Reheating After Multifield Inflation

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This work is dedicated to the memory of Lev Kofman.

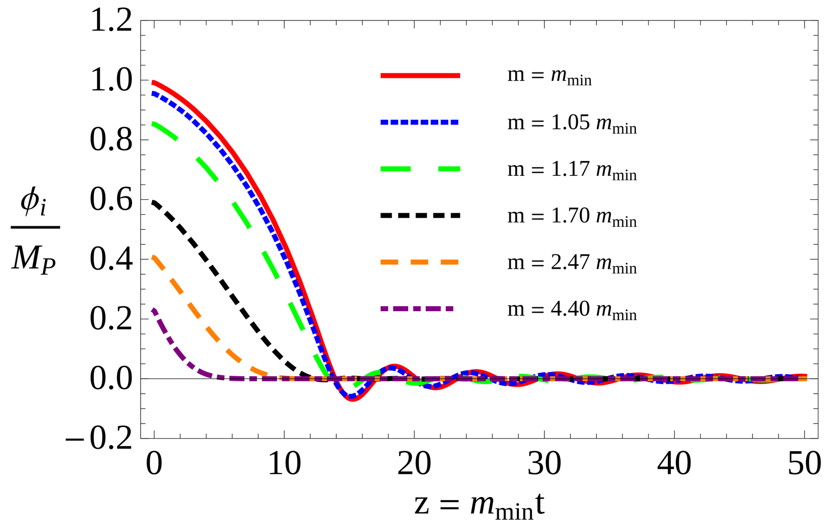
Introduction

A reheating mechanism is required in any inflationary model to transfer energy to the Standard Model and start the hot big bang. This process has been well-studied when only a single or, at most, a few inflatons are relevant during reheating; much less is known about the dynamics if energy is distributed among many inflatons at the end of inflation. Here, we investigate the reheating dynamics in a simple model of multi-field inflation.

Inflation and Reheating Model

Inflaton potential:

$$V(\phi_1, \cdots, \phi_N) = \sum V_i(\phi_i) = \sum \frac{1}{2} m_i^2 \phi_i^2$$



During reheating

$$\phi_i \simeq \frac{\phi_{0,i}}{a^{3/2}} \sin(m_i t + \theta_i)$$

Fig. 1: Dynamics of homogeneous inflaton condensates.

Couple inflatons to one additional light scalar "matter" field χ.
Inflaton mass diagonalization $\rightarrow$ interaction mixing.

$$\mathcal{L}_{int} = -\sum \frac{g_i^2 \phi_i^2}{2} \chi^2 - \sum \frac{\sigma_i \phi_i}{2} \chi^2$$

Formalism: Mode Functions

- Quantum fluctuations of "matter" field obey mode equation

$$\frac{d^2}{dt^2}(a^{3/2}\chi_k) + \left(\frac{k^2}{a^2} + \sum \frac{g_i^2 \phi_{0,i}^2}{a^3} \sin^2(m_i t + \theta_i) + \frac{\sigma_i \phi_{0,i}}{a^{3/2}} \sin(m_i t + \theta_i) \right) (a^{3/2}\chi_k) = 0$$

- Growth of mode functions indicates particle production.
  - Adiabaticity violation: $\dot{\omega}/\omega^2 \gtrsim 1$ (parametric resonance)
  - Tachyonic mass: $\omega^2 < 0$ (tachyonic resonance)

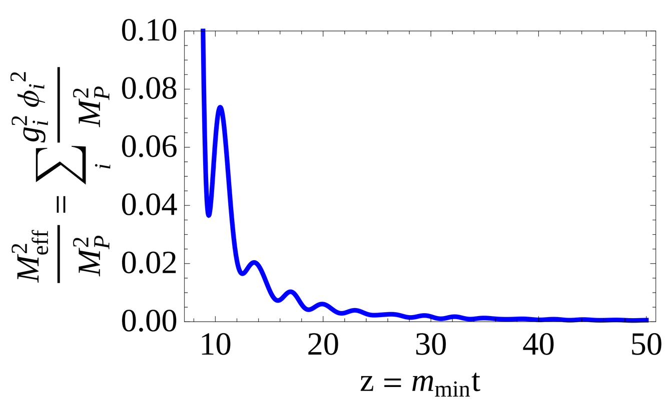


Fig. 2: Typical M_{eff}^2 for 4-legs interaction.

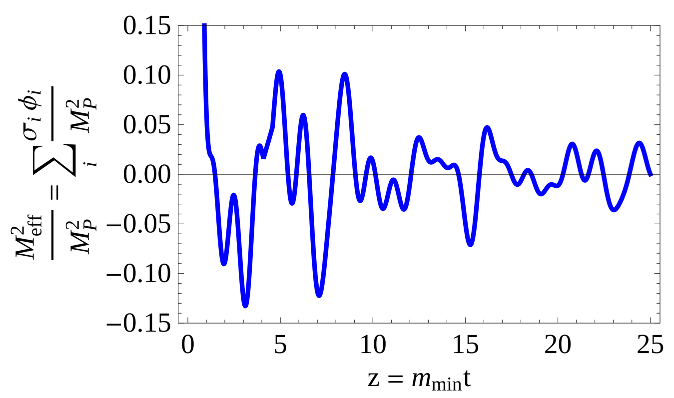


Fig. 3: M_{eff}^2 for 3-legs interaction and 5 fields.

- Adiabaticity never violated for 4-legs interaction $\rightarrow$ no preheating.
- Tachyonic regimes for 3-legs effective mass.

The Quasiperiodic Mathieu Equation

Evolution of quantum fluctuations resembles quasiperiodic Mathieu equation.

$$\frac{d^2 X}{dz^2} + \left(A(z) + \sum 2q_i(z) \cos\left(2\frac{m_i}{m} z + \theta_i \right) \right) X = 0$$

For certain values of A, q, modes grow exponentially $X \sim e^{\mu z}$.

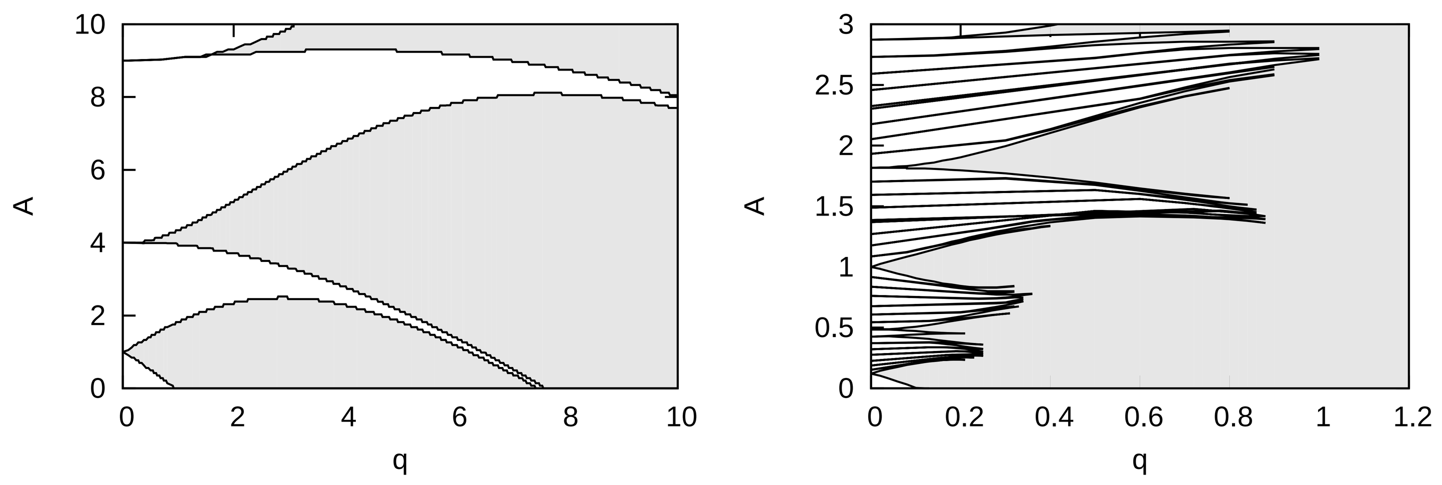


Fig. 4: Stability diagram for **Left:** single oscillator (Mathieu equation) and **Right:** 2 oscillators with $m_2 = 0.3475 m_1$ and $q_1 = q_2 \equiv q$ (QP Mathieu equation). Solutions for parameters in shaded regions are unstable.

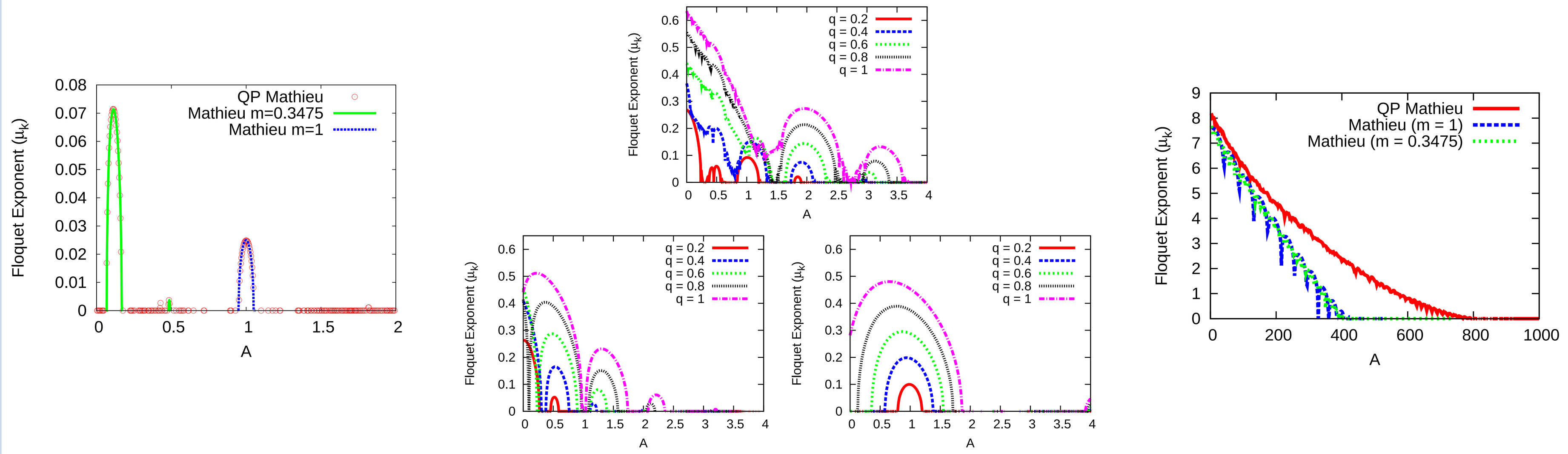


Fig. 5: Floquet exponents for **Left:** small q, **Center:** intermediate q, and **Right:** large q.

- **Small q:** New instability "tongues" relative to single field.
- **Intermediate q:** Instability regions overlap.
- **Large q:** Instability stronger than single field case.

3-legs Interaction (Preheating Possible)

$$A_k = \frac{4k^2}{m^2 a^2} \quad , \quad q_i = \frac{2\sigma_i \phi_{0,i}}{m^2 a^{3/2}}$$

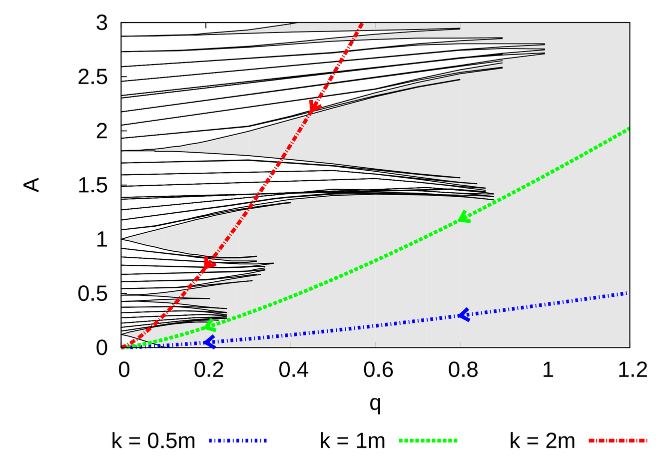


Fig. 6: Paths followed by resonance parameters with $g_i^2 = 0$.

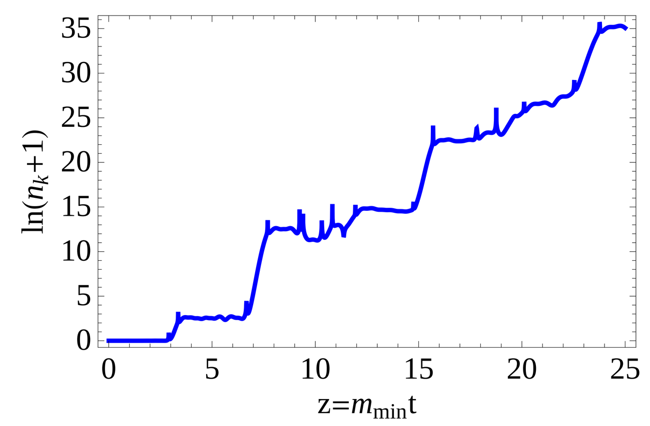


Fig. 7: Growth of particle occupation number for $k = 40m$ mode and M_{eff}^2 from Fig. 3.

- Rapid growth of particle occupation numbers due to tachyonic resonance.

4-legs Interaction (Perturbative Decays)

$$A_k = \frac{k^2}{m^2 a^2} + \sum_i 2q_i \; , \; q_i = \frac{g_i^2 \phi_{0,i}^2}{4m^2 a^3} \quad \rightarrow \quad A_k \geq \sum 2q_i$$

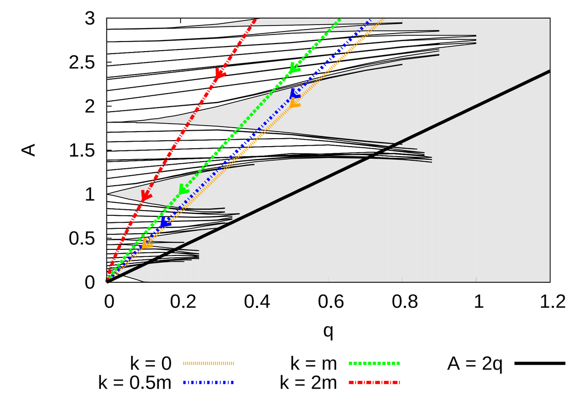


Fig. 8: Paths followed by resonance parameters with $\sigma_i = 0$.

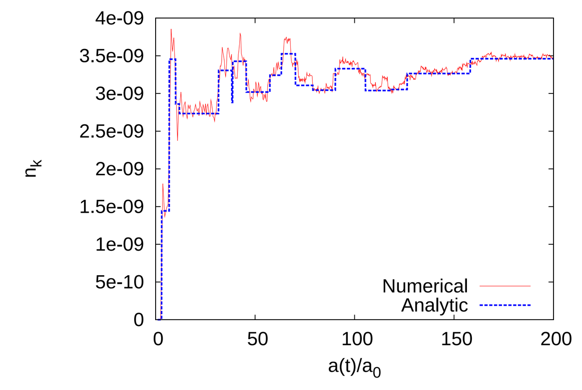


Fig. 9: Typical evolution of particle number with $N = 20$ inflatons.

- Mode functions experience weak resonance $\rightarrow$ perturbative decays.

Perturbative Decays

- For small resonance parameters, we can identify each tongue with a Feynman diagram.
- Analytic solution gives

$$\frac{1}{a^4}\frac{d}{dt}(a^4 \rho_\chi) = \sum \frac{g_i^4}{32\pi m_i^3} \rho_{\phi_i}^2 + \sum \frac{\sigma_i^2}{32\pi m_i} \rho_{\phi_i} + (\text{oscillating terms})$$

- Oscillating piece from QM interference (inflaton condensate *not* particles).
  - Time average is zero $\rightarrow$ looks like particle decays/annihilations.
- 4-legs decays never complete, need 3-legs interactions.

Summary / Conclusions

- Reheating dynamics with many inflatons approximated by quasiperiodic Mathieu equation.
- 4-legs coupling perturbative and incomplete.
- 3-legs coupling can be non-perturbative and does complete.
- Condensate nature of inflaton leads to QM interference

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