Standard Leptogenesis Scenarios: Summary, Plots & References

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1 Useful formulae

- **General lepton Yukawa Lagrangian**

$$\mathcal{L}_Y = f_{ij}\,\overline{e}_{R_i}\ell_{L_j}H^\dagger + h_{ij}\,\overline{\nu}_{R_i}\ell_{L_j}H - \frac{1}{2}(M_R)_{ij}\,\overline{\nu}^c_{R_i}\nu_{R_j} \tag{1}$$

After integrating out the heavy right-handed neutrinos, one has the Lagrangian

$$\mathcal{L}_{Y(\nu)} = -\frac{1}{2}\overline{\ell}_{L_i}(m_\nu)_{ij}\ell_{L_j}\,, \tag{2}$$

at low energies, where the light neutrino mass matrix is given by the seesaw mechanism, i.e.,

$$m_\nu = -m_D^T M_R^{-1} m_D\,, \tag{3}$$

and the Dirac mass matrix $m_D = h_{ij}\,v$ is a product of the matrix of Yukawa couplings, h_{ij}, and the VEV of the Higgs doublet, $v \equiv \langle H \rangle$.

- **CP asymmetry**

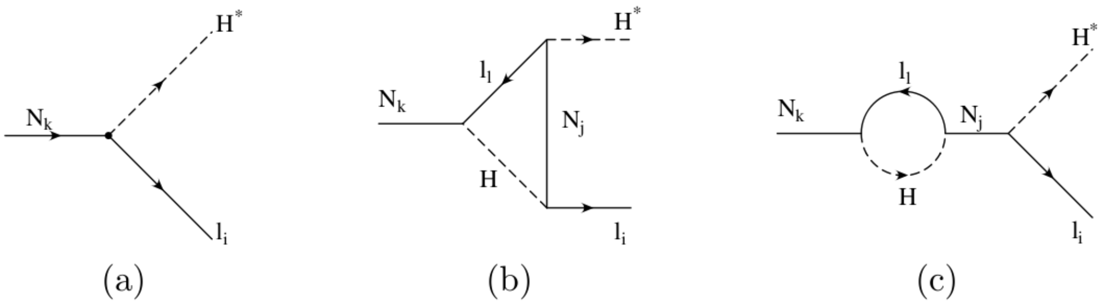


Fig. 1.7. Diagrams in SM with RH neutrinos that contribute to the lepton number asymmetry through the decays of the RH neutrinos. The asymmetry is generated due to the interference of the tree-level diagram (a) and the one-loop vertex correction (b) and self-energy (c) diagrams.

Assuming $|M_i - M_1| \gg |\Gamma_i - \Gamma_1|$, the CP asymmetry from decay of N_1 in the one flavour approximation is

$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]} \tag{4}$$

$$\simeq \frac{1}{8\pi} \frac{1}{(hh^\dagger)_{11}} \sum_{i=2,3} \Im\mathfrak{m}\left\{(hh^\dagger)^2_{1i}\right\} \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right)\right] \tag{5}$$

$$\xrightarrow{M_1 \ll M_2, M_3} -\frac{3}{16\pi} \frac{1}{(hh^\dagger)_{11}} \sum_{i=2,3} \Im\mathfrak{m}\left\{(hh^\dagger)^2_{1i}\right\} \frac{M_1}{M_i} , \tag{6}$$

where

$$f(x) = \sqrt{x}\left[1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \tag{7}$$

is the one-loop vertex contribution and

$$g(x) = \frac{\sqrt{x}}{1-x} \tag{8}$$

comes from the self-energy diagram.

- **Casas-Ibarra parameterization**

  The Casas-Ibarra parameterization is

$$h = \frac{1}{v}\sqrt{D_M} R \sqrt{D_m} U^\dagger , \tag{9}$$

  with R a complex orthogonal matrix, and D_M and D_m the diagonal matrices containing the heavy and light neutrino mass eigenvalues, respectively. U is the PMNS matrix.

  Using Eq. 9, the CP asymmetry in Eq. 6 can be written as

$$\epsilon_1 = -\frac{3M_1}{16\pi v^2} \frac{\Im\mathfrak{m}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta |R_{1\beta}|^2} . \tag{10}$$

  Including the effects of flavour, the asymmetry in each flavour can be written as

$$\epsilon_{1_\alpha} = -\frac{3M_1}{16\pi v^2} \frac{\Im\mathfrak{m}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2} \tag{11}$$

- **Baryon asymmetry**

  The final lepton asymmetry is

$$Y_L \equiv \frac{n_L - \overline{n}_L}{s} = \kappa \frac{\epsilon_1}{g_*} , \tag{12}$$

  with g_* the number of relativistic degrees of freedom ($\simeq 106.75$ in the SM), s the entropy density and κ the washout parameter, obtained from solving the Boltzmann equations. Finally, the baryon asymmetry is given by

$$Y_B \equiv \frac{n_B - \overline{n}_B}{s} = c\, Y_{B-L} = \frac{c}{c-1} Y_L , \tag{13}$$

  with $c = (8N_f + 4)/(22N_f + 13)$, as shown in Kher Sham's talk.

2 Plots

2.1 Mass bounds

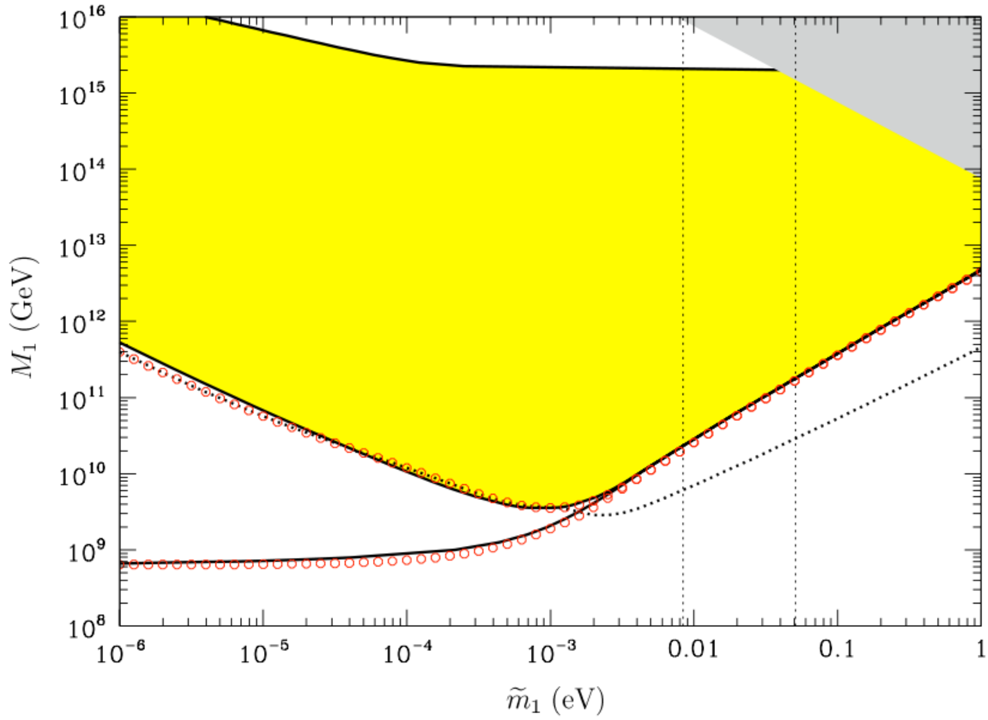


Fig. 1.13. Lower bound on the lightest RH neutrino mass, M_1 (circles) and the initial temperature, T_i (dotted line), for $m_1 = 0$ and $\eta_B^{CMB} = 6 \times 10^{-10}$. The red circles (solid lines) denote the analytical (numerical) results. The vertical dashed lines indicate the range $(\sqrt{\Delta m^2_{\rm sol}}, \sqrt{\Delta m^2_{\rm atm}})$. Figure taken from Ref. [28].

2.2 Flavoured leptogenesis

(Plots from Ref. [8])

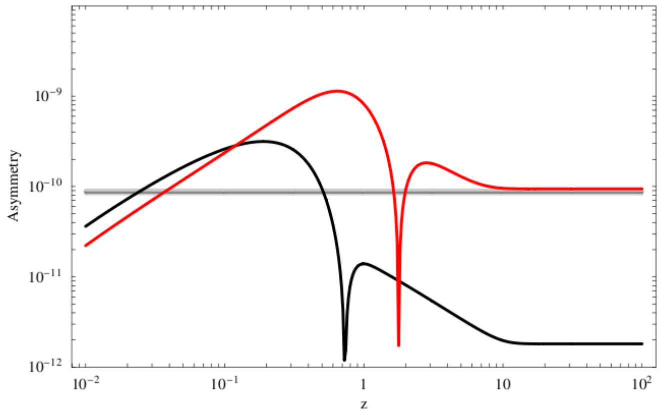


Figure 1: The total baryon asymmetry in the two flavour calculation (upper) and within the one-flavour approximation (lower) as a function of z. The chosen parameters are $K_{\tau\tau} = 10$, $K_{\mu\mu} = 30$, $K_{ee} = 30$, $\epsilon_{\tau\tau} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{ee} = 10^{-7}$ and $M_1 = 10^{10}$ GeV. *See the second Note Added at the beginning of the manuscript.*

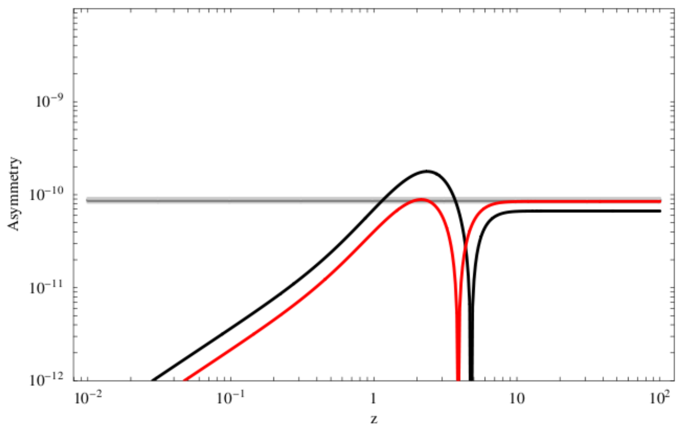


Figure 2: The total baryon asymmetry in the two flavour calculation (upper) and within the one-flavour approximation (lower) as a function of z. The chosen parameters are $K_{\tau\tau} = 4.5 \times 10^{-1}$, $K_{\mu\mu} = 10^{-2}$, $K_{ee} = 10^{-3}$, $\epsilon_{\tau\tau} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{ee} = 10^{-7}$ and $M_1 = 10^{10}$ GeV.

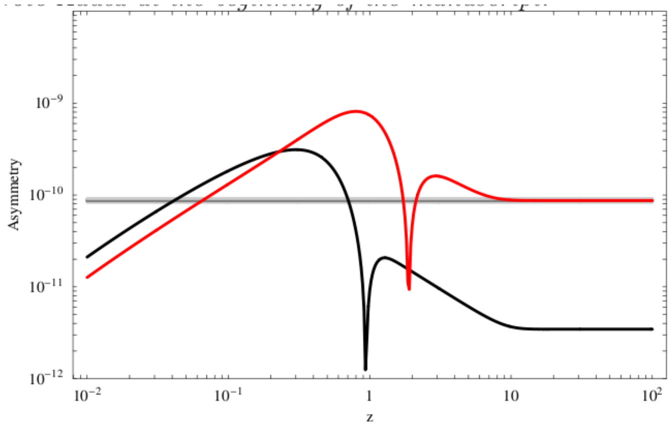


Figure 3: The total baryon asymmetry in the two flavour calculation (upper) and within the one-flavour approximation (lower) as a function of z. The chosen parameters are $K_{\tau\tau} = 10$, $K_{\mu\mu} = 30$, $K_{ee} = 10^{-2}$, $\epsilon_{\tau\tau} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{ee} = 10^{-7}$ and $M_1 = 10^{10}$ GeV. *See the second Note Added at the beginning of the manuscript.*

2.3 Connection to low energy observables (model-dependent)

(Plots from Ref. [13])

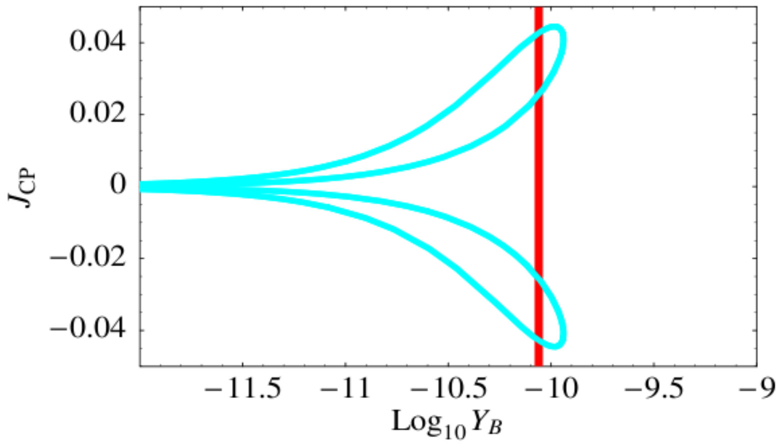


FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ range for the baryon asymmetry.

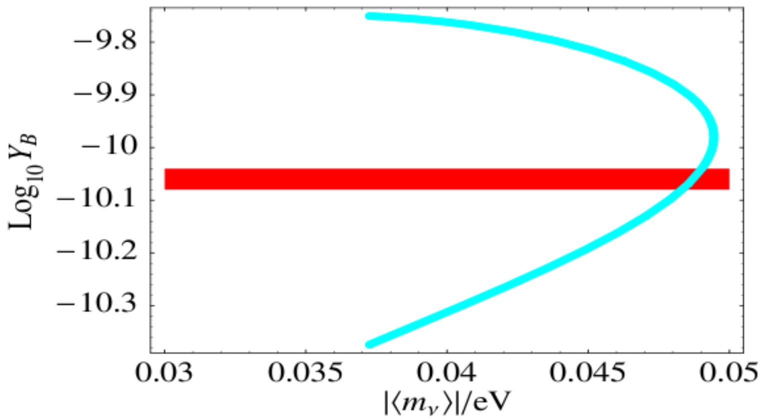


FIG. 2. The baryon asymmetry $|Y_{\rm B}|$ versus the effective Majorana mass in neutrinoless double beta decay, $\langle m_\nu \rangle$, in the case of Majorana CP-violation, hierarchical RH neutrinos and IH light neutrino mass spectrum, for $\delta = 0$, $s_{13} = 0$, purely imaginary $R_{11}R_{12}$, $|R_{11}| = 1.05$ and $M_1 = 2 \times 10^{11}$ GeV. The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

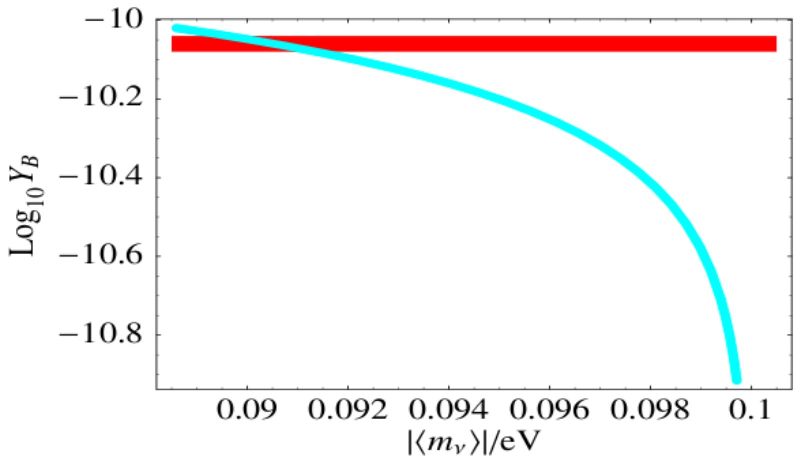
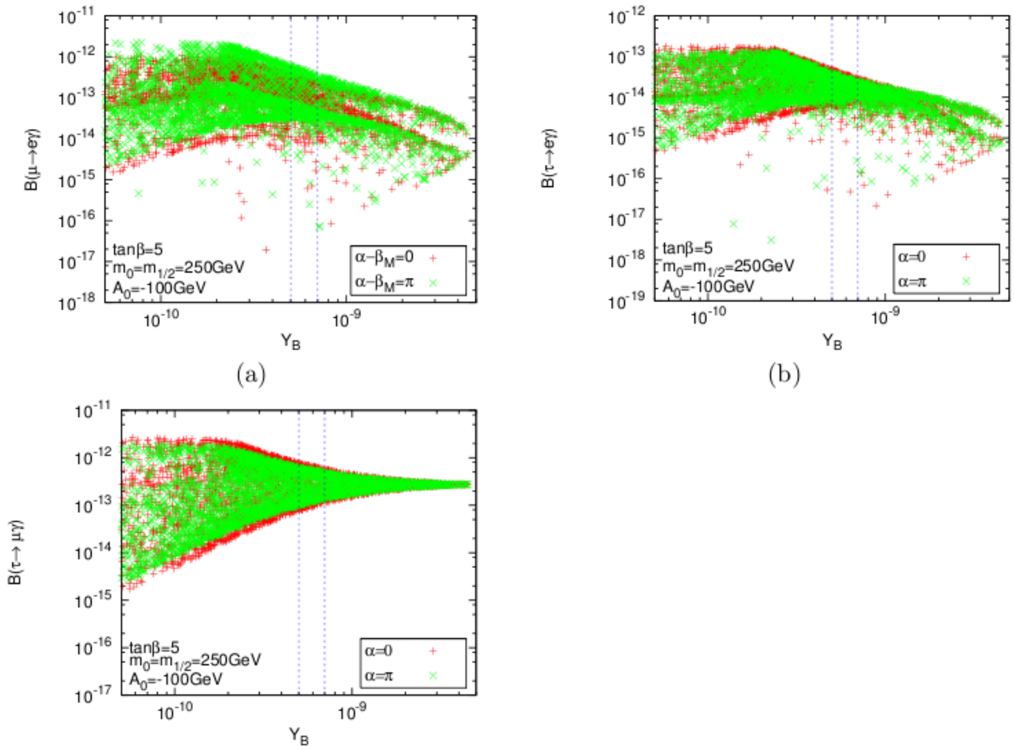


FIG. 3. The quantity $|\langle m_\nu \rangle|$ versus the baryon asymmetry varying α_{32} between 0 and $\pi/3$ for the case of degenerate RH neutrinos and QD for light neutrinos for $\delta = \pi/3$, $s_{13} = 0.01$, $M_1 = 10^{10}$ GeV and $m = 0.1$ eV.

2.4 Leptogenesis and LFV in SUSY models

(Plots from Ref. [12])



(c)

Figure 2: The correlation between the predicted values of the LFV decay branching ratios B($\mu \to e + \gamma$) (a), B($\tau \to e + \gamma$) (b), B($\tau \to \mu + \gamma$) (c) and of the baryon asymmetry Y_B in the thermal leptogenesis scenario, for $M_1 = 6 \times 10^{10}$ GeV, $M_2 = 10^{12}$ GeV and NH light neutrino mass spectrum. The figure was obtained for the "benchmark" values of the soft SUSY breaking parameters $m_0 = m_{1/2} = 250$ GeV, $a_0 m_0 = -100$ GeV and the minimal value of $\tan\beta = 5$. The region between the two vertical dashed lines corresponds to the observed baryon asymmetry: $5.0 \times 10^{-10} \leq Y_B \leq 7.0 \times 10^{-10}$. Results for two values of the Majorana phase $(\alpha - \beta_M)$ equal to 0 (red+green areas) and π (green areas) are shown.

Notes:
Refs. [1–7] are reviews, Refs. [8, 9] discuss flavour effects, Refs. [10–14] contain phenomenological studies related to leptogenesis and Refs. [15, 16] are some of the older original works on the topic.

References

[1] M. -C. Chen, “TASI 2006 Lectures on Leptogenesis,” [hep-ph/0703087].

The basis for this talk. Provides a good overview of the topic, although omitting many details.

[2] Y. Nir, “Leptogenesis: A Pedagogical Introduction,” Lectures given at the International Neutrino Summer School, Fermilab, 6–17 July 2009, `http://projects.fnal.gov/nuss/`

Brief non-technical introduction. These notes cannot be found on the arXiv or SPIRES. Click on “Indico Schedule” to download the PDF file.

[3] W. Buchmuller, R. D. Peccei, T. Yanagida, “Leptogenesis as the origin of matter,” Ann. Rev. Nucl. Part. Sci. **55**, 311-355 (2005), [hep-ph/0502169].

Well written review, Ref. [1] follows this review in some places. More discussion on decays and inverse decays. Also includes a section on dark matter and axions.

[4] S. Davidson, E. Nardi, Y. Nir, Phys. Rept. **466**, 105-177 (2008), [arXiv:0802.2962 [hep-ph]].

The most comprehensive review on leptogenesis, over 100 pages long. Very well written and good to use as a starting point to study different aspects, since it includes over 300 references. Chapters on technical details can be omitted without losing the overall picture. The general comments/conclusion is very useful and thought-provoking.

[5] W. Buchmuller, P. Di Bari, M. Plumacher, “Leptogenesis for pedestrians,” Annals Phys. **315**, 305-351 (2005), [hep-ph/0401240].

Another good review. More discussion on the Boltzmann equations and subtraction of real intermediate states (see Alex’s talk).

[6] W. Buchmuller, P. Di Bari, M. Plumacher, “Some aspects of thermal leptogenesis,” New J. Phys. **6**, 105 (2004), [hep-ph/0406014].

After a short review of the basics, this work discusses some phenomenological aspects, bounds on neutrino masses and CP violating parameters.

[7] Y. Nir, “Introduction to leptogenesis,” [hep-ph/0702199].

Short and sweet, this is a very nice concise introduction to the topic.

[8] A. Abada, S. Davidson, A. Ibarra, F. X. Josse-Michaux, M. Losada and A. Riotto, “Flavour matters in leptogenesis,” JHEP **0609**, 010 (2006), [arXiv:hep-ph/0605281].

Analytical and numerical study of flavour effects, including flavour-dependent washout processes. There is a study of the two right-handed neutrino model.

[9] S. Davidson, "Flavoured Leptogenesis," [arXiv:0705.1590 [hep-ph]].

A conference talk summarizing the main results of Ref. [8], without going into the details of Boltzmann equations.

[10] J. A. Casas, A. Ibarra, "Oscillating neutrinos and $\mu \to e, \gamma$," Nucl. Phys. **B618**, 171-204 (2001), [hep-ph/0103065].

The original reference on the Casas-Ibarra parameterization. The emphasis is on charged lepton flavour violation.

[11] S. Davidson, A. Ibarra, "A Lower bound on the right-handed neutrino mass from leptogenesis," Phys. Lett. **B535**, 25-32 (2002), [hep-ph/0202239].

The original reference on the Davidson-Ibarra bound.

[12] S. T. Petcov, W. Rodejohann, T. Shindou *et al.*, "The See-saw mechanism, neutrino Yukawa couplings, LFV decays $l_i \to l_j + \gamma$ and leptogenesis," Nucl. Phys. **B739**, 208-233 (2006). [hep-ph/0510404].

Phenomenological analysis using the Casas-Ibarra parameterization and connecting LFV and leptogenesis.

[13] S. Pascoli, S. T. Petcov, A. Riotto, "Connecting low energy leptonic CP-violation to leptogenesis," Phys. Rev. **D75**, 083511 (2007). [hep-ph/0609125].

Phenomenological study of baryon asymmetry in the flavoured leptogenesis case, connecting low energy CP phases to leptogenesis for certain examples.

[14] E. K. .Akhmedov, W. Rodejohann, "A Yukawa coupling parameterization for type I + II seesaw formula and applications to lepton flavor violation and leptogenesis," JHEP **0806**, 106 (2008), [arXiv:0803.2417 [hep-ph]].

Extension of the Casas-Ibarra parameterization to type I + II seesaw, along with phenomenological analyses of certain scenarios.

[15] V. A. Kuzmin, V. A. Rubakov, M. E. Shaposhnikov, "On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe," Phys. Lett. **B155**, 36 (1985),
M. Fukugita, T. Yanagida, "Baryogenesis Without Grand Unification," Phys. Lett. **B174**, 45 (1986).

The first authors to discuss the idea of leptogenesis, i.e., how the lepton asymmetry could occur in the early universe and be transmitted to baryons via sphaleron processes.

[16] L. Covi, E. Roulet, F. Vissani, "CP violating decays in leptogenesis scenarios," Phys. Lett. **B384**, 169-174 (1996), [hep-ph/9605319].

Introduction of the self-energy contribution to the CP violating asymmetry, also extended to the SUSY version of the model.