Thermal leptogenesis in $SO(10) \times U(1)$GUT (on going work)

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Introduction

- There are some problems in SM.
  - Baryon asymmetry
  - left-handed neutrino mass
  - Dark matter
  - strong CP etc...
- We focused on Right-Handed Neutrino (RHN) that can explain two problems.
  - leptogenesis → baryon asymmetry
  - seesaw mechanism → left-handed neutrino mass
- I thought it would be nice if there is a theory that could introduce RHNs naturally...
  - $SO(10)$Grand Unified Theory is a candidate of it.

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$SO(10)$ Grand Unified Theory(GUT)

- advantage of $SO(10)$GUT
  - Unify SM particles+ RHN N_i

$$\Psi_{\mathbf{16}} = \mathrm{SM}_{\mathbf{10},\overline{\mathbf{5}}} + \mathrm{RHN}_{\mathbf{1}} \tag{1}$$

- some problems in $SO(10)$GUT
  - doublet-triplet splitting problem
  - GUT relation

$$Y_{ij}\Psi_i\Psi_j H \quad \to \quad Y = Y_u = Y_d = Y_e^T = Y_\nu \tag{2}$$

- We need a theory that addresses these problems!

$SO(10) \times U(1)_A$GUT

- Two methods are used to avoid these problems.
  - Adding new field Θ C.D.Frogatt, H.B.Nielsen (1979)
    - $U(1)_A$ charge: $\theta = -1$
    - VEV: $\langle\Theta\rangle = \lambda\Lambda \qquad (\lambda \sim 0.22)$

$$\left(\frac{\Theta}{\Lambda}\right)^{\psi_i+\psi_j+h} \Psi_i\Psi_j H \quad \rightarrow Y_{ij} \sim \lambda^{\psi_i+\psi_j+h} \tag{3}$$

  - field $T_{\mathbf{10}}$ → Yukawa matrix consistent with experiment.
- $SO(10) \times U(1)_A$GUT is consistent with experiment.
  - determin the neutrino yukawa Y_ν and the RHN mass M_i^0

$$Y_\nu = \begin{pmatrix} \lambda^6 & \lambda^{5.5} & \lambda^5 \\ \lambda^5 & \lambda^{4.5} & \lambda^4 \\ \lambda^3 & \lambda^{2.5} & \lambda^2 \end{pmatrix}, \quad M_i^0 = \Lambda_G \text{diag}(\lambda^{12}, \lambda^{10}, \lambda^6) \tag{4}$$

The M_i enhancement

- RHN Majorana mass term(M_i^0 term)

$$\lambda^{2\psi_i + 2\overline{c}} \frac{1}{\Lambda} \Psi_i \Psi_i \overline{C}\overline{C} \tag{5}$$

- another term

$$\lambda^{2\psi_i + 2\overline{c} + a} \frac{1}{\Lambda} \Psi_i \Psi_i \overline{C}\overline{C} A \tag{6}$$

- Because $\langle A \rangle = \Lambda \lambda^{-a}$, these give the same contribution
  - enhancement to $M_i^0 \to c_1 * M_i^0 =: M_i$

$$\lambda^{2\psi_i + 2\overline{c} + a} \frac{1}{\Lambda} \Psi_i \Psi_i \overline{C}\overline{C} \langle A \rangle = \lambda^{2\psi_i + 2\overline{c}} \frac{1}{\Lambda} \Psi_i \Psi_i \overline{C}\overline{C} \tag{7}$$

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Thermal leptogenesis

- a kind of mechanisms to explain baryon asymmetryM.Fukugita, T.Yanagida (1986)
  - Thermalizing right-handed neutrinos produce lepton numbers
  - Convert lepton number to baryon number (sphaleron process)F.R.Klinkhamer, N.S. Manton,(1984)
- CP asymmetrty:$\epsilon\rightarrow$ lepton number $\propto \epsilon_1$

$$\epsilon_i := \frac{\Gamma(N_i \rightarrow \ell + H) - \Gamma(N_i \rightarrow \bar{\ell} + H^\dagger)}{\Gamma(N_i \rightarrow \ell + H) + \Gamma(N_i \rightarrow \bar{\ell} + H^\dagger)} \simeq -\frac{1}{8\pi}\frac{1}{(Y_\nu Y_\nu^\dagger)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(Y_\nu Y_\nu^\dagger)_{ij}^2\right] f\left(\frac{M_j^2}{M_i^2}\right) \tag{8}$$

- decay parameter: $K\rightarrow$ lepton number is maximized at K $\sim$1
  - $1 \ll K \leftrightarrow$ strong wash-out, $1 \gg K \leftrightarrow$ weak wash-out

$$K_i := \frac{\Gamma_{N_i}(T=0)}{H(T=M_i)} \simeq \sqrt{\frac{45}{4\pi^3 g_*}}\frac{(Y_\nu Y_\nu^\dagger)_{ii}}{8\pi}\frac{M_{pl}}{M_i} \tag{9}$$

the relationship Y_{B-L} between M_1

- ϵ_1 and K_1 depend on M_1
  - the lepton number depends on M_1
  - M_i is determined from consistency with cosmic observations

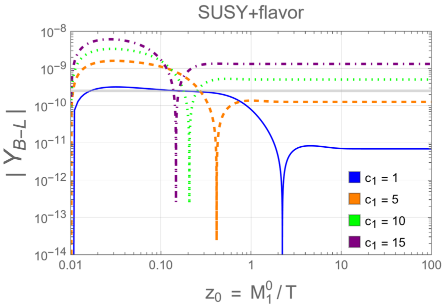

Fig 1: c_1 dependence of Y_{B-L}

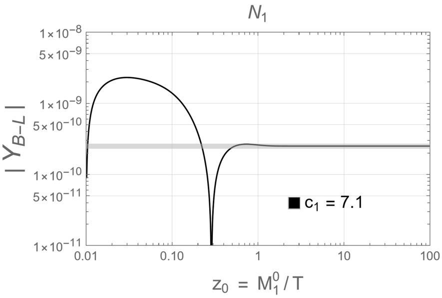

Fig 2: M_1 and Y_{B-L} consistent with observations

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Results of this study

we worked on in this study

The first consideration of thermal leptogenesis in $SO(10) \times U(1)_A$GUT.

Main Results

Result 1 Presenting the possibility of thermal leptogenesis in SUSY $SO(10)$ GUT.

Result 2 Calculating the contribution of N_2

Result 1

- There is some bound to the M_1.
  - lower bound to M_1 (Ibarra bound) S.Davidson, A.Ibarra (2002)
  - neutrino seesaw + $\sum m_\nu$

$$m_\nu = v_u^2 Y_\nu^T M^{-1} Y_\nu \tag{10}$$

- We need to avoid these bounds.
  - In minmal SO(10), it is difficult to avoid this.
  - non-thermal leptogenesis can avoid these bounds.Asaka. T (2003) 等
- $SO(10) \times U(1)_A$GUT can avoid these bound
  - This presents the possibility of thermal leptogenesis in SO(10)GUT.

Result 2

- flavor leptogenesis
    - Temperatures reaching thermal equilibrium vary from each flavor.
    - Consider the lepton doublet flavor.

$$\epsilon_{\alpha i} = \frac{\Gamma(N_i \to L_\alpha + H) - \Gamma(N_i \to \overline{L}_\alpha + H^\dagger)}{\Gamma(N_i \to L_\alpha + H) + \Gamma(N_i \to \overline{L}_\alpha + H^\dagger)}$$

$$\simeq -\frac{1}{8\pi}\frac{1}{(Y_\nu Y_\nu^\dagger)_{ii}}\sum_{j\neq i} \mathrm{Im}\left[Y_{\nu\,\alpha i} Y^*_{\nu\,\alpha j}(Y_\nu Y_\nu^\dagger)_{ij}\right] f(M_j^2/M_i^2) \tag{11}$$

$$K_{\alpha i} \simeq \sqrt{\frac{45}{4\pi^3 g_*}}\frac{|Y_{\nu\,\alpha i}|^2}{8\pi}\frac{M_{pl}}{M_i} \tag{12}$$

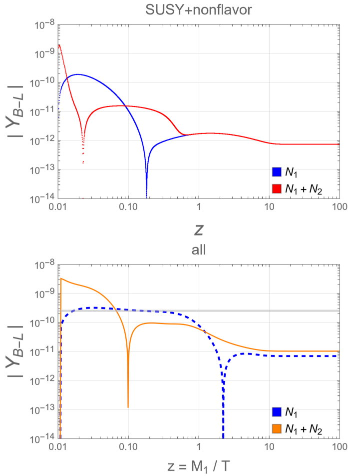
Result 2

- Comparing flavor leptogenesis with non-flavor leptogenesis

non-flavor: all flavor have same $K_1 \sim 50$
strong wash-out
→ no N_2 contribution

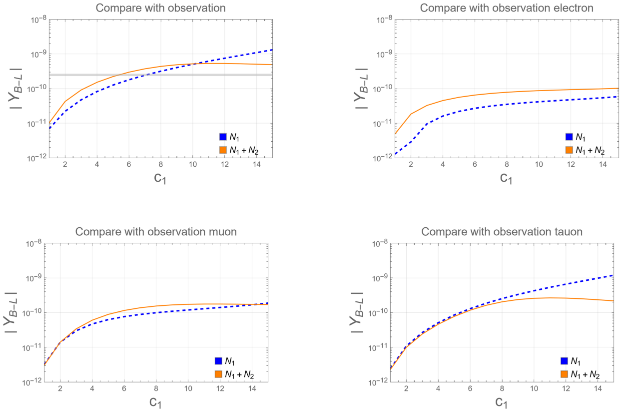
flavor: $K_{1e} \sim 2, K_{1\mu} \sim 9, K_{1\tau} \sim 40$
→ N_2 contribution appears

- This contribution cannot be negligible in this model.



Result 2

- c_1 dependence of lepton number
- lepton number of N_2 remain in electron flavor
  - weak wash-out in e flavor strong wash-out in μ, τ flavor
- For larger c_1, lepton number of $N_1 + N_2$ are strong washed-out.



Result 2

- M_1 consistent with cosmological observations.

$$c_1 := \frac{M_1}{M_1^0} \simeq 7.1(N_1 \text{ only}) \to 5.4(N_1 + N_2) \quad (13)$$

- Estimating the mass of the lightest left-handed neutrino from the seesaw mechanism.

$$m_\nu = v_u^2 Y_\nu^T M^{-1} Y_\nu \quad (14)$$

$$m_1 \sim m_1^0 / c_1 \quad (15)$$

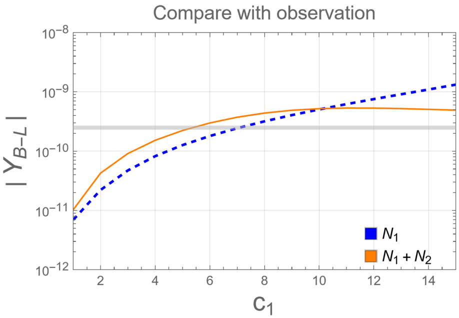


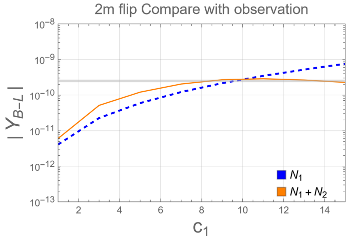
Fig 3: Relationship between c_1 and lepton number

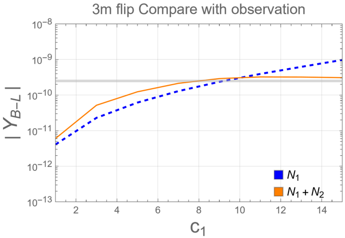
conclusion

- First consideration of thermal leptogenesis in $SO(10)\times U(1)$GUT
    - Presenting the possibility of thermal leptogenesis in $SO(10)$GUT.
    - Clarification of the contribution of N_2 in flavor leptogenesis.
    - Estimating the mass of lightest left-handed neutrinos through seesaw mechanisms.
        - ★ It is suppressed.$(1/c_1 \sim 0.19)$

Comments and Future work

- $O(1)$ coefficients exist
    - Lepton number varies with $O(1)$ coefficient.
- We will examine the contribution of N_3.
    - We estimate the contribution to be small.
    - Other calculation methods are needed to deal with different equilibrium states.


2m flip Compare with observation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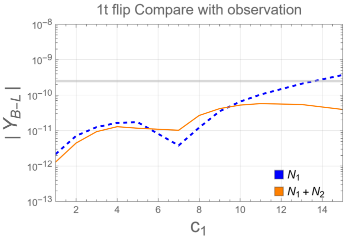
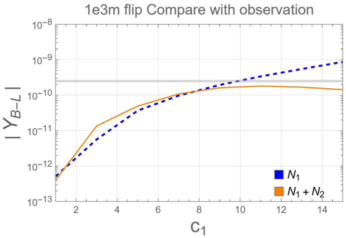

1t flip Compare with observation


1e3m flip Compare with observation