Leptogenesis with low-energy CP-violation

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Low-energy CP-violation and leptogenesis

- Leptogenesis is a mechanism to explain the baryon asymmetry of the Universe (BAU) with theories of neutrino properties
- CP-violation is necessary (Sakharov)
- Type-I seesaw implementation allows CP-violation from: PMNS phases $(\delta, \alpha_{21}, \alpha_{31})$, R-matrix (Casas-Ibarra parametrisation)
- *When is the CP-violation from the PMNS matrix sufficient to produce the observed BAU?*
- We restrict ourselves to decays of heavy neutrinos in type-I seesaw in a nonresonant regime

$10^9 < M_1 \text{ (GeV)} < 10^{12}$

- Revisiting the scenario of [arXiv:hep-ph/0611338]
- We solve density matrix equations (generalisation of Boltzmann equations):

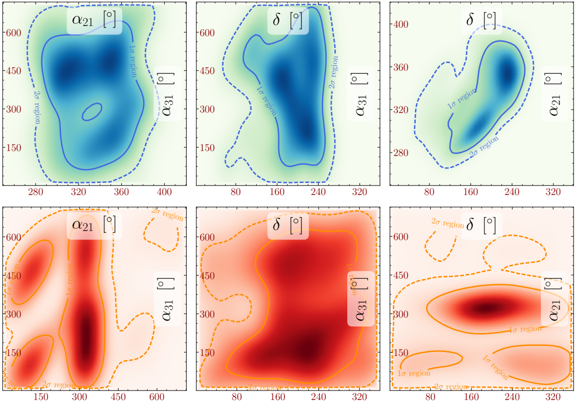
$$\frac{dn_{N_i}}{dz} = -\, D_i(n_{N_i} - n_{N_i}^{\rm eq})$$

$$\frac{dn_{\alpha\beta}}{dz} = \sum_i \left(\epsilon^{(i)}_{\alpha\beta} D_i (n_{N_i} - n^{\rm eq}_{N_i}) - \frac{1}{2} W_i \left\{ P^{0(i)}, n \right\}_{\alpha\beta} \right)$$

$$- \frac{\Im(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta}$$

$$- \frac{\Im(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta}$$

$10^9 < M_1\ (\mathrm{GeV}) < 10^{12}$



$M_1 = 10^{10}$ GeV
blue/green (NO)
red/orange (IO)

- Thorough exploration of the parameter space in models with 2 or 3 heavy Majorana neutrinos
- Dirac and Majorana phases (together or separately) are sufficient to produce the observed BAU

$M_1 \ll 10^9$ GeV

- At "intermediate" scales, for successful leptogenesis (thermal, nonresonant) consistent with data, we must fine-tune the light neutrino masses

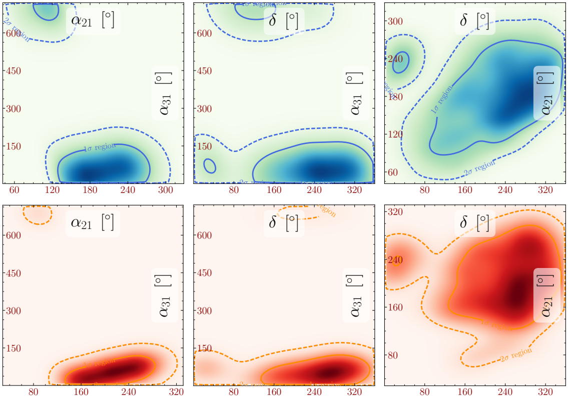
$$\frac{m^{\text{tree}}}{m^{\text{tree}} + m^{\text{1-loop}}} \gg 1 \tag{1}$$

- Imposes a structure on the R-matrix [arXiv:1804.05066 [hep-ph]]

$$R \approx \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ \pm i R_{22} & R_{22} & R_{23} \\ -R_{22} & \pm i R_{22} & \pm i R_{23} \end{pmatrix} \tag{2}$$

- Simple "real R" solutions are insufficient

$M_1 \ll 10^9$ GeV



$M_1 = 10^6$ GeV
blue/green (NO)
red/orange (IO)

- Light masses prefer to be larger (than in previous case) ~ 0.1 eV
- Dirac and Majorana phases individually may be sufficient for observed BAU

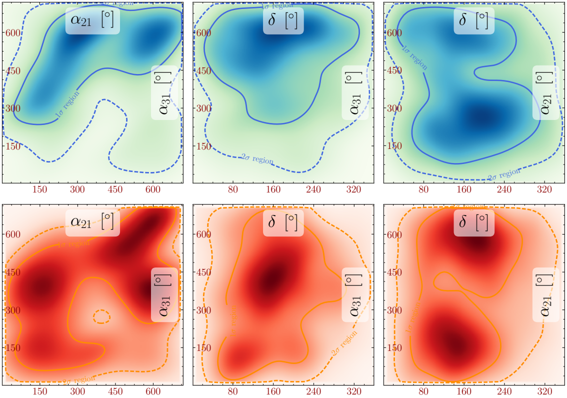
$M_1 \gg 10^{12}$ GeV

- Purely low energy CP-violation imposes $\mathrm{Tr}\epsilon^{(1)} = 0$

- Under these conditions flavour effects remain dominant well above $M_1 = 10^{12}$ GeV (where they usually become negligible)

- The relative dominance is sufficient to provide the baryon asymmetry of the Universe

$M_1 \gg 10^{12}$ GeV



$M_1 = 10^{13}$ GeV
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- Majorana phases individually may be sufficient for observed BAU
- Dirac phase is insufficient without also introducing $\mathcal{O}(100)$ fine-tuning

Summary

- Thermal nonresonant leptogenesis may be successful with purely PMNS phase CP-violation over a wide range of scales $10^6 < M_1$ (GeV) $< 10^{13}$
- Below 10^9 GeV requires significant fine-tuning in the masses