Dissipative Effects on Reheating after Inflation

Kyohei Mukaida (Univ. of Tokyo)

Based on: **1212.1985**,**1208.3399** with **K. Nakayama**;
[JCAP01(2013)017, JCAP03(2013)002],

also **1304.6597** with **T. Moroi**, **K. Nakayama** and **M. Takimoto;**
[JHEP1306(2013)040]

Introduction

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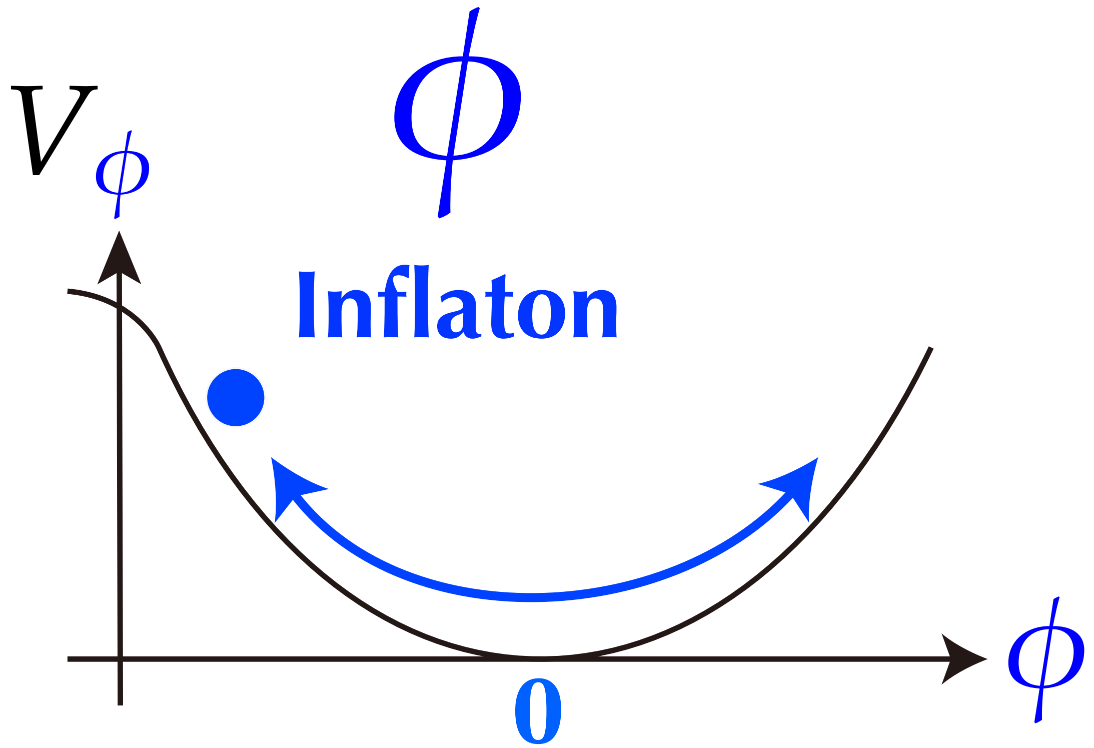
- After the inflation, the inflaton should convert its energy to radiation: **Reheating**.

- How does the **reheating** proceed ?

▸"Standard" picture of **reheating:**



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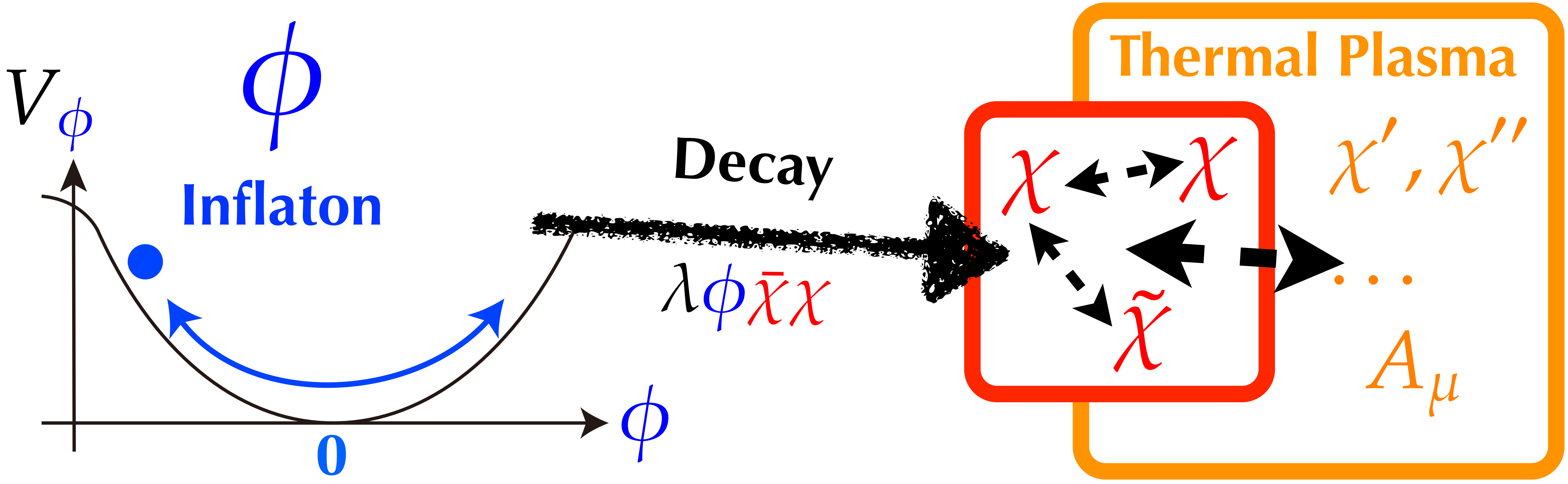

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- •Reheating temperature: $T_R \sim \left[\frac{90}{\pi^2 g_*}\right]^{1/4} \sqrt{M_{pl}\,\Gamma_\phi^{(pert)}}$

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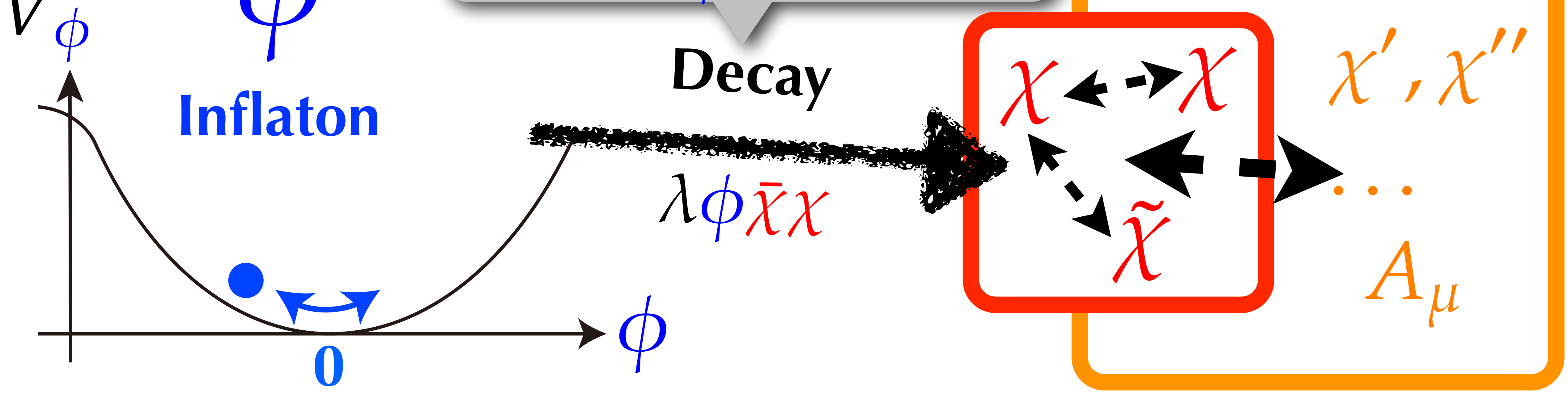
$@\, H \sim \Gamma_\phi^{(pert.)} \sim \lambda^2 m_\phi$



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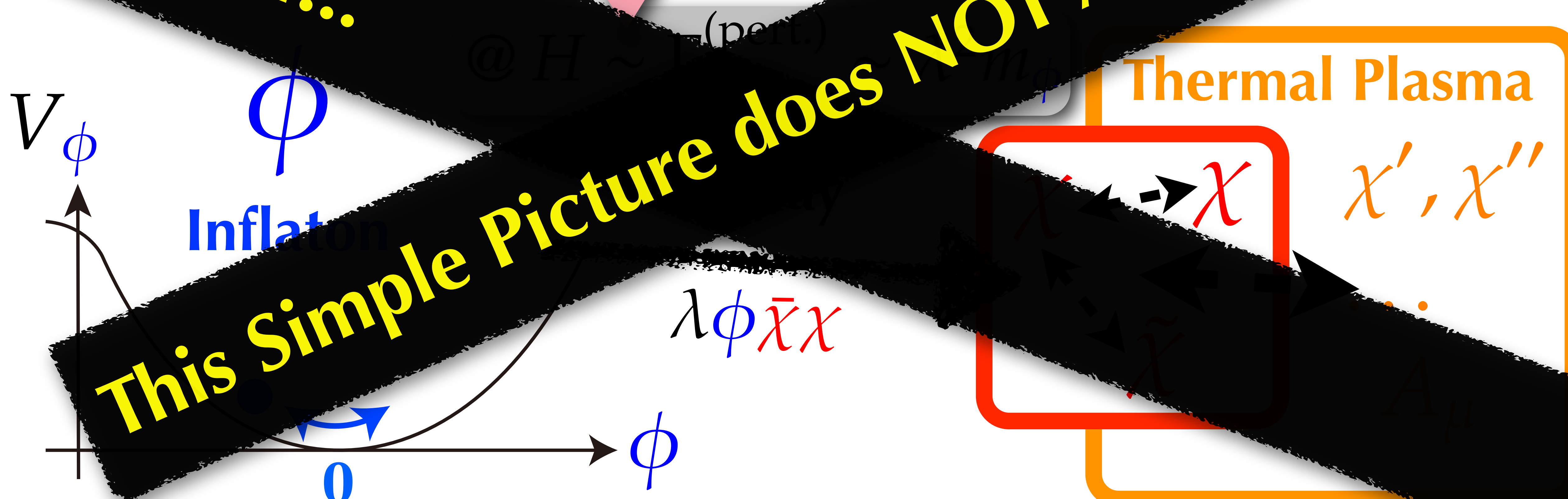

However...

This Simple Picture does NOT ALWAYS hold !

Introduction

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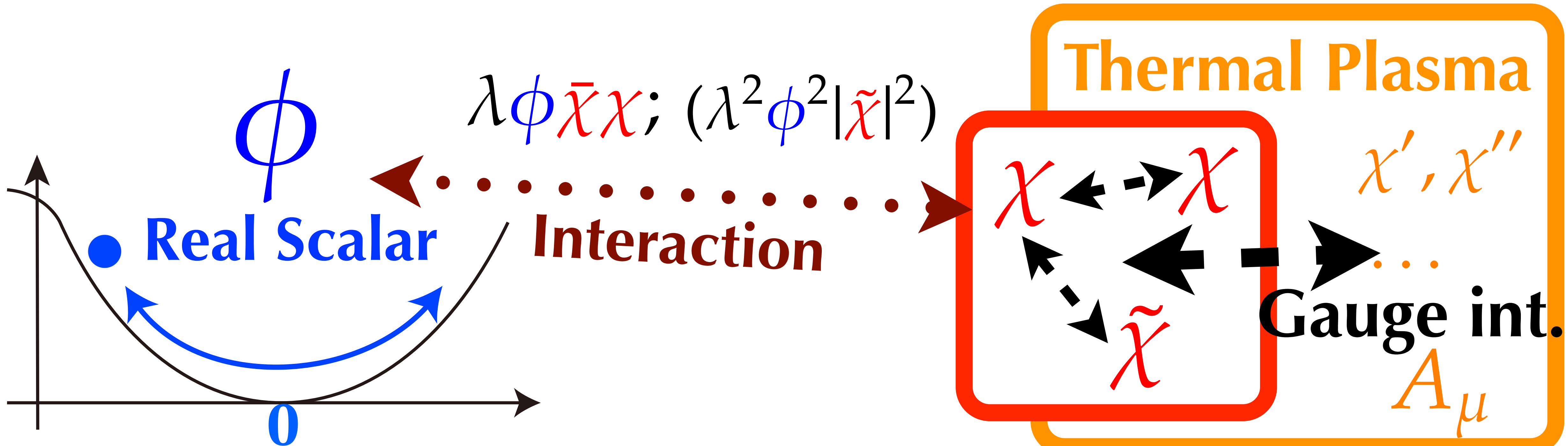

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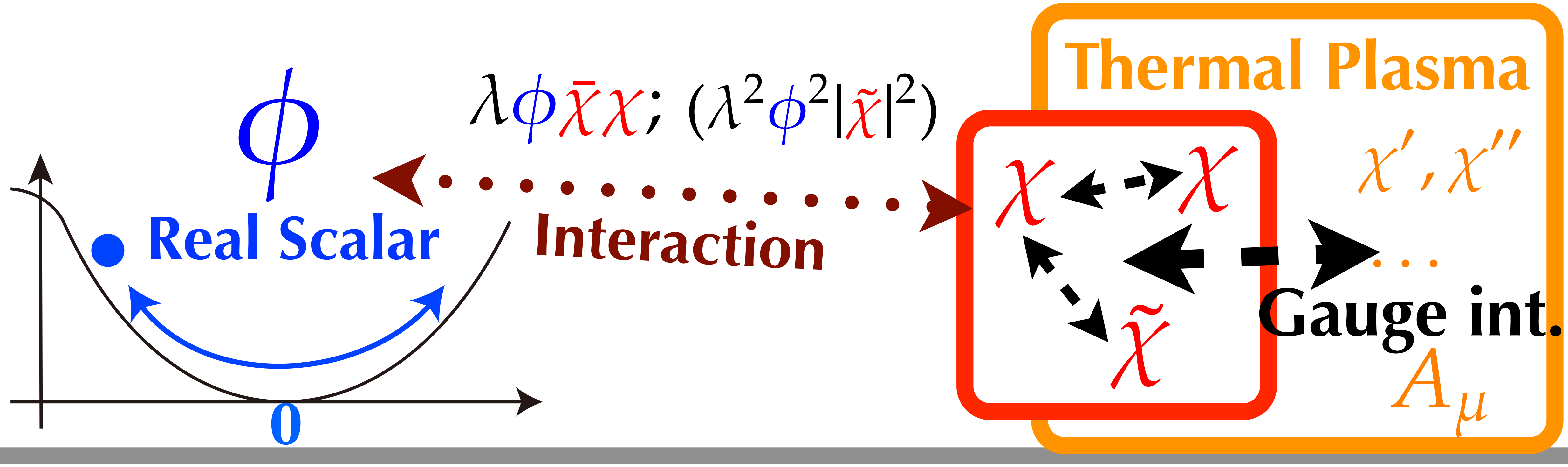
- Missing **Two** effects (at least):
  - Before going into details, let us clarify our setup:

$$\mathcal{L}_{\rm kin} - \frac{1}{2}m_\phi^2\phi^2 + \lambda\phi\left(\bar{\chi}_{\rm L}\chi_{\rm R} + {\rm h.c.}\right) + \mathcal{L}_{\rm other}$$



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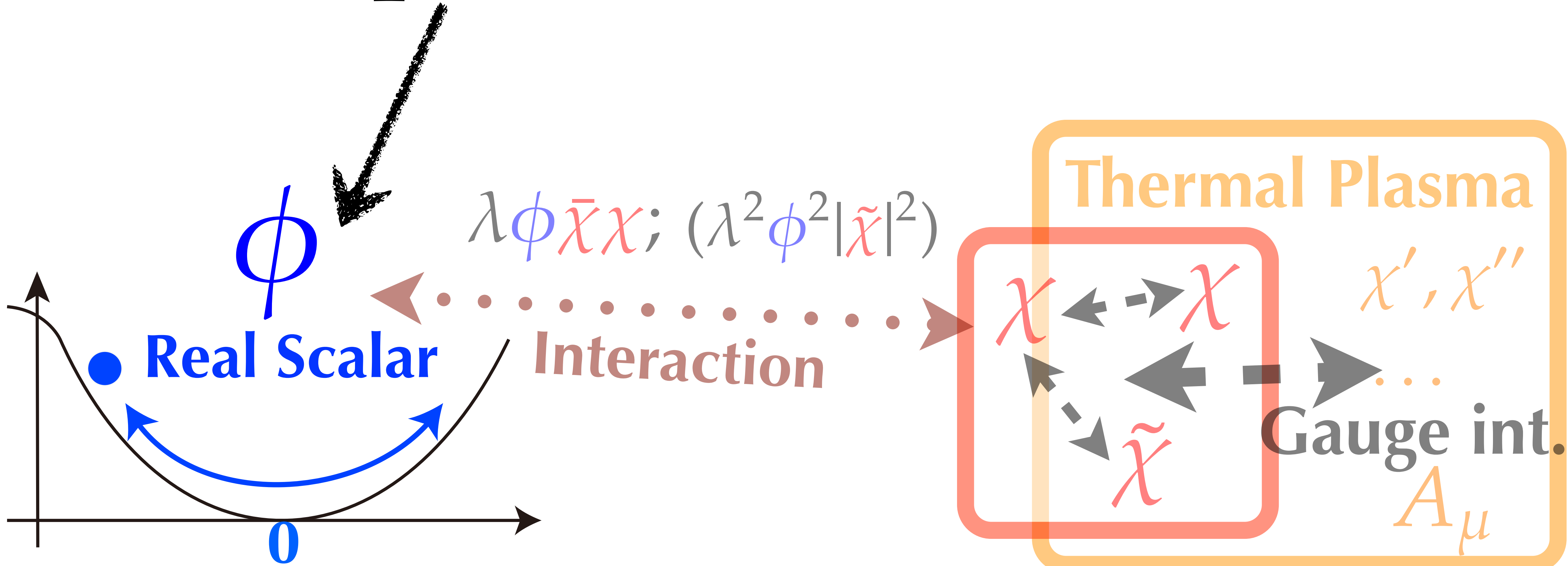

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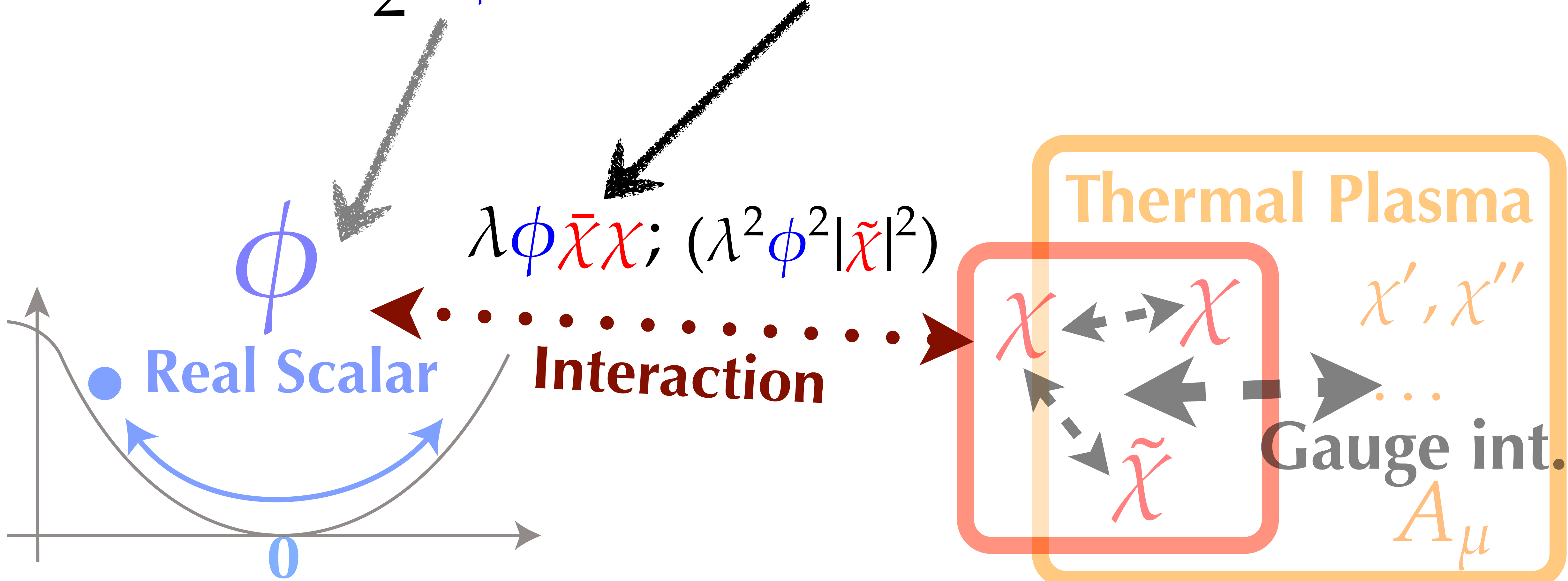

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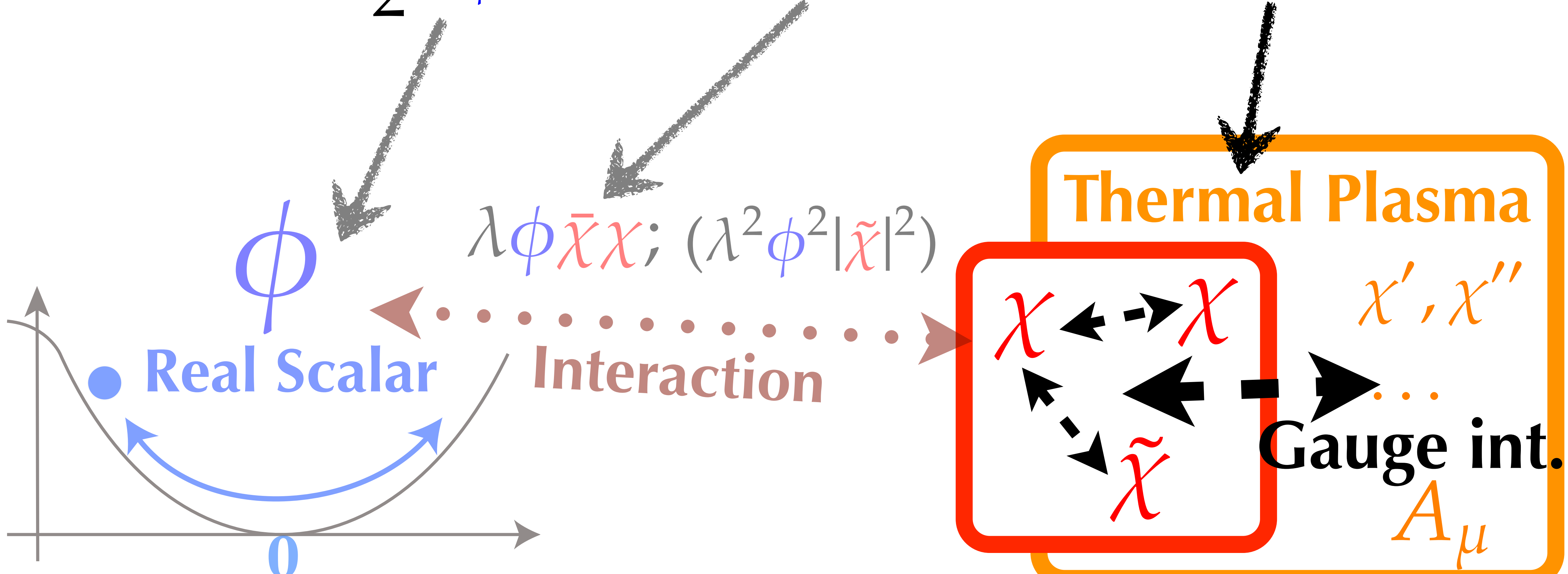

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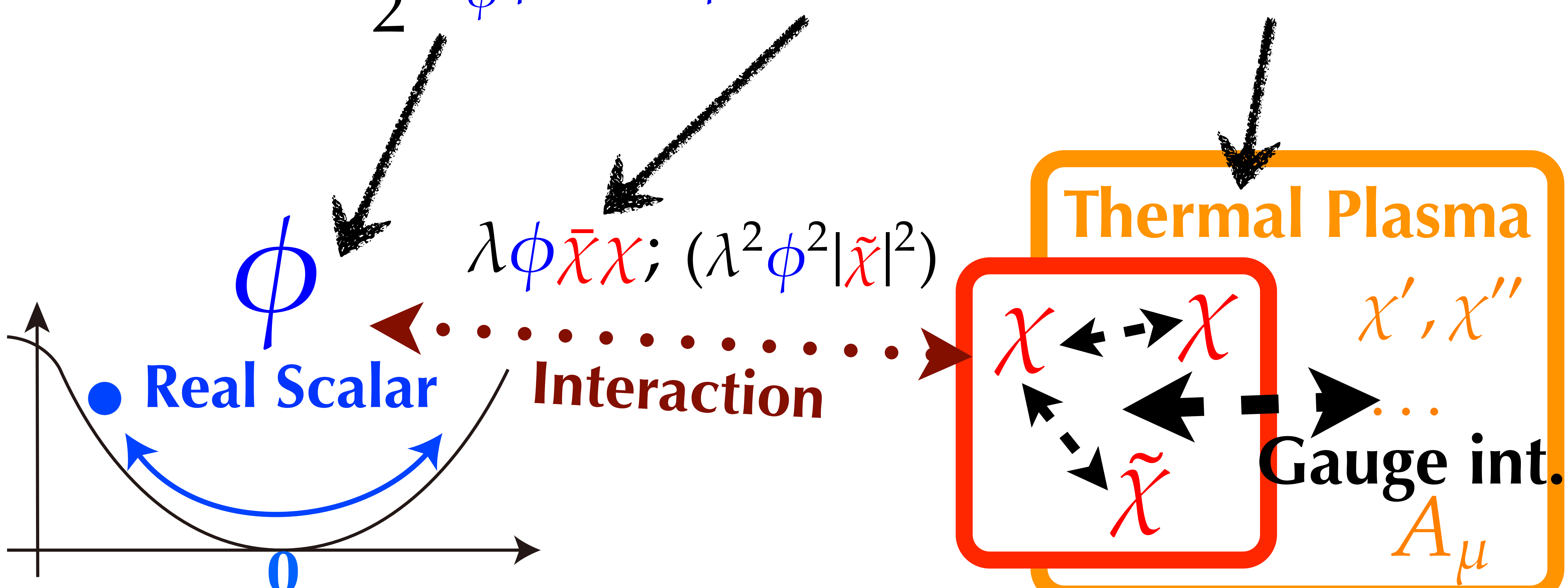

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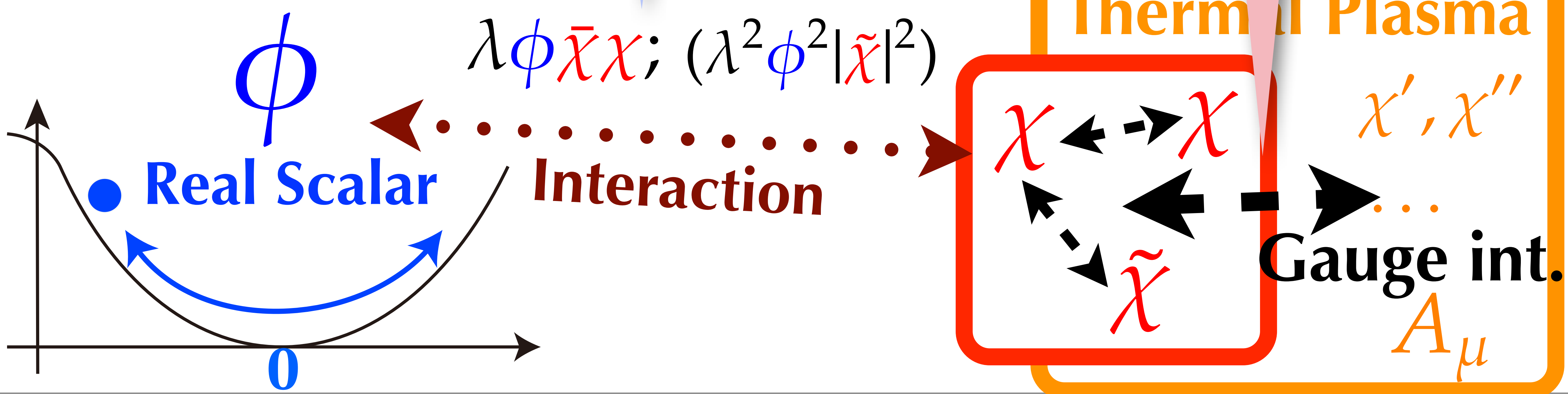
  - What if $m_{\mathrm{eff},\chi} \gg m_\phi$??

$\Gamma_\phi^{(\mathrm{pert.})}$??

$$m_{\mathrm{eff},\chi}^2 = \lambda^2\phi(t)^2 + m_\chi^{\mathrm{th}}(T)^2 \quad \sim g^2T^2$$

$\lambda\phi\bar{\chi}\chi;\ (\lambda^2\phi^2|\tilde{\chi}|^2)$



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1. If $m_{\mathrm{eff},\chi} \sim \lambda \tilde{\phi} \gg m_\phi$

➡ Non-perturbative particle production (**Preheating**)

e.g., [L. Kofman, A. Linde, A. Starobinsky]

2. If $m_{\mathrm{eff},\chi} \sim m_\chi^{\mathrm{th}} \gg m_\phi$

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Main Message

- Possible sketch of reheating after inflation w/ $m_\phi \ll \lambda\phi_\mathrm{i}$.

End of inflation. ($m_\phi \ll \lambda\phi_\mathrm{i}$)

Preheating

High T plasma; $m_\phi \lll T$ is produced and the preheating terminates: $k_* \sim m_\chi^\mathrm{th}$.

Dissipation (Scat.) into **high T plasma**

T_R

Time

Reheating can be completed by **Thermal Dissipation!**

Outline

- Introduction
- Preheating (Non-perturb. production)
- Dissipation to Thermal Plasma
- Numerical Results

Preheating

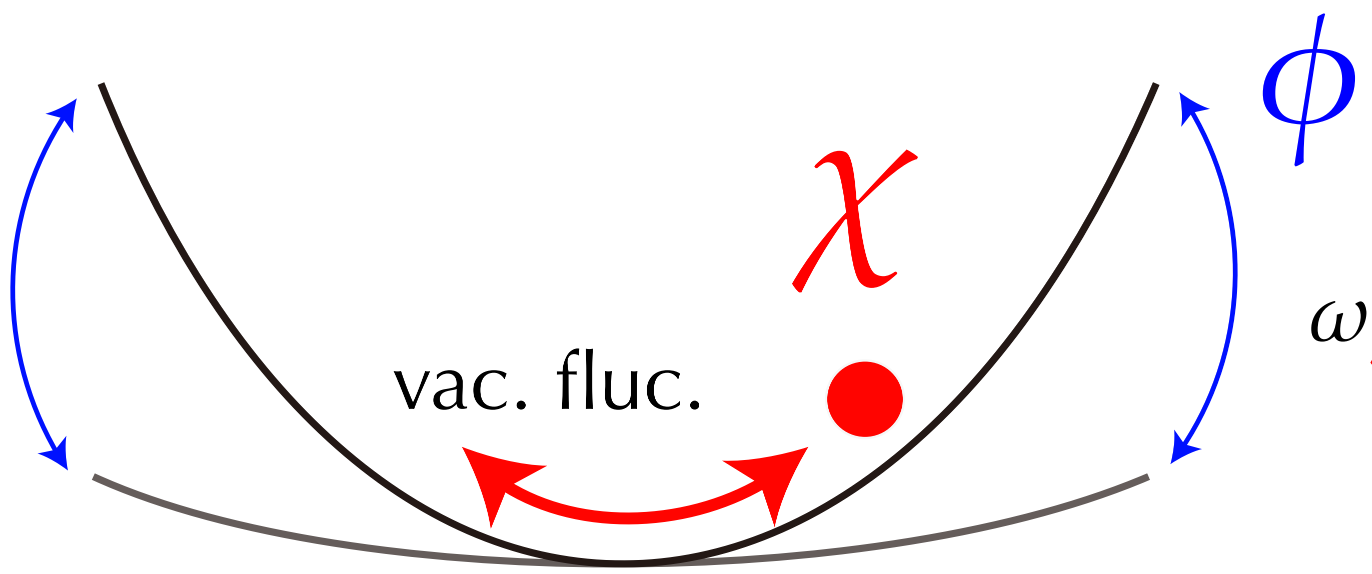
Non-pert. Production

- The non-perturbative particle production occurs if

[L. Kofman, A. Linde, A. Starobinsky]

Φ's amplitude: $\tilde{\phi}$

$$\lambda\tilde{\phi} \gg \max\left[m_\phi, \frac{m_\chi^{\rm th}(T)^2}{m_\phi}\right]$$



$$\omega_\chi = \sqrt{\mathbf{k}^2 + m_\chi^{\rm th}(T)^2 + \lambda^2\phi^2(t)}$$

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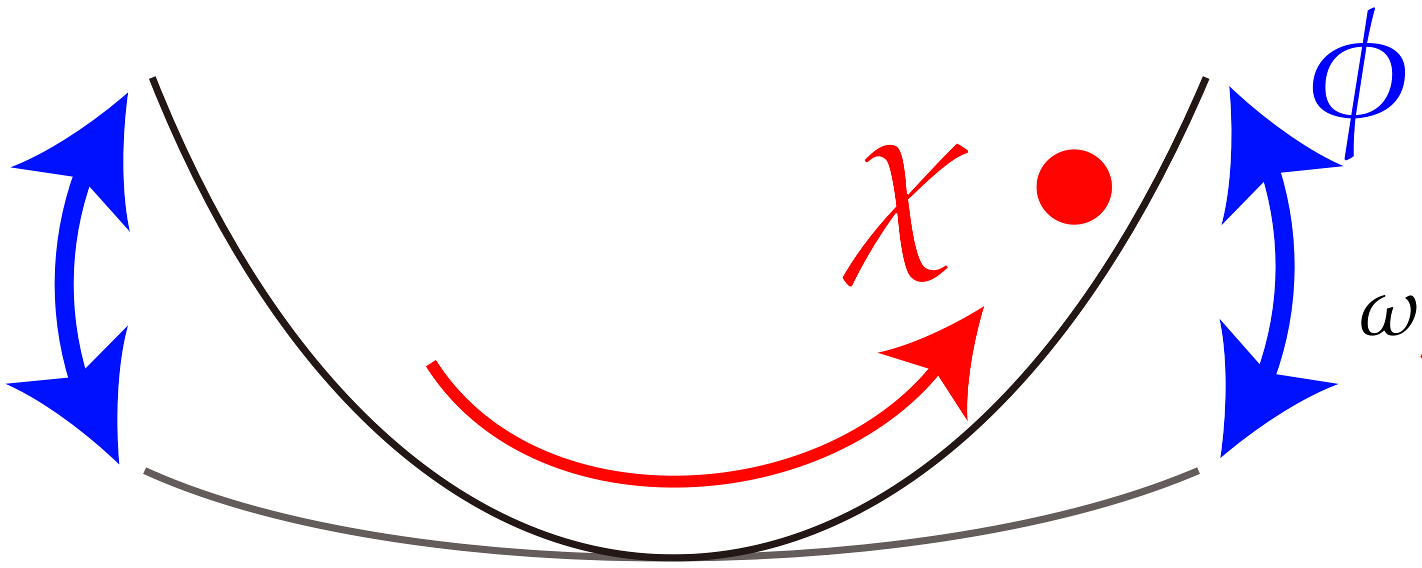

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- Implies that the non-pert. production is "blocked" if

$$m_\chi^{\rm th}(T) \sim k_* = \sqrt{\lambda m_\phi \tilde{\phi}}.$$

[KM, K. Nakayama; K. Enqvist, D. Figueroa, R. Lerner]

Non-pert. Production

- If χ **is not stable**, then...
- Non-perterbatively produced χ can decay within each crossings of Φ~0. e.g.,[J. Garcia-Bellido, D. Figueroa, J. Rubio]

$$\Gamma_{\chi} \sim \kappa^2 m_{\chi}(\phi(t)) \sim \kappa^2 \lambda |\phi(t)|;$$

▸χ decays completely before the Φ moves back to its origin if

$$\kappa^2 \lambda \tilde{\phi} \gg m_{\phi}.$$

- Parametric Resonance is absent in this case;

even if χ is boson.

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- χ decays completely before the Φ moves back to its origin if $\kappa^2 \lambda \tilde{\phi} \gg m_\phi .$ ➔ $\Gamma_\phi \sim N_{\rm d.o.f.} \dfrac{\lambda^2 m_\phi}{2\pi^4 |\kappa|}.$

- This process ends @ $[\lambda m_\phi \tilde{\phi}]^{1/2} \sim k_* \sim m_\chi^{\rm th}(T) \sim gT.$

[KM, K. Nakayama]

Thermal Effects

Thermal Effects

- Thermal Dissipation (Scattering):

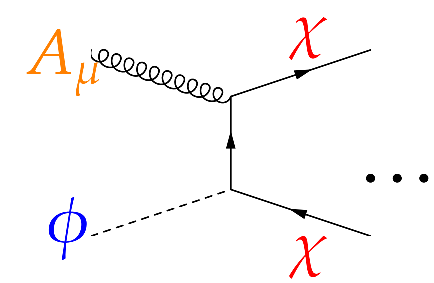
e.g.,[Hosoya, Sakagami; J. Yokoyama; M. Drewes]

$$\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + {m_\phi}^2\phi = -\frac{\partial \mathcal{F}}{\partial \phi}$$

Friction coefficient from Kubo-formula: $\Gamma_\phi \simeq \lim_{\omega \to 0} \frac{\Pi_J(\omega, \mathbf{0})}{2\omega}$.

-Small Φ: $\lambda\phi \ll T$ ⇒ scatterings including χ.

$$\Gamma_\phi \sim \lambda^2 \alpha T \left(\Gamma_\phi \sim \lambda^4\phi^2/(\alpha T)\right)$$



-Large Φ: $\lambda\phi \gg T$ ⇒ scatterings by gauge bosons.

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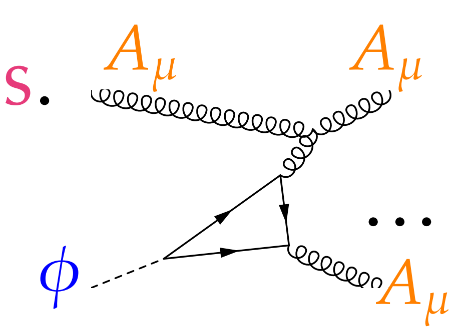

[D. Bodeker; M. Laine]

Thermal Effects

- For $m_\phi << gT$, the inflaton loses its energy by the thermal dissipation (multiple scattering); not by the perturbative decay!

$\omega \to 0$ 2ω

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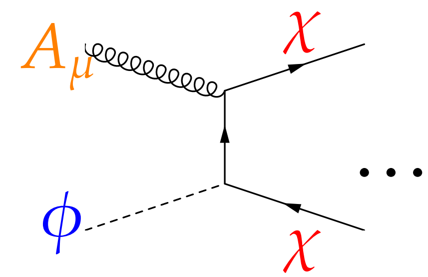

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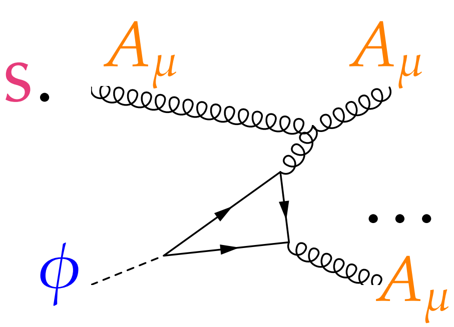
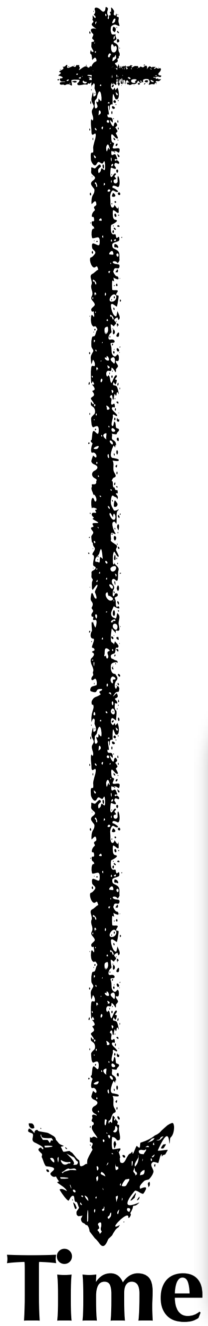


[D. Bodeker; M. Laine]

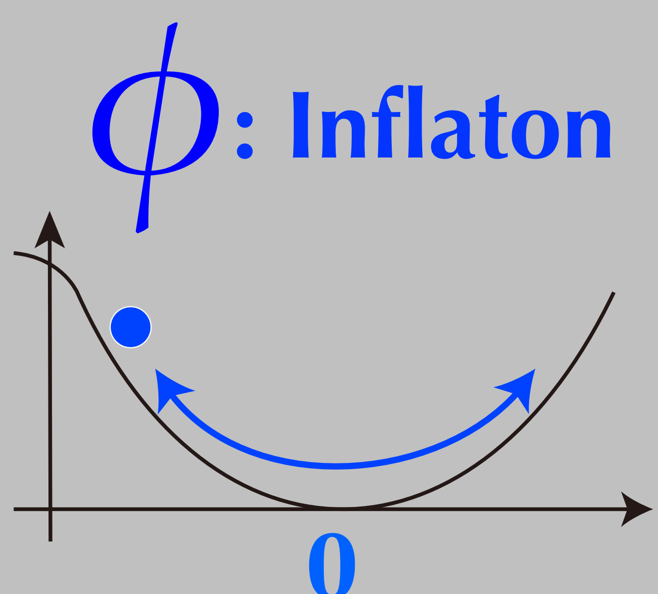
Brief Summary

Reheating after Inflation

- Rough sketch of reheating after inflation w/ $m_\phi \ll \lambda\phi_{\rm i}$.



End of inflation. ($m_\phi \ll \lambda\phi_{\rm i}$)



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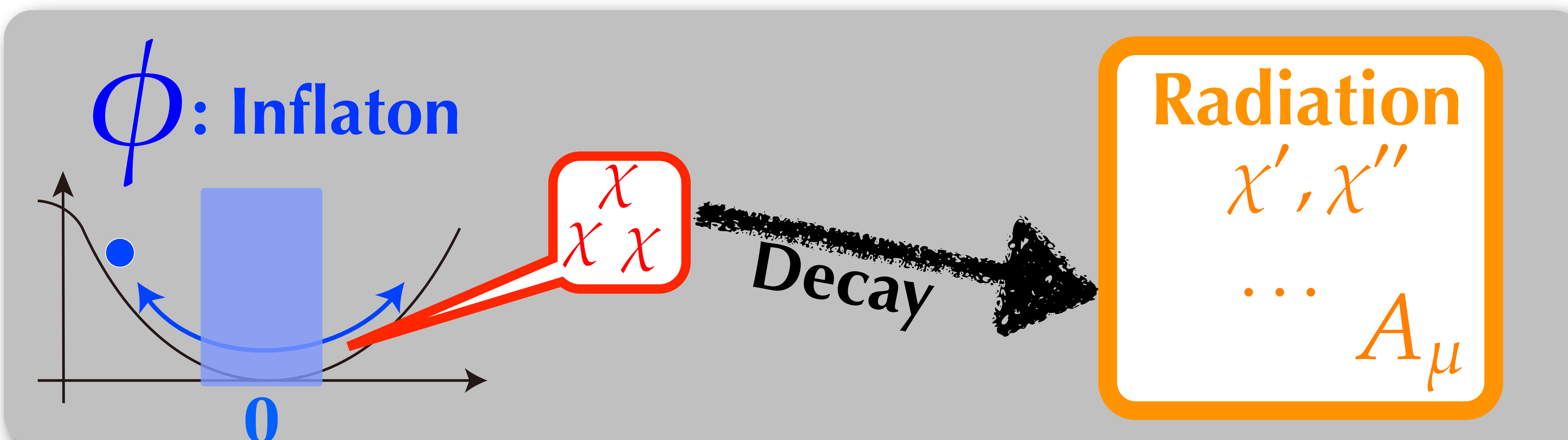

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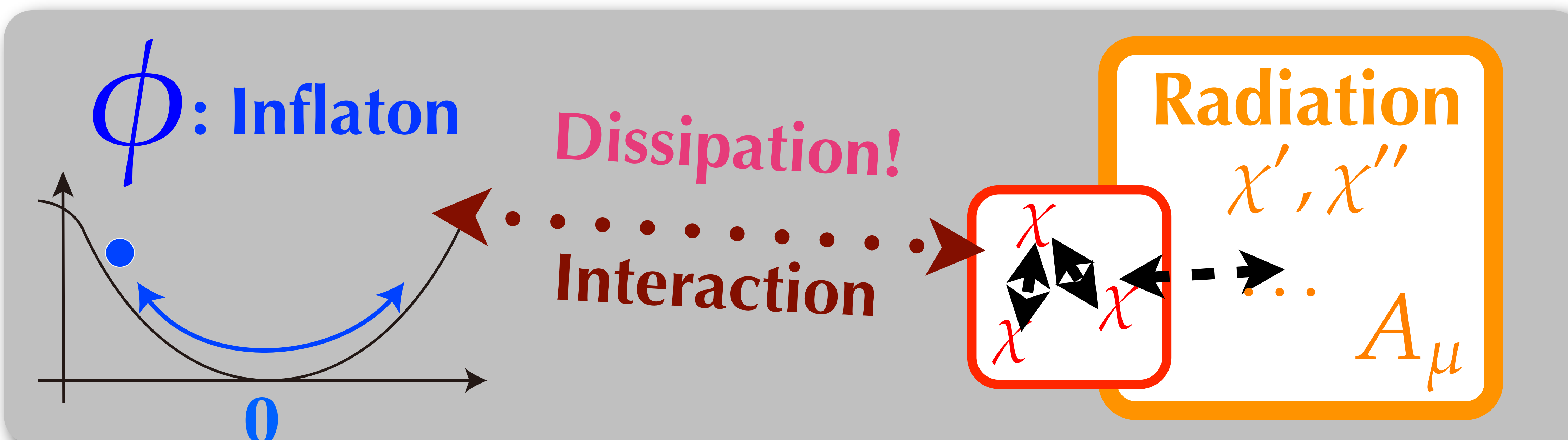

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Numerical Results

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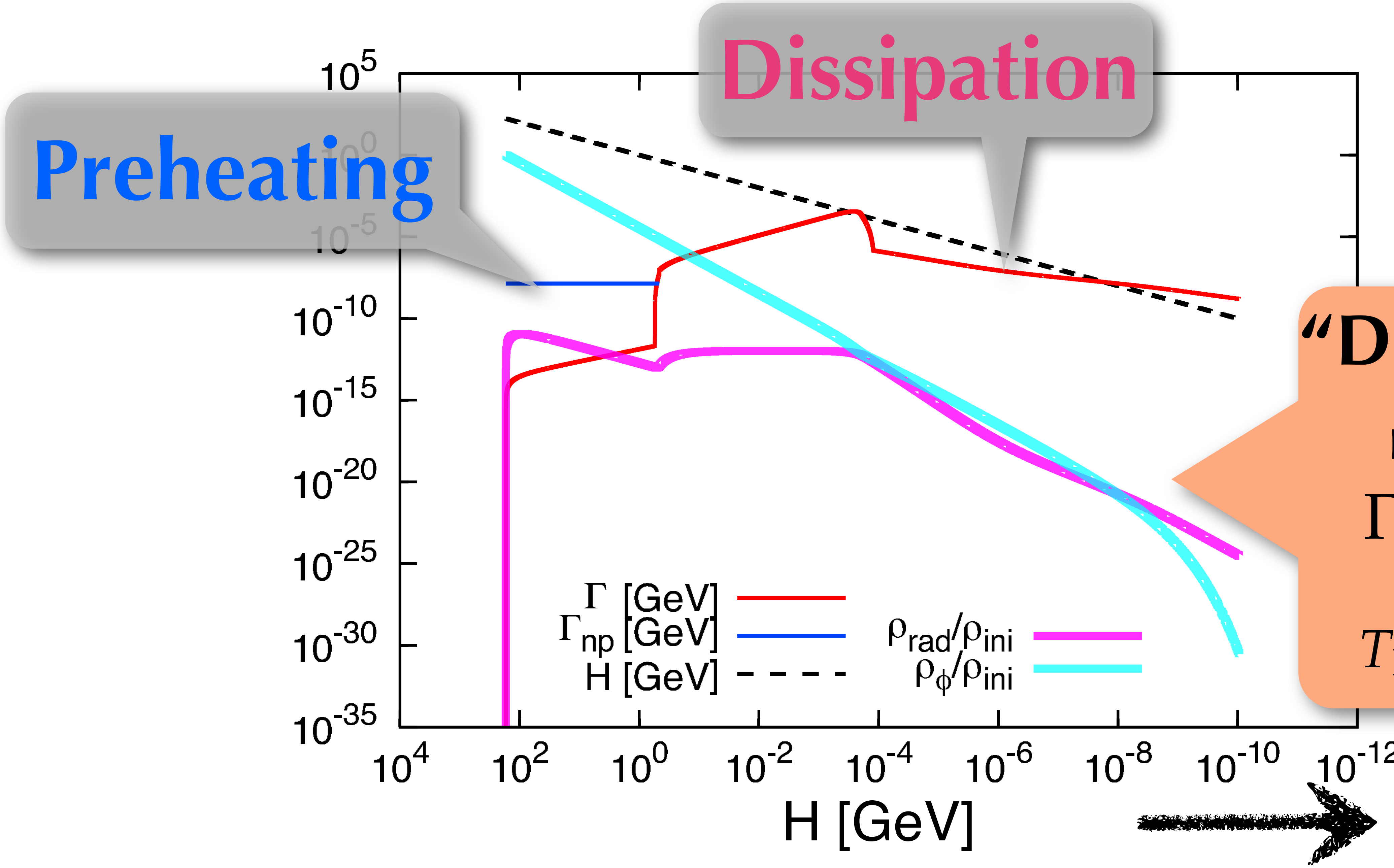
- **Reheating** via thermal dissipation.



$m_\phi = 1$ TeV
$\phi_i = 10^{18}$ GeV
$\lambda = 10^{-5}$
$\alpha = 0.05$

"Dissipation"

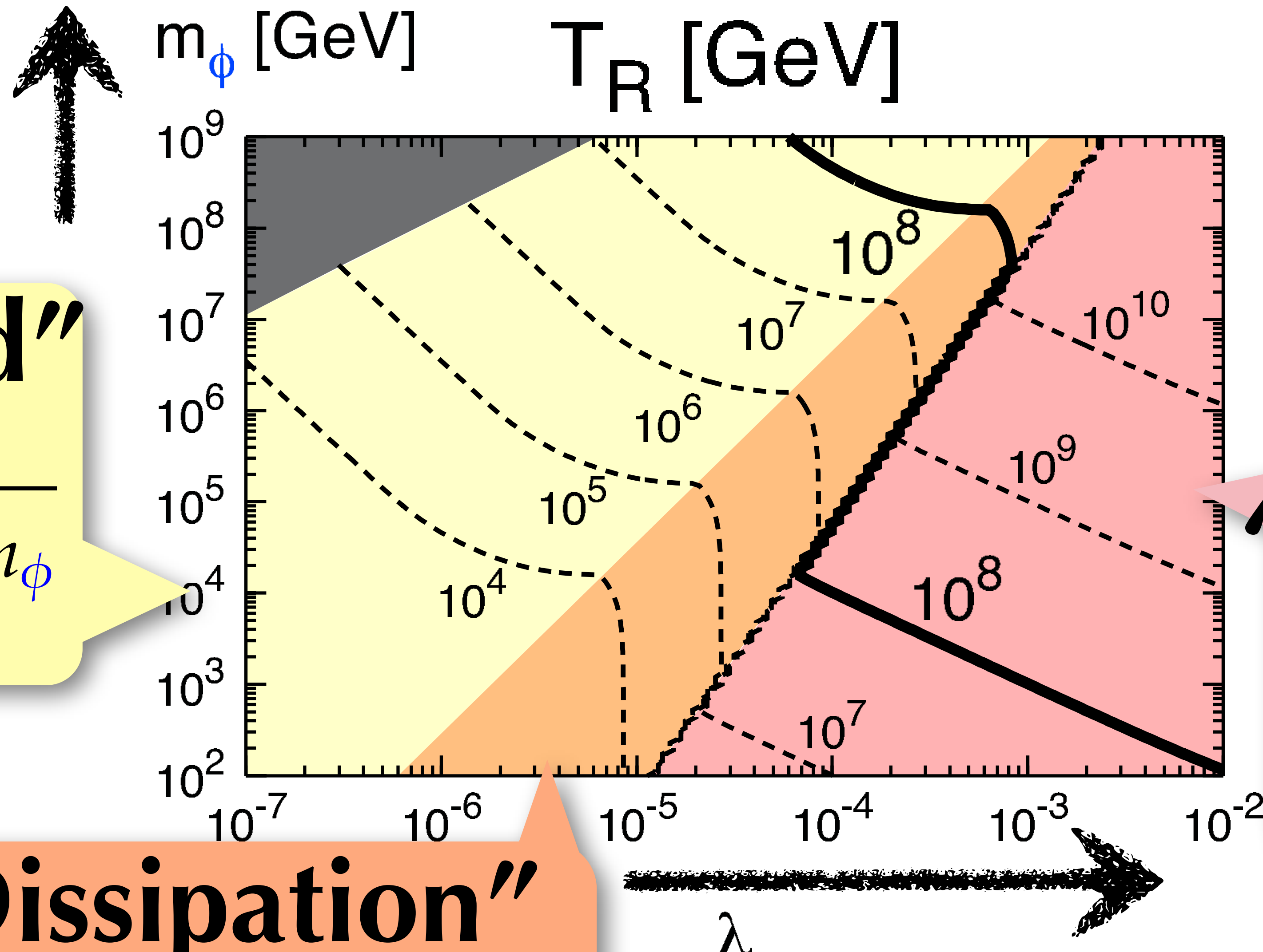
Reheating via

$\Gamma_\phi^{\rm eff} \sim \lambda^2 \alpha T$

$T_{\rm R} \sim 10^5$ GeV

Numerical Results

- Contour plot of T_R as a function of λ and m_ϕ.



Coupling btw Φ & radiation

"Standard"

$T_R \propto \sqrt{\lambda^2 M_{pl} m_\phi}$

"Dissipation"

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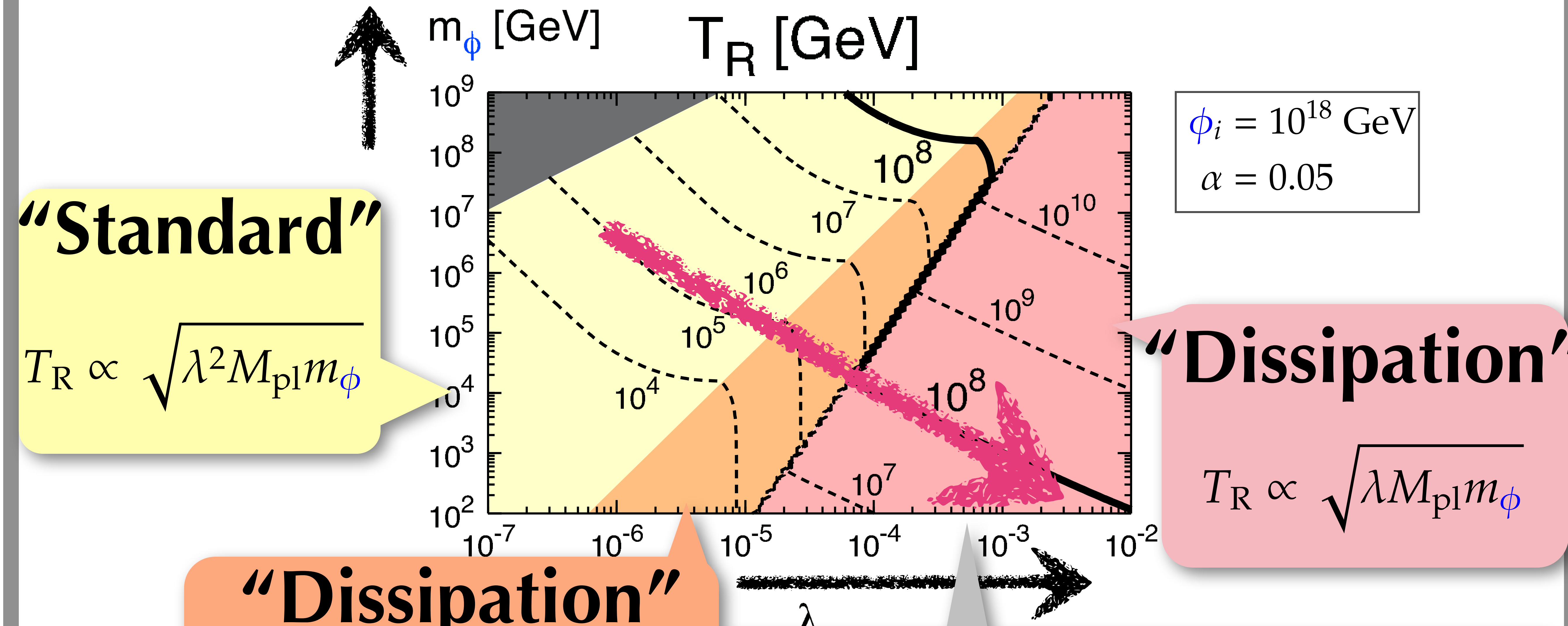

Thermal Dissipation dominates the **reheating** for small m_ϕ and not small λ.

Summary

- We studied in detail processes of reheating:
  - particle production from inflaton
  - their subsequent thermalization
  - evolution of inflaton/plasma system
- If the mass of inflaton is not heavy, T_R is dramatically changed due to the thermal dissipation.

  e.g., Higgs inflation and its variants;
  Inflation w/ SUSY flat direction (MSSM inflation);
  Some class of thermal inflation
- There are other examples than inflaton.

  [T. Moroi, KM, K. Nakayama and T. Takimoto]