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Scotogenic models: neutrinos, dark matter and more

Avelino Vicente[a,b,*]

[a] *Instituto de Física Corpuscular, CSIC-Universitat de València, 46980 Paterna, Spain*
[b] *Departament de Física Teòrica, Universitat de València, 46100 Burjassot, Spain*

E-mail: avelino.vicente@ific.uv.es

The Scotogenic model is a popular scenario beyond the Standard Model that induces Majorana neutrino masses at the 1-loop level and includes a viable dark matter candidate. Based on the original model, many variants can be constructed. We discuss two specific variations of the Scotogenic model with alternative representations under the Standard Model gauge group and additional Scotogenic states. These variants have novel phenomenological predictions and may explain some long-standing anomalies.

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1. Introduction

The Scotogenic model [1] is a popular setup that extends the Standard Model (SM) particle content with three new fermion singlets, $N_{1,2,3}$, and a scalar doublet, η. The new states are assumed to be odd under a new $\mathbb{Z}_2$ symmetry under which the rest of the fields are even. These ingredients are enough to induce Majorana neutrino masses at the 1-loop level, while the lightest $\mathbb{Z}_2$-odd state is completely stable and can be a viable DM candidate. Many variations of this setup that keep the positive properties of the original model but lead to different phenomenological predictions exist. There are also several attactive extensions of the minimal setup with new features. In summary, there are multiple *Scotogenic paths* to explore:

(i) Number of generations of each Scotogenic state: while the minimal model includes three copies of N and one of η, other possibilities are equally valid [2].

(ii) Representations under the gauge group: one may consider variants with $\mathrm{SU}(2)_\mathrm{L}$ representations beyond the doublet or with alternative hypercharge values [3, 4].

(iii) Additional Scotogenic states: in addition to N and η, other $\mathbb{Z}_2$-odd states can be added to the particle spectrum [5].

(iv) Spontaneous violation of lepton number: the violation of lepton number is usually assumed to be explicit, but the spontaneous version of the Scotogenic model is also viable and leads to novel experimental signals [6–8].

2. Two example models

A "charged" Scotogenic model

First, we discuss a variant with Scotogenic states with higher hypercharges. Instead of the usual singlet fermions, the model introduced in [3] and later studied in [4] features charged fermions and a doublet with hypercharge 3/2. This has an impact on the DM phenomenology, as shown on the left side of Fig. 1. The observed DM relic density can be reproduced in the usual parameter space regions in the original Scotogenic model. In addition, the charged fermions can mediate the co-annihilation of charged scalars and open up new viable regions.

A Scotogenic model "for everything"

The model of Ref. [5] is an extension of the Scotogenic model with two new $\mathbb{Z}_2$-odd states: a scalar leptoquark $S \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$ and a charged scalar $\phi \sim (\mathbf{1},\mathbf{1})_{-1}$. In addition to generating neutrino masses and providing a valid DM candidate, this model can address the $b \to s$ anomalies and the muon $g-2$ discrepancy, as shown on the right side of Fig. 1. This figure is the result of a χ^2 fit of the parameters of the model that proves that one can accommodate all anomalies, as well as neutrino oscillation data, in a region of parameter space consistent with all constraints.

3. Summary

We have presented two particular realizations of the Scotogenic setup beyond the original model. They constitute two out of the many possible models that one may construct based on the Scotogenic setup and illustrate the novel phenomenological possibilities that one may find in doing so.

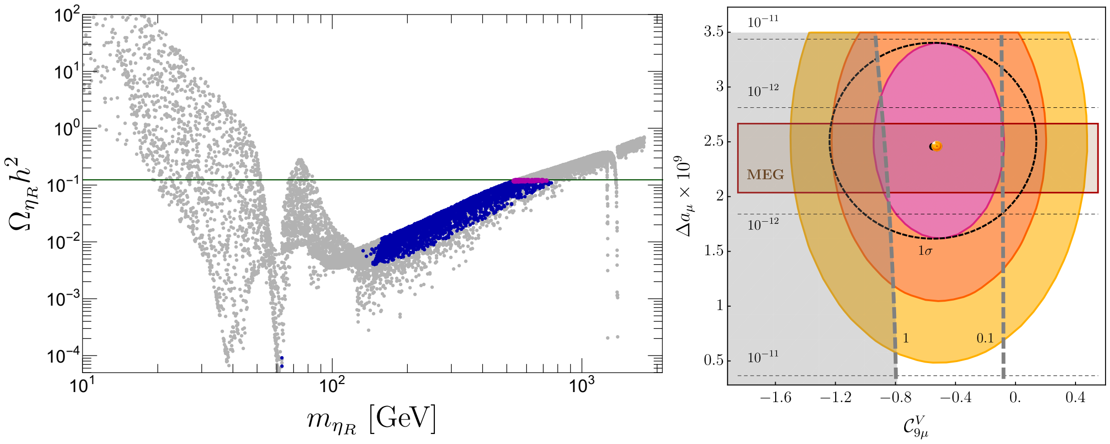

Figure 1: Left: Relic abundance of η_R as a function of m_{η_R} in the model of Ref. [4]. Magenta points lead to the observed DM relic density (horizontal band, 3σ interval), blue points correspond to underabundant DM and gray points are excluded by one or several constraints. **Right:** Results of a χ^2 fit of the model parameters in Ref. [5], displayed in the plane of $C^V_{9\mu}$ (the coefficient of the $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$ operator) and Δa_μ (the new physics contribution to the muon $g-2$). The $1\,\sigma$ (pink), $2\,\sigma$ (orange) and $3\,\sigma$ (yellow) regions as well as the best-fit point (orange dot) are shown. The dark red region is allowed by $\mu \to e\gamma$ searches and the horizontal dashed lines correspond to contours of the branching ratio. The shaded region is excluded by $b \to s\gamma$, the thick gray lines are contours of the relevant product of Yukawa couplings and the black dashed line and dot are the $1\,\sigma$ region and central value, respectively, determined by experiments.

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