# Affleck-Dine leptogenesis via multiscalar evolution in a seesaw model

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# Outline

1 Introduction

- Leptogenesis via Affleck-Dine mechanism:

  an alternative to thermal leptogenesis in SUSY

- $\tilde{N}$ only (Allahverdi & Drees, PRD69(2004)103522)

  ⟶ multiscalar $LH_u$-direction and RH-sneutrino

2 Set-up

- Scalar potential
- initial condition

3 Evolution of scalar fields

4 Evolution of asymmetry

5 Constraints

6 Resultant baryon asymmetry

7 Summary

# 1. Introduction

Standard Model (SM) + Heavy right-handed Majorana neutrino

→ possible solution of two unsolved problem of SM

1) Origin of small neutrino mass $m_\nu \lesssim \mathcal{O}(0.1)\mathrm{eV}$

seesaw mechanism

Majorana mass: $M\bar{\nu}_R\nu_R$ Dirac mass: $m\bar{L}\nu_R$ $\nu_R$ : right-handed neutrino

→ lighter mass eigenvalue $\sim \dfrac{m^2}{M}$

2) Origin of baryon asymmetry

baryon-to-entropy ratio: $\dfrac{n_B}{s} = (8.74 \pm 0.23) \times 10^{-11}$ (WMAP)

# 1. Introduction

■ thermal leptogenesis

・sufficient baryon asymmetry requires $T_R > M > 10^9 \mathrm{GeV}$

$\longleftrightarrow$ in SUSY, gravitino is overproduced unless $T_R < 10^{6-9} \mathrm{GeV}$

$\longrightarrow$ alternatives ?

many non-thermal leptogenesis scenarios are considered...

■ Affleck-Dine leptogenesis from right-handed sneutrino

・$LH_u$-flat direction $L = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix}, \quad H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}$

- $LH_u$-flat direction has large vev
  - AD mechanism in multiscalar evolution (Senami & Yamamoto, 2003)
- $LH_u$-flat direction has vanishing vev
  - $LH_u$- flat direction is irrelevant? (Allahverdi & Drees, 2004)

# 1. Introduction: Affleck-Dine mechanism

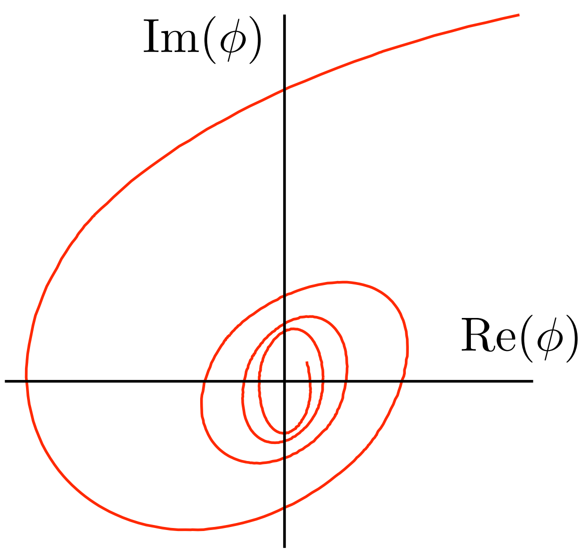
■ complex scalar field $\phi$ with baryon (or lepton) number $1$

total baryon (or lepton) number in homogeneous condensate of $\phi$

$$n = n_\phi - \bar{n}_\phi = i(\dot{\phi}^* \phi - \phi^* \dot{\phi}) = 2|\phi|^2 \dot{\theta} \qquad \phi = |\phi| e^{i\theta}$$

"angular momentum" of $\phi$ ⟶ baryon (lepton) number

rotational motion after inflation




⟷

baryon (lepton) number in $\phi$ condensate

↓ $B$- ($L$-) conserving decay

baryon (lepton) number in SM particles

# 1. Introduction

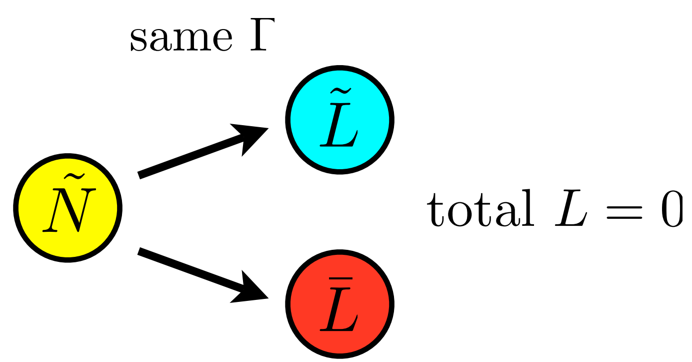
## ■ Allahverdi & Drees's scenario (brief review)

$$V(\tilde{N}) = m_0^2|\tilde{N}|^2 + C_I H^2|\tilde{N}|^2 + (Bm_{3/2}\tilde{N}^2 + h.c.) + (bH\tilde{N}^2 + h.c.)$$

- asymmetry $n_{\tilde{N}} - n_{\tilde{N}^*}$ is produced via Affleck-Dine mechanism
- $n_{\tilde{N}} - n_{\tilde{N}^*} \longrightarrow$ SM sector lepton number

tree level: $\Gamma_{\tilde{N}\to H_u\tilde{L}} = \Gamma_{\tilde{N}\to\bar{\tilde{H}}_u\bar{L}}$

bosonic, $\Delta L = +1$ fermionic, $\Delta L = -1$




- asymmetry is oscillating: $n_{\tilde{N}} - n_{\tilde{N}^*} \simeq t^{-2}M_N^{-1}N_0^2 \underline{\sin(2Bm_{3/2}t)}\delta_{\text{eff}}$

$\longrightarrow$ tuning $|B|m_{3/2} \simeq \Gamma_{\tilde{N}}$ is needed (decay at maximum)

assumption: $LH_u$-direction does not contribute (always $\langle\phi\rangle = 0$ )

$\longleftrightarrow$ due to interaction with $\tilde{N}$, $LH_u$-flat direction gets large value!

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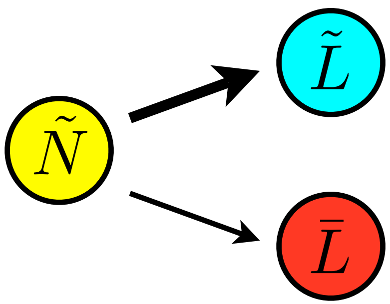
SUSY-breaking from thermal effect

Pauli blocking and stimulated emisson

$\longrightarrow \Gamma_{\tilde{N}\to H_u\tilde{L}} \neq \Gamma_{\tilde{N}\to\bar{\tilde{H}}_u\bar{L}}$

bosonic, $\Delta L = +1$ fermionic, $\Delta L = -1$

$\Gamma_{\Delta L=+1} \neq \Gamma_{\Delta L=-1}$




total $L \neq 0$

- asymmetry is oscillating: $n_{\tilde{N}} - n_{\tilde{N}^*} \simeq t^{-2}M_N^{-1}N_0^2\sin(2Bm_{3/2}t)\delta_{\rm eff}$

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# 2. Set-up of the model: scalar potential

- **superpotential:** $W = W_{\rm MSSM} + y_\nu N L H_u + \frac{M_N}{2} N^2 + \frac{\lambda}{4 M_{\rm Pl}} N^4$

source of CP-violation

$$V(\phi, \tilde{N}) = \frac{y_\nu^2}{4}|\phi|^4 + M_N|\tilde{N}|^2 + y_\nu^2|\phi|^2|\tilde{N}|^2 + \frac{\lambda^2}{M_{\rm Pl}^2}|\tilde{N}|^6$$

F-term

$$+ \left[\left(\frac{y_\nu}{2} M_N \phi^2 \tilde{N}^* + \frac{y_\nu \lambda}{2 M_{\rm Pl}} \phi^2 \tilde{N}^{*3} + \frac{\lambda M_N}{M_{\rm Pl}} \tilde{N} \tilde{N}^{*3}\right) + h.c.\right]$$

cross term in F-term

$$+ c_\phi H^2 |\phi|^2 - c_N H^2 |\tilde{N}|^2$$

Hubble-induced SUSY breaking mass term

$$+ \left[\left(\frac{bH}{2} M_N \tilde{N}^2 + \frac{a_y y_\nu}{2} H \phi^2 \tilde{N} + \frac{a_\lambda \lambda}{4 M_{\rm Pl}} H \tilde{N}^4\right) + h.c.\right]$$

Hubble-induced SUSY breaking A- and B-term

$$+ V_{\rm th}(\phi)$$

thermal-mass correction

※ $c_\phi \sim 1 > 0, \ c_N \sim 1 > 0, \ |a| \sim 1, \ |b| \sim 1$

※ after inflation, rapid oscillation of inflaton $\langle a, b - \mathrm{term}\rangle \propto \langle I \rangle = 0$

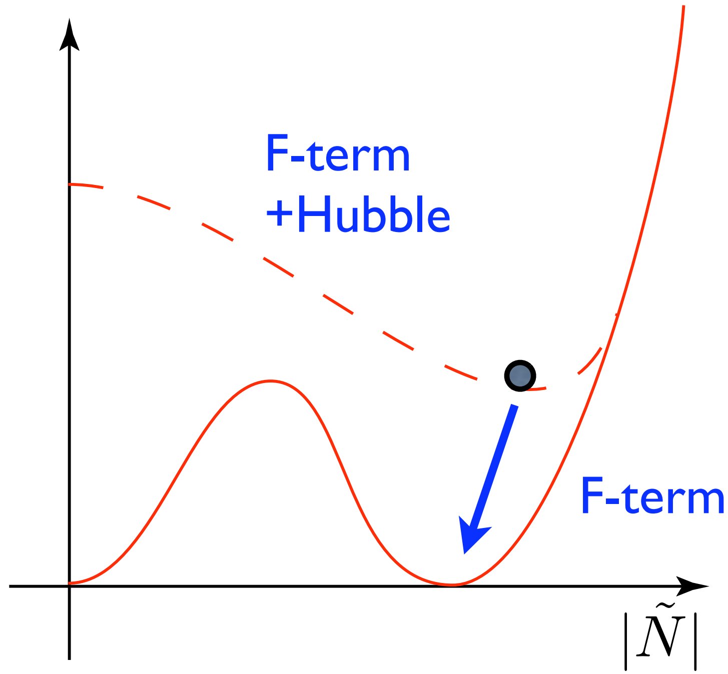
$\phi$ : $LH_u$ direction $L = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi \\ 0\end{pmatrix}, \ H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ \phi\end{pmatrix}$ $\tilde{N}$ : RH-sneutrino

## 2. Set-up of the model: initial conditions

during the inflation, $H \gg M_N$

- $\tilde{N}$ : displaced from the origin
  - radial direction: $|\tilde{N}_{\rm ini}| = M_{\rm GUT}$
    (Hubble-induced mass and D-term)
    ※ $M/\lambda > M_{\rm GUT}^2/M_{\rm Pl}$ is assumed
    (avoid wrong vacuum)
  - phase direction :
    trapped at B-term minima

NR F-term can not be used to trap $\tilde{N}_{\rm ini}$




- $\phi$ : fixed at the origin due to large effective mass $m_{\rm eff} \sim y_\nu M_{\rm GUT}$

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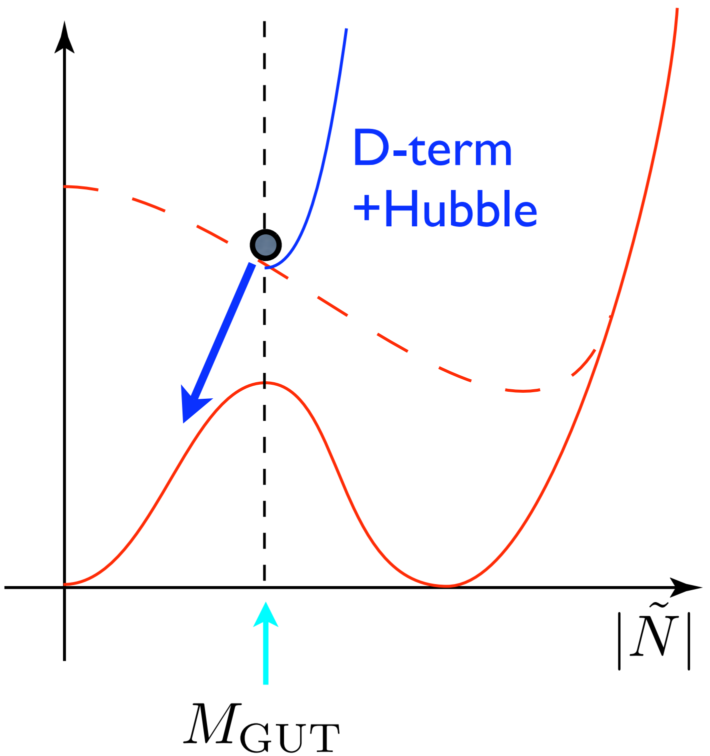


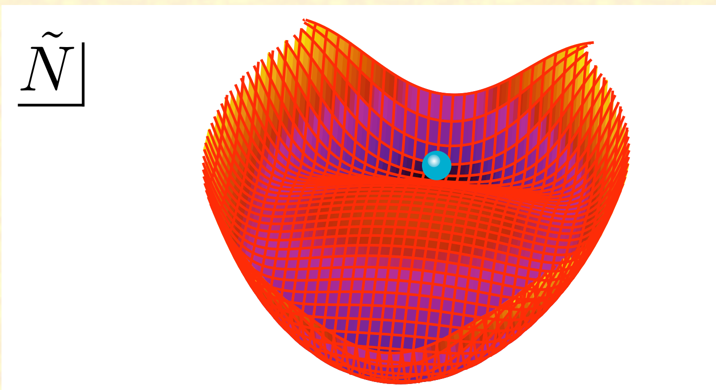

※hereafter, $M_{\rm GUT} = 10^{16}{\rm GeV}$

- $\phi$ : fixed at the origin due to large effective mass $m_{\rm eff} \sim y_\nu M_{\rm GUT}$

# 3. Evolution of scalar fields

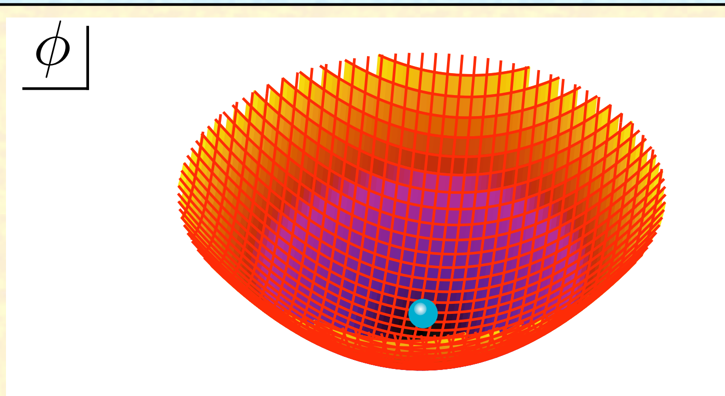
① during inflation: $H = H_{\rm inf} > M_N$

$$V_{\tilde{N}} \sim -c_N H^2 |\tilde{N}|^2 + \left( \frac{bH}{2} M_N \tilde{N}^2 + h.c. \right) + D\text{−term}$$




- due to balance between Hubble-induced mass and D-term, $|\tilde{N}| \sim M_{\rm GUT}$
- phase-direction is assumed to be trapped at the minimum of B-term contribution

$$V_\phi \simeq c_\phi H^2 |\phi|^2 + y_\nu^2 |\tilde{N}|^2 |\phi|^2$$



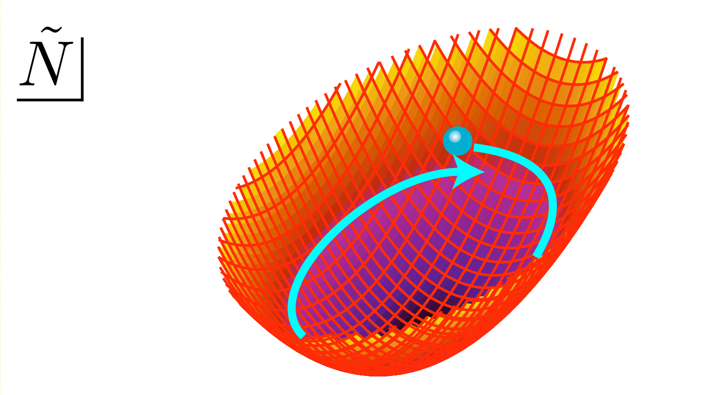

- $\phi$ is trapped at the origin

# 3. Evolution of scalar fields

② after inflation: $H < M_N$

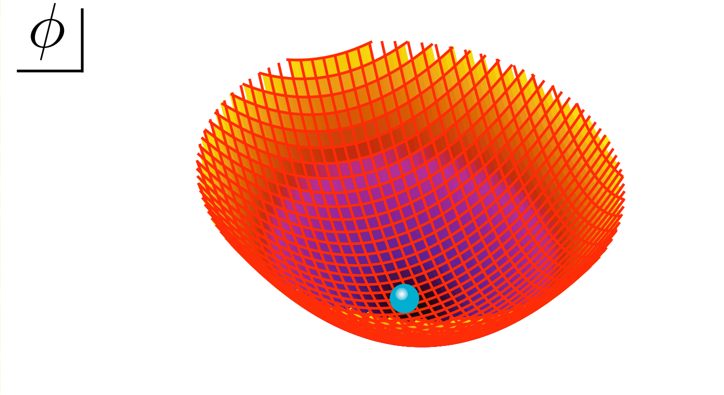
※ in general, Hubble-induced A- and B-terms are effective only during inflation

$$V_{\tilde{N}} \simeq M_N^2|\tilde{N}|^2 + \left(\frac{\lambda M_N}{M_{\rm Pl}}\tilde{N}\tilde{N}^{*3} + h.c.\right)$$




- $\tilde{N}$ oscillates with $|\tilde{N}| \propto H$
- cross term in F-term contribution serves as a source of asymmetry
- displacement between B-term and cross term gives $CP$ -violation

$$V_{\phi} \simeq c_{\phi}H^2|\phi|^2 + y_{\nu}^2|\tilde{N}|^2|\phi|^2 + \left(\frac{y_\nu}{2}M_N\phi^2\tilde{N}^* + h.c.\right)$$



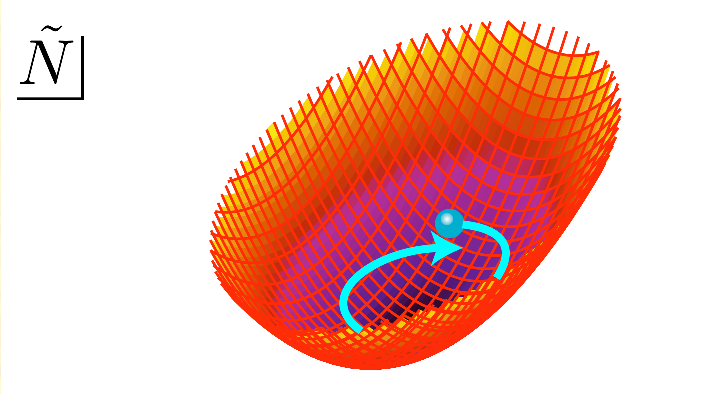

- $\phi$ is trapped at the origin

# 3 . Evolution of scalar fields

③ destabilization:

※ Allahverdi & Drees did not consider this process

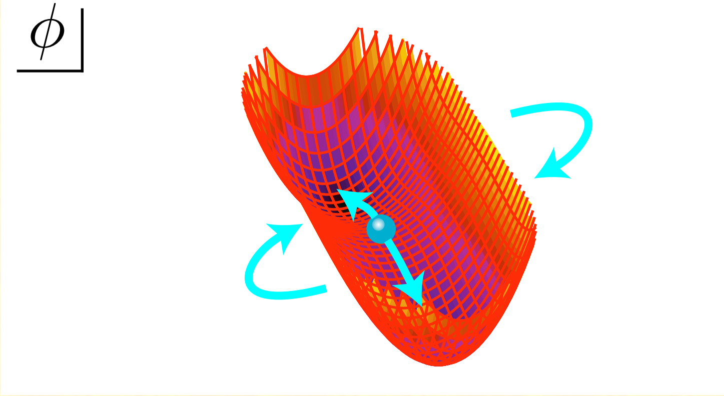
$$V_{\tilde{N}} \simeq M_N^2 |\tilde{N}|^2 + \left( \frac{\lambda M_N}{M_{\rm Pl}} \tilde{N} \tilde{N}^{*3} + h.c. \right)$$




- after $|\tilde{N}|$ and $H$ decrease sufficiently,

$$y_\nu M_N |\tilde{N}| \sim y_\nu^2 |\tilde{N}|^2 + c_\phi H^2$$

$$V_\phi \simeq y_\nu^2 |\tilde{N}|^2 |\phi|^2 + \left( \frac{y_\nu}{2} M_N \phi^2 \tilde{N}^* + h.c. \right) + y_\nu^2 |\phi|^4 / 4$$



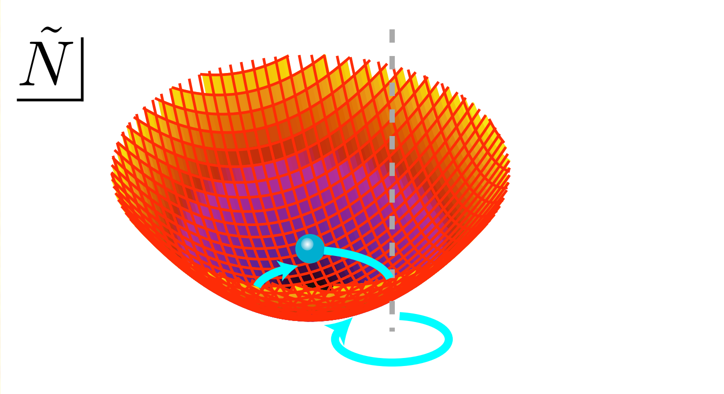

- two minima appear in opposite directions minimize the cross term
- these two minima are determined by $\tilde{N}$

⟶ position of these minima rotate together with the rotation of $\tilde{N}$

# 3. Evolution of scalar fields

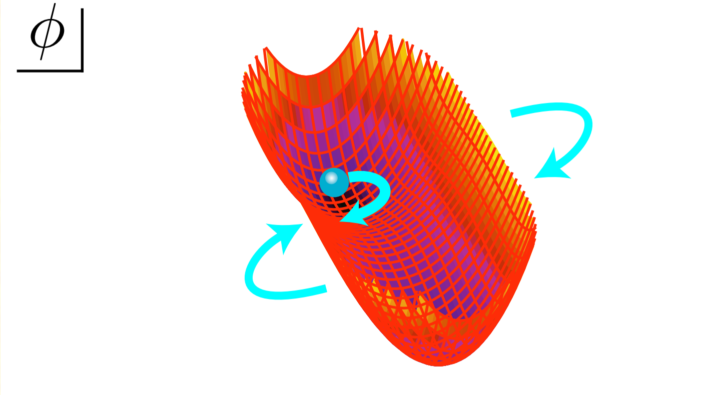
④ after destabilization: $H < M_N,\ y_\nu M_N|\tilde{N}| > y_\nu^2|\tilde{N}|^2 + c_\phi H^2$

$$V_{\tilde{N}} \simeq M_N^2|\tilde{N}|^2 + y_\nu^2|\tilde{N}|^2|\phi|^2 + \left(\frac{y_\nu}{2}M_N\phi^2\tilde{N}^* + h.c.\right)$$




- $\tilde{N}$ oscillates around the minimum determined by rotating $\phi$

$$V_\phi \simeq y_\nu^2|\tilde{N}|^2|\phi|^2 + \left(\frac{y_\nu}{2}M_N\phi^2\tilde{N}^* + h.c.\right) + y_\nu^2|\phi|^4/4$$

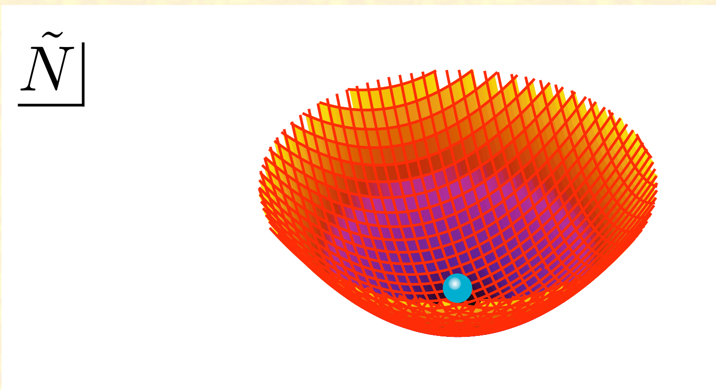



- $\phi$ oscillates around one of minima determined by the cross term
- to which minima $\phi$ falls is determined by quantum fluctuation

# 3 . Evolution of scalar fields

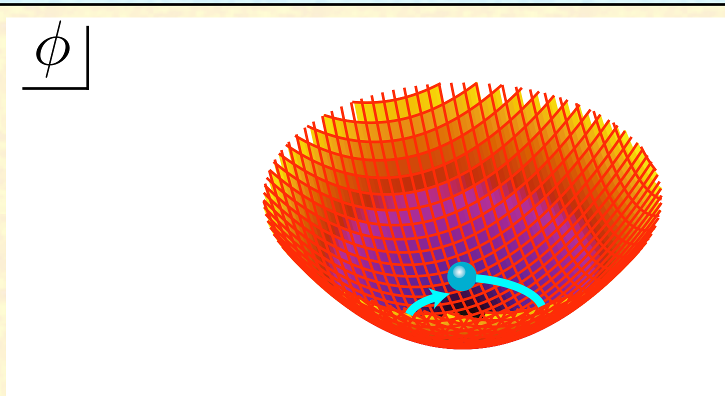
⑤ after decay of $\tilde{N}$: $H < \Gamma_{\tilde{N}} = y_\nu^2 M_N/(4\pi)$

(friction term dominates the evolution of $\tilde{N}$ )




- after the condensate of $\tilde{N}$ decays, $\tilde{N}$ is fixed at the minima

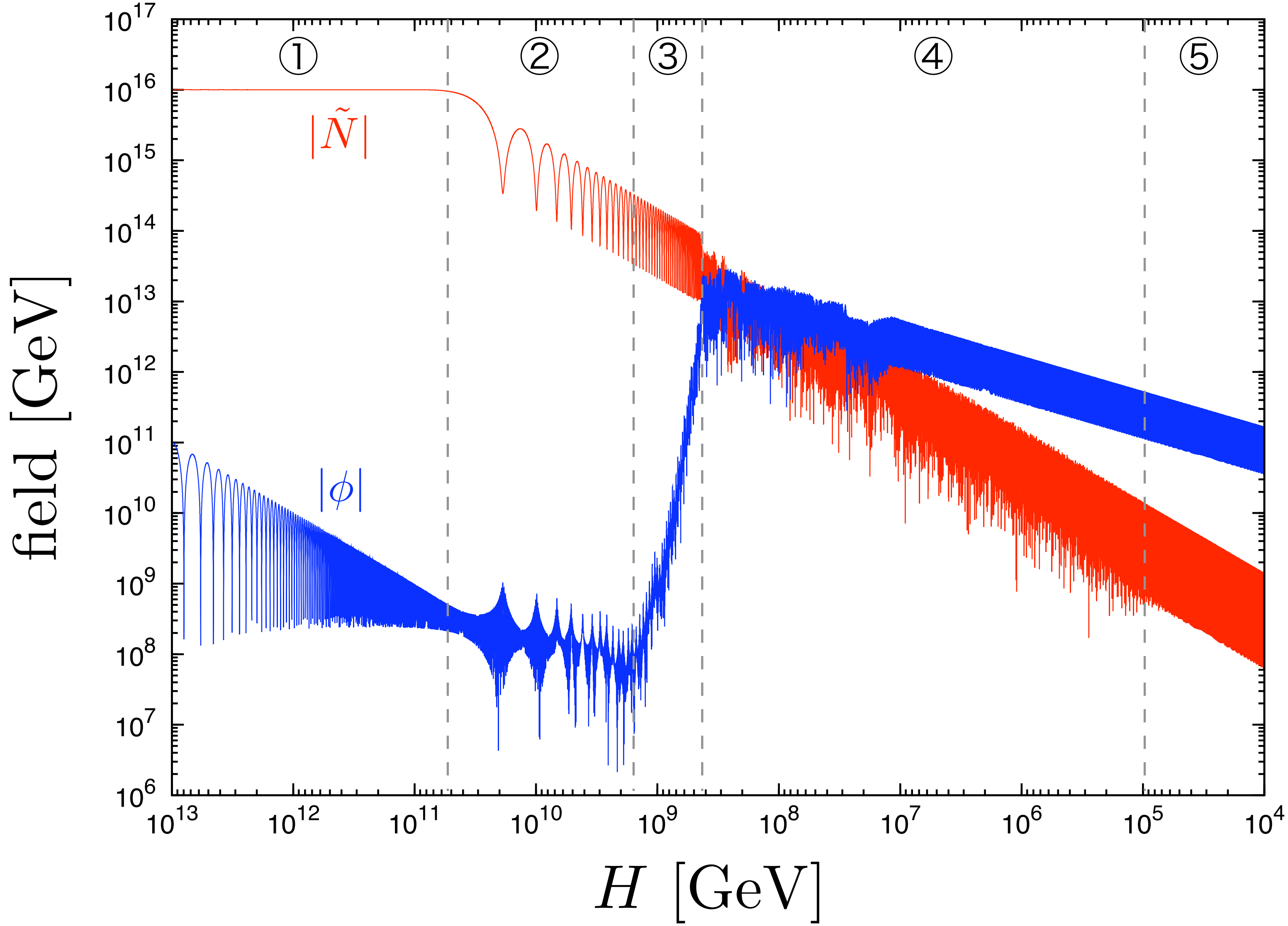
$$V_{\phi,\mathrm{eff}} \simeq \frac{y_\nu^4}{4}\frac{|\phi|^6}{M_N^2} + V_{\mathrm{th}}(\phi)$$




- $\phi$ oscillates around the origin
- the direction of rotation is determined by the rotation of $\tilde{N}$ at ②

# 3 . Evolution of scalar fields: numerical result

- evolution of scalar fields (numerical calculation)

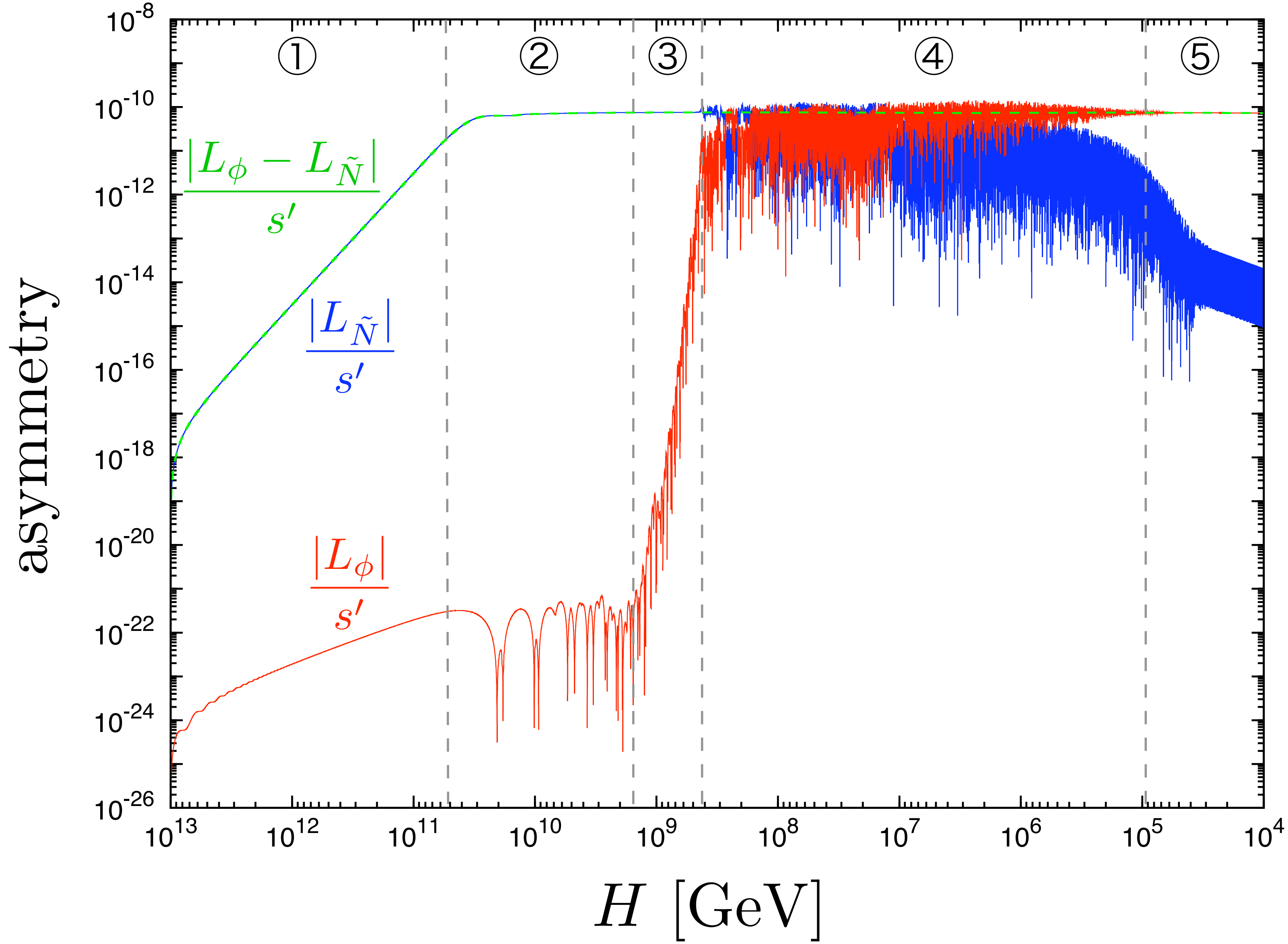



$$M_N = 10^{11}\text{GeV},\ y_\nu = 10^{-1},\ T_R = 2 \times 10^6\text{GeV}$$

$$c_\phi = c_N = 1, \lambda = 10^{-4}$$

# 4. Evolution of asymmetry: numerical result

- evolution of asymmetry (numerical calculation)




- lepton asymmetry is directly transfered to $LH_u$-direction

# 4 . Evolution of asymmetry: homogeneity of $\mathrm{sgn}(L_\phi)$

- $L_\phi$ vanishes on an average over the universe?

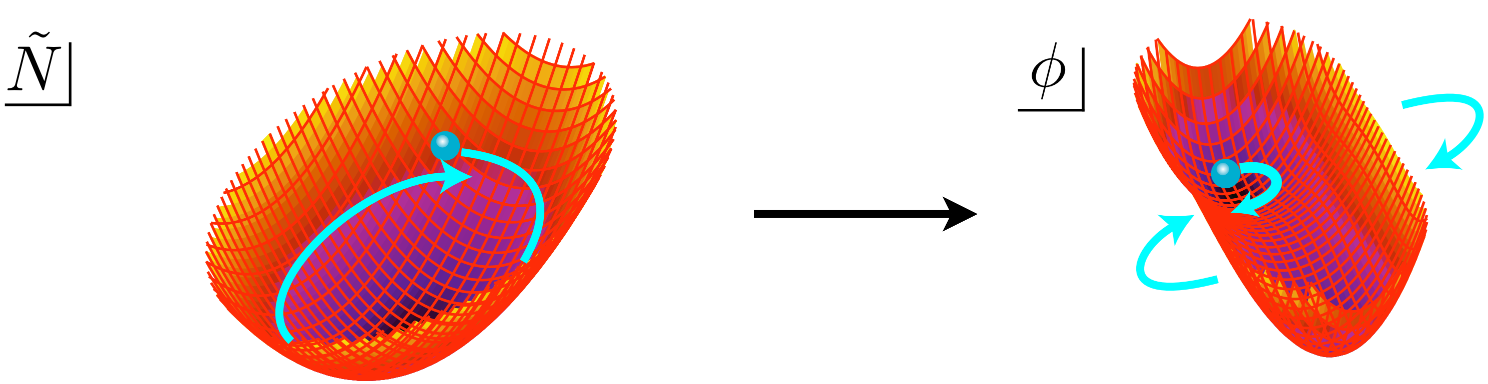
> → because $L_{\tilde{N}}$ is homogeneous,
> final $L_\phi$ averaged over the fluctuation is non-vanishing

$L_\phi$ and $L_{\tilde{N}}$ oscillate rapidly, but conserving $L_\phi - L_{\tilde{N}}$

→ center of the oscillation of $L_\phi$ is determined by homogeneous $L_{\tilde{N}}$ at the destabilization

> ※potential minima of $\phi$ is determined by homogeneous $\tilde{N}$

the direction of the rotation of these minima is one definite direction all over the universe




※Hubble radius at destabilization epoch: typically $k^{-1} \sim \mathcal{O}(10)\mathrm{km}$

# 5. Constraints on this scenario

■ gravitino problem

→ reheating temperature must be sufficiently low:

$$T_R < 10^{6-9}\mathrm{GeV}$$

■ in ②, $\tilde{N}$ must not be trapped at the minima of F-term contribution

$$V_{N,F_{NR}} = M_N^2|\tilde{N}|^2 - \frac{2\lambda M_N}{M_{\mathrm{Pl}}}|\tilde{N}|^4 + \frac{\lambda^2}{M_{\mathrm{Pl}}^2}|\tilde{N}|^6$$

$$M/\lambda > M_{\mathrm{GUT}}^2/M_{\mathrm{Pl}}$$

# 5. Constraints on this scenario

■ positive thermal-mass can prevent the destabilization

⟶ reheating temperature must be sufficiently low:

$$T_R < 6.5 \times 10^6 \mathrm{GeV} \times \left(\frac{g_*}{100}\right)^{\frac{1}{4}} \left(\frac{m_\nu}{0.01\mathrm{eV}}\right)^{\frac{1}{4}} \left(\frac{M_N}{10^9\mathrm{GeV}}\right)^{\frac{5}{4}}$$

※thermal bath from partial decay of inflaton $T \sim (H T_R^2 M_{\rm Pl})^{\frac{1}{4}}$

■ baryon isocurvature perturbation

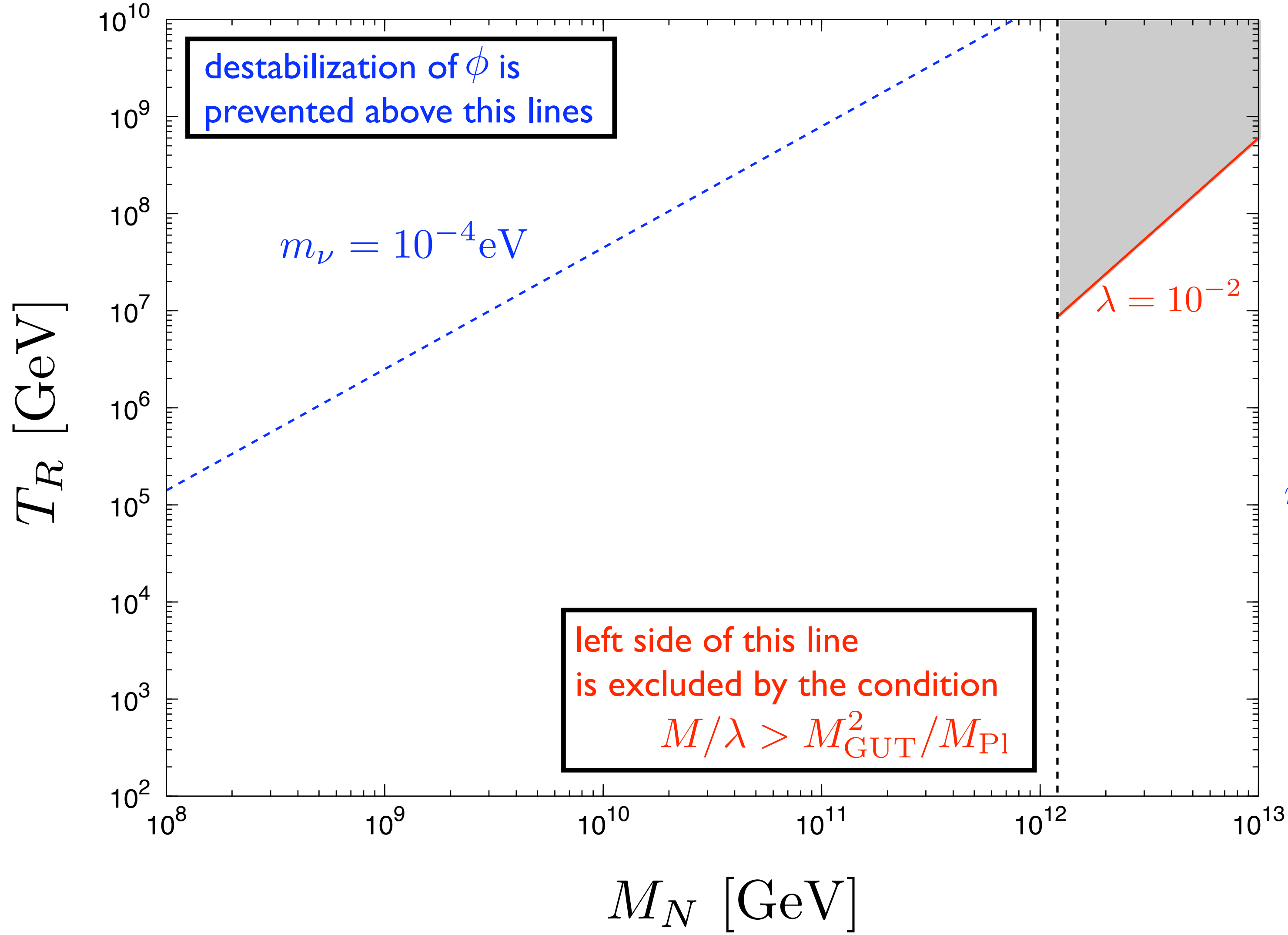
⟶ isocurvature perturbation of $\theta_{\tilde{N}}$ ⟶ baryon isocurvature perturbation

$$B_a = \sqrt{\frac{\mathcal{P}_\mathcal{S}}{\mathcal{P}_\mathcal{R}}} < 0.31 \longrightarrow M_N < H_{\rm inf} < 3 \times 10^{12}\mathrm{GeV}$$

※if the phase minimum is displaced from the minimum of B-term during the inflation, this constraint can be avoided

# 6 . Resultant baryon asymmetry: constraint on parameters

- parameter region which give $n_B/s > 8.7 \times 10^{-11}$ (shaded region)




$\lambda$ : coefficient of non-renormalizable term

$m_\nu = \frac{y_\nu^2 v^2}{M_N}$

analytically,

$$\frac{n_B}{s} \sim 8.7 \times 10^{-11} \times \left(\frac{\lambda}{10^{-4}}\right)\left(\frac{M_{\rm GUT}}{10^{16}\mathrm{GeV}}\right)^4\left(\frac{M_N}{10^{11}\mathrm{GeV}}\right)^{-2}\left(\frac{T_R}{6\times10^6\mathrm{GeV}}\right)$$

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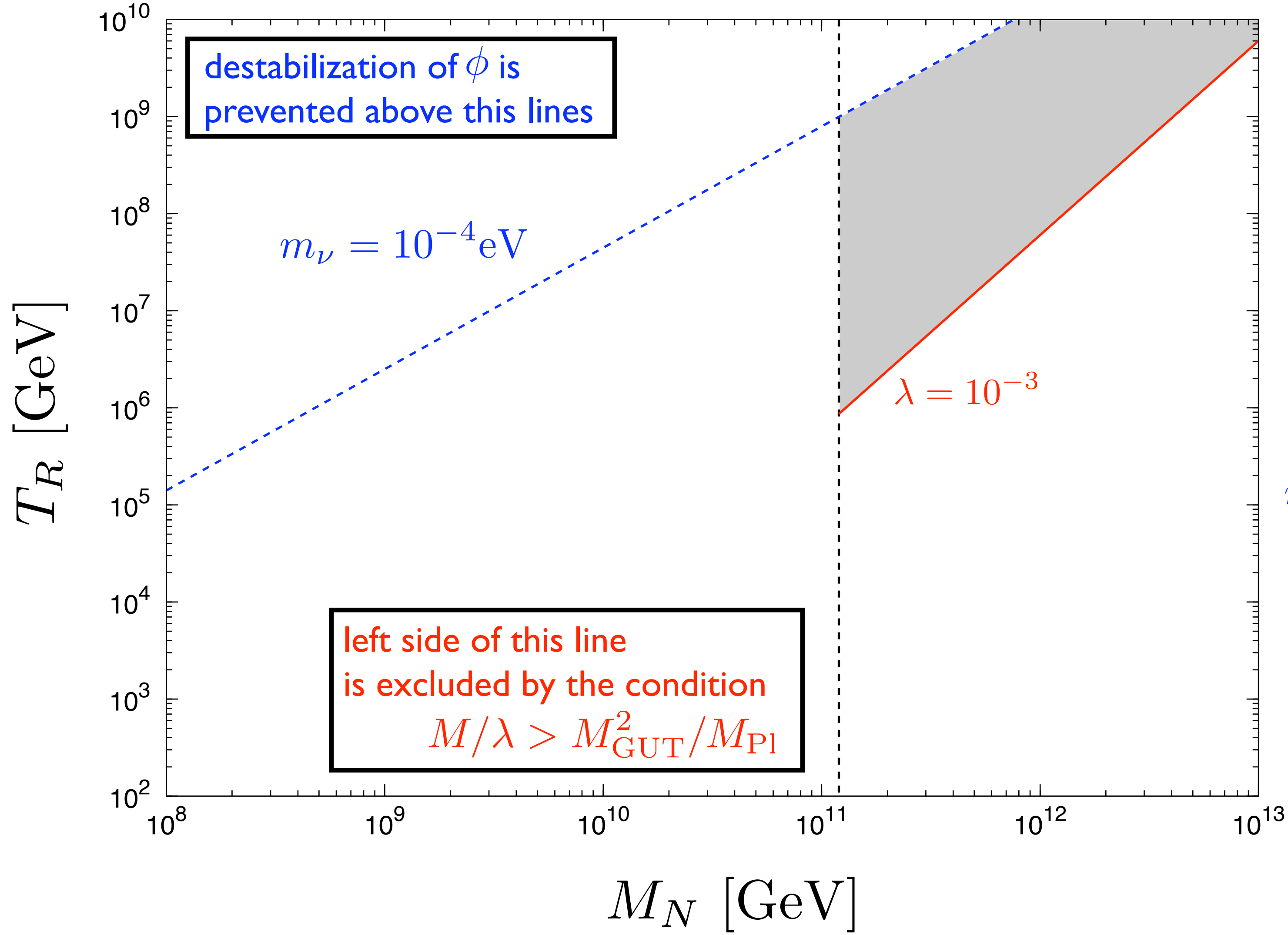


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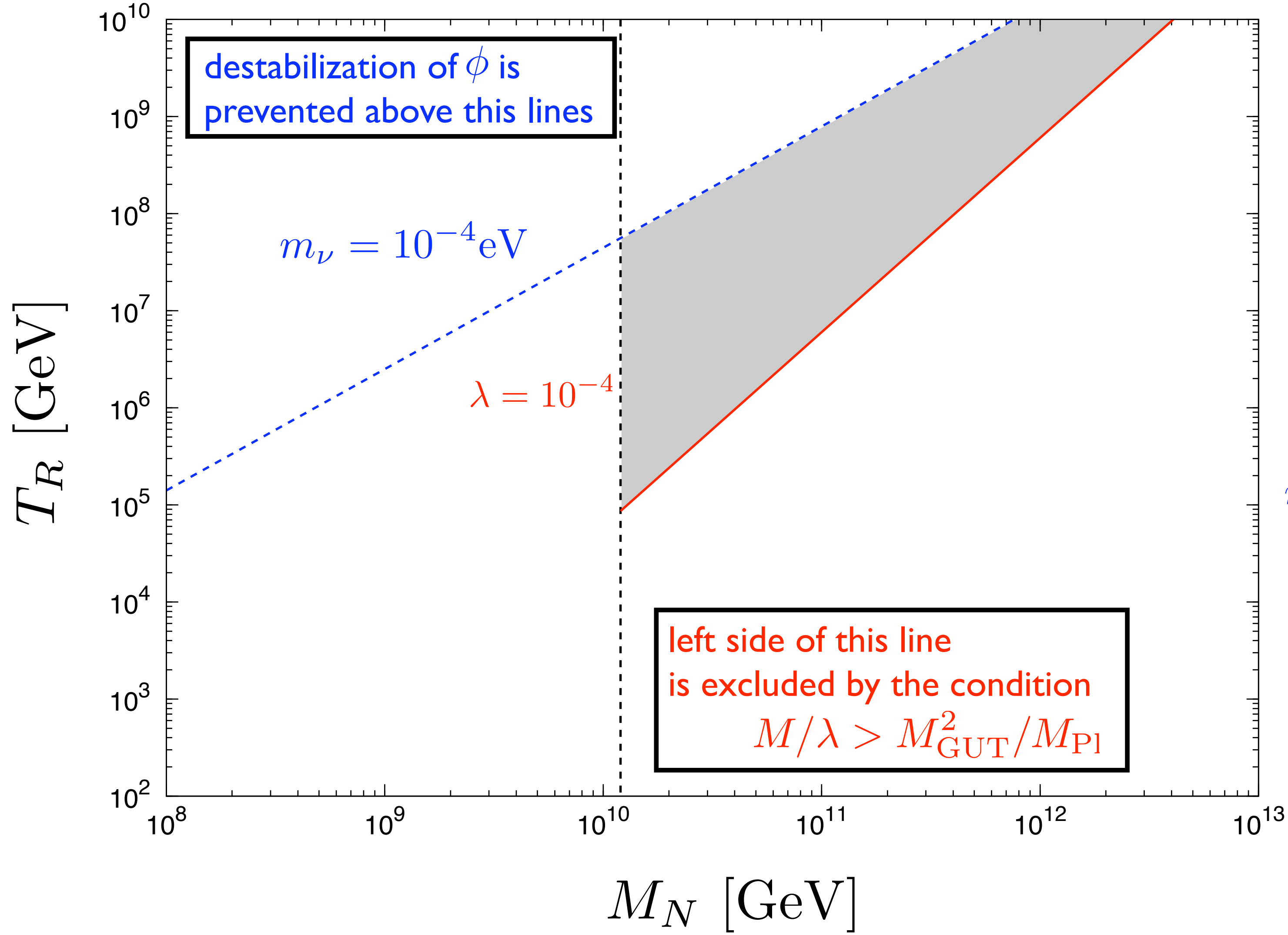


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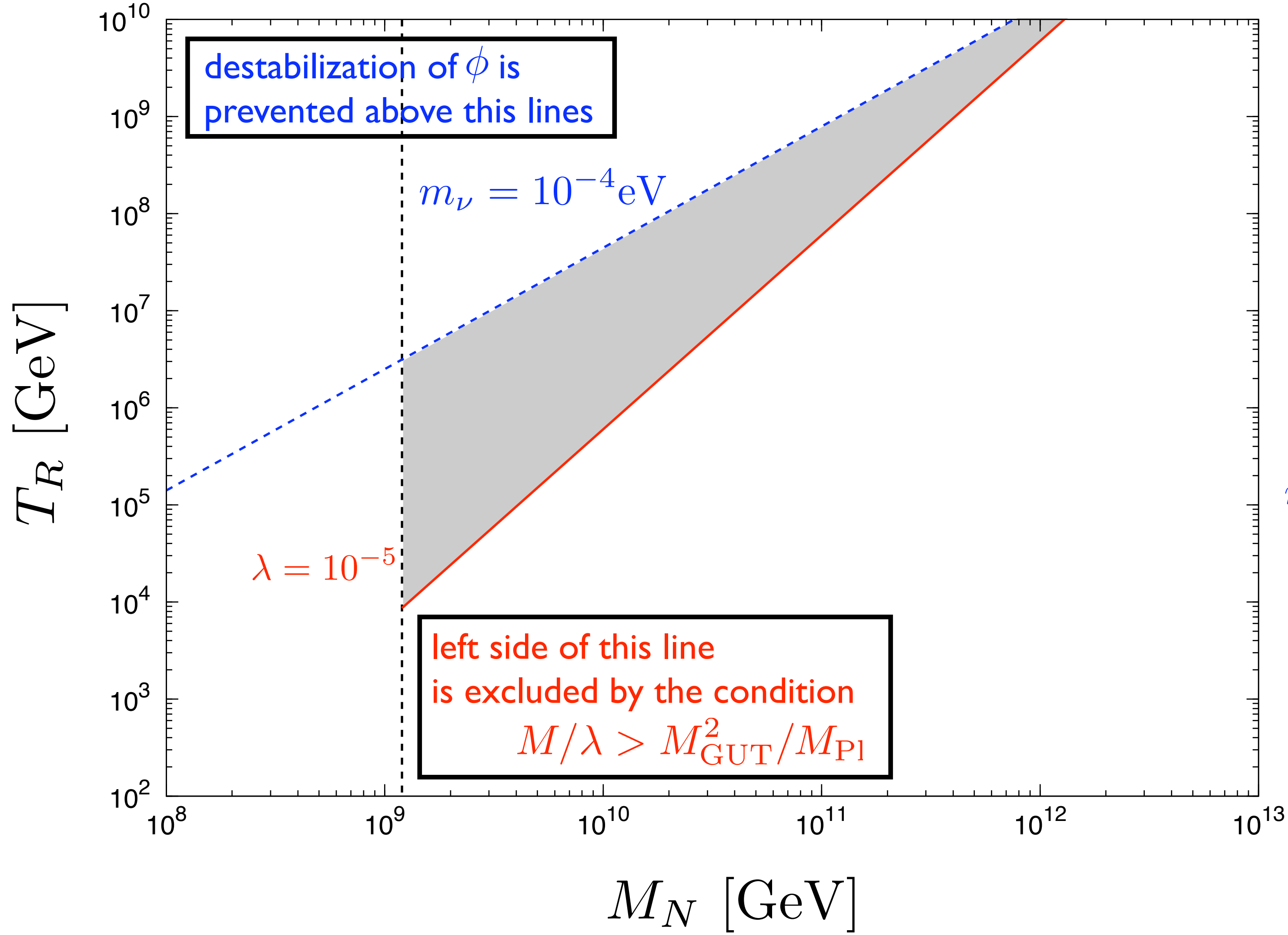


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# 7 . Summary

■ we reconsidered Affleck-Dine leptogenesis in SUSY seesaw model

■ $LH_u$-flat direction is relevant even if it has positive Hubble-induced mass term

■ charge asymmetry is generated in $\tilde{N}$ condensate,
then directly transfered to $LH_u$ -flat direction
⟶ sufficient baryon asymmetry can be generated

※only the initial evolution of $\tilde{N}$ determines the final baryon asymmetry

※small $\lambda$ is desirable for this scenario