Reheating-era leptogenesis

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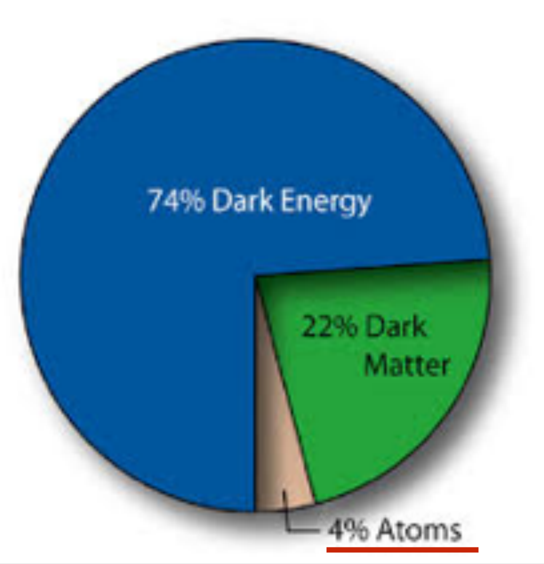
Higgs boson

- M_H=125GeV.
- consistent with SM prediction.
- SM is completed.

Baryogenesis

- There remains mystery in particle physics.
- We do not understand
  - dark energy
  - dark matter
  - why energy density of atom is so large(baryon asymmetry)



$$\frac{n_B}{s} \simeq (8.68 \pm 0.05) \times 10^{-11}$$

Sakharov's three conditions

1. Violation of baryon number
2. Violation of C and CP
    - Initial state : C and CP symmetric
      Final state : C and CP asymmetric
3. Out of thermal equilibrium
    - otherwise inverse process exists.

Leptogenesis

- One of simplest scenarios : Leptogenesis

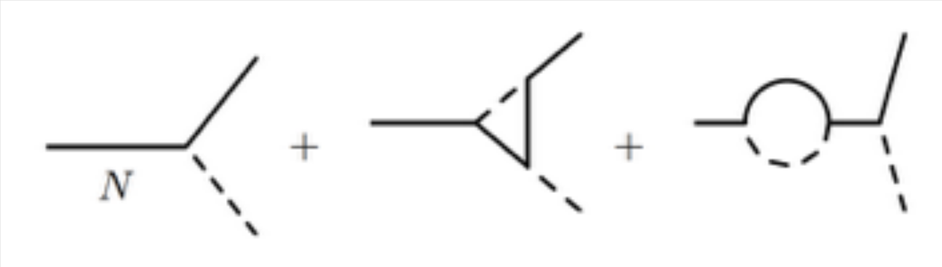
★ Asymmetry by decay of RH neutrino

- RHν is produced in thermal plasma for $T_R \gtrsim M_R$

['86 Fukugita, Yanagida]

by inflaton decay for $m_{inf} \gtrsim M_R$

['91 Lazarides, Shafi]



Our work

Asymmetry by scattering between lepton and Higgs at reheating era

['15 YH Kawana]

Plan

1. Leptogenesis at reheating-era
2. seesaw models

Plan

1. Leptogenesis at reheating-era
2. seesaw models

Setup : Action

- Assume the existence of inflaton other than SM.
- Introduce following dim5 and 6 operators.

['97 Aoki and Kawai]

$$S = \int d^4x \left(\mathcal{L}_{\rm SM} + \frac{\lambda^{(1)}_{ij}}{\Lambda_1}(\overline{L_i}\widetilde{\Phi})(\overline{L_j}\widetilde{\Phi}) + \frac{\lambda^{(2)}_{ijkl}}{\Lambda_2^2}(\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \text{h.c.} \right)$$

LH **ν** Majorana mass
$\Lambda_1 \sim 10^{14\text{-}15}$GeV

For $\lambda_1=1$ and $m_\nu=0.1$eV.

UV Model dep.
If type-I seesaw
$\Lambda_2 \sim 10^{15\text{-}16}$GeV(later).

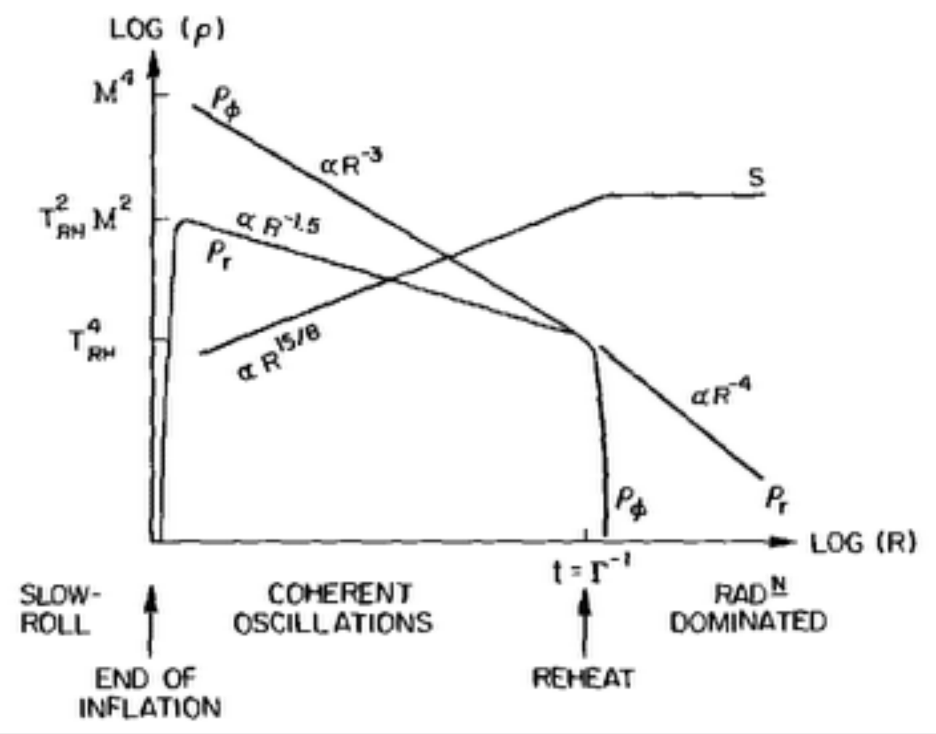
- Inflaton sector is characterized by reheating temperature T_R, inflaton mass $m_{\rm inf}$ and branching ratio of inflaton to L, Br_L.

Intuitive explanation

- before the reheating process is completed.
- Collision between lepton in thermal plasma and one by inflaton decay.
- LL→ΦΦ by

$$\frac{\lambda^{(1)}_{ij}}{\Lambda_1}\overline{L_i}\tilde{\Phi}\overline{L_j}\tilde{\Phi}$$

- B is mainly produced @time reheating is just completed.



[Kolb, Turner]

Sakharov's three conditions

1. Violation of baryon number

$$S = \int d^4x \left(\mathcal{L}_{\rm SM} + \frac{\lambda^{(1)}_{ij}}{\Lambda_1}(\overline{L_i}\widetilde{\Phi})(\overline{L_j}\widetilde{\Phi}) + \frac{\lambda^{(2)}_{ijkl}}{\Lambda_2^2}(\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \text{h.c.} \right)$$

- L-number violation + sphaleron process
  → B-violation

Sakharov's three conditions

2. Violation of C and CP

$$S = \int d^4x \left(\mathcal{L}_{\rm SM} + \frac{\lambda^{(1)}_{ij}}{\Lambda_1} (\overline{L_i}\widetilde{\Phi})(\overline{L_j}\widetilde{\Phi}) + \frac{\lambda^{(2)}_{ijkl}}{\Lambda_2^2} (\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \text{h.c.} \right)$$

- Coupling λ_1 becomes real by unitary transformation
- λ_2 can have complex phase

Sakharov's three conditions

3. Out of thermal equilibrium

- After reheating, all SM particles are in thermal plasma.
- At the era of inflaton domination, universe is out of equilibrium.

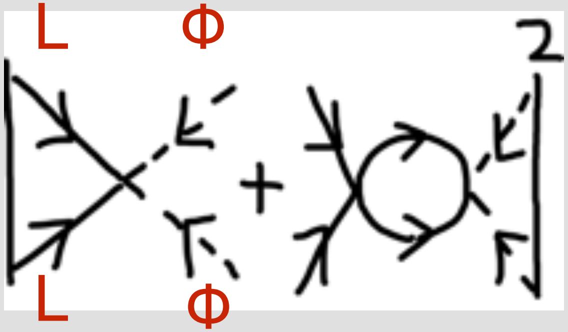
Decay of inflaton

inf→X + L

$E \sim m_{inf}$

Thermal plasma

$E \sim T_R$



L asymmetry

Rough estimation

- The rough estimation of asymmetry

$$\frac{n_B}{s} \simeq \frac{n_{\rm inf}}{s} {\rm Br} \frac{\Gamma_{\cancel{L}}}{\Gamma_{\rm brems}} \epsilon_i$$

Inflaton abundance $\simeq \frac{T_R}{m_{\rm inf}}$

T_R : reheating temperature
$m_{\rm inf}$: inflaton mass

Rough estimation

- The rough estimation of asymmetry

$$\frac{n_B}{s} \simeq \frac{n_{\rm inf}}{s} {\rm Br} \frac{\Gamma_{\not{L}}}{\Gamma_{\rm brems}} \epsilon_i$$

Branching ratio of inflaton to leptons

Rough estimation

- The rough estimation of asymmetry

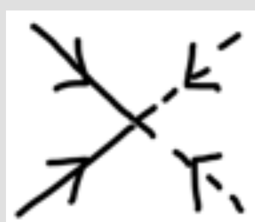
$$\frac{n_B}{s} \simeq \frac{n_{\rm inf}}{s} \mathrm{Br} \frac{\Gamma_{\not{L}}}{\Gamma_{\rm brems}} \epsilon_i$$

Probability that lepton violation interaction occurs before L loses energy E~$m_{\rm inf}$

$$\Gamma_{L_i} \simeq \frac{11}{4\pi^3}\zeta(3)\frac{m_{\nu,i}^2}{v^4}T_R^3$$

L

L



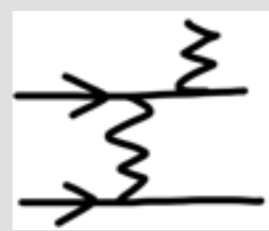
Φ

Φ

L violation

vs

L



$$\Gamma_{\rm brems} \simeq \alpha_2^2 T_R \sqrt{\frac{T_R}{m_{\rm inf}}}$$

Thermalized w/o L violation

[‘13 Harigaya, Mukaida]

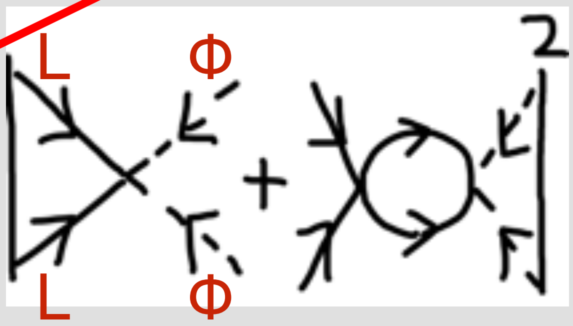
Rough estimation

- The rough estimation of asymmetry

$$\frac{n_B}{s} \simeq \frac{n_{\rm inf}}{s}\,\mathrm{Br}\,\frac{\Gamma_{\not{L}}}{\Gamma_{\rm brems}}\,\epsilon_i$$

$$\epsilon_i \simeq \sum_j \frac{1}{2\pi}\frac{12 m_{\rm inf} T_R}{\Lambda_2^2}\frac{\lambda_{jj}^{(1)}\mathrm{Im}(\lambda_{ijij}^{(2)})}{\lambda_{ii}^{(1)}}$$

interference between
tree and one-loop



Numerical calculation

- Boltzmann equation for first contribution

$$H^2 = \frac{1}{3M_{pl}^2}\left(\rho_{\rm inf} + \frac{\pi^2 g_*}{30}T^4 + \frac{m_{\rm inf}}{2}n_l\right)$$ Friedmann eq

$$\dot\rho_R + 4H\rho_R = (1-{\rm Br})\Gamma_{\rm inf}\,\rho_{\rm inf} + \frac{m_{\rm inf}}{2}n_l\Gamma_{\rm brems},$$ radiation energy

$$\dot n_L + 3Hn_L = \Gamma_{\not L}2\epsilon\, n_l - \Gamma_{\rm wash}n_L,$$ lepton asymmetry

$$\dot n_l + 3Hn_l = \frac{\Gamma_{\rm inf}\,\rho_{\rm inf}}{m_{\rm inf}}{\rm Br} - n_l(\Gamma_{\rm brems} + H),$$ high energy(~$m_{\rm inf}$) lepton

$$\rho_{\rm inf} = \Lambda_{\rm inf}^4\left(\frac{a(t=t_{\rm end})}{a}\right)^3 e^{-\Gamma_{\rm inf}t},$$ inflaton energy

n_L: lepton asymmetry

n_l: high energy(~$m_{\rm inf}$) lepton

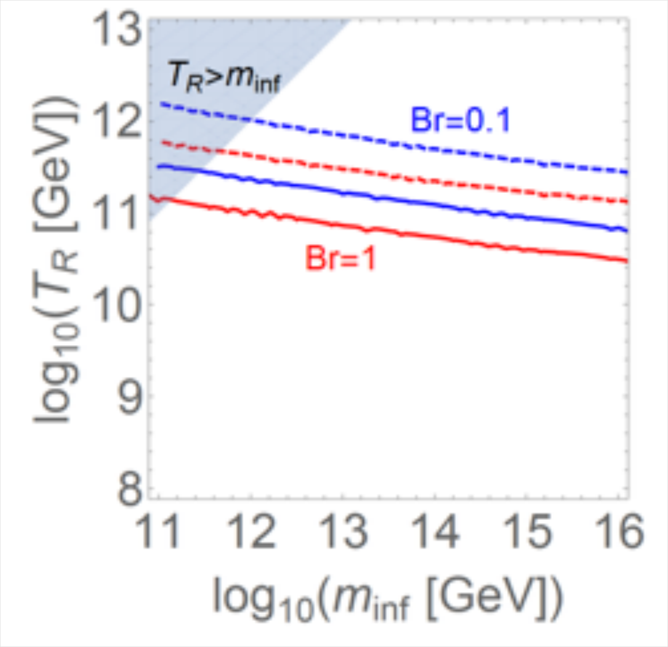
$\Gamma_{\rm wash}$: washout rate

$$T \equiv \left(\frac{90}{\pi^2 g_*}\rho_R\right)^{1/4}$$

Numerical Result

['15 YH, Kawana]

- dashed : $\Lambda_2 = 10^{15}$ GeV
  solid : $\Lambda_2 = 10^{14}$ GeV



$$S = \int d^4x \left(\mathcal{L}_{\rm SM} + \frac{\lambda^{(1)}_{ij}}{\Lambda_1} (\overline{L_i}\widetilde{\Phi})(\overline{L_j}\widetilde{\Phi}) + \frac{\lambda^{(2)}_{ijkl}}{\Lambda_2^2} (\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \text{h.c.} \right)$$

Plan

1. Leptogenesis at reheating-era

2. various seesaw models

Origin of higher dimensional operator

- origin of dimension 5 & 6 operators

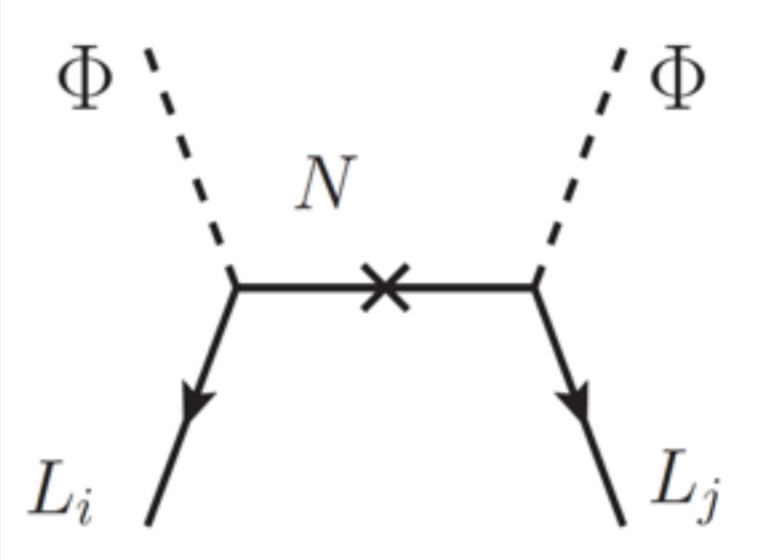
$$S = \int d^4x \left(\mathcal{L}_{\rm SM} + \frac{\lambda^{(1)}_{ij}}{\Lambda_1} (\overline{L_i}\widetilde{\Phi})(\overline{L_j}\widetilde{\Phi}) + \frac{\lambda^{(2)}_{ijkl}}{\Lambda_2^2} (\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l) + \text{h.c.} \right)$$

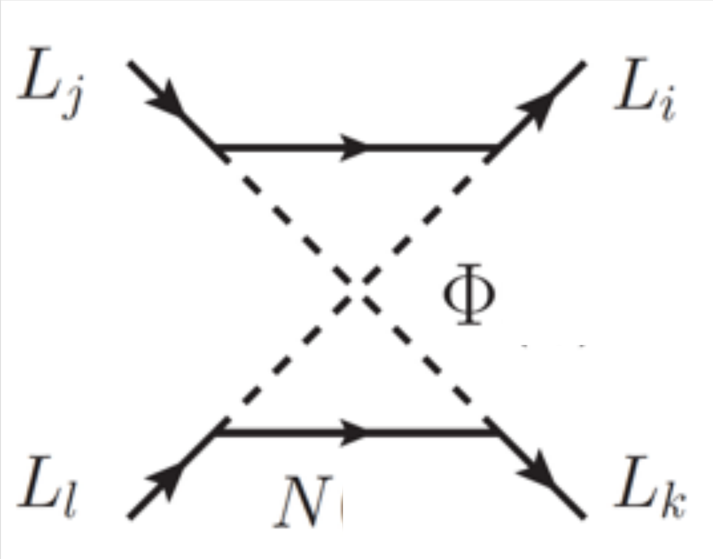
- seesaw models
  - type-I, (-II, -III), tree-level seesaw
  - Ma model, radiative seesaw

type-I seesaw

- Lagrangian

$$\Delta\mathcal{L}^{\text{Type-I}} = y^{\text{I}}_{ij}\overline{L_i}N_{Rj}\widetilde{\Phi} + \frac{M_{R,i}}{2}\overline{N^c_{Ri}}N_{Ri} + \text{h.c.}$$





type-I seesaw

- dim-5&6 terms

$$\frac{\lambda^{(1)}_{ij}}{\Lambda_1} = y^{\mathrm{I}} M_R^{-1} {y^{\mathrm{I}}}^T = \delta_{ij} \frac{2}{v^2} m_{\nu i}$$

$$\frac{\mathrm{Im}(\lambda^{(2)}_{ijkl})}{\Lambda_2^2} \simeq \frac{1}{(8\pi)^2} \sum_{m,n} \frac{\mathrm{Im}(y^{\mathrm{I}}_{im} y^{\mathrm{I}*}_{lm} y^{\mathrm{I}}_{kn} y^{\mathrm{I}*}_{jn})}{M_{R,m}^2 - M_{R,n}^2} \log \frac{M_{R,m}^2}{M_{R,n}^2}$$

- Casas-Ibarra

R is complex orthogonal matrix

$$y^{\mathrm{I}}_{ij} = i \, \frac{\sqrt{2}}{v} \sqrt{m_{\nu,i}} \, R_{ij} \, \sqrt{M_{R,j}}$$

type-I seesaw

$$\frac{\lambda^{(1)}_{ij}}{\Lambda_1} = y^{\mathrm{I}} M_R^{-1} {y^{\mathrm{I}}}^T = \delta_{ij} \frac{2}{v^2} m_{\nu i}$$

$$\frac{\mathrm{Im}(\lambda^{(2)}_{ijkl})}{\Lambda_2^2} \simeq \frac{1}{(8\pi)^2} \sum_{m,n} \frac{\mathrm{Im}(y^{\mathrm{I}}_{im} y^{\mathrm{I}*}_{lm} y^{\mathrm{I}}_{kn} y^{\mathrm{I}*}_{jn})}{M^2_{R,m} - M^2_{R,n}} \log \frac{M^2_{R,m}}{M^2_{R,n}}$$

- We can see
  $\Lambda_1 \sim 10^{14\text{-}15}$ GeV for m_ν=0.1eV,
  $\Lambda_2 \sim 10^{15\text{-}16}$ GeV for m_ν=0.1eV & R=1-10.

Parameter region

- type-I

investigate region where BAU can be generated

parameters: T_R, m_{inf}, M_R, R, Br, CP phase

Take $m_{\rm inf} = M_R$ or $m_{\rm inf} = M_1$

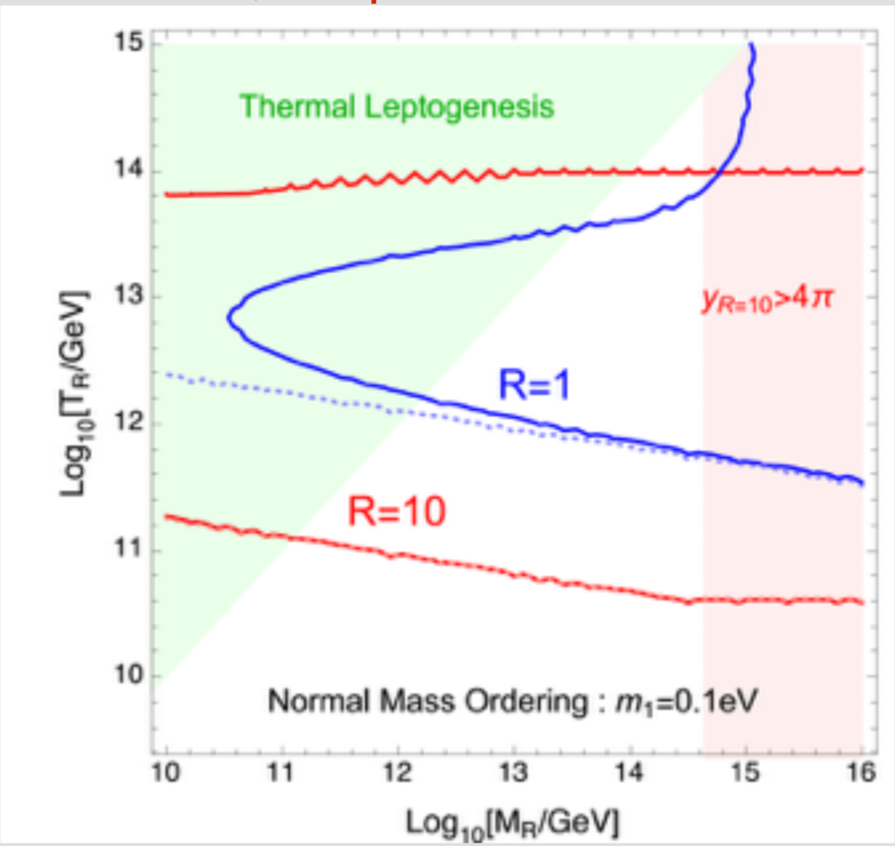
to maximize the asymmetry

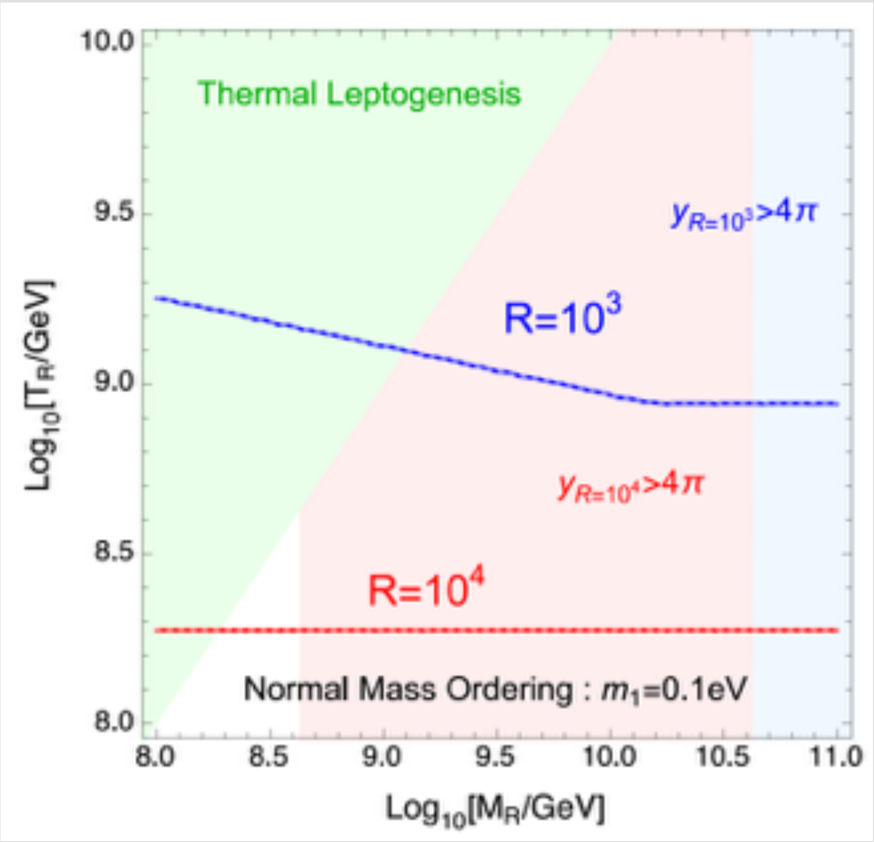
$$\epsilon\big|_{m_{\rm inf}=M_1} := 1$$

Figure: type-I seesaw

Br=1, CP phase=1 are taken

['15 YH, Tsumura, Yasuhara]



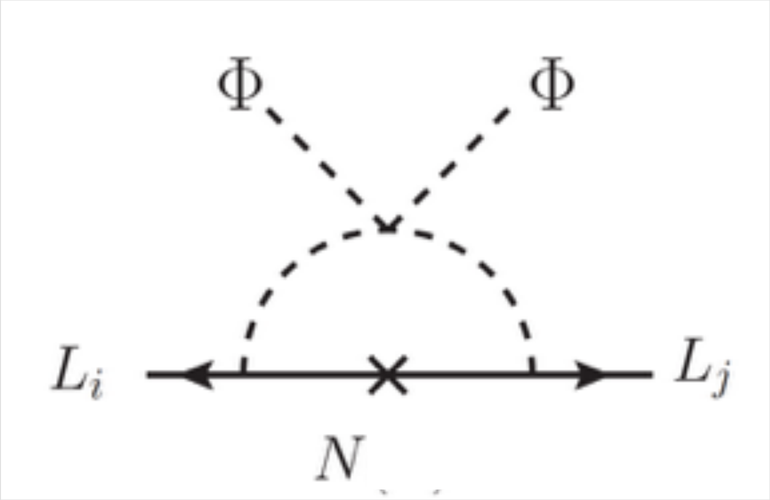


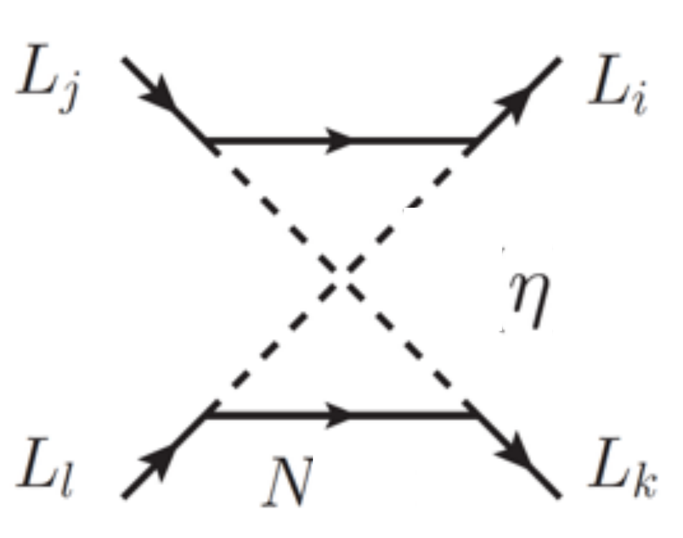
Almost same result is obtained for inverted mass ordering case.

Ma model(radiative seesaw)

- Lagrangian, ν mass is radiatively generated.

$$\Delta\mathcal{L} = y^{\mathrm{M}}_{ij}\overline{L_i}N_{Rj}\widetilde{\eta} + \frac{M_{R,i}}{2}\overline{N^c_{Ri}}N_{Ri} + \frac{\lambda_5}{2}(\eta^\dagger\Phi)^2 + \mathrm{h.c.}$$





Ma model(radiative seesaw)

- $y^{l} \to y^{M}$, $M_R \to M_R^{eff}$

$$\frac{\lambda_{ij}^{(1)}}{\Lambda_1} = y^{\mathrm{M}} (M_R^{\mathrm{eff}})^{-1} y^{\mathrm{M}\,T} = \delta_{ij} \frac{2}{v^2} m_{\nu i}$$

$$\frac{\mathrm{Im}(\lambda_{ijkl}^{(2)})}{\Lambda_2^2} \simeq \frac{1}{(8\pi)^2} \sum_{m,n} \frac{\mathrm{Im}(y_{im}^{\mathrm{M}} y_{lm}^{\mathrm{M}*} y_{kn}^{\mathrm{M}} y_{jn}^{\mathrm{M}*})}{M_{R,m}^2 - M_{R,n}^2} \log \frac{M_{R,m}^2}{M_{R,n}^2}$$

$$(M_R^{\mathrm{eff}})^{-1} = \frac{\lambda_5}{(2\pi)^2} F(M_R^2/M_\eta^2)\, M_R^{-1} \qquad F(x) = \frac{x}{x-1}\left(\frac{x}{x-1}\log x - 1\right)$$

- We can see
  $\Lambda_1 \sim 10^{14\text{-}15}$ GeV for m_ν=0.1eV,
  $\Lambda_2 \sim 10^{13\text{-}15}$ GeV depending on parameters.

Parameter region

- Ma model
  region where BAU can be generated

$$y^{\mathrm{M}}_{ij} = i\,\frac{\sqrt{2}}{v}\sqrt{m_{\nu,i}}\,R_{ij}\,\frac{2\pi}{\sqrt{\lambda_5}}\left(F\left(\frac{M^2_{Rj}}{m^2_\eta}\right)\right)^{-1/2}$$

parameters: T_R, m_{inf}, M_R, R^2/λ_5, Br, CP phase

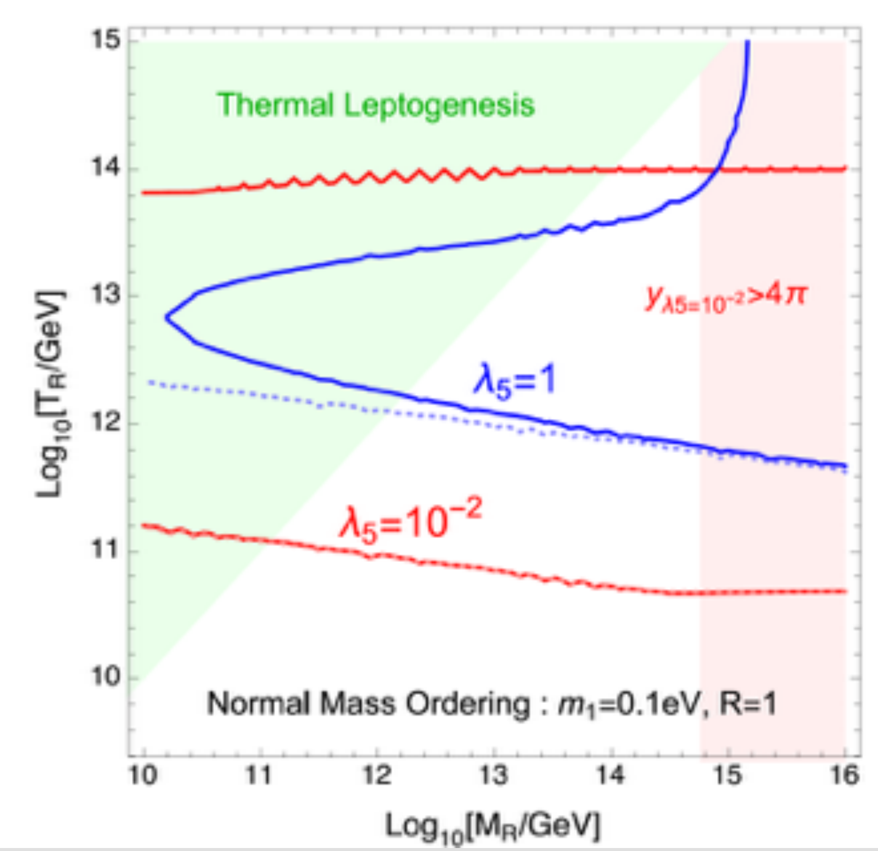
Take $m_{\rm inf} = M_R$ or $m_{\rm inf} = M_1$

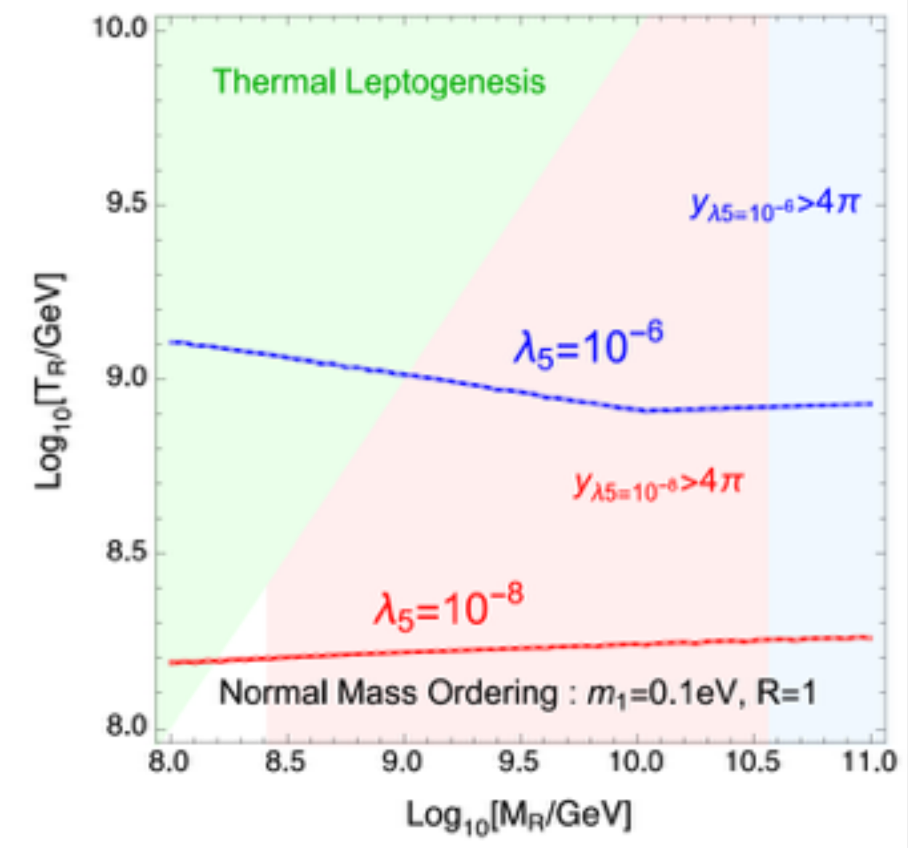
to maximize the asymmetry

Figure: Ma model

['15 YH, Tsumura, Yasuhara]

Br=1, CP phase=1, R=1 are taken





Summary

- We propose the new way to produce BAU.
- Even if RHν is not produce in the early universe, the baryon asymmetry can be explained.
- Embedding in seesaw models are discussed.