Leptogenesis during the reheating era

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based on collaboration with Yuta Hamada (Kyoto U.) , arXiv:1510.05186

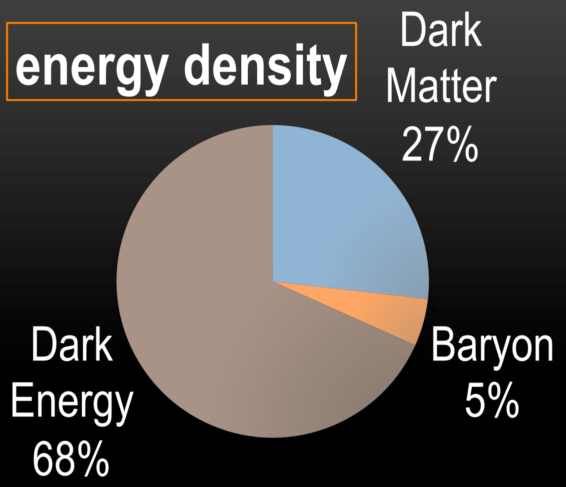
Introduction

Baryon number of the universe

$$\eta = \frac{n_B}{s} = 8 \times 10^{-10}$$

n_B: baryon number density , s: entropy density

energy density



We must explain this asymmetry !
But, How ?

In the Standard Model, the baryon number is related to the B-L number through the Sphaleron process:

$$n_B \simeq \frac{28}{79} n_{B-L} = \frac{28}{79} n_{-L}$$

If there is no baryon at first.

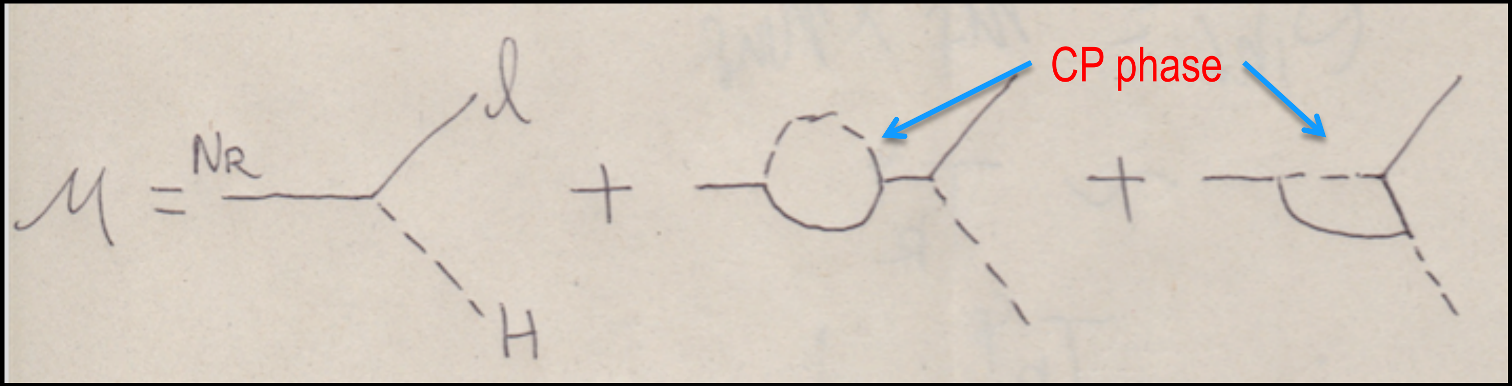
Baryon number can be produced from the lepton number !
(Leptogenesis)

Thermal Leptogenesis

Fukugida, Yanagida ('86)

- One of the simplest scenario of leptogenesis.
- Model

$$\mathrm{SM} + N_R \text{ (Right handed neutrino)}$$



✴ Lepton number is produced by the decay of N_R

In this scenario, $T_R > M_R$ is needed.

(T_R: reheating temperature, M_R: mass of N_R)

If we assume the seesaw mechanism, this means

$$T_R \gtrsim 10^{12-14}\mathrm{GeV}$$

✴ very high temperature !

Can we realize leptogenesis even if $T_R < M_R$?

This Talk (Brief summary)

- We propose a new scenario of leptogenesis which is possible even if T_R is smaller than 10^{12} GeV.

- As a new particle, we only assume an inflaton which decays into the SM particles.

- We consider the dim 5 and 6 operators of the SM leptons. (Namely, the effect of N_R appears as these operators.)

Plan of Talk

1. Idea and Sakharov's conditions
2. Qualitative understanding and numerical result
3. Summary

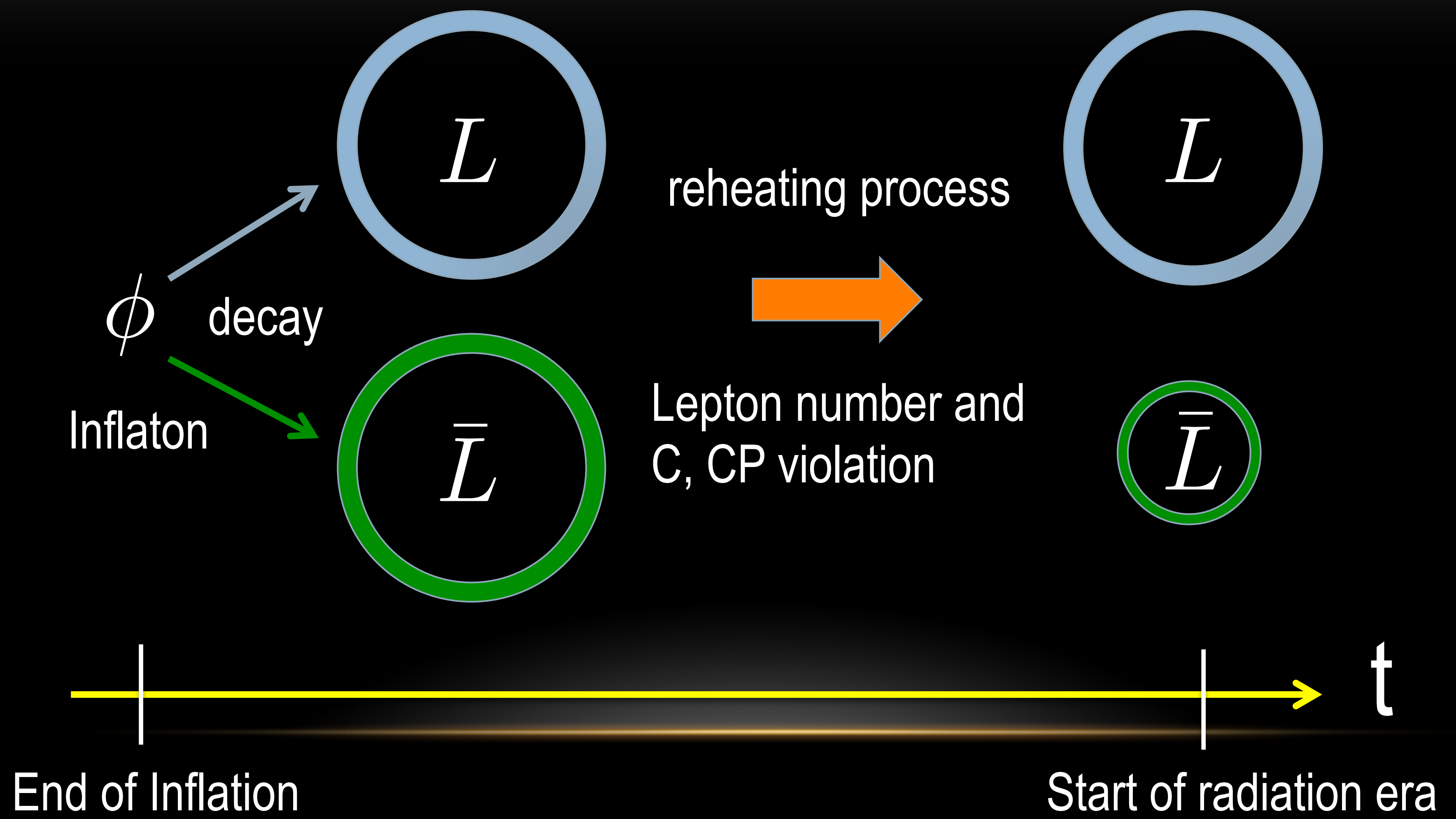
1. Idea and Sakharov’s conditions

Idea

- Unlike thermal leptogenesis, the lepton asymmetry is produced during the reheating era !

- Asymmetry is produced by the difference of the interaction rates between L and $\cancel{L}$.

Image of Leptogenesis



Sakharov's three conditions

(i) Out of thermal equilibrium

$\longrightarrow$ We consider the reheating era.

(ii) Violation of Lepton number (iii) Violation of C and CP

$$\mathcal{L} \ni \int d^4x \left(\frac{\lambda_{1,ij}}{\Lambda_1} H H \bar{L}_i^c L_j + \frac{\lambda_{2,ijkl}}{\Lambda_2^2} (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma_\mu L_l) + \mathrm{h.c} \right)$$

$$\lambda_{1,ij} : \mathrm{real} \; , \; \lambda_{2,ijkl} : \mathrm{complex}$$

2. Qualitative understanding and numerical result

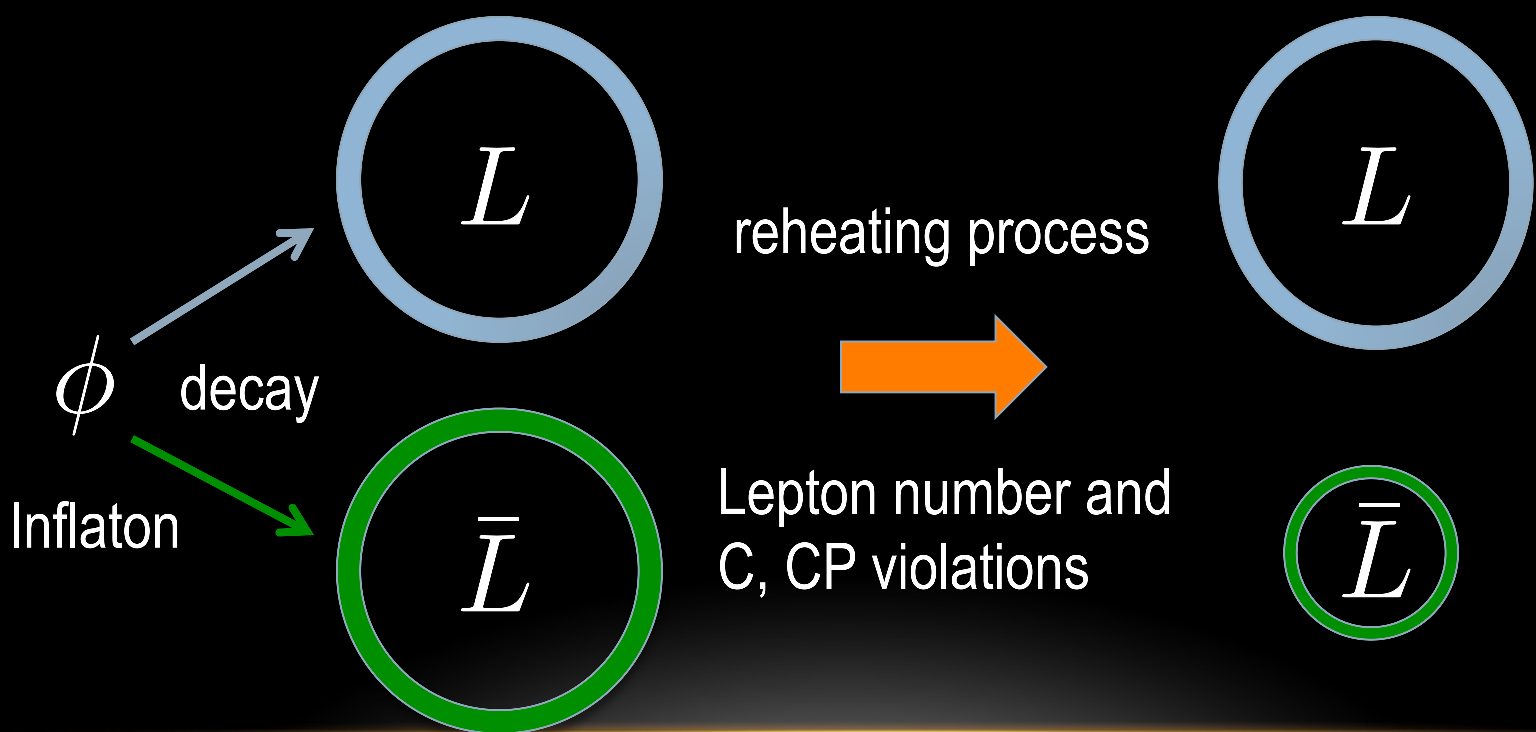
Rough estimation of η

The observed asymmetry is roughly given by

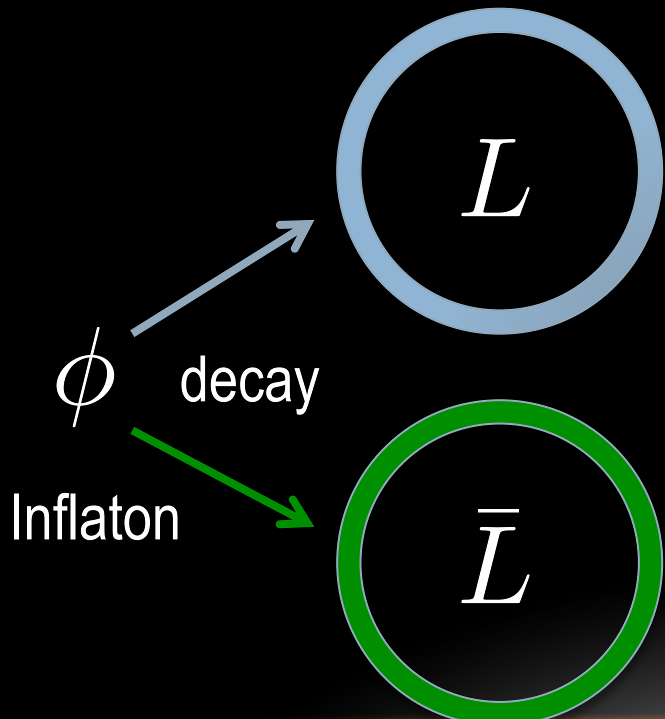
$$\frac{n_L}{s} \sim \frac{n_{\rm Inf}}{s} {\rm Br} \frac{\Gamma_{\not L}}{\Gamma_{\rm brems}} \epsilon$$

⭐ In the following, I explain each factor.

$$\frac{n_L}{s} \sim \frac{n_{\mathrm{Inf}}}{s}\,\mathrm{Br}\,\frac{\Gamma_{\not{L}}}{\Gamma_{\mathrm{brems}}}\,\epsilon$$



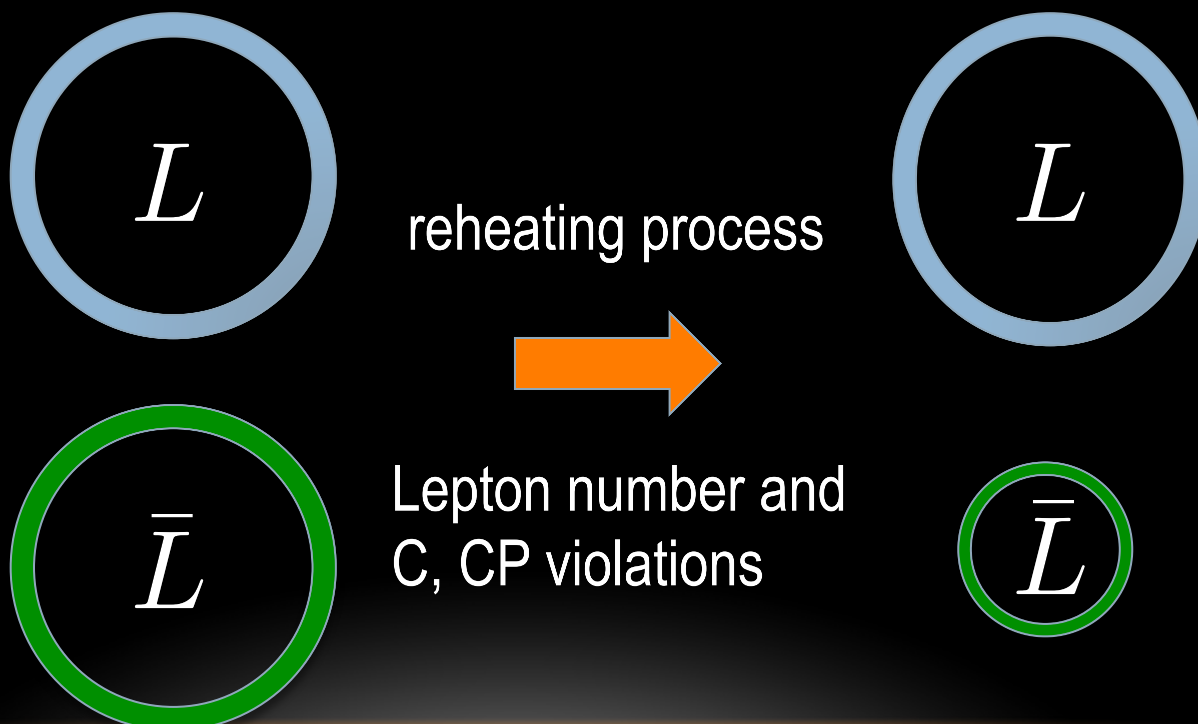
$$\frac{n_L}{s} \sim \boxed{\frac{n_{\mathrm{Inf}}}{s}\mathrm{Br}}\,\frac{\Gamma_{\not{L}}}{\Gamma_{\mathrm{brems}}}\,\epsilon$$



n_{Inf} :number density of inflaton

Br :branching ratio of inflaton

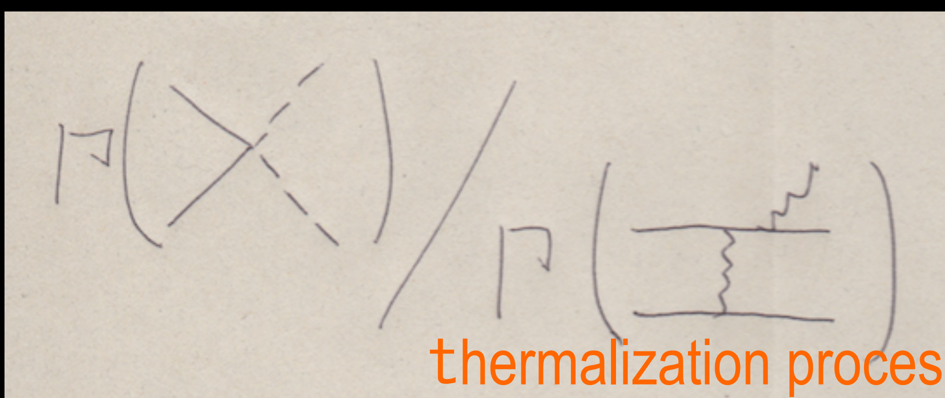
$$\frac{n_L}{s} \sim \frac{n_{\mathrm{Inf}}}{s} \mathrm{Br} \boxed{\frac{\Gamma_{\not{L}}}{\Gamma_{\mathrm{brems}}} \epsilon}$$

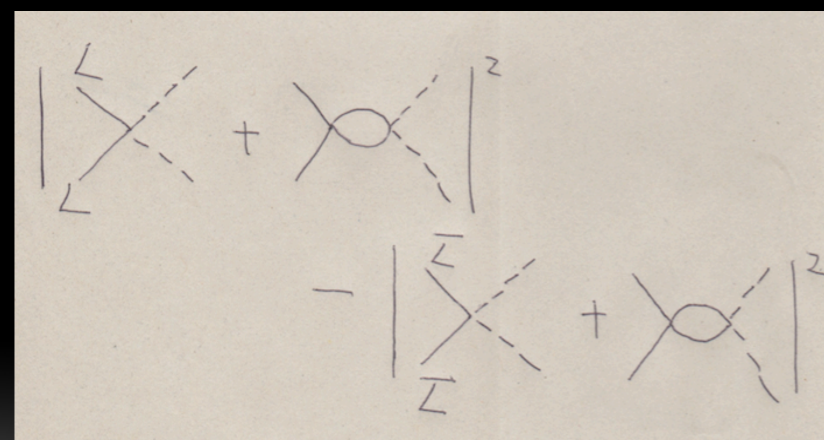


$$\frac{n_L}{s} \sim \frac{n_{\mathrm{Inf}}}{s}\,\mathrm{Br}\,\frac{\Gamma_{\not{L}}}{\Gamma_{\mathrm{brems}}}\,\epsilon$$

Probability of $\not{L}$ processes occur.

efficiency





$$\epsilon = 2\,\frac{\sigma(LL \to HH) - \sigma(\bar{L}\bar{L} \to HH)}{\sigma(LL \to HH) + \sigma(\bar{L}\bar{L} \to HH)}$$

Explicit form

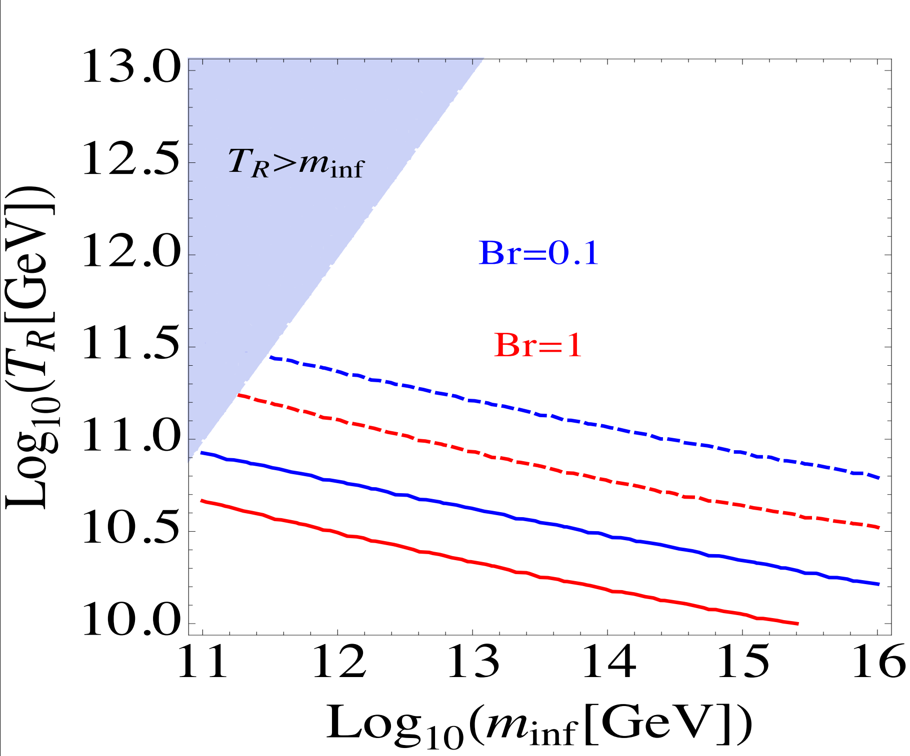
$$\frac{n_B}{s} \simeq 8.7 \times 10^{-11} \left(\frac{4 \times 10^{-4}}{\alpha_2^2}\right) \left(\frac{m_{\rm inf}}{2 \times 10^{13}{\rm GeV}}\right)^{3/2} \left(\frac{T_R}{7 \times 10^{10}{\rm GeV}}\right)^{5/2}$$
$$\times \left(\frac{m_\nu}{0.1{\rm eV}}\right)^2 \left(\frac{10^{15}{\rm GeV}}{\Lambda_2}\right)^2 \left(\frac{{\rm Br} \times \sum_j \lambda_{1,jj} {\rm Im}(\lambda_{2,1j})}{2}\right)$$

$m_{\rm inf}$: inflaton mass , m_ν : neutrino mass

Leptogenesis is possible even if $T_R < M_R$!

Numerical result

- We can, of course, numerically calculate η by solving the Friedman equation and Boltzmann equation.



Contours of observed η

Solid: $\Lambda_2 = 10^{14}$ GeV
Dashed: $\Lambda_2 = 10^{15}$ GeV

3. Summary

- I have discussed the leptogensis during the reheating era, which is possible even if $T_R < M_R$.
- Because our scenario is based on the effective operators, this is applicable to other UV models (such as other seesaw models).

Thank you !

Appendix A: Reheating Temperature

- Reheating temperature is determined by the decay rate of the inflaton.

$$T_R \sim \begin{cases} \rho_I^{\frac{1}{4}} & (\text{for } \Gamma_I \gg H_I) \\ \sqrt{\Gamma_I M_{pl}} & (\text{for } \Gamma_I \ll H_I) \end{cases}$$

determined by $H \sim \Gamma_I$

Appendix B: Friedman eq and Boltzmann eq

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

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

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

$$\dot{n}_l + 3Hn_l = \frac{\Gamma_{\rm inf}\,\rho_{\rm inf}}{m_{\rm inf}}{\rm Br} - n_l\Gamma_{\rm brems},$$

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