REHEATING THE UNIVERSE
(Some Theoretical Aspects)

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PHYSICAL CONTEXT: REHEATING

INFLATION $\rightarrow$ REHEATING $\rightarrow$ BIG BANG THEORY
PHYSICAL CONTEXT: REHEATING

INFLATION $\rightarrow$ REHEATING $\rightarrow$ BIG BANG THEORY

INITIAL CONDITIONS:
NO Particles, ONLY Vacuum Energy

FINAL CONDITIONS:
Thermal Equilibrium, $T_{RH}$

$\alpha \sim e^{Ht}$

$a \sim t^{q(t)}$

$a \sim t^{1/2}$
PHYSICAL CONTEXT: REHEATING

INFLATION $\rightarrow$ REHEATING $\rightarrow$ BIG BANG THEORY
PHYSICAL CONTEXT: REHEATING

INFLATION $\rightarrow$ REHEATING $\rightarrow$ BIG BANG THEORY

\[ \mathcal{L} = \mathcal{L}(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, \ldots) \]

\[ a \sim e^{Ht}, \quad a \sim t^{q(t)}, \quad a \sim t^{1/2} \]

THERMAL EQUILIBRIUM
SIMPLE EXAMPLES: SCALAR REHEATING

\[ V(\phi, \chi) = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} m^2 \chi^2 + \frac{1}{2} g^2 \phi^2 \chi^2 \] (Chaotic)

\[ V(\phi, \chi) = \frac{1}{2} \mu^2 \phi^2 + \frac{\lambda}{4} (\chi^2 - v^2)^2 + \frac{1}{2} g^2 \phi^2 \chi^2 \] (Hybrid)
SIMPLE EXAMPLES: SCALAR REHEATING

\[ V(\phi, \chi) = \frac{1}{4} \lambda \phi^4 + \frac{1}{2} m^2 \chi^2 + \frac{1}{2} g^2 \phi^2 \chi^2 \quad \text{(Chaotic)} \]

\[ V(\phi, \chi) = \frac{1}{2} \mu^2 \phi^2 + \frac{\lambda}{4} (\chi^2 - v^2)^2 + \frac{1}{2} g^2 \phi^2 \chi^2 \quad \text{(Hybrid)} \]

\[ \ddot{\phi}(t) + 3H \dot{\phi} + V'(\phi) = 0 \quad \text{(Inflaton Zero-Mode : Damped Oscillator)} \]

\[ \Box \phi_k + F(\int dq \phi_q \chi_{|k-q|}) \phi_k + ... = 0 \quad \text{(Inflaton Fluctuations)} \]

\[ \Box \chi_k + F(\int dq \chi_q, \phi_{|k-q|}) \chi_k + ... = 0 \quad \text{(Matter Fluctuations)} \]

**DYNAMICS:**

Non-Linear, Non-Perturbative & Far-From-Equilibrium

\[ k_i \pm \Delta k_i \rightarrow \varphi_k(t), n_k(t) \sim \exp\{\mu_k t\} \rightarrow \text{PREHEATING} \]
Traschen et al’90, Kofman et al’94,’97, Shtanov et al’95

\[ V(\phi, \chi) = V(\phi) + \frac{1}{2}m_{\chi}^2\chi^2 + \frac{1}{2}g^2\phi^2\chi^2 \quad (\text{Chaotic Models}) \]

\[ X''_k + [\kappa^2 + m^2(\phi)]X_k = 0 \quad (\text{Fluctuations of Matter}) \]
Reheating after Inflation: PARAM. RESONANCE

Traschen et al’90, Kofman et al’94,’97, Shtanov et al’95

\[
V(\phi, \chi) = V(\phi) + \frac{1}{2}m_\chi^2 \chi^2 + \frac{1}{2}g_\phi^2 \phi^2 \chi^2 \quad \text{(Chaotic Models)}
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X''_k + [\kappa^2 + m^2(\phi)]X_k = 0 \quad \text{(Fluctuations of Matter)}
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(p)Reheating after Inflation: PARAM. RESONANCE

Traschen et al’90, Kofman et al’94,’97, Shtanov et al’95

\[ V(\phi, \chi) = V(\phi) + \frac{1}{2} m_\chi^2 \chi^2 + \frac{1}{2} g^2 \phi^2 \chi^2 \]  
(Chaotic Models)

\[ X_k'' + [\kappa^2 + m^2(\phi)] X_k = 0 \]  
(Fluctuations of Matter)

\[ \text{ADIABATIC REGION} \quad \dot{m}(\phi) < m^2(\phi) \quad \text{V(\phi)} \quad \text{ADIABATIC REGION} \quad \dot{m}(\phi) < m^2(\phi) \]

\[ k_k \pm \Delta k \]
\[ n_k >> 1 \]
\[ \bullet \quad \bullet \quad \bullet \quad \bullet \]

\[ \phi \]
PROBING/IMPROVING REHEATING (2 APPROACHES)

1. Poor Understanding of RH:

   **ABSENCE**: SM, DM, Thermalization,…
   **DIFFICULTIES**: Many *dof*, Non-Linear, Non-Perturbative, Out-of-Eq.

2. Probing RH:

   - Phenomenological effects with observable consequences
   - Gravitational Waves Production
   - Non-Gaussianity in Matter Density Perturbations
   - Baryogenesis Mechanisms

3. Improving RH:

   - Embedding into Gauge Framework
   - Adding Fermions
   - Identify Fields with SM *dof* (and DM)
   - Study Thermalization
PROBING/IMPROVING REHEATING (2 APPROACHES)

1. Poor Understanding of RH:

   **ABSENCE**: SM, DM, Thermalization, ...
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2. Probing RH: \[
\text{Phenomenological effects with observable consequences}
\]

\[\begin{array}{c}
\text{Gravitational Waves Production} \\
\text{Non-Gaussianity in Matter Density Perturbations} \\
\text{Baryogenesis Mechanisms}
\end{array}\]

3. Improving RH:

\[
\begin{array}{c}
\text{Embedding into Gauge Framework} \\
\text{Adding Fermions} \\
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\end{array}
\]
PROBING/IMPROVING REHEATING (2 APPROACHES)

1. Poor Understanding of RH:
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   - Study Thermalization
Improving Reheating: Including the SM dof

REHEATING WITHIN THE STANDARD MODEL:

COMBINED REHEATING MECHANISM
Reheating after HIGSS-INFLATION

**SM + GR + NON-MINIMAL COUPLING:**

\[ S_{G+S} \equiv \int d^4x \sqrt{-g} \left\{ \frac{1}{2} M_P^2 R + \lambda \left( \Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 + \xi \Phi^\dagger \Phi R \right\} \]

- HILBERT-EINSTEIN
- SSB
- NON-Minimal
- CST

\[ \lambda \sim 0.1 \]

**MODEL**

- Good Candidate for Inflation (Bezrukov et al. 07)
- Extensive Discussion on Viability: Unitarity,… (Bezrukov et al., De Simone et al., Burgess et al., Lerner et al.,…)
- The price to pay: \[ \xi \sim 5 \times 10^4 \]

Here I will only focus on REHEATING, after inflation ends
(p)Reheating after HIGSS-INFLATION

SM + GR + NON-MINIMAL COUPLING:

- UNITARY GAUGE: $\Phi = h/\sqrt{2}$
- CONFORMAL TRANSFORMATION: $\tilde{g}_{\mu\nu} = \Omega^2(h)g_{\mu\nu}$
- HIGGS REDEFINITION: $h \longrightarrow \chi(h)$

\[
\int d^4x \sqrt{-g} \left[ \frac{m_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V(\chi) \right]
\]

EINSTEIN FRAME:

HIGGS POTENTIAL:

$V(\chi) = \frac{\lambda m_P^4}{4\xi^2} \left( 1 - e^{-\alpha \kappa \chi} \right)^2 \approx \frac{1}{2} M^2 \chi^2 + \Delta V$

$\sim M_{\text{GUT}}^4$

$10^{-5} M_p$
Reheating after HIGSS-INFLATION

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- **UNITARY GAUGE:** $\Phi = h/\sqrt{2}$
- **CONFORMAL TRANSFORMATION:** $\tilde{g}_{\mu\nu} = \Omega^2(h) g_{\mu\nu}$
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**EINSTEIN FRAME:**

$$\int d^4x \sqrt{-g} \left[ \frac{m_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V(\chi) \right]$$

**HIGGS POTENTIAL:**

$$V(\chi) = \frac{\lambda m_P^4}{4 \xi^2} \left(1 - e^{-\alpha \kappa \chi}\right)^2 \approx \frac{1}{2} M^2 \chi^2 + \Delta \chi$$

$\sim M_{\text{GUT}}^4$

$10^{-5} M_p$
Reheating the SM: Non-Perturbative Effects

**EINSTEIN FRAME: HIGGS POTENTIAL**

![Diagram of Higgs potential with inflation and mass gap](image)
Reheating the SM: **Non-Perturbative Effects**

\[
\cos^2 \theta_W \tilde{m}_W^2 = \tilde{m}_W^2 = \frac{g_2^2 m_P^2 (1 - e^{-\alpha \kappa \chi})}{4 \xi}
\]
Reheating the SM: Non-Perturbative Effects

\[ \cos^2 \theta_W \tilde{m}_Z^2 = \tilde{m}_W^2 = \frac{g_2^2 m_P^2 (1 - e^{-\alpha \kappa |\chi|})}{4 \xi} \]

\[ V(\chi) \]

\[ \Delta \chi \]

INFLATION
Reheating the SM: Non-Perturbative Effects

NON-ADIABATICITY: \[ |\Delta \chi| \ll 10^{-2} X(j) \]
Reheating the SM: Non-Perturbative Effects

PARAMETRIC RESONANCE

$V(\chi)$

$\Delta \chi$

INFLATION

$\chi$
Reheating the SM: Non-Perturbative Effects
Reheating the SM: **Perturbative Effects**

\[
\Gamma_{W^\pm}^E = \frac{3 \cos^3 \theta_W}{2 \text{Lips}} \quad \Gamma_Z^E = \frac{3g_3^3 m_P}{32 \pi \xi^{1/2}} \left(1 - e^{-\alpha \bar{\chi} |\chi|}\right)^{1/2}
\]
Reheating the SM: Perturbative Effects

\[ \Gamma_{W^\pm}^E = \frac{3 \cos^3 \theta_W}{2 \text{Lips}} \Gamma_Z^E = \frac{3 g_3^3 m_P}{32 \pi \xi^{1/2}} \left(1 - e^{-\alpha \kappa |\chi|}\right)^{1/2} \]
Reheating the SM: **Perturbative Effects**

\[
\Gamma_{W^\pm}^E = \frac{3 \cos^3 \theta_W}{2 \text{Lips}} \Gamma_Z^E = \frac{3g_\gamma^3 m_P}{32\pi \xi^{1/2}} \left(1 - e^{-\alpha_R |\chi|}\right)^{1/2}
\]
Reheating the SM: **Perturbative Effects**

\[
\Gamma_{W^\pm}^E = \frac{3 \cos^3 \theta_W}{2 \text{Lips}} \Gamma^E_Z = \frac{3 g_3^3 m_P}{32 \pi \xi^{1/2}} \left(1 - e^{-\alpha_K |\chi|}\right)^{1/2}
\]
Reheating the SM: **Perturbative Effects**

\[
\Gamma_{W^\pm}^E = \frac{3 \cos^3 \theta_W}{2 \text{Lips}} \quad \Gamma_{Z}^E = \frac{3 g_3^3 m_P}{32 \pi \xi^{1/2}} \left(1 - e^{-\alpha \kappa |\chi|}\right)^{1/2}
\]
Reheating the SM: Perturbative Effects
pReheating after HIGGS-INFLATION: Combined Reheating

Higgs: $\Phi \xrightarrow{g^2} \chi \xrightarrow{h^2} \Psi$

Non-Perturbative

Perturbative

CHILDREN-PARTICLES:

$$n_{k}^{j+1} = \begin{cases} W_j(k) \quad \text{SPONTANEOUS} \\ + (2W_j(k) + 1)n_k^j e^{-\Gamma_j \frac{T}{2}} \quad \text{STIMULATED} \\ + 2\sqrt{n_k^j} e^{-\Gamma_j \frac{T}{2}} (1 + n_k^j e^{-\Gamma_j \frac{T}{2}}) \sqrt{W_j(k) [W_j(k) + 1]} \sin \theta_j \quad \text{STOCHASTIC} \end{cases}$$

GRAND-CHILDREN PARTICLES: $\tilde{n}_k^j = \sum_{i=1}^{j} (1 - e^{-\Gamma_i \frac{T}{2}}) n_k^i$

PERTURBATIVE DECAYS
**pReheating after HIGGS-INFLATION: Combined Reheating**

<table>
<thead>
<tr>
<th>Higgs</th>
<th>$\Phi$</th>
<th>$g^2$</th>
<th>Children</th>
<th>$\chi$</th>
<th>$h^2$</th>
<th>Grand-Children</th>
<th>$\Psi$</th>
</tr>
</thead>
</table>

Non-Perturbative

Perturbative

**CHILDREN-PARTICLES:**

\[
\begin{align*}
n_{k}^{j+1} &= \left\{ 
\begin{array}{c}
W_j(k) \\
+ (2W_j(k) + 1) n_k^j e^{-\Gamma_j \frac{T}{2}} \\
+ 2 \sqrt{n_k^j e^{-\Gamma_j \frac{T}{2}}} \left(1 + n_k^j e^{-\Gamma_j \frac{T}{2}}\right) \sqrt{W_j(k) [W_j(k) + 1]} \sin \theta_j
\end{array}
\right. \\
\rightarrow W(k) \begin{cases}
\sim O(1), & k \ll k^*_j (g^2, \Phi, T_j) \\
\ll 1, & k \gg k^*_j (g^2, \Phi, T_j)
\end{cases}
\rightarrow \text{STIMULATED}
\rightarrow \text{STOCHASTIC}
\end{align*}
\]

**GRAND-CHILDREN PARTICLES:**

\[
\tilde{n}_k^j = \sum_{i=1}^{j} (1 - e^{-\Gamma_i \frac{T}{2}}) n_k^i
\]

PERTURBATIVE DECAYS
pReheating after HIGGS-INFLATION: Combined Reheating

Higgs \[ \Phi \xrightarrow{g^2} \chi \xrightarrow{h^2} \Psi \]

Non-Perturbative \hspace{0.5cm} Perturbative

**CHILDREN-PARTICLES:**

\[
\begin{aligned}
\tilde{n}_{jk}^{j+1} &= \left\{ \begin{array}{l}
W_j(k) \\
+ (2W_j(k) + 1)n_k^j e^{-\Gamma_j \frac{T}{2}} \\
+ 2\sqrt{n_k^j e^{-\Gamma_j \frac{T}{2}} (1 + n_k^j e^{-\Gamma_j \frac{T}{2}})} \sqrt{W_j(k)[W_j(k) + 1]} \sin \theta_j
\end{array} \right. \\
\end{aligned}
\]

SPONTANEOUS \hspace{2cm} STIMULATED

**GRAND-CHILDREN PARTICLES:**

\[
\tilde{n}_k^j = \sum_{i=1}^{j} (1 - e^{-\Gamma_i \frac{T}{2}}) n_k^i
\]

PERTURBATIVE DECAYS
pReheating after HIGGS-INFLATION: Combined Reheating

![Graph showing Higgs, Fermions, and Bosons over time with Efficient Reheating (j~110)]
pReheating with many DOF: Combined Reheating

Inflaton $\Phi \xrightarrow{g^2} \chi \xrightarrow{h^2} \Psi$

Non-Perturbative

Perturbative

CHILDREN-PARTICLES:

$$\begin{align*}
\frac{n_k^j + 1}{n_k^j} = & \quad W_j(k) \xrightarrow{\text{SPONTANEOUS}} \\
& + (2W_j(k) + 1)n_k^je^{-\Gamma_j \frac{T}{2}} \xrightarrow{\text{STIMULATED}} \\
& + 2\sqrt{n_k^j e^{-\Gamma_j \frac{T}{2}} (1 + n_k^j e^{-\Gamma_j \frac{T}{2}})} \sqrt{W_j(k)[W_j(k) + 1]} \sin \theta_j
\end{align*}$$

GRAND-CHILDREN PARTICLES:

$$\tilde{n}_k^j = \sum_{i=1}^{j} (1 - e^{-\Gamma_i \frac{T}{2}})n_k^i$$

PERTURBATIVE DECAYS
pReheating with many DOF: Combined Reheating

Inflaton $\Phi \rightarrow \chi \rightarrow \Psi$

Non-Perturbative $\rightarrow$ Perturbative

$\frac{\Delta \rho_\chi}{\rho_\Phi}(j) = \text{Fraction Energy Transferred per zero} - \text{Crossing}(\Phi \rightarrow \chi)$

$t_{\text{dec}}(j) \sim \Gamma_j^{-1}$ Decaying time $[t_j, t_{j+1}](\chi \rightarrow \Psi)$
**pReheating with many DOF: Combined Reheating**

<table>
<thead>
<tr>
<th>Inflaton</th>
<th>Children</th>
<th>Grand-Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi$</td>
<td>$\chi$</td>
<td>$\Psi$</td>
</tr>
<tr>
<td>$g^2$</td>
<td>$h^2$</td>
<td></td>
</tr>
</tbody>
</table>

Non-Perturbative | Perturbative

<table>
<thead>
<tr>
<th>$t_{\text{dec}}(j)$</th>
<th>$T_\Phi + \frac{\Delta \rho_\chi}{\rho_\Phi} \lesssim 1 \ll 1$</th>
<th>Par. Resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_{\text{dec}}(j) \lesssim T_\Phi + \frac{\Delta \rho_\chi}{\rho_\Phi} \ll 1$</td>
<td>NonP. &amp; P. Effects</td>
</tr>
<tr>
<td></td>
<td>$t_{\text{dec}}(j) \lesssim T_\Phi + \frac{\Delta \rho_\chi}{\rho_\Phi} \lesssim \mathcal{O}(1)$</td>
<td>Instant Preheating</td>
</tr>
<tr>
<td></td>
<td>$t_{\text{dec}}(j) \ll T_\Phi + \frac{\Delta \rho_\chi}{\rho_\Phi} \ll 1$</td>
<td>Inefficient Preheating</td>
</tr>
<tr>
<td></td>
<td>$t_{\text{dec}}(j) \ll T_\Phi + \frac{\Delta \rho_\chi}{\rho_\Phi} \lesssim \mathcal{O}(1)$</td>
<td>MSSM preheating</td>
</tr>
</tbody>
</table>

pReheating after MSSM-INFLATION: Combined Reheating

Allahverdi et al. 2006, 2011: MSSM-Flat Direction (LLe) = Inflaton

\[ \phi^2 \rightarrow n_{\chi_1}, n_{\psi_1}, n_{A_{\mu}} \]  
(Produced per Zero-Crossing)

\[ \begin{align*}
\Gamma_{\chi_1} &= \Gamma_{\chi_2} = \Gamma_{\chi_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \\
\Gamma_{\chi_4} &= \frac{9g_Y^3\phi}{16\pi\sqrt{2}} \\
\Gamma_{W^+} &= \Gamma_{W^-} = \Gamma_{W_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \\
\Gamma_B &= \frac{9g_Y^3\phi}{16\pi\sqrt{2}} \\
\Gamma_{\psi_1} &= \Gamma_{\psi_2} = \Gamma_{\psi_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \\
\Gamma_{\psi_4} &= \frac{9g_Y^3\phi}{16\pi\sqrt{2}}
\end{align*} \]

Scalars

Vectors

Fermions
Combined Reheating

Allahverdi et al. 2006, 2011: MSSM-Flat Direction (LLe) = Inflaton

Efficient Reheating!

Grand-Children

InFlaton

Children
pReheating after MSSM-INFLATION: Combined Reheating

Allahverdi et al. 2006, 2011: MSSM-Flat Direction (LLe) = Inflaton

Grand-Children

Efficient Reheating!

InFlaton

Children

99 % InFlatoN Energy transferred in 20 Osc.
IS THIS ALL WE NEED, COMBINED (p)REHEATING??

BACKREACTION, (Re)SCATTERING, THERMALIZATION
BackReaction in HIGGS-INFLATION Reheating
BackReaction in HIGGS-INFLATION Reheating

Higgs

THERMALIZATION ??

Fermions

Efficient Reheating (j ~ 0)

Bosons
BackReaction in MSSM-INFLATION Reheating

Efficient Reheating!

Grand-Children

InFlaton

Children

BackReaction Negligible
BackReaction in MSSM-INFLATION Reheating

Grand-Children

Efficient Reheating!

InFlaton

Children

Thermalization after 100 Osc.
Reheating from the SM: Summary

1. Realistic Scenarios with Many *dof*: Combined Mechanism mixing Non-Perturbative Production + Perturbative Decays
2. Depending on the couplings/model: Param. Resonance, Mix nonP/P Effects, Instant Preheating, Inefficient, MSSM Preheating
3. Backreaction, ReScattering and Thermalization $\leftrightarrow$ specific Models
5. MSSM-Inflation: Efficient Reheating achieved after $\sim 20$ oscillations Backreaction is negligible, Thermalization ($T_{rh} \sim 10^8$ GeV)
6. THANKS 4 YOUR ATTENTION!!!
Reheating from the SM: **Summary**

1. **Realistic Scenarios with Many \( \textit{dof} \):** Combined Mechanism mixing Non-Perturbative Production + Perturbative Decays

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Reheating from the SM: **Summary**

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Reheating from the SM: **Summary**

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2. Depending on the couplings/model: Param. Resonance, Mix nonP/P Effects, Instant Preheating, Inefficient, MSSM Preheating
3. Backreaction, ReScattering and Thermalization $\leftrightarrow$ specific Models
4. **Higgs-Inflation**: Efficient Reheating after $\sim 100$ osc.: Param. Resonance initially blocked, later active. Backreaction important.
5. MSSM-Inflation: Efficient Reheating achieved after $\sim 20$ oscillations. Backreaction is negligible, Thermalization ($T_{rh} \sim 10^8$ GeV)
6. **THANKS 4 YOUR ATTENTION!!!**
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BACK SLIDES
Back Reaction in HIGGS-INFLATION Reheating

\[ \omega^2 \approx M^2 + \frac{\alpha gw \, n_W(j)}{2 \sqrt{\xi |\chi|}} \frac{1}{(\alpha \kappa |\chi|)^{1/2}} + \frac{\alpha gZ \, n_Z(j)}{2 \sqrt{\xi |\chi|}} \frac{1}{(\alpha \kappa |\chi|)^{1/2}} \]

**HIGGS EFFECTIVE FREQUENCY**

\[ \omega^2((j_{backr})) \approx 2 \, M^2 \quad \Rightarrow \]

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j_{backr} )</td>
<td>107</td>
<td>110</td>
<td>112</td>
<td>113</td>
<td>114</td>
</tr>
</tbody>
</table>

\( j_{backr} < j_{eff} \): Back Reaction occurs earlier than Efficient Reheating!:
We can not trust previous estimations of Efficient Reheating!
BackReaction in HIGGS-INFLATION Reheating

![Graph showing BackReaction in HIGGS-INFLATION Reheating](image-url)

- Higgs
- Fermions
- Bosons

Efficient Reheating ($j \sim 110$)
Back Reaction in Higgs-Inflation Reheating