Cosmological Family Asymmetry and CP violation

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1. Introduction

Low-energy physics - - - - - - - - - - - - - - - - Cosmology

connection ?

Neutrino oscillations

SK, K2K, SNO, KamLAND . . . .

Baryon asymmetry

CMB, BBN, . . .

Beyond the standard model

Seesaw model : SM + Right-handed heavy neutrinos

CP violation ------------------------------ **Leptogenesis**

in ν oscillations

$$m_\nu = \frac{(y_\nu v)^2}{M}$$

Fukugita and Yanagida ('86)

But, there is no direct connection (many parameters).

Branco, Morozumi, Nobre and Rebelo ('01)

Pascoli, Petcov and Redejohann ('03) . . .

This work

We discuss cosmological lepton family asymmetry ($Y_L = Y_e + Y_\mu + Y_\tau$) produced in right-handed neutrino decay (leptogenesis) in the mininal seesaw model.

↓

SM + 2 heavy right-handed neutrino ($m_{\nu\,\mathrm{lightest}} = 0$)

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We also discuss the constraints from neutrino oscillations on concrete mass textures in which one lepton family asymmetry dominant leptogenesis can naturally realized.

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Plan of the talk

1. Introduction
2. CP violation in minimal seesaw model
3. Cosmological lepton family asymmetry and low-energy observables
4. Summary

2. CP violation in minimal seesaw model

$$-\mathcal{L} = y_\ell^i \, \overline{L}_i \, \ell_{Ri} \, \phi + y_\nu^{ik} \, \overline{L}_i \, N_k \, \tilde{\phi} + \frac{1}{2} \, \overline{N}_k^c \, M_k \, N_k + \text{h.c.}$$

$$(\, i = e, \mu, \tau, \quad k = 1, 2 \,)$$

$$m_i = y_\ell^i \, v/\sqrt{2} \, , \quad m_{Dik} = y_\nu^{ik} \, v/\sqrt{2} \qquad m_\nu = \frac{(y_\nu v)^2}{M}$$

N_k : right-handed Majorana neutrinos ($v \ll M_k$)

(1) bi-unitary parametrization

$$m_D = U_L \, m \, V_R \quad : \quad U_L = U(\theta_{L23}, \theta_{L13}, \theta_{L12}, \delta_L) \cdot diag(1, e^{-i\frac{\gamma_L}{2}}, e^{i\frac{\gamma_L}{2}})$$

$$: \quad V_R = V(\theta_{L12}) \cdot diag(1, e^{-i\frac{\gamma_R}{2}}, e^{i\frac{\gamma_R}{2}})$$

(2) unit vector parametrization

$$m_D = (\mathbf{m_{D1}}, \mathbf{m_{D2}}) = \begin{pmatrix} m_{De1} & m_{De2} \\ m_{D\mu1} & m_{D\mu2} \\ m_{D\tau1} & m_{D\tau2} \end{pmatrix} = (\mathbf{u_1}, \mathbf{u_2}) \begin{pmatrix} m_{D1} & \\ & m_{D2} \end{pmatrix}$$

$$\mathbf{u_k} = \frac{\mathbf{m_{Dk}}}{m_{Dk}} \quad ; \quad m_{Dk} = |\mathbf{m_{Dk}}|$$

m_{Di2} are taken to be complex
(3 CP violating phases)

CP violating phases

In (1) bi-unitary parametrization,

$$H_R \equiv m_D^\dagger m_D = U_R^\dagger (m_D^{\rm diag})^2 U_R$$

---> **Total lepton asymmetry in leptogenesis** (A)

$$m_\nu = m_D M^{-1} m_D^T = U_L^\dagger m_D^{\rm diag} U_R M^{-1} U_R^\dagger m_D^{\rm diag} U_L$$

---> **CP violation in neutrino oscillations** (B)

$$\textbf{CPV} \ : P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

$$= 16 \underbrace{s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23} \sin\delta}_{\equiv J_{CP}} \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

The phases that contributes to (A) and (B) is different.

CP violation in ν osillation $\Leftarrow$ δ, ρ $\}$ m_ν seesaw m_D $\{$ δ_L; γ_L $\Rightarrow$ lepton family asymmetry; γ_R $\Rightarrow$ total lepton asymmetry

(Thermal) Leptogenesis

Fukugita and Yanagida ('86), Luty ('92), Covi et al ('96), Buchmuller and Plumacher ('98~) . . .

Majorana neutrino decay ---> Lepton number violation

CP violation ↓ Out of equilibrium

Lepton asymmetry ($Y_L \neq 0$)

sphaleron ↓

Baryon asymmetry ($Y_B \neq 0$)

$L=B=0 \rightarrow L=-1, B=0 \rightarrow L=-2/3, B=1/3$

↑ leptogenesis ↑ sphaleron : B-L conserving

$$\textbf{CMB} \quad : \quad \eta_B^{\rm CMB} \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10} \qquad (\textbf{2003})$$

$$\textbf{BBN} \quad : \quad \eta_B^{\rm BBN} \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.1 \pm 0.5) \times 10^{-10} \qquad (\textbf{2001}, \textbf{2003})$$

CP violation in heavy neutrino decay

Fukugita and Yanagida ('86), Luty ('92), Covi et al ('96), . . .

$$\epsilon^k = \sum_{i=e,\mu,\tau} \epsilon_i^k \,\mathrm{Br}(N^k \to \ell_i^\pm \phi^\mp) \quad ; \quad \epsilon_i^k = \frac{\Gamma(N^k \to \ell_i^- \phi^+) - \Gamma(N^k \to \ell_i^+ \phi^-)}{\Gamma(N^k \to \ell_i^- \phi^+) + \Gamma(N^k \to \ell_i^+ \phi^-)}$$

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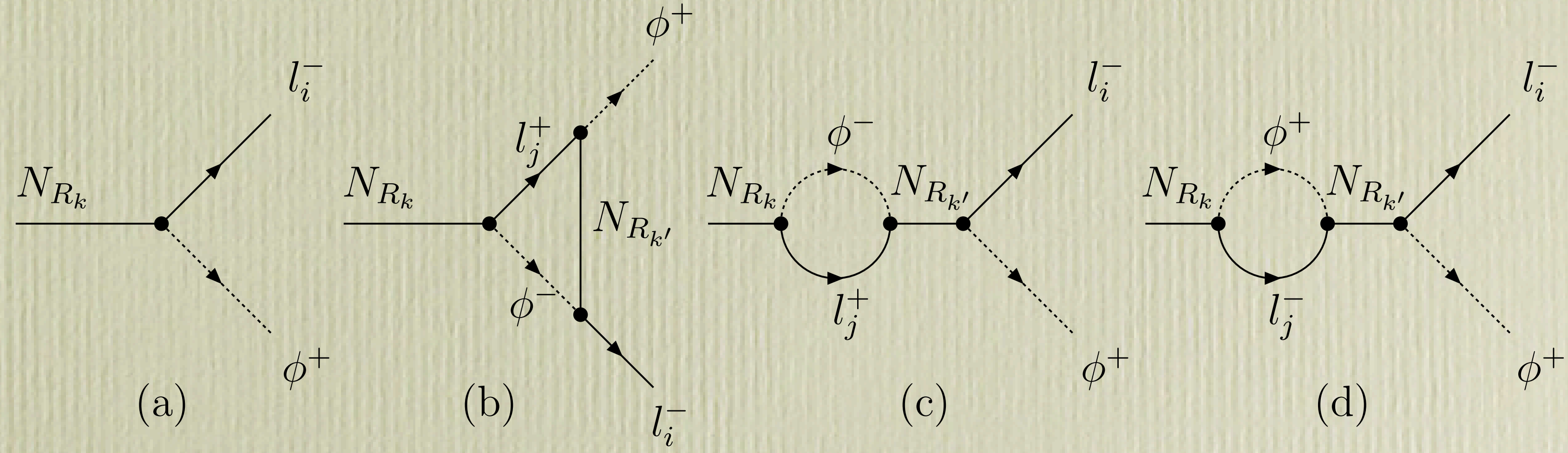
lepton family asymmetry



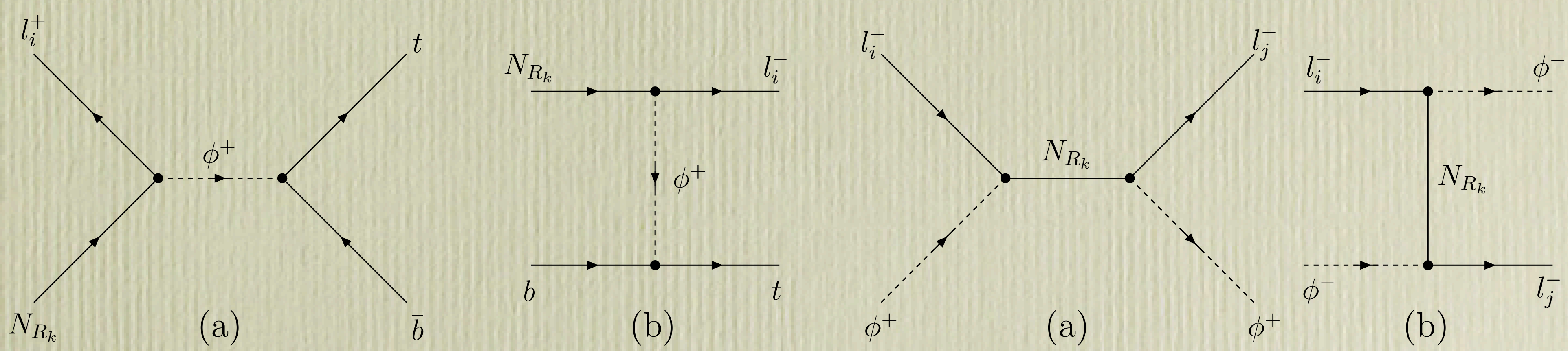
$$\epsilon_i^k = \frac{1}{8\pi} \sum_{k' \neq k} \left[I(x_{k'k}) \frac{\mathrm{Im}\left[(y_\nu^\dagger y_\nu)_{kk'} (y_\nu)_{ik}^* (y_\nu)_{ik'}\right]}{|(y_\nu)_{ik}|^2} + \frac{1}{1 - x_{k'k}} \frac{\mathrm{Im}\left[(y_\nu^\dagger y_\nu)_{k'k} (y_\nu)_{ik}^* (y_\nu)_{ik'}\right]}{|(y_\nu)_{ik}|^2} \right]$$

$$\left(x_{k'k} = M_{k'}^2 / M_k^2, \quad I(x) = \sqrt{x}\left[1 + \frac{1}{1-x} + (1+x) \ln \frac{x}{1+x}\right] \right)$$

Baryogenesis via leptogenesis

$$\eta_B \simeq 10^{-2} \sum_k \epsilon^k \, \kappa(\widetilde{m}_k, M_k \, \overline{m}_k^2) \quad \left(\widetilde{m}_k \equiv \frac{(m_D^\dagger m_D)_{kk}}{M_k}, \; \overline{m}_k^2 \equiv m_1^2 + m_2^2 + m_3^2 \right)$$

- κ : efficiency factor (washout due to scattering processes)



Baryon asymmetry η_B can be systematically calculated by solving Boltzmann equations.

3. Cosmological lepton family asymmetry and low-energy observables

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$$m_1 = 0 \,, \quad m_2 = \sqrt{\Delta m^2_{\rm sol}} \simeq 7 \times 10^{-3}\,{\rm eV} \,, \quad m_3 = \sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}\,{\rm eV}$$

$$\theta_{L12} = \theta_{\rm sol} = \frac{\pi}{6} \,, \quad \theta_{L23} = \theta_{\rm atm} = \frac{\pi}{4} \,, \quad \theta_{L13} = 0$$

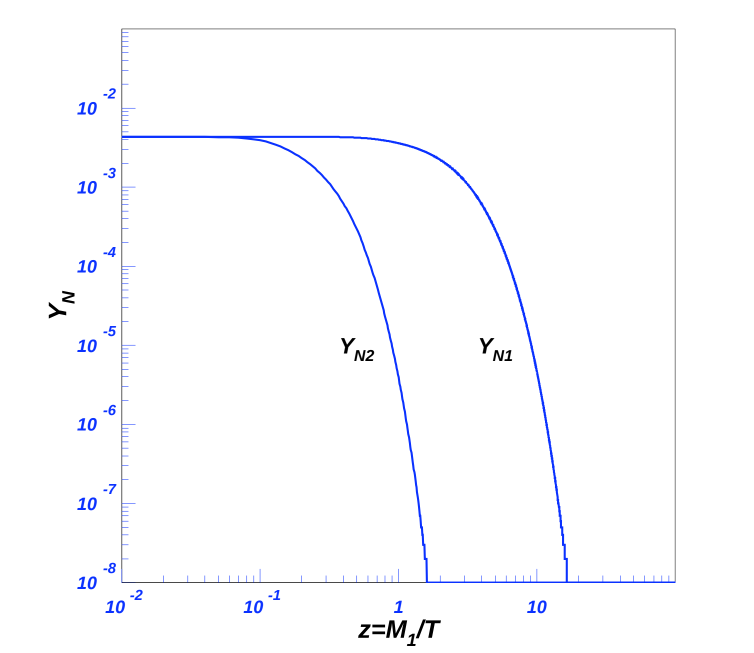
$$M_1 = 2 \times 10^{11}\,{\rm GeV} \,, \quad M_2 = 2 \times 10^{12}\,{\rm GeV}$$

$$Y_{N_k} = Y^{\rm eq}_{N_k} \,, \quad Y_{L_i} = 0 \;\; {\rm at} \;\; T \ll M_1 \; (z = M_1/T = 10^{-2})$$

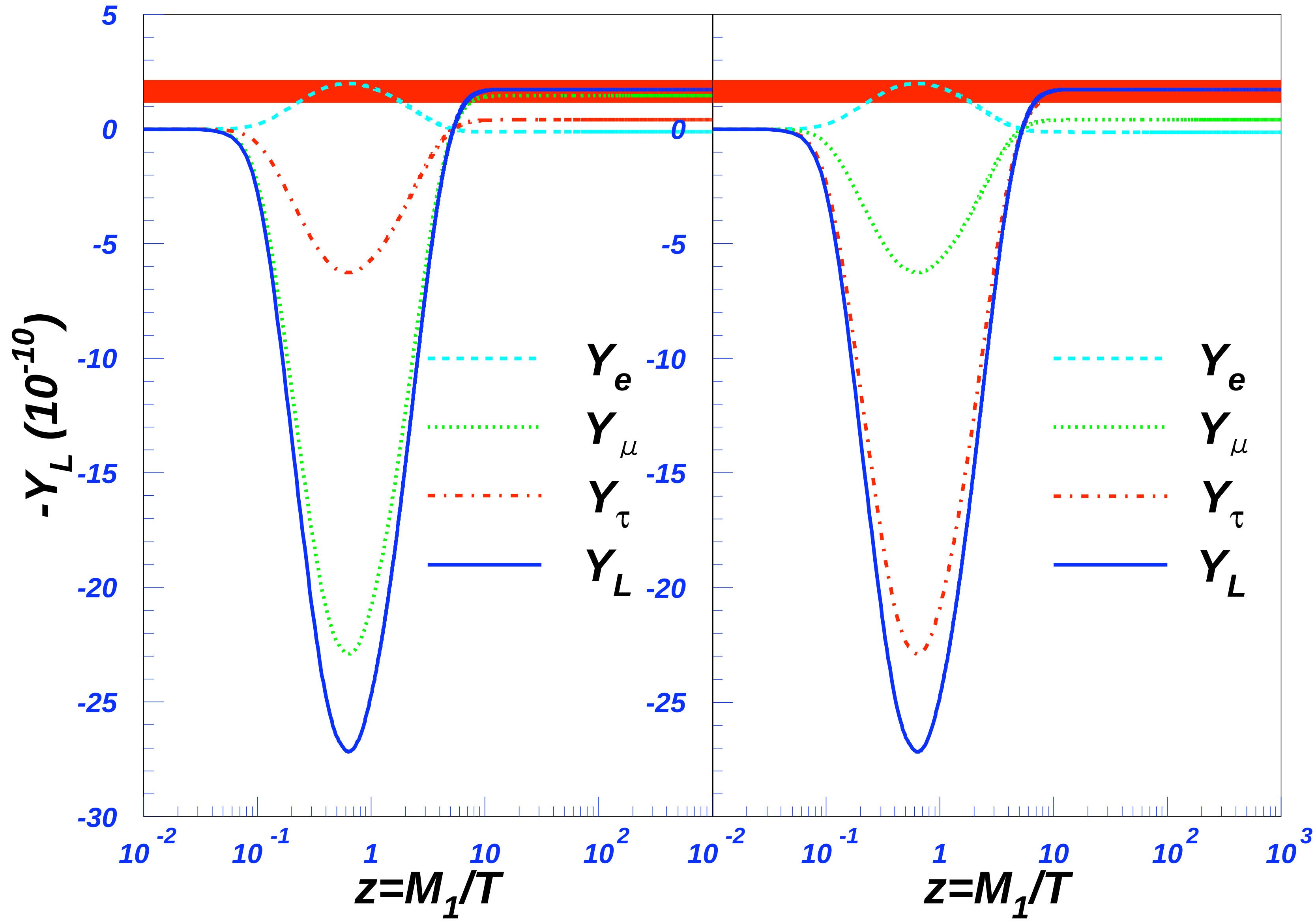
(1) bi-unitary parametrization

$$m_D = U_L\, m\, V_R \quad : \quad U_L = U(\theta_{L23}, \theta_{L13}, \theta_{L12}, \delta_L) \cdot diag(1, e^{-i\frac{\gamma_L}{2}}, e^{i\frac{\gamma_L}{2}})$$

$$: \quad V_R = V(\theta_{L12}) \cdot diag(1, e^{-i\frac{\gamma_R}{2}}, e^{i\frac{\gamma_R}{2}})$$



$\gamma_L = 0$ $\gamma_L = \pi$



Y_μ dominant leptogenesis **Y_τ dominant leptogenesis**

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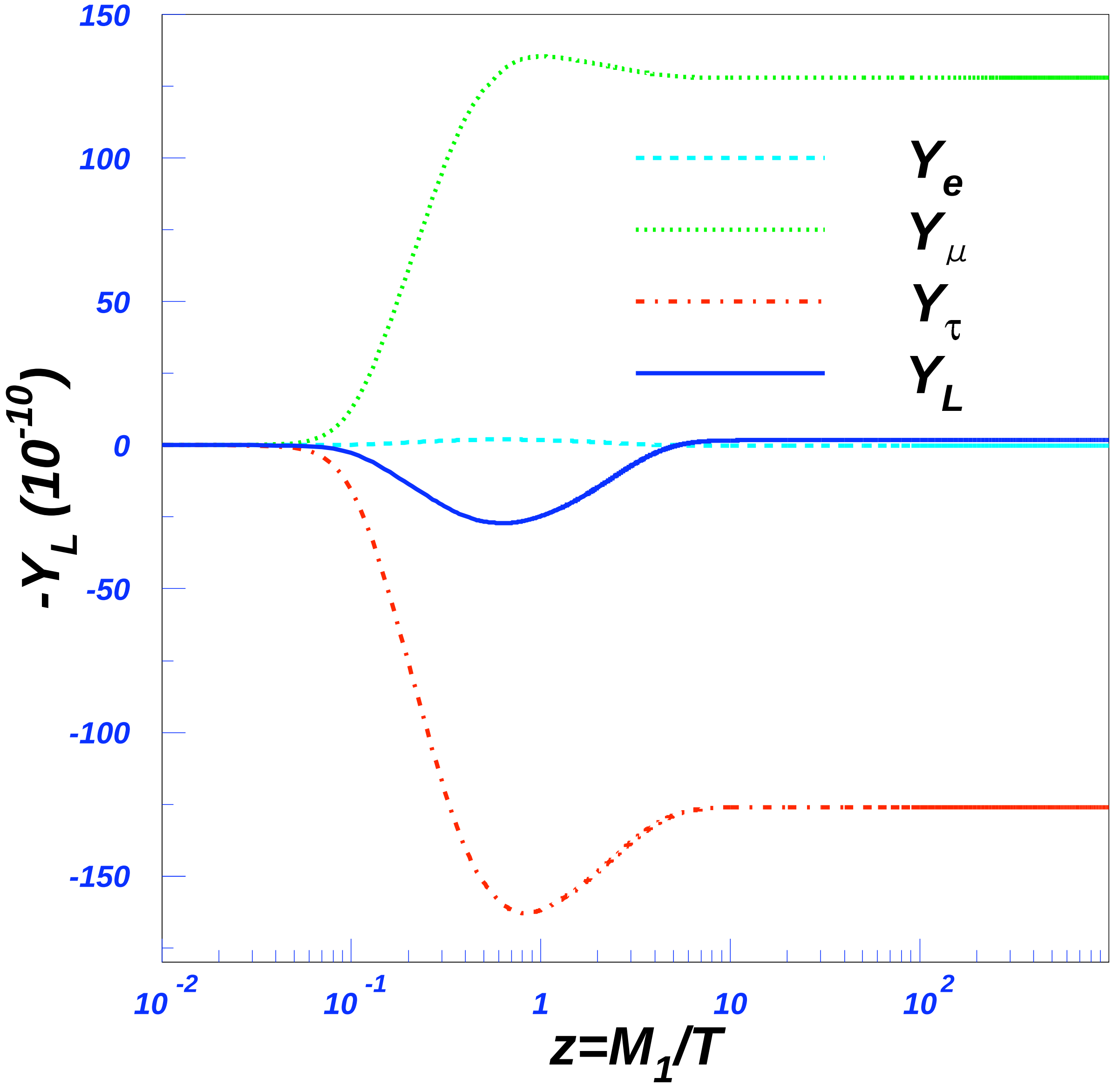
$\gamma_L = \pi/2$



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Connection to low-energy observables

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(2) unit vector parametrization

$$m_D = (\mathbf{m_{D1}}, \mathbf{m_{D2}}) = \begin{pmatrix} m_{De1} & m_{De2} \\ m_{D\mu 1} & m_{D\mu 2} \\ m_{D\tau 1} & m_{D\tau 2} \end{pmatrix} = (\mathbf{u_1}, \mathbf{u_2}) \begin{pmatrix} m_{D1} & \\ & m_{D2} \end{pmatrix}$$

$$\mathbf{u_k} = \frac{\mathbf{m_{Dk}}}{m_{Dk}} \quad ; \quad m_{Dk} = |\mathbf{m_{Dk}}|$$

m_{Di2} are taken to be complex
(3 CP violating phases)

$$M = \begin{pmatrix} M_1 & \\ & M_2 \end{pmatrix}$$

$$-m_\nu = m_D \, M^{-1} \, m_D^T = \mathbf{u_1} \mathbf{u_1^T} X_1 + \mathbf{u_2} \mathbf{u_2^T} X_2 \quad ; \quad X_k \equiv \frac{m_{Dk}^2}{M_k} \ (k = 1, 2)$$

CP violation in neutrino oscillation

$$J_{\rm CP} = \frac{\Delta}{(m_1^2 - m_2^2)(m_2^2 - m_3^2)(m_3^2 - m_1^2)} \ , \quad \Delta = {\rm Im}[(m_\nu m_\nu^\dagger)_{e\mu}(m_\nu m_\nu^\dagger)_{\mu\tau}(m_\nu m_\nu^\dagger)_{\tau e}]$$

$$\begin{aligned}
&\Delta = \left(1 - |\mathbf{u_1^\dagger} \cdot \mathbf{u_2}|^{\mathbf{2}}\right) \times \\
&\Big[X_1^4 X_2^2 \left\{ {\rm Im}\left[\left(u_{e1}^* u_{e2} u_{\mu1} u_{\mu2}^*\right) |u_{\tau1}|^2 + \left(u_{\mu1}^* u_{\mu2} u_{\tau1} u_{\tau2}^*\right) |u_{e1}|^2 + (u_{\tau1}^* u_{\tau2} u_{e1} u_{e2}^*) |u_{\mu1}|^2\right]\right\} \\
&+X_1^3 X_2^3 \left\{ {\rm Im}[(u_{e1}^* u_{e2})(\mathbf{u_1^\dagger} \cdot \mathbf{u_2})(|u_{\tau1} u_{\mu2}|^2 - |u_{\mu1} u_{\tau2}|^2) + (u_{\mu1}^* u_{\mu2})(\mathbf{u_1^\dagger} \cdot \mathbf{u_2})(|u_{e1} u_{\tau2}|^2 - |u_{\tau1} u_{e2}|^2) \right. \\
&\qquad \left. +(u_{\tau1}^* u_{\tau2})(\mathbf{u_1^\dagger} \cdot \mathbf{u_2})(|u_{\mu1} u_{e2}|^2 - |u_{e1} u_{\mu2}|^2)] \right\} \\
&-X_1^2 X_2^4 \left({\rm Im}\left[\left(u_{e1}^* u_{e2} u_{\mu1} u_{\mu2}^*\right) |u_{\tau2}|^2 + \left(u_{\mu1}^* u_{\mu2} u_{\tau1} u_{\tau2}^*\right) |u_{e2}|^2 + (u_{\tau1}^* u_{\tau2} u_{e1} u_{e2}^*) |u_{\mu2}|^2\right]\right) \Big]
\end{aligned}$$

Δ is determined by u_{ik} and X_k.

Two interesting cases

(1) $\mathbf{u_1^\dagger} \cdot \mathbf{u_2} = 0$

No leptogenesis

Non-vanishing CP violation in neutrino oscillation

$$\Delta = X_1^2\, X_2^2\, (X_1^2 - X_2^2)\, \mathrm{Im}[u_{\tau 1}^* u_{\tau 2} u_{e1} u_{e2}^*]$$

(2) $\mathbf{u_1^\dagger} \cdot \mathbf{u_2} = u_{a1}^* u_{a2} \quad (a = e, \mu, \tau)$

One family dominant leptogenesis

Natural possibility : consider two zero elements in m_D

Type I

$\Delta \neq 0$

allowed --> (90%CL)

Type		Δ
Type I (a) e-leptogenesis	$\begin{pmatrix} u_{e1} & u_{e2} \\ u_{\mu 1} & 0 \\ 0 & u_{\tau 2} \end{pmatrix}$	$(1-\lvert u_{e1}u_{e2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{e1}^*u_{e2})^2(-\lvert u_{\tau 2}\rvert^2\lvert u_{\mu 1}\rvert^2)$
Type I(b) e-leptogenesis	$\begin{pmatrix} u_{e1} & u_{e2} \\ 0 & u_{\mu 2} \\ u_{\tau 1} & 0 \end{pmatrix}$	$(1-\lvert u_{e1}u_{e2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{e1}^*u_{e2})^2\lvert u_{\tau 1}\rvert^2\lvert u_{\mu 2}\rvert^2.$
Type I (a) μ leptogenesis	$\begin{pmatrix} u_{e1} & 0 \\ u_{\mu 1} & u_{\mu 2} \\ 0 & u_{\tau 2} \end{pmatrix}$	$(1-\lvert u_{\mu 1}u_{\mu 2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{\mu 1}^*u_{\mu 2})^2(\lvert u_{\tau 2}\rvert^2\lvert u_{e1}\rvert^2)$
Type I (b) μ leptogenesis	$\begin{pmatrix} 0 & u_{e2} \\ u_{\mu 1} & u_{\mu 2} \\ u_{\tau 1} & 0 \end{pmatrix}$	$(1-\lvert u_{\mu 1}u_{\mu 2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{\mu 1}^*u_{\mu 2})^2(-\lvert u_{e2}\rvert^2\lvert u_{\tau 1}\rvert^2)$
Type I (a) τ leptogenesis	$\begin{pmatrix} u_{e1} & 0 \\ 0 & u_{\mu 2} \\ u_{\tau 1} & u_{\tau 2} \end{pmatrix}$	$(1-\lvert u_{\tau 1}u_{\tau 2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{\tau 1}^*u_{\tau 2})^2(-\lvert u_{e1}\rvert^2\lvert u_{\mu 2}\rvert^2)$
Type I (b) τ leptogenesis	$\begin{pmatrix} 0 & u_{e2} \\ u_{\mu 1} & 0 \\ u_{\tau 1} & u_{\tau 2} \end{pmatrix}$	$(1-\lvert u_{\tau 1}u_{\tau 2}\rvert^2)X_1^3X_2^3\mathrm{Im}(u_{\tau 1}^*u_{\tau 2})^2(\lvert u_{e2}\rvert^2\lvert u_{\mu 1}\rvert^2)$

Type II

$\theta_{13} = 0$

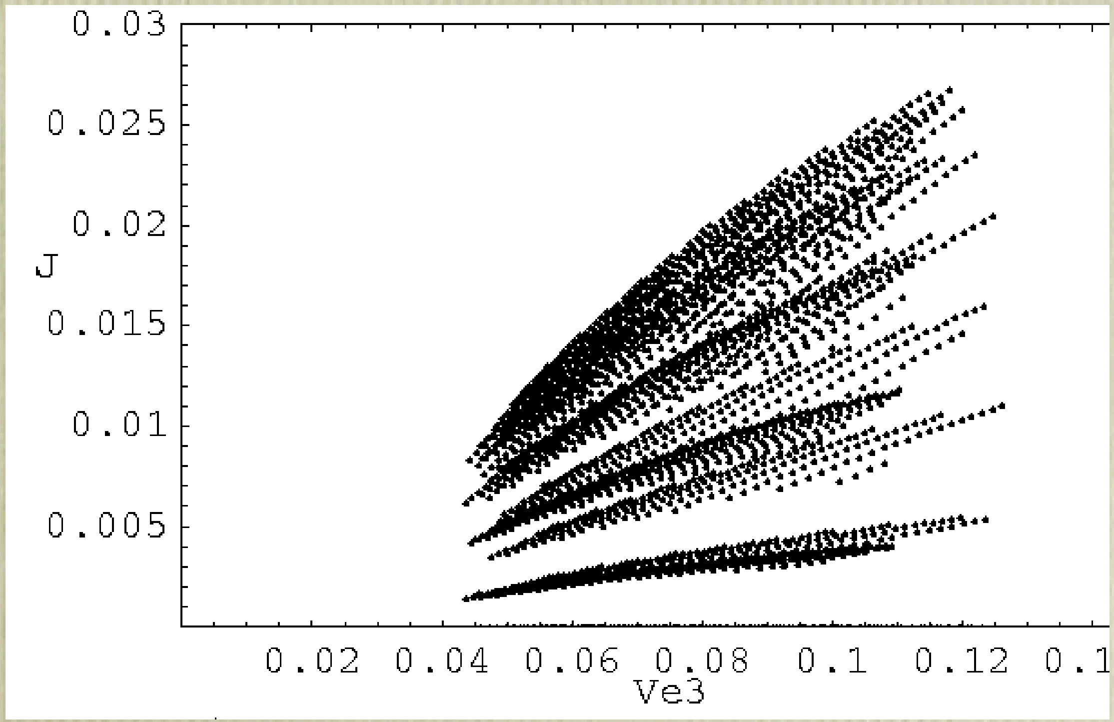
$\Delta = 0$

type	(a)	(b)	V^{MNSN}	V^{MNSI}
type II (e-leptogenesis)	$\begin{pmatrix} u_{e1} & u_{e2} \\ 0 & u_{\mu 2} \\ 0 & u_{\tau 2} \end{pmatrix}$	$\begin{pmatrix} u_{e1} & u_{e2} \\ u_{\mu 1} & 0 \\ u_{\tau 1} & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$	$\begin{pmatrix} * & * & 0 \\ * & * & * \\ * & * & * \end{pmatrix}$
type II (μ -leptogenesis)	$\begin{pmatrix} 0 & u_{e2} \\ u_{\mu 1} & u_{\mu 2} \\ 0 & u_{\tau 2} \end{pmatrix}$	$\begin{pmatrix} u_{e1} & 0 \\ u_{\mu 1} & u_{\mu 2} \\ u_{\tau 1} & 0 \end{pmatrix}$	$\begin{pmatrix} * & * & * \\ 0 & * & * \\ * & * & * \end{pmatrix}$	$\begin{pmatrix} * & * & * \\ * & * & 0 \\ * & * & * \end{pmatrix}$
type II (τ -leptogenesis)	$\begin{pmatrix} 0 & u_{e2} \\ 0 & u_{\mu 2} \\ u_{\tau 1} & u_{\tau 2} \end{pmatrix}$	$\begin{pmatrix} u_{e1} & 0 \\ u_{\mu 1} & 0 \\ u_{\tau 1} & u_{\tau 2} \end{pmatrix}$	$\begin{pmatrix} * & * & * \\ * & * & * \\ 0 & * & * \end{pmatrix}$	$\begin{pmatrix} * & * & * \\ * & * & * \\ * & * & 0 \end{pmatrix}$

Regions of observable parameters

type	$\lvert V_{e1}^{MNS} \rvert$	$\lvert V_{e2}^{MNS} \rvert$	$\lvert V_{e3}^{MNS} \rvert$	$\lvert V_{\mu 3}^{MNS} \rvert$	$\lvert V_{\tau 3}^{MNS} \rvert$	$\lvert J \rvert$
exp. (90%)	$0.79 \sim 0.86$	$0.50 \sim 0.61$	$0 \sim 0.16$	$0.63 \sim 0.79$	$0.60 \sim 0.77$	
I(a) μ normal $X_1 \leq X_2$	$0.79 \sim 0.86$	$0.50 \sim 0.61$	$0.058 \sim 0.11$	$0.63 \sim 0.79$	$0.60 \sim 0.77$	$0 \sim 0.023$
I(b) μ normal $X_2 \leq X_1$	$0.79 \sim 0.86$	$0.50 \sim 0.61$	$0.058 \sim 0.11$	$0.64 \sim 0.79$	$0.61 \sim 0.77$	$0 \sim 0.024$
I(a) τ normal $X_1 \leq X_2$	$0.79 \sim 0.86$	$0.50 \sim 0.61$	$0.054 \sim 0.10$	$0.63 \sim 0.79$	$0.61 \sim 0.77$	$0 \sim 0.022$
I(b) τ normal $X_2 \leq X_1$	$0.79 \sim 0.86$	$0.50 \sim 0.61$	$0.054 \sim 0.10$	$0.63 \sim 0.79$	$0.61 \sim 0.77$	$0 \sim 0.022$

All other textures and hierarchies are excluded (90%CL).



<--- I (a) τ normal

4. Summary

We study CP violation in neutrino oscillations and its possible connection with lepton family asymmetries generated from heavy Majorana neutrino decays. This strongly depends on left-handed CP violating phase γ_L.

We identify the two zeros texture models in which lepton asymmetry is dominated by a particular family asymmetry (e-, □-, □-leptogenesis).

We have predicted the possible ranges of U_{e3} and the low energy CP violation observable J_{CP}.

Questions

How can we observe cosmological lepton family asymmetry ?

What is the solution of cosmological gravitino problem ?
(SUSY model)