LOW SCALE SEESAW MODELS AND LEPTOGENESIS

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Based on works in collaboration with A. Abada, G. Arcadi, V. Domcke, M. Drewes and J. Klaric
Observational problems of the SM

Two seemingly unrelated observations cannot be accounted for in the Standard Model

Neutrinos are massive and leptons mix


The Universe has a negligible amount of antimatter

\[ \eta_{\Delta B} = (6.13 \pm 0.03) \times 10^{-10} \]

The natural (simple) way

Complete the SM field pattern with right-handed neutrinos

Figure from S. Alekhin et al., arXiv:1504.04855 [hep-ph]
Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions $N_i$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i \overline{N_I} \phi N_I - \left( F_{\alpha I} \overline{\ell_L} \tilde{\phi} N_I + \frac{M_{IJ}}{2} \overline{N^c_I} N_J + h.c. \right)$$

After electroweak phase transition $< \Phi > = v \approx 174$ GeV

$$m_\nu = -v^2 F \frac{1}{M} F^T$$

The Lagrangian provides the ingredients for leptogenesis too

Sakharov conditions

- Complex Yukawa couplings $F$ as a source of $\mathrm{CP}$
- $B$ from sphaleron transitions until $T_{\text{EW}} \approx 140$ GeV
- Sterile neutrinos deviations from thermal equilibrium
Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions $N_i$

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Sakharov conditions

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Leptogenesis realisations

3rd Sakharov condition: deviation from thermal equilibrium

At which temperature(s) do sterile neutrinos enter/deviate from thermal equilibrium?
**BAU: Thermal leptogenesis**

Sterile neutrinos in thermal equilibrium if $|F| \gtrsim 10^{-7}$

**Thermal leptogenesis**: sterile neutrinos in equilibrium at large temperatures

$$Y =$$

![Diagram showing decoupling and out of equilibrium decay before $T_{EW}$]

Generation of a lepton asymmetry due to the CP-violating decay of the particles


- $M > 10^6$ GeV to reproduce observed BAU (relaxed to $M > \text{TeV}$ for degenerate masses)

- Difficult to test in laboratory

**References**

BAU: ARS mechanism
T. Asaka and M. Shaposhnikov, hep-ph/0505013

Sterile neutrinos out of equilibrium at large temperatures

\[ m_\nu = -v^2 F \frac{1}{M} F^T \simeq 0.3 \left( \frac{\text{GeV}}{M} \right) \left( \frac{F^2}{10^{-14}} \right) \text{ eV} \]

M \sim \text{GeV} to reproduce v masses

Testable
ARS leptogenesis


How does the mechanism work?

Two kinds of \( CP \) processes

Lepton number conserving
(neutrino generation and oscillations)

Lepton number violating
(thermal Higgs decay)


\[ \propto \frac{M^2}{T^2} \] relevant at late times
Asymmetry generation example with 3 RHN

\[ x = \frac{T}{T_{EW}} \quad T_{EW} = 140 \text{ GeV} \quad R : \text{sterile neutrinos density matrix} \quad \mu_{\alpha} : \text{active flavours chemical potentials} \]

**Sterile neutrinos abundances**

- Deviation from thermal equilibrium

**Active flavours asymmetries**

- We switch off sterile neutrino oscillations when they become ineffective

**Sterile flavours asymmetries**

- Washout when states equilibrate

**Total asymmetries**

- Lepton number violating processes relevant at low temperatures
Testability?

Seesaw scaling \[ m_\nu = -\nu^2 F \frac{1}{M} F^T \]

In the **absence** of any **structure** in the \( F \) and \( M \) matrices

\[ |U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5} \sqrt{\frac{\text{GeV}}{M}} \]

But these are (complex) matrices: cancellations are possible
SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) \[ \Delta L = 2 \]

\[ \frac{1}{2} \frac{c_{\alpha \beta}}{\Lambda} \left( \overline{l_L^c} \Phi^* \right) \left( \Phi^\dagger l_L^\beta \right) + h.c. \]

EWsb

\[ \frac{v^2}{2} \frac{c_{\alpha \beta}}{\Lambda} \nu_L^c \nu_L^\beta + h.c. \]

New physics scale

Why are neutrinos so light?

\[ c_{\alpha \beta} \frac{v}{\Lambda} v \lesssim eV \ll v \]

Suppression mechanisms

\[ \frac{v}{\Lambda} \ll 1 \]

High NP scale

\[ c_{\alpha \beta} \ll 1 \]

Symmetry (Lepton number)

\[ c_{\alpha \beta} \ll 1 \]

Accidental cancellations

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SM as an effective theory

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EWWSB

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\frac{v}{\Lambda} \ll 1 \quad \text{High NP scale} \]

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\[ c_{\alpha \beta} \ll 1 \quad \text{Accidental cancellations} \]

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We compute neutrino masses $m_\nu$ at 1-loop, and quantify the level of fine-tuning of a solution as

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left( \frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

- $m_i^{\text{loop}}$: 1-loop neutrino mass spectrum
- $m_i^{\text{tree}}$: tree-level neutrino mass spectrum

If a symmetry is present in the Lagrangian, it will be manifest at any order in perturbation theory, suggesting the presence of an underlying symmetry. The neutrino mass scale is stable under radiative corrections, implying the presence of an underlying lepton number symmetry.

One can thus link the smallness of neutrino masses with the smallness of the lepton-number violating parameters in the theory to vary as reported in Table 1. This quantity can be determined by neutrino masses and mixing, any possibility to disentangle among the effective operators. Neutrino mass generation relies on an approximate lepton number, and the 6-dimensional operators, which encode new-physics effects other than neutrino oscillations and which can be either lepton-number-violating or -conserving. If there is no symmetry, although at tree-level accidental cancellations can result in small neutrino masses, then the combination of large Yukawa couplings and low-scale seesaw, without any symmetry protecting neutrino masses, will in general result in large loop corrections, spoiling small neutrino masses.
The minimal scenario: 2 RH-Neutrinos

Two RH-neutrinos suffice to account for neutrino oscillation data

P. H. Frampton, S. L. Glashow and T. Yanagida, hep-ph/0208157

Constrained flavour pattern


Large hierarchies in the couplings to different SM flavours not allowed
Leptogenesis with 2 RH-neutrinos

Too large active-sterile couplings enable equilibration of HNL and asymmetry washout

Washout is flavour-dependent, but “democratic” couplings for 2 RHN

Not possible to store the asymmetry in a feebly coupled flavour while the other mixings are large


Leptogenesis with 3 RH-neutrinos

New effects peculiar to 3 RHN case

Larger flavour hierarchies are allowed

Asymmetry in the heavy neutrino oscillations

2 flavour oscillations are CP-conserving
3 flavour oscillations are CP-violating

→ New source term

Resonantly enhanced asymmetry

A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L.,
Mass spectrum with 3 right-handed neutrinos and B - L approximate symmetry

How to preserve lepton number with Majorana states?

Pair two states to form a Dirac state
(equal masses, maximal mixing, opposite CP)

or

Decouple a state

If there is an odd number of right-handed neutrinos and B - L approximate symmetry

Suppressed Yukawa couplings

Pseudo-Dirac state
New mechanism: resonant asymmetry production in the B - L symmetry

\[ T_{\text{crossing}} \approx \frac{2\sqrt{2}M \sqrt{\mu^2 - 1}}{\sqrt{\sum_a |F_a|^2}} = 2.8 \times 10^5 \text{ GeV} \left( \frac{\bar{M}}{\text{GeV}} \right) \sqrt{\frac{\mu^2 - 1}{\sum_a |(F_a/10^{-5})|^2}} \]

Mass spectrum with 3 right-handed neutrinos and B - L symmetry

If the vacuum mass of the decoupled state is heavier than the pseudo-Dirac one, there is necessarily a level crossing at some finite temperature!
Level crossing: resonant asymmetry production

\[ x = \frac{T}{T_{EW}} \quad T_{EW} = 140 \text{ GeV} \quad \mathcal{R} : \text{sterile neutrinos density matrix} \quad \mu_\alpha : \text{active flavours chemical potentials} \]

### Sterile neutrinos abundances

\[ x \]

### Active flavours asymmetries

\[ \Delta \mu_\alpha \]

### Energy eigenvalues

\[ \lambda_i(H) \quad [\text{GeV}] \]

Level crossing at \( x \sim 0.13 \)

### Total asymmetries

\[ \Sigma_\alpha \Delta \mu_\alpha ; \Sigma_\lambda \Delta \mathcal{R}_{ii} \]
Conclusion

Low-scale leptogenesis with RH-neutrinos at the GeV scale is an attractive mechanism for the BAU generation.

We performed the first systematic study for low-scale leptogenesis in the Standard Model extended with 3 RH-neutrinos.

Low-scale solutions are testable in current experiments in the large-mixing region.

We find a new mechanism that:

• dynamically creates resonantly enhanced asymmetries
• protects them from washout
• works precisely in the $B - L$ approximate symmetry
Backup
Kinetic equations for freeze-in leptogenesis


\[
\frac{dR_N}{dt} = -i \left[ \langle H \rangle, R_N \right] - \frac{1}{2} \langle \gamma^{(0)} \rangle \left\{ F^\dagger F, R_N - I \right\} - \frac{1}{2} \langle \gamma^{(1b)} \rangle \left\{ F^\dagger \mu F, R_N \right\} + \langle \gamma^{(1a)} \rangle F^\dagger \mu F + \\
- \frac{1}{2} \langle \tilde{\gamma}^{(0)} \rangle \left\{ M_M F^T F^* M_M, R_N - I \right\} + \frac{1}{2} \langle \tilde{\gamma}^{(1b)} \rangle \left\{ M_M F^T \mu F^* M_M, R_N \right\} + \\
- \langle \tilde{\gamma}^{(1a)} \rangle M_M F^T \mu F^* M_M ,
\]

\[
\frac{d\mu_{\Delta a}}{dt} = - \frac{9 \zeta(3)}{2N_D \pi^2} \left\{ \langle \gamma^{(0)} \rangle \left( FR_N F^\dagger - F^* R_N F^T \right) - 2\langle \gamma^{(1a)} \rangle \mu F F^\dagger + \\
+ \langle \gamma^{(1b)} \rangle \mu \left( FR_N F^\dagger + F^* R_N F^T \right) \\
+ \langle \tilde{\gamma}^{(0)} \rangle \left( F^* M_M R_N M_M F^T - F M_M R_N M_M F^\dagger \right) - 2\langle \tilde{\gamma}^{(1a)} \rangle \mu F^* M_M^2 F^T \\
+ \langle \tilde{\gamma}^{(1b)} \rangle \mu \left( F^* M_M R_N M_M F^T + F M_M R_N M_M F^\dagger \right) \right\}_{aa} ,
\]

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The role of lepton number

M. Shaposhnikov, hep-ph/0605047

An approximate $B - L$ symmetry:

- enhances the asymmetry production
- allows for large active-sterile mixings

General seesaw parametrisation

$$F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e (1 + \epsilon_e) & i F_e (1 - \epsilon_e) & F_e \epsilon'_e \\ F_\mu (1 + \epsilon_\mu) & i F_\mu (1 - \epsilon_\mu) & F_\mu \epsilon'_\mu \\ F_\tau (1 + \epsilon_\tau) & i F_\tau (1 - \epsilon_\tau) & F_\tau \epsilon'_\tau \end{pmatrix}$$

$$M_M = \tilde{M} \begin{pmatrix} 1 - \mu & 0 & 0 \\ 0 & 1 + \mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

In the limit $\epsilon_\alpha, \epsilon'_\alpha, \mu \ll 1$

Approximate $B - L$ conservation
Neutrinoless effective mass

$0\nu\beta\beta$ decay is a lepton number violating process. It violates the $B-L$ symmetry.

Normal Ordering

![Graph showing Neutrinoless effective mass](image-url)
The νMSM
T. Asaka and M. Shaposhnikov, hep-ph/0505013
M. Shaposhnikov and I. Tkachev, hep-ph/0604236

**Type-I Seesaw with a phenomenologically motivated mass spectrum**

At the origin of the lepton asymmetries of the Universe and of neutrino masses

Dark matter candidate (does not significantly contribute to ν masses)

Active neutrinos

<table>
<thead>
<tr>
<th>Mass</th>
<th>GeV</th>
<th>keV</th>
<th>sub-eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**vMSM thermal history**


**Figure 1:** The thermal history of the universe in the νMSM.

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For all parameter choices we are interested in \( \bar{M} \approx M \) holds in very good approximation. The masses \( M^2, M^3 \) are too big to be sensitive to loop corrections. In contrast, the splitting \( \delta M \) can be considerably smaller than the size of radiative corrections \[^44\]. The above expressions have a different shape than those given in \cite{6} because we use a different base in flavor space, see appendix B.

These above formulae hold for the (zero temperature) masses in the microscopic theory. At finite temperature the system is described by a thermodynamic ensemble, the properties of which can usually be described in terms of quasiparticles with temperature dependent dispersion relations. We approximate these by temperature dependent “thermal masses.”

**2.4 Thermal History of the Universe in the νMSM**

Apart from the very weakly coupled sterile neutrinos, the matter content of the νMSM is the same as that of the SM. Therefore the thermal history of the universe during the radiation dominated phase is as follows:

- **A**
  - thermal production of \( N_2, N_3 \)
  - lepton asymmetry generated

- **B**
  - \( T_{\text{EW}} \) \( \approx 200 \) GeV
  - \( N_2, N_3 \) reach equilibrium
  - lepton asymmetry washed out

- **C**
  - \( T \) \( \approx \text{few GeV} \)
  - \( N_2, N_3 \) freeze out
  - lepton asymmetry generated

- **D**
  - \( T_d \) \( \approx 100 \) MeV
  - \( N_2, N_3 \) decay
  - lepton asymmetry generated

At the time \( T_{dm} \) \( \approx 100 \) MeV, resonant \( N_1 \) Dark Matter production occurs.
**νMSM dark matter solution**

**Shi-Fuller mechanism:** lepton number-driven resonant MSW conversion of active neutrinos

X. D. Shi and G. M. Fuller, astro-ph/9810076

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**Required lepton asymmetry**

\[
\mu_\alpha = \frac{n_\alpha}{s} \gtrsim 8 \cdot 10^{-6}
\]

**Required mass degeneracy**

\[
\frac{\delta M}{M} \lesssim 10^{-14}
\]
The Inverse Seesaw (ISS)

Enlarge the SM field content with:

- right handed neutrino fields, $\nu_R$
- fermionic sterile singlets, $s$

In the basis $n_L \equiv (\nu_L, \nu_R^C, s)^T$ the ISS neutrino mass terms read:

$$-\mathcal{L}_{\nu\nu} = \frac{1}{2} n_L^T \mathcal{C} \mathcal{M} n_L + h.c.,$$

$$\mathcal{M} = \begin{pmatrix}
0 & d & 0 \\
-d^T & 0 & n \\
0 & n^T & \mu
\end{pmatrix}$$

$t'$Hooft naturalness criterium: terms violating $L$ are "small", i.e.

$$|\mu| \ll |n|, |d|$$

Neutrino masses in the limit $|\mu| \ll |d| \ll |n|:

$$m_\nu \simeq d \left( n^{-1} \right)^T \mu \left( n^{-1} \right) d^T$$

One could link the smallness of $\mu$ with the one of $m_\nu$ (mechanism viable with large Yukawas), thus interesting phenomenology

Presence of sterile states ($\nu$ anomalies or DM candidates)
3.1 General feature of the ISS models: 2 or 3 different mass scales:

- \( \text{#} L_\nu + (\text{#} s - \text{#} v_R) \) light states
- \( \text{#} v_R \) pseudo-Dirac couples

\[ \approx O(n) \]

2 \( \text{#} v_R \) heavy states (pseudo-Dirac pairs)

\[ \approx O(\mu) \]

*only if \( \text{#} s > \text{#} v_R \)*

(\( \text{#} s - \text{#} v_R \)) light sterile states

\[ \approx O(\mu)O(k) \]

\[ k = \frac{|d|}{|n|} \]

\( E.g. \)

TeV (testable)

eV

meV

For each ISS realisation:

ISS mass scales

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Minimal ISS spectra

(2,2) ISS

4 heavy states (pseudo-Dirac pairs)

3 active neutrinos

(2,3) ISS

4 heavy states (pseudo-Dirac pairs)

1 light sterile state

3 active neutrinos
ARS leptogenesis in the (2,2) ISS

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Mass splitting

Yukawas

$Y_B > 10^{-10}$

$Y_B > 10^{-11}$

$Y_B > 10^{-12}$
A large fraction of solutions is testable in future experiments