Leptogenesis in a Singlet-Doublet Scotogenic Model

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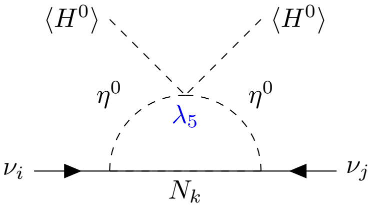
Outline

Scotogenic Models

- *Classic* form: Standard Model (SM) extended with a scalar SU(2) doublet $\eta = \left[\eta^+ \; \eta^0\right]^{\mathsf{T}}$ and 3 singlet fermions N_i charged odd under a $\mathbb{Z}_2$ symmetry.

  E. Ma (2006)

- SM neutrinos remain massless at tree-level, masses generated at one-loop level $\rightarrow$ suppressed by a factor $\frac{\lambda_5}{16\pi^2}$ $\rightarrow$ allows for lower masses for N_i (compared to Seesaw models).



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- SM neutrinos remain massless at tree-level, masses generated at one-loop level $\rightarrow$ suppressed by a factor $\frac{\lambda_5}{16\pi^2}$ $\rightarrow$ allows for lower masses for N_i (compared to Seesaw models).

- The $\mathbb{Z}_2$ symmetry allows for a dark matter (DM) candidate.

- The fermionic singlets can drive leptogenesis.
  C. S. Fong, E. Nardi, A. Riotto (2013); T. Hugle, M. Platscher and K. Schmitz (2018); S. Baumholzer, V. Brdar, P. Schwaller (2018)

THIS Scotogenic Model

- Two fermionic singlets $N_{1,2}$ and a scalar doublet η.
- Extra singlet scalar S in the scalar sector.
- Extra two fermionic doublets $\Psi_{L,R}$ with equal $\mathrm{U}(1)_Y$ hypercharge.

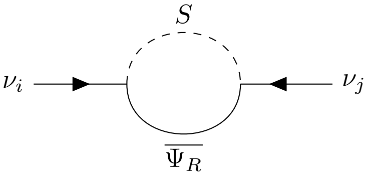
$$\Psi_{L,R} = \begin{bmatrix} \psi^0_{L,R} \\ \psi^-_{L,R} \end{bmatrix}$$

Field Content and Interactions

	N_i	$\Psi_{L,R}$	η	S	H	L_i	$e_{R,i}$
$\mathrm{SU(2)_L}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	0	-1	+1	0	+1	-1	-2
$\mathbb{Z}_2$	-1	-1	-1	-1	+1	+1	+1

$$
\begin{aligned}
-\mathcal{L}_{\text{i.a.}} = & g_N N_i (L \cdot \eta) + g_R \, \eta^\dagger \Psi_L e_R^C + g_\Psi \, (\overline{\Psi}_R \cdot L) S \\
& + y_L (\Psi_L \cdot H) N_i + y_R (\Psi_R \cdot H) \overline{N}_i + \kappa \, \eta^\dagger H S + \text{h.c.}
\end{aligned}
$$

Have additional contributions to neutrino masses, for e.g.



Field Content and Interactions

	N_i	$\Psi_{L,R}$	η	S	H	L_i	$e_{R,i}$
$\mathrm{SU}(2)_\mathrm{L}$	**1**	**2**	**2**	**1**	**2**	**2**	**1**
$\mathrm{U}(1)_\mathrm{Y}$	0	-1	+1	0	+1	-1	-2
$\mathbb{Z}_2$	-1	-1	-1	-1	+1	+1	+1
Lepton No.	**0**	**+1**	**0**	**0**	**0**	**+1**	**+1**

$$
\begin{aligned}
-\mathcal{L}_{\text{i.a.}} =& g_N N_i (L\cdot\eta) + g_R\,\eta^\dagger \Psi_L e_R^C + g_\Psi\,(\overline{\Psi}_R \cdot L) S \\
&+ y_L (\Psi_L \cdot H) N_i + y_R (\Psi_R \cdot H)\overline{N}_i + \kappa\,\eta^\dagger H S + \text{h.c.}
\end{aligned}
$$

Sakharov Conditions for Leptogenesis

- $\Delta L \neq 0$ processes $\rightarrow$ satisfied by processes mediated by the Yukawa couplings g_N, y_L and y_R.
  (Need active sphaleron transitions to convert the lepton asymmetry to a baryon asymmetry.)
- Out-of-equilibrium decay of at least one of the N_i.
- C and CP violation $\rightarrow$ satisfied by complex phases in one or more of g_N, y_L and y_R.

Lepton Asymmetry ϵ

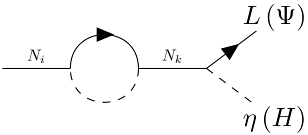
- Difference between decay rates of the N_i into leptons and anti-leptons.

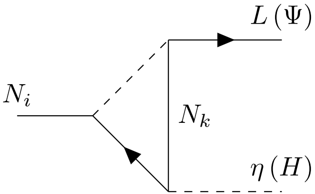
- At tree-level, this is 0; generated at lowest order by interference between tree-level and one-loop diagrams.

ϵ for this model

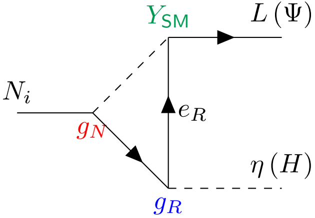
- Have the usual self-energy and triangle diagrams in "vanilla leptogenesis". These can be related to the SM neutrino masses.

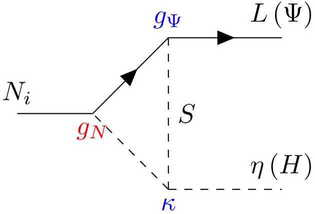
T. Hugle, M. Platscher and K. Schmitz (2018)





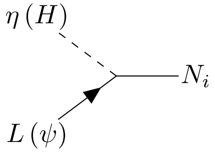
- But also have additional triangle diagrams with different coupling combinations.



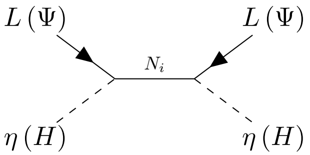


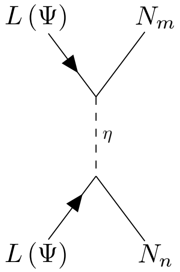
Washout Processes

- Attempt to erase any lepton asymmetry generated.
- Inverse decays, i.e. production of the N_i



- Two-to-two scatterings that modify lepton number, for e.g.





Washout Processes

- Effectiveness of processes determined by ratio of relevant rate w.r.t. the Hubble parameter, i.e.

$$W_D = \frac{\langle \Gamma_{N_i} \rangle}{H(M_i)\, z_i}\,, \qquad \Delta W = \frac{\langle \sigma v \rangle_{\Delta L \neq 0}}{H(M_i)\, z_i}$$

  where $\langle \ldots \rangle$ denotes velocity averaging.

- Define decay parameter

$$K_i = \frac{\Gamma_{N_i}^{\text{tree}}}{H(M_i)}$$

  This can be related to the SM neutrino masses.

  See for e.g. **W. Buchmuller, P. Di Bari and M. Plumacher (2004)** or **S. Davidson, E. Nardi and Y. Nir (2008)**

- Different washout regimes characterized by values of K_i

- $K_i > 3$: strong washout regime, where inverse decays are dominant source of washout.

Boltzmann Equations

Define variables $z_i = \frac{M_i}{T}$, so $z_2 = \frac{M_2}{M_1} z_1$.

$$\frac{dN_{N_i}}{dz_i} = -z_i\, K_i\, \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} \left(N_{N_i} - N_{N_i}^{\text{eq.}}\right) \rightarrow \text{Out of equilib. decays of } N_i$$

$$\frac{dN_{B-L}}{dz_1} = \underbrace{-\, z_1 \left[\sum_{i=1}^{2} \epsilon_i\, K_i\, \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} \left(N_{N_i} - N_{N_i}^{\text{eq}}\right)\right]}_{\text{production of asymmetry}} - \underbrace{(W_D + \Delta W) N_{B-L}}_{\text{washout of asymmetry}} .$$

Solving the Equations

- Start at $T \gg M_2$ with the initial conditions

$$N_{N_i} = N_{N_i}^{\text{eq.}} \quad \text{and} \quad N_{B-L} = 0$$

- Track the number densities down to low temperatures and ascertain $N_{B-L}^{f} = N_{B-L}(z_1 \gg 1)$

- This value is converted to be compared to the observed baryon-to-photon ratio η_B as

$$\eta_B = \left(\frac{3}{4} \, C_{\text{sph.}} \, \frac{g_*^0}{g_*} \right) N_{B-L}^{f}$$

where $C_{\text{sph.}} = \frac{8}{23}$, $g_*^0 = \frac{43}{11}$ and $g_* = 122.25$.

Choice of Parameters

- Large parameter space makes phenomenological analysis difficult $\rightarrow$ focus on fitting certain observables and adhering to important constraints from experiments.
- Observables focused on: $(\mathbf{g}-\mathbf{2})_\mu$ **anomaly** and **neutrino oscillation data** $\rightarrow$ g^μ_Ψ, g^μ_R need to be $\mathcal{O}(1)$ and simultaneously need to suppress g_N and $y_{L,R}$.
- Important constraints come from lepton-flavor violating processes.
- **Result: in the strong washout regime for most of the parameter space!**
  In fact, find $K_i > 10^3$ in some cases.

Dark Matter

- Dark Matter (DM) is stabilized by the $\mathbb{Z}_2$ symmetry.
- Can be fermionic or (pseudo-)scalar DM depending on the mass hierarchies
- Can DM be accommodated with successful leptogenesis, i.e. fit the relic density of $\Omega_{\mathsf{CDM}} h^2 = 0.120 \pm 0.001$?
  PLANCK Collab. (2018).

Putting it all together (Preliminary Results)

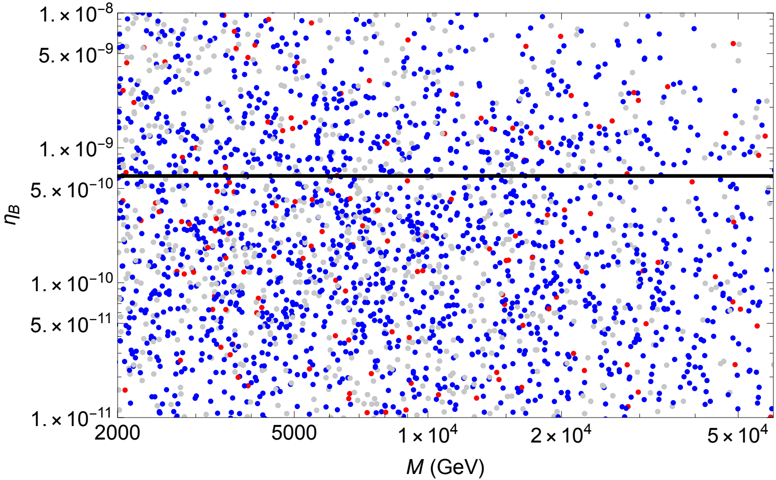


Figure: The **black line** denotes the observed baryon-to-photon ratio of 6.1×10^{-10} (PLANCK 2018). Blue: Points where DM is underproduced. Red: Points which are compatible with the DM relic density. Gray: Points where DM is overproduced.

Putting it all together (Preliminary Results)

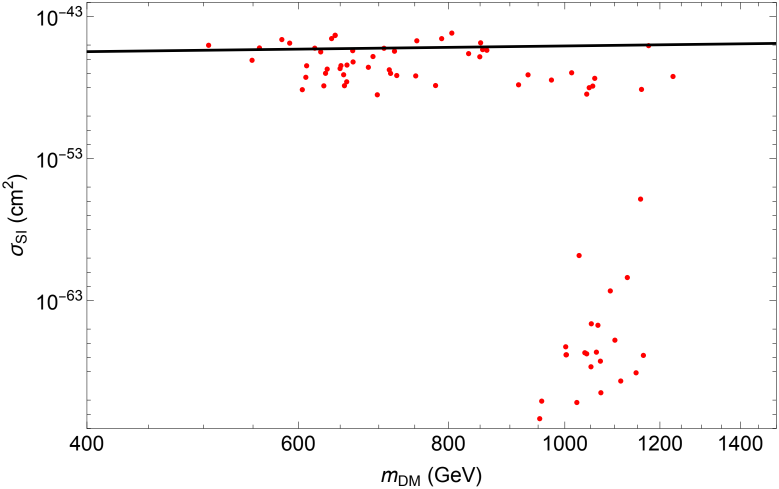


Figure: The **black line** denotes the constraint on the spin independent cross section from XENON1T (2018). Points in red are those that are consistent with the relic abundance of DM and are $\eta_B = \mathcal{O}(10^{-10})$.

Conclusions

- This model allows for correct fitting of neutrino oscillation data and the $(g-2)_\mu$ anomaly, while simultaneously allowing leptogenesis and can allow for a DM candidate.
- Low-scale leptogenesis is achievable in this model despite being in the strong washout regime

  (compare to **T. Hugle, M. Platscher and K. Schmitz (2018))**
- This is due to large asymmetries generated by the additional diagrams, which are not directly linked to the SM neutrino masses.

Thank you for your attention!

Backup: Points that (Nearly) Satisfy All Constraints

	I	II	III
M_i (GeV)	$(2995.87,\ 29098.4)$	$(6245.84, 8344.45)$	$(28107.1, 50511.8)$
m_Ψ (GeV)	1550.17	1082.31	961.334
m_η (GeV)	871.799	688.1	985.834
m_S (GeV)	1032.75	815.851	1714.54
κ (GeV)	-95.6814	-74.9958	213.463
m_{DM} (GeV)	604.507	658.2	956.598

Backup: Points that (Nearly) Satisfy All Constraints

Point I: Yukawas

Abs$[g_N]$	$\begin{bmatrix} 0.000196875 & 0.000258659 & 0.000290772 \\ 0.000164498 & 0.000269855 & 0.00033933 \end{bmatrix}$
Arg$[g_N]$	$\begin{bmatrix} -0.167833 & -3.01165 & -0.000194745 \\ -2.90506 & -0.0748 & 0.00113468 \end{bmatrix}$
y_L	$(-3.11548 \times 10^{-7},\ -4.98527 \times 10^{-7})$
y_R	$(-1.3845 \times 10^{-6},\ 4.753 \times 10^{-8})$
Abs$[g_\Psi]$	$(1.94784 \times 10^{-16},\ 1.27257,\ 0.00001)$
Arg$[g_\Psi]$	$(-1.6421, -1.57181, -1.11022 \times 10^{-11})$
Abs$[g_R]$	$(4.15957 \times 10^{-8}, 2.03444, 0.000542719)$
Arg$[g_R]$	$(0, -1.5708, 0)$

Backup: Points that (Nearly) Satisfy All Constraints

Point II: Yukawas

Abs$[g_N]$	$\begin{bmatrix} 0.00025192 & 0.000324012 & 0.000372069 \\ 0.0000977959 & 0.000148393 & 0.000187301 \end{bmatrix}$
Arg$[g_N]$	$\begin{bmatrix} -0.168378 & -3.04506 & -0.000740242 \\ 0.222556 & 2.87647 & -3.13712 \end{bmatrix}$
y_L	$(-2.70576 \times 10^{-7}, -1.08754 \times 10^{-8})$
y_R	$(-2.65633 \times 10^{-8}, -3.91531 \times 10^{-6})$
Abs$[g_\Psi]$	$(1.11886 \times 10^{-16}, 1.18162, 0.00001)$
Arg$[g_\Psi]$	$(1.44644, 1.56707, -1.11022 \times 10^{-11})$
Abs$[g_R]$	$(2.2584 \times 10^{-8}, 1.10311, 0.000294736)$
Arg$[g_R]$	$(0, 1.5708, 0)$

Backup: Points that (Nearly) Satisfy All Constraints

Point III: Yukawas

Abs$[g_N]$	$\begin{bmatrix} 0.0000868255 & 0.000114045 & 0.000128236 \\ 0.0000340783 & 0.0000575288 & 0.0000716666 \end{bmatrix}$
Arg$[g_N]$	$\begin{bmatrix} -0.167697 & -3.05482 & -0.0000591915 \\ -2.9013 & -0.0832459 & 0.000341734 \end{bmatrix}$
y_L	$(-1.3886 \times 10^{-6},\ 1.89154 \times 10^{-6})$
y_R	$(-1.09227 \times 10^{-6},\ -2.12273 \times 10^{-6})$
Abs$[g_\Psi]$	$(2.36783 \times 10^{-14},\ 0.834252,\ 0.00001)$
Arg$[g_\Psi]$	$(-0.0562951, -1.57111, 2.88658 \times 10^{-10})$
Abs$[g_R]$	$(2.37749 \times 10^{-8}, 1.16409, 0.000310295)$
Arg$[g_R]$	$(0, 1.5708, 0)$

Backup: Diagrams for $(g-2)_\mu$

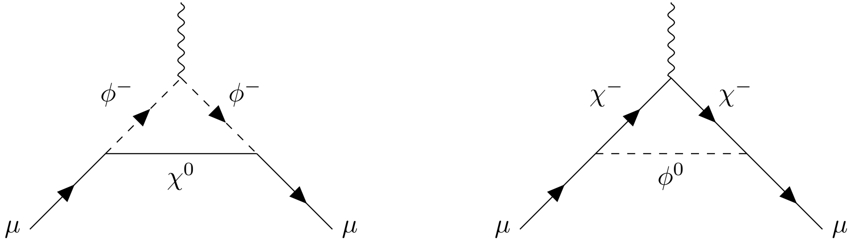


Figure: Contribution to $(g-2)_\mu$ within this scotogenic model.