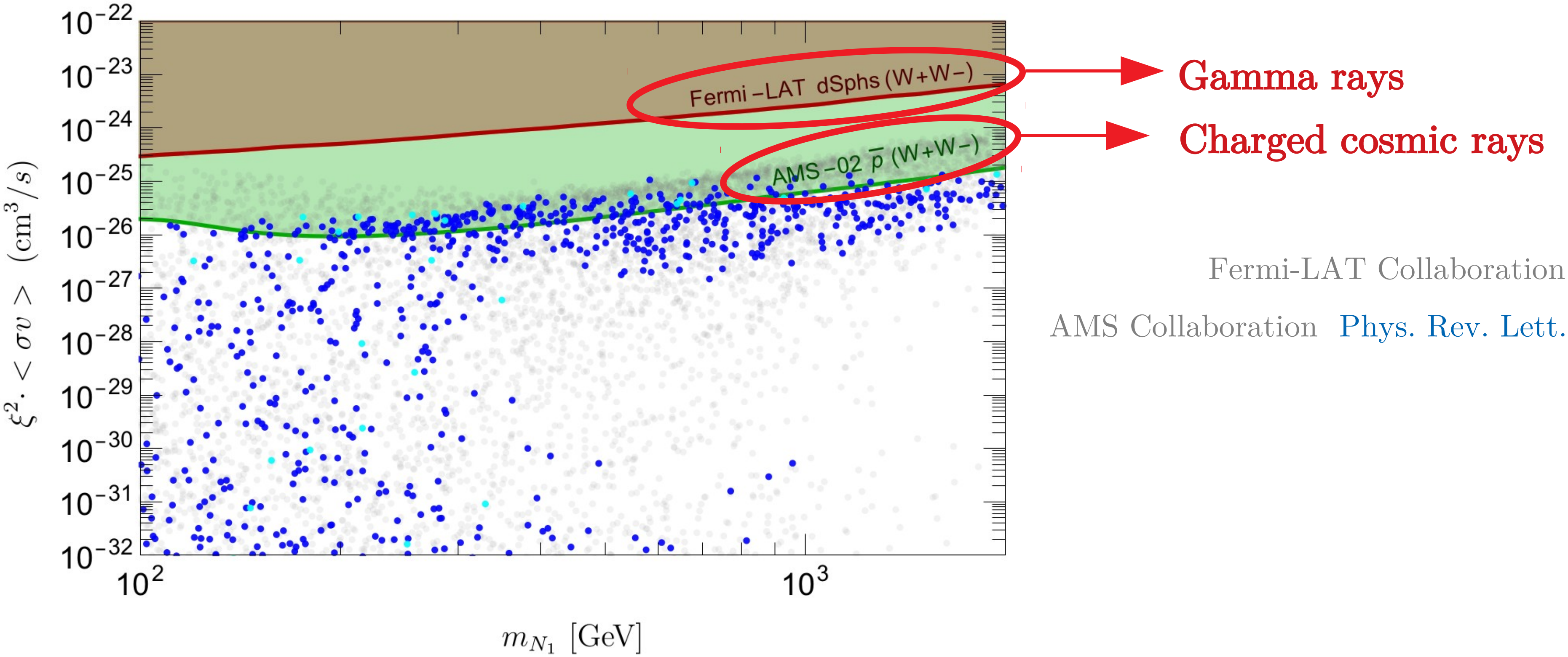
$$N_1 N_1 \to h_1 h_1, h_2 h_2, h_1 h_2, Z^0 Z^0, h_i J, \tau^+ \tau^-, q\,\bar{q}, W^+ W^-$$

The hadronization of the final states will produce neutral pions, which decay into photons giving rise to a gamma-ray flux which may be within reach of DM indirect detection experiments

- The detection of N_1 annihilations into charged cosmic rays is more challenging due to uncertainties in the treatment of their propagation

3. Dark matter: N_1 indirect detection

N_1 total annihilation cross section as a function of m_{N_1}



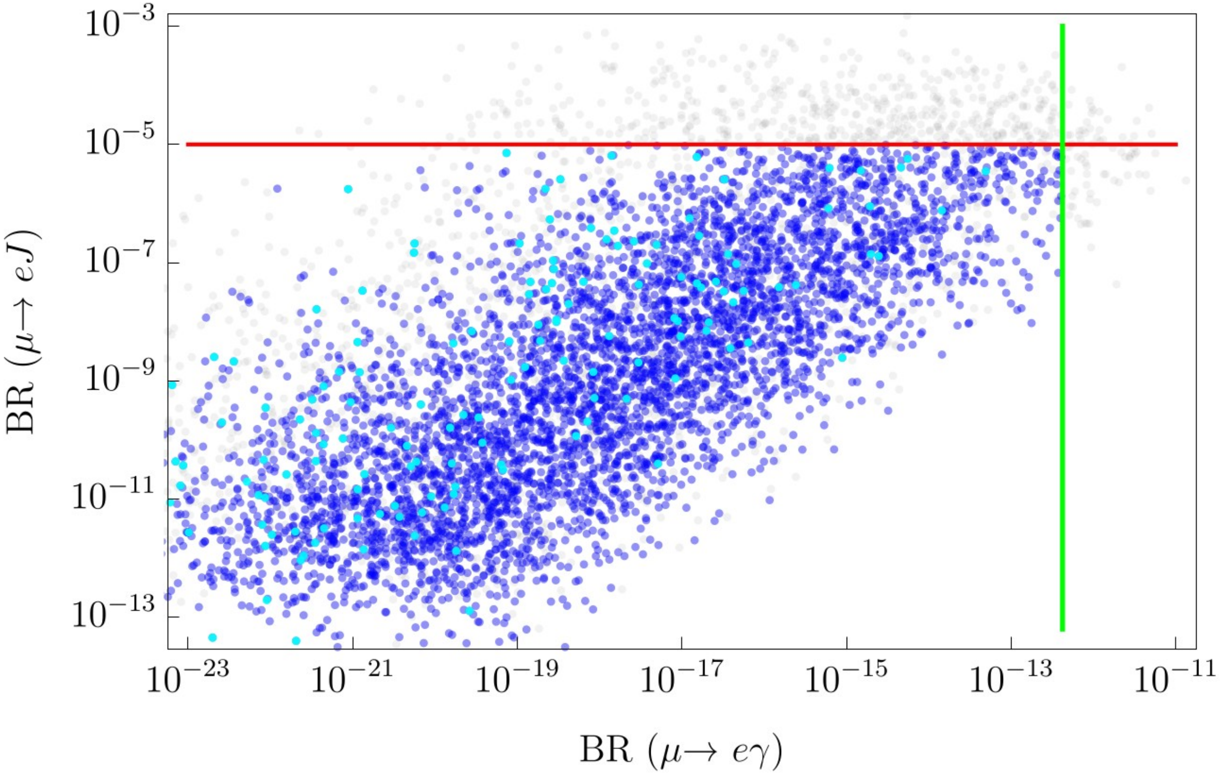
Fermi-LAT Collaboration 1503.02641

AMS Collaboration Phys. Rev. Lett. 117, 091103

- Both upper limits are depicted assuming that $N_1 N_1 \to W^+ W^-$ is the main annihilation channel
- Few solutions already fall within the region currently excluded by AMS-02 data
- Forthcoming data will allow to further probe the singlet fermion as a DM candidate via it multi-messenger signals

3. Dark matter: LFV

$\mathrm{BR}(\mu \to eJ)$ as a function of $\mathrm{BR}(\mu \to e\gamma)$



- LFV procesess strongly restrict the available parameter space of the model
- Some parameter points are already excluded by the current experimental limits, although the scan also finds many valid points leading to very low values of both LFV branching ratios
  - Because random R matrices where considered so some points have suppressed $\mu - e$ flavor violation

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.

3. Summary and discussion

- Focusing on the DM candidate N_1, it can explain the observed DM abundance in three regions:
  - A resonant region where it annihilates via Higgs
  - A second resonant region where it annihilates via h_2
  - A region of coannihilations at masses around the TeV

- If coannihilations are relevant, more solutions are found, either explaining the totality of DM or a sizeable part of it

- Indirect detection searches constitute a promising tool to probe N_1 as DM via its multi-messenger signal

Thanks for your attention!