Three-Flavoured Leptogenesis during Reheating

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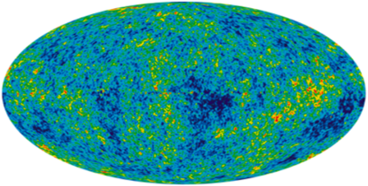
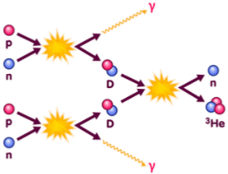
Baryon Asymmetry of the Universe (BAU)

- Cosmological Puzzle: Why is there more matter than antimatter?
- Actual measurement of the asymmetry is the BAU [4][1].

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \approx \frac{n_B}{s} = (8.72 \pm 0.08) \times 10^{-11} \quad (1)$$

- Measured from CMB and BBN seperately [5][2].





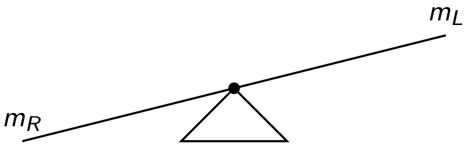
- Leptogenesis is an elegant solution to this problem that has its roots in neutrino physics.

Type-1 Seesaw Mechanism

- Neutrinos in SM do not have mass. Neutrinos in the real world do....why do they have mass and why is that mass so small?
- Add right-handed neutrinos to the SM Lagrangian [6]. Two terms are allowed.
  1. Dirac Mass Term: $-Y\bar{L_L}\tilde{H}N_R + h.c.$
  2. Majorana Mass Term: $-M_m\bar{N_R^c}N_R + h.c.$
- See-Saw Mechanism is the limit $M_m >> m_D$:

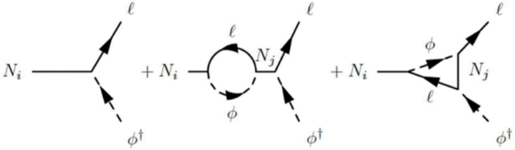
$$m_L \approx \frac{(Yv)^2}{M_m}, \quad m_R \approx M_m \tag{2}$$

explains the smallness of standard model neutrino masses.



Leptogenesis

- At one loop, we find that the probability of $N \to HL$ is greater than $N \to H^\dagger \bar{L}$. Lepton asymmetry is produced by sterile neutrino decays at one-loop [3]:



- The CP violation parameter is defined as

$$\epsilon = \frac{\Gamma(N \to LH) - \Gamma(N \to \bar{L}H^\dagger)}{\Gamma(N \to LH) + \Gamma(N \to \bar{L}H^\dagger)}, \qquad \epsilon_{\max} \propto M_N \tag{3}$$

- This creates a lepton asymmetry. Then a lepton asymmetry is transferred to a baryon asymmetry by sphaleron processes

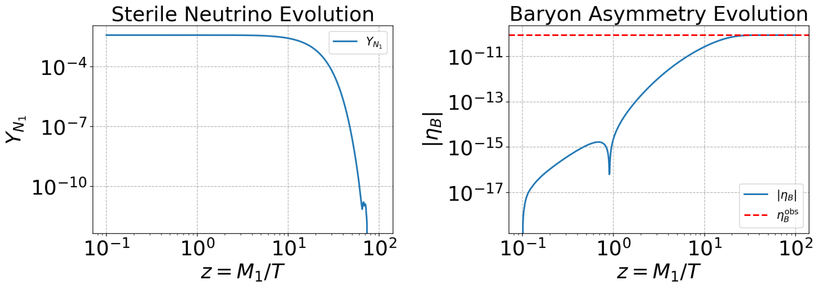
$$Y_B = \frac{28}{79}\, Y_{B-L}\ . \tag{4}$$

Bolztmann Equations

- The baryon asymmetry is then calculated by Bolztmann equations,

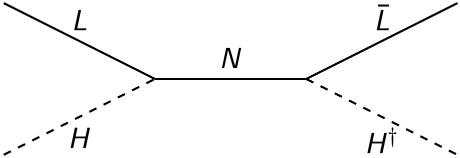
$$\frac{dY_N}{dz} = -D(z)(Y_N - Y_N^{eq})$$
$$\frac{dY_{B-L}}{dz} = \epsilon D(z)(Y_N - Y_N^{eq}) - W(z)Y_{B-L}$$

D and W denote the decay and washout terms and $z = M_1/T$ is the time evolution variable. ϵ and the D determine how much asymmetry can be created. W determines the efficiency.



Washout

- Inverse decays and scatterings look to reduce the asymmetry.



- Whether they have any effect is determined by the effective neutrino mass of the right-handed neutrino, $\tilde{m}_i$. This parameter is independent of the mass and is related to the decay rate,

$$\Gamma_i = \frac{M_i^2 \tilde{m}_i}{8\pi v^2}, \quad \tilde{m}_i = \frac{(Y^\dagger Y)_{ii}}{M_i} \tag{5}$$

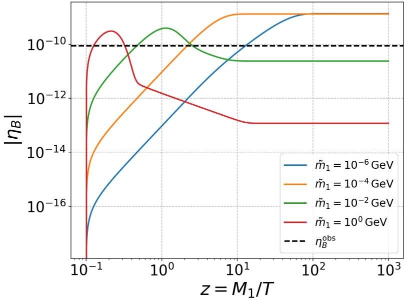
The values of the effective neutrino mass are determined by a complex orthogonal matrix.

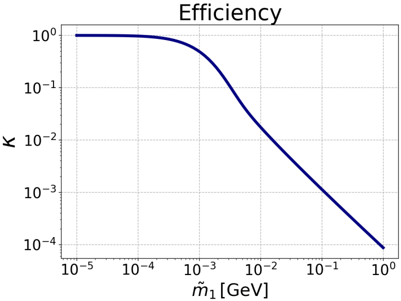
$$\tilde{m}_i = \sum_k m_k \left|R_{ki}\right|^2. \tag{6}$$

where m_i are the active neutrino masses.

Vanilla Lepto Results

- We performed parameter scans to illustrate how the effective neutrino mass $\tilde{m}$ controls the washout strength:





- If washout becomes significant, flavour effects become essential.

Flavoured Boltzmann equations

- At temperatures below the flavour thresholds, charged–lepton Yukawa interactions become fast enough to distinguish individual lepton flavours.
- This means each flavour suffers *different washout* $W_e \neq W_\mu \neq W_\tau$, and the asymmetry cannot be treated as a single quantity.
- For temperatures $T \lesssim 10^9$ GeV the the lepton flavours are decohered, and the evolution must be tracked for each flavour separately.

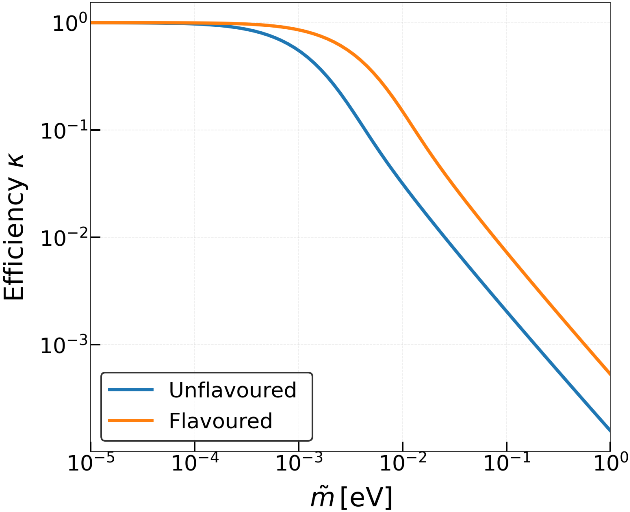
$$\frac{dY^\alpha_{B-L}}{dz} = \epsilon_\alpha \, D(z) \left(Y_N - Y_N^{\mathrm{eq}}(z) \right) - W_{1\alpha}(z) \, Y^\alpha_{B-L} \qquad (\alpha = e, \mu, \tau) \tag{7}$$

where,

$$\epsilon_\alpha = \frac{\Gamma(N_1 \to L_\alpha H) - \Gamma(N_1 \to \bar{L}_\alpha H^\dagger)}{\Gamma(N_1 \to L_\alpha H) + \Gamma(N_1 \to \bar{L}_\alpha H^\dagger)} \tag{8}$$

Benefits of Flavour effects

- Flavour effects as well as being essential for a proper treametent can lower the scale of leptogenesis.



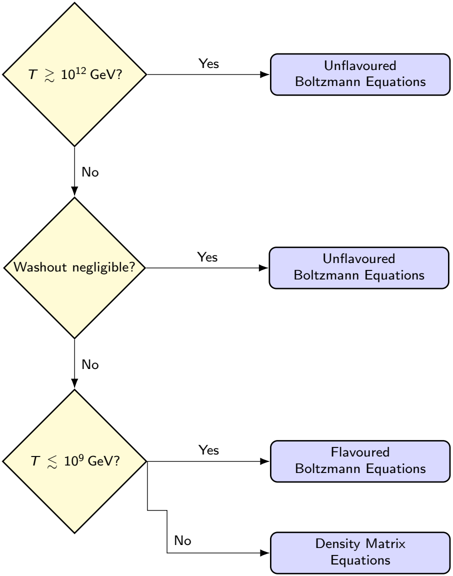
Density Matrix Equations

- For $10^{12}\,\text{GeV} \gtrsim T \gtrsim 10^{9}\,\text{GeV}$, partial flavour decoherence occurs and density matrix equations are required.
- The flavour–density evolution is

$$\frac{dY^{\alpha\beta}_{B-L}}{dz} = \epsilon_{\alpha\beta} D(Y_N - Y_N^{\rm eq}) - \frac{1}{2} W \left\{P_0, Y_{B-L}\right\}_{\alpha\beta} - \Lambda_\tau \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_{B-L} \right] \right]_{\alpha\beta} - \Lambda_\mu \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_{B-L} \right] \right]_{\alpha\beta} . \qquad (9)$$

- The final baryon asymmetry is $Y_B = \frac{28}{79} \sum_\alpha (Y_{B-L})_{\alpha\alpha}$.
- These equations include all flavour effects and remain valid in every temperature regime.

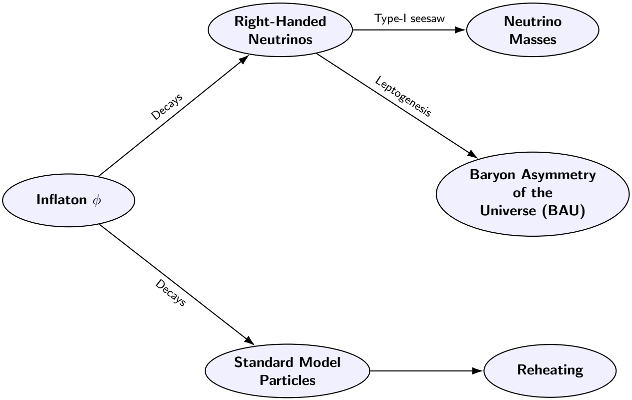
When to use what



Decision scheme for the theoretical treatment of leptogenesis

Leptogenesis during Reheating

- After inflation, ϕ decays into SM particles and RH neutrinos.



- If your universe history begins with inflation and explains neutrino masses by Type I seesaw. This process MUST have taken place unless there is a symmetry forbidding ϕNN or $M_N > M_\phi$

Leptogenesis durng reheating

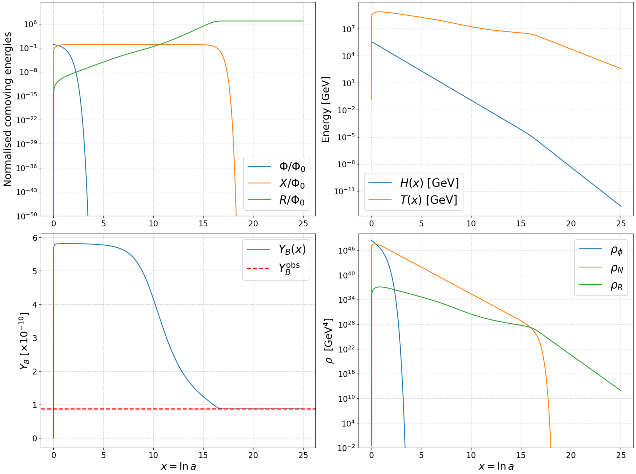
- We would normally solve the Bolztamnn equations...

$$
\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi(\rho_\phi - \rho_\phi^{\rm eq}), \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi(\rho_\phi - \rho_\phi^{\rm eq}) - \Gamma_N(\rho_N - \rho_N^{\rm eq}), \\
\dot{\rho}_R &= -4H\rho_R + \Gamma_N(\rho_N - \rho_N^{\rm eq}), \\
\dot{n}_{B-L} &= -3Hn_{B-L} - \epsilon\Gamma_N(n_N - n_N^{\rm eq}) - W\ n_{B-L},
\end{aligned}
\tag{10}
$$

- There is an abundance of right-handed neutrinos and the mass bound can be lowered to 10^7 GeV.
- But as we are evolving during reheating we have to have leptogenesis occurring at temperatures less than 10^{12} GeV.
- So if we have washout that means we need to be more careful and instead use density matrix formalism.

Benchmark

- As a benchmark we have $M_1 = 5 \times 10^7$ GeV, $\tilde{m} = 10^{-5}$ eV, $Br_N = 1$ and $y_1 = 10^{-3}$.



Flavoured Leptogenesis during reheating

- Now we solve the flavoured Bolztmann equations...

$$\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi(\rho_\phi - \rho_\phi^{\mathrm{eq}}), \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi(\rho_\phi - \rho_\phi^{\mathrm{eq}}) - \Gamma_N(\rho_N - \rho_N^{\mathrm{eq}}), \\
\dot{\rho}_R &= -4H\rho_R + \Gamma_N(\rho_N - \rho_N^{\mathrm{eq}}), \\
\dot{n}_{B-L}^\alpha &= -3Hn_{B-L}^\alpha - \epsilon^\alpha\Gamma_N(n_N - n_N^{\mathrm{eq}}) - W^\alpha\ n_{B-L},
\end{aligned} \tag{11}$$

- There is an abundance of right-handed neutrinos and the mass bound can be lowered to 10^7 GeV.
- But as we are reheating we have to have leptogenesis occuring at temperatures less than 10^{12} GeV.
- So if we have washout that means we need to be more careful and instead use density matrix formalism.

Three-Flavoured Leptogenesis during Reheating

- We therefore need to solve the density matrix equations during reheating which are.....

$$
\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi(\rho_\phi - \rho_\phi^{\text{eq}}), \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi(\rho_\phi - \rho_\phi^{\text{eq}}) - \Gamma_N(\rho_N - \rho_N^{\text{eq}}), \\
\dot{\rho}_R &= -4H\rho_R + \Gamma_N(\rho_N - \rho_N^{\text{eq}}), \\
\dot{n}_{B-L}^{\alpha\beta} &= -3H\, n_{B-L}^{\alpha\beta} + \epsilon_{\alpha\beta}\,\Gamma_N(n_N - n_N^{\text{eq}}) \\
&\quad - \frac{\Gamma_W}{2}\,\{P_0,\, n_{B-L}\}_{\alpha\beta} - \Gamma_\tau[P_\tau, [P_\tau, n_{B-L}]]_{\alpha\beta} \\
&\quad - \Gamma_\mu[P_\mu, [P_\mu, n_{B-L}]]_{\alpha\beta}.
\end{aligned}
\tag{12}
$$

- Results coming soon in early 2026!

Conclusions

- Introduced the Type I seesaw mechanism
- Introduced Vanilla leptogenesis.
- Clarified when flavour effects become important and why a density–matrix treatment is required.
- Reviewed leptogenesis in the reheating era.
- Argued that reheating-era leptogenesis is a natural and plausible outcome in a Universe with inflation and the type I seesaw.
- Outlined the ingredients needed for a fully consistent treatment of leptogenesis during reheating.
- Showed we can guarantee that for non-negligible washout this will lower the mass bounds for successful leptogenesis.

References I

[1] N. Aghanim et al. “Planck2018 results: VI. Cosmological parameters”. In: *Astronomy amp; Astrophysics* 641 (Sept. 2020), A6. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201833910. URL: http://dx.doi.org/10.1051/0004-6361/201833910.

[2] Wikipedia Contributors. *Cosmic Microwave Background*. Photo retrieved from the Wikipedia article on the Cosmic Microwave Background. Accessed: 2024-12-04. 2024. URL: https://en.wikipedia.org/wiki/Cosmic_microwave_background.

[3] Pasquale Di Bari. “An introduction to leptogenesis and neutrino properties”. In: *Contemp. Phys.* 53.4 (2012), pp. 315–338. DOI: 10.1080/00107514.2012.701096. arXiv: 1206.3168 [hep-ph].

References II

[4] Ivan Esteban et al. "The fate of hints: updated global analysis of three-flavor neutrino oscillations". In: *Journal of High Energy Physics* 2020.9 (Sept. 2020). ISSN: 1029-8479. DOI: 10.1007/jhep09(2020)178. URL: http://dx.doi.org/10.1007/JHEP09(2020)178.

[5] Max Planck Institute for Gravitational Physics (Albert Einstein Institute). *Big Bang Nucleosynthesis*. Photo retrieved from the Einstein Online webpage. Accessed: 2024-12-04. 2024. URL: https://www.einstein-online.info/en/spotlight/bbn/.

[6] Peter Minkowski. "$\mu \to e\gamma$ at a Rate of One Out of 1-Billion Muon Decays?" In: *Phys. Lett. B* 67 (1977), pp. 421–428. DOI: 10.1016/0370-2693(77)90435-X.