BAM

Barolo Astroparticle Meeting

Aspects of High Scale Leptogenesis with Low-Energy Leptonic CP Violation

A. G., K. Moffat and S. T. Petcov, arXiv:2107.02079

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SISSA

Motivations

- **Neutrino Masses and Mixing:** $\nu_{\alpha L}(x) = \sum_{a=1}^{3} U_{\alpha a}\nu_{aL}(x)$.
- **Baryon Asymmetry of the Universe (BAU):** $\eta_B \equiv (n_B - n_{\bar{B}})/n_\gamma \cong 6.1 \times 10^{-10}$.

Framework

- **Type-I seesaw model (with $n \geq 2$ heavy neutrinos N_i):** $\mathcal{L}_{\mathrm{Y,M}}(x) = -\left(Y_{\alpha i}\overline{\psi_{\alpha L}}(x)\, i\tau_2\, \Phi^*(x)\, N_{iR}(x) + \mathrm{h.c.}\right) - \frac{1}{2} M_i\, \overline{N_i}(x)\, N_i(x)$.
  - Light neutrino mass generation: $m_\nu \approx -\frac{v^2}{2} Y M^{-1} Y^T$;
  - Casas-Ibarra parametrisation: $\boxed{Y_{\alpha j} = \pm i \frac{\sqrt{2}}{v} U_{\alpha a}\sqrt{m_a} R_{ja}\sqrt{M_j}}$

    R: 3x3 complex orthogonal matrix parametrised by $\theta_{1,2,3} = x_{1,2,3} + iy_{1,2,3}$, or just $\theta = x + iy$ for $m_1 \simeq 0$ (NH) or $m_3 \simeq 0$ (IH).
- **Leptogenesis (LG):** lepton asymmetry generation via out-of-equilibirum, L-, C- and CP- violating N_i decays and inverse decays in the early Universe. The lepton asymmetry is converted into the BAU by the SM sphalerons ($T \gtrsim 131.7$ GeV).

Low-energy CP violation ($\not{C}\not{P}$): the only sources of CP violation being Dirac phase δ and/or the Majorana phases α_{21} and/or α_{31} of the PMNS matrix U (CP-conserving R-matrix, i.e. $y = 0$ or $x = 0, \pi, \ldots$).

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The effects of lepton flavours in LG

$N_i \to \Phi\psi_i$, $\psi_i = \sum_{\alpha=e,\mu,\tau} C_{i\alpha}\psi_\alpha$: coherent superpositions of lepton flavours.

Decoherence effects: the SM τ- and μ-Yukawa interactions (Γ_τ, Γ_μ) destroy the coherence making flavours distinguishable.

- **Single-flavour regime:** $T \gg 10^{12}$ GeV ($\Gamma_{\tau,\mu} \ll H$).
  - Flavours indistinguishable.
  - *Single-flavour approx.:* neglect τ- and μ-Yukawas and *Single-flavoured Boltzmann Equations* (BE1F).
- **Two-flavour regime:** $10^9 \lesssim T/\text{GeV} \lesssim 10^{12}$ ($\Gamma_\tau \gg H$ and $\Gamma_\mu \ll H$).
  - The τ-flavour is distinguishable from the other two.
  - *Two-flavour approx.:* neglect the μ-Yukawa interactions.
  - *Two-flavoured Boltzmann Equations* (BE2F) if τ-Yukawa fast enough.
- **Three-flavour regime:** $T \ll 10^9$ GeV ($\Gamma_{\tau,\mu} \gg H$).
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  - *Three-flavoured Boltzmann Equations* (BE3F) if τ- and μ-Yukawas fast enough.

Density Matrix Equations (DMEs)

The **DMEs** account for quantum decoherence processes due to SM Yukawas.

- Valid also in the intermediate regimes.
- They reproduce the BEs.

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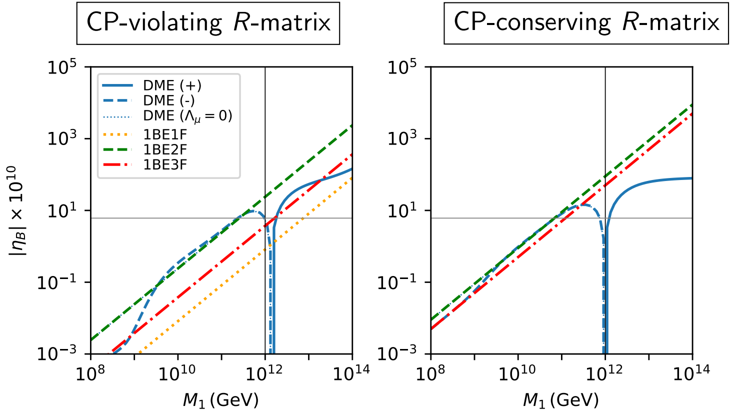
LG for $10^8 \lesssim M_1/\text{GeV} \lesssim 10^{14}$ and $M_1 \ll M_2 \ll M_3$ solving BE1F, BE2F, BE3F and DMEs with ULYSSES Python package (A.G., K. Moffat, Y. Perez-Gonzalez, H. Schulz, J. Turner, *Computer Physics Communication* **262** (2021) 107813, [2007.09150]).

General features



Vanishing Initial Abundance ($N_{N_1}(z_i) = 0$), "standard" behaviour of η_B

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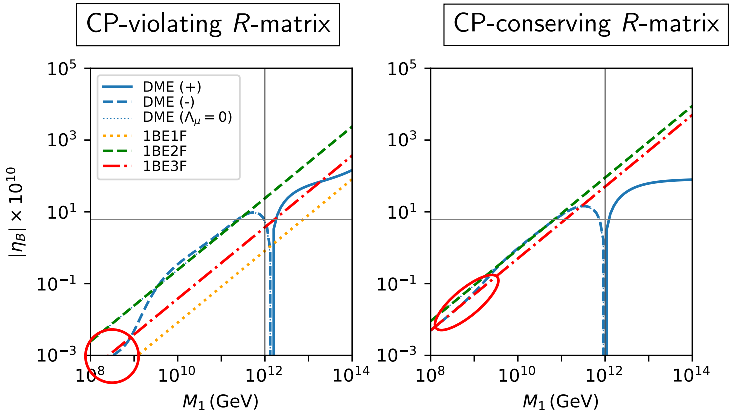

$$\eta_B^{\text{DME}} = \eta_B^{\text{BE3F}}$$

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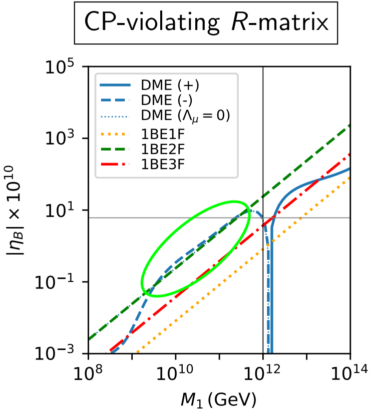

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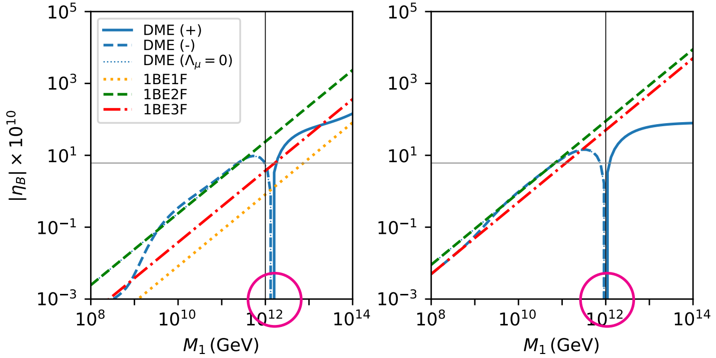
CP-violating R-matrix

CP-conserving R-matrix



1-to-2-flavour transition

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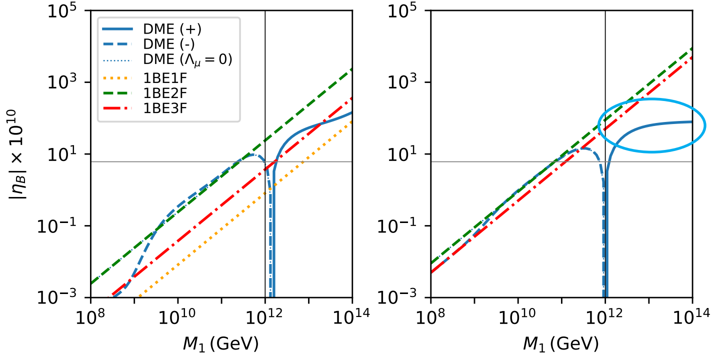

Pleateau region due to τ-decoherence effects

High-Scale LG with Low-Energy Leptonic $\not{CP}$

Sign Change

$$\eta_{B-L}(z_f) \propto \Lambda_\tau \mathcal{I}_2(\kappa_1; z_f)\epsilon^{(1)}_{\tau\tau}(p_{1\tau^\perp} - p_{1\tau}) + \mathcal{O}(\Lambda_\tau^2), \text{ with } \Lambda_\tau \equiv \Gamma_\tau/Hz.$$

Strong wash-out regime ($\Gamma_N \gg H$ at $z = 1$)

Vanishing Initial Abundance	**Thermal Initial Abundance**
$\eta^{1BE2F}_{B-L}(z_f) \propto \epsilon^{(1)}_{\tau\tau}(p_{1\tau^\perp} - p_{1\tau})$	$\eta^{1BE2F}_{B-L}(z_f) \propto \epsilon^{(1)}_{\tau\tau}(p_{1\tau^\perp} - p_{1\tau})$
$\mathcal{I}_2(\kappa_1; zf) < 0$	$\mathcal{I}_2(\kappa_1; zf) > 0$
Sign change: ✓	*Sign change:* ✗

Weak wash-out regime ($\Gamma_N \ll H$ at $z = 1$)

Vanishing Initial Abundance	**Thermal Initial Abundance**
$\eta^{1BE2F}_{B-L} \propto -\epsilon^{(1)}_{\tau\tau}(p_{1\tau^\perp} - p_{1\tau})$	$\eta^{1BE2F}_{B-L} \propto \epsilon^{(1)}_{\tau\tau}(p_{1\tau^\perp} - p_{1\tau})$
$\mathcal{I}_2(\kappa_1; zf) < 0$	$\mathcal{I}_2(\kappa_1; zf) > 0$
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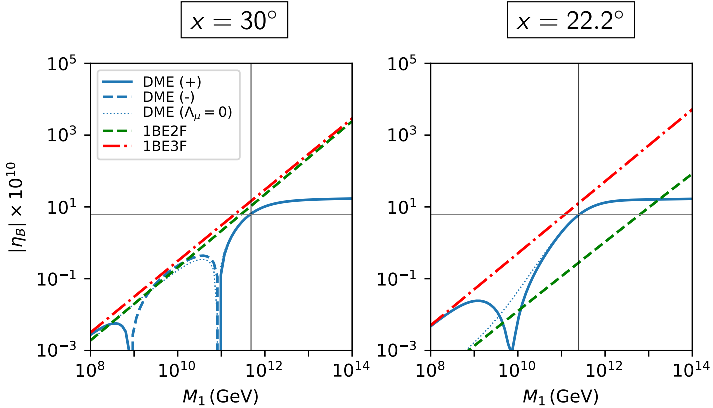
High-Scale LG with Low-Energy Leptonic $\not{C}\!\not{P}$

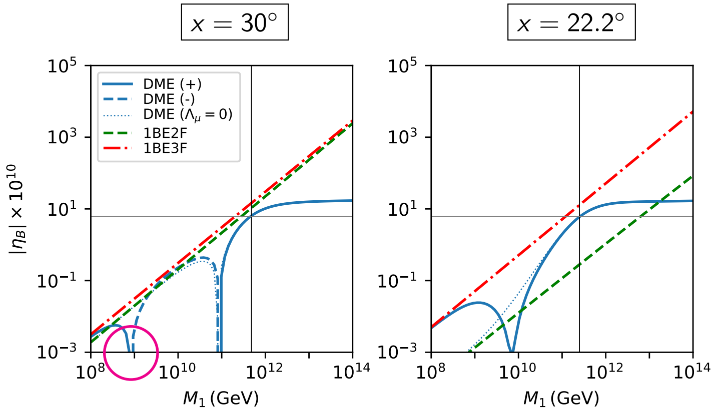
The case of decoupled N_3 — $\not{C}\!\not{P}$ from Dirac phase ($\delta = 3\pi/2$, $\alpha_{21} = \alpha_{31} = 0$), NH spectrum, real R-matrix ($y = 0$)



"Non-standard" behaviour of η_B

High-Scale LG with Low-Energy Leptonic $\not{CP}$

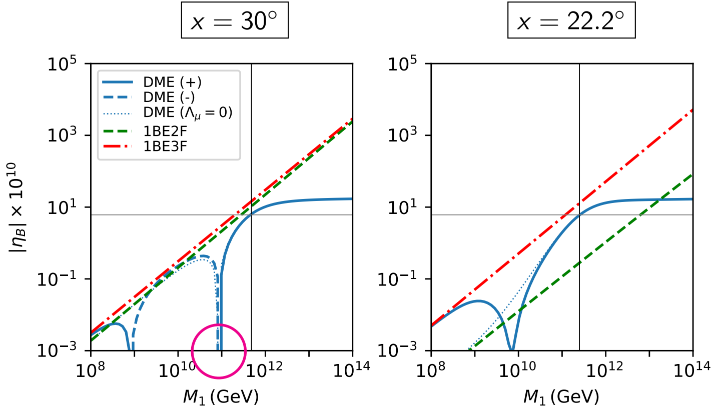
The case of decoupled N_3 — $\not{CP}$ from Dirac phase ($\delta = 3\pi/2$, $\alpha_{21} = \alpha_{31} = 0$), NH spectrum, real R-matrix ($y = 0$)



2-to-3-flavour transition with sign change

High-Scale LG with Low-Energy Leptonic $\not{CP}$

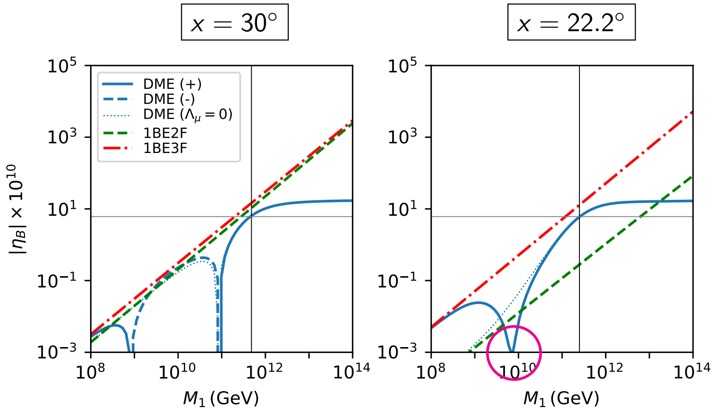
The case of decoupled N_3 — $\not{CP}$ from Dirac phase ($\delta = 3\pi/2$, $\alpha_{21} = \alpha_{31} = 0$), NH spectrum, real R-matrix ($y = 0$)



1-to-2-flavour transition at $M_1 \ll 10^{12}$ GeV

High-Scale LG with Low-Energy Leptonic $\not{CP}$

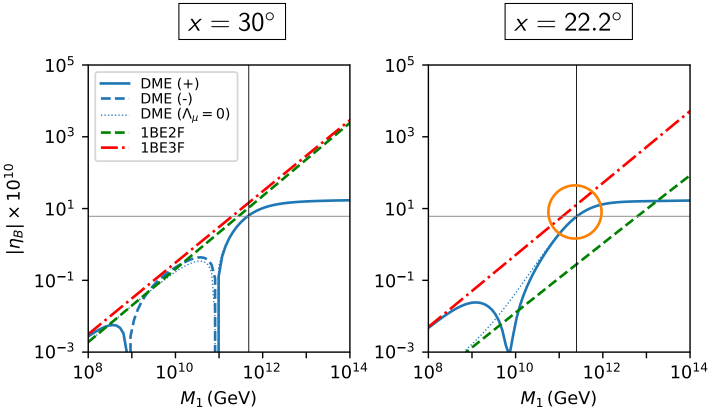
The case of decoupled N_3 — $\not{CP}$ from Dirac phase ($\delta = 3\pi/2$, $\alpha_{21} = \alpha_{31} = 0$), NH spectrum, real R-matrix ($y = 0$)



Overlap of the transitions at $M \ll 10^{12}$ GeV

High-Scale LG with Low-Energy Leptonic $\not{C}\not{P}$

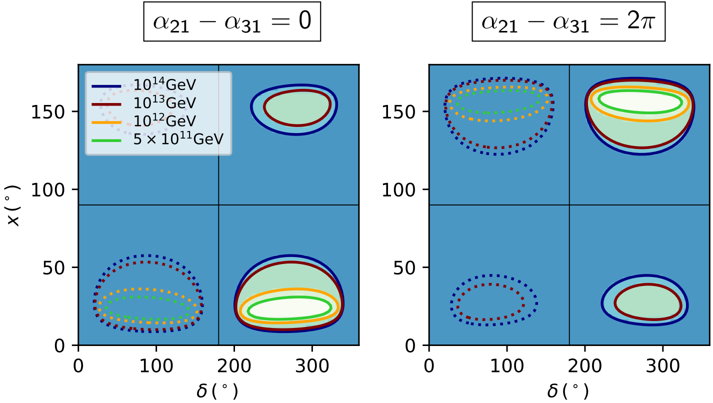
The case of decoupled N_3 — $\not{C}\not{P}$ from Dirac phase ($\delta = 3\pi/2$, $\alpha_{21} = \alpha_{31} = 0$), NH spectrum, real R-matrix ($y = 0$)



Successful LG at $M_1 \simeq 2.55 \times 10^{11}$ GeV, $\mathcal{O}(10)$ enhancement.

High-Scale LG with Low-Energy Leptonic $\not{CP}$

The case of decoupled N_3 — $\not{CP}$ from Dirac phase, NH spectrum, real R-matrix ($y = 0$)

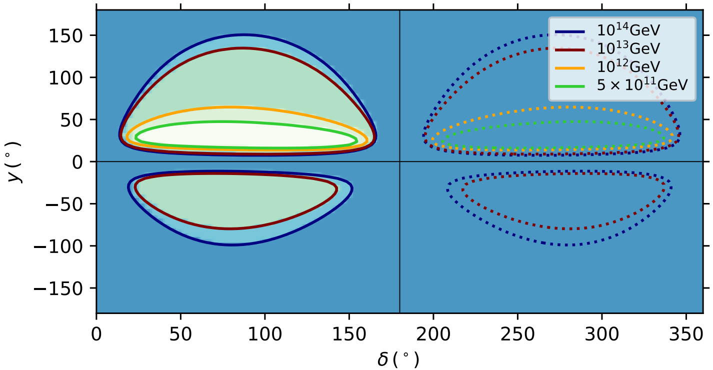


Regions of successful LG: viable only if $\delta \in (\pi, 2\pi)$

Minimal mass scale $M_1 \simeq 2.55 \times 10^{11}$ GeV,

High-Scale LG with Low-Energy Leptonic $\not{CP}$

The case of decoupled N_3 — NH spectrum, $\not{CP}$ from Dirac phase ($\alpha_{21} - \alpha_{31} = \pi$), purely imaginary $R_{11}R_{12}$ ($R_{12}R_{13}$) ($x = 0, \pi, \ldots$)

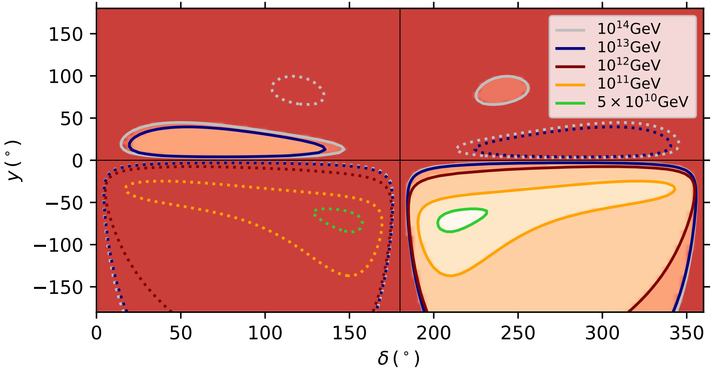


For NH, LG is viable only if $\delta \in (0, \pi)$

Minimal mass scale for viable LG: $M_1 \simeq 1.7 \times 10^{11}$ GeV,

High-Scale LG with Low-Energy Leptonic $\not{CP}$

The case of decoupled N_3 — IH spectrum, $\not{CP}$ from Dirac phase ($\alpha_{21} = \pi$), purely imaginary $R_{11}R_{12}$ ($R_{12}R_{13}$) ($x = 0, \pi, \ldots$)

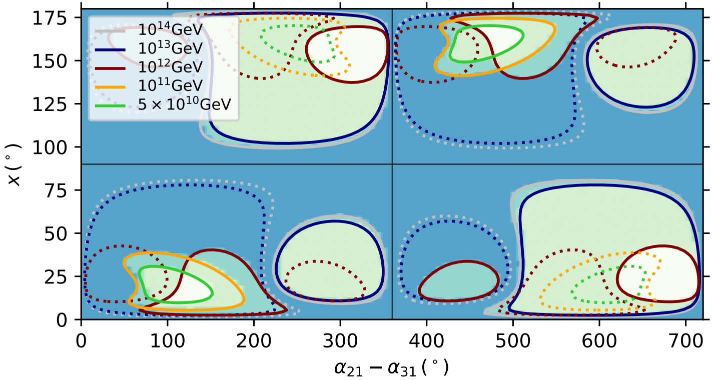


For IH, LG is viable for $\delta \in (0, \pi)$ only if $M \gtrsim 10^{13}$ GeV.

Otherwise, LG is viable only for $\delta \in (\pi, 2\pi)$ and $M_1 \gtrsim 4.6 \times 10^{10}$ GeV.

High-Scale LG with Low-Energy Leptonic $\not{CP}$

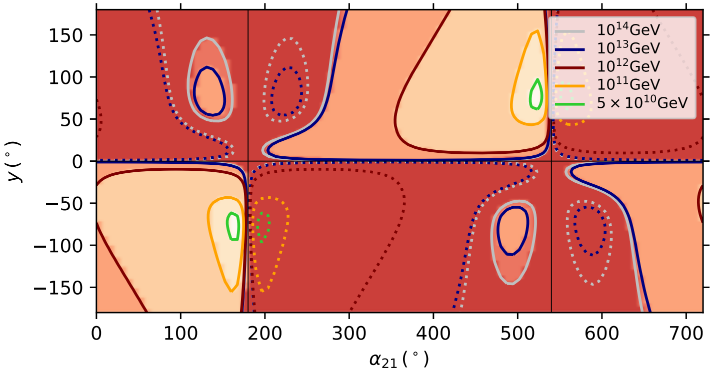
The case of decoupled N_3 — NH spectrum, $\not{CP}$ from Majorana phases ($\delta = \pi$), Real R ($x = 0, \pi, \dots$)



Minimal mass scale for viable LG: $M_1 \simeq 3.3 \times 10^{10}$ GeV,

High-Scale LG with Low-Energy Leptonic $\not{CP}$

The case of decoupled N_3 — IH spectrum, $\not{CP}$ from Majorana phases ($\delta = \pi$), purely imaginary $R_{11}R_{12}$ ($R_{12}R_{13}$) ($x = 0, \pi, \ldots$)



Minimal mass scale for viable LG: $M_1 \simeq 4.3 \times 10^{10}$ GeV,

Conclusions

LG for $10^8 \lesssim M_1/\text{GeV} \lesssim 10^{14}$ and $M_1 \ll M_2 \ll M_3$ solving BEs and DMEs.

1. Detailed analysis of the **1-to-2-** and **2-to-3-flavour transitions**.
   - η_B may **change** its **sign** at the transitions.
2. The τ**-decoherence effects** can still generate **BAU** in the **single-flavour regime** at $M \gtrsim 10^{12}$ GeV with low-energy $\not{CP}$.
   Confirmation of K. Moffat, S. Pascoli, S. T. Petcov and J. Turner, arXiv:1809.08251.
3. The **BE2F** can be very **inaccurate** even in the **two-flavour regime** for $10^9 \lesssim M_1/\text{GeV} \lesssim 10^{12}$.
4. In the case of decoupled N_3 (**NH** and **IH**) and low-energy $\not{CP}$ from the Dirac phase δ, the **sign of** η_B is in **one-to-one correspondence** with the **sign of** $\sin\delta$.
5. Revisited **ranges of masses and PMNS phases** for **viable LG** in the case of low-energy $\not{CP}$ and decoupled N_3 (**NH** and **IH**).
6. The considered different scenarios of LG are **testable** and **falsifiable** in low-energy neutrino experiments.

```
for your_attention in this_talk():
    print('Thanks!')
```

Back-up Slides | ULYSSES Python package

A.G., K. Moffat, Y. Perez-Gonzalez, H. Schulz, J. Turner, *Computer Physics Communication* **262** (2021) 107813, [2007.09150].

```
ULYSSES is a Python package that calculates the BAU in LG within the
type-I seesaw mechanism, solving semi-classical BEs.
@properties
```

- `Exhaustive` It calculates the evolution of all LG ingredients (e.g., N_i-distributions, wash-out factors, asymmetries in different flavours, BAU).
- `Universal` An "Odyssey" of more than 14 orders of magnitude with many different sets of eqs., e.g. BE1F, BE2F, BE3F, DME with 1,2 or 3 heavy neutrinos.
- `Precise` E.g., loop corrections, scattering contributions, flavour effects, decoherence effects.
- `Flexible` Easily modify-able or implement-able with new models.
- `Slim` Very fast and with small size ($\sim$ 400 kB).
- `Public` Freely available at https://github.com/earlyuniverse/ulysses.

Still missing features: thermal effects, spectator processes, next-to-leading-order corrections for the source term, LG via oscillations.

Single-flavoured Boltzmann Equations (1BE1F) [a]

[a] The equations are written in the hierarchical limit $M_1 \ll M_2 \ll M_3$.

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq}\right), \quad (1)$$

$$\frac{dN_{B-L}}{dz} = \epsilon^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 N_{B-L}. \quad (2)$$

N_{N_1} ($N_{N_1}^{eq}$): number of N_1 in a comoving volume (if in thermal equilibrium).

Back-up Slides | Equations

Single-flavoured Boltzmann Equations (1BE1F) [a]

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$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) , \quad (1)$$

$$\frac{dN_{B-L}}{dz} = \epsilon^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 N_{B-L} . \quad (2)$$

N_{B-L}: $B - L$ asymmetry in a comoving volume.

$$\eta_B \simeq \frac{28}{79}\frac{1}{27} N_{B-L} .$$

Back-up Slides | Equations

Single-flavoured Boltzmann Equations (1BE1F) [a]

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$$\frac{dN_{B-L}}{dz} = \epsilon^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 N_{B-L} . \quad (2)$$

$D_1 = \langle \Gamma_{N_1} \rangle / Hz = \kappa_1 z \frac{K_1(z)}{K_2(z)}$ and $\kappa_1 = \Gamma_{N_1}/H(z=1)$: decay parameters.

Back-up Slides | Equations

Single-flavoured Boltzmann Equations (1BE1F) [a]

[a] The equations are written in the hierarchical limit $M_1 \ll M_2 \ll M_3$.

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$$\frac{dN_{B-L}}{dz} = \epsilon^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 N_{B-L} . \quad (2)$$

$W_1 = \left\langle \Gamma_{N_1}^{\mathrm{ID}} \right\rangle / 2Hz$: wash-out factor.

Single-flavoured Boltzmann Equations (1BE1F) [a]

[a] The equations are written in the hierarchical limit $M_1 \ll M_2 \ll M_3$.

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) , \quad (1)$$

$$\frac{dN_{B-L}}{dz} = \epsilon^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 N_{B-L} . \quad (2)$$

$\epsilon^{(1)} = -\left(\Gamma_{N_1 \to \Phi^+ \psi_1} - \Gamma_{N_1 \to \Phi^- \overline{\psi_1}}\right) / \Gamma_{N_1}$: CP-asymmetry parameter.

Back-up Slides | Equations

Two-flavoured Boltzmann Equations (1BE2F)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq} \right) , \quad (3)$$

$$\frac{dN_{\tau\tau}}{dz} = \epsilon_{\tau\tau}^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq} \right) - W_1 p_{1\tau} N_{\tau\tau} , \quad (4)$$

$$\frac{dN_{\tau^\perp\tau^\perp}}{dz} = \epsilon_{\tau^\perp\tau^\perp}^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq} \right) - W_1 p_{1\tau^\perp} N_{\tau^\perp\tau^\perp} . \quad (5)$$

$N_{\alpha\alpha}$: asymmetry $\frac{1}{3}B - L_\alpha$ in a comoving volume, $N_{\tau^\perp\tau^\perp} = N_{ee} + N_{\mu\mu}$.

$$N_{B-L} = N_{\tau\tau} + N_{\tau^\perp\tau^\perp} .$$

Back-up Slides | Equations

Two-flavoured Boltzmann Equations (1BE2F)

$$\frac{dN_{N_1}}{dz} = -D_1\left(N_{N_1} - N_{N_1}^{eq}\right), \quad (3)$$

$$\frac{dN_{\tau\tau}}{dz} = \epsilon_{\tau\tau}^{(1)} D_1\left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\tau} N_{\tau\tau}, \quad (4)$$

$$\frac{dN_{\tau^\perp\tau^\perp}}{dz} = \epsilon_{\tau^\perp\tau^\perp}^{(1)} D_1\left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\tau^\perp} N_{\tau^\perp\tau^\perp}. \quad (5)$$

$p_{1\alpha} = |C_{1\alpha}|^2$ and $p_{1\tau^\perp} = |C_{1e}|^2 + |C_{1\mu}|^2 = 1 - p_{1\tau}$ (*projection probabilities*).

Two-flavoured Boltzmann Equations (1BE2F)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) , \quad (3)$$

$$\frac{dN_{\tau\tau}}{dz} = \epsilon^{(1)}_{\tau\tau} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\tau} N_{\tau\tau} , \quad (4)$$

$$\frac{dN_{\tau^\perp\tau^\perp}}{dz} = \epsilon^{(1)}_{\tau^\perp\tau^\perp} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\tau^\perp} N_{\tau^\perp\tau^\perp} . \quad (5)$$

$$\epsilon^{(1)}_{\alpha\alpha} = -\left(p_{1\alpha}\Gamma_{N_1\to\Phi^+\psi_1} - p_{1\alpha}\Gamma_{N_1\to\Phi^-\overline{\psi_1}}\right)/\Gamma_{N_1},\ \epsilon^{(1)}_{\tau^\perp\tau^\perp} = \epsilon^{(1)}_{ee} + \epsilon^{(1)}_{\mu\mu}$$

Back-up Slides | Equations

Three-flavoured Boltzmann Equations (1BE3F)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) , \quad (6)$$

$$\frac{dN_{ee}}{dz} = \epsilon_{ee}^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1e} N_{ee} , \quad (7)$$

$$\frac{dN_{\mu\mu}}{dz} = \epsilon_{\mu\mu}^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\mu} N_{\mu\mu} , \quad (8)$$

$$\frac{dN_{\tau\tau}}{dz} = \epsilon_{\tau\tau}^{(1)} D_1 \left(N_{N_1} - N_{N_1}^{eq}\right) - W_1 p_{1\tau} N_{\tau\tau} . \quad (9)$$

$$\boxed{N_{B-L} = \sum_{\alpha=e,\,\mu,\,\tau} N_{\alpha\alpha}.}$$

Back-up Slides | Equations

Density Matrix Equations (DMEs)

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}}) \quad (10)$$

$$\frac{dN_{\alpha\beta}}{dz} = \epsilon^{(1)}_{\alpha\beta} D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - \frac{1}{2} W_1 \left\{ P^{0(1)}, N \right\}_{\alpha\beta} - \frac{\Gamma_\tau}{Hz} [I_\tau, [I_\tau, N]]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz} [I_\mu, [I_\mu, N]]_{\alpha\beta} \,. \quad (11)$$

$N = \sum_{\alpha,\beta} N_{\alpha\beta} |\psi_\alpha\rangle\langle\psi_\beta|$, density matrix; $N_{B-L} = \mathrm{Tr}(N) = \sum_{\alpha=e,\,\mu,\,\tau} N_{\alpha\alpha}$.

Back-up Slides | Equations

Density Matrix Equations (DMEs)

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}}) \qquad (10)$$

$$\frac{dN_{\alpha\beta}}{dz} = \epsilon_{\alpha\beta}^{(1)} D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - \frac{1}{2} W_1 \left\{ P^{0(1)}, N \right\}_{\alpha\beta} - \frac{\Gamma_\tau}{Hz} [I_\tau, [I_\tau, N]]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz} [I_\mu, [I_\mu, N]]_{\alpha\beta} \, . \qquad (11)$$

$P_{\alpha\beta}^{0(1)} \equiv C_{1\alpha} C_{1\beta}^{*}$: projection matrices.

Back-up Slides | Equations

Density Matrix Equations (DMEs)

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\rm eq}) \tag{10}$$

$$\frac{dN_{\alpha\beta}}{dz} = \epsilon^{(1)}_{\alpha\beta} D_1(N_{N_1} - N_{N_1}^{\rm eq}) - \frac{1}{2} W_1 \left\{ P^{0(1)}, N \right\}_{\alpha\beta} - \frac{\Gamma_\tau}{Hz} [I_\tau, [I_\tau, N]]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz} [I_\mu, [I_\mu, N]]_{\alpha\beta} \,. \tag{11}$$

I_τ and I_μ: 3×3 matrices such that $(I_\tau)_{\alpha\beta} = \delta_{\alpha\tau}\delta_{\beta\tau}$ and $(I_\mu)_{\alpha\beta} = \delta_{\alpha\mu}\delta_{\beta\mu}$

Density Matrix Equations (DMEs)

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\text{eq}}) \tag{10}$$

$$\frac{dN_{\alpha\beta}}{dz} = \epsilon_{\alpha\beta}^{(1)} D_1(N_{N_1} - N_{N_1}^{\text{eq}}) - \frac{1}{2} W_1 \left\{ P^{0(1)}, N \right\}_{\alpha\beta} - \frac{\Gamma_\tau}{Hz} [I_\tau, [I_\tau, N]]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz} [I_\mu, [I_\mu, N]]_{\alpha\beta} \, . \tag{11}$$

$\epsilon_{\alpha\beta}^{(1)}$: CP-asymmetry projected into α- and β-flavours.