Inhomogeneous preheating in multi-field models

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Abstract

We consider an inhomogeneous preheating in multi-field models. After preheating, there are two fields trapped at the ESP. One is the oscillating field ϕ_1 and the other is the light field ϕ_2 that plays important role in generating the perturbation. We consider two types of the potential for the light field,

$$V(\phi_2) = \begin{cases} -\frac{1}{2}m^2\phi_2^2 + \lambda\frac{\phi_2^n}{M^{n-4}} & \sim 1.\ \text{Shoulder Inflation} \\ \frac{\Lambda}{\phi_2^n} & \sim 2.\ \text{Quintessence} \end{cases} \tag{1}$$

Motivation for the "Alternatives"

Traditional Scenario

According to the traditional inflationary scenario, the spectrum of the curvature perturbation is generated by the inflaton field.

$\downarrow$

The spectrum is essentially determined by the inflation model alone.

"Alternatives" to the traditional inflation

Of course, the traditional scenario is **not** the only way to generate the cosmological perturbation. The primordial density perturbation may instead originate from the vacuum fluctuation of "non-inflaton" field.

$\downarrow$

We introduce ϕ_2 as the non-inflaton field .

Our expectation is...

Considering alternatives to the traditional scenario, the inflation model is liberated from the generation of the curvature perturbation.
Thus, the inflation may be liberated from the problems related to the generation of cosmological perturbation.

Problem in Low-scale Inflation (Typical example)

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{1}{24\pi^2 M_p^4}\frac{V_I}{\epsilon_I} \quad \text{(Traditional Inflation)}$$

Assuming that the scale of inflation is much smaller than the Planck scale, one will encounter a serious fine-tuning;

$$V_I^{1/4} \sim 10^7 GeV \quad \rightarrow \epsilon_I \sim 2.7 \times 10^{-13}$$

∗ Low-scale gravity model is still an important possibility that could be tested in future experiments. This may put a bound around $V_I^{1/4} \sim \mathcal{O}(\mathrm{TeV})$.

These are "Alternatives" to the traditional inflation

- Curvatons
- Inhomogeneous Reheating
- Inhomogeneous Preheating
- Generating δN_e at the end of inflation
- and others...(They are equally important)

In this talk, we will mainly consider Inhomogeneous Preheating combined with Curvatons or δN_e generation at the end of Inflation.

What is the "Inhomogeneous Preheating"?

1. We will start with

   "Simple Preheating",

and then add a field ϕ_2 to discuss

   "Multi-field Preheating".

2. Then we will explain how the

   "Multi-field Preheating"

induces

   "Inhomogeneous Preheating".

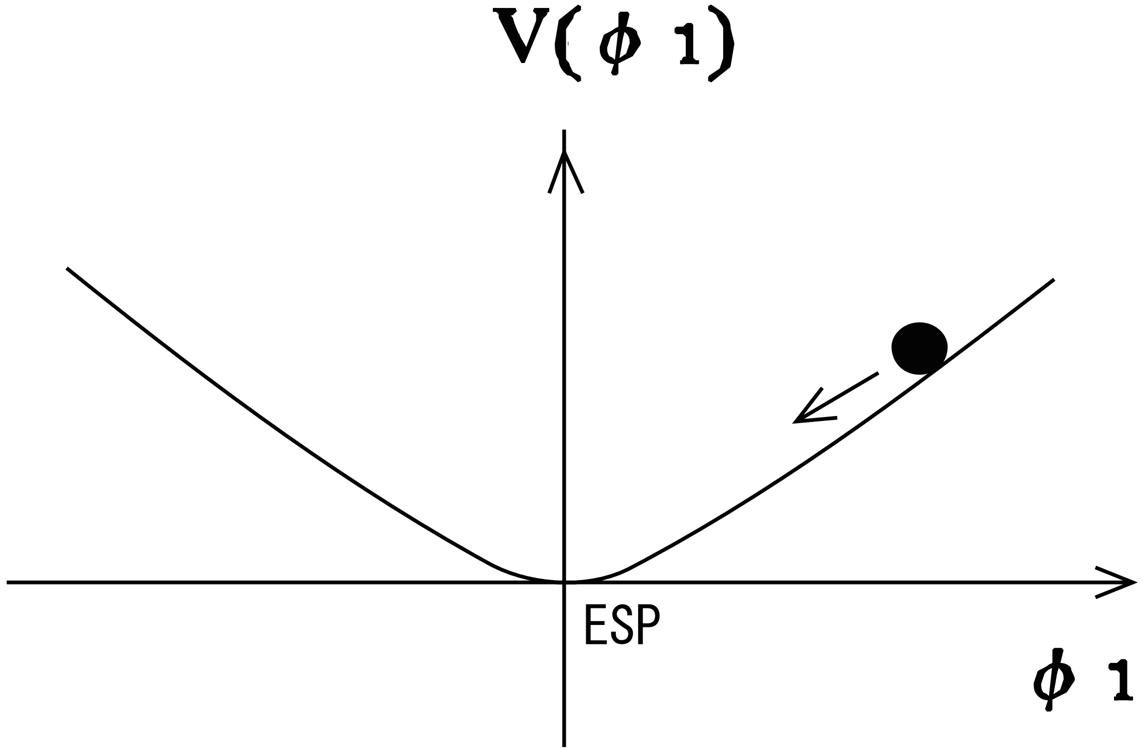
3. Finally, we will discuss

   "generation of the cosmological perturbation"

from "Inhomogeneous Preheating" combined with "Curvatons" or "δN_e generation".

Preheating : (*Kofman, Linde, Starobinsky '97*)

"Preheating" is induced by an oscillating field ϕ_1(usually an inflaton).



We will assume that that there is an interaction given by

$$\mathcal{L} = -\frac{1}{2} g^2 |\phi_1|^2 \chi^2. \qquad (2)$$

Preheating

At the ESP the effective mass of the preheat field vanishes, and there is Non-adiabatic Excitation of χ.

$\downarrow$ Efficient generation of the preheat field χ

The number density of the preheat field n_χ that is generated at the first scattering is given by

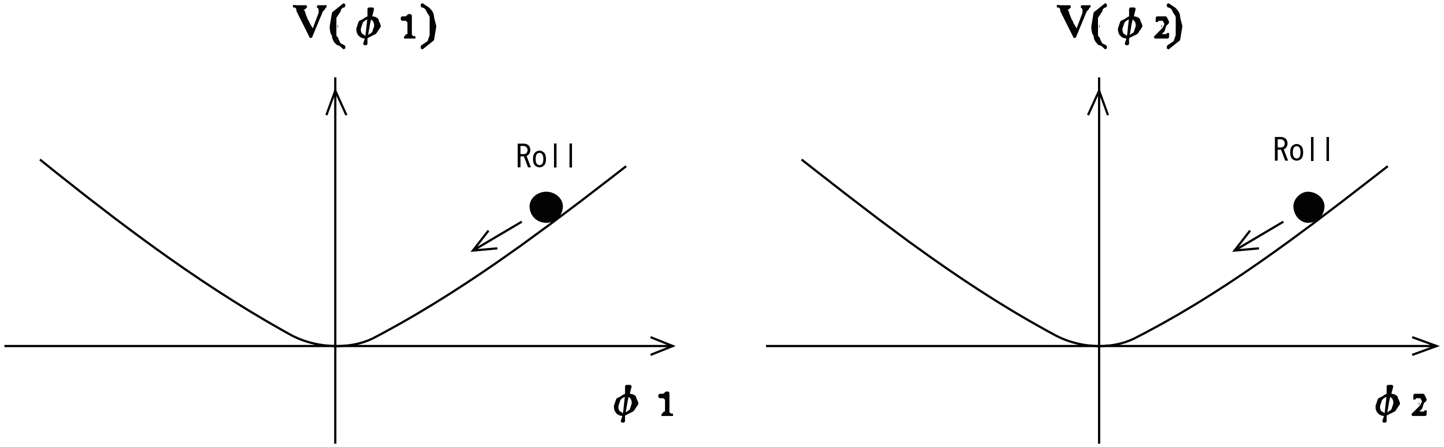
$$n_\chi = \frac{(g|\dot{\phi}_1(t_*)|)^{3/2}}{8\pi^3} \exp\left[-\frac{\pi m_\chi^2}{g|\dot{\phi}_1(t_*)|}\right]. \tag{3}$$

$\downarrow$

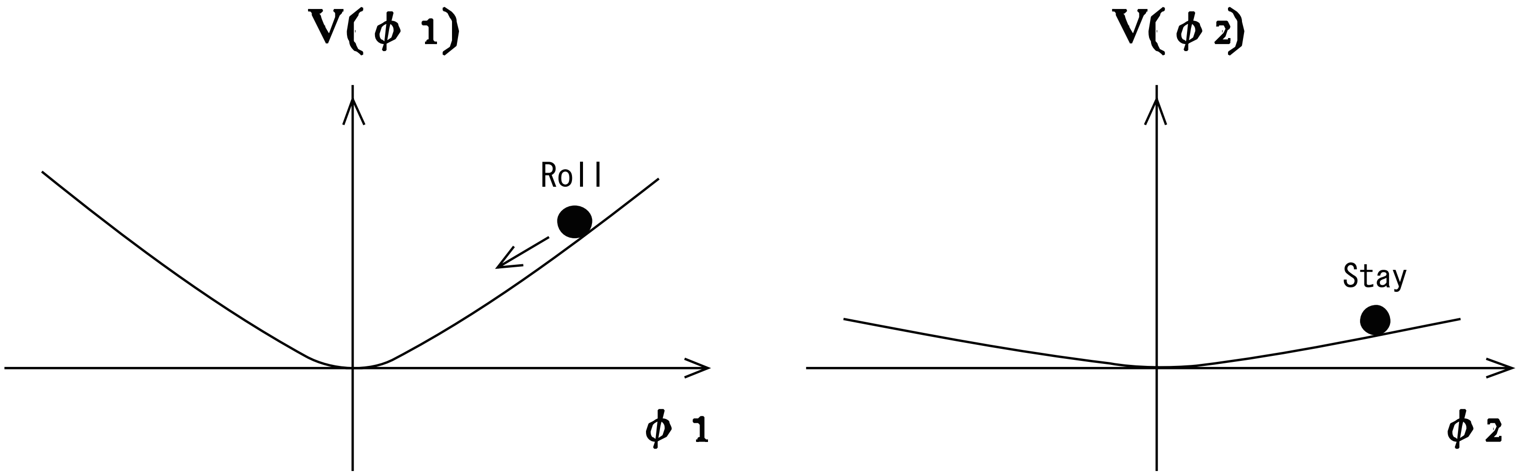
Besides the oscillating field ϕ_1, one may **add ϕ_2** that has the same coupling as ϕ_1. This leads to

Multi-Field Preheating (continue $\rightarrow$).

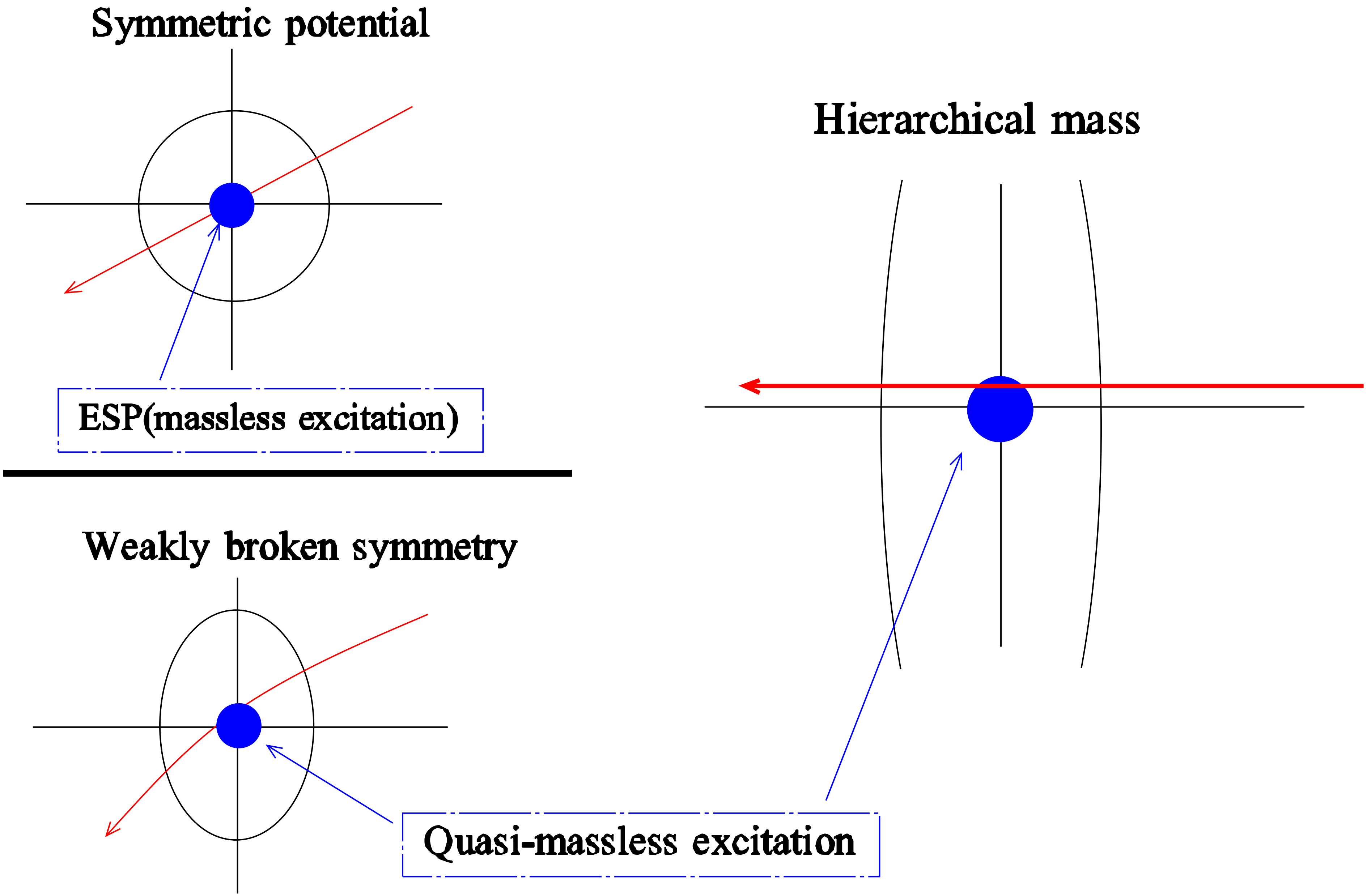
↓ Symmetric potential $V(\phi_1, \phi_2)$



↓ Global Symmetry is badly broken (Hierarchical mass difference)



Oscillation Trajectory of the multi-field preheating



Origin of the fluctuation in Multi-Field Preheating

Except for the symmetric potential in which the trajectory hits precisely at the origin, the effective mass m_χ does not vanish during preheating, and it depends on the initial condition $m_\chi(\theta)$ or $m_\chi(\phi_2)$.

For the "slightly broken symmetry", the origin of the fluctuation is denoted by $\delta\theta$. ($\sim \theta$ is the $U(1)$ angle)

For the "hierarchical mass", the origin of the fluctuation is denoted by $\delta\phi_2$. ($\sim \phi_2$ is the additional light field)

These are the fluctuation on the equipotential surface, and they will lead to the fluctuation of δm_χ, which leads to the fluctuation of the number density δn_χ.

Note that there is the relation

$$n_\chi = \frac{(g|\dot{\phi}_1(t_*)|)^{3/2}}{8\pi^3} \exp\left[-\frac{\pi {m_\chi}^2}{g|\dot{\phi}_1(t_*)|}\right]. \tag{4}$$

In the "hierarchical mass" model the light field ϕ_2 gives mass to the preheat field at the ESP;

$$m_\chi|_{ESP} \simeq g\phi_2 \tag{5}$$

Therefore, the primordial fluctuation $\delta\phi_2$ will lead to the fluctuation of the mass δm_χ, which finally induces inhomogeneous preheating and $\delta n_\chi \neq 0$.

$\ast$ The magnitude and the typical length scale of the fluctuation $\delta\phi_2$ is determined by the primordial inflation. Note that $\delta\phi_2$ is **generated and exits horizon during the primordial inflation**.

Previous approaches (Instant decay is assumed)

1. Slightly broken symmetry

E. W. Kolb, A. Riotto, A. Vallinotto.

∗ The origin of the fluctuation is $\delta\theta$.

2. Hierarchical mass difference(Badly broken symmetry)

T. Matsuda.

∗ The origin of the fluctuation is $\delta\phi_2$.

∗ In these models χ is assumed to decay instantaneously after preheating. Generation of the cosmological perturbation and the reheating occurs just after the Inhomogeneous preheating. $\left.\frac{\rho_\chi}{\rho_{total}}\right|_{ini} \sim 1$ is needed.

↓

What if χ does **not** decay instantaneously?

Is it possible to remove the condition $\left.\frac{\rho_\chi}{\rho_{total}}\right|_{ini} \sim 1$?

Back reaction from the preheat field

The effective potential induced by the stable χ-field induces an attractive confining force to both ϕ_1 and ϕ_2. For the single-field preheating, a similar situation has been discussed by

Moduli Trapping (* Single field)

L. Kofman, A. Linde, X. Liu, A. Maloney, L. McAllister, E. Silverstein

The preheat field induces confining potential $V_c(\phi_i) \sim g n_\chi |\phi_i|$.

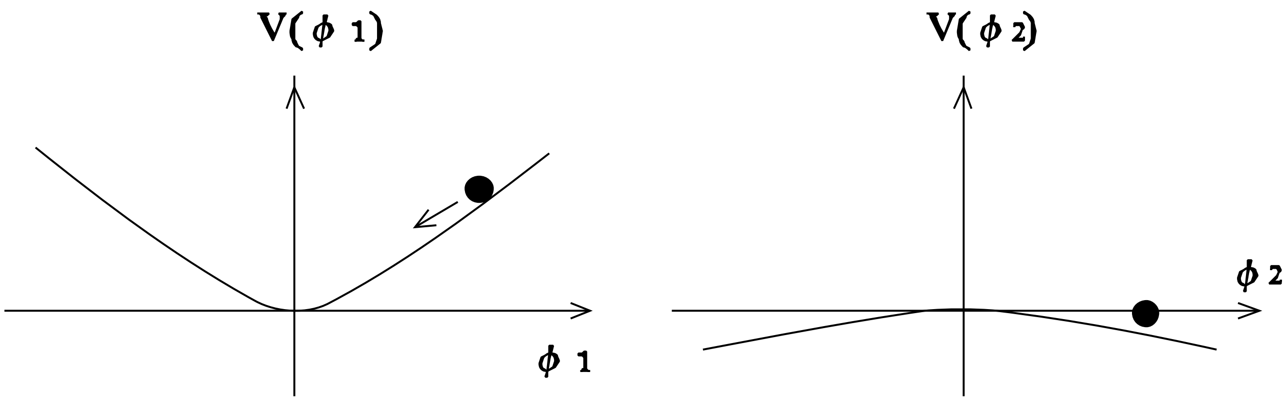
We use this "Trapping" to generate the cosmological perturbation from inhomogeneous preheating.

1. We do not assume instant decay.
2. We do not assume $\left.\frac{\rho_\chi}{\rho_{total}}\right|_{ini} \sim 1$.

“Trapping” after “Inhomogeneous Preheating”

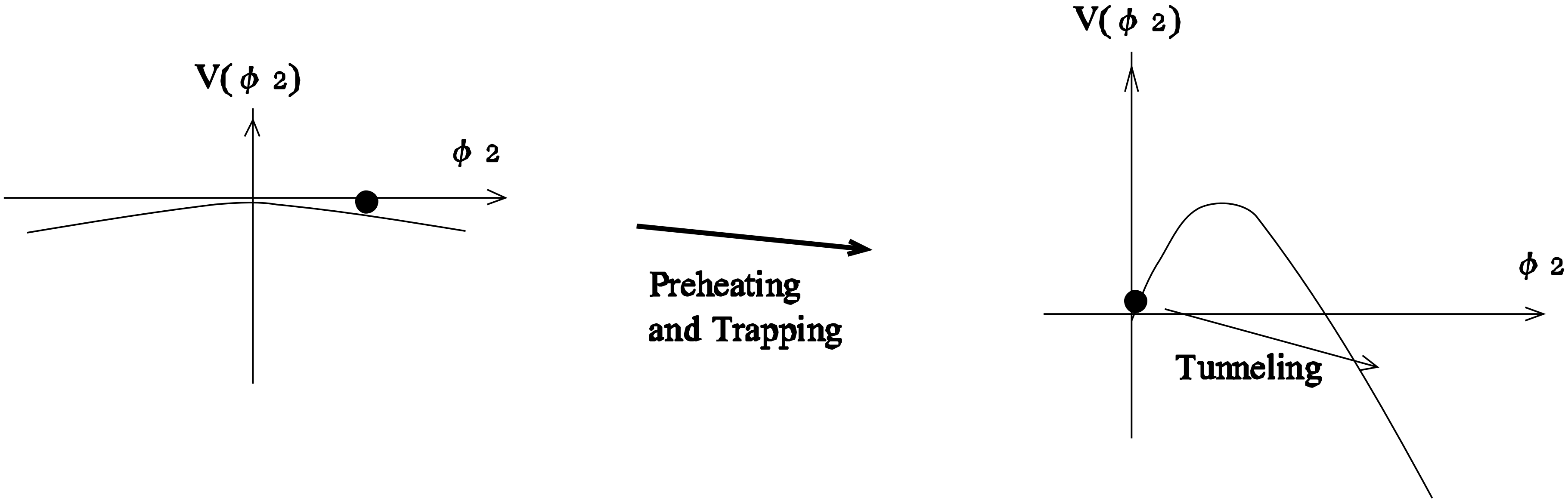
First, we will discuss how to generate δN_e at the end of Trapping Inflation with the potential:

$$V(\phi_2) = -\frac{1}{2}m^2\phi_2^2 + \lambda\frac{\phi_2^n}{M^{n-4}} \quad (6)$$

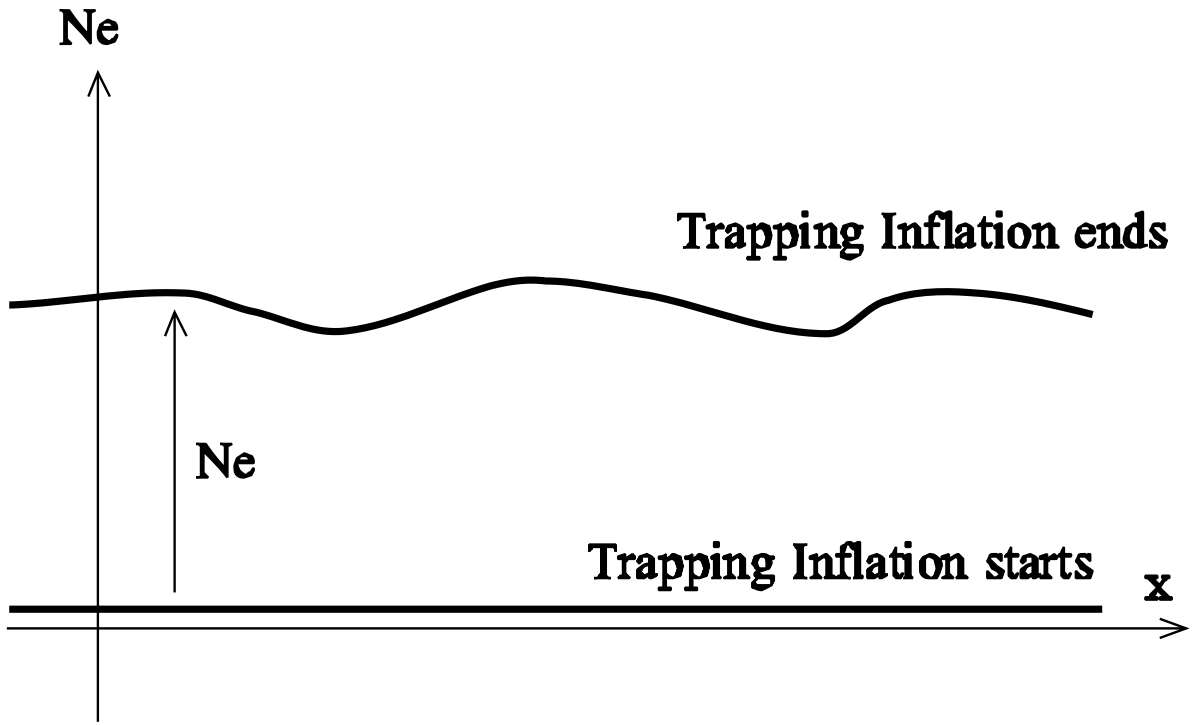


“Thermal Inflation” is induced by “Thermal Trapping”, while “Trapping Inflation” is induced by “Trapping after Preheating”.

Model 1. Generating δN_e at the end of trapping inflation.



- Preheating occurs due to the ϕ_1-oscillation, while the trapping occurs for both fields.
- ϕ_2 is trapped at the local minimum.
- The potential barrier ΔV decreases as $\Delta V \propto n_\chi^2$. Trapping Inflaton ends with the ϕ_2-tunneling.



Generating δN_e from δn_χ

The start-line of the trapping inflation is independent of the fluctuation δn_χ and is given by the flat surface (the straight line at $N_e = 0$). On the other hand, the end-line is determined by the number density of the preheat field χ, which has the fluctuation δn_χ. Please remember that Trapping inflation is **not** the primary inflation but an additional inflationary stage.

Calculations

During trapping inflation, $V^{eff}(\phi_2)$ is given by

$$V_2^{eff}(\phi_2) = V_0 - \frac{1}{2}m^2\phi_2^2 + \frac{\lambda|\phi_2|^{n_2}}{M_2^{n_2-4}} + gn_\chi|\phi_2|. \tag{7}$$

Looking at the effective potential near the origin, the effective potential for $\phi_2 > 0$ is written as

$$V_2^{eff}(\phi_2) \simeq V_0 - \frac{1}{2}m^2\left(\phi_2 - \frac{gn_\chi}{m^2}\right)^2 + \frac{g^2n_\chi^2}{2m^2}. \tag{8}$$

The tunneling occurs when

$$B \sim \frac{(\Delta\phi_2)^4}{\Delta V} \sim 1. \tag{9}$$

Trapping inflation will be terminated when n_χ decreases with time and finally the tunneling from $\phi_2 = 0$ to $\phi_2 > 2\Delta\phi_2 \equiv 2gn_\chi/m^2$ occurs. Therefore, trapping inflation will be terminated when n_χ is diluted down to $n_\chi < m^3/g$. The number of e-foldings elapsed during the trapping inflation is given by

$$N_e \sim \frac{1}{3}\ln\left(\frac{n_\chi(t_i)}{n_\chi(t_e)}\right). \tag{10}$$

δN_e generated at the end of inflation is

$$\delta N_e \sim \frac{g\phi_2\delta\phi_2}{v}, \tag{11}$$

where v is the velocity of the oscillating field at the ESP.

Result:

Low-scale inflation ($H_I \sim GeV$) is successful

$$H_I > 10^{-5}\sqrt{\frac{m_1\phi_1}{g}}. \tag{12}$$

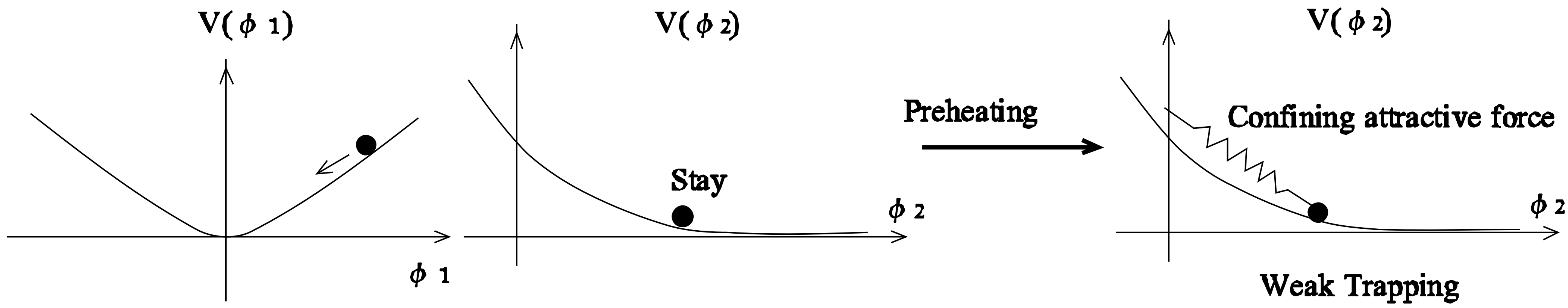
Non-Gaussian parameter is always large $|f_{NL}| > 1$

$$-\frac{3}{5}f_{NL} \simeq \frac{3v}{4\pi g\phi_2^2} - \frac{3}{2}, \tag{13}$$

Unfortunately, these results depend crucially on the initial condition.

Model 2. Weak trapping and Non-Oscillating(NO) Curvatons

$$V(\phi_2) = \frac{\Lambda}{(\phi_2)^n} \tag{14}$$



1. "Preheat Field χ" is identified with the curvatons .

2. There is the back reaction from the preheat field($=$ Curvatons).

The late-time evolution is obtained from the force-balance equation

$$g n_\chi(t) - \frac{n M^{n+4}}{\phi_2^{n+1}} = 0, \tag{15}$$

which leads to the evolution of the expectation value $\phi_2(t)$,

$$\phi_2(t) = M \left(\frac{n M^3}{g n_\chi(t)} \right)^{1/(n+1)} . \tag{16}$$

From these equations we can calculate the ratio of ρ_χ to $V(\phi_2)$

$$\frac{\rho_\chi}{V(\phi_2)} = n. \tag{17}$$

Since the number density n_χ evolves as $n_\chi \propto a^{-3}$, the energy density of the preheat field ρ_χ will evolve as

$$\rho_\chi \propto a^{-3\left(1-\frac{1}{n+1}\right)}. \tag{18}$$

Note that the mass of the curvaton m_χ grows as

$$m_\chi \simeq g\phi_2(t) \propto a^{\frac{3}{n+1}}. \tag{19}$$

The obvious difference from the normal curvaton is

1. The time of the "Oscillation" is determined by the mass of the oscillating field ϕ_1, which is independent of the curvaton mass m_χ. (ϕ_1 may or may not be inflaton)

2. The time of the "Curvaton Decay" is determined by $m_\chi(t)$, which grows with time.

3. The density of the NO curvaton decreases slower than the matter density.

As a result, the cosmological bound for the NO curvaton is very different from the normal curvaton.

Example:

For the Quintessential potential

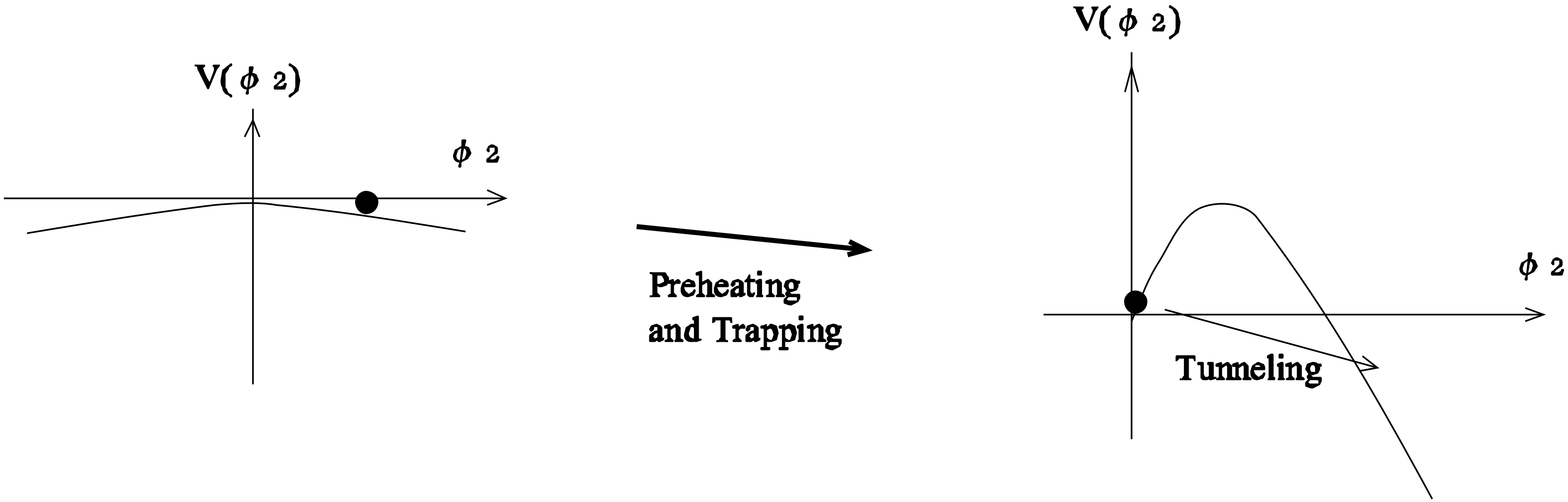
$$V(\phi_2) = \frac{M^8}{(\phi_2)^4}, \qquad M = 10^2 GeV \tag{20}$$

we obtained $T_R \simeq 1$MeV.

There is no obvious bound for the Hubble parameter above $H_I \sim \mathcal{O}$(GeV), but the results depend crucially on the initial condition.

Conclusions and summary

Model 1. "Inhomogeneous Preheating" + "Trapping Inflation"

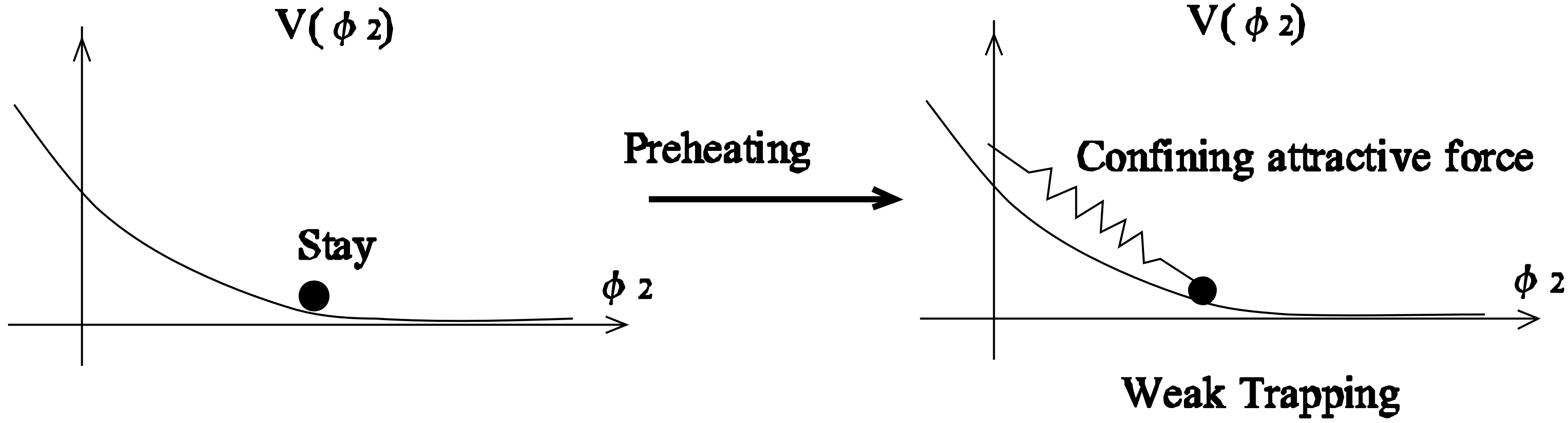


1. The primordial fluctuation $\delta\phi_2$ leads to the fluctuation of the mass of the preheat field δm_χ.

2. δm_χ induces δn_χ through "Inhomogeneous Preheating".

3. δn_χ leads to the fluctuation δN_e at the end of the trapping inflation.

Model 2. "Inhomogeneous Preheating" + "Curvatons"



1. The curvaton is generated by the ϕ_1-oscillation. $(\rho_\chi \simeq \rho_{\phi_1} \simeq H_{osc}^2 \phi_1^2)$
   The NO curvaton is liberated from the usual condition $H_{osc} \simeq m_\chi(t_{osc})$.

2. ϕ_2(quintessence) feels attractive force $F_c \simeq g n_\chi \propto a^{-3}$ till the curvaton decay.

3. Even if ρ_χ is initially a small fraction of the total, it grows with time.(Not due to the kinetic energy damping in usual quintessential inflation. There is no such damping.)

4. The curvaton decay is determined by $m_\chi(t)$, which grows with time.

As a result, we conclude that "Inhomogeneous Preheating" is an interesting possibility. The traditional scenario for generating cosmological perturbations can be replaced by these "Alternatives".

Future cosmological observations should distinguish these Alternatives. Non-Gaussianity may be the key observation, but we need more efficient way to pick up THE ONE.

To be continued...