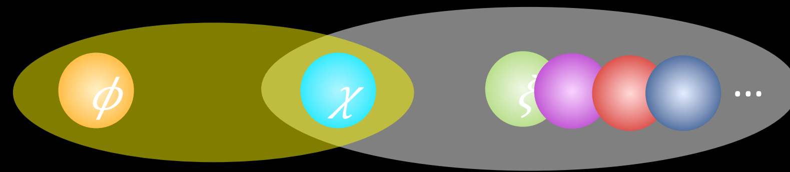
If too much light fields which do not have direct interaction with inflaton exist in the theory, it spoils parametric resonance in preheating

For instance…



Quenching preheating due to interactions

[Based on: *Phys. Rev. D* **96**, *no*. 2, 023510 (2017) (arXiv:1701.00015 [hep-ph]]

Seishi Enomoto (Univ. of Florida, USA)

Collaborators : Olga Czerwińska and Zygmunt Lalak
(Univ. of Warsaw, Poland)

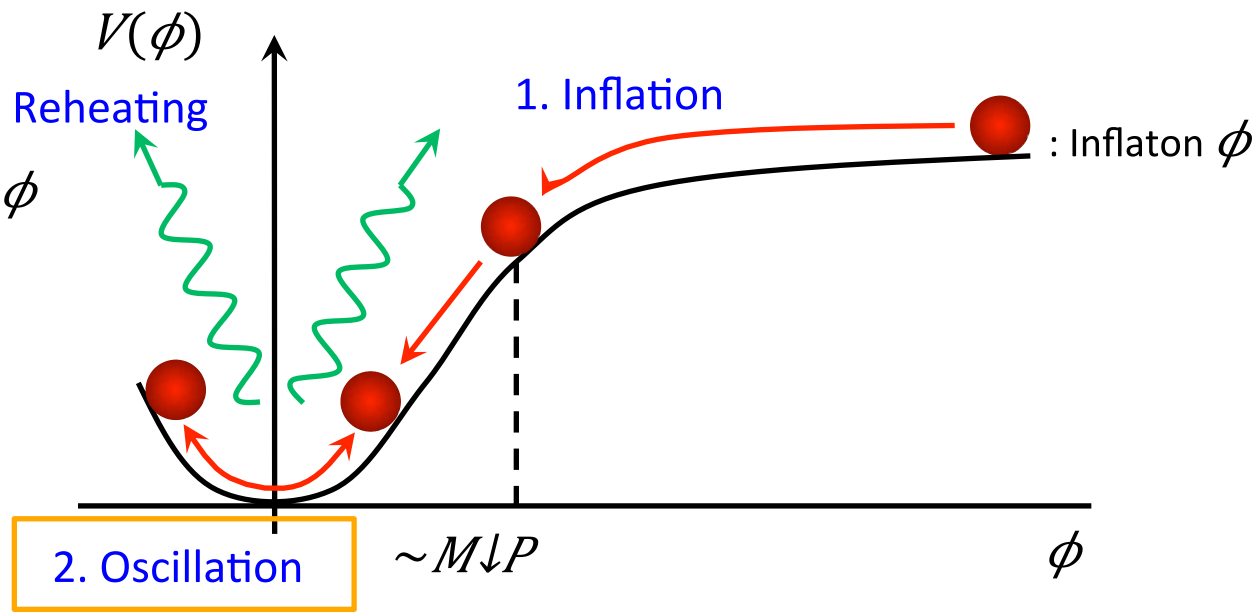
Outlook

1. Introduction
   - Brief summary of preheating
2. Particle number in interacted theory
   - Our aim and approach
3. Applications
   - Showing numerical results
4. Summary

1. Introduction

After inflation to reheating

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



Considering with QFT → resonant particle production (preheating)

[L. Kofman, A. D. Linde, A. A. Starobinsky, *Phys. Rev. Lett.* **73**, 3195 (1994)]

[L. Kofman, A. D. Linde, A. A. Starobinsky, *Phys. Rev.* **D 56**, 3258 (1997)]

Preheating (without spatial expanding)

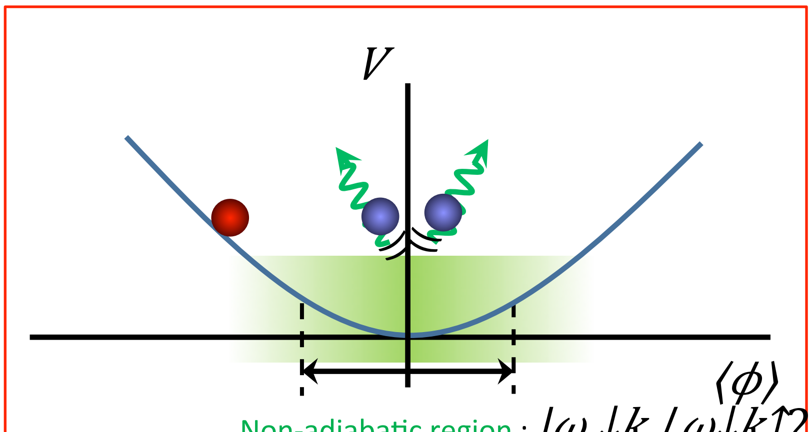
[L. Kofman, A. D. Linde, A. A. Starobinsky, *Phys. Rev.* **D 56**, 3258 (1997)]

Parametric resonance

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

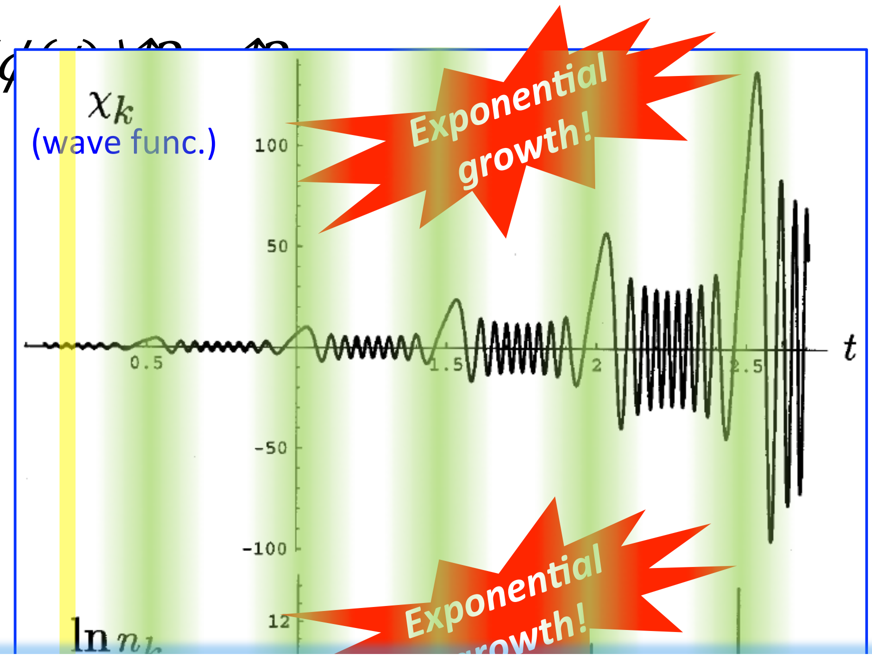
: background

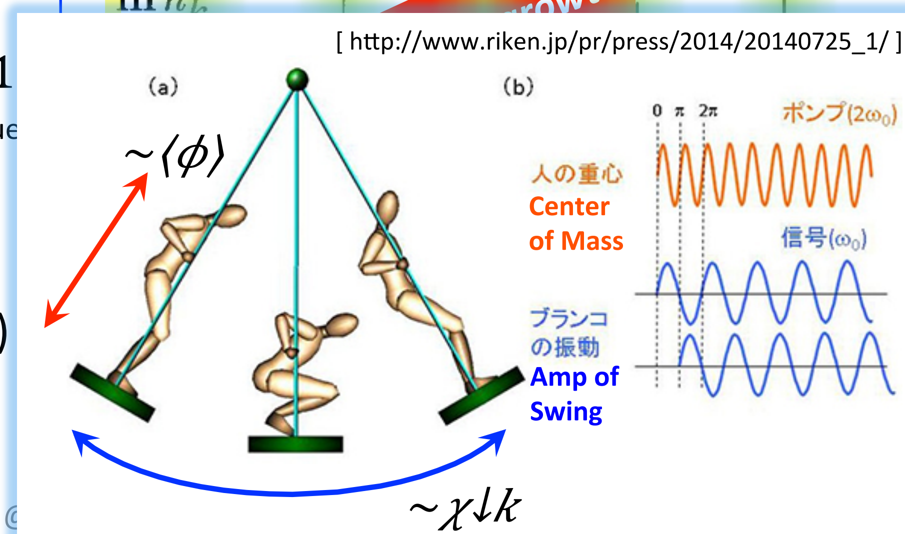
: real scalar (*quantum field*)



Non-adiabatic region : $|\dot{\omega}_k / \omega_k^2| > 1$

($\omega_k \equiv \sqrt{k^2 + g^2 \langle\phi\rangle^2}$: freque…



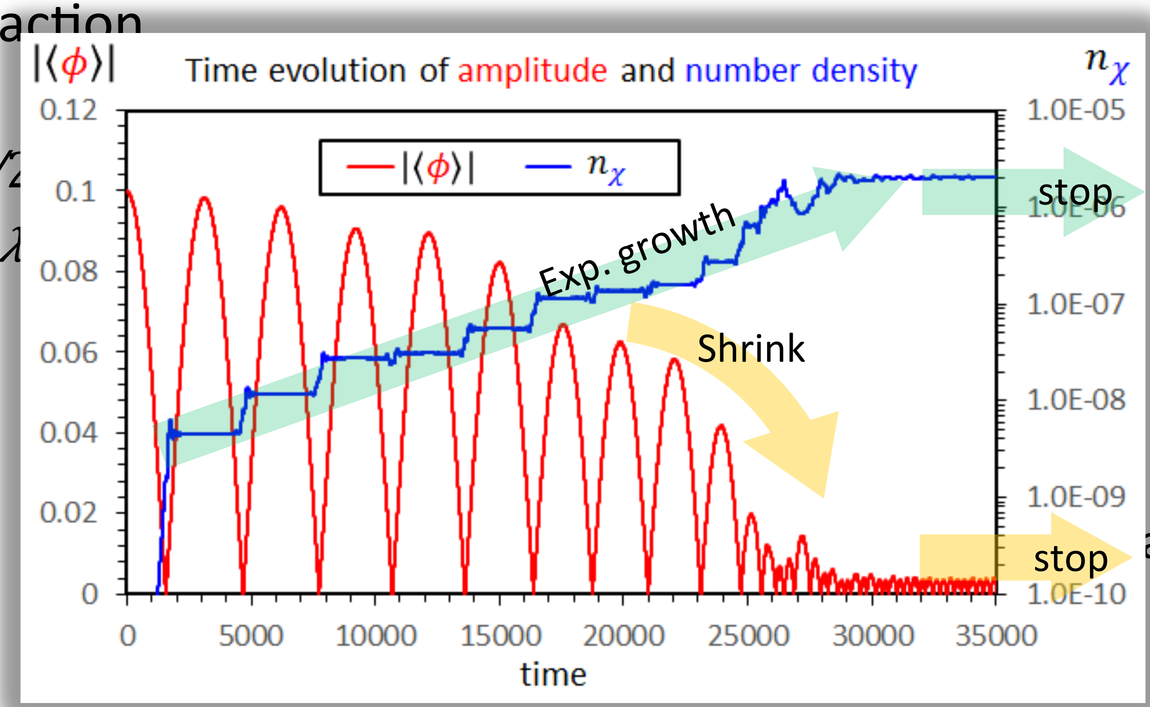


Particle production happens

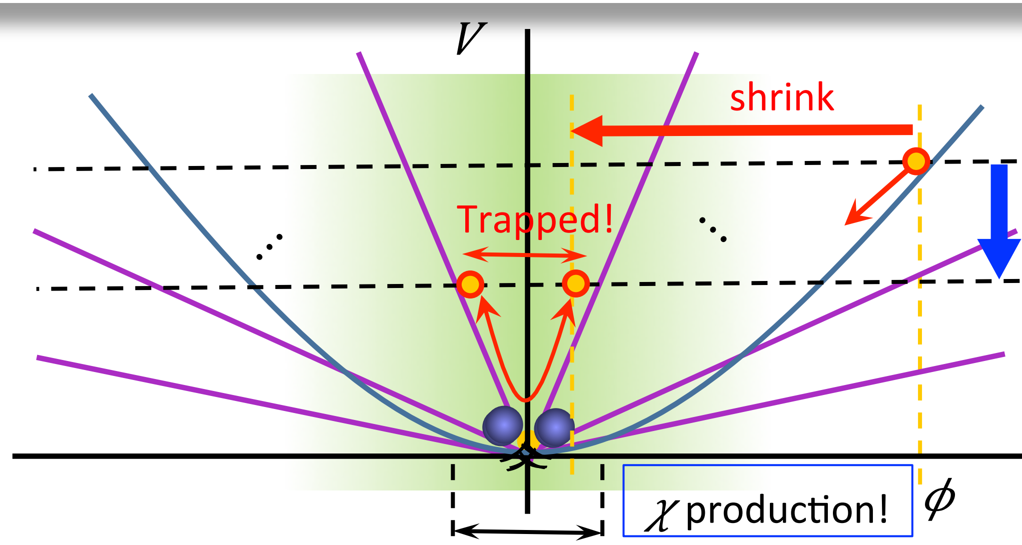
- exponentially (bosonic effect)
- around <u>*massless point*</u> ($\langle\phi\rangle \sim 0$)

Backreaction

$\mathcal{H}=1/2$ … $\uparrow 2 + 1/2\, g \uparrow 2$
$\langle\phi\rangle\uparrow 2\ \chi$ …



…ablished for ϕ!



Energy drain
$\Delta V \sim \rho_\chi \sim n_\chi \cdot g\langle\phi\rangle$

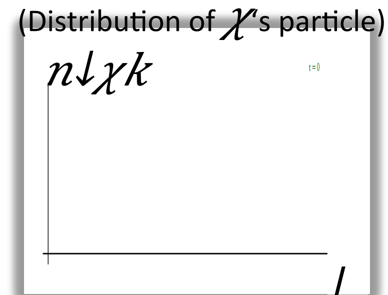
Non-adiabatic region $\sim \sqrt{m_\phi \phi_0 / g}$

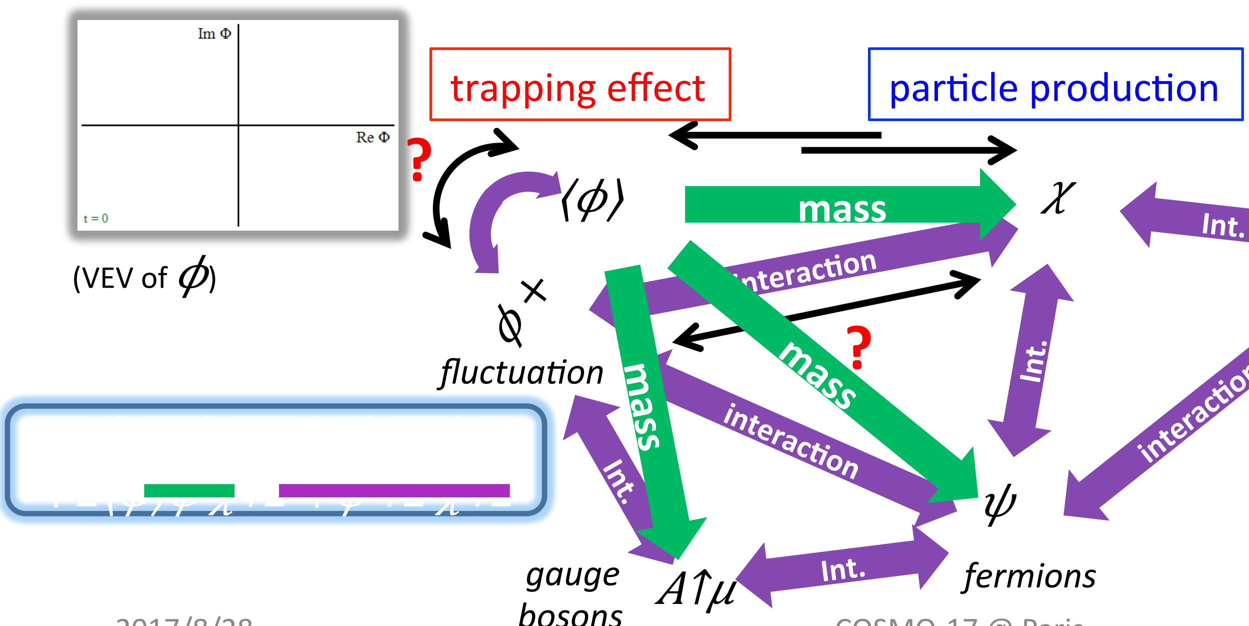
2. Particle number in interacted theory

- Motivation
  - Since the classical background field interacts as a mass term(s), the dynamics of preheating can be treated as a "free" field theory
  - In general, however, it is natural that the system has yukawa-like interaction term(s), not as the mass terms
  - What effects does appear?

2 point

3-4 point





How to evaluate

1. Occupation number for complex scalar Φ

$$N_{\mathbf{k}}^{(\pm)}(t) = {}_{\rm in}\langle 0| \frac{1}{2}\left[N_{\mathbf{k}}^{\rm tot}(t) \pm N_{\mathbf{k}}^{\rm net}(t)\right] |0\rangle_{\rm in}$$

- Where
  - $N_{\mathbf{k}}^{\rm tot} = a_{\mathbf{k}}^\dagger a_{\mathbf{k}} + b_{\mathbf{k}}^\dagger b_{\mathbf{k}} = \frac{1}{\omega_k}\left(\Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}} + \omega_k^2 \Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}}\right) - V$ (total #)
  - $N_{\mathbf{k}}^{\rm net} = a_{\mathbf{k}}^\dagger a_{\mathbf{k}} - b_{\mathbf{k}}^\dagger b_{\mathbf{k}} = i\left(\Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}} - \Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}}\right) + V$ (net #)

(kinetic energy) / (1 particle energy)

U(1) Noether charge

$$\left(\Phi_{\mathbf{k}} \equiv \int d^3x\, e^{-i\mathbf{k}\cdot\mathbf{x}}\, \Phi(t,\mathbf{x}), \quad V = \text{(Volume of the system)} \right)$$

2. Equation of Motion

$$0 = \partial_t^2 \Phi_{\mathbf{k}} + \omega_k^2 \Phi_{\mathbf{k}} + (\text{Source terms}) \qquad \left(\omega_k \equiv \sqrt{k^2 + M_\Phi^2} \right)$$

- The dynamics can be known if we follow the time evolution of

$$\langle \Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}} \rangle, \ \langle \Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}} \rangle, \ \langle \Phi_{\mathbf{k}}^\dagger \Phi_{\mathbf{k}} \rangle.$$

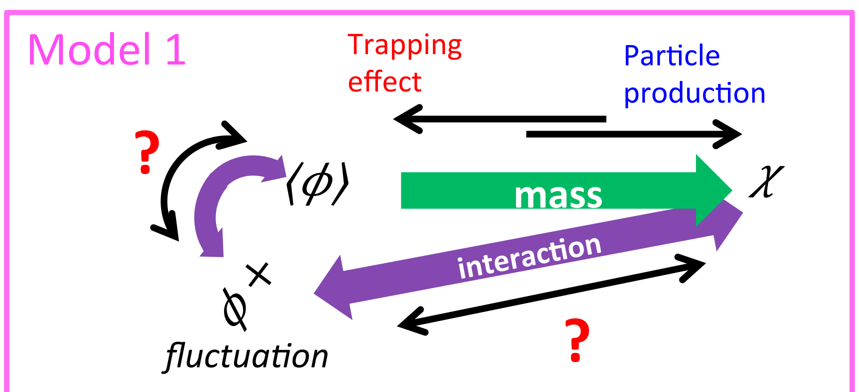
3. Applications

- Model 1 : 2 real scalars (ϕ, χ) system

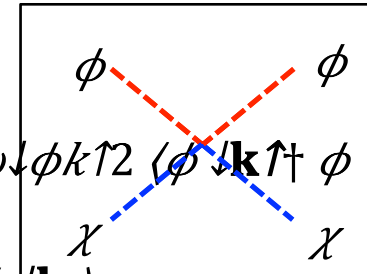
$$\mathcal{L}=\frac{1}{2}(\partial\phi)^2+\frac{1}{2}(\partial\chi)^2-\frac{1}{2}m_\phi^2\phi^2-\frac{1}{4}g^2\phi^2\chi^2$$

- Model 2 : Model 1 + multi real scalars (ξ_n)

$$\mathcal{L}=\frac{1}{2}(\partial\phi)^2+\frac{1}{2}(\partial\chi)^2+\sum_n\frac{1}{2}(\partial\xi_n)^2-\frac{1}{2}m_\phi^2\phi^2-\frac{1}{4}g^2\phi^2\chi^2-\sum_n\frac{1}{4}y_n^2\chi^2\xi_n^2$$



Equations of motion ($\langle\ldots\rangle \equiv {}_0\langle \text{in}|\ldots|0\rangle_{\text{in}}$, $\phi \equiv \phi - \langle\phi\rangle$, $V \equiv$ (Volume))

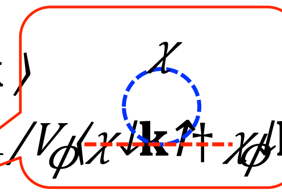


background
- $\langle\phi\rangle = -M_\phi^2 \langle\phi\rangle$

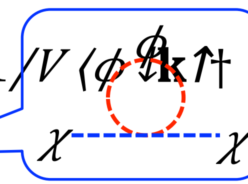
2 point func
- $\langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle^\cdot = \langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} + \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle$
- $\langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} + \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle^\cdot = 2\langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle - 2\omega_{\phi k}^2 \langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle + \mathcal{O}(g^4)$
- $\langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle^\cdot = -\omega_{\phi k}^2 \langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} + \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle$

2 point func
- $\langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle^\cdot = \langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} + \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle$
- $\langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} + \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle^\cdot = 2\langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle - 2\omega_{\chi k}^2 \langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle + \mathcal{O}(g^4)$
- $\langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle^\cdot = -\omega_{\chi k}^2 \langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} + \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle$

mass
- $M_\phi^2 = m_\phi^2 + \frac{1}{2} g^2 \int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \chi_{\mathbf{k}}^\dagger \chi_{\mathbf{k}} \rangle - \frac{1}{2\omega_{\chi k}} \right) + \mathcal{O}(g^4)$



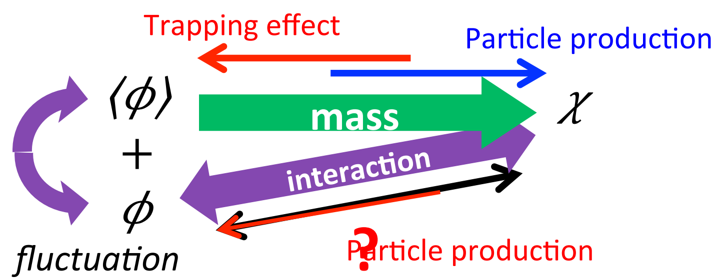
mass
- $M_\chi^2 = \frac{1}{2} g^2 \langle\phi\rangle^2 + \frac{1}{2} g^2 \int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle - \frac{1}{2\omega_{\phi k}} \right) + \mathcal{O}(g^4)$

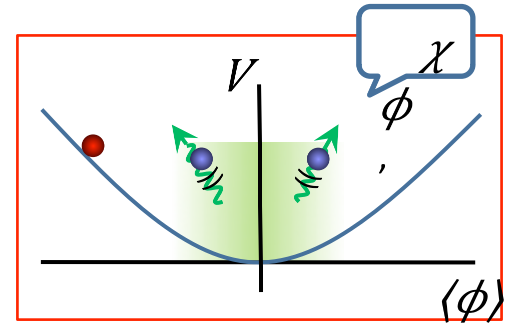


including 1-loop correction

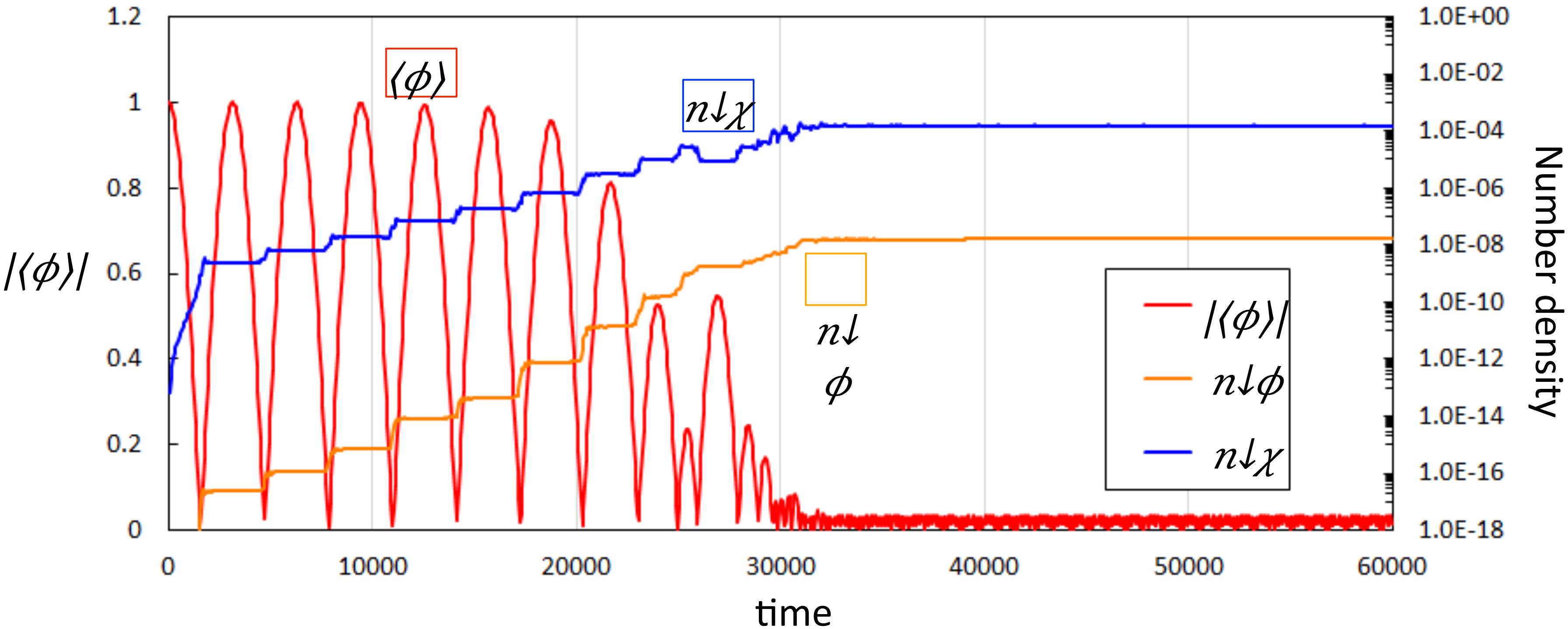
Model 1 : 2 real scalars (ϕ, χ) system

$$\mathcal{L}=\frac{1}{2}(\partial\phi)^2+\frac{1}{2}(\partial\chi)^2-\frac{1}{2}m_\phi^2\phi^2-\frac{1}{4}g^2\phi^2\chi^2$$





Numerical results : ($g=0.1,\ \langle\phi_0\rangle=1,\ \langle\phi_0\rangle=0,\ m_\phi=0.001$)



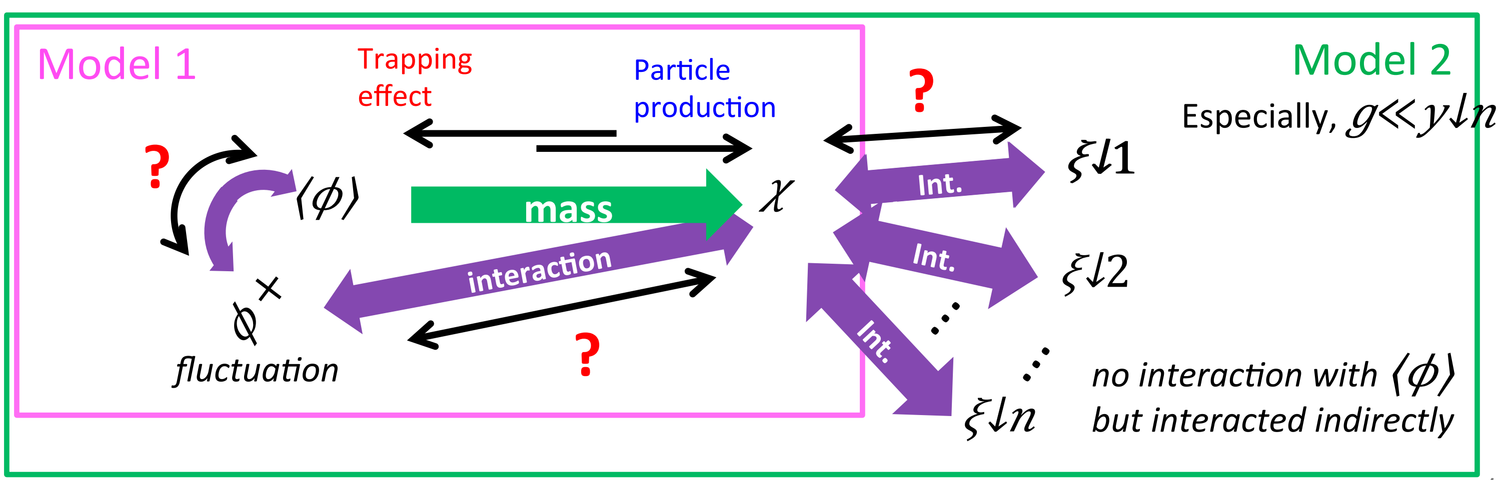
3. Applications

- Model 1 : 2 real scalars (ϕ, χ) system

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}g^2\phi^2\chi^2$$

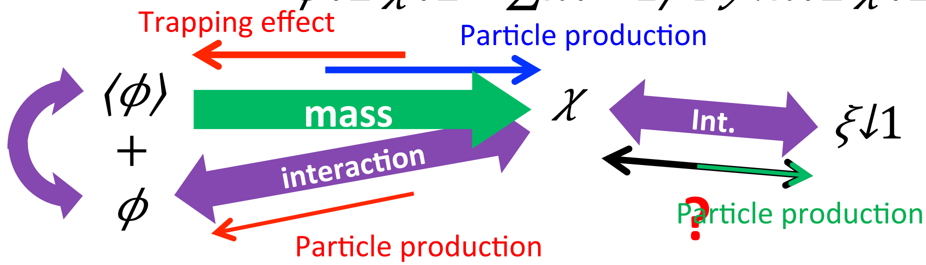
- Model 2 : Model 1 + multi real scalars (ξ_n)

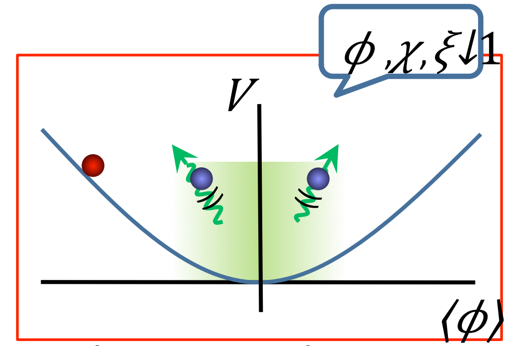
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 + \sum_n \frac{1}{2}(\partial\xi_n)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}g^2\phi^2\chi^2 - \sum_n \frac{1}{4}y_n^2\chi^2\xi_n^2$$



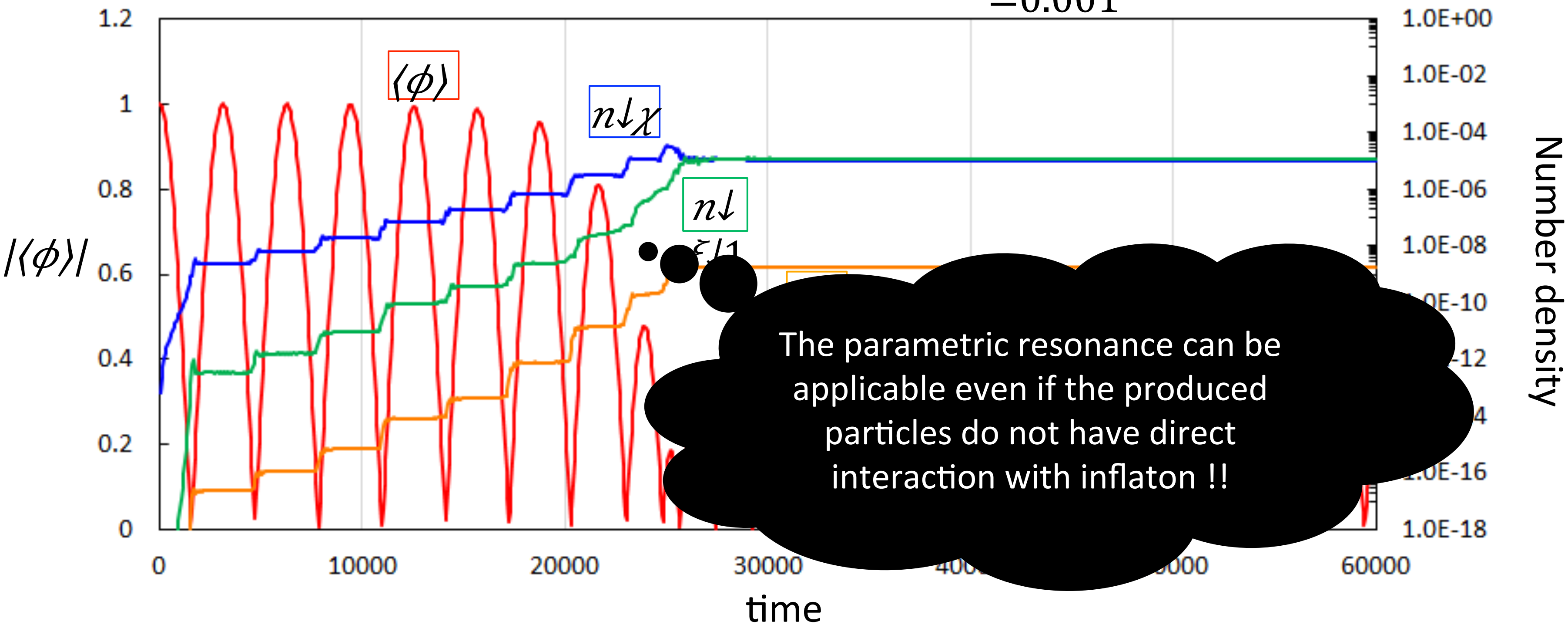
Model 2-1 : 2 real scalars (ϕ, χ) + multi real scalars (ξ_n)

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 + \sum_n \frac{1}{2}(\partial\xi_n)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{4} g^2 \phi^2 \chi^2 - \sum_n \frac{1}{4} y_n^2 \chi^2 \xi_n^2$$





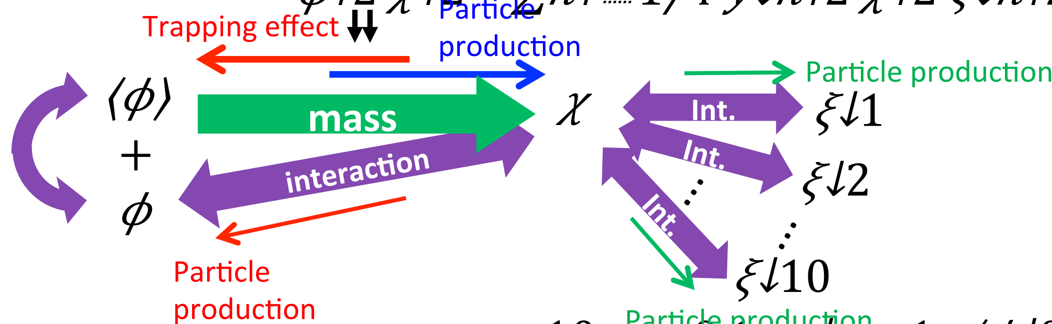
Numerical results : ($n=1,\ g=0.1,\ y_1=1,\ \langle\phi_0\rangle=1,\ \langle\phi_0\rangle=0,\ m_\phi=0.001$)

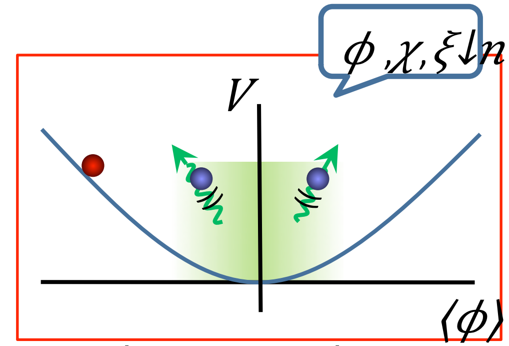


The parametric resonance can be applicable even if the produced particles do not have direct interaction with inflaton !!

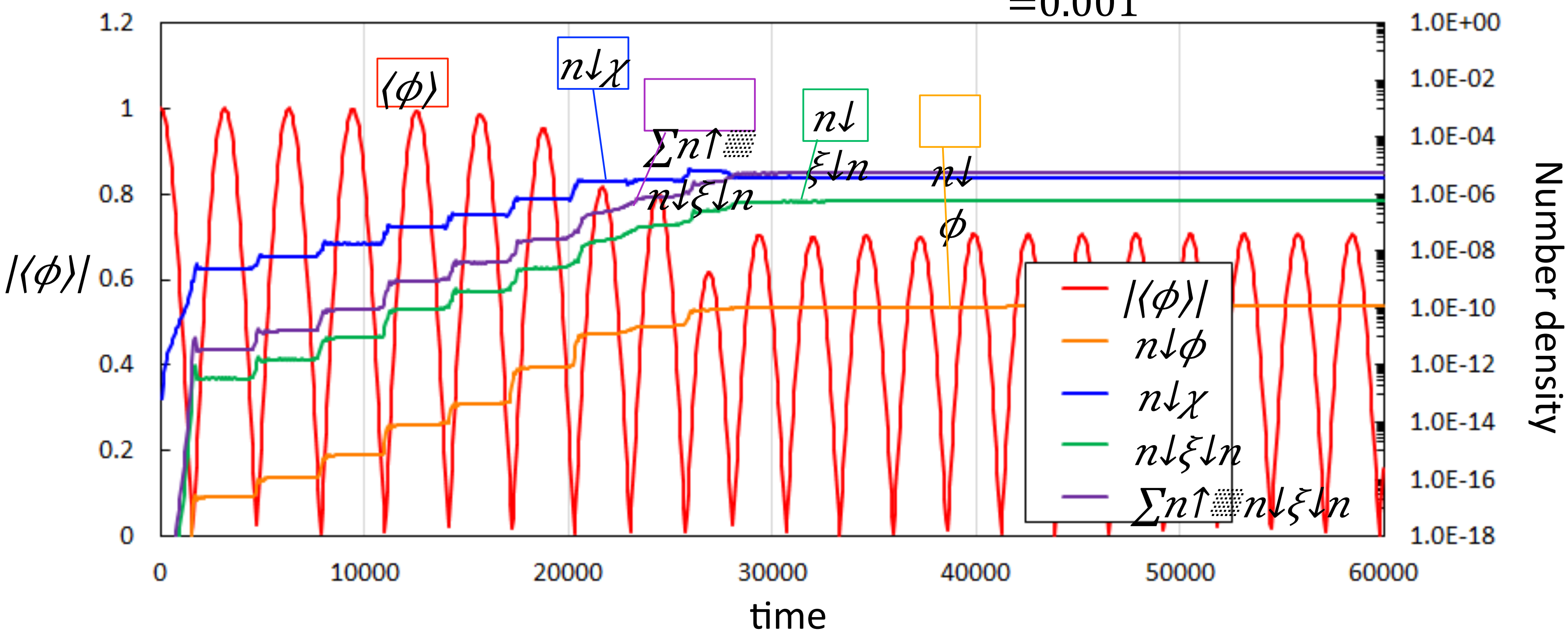
Model 2-2 : 2 real scalars (ϕ, χ) + multi real scalars (ξ_n)

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 + \sum_n \frac{1}{2}(\partial\xi_n)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}g^2\phi^2\chi^2 - \sum_n \frac{1}{4}y_n^2\chi^2\xi_n^2$$



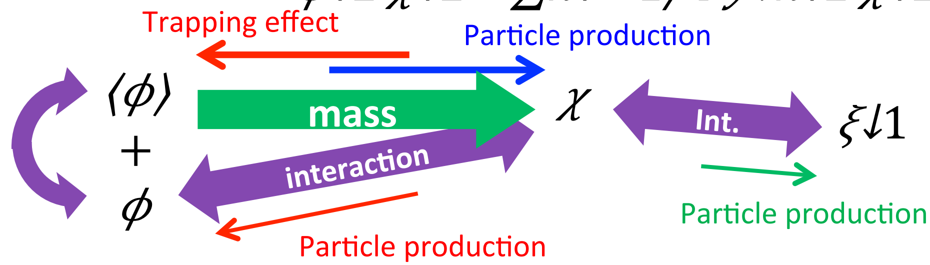


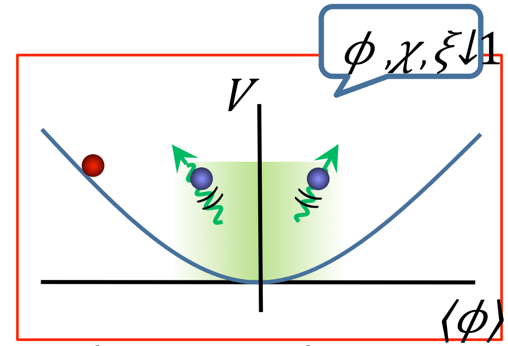
Numerical results : ($n=10,\ g=0.1,\ y_n=1,\ \langle\phi_0\rangle=1,\ \langle\dot{\phi}_0\rangle=0,\ m_\phi=0.001$)



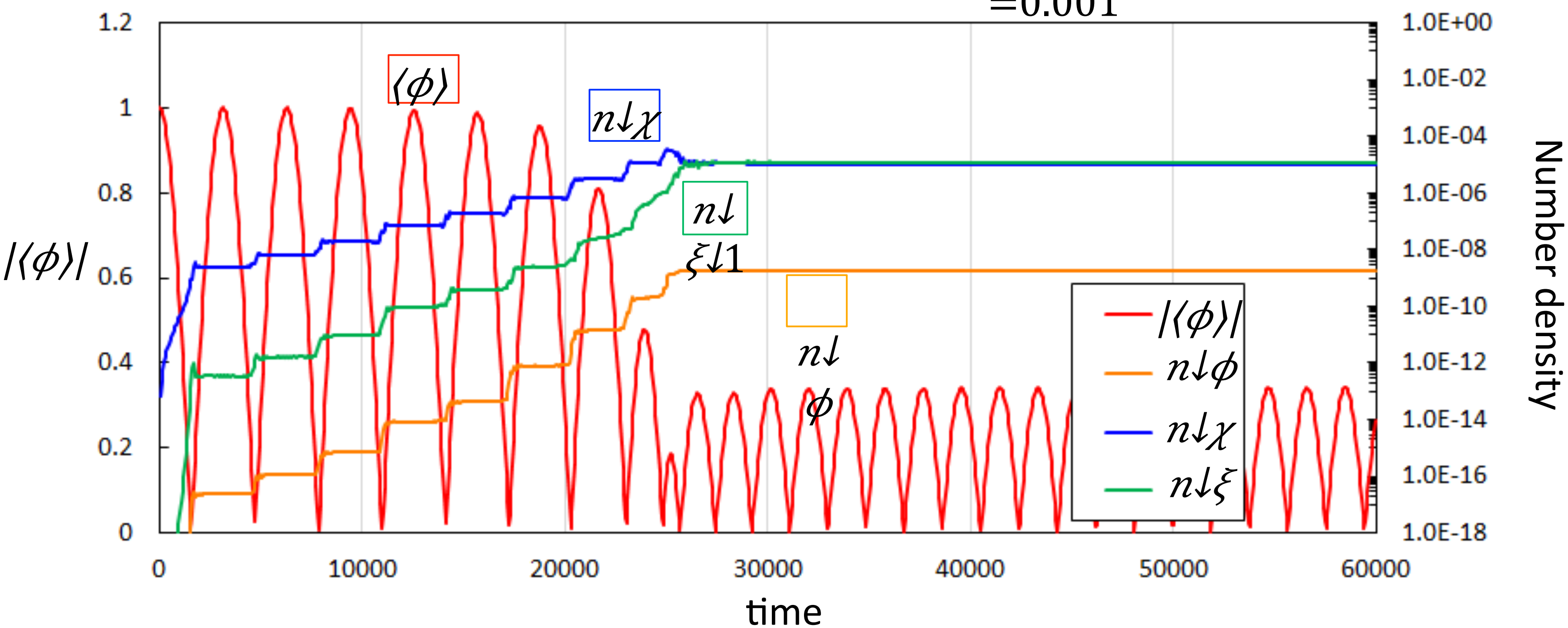
Model 2-1 : 2 real scalars (ϕ, χ) + multi real scalars (ξ_n)

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 + \sum_n \frac{1}{2}(\partial\xi_n)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{4} g^2 \phi^2 \chi^2 - \sum_n \frac{1}{4} y_n^2 \chi^2 \xi_n^2$$



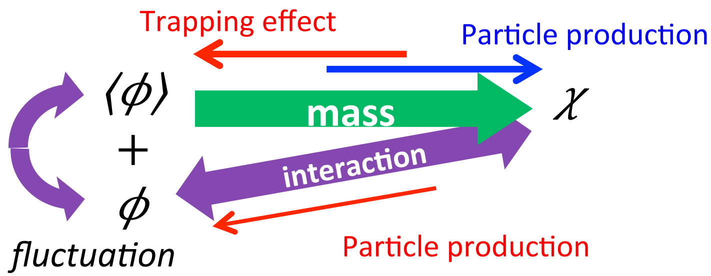


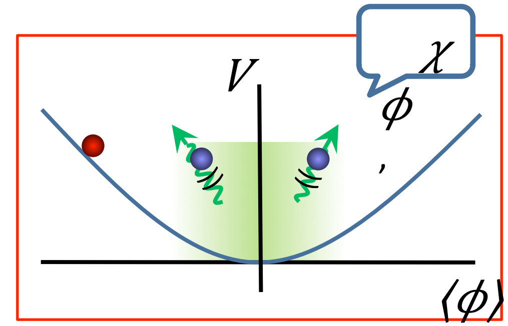
Numerical results : ($n=1,\ g=0.1,\ y_1=1,\ \langle\phi_0\rangle=1,\ \langle\phi_0\rangle=0,\ m_\phi=0.001$)



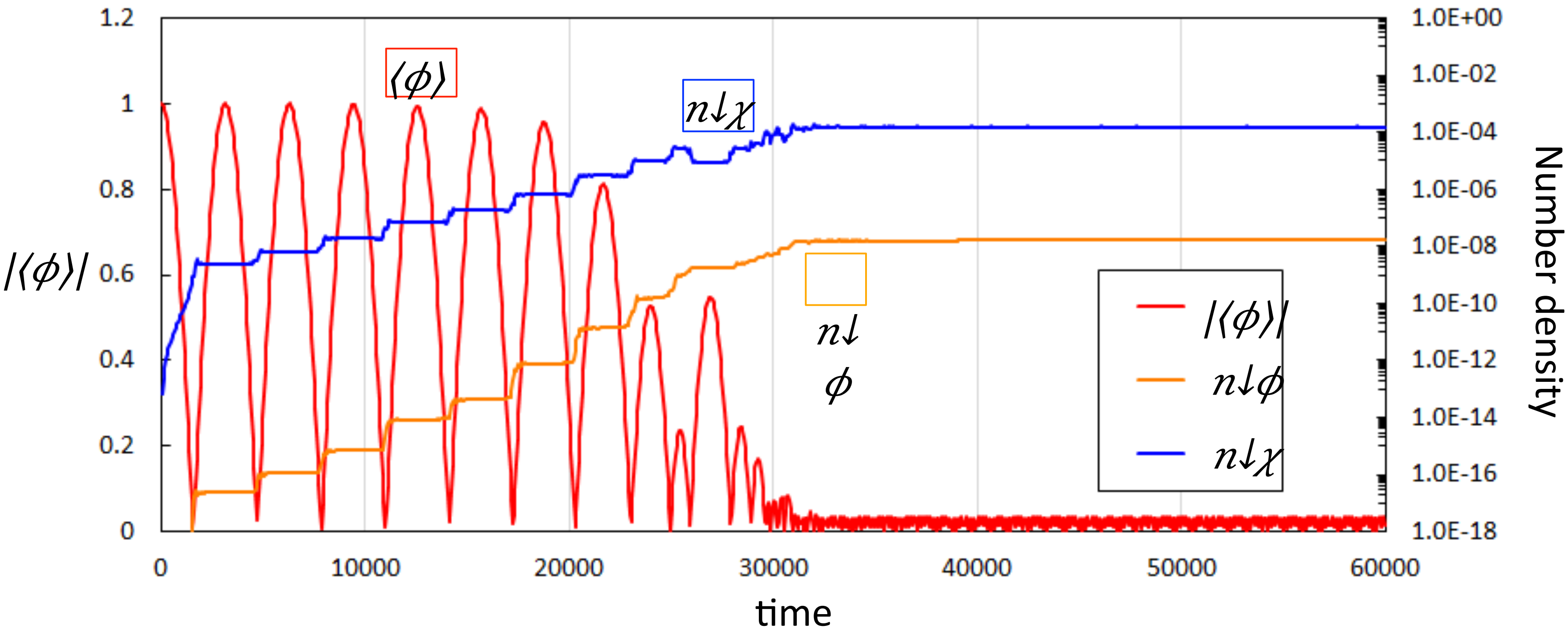
Model 1 : 2 real scalars (ϕ, χ) system

$$\mathcal{L}=1/2\,(\partial\phi)^2+1/2\,(\partial\chi)^2-1/2\,m_\phi^2\,\phi^2-1/4\,g^2\,\phi^2\,\chi^2$$



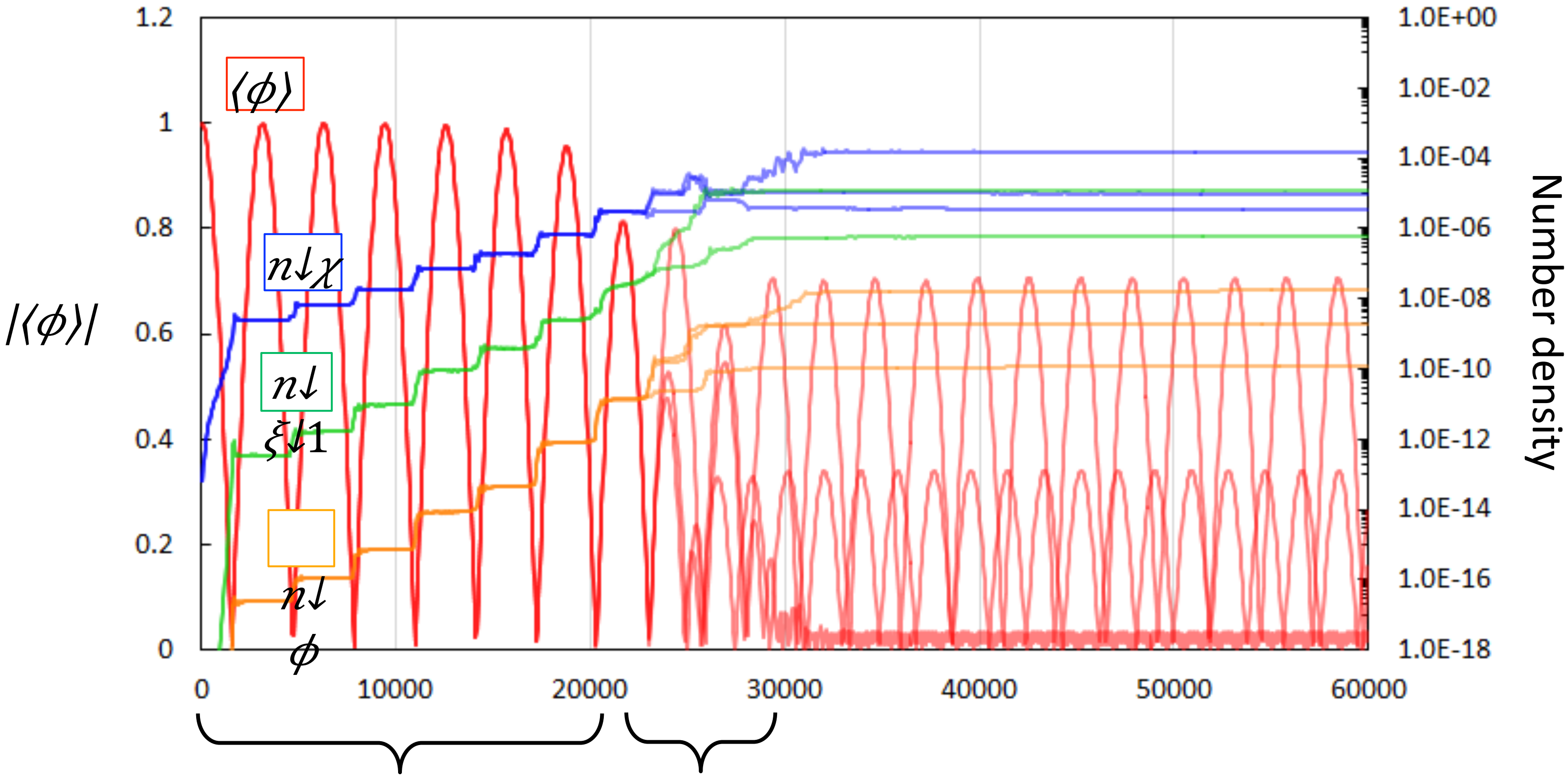


Numerical results : ($g=0.1$, $\langle\phi_0\rangle=1$, $\langle\phi_0\rangle=0$, $m_\phi=0.001$)



Why does the trapping effect (energy transfer) become worse?

- All lines for previous 3 results



<u>Answer : due to generating effective masses</u>

→ The particle production is suppressed → "Quenching preheating"

Effective mass in equilibrium = "Thermal" mass

- Mass of χ

$$M_\chi^2 = \frac{1}{2} g^2 \langle\phi\rangle^2 + \frac{1}{2} g^2 \int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \phi_{\mathbf{k}}^\dagger \phi_{\mathbf{k}} \rangle - \frac{1}{2\omega_{\phi k}} \right)$$

$$+ \sum_n \frac{1}{2} y_n^2 \int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \xi_{n\mathbf{k}}^\dagger \xi_{n\mathbf{k}} \rangle - \frac{1}{2\omega_{\xi_n k}} \right) + \mathcal{O}(g^4, g^2 y^2, y^4)$$

Quantum corrections

- Physical interpretation
  - When the system is in equilibrium, then

$$\langle \xi_{n\mathbf{k}}^\dagger \xi_{n\mathbf{k}} \rangle \sim \omega_{\xi_n k}^2 \langle \xi_{n\mathbf{k}}^\dagger \xi_{\ldots}$$

$$\rightarrow \int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \xi_{n\mathbf{k}}^\dagger \xi \ldots \right.$$

$$\sim \int \frac{d^3k}{(2\pi)^3} \frac{1}{\omega_{\xi_n k}} \left(\frac{1}{V} \langle \xi \ldots k^2 \langle \xi_{n\mathbf{k}}^\dagger \xi_{n\mathbf{k}} \rangle / 2\omega_{\xi_n k} - \frac{1}{2} \right) \sim \int \frac{d^3 \ldots}{(2\pi)^3} \frac{1}{\omega_{\xi_n k}} \cdot n_{\xi_n k}$$

Produced "plasma" breaks its resonance

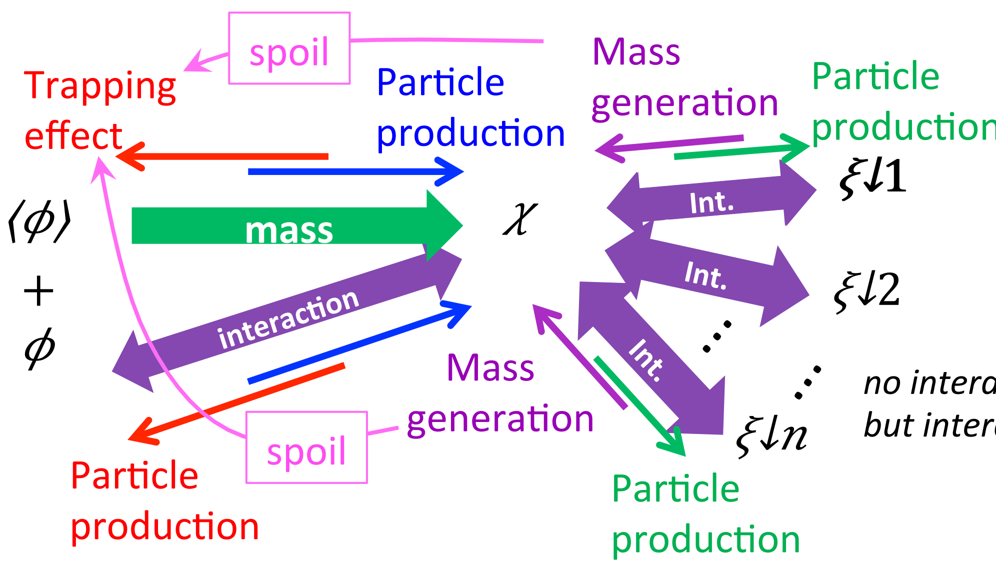
  - If $n_{\xi_n k} = [\exp(|\mathbf{k}|/T) - 1]^{-1}$ (BE distribution), then

$$\int \frac{d^3k}{(2\pi)^3} \left(\frac{1}{V} \langle \xi_{n\mathbf{k}}^\dagger \xi_{n\mathbf{k}} \rangle - \frac{1}{2\omega_{\xi_n k}} \right) \sim T^2/6 \quad \rightarrow \text{Thermal mass!}$$

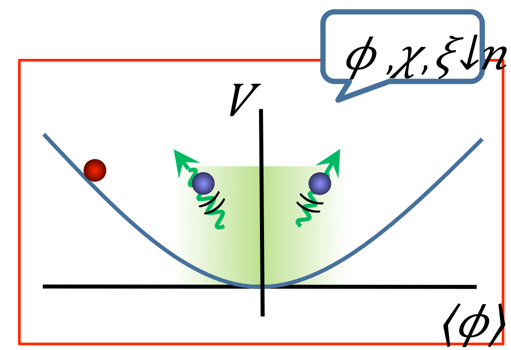
"Plasma frequency"

4. Summary

- We studied the effect of interactions in parametric resonance
- The parametric resonance happens even if the produced particles do not have direct interaction with inflaton field
- However, too many light fields, which do not have time-varying mass itself but interact to time-varying mass particles, spoil the resonance particle production



no interaction with background but interacted indirectly



Challenges

- These results are performed by the first principle calculation
  - No expanding effect for simplicity
  - Calculated up to 2 point correlation function
- In order to calculate more accurate, we need to include
  - Expanding effect
  - Decays, scatterings
    - Higher perturbation terms in EOM
    - More than 3 point correlation function