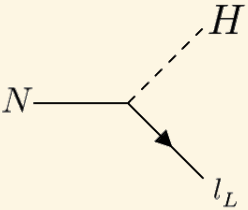

Hot Leptogenesis

A naturalness-motivated solution to baryon asymmetry

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Leptogenesis: the answer to the origin of the BAU?

Seesaw mechanism introduces heavy Majorana right-handed neutrinos (RHN) with Yukawa coupling $Y_{\alpha i}\overline{L_\alpha}\widetilde{H}N_i$.

$$m_\nu^{\text{tree}} \approx v^2 Y^T M_R^{-1} Y \,, \tag{1}$$

Leptogenesis

Out-of-equilibrium **decays** of heavy RHN could seed a L asymmetry that is converted to a B asymmetry through $B+L$ violating sphaleron interactions [Fukugita and Yanagida, 1986].

Requires a lightest RHN mass of $m_N \gtrsim 10^8$ GeV [1] to generate the **observed** baryon asymmetry [2] of $\eta_B = (5.8 - 6.3) \times 10^{-10}$.

Naturalness constraints ***limit*** $m_N \lesssim 7.4 \times 10^7$ GeV [3].

[1] [Davidson and Ibarra, 2002]
[2] PDG 2023
[3] [Vissani, 1998]

Hot Leptogenesis

Increase the RHN temperature!

A thermally disconnected hot RHN sector, with a thermal number density could allow for the observed η_B to be produced with a lower RHN mass spectrum.

First proposed in [Bernal and Fong, 2017], we present a comprehensive model and numerical analysis of this scenario.

Kinetic equilibrium

Requires fast (vs Hubble) elastic scattering processes.

$$\frac{n}{n_{\text{eq}}} = \frac{f}{f_{\text{FD}}} \tag{2}$$

Kinetic + chemical equilibrium

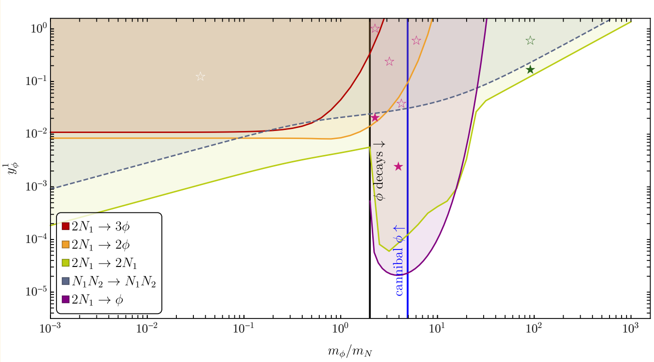
Kinetic + chemical equilibrium requires fast number changing processes as well.

$$n = n_{\text{eq}} \tag{3}$$

Coupling constraints

Introduce a scalar ϕ with coupling $y_\phi \phi \overline{N}_i N_i$ and $\frac{\lambda}{4!}\phi^4$.

Compute thermally averaged number-changing interaction rates $\Gamma_{2N_1\to3\phi}$, $\Gamma_{2N_1\to2\phi}$, $\Gamma_{2N_1\to\phi}$, and the elastic scattering rates $\Gamma_{2N_i\to2N_i}$, and compare to Hubble at $T_H = m_{N_1}$.



Boltzmann equations

$$aH\frac{dN_{N_1}}{da} = -\Gamma_{D_1}(z_{N_1})N_{N_1} + \Gamma_{D_1}(z_{\mathrm{SM}})N_{N_1}^{\mathrm{eq}}\,, \tag{4}$$

$$aH\frac{dN_{N_2}}{da} = -\Gamma_{D_2}(z_{N_2})\left(N_{N_2} - N_{N_2}^{\mathrm{eq}}\right)\,, \tag{5}$$

$$aH\frac{dN_{N_3}}{da} = -\Gamma_{D_3}(z_{N_3})\left(N_{N_3} - N_{N_3}^{\mathrm{eq}}\right)\,, \tag{6}$$

$$\frac{dT_{\mathsf{SM}}}{da} = \left(\frac{ds_{\mathsf{SM}}}{dT_{\mathsf{SM}}}\right)^{-1}\left(\frac{1}{a^3 T_{\mathsf{SM}}}\frac{dQ}{da} - 3\frac{s_{\mathsf{SM}}}{a}\right)\,, \tag{7}$$

The T_{SM} evolution is derived from the second law of thermodynamics.

If chemical equilibrium holds, T_H is dictated by $N_N = N_N^{\mathsf{eq}}(z_H)$, else the evolution of T_H can be derived from comoving energy density conservation.

N_{B-L} density matrix equation

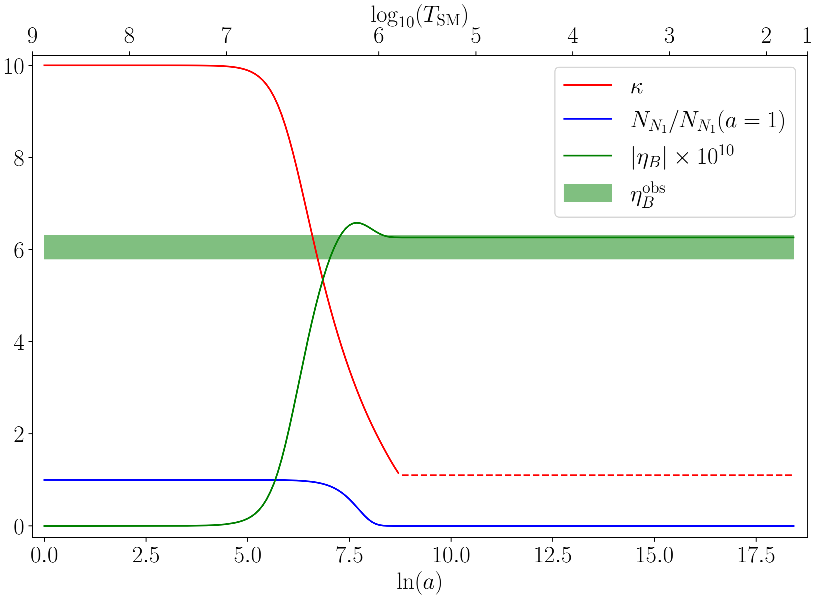
$$aH\frac{dN_{\alpha\beta}}{da} = \epsilon^{(1)}_{\alpha\beta}\left(\Gamma_{D_1}(z_{N_1})N_{N_1} - \Gamma_{D_1}(z_{\rm SM})N^{\rm eq}_{N_1}\right) - \frac{1}{2}W_1\left\{P^{(1)}, N\right\}_{\alpha\beta}$$

$$+ \sum_{i=2}^{3}\epsilon^{(i)}_{\alpha\beta}\Gamma_{D_i}(z_{N_i})\left(N_{N_i} - N^{\rm eq}_{N_i}\right) - \frac{1}{2}W_i\left\{P^{(i)}, N\right\}_{\alpha\beta}$$

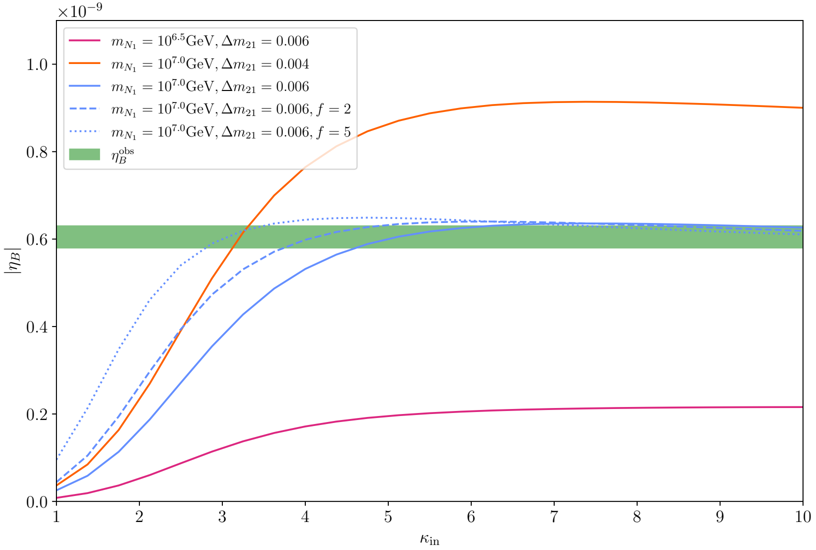
$$- \Lambda_\tau\left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N\right]\right]_{\alpha\beta} \tag{8}$$

$$- \Lambda_\mu\left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N\right]\right]_{\alpha\beta}, \tag{9}$$

Leptogenesis evolution



Increasing the temperature



Casas-Ibarra Parametrisation

For the seesaw mechanism, the Yukawa matrix can be written as,

$$Y = \frac{1}{v} U \sqrt{\widehat{m}_\nu} R^T \sqrt{M_R}\,. \tag{10}$$

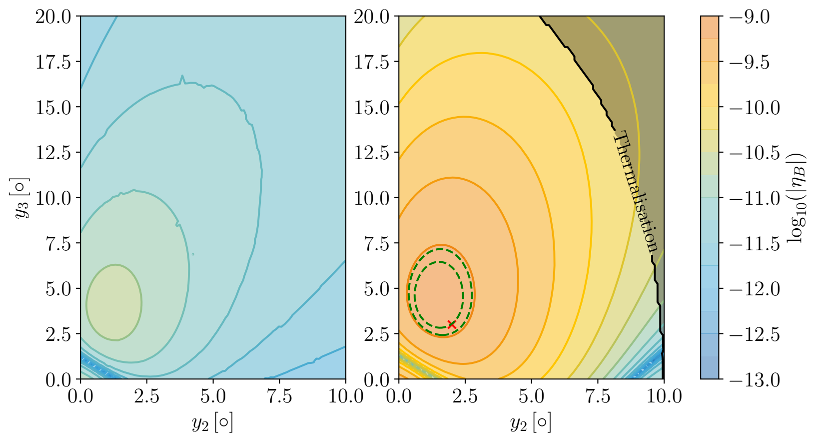
R is given by

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{11}$$

where the complex angle $\omega_i = x_i + iy_i$.

Scan of Casas-Ibarra parameters

We calculate η_B in vanilla leptogenesis and in hot leptogenesis for varying y_2 (x-axis) and y_3 (y-axis).



Benchmark fine-tuning comparison[4]

$$\Delta_\nu = \frac{\sum_{i=1}^{3} \mathrm{SVD}[M_\nu]_i}{\sum_{i=1}^{3} \mathrm{SVD}[M_\nu^{\text{1-loop}}]_i} , \tag{12}$$

$$|\delta\mu^2| \approx \frac{1}{4\pi^2} \mathrm{Tr}\left[Y M_N^2 Y^\dagger \right] . \tag{13}$$

$$\Delta_H = \sqrt{\frac{(\mu_H^{\text{tree}})^2 - |\delta\mu^2|}{\frac{1}{2}((\mu_H^{\text{tree}})^2 + |\delta\mu^2|)}} \approx \sqrt{\frac{\mu_H^2}{|\delta\mu^2|}} , \tag{14}$$

Benchmark	S_1	S_2	S_3	$\overline{S_1}$	$\overline{S_2}$	$\overline{S_3}$	Our Benchmark
Δ_ν [%]	0.2	0.3	0.2	0.6	0.7	0.4	855
Δ_H [%]	0.08	0.02	0.004	0.3	0.06	0.1	10.4

[4] [Moffat et al., 2018]

Conclusions

Hot leptogenesis is possible under two scenarios; a hot sector in kinetic equilibrium, or thermal equilibrium.

A hot RHN sector can resolve the tension between the Davidson-Ibarra bound and the Vissani bound.

> ***Thanks for listening!***
>
> Any questions?

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