Dissipative Effects on Reheating after Inflation

Kyohei Mukaida (Univ. of Tokyo)

Based on: **1212.4985**,**1208.3399** with **K. Nakayama**;
[JCAP03(2013)002, JCAP01(2013)017],

also **1308.4394** with **K. Nakayama** and **M. Takimoto**

Introduction

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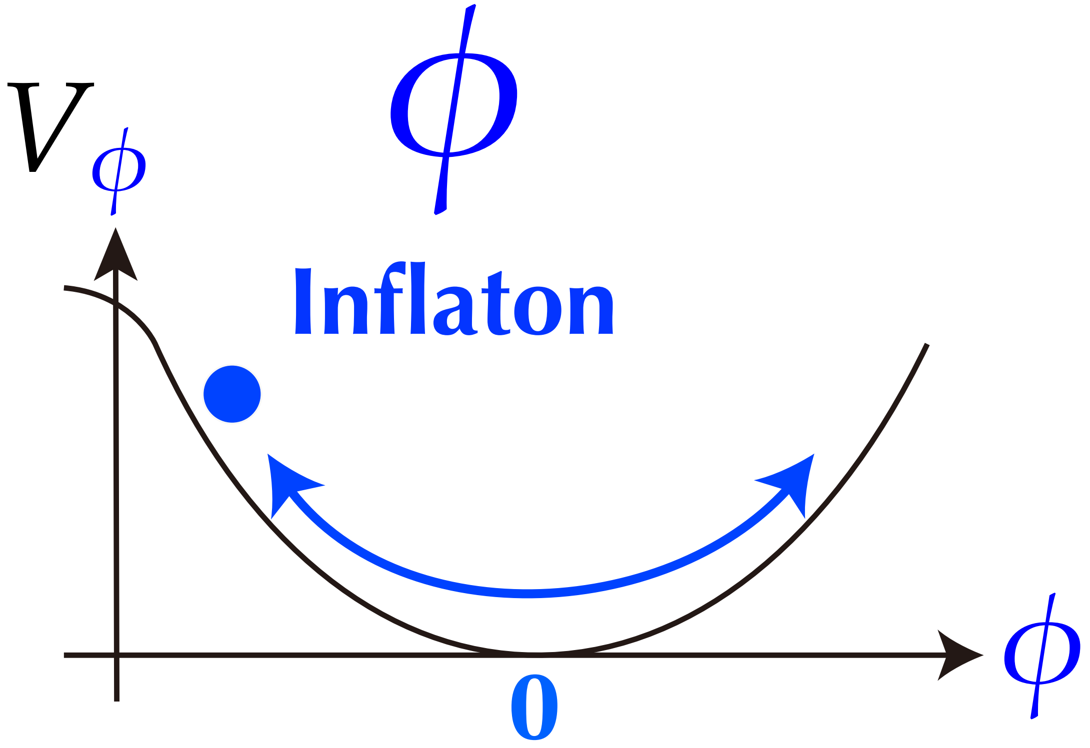
- After the inflation, the inflaton should convert its energy to radiation: **Reheating**.

- How does the **reheating** proceed ?

‣ "Standard" picture:



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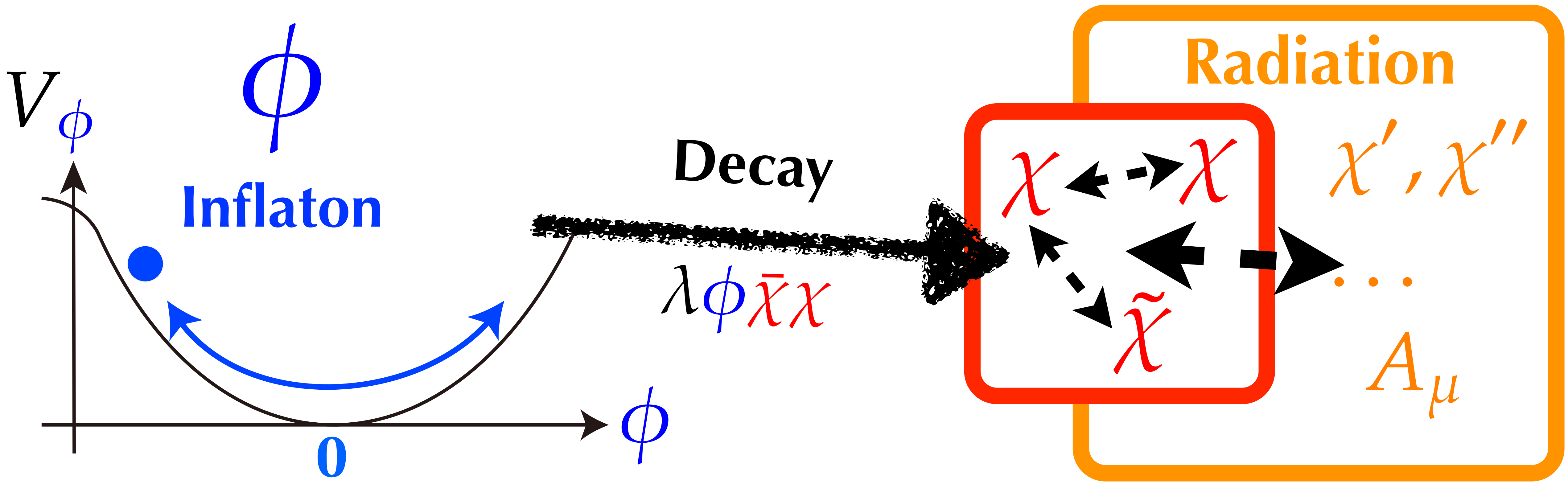

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• Reheating temperature: $T_R \sim \left[\frac{90}{\pi^2 g_*}\right]^{1/4} \sqrt{M_{pl}\,\Gamma_\phi^{(pert)}}$

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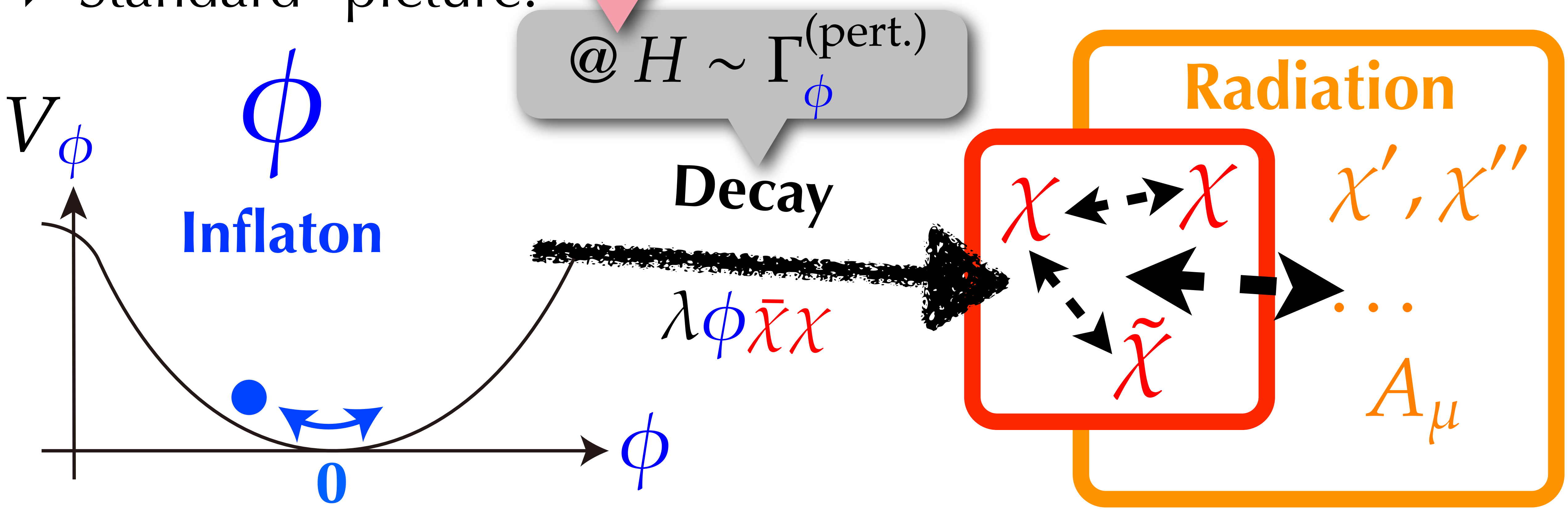

▸ T_R characterizes the thermal history of Universe:

- Efficiencies of Lepto/Baryogenesis
- Abundance of (unwanted) relics: gravitino, moduli, axion, axino...
- Precise calc. of spectral index
- ...

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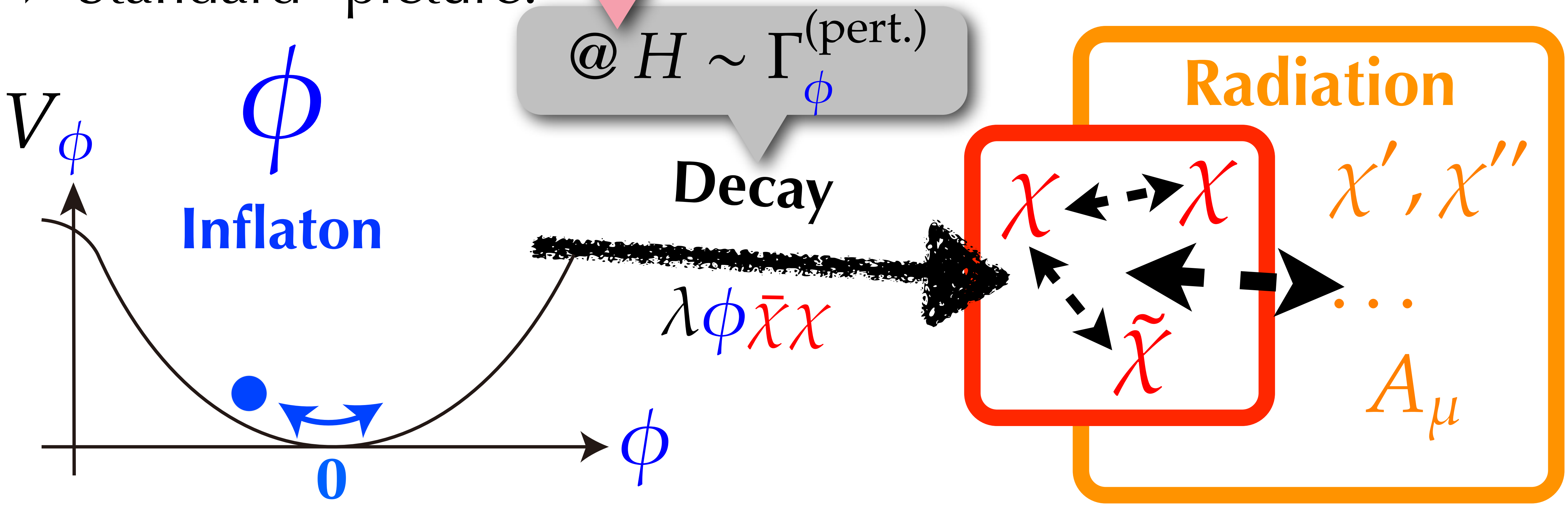

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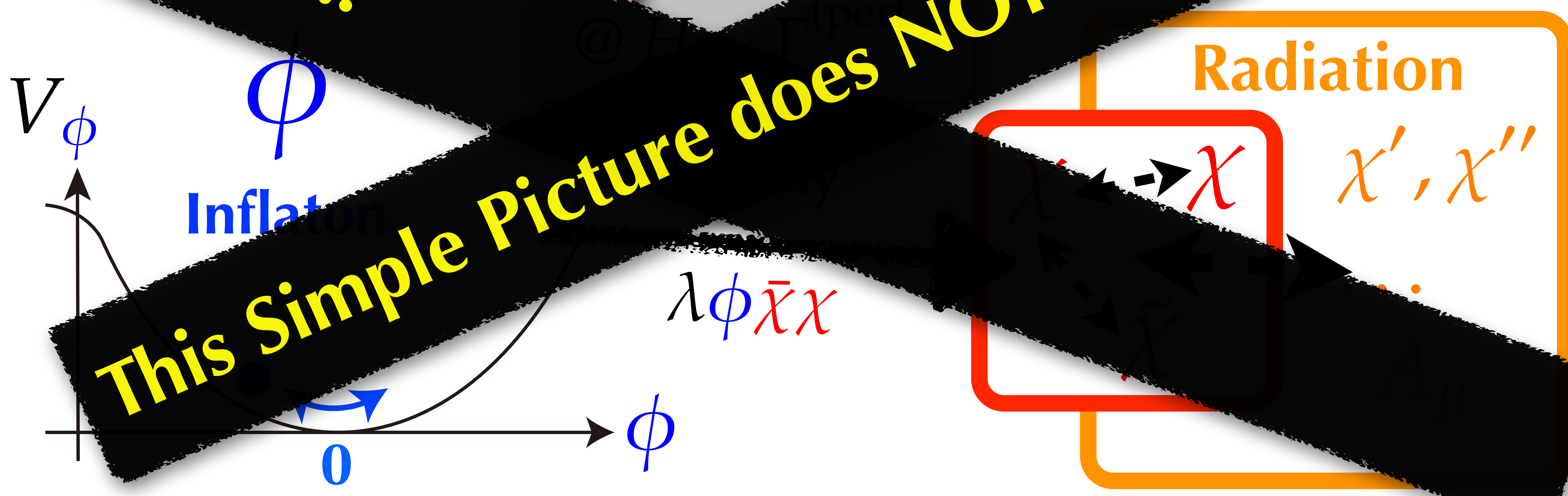


However...

This Simple Picture does NOT ALWAYS hold !

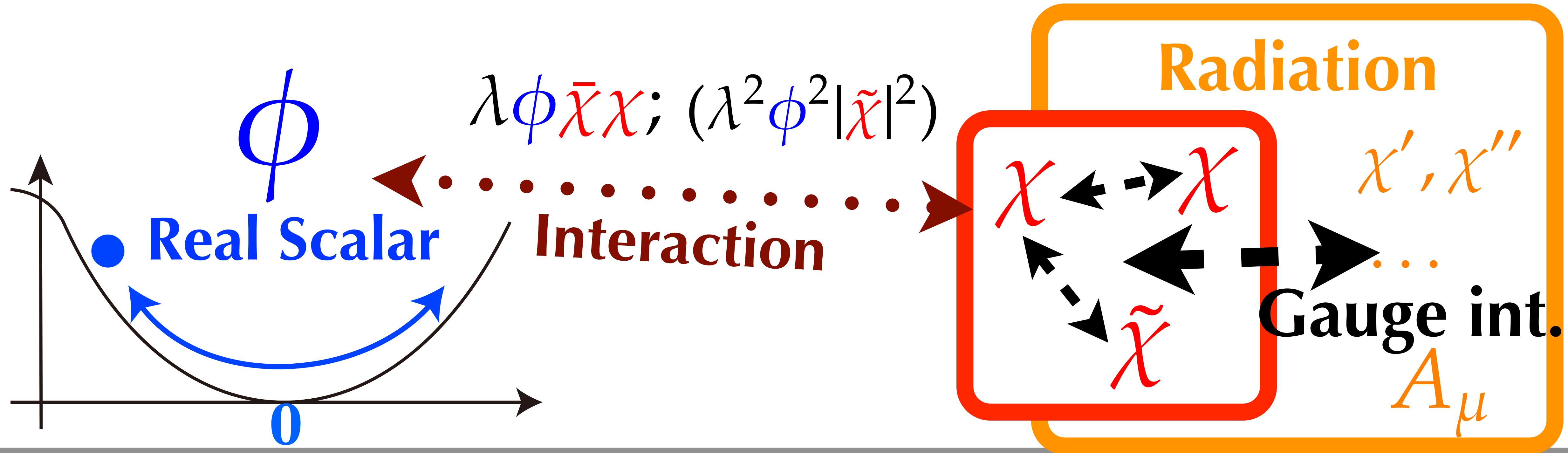
Outline

- Introduction
- Non-Thermal/Thermal Dissipation
- Numerical Results

Dissipation

Dissipation

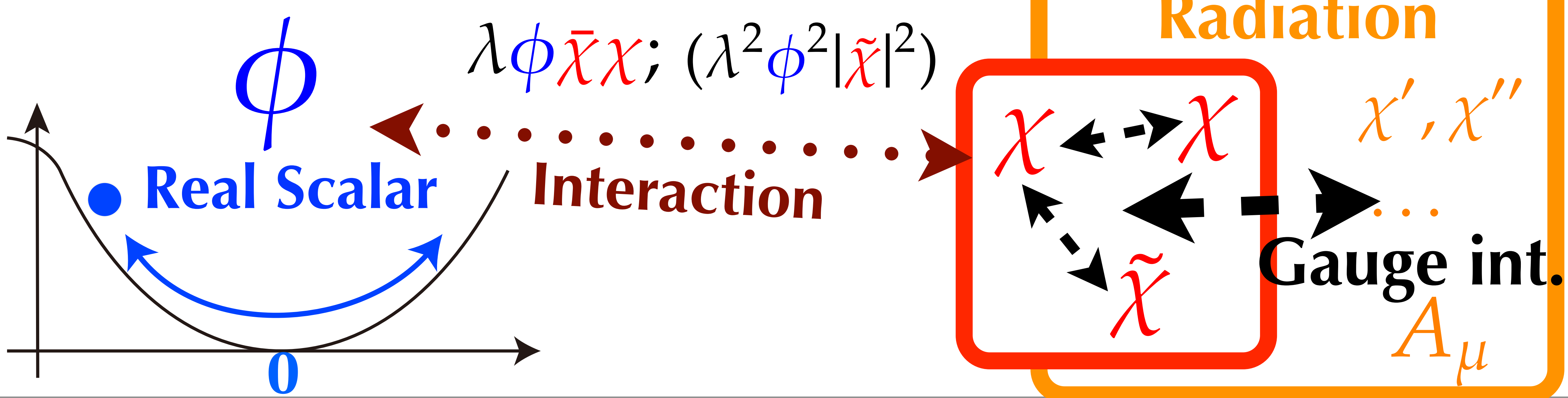
- Missing **Two** effects:



Dissipation

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

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



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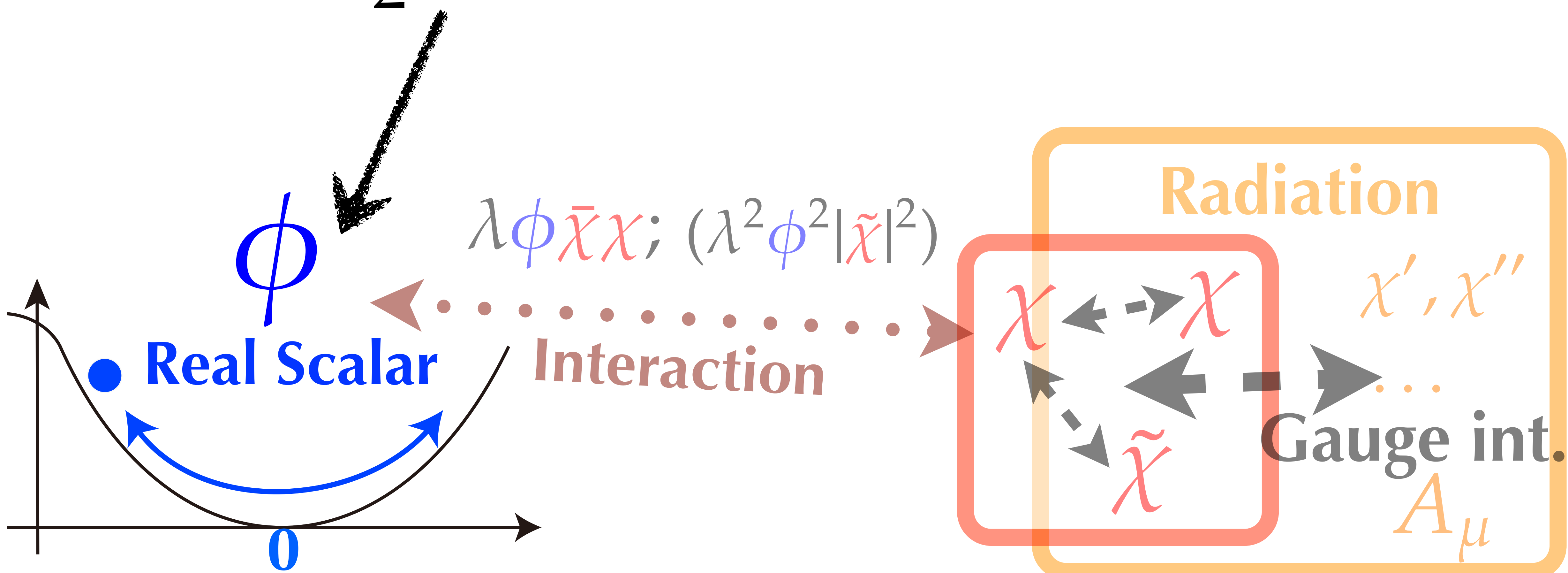

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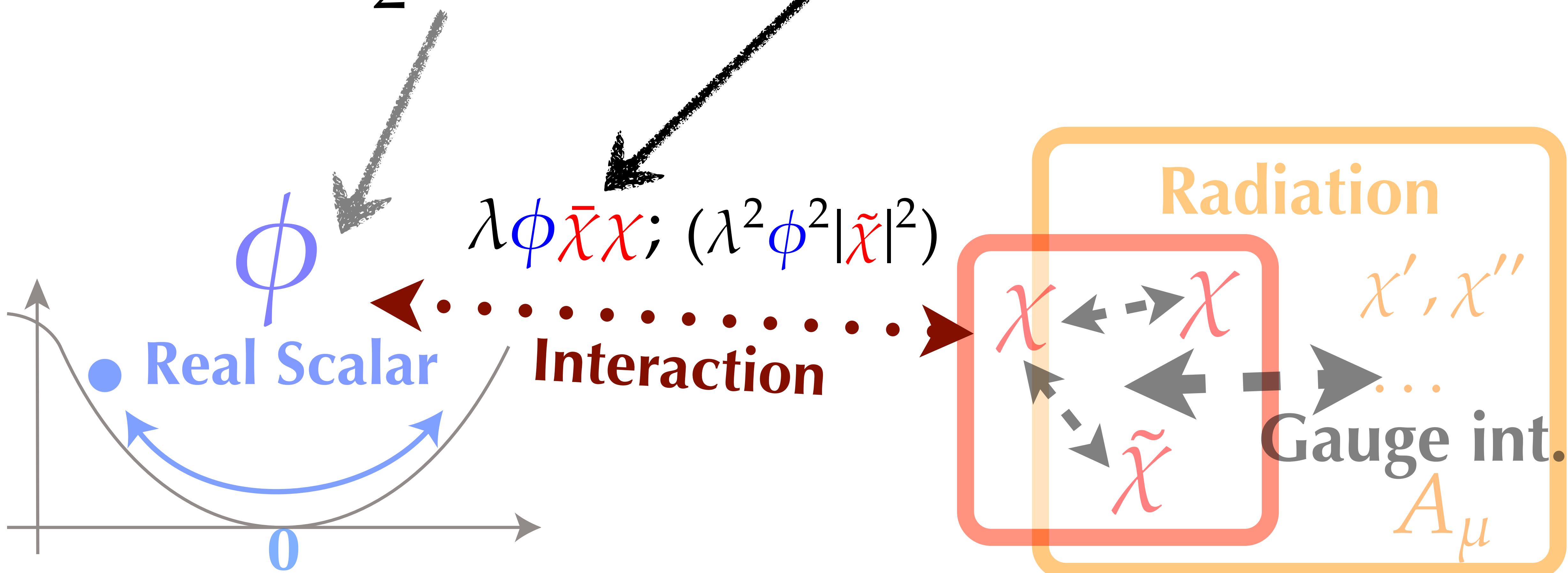

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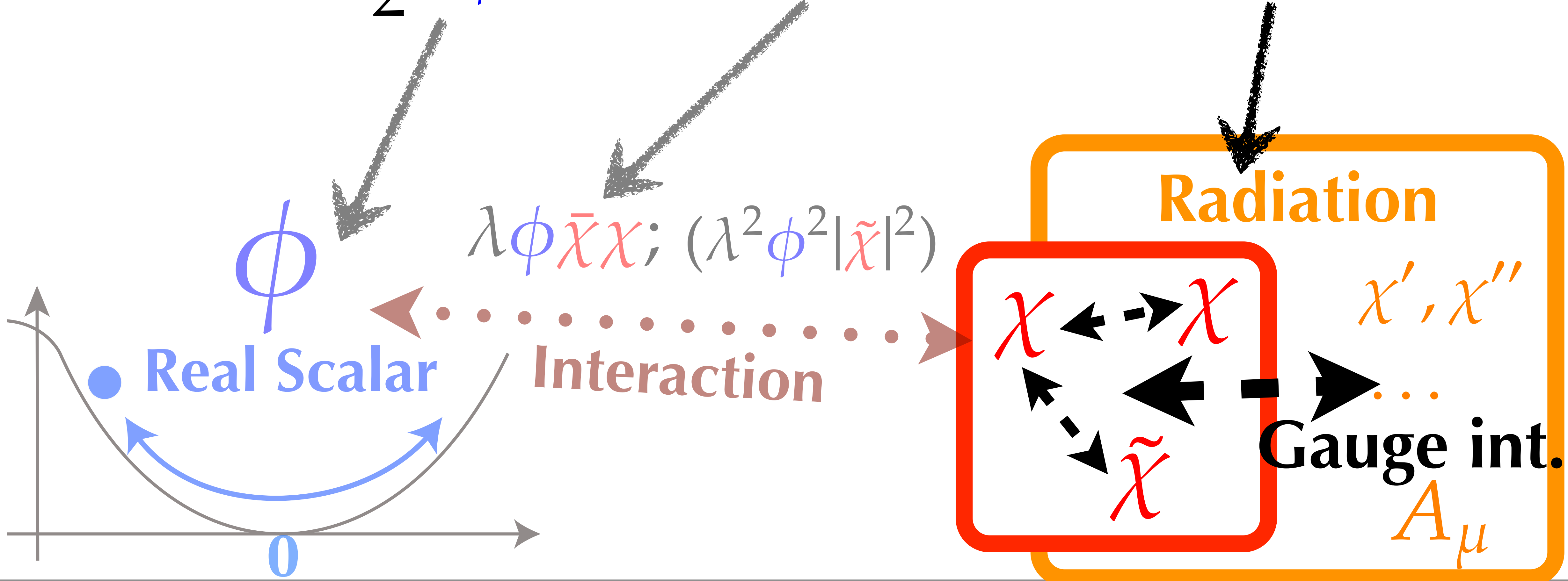

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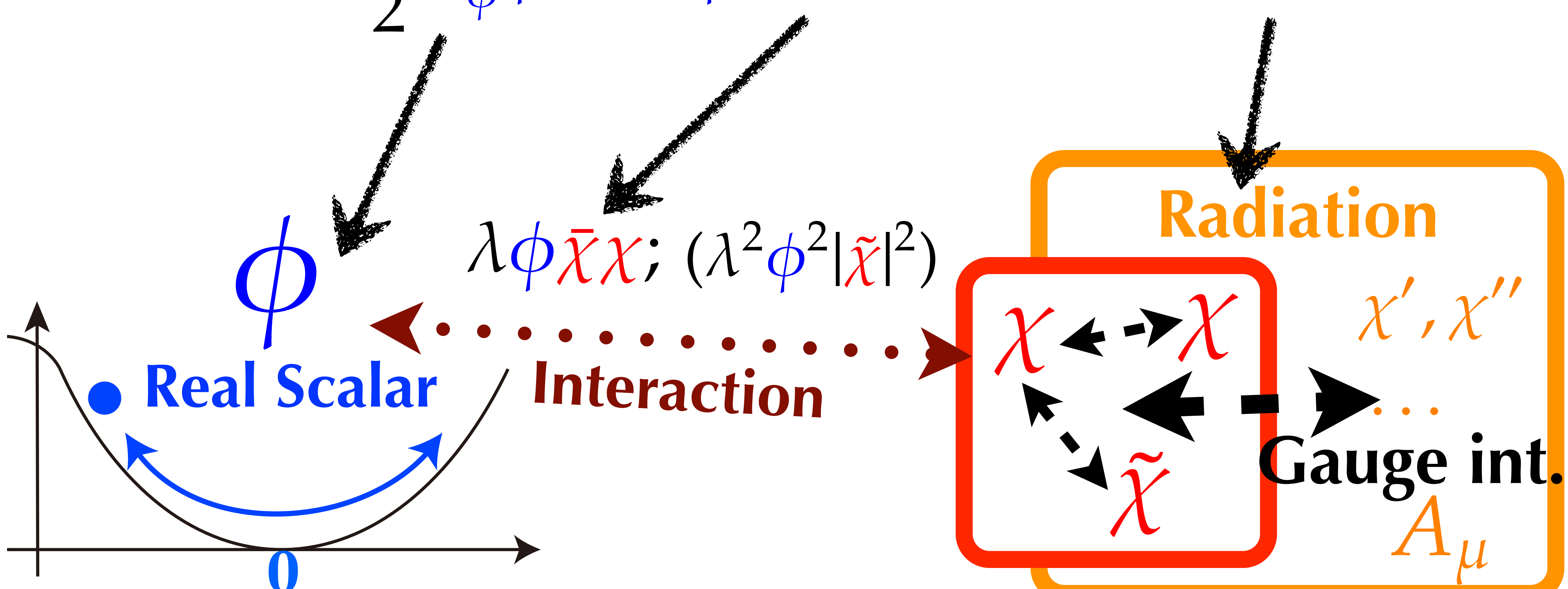

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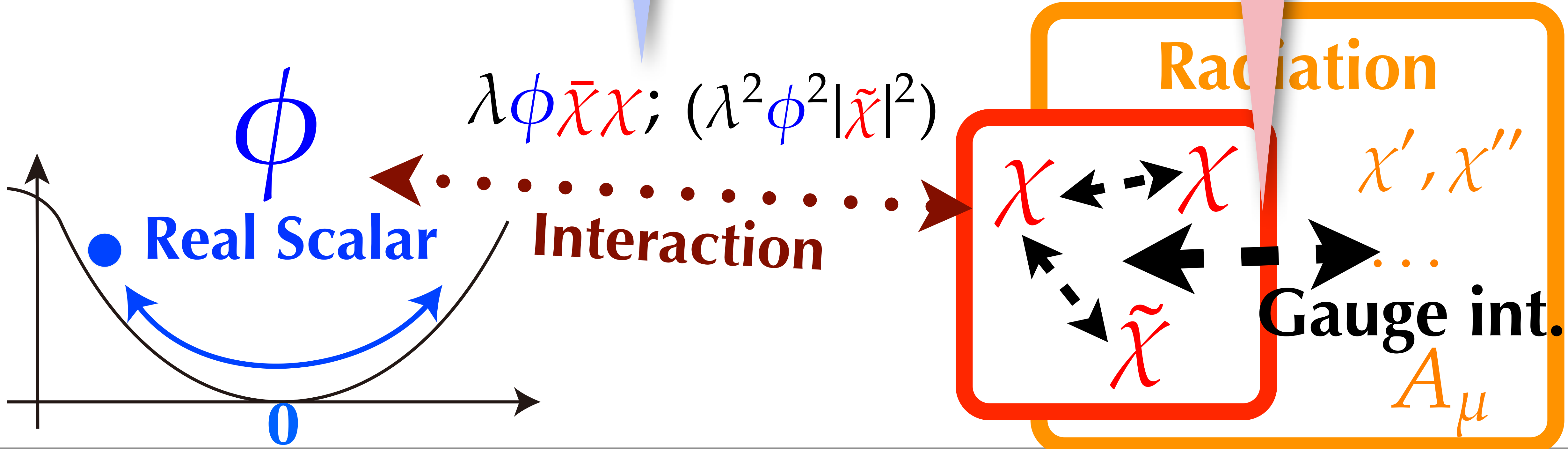
  - What if $m_{\mathrm{eff},\chi} \gg m_\phi$?? — $\Gamma_\phi^{(\mathrm{pert.})}$??

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



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➡ Non-perturb. particle production (**Non-Thermal**)

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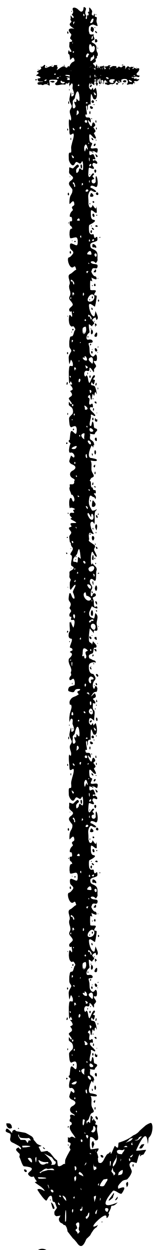
  - End of inflation. ($m_\phi \ll \lambda \phi_\mathrm{i}$)



Time

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Non-Thermal Dissipation (Preheating)

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Non-Thermal Dissipation
(Preheating)

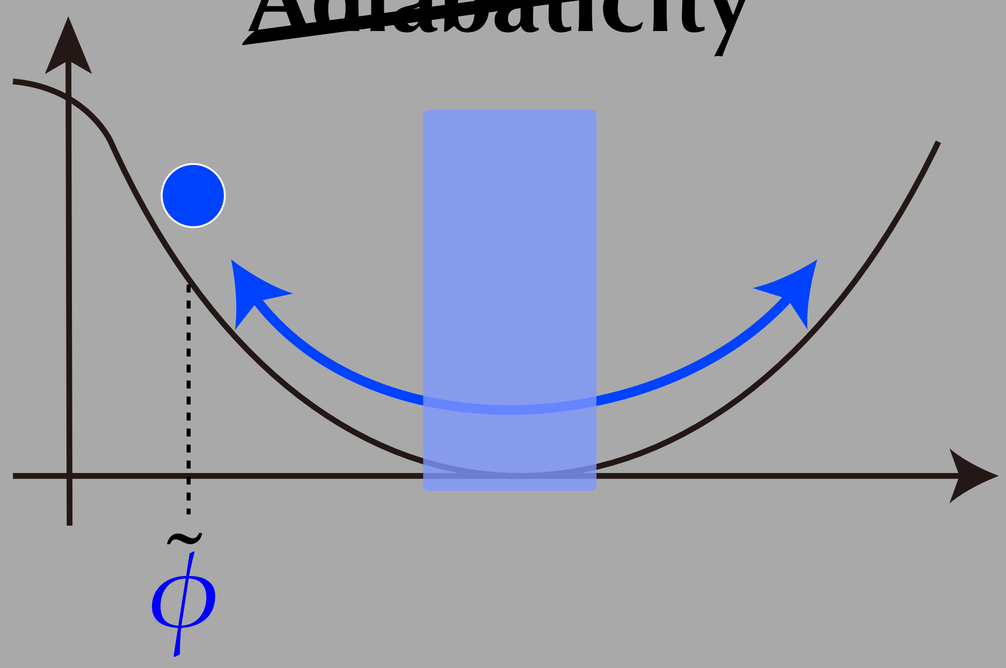
Non-Thermal Dissipation

- The non-perturbative particle production occurs if

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

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

~~Adiabaticity~~



$$\dot{\omega}_\chi/\omega_\chi{}^2 \gg 1$$

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

$\sim g^2T^2$

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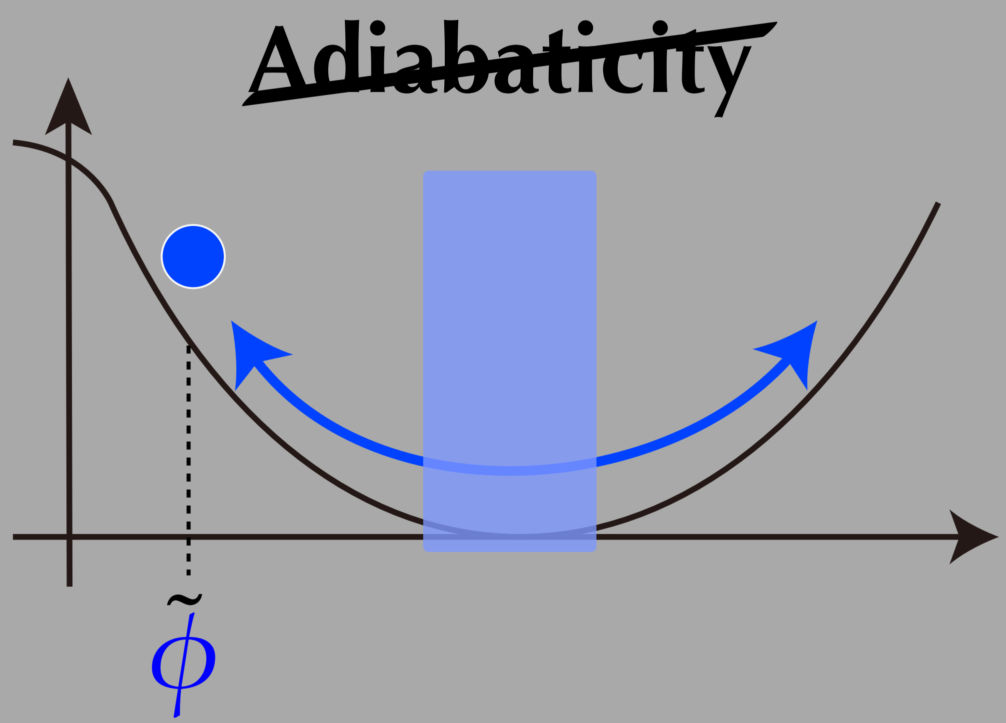

- If the produced χ is not stable...

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

- χ can decay completely before ϕ moves back if

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- Effective dissipation of ϕ: $\Gamma_\phi \sim N_{\rm d.o.f.}\dfrac{\lambda^2 m_\phi}{2\pi^4|\kappa|}.$

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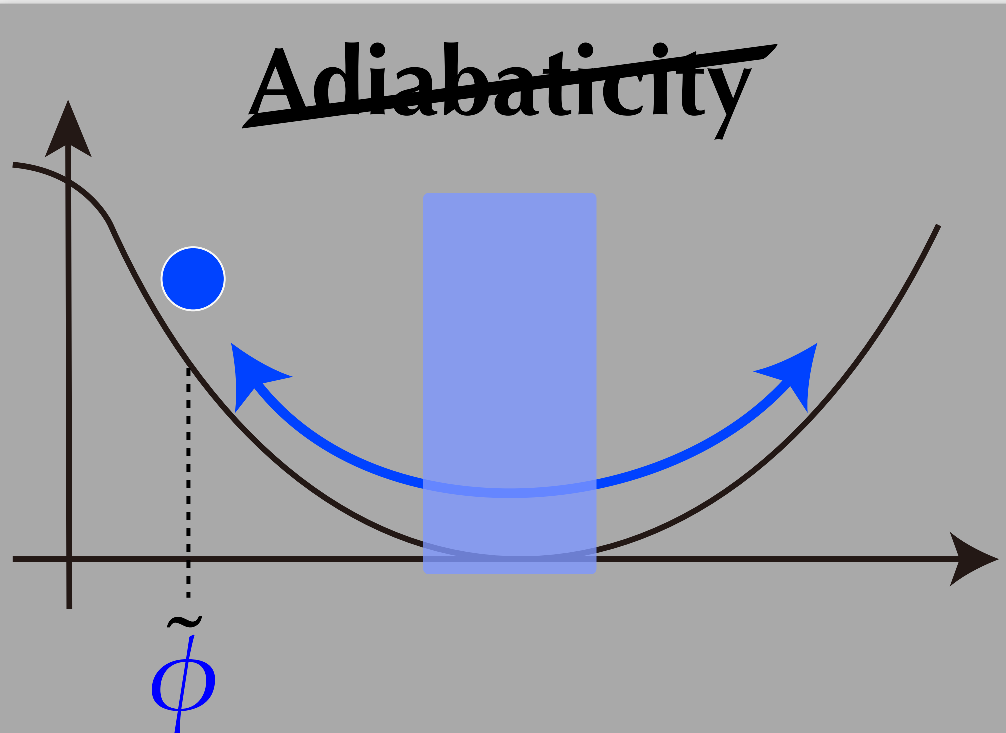
preheating ends!



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

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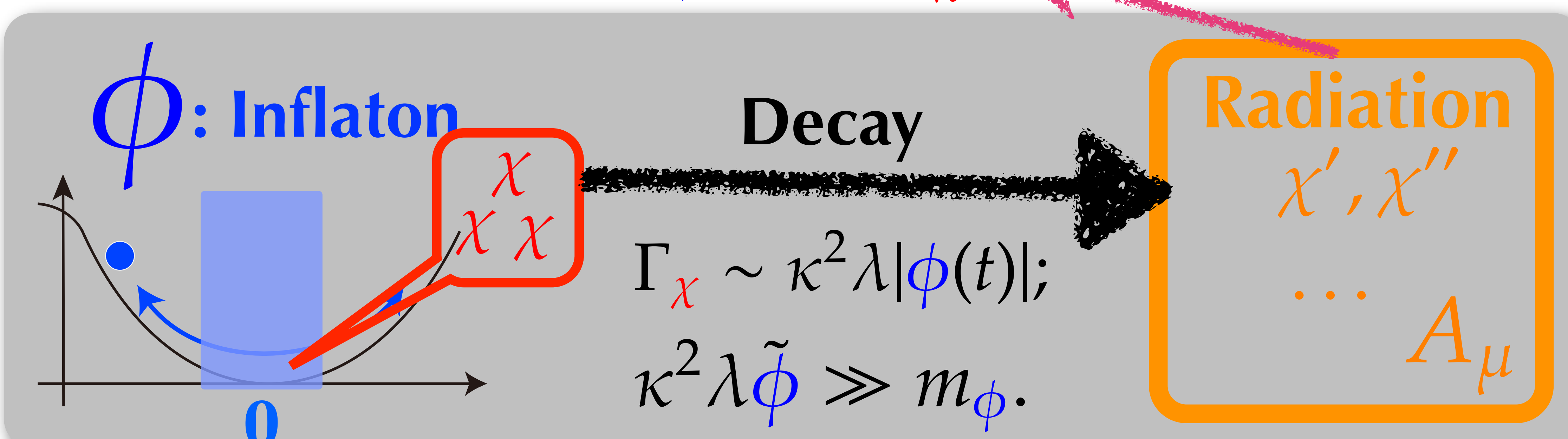
High T plasma; $m_\phi \lll T$ is produced and the preheating ends: $[\lambda\tilde{\phi}m_\phi]^{1/2} \sim m_\chi^{\rm th}$.



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Thermal Dissipation

Time

Thermal Dissipation

Thermal Dissipation

■ Thermal Dissipation (due to abundant particles):

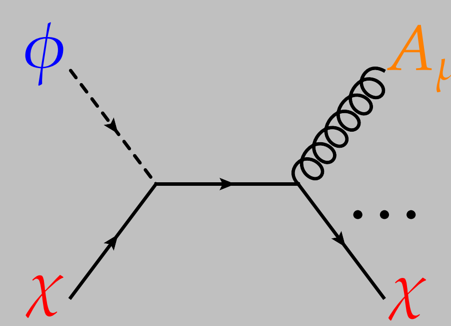
e.g.,[Hosoya, Sakagami; Yokoyama; Drewes; Berara et al.]

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

Friction coefficient from Kubo-formula: $\Gamma_\phi \simeq -\lim_{\omega \to m_\phi} \frac{\Im \Pi_{\rm ret}(\omega, \mathbf{0})}{\omega}.$

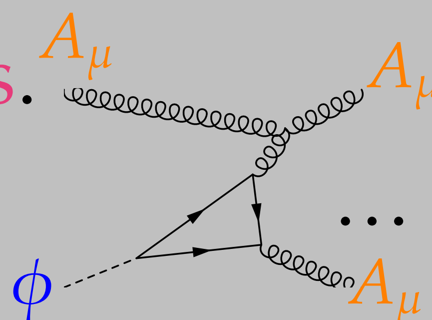
▸Small Φ: $\lambda\phi \ll T$ ➡ scatterings including χ.

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



▸Large Φ: $\lambda\phi \gg T$ ➡ scatterings by gauge bosons.

$$\Gamma_\phi \sim \alpha^2 \frac{T^3}{\phi^2}$$



[D. Bodeker; M. Laine]

Main Message

[KM, K. Nakayama]

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

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Thermal Dissipation

T_R

Time

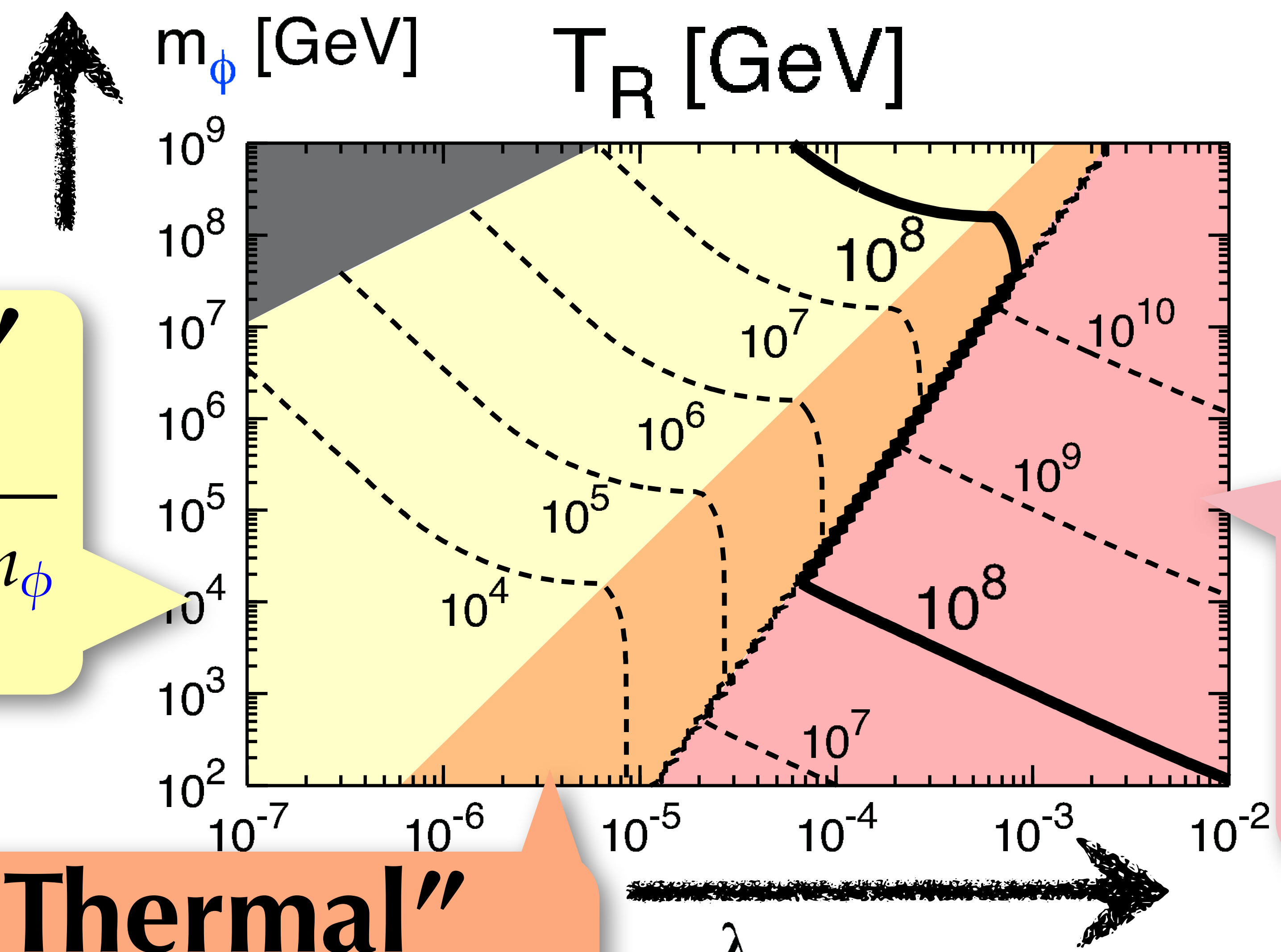
Reheating by

Thermal Dissipation!?

Numerical Results

Numerical Results

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



"Decay"

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

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Coupling btw Φ & radiation

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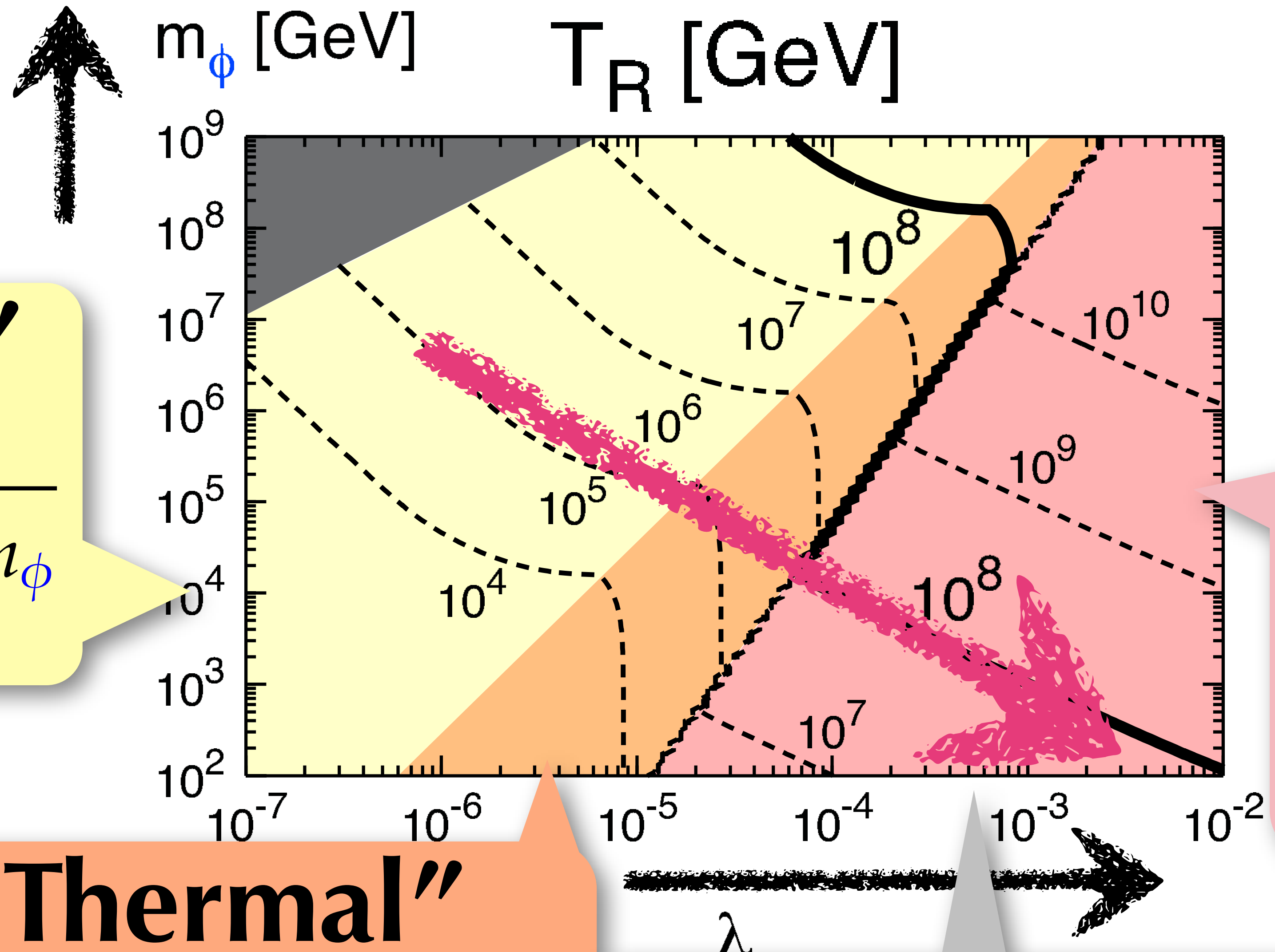

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"Thermal"

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

Summary

- The dynamics of reheating can be changed dramatically by non-thermal/thermal effects.
- Most prominent for an inflaton w/ a **small** mass and a relatively large coupling to radiation.

  e.g., Higgs inflation and its variants;
  Dark Matter inflation;
  Inflation w/ SUSY flat direction (MSSM inflation);

- Other examples where thermal effects may play important roles: saxion, curvaton, Affleck-Dine...

[T. Moroi, KM, K. Nakayama and T. Takimoto; 1304.6597]
[KM, K. Nakayama and T. Takimoto; 1308.4394]

Back Up

Numerical Results

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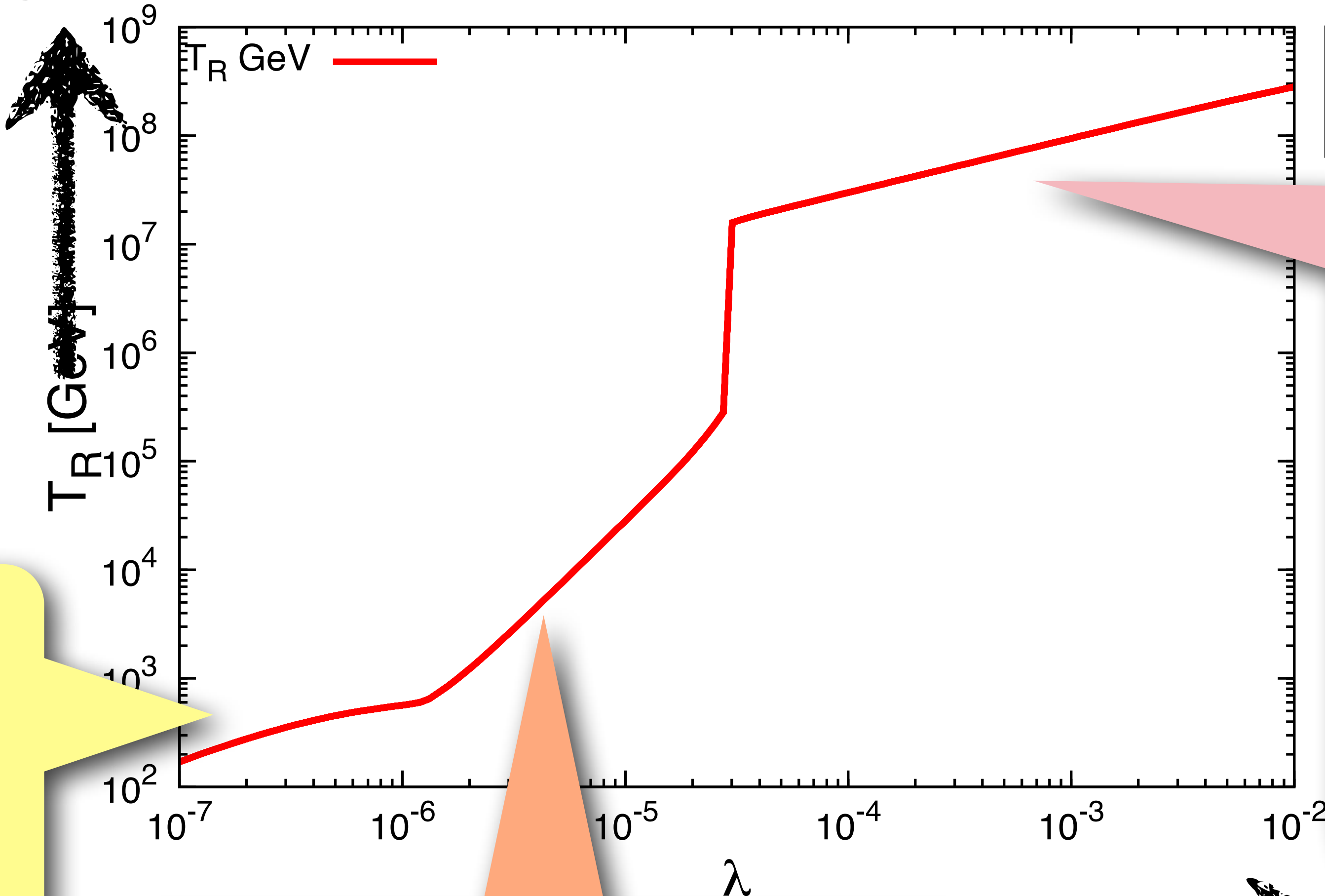
- Reheating temperature T_R as a function of λ.

T_R [GeV]



λ

$m_\phi = 1$ TeV

"Decay"

reheating via

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

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

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$\Gamma_\phi^{\rm eff} \sim \lambda^2 \alpha T \quad T_R \propto \lambda^2 M_{\rm pl}$

"Thermal"

reheating via

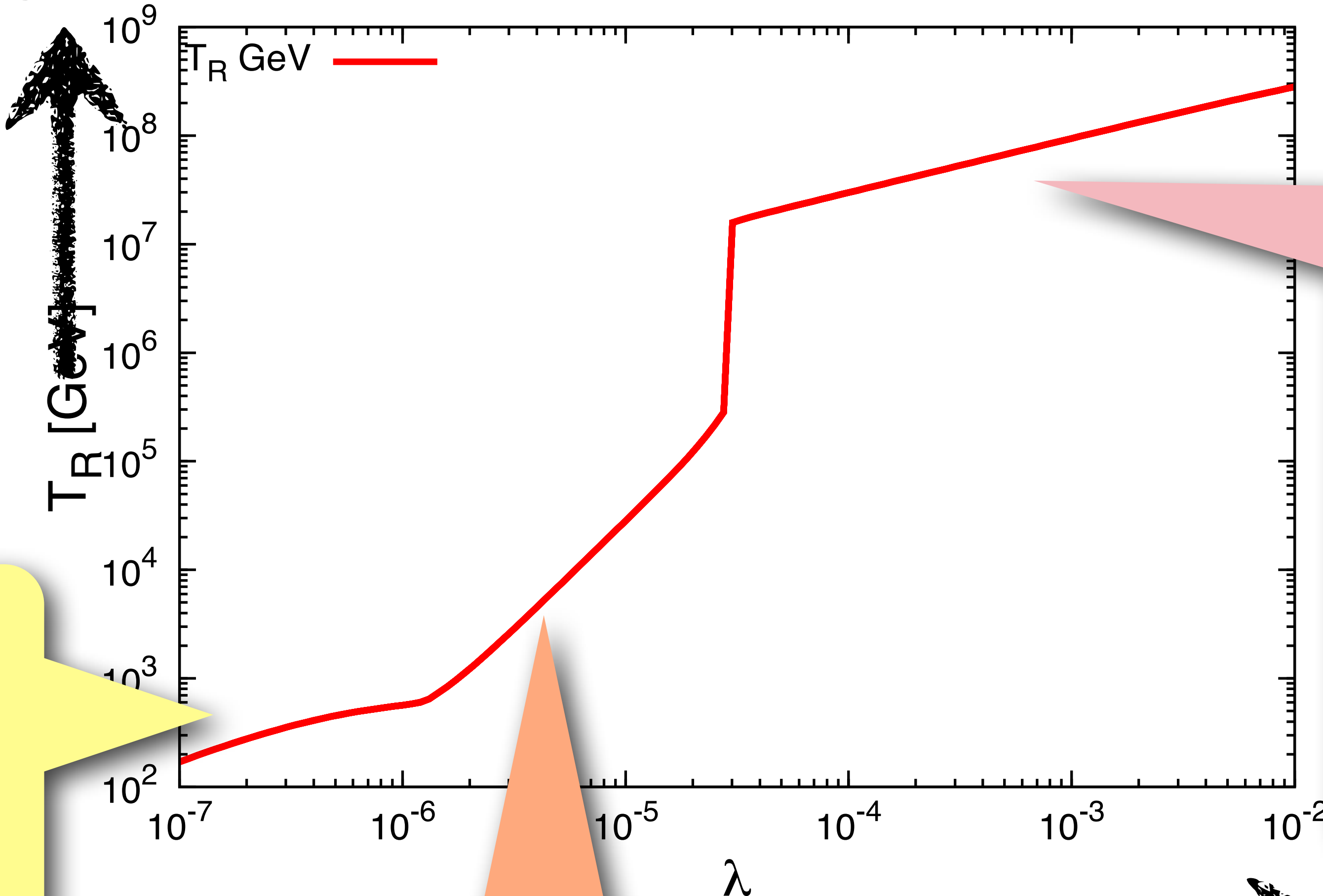
$\Gamma_\phi^{\rm eff} \sim \frac{\lambda}{\alpha}\frac{T^2}{\tilde{\phi}}$

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

- T_R can be much higher than m_ϕ.

■ Reheating temperature T_R as a function of λ.

T_R [GeV]



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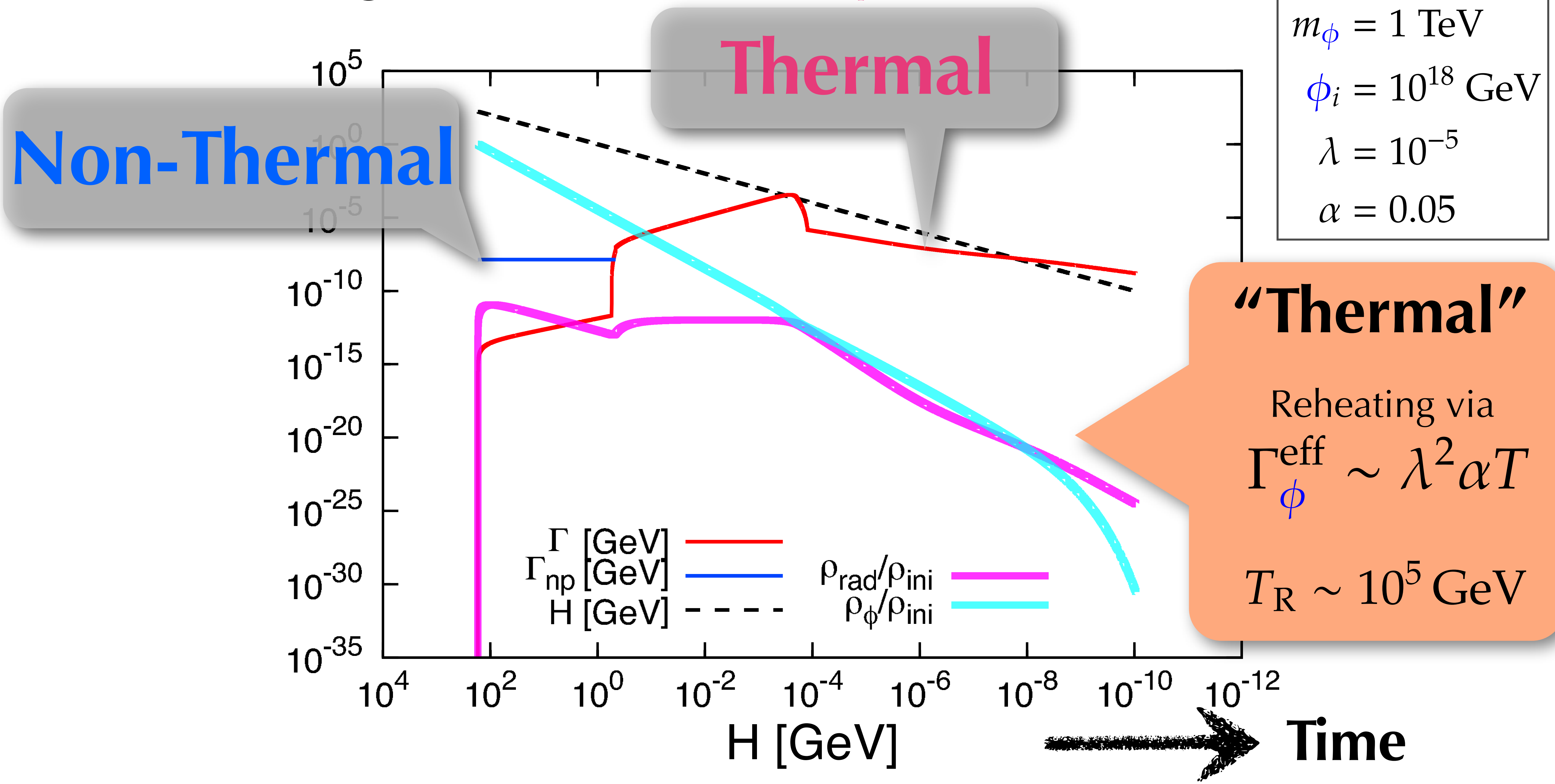
Numerical Results

- Reheating via thermal dissipation.

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



Numerical Results

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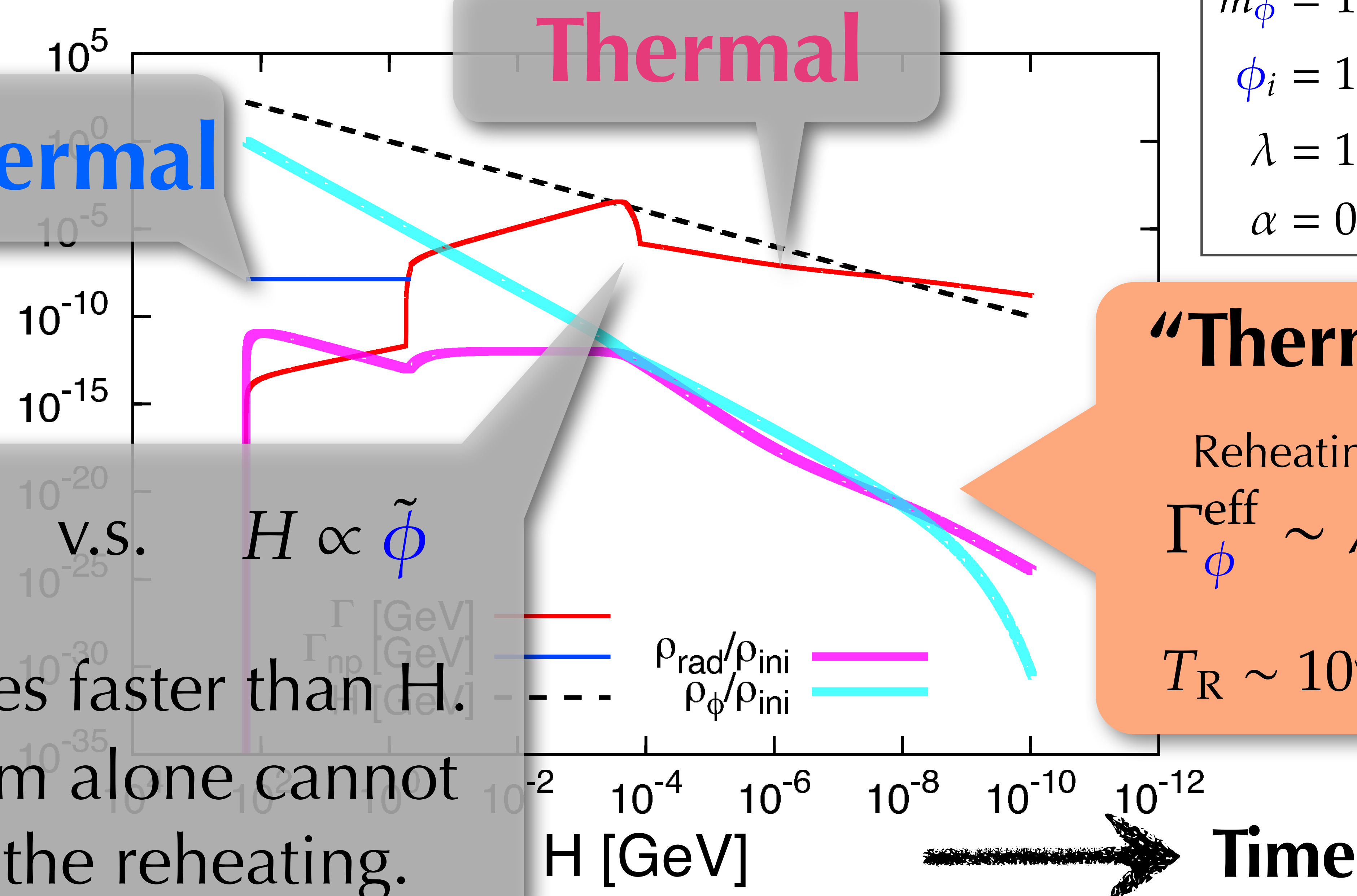

$m_\phi = 1$ TeV

$\phi_i = 10^{18}$ GeV

$\lambda = 10^{-5}$

$\alpha = 0.05$

$\Gamma_\phi^{\rm eff} \propto \tilde{\phi}^2$ v.s. $H \propto \tilde{\phi}$

Γ decreases faster than H.

→This term alone cannot complete the reheating.

"Thermal"

Reheating via

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

$T_R \sim 10^5$ GeV

Preheating

Non-Thermal Dissipation

- For $\kappa^2 \lambda \tilde{\phi} \ll m_\phi$ (or stable χ); the parametric resonance may occur while

$$k_*^2 \gtrsim m_{\mathrm{scr},\chi}^2 \sim g^2 \frac{n_\chi}{k_*}.$$

$$\lambda \tilde{\phi} \gg \max\left[m_\phi, \frac{m_{\mathrm{scr},\chi}^2}{m_\phi} \right]$$

where $k_* = \sqrt{\lambda m_\phi \tilde{\phi}}$.

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$$k_*^2 \gtrsim m_{\mathrm{scr},\chi}^2 \sim g^2 \frac{n_\chi}{k_*}.$$

- Around that time, the bottleneck process of the energy loss of scalar is the annihilation of χ:

$$\dot{\rho}_\phi + \bar{\Gamma}_\phi^{(\chi-\mathrm{ann})} \rho_\phi = 0;$$

where the oscillation time averaged Γ is defined as

$$\bar{\Gamma}_\phi^{(\chi-\mathrm{ann})} \rho_\phi = \overline{m_{\mathrm{eff},\chi} \langle \sigma_{\mathrm{ann}} |v| \rangle n_\chi^2} + \cdots .$$

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

Non-Thermal Dissipation

- Non-perturbative particle production occurs:

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

- The evolution crucially depends on χ's property:

  ‣ For $\kappa^2\lambda\tilde{\phi} \gg m_\phi$; the energy loss of scalar → the decay of χ, and this process ends at $k_* \sim m_\chi^{\rm th}(T)$.

  ‣ For $\kappa^2\lambda\tilde{\phi} \ll m_\phi$; the parametric resonance may occur and the energy loss of scalar → χ's annihilation.

Bulk Viscosity

Bulk Viscosity

- The dissipation rate at large Φ is directly related to the bulk viscosity of Yang-Mills plasma.

$$\Gamma_\phi = -\lim_{\omega\to 0} \frac{\Im \Pi_{\rm ret}(\omega, \mathbf{0})}{\omega}$$

$$= \lim_{\omega\to 0} \frac{1}{2\omega} \int d^4x\, e^{-i\omega t} \langle [\hat{O}(t,\mathbf{x}), \hat{O}(0)] \rangle; \ \hat{O}(x) = \frac{A}{8\pi^2\phi} F^{a\mu\nu}(x) F^a_{\mu\nu}(x)$$

[D. Bodeker; M. Laine]

Bulk Viscosity: $\zeta = \frac{1}{9} \int d^4x\, e^{-i\omega t} \langle [T^\mu{}_\mu(t,\mathbf{x}), T^\nu{}_\nu(0,\mathbf{0})] \rangle$

$\zeta \sim \frac{\alpha^2 T^3}{\ln[1/\alpha]}$; @ weak coupling

[Arnold, Dogan, Moore; hep-ph/0608012]