Leptogenesis and Colliders

Bhupal Dev

*Washington University in St. Louis*

ACFI Workshop on Neutrinos at the High Energy Frontier

UMass Amherst

July 19, 2017
Matter-Antimatter Asymmetry

\[ \eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.1 \times 10^{-10} \]

One number $\rightarrow$ BSM Physics
Leptogenesis

A cosmological consequence of the seesaw mechanism.

- Provides a common link between neutrino mass and baryon asymmetry.
- Naturally satisfies all the Sakharov conditions.
  - $L$ violation due to the Majorana nature of heavy RH neutrinos.
  - New source of $CP$ violation in the leptonic sector (through complex Dirac Yukawa couplings and/or PMNS $CP$ phases).
  - Departure from thermal equilibrium when $\Gamma_N \lesssim H$.
- Freely available: $\mathcal{L} \to \mathcal{B}$ through EW sphaleron interactions.
Popularity of Leptogenesis

[INSPIRE Database]
Popularity of Leptogenesis

~ 3000 citations

[INSPIRE Database]
Three basic steps:

1. Generation of $L$ asymmetry by heavy Majorana neutrino decay:

2. Partial washout of the asymmetry due to inverse decay (and scatterings):

3. Conversion of the left-over $L$ asymmetry to $B$ asymmetry at $T > T_{sph}$.
Boltzmann Equations

\[ \frac{dN_N}{dz} = -(D + S)(N_N - N_N^{eq}), \]
\[ \frac{dN_{\Delta L}}{dz} = \varepsilon D(N_N - N_N^{eq}) - N_{\Delta L} W, \]

(\text{where } z = m_{N_1}/T \text{ and } D, S, W = \Gamma_{D,S,W}/Hz \text{ for decay, scattering and washout rates.})

- Final baryon asymmetry:
  \[ \eta^{\Delta B} = d \cdot \varepsilon \cdot \kappa_f \]

- \( d \approx \frac{28}{51} \frac{1}{27} \approx 0.02 \) (\( \mathcal{L} \rightarrow \mathcal{B} \) conversion at \( T_c \) + entropy dilution from \( T_c \) to \( T_{\text{recombination}} \)).

- \( \kappa_f \equiv \kappa(z_f) \) is the final efficiency factor, where
  \[ \kappa(z) = \int_{z_i}^z dz' \frac{D}{D + S} \frac{dN_N}{dz'} e^{-\int_{z'}^{z''} dz'' W(z'')} \]
Importance of self-energy effects (when $|m_{N_1} - m_{N_2}| \ll m_{N_1}$, $m_{N_2}$)

$\text{[J. Liu, G. Segré, PRD48 (1993) 4609; }
\text{L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169; . . . . ]}$

Importance of the heavy-neutrino width effects:


Warsaw, 22–27 June 2014

Flavour Covariance in Leptogenesis

A. Pilaftsis

tree

self-energy

vertex

Importance of self-energy effects

$\mathcal{E}_{l\alpha} = \frac{\Gamma(N_{\alpha} \rightarrow L_l\Phi) - \Gamma(N_{\alpha} \rightarrow L^c_l\Phi^c)}{\sum_k \left[ \Gamma(N_{\alpha} \rightarrow L_k\Phi) + \Gamma(N_{\alpha} \rightarrow L^c_k\Phi^c) \right]} \equiv \frac{|\hat{h}_{l\alpha}|^2 - |\hat{h}_{l\alpha}^c|^2}{(\hat{h}^\dagger\hat{h})_{\alpha\alpha} + (\hat{h}^c_{\alpha\alpha}^\dagger\hat{h}^c_{\alpha\alpha})}$

with the one-loop resummed Yukawa couplings [Pilaftsis, Underwood '03]

$\hat{h}_{l\alpha} = \hat{h}_{l\alpha} - i \sum_{\beta, \gamma} |\epsilon_{\alpha\beta\gamma}| \hat{h}_{l\beta}$

$\times \frac{m_{\alpha} (m_{\alpha} A_{\alpha\beta} + m_{\beta} A_{\beta\alpha}) - i R_{\alpha\gamma}[m_{\alpha} A_{\gamma\beta} (m_{\alpha} A_{\beta\alpha} + m_{\gamma} A_{\gamma\alpha}) + m_{\beta} A_{\beta\gamma} (m_{\alpha} A_{\gamma\alpha} + m_{\gamma} A_{\gamma\alpha})]}{m_{\alpha}^2 - m_{\beta}^2 + 2im_{\alpha} A_{\beta\beta} + 2i\text{Im}(R_{\alpha\gamma})[m_{\alpha} |A_{\beta\gamma}|^2 + m_{\beta} m_{\gamma} \text{Re}(A_{\beta\gamma}^2)]}$

$R_{\alpha\beta} = \frac{m_{\alpha}^2}{m_{\alpha}^2 - m_{\beta}^2 + 2im_{\alpha} A_{\beta\beta}}$ ; \quad $A_{\alpha\beta}(\hat{h}) = \frac{1}{16\pi} \sum_l \hat{h}_{l\alpha} \hat{h}_{l\beta}^*$.
Testability of Seesaw

In a bottom-up approach, no definite prediction of the seesaw scale.

Figure 4: A schematic illustration of the relation between $\text{rmtrF}^\dagger \text{F}$ and $M_I$ imposed by neutrino oscillation data (plot taken from Ref. [22]). Individual elements of $F$ can deviate considerably from $F_0$ if there are cancellations in (6). Cosmological constraints allow to further restrict the mass range, see Fig. 5.

Figure 5: The allowed mass ranges for $n = 3$ heavy neutrinos $N_I$ depend upon whether the lightest active neutrino is heavier (left panel) or lighter (right panel) than $3 \times 10^{-3}$ eV [24]. The difference between the two cases comes from a combination of neutrino oscillation data and early universe constraints. If the lightest active neutrino is relatively heavy, then all three $N_I$ need to have sizable mixings with active neutrinos to generate the three neutrino masses (sterile neutrinos that mix with the active neutrinos can generate an active neutrino mass via the seesaw mechanism). This means that all of them are produced in significant amounts in the early universe. In this case there exists a mass range $1 \text{eV} \lesssim M_I \lesssim 100 \text{MeV}$ that is excluded for all $N_I$ by cosmological considerations, in particular big bang nucleosynthesis and constraints on the number of effective neutrino species $N_{\text{eff}}$. If the lightest active neutrino is massless or rather light, then one heavy neutrino (here chosen to have a tiny mixing $U_{2\alpha}$). This allows to circumvent the cosmological bounds, and $N_1$ can essentially have any mass. In both cases the upper end of the plot is not an upper bound on the mass; indeed there exists no known upper bound for the $M_I$.

[24]

In a bottom-up approach, no definite prediction of the seesaw scale.
Testability of Leptogenesis

Three regions of interest:

- **High scale:** $10^9$ GeV $\lesssim m_N \lesssim 10^{14}$ GeV.
  
  Can be falsified with an LNV signal at LHC. – see Julia’s talk

- **Collider-friendly scale:** $100$ GeV $\lesssim m_N \lesssim$ few TeV.
  
  Can be tested in collider and/or low-energy ($0\nu\beta\beta$, LFV) searches. – this talk

- **Low-scale:** $1$ GeV $\lesssim m_N \lesssim 5$ GeV.
  
  Can be tested at the intensity frontier: SHiP, DUNE or B-factories (LHCb, Belle-II).
  
  – see Jacobo’s talk
Testability of Leptogenesis

Three regions of interest:

- **GUT/high scale**: $10^9$ GeV $\lesssim m_N \lesssim 10^{14}$ GeV.
  Can be falsified with an LNV signal at LHC. [Deppisch, Harz, Hirsch '14] – see Julia’s talk

- **Collider-friendly scale**: 100 GeV $\lesssim m_N \lesssim$ few TeV.
  Can be tested in collider and/or low-energy ($0\nu\beta\beta$, LFV) searches. –this talk

- **Low-scale**: 1 GeV $\lesssim m_N \lesssim$ 5 GeV.
  Can be tested at the intensity frontier: SHiP, DUNE or B-factories (LHCb, Belle-II). –see Jacobo’s talk
Testability of Leptogenesis

Three regions of interest:

- **GUT/high scale**: $10^9 \text{ GeV} \lesssim m_N \lesssim 10^{14} \text{ GeV}$. Can be falsified with an LNV signal at LHC. [Deppisch, Harz, Hirsch '14] – see Julia’s talk

- **Collider-friendly scale**: $100 \text{ GeV} \lesssim m_N \lesssim \text{ few TeV}$. Can be tested in collider and/or low-energy ($0\nu\beta\beta$, LFV) searches. –this talk

- **Low-scale**: $1 \text{ GeV} \lesssim m_N \lesssim 5 \text{ GeV}$. Can be tested at the intensity frontier: SHiP, DUNE or B-factories (LHCb, Belle-II). –see Jacobo’s talk
Vanilla Leptogenesis

- Hierarchical heavy neutrino spectrum ($m_{N_1} \ll m_{N_2} < m_{N_3}$).
- Both vertex correction and self-energy diagrams are relevant.
- For type-I seesaw, the maximal $CP$ asymmetry is given by

$$\varepsilon_1^{\text{max}} = \frac{3}{16\pi} \frac{m_{N_1}}{v^2} \sqrt{\Delta m^2_{\text{atm}}}$$

- **Lower bound on $m_{N_1}$**: [Davidson, Ibarra ’02; Buchmüller, Di Bari, Plümacher ’02]

$$m_{N_1} > 6.4 \times 10^8 \text{ GeV} \left( \frac{\eta_B}{6 \times 10^{-10}} \right) \left( \frac{0.05 \text{ eV}}{\sqrt{\Delta m^2_{\text{atm}}}} \right) \kappa_f^{-1}$$
Vanilla Leptogenesis

- Hierarchical heavy neutrino spectrum \( m_{N_1} \ll m_{N_2} < m_{N_3} \).
- Both vertex correction and self-energy diagrams are relevant.
- For type-I seesaw, the maximal CP asymmetry is given by
  \[
  \varepsilon_{1}^{\text{max}} = \frac{3}{16\pi} \frac{m_{N_1}}{v^2} \sqrt{\Delta m_{\text{atm}}^2}
  \]

- Lower bound on \( m_{N_1} \): [Davidson, Ibarra ’02; Buchmüller, Di Bari, Plümacher ’02]
  \[
  m_{N_1} > 6.4 \times 10^8 \text{ GeV} \left( \frac{\eta_B}{6 \times 10^{-10}} \right) \left( \frac{0.05 \text{ eV}}{\sqrt{\Delta m_{\text{atm}}^2}} \right) \kappa_f^{-1}
  \]

- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature \( T_{\text{rh}} \gtrsim 10^9 \text{ GeV} \).
- In supergravity models, need \( T_{\text{rh}} \lesssim 10^6 \text{ -- } 10^9 \text{ GeV} \) to avoid the gravitino problem.
  [Khlopov, Linde ’84; Ellis, Kim, Nanopoulos ’84; Cyburt, Ellis, Fields, Olive ’02; Kawasaki, Kohri, Moroi, Yotsuyanagi ’08]
- Also in conflict with the Higgs naturalness bound \( m_N \lesssim 10^7 \text{ GeV} \). [Vissani ’97; Clarke, Foot, Volkas ’15; Bambhaniya, BD, Goswami, Khan, Rodejohann ’16]
Resonant Leptogenesis

 Dominant self-energy effects on the $CP$-asymmetry ($\varepsilon$-type) [Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].

 Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N / 2 \ll m_{N_1,2}$.

 [Pilaftsis '97; Pilaftsis, Underwood '03]

 The quasi-degeneracy can be naturally motivated as due to approximate breaking of some symmetry in the leptonic sector.

 Heavy neutrino mass scale can be as low as the EW scale.

 [Pilaftsis, Underwood '05; Deppisch, Pilaftsis '10; BD, Millington, Pilaftsis, Teresi '14]

 A testable leptogenesis scenario at both Energy and Intensity Frontiers.
Flavor-diagonal Rate Equations

\[ \frac{n^\gamma H_N}{z} \frac{d\eta^N_\alpha}{dz} = \left(1 - \frac{\eta^N_\alpha}{\eta^N_{eq}}\right) \sum_l \gamma^N_{l_\Phi} \]

\[ \frac{n^\gamma H_N}{z} \frac{d\delta\eta^L_l}{dz} = \sum_{\alpha} \left(\frac{\eta^N_{\alpha}}{\eta^N_{eq}} - 1\right) \varepsilon_{l_\Phi} \sum_k \gamma^N_{L_k_\Phi} - \frac{2}{3} \delta\eta^L_l \sum_k \left[ \gamma^{L_{k_\Phi}c} + \gamma^{L_{k_\Phi}} + \delta\eta^L_k \left(\gamma^{L_{k_\Phi}c} - \gamma^{L_{k_\Phi}}\right) \right] \]

\[ \hat{N}_\beta(p, s) \rightarrow [\hat{h}^\gamma]^\beta_k \rightarrow L_k(k, r) \]

\[ \hat{N}_\alpha(p, s) \rightarrow [\hat{h}^\gamma]^l_{\alpha} \rightarrow L^l(k, r) \]

\[ L^n(k_2, r_2) \rightarrow \hat{h}^\gamma_\beta \rightarrow \hat{N}_\beta(p) \]

\[ L^n(k_1, r_1) \rightarrow \hat{h}^\gamma_\beta \rightarrow \hat{N}_\beta(p) \]

\[ L^m(k_2, r_2) \rightarrow [\hat{h}^\gamma]^m_\beta \rightarrow \hat{N}_\beta(p) \]

\[ L^m(k_1, r_1) \rightarrow [\hat{h}^\gamma]^m_\beta \rightarrow \hat{N}_\beta(p) \]
Analytic Solution

\[ \eta_L(z) \approx \frac{3}{2z} \sum_l \sum_{\alpha} \frac{\varepsilon l_\alpha}{K_l^{\text{eff}}} \quad (z_2 < z < z_3) \]
Flavordynamics

Figure 1: The ten different three RH neutrino mass patterns requiring 10 different sets of Boltzmann equations for the calculation of the asymmetry [17].

Therefore, it is necessary to extend the density matrix formalism beyond the traditional $N_1$-dominated scenario [6, 11, 19] and account for heavy neutrino flavours in order to calculate the final asymmetry for an arbitrary choice of the RH neutrino masses. This is the main objective of this paper. At the same time we want to show how Boltzmann equations can be recovered from the density matrix equations for the hierarchical RH neutrino mass patterns shown in Fig. 1 allowing an explicit analytic calculation of the final asymmetry. In this way we will confirm and extend results that were obtained within an implict quantum mechanical description.

In Section 2 we discuss the derivation of the kinetic equations for the $N_1$-dominated scenario in the absence of heavy neutrino flavours. This is useful both to show the extension from classical Boltzmann to density matrix equations and to highlight some...
Flavor effects important at low scale [Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; De Simone, Riotto '06; Blanchet, Di Bari, Jones, Marzola '12; BD, Millington, Pilaftsis, Teresi '14]

Two sources of flavor effects:
- Heavy neutrino Yukawa couplings $h^\alpha_l$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
- Charged lepton Yukawa couplings $y^k_l$ [Barbieri, Creminelli, Strumia, Tetrads '00]

*Three* distinct physical phenomena: mixing, oscillation and decoherence.

Captured consistently in the Boltzmann approach by the *fully* flavor-covariant formalism. [BD, Millington, Pilaftsis, Teresi '14; '15]
In quantum statistical mechanics,

\[ n^X(t) \equiv \langle \hat{n}^X(\tilde{t}; \tilde{t}_i) \rangle_t = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \hat{n}^X(\tilde{t}; \tilde{t}_i) \right\} . \]

Differentiate w.r.t. the macroscopic time \( t = \tilde{t} - \tilde{t}_i \):

\[
\frac{d n^X(t)}{dt} = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \frac{d \hat{n}^X(\tilde{t}; \tilde{t}_i)}{d \tilde{t}} \right\} + \text{Tr} \left\{ \frac{d \rho(\tilde{t}; \tilde{t}_i)}{d \tilde{t}} \hat{n}^X(\tilde{t}; \tilde{t}_i) \right\} \equiv \mathcal{I}_1 + \mathcal{I}_2 .
\]

Use the Heisenberg EoM for \( \mathcal{I}_1 \) and Liouville-von Neumann equation for \( \mathcal{I}_2 \).

Markovian master equation for the number density matrix:

\[
\frac{d}{dt} n^X(k, t) \simeq i \langle [H^X_0, \hat{n}^X(k, t)] \rangle_t - \frac{1}{2} \int_{-\infty}^{+\infty} dt' \langle [H_{\text{int}}(t'), [H_{\text{int}}(t), \hat{n}^X(k, t)]] \rangle_t .
\]
In quantum statistical mechanics,

\[ n^X(t) \equiv \langle \mathbf{n}^X(\tilde{t}; \tilde{t}_i) \rangle_t = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \mathbf{n}^X(\tilde{t}; \tilde{t}_i) \right\} . \]

Differentiate w.r.t. the macroscopic time \( t = \tilde{t} - \tilde{t}_i \):

\[ \frac{d n^X(t)}{dt} = \text{Tr} \left\{ \rho(\tilde{t}; \tilde{t}_i) \frac{d \mathbf{n}^X(\tilde{t}; \tilde{t}_i)}{d \tilde{t}} \right\} + \text{Tr} \left\{ \frac{d \rho(\tilde{t}; \tilde{t}_i)}{d \tilde{t}} \mathbf{n}^X(\tilde{t}; \tilde{t}_i) \right\} \equiv I_1 + I_2. \]

Use the Heisenberg EoM for \( I_1 \) and Liouville-von Neumann equation for \( I_2 \).

**Markovian master equation** for the number density matrix:

\[ \frac{d n^X(k, t)}{dt} \simeq i \langle [H^X_0, \mathbf{n}^X(k, t)] \rangle_t - \frac{1}{2} \int_{-\infty}^{+\infty} dt' \langle [H_{\text{int}}(t'), [H_{\text{int}}(t), \mathbf{n}^X(k, t)] ] \rangle_t. \]

(Oscillation) \hspace{1cm} (Mixing)

**Generalization of the density matrix formalism.** [Sigl, Raffelt '93]
Collision Rates for Decay and Inverse Decay

\[ n^\Phi [n^L]_l^k [\gamma(L^\Phi \rightarrow N)]_k^l \beta \]

\[ \hat{N}^\beta \rightarrow \hat{N}_\alpha \]

\[ L_k(k, r) \]

\[ n^\Phi(q)[n^L_r(k)]_l^k \]

\[ L^l(k, r) \]

\[ \hat{N}_\alpha(p, s) \]
Collision Rates for $2 \leftrightarrow 2$ Scattering

\[ n^\Phi \left[ n^L \right]^k_l \left[ \gamma(L\Phi \rightarrow L\Phi) \right]_k^l m^n \]
Final Rate Equations

\[
\frac{H_N n^\gamma}{z} \frac{d[\eta^N]}{dz} = -i \frac{n^\gamma}{2} \left[ \mathcal{E}_N, \delta \eta^N \right]_\alpha \beta + \left[ \text{Re}(\gamma_L^N) \right]_\alpha \beta - \frac{1}{2 \eta^N_{eq}} \left\{ \eta^N, \text{Re}(\gamma_L^N) \right\}_\alpha \beta
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^N]}{dz} = -2i n^\gamma \left[ \mathcal{E}_N, \eta^N \right]_\alpha \beta + 2i \left[ \text{Im}(\delta \gamma_L^N) \right]_\alpha \beta - \frac{i}{\eta^N_{eq}} \left\{ \eta^N, \text{Im}(\delta \gamma_L^N) \right\}_\alpha \beta
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^L]}{dz} = -\left[ \delta \gamma_L^N \right]_l^m + \left[ \frac{\eta^N}{\eta^N_{eq}} \delta \gamma_L^N \right]_l^m \alpha + \left[ \frac{\delta \eta^N}{2 \eta^N_{eq}} \gamma_L^N \right]_l^m \alpha
\]

\[
- \frac{1}{3} \left\{ \delta \eta^L, \gamma_{L\tilde{c}\Phi\tilde{c}} \right\}_l^m + \frac{2}{3} \left[ \delta \eta^L \right]_k^n \left( \left[ \gamma_{L\tilde{c}\Phi\tilde{c}} \right]_n^k m - \left[ \gamma_{L\Phi} \right]_n^k \right)
\]

\[
- \frac{2}{3} \left\{ \delta \eta^L, \gamma_{\text{dec}} \right\}_l^m + \left[ \delta \gamma_{\text{dec}} \right]_l^m
\]
Final Rate Equations: Mixing

\[
\frac{H_N}{z} \frac{n^\gamma}{d}\left[\eta^N\right]^\beta = -i \frac{n^\gamma}{2} \left[\mathcal{E}_N, \delta\eta^N\right]^\beta + \left[\tilde{\text{Re}}(\gamma^N_{L\Phi})\right]^\beta_{\alpha} - \frac{1}{2 \eta^N_{eq}} \left\{\eta^N, \tilde{\text{Re}}(\gamma^N_{L\Phi})\right\}^\beta_{\alpha}
\]

\[
\frac{H_N}{z} \frac{n^\gamma}{d}\left[\delta\eta^N\right]^\beta = -2i n^\gamma \left[\mathcal{E}_N, \eta^N\right]^\beta_{\alpha} + 2i \left[\tilde{\text{Im}}(\delta\gamma^N_{L\Phi})\right]^\beta_{\alpha} - \frac{i}{\eta^N_{eq}} \left\{\eta^N, \tilde{\text{Im}}(\delta\gamma^N_{L\Phi})\right\}^\beta_{\alpha}
\]

\[
\frac{H_N}{z} \frac{n^\gamma}{d}\left[\delta\gamma^L_{dec}\right]_m = -\left[\delta\gamma^N_{L\Phi}\right]_m + \frac{\left[\eta^N\right]^{\alpha}_{\beta}}{\eta^N_{eq}} \left[\delta\gamma^N_{L\Phi}\right]_m^\beta + \frac{\left[\delta\eta^N\right]^{\alpha}_{\beta}}{2 \eta^N_{eq}} \left[\gamma^N_{L\Phi}\right]_m^\alpha
\]

\[
- \frac{1}{3} \left\{\delta\eta^L, \gamma^L_{L\Phi\bar{\Phi}} + \gamma^L_{L\Phi}\right\}_m^\beta - \frac{2}{3} \left[\delta\eta^L\right]_k^n \left(\left[\gamma^L_{L\Phi\bar{\Phi}}\right]_{n \beta} - \left[\gamma^L_{L\Phi}\right]_{n \beta}\right)
\]

\[
- \frac{2}{3} \left\{\delta\eta^L, \gamma^L_{dec}\right\}_m^\beta + \left[\delta\gamma^L_{dec}\right]_m^\beta
\]
Final Rate Equations: Oscillation

\[
\frac{H_N n^\gamma}{z} \frac{d[\eta^N]}{dz} = -i \frac{n^\gamma}{2} \left[ \mathcal{E}_N, \delta \eta^N \right]_\alpha^\beta + \left[ \tilde{\text{Re}}(\gamma_L^N) \right]_\alpha^\beta - \frac{1}{2\eta_{eq}^N} \left\{ \eta^N, \tilde{\text{Re}}(\gamma_L^N) \right\}^\beta_\alpha
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^N]}{dz} = -2i n^\gamma \left[ \mathcal{E}_N, \eta^N \right]_\alpha^\beta + 2i \left[ \tilde{\text{Im}}(\delta \gamma_L^N) \right]_\alpha^\beta - \frac{i}{\eta_{eq}^N} \left\{ \eta^N, \tilde{\text{Im}}(\delta \gamma_L^N) \right\}^\beta_\alpha
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^L]}{dz} = -\left[ \delta \gamma_L^N \right]_l^m + \frac{[\eta^N]}{\eta_{eq}^N} \left[ \delta \gamma_L^N \right]_l^m \alpha^\beta + \frac{[\delta \eta^N]}{2\eta_{eq}^N} \left[ \gamma_L^N \right]_l^m \alpha^\beta
\]

\[
- \frac{1}{3} \left\{ \delta \eta^L, \gamma_L^{\Phi \Phi} + \gamma_L^\Phi \right\}_l^m - \frac{2}{3} \left[ \delta \eta^L \right]_k^n \left( \left[ \gamma_L^{\Phi \Phi} \right]_n^l - \left[ \gamma_L^\Phi \right]_n^l \right)
\]

\[
- \frac{2}{3} \left\{ \delta \eta^L, \gamma_{\text{dec}} \right\}_l^m + \left[ \delta \gamma_{\text{dec}}^\text{back} \right]_l^m
\]
Final Rate Equations: Charged Lepton Decoherence

\[
\frac{H_N n^\gamma}{z} \frac{d[\eta^N]}{dz} \beta = -i \frac{n^\gamma}{2} \left[ \mathcal{E}_N, \delta \eta^N \right]_\alpha \beta + \left[ \tilde{\text{Re}}(\gamma^N_L\Phi) \right]_\alpha \beta - \frac{1}{2 \eta^N_{\text{eq}}} \left\{ \eta^N, \tilde{\text{Re}}(\gamma^N_L\Phi) \right\} \beta
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^N]}{dz} \beta = -2i n^\gamma \left[ \mathcal{E}_N, \eta^N \right]_\alpha \beta + 2i \left[ \tilde{\text{Re}}(\delta \gamma^N_L\Phi) \right]_\alpha \beta - \frac{i}{\eta^N_{\text{eq}}} \left\{ \eta^N, \tilde{\text{Re}}(\delta \gamma^N_L\Phi) \right\} \beta
\]

\[
\frac{H_N n^\gamma}{z} \frac{d[\delta \eta^L]}{dz} \beta = -[\delta \gamma^N_L]\eta^N_{\text{eq}} \left[ \gamma^N_L\Phi \right]_\alpha \beta + \frac{[\delta \eta^N]}{2 \eta^N_{\text{eq}}} \left[ \gamma^N_L\Phi \right]_\alpha \beta
\]

\[
- \left\{ \delta \eta^L, \gamma^L \Phi \right\}_\beta \right\} \beta + \frac{2}{3} \left[ \delta \eta^L \right]_k \left( \left[ \gamma^L \Phi \right]_{n l} - \left[ \gamma^L \Phi \right]_{k m} \right)
\]

\[
- \frac{2}{3} \left\{ \delta \eta^L, \gamma_{\text{dec}} \right\}_\beta \right\} \beta + \left[ \delta \gamma_{\text{back}} \right]_\beta \right\} \beta
\]
Combination \( \delta \eta^L \div \delta \eta^L_{\text{osc}} \) yields a factor of 2 enhancement compared to the isolated contributions for weakly-resonant RL.

\[
\delta \eta_{\text{mix}}^L \simeq \frac{g_N}{2} \frac{3}{2Kz} \sum_{\alpha \neq \beta} \frac{\Im \left( \hat{h}^\dagger \hat{h} \right)_{\alpha\beta}^2}{\left( \hat{h}^\dagger \hat{h} \right)_{\alpha\alpha} \left( \hat{h}^\dagger \hat{h} \right)_{\beta\beta}} \left( M_{N, \alpha}^2 - M_{N, \beta}^2 \right) \frac{M_N \hat{\Gamma}^{(0)}_{\beta\beta}}{\left( M_{N, \alpha}^2 - M_{N, \beta}^2 \right)^2 + \left( M_N \hat{\Gamma}^{(0)}_{\beta\beta} \right)^2},
\]

\[
\delta \eta_{\text{osc}}^L \simeq \frac{g_N}{2} \frac{3}{2Kz} \sum_{\alpha \neq \beta} \frac{\Im \left( \hat{h}^\dagger \hat{h} \right)_{\alpha\beta}^2}{\left( \hat{h}^\dagger \hat{h} \right)_{\alpha\alpha} \left( \hat{h}^\dagger \hat{h} \right)_{\beta\beta}} \left( M_{N, \alpha}^2 - M_{N, \beta}^2 \right) \frac{M_N \left( \hat{\Gamma}^{(0)}_{\alpha\alpha} + \hat{\Gamma}^{(0)}_{\beta\beta} \right)}{\left( M_{N, \alpha}^2 - M_{N, \beta}^2 \right)^2 + M_N^2 \left( \hat{\Gamma}^{(0)}_{\alpha\alpha} + \hat{\Gamma}^{(0)}_{\beta\beta} \right)^2} \frac{\Im \left( \hat{h}^\dagger \hat{h} \right)_{\alpha\beta}^2}{\left( \hat{h}^\dagger \hat{h} \right)_{\alpha\alpha} \left( \hat{h}^\dagger \hat{h} \right)_{\beta\beta}}.
\]
Testable Models

- Need $m_N \lesssim O(\text{TeV})$.
- Naive type-I seesaw requires mixing with light neutrinos to be $\lesssim 10^{-5}$.
- Collider signal suppressed in the minimal set-up (SM+RH neutrinos).
- Two ways out:
  - Construct a TeV seesaw model with large mixing (special textures of $m_D$ and $m_N$).
  - Go beyond the minimal SM seesaw (e.g. $U(1)_{B-L}$, Left-Right).
- Observable low-energy signatures (LFV, $0\nu\beta\beta$) possible in any case.
- Complementarity between high-energy and high-intensity frontiers.
- Leptogenesis brings in additional powerful constraints in each case.
- Can be used to test/falsify leptogenesis.
**A Minimal Model of RL**

- **$O(N)$-symmetric heavy neutrino sector at a high scale $\mu_X$.**
- **Radiative RL:** Small mass splitting at low scale from RG effects. [Branco, Gonzalez Felipe, Joaquim, Masina, Rebelo, Savoy ’03]

\[
M_N = m_N 1 + \Delta M_N^{RG}, \quad \text{with} \quad \Delta M_N^{RG} = -\frac{m_N}{8\pi^2} \ln \left( \frac{\mu_X}{m_N} \right) \text{Re} \left[ h^\dagger(\mu_X) h(\mu_X) \right].
\]

- A specific realization: Resonant $\ell$-genesis (RL$_\ell$). [Pilaftsis ’04; Deppisch, Pilaftsis ’11]
- An example of RL$_\tau$ with $U(1)_{L_e+L_\mu} \times U(1)_{L_\tau}$ flavor symmetry:

\[
h = \begin{pmatrix}
0 & ae^{-i\pi/4} & ae^{i\pi/4} \\
0 & be^{-i\pi/4} & be^{i\pi/4} \\
0 & 0 & 0
\end{pmatrix} + \delta h,
\]

\[
\delta h = \begin{pmatrix}
\epsilon_e & 0 & 0 \\
\epsilon_\mu & 0 & 0 \\
\epsilon_\tau & \kappa_1 e^{-i(\pi/4-\gamma_1)} & \kappa_2 e^{i(\pi/4-\gamma_2)}
\end{pmatrix},
\]

- But $CP$ asymmetry vanishes up to $O(h^4)$. [BD, Millington, Pilaftsis, Teresi ’15]
A Next-to-minimal Model

[BD, Millington, Pilaftsis, Teresi '15]

- Add an additional flavor-breaking $\Delta M_N$:

$$M_N = m_N 1 + \Delta M_N + \Delta M_N^{\text{RG}}, \quad \text{with } \Delta M_N = \begin{pmatrix} \Delta M_1 & 0 & 0 \\ 0 & \Delta M_2/2 & 0 \\ 0 & 0 & -\Delta M_2/2 \end{pmatrix},$$

$$h = \begin{pmatrix} 0 & ae^{-i\pi/4} & ae^{i\pi/4} \\ 0 & be^{-i\pi/4} & be^{i\pi/4} \\ 0 & ce^{-i\pi/4} & ce^{i\pi/4} \end{pmatrix} + \begin{pmatrix} \epsilon_e & 0 & 0 \\ \epsilon_\mu & 0 & 0 \\ \epsilon_\tau & 0 & 0 \end{pmatrix}.$$

- Light neutrino mass constraint:

$$M_\nu \approx -\frac{v^2}{2} hM_N^{-1} h^\top \approx \frac{v^2}{2m_N} \left( \begin{array}{ccc} \frac{\Delta m_N}{m_N} a^2 - \epsilon_e^2 & \frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & \frac{\Delta m_N}{m_N} b^2 - \epsilon_\mu^2 \\ \frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & -\epsilon_e \epsilon_\tau & -\epsilon_\mu \epsilon_\tau \\ \frac{\Delta m_N}{m_N} b^2 - \epsilon_\mu^2 & -\epsilon_\mu \epsilon_\tau & -\epsilon_\tau^2 \end{array} \right),$$

where

$$\Delta m_N \equiv 2 [\Delta M_N]_{23} + i \left( [\Delta M_N]_{33} - [\Delta M_N]_{22} \right) = -i \Delta M_2.$$
## Benchmark Points

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_N$</td>
<td>120 GeV</td>
<td>400 GeV</td>
<td>5 TeV</td>
</tr>
<tr>
<td>$c$</td>
<td>$2 \times 10^{-6}$</td>
<td>$2 \times 10^{-7}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Delta M_1/m_N$</td>
<td>$-5 \times 10^{-6}$</td>
<td>$-3 \times 10^{-5}$</td>
<td>$-4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta M_2/m_N$</td>
<td>$(-1.59 - 0.47 i) \times 10^{-8}$</td>
<td>$(-1.21 + 0.10 i) \times 10^{-9}$</td>
<td>$(-1.46 + 0.11 i) \times 10^{-8}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$(5.54 - 7.41 i) \times 10^{-4}$</td>
<td>$(4.93 - 2.32 i) \times 10^{-3}$</td>
<td>$(4.67 - 4.33 i) \times 10^{-3}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$(0.89 - 1.19 i) \times 10^{-3}$</td>
<td>$(8.04 - 3.79 i) \times 10^{-3}$</td>
<td>$(7.53 - 6.97 i) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>$3.31 i \times 10^{-8}$</td>
<td>$5.73 i \times 10^{-8}$</td>
<td>$2.14 i \times 10^{-7}$</td>
</tr>
<tr>
<td>$\epsilon_{\mu}$</td>
<td>$2.33 i \times 10^{-7}$</td>
<td>$4.30 i \times 10^{-7}$</td>
<td>$1.50 i \times 10^{-6}$</td>
</tr>
<tr>
<td>$\epsilon_\tau$</td>
<td>$3.50 i \times 10^{-7}$</td>
<td>$6.39 i \times 10^{-7}$</td>
<td>$2.26 i \times 10^{-6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
<th>Current Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(\mu \rightarrow e\gamma)$</td>
<td>$4.5 \times 10^{-15}$</td>
<td>$1.9 \times 10^{-13}$</td>
<td>$2.3 \times 10^{-17}$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow \mu\gamma)$</td>
<td>$1.2 \times 10^{-17}$</td>
<td>$1.6 \times 10^{-18}$</td>
<td>$8.1 \times 10^{-22}$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{BR}(\tau \rightarrow e\gamma)$</td>
<td>$4.6 \times 10^{-18}$</td>
<td>$5.9 \times 10^{-19}$</td>
<td>$3.1 \times 10^{-22}$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\text{BR}(\mu \rightarrow 3e)$</td>
<td>$1.5 \times 10^{-16}$</td>
<td>$9.3 \times 10^{-15}$</td>
<td>$4.9 \times 10^{-18}$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{Ti}$</td>
<td>$2.4 \times 10^{-14}$</td>
<td>$2.9 \times 10^{-13}$</td>
<td>$2.3 \times 10^{-20}$</td>
<td>$&lt; 6.1 \times 10^{-13}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{Au}$</td>
<td>$3.1 \times 10^{-14}$</td>
<td>$3.2 \times 10^{-13}$</td>
<td>$5.0 \times 10^{-18}$</td>
<td>$&lt; 7.0 \times 10^{-13}$</td>
</tr>
<tr>
<td>$R_{\mu \rightarrow e}^{Pb}$</td>
<td>$2.3 \times 10^{-14}$</td>
<td>$2.2 \times 10^{-13}$</td>
<td>$4.3 \times 10^{-18}$</td>
<td>$&lt; 4.6 \times 10^{-11}$</td>
</tr>
<tr>
<td>$</td>
<td>\Omega</td>
<td>_{e\mu}$</td>
<td>$5.8 \times 10^{-6}$</td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
A Discrete Flavor Model for RL

- Based on residual leptonic flavor $G_f = \Delta(3n^2)$ or $\Delta(6n^2)$ (with $n$ even, $3 \nmid n$, $4 \nmid n$) and CP symmetries. [Luhn, Nasri, Ramond ’07; Escobar, Luhn ’08; Feruglio, Hagedorn, Zieglar ’12]

- LH lepton doublets $L_\ell$ transform in a faithful complex irrep $\mathbf{3}$, RH neutrinos $N_\alpha$ in an unfaithful real irrep $\mathbf{3}’$ and RH charged leptons $\ell_R$ in a singlet $\mathbf{1}$ of $G_f$.

- CP symmetry is given by the transformation $X(s)(r)$ in the representation $r$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro ’14]
Based on residual leptonic flavor $G_f = \Delta (3n^2)$ or $\Delta (6n^2)$ (with $n$ even, $3 \nmid n$, $4 \nmid n$) and CP symmetries. [Luhn, Nasri, Ramond '07; Escobar, Luhn '08; Feruglio, Hagedorn, Zieglar '12]

LH lepton doublets $L_\ell$ transform in a faithful complex irrep $3$, RH neutrinos $N_\alpha$ in an unfaithful real irrep $3'$ and RH charged leptons $\ell_R$ in a singlet $1$ of $G_f$.

CP symmetry is given by the transformation $X(s)(r)$ in the representation $r$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro '14]
Based on residual leptonic flavor $G_f = \Delta(3n^2)$ or $\Delta(6n^2)$ (with $n$ even, $3 \nmid n$, $4 \nmid n$) and CP symmetries. [Luhn, Nasri, Ramond '07; Escobar, Luhn '08; Feruglio, Hagedorn, Zieglar '12]

LH lepton doublets $L_\ell$ transform in a faithful complex irrep $3$, RH neutrinos $N_\alpha$ in an unfaithful real irrep $3'$ and RH charged leptons $\ell_R$ in a singlet $1$ of $G_f$.

CP symmetry is given by the transformation $X(s)(r)$ in the representation $r$ and depends on the integer parameter $s$, $0 \leq s \leq n - 1$. [Hagedorn, Meroni, Molinaro '14]

One example: [BD, Hagedorn, Molinaro (in prep)]

$$Y_D = \Omega(s)(3) \ R_{13}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} \ R_{13}(-\theta_R) \ \Omega(s)(3')^\dagger .$$

$$M_R = M_N \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$\theta_L \approx 0.18(2.96)$ gives $\sin^2 \theta_{23} \approx 0.605(0.395)$, $\sin^2 \theta_{12} \approx 0.341$ and $\sin^2 \theta_{13} \approx 0.0219$ (within $3\sigma$ of current global-fit). [Hagedorn, Molinaro '16]
Light neutrino masses given by the type-I seesaw:

\[
M_{\nu}^2 = \frac{v^2}{M_N} \begin{pmatrix}
    y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
    y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \\
    -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
    -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R
\end{pmatrix}
\]

(s even),

\[
M_{\nu}^2 = \frac{v^2}{M_N} \begin{pmatrix}
    -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
    y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \\
    -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
    0 & y_2^2 & 0 \\
    y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R
\end{pmatrix}
\]

(s odd).

For \( y_1 = 0 \) (\( y_3 = 0 \)), we get strong normal (inverted) ordering, with \( m_{\text{lightest}} = 0 \).

\[
\text{NO: } y_1 = 0, \quad y_2 = \pm \frac{\sqrt{M_N \sqrt{\Delta m^2_{\text{sol}}}}}{v}, \quad y_3 = \pm \frac{\sqrt{M_N \sqrt{|\Delta m^2_{\text{atm}}|}}}{v},
\]

\[
\text{IO: } y_3 = 0, \quad y_2 = \pm \frac{\sqrt{M_N \sqrt{|\Delta m^2_{\text{atm}}|}}}{v}, \quad y_1 = \pm \frac{\sqrt{M_N \sqrt{(|\Delta m^2_{\text{atm}}| - \Delta m^2_{\text{sol}})}}}{v},
\]

Only free parameters: \( M_N \) and \( \theta_R \).
Low Energy CP Phases and $0\nu\beta\beta$

- Dirac phase is trivial: $\delta = 0$.
- For $m_{\text{lightest}} = 0$, only one Majorana phase $\alpha$, which depends on the chosen CP transformation:
  \[
  \sin \alpha = (-1)^{k+r+s} \sin 6 \phi_s \quad \text{and} \quad \cos \alpha = (-1)^{k+r+s+1} \cos 6 \phi_s \quad \text{with} \quad \phi_s = \frac{\pi S}{n},
  \]
  where $k = 0$ ($k = 1$) for $\cos 2 \theta_R > 0$ ($\cos 2 \theta_R < 0$) and $r = 0$ ($r = 1$) for NO (IO).
- Restricts the light neutrino contribution to $0\nu\beta\beta$:
  \[
  m_{\beta\beta} \approx \frac{1}{3} \left\{ \begin{array}{l}
    \sqrt{\Delta m^2_{\text{sol}}} + 2 (-1)^{s+k+1} \sin^2 \theta_L e^{6i\phi_s} \sqrt{\Delta m^2_{\text{atm}}}, \\
    1 + 2 (-1)^{s+k} e^{6i\phi_s} \cos^2 \theta_L \sqrt{\Delta m^2_{\text{atm}}} \end{array} \right\} \quad \text{(NO)}. \]
  \[
  \left| \begin{array}{l}
    \sqrt{\Delta m^2_{\text{sol}}} + 2 (-1)^{s+k+1} \sin^2 \theta_L e^{6i\phi_s} \sqrt{\Delta m^2_{\text{atm}}} \cos 2 \theta_L \sqrt{\Delta m^2_{\text{atm}}} \end{array} \right| \quad \text{(IO)}. \]
- For $n = 26$, $\theta_L \approx 0.18$ and best-fit values of $\Delta m^2_{\text{sol}}$ and $\Delta m^2_{\text{atm}}$, we get
  \[
  0.0019 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.0040 \text{ eV} \quad \text{(NO)} \]
  \[
  0.016 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.048 \text{ eV} \quad \text{(IO)}. \]
At leading order, three degenerate RH neutrinos.
Higher-order corrections can break the residual symmetries, giving rise to a quasi-degenerate spectrum:

\[ M_1 = M_N (1 + 2 \kappa) \quad \text{and} \quad M_2 = M_3 = M_N (1 - \kappa). \]

CP asymmetries in the decays of \( N_i \) are given by

\[ \epsilon_{i \alpha} \approx \sum_{j \neq i} \text{Im} \left( \hat{Y}_{D, i}^* \hat{Y}_{D, j} \right) \text{Re} \left( \left( \hat{Y}_{D}^\dagger \hat{Y}_{D} \right)_{ij} \right) F_{ij} \]

\( F_{ij} \) are related to the regulator in RL and are proportional to the mass splitting of \( N_i \).

We find \( \epsilon_{3 \alpha} = 0 \) and

\[ \epsilon_{1 \alpha} \approx \frac{y_2 y_3}{9} \left( -2 y_2^2 + y_3^2 (1 - \cos 2 \theta_R) \right) \sin 3 \phi_s \sin \theta_R \sin \theta_{L, \alpha} F_{12} \quad (\text{NO}) \]
\[ \epsilon_{1 \alpha} \approx \frac{y_1 y_2}{9} \left( -2 y_2^2 + y_1^2 (1 + \cos 2 \theta_R) \right) \sin 3 \phi_s \cos \theta_R \cos \theta_{L, \alpha} F_{12} \quad (\text{IO}) \]

with \( \theta_{L, \alpha} = \theta_L + \rho_\alpha 4\pi/3 \) and \( \rho_e = 0, \rho_\mu = 1, \rho_\tau = -1 \).

\( \epsilon_{2 \alpha} \) are the negative of \( \epsilon_{1 \alpha} \) with \( F_{12} \) being replaced by \( F_{21} \).
Correlation between BAU and $0\nu\beta\beta$

[BD, Hagedorn, Molinaro (in prep)]

[Bhupal Dev (Washington U.)  Leptogenesis and Colliders  ACFI Workshop]
Correlation between BAU and $0^{\nu}\beta\beta$

![Graph showing correlation between BAU and $0^{\nu}\beta\beta$. The graph plots $\eta_B$ against $m_{\beta\beta}$ in eV. The data points are marked with numbers representing different sets of parameters. The data comes from BD, Hagedorn, and Molinaro (in prep).](image)
Correlation between BAU and $0^{\nu}\beta\beta$

[BD, Hagedorn, Molinaro (in prep)]
For RH Majorana neutrinos, \( \Gamma_\alpha = M_\alpha (\hat{Y}_D^\dagger \hat{Y}_D)_{\alpha\alpha}/(8\pi) \). We get

\[
\Gamma_1 \approx \frac{M_N}{24\pi} \left( 2y_1^2 \cos^2 \theta_R + y_2^2 + 2y_3^2 \sin^2 \theta_R \right),
\]

\[
\Gamma_2 \approx \frac{M_N}{24\pi} \left( y_1^2 \cos^2 \theta_R + 2y_2^2 + y_3^2 \sin^2 \theta_R \right),
\]

\[
\Gamma_3 \approx \frac{M_N}{8\pi} \left( y_1^2 \sin^2 \theta_R + y_3^2 \cos^2 \theta_R \right).
\]

For \( y_1 = 0 \) (NO), \( \Gamma_3 = 0 \) for \( \theta_R = (2j + 1)\pi/2 \) with integer \( j \).

For \( y_3 = 0 \) (IO), \( \Gamma_3 = 0 \) for \( j\pi \) with integer \( j \).

In either case, \( N_3 \) is an ultra long-lived particle.

Suitable for MATHUSLA [Chou, Curtin, Lubatti ’16] — see Henry’s talk

In addition, \( N_{1,2} \) can have displaced vertex signals at the LHC.
$L (m)$

$LHC$ displaced

$\theta_{R}/\pi$

$MATHUSLA$

$NO$

$N_1$ (red), $N_2$ (blue), $N_3$ (green).

$M_N=150$ GeV (dashed), 250 GeV (solid).
$L(m)$

$\theta_{R}/\pi$

$N_1$ (red), $N_2$ (blue), $N_3$ (green).

$M_N=150$ GeV (dashed), 250 GeV (solid).
Collider Signal

- Need an efficient production mechanism.
- $y_i \lesssim 10^{-6}$ (our case) suppresses the Drell-Yan production $pp \rightarrow W^{(*)} \rightarrow N_i \ell_\alpha$.
- Let us consider a minimal $U(1)_{B-L}$ portal.
- Production cross section is no longer Yukawa-suppressed, while the decay is, giving rise to displaced vertex at the LHC. [Deppisch, Desai, Valle '13]
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.
**Bound on Z’ Mass**

- Z’ interactions induce additional dilution effects, e.g. \( NN \rightarrow Z' \rightarrow jj \).
- Successful leptogenesis requires a lower bound on \( M_{Z'} \). [Blanchet, Chacko, Granor, Mohapatra '09; Heeck, Teresi '17; BD, Hagedorn, Molinaro (in prep)]

![Diagram showing the bound on Z’ mass](image)
**RL in LR and Bound on $W_R$ Mass**

- Additional dilution effects induced by $W_R$, e.g. $Ne_R \rightarrow W_R \rightarrow \bar{u}_Rd_R$.
- Lower limit on $M_{W_R} \gtrsim 10$ TeV. [Frere, Hambye, Vertongen ’09; BD, Lee, Mohapatra ’15]

![Contour plots of $|\chi_L(z_c)| = 2.47 \times 10^8$ for $h = 10^3.8$ (dashed lines) and $h = 10^3.5$ (solid lines) with $Y_{tot} = 1$ (red lines) and $Y_{tot} = 3$ (blue lines). The green dot corresponds to the example fit value presented in Section 3.](image-url)
Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry of the universe.

Resonant Leptogenesis provides a way to test this idea in laboratory experiments.

Flavor effects are important in the calculation of lepton asymmetry.

Testable models of RL.

Predictive in both low and high-energy sectors.

Correlation between BAU and $0\nu\beta\beta$.

In gauge-extended models, LNV signals (including displaced vertex) at the LHC.

Discovery of a heavy gauge boson could falsify leptogenesis.
Leptogenesis provides an attractive link between neutrino mass and observed baryon asymmetry of the universe.

Resonant Leptogenesis provides a way to test this idea in laboratory experiments.

Flavor effects are important in the calculation of lepton asymmetry.

Testable models of RL.

Predictive in both low and high-energy sectors.

Correlation between BAU and $0\nu\beta\beta$.

In gauge-extended models, LNV signals (including displaced vertex) at the LHC.

Discovery of a heavy gauge boson could falsify leptogenesis.

THANK YOU
Backup Slides
\[-\mathcal{L}_N = h_l^\alpha \overline{L}^l \tilde{\Phi} N_{R,\alpha} + \frac{1}{2} \overline{N}_{R,\alpha} [M_N]^\alpha\beta N_{R,\beta} + \text{H.c.} \]

- Under \( U(N_L) \otimes U(N_N) \),
  \[ L_l \rightarrow L'_l = V^m_l L_m , \quad L' \equiv (L_l)^\dagger \rightarrow L''_l = V^m_l L^m , \]

  \[ N_{R,\alpha} \rightarrow N'_{R,\alpha} = U^\alpha_\beta N_{R,\beta}, \quad N^\alpha_R \equiv (N_{R,\alpha})^\dagger \rightarrow N^\alpha'_R = U^\alpha_\beta N^\beta_R . \]

  \[ h_l^\alpha \rightarrow h'_l^\alpha = V^m_l U^\alpha_\beta h^\beta_m , \quad [M_N]^\alpha\beta \rightarrow [M'_N]^\alpha\beta = U^\alpha_\gamma U^\beta_\delta [M_N]^\gamma\delta . \]
Flavor Transformations

\[-\mathcal{L}_N = h_l^\alpha \bar{L}^l \Phi N_{R,\alpha} + \frac{1}{2} N_{R,\alpha}^C [M_N]^{\alpha\beta} N_{R,\beta} + \text{H.c.} \]

- Under \( U(\mathcal{N}_L) \otimes U(\mathcal{N}_N) \),

\[ L_l \to L'_l = V_l^m L_m , \quad L'^l \equiv (L_l)^\dagger \to L''_l = V'_m L^m , \]

\[ N_{R,\alpha} \to N'_{R,\alpha} = U_{\alpha}^\beta N_{R,\beta} , \quad N_{R,\alpha}^\dagger \equiv (N_{R,\alpha})^\dagger \to N''_{R,\alpha} = U^\alpha_{\beta} N_{R,\beta} . \]

\[ h_l^\alpha \to h'_l^\alpha = V_l^m U^\alpha_{\beta} h_m^\beta , \quad [M_N]^{\alpha\beta} \to [M'_N]^{\alpha\beta} = U^\alpha_{\gamma} U^\beta_{\delta} [M_N]^{\gamma\delta} . \]

- Number densities:

\[ [n^L_{s_1s_2}(p, t)]_l^m \equiv \frac{1}{\nu_3} \langle b^m(p, s_2, \tilde{t}) b_l(p, s_1, \tilde{t}) \rangle_t , \]

\[ [\bar{n}^L_{s_1s_2}(p, t)]_l^m \equiv \frac{1}{\nu_3} \langle d^\dagger_l(p, s_1, \tilde{t}) d^\dagger_{l,m}(p, s_2, \tilde{t}) \rangle_t , \]

\[ [n^N_{r_1r_2}(k, t)]_\alpha^\beta \equiv \frac{1}{\nu_3} \langle a^\beta(k, r_2, \tilde{t}) a_\alpha(k, r_1, \tilde{t}) \rangle_t , \]

\[ [\bar{n}^N_{r_1r_2}(k, t)]_\alpha^\beta \equiv \frac{1}{\nu_3} \langle G_{\alpha\gamma} a^\gamma(k, r_1, \tilde{t}) G^\beta_{\delta} a_\delta(k, r_2, \tilde{t}) \rangle_t , \]

- Total number density:

\[ n^N(t) \equiv \sum_{r = -, +} \int_k n^N_{rr}(k, t) , \quad n^L(t) \equiv \text{Tr} \sum_{s = -, +} \int_p n^L_{ss}(p, t) . \]
Explicitly, for charged-lepton and heavy-neutrino matrix number densities,

\[
\frac{d}{dt} \left[ n_{s_1 s_2}^L (p, t) \right]_l^m = -i \left[ E_L(p), n_{s_1 s_2}^L (p, t) \right]_l^m + [C_{s_1 s_2}^L (p, t)]_l^m
\]

\[
\frac{d}{dt} \left[ n_{r_1 r_2}^N (k, t) \right]_\alpha^\beta = -i \left[ E_N(k), n_{r_1 r_2}^N (k, t) \right]_\alpha^\beta + [C_{r_1 r_2}^N (k, t)]_\alpha^\beta + G_{\alpha \lambda} [\overline{C}_{r_2 r_1}^N (k, t)]_\mu^\lambda G^{\mu \beta}
\]

Collision terms are of the form

\[
[C_{s_1 s_2}^L (p, t)]_l^m = -\frac{1}{2} \left[ \mathcal{F}_{s_1 s r_1 r_2} (p, q, k, t) \right]_l^m \left[ \Gamma_{s s_2 r_2 r_1} (p, q, k) \right]_n^\beta
\]

where \( \mathcal{F} \) are statistical tensors, and \( \Gamma \) are the rank-4 absorptive rate tensors describing heavy neutrino decays and inverse decays.