Dissipative Effects on Reheating after Inflation

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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
Introduction

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

- How does the reheating proceed?

▷ “Standard” picture:

\[ V_\phi \]

\[ \phi \]

\[ \text{Inflaton} \]
Introduction

- After the inflation, the inflaton should convert its energy to radiation: Reheating.
- How does the reheating proceed?

“Standard” picture:

\[ V_\phi \]

[Diagram showing inflation, decay, and radiation processes]
Introduction

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

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

- "Standard" picture:

\[ V_\phi \]

\[ \phi \]

Inflaton

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

Decay

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

Radiation

\[ \chi, \chi' , \chi'' \]

\[ A_\mu \]
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
- ...

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

“Standard” picture:

\[ V_\phi \]

\[ \phi \]

Inflaton

Decay

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

Radiation

\[ \chi, \chi', \chi'' \]

\[ \tilde{\chi} \]

\[ A_\mu \]

@ \( H \sim \Gamma^{(\text{pert})}_\phi \)
Introduction

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

- Reheating temperature: $T_R \sim \left[ \frac{90}{\pi^2 \varphi} \right]^{1/4}$

However...

This Simple Picture does NOT ALWAYS hold!

energy to \textit{radiation}: \textit{Reheating}.

$V_\phi$ \quad Inflaton

$\phi$ \quad $0$

$\lambda \phi \bar{\chi} \chi$

Radiation $\chi, \chi', \chi''$

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Outline

- Introduction
- Non-Thermal/Thermal Dissipation
- Numerical Results
Dissipation
Missing Two effects:

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

Real Scalar

Interaction

Radiation

\[ \chi', \chi'' \]

Gauge int.

A_\mu
Missing Two effects:

Before going into details, let us clarify our setup:

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

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

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

- Real Scalar
- Interaction
- Radiation
- \( \chi', \chi'' \)
- Gauge int. \( A_\mu \)
Missing **Two** effects:

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Missing **Two** effects:

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\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}}
\]

\(\phi\) Real Scalar

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

Interaction

Radiation

Gauge int.

\(\chi', \chi''\)
Missing Two effects:

Before going into details, let us clarify our setup:

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

- Missing **Two** effects:

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

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

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

- Real Scalar

- Interaction

- Radiation

- $\chi, \tilde{\chi}$

- Gauge int. $A_\mu$
Missing Two effects:

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

2. If \( m_{\text{eff}, \chi} \sim m_{\chi} \gg m_\phi \)
   - Scatterings by abundant thermal particles (Thermal)
     e.g., [J. Yokoyama; M. Drewes; A. Berera, Mar Bastero-gil, R. Ramos, J. Rosa]
Dissipation

- Missing Two effects:
  - 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-perturb. particle production (Non-Thermal)
     - e.g., [L. Kofman, A. Linde, A. Starobinsky]

2. If $m_{\text{eff},\chi} \sim m_\chi^{\text{th}} \gg m_\phi$
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Rough sketch of reheating after inflation w/ $m_\phi \ll \lambda \phi_i$. End of inflation. ($m_\phi \ll \lambda \phi_i$)
Reheating After Inflation

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

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

  **Non-Thermal Dissipation (Preheating)**
Non-Thermal Dissipation (Preheating)
Non-Thermal Dissipation

The non-perturbative particle production occurs if

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

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

Adiabaticity

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

\[ \omega_\chi = \sqrt{k^2 + m_{\text{th}}(T)^2 + \lambda^2 \phi^2(t)} \sim g^2 T^2 \]
Non-Thermal Dissipation

The non-perturbative particle production occurs if

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

- If the produced $\chi$ is not stable...
  $$\Gamma_\chi \sim \kappa^2 m^2_{\text{eff,}\chi} \sim \kappa^2 \lambda |\phi(t)|$$
  - $\chi$ can decay completely before $\Phi$ moves back if
    $$\kappa^2 \lambda \tilde{\phi} \gg m_\phi.$$  
- Effective dissipation of $\Phi$:  
  $$\Gamma_\phi \sim N_{\text{d.o.f.}} \frac{\lambda^2 m_\phi}{2\pi^4 |\kappa|}.$$
Non-Thermal Dissipation

- The non-perturbative particle production occurs if

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

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

Adiabaticity

- If the produced \( \chi \) is not stable...

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- \( \chi \) can decay completely before \( \Phi \) moves back if

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

- Effective dissipation of \( \Phi \): \( \Gamma_\phi \sim N_{\text{d.o.f.}} \frac{\lambda^2 m_\phi}{2\pi^4 |\kappa|} \).
Reheating After Inflation

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

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

Non-Thermal Dissipation (Preheating)

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

$\phi$: Inflaton

Decay

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

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

Radiation $\chi', \chi''$, ...

$A_\mu$
Reheating After Inflation

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

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

Non-Thermal Dissipation (Preheating)

High \( T \) plasma; \( m_\phi \ll T \) is produced and the preheating ends: \([\lambda \tilde{\phi} m_\phi]^{1/2} \sim m^\text{th}_\chi\).

Thermal Dissipation
Thermal Dissipation
Thermal Dissipation

Thermal Dissipation (due to abundant particles):

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

Friction coefficient from Kubo-formula:

\[ \Gamma_{\phi} \approx -\lim_{\omega \to m_{\phi}} \frac{\Im \Pi_{\text{ret}}(\omega, 0)}{\omega} \]

- 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]
Main Message

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

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

Non-Thermal Dissipation (Preheating)

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

Thermal Dissipation

Reheating by Thermal Dissipation!?
Numerical Results
Numerical Results

- Contour plot of $T_R$ as a function of $\lambda$ and $m_\phi$.

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

"Decay"

$\phi_i = 10^{18}$ GeV
$\alpha = 0.05$

"Thermal"

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

Coupling btw $\Phi$ & radiation
Numerical Results

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

\[ T_R \propto \sqrt{\lambda^2 M_{pl} m_\Phi} \]

\[ T_R \propto \sqrt{\lambda M_{pl} m_\Phi} \]

$\phi_i = 10^{18}$ GeV
$\alpha = 0.05$

"Decay"

"Thermal"

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

\[ \frac{T_R}{q} \sim \frac{m_\Phi}{M_{pl}} \]

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Summary

- The dynamics of reheating can be changed dramatically by non-thermal/thermal effects.

- Most prominent for an inflaton with a small mass and a relatively large coupling to radiation.
  
  e.g., Higgs inflation and its variants;
  Dark Matter inflation;
  Inflation with 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
Numerical Results

- Reheating temperature $T_R$ as a function of $\lambda$.

$$T_R \ [\text{GeV}]$$

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$m_\phi = 1 \text{ TeV}$

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“Decay”

reheating via

$\Gamma^\text{eff}_\phi \sim \lambda^2 m_\phi$

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

“Thermal”

reheating via

$\Gamma^\text{eff}_\phi \sim \frac{\lambda T^2}{\alpha \tilde{\phi}}$

$T_R \propto \sqrt{\lambda M_{\text{pl}} m_\phi}$
• $T_R$ can be much higher than $m_\phi$.

- Reheating temperature $T_R$ as a function of $\lambda$.

$T_R \ [\text{GeV}]$

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“Decay”

reheating via

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

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

“Thermal”

reheating via

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

$T_R \propto \sqrt{\lambda M_{\text{pl}} m_\phi}$
Numerical Results

- Reheating via \textit{thermal} dissipation.

\begin{align*}
    m_\phi &= 1 \text{ TeV} \\
    \phi_i &= 10^{18} \text{ GeV} \\
    \lambda &= 10^{-5} \\
    \alpha &= 0.05
\end{align*}

\begin{align*}
    \text{“Thermal”} \\
    \Gamma_{\phi}^{\text{eff}} &\sim \lambda^2 \alpha T \\
    T_R &\sim 10^5 \text{ GeV}
\end{align*}
Numerical Results

- Reheating via thermal dissipation.

\[ \Gamma^\text{eff}_\phi \propto \tilde{\phi}^2 \quad \text{v.s.} \quad H \propto \tilde{\phi} \]

\( \Gamma \) decreases faster than \( H \).
\( \rightarrow \) This term alone cannot complete the reheating.

- "Thermal"
  
  Reheating via
  
  \[ \Gamma^\text{eff}_\phi \sim \lambda^2 \alpha T \]

\( T_R \sim 10^5 \text{ GeV} \)

\( m_\phi = 1 \text{ TeV} \)
\( \phi_i = 10^{18} \text{ GeV} \)
\( \lambda = 10^{-5} \)
\( \alpha = 0.05 \)
Preheating
Non-Thermal Dissipation

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

\[ k_*^2 \geq m_{\text{scr,}\chi}^2 \sim g^2 \frac{n_\chi}{k_*}. \]

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

where $k_* = \sqrt{\lambda m_\phi \tilde{\phi}}$. 
**Non-Thermal Dissipation**

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

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

- Around that time, the bottleneck process of the energy loss of scalar is the annihilation of $\chi$:

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

where the oscillation time averaged $\bar{\Gamma}$ is defined as

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

[T. Moroi, KM, K. Nakayama and T. Takimoto]
Non-Thermal Dissipation

Non-perturbative particle production occurs:

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

The evolution crucially depends on $\chi$’s property:

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

- For $\kappa^2 \lambda \tilde{\phi} \ll m_\phi$; the parametric resonance may occur and the energy loss of scalar $\rightarrow$ $\chi$’s annihilation.
Bulk Viscosity
Bulk Viscosity

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

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

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

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

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

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