Reheating, Preheating, and Thermalization:
Getting the Bang from Inflation

Patrick B. Greene
Assistant Prof., UTSA
& Visitor w/ Weinberg Theory Group

(work with Kofman, Linde, Starobinsky,
Felder, Kadota...)

1st Texas Cosmology Network Meeting, Austin, 15 Sep. 2006

What is Reheating?

Inflation leaves the early universe <u>Cold and Empty</u>
(All energy is in the inflaton)*

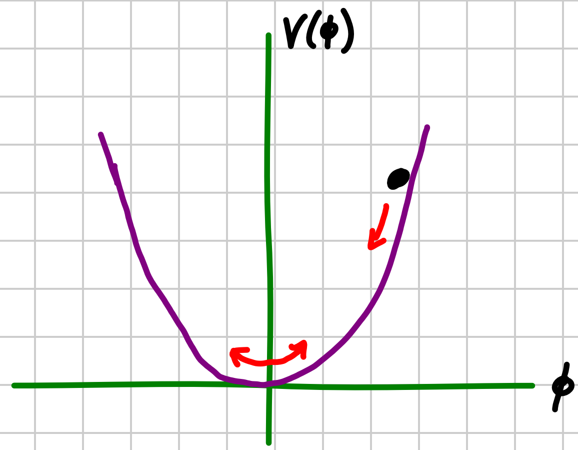
But hot, Big Bang cosmology works, so this state must not be the whole story.

Conclusion: The inflaton must transfer it's energy to a radiation dominated plasma in LTE at a temperature sufficient to allow standard nucleosythesis. So, the universe must be "heated" or "reheated" after inflation.

How to Reheat?

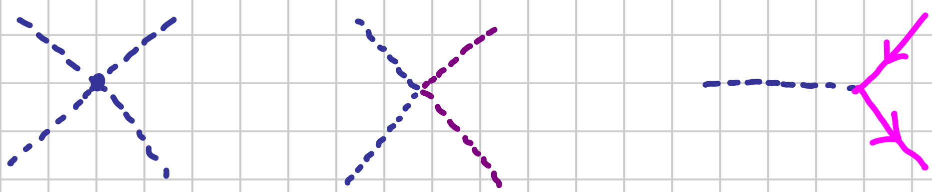
The inflaton couples (weakly!) to other lighter fields and to itself. Thus, it can decay.

Example: Chaotic Inflation



$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

$$\mathcal{L}_{int} = \frac{\lambda}{4!}\phi^4 + \frac{1}{2}\Big(\sum_i g_i^2 \chi_i^2\Big)\phi^2 + \Big(\sum_{ij} h_{ij} \bar{\psi}_i \psi_j\Big)\phi$$



The Standard Lore
(Perturbative Reheating)

The oscillating inflaton field can be treated as a condensate of inflaton particles. Each decays perturbatively at some rate, Γ_ϕ.

A four step process ensues:

A. The inflaton decays and redshifts.

B. The decay products interact and redshift.

C. When the loss due to decay exceeds that due to redshifting, $H \lesssim \Gamma_\phi$, the decay products come to dominate quickly.

C'. The decay products can thermalize before or after they dominate.

Some Complications

a) It can be that $T_{MAX} \gg T_{RH}$ (D. Chung, Kolb, et al)

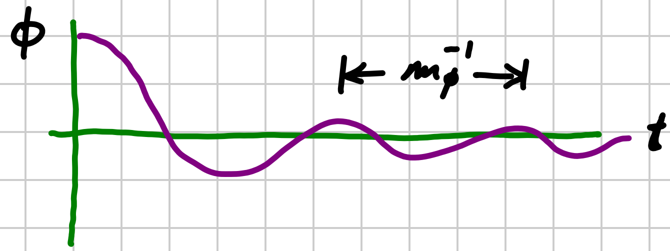
b) In some models, $H > \Gamma_\phi$ always, so perturbative reheating doesn't happen. (Kofman, Linde, ...)

c) Thermalization can be incomplete.
e.g. LK(inetic)E but not LC(hemical)E
or completely non-thermal relics

Enter Preheating!

However, the standard story is incomplete:

1. A small coupling constant does not guarantee that perturbation theory is accurate.
2. The inflaton is a coherently oscillating field with a large amplitude. It is not an incoherent "gas" of scalar particles.



e.g. Chaotic inflation again:

$$\mathcal{L}_{int} = \frac{1}{2} g^2 \chi^2 \phi^2$$

$$|\Phi| \sim M_{pl}$$

$$m_\phi \sim 10^{-6} M_{pl}$$

Res. param. $q \equiv \frac{g^2 \phi^2}{m_\phi^2} \sim g^2 10^{12}$!!!

Quantum Field Theory in Strong Background Fields

If the decay is non-perturbative, what do we do?

Answer: Look at the evolution of quantum fluctuations in the presence of the classical background $\hat{\chi}_k$ $\Phi(t) = \langle \hat{\phi} \rangle$

$$\chi_k'' + 3\frac{H}{m_\phi}\chi_k' + \left(\frac{k^2}{m_\phi^2} + \frac{g^2\Phi^2}{m_\phi^2}\right)\chi_k = 0$$

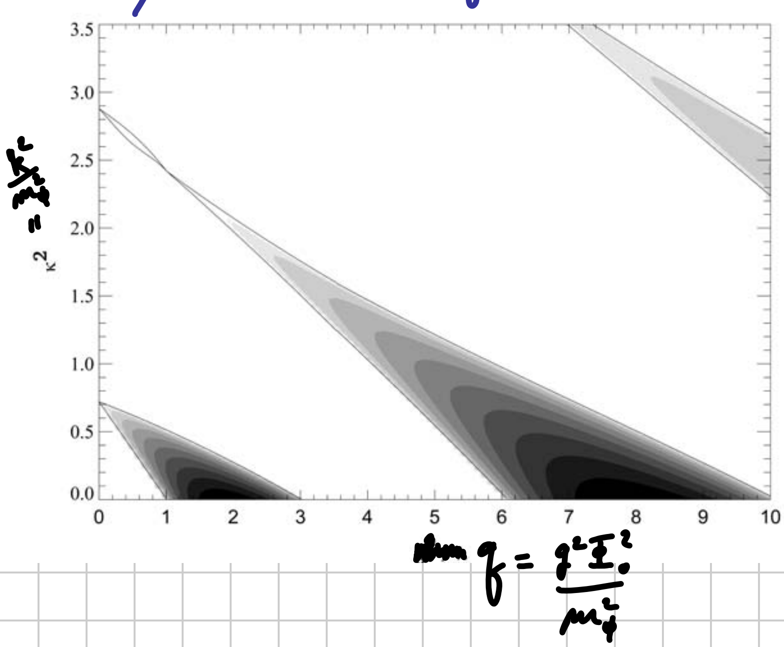
If we ignore expansion for a moment:

$$\chi_k \sim e^{\pm \mu_k m_\phi t}$$

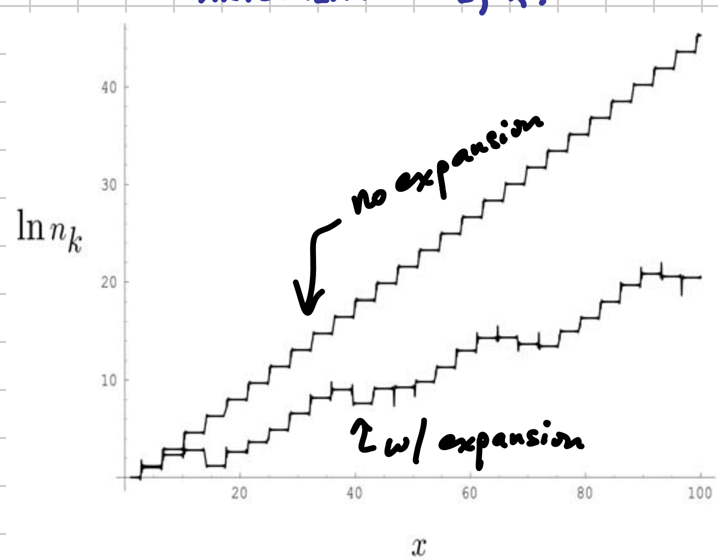
← Floquet index (μ_k)

Conclusion: some modes of the field will grow exponentially! Hence, the occupation number of particles in these modes grows exponentially!

$\mathrm{Re}(\mu_k)$ FOR VARIOUS q, k



ONE PARTICULAR MODE, k.



Backreaction/Rescattering

Preheating leads to exponentially large occupation numbers in certain bosonic modes with well defined phase relations. These are just classical waves!

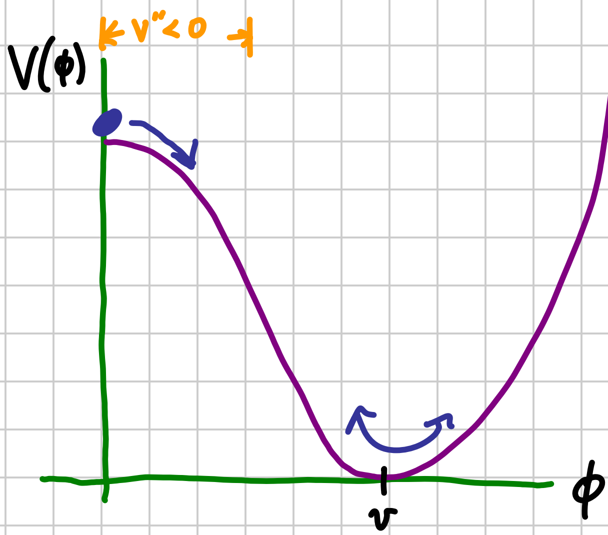
Hence, we can study mode-mode interactions (aka rescattering) and the backreaction on the inflaton itself using classical scalar field theory.

Felder and Tkachev have developed LatticeEASY to solve classical scalar wave equations in FRW spacetimes.

Preheating is Ubiquitous!

Preheating is a stage of classical wave scattering with a non-thermal spectrum. (Also, fermionic preheating!)

Tachyonic Preheating occurs when there are spinodal instabilities, e.g. in Hybrid Inflation



$$n_k \sim e^{2\omega_k t}$$

$$\omega_k^2 = |V''| - k^2$$

Open Issues?

Current picture of reheating:

Preheating => Rescattering => ??? => Thermalization

1. We still don't know the reheating temperature!

2. It is difficult to follow the rescattering process for long times. What happens: Turbulence and scaling?
An effective equation of state? (Tkachev & Mischa, Felder & Kofman, etc.)

3. Relic production during Preheating has been studied. What about during rescattering? (Similar to bubble collision problem!)