WIMP Dark Matter in a Type-II Scotogenic model

Roberto A. Lineros

Departamento de Física, Universidad Católica del Norte

Work in collaboration with Mathias Pierre (IFT UAM/CSIC)

arxiv:2011.08195

Workshop on New Trends in Dark Matter
7 to 9 December 2020
Science around Antofagasta

When Dark Matter will be observed?

Atacama Large Millimeter Array

(Probably) The Southern Wide-field Gamma-ray Observatory

Universities with PhD program

Cerro Paranal – Very Large Telescope

LLAMAS

Cherenkov Telescope Array South

Milky Way

Cerro Paranal – Very Large Telescope

Cherenkov Telescope Array South

© V. Gammaldi
The Plan

1. Introduction
2. Dark Matter and Neutrinos
3. The Model
4. Conclusions
The Standard Model

SM matter families

Symmetries
- Lorentz
- SU(3)_c: Color
- SU(2)_L: Isospin
- U(1)_y: Hypercharge

Matter content
- 3 families quarks
- 3 families leptons

Higgs field
- SU(2)_L x U(1)_y → U(1)_EM
- Mass to fundamental particles
Dark Matter

Observations support Dark Matter

- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

$$\Omega_{DM} h^2 = 0.1196 \pm 0.0031$$
Dark Matter Searches

relic abundance

$$\Omega_{DM} h^2 = 0.1196 \pm 0.0031$$

indirect detection

direct detection

particle collider

astrophysical probes
Neutrinos

The $\text{SM}$ predicts zero neutrino mass

Beyond $\text{SM}$ physics is required to explain mass spectrum and mixing angles

Forero, Tortola and Valle PRD 90 (2014) 093006
Neutrino mass mechanisms

A large fraction of the models uses the 5-dim *Weinberg operator* to generate *majorana* neutrino masses

\[ \mathcal{O}_{5ij} = \frac{1}{\Lambda} (L_i H)^T (L_j H) \]

This operator preserves SM symmetries but it breaks lepton number in 2 units

\[ \mathcal{O}_{5ij} = \frac{v^2}{\Lambda} \nu_j \nu_i = M_{ij} \nu_j \nu_i \]
Neutrino mass mechanisms

The most known schemes are see-saw mechanisms

Type-I

\[ m_\nu \propto \frac{v^2 y^2}{M_N} \]

Type-II

\[ m_\nu \propto \frac{v^2 y\mu}{M_\Delta^2} \]

Type-III

\[ m_\nu \propto \frac{v^2 y^2}{M_\Sigma} \]
Radiative seesaw

To connect neutrino mass mechanism and dark matter

(See Restrepo et al. JHEP arxiv:1308.3655)

We focus on scotogenic models:

E. Ma, Phys.Rev.D73:077301,2006

Scotogenic models

DM candidates:

Type I: \( N \eta^0 \eta^A \) 

Type III: \( \Sigma^0 \eta^0 \eta^A \)

Fermion singlet

E. Ma, Phys. Rev. D73:077301, 2006

Scalar SU(2) doublet

Type II

Fermion SU(2) triplet

A type-II inspired Scotogenic model

The minimal construction of the model requires:

- 2 scalar triplets
- 2 fermion doublets (vector-like)

DM candidates:

- $S_1^0$
- $\tilde{S}^0$
- $f^0$

CP-even scalar
CP-odd scalar
Dirac fermion

Scalar triplet with hypercharge
Scalar triplet no hypercharge

Vector-like doublet fermion
Charge assignment

<table>
<thead>
<tr>
<th>Field</th>
<th>$L_i$</th>
<th>$f_L$</th>
<th>$f_R$</th>
<th>$\Delta$</th>
<th>$\Omega$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>1/2</td>
<td>1/2</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Chirality</td>
<td>L</td>
<td>L</td>
<td>R</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SU(2)$_L$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>U(1)$_Y$</td>
<td>-1/2</td>
<td>1/2</td>
<td>1/2</td>
<td>1</td>
<td>0</td>
<td>1/2</td>
</tr>
<tr>
<td>$\mathbb{Z}_2$</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
</tr>
</tbody>
</table>

The $\mathbb{Z}_2$ symmetry is the minimal addition to the model, besides the fields.

After considering, neutrino masses, scalar potential minimization and stability, and minimal DM phenomenology.

The DM candidate is only one: $S^0_1$
The model’s lagrangian

\[ \mathcal{L} \supset -y^i_{\Delta} \left( f_R \Delta L_i + \text{h.c.} \right) - y^i_{\Omega} \left( f^c_L i \sigma_2 \Omega L_i + \text{h.c.} \right) - m_f \left( f_L f_R + \bar{f}_R f_L \right) - V_{\text{scalar}} \]

\[ V_{\text{scalar}} = -\mu_h^2 |H|^2 + \lambda_h |H|^4 + \frac{m^2_{\Delta}}{2} \text{Tr} [\Delta^\dagger \Delta] + \frac{\lambda_{\Delta}}{4} \text{Tr} [\Delta^\dagger \Delta \Delta^\dagger \Delta] + \frac{\lambda'_{\Delta}}{4} \text{Tr} [\Delta^\dagger \Delta]^2 \]

\[ \quad + \frac{m^2_{\Omega}}{4} \text{Tr} [\Omega^\dagger \Omega] + \frac{\lambda_{\Omega}}{16} \text{Tr} [\Omega^\dagger \Omega]^2 + \frac{1}{8} \lambda_{\Delta \Omega} \text{Tr} [\Delta^\dagger \Delta] \text{Tr} [\Omega^\dagger \Omega] \]

\[ \quad + \frac{1}{2} \lambda_{H \Delta} H^\dagger \Delta \Delta^\dagger H + \frac{1}{2} \lambda'_{H \Delta} \text{Tr} [\Delta^\dagger \Delta] H^\dagger H + \frac{1}{2} \lambda_{H \Omega} H^\dagger \Omega \Omega^\dagger H \]

\[ \quad + \frac{1}{4} s_{\kappa} \kappa \left( H^T \tilde{\Delta} \Omega H + \text{h.c.} \right) \]
Neutrino masses

The scotogenic mechanism in this model gives non-zero mass to 2 neutrino, but one remains massless.

\[ m_{ij} = \frac{1}{16\sqrt{2}\pi^2} \left( y_\Delta y_\Omega^j + y_\Omega^i y_\Delta^j \right) m_f F_{\text{loop}}(m_{S_1^0}, m_{S_1^\pm}, m_f) \]

\[ m_{\nu_1} = 0 \]

\[ m_{\nu_2} = -2\hat{y}_\Delta \hat{y}_\Omega \sin^2(\phi_N) m_f F_{\text{loop}} \]

\[ m_{\nu_3} = -2\hat{y}_\Delta \hat{y}_\Omega \cos^2(\phi_N) m_f F_{\text{loop}} \]

\[ \phi_N \equiv \arctan \left( \left( \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \right)^{1/4} \right) \]

\[ \hat{y}_\Omega \equiv \frac{\sqrt{\Delta m_{21}^2}}{2\hat{y}_\Delta \sin^2(\phi_N) m_f F_{\text{loop}}} \]
Indirect searches channels

The model has many annihilation channels. Among them some are shared with Minimal DM scenarios. However other are genuine due to the scotogenic construction.
Indirect searches: W channel

The ElectroWeak channel are strong due to DM comes from triplets. Beyond ~1.5 TeV, those are not enough to explain DM relic abundance

\[ \langle \sigma v \rangle_{W^+W^-} \simeq 5 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \left( \frac{1.15 \text{ TeV}}{m_{S_1^0}} \right)^2 \]
Indirect searches: tau channel

The interaction due to the scotogenic mechanism produces a large flux into leptons.
Indirect searches: neutrinos

Neutrino flux large enough to be detected in KM3Net

\[ \langle \sigma v \rangle_{\nu\nu} \text{ [cm}^3 \text{s}^{-1}] \]

\begin{align*}
\times 10^{-25} & \quad \times 10^{-26} \\
\times 10^{-27} & \quad \times 10^{-28} \\
\times 10^{-29} & \quad \times 10^{-30} \\
\times 10^{-31} & \quad \times 10^{-32} \\
\end{align*}

\begin{align*}
10^3 & \quad \times 10^4 \\
\end{align*}

\text{mS}_0 [\text{GeV}]
Direct detection: Tree-level vs One-loop

Tree-level

Higgs portal

Higgs portal + electroweak loops

Tree-level + one-loop
Conclusions

• Neutrinos observables and DM are keys to unveil New Physics

• Scotogenic mechanism connects DM stability and neutrino masses

• A type-II seesaw inspired scotogenic model provide an interesting TeV DM candidate

• The complementarity between CTA, KM3Net, and Darwin is key to explore the model.
Thanks
Neutrino masses

\[
m_{\nu_1} = 0, \\
m_{\nu_2} = -2\hat{y}_\Delta \hat{y}_\Omega \sin^2(\phi_N) m_f F_{\text{loop}}(m_{S^0_{1,2}}, m_{S^\pm_{1,2}}, m_f), \\
m_{\nu_3} = -2\hat{y}_\Delta \hat{y}_\Omega \cos^2(\phi_N) m_f F_{\text{loop}}(m_{S^0_{1,2}}, m_{S^\pm_{1,2}}, m_f).
\]