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

How does the **reheating** proceed?

"Standard" picture of **reheating**:

\[ V_\phi \quad \phi \]

Inflaton
Introduction

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

- How does the **reheating** proceed?

  ▶️ "Standard" picture of **reheating**:
Introduction

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

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

“Standard” picture of reheating:

\[ V_\phi \]

\[ \phi \]

Inflaton

\[ @ H \sim \Gamma^{(\text{pert.})}_\phi \sim \lambda^2 m_\phi \]

Decay

\[ \lambda \phi \tilde{\chi} \chi \]

\[ \tilde{\chi} \to \chi', \chi'' \]

\[ A_\mu \]

Thermal Plasma
Introduction

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

Reheating temperature: \( T_R \sim \left( \frac{90}{\pi^2 g_*} \right)^{1/4} \sqrt{M_{pl}} \)

However...

This Simple Picture does NOT ALWAYS hold!
Introduction

- Missing Two effects (at least):
Missing Two effects (at least):

Before going into details, let us clarify our setup:

\[ \mathcal{L}_{\text{kin}} - \frac{1}{2} m_\phi^2 \phi^2 + \lambda \phi (\bar{\chi}_L \chi_R + \text{h.c.}) + \mathcal{L}_{\text{other}} \]
Introduction

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

\[
\mathcal{L}_{\text{kin}} - \frac{1}{2} m^2 \phi^2 + \lambda \phi (\bar{\chi} \chi + \text{h.c.}) + \mathcal{L}_{\text{other}}
\]

![Diagram of Real Scalar and Gauge Interaction]

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

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

\[
\mathcal{L}_{\text{kin}} \equiv \frac{1}{2} m_\phi^2 \phi^2 + \lambda \phi (\bar{\chi}_L \chi_R + \text{h.c.}) + \mathcal{L}_{\text{other}}
\]

\[
\lambda \phi \bar{\chi} \chi; (\lambda^2 \phi^2 |\tilde{\chi}|^2)
\]
Missing Two effects (at least):

Before going into details, let us clarify our setup:

\[ \mathcal{L}_{\text{kin}} - \frac{1}{2} m^2 \phi^2 + \lambda \phi (\bar{\chi}_L \chi_R + \text{h.c.}) + \mathcal{L}_{\text{other}} \]
Introduction

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

\[
\mathcal{L}_{\text{kin}} - \frac{1}{2} m^2_{\phi} \phi^2 + \lambda \phi (\bar{\chi} L \chi_R + \text{h.c.}) + \mathcal{L}_{\text{other}}
\]

- Real Scalar

\[\phi\]

- Interaction

\[\lambda \phi \bar{\chi} \chi; (\lambda^2 \phi^2 |\tilde{\chi}|^2)\]
Introduction

- Missing Two effects (at least):
  > What if $M_{\text{eff}, \chi} \gg m_\phi$ ??

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

- Real Scalar
- Interaction

- Thermal Plasma $\chi', \chi''$
- Gauge int. $A_\mu$
Introduction

- Missing Two effects (at least):
  - What if $M_{\text{eff},\chi} \gg m_\phi$ ??
    
    $$m_{\text{eff},\chi}^2 = \lambda^2 \phi(t)^2 + m_\chi^{\text{th}}(T)^2 \sim g^2 T^2$$

1. If $m_{\text{eff},\chi} \sim \lambda \tilde{\phi} \gg m_\phi$
   - Non-perturbative particle production (Preheating)
     e.g., [L. Kofman, A. Linde, A. Starobinsky]

2. If $m_{\text{eff},\chi} \sim m_\chi^{\text{th}} \gg m_\phi$
   - Thermal dissipation into radiation (via Scatterings)
     e.g., [J. Yokoyama; M. Drewes; A. Berera et al.]
Introduction

- **Missing Two effects (at least):**
  - What if \( m_{\text{eff, } \chi} \gg m_\phi \)?

\[
m_{\text{eff, } \chi}^2 = \lambda^2 \phi(t)^2 + m_{\chi}^{\text{th}}(T)^2 \sim g^2 T^2
\]

1. If \( m_{\text{eff, } \chi} \sim \lambda \tilde{\phi} \gg m_\phi \)
   - Non-perturbative particle production (Preheating)
     e.g., [L. Kofman, A. Linde, A. Starobinsky]

2. If \( m_{\text{eff, } \chi} \sim m_{\chi}^{\text{th}} \gg m_\phi \)
   - Thermal dissipation into radiation (via Scatterings)
     e.g., [J. Yokoyama; M. Drewes; A. Berera et al.]
Introduction

- **Missing Two** effects (at least):
  - What if $m_{\text{eff},\chi} \gg m_\phi$ ??

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

1. **If** $m_{\text{eff},\chi} \sim \lambda \tilde{\phi} \gg m_\phi$
   - Non-perturbative particle production (**Preheating**)
     - e.g., [L. Kofman, A. Linde, A. Starobinsky]

2. **If** $m_{\text{eff},\chi} \sim m_{\chi}^{\text{th}} \gg m_\phi$
   - Thermal dissipation into radiation (**Scatterings**)
     - e.g., [J. Yokoyama; M. Drewes; A. Berera et al.]
Main Message

Possible sketch of reheating after inflation \( w/m_{\phi} \ll \lambda \phi_i \).

End of inflation. \( (m_{\phi} \ll \lambda \phi_i) \)

Preheating

High T plasma; \( m_{\phi} \ll T \) is produced and the preheating terminates: \( k_* \sim m^{th}_\chi \).

Dissipation (Scat.) into high T plasma

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

\[ \Phi \]'s amplitude:

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

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

\[ \omega_\chi = \sqrt{k^2 + m^{\text{th}}(T)^2 + \lambda^2 \phi^2(t)} \approx g^2 T^2 \]
Non-pert. Production

- The non-perturbative particle production occurs if

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

\[ \tilde{\phi} \]

\[ \lambda \phi \]

\[ \chi \]

\[ \omega_{\chi} = \sqrt{k^2 + m_{\chi}^\text{th}(T)^2 + \lambda^2 \phi^2(t)} \sim g^2 T^2 \]
The non-perturbative particle production occurs if

\[ \Phi 's \text{ amplitude: } \tilde{\phi} \]

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

Implies that the non-pert. production is “blocked” if

\[ m_{\chi}^\text{th}(T) \sim k_* = \sqrt{\lambda m_{\phi} \tilde{\phi}}. \]

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

[KM, K. Nakayama; K. Enqvist, D. Figueroa, R. Lerner]
Non-pert. Production

- If $\chi$ is not stable, then...

- Non-perturbatively produced $\chi$ can decay within each crossings of $\Phi \sim 0$.

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

- $\chi$ decays completely before the $\Phi$ moves back to its origin if

$$\kappa^2 \lambda \phi \gg m_\phi.$$

- Parametric Resonance is absent in this case; even if $\chi$ is boson.

E.g., [J. Garcia-Bellido, D. Figueroa, J. Rubio]
Non-pert. Production

- If \( \chi \) is not stable, then...

- Non-perterbatively produced \( \chi \) can decay within each crossings of \( \Phi \sim 0 \).

\[
\Gamma_\chi \sim \kappa^2 m_\chi(\phi(t)) \sim \kappa^2 \lambda |\phi(t)|;
\]

\( \chi \) decays completely before the \( \Phi \) moves back to its origin if

\[
\kappa^2 \lambda \tilde{\phi} \gg m_\phi. \quad \Rightarrow \quad \Gamma_\phi \sim N_{\text{d.o.f.}} \frac{\lambda^2 m_\phi}{2\pi^4|\kappa|}.
\]

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

[KM, K. Nakayama]
Thermal Effects
Thermal Effects

Thermal Dissipation (Scattering):

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

Friction coefficient from Kubo-formula: \( \Gamma_\phi \approx \lim_{\omega \to 0} \frac{\Pi_f(\omega, 0)}{2\omega} \).

- Small \( \phi \): \( \lambda \phi \ll T \Rightarrow \) scatterings including \( \chi \).
  \[ \Gamma_\phi \sim \lambda^2 \alpha T \quad (\Gamma_\phi \sim \lambda^4 \phi^2 / (\alpha T)) \]

- Large \( \phi \): \( \lambda \phi \gg T \Rightarrow \) scatterings by gauge bosons.
  \[ \Gamma_\phi \sim \alpha^2 \frac{T^3}{\phi^2} \]

[D. Bodeker; M. Laine]
Thermal Effects

- For $m \Phi \ll g T$, the inflaton loses its energy by the **thermal dissipation** (multiple scattering); not by the perturbative decay!

- Small $\Phi$: $\lambda \Phi \ll T \Rightarrow$ scatterings including $\chi$.

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

- Large $\Phi$: $\lambda \Phi \gg T \Rightarrow$ scatterings by gauge bosons.

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

[D. Bodeker; M. Laine]
Reheating after Inflation

- Rough sketch of reheating after inflation with $m_\phi \ll \lambda \phi_i$. End of inflation. ($m_\phi \ll \lambda \phi_i$)
Reheating after Inflation

- Rough sketch of reheating after inflation w/ \( m_\phi \ll \lambda \phi_i \).

End of inflation. \( (m_\phi \ll \lambda \phi_i) \)

Preheating

\( \phi: \text{Inflaton} \)

\( \chi, \chi' \)

\( \text{Radiation} \)

\( \chi', \chi'' \)

\( \cdots \)

\( A_\mu \)
Reheating after Inflation

- Rough sketch of reheating after inflation with $m_\phi \ll \lambda \phi_i$.

End of inflation. ($m_\phi \ll \lambda \phi_i$)

**Preheating**

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

- **$\phi$: Inflaton**
- **Interaction**
- **Radiation $\chi', \chi''$**
- $A_\mu$
Reheating after Inflation

- Rough sketch of reheating after inflation with $m_\phi \ll \lambda \phi_i$.

  End of inflation. ($m_\phi \ll \lambda \phi_i$)

Preheating

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

$\phi$: Inflaton

Interaction

Dissipation!

Radiation $\chi', \chi''$

$A_\mu$
Reheating after Inflation

- Rough sketch of reheating after inflation with $m_\phi \ll \lambda \phi_i$.

End of inflation. ($m_\phi \ll \lambda \phi_i$)

Preheating

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

Dissipation (Scat.) into high $T$ plasma

Reheating can be completed by Thermal Dissipation!
Numerical Results
Numerical Results

- **Reheating via thermal dissipation.**

![Graph]

- **Preheating**

- **Dissipation**

- **“Dissipation”**

- **Reheating via**

\[ \Gamma_{\text{eff}} \sim \lambda^2 \alpha T \]

\[ T_R \sim 10^5 \text{ GeV} \]

- **Parameters**

\[ m_\phi = 1 \text{ TeV} \]
\[ \phi_i = 10^{18} \text{ GeV} \]
\[ \lambda = 10^{-5} \]
\[ \alpha = 0.05 \]
Numerical Results

Contour plot of $T_R$ as a function of $\lambda$ and $m_{\Phi}$.

- **"Standard"**
  
  $T_R \propto \sqrt{\lambda^2 M_{pl} m_{\Phi}}$

- **"Dissipation"**
  
  $T_R \propto \sqrt{\lambda M_{pl} m_{\Phi}}$

  Coupling btw $\Phi$ & radiation

$\phi_i = 10^{18}$ GeV

$\alpha = 0.05$
Numerical Results

- Contour plot of $T_R$ as a function of $\lambda$ and $m\Phi$.

"Standard"

$T_R \propto \sqrt{\lambda^2 M_{pl} m\Phi}$

"Dissipation"

$T_R \propto \sqrt{\lambda M_{pl} m\Phi}$

$\phi_i = 10^{18}$ GeV

$\alpha = 0.05$

Thermal Dissipation dominates the reheating for small $m\Phi$ and not small $\lambda$. 
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]