Leptogenesis Left-Right Symmetry and Double Seesaw

Purushottam Sahu

Indian Institute of Technology Bombay India

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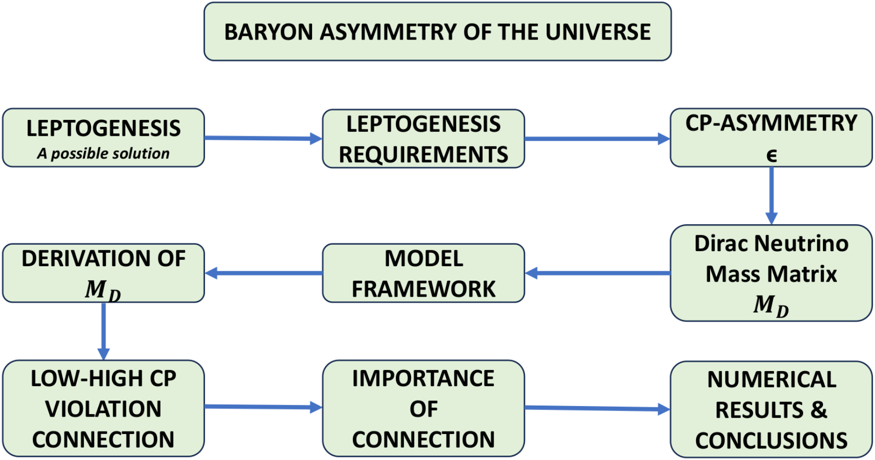
Plan of the Talk



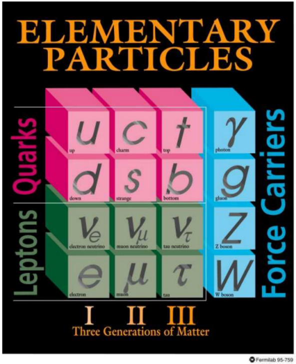
Introduction

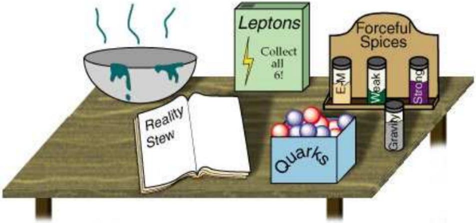
What is the world made up of??

- In ancient times, people sought to organize the world into fundamental elements: Earth, Air, fire and water.
- Even in ancient Indian mythology, the five basic elements were: Space, Air, Fire, Water and Earth.
- Fundamental elements mean objects that are simple and without an internal structure.

So, were they really the fundamental elements?

The Incomplete Standard Model of Particle Physics





With the advent of scientific technology and human curiosity, we now know that all the known particles are composite of 6 quarks and 6 leptons and they interact by exchanging force carriers:

- Electromagnetic (γ), Weak (Z^0, $W^{\pm}$), Strong (gluons).
- and Gravity (not yet in the model...)

The Complete Standard Model of Particle Physics

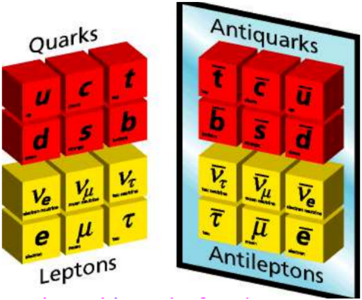


Figure: All the particles have a partner anti-particle associated with it. The two differ from each other by their opposite charge signs under various properties.
[Image ref: Lepton Photon 2003]

- The antimatter was first introduced theoretically by Paul Dirac(Noble Prize 1933) in 1928.

- In 1932, the first antiparticle, positron was discovered experimentally in a cloud chamber by Carl Anderson.
- Charge neutral force carriers (Z^0, γ) are their own antiparticles.

Anticlimactic Antimatter

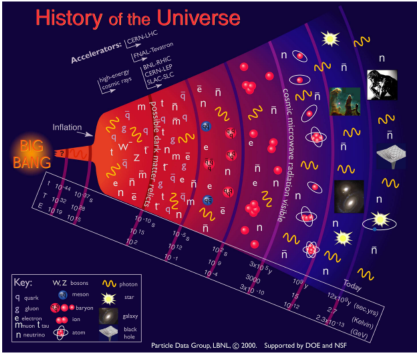
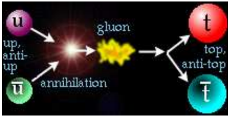


Figure: The universe came with a bang. Equal numbered matter and anti-matter⇔Charge neutral universe. Then universe began to expand and cool reaching to present times.

- Our universe now is matter dominated(absence of anti matter). How do we know that?
- When matter & antimatter meet, they annihilate leaving only photons and neutrinos.



No such energy in our daily life or up in the nearby cosmos.

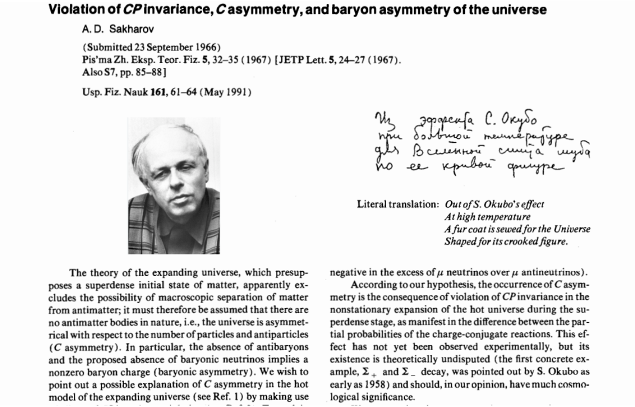
- There are other evidences too!!.

$$Y_{\Delta B} = \frac{n_B - \bar{n}_B}{s} \approx 6 \times 10^{-10}$$

Accomodating asymmetry

Once a asymmetry in the baryon number was established, researchers put forward theories to accomodate such a event within the cosmological evolution of universe.

- Andrei Sakharov (a renowned physicist and Noble peace prize winner) argued that one can naturally achieve matter dominance by exploiting CP invariance violations.



Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding universe (see Ref. 1) by making use

negative in the excess of μ neutrinos over μ antineutrinos).

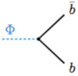
According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

Sakharov Conditions

The 3 minimum conditions:

- Baryon number violating interactions.

- Thermal non-equilibrum situation.



Rate of backward reaction($\bar{b}b \rightarrow \phi$) is less than forward.

- C & CP violations.

$$\Gamma(A+B \rightarrow C) \neq \Gamma(\bar{A}+\bar{B} \rightarrow \bar{C})$$

Images taken from reference (Elor et al., 2019).

Testing conditions within SM:

- $B-L$ is conserved, but $B+L$ is violated.
- CP is violated by δ_{CKM}.
- Departure from thermal equilibrium can be achieved at the Electro-weak Phase Transition (EWPT).

SM fails on 2 aspects:

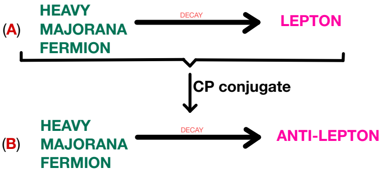
- Higgs sector does not give a strongly first order PT.
- CKM CP violations are too suppressed.

Look out for alternate scenarios

We need to look out for extensions of SM that can incorporate a viable source of asymmetry. The scenario must have atleast:

- New sources of *CP* violations.
- Either a new departure from thermal equilibrium and B-L violations.
- Or a modification of the EWPT.

A mechanism called "Leptogenesis"(introduced by Fukugita and Yanagida, 1986) can induce a matter-antimatter asymmetry in the lepton sector, which via other mechanism can be transferred to the baryon sector.



Decay Rate (A) > Decay Rate (B)

Leptogenesis Requirements

From the 3 Sakharov Conditions

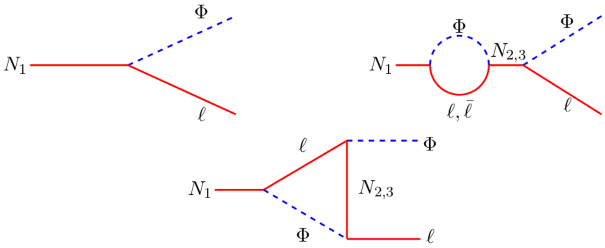
(i.) Lepton Number Violation: Could be facilitated by the Majorana mass terms in the Lagrangian.

(ii.) C and CP Violations: Parametrized by CP-asymmetry parameter ($\varepsilon \neq 0$) [will talk about it in the upcoming slides].

(iii.) Out of Thermal Equilibrium: Achieved when the decaying particle N **(a Heavy Majorana Fermion)** satisfies:

$$\Gamma_N \leq H(T = m_N)$$

Leptogenesis at work



- Lepton number violations at tree level.
- Direct CP violations at one loop.
- Requires at least 2 N's.

$$\varepsilon \equiv \frac{\Gamma\left(N_1 \rightarrow \Phi \ell\right) - \Gamma\left(N_1 \rightarrow \Phi^{\dagger} \bar{\ell}\right)}{\Gamma\left(N_1 \rightarrow \Phi \ell\right) + \Gamma\left(N_1 \rightarrow \Phi^{\dagger} \bar{\ell}\right)}$$

Here, ε parameterizes the strength of required asymmetry and is usually referred as the 'asymmetry parameter'.

CP-Asymmetry (ε)

- ε for single flavor can be written as:

$$\varepsilon_1 \approx -\frac{3.m_{N_1}}{16\pi(Y_D^\dagger Y_D)_{11}}\left[\frac{Im[(Y_D^\dagger Y_D)^2_{21}]}{m_{N_2}} + \frac{Im[(Y_D^\dagger Y_D)^2_{31}]}{m_{N_3}}\right]$$

[Covi et al. Phys.Lett. B384 (1996) 169-174]

- Here Y_D is Dirac neutrino Yukawa coupling matrix. As $M_D = v.Y_D$, we have

$$\varepsilon_1 \approx -\frac{3.m_{N_1}}{16\pi v^2(M_D^\dagger M_D)_{11}}\left[\frac{Im[(M_D^\dagger M_D)^2_{21}]}{m_{N_2}} + \frac{Im[(M_D^\dagger M_D)^2_{31}]}{m_{N_3}}\right]$$

! WE NEED TO DERIVE M_D !

Model Framework

LRSM + Sterile Neutrinos S_L

1. Fermion Sector

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} ; \;\; \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \;\; \text{(SM Doublets)}$$

$$q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} ; \;\; \ell_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \;\; (N_R \text{ As Extra Field})$$

$$+ \underbrace{S_L}_{\text{Singlet \& per gen}}$$

Model Framework

LRSM + Sterile Neutrinos S_L

2. Scalar Sector

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \text{(Higgs bidoublet)} \,,$$

$$H_L = \begin{pmatrix} h_L^+ \\ h_L^0 \end{pmatrix} \text{(Higgs doublet)} \,,$$

$$H_R = \begin{pmatrix} h_R^+ \\ h_R^0 \end{pmatrix} \text{(Higgs doublet)} \,.$$

3. LR Symmetry

Charge Conjugation: C

Model Framework (Symmetry Breaking)

SSB of LRSM

$$\underbrace{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$

$$\Big\downarrow \langle H_R(1,2,1) \rangle$$

$$\underbrace{SU(2)_L \times U(1)_Y}$$

$$\Big\downarrow \langle \phi(1_L, 1/2_Y) \rangle \subset \Phi(2,2,0)$$

$$U(1)_{em}$$

- The electroweak symmetry breaking ($SU(2)_L \times U(1)_Y \to U(1)_{em}$) is achieved by assigning non-zero VEVs: $\langle \phi_1^0 \rangle \equiv v_1$ and $\langle \phi_2^0 \rangle \equiv v_2$ to the neutral components of Higgs bidoublet Φ, with $v = \sqrt{v_1^2 + v_2^2} \simeq 246$ GeV.

Double Seesaw (Neutrino Mass Generation)

- Interaction Lagrangian

$$-\mathcal{L}_{LRDSM} = \underbrace{\mathcal{L}_{M_D}}_{\text{Dirac mass term } (\nu_L - N_R)} + \underbrace{\mathcal{L}_{M_{RS}}}_{\text{Dirac mass term } (N_R - S_L)} + \underbrace{\mathcal{L}_{M_S}}_{\text{Majorana mass term}}$$

- After SSB, the complete 9×9 neutral fermion mass matrix in the flavor basis of (ν_L, N_R^c, S_L):

$$\mathcal{M}_{LRDSM} = \begin{bmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^T & \mathbf{0} & M_{RS} \\ \mathbf{0} & M_{RS}^T & M_S \end{bmatrix}$$

[Mohapatra R. N., Phys. Rev. Lett. 56.561 (1986)]

Double Seesaw (Neutrino Mass Generation)

- Block diagonalization with the assumption $|M_D| \ll |M_{RS}| < |M_s|$, gives

$$m_\nu \cong -M_D \left(-M_{RS} M_S^{-1} M_{RS}^T \right)^{-1} M_D^T$$
$$m_N \equiv M_R \cong -M_{RS} M_S^{-1} M_{RS}^T,$$
$$m_S \cong M_S\,.$$

[S. Patra et al., Phys. Rev. D 107, 075037 (2023)]

Deriving M_D

Basis Choice

- In our basis, charged lepton mass matrix is diagonal.
- Light neutrino Majorana mass matrix is diagonalized with $U_\nu \equiv U_{PMNS}$, $\hat{m}_\nu = U_\nu^\dagger M_\nu U_\nu^*$.
- Right handed neutrino mass matrix is diagonalized by U_N as $\hat{m}_N = U_N^\dagger m_N U_N^*$.

Screening

- We considered the screening condition:

$$\boxed{M_D = \frac{M_{RS}^T}{k}} \rightarrow M_S = k^2 m_\nu \implies U_S = U_\nu$$

$$\implies \hat{m}_S = U_\nu^\dagger M_S U_\nu^*$$

[A.Y. Smirnov, X. Xu, Phys. Rev. D 97, 095030 (2018)]

Deriving M_D

- We have
$$m_N = -M_{RS} M_S^{-1} M_{RS}^T$$
and $\hat{m}_N = U_N^\dagger m_N U_N^*$
- Using screening result for M_S, we can have:
$$\hat{m}_N = U_N^\dagger m_N U_N^* = -\underbrace{U_N^\dagger M_{RS} U_\nu^*}\, \hat{m}_S^{-1} \underbrace{U_\nu^\dagger M_{RS}^T U_N^*}$$
- For above equation to be consistent, RHS should be diagonal. As $\hat{m}_S^{-1}$ is diagonal, it implies that
$$U_N^\dagger M_{RS} U_\nu^* = \hat{m}_{RS}$$
- We have considered C symmetry as the additional discrete symmetry in our model framework, therefore M_D and M_{RS} are symmetric matrices. This implies that
$$\boxed{U_N = U_\nu}$$

Deriving M_D

- We have relations:

$$m_N = -M_{RS} M_S^{-1} M_{RS}^T;$$
$$M_S = k^2 m_\nu$$
$$\implies M_{RS} = m_\nu \sqrt{-k^2 m_\nu^{-1} m_N}$$

- Using all the results deduced for unitary matrices, we get M_D as:

$$M_D = \frac{1}{k} M_{RS} = i.U_\nu \hat{m}_\nu (\hat{m}_\nu^{-1} \hat{m}_N)^{1/2} U_\nu^T$$

- Simplifying and rewriting in matrix form, we have

$$M_D = i.U_\nu \begin{bmatrix} \sqrt{m_1.m_{N_1}} & 0 & 0 \\ 0 & \sqrt{m_2.m_{N_2}} & 0 \\ 0 & 0 & \sqrt{m_3.m_{N_3}} \end{bmatrix} U_\nu^T$$

[U. Patel, P. Adarsh, S. Patra and P. Sahu, JHEP 03 (2024) 029]

Low-High CP-Violation Connection

$$\varepsilon \approx -\frac{3.m_{N_1}}{16\pi v^2 (M_D^\dagger M_D)_{11}} \left[\frac{Im[(M_D^\dagger M_D)^2_{21}]}{m_{N_2}} + \frac{Im[(M_D^\dagger M_D)^2_{31}]}{m_{N_3}} \right]$$

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$$U_\nu = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{pmatrix}$$

with $\delta \longrightarrow$ CP-violating Dirac phase and $\alpha, \beta \longrightarrow$ CP-violating Majorana phases

Importance of Connection

- We derived

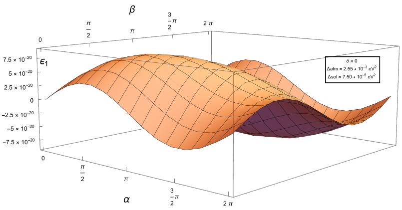
$$M_D = i.U_\nu \begin{bmatrix} \sqrt{m_1.m_{N_1}} & 0 & 0 \\ 0 & \sqrt{m_2.m_{N_2}} & 0 \\ 0 & 0 & \sqrt{m_3.m_{N_3}} \end{bmatrix} U_\nu^T$$

  M_D depends solely on neutrino oscillation parameters, the two kind of CP-violating phases and masses of heavy right-handed neutrinos.

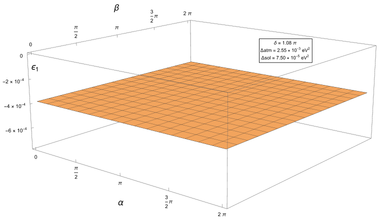
- In literature, M_D is parametrized to depend on U_ν (which contains oscillation parameter) but such parametrization also involves unknown high energy phases which requires fitting to explain the observations. One such famous parametrization is

$$M_D = \underbrace{iU_\nu \sqrt{diag(m_1, m_2, m_3)}\, R \sqrt{diag(m_{N_1}, m_{N_2}, m_{N_3})}}_{\text{Casas-Ibarra parametrization}}$$

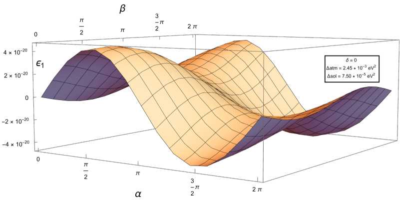
Dependence on Majorana Phases



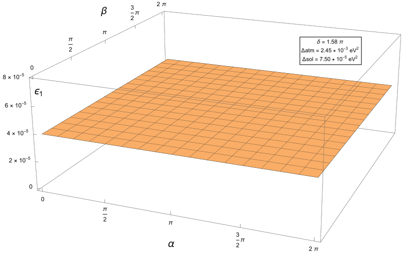
NO with $\delta = 0$.



NO with $\delta =$ best fit.

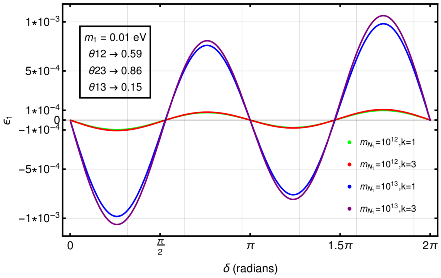


IO with $\delta = 0$.

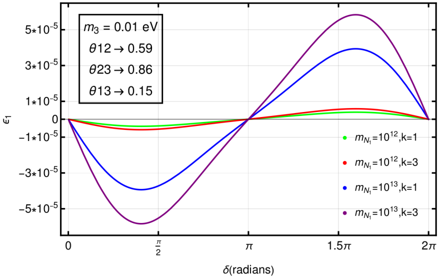


IO with $\delta =$ best fit.

Dependence on Dirac Phase



Normal Ordering (NO) case



Inverted Ordering (IO) case

As we have negligible dependence on Majorana Phases, so for producing these plots, we have set both α and β equal to 0.

Numerical Results

After putting-in all the values for the relevant input parameters for the **normal ordering (NO)** mass spectrum of active neutrinos and choosing a set of right handed neutrino masses (for thermal unflavored leptogenesis):

$$m_{N_1} = 10^{13}\ \text{GeV};\ m_{N_2} = 3 \times 10^{14}\ \text{GeV};\ m_{N_3} = 5 \times 10^{14}\ \text{GeV}$$

We get CP-Asymmetry (fairly close to the observational value)

$$\varepsilon \approx -3.8 \times 10^{-4}$$

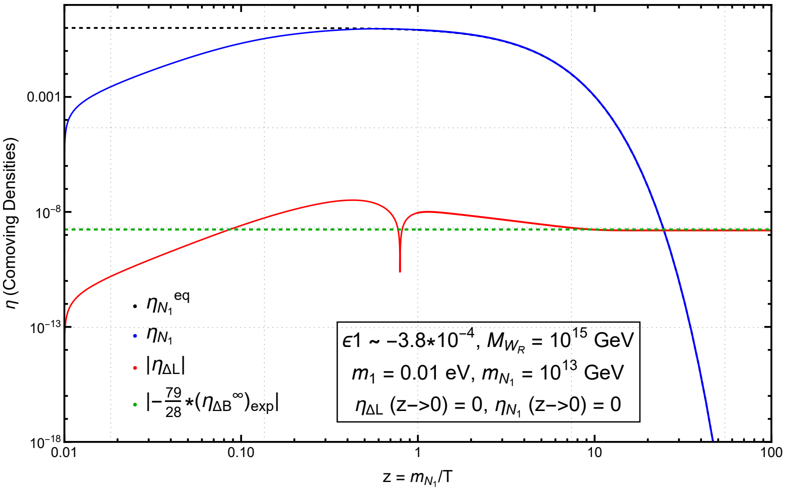
$$\Big\downarrow \text{Boltzmann Evolution}$$

$$Y_{\Delta B} \approx 6 \times 10^{-10}$$

For the **inverted ordering (IO)**, we obtain the $Y_{\Delta B}$ value with a negative sign ($Y_{\Delta B} \approx -6 \times 10^{-10}$) for the considered parameter space.

Numerical Results

Cosmological evolution of lepton asymmetry incorporating all the relevant decays, inverse-decays, scatterings and washout interactions for the **NO case**



Conclusion and Future Aspects

1. We developed a direct connection between low and high-energy CP violations by deriving M_D in the context of double-seesaw within the LRSM framework. The connection is independent of arbitrary factors and depends solely on neutrino oscillation parameters and heavy neutrino masses. The obtained CP asymmetry (ε_1) provides us with a value of baryon asymmetry which is fairly comparable to the observational results.

2. We also see that in our analysis, the value of (ε_1) exhibits negligible dependence on the Majorana phases α and β for the given set of input parameters in both the NO and IO cases. This highlights δ as the prime source for generating the required baryon asymmetry. Nevertheless, for some other choice of input parameters, one may obtain a distinct dependence of ε_1 on α and β but such a choice might deviate us from the thermal unflavoured regime.

3. Thus, we plan on extending this work to study the impact of non-zero Majorana phases in the flavoured or resonant regime of leptogenesis.

Thank You!