Entropy production and curvature perturbation from **Dissipative curvatons/** **arXiv:1008.0164 and 1007.3636**

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Abstract

We will consider a scenario when curvaton field ϕ has significant interaction with heavy "catalyst "field χ, which leads to strong **dissipation**.

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This would be the first attempt to realize **Dissipative curvatons**

We propose new scenarios of generating curvature perturbations when curvatons dissipate.

Before discussing the main subject, it would be better to explain :
"What is the **Dissipation** considered in this scenario?"
Let me explain a few basic ideas for the model$\rightarrow$

In this talk, we will consider the curvaton field that follows

The dissipative field equation

$$\ddot{\phi} + 3H(1 + r_\Upsilon)\dot{\phi}_N + V(\phi_N, T)_{\phi_N} = 0 \quad (1)$$

Here the frictional force $\Upsilon\dot{\phi} \equiv [3Hr_\Upsilon]\dot{\phi}$ is caused by the dissipation.

This term reminds us of the conventional air resistance. One will be satisfied with this term, **But** there had been some **Debate** on the origin and its significance.

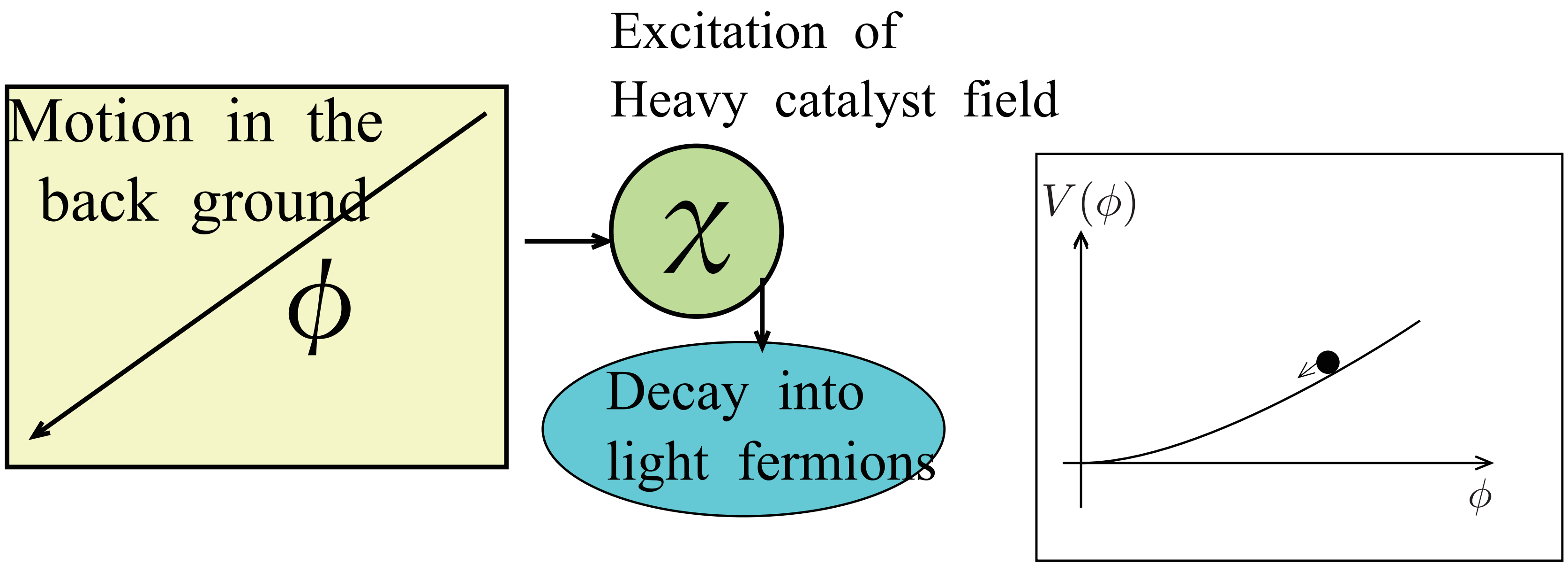
In this talk, we will not touch upon historical delicate issues; there are many debates for the quantum ($T = 0$) and the thermal ($T \neq 0$) dissipation. The difficulties arise because the dissipation is basically caused by the non-local dynamics (time-integral) of the field. Also, conventional perturbative expansion may fail.

SUSY two-step model is expected to alleviate these difficulties. We will always consider this model. However, obtaining **exact** analytic solution for the dissipation coefficient is (probably) impossible.→ More...

Two-step model

Dissipative Curvaton ϕ couples to catalyst field χ by the interaction given by (* we are implicitly considering "SUSY version")

$$\mathcal{L}_{int} \sim \frac{1}{2} g^2 (\phi - v)^2 \chi^2 + h\chi\overline{\psi}\psi. \qquad (2)$$



Radiation-ϕ interactions are suppressed when the intermediate field χ is heavy.

The origin of the dissipation term $\Upsilon\dot{\phi}$ in the field equation is $g < \chi\chi > \phi$ $\rightarrow$ more...

It is not a trivial task to find $\Upsilon\dot{\phi}$ in $g < \chi\chi > \phi$.

A. Quantum dissipation $(T = 0)$

1. Quantum excitation $n_\chi \neq 0$ may appear when the background is changing

Using Bogoliubov transformation, one will find $n_\chi \neq 0$ for the background $\dot{m}_\chi \neq 0$.

$\Downarrow$

2. Energy loss and entropy production would be inevitable if χ-excitation decays

Since the decay $\chi \to 2\psi$ is irreversible, entropy production and energy loss may occur.

$\Downarrow$

3. Dissipation / Berrera and Ramos '01

Since the whole process is due to the field motion $\dot{\phi} \neq 0$, it would be natural to expect that the energy loss and entropy production may cause friction proportional to $\dot{\phi}$. e.g.,

$$\Upsilon_1 \simeq C_1\phi, \qquad C_1 \sim 0.1 \times h^4 N_\chi N_\psi^2 \tag{3}$$

Despite the simplicity of the idea, calculation of the dissipation coefficient is not simple. The dissipation term turns out to be **non-local**(time-integral), which requires delicate approximations to be put into local field equation.

B. Low-temperature dissipation $(T \ll m_\chi)$

1. $n_\chi(T) \neq 0$ is obvious if χ interacts with radiation. $\dot{\phi}$ is not needed for $n_\chi \neq 0$.

$\Downarrow$ What happens if the catalyst field χ decays into light fermions?

2. Small shift from the equilibrium leads to a formidable non-equilibrium dynamics

We need simplification to localize the non-equilibrium term: e.g, $n_\chi^{eq} - n_\chi \simeq \frac{dn_\chi^{eq}}{d\phi}\dot{\phi}\Gamma_\chi^{-1}$

$\Downarrow$ non-equilibrium part of $g < \chi^2 > \phi$ contains dissipation term

3.Dissipation at low temperature / Moss & Xiong '06

SUSY two-step model can be localized to give $\Upsilon_2\dot{\phi}$.

$$\Upsilon_2 \simeq C_2 \frac{T^3}{\phi^2}, \qquad C_2 \sim 0.1 \times N_\chi/\sqrt{N_\psi} g^3/h \tag{4}$$

In this talk, we will focus on strong dissipation $r_\Upsilon \gg 1$ (SD). ($r_\Upsilon \equiv \frac{\Upsilon}{3H}$)

$r_\Upsilon \sim 1$ is not natural; strength of the dissipation is basically independent of H.

Since the **friction** term $\underline{3H\dot{\phi}}$ is enhanced $\underline{3H(1+r_\Upsilon)\dot{\phi}}$, the effective slow-roll parameters are different from the conventional ones. Naively, they are given by

"Naive" slow-roll parameters for SD motion

$$\epsilon < (1+r_\Upsilon)^2 \qquad \eta < (1+r_\Upsilon)^2 \tag{5}$$

These "Naive" conditions are not enough. We must consider conditions related to the evolution of the radiation. Before discussing the modified slow-roll conditions, let us remember two scenarios of inflation in which radiation is used:

1. Warm inflation : Radiation is sourced by the decay product and sustained.
   The temperature is nearly constant $\rightarrow \dot{\rho}_R \simeq 0$

2. Thermal inflation : The radiation redshifts as $\rho_R \propto a^{-4}$

We call the phase with $\dot{\rho}_R \simeq 0 \rightarrow$ "warm phase", and $\rho_R \propto a^{-4} \rightarrow$ "thermal phase".

Using these "phases", "slow-roll" conditions can be improved $\rightarrow$

In the Warm phase

1. $\dot{\rho}_R \simeq 0$ is equivalent to $4H\rho_R \simeq \Upsilon\dot{\phi}^2$ (Energy conservation)

2. Combined with slow-roll field equation, more stringent conditions will appear:

$$\epsilon < (1 + r_\Upsilon) \qquad \eta < (1 + r_\Upsilon) \tag{6}$$

In the Thermal phase

1. We consider $\dot{V} < 4HV$, which ensures that the potential energy decreases slower than the radiation.

2. Using slow-roll equation, the above condition is almost identical to

$$\epsilon < (1 + r_\Upsilon) \tag{7}$$

These two distinctive "phases" must be considered for the dissipative curvaton dynamics.

Next, we will see the typical evolution of the curvaton density after reheating $\rightarrow$

Standard curvaton scenario after reheating is...

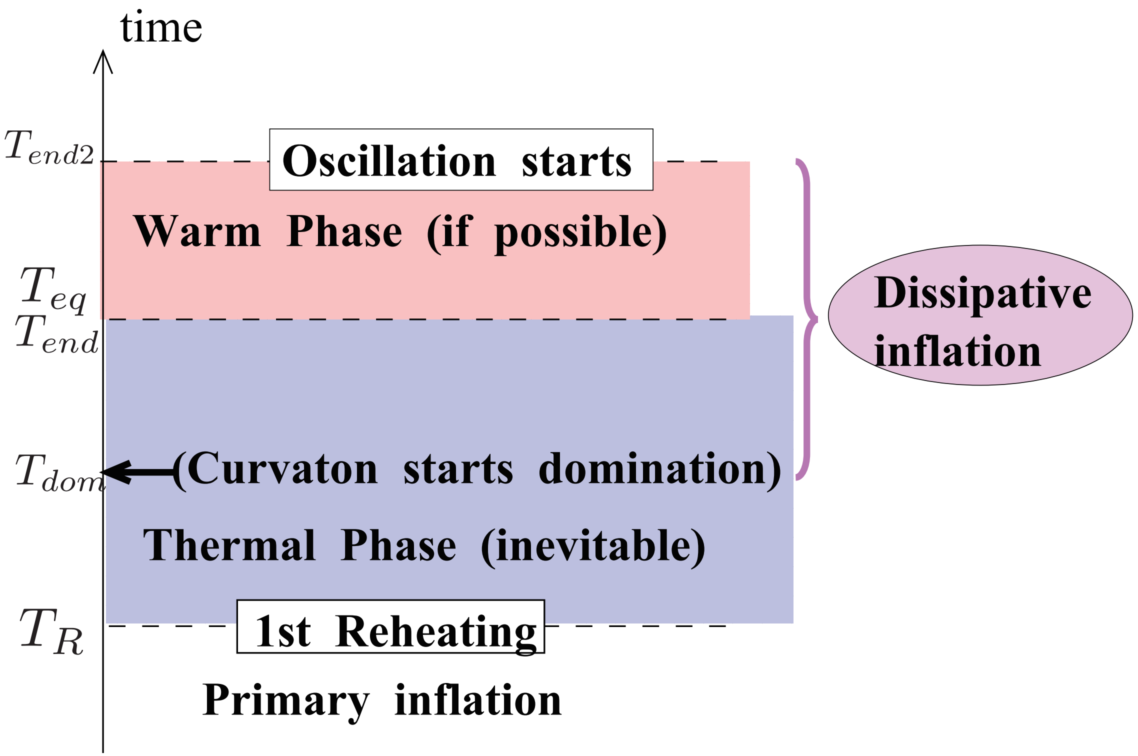
1. $H > m_\phi$: Hubble-friction slow-roll $\rightarrow$ Ratio grows as $\frac{\rho_\phi}{\rho_{rad}} \propto \frac{a^0}{a^{-4}} \sim a^4$
2. $\Gamma_\phi < H < m_\phi$: Long-time oscillation $\rightarrow$ Ratio grows as $\frac{\rho_\phi}{\rho_{rad}} \propto \frac{a^{-3}}{a^{-4}} \propto a^1$
3. $\Gamma_\phi \simeq H$: Curvaton decays to reheat the Universe again.

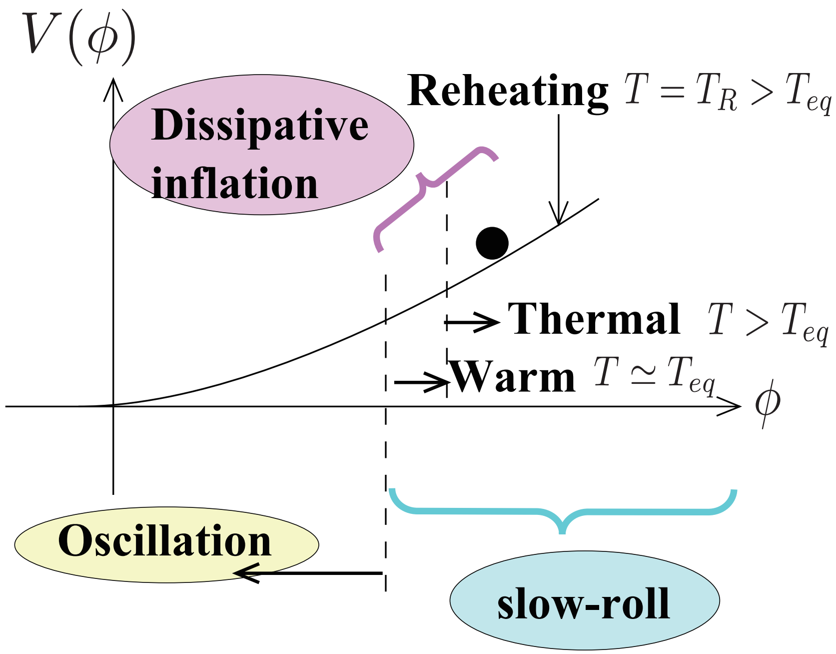
Evolution in the dissipative curvaton scenario is very **different** from the original.

Dissipative curvaton scenario after reheating is...

1. $H > \frac{m_\phi}{(1+r_\Upsilon)}$: The first slow-roll period is extended
2. When ρ_ϕ dominate $\rightarrow$ Dissipative inflation starts (firstly “thermal” and then “warm”)
3. Long-time oscillation is not realistic since strong interactions will cause fast decay.

We will explain the situation using pictures$\rightarrow$





1. Reheating : After primordial inflation, the temperature reaches $T = T_R$.
2. Thermal phase: At $T \simeq T_{dom}$ curvaton starts dominating, then Dissipative inflation starts ($T_{dom} > T > T_{end}$). Thermal phase may end either by breaking the slow-roll condition or by connecting to the warm phase ($T_{end} \equiv T_{eq}$). The number of e-foldings is given by $N_{th} \simeq \ln\left(\frac{T_{dom}}{T_{end}}\right)$
3. Warm phase of the dissipative inflation (warm inflation)
Thermal phase may be connected to warm inflation if slow-roll lasts until $T \simeq T_{eq}(\phi_w)$. The evolution is highly model-dependent.

Significant differences

1. There is no Long-time oscillation:

   The slow-roll period is extended until late and the curvaton can start dominating the Universe during slow-roll.

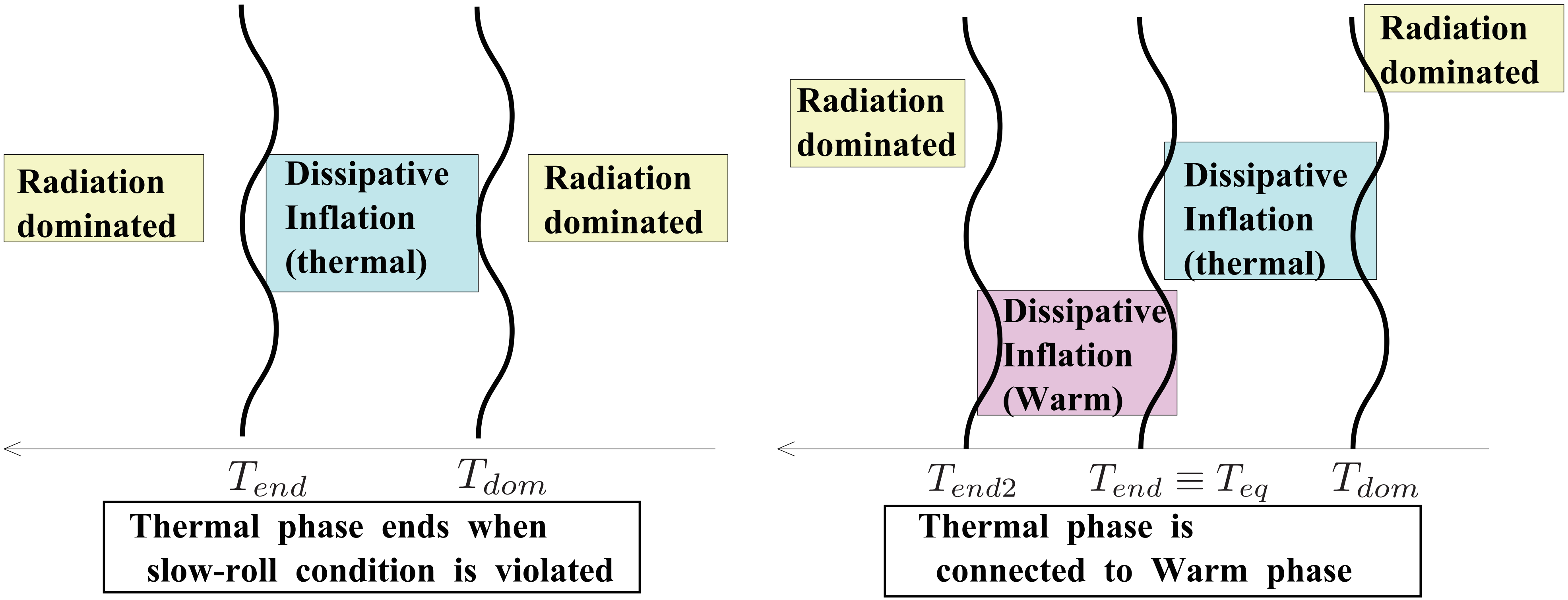
2. Quadratic potential is not essential for the scenario:

   This is possible because the matter-like evolution during long-time oscillation is not needed for the scenario.
   $\rightarrow$ There would be some implications for the recently-posed non-gaussian spectrum due to $V(\phi) \propto \phi^n$ / *Byrnes, Enqvist, Takahashi '10*

Creation of curvature perturbation is possible if δN is created at the boundaries of these cosmological epochs. (e.g., $\delta T_{dom} \neq 0$, $\delta T_{end} \neq 0$ or $\delta \phi_w \neq 0 ...$)

We will show you some pictures for the δN sources $\rightarrow$

These pictures show how δN can be generated in the scenario of dissipative curvatons.



In the left picture, you can find two "chances" for the modulation, appearing at $T = T_{dom}$ and T_{end}.

In the right, you may find modulation at $T = T_{dom}, T_{end}$ and T_{end2}. They can introduce modulated/inhomogeneous boundaries that cause δN. $\rightarrow$ more...

1. Modulation of Initial boundary at $T = T_{dom}$
   Considering $\delta N \simeq \frac{\delta T_{dom}}{T_{dom}} \simeq \frac{1}{4}\frac{\delta V}{V}$ for the inhomogeneous/modulated boundary, we find $\delta N \simeq \frac{n}{4}\frac{\delta\phi}{\phi} + O(\delta\phi^2)$ for the potential $V \propto \phi^n$.

2. Modulation of End boundary at $T = T_{end}$ or T_{end2} (at the end of slow-roll)
   Inhomogeneous boundary would be induced by the modulation of the couplings ($\delta g \neq 0$ or $\delta h \neq 0$) that causes $\delta\Upsilon \neq 0$. The situation reminds us of the modulation in hybrid inflation (δN at the end of inflation). However, modulation here is far easier. The flatness of the moduli potential is not ruined by the large inflaton expectation value because moduli-ϕ interaction is not essential for $\delta h(\leftarrow h\chi\overline{\psi}\psi)$.

3. Modulation of Intermediate boundary at $T = T_{eq}$(if connected to warm inflation)
   Considering conventional formula $\delta N \simeq H\frac{\delta\phi_w}{\dot{\phi}}$, we find $\delta N \simeq \frac{H\Upsilon}{V_\phi}\delta\phi_w$. Although the formula looks similar to the conventional inflation, the mechanism should be **discriminated**. Here the isocurvature perturbation creates curvature perturbation at later cosmological event at $T = T_{eq}$.

$\delta\phi$ Horizon exit is displaced from δN creation

They can be discriminated using the spectral index.$\rightarrow$ See next slide

Spectral index : We use $\{\epsilon_i, \eta_i\}$ for inflaton, $\{\epsilon_\phi, \eta_\phi\}$ for curvatons

Standard Curvatons

In the standard curvatons $2\eta_\phi$ appears because the perturbation evolves as $\delta\phi \propto \exp\left[-\eta_\phi H t\right]$. Considering $2\epsilon_i$ from $\dot{H}$, the spectral index is $n_s - 1 = 2\eta_\phi - 2\epsilon_i$.

Dissipative curvatons

We have at least two options for the model.

1. If the curvaton is dissipating already at the horizon exit, the equation for the perturbation $\delta\phi$ gives $\delta\ddot{\phi} + 3H(1+r_\phi)\delta\dot{\phi} + V'' = 0$, which leads to $2\eta_\phi/(1+r_\phi)$ in the spectral index.

2. If the primary inflation is warm, $\delta\phi$ may be enhanced by the thermal effect and the amplitude is $\delta\phi|_{T\neq 0} \simeq \left[\left(\frac{\pi r_i}{4}\right)^{1/4}\sqrt{TH}\right]$. In this case, variation of T is important for the spectral index.

Basic equations for $r > 1$ (SD) motion

$$\frac{1}{H}\frac{d\ln H}{dt} = -\frac{1}{r}\epsilon \tag{8}$$

$$\frac{1}{H}\frac{d\ln T}{dt} = -\frac{1}{4r}\left(2\eta - \beta - \epsilon\right) \tag{9}$$

$$\frac{1}{H}\frac{d\ln \dot{\phi}}{dt} = -\frac{1}{r}\left(\eta - \beta\right) \tag{10}$$

$$\frac{1}{H}\frac{d\ln \Upsilon}{dt} = -\frac{1}{r}\beta, \tag{11}$$

where $\beta \equiv \frac{1}{M_p^2}\frac{\Upsilon' V'}{\Gamma V}$. $\dot{T}$ is calculated in the warm phase. For the simplest case $\delta N \propto \frac{\delta\phi}{\phi}$

	Cold primary inflation $(\delta\phi\|_{T=0})$	Warm primary inflation $(\delta\phi\|_{T\neq 0})$
$r < 1$ (Always) Non-dissipative	$2\eta_\phi - 2\epsilon_i$ **Standard Curvatons**	$2\eta_\phi - \frac{1}{r_i}\left(\frac{\epsilon_i}{4} + \frac{\eta_i}{2} + \frac{\beta_i}{4}\right)$ **New scenario 1**
$r > 1$ (Always) Dissipative	$\frac{2\eta_\phi}{r_\phi} - 2\epsilon_i$ **New scenario 2**	$\frac{2\eta_\phi}{r_\phi} - \frac{1}{r_i}\left(\frac{\epsilon_i}{4} + \frac{\eta_i}{2} + \frac{\beta_i}{4}\right)$ **New scenario 3**

Conclusions and discussions

In this talk we presented a scenario of curvatons when the dissipative effect is significant.

Previous arguments for the dissipation has been mostly for primary inflation (warm inflation). However, we must remember that any field that couples to catalyst field may dissipate, and then it may cause creation of curvature perturbations at later cosmological event, such as inhomogeneous/modulated reheating, phase transitions or preheating.

On the other hand, we must also remember that for the dissipative motion, there would be some debates on the procedure for dealing with the non-local and non-equilibrium term in the field equation.

In conclusion, we would like to declare that
Dissipation would be there, but we must work harder to reveal its efficiency in particle cosmology.

I am preparing very interesting application of the dissipation, which will appear soon.

Thank you!