Asymmetric particle production due to oscillating background field

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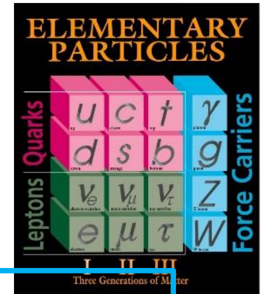
arXiv:2005.08037 [hep-ph]

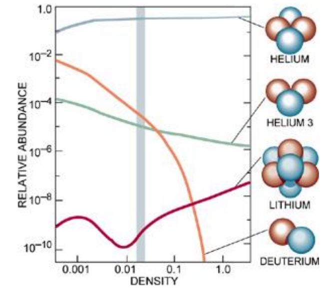
Outlook

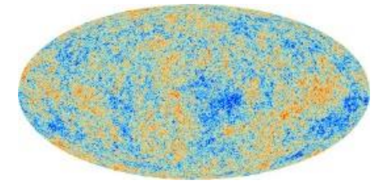
1. Introduction
2. Asymmetric particle production
    1. Demonstration in simple model
    2. Application to Type-I seesaw model
3. Summary

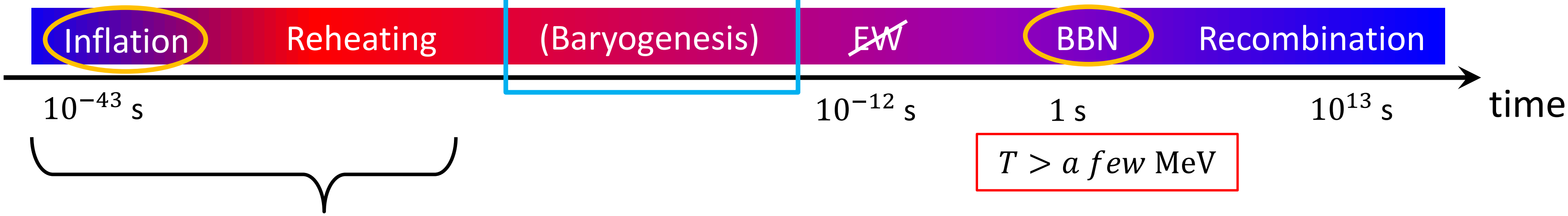
1. Introduction

History of the Universe

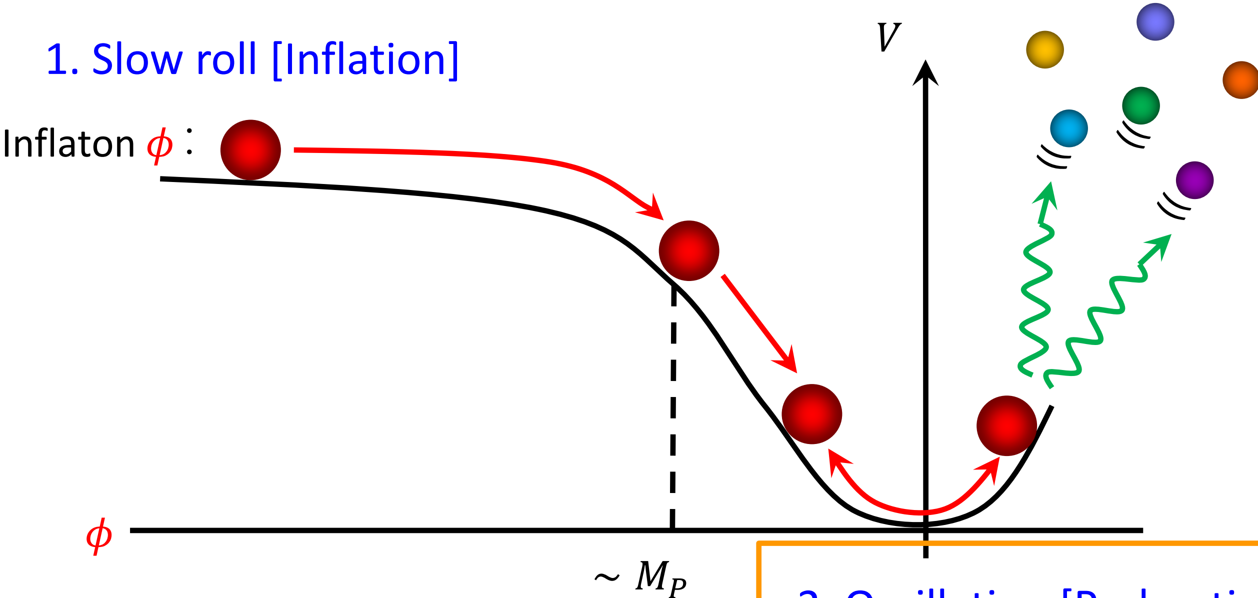








1. Slow roll [Inflation]



2. Oscillation [Preheating]

3. Decay [Reheating]

$$T_R \sim 0.2\sqrt{\Gamma_\phi M_P}$$

$(M_P \sim 10^{19}\ \mathrm{GeV})$

Preheating (without spatial expanding)

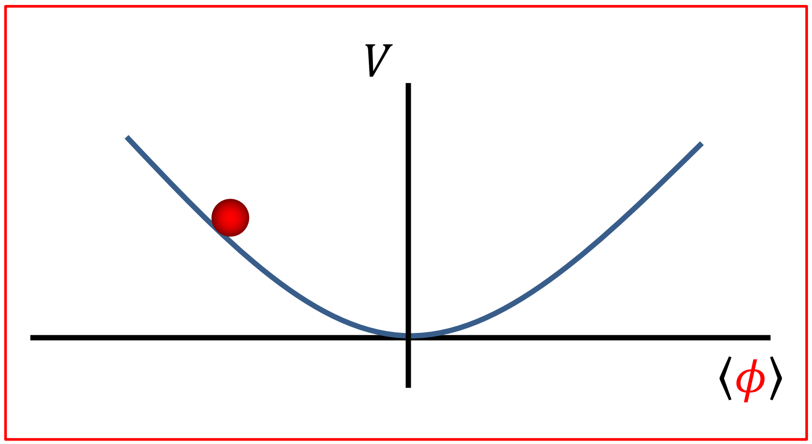
[J. H. Traschen and R. H. Brandenberger (1990), L. Kofman, A. D. Linde, A. A. Starobinsky (1994, 1997)]

Parametric resonance

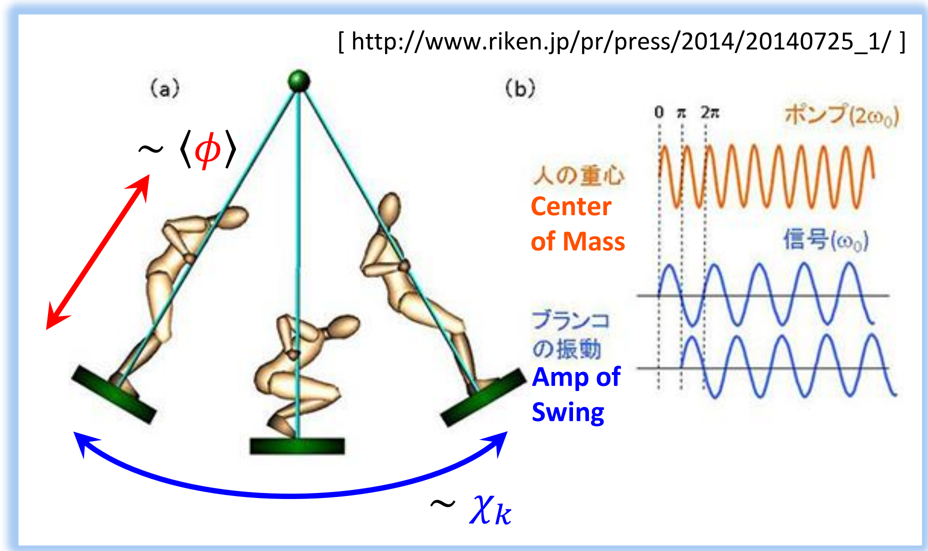
$$V = \frac{1}{2} m_\phi^2 \langle \phi(t) \rangle^2 + \frac{1}{2} g^2 \langle \phi(t) \rangle^2 \chi^2$$

ϕ : background (classical field)

χ : real scalar (*quantum field*)



$$\left[\ \langle \phi(t) \rangle \sim \langle \phi_0 \rangle \cos m_\phi t\ \right]$$



Equation of motion for χ

$$0 = \partial_t^2 \chi_k + \left(\mathbf{k}^2 + \langle \phi_0 \rangle^2 \cos^2 m_\phi t\right) \chi_k \qquad \left(\ \chi(t, \mathbf{x}) = \sum_k \left[e^{i\mathbf{k}\cdot\mathbf{x}} \chi_k(t) a_k + (h.c.) \right]\ \right)$$

→ "*Mathieu equation*" … motion of a swing with pumping person

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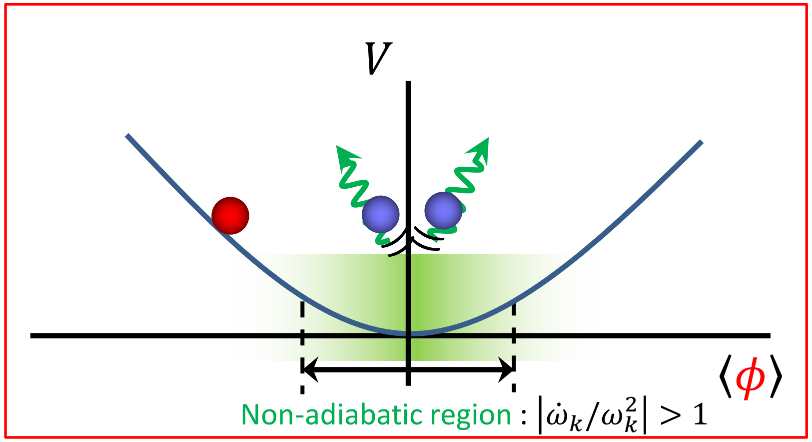
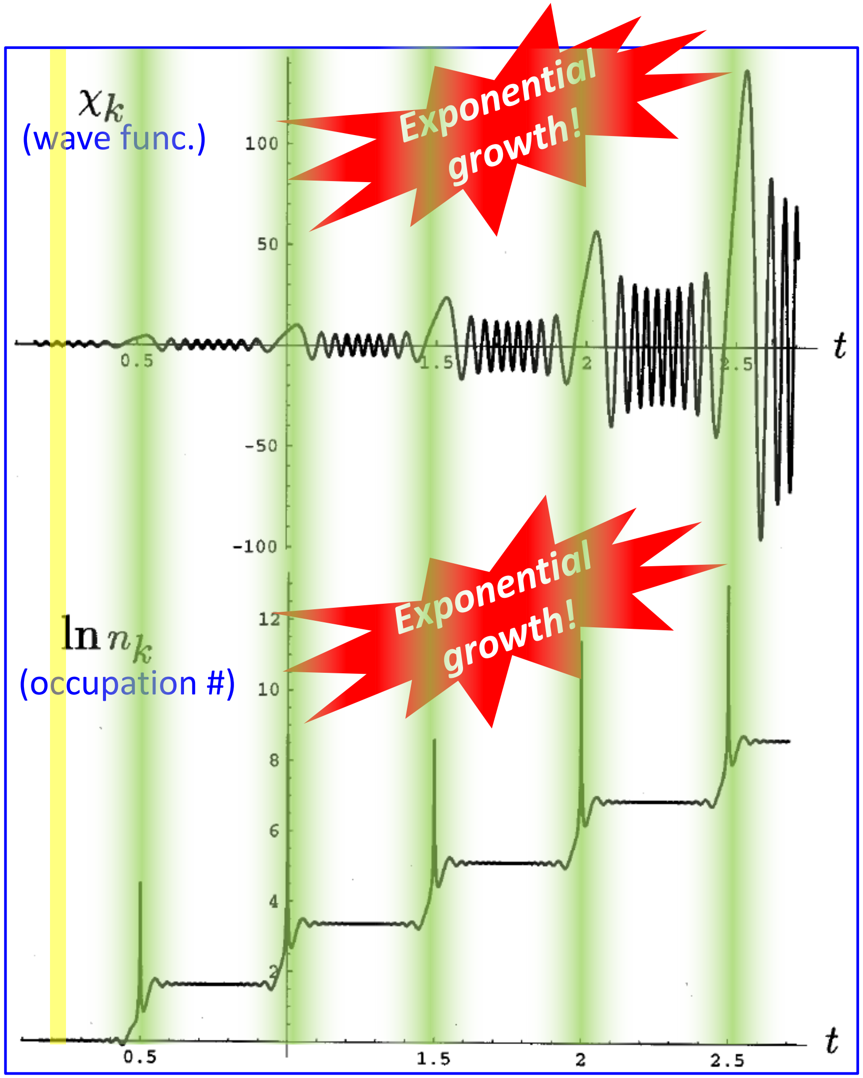


($\omega_k \equiv \sqrt{|\mathbf{k}|^2 + g^2 \langle \phi \rangle^2}$: frequency of χ)



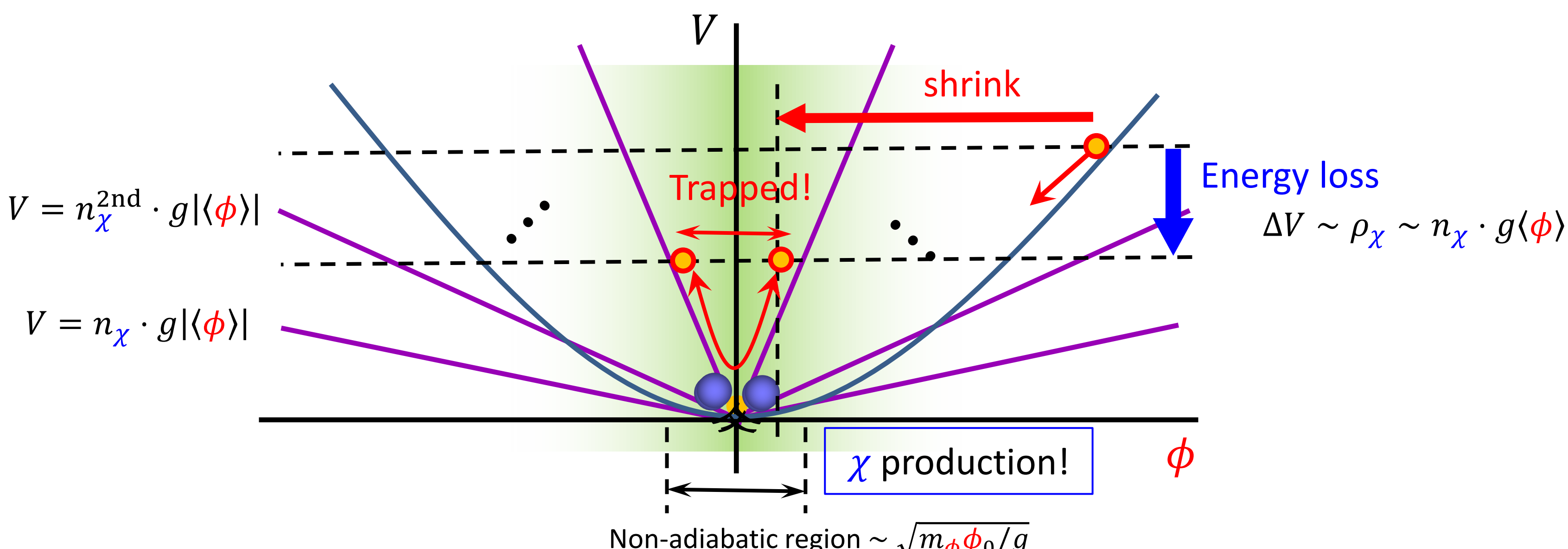
- Particle production happens
  - Exponentially (parametric resonance)
  - at non-adiabatic region (around a massless point: $\langle \phi \rangle \sim 0$)

Backreaction

$$\mathcal{H} = \frac{1}{2}\langle\dot{\phi}\rangle^2 + \frac{1}{2}m_\phi^2\langle\phi\rangle^2 + \frac{1}{2}\dot{\chi}^2 + \frac{1}{2}(\nabla\chi)^2 + \frac{1}{2}g^2\langle\phi\rangle^2\chi^2$$

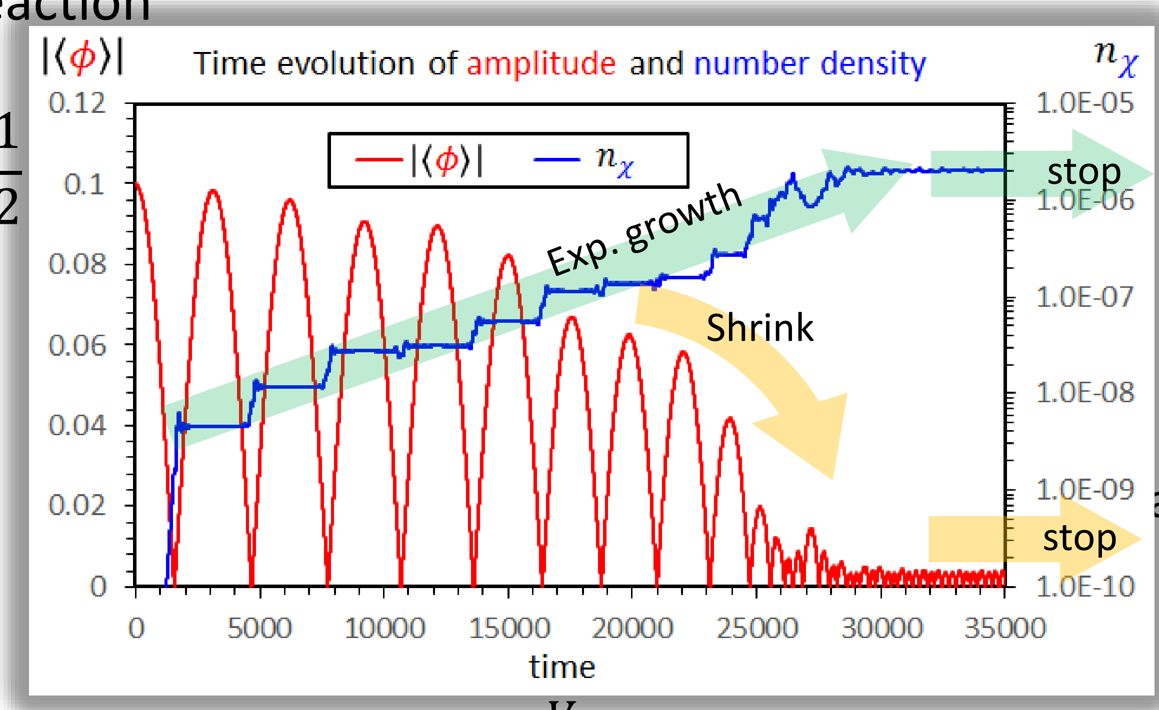
$= \rho_\chi \sim n_\chi \cdot g\langle\phi\rangle$

Linear potential is established for ϕ!

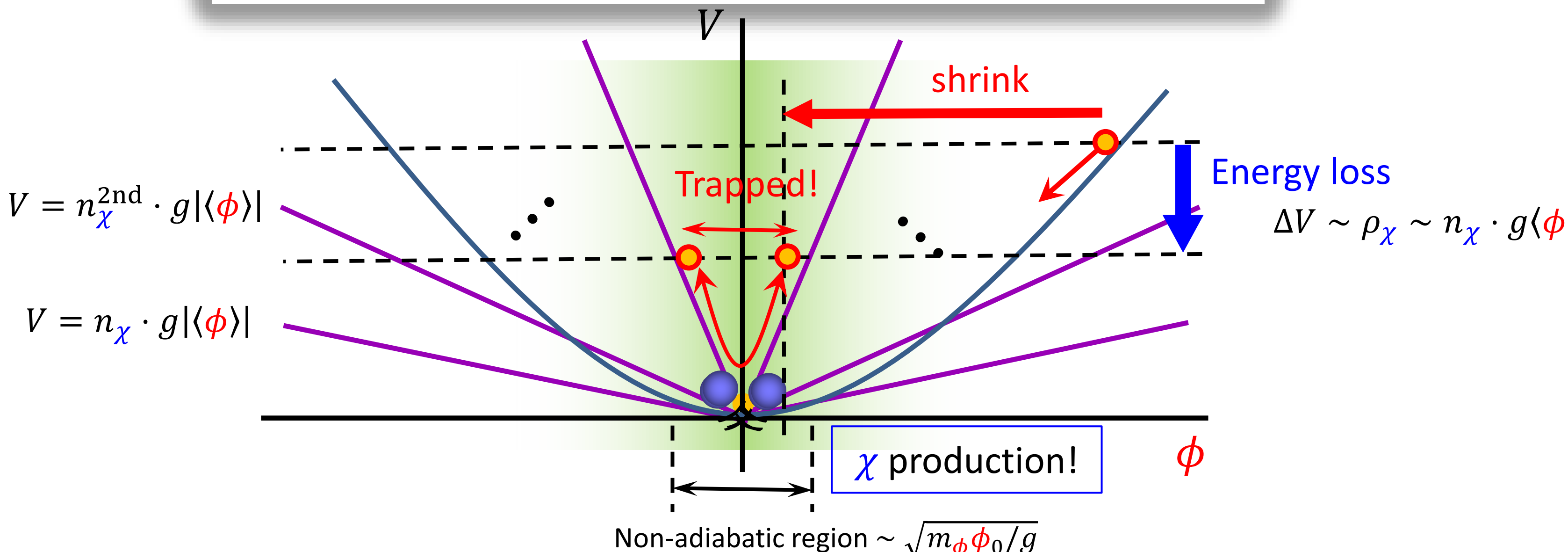


Backreaction

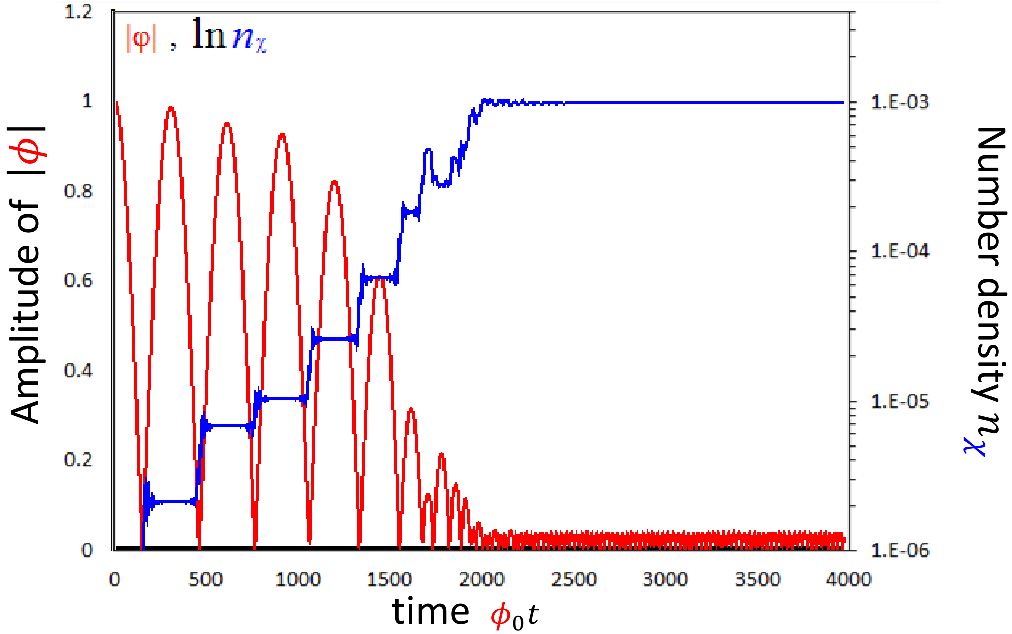
$\mathcal{H} = \frac{1}{2}$

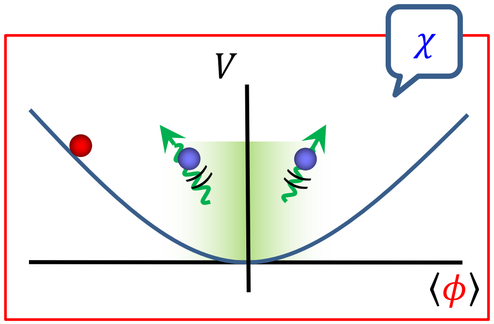


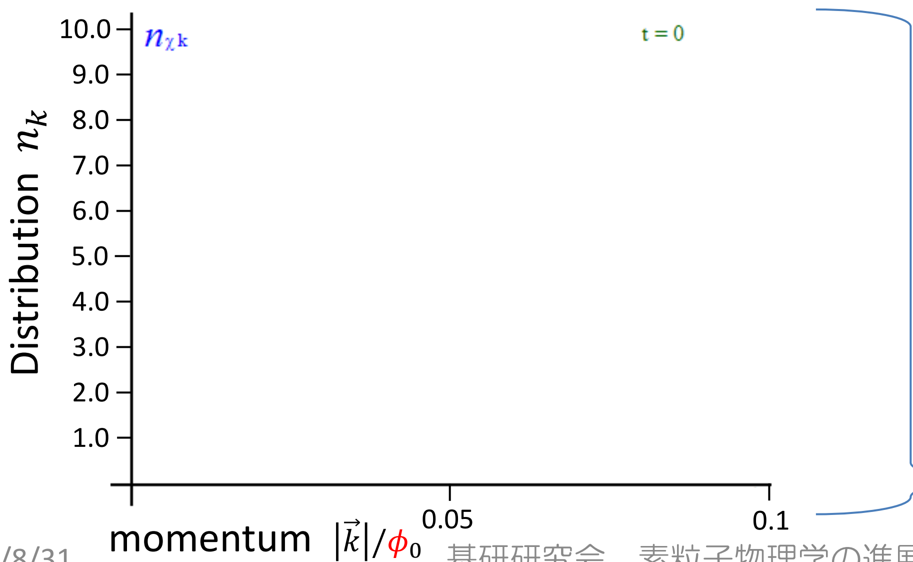
ablished for ϕ!

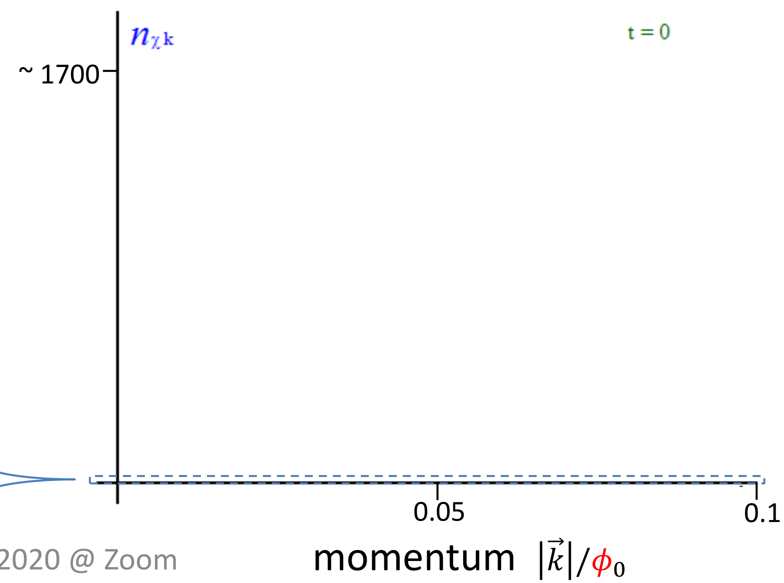


Numerical results ($\phi_0 = 1,\ \dot{\phi}_0 = 0,\ \ g = 1,\ m_\phi/\phi_0 = 0.01$, no expansion)

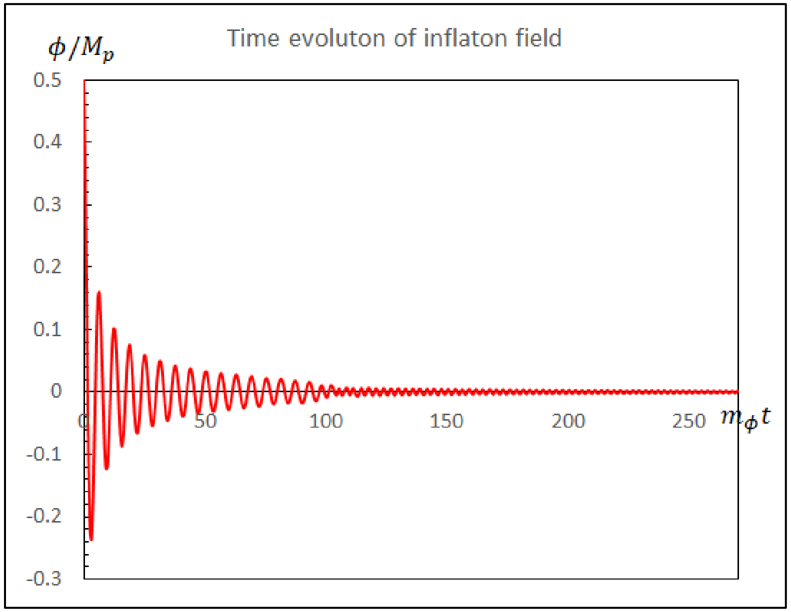


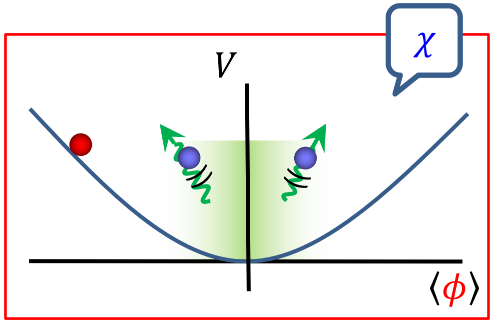


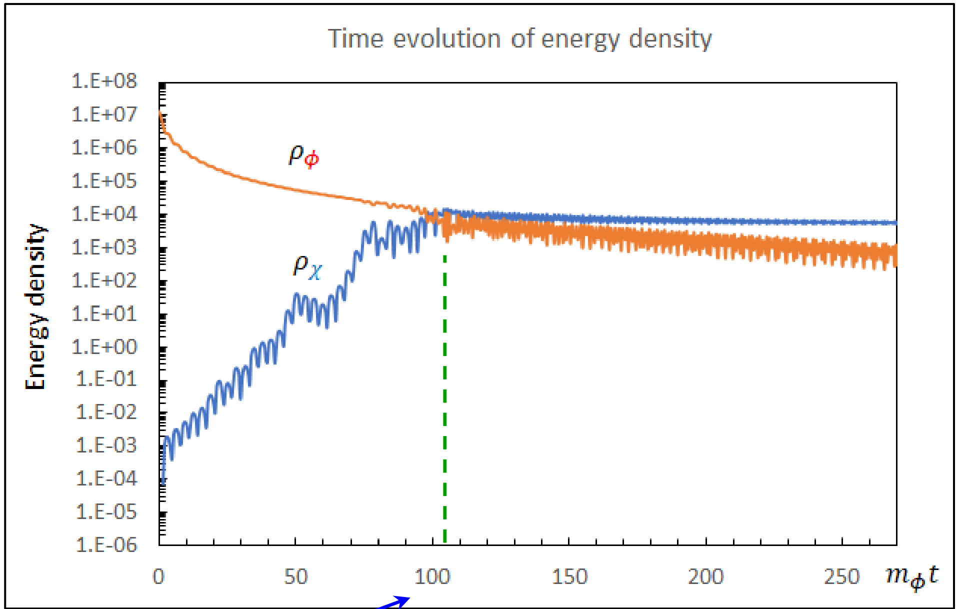




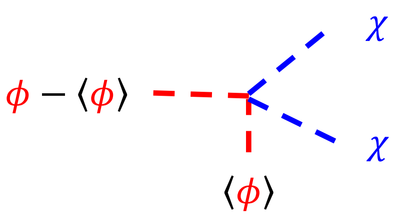
With expansion effect ($g = 10^{-4},\ m_\phi = 10^{13}$ GeV)







Decay rate of inflaton



$\sim\ -ig^2\langle\phi\rangle$

$$\Gamma_\phi \sim \frac{g^4\langle\phi\rangle^2}{16\pi m_\phi}\theta\left(m_\phi^2 - 4\left(m_\chi^2 + g^2\langle\phi\rangle^2\right)\right) \lesssim \frac{g^2 m_\phi}{64\pi}$$

$$\therefore\ m_\phi t_{\rm reh} \sim \frac{m_\phi}{\Gamma_\phi} \sim \frac{64\pi}{g^2} = 2\times 10^{10} \gg 100$$

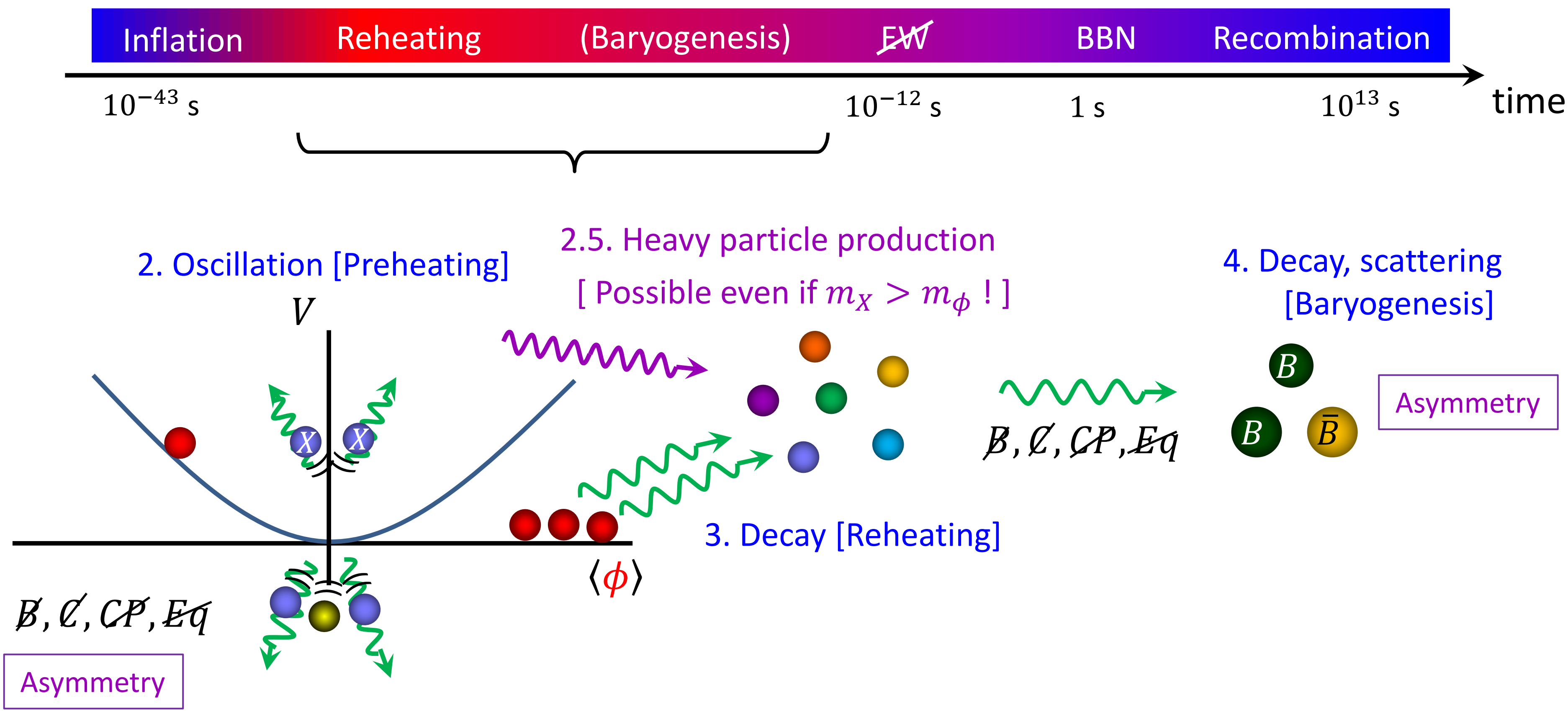
"Reheating" happens much faster than inflaton "decay!"

2. Asymmetric particle production

2-1. Demonstration in simple model

2-2. Application to Type-I seesaw model

Baryogenesis through preheating



3. Asymmetry generation in preheating

- Can the particle production causes the asymmetry generation simultaneously?

[K. Funakubo, A. Kkuto, S. Otsuki, F. Toyoda ('00)]
[R. Rangarajan, D. V. Nanopoulos ('01)] etc.

A simple CP violating model: [SE, T. Matsuda (2017)]

Contents : 1 complex scalar + 1 real scalar (+ oscillating mass)

$$\mathcal{L} = |\partial\chi|^2 - m_\chi^2(t)|\chi|^2 - \frac{1}{2}\left(\epsilon\chi^2 + (h.c.)\right) + \frac{1}{2}(\partial\xi)^2 - \frac{1}{2}m_\xi^2(t)\xi^2 - \left(g\chi\xi + (h.c.)\right)$$

- One of couplings can be real, but both cannot → CP can be violated
- EOMs

$$\chi(x) = \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \chi_{\mathbf{k}}(t), \qquad \chi(x) = \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \chi_{\mathbf{k}}(t)$$

  - $$0 = \partial_t^2 \begin{pmatrix} \chi_{\mathbf{k}} \\ \chi_{-\mathbf{k}}^\dagger \\ \xi_{\mathbf{k}} \end{pmatrix} + \begin{pmatrix} \omega_{\chi,k}^2 & \epsilon^* & g^* \\ \epsilon & \omega_{\chi,k}^2 & g \\ g & g^* & \omega_{\xi,k}^2 \end{pmatrix} \begin{pmatrix} \chi_{\mathbf{k}} \\ \chi_{-\mathbf{k}}^\dagger \\ \xi_{\mathbf{k}} \end{pmatrix}$$

$$\left(\omega_{\chi,k} \equiv \sqrt{|\mathbf{k}|^2 + m_\chi^2} \right)$$

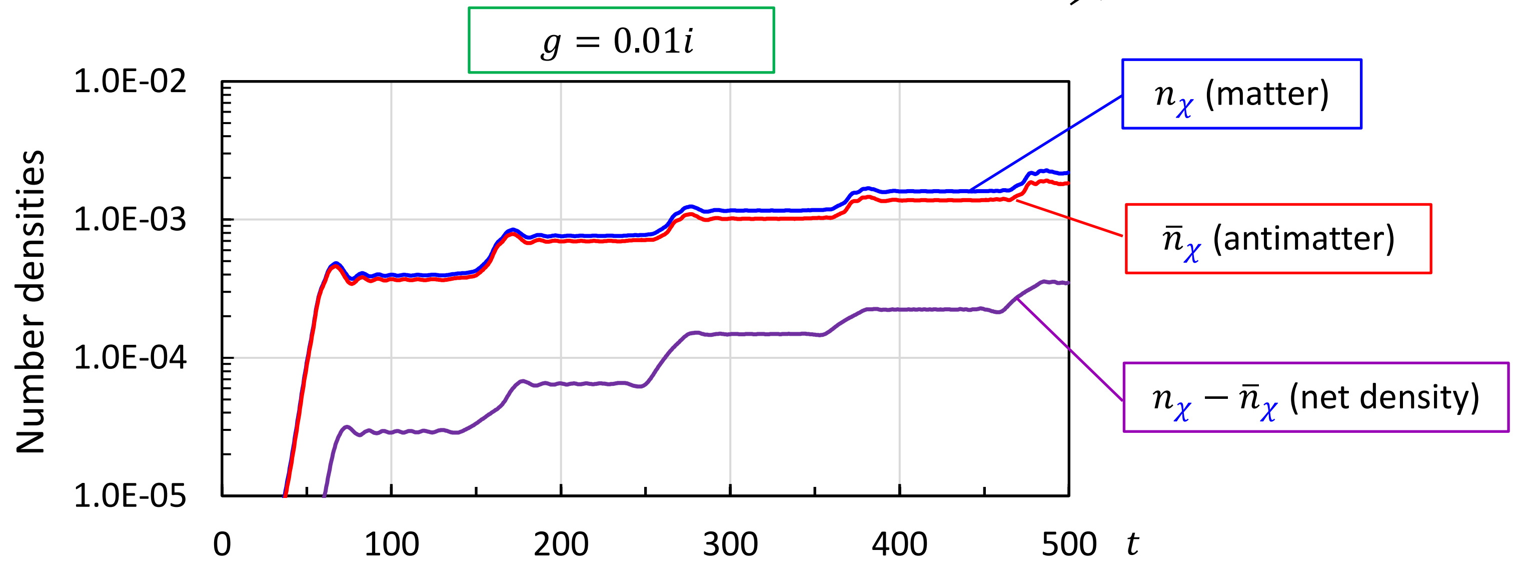
$$\left(\omega_{\xi,k} \equiv \sqrt{|\mathbf{k}|^2 + m_\xi^2} \right)$$

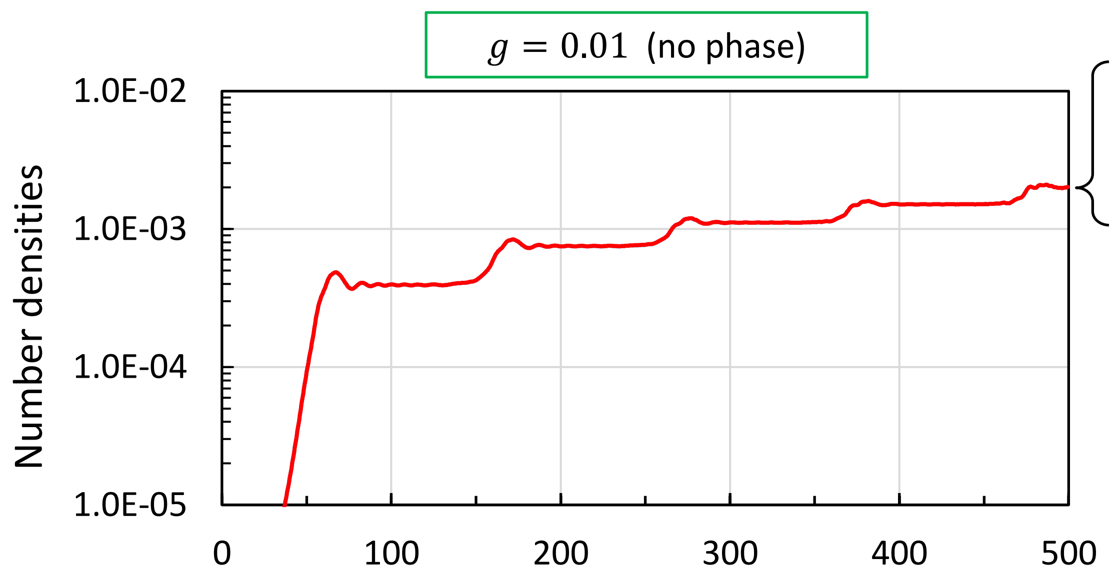
- We follow the time evolution of
  - Total number density of χ : $n_{\mathrm{tot}} = \int \frac{d^3k}{(2\pi)^3}\left(\frac{1}{\mathrm{Vol.}} \cdot \frac{\langle \dot{\chi}_{\mathbf{k}}^\dagger \dot{\chi}_{\mathbf{k}} \rangle + \omega_{\chi,k}^2 \langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle}{\omega_{\chi,k}} - 1\right)$
  - net number density of χ : $n_{\mathrm{net}} = \int \frac{d^3k}{(2\pi)^3}\left(1 - \frac{1}{\mathrm{Vol.}} \cdot 2\mathrm{Im}\langle \chi_{\mathbf{k}}^\dagger \cdot \partial_t \chi_{\mathbf{k}} \rangle\right)$

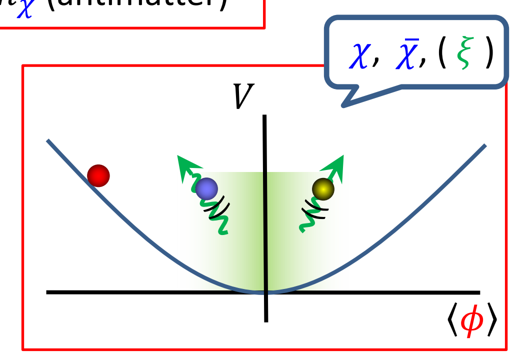
Numerical results 1

$$m_\chi^2 = 0.15^2 + 4\cos^2 0.03t, \quad m_\xi^2 = 0.1^2, \ \epsilon = 10^{-4}$$

$\sim \langle\phi\rangle^2$





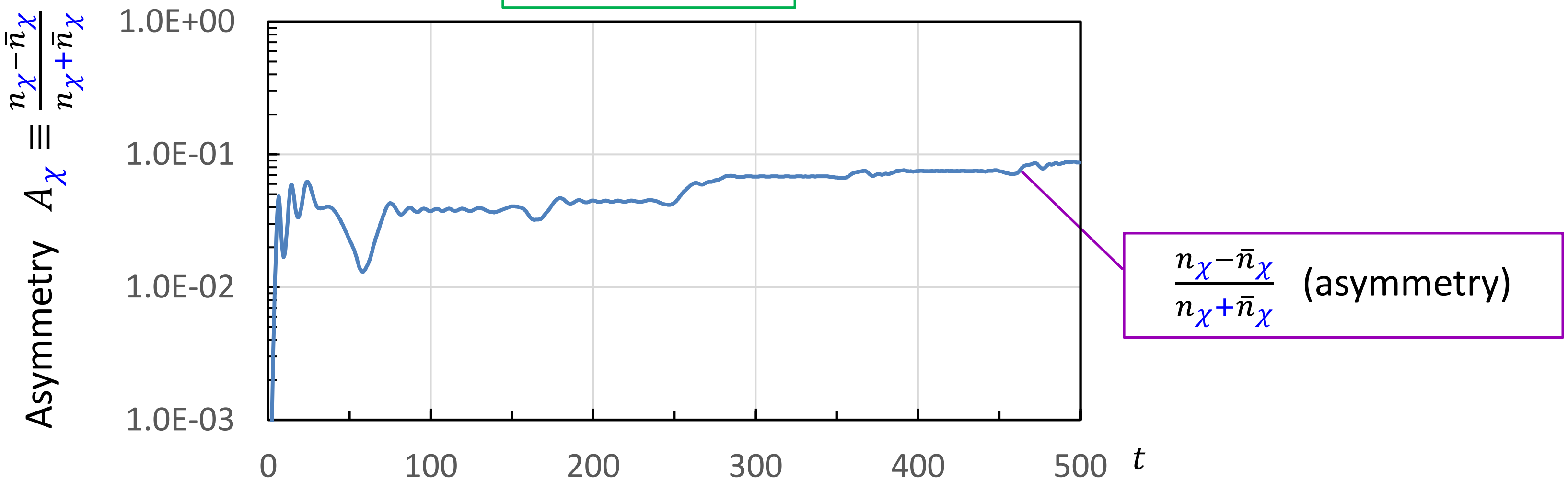


Numerical results 2

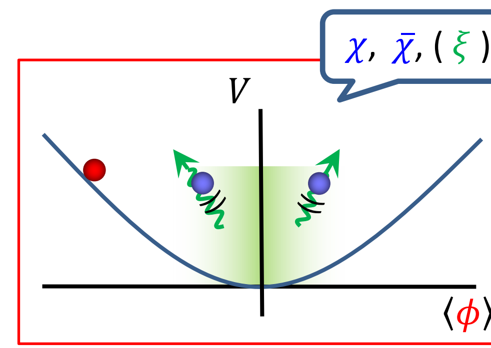
$m_\chi^2 = 0.15^2 + 4\cos^2 0.03t,\ \ m_\xi^2 = 0.1^2,\ \epsilon = 10^{-4}$

$\sim \langle\phi\rangle^2$

$g = 0.01i$



- While the growth of each number densities are exponential, the asymmetry $A_\chi \equiv \frac{n_\chi - \bar{n}_\chi}{n_\chi + \bar{n}_\chi}$ seems not to grow (nearly constant)



What is the essence?

EOM (again)

$$0 = \partial_t^2 \Psi_{\mathbf{k}} + \left(\mathbf{k}^2 + M^2(t)\right)\Psi_{\mathbf{k}}$$

$$\Psi_{\mathbf{k}} = \begin{pmatrix} \chi_{\mathbf{k}} \\ \chi_{-\mathbf{k}}^{\dagger} \\ \xi_{\mathbf{k}} \end{pmatrix}, \qquad M^2(t) = \begin{pmatrix} m_\chi^2(t) & \epsilon^* & g^* \\ \epsilon & m_\chi^2(t) & g \\ g & g^* & m_\xi^2(t) \end{pmatrix}$$

"Diagonalization": $M_{\rm diag}^2 \equiv U^\dagger M^2 U$, U : diagonalizing unitary matrix

$$0 = \partial_t^2 (U^\dagger \Psi_{\mathbf{k}}) - 2i\gamma\partial_t (U^\dagger \Psi_{\mathbf{k}}) + \left(M_{\rm diag}^2 - i\partial_t \gamma - \gamma^2\right)(U^\dagger \Psi_{\mathbf{k}})$$

(where $\gamma \equiv iU^\dagger \partial_t U$: Hermite, non-diagonal)

→ EOM cannot be diagonalized as long as $\partial_t U \neq 0$

$\gamma \equiv iU^\dagger \partial_t U$ plays role as a "gauge field" (Berry connection)

→ Gauge field couples to a current ~ Chemical potential

c.f. Gauge operator $(D^\mu D_\mu - m^2)\phi = \partial^2\phi - 2igA\cdot\partial\phi + (m^2 - ig\partial\cdot A - g^2 A^2)\phi$

c.f. Berry connection : $\mathcal{A}_{\mathbf{R}} = i\langle n(\mathbf{R})|\nabla_{\mathbf{R}}|n(\mathbf{R})\rangle$

2. Asymmetric particle production

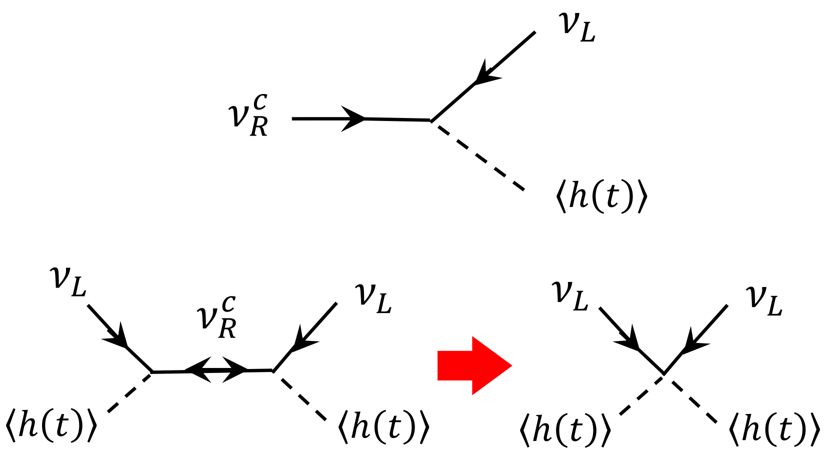
2-1. Demonstration in simple model

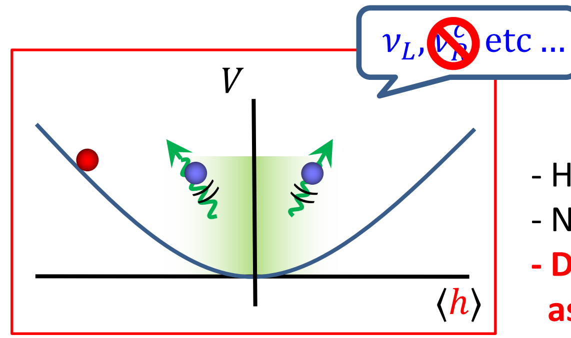
2-2. Application to Type-I seesaw model

Application to Type-I seesaw model

[SE, C. Cai, Z. H. Yu, H. H. Zhang (2020)]

$\not{B}, (\not{L},)\ \not{CP}$ and oscillating background → Type-I seesaw





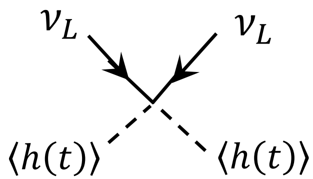
- Heavy particle production
- Non-thermal leptogenesis
- **Direct production of asymmetric LHν**

Situation

- Higgs background oscillates coherently
- (RHν mass scale) >> (Higgs oscillation scale)
  - RHν is not produced, but LHν might be produced with asymmetry
- <u>Advantage</u>: the process occurs in out-of-equillibrium during and after the production

CPV process

Is it enough to consider with Weinberg operator ? → No

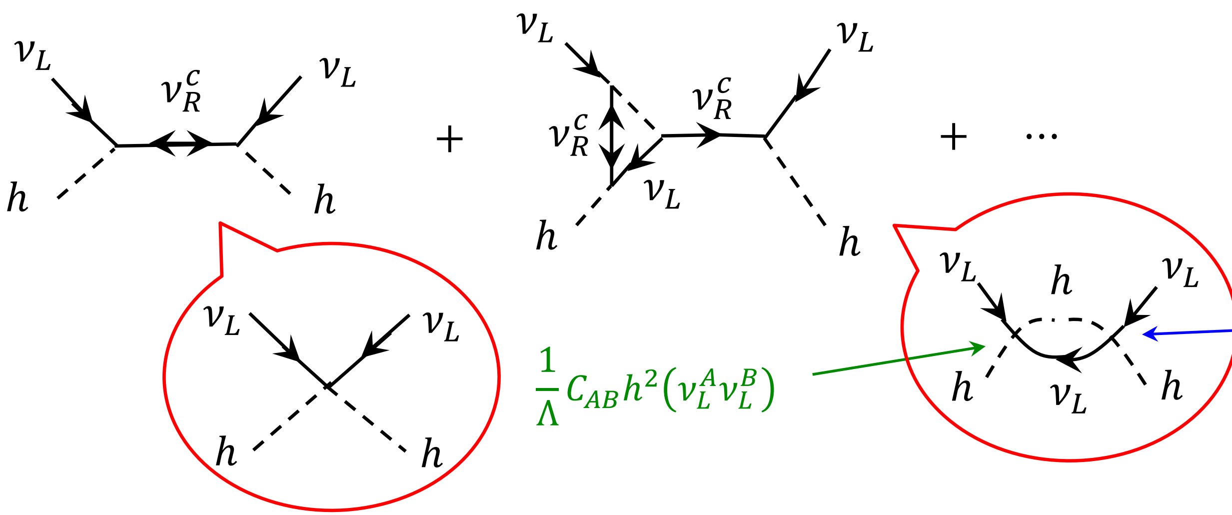


$$\frac{1}{\Lambda} C_{AB} h^2 (\nu_L^A \nu_L^B)$$

- LHν mass term
- This can be diagonalized

Other interaction is required in order to remain the CP phase

Reminds scattering process in thermal leptogenesis



$$\frac{1}{\Lambda} C_{AB} h^2 (\nu_L^A \nu_L^B)$$

$$\frac{p_\mu}{\Lambda^2} D_{AB} h^2 (\nu_L^{A\dagger} \bar{\sigma}^\mu \nu_L^B)$$

Two type couplings are required for CP-violation in the effective theory

Procedure to estimate the lepton asymmetry

1. Starting point: SM + singlet RHν (3 generation)

$$\mathcal{L}_{\rm lepton} = \sum_A \left(\ell^{aA\dagger}\bar{\sigma}^\mu i D_\mu \ell^{aA} + e_R^{cA\dagger}\bar{\sigma}^\mu i D_\mu e_R^{cA} + \underline{\nu_R^{cA\dagger}\bar{\sigma}^\mu i\partial_\mu \nu_R^{cA}} \right)$$
$$- \sum_{A,B} \left(\underline{\frac{1}{2} M_R^{AB}\nu_R^{cA}\nu_R^{cB}} + \sqrt{2} y_e^{AB} H^{a\dagger}\ell^{aA} e_R^{cB} - \sqrt{2} y_\nu^{AB}\epsilon^{ab} H^a \ell^{bA}\nu_R^{cB} + ({\rm h.c.}) \right)$$

Mass of RHν: taken to be real

2. Driving the operator EOMs and constructing the effective theory

3. Constructing the EOMs for the Higgs background and two-point functions based on the op. Eqs.

4. Solving them numerically

- Net lepton number density by the two point function

$$n_L = \frac{1}{\rm Vol.}\int d^3x \sum_A \left[\frac{1}{2}\left(\langle \nu_L^{A\dagger}\bar{\sigma}^0\nu_L^A\rangle - \langle \nu_L^A \sigma^0 \nu_L^{A\dagger}\rangle \right) + \cancel{\langle e_L^{A\dagger}\bar{\sigma}^0 e_L^A\rangle - \langle e_R^{cA\dagger}\bar{\sigma}^0 e_R^{cA}\rangle} \right]$$

- We neglect the expansion effect for simplicity

Operator EOMs

RHν (iterative approximation by $M_R^{-1}\partial$)

$$0 = \begin{pmatrix} -M_R & \sigma^\mu \cdot i\partial_\mu \\ \bar{\sigma}^\mu \cdot i\partial_\mu & -M_R \end{pmatrix}^{AB} \begin{pmatrix} \nu_R^c \\ \nu_R^{c\dagger} \end{pmatrix}^B - h \begin{pmatrix} y_\nu^T \nu_L \\ y_\nu^\dagger \nu_L^\dagger \end{pmatrix}^A$$

$$\therefore \begin{pmatrix} \nu_R^c \\ \nu_R^{c\dagger} \end{pmatrix}^A = \begin{pmatrix} M_R^{-1} & \\ & M_R^{-1} \end{pmatrix}^{AB} \left(-h \begin{pmatrix} y_\nu^T \nu_L \\ y_\nu^\dagger \nu_L^\dagger \end{pmatrix} + \begin{pmatrix} & \sigma^\mu \cdot i\partial_\mu \\ \bar{\sigma}^\mu \cdot i\partial_\mu & \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \nu_R^{c\dagger} \end{pmatrix} \right)^B$$

$$= \begin{pmatrix} M_R^{-1} & \\ & M_R^{-1} \end{pmatrix}^{AB} \left(-h \begin{pmatrix} y_\nu^T \nu_L \\ y_\nu^\dagger \nu_L^\dagger \end{pmatrix} - \begin{pmatrix} & \sigma^\mu \cdot i\partial_\mu \\ \bar{\sigma}^\mu \cdot i\partial_\mu & \end{pmatrix} \begin{pmatrix} h \cdot M_R^{-1} y_\nu^T \nu_L \\ h \cdot M_R^{-1} y_\nu^\dagger \nu_L^\dagger \end{pmatrix} + \mathcal{O}(M_R^{-2}\partial^2) \right)^B$$

LHν (approximation: neglecting the gauge interaction)

$$0 = \bar{\sigma}^\mu \cdot i\partial_\mu \nu_L^A - h\left(y_\nu^* \nu_R^{c\dagger}\right)^A$$
$$= \bar{\sigma}^\mu \cdot i\partial_\mu \nu_L^A + \underline{h^2\left(y_\nu^* M_R^{-1} y_\nu^\dagger \nu_L^\dagger\right)}^A + \underline{ih\dot{h}(y_\nu^* M_R^{-2} y_\nu^T} \cdot \bar{\sigma}^0 \nu_L)^A + \cdots$$

$\frac{1}{\Lambda} C_{AB} h^2 \left(\nu_L^A \nu_L^B\right)$ ⟷ $\equiv m_\nu(t)$ (Seesaw formula) $\equiv iZ(t)$ ⟷ $\frac{p_\mu}{\Lambda^2} D_{AB} h^2 \left(\nu_L^{A\dagger} \bar{\sigma}^\mu \nu_L^B\right)$

- We choose $m_\nu(t)$ to be real and diagonal -> $Z(t)$ cannot be diagonalized!

$$\rightarrow \quad y_\nu = -\frac{i}{246\ \text{GeV}} U_{\text{PMNS}}^* \, m_{\nu,\text{now}}^{1/2} \, O \, M_R^{1/2}, \qquad m_{\nu,\text{now}} = \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix}$$

[Casas-Ibarra parametrization, O is a complex orthogonal matrix]

- Other fermions
  - We ignore them because we focus on the generation of the lepton asymmetry

- Equations for two point functions

$$\partial_t\langle\nu_{\mathbf{k}}^{sI\dagger}\nu_{\mathbf{k}}^{sJ}\rangle = -\sum_K\left(\langle\nu_{\mathbf{k}}^{sI\dagger}\nu_{\mathbf{k}}^{sK}\rangle(Z^*)^{KJ} + (Z^*)^{IK}\langle\nu_{\mathbf{k}}^{sK\dagger}\nu_{\mathbf{k}}^{sJ}\rangle\right) + im_\nu^{II}[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sI}\nu_{\mathbf{k}}^{sJ}\rangle] - im_\nu^{JJ}[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sJ}\nu_{\mathbf{k}}^{sI}\rangle]^*$$

$$\partial_t\langle\nu_{-\mathbf{k}}^{sI}\nu_{-\mathbf{k}}^{sJ\dagger}\rangle = -\sum_K\left(\langle\nu_{-\mathbf{k}}^{sI}\nu_{-\mathbf{k}}^{sK\dagger}\rangle Z^{KJ} + Z^{IK}\langle\nu_{-\mathbf{k}}^{sK}\nu_{-\mathbf{k}}^{sJ\dagger}\rangle\right) + im_\nu^{II}[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sJ}\nu_{\mathbf{k}}^{sI}\rangle]^* - im_\nu^{JJ}[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sI}\nu_{\mathbf{k}}^{sJ}\rangle]$$

$$\begin{aligned}\partial_t[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sI}\nu_{\mathbf{k}}^{sJ}\rangle] &= 2is|\mathbf{k}|[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sI}\nu_{\mathbf{k}}^{sJ}\rangle] \\ &-\sum_K\left([se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sI}\nu_{\mathbf{k}}^{sK}\rangle](Z^*)^{KJ} + (Z^*)^{IK}[se^{i\theta_{\mathbf{k}}}\langle\nu_{-\mathbf{k}}^{sK}\nu_{\mathbf{k}}^{sJ}\rangle]\right) + im_\nu^{II}\langle\nu_{\mathbf{k}}^{sI\dagger}\nu_{\mathbf{k}}^{sJ}\rangle - im_\nu^{JJ}\langle\nu_{-\mathbf{k}}^{sI}\nu_{-\mathbf{k}}^{sJ\dagger}\rangle.\end{aligned}$$

$$(\nu_L^I)_\alpha = \int\frac{d^3k}{(2\pi)^3}e^{i\mathbf{k}\cdot\mathbf{x}}\sum_{s=\pm}(e_{\mathbf{k}}^s)_\alpha\nu_{\mathbf{k}}^{sI},$$

$(e_{\mathbf{k}}^s)_\alpha$: eigen spinor for the helicity op.

$$-k^i(\bar\sigma^i e_{\mathbf{k}}^s)_\alpha = sk(\bar\sigma^0 e_{\mathbf{k}}^s)_\alpha$$

- Net lepton number density

$$n_L \sim \frac{1}{\mathrm{Vol.}}\int d^3x\sum_A\frac{1}{2}\left(\langle\nu_L^{A\dagger}\bar\sigma^0\nu_L^A\rangle - \langle\nu_L^A\sigma^0\nu_L^{A\dagger}\rangle\right)$$

$$= \frac{1}{\mathrm{Vol.}}\int\frac{d^3k}{(2\pi)^3}\sum_I\sum_{s=\pm}\frac{1}{2}\left(\langle\nu_{\mathbf{k}}^{sI\dagger}\nu_{\mathbf{k}}^{sI}\rangle - \langle\nu_{-\mathbf{k}}^{sI}\nu_{-\mathbf{k}}^{sI\dagger}\rangle\right)$$

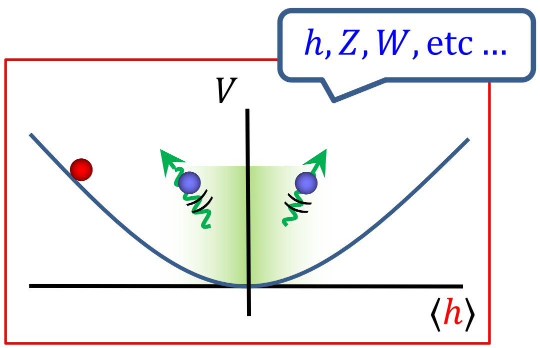
Higgs background

$$0 = \partial_t^2 \langle h \rangle + \left(\lambda \langle h \rangle^2 + M_{\rm BR}^2\right)\langle h \rangle$$

λ : Higgs self coupling ~ 0.001

- $M_{\rm BR}^2 = \mathcal{N}_{\rm deg} \cdot \frac{1}{4} g_W^2 \int \frac{d^3k}{(2\pi)^3} \left(|u_k|^2 - \frac{1}{2\omega_k} \right)$ (Relating to "thermal mass")
  - u_k: Solution of $0 = \partial_t^2 u_k + \left(|\mathbf{k}|^2 + \frac{1}{4} g_W^2 \langle h \rangle^2 \right) u_k$
  - $\mathcal{N}_{\rm deg} \sim \frac{12\lambda}{g_W^2} \cdot 1 + \left(1 + \frac{g_Y^2}{g_W^2}\right) \cdot 3 + 6 \sim 12$ (Higgs, Z, W)

The backreaction has an important role for the asymmetry generation (we will see later)



Parameters

- Gauge couplings: $\alpha_Y = \alpha_W = 1/40$
- Present LHν masses: $m_{\nu,\text{now}} = \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix}$

$$m_1 = 0$$
$$m_2 = \sqrt{\Delta m_{21}^2} = \sqrt{7.5 \times 10^{-5}}\ \text{eV}$$
$$m_1 = \sqrt{\Delta m_{32}^2} = \sqrt{2.5 \times 10^{-3}}\ \text{eV}$$

- RHν masses: $M_R = M_1 \begin{pmatrix} 1 & & \\ & 10 & \\ & & 100 \end{pmatrix}$
- Complex orthogonal matrix: $\theta_{12} = \frac{\pi}{6} + 0.1i, \quad \theta_{23} = \frac{\pi}{12} + 0.2i, \quad \theta_{13} = \frac{\pi}{4} + 0.3i$

$$O = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13} \\ & 1 & \\ s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

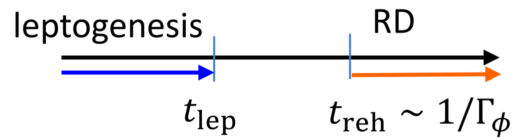
$$c_{ij} = \cos\theta_{ij} = \cosh(\text{Im}\,\theta_{ij}) \cdot \cos(\text{Re}\,\theta_{ij}) - i\sinh(\text{Im}\,\theta_{ij}) \cdot \sin(\text{Re}\,\theta_{ij})$$
$$s_{ij} = \sin\theta_{ij} = \cosh(\text{Im}\,\theta_{ij}) \cdot \sin(\text{Re}\,\theta_{ij}) - i\sinh(\text{Im}\,\theta_{ij}) \cdot \cos(\text{Re}\,\theta_{ij})$$

Scale of particle production

- The non-adiabatic condition for LHν gives

$$\Delta k \sim \left(\frac{m_3 \cdot (\partial_t h_*)^2}{(246\ \text{GeV})^2}\right)^{\frac{1}{3}} = \left(\frac{\sqrt{\partial_t h_*}}{1.05 \times 10^{15}\ \text{GeV}}\right)^{\frac{4}{3}} \times 10^{15}\ \text{GeV}$$

Entropy



Case A: from inflaton decay ($t_{\rm lep} \ll t_{\rm reh}$)

$$\frac{n_L}{s} = \frac{n_L(t_{\rm reh})}{s(t_{\rm reh})} = \frac{n_L(t_{\rm lep})}{s(t_{\rm reh})} \cdot \left(\frac{a(t_{\rm lep})}{a(t_{\rm reh})}\right)^3$$

$$\sim 10^{-7} \times \frac{n_L(t_{\rm lep})}{\Delta k^3} \cdot \left(\frac{t_{\rm lep}\Delta k}{100}\right)^2 \cdot \left(\frac{\Gamma_\phi/m_\phi}{10^{-8}}\right)^{1/2} \cdot \left(\frac{\sqrt{\partial_t h_*}}{10^{15}\ \mathrm{GeV}}\right)^{4/3}$$

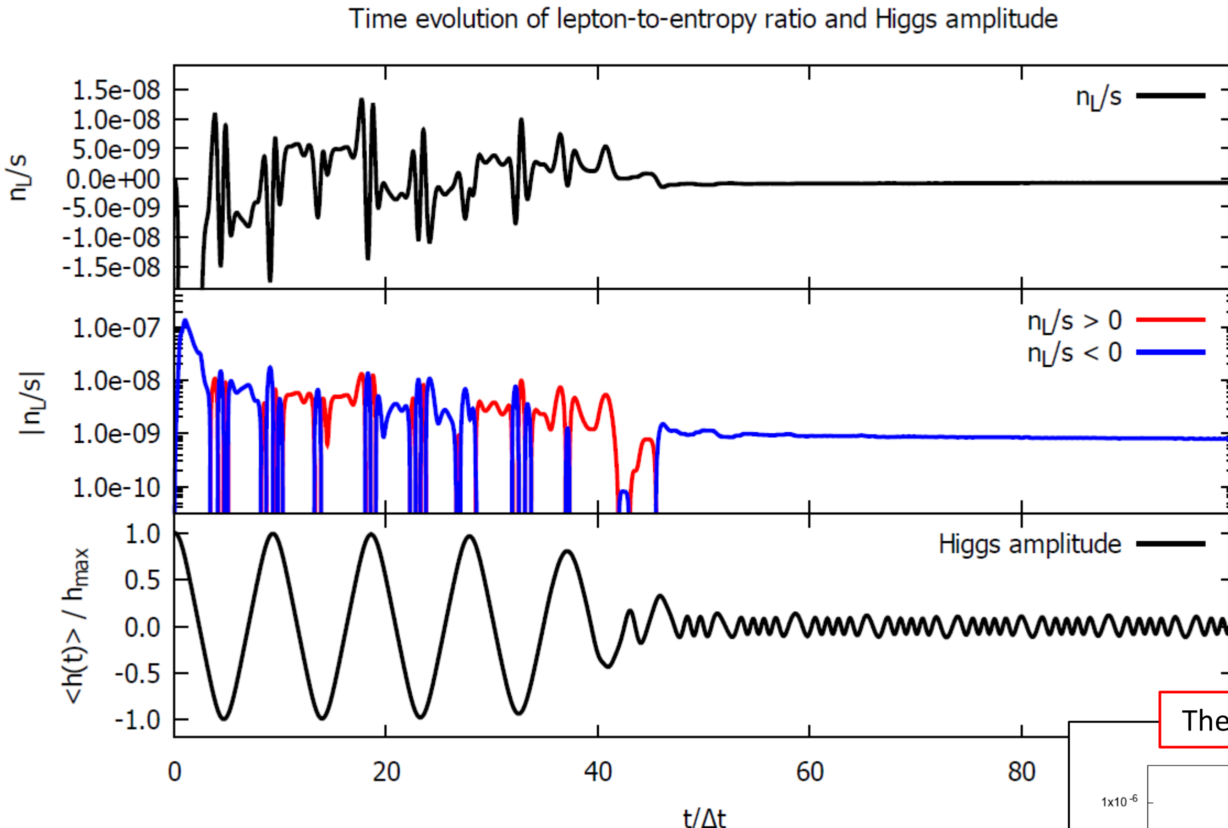
- We need $n_L/s \sim 2.4 \times 10^{-10}$, therefore the produced net lepton number might be strongly diluted

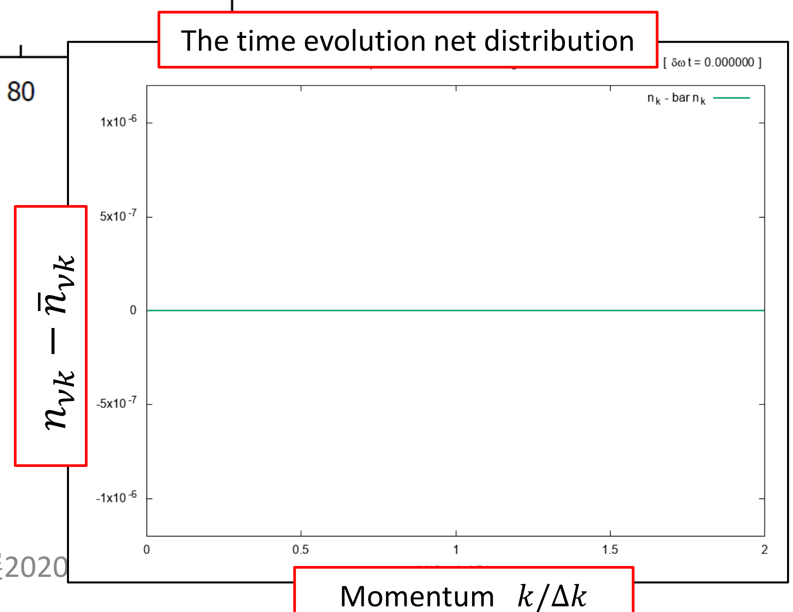
Case B: from the parametric resonance by Higgs oscillation

- W and Z bosons are produced exponentially
- We must assume that the additional entropy production never happen after the leptogenesis completes
- The formula of entropy density from the distribution function

$$s = \sum_{\rm i=bosons} \int \frac{d^3k}{(2\pi)^3} \left[\left(1+f_k^i\right)\ln\left(1+f_k^i\right) - f_k^i \ln f_k^i\right]$$

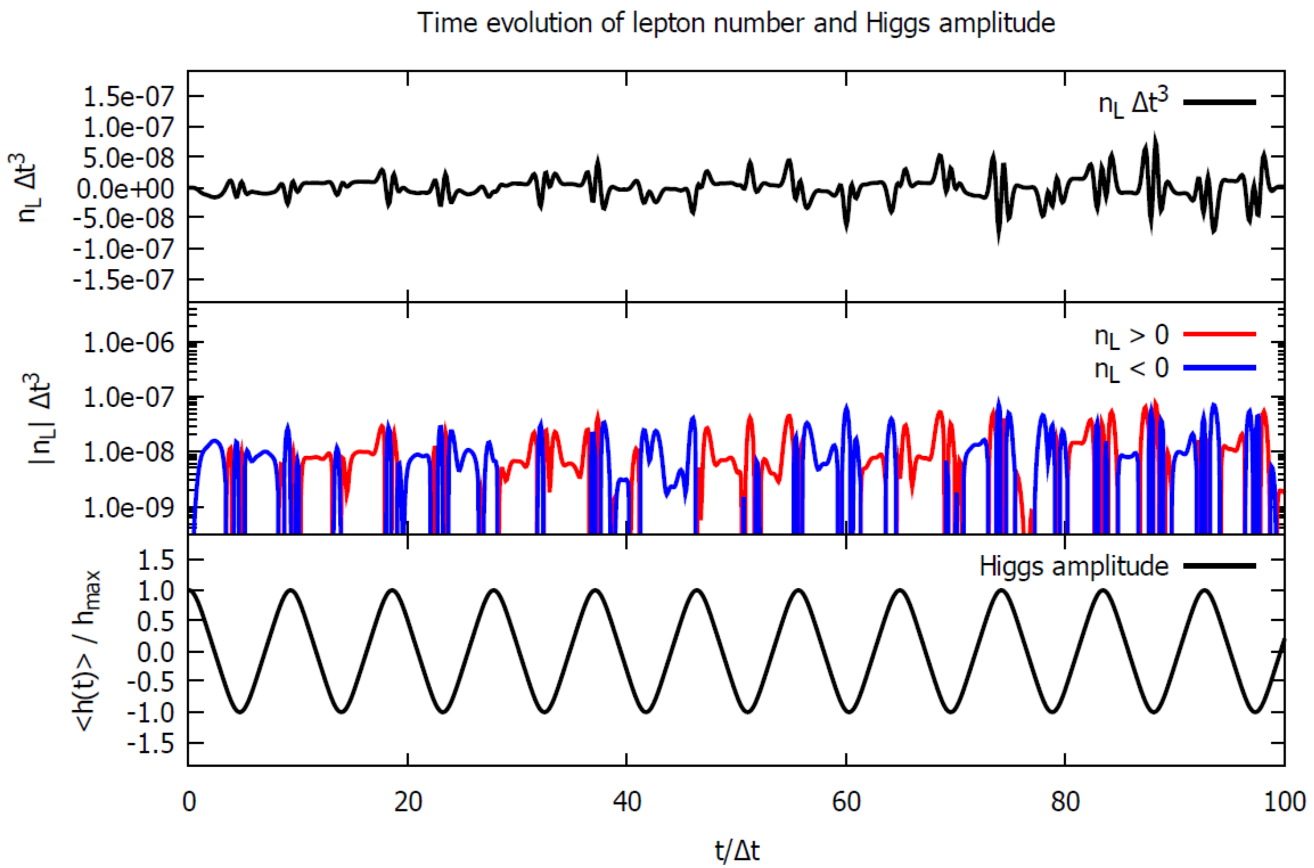
Numerical result ($\langle h(0) \rangle = 1.5 \times 10^{14}$ GeV , $M_1 = 10^{15}$ GeV)





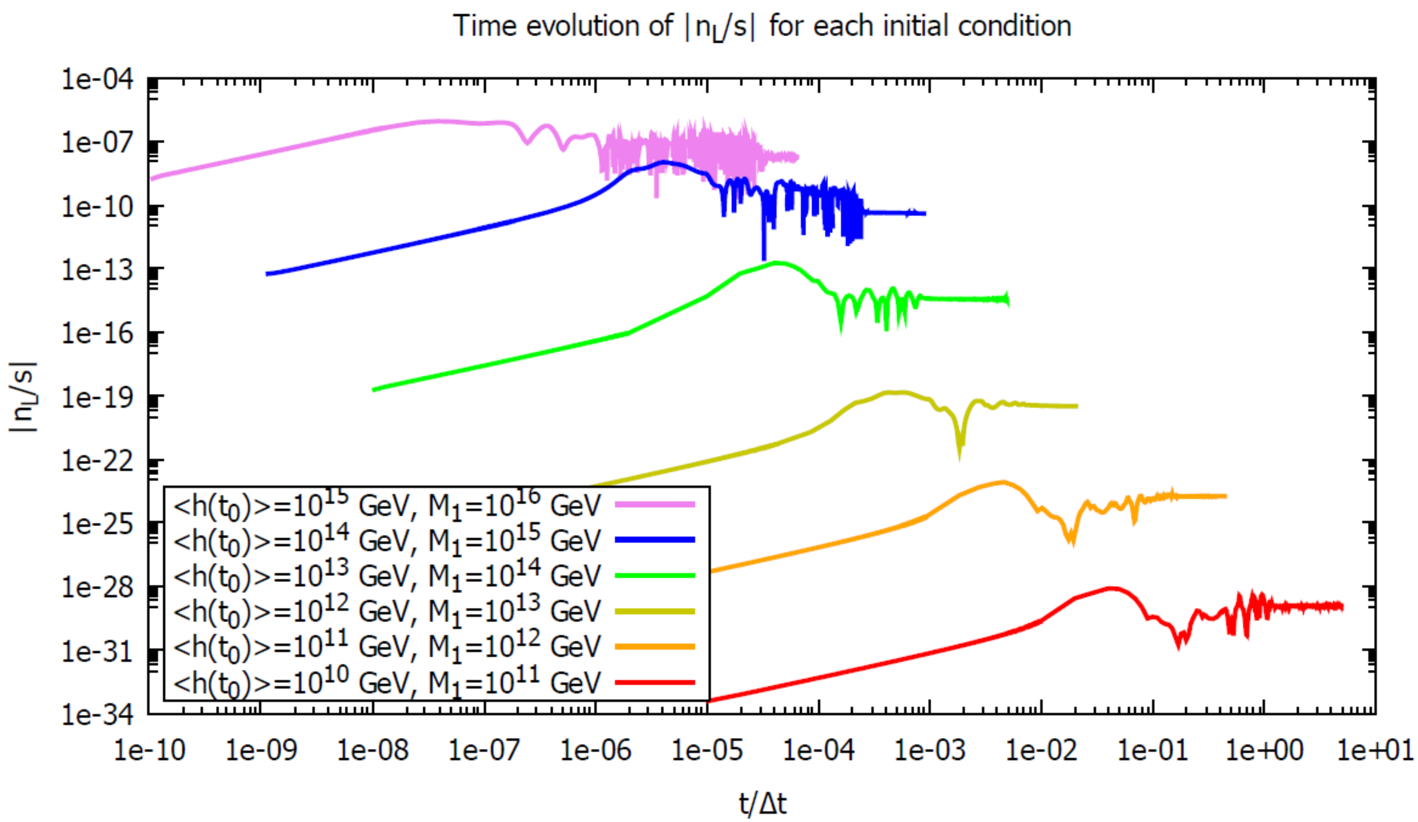
- The sign flipping of asymmetry happens when the Higgs background through the edge of oscillation
- The time evolution stops by the backreaction

In case of no backreaction



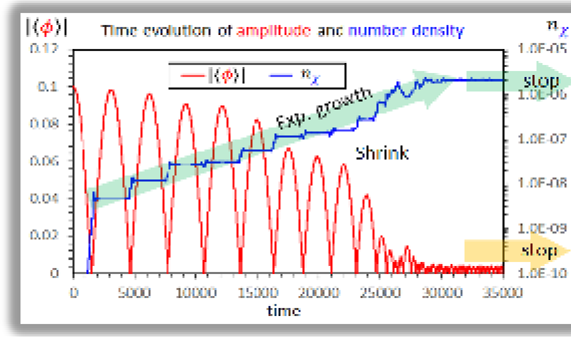
- If there are no backreaction, the sign flipping never finishes

Parameter dependence

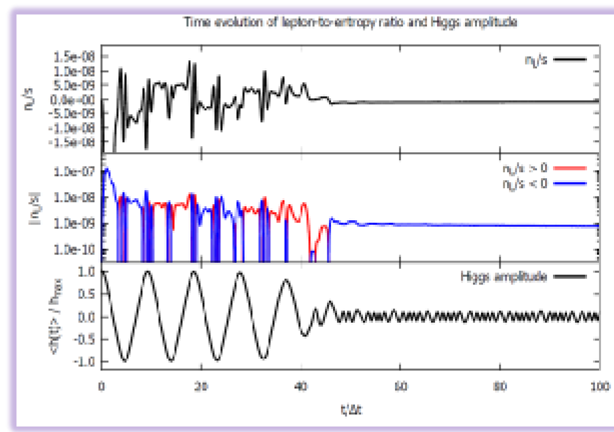


- To explain the current observation, larger initial amplitude of the Higgs than $\langle h_0 \rangle \gtrsim 10^{14}$ GeV is required

3. Summary

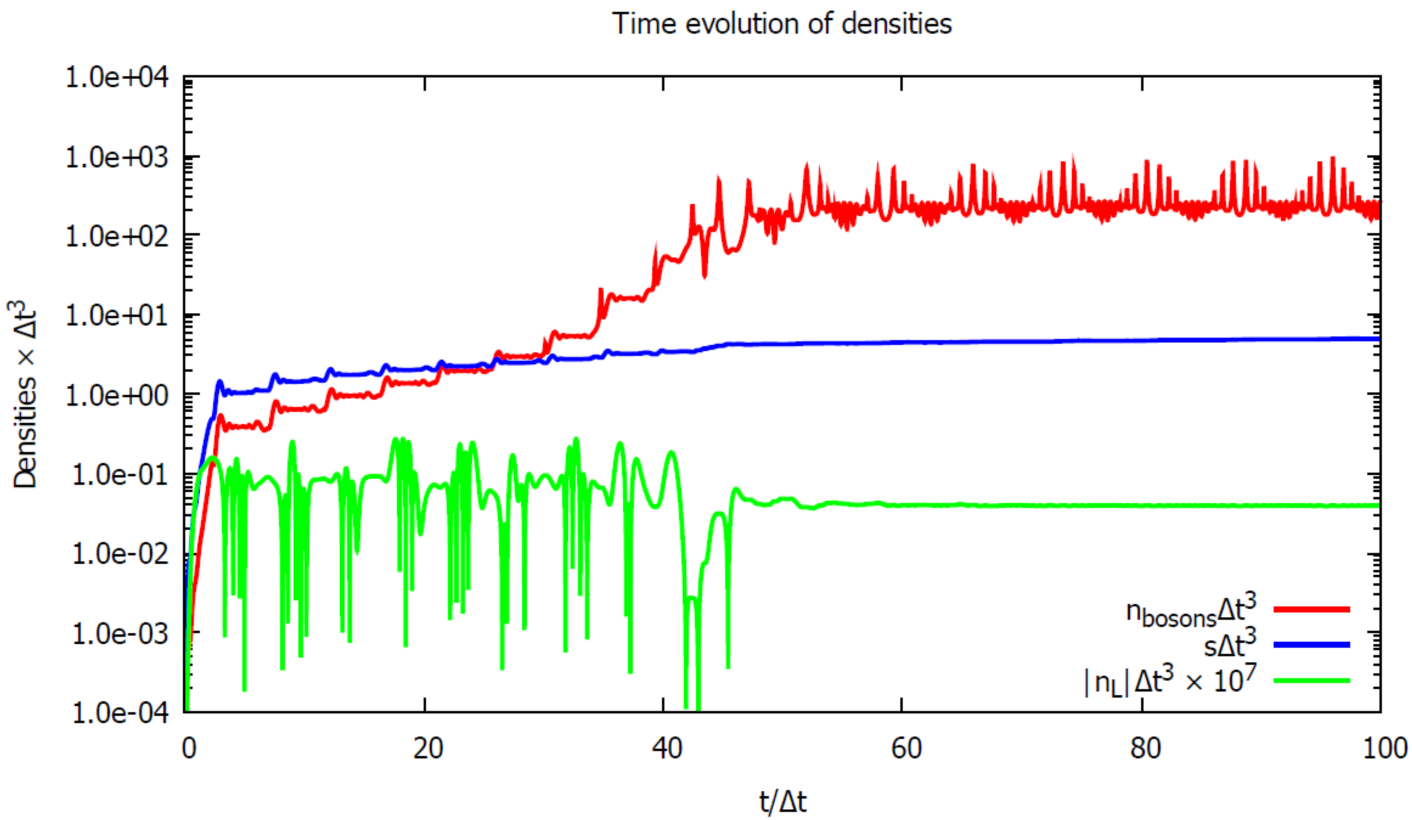


- I reviewed the mechanism of the parametric resonance in preheating era
- I demonstrated that the non-perturbative particle production due to the oscillating background can produced not only the particles but also can generate the asymmetry simultaneously
- As an application, the Type-I seesaw model was discussed
  - I showed some numerical results, but few analytic result is found because of the difficulty to solve
  - Expanding effect is not included yet
  - In this scenario, the Higgs oscillation should produce the entropy



back up

Time evolution of produced gauge bosons



$$\frac{n_{\nu,h}\sigma v}{H} \sim \frac{T^3 \cdot \frac{y^4}{M_R^4} T^2 \cdot 1}{\frac{T^2}{M_p}} \ll 1$$

$$\therefore \quad T \ll \left(\frac{M_R}{y^4 M_p}\right)^{1/3} M_R$$