Leptogenesis and Colliders

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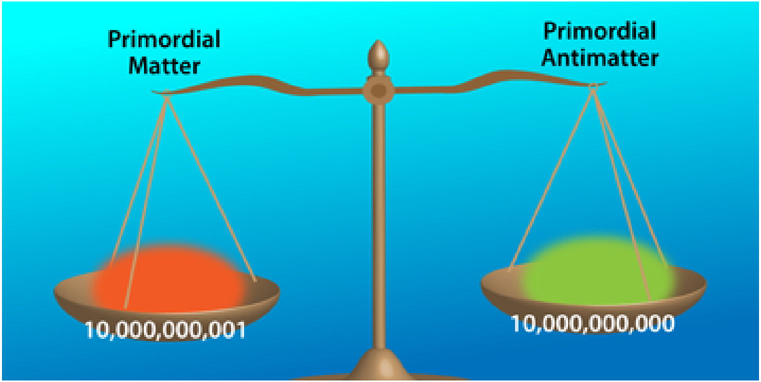
ACFI Workshop on Neutrinos at the High Energy Frontier

UMass Amherst

July 19, 2017

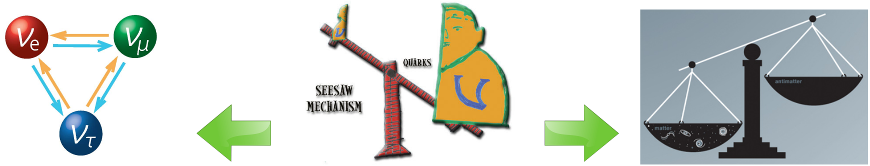
Matter-Antimatter Asymmetry



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

One number $\longrightarrow$ BSM Physics

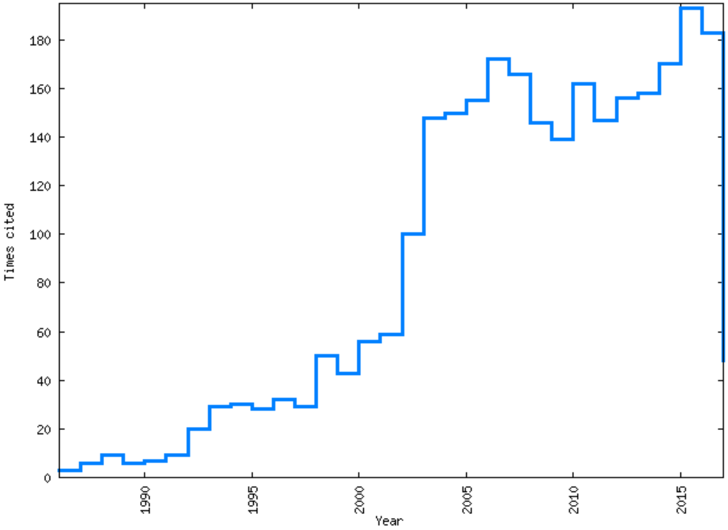
[Fukugita, Yanagida '86]



A cosmological consequence of the seesaw mechanism.

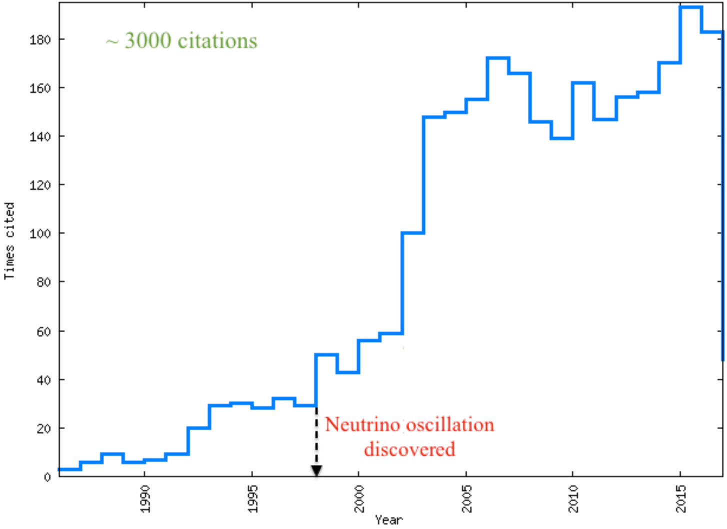
- Provides a common link between neutrino mass and baryon asymmetry.
- Naturally satisfies all the Sakharov conditions.
  - L violation due to the Majorana nature of heavy RH neutrinos.
  - New source of CP violation in the leptonic sector (through complex Dirac Yukawa couplings and/or PMNS CP phases).
  - Departure from thermal equilibrium when $\Gamma_N \lesssim H$.
- Freely available: $\not{L} \to \not{B}$ through EW sphaleron interactions.

Popularity of Leptogenesis



[INSPIRE Database]

Popularity of Leptogenesis



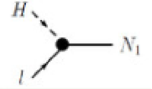
[INSPIRE Database]

[Buchmüller, Di Bari, Plümacher '05]

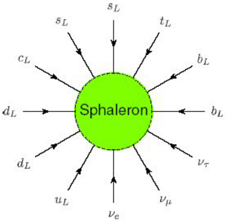
Three basic steps:

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 $T > T_{\rm sph}$.



Boltzmann Equations

[Buchmüller, Di Bari, Plümacher '02]

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

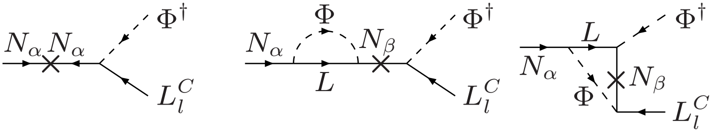
(where $z = m_{N_1}/T$ and $D, S, W = \Gamma_{D,S,W}/Hz$ for decay, scattering and washout rates.)

- FInal baryon asymmetry:

$$\eta^{\Delta B} = d \cdot \varepsilon \cdot \kappa_f$$

- $d \simeq \frac{28}{51}\frac{1}{27} \simeq 0.02$ ($\not{L} \to \not{B}$ conversion at T_c + entropy dilution from T_c to $T_{\rm recombination}$).
- $\kappa_f \equiv \kappa(z_f)$ is the final efficiency factor, where

$$\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D+S}\frac{dN_N}{dz'}\, e^{-\int_{z'}^{z} dz'' W(z'')}$$



tree self-energy vertex

$$\varepsilon_{l\alpha} = \frac{\Gamma(N_\alpha \to L_l \Phi) - \Gamma(N_\alpha \to L_l^c \Phi^c)}{\sum_k \left[\Gamma(N_\alpha \to L_k \Phi) + \Gamma(N_\alpha \to L_k^c \Phi^c)\right]} \equiv \frac{|\widehat{\mathbf{h}}_{l\alpha}|^2 - |\widehat{\mathbf{h}}^c_{l\alpha}|^2}{(\widehat{\mathbf{h}}^\dagger \widehat{\mathbf{h}})_{\alpha\alpha} + (\widehat{\mathbf{h}}^{c\dagger} \widehat{\mathbf{h}}^c)_{\alpha\alpha}}$$

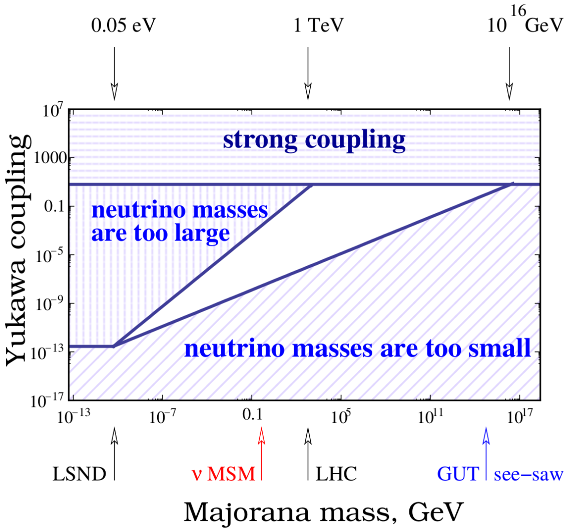
with the one-loop resummed Yukawa couplings [Pilaftsis, Underwood '03]

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

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

$$R_{\alpha\beta} = \frac{m_\alpha^2}{m_\alpha^2 - m_\beta^2 + 2 i m_\alpha^2 A_{\beta\beta}} ; \qquad A_{\alpha\beta}(\widehat{h}) = \frac{1}{16\pi} \sum_l \widehat{h}_{l\alpha} \widehat{h}^*_{l\beta} .$$

[Drewes '15]



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

Three regions of interest:

- High scale: $10^9\ \mathrm{GeV} \lesssim m_N \lesssim 10^{14}\ \mathrm{GeV}$.
  Can be falsified with an LNV signal at LHC. – see Julia's talk
- Collider-friendly scale: $100\ \mathrm{GeV} \lesssim m_N \lesssim \mathrm{few\ TeV}$.
  Can be tested in collider and/or low-energy ($0\nu\beta\beta$, LFV) searches. –this talk
- Low-scale: $1\ \mathrm{GeV} \lesssim m_N \lesssim 5\ \mathrm{GeV}$.
  Can be tested at the intensity frontier: SHiP, DUNE or B-factories (LHCb, Belle-II). –see Jacobo's talk

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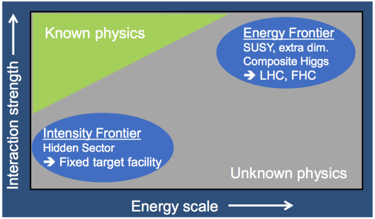

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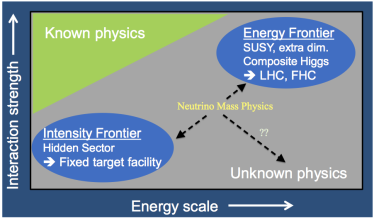

- Hierarchical heavy neutrino spectrum ($m_{N_1} \ll m_{N_2} < m_{N_3}$).
- Both vertex correction and self-energy diagrams are relevant.
- For type-I seesaw, the maximal *CP* asymmetry is given by

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

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

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

Vanilla Leptogenesis

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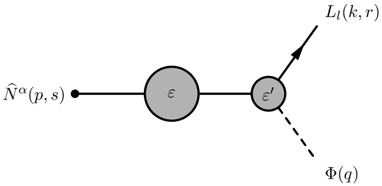
- Experimentally inaccessible!
- Also leads to a lower limit on the reheating temperature $T_{\rm rh} \gtrsim 10^9$ GeV.
- In supergravity models, need $T_{\rm rh} \lesssim 10^6 - 10^9$ GeV to avoid the gravitino problem.
  [Khlopov, Linde '84; Ellis, Kim, Nanopoulos '84; Cyburt, Ellis, Fields, Olive '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]

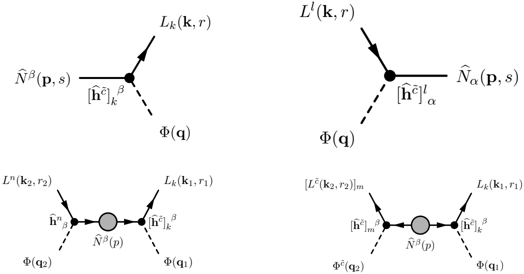


- Dominant self-energy effects on the *CP*-asymmetry (ε-type) [Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].
- Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N/2 \ll m_{N_{1,2}}$. [Pilaftsis '97; Pilaftsis, Underwood '03]
- The quasi-degeneracy can be naturally motivated 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

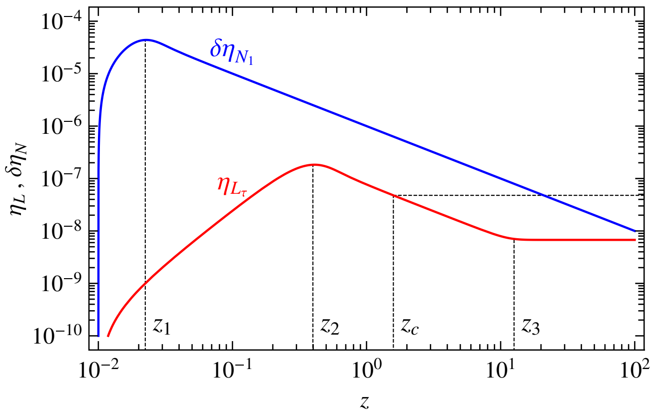
$$\frac{n^\gamma H_N}{z}\frac{\mathrm{d}\eta^N_\alpha}{\mathrm{d}z} = \left(1-\frac{\eta^N_\alpha}{\eta^N_{\rm eq}}\right)\sum_l \gamma^{N_\alpha}_{L_l\Phi}$$

$$\frac{n^\gamma H_N}{z}\frac{\mathrm{d}\delta\eta^L_l}{\mathrm{d}z} = \sum_\alpha\left(\frac{\eta^N_\alpha}{\eta^N_{\rm eq}}-1\right)\varepsilon_{l\alpha}\sum_k \gamma^{N_\alpha}_{L_k\Phi} - \frac{2}{3}\delta\eta^L_l\sum_k\left[\gamma^{L_l\Phi}_{L^c_k\Phi^c}+\gamma^{L_l\Phi}_{L_k\Phi}+\delta\eta^L_k\left(\gamma^{L_k\Phi}_{L^c_l\Phi^c}-\gamma^{L_k\Phi}_{L_l\Phi}\right)\right]$$



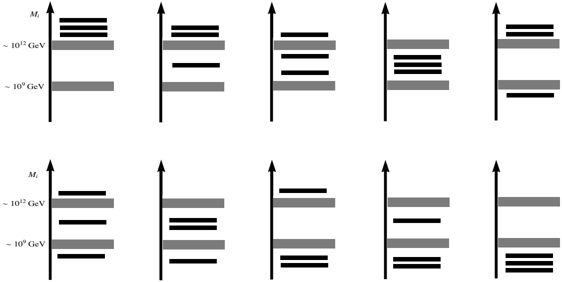
Analytic Solution

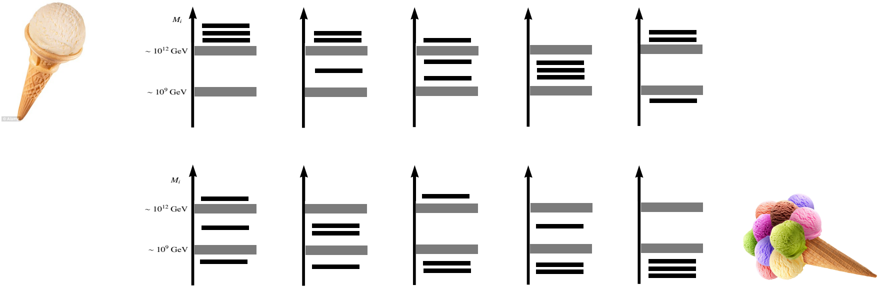
[Deppisch, Pilaftsis '11]



$$\eta_L(z) \simeq \frac{3}{2z} \sum_l \frac{\sum_\alpha \varepsilon_{l\alpha}}{K_l^{\rm eff}} \qquad (z_2 < z < z_3)$$

Flavordynamics





- 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 $h_l^{\ \alpha}$ [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
  - Charged lepton Yukawa couplings $y_l^{\ k}$ [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]

Master Equation for Transport Phenomena

- In quantum statistical mechanics,

$$\boldsymbol{n}^X(t) \;\equiv\; \langle \check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\rangle_t \;=\; \mathrm{Tr}\left\{\rho(\tilde{t};\tilde{t}_i)\;\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\right\}\;.$$

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

$$\frac{\mathrm{d}\boldsymbol{n}^X(t)}{\mathrm{d}t} \;=\; \mathrm{Tr}\left\{\rho(\tilde{t};\tilde{t}_i)\,\frac{\mathrm{d}\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}\right\} \;+\; \mathrm{Tr}\left\{\frac{\mathrm{d}\rho(\tilde{t};\tilde{t}_i)}{\mathrm{d}\tilde{t}}\,\check{\boldsymbol{n}}^X(\tilde{t};\tilde{t}_i)\right\} \;\equiv\; \mathcal{I}_1 \;+\; \mathcal{I}_2.\;.$$

- 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:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{n}^X(\mathbf{k},t) \;\simeq\; i\langle\,[H_0^X,\;\check{\boldsymbol{n}}^X(\mathbf{k},t)]\,\rangle_t - \frac{1}{2}\int_{-\infty}^{+\infty}\mathrm{d}t'\;\langle\,[H_{\mathrm{int}}(t'),\;[H_{\mathrm{int}}(t),\;\check{\boldsymbol{n}}^X(\mathbf{k},t)]]\,\rangle_t\;.$$

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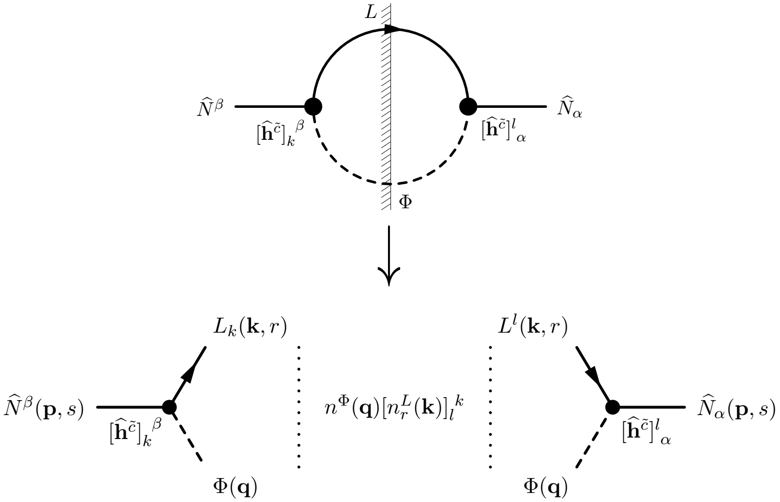
(Oscillation) (Mixing)

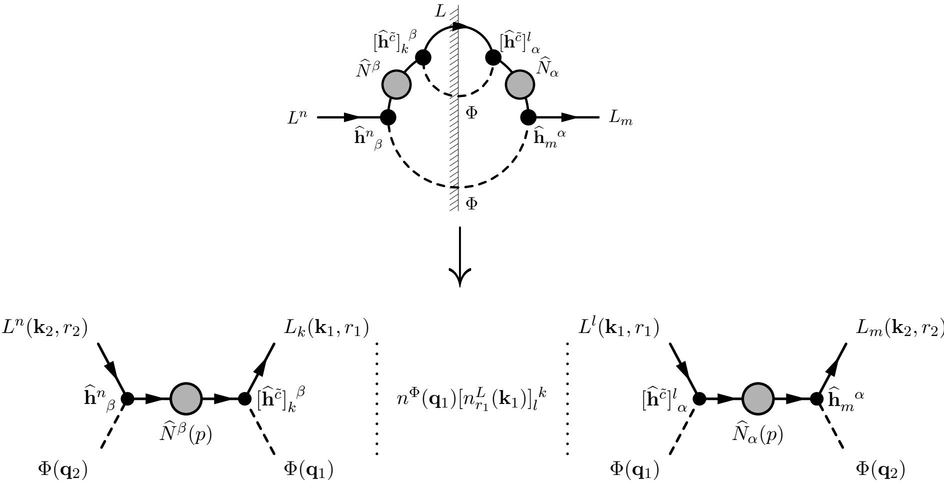
- Generalization of the density matrix formalism. [Sigl, Raffelt '93]

Collision Rates for Decay and Inverse Decay

$$\boxed{n^{\Phi}\ [n^{L}]_{l}^{\ k}\ [\gamma(L\Phi \to N)]_{k\ \alpha}^{\ l\ \ \beta}}$$



$$n^{\Phi}\,[n^L]_l^{\;k}\,[\gamma(L\Phi \to L\Phi)]_{k\;m}^{\;l\;\;n}$$



Final Rate Equations

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

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,2\,i\,n^\gamma\left[\mathcal{E}_N,\,\underline{\eta}^N\right]_\alpha^{\;\;\beta} + 2\,i\left[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right]_\alpha^{\;\;\beta} - \frac{i}{\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right\}_\alpha^{\;\;\beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\delta\eta^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha^{\;\;\beta}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l{}^m}{\mathrm{d}z} = -\,[\delta\gamma^N_{L\Phi}]_l^{\;\;m} + \frac{[\underline{\eta}^N]_\beta{}^\alpha}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta + \frac{[\delta\eta^N]_\beta{}^\alpha}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta - \frac{1}{3}\left\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}} + \gamma^{L\Phi}_{L\Phi}\right\}_l^{\;\;m} - \frac{2}{3}\,[\delta\eta^L]_k^{\;\;n}\left([\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}}]_n{}^k{}_l{}^m - [\gamma^{L\Phi}_{L\Phi}]_n{}^k{}_l{}^m\right) - \frac{2}{3}\left\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\right\}_l^{\;\;m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\;\;m}$$

Final Rate Equations: Mixing

$$\frac{H_N\, n^\gamma}{z}\, \frac{\mathrm{d}[\underline{\eta}^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,i\, \frac{n^\gamma}{2}\, \Big[\mathcal{E}_N,\, \delta\eta^N\Big]_\alpha{}^\beta + \Big[\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big]_\alpha{}^\beta - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\, \Big\{\underline{\eta}^N,\, \widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta$$

$$\frac{H_N\, n^\gamma}{z}\, \frac{\mathrm{d}[\delta\eta^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,2\,i\, n^\gamma\, \Big[\mathcal{E}_N,\, \underline{\eta}^N\Big]_\alpha{}^\beta + 2\,i\, \Big[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big]_\alpha{}^\beta - \frac{i}{\eta^N_{\mathrm{eq}}}\, \Big\{\underline{\eta}^N,\, \widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\, \Big\{\delta\eta^N,\, \widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\Big\}_\alpha{}^\beta$$

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Final Rate Equations: Oscillation

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$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l{}^m}{\mathrm{d}z} = -\,[\delta\gamma^N_{L\Phi}]_l^{\ m} + \frac{[\underline{\eta}^N]_\beta{}^\alpha}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta + \frac{[\delta\eta^N]_\beta{}^\alpha}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta - \frac{1}{3}\left\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}} + \gamma^{L\Phi}_{L\Phi}\right\}_l^{\ m} - \frac{2}{3}\,[\delta\eta^L]_k^{\ n}\left([\gamma^{L\Phi}_{L^{\tilde c}\Phi^{\tilde c}}]_n{}^k{}_l{}^m - [\gamma^{L\Phi}_{L\Phi}]_n{}^k{}_l{}^m\right) - \frac{2}{3}\left\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\right\}_l^{\ m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\ m}$$

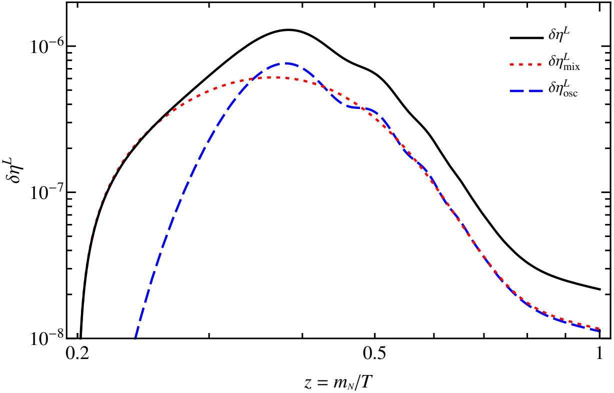
Final Rate Equations: Charged Lepton Decoherence

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

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^N]_\alpha{}^\beta}{\mathrm{d}z} = -\,2\,i\,n^\gamma\left[\mathcal{E}_N,\,\underline{\eta}^N\right]_\alpha^{\;\;\beta} + 2\,i\left[\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right]_\alpha^{\;\;\beta} - \frac{i}{\eta^N_{\mathrm{eq}}}\left\{\underline{\eta}^N,\,\widetilde{\mathrm{Im}}(\delta\gamma^N_{L\Phi})\right\}_\alpha^{\;\;\beta}$$
$$-\,\frac{1}{2\,\eta^N_{\mathrm{eq}}}\left\{\delta\eta^N,\,\widetilde{\mathrm{Re}}(\gamma^N_{L\Phi})\right\}_\alpha^{\;\;\beta}$$

$$\frac{H_N\, n^\gamma}{z}\,\frac{\mathrm{d}[\delta\eta^L]_l{}^m}{\mathrm{d}z} = -\,[\delta\gamma^N_{L\Phi}]_l^{\;\;m} + \frac{[\underline{\eta}^N]_\beta^{\;\;\alpha}}{\eta^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l^{\;\;m}{}_\alpha^{\;\;\beta} + \frac{[\delta\eta^N]_\beta^{\;\;\alpha}}{2\,\eta^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l^{\;\;m}{}_\alpha^{\;\;\beta}$$
$$-\,\frac{1}{3}\left\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}} + \gamma^{L\Phi}_{L\Phi}\right\}_l^{\;\;m} - \frac{2}{3}\,[\delta\eta^L]_k^{\;\;n}\left([\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}}]_n^{\;\;k}{}_l^{\;\;m} - [\gamma^{L\Phi}_{L\Phi}]_n^{\;\;k}{}_l^{\;\;m}\right)$$
$$-\,\frac{2}{3}\left\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\right\}_l^{\;\;m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\;\;m}$$

Key Result



$$\delta\eta^L_{\rm mix} \simeq \frac{g_N}{2}\frac{3}{2{\rm K}z}\sum_{\alpha\neq\beta}\frac{\Im\left(\widehat{h}^\dagger\widehat{h}\right)^2_{\alpha\beta}}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}\;\frac{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)M_N\widehat{\Gamma}^{(0)}_{\beta\beta}}{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)^2+\left(M_N\widehat{\Gamma}^{(0)}_{\beta\beta}\right)^2}\,,$$

$$\delta\eta^L_{\rm osc} \simeq \frac{g_N}{2}\frac{3}{2{\rm K}z}\sum_{\alpha\neq\beta}\frac{\Im\left(\widehat{h}^\dagger\widehat{h}\right)^2_{\alpha\beta}}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}\;\frac{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)M_N\left(\widehat{\Gamma}^{(0)}_{\alpha\alpha}+\widehat{\Gamma}^{(0)}_{\beta\beta}\right)}{\left(M^2_{N,\,\alpha}-M^2_{N,\,\beta}\right)^2+M^2_N(\widehat{\Gamma}^{(0)}_{\alpha\alpha}+\widehat{\Gamma}^{(0)}_{\beta\beta})^2\,\frac{\Im[(\widehat{h}^\dagger\widehat{h})_{\alpha\beta}]^2}{(\widehat{h}^\dagger\widehat{h})_{\alpha\alpha}(\widehat{h}^\dagger\widehat{h})_{\beta\beta}}}$$

Testable Models

- Need $m_N \lesssim \mathcal{O}(\text{TeV})$.
- 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 μ_X.
- Radiative RL: Small mass splitting at low scale from RG effects. [Branco, Gonzalez Felipe, Joaquim, Masina, Rebelo, Savoy '03]

$$\boldsymbol{M}_N = m_N \mathbf{1} + \boldsymbol{\Delta M}_N^{\rm RG}, \quad \text{with} \quad \boldsymbol{\Delta M}_N^{\rm RG} = -\frac{m_N}{8\pi^2} \ln\left(\frac{\mu_X}{m_N}\right) \mathrm{Re}\left[\boldsymbol{h}^\dagger(\mu_X)\boldsymbol{h}(\mu_X)\right] .$$

- A specific realization: Resonant ℓ-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:

$$\boldsymbol{h} = \begin{pmatrix} 0 & a e^{-i\pi/4} & a e^{i\pi/4} \\ 0 & b e^{-i\pi/4} & b e^{i\pi/4} \\ 0 & 0 & 0 \end{pmatrix} + \boldsymbol{\delta h},$$

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

- But CP asymmetry vanishes up to $\mathcal{O}(h^4)$. [BD, Millington, Pilaftsis, Teresi '15]

A Next-to-minimal Model

[BD, Millington, Pilaftsis, Teresi '15]

- Add an additional flavor-breaking $\boldsymbol{\Delta M}_N$:

$$\boldsymbol{M}_N \; = \; m_N \mathbf{1} \, + \, \boldsymbol{\Delta M}_N \, + \, \boldsymbol{\Delta M}_N^{\rm RG} \, , \quad \text{with } \boldsymbol{\Delta M}_N \; = \; \begin{pmatrix} \Delta M_1 & 0 & 0 \\ 0 & \Delta M_2/2 & 0 \\ 0 & 0 & -\Delta M_2/2 \end{pmatrix} ,$$

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

- Light neutrino mass constraint:

$$\boldsymbol{M}_\nu \; \simeq \; -\frac{v^2}{2} \boldsymbol{h} \boldsymbol{M}_N^{-1} \boldsymbol{h}^{\sf T} \; \simeq \; \frac{v^2}{2m_N} \begin{pmatrix} \frac{\Delta m_N}{m_N} a^2 - \epsilon_e^2 & \frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & -\epsilon_e \epsilon_\tau \\ \frac{\Delta m_N}{m_N} ab - \epsilon_e \epsilon_\mu & \frac{\Delta m_N}{m_N} b^2 - \epsilon_\mu^2 & -\epsilon_\mu \epsilon_\tau \\ -\epsilon_e \epsilon_\tau & -\epsilon_\mu \epsilon_\tau & -\epsilon_\tau^2 \end{pmatrix},$$

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	BP1	BP2	BP3
m_N	120 GeV	400 GeV	5 TeV
c	2×10^{-6}	2×10^{-7}	2×10^{-6}
$\Delta M_1/m_N$	-5×10^{-6}	-3×10^{-5}	-4×10^{-5}
$\Delta M_2/m_N$	$(-1.59 - 0.47\,i) \times 10^{-8}$	$(-1.21 + 0.10\,i) \times 10^{-9}$	$(-1.46 + 0.11\,i) \times 10^{-8}$
a	$(5.54 - 7.41\,i) \times 10^{-4}$	$(4.93 - 2.32\,i) \times 10^{-3}$	$(4.67 - 4.33\,i) \times 10^{-3}$
b	$(0.89 - 1.19\,i) \times 10^{-3}$	$(8.04 - 3.79\,i) \times 10^{-3}$	$(7.53 - 6.97\,i) \times 10^{-3}$
ϵ_e	$3.31\,i \times 10^{-8}$	$5.73\,i \times 10^{-8}$	$2.14\,i \times 10^{-7}$
ϵ_μ	$2.33\,i \times 10^{-7}$	$4.30\,i \times 10^{-7}$	$1.50\,i \times 10^{-6}$
ϵ_τ	$3.50\,i \times 10^{-7}$	$6.39\,i \times 10^{-7}$	$2.26\,i \times 10^{-6}$

Observables	BP1	BP2	BP3	Current Limit
$\mathrm{BR}(\mu \to e\gamma)$	4.5×10^{-15}	1.9×10^{-13}	2.3×10^{-17}	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\tau \to \mu\gamma)$	1.2×10^{-17}	1.6×10^{-18}	8.1×10^{-22}	$< 4.4 \times 10^{-8}$
$\mathrm{BR}(\tau \to e\gamma)$	4.6×10^{-18}	5.9×10^{-19}	3.1×10^{-22}	$< 3.3 \times 10^{-8}$
$\mathrm{BR}(\mu \to 3e)$	1.5×10^{-16}	9.3×10^{-15}	4.9×10^{-18}	$< 1.0 \times 10^{-12}$
$\mathrm{R}^{\mathrm{Ti}}_{\mu\to e}$	2.4×10^{-14}	2.9×10^{-13}	2.3×10^{-20}	$< 6.1 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Au}}_{\mu\to e}$	3.1×10^{-14}	3.2×10^{-13}	5.0×10^{-18}	$< 7.0 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Pb}}_{\mu\to e}$	2.3×10^{-14}	2.2×10^{-13}	4.3×10^{-18}	$< 4.6 \times 10^{-11}$
$\lvert\Omega\rvert_{e\mu}$	5.8×10^{-6}	1.8×10^{-5}	1.6×10^{-7}	$< 7.0 \times 10^{-5}$

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_ℓ transform in a faithful complex irrep **3**, RH neutrinos N_α in an unfaithful real irrep $\mathbf{3}'$ and RH charged leptons ℓ_R in a singlet **1** of G_f.
- CP symmetry is given by the transformation $X(s)(\mathrm{r})$ 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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- CP symmetry is given by the transformation $X(s)(\mathrm{r})$ 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)]

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

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

- $\theta_L \approx 0.18(2.96)$ 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 3σ of current global-fit). [Hagedorn, Molinaro '16]

- Light neutrino masses given by the type-I seesaw:

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

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

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

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

- Only free parameters: M_N and θ_R.

Low Energy CP Phases and $0\nu\beta\beta$

- Dirac phase is trivial: $\delta = 0$.
- For $m_{\rm lightest} = 0$, only one Majorana phase α, which depends on the chosen CP transformation:

$$\sin\alpha = (-1)^{k+r+s}\,\sin 6\,\phi_s \quad \text{and} \quad \cos\alpha = (-1)^{k+r+s+1}\,\cos 6\,\phi_s \;\; \text{with } \phi_s = \frac{\pi\, s}{n}\,,$$

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 $0\nu\beta\beta$:

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

- For $n = 26$, $\theta_L \approx 0.18$ and best-fit values of $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$, we get

$$0.0019\,{\rm eV} \lesssim m_{\beta\beta} \lesssim 0.0040\,{\rm eV} \qquad \text{(NO)}$$
$$0.016\,{\rm eV} \lesssim m_{\beta\beta} \lesssim 0.048\,{\rm eV} \qquad \text{(IO)}.$$

High Energy CP Phases and Leptogenesis

- At leading order, three degenerate RH neutrinos.
- Higher-order corrections can break the residual symmetries, giving rise to a quasi-degenerate spectrum:

$$M_1 = M_N (1 + 2\kappa) \text{ and } M_2 = M_3 = M_N (1 - \kappa)\,.$$

- CP asymmetries in the decays of N_i are given by

$$\varepsilon_{i\alpha} \approx \sum_{j \neq i} \mathrm{Im}\left(\hat{Y}^{\star}_{D,\alpha i} \hat{Y}_{D,\alpha j}\right) \mathrm{Re}\left(\left(\hat{Y}_D^{\dagger} \hat{Y}_D\right)_{ij}\right) F_{ij}$$

- F_{ij} are related to the regulator in RL and are proportional to the mass splitting of N_i.
- We find $\varepsilon_{3\alpha} = 0$ and

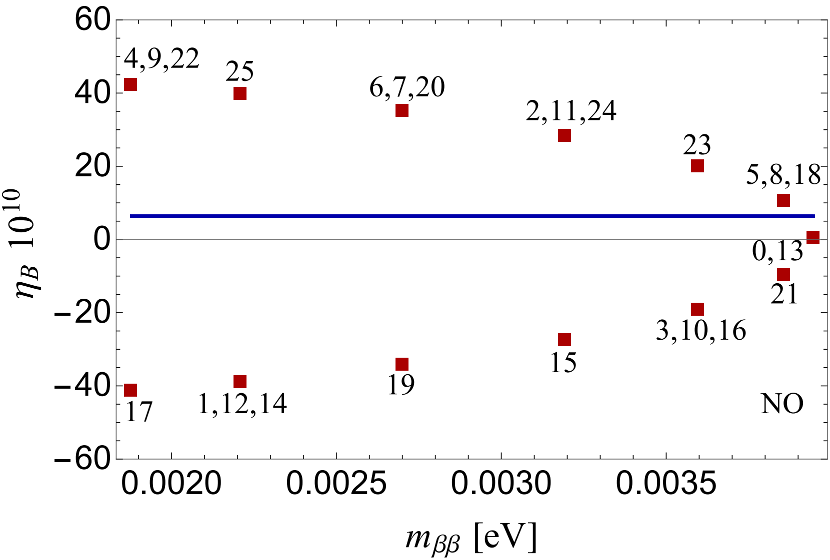
$$\varepsilon_{1\alpha} \approx \frac{y_2\, y_3}{9} \left(-2\, y_2^2 + y_3^2 \left(1 - \cos 2\,\theta_R\right)\right) \sin 3\,\phi_s \, \sin\theta_R \, \sin\theta_{L,\alpha} \, F_{12} \quad \text{(NO)}$$

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

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

- $\varepsilon_{2\alpha}$ 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)]

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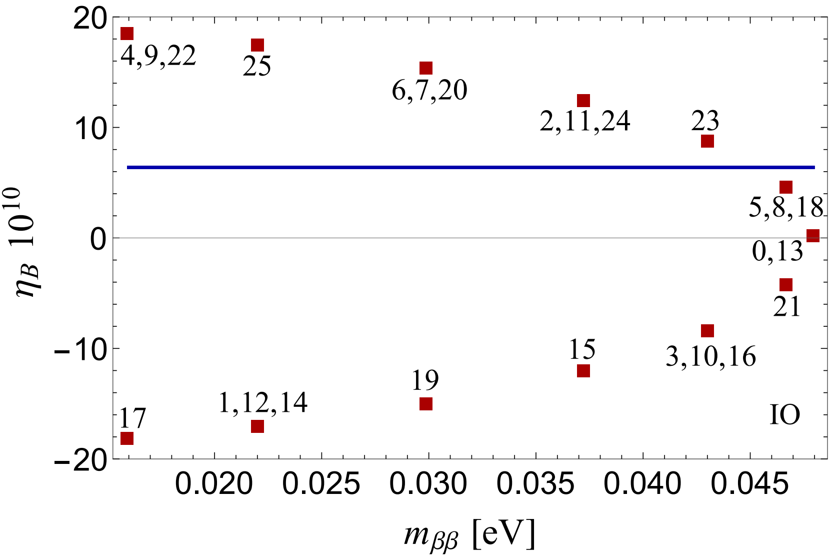

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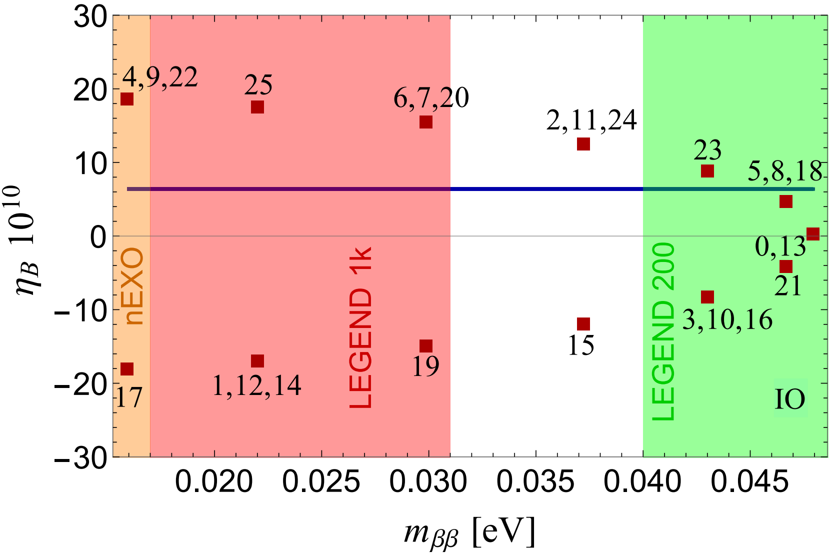

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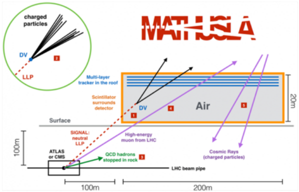
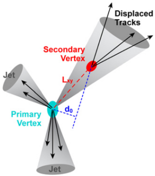
Decay Length

- For RH Majorana neutrinos, $\Gamma_\alpha = M_\alpha \, (\hat{Y}_D^\dagger \, \hat{Y}_D)_{\alpha\alpha}/(8\,\pi)$. We get

$$\begin{aligned}
\Gamma_1 &\approx \frac{M_N}{24\,\pi} \left(2\,y_1^2 \cos^2\theta_R + y_2^2 + 2\,y_3^2 \sin^2\theta_R\right) , \\
\Gamma_2 &\approx \frac{M_N}{24\,\pi} \left(y_1^2 \cos^2\theta_R + 2\,y_2^2 + y_3^2 \sin^2\theta_R\right) , \\
\Gamma_3 &\approx \frac{M_N}{8\,\pi} \left(y_1^2 \sin^2\theta_R + y_3^2 \cos^2\theta_R\right) .
\end{aligned}$$

- 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.





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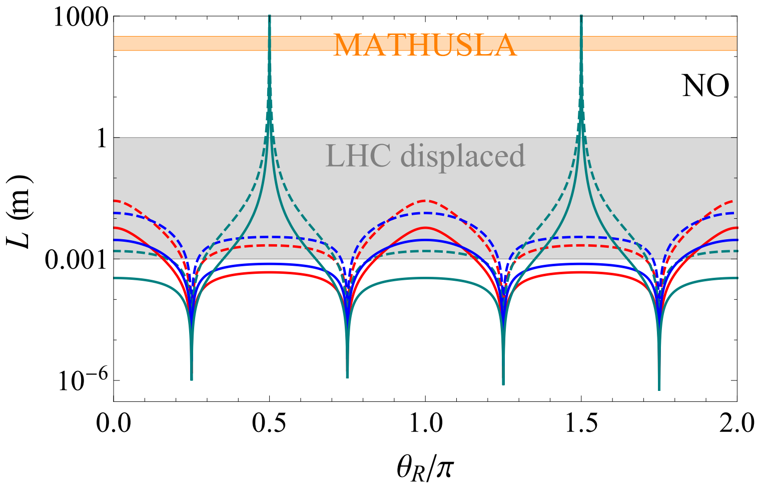
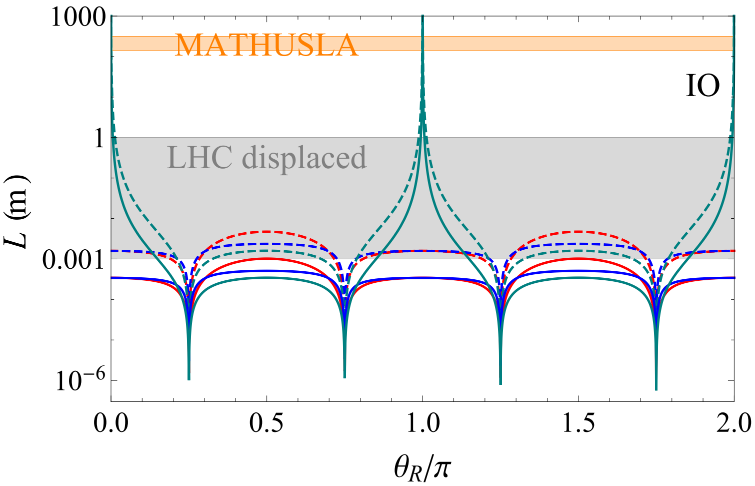


N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

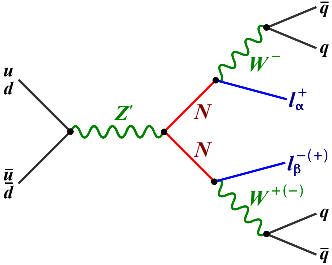
Decay Length

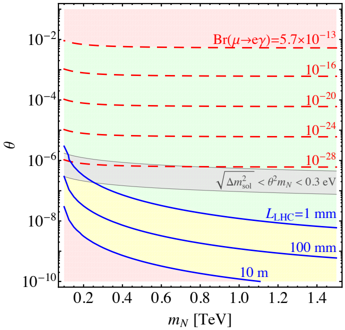


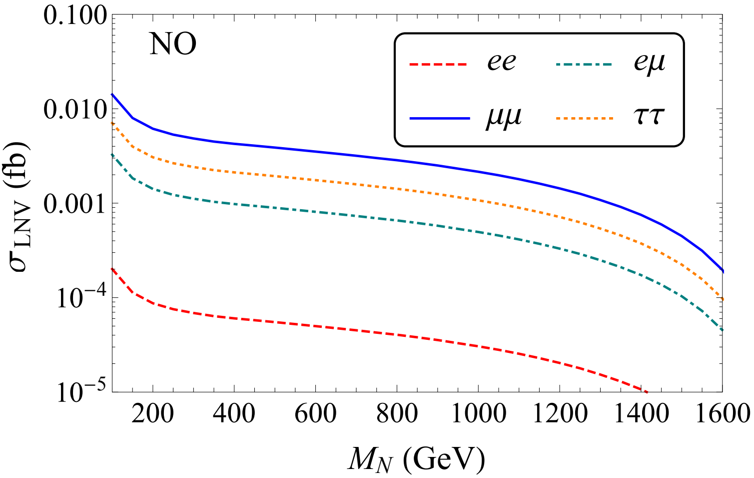
N_1 (red), N_2 (blue), N_3 (green).
M_N=150 GeV (dashed), 250 GeV (solid).

Collider Signal

- Need an efficient production mechanism.
- $y_i \lesssim 10^{-6}$ (our case) suppresses the Drell-Yan production $pp \to W^{(*)} \to N_i \ell_\alpha$.
- 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.

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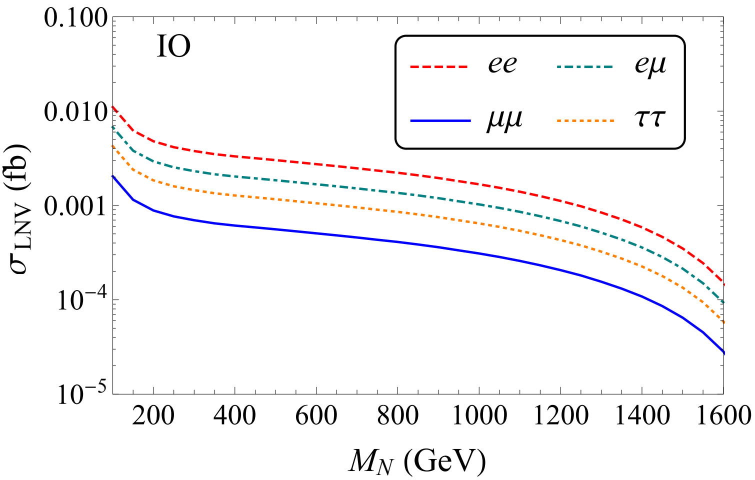
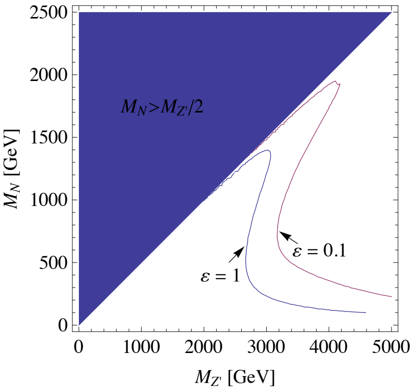


At $\sqrt{s} = 14$ TeV LHC and for $M_{Z'} = 3.5$ TeV.

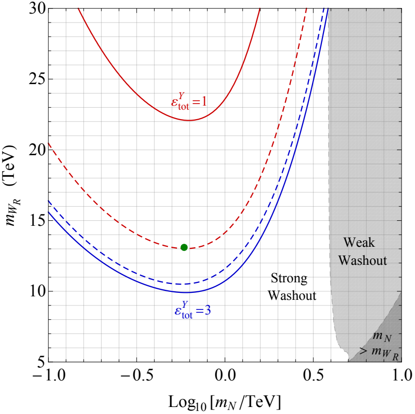
Bound on Z' Mass

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



RL in LR and Bound on W_R Mass

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



Conclusion

- 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.

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Backup Slides

$$-\mathcal{L}_N = h_l^{\ \alpha}\, \overline{L}^l\, \widetilde{\Phi}\, N_{\mathrm{R},\alpha} + \frac{1}{2}\, \overline{N}^C_{\mathrm{R},\alpha}\, [M_N]^{\alpha\beta}\, N_{\mathrm{R},\beta} + \mathrm{H.c.}\ .$$

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

$$L_l \rightarrow L'_l = V_l^{\ m}\, L_m\ , \qquad L^l \equiv (L_l)^\dagger \rightarrow L'^l = V^l_{\ m}\, L^m\ ,$$

$$N_{\mathrm{R},\alpha} \rightarrow N'_{\mathrm{R},\alpha} = U_\alpha^{\ \beta}\, N_{\mathrm{R},\beta}\ , \qquad N_{\mathrm{R}}^{\ \alpha} \equiv (N_{\mathrm{R},\alpha})^\dagger \rightarrow N'^{\ \alpha}_{\mathrm{R}} = U^\alpha_{\ \beta}\, N_{\mathrm{R}}^{\ \beta}\ .$$

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

Flavor Transformations

$$-\mathcal{L}_N \;=\; h_l^{\ \alpha}\, \overline{L}^l\, \widetilde{\Phi}\, N_{\mathrm{R},\alpha} \;+\; \frac{1}{2}\, \overline{N}^C_{\mathrm{R},\alpha}\, [M_N]^{\alpha\beta}\, N_{\mathrm{R},\beta} \;+\; \mathrm{H.c.}\;.$$

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

$$L_l \;\to\; L'_l \;=\; V_l^{\ m}\, L_m\,, \qquad L^l \;\equiv\; (L_l)^\dagger \;\to\; L'^l \;=\; V^l_{\ m}\, L^m\,,$$

$$N_{\mathrm{R},\alpha} \;\to\; N'_{\mathrm{R},\alpha} \;=\; U_\alpha^{\ \beta}\, N_{\mathrm{R},\beta}\,, \qquad N_{\mathrm{R}}^{\ \alpha} \;\equiv\; (N_{\mathrm{R},\alpha})^\dagger \;\to\; N'^{\ \alpha}_{\mathrm{R}} \;=\; U^\alpha_{\ \beta}\, N_{\mathrm{R}}^{\ \beta}\,.$$

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

- Number densities:

$$[n^L_{s_1 s_2}(\mathbf{p},t)]_l^{\ m} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle b^m(\mathbf{p},s_2,\tilde{t})\, b_l(\mathbf{p},s_1,\tilde{t})\rangle_t\,,$$

$$[\bar{n}^L_{s_1 s_2}(\mathbf{p},t)]_l^{\ m} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle d_l^\dagger(\mathbf{p},s_1,\tilde{t})\, d^{\dagger,m}(\mathbf{p},s_2,\tilde{t})\rangle_t\,,$$

$$[n^N_{r_1 r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle a^\beta(\mathbf{k},r_2,\tilde{t})\, a_\alpha(\mathbf{k},r_1,\tilde{t})\rangle_t\,,$$

$$[\bar{n}^N_{r_1 r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle G_{\alpha\gamma}\, a^\gamma(\mathbf{k},r_1,\tilde{t})\, G^{\beta\delta}\, a_\delta(\mathbf{k},r_2,\tilde{t})\rangle_t\,,$$

- Total number density:

$$\boldsymbol{n}^N(t) \;\equiv\; \sum_{r=-,+} \int_{\mathbf{k}} \boldsymbol{n}^N_{rr}(\mathbf{k},t)\,, \qquad \boldsymbol{n}^L(t) \;\equiv\; \mathop{\mathrm{Tr}}_{\mathrm{iso}} \sum_{s=-,+} \int_{\mathbf{p}} \boldsymbol{n}^L_{ss}(\mathbf{p},t)\,.$$

Explicitly, for charged-lepton and heavy-neutrino matrix number densities,

$$\frac{\mathrm{d}}{\mathrm{d}t}\,[n^L_{s_1 s_2}(\mathbf{p},t)]_l^{\ m} \;=\; -\,i\left[E_L(\mathbf{p}),\; n^L_{s_1 s_2}(\mathbf{p},t)\right]_l^{\ m} \;+\; [C^L_{s_1 s_2}(\mathbf{p},t)]_l^{\ m}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\,[n^N_{r_1 r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;=\; -\,i\left[E_N(\mathbf{k}),\; n^N_{r_1 r_2}(\mathbf{k},t)\right]_\alpha^{\ \beta} \;+\; [C^N_{r_1 r_2}(\mathbf{k},t)]_\alpha^{\ \beta} + \; G_{\alpha\lambda}\,[\overline{C}^N_{r_2 r_1}(\mathbf{k},t)]_\mu^{\ \lambda}\,G^{\mu\beta}$$

Collision terms are of the form

$$[C^L_{s_1 s_2}(\mathbf{p},t)]_l^{\ m} \;\supset\; -\frac{1}{2}\,[\mathcal{F}_{s_1 s\, r_1 r_2}(\mathbf{p},\mathbf{q},\mathbf{k},t)]_l^{\ n}{}_\alpha^{\ \beta}\;[\Gamma_{s\, s_2 r_2 r_1}(\mathbf{p},\mathbf{q},\mathbf{k})]_n^{\ m}{}_\beta^{\ \alpha},$$

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