BARYOGENESIS IN INVERSE SEESAW MODEL

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BARYON ASYMMETRY: OBSERVATION AND MEASUREMENT

- Baryogenesis through leptogenesis (one kind of explanation behind the baryon asymmetry)
- $\eta_B^{\text{CMB}} = (6 - 6.18) \times 10^{-10}, Y_B = \frac{n_B - n_{\bar{B}}}{7 n_\gamma} = \frac{\eta_B}{7}$ (PLANCK 2018)
- CMB and BBN measurement

Criteria for baryogensis through leptogenesis: **Sakharov's conditions**

- B violation, C and CP violation, an out of equilibrium decay $\Longrightarrow$ success of leptogenesis. Sakharov 1938
- Out of equilibrium decay implies the decay rate has to be smaller than the Hubble expansion rate $\Gamma < H$ (Our main focus)

How to calculate η_B in connection with neutrino mass generation :

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

M. Fukugita and T. Yanagida, PL**B174**(1986)

Leptogenesis is an obvious consequence of the seesaw mechanisms. However, the success is not always true.

MOTIVATION: IMPORTANCE OF THE PROBLEM

A TeV scale leptogenesis is interesting, from the testability perspective. Inverse seesaw (ISS) is a natural example, which accommodates a TeV scale right handed neutrino.

- R. Volkas et al., **JCAP06(2018)012**, K. Agashe et al. **JHEP04(2019)029** : ISS alone can't offer a successful leptogenesis. The reasons being:
  1. Dirac CP violation does not yield enough lepton asymmetry ($\varepsilon \approx 10^{-9}$)
  2. Due to huge washout ($\Gamma/H \approx 10^{12}$) in ISS the final baryon asymmetry is diminished by several orders of magnitude
  3. Remedy : (Inverse + Linear) seesaw together resolves the issue.
  4. However the parameter space for leptogenesis yield $\text{Br}^{\mu\to e\gamma} < 10^{-30}$.
- We found a large lepton asymmetry $\varepsilon \sim \mathcal{O}(1)$ in a pure ISS scenario (economic !).
- Enhanced $\text{Br}^{\mu\to e\gamma} = 10^{-18}$, by several orders of magnitude.

BRIEFING INVERSE SEESAW MODEL

Additional particles: 3 TeV right-handed neutrinos and 3 sterile fermions

$$-\mathscr{L}^{\rm ISS} = Y_\nu^{\ell i}\,\overline{L_\ell}\,\widetilde{H}\,N_{R_i} + M_R\,\overline{(N_{R_i})^c}\,S^c_{L_i} + \frac{1}{2}\mu\bar{S}_{L_i}(S_L)^c + h.c. \qquad (1)$$

$$m_\nu^{3\times 3} = m_D(M_R^T)^{-1}\mu M_R^{-1}m_D^T. \qquad (2)$$

- The above ($m_\nu \sim 0.1$ eV) demands: $m_D \sim 100$GeV, $M_R \sim 10$TeV,$\mu \sim 1$keV.

$$M_\nu^{6\times 6} = \begin{pmatrix} 0 & M_R \\ M_R^T & \mu \end{pmatrix},$$

The final Mass states: $M_N = \frac{1}{2}\left(\mu \pm \sqrt{\mu^2 + 4M_R^2}\right)$

Extracting ISS Yukawa coupling : Thanks to Casas & Ibarra 2001

$$Y_\nu^{\rm ISS} = \frac{1}{v}\,U\,m_n^{1/2}\,R\,\mu^{-1/2}\,M_R^T$$

N.B.: $\mu \sim 1$keV results into a large washout of the order of 10^{12}, erase most of the asymmetries created.

INGREDIENT OF LEPTON ASYMMETRY : A COMPLEX YUKAWA

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

with, U as the PMNS matrix. R can be any orthogonal matrix satisfying, $RR^T = \mathbb{I}$, if $R = e^{iA}(e^{A}) \rightarrow$ **A** is skew-symmetric matrix.
$m_n \equiv \mathrm{diag(m_1, m_2, m_3), M_R \equiv diag(MR_1, MR_2, MR_3)}$ Pascoli 2003

$$R = e^{i\mathbf{A}} = 1 - \frac{\cosh r - 1}{r^2}\mathbf{A}^2 + i\frac{\sinh r}{r}\mathbf{A}, \text{ with } r = \sqrt{a^2+b^2+c^2}.$$

Minimal number of parameter choice $\implies a = b = c = \kappa$.

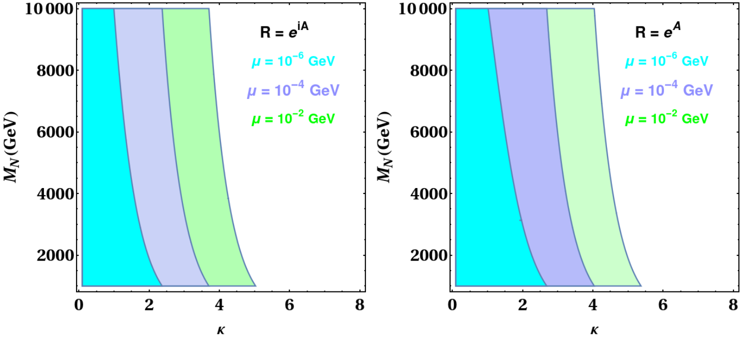
$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} U_{\text{M}},$$

where, U_M be the Majorana phase matrix, c_{ij}, s_{ij} are the mixing angles for three generations, δ the Dirac CP phase.

ORDER OF YUKAWA COUPLING FOR LEPTOGENESIS + RESTRICTION FROM $Y_\nu \leq \sqrt{4\pi}$

$$\text{When } R{=}e^{iA}\text{: } \mathrm{Cosh}[\sqrt{3}\;\kappa] \leq \left| \left(153.744\sqrt{-\frac{\mu}{m_\nu M_N^2}} + \frac{272.598\sqrt{\mu}}{\sqrt{m_\nu}M_N}\right)\mathrm{GeV} - 0.173136 \right|$$

$$\text{When } R{=}e^{A}\text{: } \mathrm{Cos}[\sqrt{3}\;\kappa] \leq \left| \left(477.809\sqrt{-\frac{\mu}{m_\nu M_N^2}} - \frac{275.863\sqrt{\mu}}{\sqrt{m_\nu}M_N}\right)\mathrm{GeV} + 1.19297 \right|$$



Importance : order of magnitude enhancement in the m_D and hence the light-heavy mixing.

Lepton asymmetry, Decay Width, Hubble rate, washout..

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

F. Deppisch 2010, G. Bambhaniya 2016

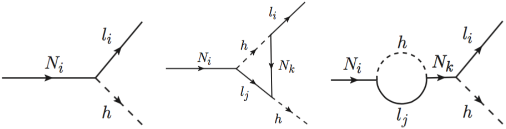
- The generated lepton asymmetry ε_i^ℓ is converted into baryon asymmetry.
- The washout factor $K_i = \Gamma_i/H$, determined mainly by the inverse decay, where, decay width : $\Gamma_i = \frac{M_i}{8\pi}(Y_\nu Y_\nu^\dagger)_{ii}$
- The Hubble rate of expansion at temperature $T \sim M_i$ (1 TeV here)

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

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

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

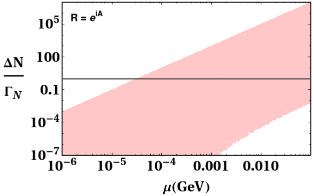
RESONANT CONDITION, $\Delta N/\Gamma_N = 1$ LEADS TO $\varepsilon \sim \mathcal{O}(1)$

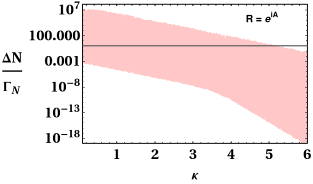


- TeV scale leptogenesis relies on the resonant enhancement of lepton asymmetry, also called **Pilaftsis-Underwood resonance**.

$$\boxed{\mathrm{M}_i - M_k \approx \Gamma_i/2}$$

- $\Delta N = (M^2_{N_2} - M^2_{N_1})/M_{N_1}$ and Γ_{N_i} is the decay width of the i-th pseudo-Dirac state (decaying particle).





ORDER OF THE YUKAWA COUPLING AND WASHOUT

Survival of the final asymmetry requires

1. Large lepton asymmetry (resonantly enhanced)
2. reduction of washout order.

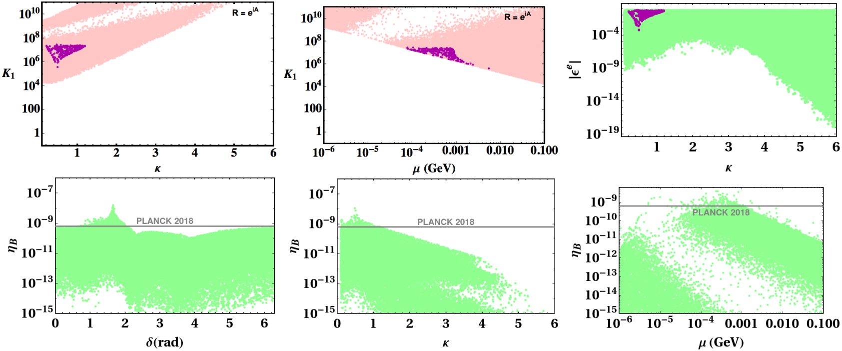
Case	Y_ν
$R = e^{i\mathbf{A}}$	$10^{-3}\begin{pmatrix} 0.275-0.568i & 0.474+0.038i & 0.171+0.253i \\ -0.848-2.704i & 1.202-1.59i & 2.047+0.299i \\ -0.929-1.188i & -0.106-1.269i & 1.469-0.373i \end{pmatrix}$
$R = e^{\mathbf{A}}$	$10^{-3}\begin{pmatrix} 0.492-0.202i & 0.344-0.143i & 0.137-0.164i \\ 1.542-0.057i & 1.207-0.04i & 1.14-0.022i \\ 0.853-0.053i & 0.476-0.037i & 0.783-0.021i \end{pmatrix}$

$$K_1^{\mathrm{complex}} \approx \frac{m_\nu M_N}{\mu} M_{\mathrm{Pl}} \left(0.926\cosh(2\sqrt{3}\kappa) + 0.073\right)$$

$$K_1^{\mathrm{real}} \approx \frac{m_\nu M_N}{\mu} M_{\mathrm{Pl}} \Big(3.32 + 0.8\sin(\sqrt{3}\kappa)(1-\cos(\sqrt{3}\kappa)) - \cos^2(\sqrt{3}\kappa) - 1.58\cos(\sqrt{3}\kappa) + 0.18\cos(2\sqrt{3}\kappa)\Big)$$

WASHOUT $K = \Gamma_i/H$ AND FINAL BARYON ASYMMETRY W.R.T. THE MODEL PARAMETERS

- Magenta points indicate $\eta_B = (6-6.2)\times 10^{-10}$ (PLANCK 2018) satisfied region



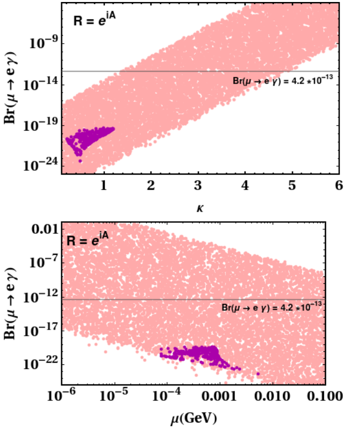
1. $\kappa = 0.1-1.46$ (the R-matrix parameter space)
2. $\mu = 10^{-4} - 10^{-3}$ (ISS LNV scale)
3. $\delta \sim \pi/2$ (Dirac CP phase)

INDIRECT PROBE THROUGH LEPTON FLAVOR VIOLATION

$$\mathrm{BR}(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_\mu^5}{M_W^4}\frac{1}{\Gamma_\mu}\left|\sum_i^9 V^*_{\mu i}V_{ei}G(y_i)\right|^2$$

Abada, et al. 2011

$$\text{light-heavy mixing : } V_{\mu i} \propto (Y^\nu v)M_R^{-1}$$



$V_{\mu i}$s are the Light-heavy mixing having a functional dependency on "κ" of R.

- Future sensitivity from **MEG II**: $\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}$ [MEG II collab. 2017].
- We still need a rise of the branching ratio by the another 5 orders of magnitude.

AM, NN, arXiv: 2204.08820

CONCLUSION AND OTHER POSSIBILITIES TO LOOK FOR

1. A pure ISS scenario can offer successful leptogenesis for a higher μ value with Dirac CP violation.
2. Decrease the washout by several orders of magnitude (increasing the Hubble expansion rate ? modified Hubble !)

   That led to:
3. Such scenario would alter the predictions for $\mu \to e\gamma$ sensitivity.
4. We expect a larger branching with the canonical μ scale (1 keV) of the ISS.
5. Another probe of the ISS-leptogenesis parameter space would be to look for the RHN mixing ($|U|^2$) at HL-LHC, SHiP, FCC-ee *etc*!

Let us plant trees!

Thank You !