RESCUING LEPTOGENESIS PARAMETER SPACE OF INVERSE SEESAW NEUTRINO MASS MODEL

Ananya Mukherjee Saha Institute of Nuclear Physics, India

Presented at **DSU 2023** at ICTP-EAIFR, University of Rwanda, Kigali

10-14th July 2023

11.07.2023

BARYON ASYMMETRY OF THE UNIVERSE

- $\eta_B^{\rm CMB} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6 - 6.18) \times 10^{-10}$ (PLANCK 2018)
- **Observation** : CMB and BBN measurement
- **Theoretical understanding** : Baryogenesis
  - LEPTOGENESIS, and
  - there exists other several ways to realize baryogenesis.
- Baryogenesis can explain the baryon asymmetry problem through leptogenesis in connection to neutrino mass : BSM issues

M. Fukugita and T. Yanagida, Phys.Lett.**B174**:45-47(1986)

- Neutrino mass can be explained by **seesaw mechanisms** by inclusion of right-handed-neutrinos. (Several seesaw models actually !)
- Produce lepton asymmetry from the decay of right-handed-neutrinos $\Longrightarrow$ leads to **Baryogenesis.**

M. Fukugita and T. Yanagida, Phys.Lett.**B174**:45-47(1986)

Seesaw models ($Y_\nu^{\ell i} \overline{L_\ell} \widetilde{H} N_{R_i}$)$\Longrightarrow$ ($N \to L\,H$ and the conjugate process)

- Are these models appealing in view of testability?

Testability issue for high scale seesaw models as $M_N \sim \mathscr{O}(10^9)$ GeV!! **TeV scale models may be interesting !**

AIM OF THE WORK : WHY ISS LEPTOGENESIS IS POTENTIALLY NOT ACHIEVABLE ?

Inverse seesaw : low scale seesaw ($\mathscr{O}(M_R) \sim$a few TeV)

- In addition with the 3 RHNs, three copies of light (keV) sterile neutrinos are included.
- The above ($m_\nu \sim 0.1$ eV) demands: $m_D \sim 100$GeV, $M_R \sim 10$TeV,$\mu \sim 1$keV.

$$-\mathscr{L} \supset Y_\nu^{\ell i}\,\overline{L_\ell}\,\widetilde{H}\,N_{R_i} + M_R\,\overline{(N_{R_i})^c}\,S^c + \frac{1}{2}\mu\overline{S}(S)^c + h.c. \qquad (1)$$

$$m_\nu = m_D(M_R^T)^{-1}\mu M_R^{-1} m_D^T$$

$$Y_\nu^{\text{ISS}} = \frac{1}{v}\,U\,m_n^{1/2}\,R\,\mu^{-1/2}\,M_R^T,\ \text{R can be real/complex}$$

$$\text{lepton asymmetry } \varepsilon \propto \mathrm{Im}[\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu]^2$$

$$\text{baryon asymmetry } \eta_B \propto \frac{\varepsilon}{K}$$

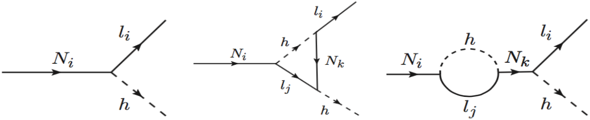
- Case A: Huge washout (K).
  - Results into huge-washout $\Longrightarrow$ erases produced asymmetry. The reason is interaction rate is larger than the Hubble expansion rate during leptogenesis.
- Case B: Not enough lepton asymmetry (ε quantitatively the order) to survive for the final baryon asymmetry.
  - Partial cancellation of the lepton asymmetries associated with each heavy pseudo-Dirac neutrino states.

WHY ISS-LEPTOGENSIS IS POTENTIALLY NOT ACHIEVABLE: SOLUTION ?

- Remedy was given by R. Volkas et al., **JCAP06(2018)012** and K. Agashe et al. **JHEP04(2019)029**, including linear seesaw in addition with ISS (controll the washout)
- However, the above scheme doesn't yield a testable parameter space in low energy experiments.
- Potential solution to these problems ....
  1. Case A: Minimizing the amount of washout considering an alternate Hubble expansion rate, ensuring $\Gamma < H$.
  2. Case B: Considering non-degeneracy among the generations of heavy RHNs of ISS, bringing a resonant enhancement to ε.
- Both the above propositions work for the testability issue through the light-heavy mixing describing lepton flavor violation.
- A region of the viable parameter space can be tested in the future muon collider experiment.

Abdallah, Khalil 2012

LEPTON ASYMMETRY, DECAY WIDTH, HUBBLE RATE, WASHOUT..



$$\varepsilon_i^{\ell} = \frac{1}{8\pi\left(Y_\nu^\dagger Y_\nu\right)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[\left(Y_\nu^\dagger Y_\nu\right)_{ij}\left(Y_\nu^\dagger\right)_{i\ell}\left(Y_\nu\right)_{\ell j}\right]\left[f(x_{ij}) + \frac{\sqrt{x_{ij}}\left(1-x_{ij}\right)}{\left(1-x_{ij}\right)^2 + \frac{1}{64\pi^2}\left(Y_\nu^\dagger Y_\nu\right)_{jj}^2}\right] + \ldots etc$$

$$\eta_B \simeq -3\times 10^{-2} \sum_{\ell,i} \frac{\varepsilon_{i\ell}}{K_\ell^{\mathrm{eff}} \min\left[z_c, 1.25\,\mathrm{Log}\,(25 K_\ell^{\mathrm{eff}})\right]} .$$

- The generated lepton asymmetry ε_i^{ℓ} is converted into baryon asymmetry.
- The washout factor $K_i = \Gamma_i / H$, determined mainly by the dominant inverse decay, where, decay width : $\Gamma_i = \frac{M_i}{8\pi}(Y_\nu Y_\nu^\dagger)_{ii}$
- The Hubble rate of expansion at temperature $T \sim M_i$ (1 TeV here ⟶ smaller expansion rate !)

$$H^{\mathrm{rad}} = 1.66\sqrt{g^*}\,\frac{M_i^2}{M_{\mathrm{Pl}}} \quad \text{with} \quad g^* \simeq 106.75 \quad \text{and} \quad M_{\mathrm{Pl}} = 1.29\times 10^{19}\,\mathrm{GeV}.$$

$$z_c = \frac{M_i}{T_c} \text{ and } T_c \sim 149 \text{ GeV (the critical temperature).}$$

F. Deppisch 2010, G. Bambhaniya 2016

CASE A: MINIMIZING WASHOUT ($K = \Gamma_i/H$) $\longrightarrow$ NON-STANDARD COSMOLOGY

The modified Hubble expansion rate..

D'Eramo et al. JCAP 1705 (2017) 012, D. Mahanta, et al. JCAP04(2020)032, Konar,Ananya, Abhijit, Sudipto, JHEP (2021),44 (2021)

$$\rho_\eta(T) = \rho_\eta(T_R)\left(\frac{g_{*s}(T)}{g_{*s}(T_R)}\right)^{(4+n)/3}\left(\frac{T}{T_R}\right)^{(4+n)} .$$

$$\begin{aligned}\rho(T) &= \rho_{rad}(T) + \rho_\eta(T) &(2)\\ &= \rho_{rad}(T)\left[1 + \frac{g_*(T_R)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_R)}\right)^{(4+n)/3}\left(\frac{T}{T_R}\right)^n\right] &(3)\end{aligned}$$

$$\begin{aligned}\mathscr{H}(T) &\approx \frac{\pi\bar{g}_*^{1/2}}{3\sqrt{10}}\frac{T^2}{M_{\rm Pl}}\left(\frac{T}{T_R}\right)^{n/2}, \quad (\text{with } \ T \gg T_R), &(4)\\ &= \mathscr{H}_R(T)\left(\frac{T}{T_R}\right)^{n/2},\end{aligned}$$

TeV scale leptogenesis relies on the resonant enhancement of lepton asymmetry, also called **Pilaftsis-Underwood resonance.** $\boxed{M_i - M_k \approx \Gamma_i/2}$

BOLTZMANN'S EQUATION IN BRIEF

$$\frac{d\eta_{N_i}}{dz} = \frac{z}{H(z=1)}\left[\left(1-\frac{\eta_{N_i}}{\eta_{N_i}^{\mathrm{eq}}}\right)\sum_{k=e,\mu,\tau}\Gamma^{D\,(ik)} - \frac{2}{3}\sum_{k=e,\mu,\tau}\eta_\ell^k\,\varepsilon_i^k \times \widehat{\Gamma}^{D\,(ik)}\right],$$

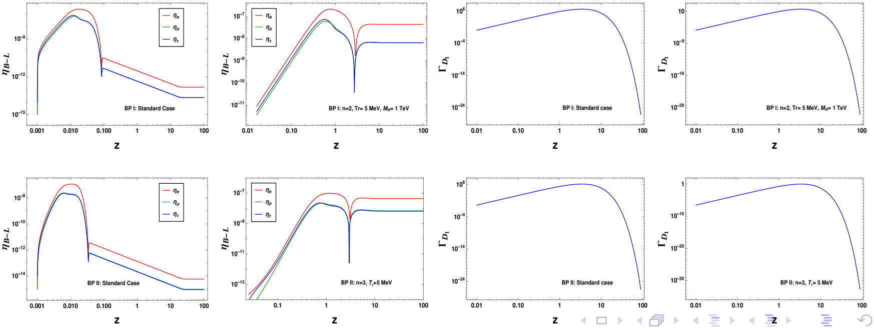
$$\frac{d\eta_\ell}{dz} = \frac{z}{H(z=1)}\left[\sum_{i=1}^{2}\varepsilon_i^\ell\left(\frac{\eta_{N_i}}{\eta_{N_i}^{\mathrm{eq}}}-1\right)\sum_{\beta=e,\mu,\tau}\Gamma^{D\,(ik)} - \frac{2}{3}\,\eta_\ell,\sum_{i=1}^{2}B_i^\ell\,\widetilde{\Gamma}^{D\,(i\ell)}\right],$$

Pilaftsis, Underwood Phys.Rev. D72 (2005) 113001

MINIMIZING WASHOUT ($K = \Gamma_i/H$) AND FINAL BARYON ASYMMETRY : NON-STANDARD COSMOLOGY

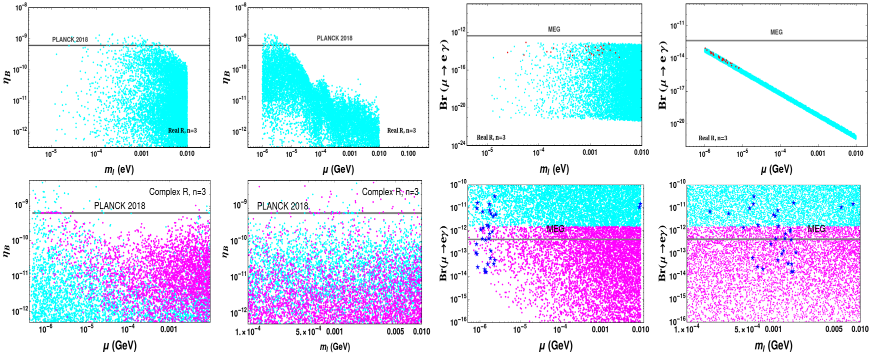
$$\text{Input ranges}: \; 5\times 10^{-7}\,\mathrm{GeV} \le \mu \le 10^{-2}\,\mathrm{GeV},$$
$$10^{-5}\ \mathrm{eV} \le m_l \le 10^{-2}\mathrm{eV}, \; -4\pi \le x, y, z \le 4\pi$$

BP	μ (GeV)	m_L (eV)	x	y	z	n	T_r (MeV)	K_1 ($z=20$)	η_B
I	2.65×10^{-3}	5.94×10^{-4}	0.63	3.02	3.05	2	5	$\mathcal{O}(10^{-5})$	6.02×10^{-10}
II	4×10^{-6}	3×10^{-4}	0.33	1.44	1.19	3	5	$\mathcal{O}(10^{-5})$	6.10×10^{-10}



TESTING LEPTOGENESIS PARAMETER SPACE THROUGH $|V_{\mu i}|^2$

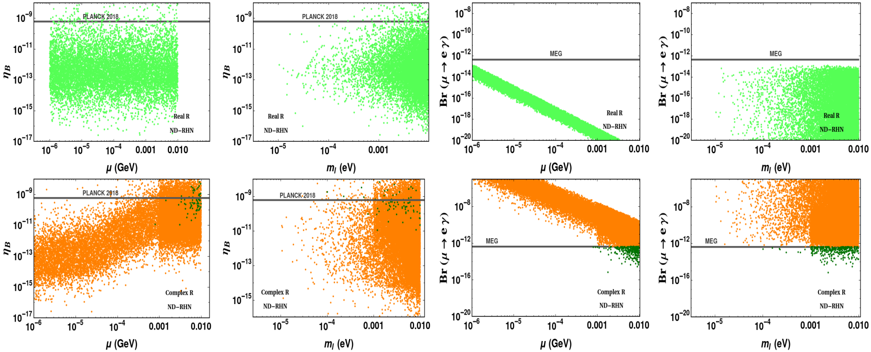
$$\mathrm{BR}(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_\mu^5}{M_W^4}\frac{1}{\Gamma_\mu}\left|\Sigma_i^9 V^*_{\mu i} V_{ei} G(y_i)\right|^2, \; V_{\mu i} \propto (Y^\nu v) M_R^{-1},$$ Abada, et al. 2011



- Future sensitivity from **MEG II**: $\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}$ [MEG II collab. 2017].
- For n=2 and complex R the corresponding parameter space does not respect non-Unitarity of lepton mixing.

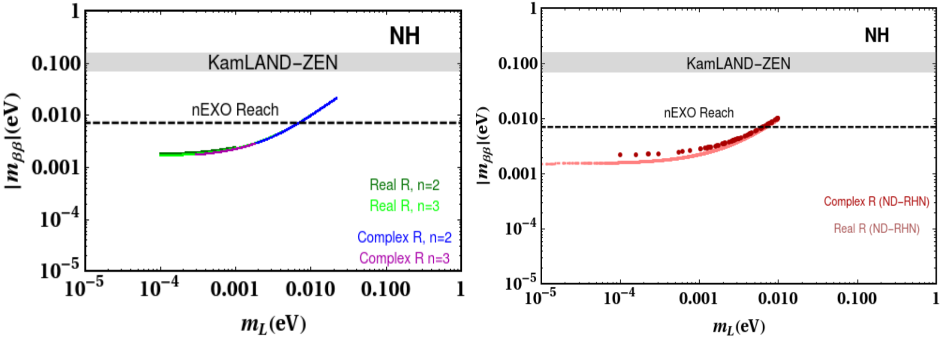
CASE B: INCREASING LEPTON ASYMMETRY, RESONANT ENHANCEMENT, $\varepsilon \sim \mathcal{O}(0.01)$

$$Y_\nu = 10^{-3}\begin{pmatrix} 0.07-0.12i & -0.45-0.58i & -0.089-0.86i \\ -0.12-0.074i & -0.58+0.45i & -0.86+0.089i \\ -1.96+2.96i & 26.81+0.97i & 26.9+22.72i \\ -2.9-1.96i & -0.97+26.8i & -22.7+26.9i \\ 5.92+3.92i & 1.96-53.5i & 45.4-53.8i \\ 3.92-5.92i & -53.5-1.96i & -53.8-45.4i \end{pmatrix},$$ with M1 = 1TeV, M2= 1001 GeV, M3= 3TeV



$Y_\nu^{ij} = -iY_\nu^{ji} \Longrightarrow$, saves the final lepton asymmetry.

EFFECTIVE NEUTRINO MASS PREDICTION, $m_{\beta\beta} = \sum_i \left|U_{ei}^2 m_i\right|$



1. Case A: n=2 choice is not favourable, doesn't satisfy η_B and non-Unitarity of lepton mixing simultaneously. Real *R*, n=3 case is favorable and also nEXO can probe the parameter space with $m_{\text{lightest}} = 10^{-4} - 0.04$ eV.
2. Case B: in case of complex *R*, $m_{\text{lightest}} = 10^{-4} - 0.02$ eV. nEXO can probe for both the choices of *R*.

CONCLUSION AND FUTURE SCOPE

1. A pure ISS scenario can offer successful leptogenesis for a higher μ range with both standard and non-standard cosmology. However, the range of μ is different for each choice of R in the CI extraction.
2. The success is independent of the choice of any PMNS phases (Dirac or Majorana) !
3. We found Br($\mu \rightarrow e\gamma$) $\sim 10^{-13,-14}$, matches the present and future sensitivity.)
4. Associated light-heavy mixing, $|V_{\mu N_{1,2}}|^2 = 10^{-7} - 10^{-4}$ (satisfying all the constraints, NU, MEG, MEGII) Restriction on the lightest neutrino mass; nEXO can shed light on m_{lightest} through $m_{\beta\beta}$.
5. Another probe of the ISS-leptogenesis parameter space would be, to look for the RHN mixing ($|V_{\mu N_{1,2}}|^2$) at Future Muon collider at 3TeV and 10TeV (under preparation with Tanumoy Mandal, Abhijit. K. Saha)

Thank You for your attention!