Flavor-Covariant Approach to Leptogenesis

BHUPAL DEV

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BD, P. Millington, A. Pilaftsis and D. Teresi,
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Nucl. Phys. B **897**, 749 (2015); J. Phys. Conf. Ser. **631**, 012087 (2015).

Exploring the Energy Ladder of the Universe

MITP, Johannes Gutenberg Universität, Mainz

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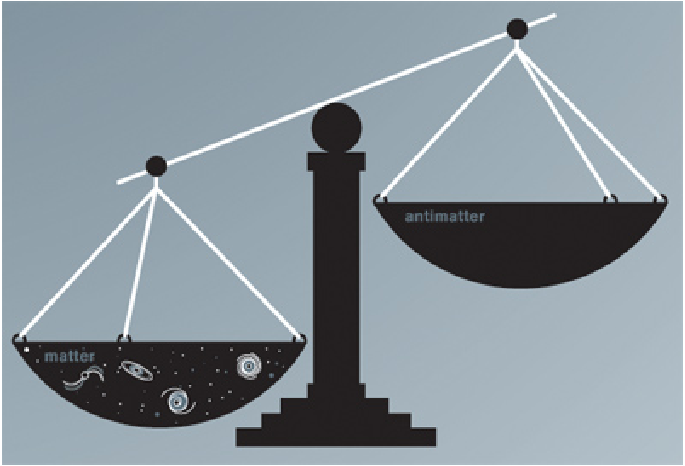
ν

$m_\nu = m_L^T - m_D M_R^{-1} m_D$

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Matter-Antimatter Asymmetry

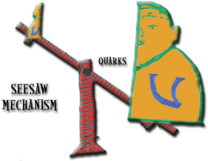


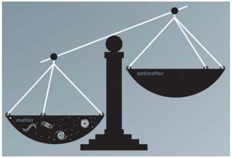
$$\eta^{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.105^{+0.086}_{-0.081}\right) \times 10^{-10} \qquad \text{[Planck (2015)]}$$

Baryogenesis

- Dynamical generation of baryon asymmetry.
- Basic **Sakharov conditions:** [Sakharov '67]
  - B violation: There must exist $X(B=0) \to Y_1(B=0) + Y_2(B \neq 0)$.
  - C *and* CP violation.
    Otherwise, $\Gamma(X \to Y_1 + Y_2) = \Gamma(\bar{X} \to \bar{Y}_1 + \bar{Y}_2) \Longrightarrow$ No net effect!
  - Out-of-equilibrium dynamics.
    Otherwise, $\Gamma(X \to Y_1 + Y_2) = \Gamma(Y_1 + Y_2 \to X) \Longrightarrow$ No net effect!
- Successful baryogenesis requires physics beyond the SM.
  - New sources of CP violation.
  - A departure from equilibrium (in addition to EWPT) or modify the EWPT itself.

Leptogenesis





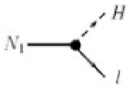
[Fukugita, Yanagida '86]

- **A cosmological consequence of the seesaw mechanism.**
- L violation due to the Majorana nature of heavy RH neutrinos.
- New source of CP violation through their complex Yukawa couplings (irrespective of the PMNS CP phases).
- Departure from equilibrium when $\Gamma_N \lesssim H$.
- $\not{L} \to \not{B}$ through sphaleron interactions. [Kuzmin, Rubakov, Shaposhnikov '85]

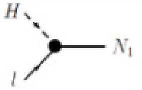
For Pedestrians

[Buchmüller, Di Bari, Plümacher '05]

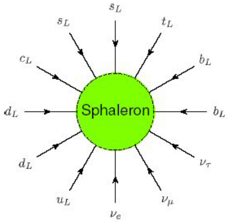
1. Generation of L asymmetry by heavy Majorana neutrino decay:



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



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



Boltzmann Equations

[Buchmüller, Di Bari, Plümacher ’02]

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

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

- FInal baryon asymmetry:

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

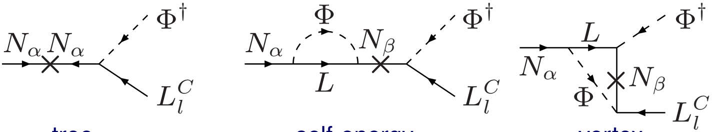
- $d \simeq 10^{-2}$ is the dilution factor.
- $\kappa_f \equiv \kappa(z_f)$ is the final efficiency factor, where

$$\kappa(z) = \int_{z_i}^{z} dz' \frac{D}{D+S} \frac{dn_{N_1}}{dz'} e^{-\int_{z'}^{z} dz'' W(z'')}$$

- Strength of (inverse-decay) washout governed by

$$K = \frac{\Gamma_D(z \to \infty)}{H(z=1)} \equiv \frac{\widetilde{m}_1}{m_*}$$

CP Asymmetry



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

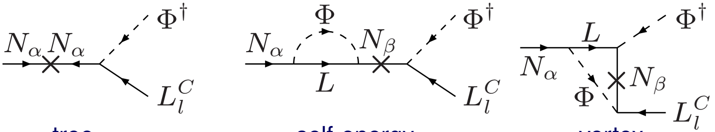
- In the two heavy-neutrino limit, self-energy term reduces to [Pilaftsis, Underwood '04]

$$\varepsilon_{l\alpha} \approx \frac{\mathrm{Im}\left[(h^*_{l\alpha}h_{l\beta})(h^\dagger h)_{\alpha\beta}\right]}{(h^\dagger h)_{\alpha\alpha}(h^\dagger h)_{\beta\beta}} \frac{\left(m^2_{N_\alpha} - m^2_{N_\beta}\right) m_{N_\alpha}\Gamma^{(0)}_{N_\beta}}{\underbrace{\left(m^2_{N_\alpha} - m^2_{N_\beta}\right)^2 + \left(m_{N_\alpha}\Gamma^{(0)}_{N_\beta}\right)^2}_{\text{regulator}}}\,.$$

- There exist other expressions for the regulator [Buchmüller, Plümacher '98; Anisimov, Broncano, Plümacher '06; Garny, Kartavtsev, Hohenegger '11; Iso, Shimada, Yamanaka '13]

$$\frac{\left(m^2_{N_\alpha} - m^2_{N_\beta}\right) m_{N_\alpha}\Gamma^{(0)}_{N_\beta}}{\left(m^2_{N_\alpha} - m^2_{N_\beta}\right)^2 + \left(m_{N_\alpha}\Gamma^{(0)}_{N_\alpha} \mp m_{N_\beta}\Gamma^{(0)}_{N_\beta}\right)^2}$$

CP Asymmetry



tree　　self-energy　　vertex

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

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A Simple Example

$$-\mathcal{L}_Y = Y_l \overline{L}_l \widetilde{\Phi} N_1 + Y'_l \overline{L}_l \widetilde{\Phi} N_2 + \frac{1}{2}\left(M \overline{N}_1 N_2^C + \mu_1 \overline{N}_1 N_1^C + \mu_2 e^{i\theta} \overline{N}_2 N_2^C \right) + \text{H.c.}\ .$$

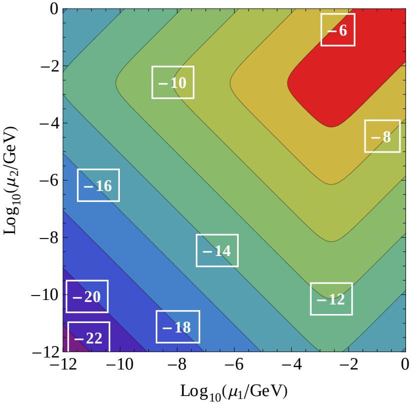
$$\mathcal{M}_{\nu N} = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y & \frac{v}{\sqrt{2}} Y' \\ \frac{v}{\sqrt{2}} Y^{\mathsf{T}} & \mu_1 & M \\ \frac{v}{\sqrt{2}} Y'^{\mathsf{T}} & M & \mu_2 e^{i\theta} \end{pmatrix} .$$

$$\widehat{h}_{l1} \simeq \frac{i}{\sqrt{2}} e^{-i(\phi-\lambda)/2} \left[\left(1 + \frac{\mu_2^2 - \mu_1^2}{4M\mu} \right) e^{i\phi} Y_l - Y'_l \right],$$

$$\widehat{h}_{l2} \simeq \frac{1}{\sqrt{2}} e^{-i(\phi+\lambda)/2} \left[\left(1 - \frac{\mu_2^2 - \mu_1^2}{4M\mu} \right) e^{i\phi} Y_l + Y'_l \right],$$

where $\mu e^{i\phi} = \mu_1 + \mu_2 e^{i\theta}$ and $\lambda = \sin\theta(\mu_1\mu_2/\mu M)$. [Blanchet, Hambye, Josse-Michaux '09]

Regulator in the L-conserving limit



$$\frac{\left(m_{N_\alpha}^2 - m_{N_\beta}^2\right) m_{N_\alpha} \Gamma_{N_\beta}^{(0)}}{\left(m_{N_\alpha}^2 - m_{N_\beta}^2\right)^2 + \left(m_{N_\alpha} \Gamma_{N_\beta}^{(0)}\right)^2}$$

leads to the correct L-conserving limit. [BD, Millington, Pilaftsis, Teresi ’14]

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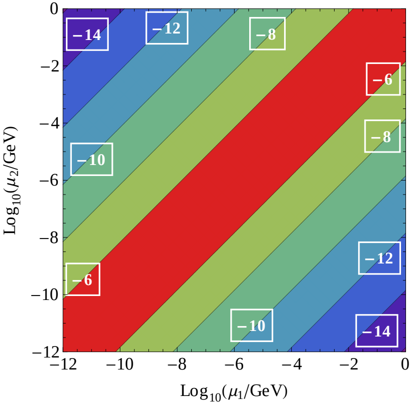

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does not lead to the correct L-conserving limit. [BD, Millington, Pilaftsis, Teresi ’14]

Vanilla Leptogenesis

- Hierarchical heavy neutrino spectrum ($m_{N_1} \ll m_{N_2} < m_{N_3}$).
- Vertex correction diagram important.
- Maximal CP asymmetry is given by

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

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

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

- Experimentally inaccessible mass range!
- Higgs naturalness implies $m_N \lesssim 10^7$ GeV. [Vissani '97; Clarke, Foot, Volkas '15]
- Also leads to a lower limit on the reheat temperature $T_{\rm rh} \gtrsim 10^9$ GeV.
- In many supergravity scenarios, 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]

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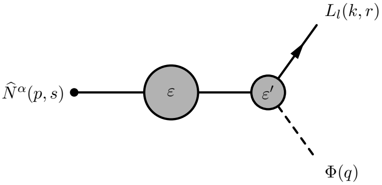
Resonant Leptogenesis



- Heavy Majorana neutrino self-energy effects on the leptonic CP-asymmetry (ε-type) become dominant [Flanz, Paschos, Sarkar '95; Covi, Roulet, Vissani '96].
- Resonantly enhanced, even up to order 1, when $\Delta m_N \sim \Gamma_N \ll m_{N_{1,2}}$. [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 '04; Pilaftsis, Underwood '05]
- A potentially testable scenario of leptogenesis, with implications at both Energy and Intensity Frontiers. [Deppisch, Pilaftsis '10; BD, Millington, Pilaftsis, Teresi '14]

Flavor-diagonal Resonant Leptogenesis

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

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

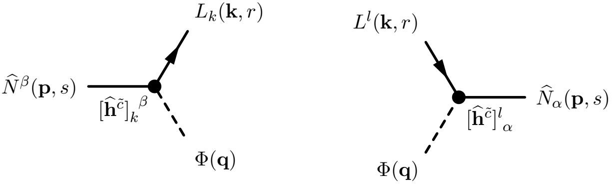


Figure : Decay and Inverse Decay.

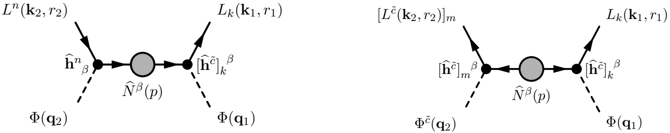
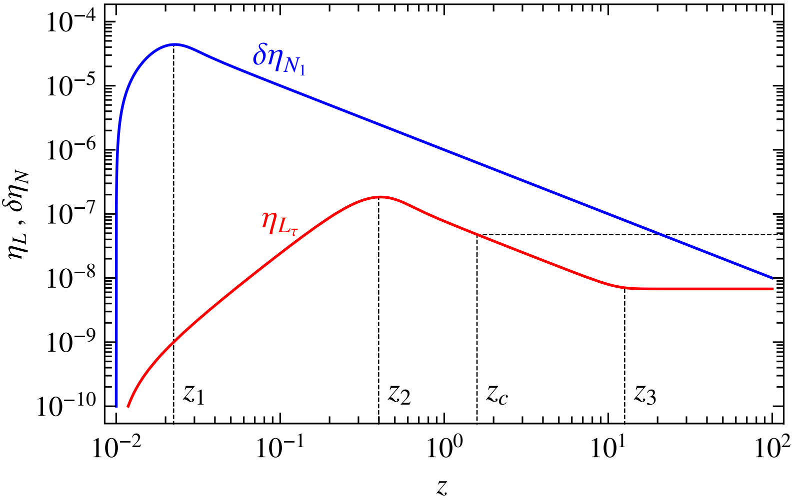


Figure : $\Delta L = 0$ and $\Delta L = 2$ scatterings.

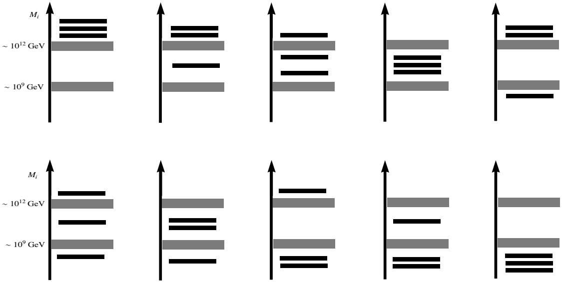
Analytic Solution



[Deppisch, Pilaftsis '11]

Flavordynamics of RL

- Flavor effects important for the time-evolution of lepton asymmetry in RL models. [Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; Blanchet, Di Bari '06; De Simone, Riotto '06; Blanchet, Di Bari, Jones, Marzola '12]



- Two sources of flavor effects:
  - Heavy neutrino Yukawa couplings h_l^{α} [Pilaftsis '04; Endoh, Morozumi, Xiong '04]
  - Charged lepton Yukawa couplings y_l^{k} [Barbieri, Creminelli, Strumia, Tetradis '00]
- Lead to *three* distinct physical phenomena: mixing, oscillation and decoherence.
- In Boltzmann approach, captured by the 'density matrix' formalism. [Sigl, Raffelt '93]
- *Fully* flavor-covariant formalism to consistently include all flavor effects in a single framework. [BD, Millington, Pilaftsis, Teresi '14]

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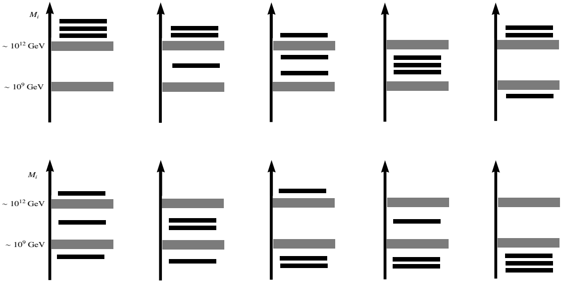

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Flavor Transformations

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

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

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

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

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

- Number densities:

$$[n^L_{s_1s_2}(\mathbf{p},t)]_l^{\ m} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle b^m(\mathbf{p},s_2,\tilde{t})\,b_l(\mathbf{p},s_1,\tilde{t})\rangle_t\ ,$$

$$[\bar{n}^L_{s_1s_2}(\mathbf{p},t)]_l^{\ m} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle d_l^\dagger(\mathbf{p},s_1,\tilde{t})\,d^{\dagger,m}(\mathbf{p},s_2,\tilde{t})\rangle_t\ ,$$

$$[n^N_{r_1r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle a^\beta(\mathbf{k},r_2,\tilde{t})\,a_\alpha(\mathbf{k},r_1,\tilde{t})\rangle_t\ ,$$

$$[\bar{n}^N_{r_1r_2}(\mathbf{k},t)]_\alpha^{\ \beta} \;\equiv\; \frac{1}{\mathcal{V}_3}\,\langle G_{\alpha\gamma}\,a^\gamma(\mathbf{k},r_1,\tilde{t})\;G^{\beta\delta}\,a_\delta(\mathbf{k},r_2,\tilde{t})\rangle_t\ ,$$

- Total number density:

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

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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 $t = \tilde{t} - \tilde{t}_i$:

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

- Use the Heisenberg EoM for $\boldsymbol{\mathcal{I}}_1$ and Liouville-von Neumann equation for $\boldsymbol{\mathcal{I}}_2$.
- Markovian master equation for the number density matrix:

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

Flavor Covariant Transport Equations for RL

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

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

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

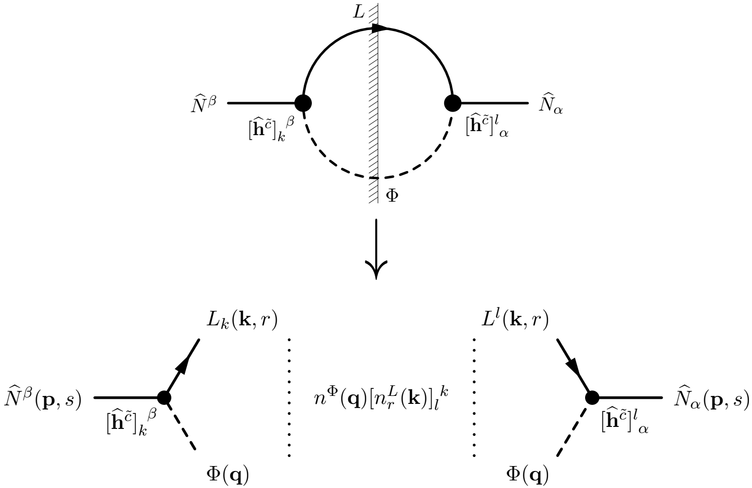
Collision terms are of the form

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

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

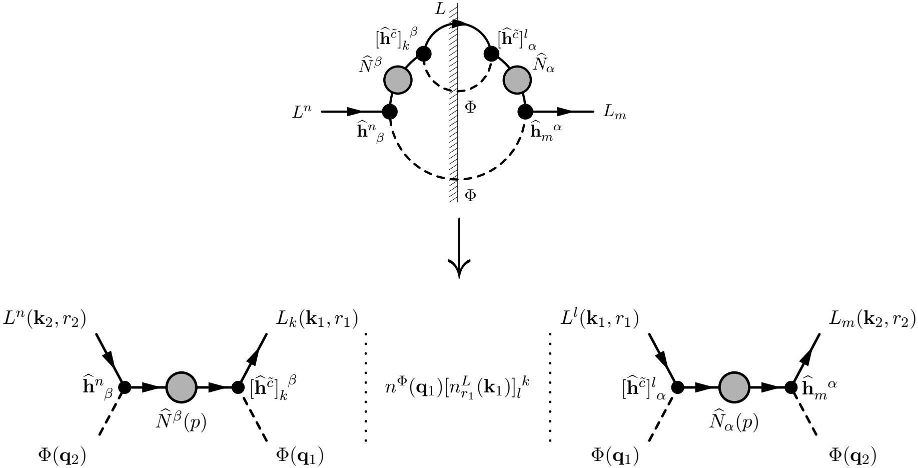
Collision Rates for Decay and Inverse Decay

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



Collision Rates for $2 \leftrightarrow 2$ Scattering

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



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

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

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

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

Final Rate Equations: Oscillation

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

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

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

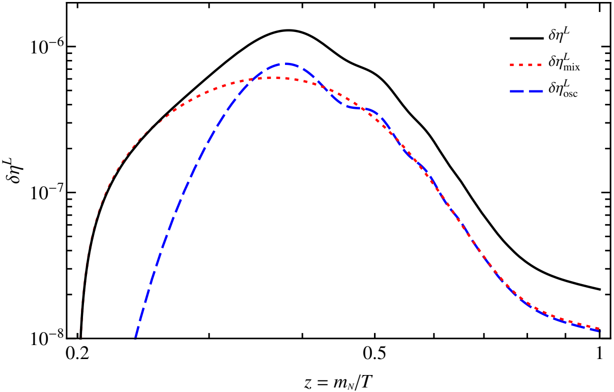
Final Rate Equations: Charged Lepton Decoherence

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

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

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

Key Result



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

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

A Minimal Model of RL

- Resonant ℓ-genesis (RL$_\ell$). [Pilaftsis (PRL '04); Deppisch, Pilaftsis '10]
- Minimal model: $O(N)$-symmetric heavy neutrino sector at a high scale μ_X.
- Small mass splitting at low scale from RG effects.

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

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

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

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

A Next-to-minimal RL_ℓ Model

[BD, Millington, Pilaftsis, Teresi '15]

- Asymmetry vanishes at $\mathcal{O}(h^4)$ in minimal RL_ℓ.
- 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:

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

where

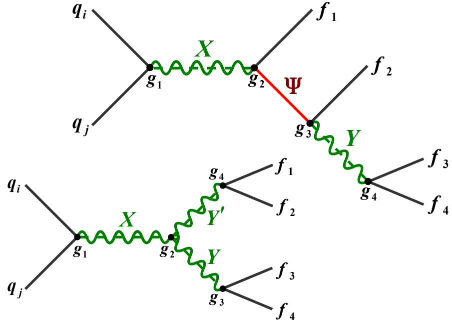
$$\Delta m_N \equiv 2\,[\Delta M_N]_{23} + i\left([\Delta M_N]_{33} - [\Delta M_N]_{22}\right) = -i\,\Delta M_2\,.$$

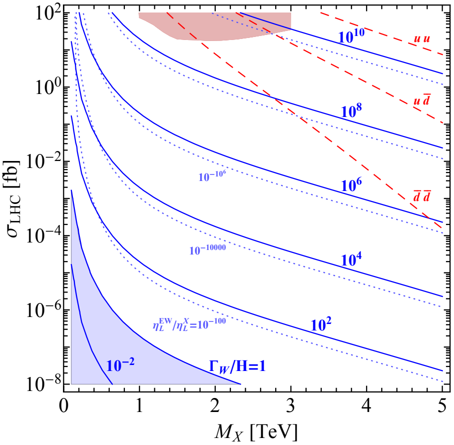
Benchmark Points

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
BR($\mu \to e\gamma$)	4.5×10^{-15}	1.9×10^{-13}	2.3×10^{-17}	$< 4.2 \times 10^{-13}$
BR($\tau \to \mu\gamma$)	1.2×10^{-17}	1.6×10^{-18}	8.1×10^{-22}	$< 4.4 \times 10^{-8}$
BR($\tau \to e\gamma$)	4.6×10^{-18}	5.9×10^{-19}	3.1×10^{-22}	$< 3.3 \times 10^{-8}$
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}	$< 4.6 \times 10^{-11}$
$\|\Omega\|_{e\mu}$	5.8×10^{-6}	1.8×10^{-5}	1.6×10^{-7}	$< 7.0 \times 10^{-5}$

Falsifying (High-scale) Leptogenesis at the LHC



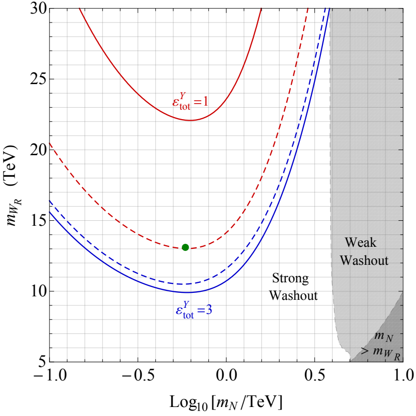


[Deppisch, Harz, Hirsch (PRL ’14)]

Falsifying (Low-scale) Leptogenesis?

- 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]



Conclusion and Outlook

- Leptogenesis provides an attractive link between neutrino mass and baryon asymmetry.
- Resonant Leptogenesis provides a way to test this idea in laboratory experiments.
- Flavor effects play a crucial role in the calculation of lepton asymmetry.
- We discussed a flavor-covariant formalism to consistently capture all flavor effects.
- Approximate analytic solutions are available for a quick phenomenological analysis.

- Possible future directions/unsettled issues:
  - A better understanding of the interplay between mixing and oscillation effects.
  - Model building: Motivating the quasi-degeneracy from flavor symmetry.
  - Dependence of lepton asymmetry on Dirac and Majorana CP phases.
  - Possible correlations of the lepton asymmetry with low-energy observables, such as LFV, EDM and $0\nu\beta\beta$ to enhance its testability.

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