REHEATING THE UNIVERSE
(Some Theoretical Aspects)

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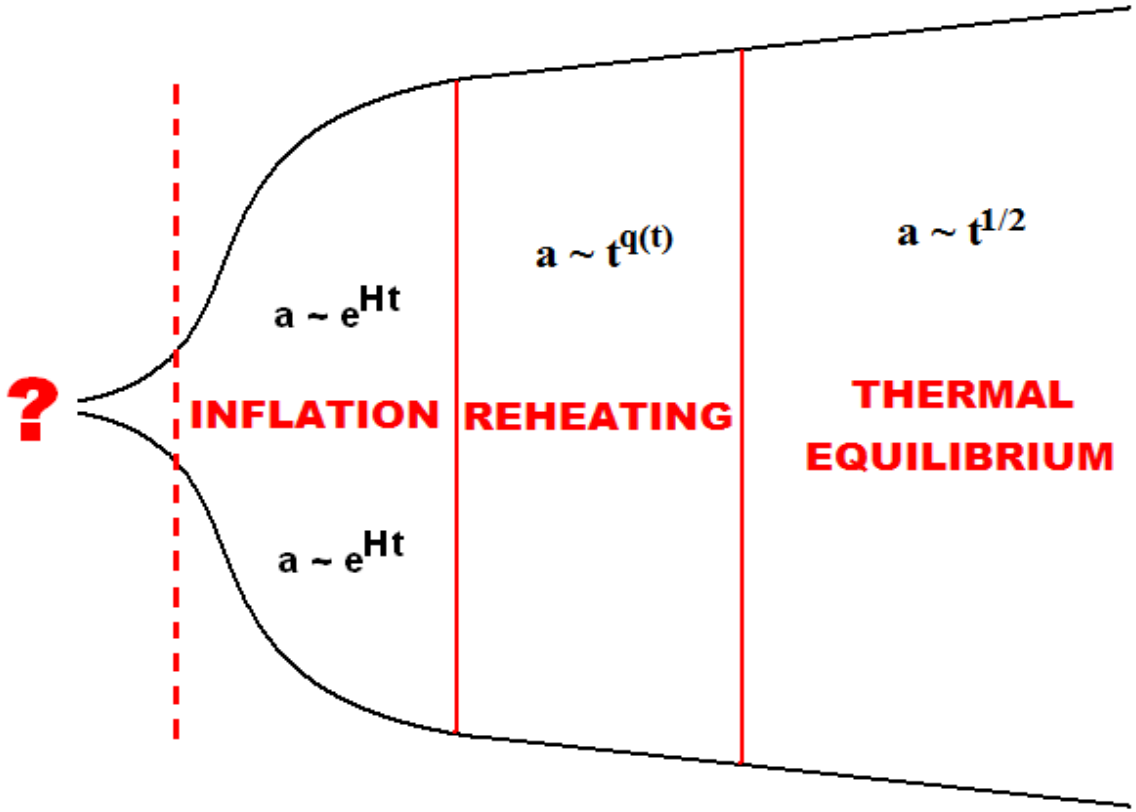
PPC 2011, June 14-18 2011, CERN, Genève, SWITZERLAND

PHYSICAL CONTEXT: REHEATING

INFLATION $\longrightarrow$ REHEATING $\longrightarrow$ BIG BANG THEORY



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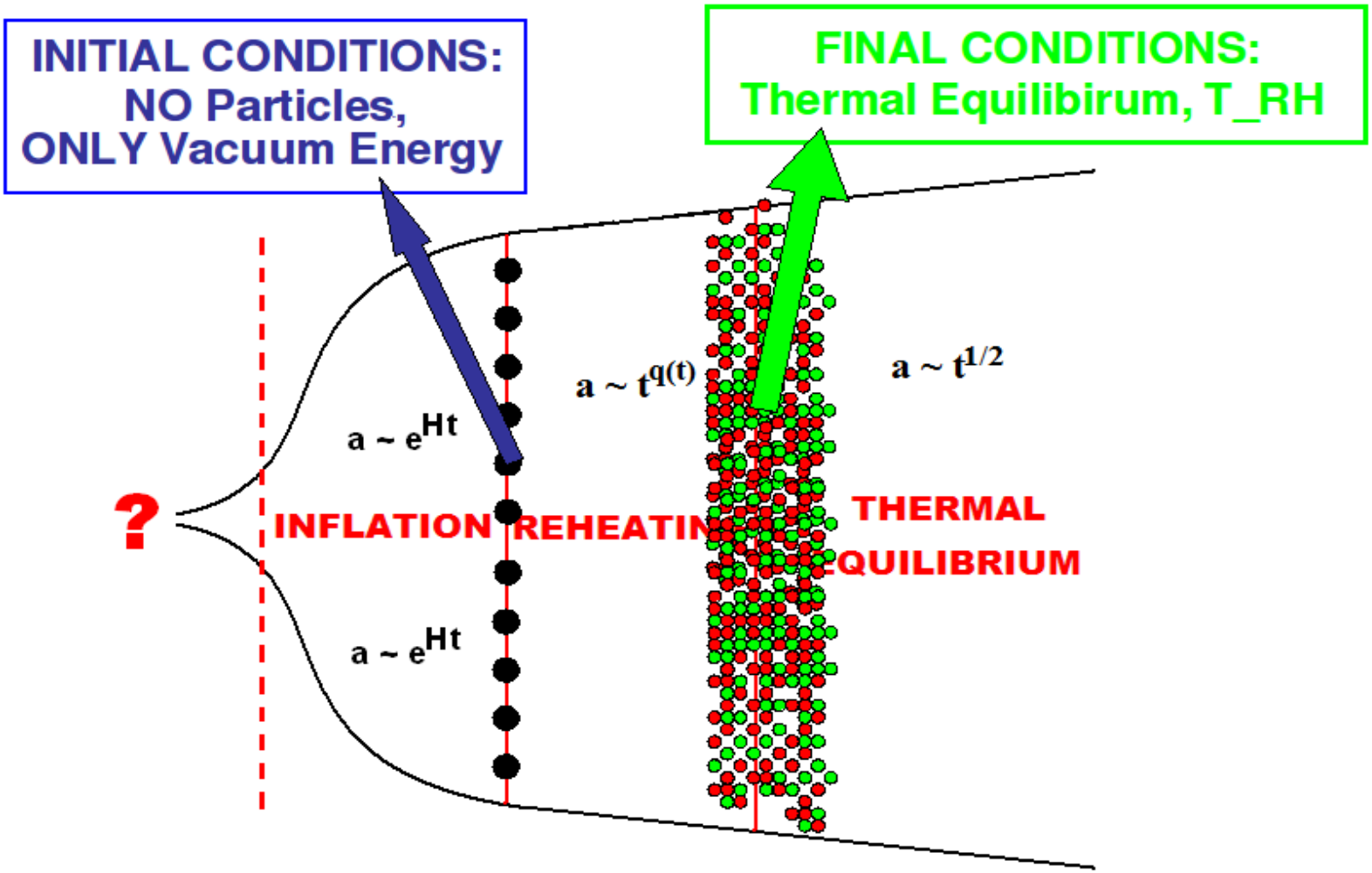

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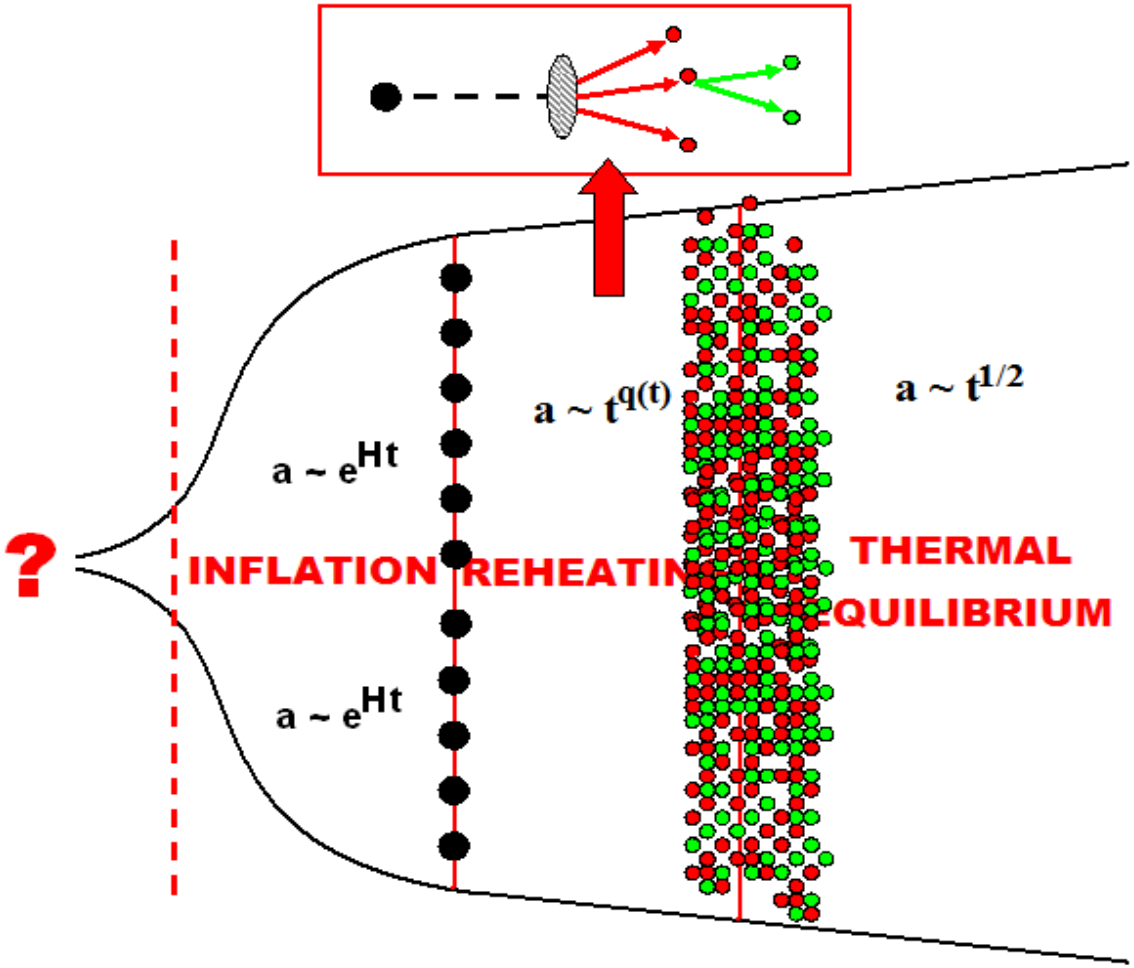

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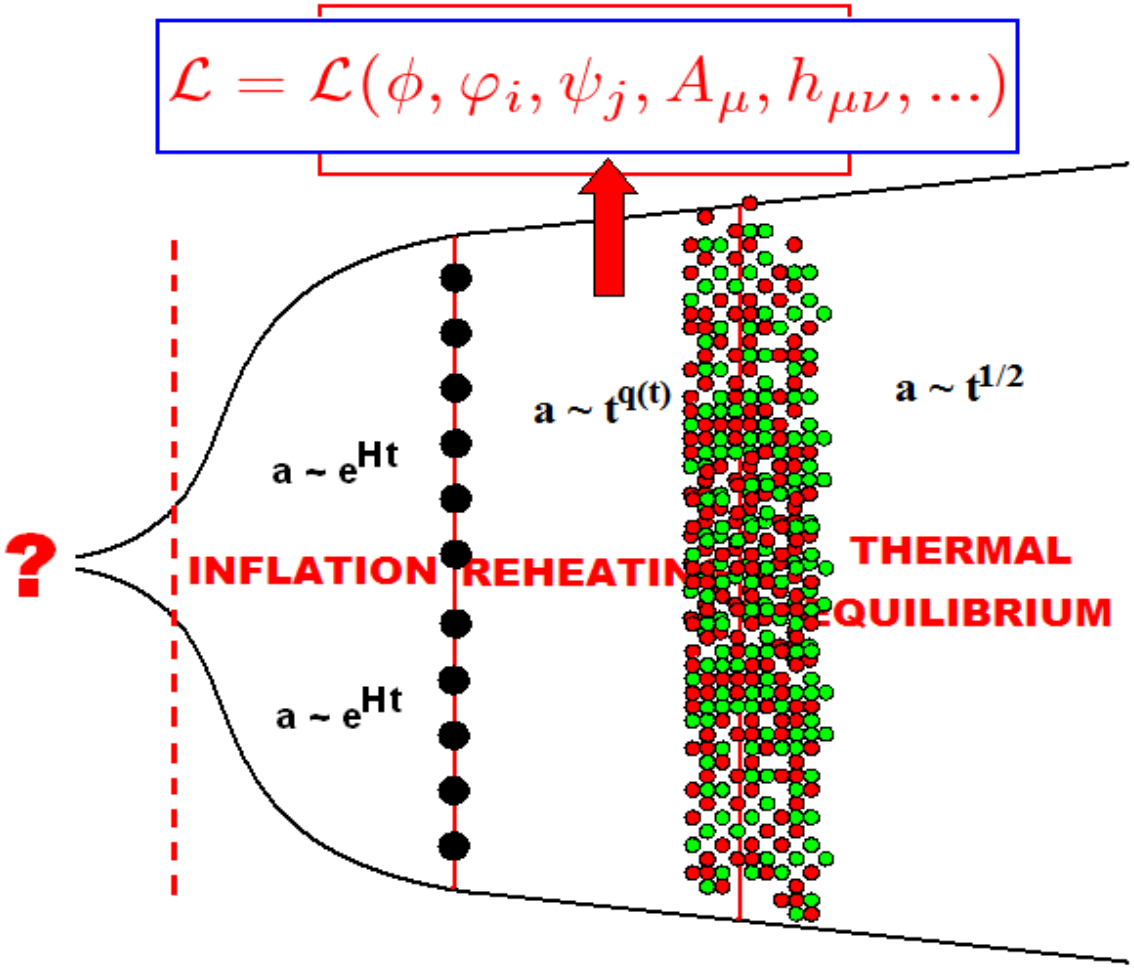

SIMPLE EXAMPLES: SCALAR REHEATING

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

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

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$$\begin{cases} \ddot{\phi}(t) + 3H\dot{\phi} + V'(\phi) = 0 & (\textbf{Inflaton Zero-Mode} : \text{Damped Oscillator}) \\ \Box\phi_k + F(\int dq\phi_q\chi_{|k-q|})\phi_k + ... = 0 & (\textbf{Inflaton Fluctuations}) \\ \Box\chi_k + F(\int dq\chi_q, \phi_{|k-q|})\chi_k + ... = 0 & (\textbf{Matter Fluctuations}) \end{cases}$$

DYNAMICS:

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

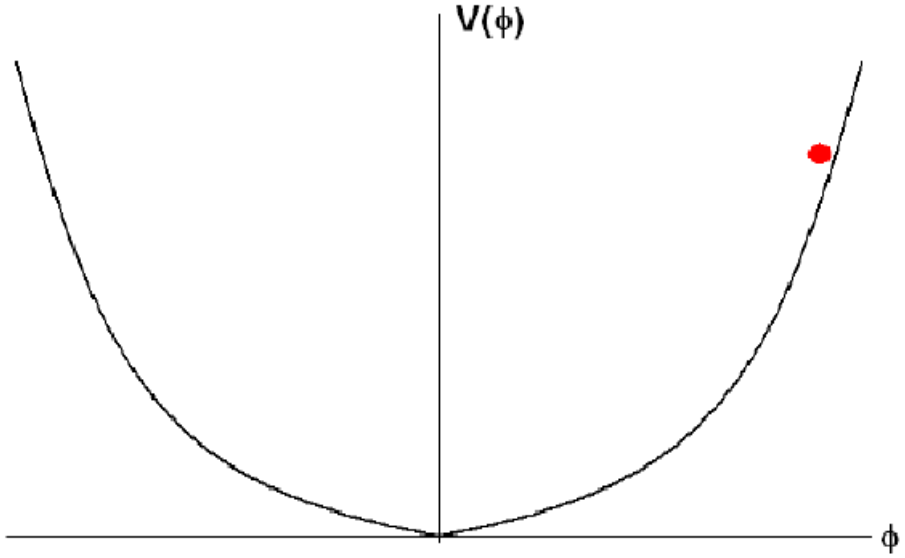
$\mathbf{k}_i \pm \Delta\mathbf{k}_i \rightarrow \varphi_k(t), n_k(t) \sim exp\{\mu_k\, t\} \rightarrow$ PREHEATING

(p)Reheating after Inflation: PARAM. RESONANCE

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

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

$$X_k'' + [\kappa^2 + m^2(\phi)]X_k = 0 \quad \text{(Fluctuations of Matter)}$$



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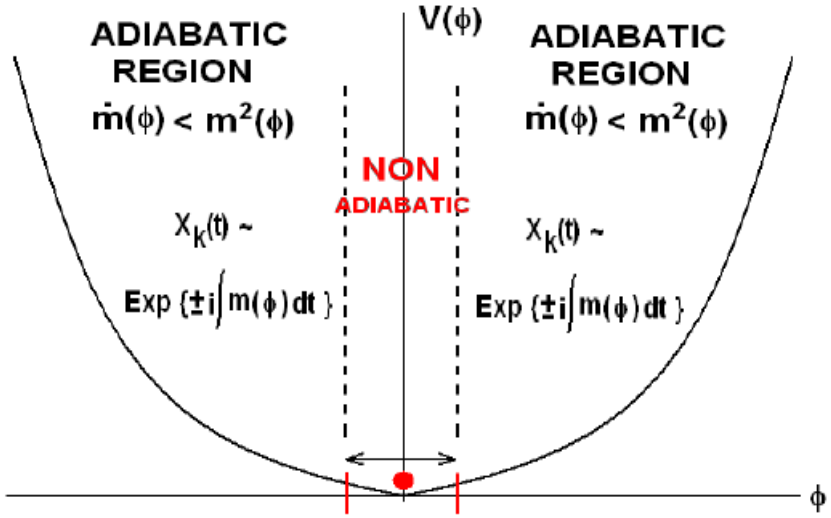

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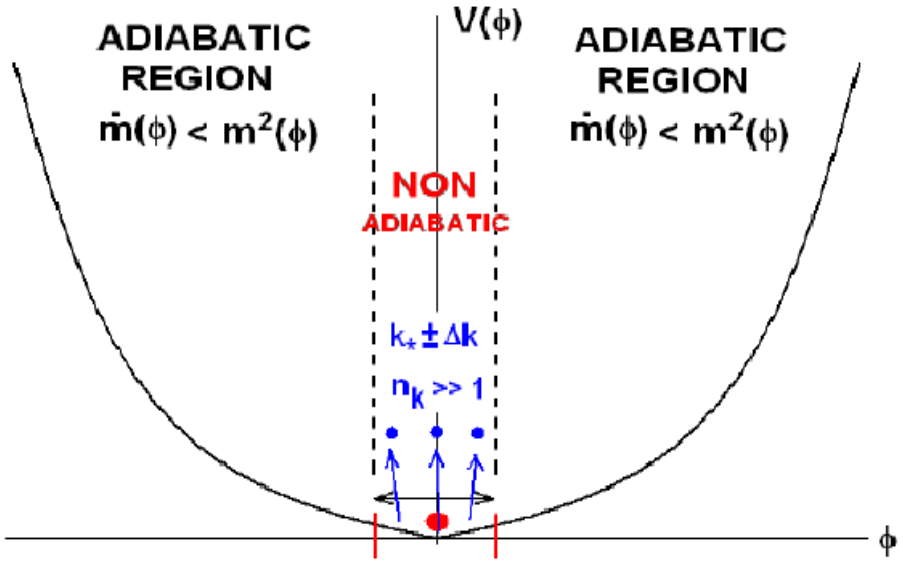

PROBING/IMPROVING REHEATING (2 APPROACHES)

1. **Poor Understanding of RH**:

   ABSENCE: SM, DM, Thermalization,...
   DIFFICULTIES: Many dof, Non-Lin, Non-Pert, Out-of-Eq.

2. **Probing RH**: $\left(\begin{array}{c}\text{Phenomenological effects}\\ \text{with observable consequences}\end{array}\right) \rightarrow$

   $\rightarrow \left\{\begin{array}{l}\textbf{Gravitational Waves}\ \text{Production}\\ \textbf{Non–Gaussianity}\ \text{in Matter Density Perturbations}\\ \textbf{Baryogenesis}\ \text{Mechanisms}\end{array}\right.$

3. **Improving RH**: $\left\{\begin{array}{l}\text{Embedding into Gauge Framework}\\ \text{Adding Fermions}\\ \text{Identify Fields with SM } dof \text{ (and DM)}\\ \text{Study Thermalization}\end{array}\right.$

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Improving Reheating: Including the SM dof

REHEATING WITHIN THE STANDARD MODEL:

COMBINED REHEATING MECHANISM

(p)Reheating after HIGSS-INFLATION

SM + GR + NON-MINIMAL COUPLING:

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

HILBERT-EINSTEIN

SSB

NON-Minimal

$\lambda \sim 0{,}1$

CST

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 HIGGS-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 : $h \longrightarrow \chi(h)$

$\Longrightarrow$

$\Longrightarrow$

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: $$V(\chi) = \underbrace{\frac{\lambda m_P^4}{4\xi^2}}_{\sim M_{GUT}^4}\left(1 - e^{-\alpha\kappa\chi}\right)^2 \simeq \boxed{\frac{1}{2}M^2\chi^2} + \Delta V$$

$10^{-5}\,M_p$

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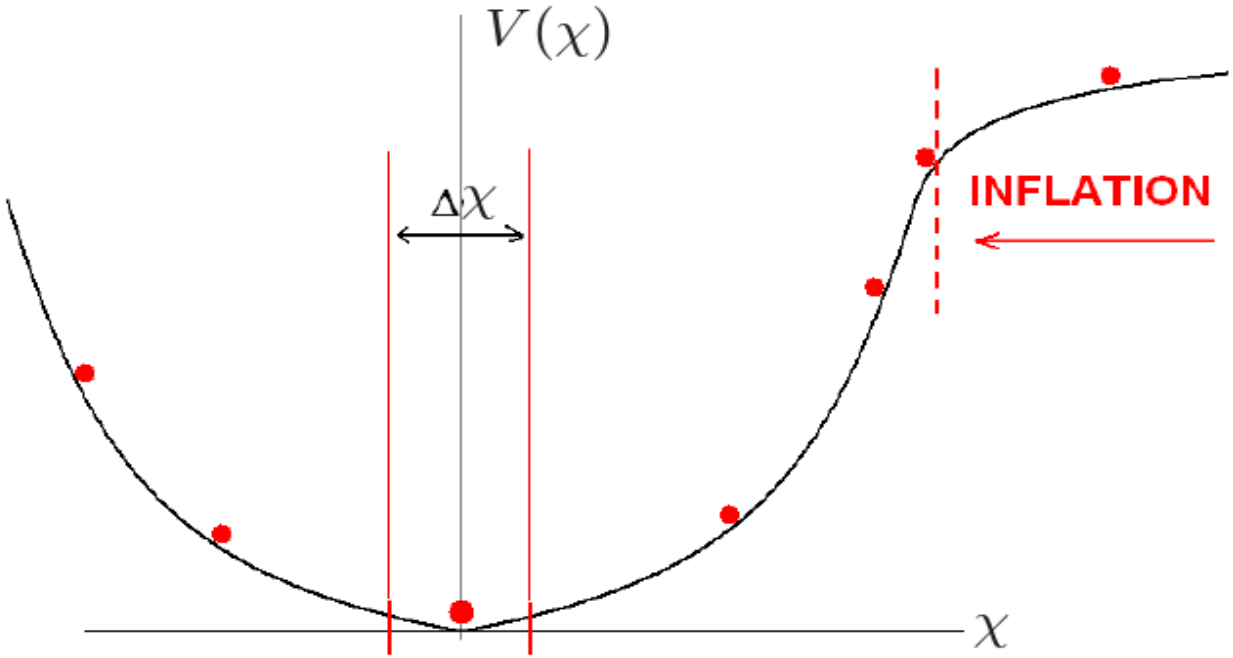
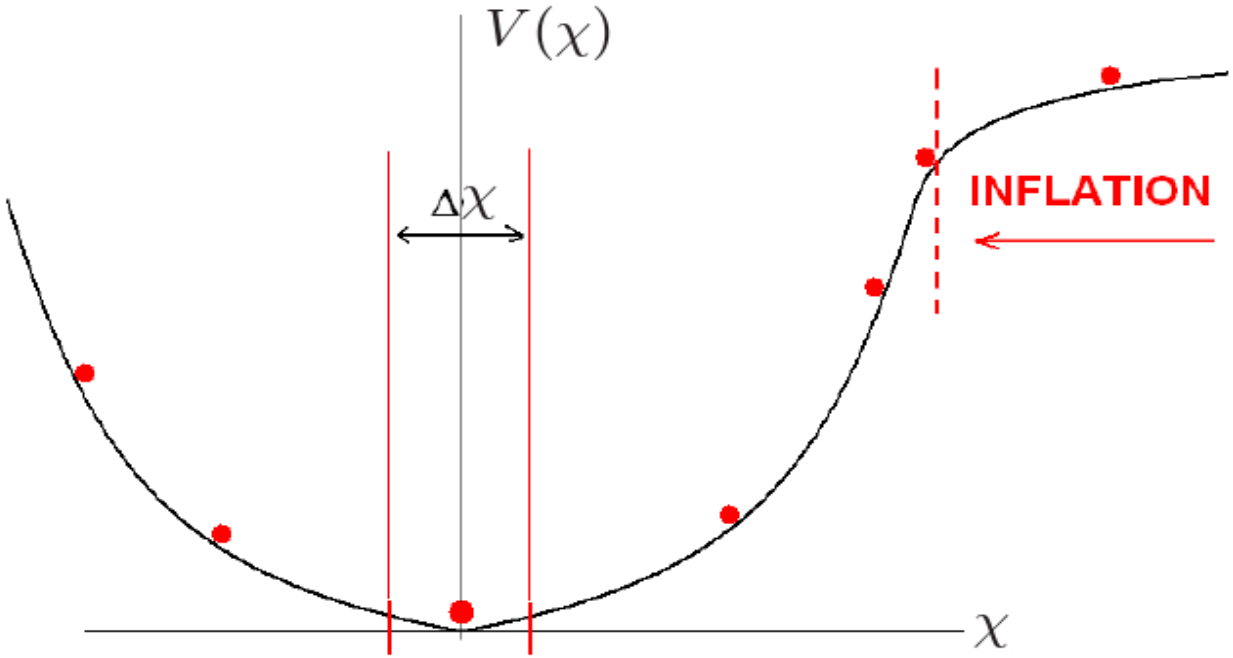
Reheating the SM: Non-Perturbative Effects

EINSTEIN FRAME: HIGGS POTENTIAL



Reheating the SM: Non-Perturbative Effects

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



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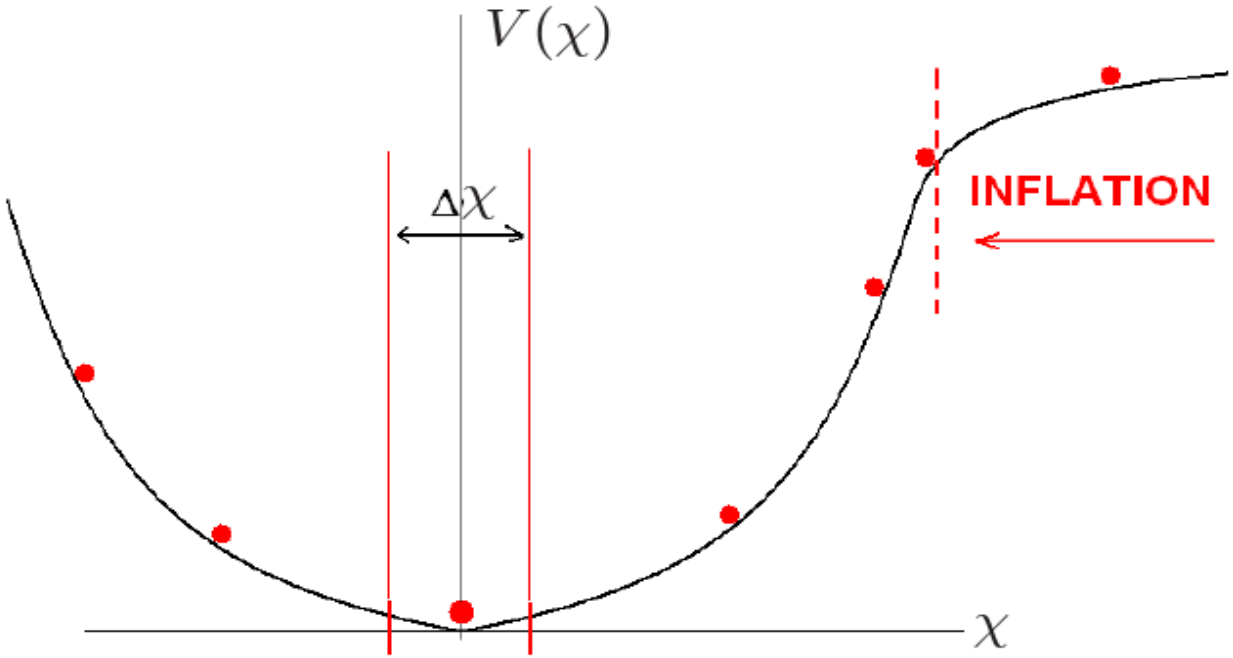
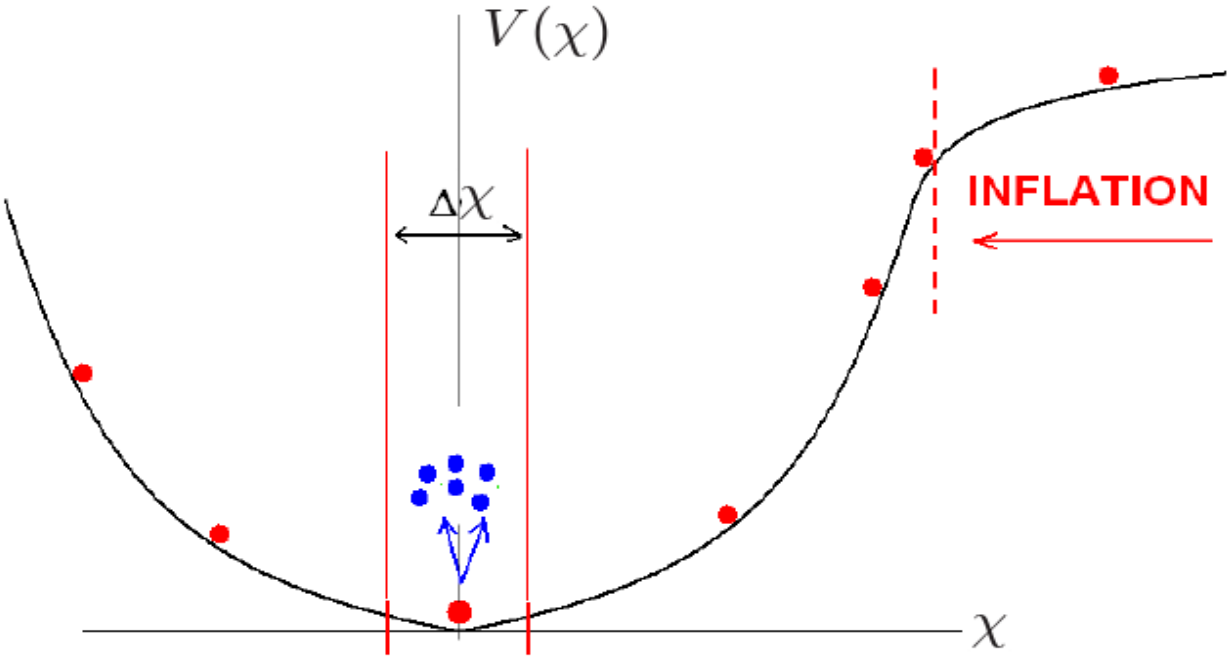


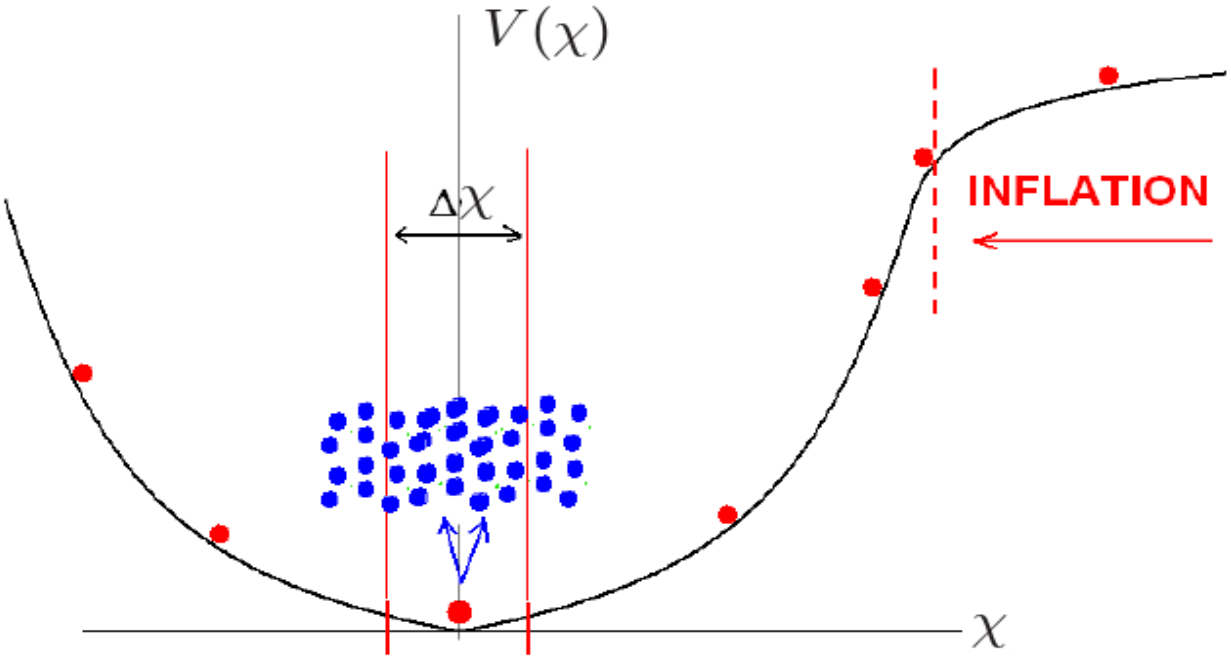
Reheating the SM: Non-Perturbative Effects

NON-ADIABATICITY: $|\Delta\chi| \ll 10^{-2}\, X(j)$



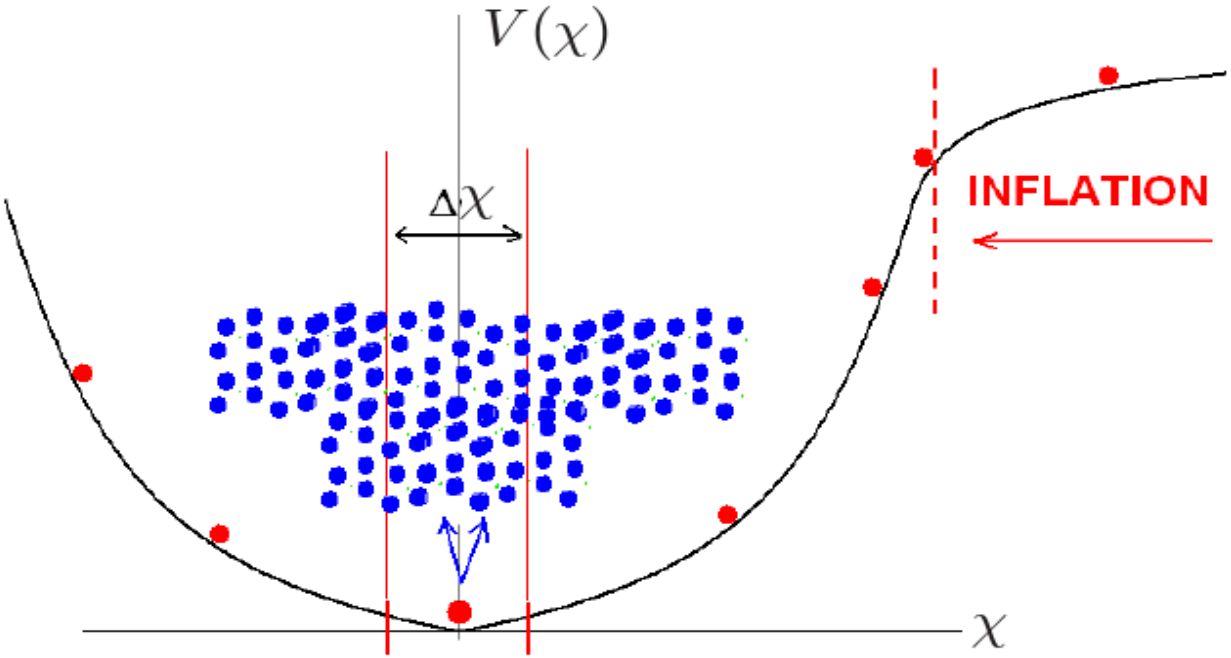
Reheating the SM: Non-Perturbative Effects

PARAMETRIC RESONANCE



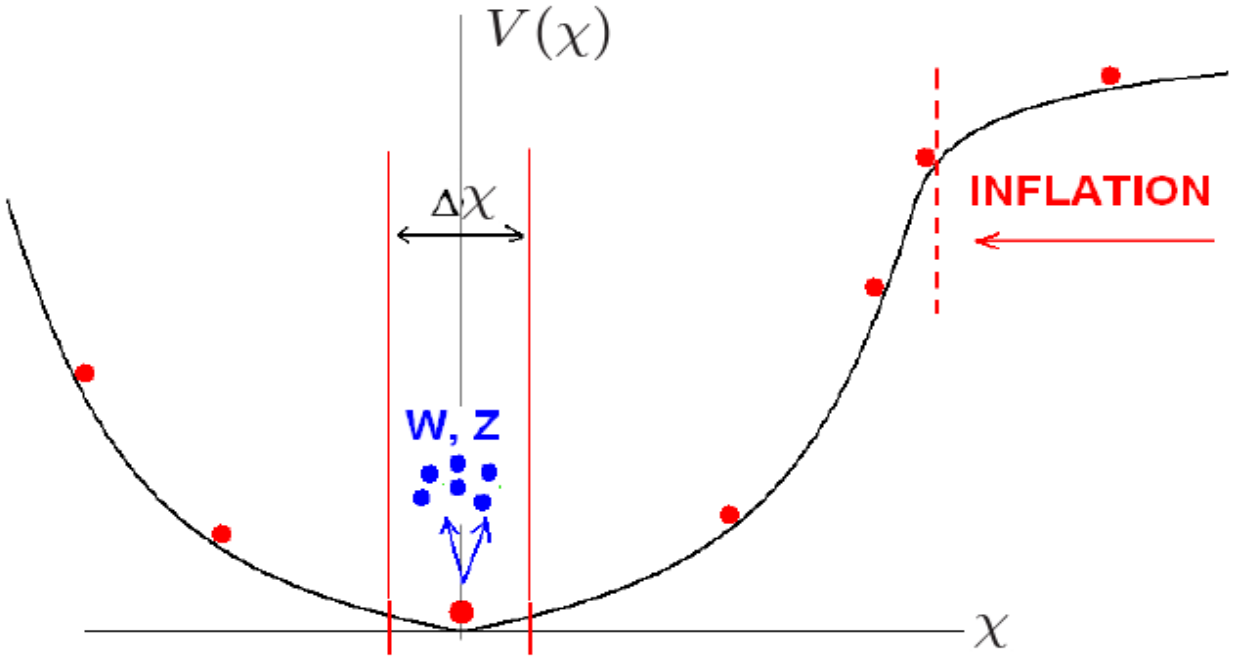
Reheating the SM: Non-Perturbative Effects

PARAMETRIC RESONANCE ?



Reheating the SM: Perturbative Effects

$$\Gamma^E_{W^\pm} = \frac{3\cos^3\theta_W}{2\mathrm{Lips}}\Gamma^E_Z = \frac{3g_2^3 m_P}{32\pi\xi^{1/2}}\left(1 - e^{-\alpha\kappa|\chi|}\right)^{1/2}$$



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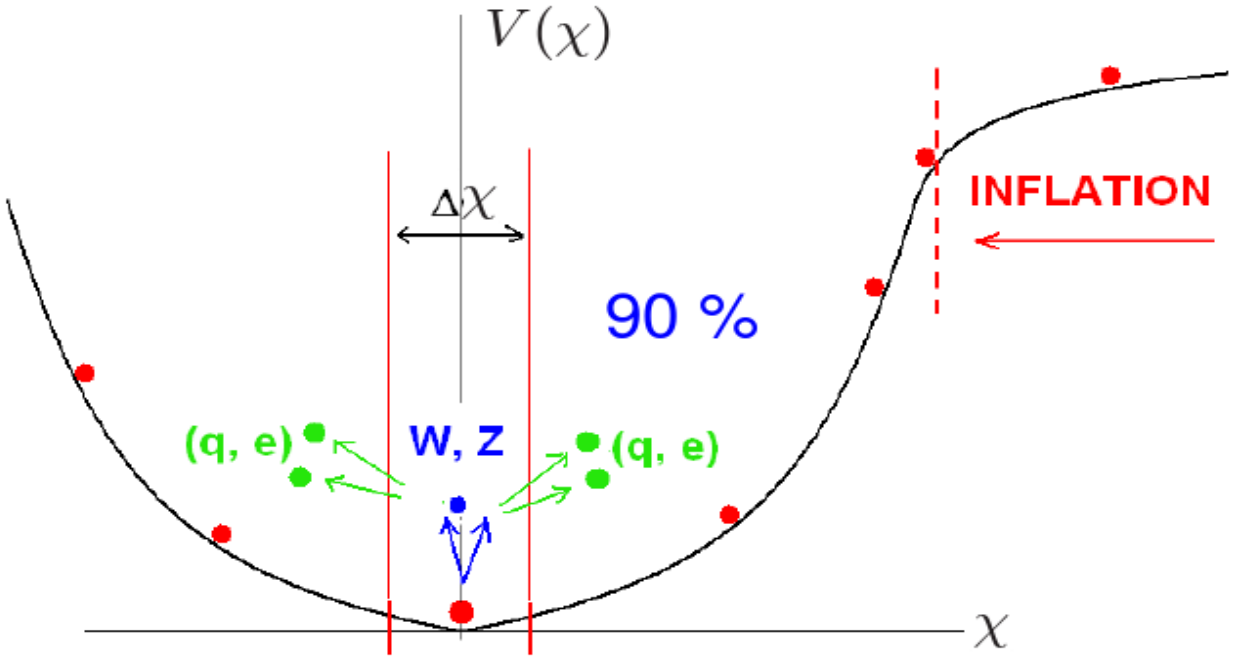

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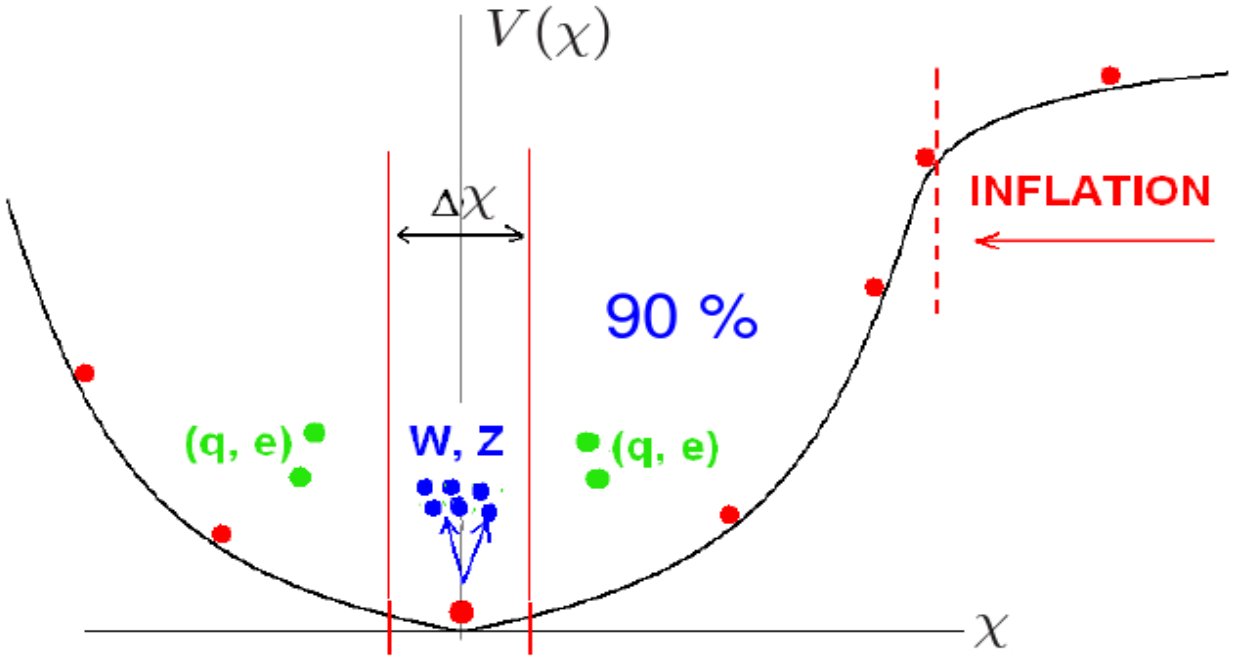

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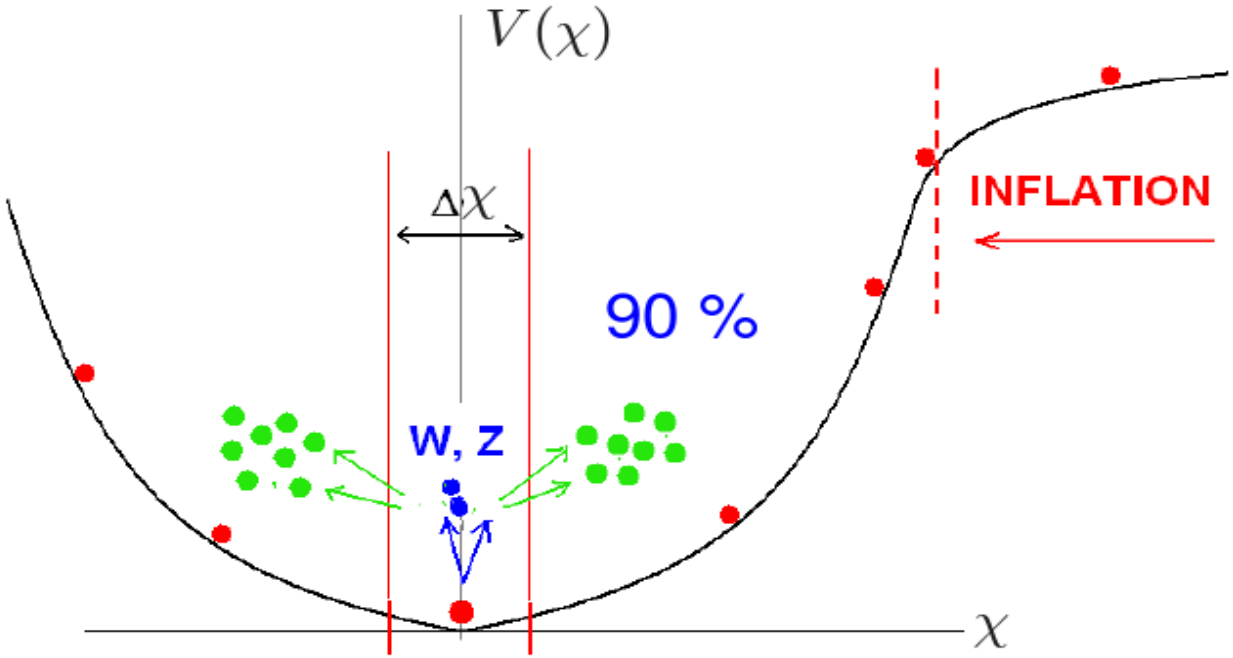

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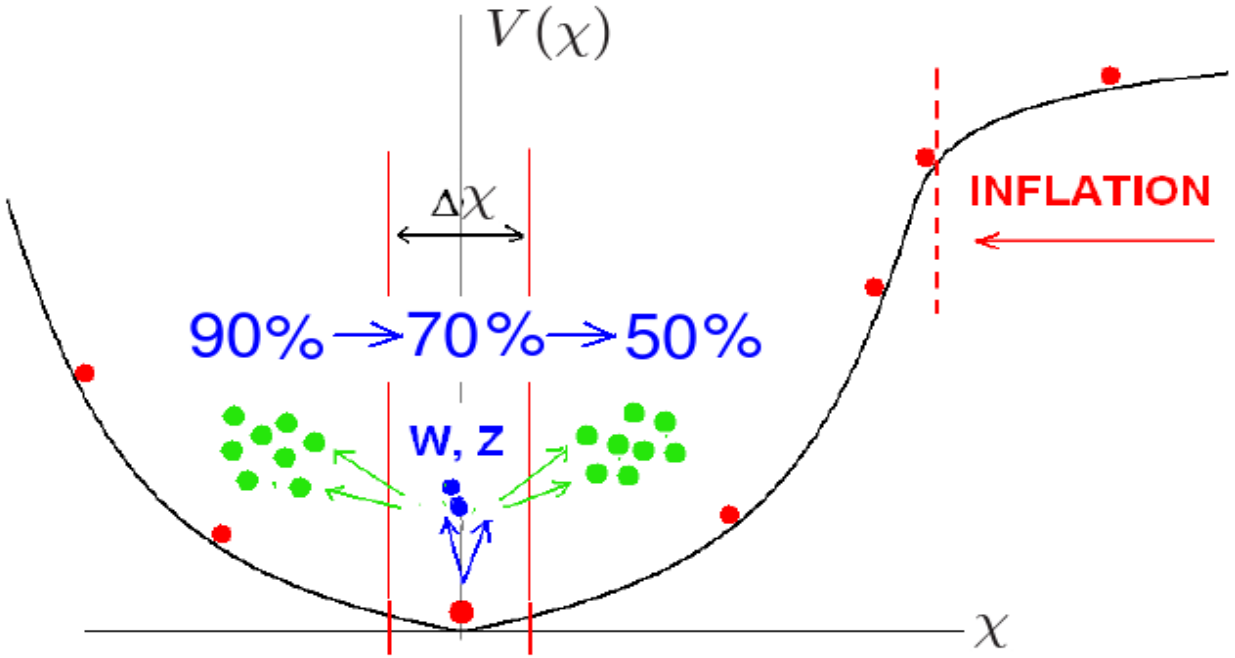

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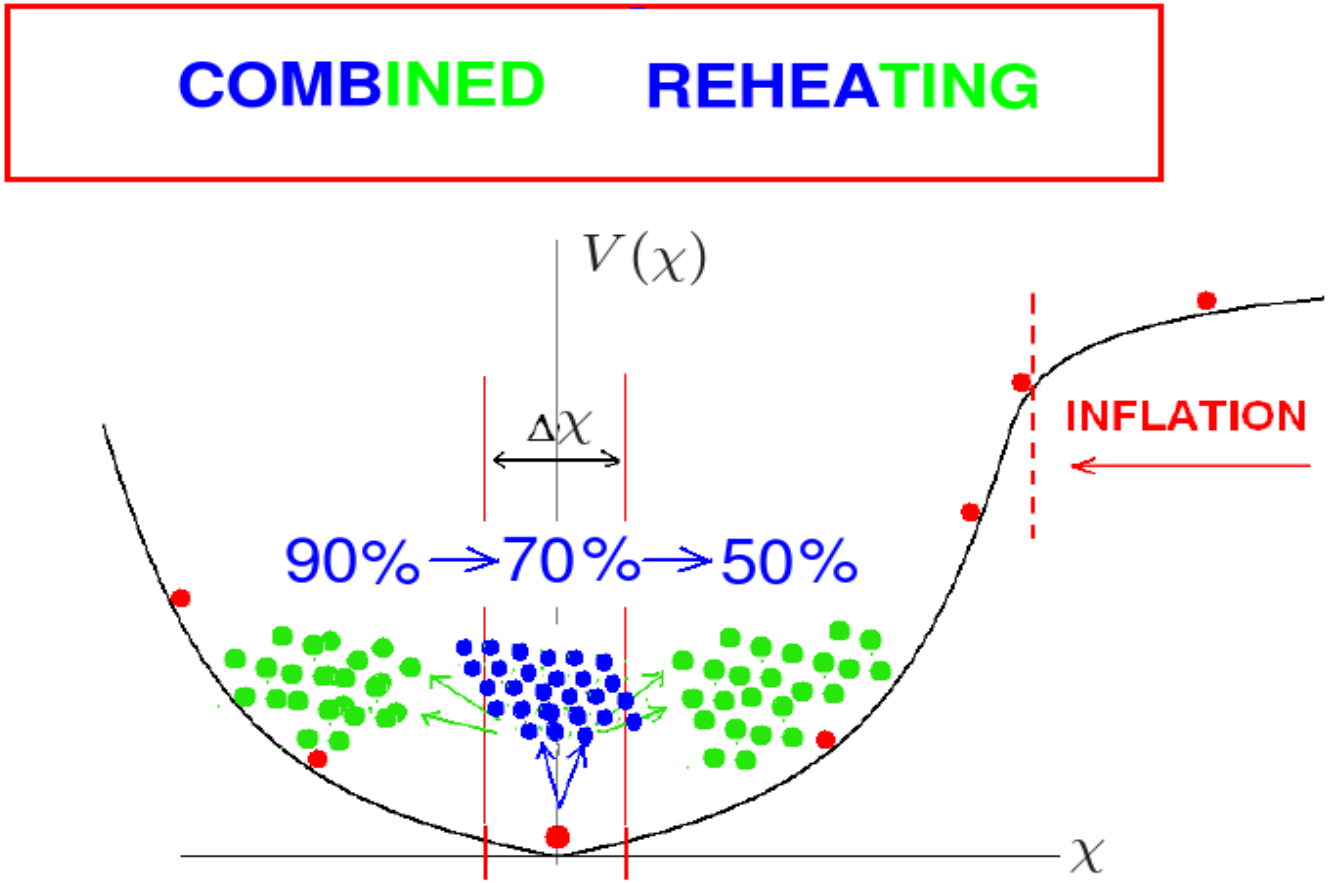

pReheating after HIGGS-INFLATION: Combined Reheating

Higgs		Children		Grand-Children
Φ	$\xrightarrow{g^2}$	χ	$\xrightarrow{h^2}$	Ψ
	Non-Perturbative		Perturbative	

CHILDREN-PARTICLES:

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

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

PERTURBATIVE DECAYS

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CHILDREN-PARTICLES:

$$n_k^{j+1} = \begin{cases} W_j(k) \longrightarrow \boxed{W(k) \begin{cases} \sim \mathcal{O}(1), & k \ll k_j^*(g^2, \Phi_o, T_j) \\ \ll 1, & k \gg k_j^*(g^2, \Phi_o, T_j) \end{cases}} \\ + \ (2W_j(k)+1) n_k^j e^{-\Gamma_j \frac{T}{2}} \longrightarrow \text{STIMULATED} \\ + \ 2\sqrt{n_k^j e^{-\Gamma_j \frac{T}{2}} (1 + n_k^j e^{-\Gamma_j \frac{T}{2}})} \sqrt{W_j(k)[W_j(k)+1]} \sin\theta_j \end{cases}$$

STOCHASTIC

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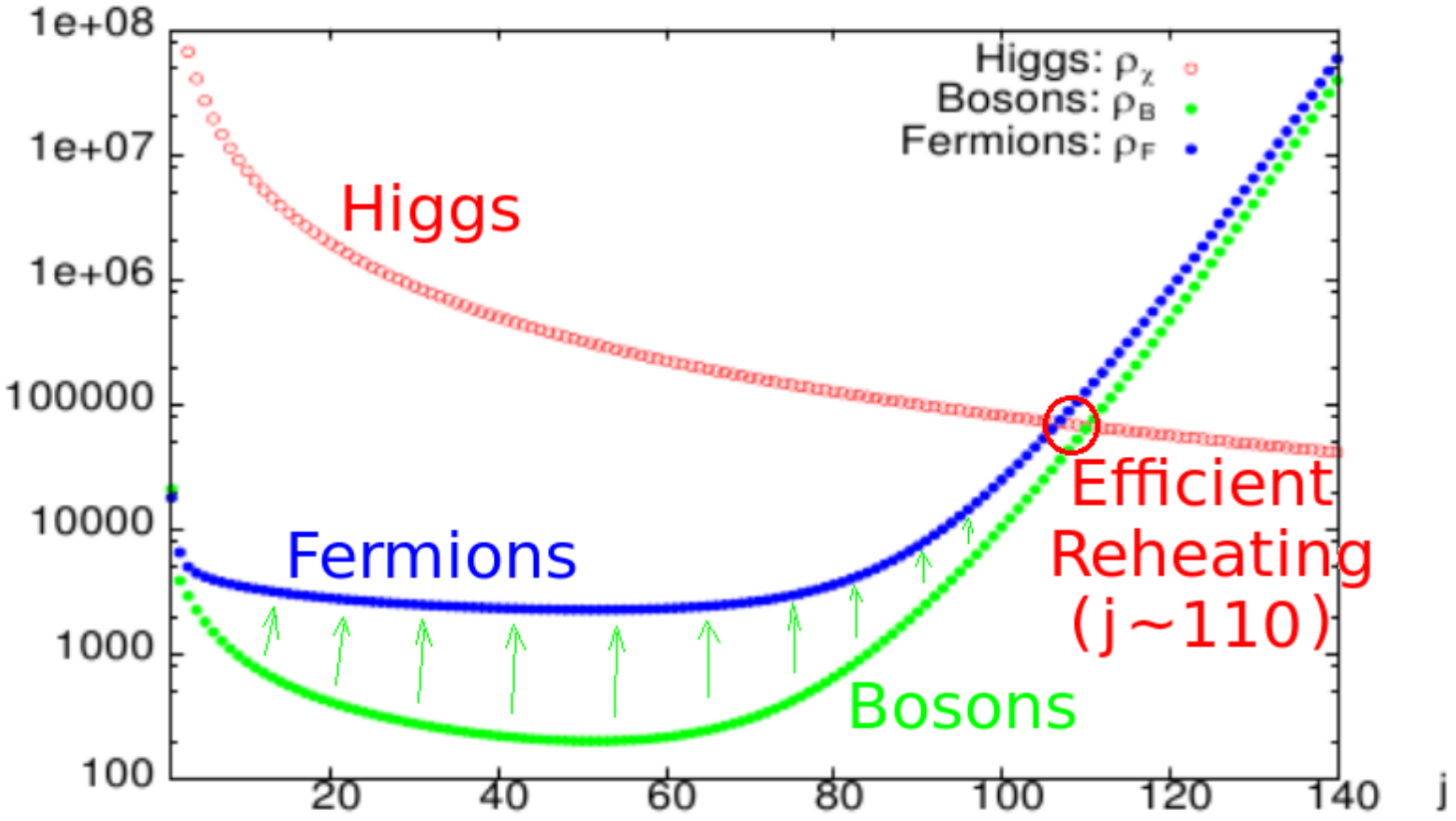

pReheating with many DOF: Combined Reheating

Inflaton		Children		Grand-Children
Φ	$\xrightarrow{g^2}$	χ	$\xrightarrow{h^2}$	Ψ
	Non-Perturbative		Perturbative	

CHILDREN-PARTICLES:

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

PERTURBATIVE DECAYS

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Φ	$\xrightarrow{g^2}$	χ	$\xrightarrow{h^2}$	Ψ
	Non-Perturbative		Perturbative	

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

$$t_{\rm dec}(j) \sim \Gamma_j^{-1} \qquad \text{Decaying time } [t_j, t_{j+1}](\chi \to \Psi)$$

pReheating with many DOF: Combined Reheating

Inflaton		Children		Grand-Children
Φ	$\xrightarrow{g^2}$	χ	$\xrightarrow{h^2}$	Ψ
	Non-Perturbative		Perturbative	

$$
\begin{cases}
t_{\rm dec}(j) \gg T_\Phi \;+\; \frac{\Delta\rho_\chi}{\rho_\Phi} \begin{matrix} \lesssim 1 \\ \ll 1 \end{matrix} \rightarrow \text{Par. Resonance} \left[\begin{matrix} \text{Kofman et al}'94,'97 \\ \text{Traschen et al}'90,'95 \end{matrix} \right] \\
t_{\rm dec}(j) \lesssim T_\Phi \;+\; \frac{\Delta\rho_\chi}{\rho_\Phi} \ll 1 \rightarrow \text{NonP. \& P. Effects} \left[\begin{matrix} \text{Bezrukov et al}'08 \\ \text{G}^{\text{a}}\text{Bellido et al}'08 \end{matrix} \right] \\
t_{\rm dec}(j) \lesssim T_\Phi \;+\; \frac{\Delta\rho_\chi}{\rho_\Phi} \lesssim \mathcal{O}(1) \rightarrow \text{Instant Preheating [Felder et al}'98] \\
t_{\rm dec}(j) \ll T_\Phi \;+\; \frac{\Delta\rho_\chi}{\rho_\Phi} \ll 1 \rightarrow \text{Inefficient Preheating [This Talk]} \\
t_{\rm dec}(j) \ll T_\Phi \;+\; \frac{\Delta\rho_\chi}{\rho_\Phi} \lesssim \mathcal{O}(1) \rightarrow \text{MSSM preheating [Allahverdi et al}'11]
\end{cases}
$$

pReheating after MSSM-INFLATION:Combined Reheating

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

$$\phi^2 \longrightarrow n_{\chi_i}, n_{\Psi_i}, n_{A_\mu}$$ (Produced per Zero-Crossing)

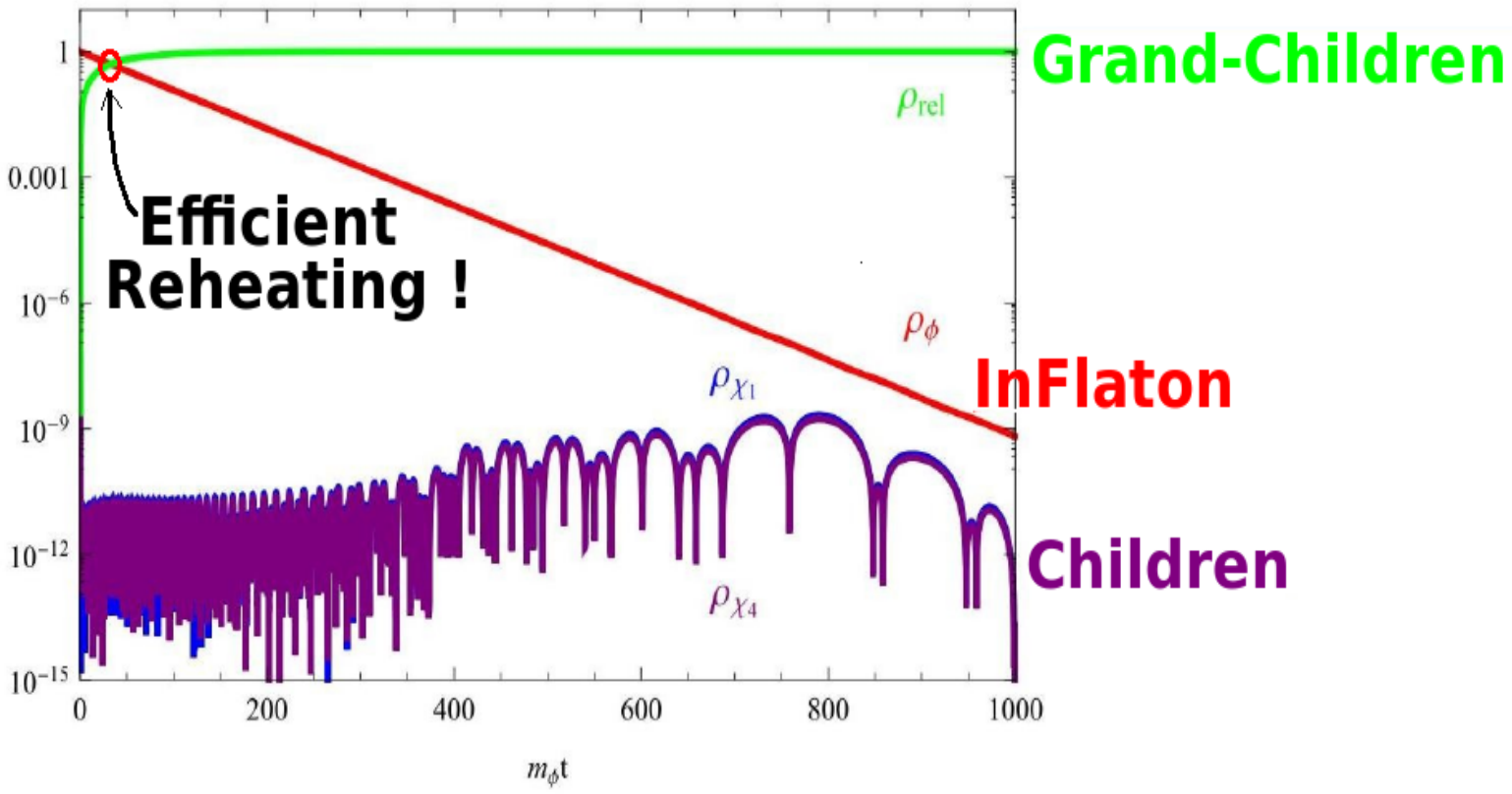
$$\Gamma_{\chi_1} = \Gamma_{\chi_2} = \Gamma_{\chi_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \quad \Gamma_{\chi_4} = \frac{9g_Y^3\phi}{16\pi\sqrt{2}}$$ **Scalars**

$$\Gamma_{W^+} = \Gamma_{W^-} = \Gamma_{W_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \quad \Gamma_B = \frac{9g_Y^3\phi}{16\pi\sqrt{2}}$$ **Vectors**

$$\Gamma_{\Psi_1} = \Gamma_{\Psi_2} = \Gamma_{\Psi_3} = \frac{3g_W^3\phi}{8\pi\sqrt{6}}, \quad \Gamma_{\Psi_4} = \frac{9g_Y^3\phi}{16\pi\sqrt{2}}$$ **Fermions**

pReheating after MSSM-INFLATION:Combined Reheating

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



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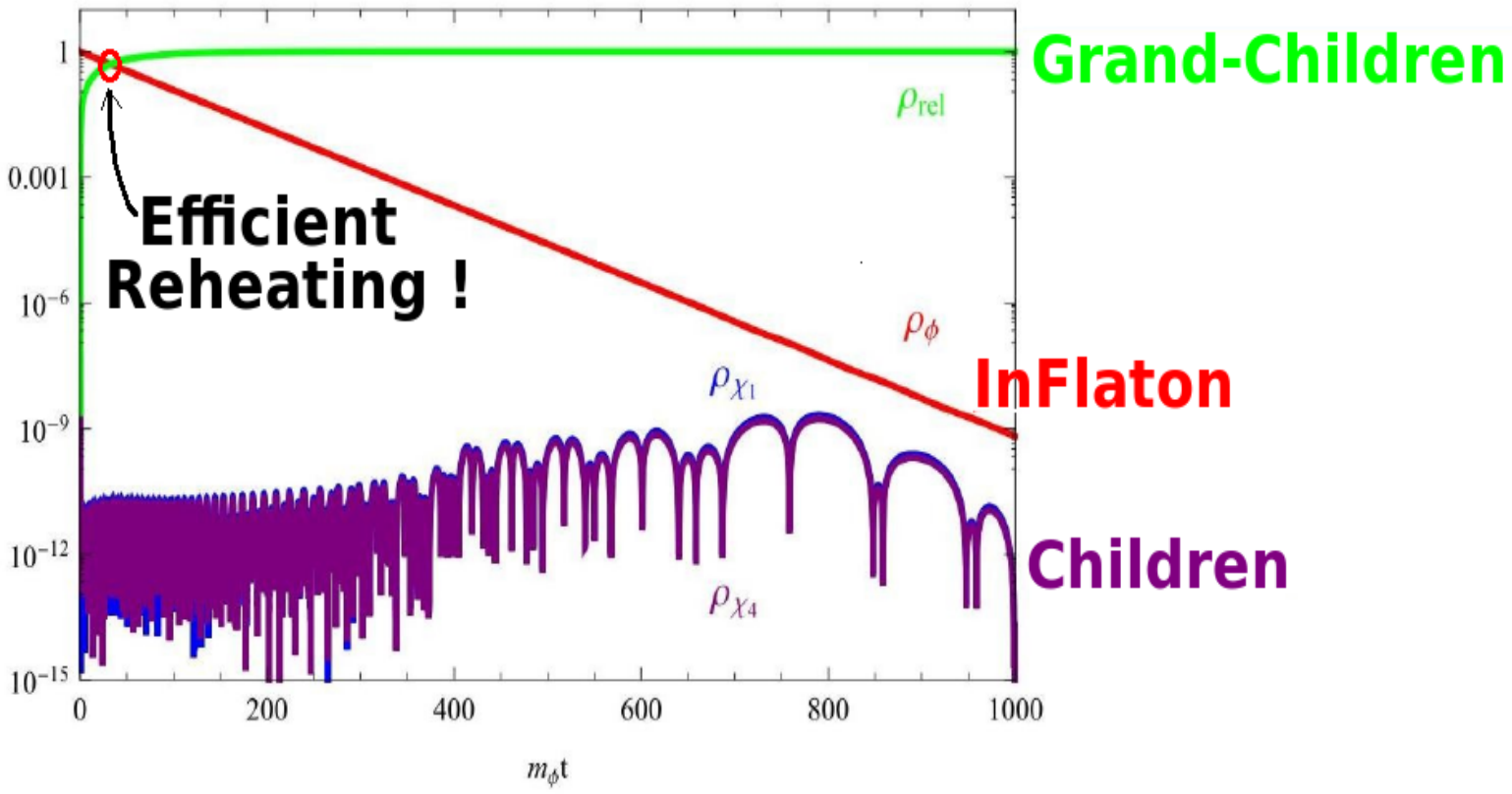


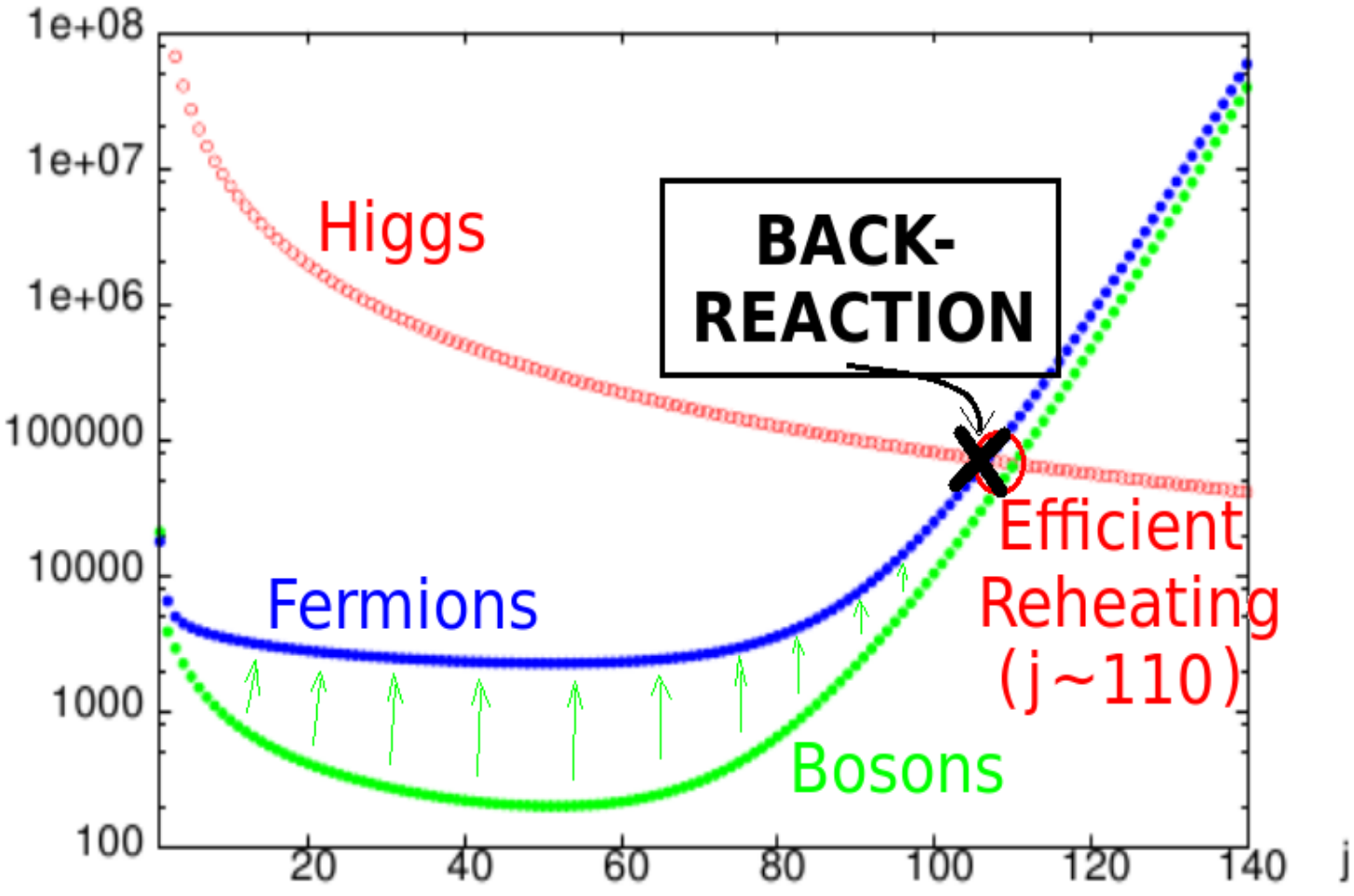
99 % InFlatoN Energy transferred in 20 Osc.

Improving Reheating: Including the SM dof

IS THIS ALL WE NEED, COMBINED (p)REHEATING??

BACKREACTION, (Re)SCATTERING, THERMALIZATION

BackReaction in HIGGS-INFLATION Reheating



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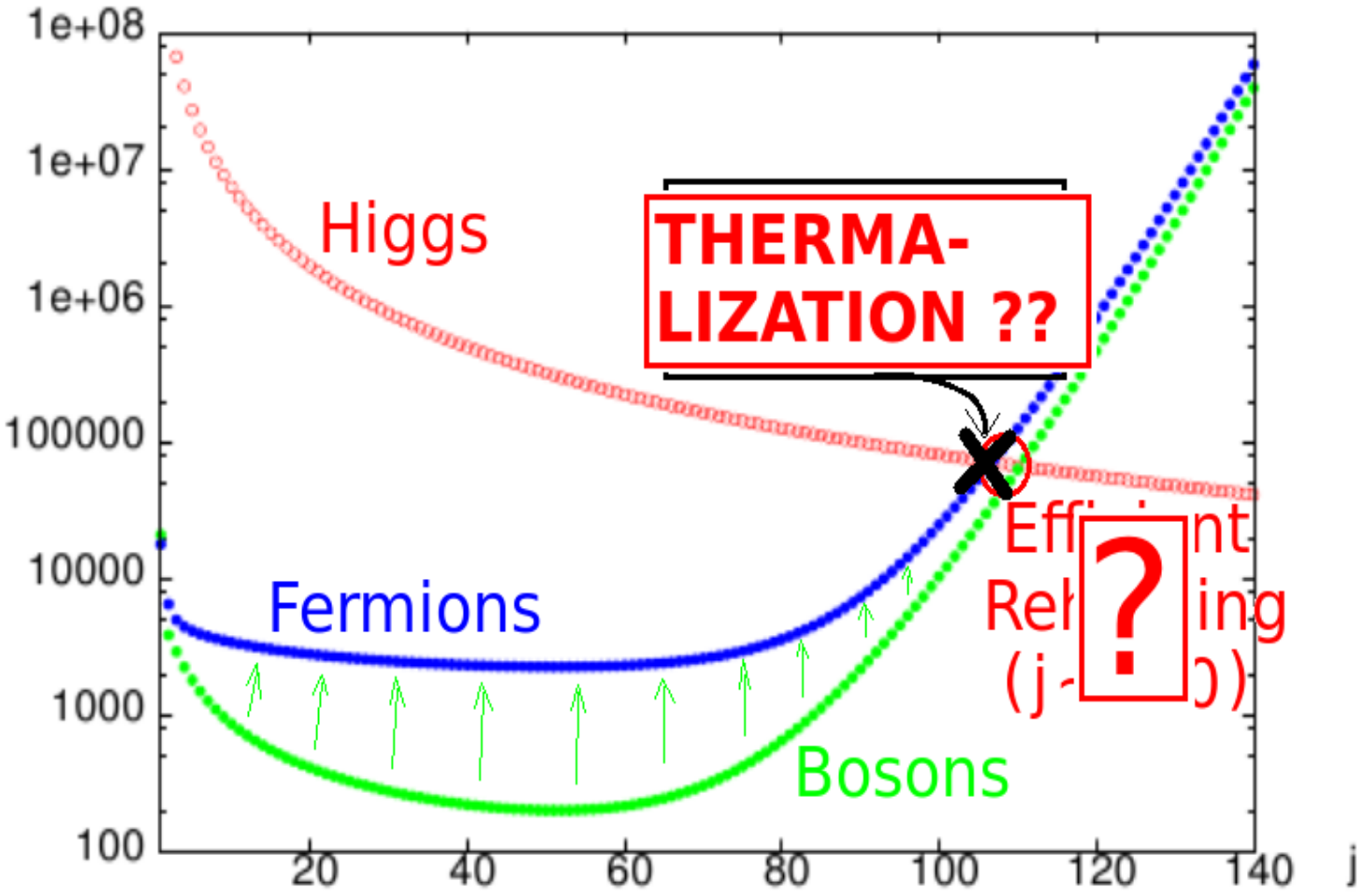

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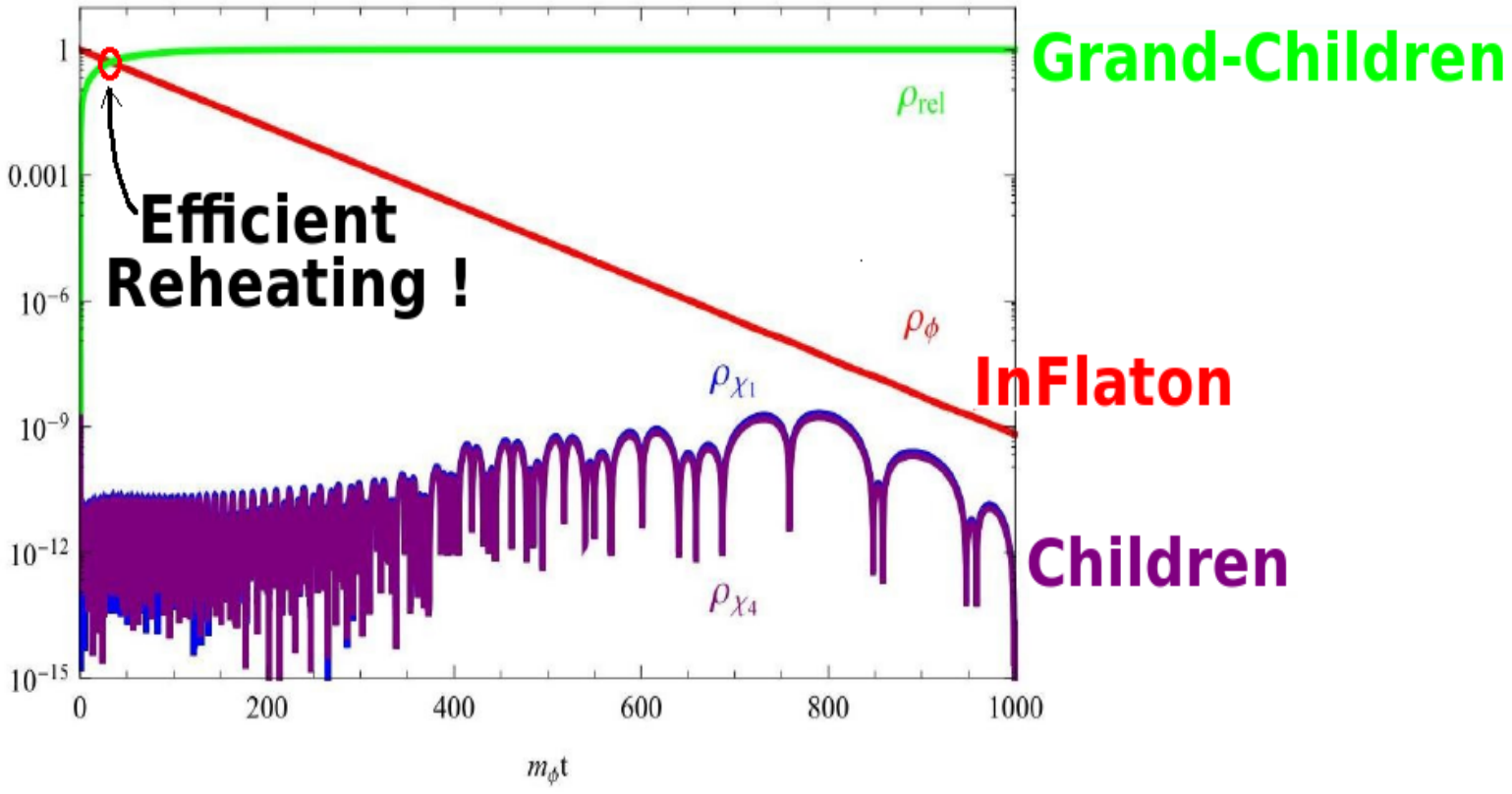
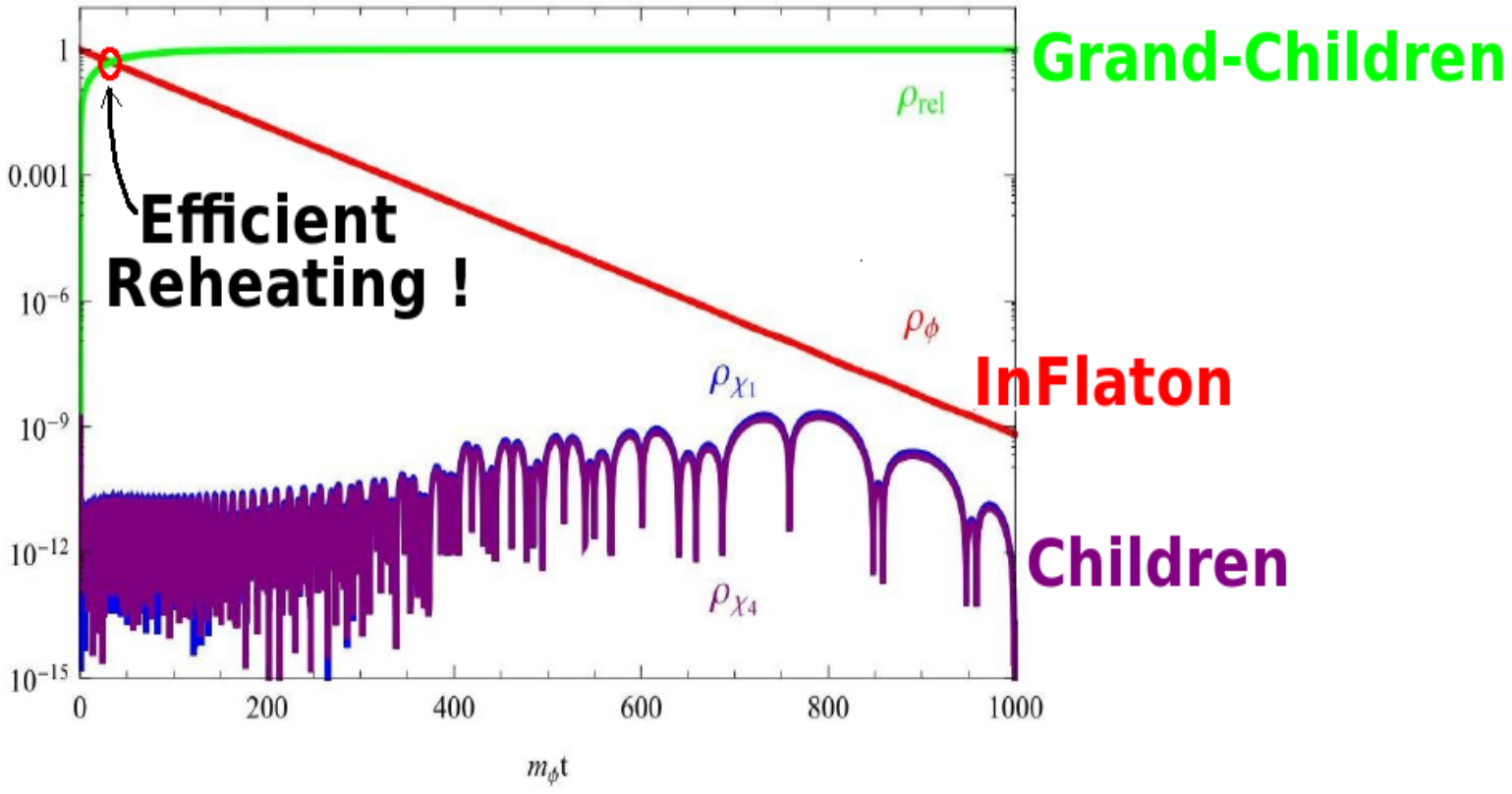


BackReaction Negligible

BackReaction in MSSM-INFLATION Reheating



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. Backreation, ReScattering and Thermalization $\leftrightarrow$ specific Models
4. Higgs-Inflation: Efficient Reheating after ~ 100 osc.: Param. Resonance initially blocked, later active. Backreaction important.
5. MSSM-Inflation: Efficient Reheating achieved after ~ 20 oscillations Backreaction is negligible, Thermalization ($T_{\rm rh} \sim 10^8$ GeV)
6. THANKS 4 YOUR ATTENTION!!!

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BACK SLIDES

BackReaction in HIGGS-INFLATION Reheating

BACKREACTION

$$\omega^2 \approx M^2 + \frac{\alpha g_W \, n_W(j)}{2\sqrt{\xi}|\chi|} \frac{1}{(\alpha\kappa|\chi|)^{1/2}} + \frac{\alpha g_Z \, n_Z(j)}{2\sqrt{\xi}|\chi|} \frac{1}{(\alpha\kappa|\chi|)^{1/2}}$$

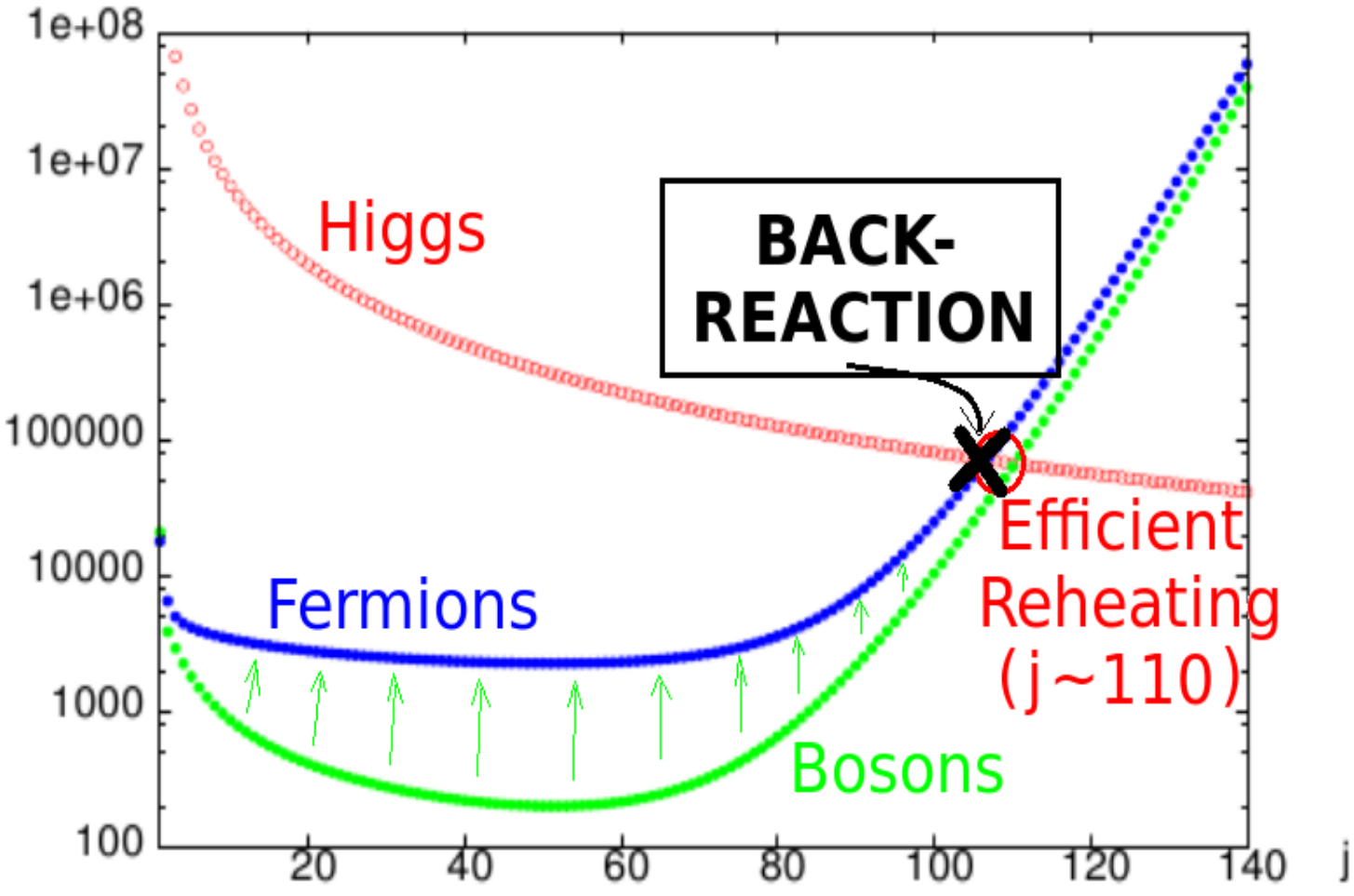
HIGGS EFFECTIVE FREQUENCY

$\omega^2((j_{\rm backr})) \approx 2\,M^2 \quad \Rightarrow$

λ	0.2	0.4	0.6	0.8	1.0
$j_{\rm backr}$	107	110	112	113	114

$j_{\rm backr} < j_{\rm eff}$:BackReaction occurs earlier than Efficient Reheating!:
We can not trust previous stimations of Efficient Reheating!

BackReaction in HIGGS-INFLATION Reheating



BackReaction in HIGGS-INFLATION Reheating