Baryo/leptogenesis

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Matter-Antimatter Asymmetry

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One number \(\rightarrow\) BSM Physics
Baryogenesis

- Dynamical generation of baryon asymmetry.
- **Basic ingredients:** [Sakharov ’67]
  - $B$ violation, $C$ & $CP$ violation, departure from thermal equilibrium
  - Necessary but not sufficient.
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For review, see e.g. J. Cline, hep-ph/0609145.

Many interesting ideas. Can broadly divide into 3 classes, based on the energy scale involved.

- **High-scale** (e.g. GUT baryogenesis, Affleck-Dine baryogenesis, vanilla leptogenesis)
  
  Problems: Monopole, gravitino overproduction, testability.

- **EW or TeV-scale** (e.g. EW baryogenesis, resonant leptogenesis, ARS leptogenesis, Higgs decay leptogenesis, cogenesis, WIMPy baryogenesis, soft leptogenesis)

- **Sub-EW scale** (e.g. Post-sphaleron baryogenesis)

This talk is mostly on Low-scale baryo/leptogenesis

Testable effects in the form of collider signatures, gravitational waves, electric dipole moment, $0\nu\beta\beta$, lepton flavor violation, $n^\nu\bar{n}$ oscillation, ... Can be used to falsify these scenarios.
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Leptogenesis

A cosmological consequence of the seesaw mechanism.

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

[Fukugita, Yanagida ’86]
Popularity of Leptogenesis
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Graph showing the number of citations over time, with a peak around 2005, labeled as "~ 3000 citations".

Key notes:
- Neutrino oscillation discovered in 2005.

Axes:
- Y-axis: Times cited
- X-axis: Year (1990 to 2015)
Leptogenesis for Pedestrians

[Buchmüller, Di Bari, Plümer '05]

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 $T > T_{sph}$. 

![Diagram of leptogenesis process]

Sphaleron
Boltzmann Equations

[Buchmüller, Di Bari, Plümacher '02]

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

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

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

- \( d \approx 28.51 \frac{1}{27} \approx 0.02 \) (\( \mathcal{L} \rightarrow \mathcal{B} \) conversion at \( T_c \) + entropy dilution from \( T_c \) to recombination epoch).

- \( \kappa_f \equiv \kappa(z_f) \) is the final efficiency factor, where

\[
\kappa(z) = \int_{z_i}^z dz' \frac{D}{D + S} \frac{dN_N}{dz'} e^{-\int_{z'}^z dz'' W(z'')} \]
\[ \varepsilon_{l\alpha} = \frac{\Gamma(N_{\alpha} \rightarrow L_l \Phi) - \Gamma(N_{\alpha} \rightarrow L_i^c \Phi^c)}{\sum_k \left[ \Gamma(N_{\alpha} \rightarrow L_k \Phi) + \Gamma(N_{\alpha} \rightarrow L_k^c \Phi^c) \right]} \equiv \frac{\hat{h}_{l\alpha}^2 - \hat{h}_{c\alpha}^2}{(\hat{h}^* \hat{h})_{\alpha\alpha} + (\hat{h}^c \hat{h}^c)_{\alpha\alpha}} \]

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

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

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

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

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

Three regions of interest:

- **High scale**: $10^9 \text{ GeV} \lesssim m_N \lesssim 10^{14} \text{ GeV}$. Can be falsified with an LNV signal at LHC.

- **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.

- **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).
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For more details, see Dedicated volume on Leptogenesis (to appear in Int. J. Mod. Phys. A)


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}
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Experimentally inaccessible!
Also leads to a lower limit on the reheating temperature $T_{rh} \gtrsim 10^9$ GeV.
In supergravity models, need $T_{rh} \lesssim 10^6 – 10^9$ 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 $m_N \lesssim 10^7$ 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 scenario at both Energy and Intensity Frontiers.
Figure 1: The ten different three RH neutrino mass patterns requiring 10 different sets of Boltzmann equations for the calculation of the asymmetry [17].

Component, escapes the washout from a lighter RH neutrino species [6]. Second, parts of the flavour asymmetries (phantom terms) produced in the one or two flavour regimes do not contribute to the total asymmetry at the production but can contribute to the final asymmetry [18].

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 important understanding. For illustrative purposes, we will proceed in a modular way, first discussing the specific effects in isolation within simplified cases and then discussing the most general case that includes all effects. The paper is organised in the following way.

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 important aspects. For example, we will show that the Boltzmann approach can capture consistently all three distinct physical phenomena: mixing, oscillation and decoherence. Captured consistently in the Boltzmann approach by the fully flavor-covariant formalism.

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 $y_{kl}$ [Barbieri, Creminelli, Strumia, Tetradis '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]
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Two sources of flavor effects:
- Heavy neutrino Yukawa couplings $h_i^{\alpha}$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
- Charged lepton Yukawa couplings $y_i^k$ [Barbieri, Creminelli, Strumia, Tetradis '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:
\[ \frac{d}{dt} n^X(k, t) \simeq i \langle [H_0^X, \hat{n}^X(k, t)] \rangle_t - \frac{1}{2} \int_{-\infty}^{+\infty} dt' \langle [H_{\text{int}}(t'), [H_{\text{int}}(t), \hat{n}^X(k, t)]] \rangle_t. \]
In quantum statistical mechanics,

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

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

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

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

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

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

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

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

$$n^\Phi \left[n^L\right]_l^k \left[\gamma(L\Phi \rightarrow N)\right]_k^l_{\alpha} \rightarrow \text{rank-4 tensor}$$
Collision Rates for 2 ↔ 2 Scattering

\[ n^\Phi [n^L]^k [\gamma (L\Phi \rightarrow L\Phi)]^l_{km} \] → rank-4 tensor
\[
\delta \eta^L \approx \frac{g_N}{2} \frac{3}{2Kz} \sum_{\alpha \neq \beta} \frac{\Im (\hat{h}^\dagger \hat{h})_{\alpha\beta}^2}{(\hat{h}^\dagger \hat{h})_{\alpha\alpha} (\hat{h}^\dagger \hat{h})_{\beta\beta}} \frac{(M_N^2, \alpha - M_N^2, \beta) M_N \hat{\Gamma}^{(0)}_{\beta\beta}}{(M_N^2, \alpha - M_N^2, \beta)^2 + (M_N \hat{\Gamma}^{(0)}_{\beta\beta})^2} \]

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

Coherent oscillations

\[ Y_{\Delta L_1} = 0 \]
\[ Y_{\Delta L_2}, Y_{\Delta L_3} = 0 \]
\[ \sum_{\alpha} Y_{\Delta L_\alpha} = 0 \]

\[ Y_{\Delta L_1} > 0 \]
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\[ Y_{\Delta L_1} > 0 \]
\[ Y_{\Delta L_2}, Y_{\Delta L_3} < 0 \]
\[ \sum_{\alpha} Y_{\Delta L_\alpha} \neq 0 \]

[Akhmedov, Rubakov, Smirnov '98]
A dominant $L$-violating part. This dominance occurs generically for Yukawa couplings large enough, even for larger mass.

**Fig. 7.** Thermal cut in the $l \bar{l} \rightarrow N \bar{N}$ decay, which gives rise to its purely-thermal $L$-conserving washout processes will effectively wash out the $L$-NC part of the $L$-VI. The detailed form for the $\bar{l} \rightarrow N \bar{N}$ processes can be found to the origin of this is clear: for large equations, the parametric dependence of the $L$-VI contribution is different from the $L$-NC ones discussed in Sec. 4.2. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size of this is clear: for large equations, the parametric dependence of the $L$-VI contribution is different from the $L$-NC ones discussed in Sec. 4.2. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size 

In the light gray region the $\bar{l} \rightarrow N \bar{N}$ decay, which gives rise to its purely-thermal $L$-conserving washout processes will effectively wash out the $L$-NC part of the $L$-VI. The detailed form for the $\bar{l} \rightarrow N \bar{N}$ processes can be found to the origin of this is clear: for large equations, the parametric dependence of the $L$-VI contribution is different from the $L$-NC ones discussed in Sec. 4.2. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size 

**Fig. 8.** Results for 2 RH neutrinos with $(\phi,\gamma)$. This process is depicted in Fig. 7. Naively, one would not expect any CP violation in this decay: in order to be kinematically accessible, this decay requires $M_N > T/2$ with respect to the $L$-NC part of the $L$-VI. The detailed form for the $\bar{l} \rightarrow N \bar{N}$ processes can be found to the origin of this is clear: for large equations, the parametric dependence of the $L$-VI contribution is different from the $L$-NC ones discussed in Sec. 4.2. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size 

Since also the other Sakharov conditions are fulfilled, as long as the RH neutrino in both the $L$-NC and $L$-VI phenomena. On the right panel we show the ratio of the $\bar{l} \rightarrow N \bar{N}$ processes can be found to the origin of this is clear: for large equations, the parametric dependence of the $L$-VI contribution is different from the $L$-NC ones discussed in Sec. 4.2. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size 

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To study the relative importance of the two phenomena beyond the linear weak-washout analytic solutions, which are valid in this regime. Instead, as argued recently therefor neglected, because the corresponding rates have a consideration negligible for the generation of the baryon asymmetry at low scale and large cancellations in the seesaw relation, the two phenomena have comparable size 

The Casas-Ibarra angle, i.e. for values of the Yukawa couplings that do not require考虑的，因为对应率有额外的洗出部分，其抑制因子$M_N^2/T^2$。在$\bar{l} \rightarrow N \bar{N}$过程中，$M_N^2/T^2$可以被找到。}

[Hambye, Teresi '16]
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.
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, Ziegler '12]

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]
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Dirac neutrino Yukawa matrix must be invariant under \( Z_2 \) and CP, i.e. under the generator \( Z \) of \( Z_2 \) and \( X(s) \). [BD, Hagedorn, Molinaro (in prep)]

\[
Z^\dagger(\mathbf{3}) \ Y_D \ Z(\mathbf{3}') = Y_D \quad \text{and} \quad X^*(\mathbf{3}) \ Y_D \ X(\mathbf{3}') = Y_D^* .
\]

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

The unitary matrices \( \Omega(s)(r) \) are determined by the CP transformation \( X(s)(r) \).

Form of the RH neutrino mass matrix invariant under flavor and CP symmetries:

\[
M_R = M_N \begin{pmatrix}
    1 & 0 & 0 \\
    0 & 0 & 1 \\
    0 & 1 & 0 
\end{pmatrix}
\]
Six real parameters: $y_i, \theta_{L,R}, M_N$.

$\theta_L \approx 0.18(2.96)$ 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 results).

Light neutrino masses given by the type-I seesaw:

$$M_{\nu}^2 = \frac{\nu^2}{M_N} \begin{cases}
\begin{pmatrix}
y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\
0 & y_2^2 & 0 \\
y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \\
-y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
0 & y_2^2 & 0 \\
-y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R \\
\end{pmatrix} & (s \text{ even}), \\
\begin{pmatrix}
y_1^2 \cos 2\theta_R & 0 & y_1 y_3 \sin 2\theta_R \\
0 & y_2^2 & 0 \\
0 & y_2^2 & 0 \\
0 & y_2^2 & 0 \\
\end{pmatrix} & (s \text{ odd})
\end{cases}.$$
Fixing Model Parameters

- Six real parameters: $y_i, \theta_L, R, M_N$.
- $\theta_L \approx 0.18(2.96)$ 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 results).
- Light neutrino masses given by the type-I seesaw:

$$M^2_{\nu} = \frac{v^2}{M_N} \left\{ \begin{pmatrix}
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  0 & y_2^2 & 0 \\
  y_1 y_3 \sin 2\theta_R & 0 & -y_3^2 \cos 2\theta_R \\
 -y_1^2 \cos 2\theta_R & 0 & -y_1 y_3 \sin 2\theta_R \\
 0 & y_2^2 & 0 \\
 -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R
\end{pmatrix} \right\}$$

(s even),

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 0 & y_2^2 & 0 \\
 -y_1 y_3 \sin 2\theta_R & 0 & y_3^2 \cos 2\theta_R
\end{pmatrix} \right\}$$

(s odd).

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

**NO:** $y_1 = 0$, $y_2 = \pm \sqrt{\frac{M_N \Delta m^2_{\text{sol}}}{v}}$, $y_3 = \pm \sqrt{\frac{M_N \Delta m^2_{\text{atm}}}{v |\cos 2\theta_R|}}$

**IO:** $y_3 = 0$, $y_2 = \pm \sqrt{\frac{M_N |\Delta m^2_{\text{atm}}|}{v}}$, $y_1 = \pm \sqrt{\frac{M_N \sqrt{|\Delta m^2_{\text{atm}}| - \Delta m^2_{\text{sol}}}}{|\cos 2\theta_R|}}$

- Only free parameters: $M_N$ and $\theta_R$. 
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 $0\nu\beta\beta$:

$$m_{\beta\beta} \approx \frac{1}{3} \begin{cases} \left| \sqrt{\Delta m^2_{\text{sol}}} + 2 (-1)^{s+k+1} \sin^2 \theta_L \ e^{6i \phi_s} \ sqrt{\Delta m^2_{\text{atm}}}$ \\ \left| 1 + 2 (-1)^{s+k} \ e^{6i \phi_s} \ \cos^2 \theta_L \sqrt{\Delta m^2_{\text{atm}}} \right| \end{cases} \quad \text{(NO)}.$$

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

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

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

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

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

\[
\varepsilon_{1 \alpha} \approx \frac{y_1 y_2}{9} (-2 y_2^2 + y_1^2 (1 + \cos 2 \theta_R)) \sin 3 \phi_s \cos \theta_R \cos \theta_{L, \alpha} F_{12} \quad \text{(IO)}
\]

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

\( \varepsilon_{2 \alpha} \) are the negative of \( \varepsilon_{1 \alpha} \) with \( F_{12} \) being replaced by \( F_{21} \).
Correlation between BAU and $0^{\nu}\beta\beta$
Correlation between BAU and $0^{\nu}_{\beta\beta}$
Correlation between BAU and $0\nu\beta\beta$
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** (MAssive Timing Hodoscope for Ultra-Stable NeutrAL PArticles) [Coccaro, Curtin, Lubatti, Russell, Shelton '16; Chou, Curtin, Lubati '16]

In addition, $N_{1,2}$ can have displaced vertex signals at the LHC.
\( N_1 \) (red), \( N_2 \) (blue), \( N_3 \) (green).

\( M_N = 150 \text{ GeV} \) (dashed), \( 250 \text{ GeV} \) (solid).
$L (m)$

$\theta_R/\pi$

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

$M_N=150$ GeV (dashed), 250 GeV (solid).
Need an efficient production mechanism.

In our scenario, $y_i \lesssim 10^{-6}$ suppresses the Drell-Yan production

$$pp \rightarrow W^{(*)} \rightarrow N_i \ell_\alpha,$$

and its variants. [Han, Zhang '06; del Aguila, Aguilar-Saavedra, Pittau '07; BD, Pilaftsis, Yang '14; Han, Ruiz, Alva '14; Deppisch, BD, Pilaftsis '15; Das, Okada '15]

Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].

Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
Collider Signal

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- Even if one assumes large Yukawa, the LNV signal will be generally suppressed by the quasi-degeneracy of the RH neutrinos [Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; BD '15].
- Need to go beyond the minimal type-I seesaw to realize a sizable LNV signal.
- We consider a minimal \( U(1)_{B-L} \) extension.
- Production cross section is no longer Yukawa-suppressed, while the decay is, giving rise to displaced vertex. [Deppisch, Desai, Valle '13]
At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.
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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)]
**Bound on $Z'$ Mass**

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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 play a crucial role in the calculation of lepton asymmetry.

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Can probe neutrino mass hierarchy (complementary to oscillation experiments).

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- Can probe neutrino mass hierarchy (complementary to oscillation experiments).
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Backup Slides
Resonant $\ell$-genesis ($\text{RL}_\ell$). [Pilaftsis (PRL '04); Deppisch, Pilaftsis '10]

Minimal model: $O(N)$-symmetric heavy neutrino sector at a high scale $\mu X$.

Small mass splitting at low scale from RG effects.

$$M_N = m_N 1 + \Delta M^\text{RG}_N,$$

with

$$\Delta M^\text{RG}_N = -\frac{m_N}{8\pi^2} \ln \left( \frac{\mu X}{m_N} \right) \text{Re} \left[ h^\dagger(\mu X) h(\mu X) \right].$$

An example of RL$\tau$ with $U(1)_{L_e+L_\mu} \times U(1)_{L_\tau}$ flavor symmetry:

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

$$\delta h = \begin{pmatrix} \epsilon_e & 0 & 0 \\ \epsilon_\mu & 0 & 0 \\ \epsilon_\tau & \kappa_1 e^{-i(\pi/4 - \gamma_1)} & \kappa_2 e^{i(\pi/4 - \gamma_2)} \end{pmatrix},$$
A Next-to-minimal \( RL_\ell \) Model

Asymmetry vanishes at \( \mathcal{O}(h^4) \) in minimal \( RL_\ell \).

Add an additional flavor-breaking \( \Delta M_N \):

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

\[
h = \begin{pmatrix} 0 & a e^{-i\pi/4} & a e^{i\pi/4} \\ 0 & b e^{-i\pi/4} & b e^{i\pi/4} \\ 0 & c e^{-i\pi/4} & c e^{i\pi/4} \end{pmatrix} + \begin{pmatrix} \epsilon_e & 0 & 0 \\ \epsilon_\mu & 0 & 0 \\ \epsilon_\tau & 0 & 0 \end{pmatrix}.
\]

Light neutrino mass constraint:

\[
M_\nu \simeq -\frac{v^2}{2} h M_N^{-1} h^T \simeq \frac{v^2}{2 m_N} \begin{pmatrix} \Delta m_N^{a^2 - \epsilon_e^2} & \Delta m_N^{ab - \epsilon_e \epsilon_\mu} & -\epsilon_e \epsilon_\tau \\ \Delta m_N^{ab - \epsilon_e \epsilon_\mu} & \Delta m_N^{b^2 - \epsilon_\mu^2} & -\epsilon_\mu \epsilon_\tau \\ -\epsilon_e \epsilon_\tau & -\epsilon_\mu \epsilon_\tau & -\epsilon_\tau^2 \end{pmatrix},
\]

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

**Parameters**

<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>

**Observables**

<table>
<thead>
<tr>
<th>Observables</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
<th>Current Limit</th>
</tr>
</thead>
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<tr>
<td>$\text{BR}(\mu \to e\gamma)$</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>$\text{BR}(\tau \to \mu\gamma)$</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>$\text{BR}(\tau \to e\gamma)$</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>$\text{BR}(\mu \to 3e)$</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>$R^H_{\mu \to e}$</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>$R^Au_{\mu \to e}$</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>$R^Pb_{\mu \to e}$</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>
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</tbody>
</table>
Falsifying (High-scale) Leptogenesis at the LHC

[Deppisch, Harz, Hirsch (PRL '14)]
One example: **Left-Right Symmetric Model.** [Pati, Salam ’74; Mohapatra, Pati ’75; Senjanović, Mohapatra 75]

**Common lore:** $M_{W_R} > 18$ TeV for leptogenesis. [Frere, Hambye, Vertongen ’09]

Mainly due to additional $\Delta L = 1$ washout effects induced by $W_R$.

- True only with generic $Y_N \lesssim 10^{-11/2}$.
- Somewhat weaker in a class of low-scale LRSM with larger $Y_N$.
  [BD, Lee, Mohapatra ’13]
- A lower limit of $M_{W_R} \gtrsim 10$ TeV.
- **A Discovery of** $M_{W_R}$ at the LHC rules out leptogenesis in LRSM.
  [BD, Lee, Mohapatra ’14, ’15; Dhuria, Hati, Rangarajan, Sarkar ’15]