LEPTOGENESIS
(Some Recent Results)

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The origin of the matter-antimatter (or baryon) asymmetry of the Universe is still a fundamental and unresolved problem in Particle Physics and Cosmology, i.e., in Astroparticle Physics. Its solution requires physics beyond that predicted by the Standard Model.

Leptogenesis offers a particularly appealing solution as it relates the generation and smallness of neutrino masses to the generation of the baryon asymmetry of the Universe (BAU).

In its simple realisation a lepton charge CP violating asymmetry is generated in the Early Universe in the CP and lepton charge non-conserving decays of the heavy Majorana neutrinos $N_{1,2,3}$ of the (type I) seesaw mechanism of neutrino mass generation. This asymmetry is converted into a BAU by (B+L) violating but (B-L) conserving sphaleron processes which exist in the SM and are effective at $T \sim (140 - 10^{12})$ GeV. The generation of BAU takes place approximately at $T \sim M_1$, assuming $M_1 < M_2 < M_3$, M_i being the mass of N_i.

In K. Moffat et al., arXiv:1804.05066 (Phys. Rev. D98 (2018) 015036),

K. Moffat et al., arXiv:1809.08251 (JHEP 03 (2019) 034),

I. Brivio et al, arXiv:1905.12642

we have addressed the following three questions:

A. How low can be the scale of non-resonant leptogenesis (LG) in the general case (i.e., in the absence of further specific (symmetry) conditions or constraints on the spectrum of masses of $N_{1,2,3}$)?

B. How low/high can be the scale of non-resonant leptogenesis (LG) in the general case (no specific additional conditions on $M_{1,2,3}$) when the requisite CP violation in LG is provided exclusively by the CP violating Dirac or Majorana phases in the PMNS neutrino mixing matrix?

C. Is leptogenesis compatible with the Neutrino Option?

Baryon Asymmetry

$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.10 \pm 0.04) \times 10^{-10}$, **CMB**

P.A.R. Ade et al. (Planck Collab.), arXiv:1502.01589

A. The Davidson-Ibarra bound (hep-ph/0202239): successful LG possible for

$T \sim M_1 \gtrsim 10^9$ **GeV**

Assumed $M_1 \ll M_2 \ll M_3$; flavour effects not included.

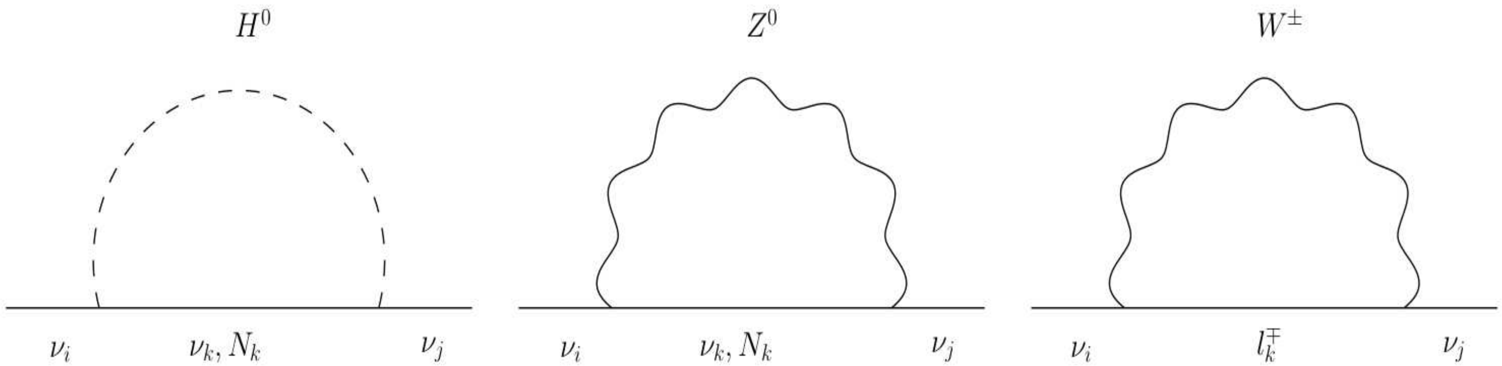
K. Moffat et al., arXiv:1804.05066

Successful LG possible for

$T \sim M_1 = 10^6$ **GeV**, $M_2 \cong 3M_1$, $M_3 \cong 3M_2$

Three-flavour LG; density matrix fromalism; 11-dim parameter space scanned (θ_{23}, δ, $\alpha_{21,31}$, m_1, 6 Casas-Ibarra matrix parameters)

Requires fine tuning; for $M_1 < 10^6$ GeV the fine tuning is "exceedingly" large.



$$m_\nu = m^{\textbf{tree}} + m^{\textbf{1-loop}}.$$

$$m^{\textbf{tree}} \approx m_D M^{-1} m_D^T\,, \quad m_D = vY\,,$$

$$m^{\textbf{1-loop}} = -\frac{1}{32\pi^2 v^2} m_D \, \textbf{diag}\left(g\left(M_1\right), g\left(M_2\right), g\left(M_3\right)\right) m_D^T,$$

$$g\left(M_i\right) \equiv M_i \left(\frac{\log\left(\frac{M_i^2}{m_H^2}\right)}{\frac{M_i^2}{m_H^2} - 1} + 3\frac{\log\left(\frac{M_i^2}{m_Z^2}\right)}{\frac{M_i^2}{m_Z^2} - 1} \right)$$

	$\theta_{23}(^\circ)$	$\delta(^\circ)$	$\alpha_{21}(^\circ)$	$\alpha_{31}(^\circ)$	$x_1(^\circ)$	$y_1(^\circ)$	$x_2(^\circ)$	$y_2(^\circ)$	$x_3(^\circ)$	$y_3(^\circ)$	$m_{1(3)}$ (eV)	M_1 (GeV)	M_2 (GeV)	M_3(GeV)
S_1	46.24	281.21	181.90	344.71	132.23	179.88	87.81	2.88	−30.25	177.5	0.120	$10^{6.0}$	$10^{6.5}$	$10^{7.0}$
S_2	46.57	88.26	116.07	420.44	44.36	171.78	86.94	2.96	97.01	174.30	0.079	$10^{6.5}$	10^{7}	$10^{7.5}$
S_3	46.63	31.71	130.95	649.65	−72.33	170.54	86.96	2.22	−1.86	178.31	0.114	$10^{6.5}$	$10^{7.2}$	$10^{7.9}$
$\overline{S_1}$	40.56	158.51	157.48	511.0	−16.23	179.29	90.04	1.29	−107.14	179.22	0.0047	$10^{6.0}$	$10^{6.5}$	$10^{7.0}$
$\overline{S_2}$	43.67	201.02	238.77	658.33	−39.88	178.68	88.12	2.46	53.97	158.01	0.0133	$10^{6.5}$	$10^{7.0}$	$10^{7.5}$
$\overline{S_3}$	43.64	57.28	179.87	292.95	86.58	174.40	91.11	1.61	134.48	173.74	0.012	$10^{6.5}$	$10^{7.2}$	$10^{7.9}$
$F.T^{\rm loop}$	44.59	140.04	537.15	291.89	164.06	−149.85	178.99	49.15	93.39	−14.50	0.15882	$10^{9.0}$	$10^{9.5}$	10^{10}
$F.T^{\rm tree}$	43.81	31.59	681.96	276.19	271.56	−125.27	14.95	−11.50	344.87	5.22	0.0041	$10^{9.0}$	$10^{9.5}$	10^{10}

The best-fit points for the leptogenesis scenarios are given and are all consistent with $\eta_B = (6.10 \pm 0.04) \times 10^{-10}$, $\theta_{13} = 8.52^\circ$ and $\theta_{12} = 33.63^\circ$. The upper (lower) three rows are the best-fit points for normal (inverted) ordering. The final two rows are the best fit points for normal ordering in the loop and tree-level dominated scenarios.

$Y_\nu \equiv \lambda = \sqrt{D_N}\; R\; \sqrt{D_\nu}\; (U_{\rm PMNS})^\dagger / v$, **all at** M_R;
R-**complex,** $R^T R = 1$.

J.A. Casas and A. Ibarra, 2001

$D_N \equiv {\rm diag}(M_1, M_2, M_3)$, $D_\nu \equiv {\rm diag}(m_1, m_2, m_3)$.

$R-$**matrix parameters:** $R = R_{23}(\omega_1)\, R_{13}(\omega_2)\, R_{12}(\omega_3)$
$\omega_j = x_j + i y_j$, $\omega_1 = \omega_{23}$, $\omega_2 = \omega_{13}$, $\omega_3 = \omega_{12}$.

B. How low/high can be the scale of non-resonant leptogenesis (LG) in the general case (no specific additional conditions on $M_{1,2,3}$) when the requisite CP violation in LG is provided exclusively by the CP violating Dirac (δ) or Majorana ($\alpha_{21,31}$) phases in the PMNS neutrino mixing matrix?

2006: N_1, N_2, $M_1 \ll M_2$, **2-flavour LG,** $M_1 \lesssim 5 \times 10^{11}$ **GeV, Dirac CPV, CP conserving Casas-Ibarra matrix** R,

$$|\sin\theta_{13}\sin\delta| \gtrsim 0.09$$

S. Pascoli, STP, A. Riotto hep-ph/0611338

K. Moffat et al., arXiv:1809.08251 (JHEP 03 (2019) 034)

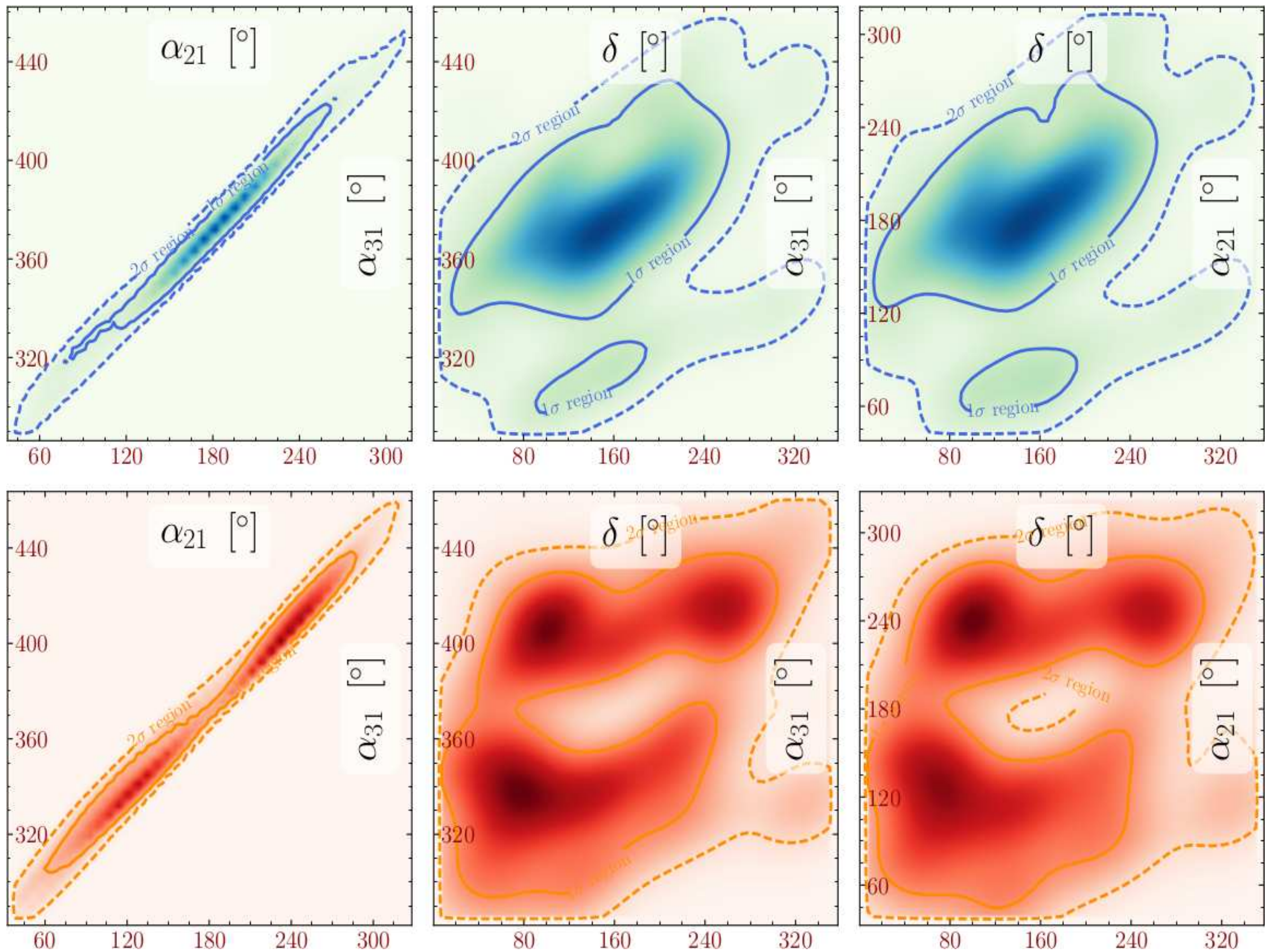
2018: N_1, N_2, N_3, $M_1 < M_2 < M_3$, **3-flavour and 2-flavour regimes investigated, assumed CP conserving** R**-matrix (= real or purely imaginary elements).**

Confirmed the 2006 PPR result.

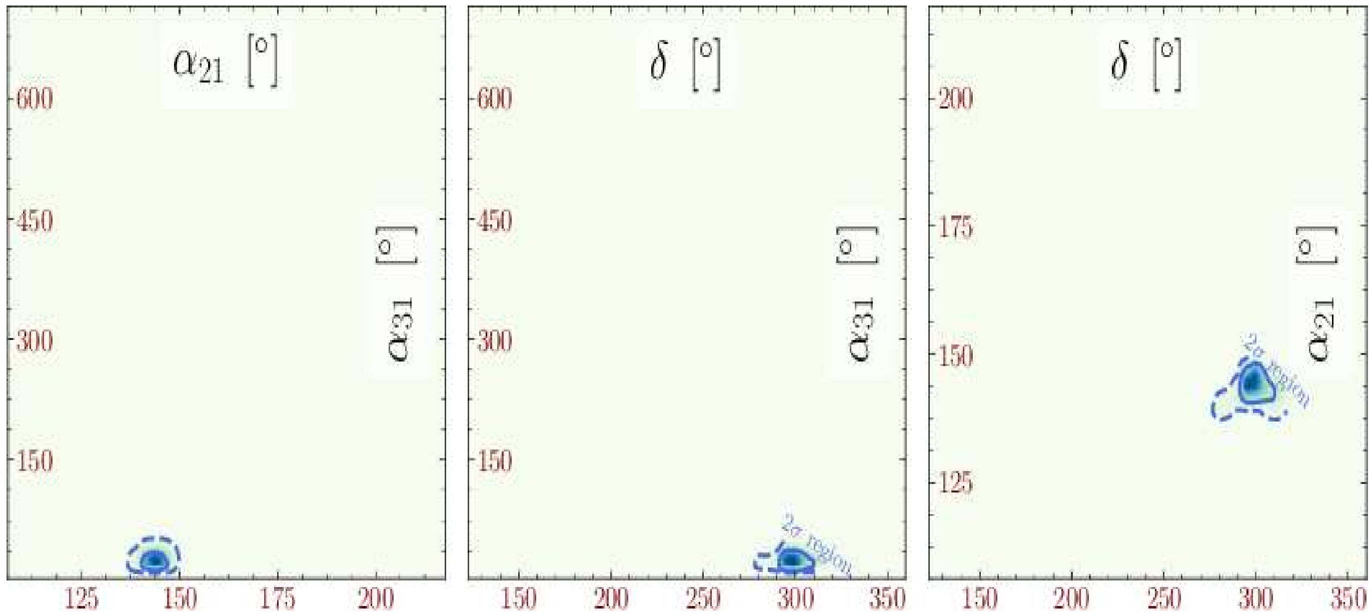
Thermal LG viable for $10^6 \lesssim T \cong M_1 \lesssim 10^{13}$ **GeV.**

At $T \cong M_1 \sim 10^6$ **GeV, "fine tuning" of the light neutrino masses necessary (as discussed in A.).**

Results presented for $M_1 < 10^9$ **GeV:**
$M_1 = 3.16 \times 10^6,\ 1.29 \times 10^8,\ 7 \times 10^8$ **GeV,**
$M_2 = 3.5 M_1$, $M_3 = 3.5 M_2$;
$x_1 = y_2 = 0$, $y_1 = y_3 = x_3 = 180^\circ$, $\cos x_2 = 0$
($R-$**matrix parameters:** $\omega_j = x_j + i y_j$, $\omega_1 = \omega_{23}$, $\omega_2 = \omega_{13}$, $\omega_3 = \omega_{12}$**).**



$M_1 = 1.29 \times 10^8$ **GeV.**



$M_1 = 3.16 \times 10^6$ **GeV,** $m_1 = 0.05$ **eV.**

Results presented also for $10^9 < M_1 < 10^{12}$ **GeV,** $9M_1 < 3M_2 < M_3$**,**

$m_1 = 0.0215$ **eV;** $x_1 = 90^\circ$, $x_3 = 180^\circ$, $y_2 = 0$, **chosen so that CP symmetry holds for** $\delta = 0$, $\alpha_{21} = 180^\circ$ **and** $\alpha_{21} = 0$ **(**$y_1 = y_3 = -33^\circ$, $x_2 = 18^\circ$**).**

i) Dirac CPV due to δ**;** $\alpha_{21} = 180^\circ$, $\alpha_{21} = 0^\circ$**.**

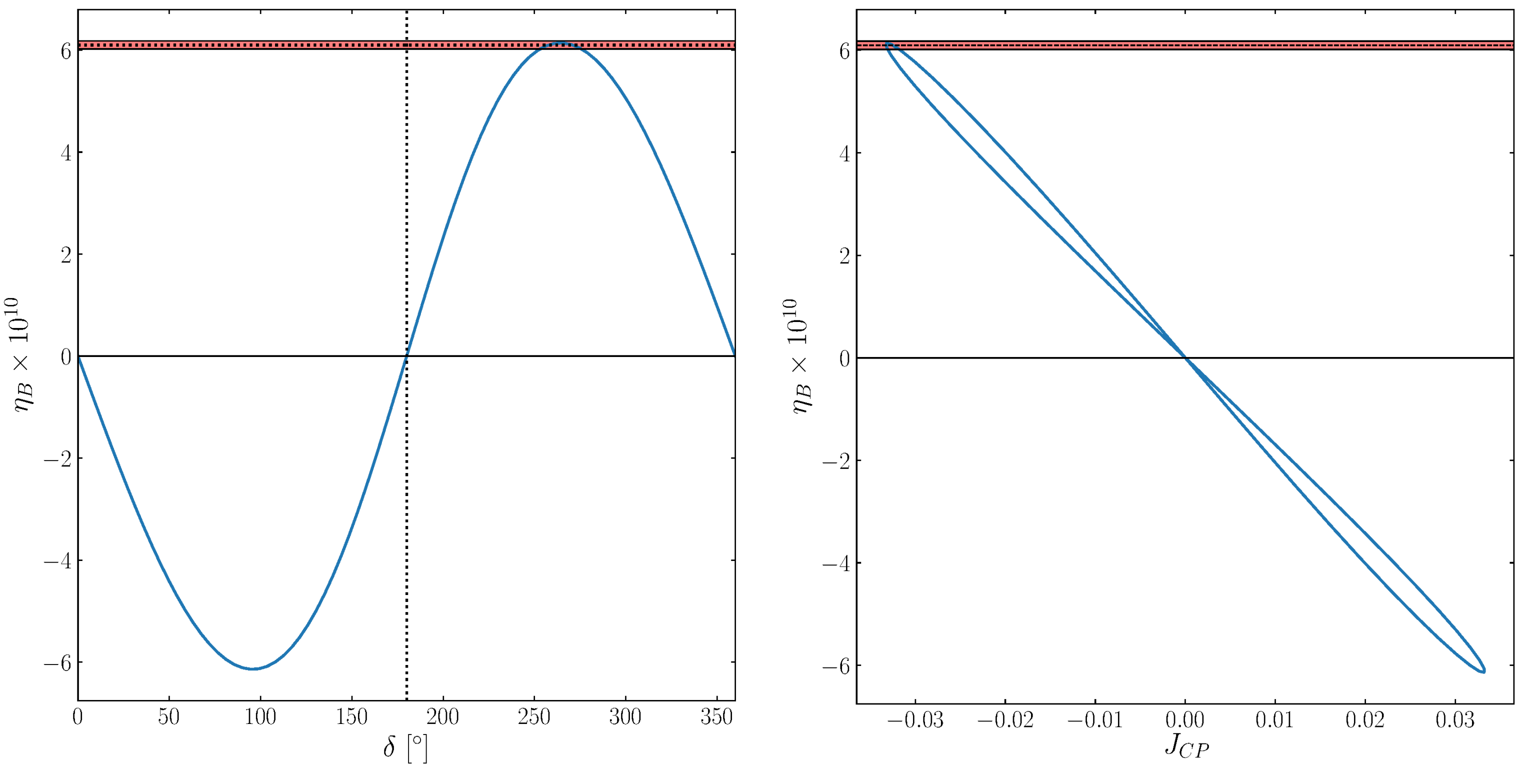
$\min(M_1) = 5.13 \times 10^{10}$ **GeV,** $M_2 = 2.19 \times 10^{12}$ **Gev,** $M_3 = 1.0110^{13}$ **GeV.**

ii) Majorana CPV due to α_{21}**:** $\delta = \alpha_{21} = 0^\circ$**.**

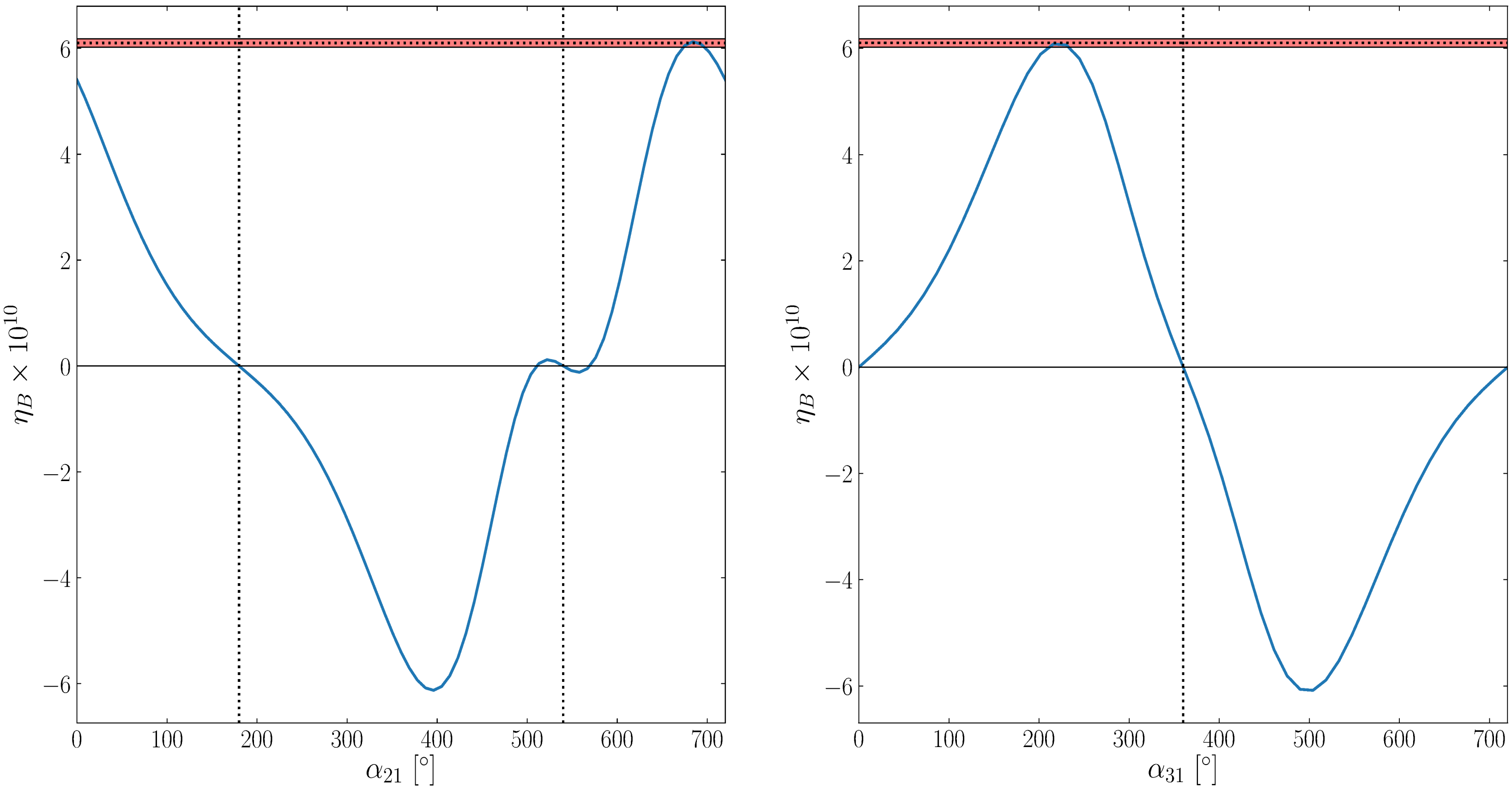
$\min(M_1) = 3.05 \times 10^{10}$ **GeV,** $M_2 = 10^{13}$ **Gev,** $M_3 = 3 \times 10^{13}$ **GeV.**

iii) Majorana CPV due to α_{31}**:** $\delta = 0$, $\alpha_{21} = 180^\circ$**.**

$\min(M_1) = 5.13 \times 10^{10}$ **GeV,** $M_2 = 10^{13}$ **Gev,** $M_3 = 3 \times 10^{13}$ **GeV.**



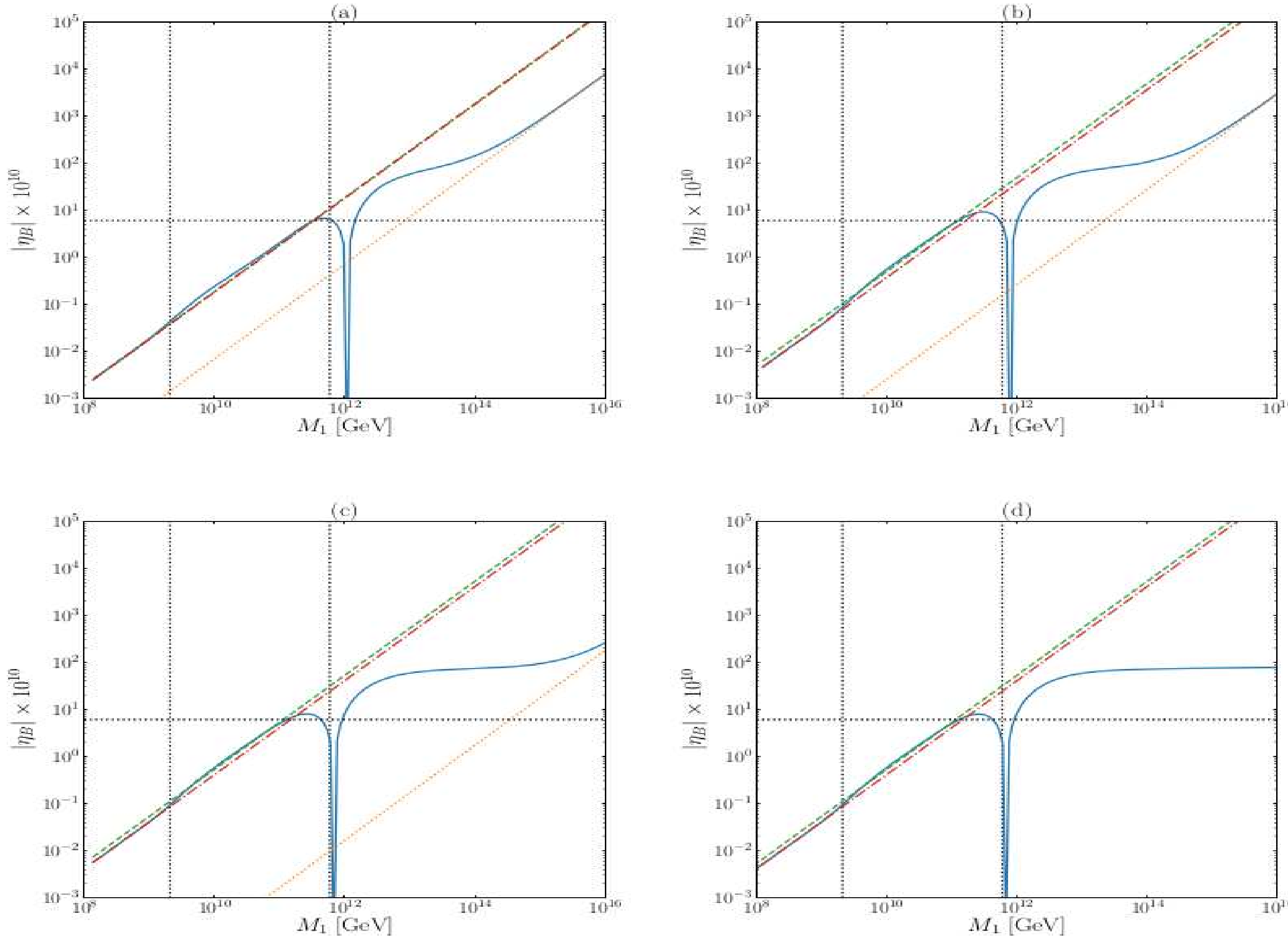
$\min(M_1) = 5.13 \times 10^{10}$ **GeV**, $M_2 = 2.19 \times 10^{12}$ **Gev**, $M_3 = 1.01 \times 10^{13}$ **GeV.**



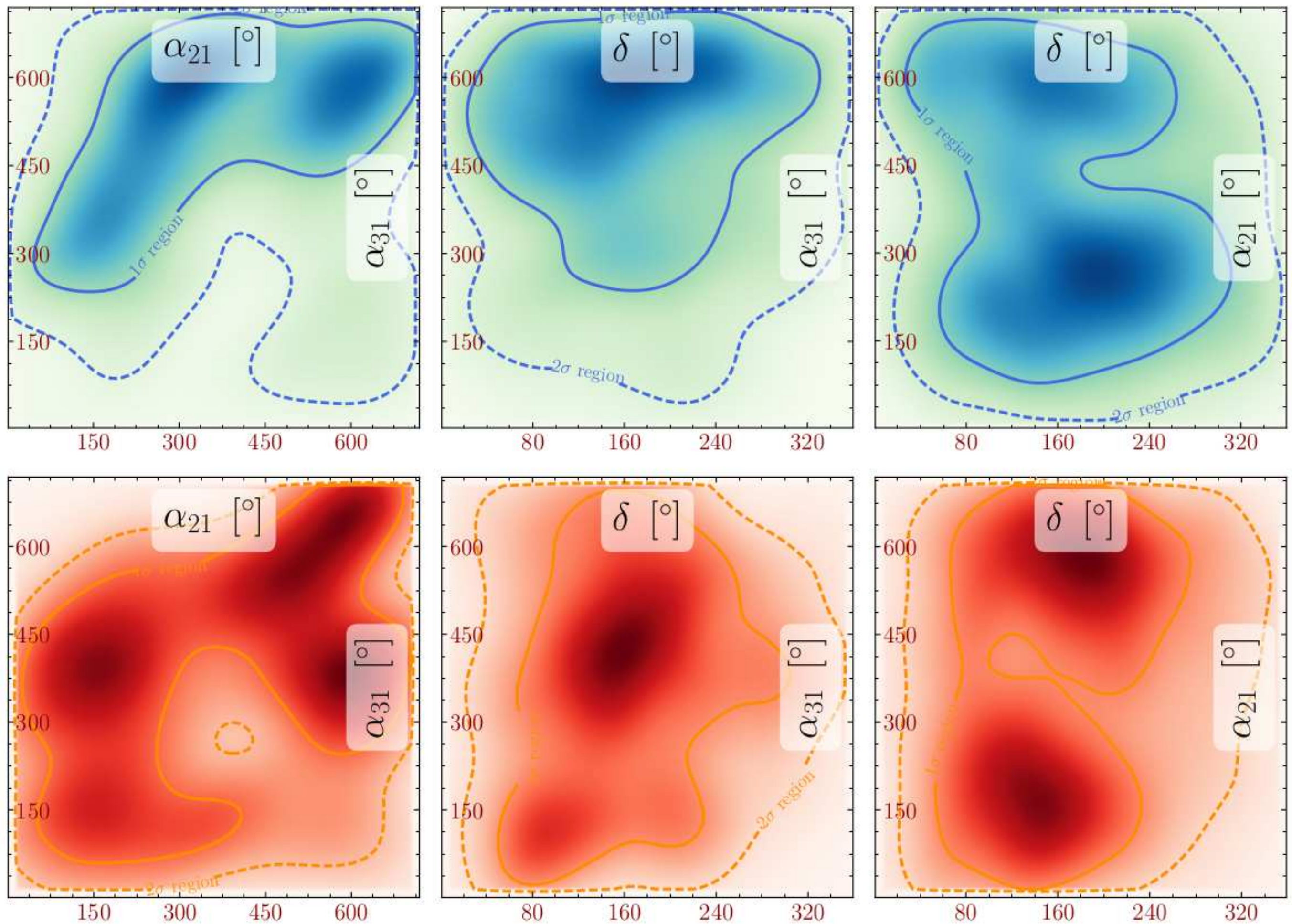
α_{21}: min(M_1) = 3.05×10^{10} **GeV**, $M_2 = 10^{13}$ **Gev**, $M_3 = 3 \times 10^{13}$ **GeV.**

α_{31}: min(M_1) = 5.13×10^{10} **GeV**, $M_2 = 10^{13}$ **Gev**, $M_3 = 3 \times 10^{13}$ **GeV.**

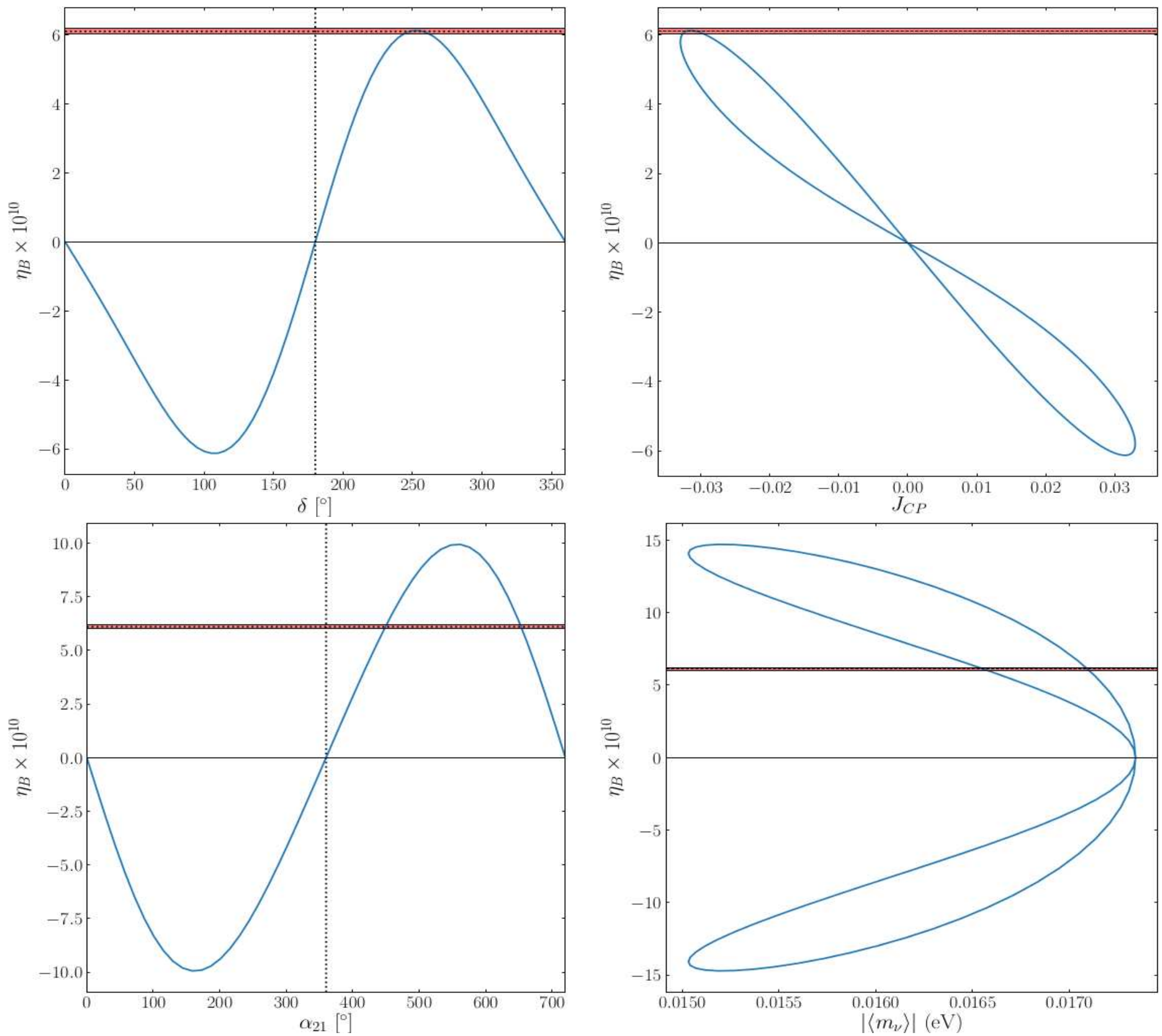
High Scale Transition



LG from M_1: dashed green - 2-flavour BE; red dot-dashed - 3-flavour BE; dotted orange - single flavour BE; solid blue - solution of density matrix equation. y_3 - the only CPV $R-$ matrix parameter: $y_3 = 30^\circ$ (a), 5° (b), 0.3° (c), 0° (d). The vertical dotted lines: $M_1 = 10^9$ and 10^{12} GeV. Case d: CPV only from δ, α_{21}, α_{31}.



CP conserving $R-$ matrix ($y_j = 0$), CPV provided by δ, α_{21} and α_{31}: $M_1 = 10^{13}$ GeV, $M_1 \ll M_2 \ll M_3$; $m_1 = 0.0159$ eV, NO; $x_1 = -96.55^\circ$, $x_2 = -105.2^\circ$ $x_3 = 141.4^\circ$.



$M_1 = 3.16 \times 10^{13}$ **GeV, CP conserving** $R-$**matrix.**

δ**:** $\alpha_{21} = \alpha_{31} = 0$**, successful LG for** $\delta \cong 250°$**, for which** $J_{CP} \cong -0.03$**.**

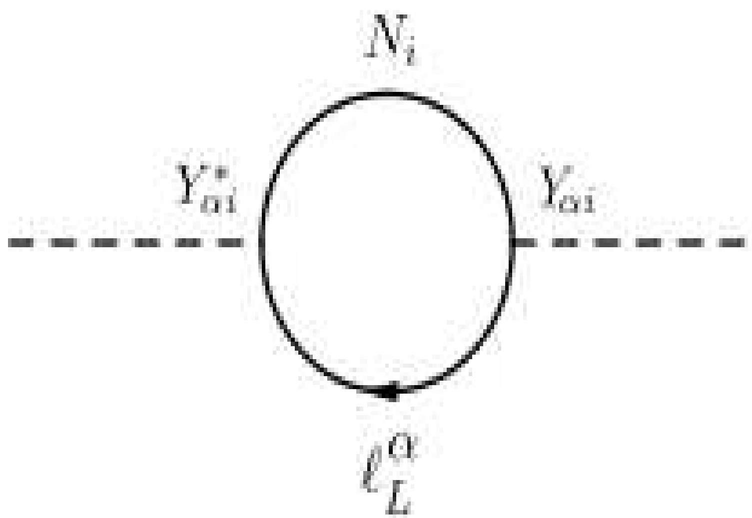
α_{21}**:** δ**=**α_{31}**=0, successful LG for** α_{21}**=449°, 653°, for which** $|<m>|$ **=0.0171, 0.0166 eV.**

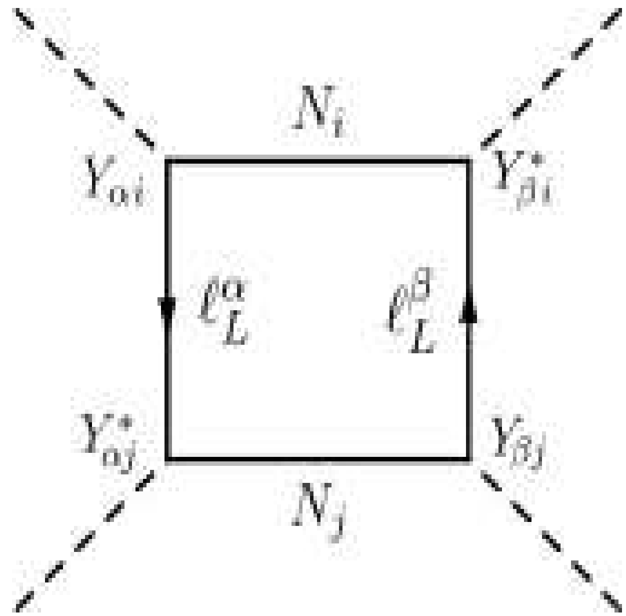
I. Brivio et al, arXiv:1905.12642

C. Is leptogenesis compatible with the Neutrino Option?

The Neutrino Option

$$V_0(\Phi) = -\frac{M_{H0}^2}{2}\Phi^\dagger\Phi + \lambda_0(\Phi^\dagger\Phi)^2,$$





I. Brivio and M. Trott, 2017 (arXiv:1703.10924

$$\Delta M_H^2 = \frac{1}{8\pi^2} \textbf{Tr} \left[Y M^2 Y^\dagger \right].$$

Our analysis:

M_{H0}^2 generated at one loop, λ_0-present in $V_0(\Phi)$.

Successful LG possible in the resonant regime.

The case of 2 heavy Majorana N_j considered:
$N_{1,2}$, $N_{1,2}$ form a pseudo-Dirac pair, $M_2 - M_1 \ll M_{1,2}$.

$$M_{H0}^2 = \Delta M_H^2 = \frac{1}{8\pi^2 v^2} \cosh(2y) M^3 (m_1 + m_2 + m_3),$$

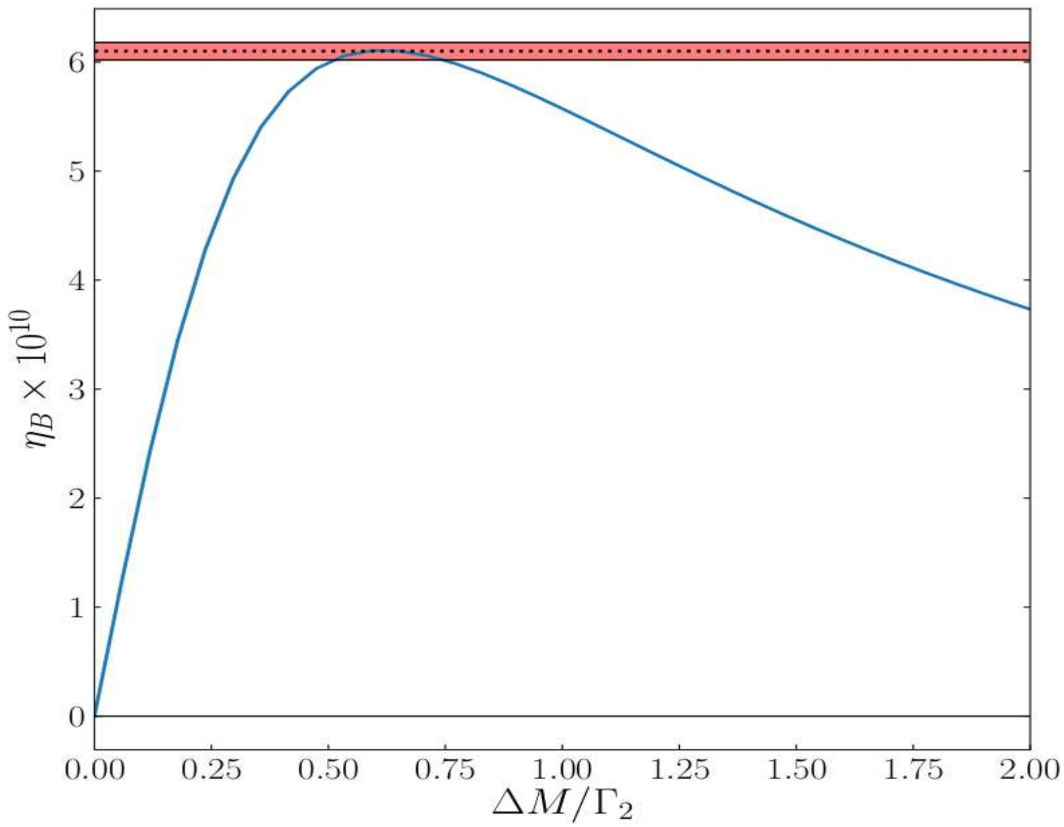
R: $R_{12} = \cos\theta$, $R_{13} = \sin\theta$, $R_{22} = -\sin\theta$, $R_{23} = \cos\theta$,
NO spectrum, $\theta = x + iy$.

The Neutrino Option and successful LG are compatible in the case of a NO (IO) neutrino mass spectrum for

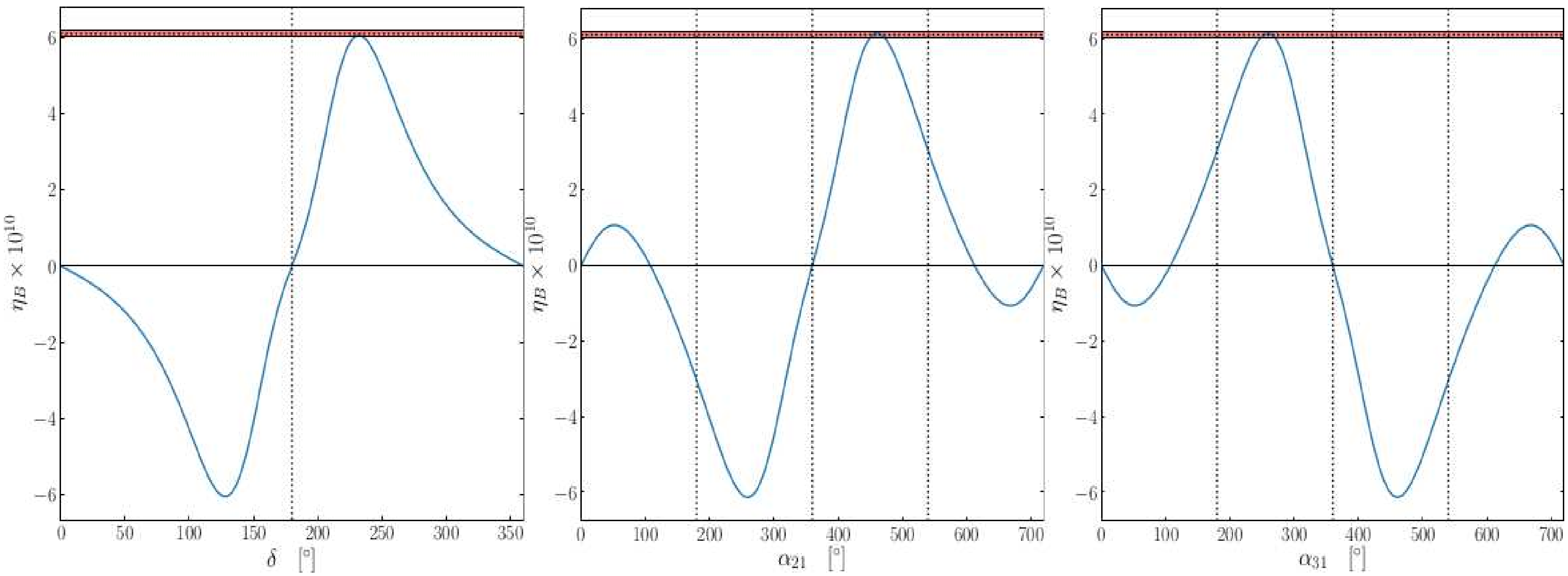
$1.2 \times 10^6 < M$ **(GeV)** $< 8.8 \times 10^6$
($2.4 \times 10^6 < M$ **(GeV)** $< 7.4 \times 10^6$**),** $M = (M_1 + M_2)/2$**.**

Successful leptogenesis requires that $\Delta M/M \equiv (M_2 - M_1)/M \sim 10^{-8}$**.**

LG can produce the BAU within the Neutrino Option scenario when the requisite CP violation in LG is provided exclusively by the Dirac or Majorana low energy CPV phases of the PMNS matrix.



$\Gamma_2 = 1.62 \times 10^{-2}$ (8.63×10^{-3}) **GeV for NO (IO) spectrum.**



$M = 8 \times 10^6$ **GeV**

Conclusions.

The see-saw mechanism provides a link between the ν-mass generation and the baryon asymmetry of the Universe (BAU).

Any of the CPV phases in $U_{\rm PMNS}$ can be the leptogenesis CPV parameters.

Low energy leptonic CPV can be directly related to the existence of BAU.

Understanding the status of the CP-symmetry in the lepton sector is of fundamental importance.

These results underline further the importance of the experimental studies for Dirac and/or Majorana leptonic CP-violation at low energies.