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:
Introduction

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

- How does the **reheating** proceed?

▷ “Standard” picture:

\[ V_\phi \]

\[ \phi \]

**Inflaton**

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

Decay

\[ \chi \leftrightarrow \tilde{\chi} \]

\[ \cdots \]

\[ A_\mu \]

Radiation

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

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

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

- “Standard” picture:

$V_\phi$  

\[ \Phi \]  

Inflaton

\[ @ H \sim \Gamma_{\phi}^{(\text{pert.})} \]

Decay

\[ \lambda \phi \chi \chi \]

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
- ...

"Standard" picture:

\[ V_\phi \]

\[ \phi \]

Inflaton

\[ \lambda \phi \phi^* \]

\[ \phi \]

@ \( H \sim \Gamma_\phi^{(pert)} \)

Radiation

Decay

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

\[ \tilde{\chi} \]

\[ A_\mu \]

Reheating temperature:

\[ T_R \sim \left[ \frac{90}{\pi^2 g_*} \right]^{1/4} \sqrt{\frac{M_{pl}}{\Gamma_\phi^{(pert)}}} \]
\( T_R \) characterizes the thermal history of Universe:

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

**Reheating**

Reheating temperature: \( T_R \sim \left[ \frac{90}{\pi^2 \varphi} \right]^{1/4} \sqrt{M} \)

**However...**

This Simple Picture does NOT ALWAYS hold!
Outline

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

- Missing Two effects:

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

Real Scalar

Interaction

\[ \chi \leftarrow \rightarrow \tilde{\chi} \]

Radiation

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

Gauge int.

\[ A_\mu \]
Missing Two effects:

Before going into details, let us clarify our setup:

$$\mathcal{L}_{\text{kin}} - \frac{1}{2} m_\phi^2 \phi^2 + \lambda \phi (\bar{\chi}_L \chi_R + \text{h.c.}) + \mathcal{L}_{\text{other}}$$
Missing Two effects:

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**Dissipation**

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- Real Scalar
- **Interaction**
- **Radiation**
- **Gauge int.**
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Dissipation

■ **Missing Two** effects:

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

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

Radiation

Gauge int.

Real Scalar

Interaction

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

$\chi \leftrightarrow \tilde{\chi}$

$\chi', \chi''$

$A_\mu$
Dissipation

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

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**Dissipation**

- Missing **Two** effects:

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Reheating After Inflation

- Rough sketch of reheating after inflation w/ $m_\phi \ll \lambda \phi_i$.
  End of inflation. ($m_\phi \ll \lambda \phi_i$)
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)
The non-perturbative particle production occurs if

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

[\text{L. Kofman, A. Linde, A. Starobinsky}]

\[ \omega_x / \omega_x^2 \gg 1 \]

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

- The non-perturbative particle production occurs if

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

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

- 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

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

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

Adiabaticity

- If the produced $\chi$ is not stable...

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

- $\chi$ can decay completely before $\Phi$ moves back if

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

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

preheating ends!
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: $[\lambda \tilde{\phi} m_\phi]^{1/2} \sim m^{th}_\chi$.

$\phi$: 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 with $m_\phi \ll \lambda \phi_i$.

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

  \[ m_\phi \quad \sim \quad \frac{1}{2} m_{\text{th}}. \]

**Non-Thermal Dissipation (Preheating)**

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

**Thermal Dissipation**

Time
Thermal Dissipation
Thermal Dissipation

Thermal Dissipation (due to abundant particles):

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

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

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 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**

  Reheating by Thermal Dissipation!?
Numerical Results
Numerical Results

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

"Decay"

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

"Thermal"

$$T_R \propto \sqrt{\lambda M_{\text{pl}} m_\Phi}$$

Coupling btw $\Phi$ & radiation

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

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Numerical Results

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

\[ T_R \propto \sqrt{\lambda^2 M_{pl} m\phi} \]

- “Decay”

\[ \frac{T_R}{q^2 M_{pl}} m \]

- “Thermal”

\[ T_R \propto \sqrt{\lambda M_{pl} m\phi} \]

\[ \phi_i = 10^{18} \text{ GeV} \]
\[ \alpha = 0.05 \]

Thermal Dissipation dominates the reheating for small $m\phi$ and not small $\lambda$. 
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 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
Numerical Results

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

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

**"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
\[ \Gamma^\text{eff}_\phi \sim \frac{\lambda}{\alpha} \tilde{T}^2 \]
\[ T_R \propto \sqrt{\lambda M_{\text{pl}} m_\phi} \]

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

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• $T_R$ can be much higher than $m_\phi$.

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

$T_R [\text{GeV}]$  

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

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

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

"Decay" (Red line)

"Thermal" (Blue line)
Numerical Results

- Reheating via \textit{thermal} dissipation.

\begin{align*}
\text{``Thermal''} & \quad \Gamma_{\text{eff}} \sim \lambda^2 \alpha T \\
T_R & \sim 10^5 \text{ GeV}
\end{align*}

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

- Reheating via thermal dissipation.

Γ_{\phi}^{\text{eff}} \propto \tilde{\phi}^2 \quad \text{v.s.} \quad H \propto \tilde{\phi}

Γ decreases faster than H. → This term alone cannot complete the reheating.

T_R \sim 10^5 \text{ GeV}

m_\phi = 1 \text{ TeV}
φ_i = 10^{18} \text{ GeV}
\lambda = 10^{-5}
α = 0.05
Preheating
Non-Thermal Dissipation

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

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

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

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

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Non-Thermal Dissipation

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

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

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

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

where the oscillation time averaged $\Gamma$ is defined as

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

[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.

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

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

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

[D. Bodeker; M. Laine]

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