SIMONE MARCIANO - UNIVERSITÀ DI ROMA TRE

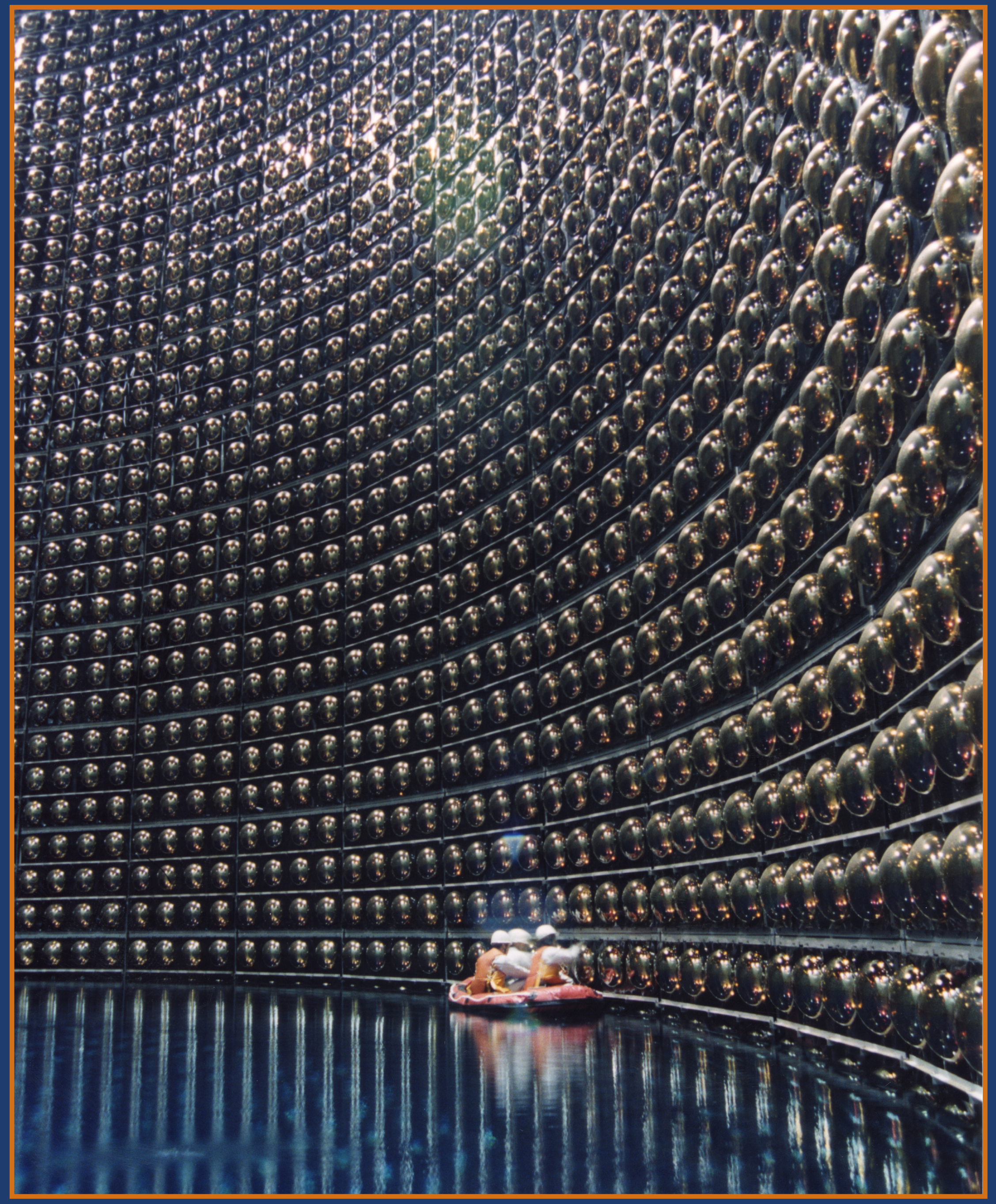
LEPTOGENESIS FROM U(1) FLAVOUR SYMMETRY

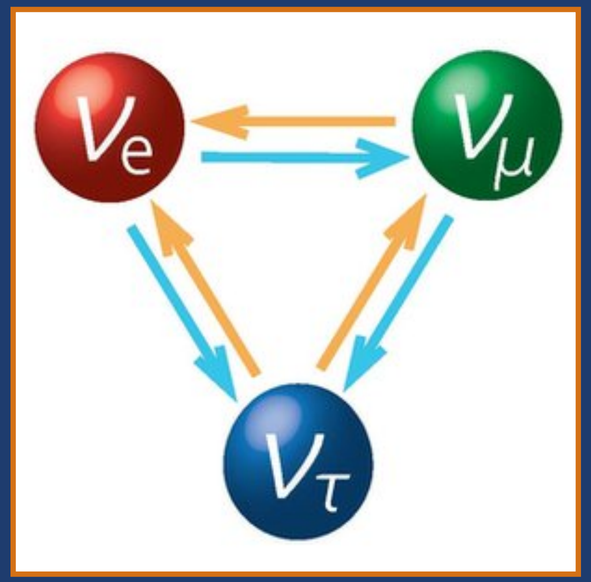
ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN ROMA TRE

OUTLINE

- Neutrino Masses: who ordered that?





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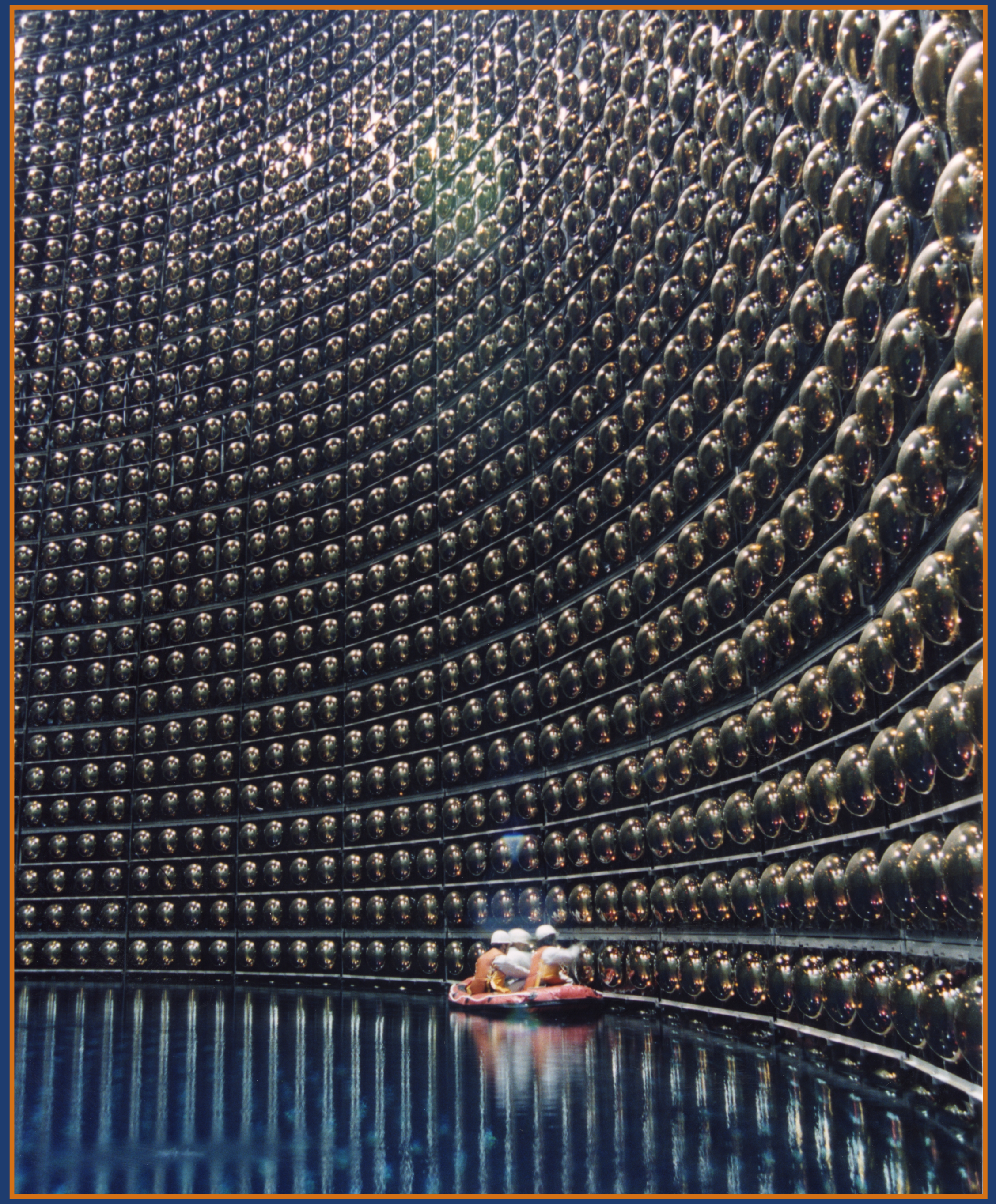

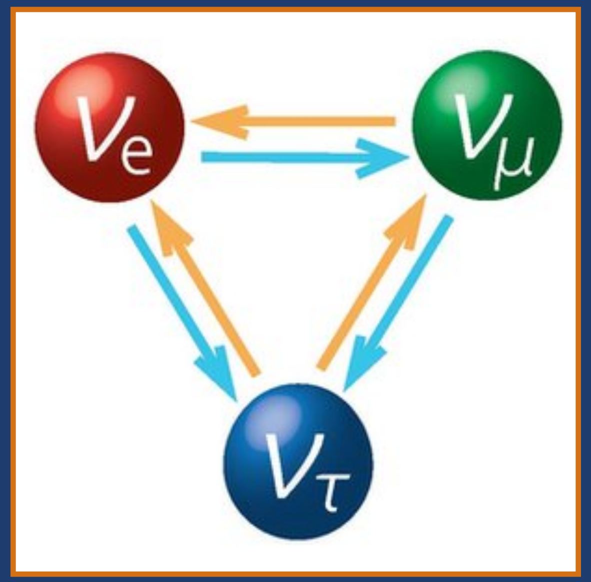

- Neutrino Masses: who ordered that?

- PMNS mixing matrix $U_{PMNS} = U_l^\dagger U_\nu$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix}$$

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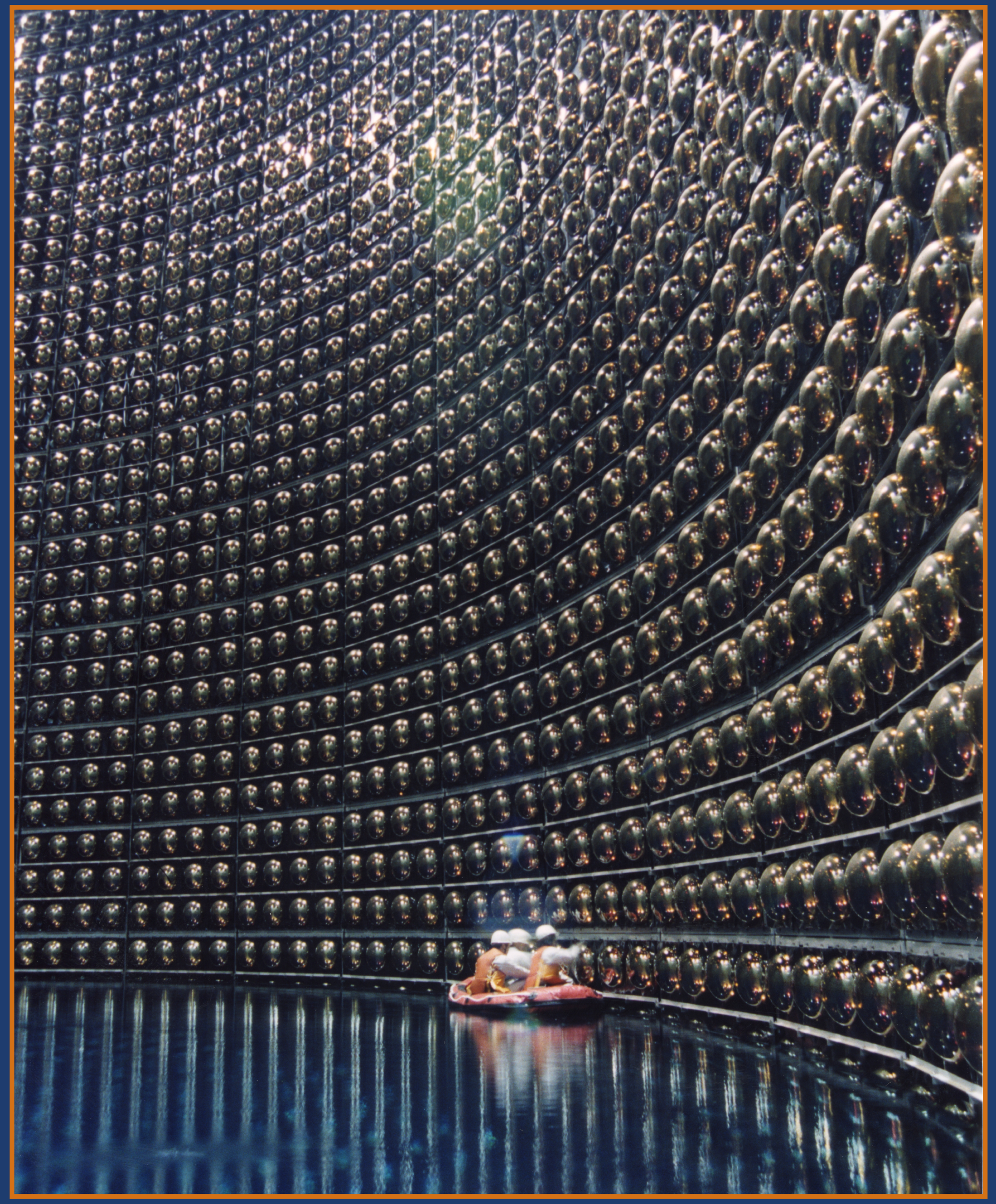

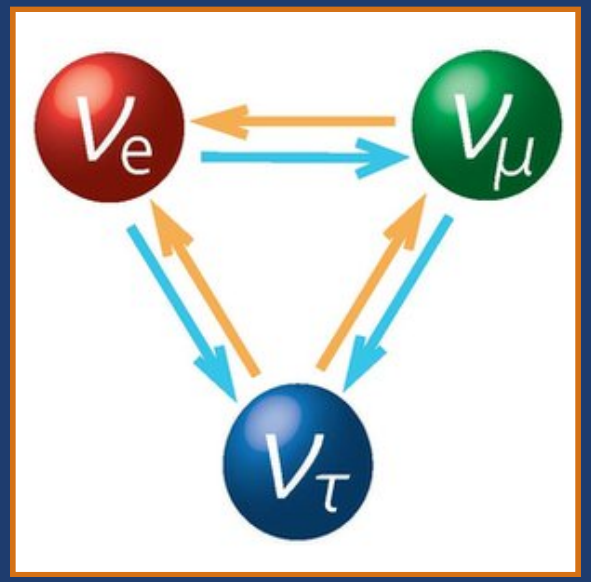

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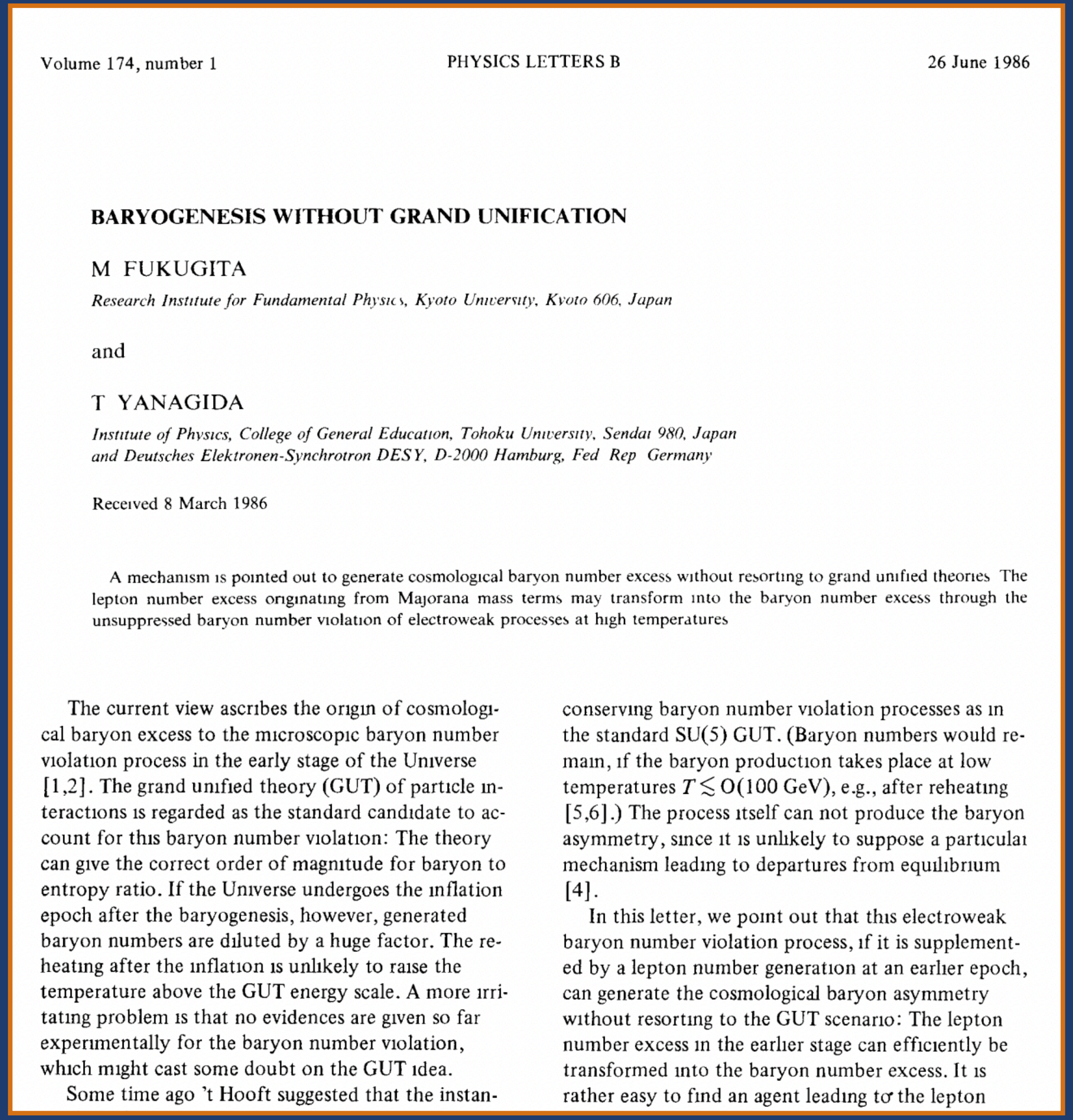
- Leptogenesis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BARYOGENESIS WITHOUT GRAND UNIFICATION

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Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures

The current view ascribes the origin of cosmological baryon excess to the microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interactions is regarded as the standard candidate to account for this baryon number violation: The theory can give the correct order of magnitude for baryon to entropy ratio. If the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more irritating problem is that no evidences are given so far experimentally for the baryon number violation, which might cast some doubt on the GUT idea.

Some time ago 't Hooft suggested that the instan- conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon numbers would remain, if the baryon production takes place at low temperatures $T \lesssim O(100$ GeV), e.g., after reheating [5,6].) The process itself can not produce the baryon asymmetry, since it is unlikely to suppose a particular mechanism leading to departures from equilibrium [4].

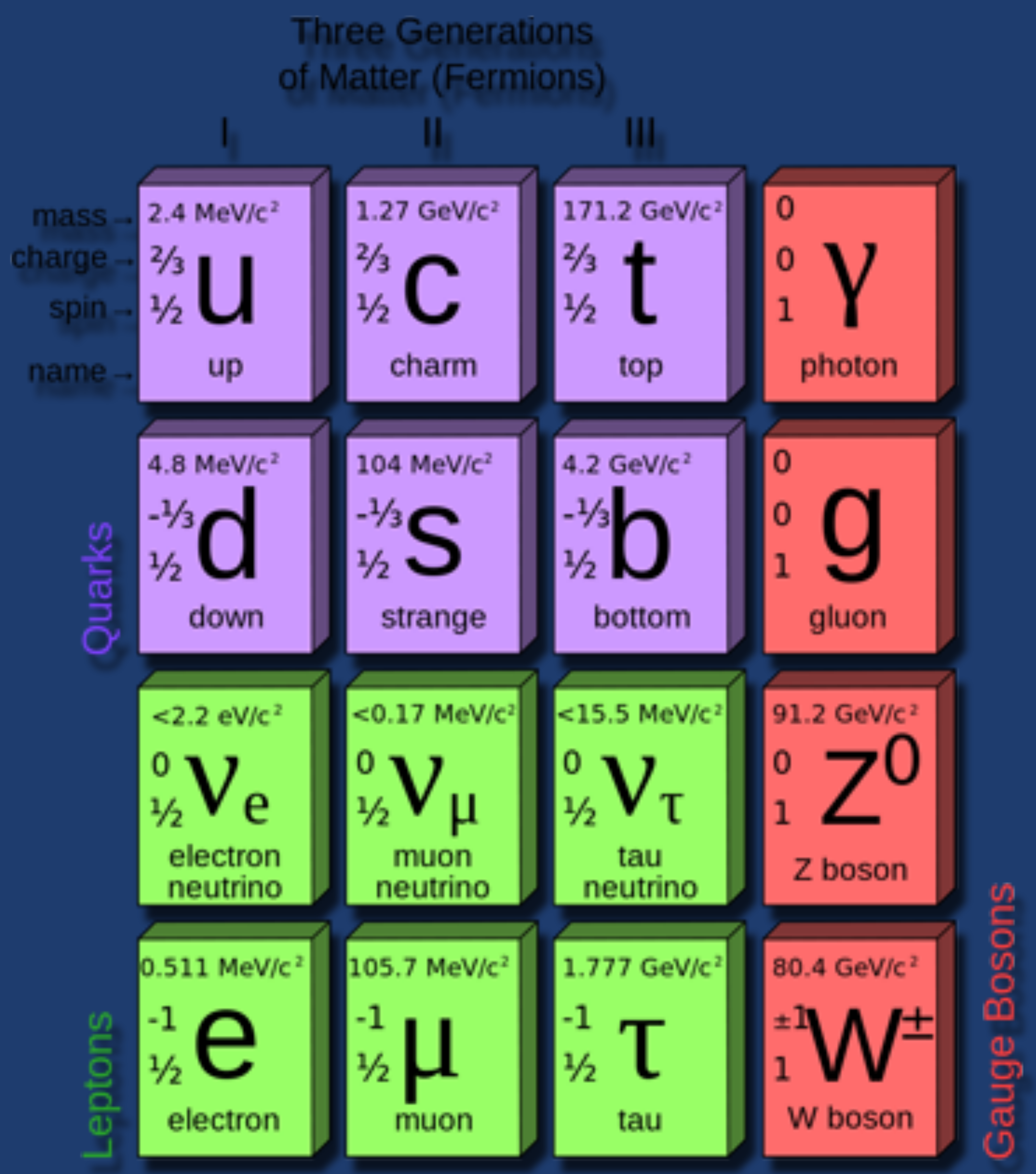
In this letter, we point out that this electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario: The lepton number excess in the earlier stage can efficiently be transformed into the baryon number excess. It is rather easy to find an agent leading to the lepton

THE MODEL

G. Arcadi, S. Marciano, D. Meloni arXiv:2205.02565

Extension of the symmetry group with an additional U(1) flavour symmetry, with a non standard leptonic number

$$Q = L_e - L_\mu - L_\tau$$



Extension of the Standard Model with two additional complex scalar fields (*flavons*) F_1, F_2 and three right-handed singlet fermions (*sterile neutrinos*) N_1, N_2, N_3

	l_e	l_μ	l_τ	l_e^c	l_μ^c	l_τ^c	F_1	F_2	H_u	H_d	N_1	N_2	N_3
$\mathrm{U(1)_F}$	+1	-1	-1	−13	7	3	2	1/2	0	0	-1	1	0

THE CHARGED LEPTON SECTOR

LOWEST DIMENSIONAL OPERATORS CONTRIBUTING TO THE MASS MATRIX

$$
\begin{aligned}
\mathscr{L} = {} & a_{11} l_e l_e^c \left(\frac{F_1}{M_F}\right)^6 H_d + a_{12} l_e l_\mu^c \left(\frac{F_1^\dagger}{M_F}\right)^4 H_d + a_{13} l_e l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right)^2 H_d + \\
& a_{21} l_\mu l_e^c \left(\frac{F_1}{M_F}\right)^7 H_d + a_{22} l_\mu l_\mu^c \left(\frac{F_1}{M_F}\right)^3 H_d + a_{23} l_\mu l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right) H_d + \\
& a_{31} l_\tau l_e^c \left(\frac{F_1}{M_F}\right)^7 H_d + a_{32} l_\tau l_\mu^c \left(\frac{F_1}{M_F}\right)^3 H_d + a_{33} l_\mu l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right) H_d + \text{h.c.}
\end{aligned}
$$

Where all a_{ij} are generic $\mathcal{O}(1)$ free parameters

After the flavour and electroweak symmetry breaking these operators provide a mass matrix with the general structure:

$$
(m_l)_{ij} \sim a_{ij} l_i l_i^c \left(\frac{\langle F_1 \rangle}{M_F}\right)^{\alpha_{ij}} \left(\frac{\langle F_2 \rangle}{M_F}\right)^{\beta_{ij}} \langle H_d \rangle \,, \text{ with}
$$

$$
\lambda = \langle F_1 \rangle / M_F = \langle F_2 \rangle / M_F
$$

$$
m_l \sim m_\tau \begin{pmatrix} a_{11}\lambda^5 & a_{12}\lambda^3 & a_{13}\lambda \\ a_{21}\lambda^6 & a_{22}\lambda^2 e^{i\phi_{22}} & a_{23} e^{i\phi_{23}} \\ a_{31}\lambda^6 & a_{32}\lambda^2 e^{i\phi_{32}} & 1 \end{pmatrix}
$$

For $\lambda = 0.23$ the mass ratio $m_e : m_\mu : m_\tau = \lambda^5 : \lambda^2 : 1$ is found, which naturally reproduces the observed pattern

THE NEUTRINO SECTOR

Masses are generated through the standard type-I seesaw mechanism. At the renormalizable level, the seesaw Lagrangian reads:

$$\mathscr{L}^{LO} = \frac{1}{2}\mathscr{M} W \overline{N}_1^c N_2 + \frac{1}{2}\mathscr{M} Z \overline{N}_3^c N_3 - a\overline{N}_1 H_u l_\mu + -b\overline{N}_1 H_u l_\tau - c\overline{N}_2 H_u l_e + \text{h.c.}$$

Where $\mathscr{M}$ is an overall mass scale while W, Z, a, b, c are dimensionless free coefficients. Higher dimensional operators appear at the Next-to-leading order (NLO), suppressed by a large mass scale M_F:

$$\begin{aligned}\mathscr{L}^{NLO} = &\frac{1}{2}\mathscr{M} m_{11} \overline{N}_1^c N_1 \left(\frac{F_1}{M_F}\right) + \frac{1}{2}\mathscr{M} m_{13} \overline{N}_1^c N_3 \left(\frac{F_2}{M_F}\right)^2 + \frac{1}{2}\mathscr{M} m_{22} \overline{N}_2^c N_2 \left(\frac{F_1^\dagger}{M_F}\right) + \\ &+\frac{1}{2}\mathscr{M} m_{23} \overline{N}_2^c N_3 \left(\frac{F_2^\dagger}{M_F}\right)^2 - d_{11}\overline{N}_1 H_u l_e \left(\frac{F_1^\dagger}{M_F}\right) - d_{22}\overline{N}_2 H_u l_\mu \left(\frac{F_1}{M_F}\right) + \\ &-d_{23}\overline{N}_2 H_u l_\tau \left(\frac{F_1}{M_F}\right) - d_{31}\overline{N}_3 H_u l_e \left(\frac{F_2^\dagger}{M_F}\right)^2 - d_{32}\overline{N}_3 H_u l_\mu \left(\frac{F_2^\dagger}{M_F}\right)^2 + \\ &-d_{33}\overline{N}_3 H_u l_\tau \left(\frac{F_2^\dagger}{M_F}\right)^2 + \text{h.c.}\end{aligned}$$

(m_{ij}, d_{ij}) are dimensionless free coefficients

THE NEUTRINO SECTOR

DIRAC AND MAJORANA MATRICES

$$Y = \frac{m_D}{v_u} \sim \overline{N} l \sim \begin{pmatrix} \lambda^2 d_{11} & a e^{i\Sigma} & b e^{i\Omega} \\ c e^{i\Phi} & \lambda^2 d_{22} & \lambda^2 d_{23} e^{i\Theta} \\ \lambda^2 d_{31} & \lambda^2 d_{32} & \lambda^2 d_{33} \end{pmatrix}$$

$$M_R \sim \overline{N} N \sim \mathscr{M} \begin{pmatrix} \lambda^2 m_{11} & W & \lambda^2 m_{13} \\ W & \lambda^2 m_{22} & \lambda^2 m_{23} \\ \lambda^2 m_{13} & \lambda^2 m_{23} & Z \end{pmatrix}$$

From the type-I seesaw master formula $m_\nu \simeq - m_D^T M_R^{-1} m_D$ we get the neutrino mass matrix (up to order $\mathcal{O}(\lambda^2)$):

$$m_\nu \simeq \frac{v_u^2}{\mathscr{M}} \times \begin{pmatrix} \frac{c e^{i\Phi}\left(c e^{i\Phi} m - 2 d_{11} W\right)\lambda^2}{W^2} & \bullet & \bullet \\ -\frac{a c e^{i(\Sigma+\Phi)}}{W} & \frac{a e^{i\Sigma}\left(a e^{i\Sigma} m - 2 d_{22} W\right)\lambda^2}{W^2} & \bullet \\ -\frac{b c e^{i(\Phi+\Omega)}}{W} & \frac{\left(a b e^{i(\Sigma+\Omega)} m - a d_{23} e^{i(\Theta+\Sigma)} W - b d_{22} e^{i\Omega} W\right)\lambda^2}{W^2} & \frac{b e^{i\Omega}\left(b e^{i\Omega} m - 2 d_{23} e^{i\Theta} W\right)\lambda^2}{W^2} \end{pmatrix}$$

THE NEUTRINO SECTOR

The neutrino mass matrix can be recast in the following form:

$$m_\nu = m_0 \begin{pmatrix} \lambda^2 x_1 & 1 & x \\ 1 & x_2\lambda^2 & x_3\lambda^2 \\ x & x_3\lambda^2 & x_4\lambda^2 \end{pmatrix}$$

Where (x, x_i) are a suitable combinations of the coefficients in the Dirac and Majorana matrices, and $m_0 = v_u^2/\mathscr{M} \times \mathcal{O}(1)$

$$x^2 = \frac{\Delta m^2_{atm}}{m_0^2} - 1$$

→

$$x \sim \mathcal{O}(1) \longrightarrow m_0 \sim \mathcal{O}(10^{-2})\ \text{eV}$$

→

$$\mathscr{M} \sim \mathcal{O}(10^{15})\ \text{GeV}$$

The masses of the three sterile neutrinos are simply given by:

$$M_1 \simeq \mathscr{M}\left[W + \mathcal{O}(\lambda^2)\right]$$
$$M_2 \simeq \mathscr{M}\left[W - \mathcal{O}(\lambda^2)\right]$$
$$M_3 \simeq \mathscr{M}\left[Z + \mathcal{O}(\lambda^3)\right]$$

→

Three heavy degenerate Majorana neutrinos at a mass scale $M_i \sim \mathcal{O}(10^{15})$ GeV

RESONANT SCENARIO

THE NEUTRINO SECTOR

$$m_\nu \simeq \frac{v_u^2}{\mathscr{M}} \times \begin{pmatrix} \frac{ce^{i\Phi}(ce^{i\Phi}m - 2d_{11}W)\lambda^2}{W^2} & \bullet & \bullet \\ -\frac{ace^{i(\Sigma+\Phi)}}{W} & \frac{ae^{i\Sigma}(ae^{i\Sigma}m - 2d_{22}W)\lambda^2}{W^2} & \bullet \\ -\frac{bce^{i(\Phi+\Omega)}}{W} & \frac{(abe^{i(\Sigma+\Omega)}m - ad_{23}e^{i(\Theta+\Sigma)}W - bd_{22}e^{i\Omega}W)\lambda^2}{W^2} & \frac{be^{i\Omega}(be^{i\Omega}m - 2d_{23}e^{i\Theta}W)\lambda^2}{W^2} \end{pmatrix}$$

Assuming $\mathscr{M} \sim \mathcal{O}(10^{13})$ GeV,
to maintain $m_0 \sim \mathcal{O}(10^{-2})$ eV
W should be around 10^2

$$m_\nu = m_0 \begin{pmatrix} \lambda^2 x_1 & 1 & x \\ 1 & x_2\lambda^2 & x_3\lambda^2 \\ x & x_3\lambda^2 & x_4\lambda^2 \end{pmatrix}$$

$$M_1 \simeq \mathscr{M}\left[W + \mathcal{O}(\lambda^2)\right]$$
$$M_2 \simeq \mathscr{M}\left[W - \mathcal{O}(\lambda^2)\right]$$
$$M_3 \simeq \mathscr{M}\left[Z + \mathcal{O}(\lambda^3)\right]$$

Two almost degenerate
states with mass $M_1 \simeq M_2 \sim 10^{15}$ GeV, and a
lighter one with mass $M_3 \simeq Z\mathscr{M} \sim 10^{13}$ GeV

HIERARCHICAL SCENARIO

PUTTING IT ALL TOGETHER

$$U_\nu = \begin{pmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2(1+x^2)}} & \frac{1}{\sqrt{2(1+x^2)}} & -\frac{x}{\sqrt{2(1+x^2)}} \\ \frac{x}{\sqrt{2(1+x^2)}} & \frac{x}{\sqrt{2(1+x^2)}} & -\frac{1}{\sqrt{1+x^2}} \end{pmatrix} + \mathcal{O}(\lambda^2)$$

$$U_l = \begin{pmatrix} -1 & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{32}e^{i(\phi_{22}+\phi_{23})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}} + a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{22}e^{i(\phi_{23}+\phi_{32})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}} + a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \end{pmatrix} + \mathcal{O}(\lambda^2)$$

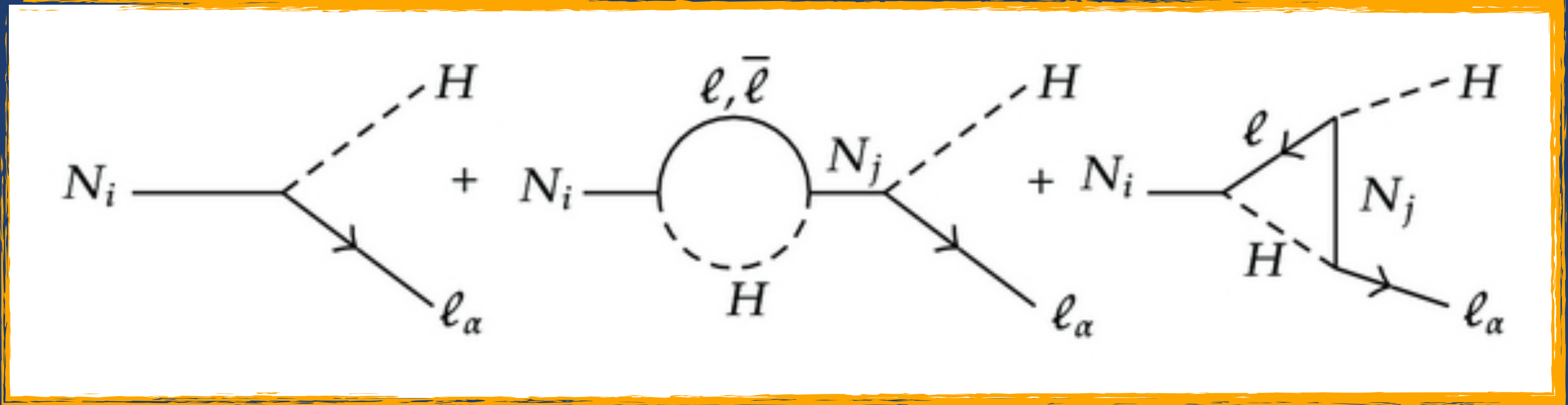
We compute the mass ratio $r = \Delta m^2_{sol}/\Delta m^2_{atm}$ and the mixing angles (using $U_{PMNS} = U_l^\dagger U_\nu$)

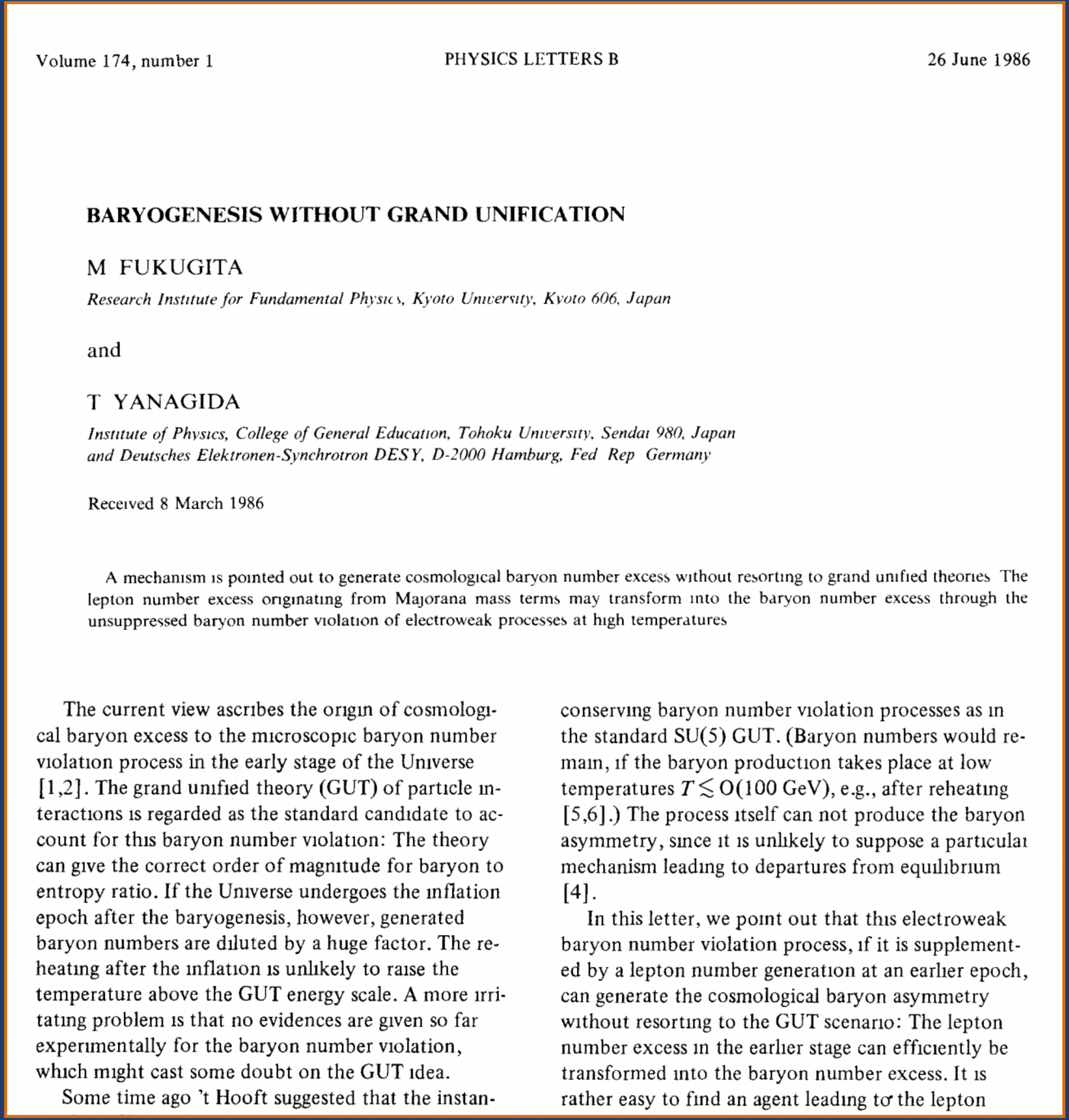
$$\begin{aligned} r &\sim \mathcal{O}(\lambda^2), \\ \tan\theta_{12} &\sim 1 + \mathcal{O}(\lambda), \\ \sin\theta_{13} &\sim \mathcal{O}(\lambda), \\ \tan\theta_{23} &\sim 1\,. \end{aligned}$$

Oscillation parameters	**Best fits (IH)**
$\theta_{12}/^\circ$	$33.45^{+0.78}_{-0.75}$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.12}$
$\theta_{23}/^\circ$	$49.3^{+1.0}_{-1.3}$
$\delta_{cp}/^\circ$	287^{+27}_{-32}
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.42^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{31}}{10^{-3}\ eV^2}$	$-2.497^{+0.028}_{-0.028}$

LEPTOGENESIS

The three Majorana neutrinos decay in the Early Universe creating a lepton asymmetry, which is consequently conversed in a baryon asymmetry through non perturbative processes, the sphalerons.





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$$\eta_B \equiv \left. \frac{n_B - n_{\bar{B}}}{n_\gamma} \right|_0 \approx 6.1 \cdot 10^{-10}$$

LEPTOGENESIS, RESONANT SCENARIO

S. Davidson, E. Nardi, and Y. Nir, Phys. Rept. 466, 105 (2008), arXiv:0802.2962 [hep-ph]

$$\eta_B \simeq 7.05 \cdot 10^{-3} \sum_i \varepsilon_i \eta_i$$

η_i : efficiency factors

ε_i : CP-violation parameters

$$\eta_i \equiv 1/K_i$$

$$\varepsilon_i(z) = \sum_{j \neq 0} \frac{\mathrm{Im}\left[(Y^\dagger Y)^2_{ij}\right]}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{\Delta M_{ij}/\Gamma_j}{1 + (\Delta M_{ij}/\Gamma_j)^2} \left[f_{ij}(z) + g_{ij}(z)\right]$$

$$K_1 \simeq \frac{27.7}{W}\left\{c^2 + \left(d_{11}^2 + d_{31}^2\right)\lambda^4 + \frac{2}{(W-Z)}\left(\frac{c^2 m^2}{(W-Z)} + \sqrt{2}\, c\, d_{31}\, m \cos(\Phi)\right)\lambda^4\right\},$$

$$K_2 \simeq \frac{27.7}{W}\left\{a^2 + (d_{22}^2 + d_{33}^2)\lambda^4\right\}, \quad K_3 \simeq \frac{27.7}{Z}\left\{b^2 + (d_{23}^2 + d_{33}^2)\lambda^4\right\}.$$

$$K_i \gg 1$$

STRONG WASHOUT REGIME

LEPTOGENESIS, RESONANT SCENARIO

$$\varepsilon_1 = +\frac{16\,\pi\,(W-Z)\,Z}{c^2\left(256\pi(W-Z)^2+b^4Z^2\right)}\left[c^2 d_{23}^2 \sin\left[2\,(\Theta-\Phi)\right]+ +bd_{11}\left(bd_{11}\sin\left[2\Omega\right]+2cd_{23}\sin\left[\Theta-\Phi+\Omega\right]\right)\right]\lambda^4+\mathcal{O}(\lambda^5)$$

$$\varepsilon_2 = -\frac{16\left(b^2\pi(W-Z)Z\sin\left[2(\Sigma-\Omega)\right]\right)}{256\pi^2(W-Z)^2+b^4Z^2} + \frac{16b^2 m\pi Z\left(256\pi^2(W-Z)^2-b^4Z^2\right)\sin\left[2\,(\Sigma-\Omega)\right]\lambda^2}{\left(256\pi^2(W-Z)^2+b^4Z^2\right)^2}+\mathcal{O}(\lambda^4)$$

$$\varepsilon_3 = +\frac{16\left(b^2\pi(W-Z)Z\sin\left[2(\Sigma-\Omega)\right]\right)}{256\pi^2(W-Z)^2+b^4Z^2} - \frac{16b^2 m\pi Z\left(256\pi^2(W-Z)^2-b^4Z^2\right)\sin\left[2\,(\Sigma-\Omega)\right]\lambda^2}{\left(256\pi^2(W-Z)^2+b^4Z^2\right)^2}+\mathcal{O}(\lambda^4)$$

We assume $\Sigma \to \Omega$ so that the leading order of the $\varepsilon_{2,3}$ goes to zero, and a further individual suppression of the phases

a	b	c	d_{11}	d_{22}	d_{23}	d_{31}	d_{32}
1.28	1.49	1.46	1.07	1.13	1.45	1.70	1.01
d_{33}	m	Σ	Ω	Θ	Φ	Z	W
1.50	1.50	0.007	0.007	-0.003	-0.004	1.38	1.27

$\varepsilon_i \sim \mathcal{O}(10^{-6})$ $\quad \eta_i \sim \mathcal{O}(10^{-2})$

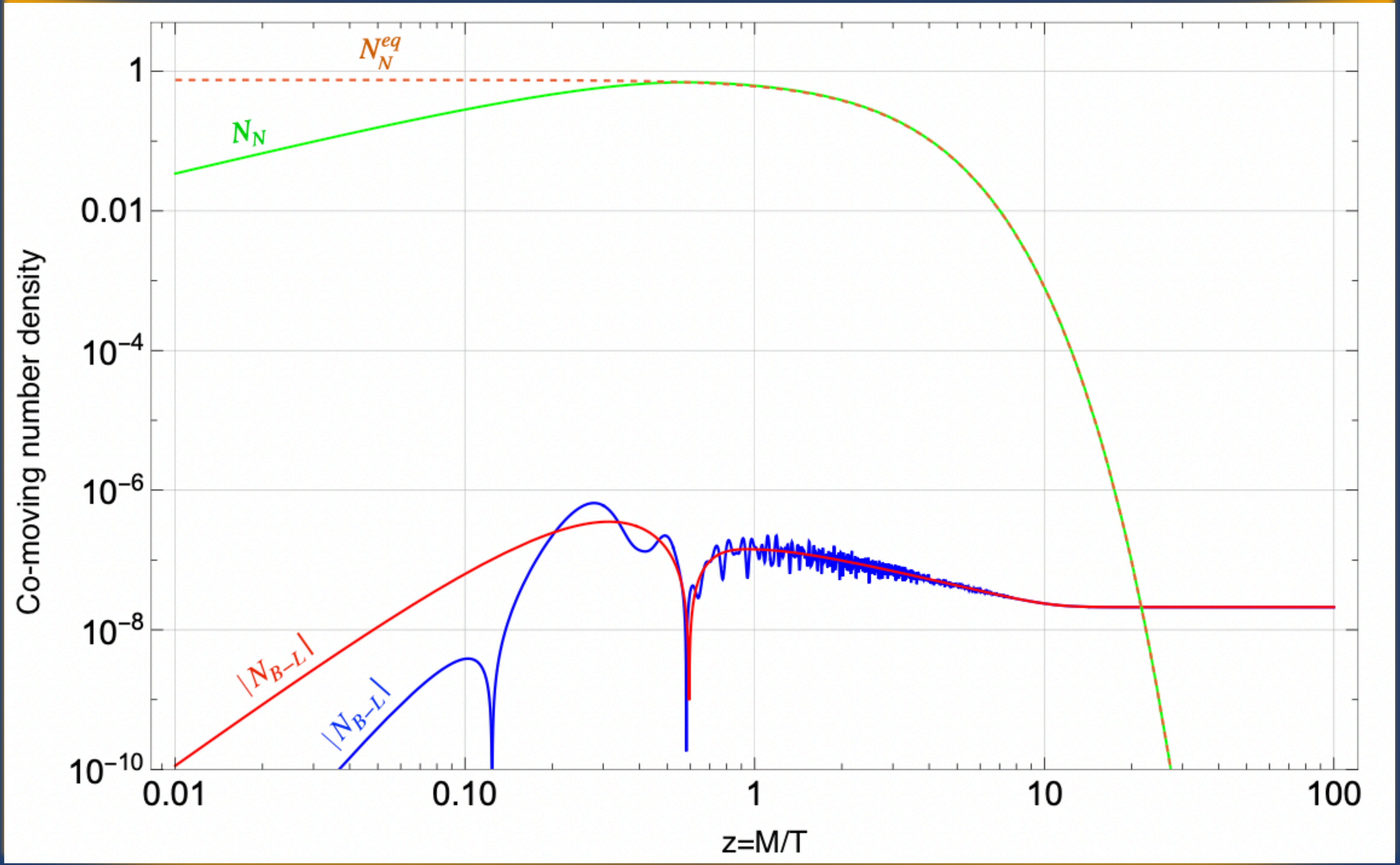
RESONANT SCENARIO, NUMERICAL RESULTS

$$\frac{dN_i}{dz} = -(D_i + S_i)\left(N_i - N_i^{\mathrm{eq}}\right) \qquad i = 1,2,3$$

$$\frac{dN_{B-L}}{dz} = \sum_i^3 \varepsilon_i D_i \left(N_i - N_i^{\mathrm{eq}}\right) - W_i N_{B-L},$$

$$N_{B-L}(\infty) = 2.11 \cdot 10^{-8},$$

$$\eta_B = 3.01 \cdot 10^{-10}.$$



LEPTOGENESIS, HIERARCHICAL SCENARIO

Considering a hierarchical spectrum with $M_3 \ll M_{1,2}$ we can assume that only the lighter neutrino decays are relevant for the Leptogenesis

$$\eta_B \simeq 7.05 \cdot 10^{-3} \varepsilon_3 \, \eta_3$$

$$\varepsilon_i = \frac{1}{8\pi \left(Y^\dagger Y\right)_{ii}} \sum_{j \neq i} \mathrm{Im}\left[\left(Y^\dagger Y\right)^2_{ij}\right] f\left[\frac{M_j^2}{M_i^2}\right]$$

$$\varepsilon_3 = f\left[\frac{M_2^2}{M_3^2}\right] \frac{1}{8b^4\pi} \cdot \Big\{ \sin\left[2(\Sigma - \Omega)\right] \left(a^2b^2 - 2a^2(d_{23}^2 + d_{33}^2)\right) + -2a\,b\,d_{22}\,d_{23} \sin\left[\Theta - \Sigma + \Omega\right] + +2\,a\,b\,d_{32}\,d_{33} \sin\left[\Sigma - \Omega\right] + \mathcal{O}(\lambda^4) \Big\}$$

$$\eta_3 \simeq 3.6 \cdot 10^{-4} \left(\frac{Z}{b^2} + O(\lambda^4)\right)$$

Loop function

$$f[x] = \sqrt{x}\left[1 - (1 + x)\log\left(1 + \frac{1}{x}\right) + \frac{1}{1 - x}\right]$$

In this scenario: $f\left[M_2^2/M_3^2\right] \simeq 10^{-2}$

HIERARCHICAL SCENARIO, NUMERICAL RESULTS

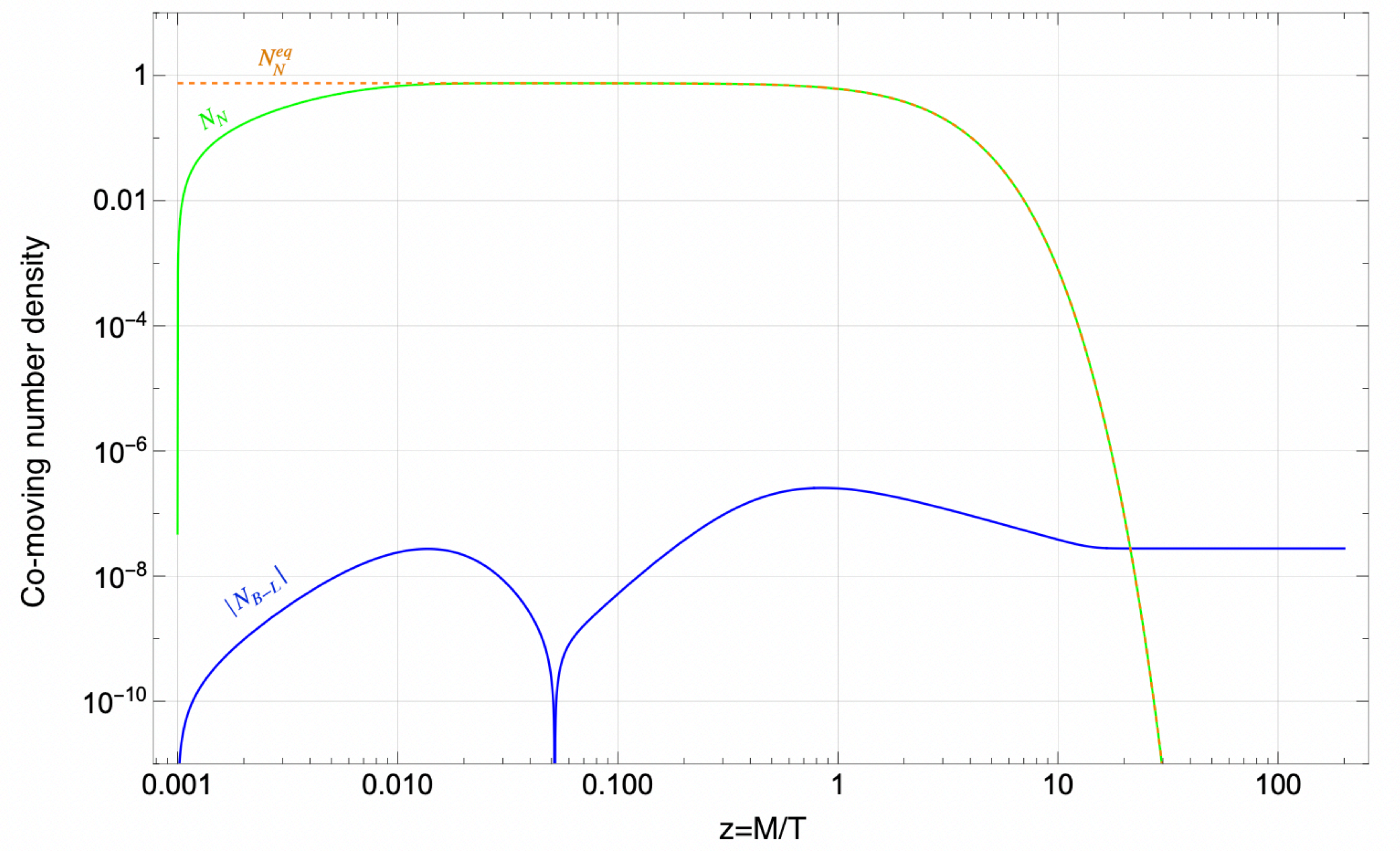
a	b	c	d_{11}	d_{22}	d_{23}	d_{31}	d_{32}
1.18	1.07	1.65	1.99	1.95	1.88	1.82	1.71
d_{33}	m	Σ	Ω	Θ	Φ	Z	W
1.83	1.50	0.39	1.02	4.10	5.11	1.41	159.97

$$\eta_3 \simeq 4.3 \cdot 10^{-4}$$
$$\varepsilon_3 \simeq 3.24 \cdot 10^{-4}$$

$$\eta_B \simeq 9.5 \cdot 10^{-10}$$

$$\frac{dN_3}{dz} = -(D_3 - S_3)\left(N_3 - N_3^{\mathrm{eq}}\right),$$
$$\frac{dN_{B-L}}{dz} = \varepsilon_3 D_3 \left(N_3 - N_3^{\mathrm{eq}}\right) - W_3 N_{B-L}$$

$$N_{B-L}(\infty) = 2.75 \cdot 10^{-8},$$
$$\eta_B = 3.96 \cdot 10^{-10}$$



CONCLUSIONS

- Proof of existence about the possibility of contemporary achieving viable masses and mixing patters for the SM neutrinos and a value of the baryon-asymmetry of the Universe (BAU), via leptogenesis, in model based on an abelian flavor symmetry $L_e - L_\mu - L_\tau$.

- The *resonant scenario* with three degenerate right-handed neutrinos at a mass scale of 10^{15} GeV. The lepton asymmetry is resonantly enhanced so that we invoke an ad-hoc suppression of the CP-violating phases in the Yukawa matrix.

- The *hierarchical scenario* in which one of the right-handed masses is lowered down to 10^{13} GeV without destroying the good agreement with the lepton masses and mixing. In this case it is possible to find parameter assignations leading to the correct value of BAU without invoking ad-hoc assignations.


THANK YOU!
XX FRASCATI SUMMER SCHOOL
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IN NUCLEAR, SUBNUCLEAR AND ASTROPARTICLE PHYSICS
LNF, July 11-15, 2022 Frascati (Italy)
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BACKUP SLIDES

THE CHARGED LEPTON SECTOR

CHARGED LEPTON MASS MATRIX

$$m_l \sim m_\tau \begin{pmatrix} a_{11}\lambda^5 & a_{12}\lambda^3 & a_{13}\lambda \\ a_{21}\lambda^6 & a_{22}\lambda^2 e^{i\phi_{22}} & a_{23}e^{i\phi_{23}} \\ a_{31}\lambda^6 & a_{32}\lambda^2 e^{i\phi_{32}} & 1 \end{pmatrix}$$

For $\lambda = 0.23$ the mass ratio $m_e : m_\mu : m_\tau = \lambda^5 : \lambda^2 : 1$ is found, which naturally reproduces the observed pattern

$$U_l = \begin{pmatrix} -1 & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{32}e^{i(\phi_{22}+\phi_{23})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}}+a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{22}e^{i(\phi_{23}+\phi_{32})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}}+a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \end{pmatrix} + \mathcal{O}(\lambda^2)$$

The (23) and (33) entries are of $\mathcal{O}(1)$, meaning that the charged lepton contribution to the atmospheric angle will be large. Being the (12) and (13) elements of $\mathcal{O}(\lambda)$, we expect a similar correction to the solar and reactor angles

THE CHARGED LEPTON SECTOR

CHARGED LEPTON MASS MATRIX

$$m_l \sim m_\tau \begin{pmatrix} a_{11}\lambda^5 & a_{12}\lambda^3 & a_{13}\lambda \\ a_{21}\lambda^6 & a_{22}\lambda^2 \mathrm{e}^{i\phi_{22}} & a_{23}\mathrm{e}^{i\phi_{23}} \\ a_{31}\lambda^6 & a_{32}\lambda^2 \mathrm{e}^{i\phi_{32}} & 1 \end{pmatrix}$$

For $\lambda = 0.23$ the mass ratio

$$m_e : m_\mu : m_\tau = \lambda^5 : \lambda^2 : 1$$

is found, which naturally reproduces the observed pattern

Diagonalizing the hermitean $m_l m_l^\dagger$ we find the left-handed rotation U_l

$$U_l = \begin{pmatrix} -1 & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{a_{13}\lambda}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{32}e^{i(\phi_{22}+\phi_{23})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}}+a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} & \frac{a_{23}e^{i\phi_{23}}}{\sqrt{1+a_{13}^2 e^{2i\phi_{23}}}} \\ -\frac{a_{13}a_{22}e^{i(\phi_{23}+\phi_{32})}\lambda}{-a_{23}a_{32}e^{i\phi_{22}}+a_{22}e^{i(\phi_{23}+\phi_{32})}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} & \frac{1}{\sqrt{1+a_{23}^2 e^{2i\phi_{23}}}} \end{pmatrix} + \mathcal{O}(\lambda^2)$$

THE CHARGED LEPTON SECTOR

LOWEST DIMENSIONAL OPERATORS CONTRIBUTING TO THE MASS MATRIX

$$\mathscr{L} = a_{11} l_e l_e^c \left(\frac{F_1}{M_F}\right)^6 H_d + a_{12} l_e l_\mu^c \left(\frac{F_1^\dagger}{M_F}\right)^4 H_d + a_{13} l_e l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right)^2 H_d +$$
$$a_{21} l_\mu l_e^c \left(\frac{F_1}{M_F}\right)^7 H_d + a_{22} l_\mu l_\mu^c \left(\frac{F_1}{M_F}\right)^3 H_d + a_{23} l_\mu l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right) H_d +$$
$$a_{31} l_\tau l_e^c \left(\frac{F_1}{M_F}\right)^7 H_d + a_{32} l_\tau l_\mu^c \left(\frac{F_1}{M_F}\right)^3 H_d + a_{33} l_\mu l_\tau^c \left(\frac{F_1^\dagger}{M_F}\right) H_d + \text{h.c.}$$

Where all a_{ij} are generic $\mathcal{O}(1)$ free parameters

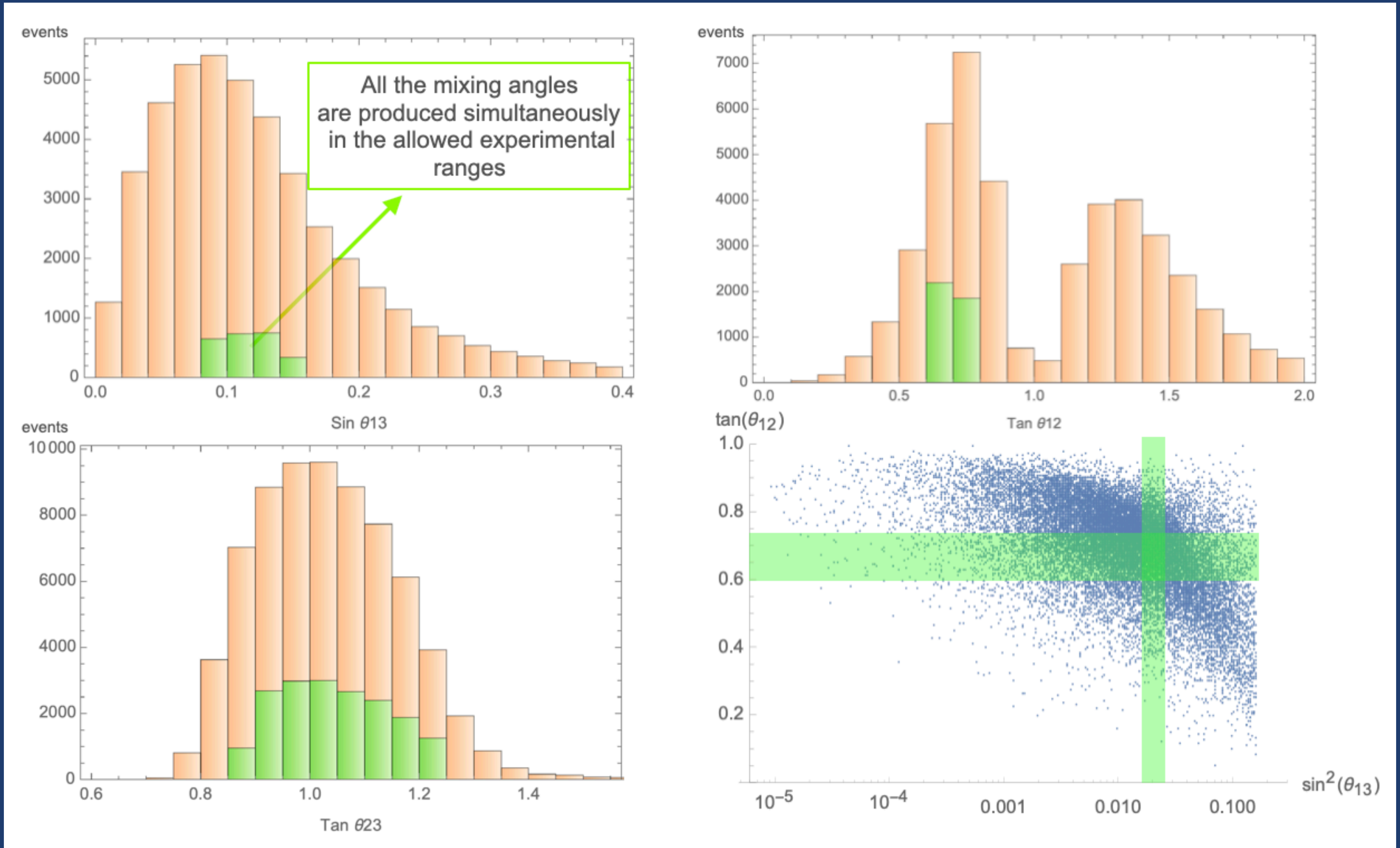
After the flavour and electroweak symmetry breaking these operators provide a mass matrix with the general structure:

$$(m_l)_{ij} \sim a_{ij} l_i l_i^c \left(\frac{\langle F_1 \rangle}{M_F}\right)^{\alpha_{ij}} \left(\frac{\langle F_2 \rangle}{M_F}\right)^{\beta_{ij}} \langle H_d \rangle\,, \text{ with}$$

$$\lambda = \langle F_1 \rangle / M_F = \langle F_2 \rangle / M_F$$

$$m_l \sim m_\tau \begin{pmatrix} a_{11}\lambda^5 & a_{12}\lambda^3 & a_{13}\lambda \\ a_{21}\lambda^6 & a_{22}\lambda^2 e^{i\phi_{22}} & a_{23} e^{i\phi_{23}} \\ a_{31}\lambda^6 & a_{32}\lambda^2 e^{i\phi_{32}} & 1 \end{pmatrix}$$

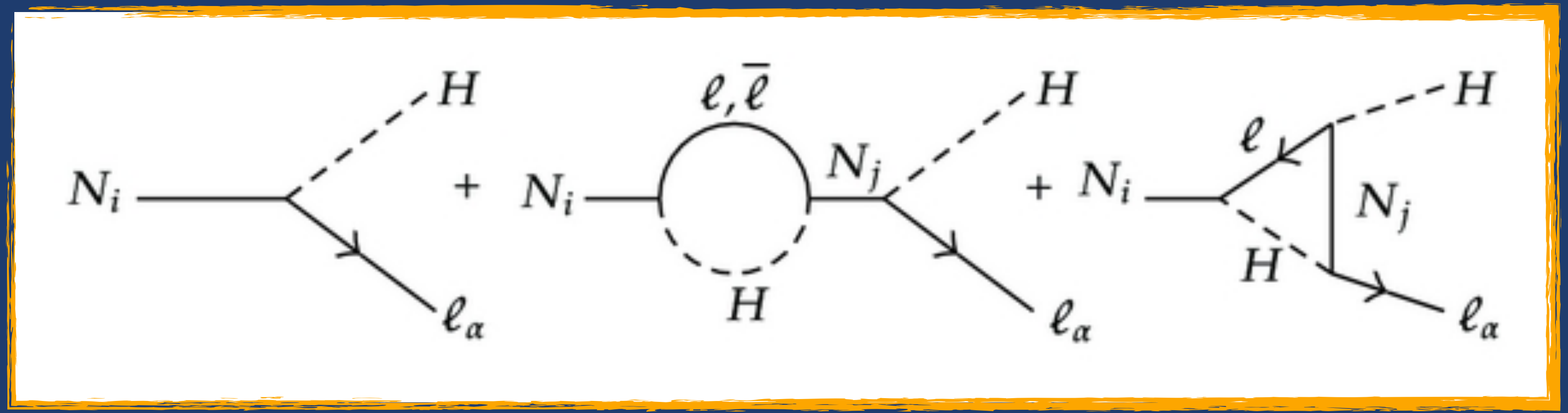
MIXING ANGLES DISTRIBUTIONS



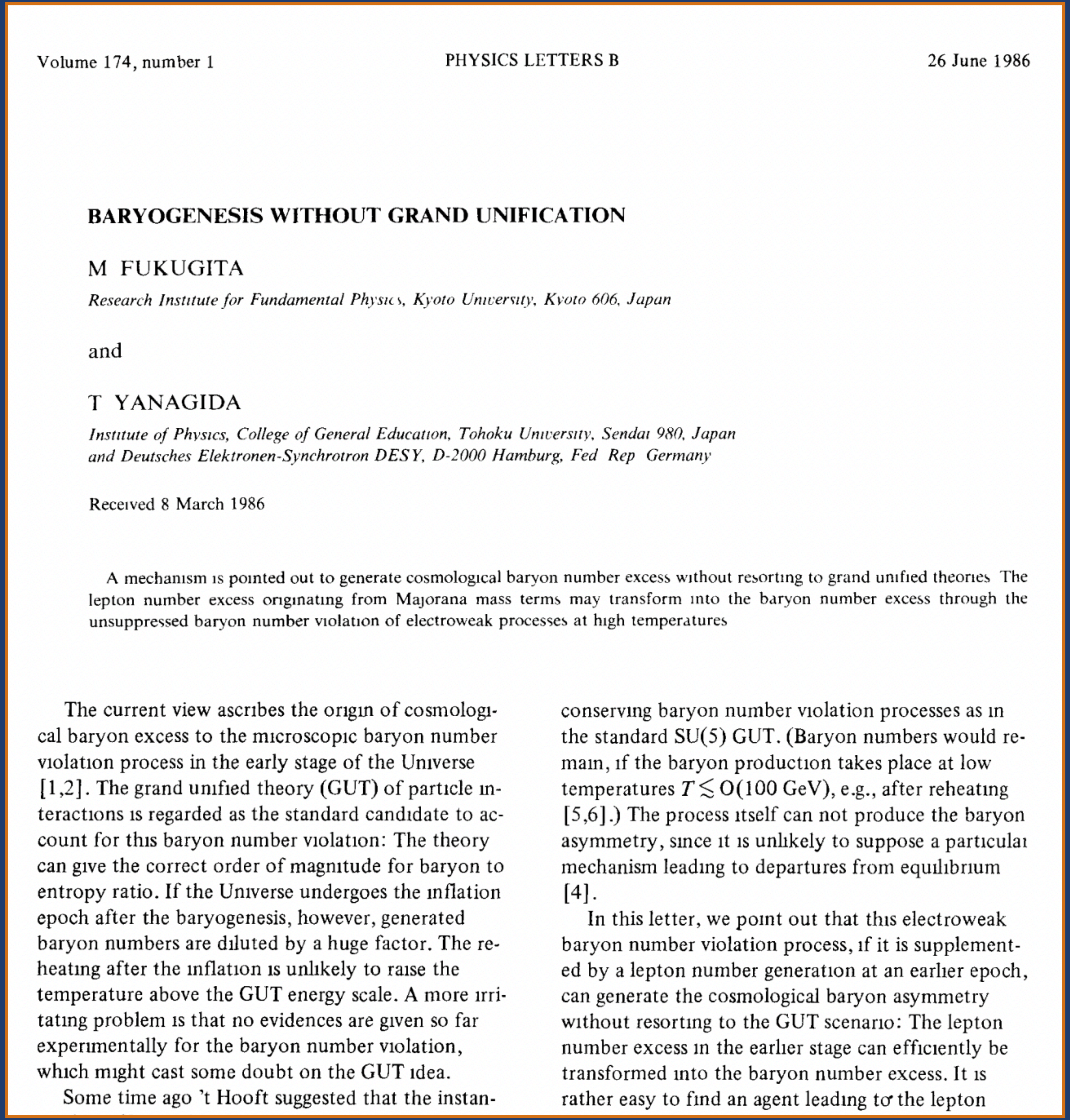
Simone Marciano 2021 *J. Phys.: Conf. Ser.* **2156** 012188

LEPTOGENESIS

The three Majorana neutrinos decay in the Early Universe creating a lepton asymmetry, which is consequently conversed in a baryon asymmetry through non perturbative processes, the sphalerons.



$$\varepsilon_i \equiv \frac{\Gamma(N_i \to \phi l_i) - \Gamma(N_i i \to \bar{\phi}\bar{l}_i)}{\Gamma(N_i \to \phi l_i) + \Gamma(N_i i \to \bar{\phi}\bar{l}_i)}$$



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BARYOGENESIS WITHOUT GRAND UNIFICATION

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A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures

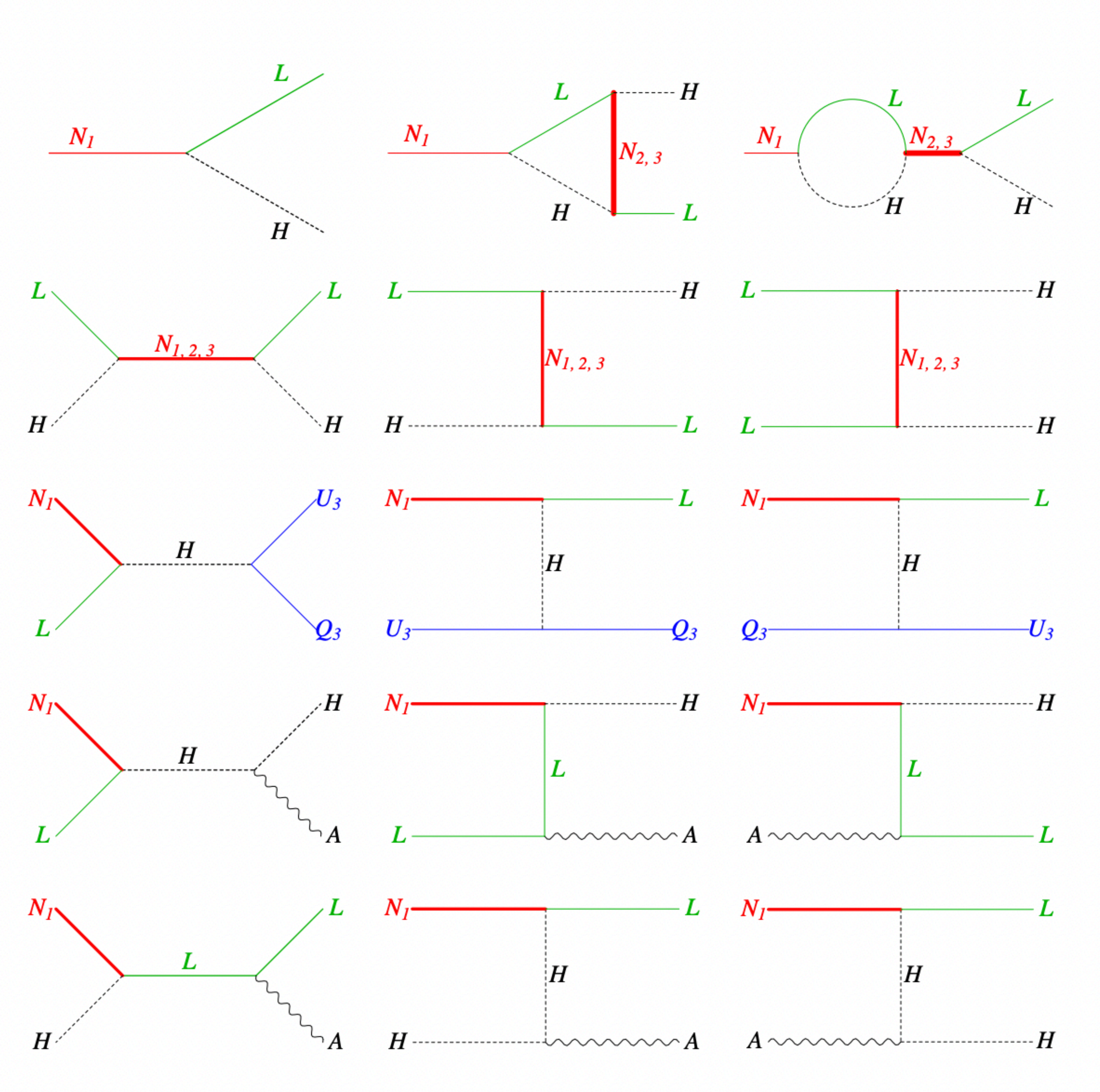
The current view ascribes the origin of cosmological baryon excess to the microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interactions is regarded as the standard candidate to account for this baryon number violation: The theory can give the correct order of magnitude for baryon to entropy ratio. If the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more irritating problem is that no evidences are given so far experimentally for the baryon number violation, which might cast some doubt on the GUT idea.

Some time ago 't Hooft suggested that the instan- conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon numbers would remain, if the baryon production takes place at low temperatures $T \lesssim O(100\text{ GeV})$, e.g., after reheating [5,6].) The process itself can not produce the baryon asymmetry, since it is unlikely to suppose a particular mechanism leading to departures from equilibrium [4].

In this letter, we point out that this electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario: The lepton number excess in the earlier stage can efficiently be transformed into the baryon number excess. It is rather easy to find an agent leading to the lepton

$$\eta_B \equiv \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_0 \approx 6.1 \cdot 10^{-10}$$

BOLTZMANN EQUATIONS



arXiv:hep-ph/0310123v2

$$\chi_s(x) = \left(\frac{x-1}{x}\right)^2 \qquad \chi_t(x) = \frac{x-1}{x}\left[\frac{x-2+2a_h}{x-1+a_h} + \frac{1-2a_h}{x-1}\log\left(\frac{x-1+a_h}{a_h}\right)\right]$$

$$f_{s,t}(z) = \frac{\int_{z^2}^{\infty} d\Psi \chi_{s,t}(\Psi/z^2)\sqrt{\Psi}\mathcal{K}_1(\sqrt{\Psi})}{z^2\mathcal{K}_2(z)} \qquad S_{s,t}(z) = \frac{K_s}{9\zeta(3)} f_{s,t}(z)$$

$$D(z) = Kz\left\langle\frac{1}{\gamma}\right\rangle \qquad \left\langle\frac{1}{\gamma}\right\rangle = \frac{\mathcal{K}_1}{\mathcal{K}_2} \qquad W_{ID}(z) = \frac{1}{2}D(z)\frac{N_1^{eq}(z)}{N_l^{eq}}$$

$$W(z) = W_{ID}(z)\left[1 + \frac{2}{D(z)}\left(2S_t(z) + \frac{N_1(z)}{N_1^{eq}(z)}S_s(z) + 2S_N(z) + 2S_{Nt}(z)\right)\right]$$

$$\Gamma_x(z) = \frac{M_1}{24\zeta(3)g_N\pi^2}\frac{\mathcal{I}_x}{\mathcal{K}_2(z)z^3} \qquad \mathcal{I}_x = \int_{z^2}^{\infty} d\Psi\hat{\sigma}_x(\Psi)\sqrt{\Psi}\mathcal{K}_1(\sqrt{\Psi})$$

$$S_x(z) = \frac{\Gamma_x(z)}{Hz}$$