Curvaton and Supersymmetry

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Refs.:
Moroi & Takahashi, PLB522 ('01) 215 [hep-ph/0110096]
Moroi & Takahashi, PRD66 ('02) 063501 [hep-ph/0206026]
Endo, Kawasaki & Moroi, hep-ph/0304126
Hamaguchi, Kawasaki, Moroi & Takahashi, hep-ph/0308174

1. Introduction

One of the important issues in cosmology

Origin of the cosmic density fluctuations

Recently, WMAP provided important informations:

The primordial density fluctuations look adiabatic and scale-invariant

- $\Rightarrow$ This may be an evidence of inflation
- $\Rightarrow$ Can there be any other mechanism?

Today, I will discuss another scenario of generating cosmic density fluctuations

$\Rightarrow$ Curvaton mechanism

[Mollerach; Linde & Mukhanov; Enqvist & Sloth; Lyth & Wands; Moroi & Takahashi]

Generating density fluctuations from primordial fluctuation of a scalar field other than the inflaton

Early works:

1. Isocurvature density fluctuation in NR matter becomes adiabatic one after the matter domination
   [Mollerach]

2. Density fluctuations from primordial fluctuation of some extra scalar field are studied
   [Linde & Mukhanov]

3. Whole density fluctuations can be from primordial fluctuation of some scalar field other than inflaton
   [Enqvist & Sloth; Lyth & Wands; Moroi & Takahashi]

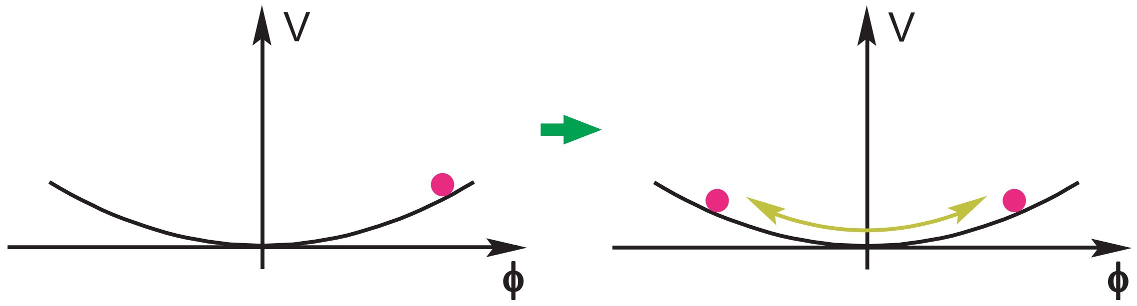
   $\Rightarrow$ Scale-invariance is easily realized

There are many related works
[Bartolo & Liddle; Fujii & Yanagida; Lyth, Ungarelli & Wands; Hofmann; Hebecker, March-Russell & Yanagida; Dimopoulos & Lyth; Moroi & Murayama; Bastero-Gil, Clemente & King; Enqvist, Kasuya & Mazumdar; Malik, Wands & Ungarelli; Postma; Feng & Li; Gordon & Lewis; Giovannini; Liddle & Urena-Lopez; Dimopoulos, Lazarides, Lyth & Ruiz de Austri; Enqvist, Jokinen, Kasuya & Mazumdar; Dimopoulos, Lyth, Notari & Riotto; Endo, Kawasaki & Moroi; Postma & Mazumdar; Postma; Kasuya, Kawasaki & Takahashi; Lyth & Wands; McDonald]

Outline

2. Overview of the Curvaton Scenario

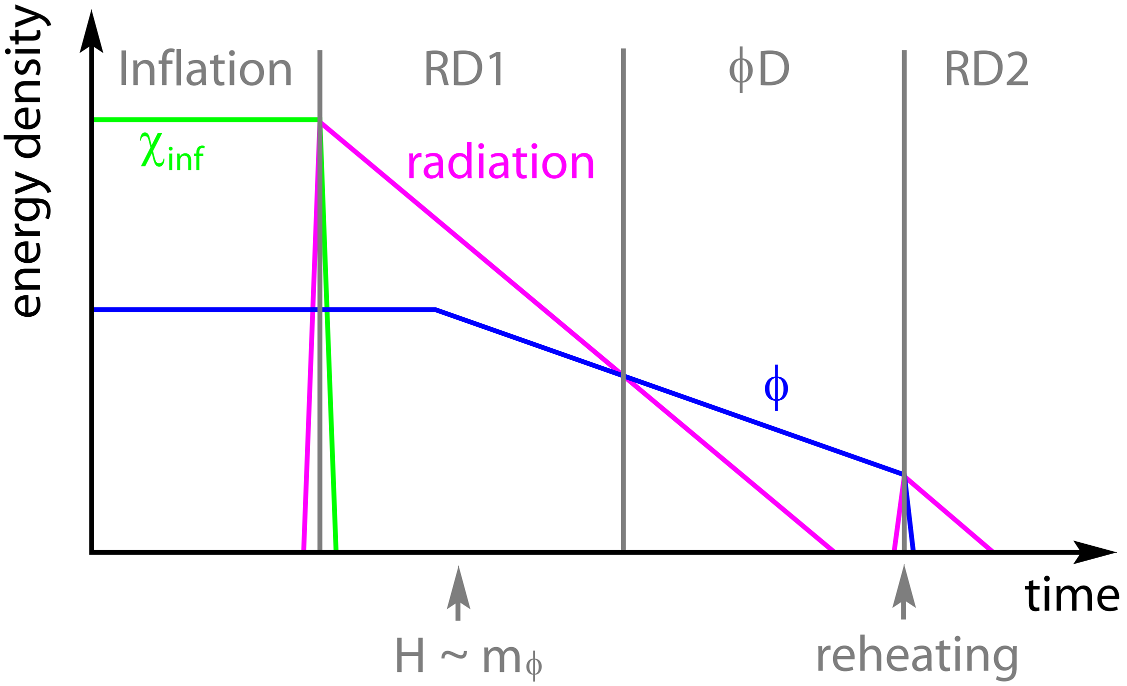
Cosmological scenario with the curvaton ϕ:



1. In the early universe, $\phi \neq 0$
2. ϕ starts to oscillate as the universe expands

   $\Rightarrow$ $\rho_\phi \propto a^{-3}$ (ϕ behaves as a NR matter)

   $\Rightarrow$ ρ_ϕ takes over $\rho_{\rm rad}$ at some epoch
3. The ϕ field decays and reheats the universe



During inflation, ϕ acquires fluctuation if $m_\phi \ll H_{\rm inf}$

$$\delta\phi(k) \simeq \frac{H_{\rm inf}}{2\pi}$$

$\Rightarrow$ There are two sources of fluctuations: $\delta\chi_{\rm inf}$ and $\delta\phi$

Metric perturbation: $ds^2 = (1+2\Psi)dt^2 - a^2(1+2\Phi)d\vec{x}^2$

$\Rightarrow$ $\Psi = \Psi^{(\rm inf)} + \Psi^{(\delta\phi)}$

with $\Psi^{(\rm inf)} \propto \delta\chi_{\rm inf}$ and $\Psi^{(\delta\phi)} \propto \delta\phi_{\rm init}$

$\Psi^{(\rm inf)}$: Inflaton contribution

- Adiabatic

Fluctuations from $\delta\phi$ is like those with primordial baryonic (or CDM) isocurvature fluctuation before ϕ decays

- Initially, the universe is dominated with radiation (i.e., RD1 epoch)
- In the RD1 epoch, source of the density fluctuations is in non-relativistic component (i.e., ϕ)

All fluctuations from $\delta\phi_{\rm init}$ are proportional to $[\delta_\phi]_{\rm init}$

$$S_{\phi\chi} \equiv \left[\frac{\delta\rho_\phi}{\rho_\phi}\right]_{\rm init} = \frac{2\delta\phi_{\rm init}}{\phi_{\rm init}}$$

After the decay of ϕ, radiation-dominated universe is realized again

$$\Psi^{(\delta\phi)}_{\text{RD2}}(k) = \frac{10}{9}\Psi^{(\delta\phi)}_{\phi\text{D}}(k) = -\frac{4}{9}\frac{\delta\phi_{\text{init}}}{\phi_{\text{init}}}$$

$\Rightarrow$ Isocurvature fluctuation in ϕ is converted to the adiabatic one

Density fluctuations from $\delta\phi_{\text{init}}$ is purely adiabatic if:

- All the components are generated from the decay products of ϕ
- Decay rate of ϕ does not fluctuate

Metric perturbation from $\delta\chi_{\text{inf}}$ and $\delta\phi$:

$$\Psi^{(\text{inf})}_{\text{RD2}}(k) = \frac{2}{3}\left[\frac{3H^2_{\text{inf}}}{V'_{\text{inf}}} \times \frac{H_{\text{inf}}}{2\pi}\right]_{k=aH}$$

$$\Psi^{(\delta\phi)}_{\text{RD2}}(k) = -\frac{4}{9}\left[\frac{1}{\phi_{\text{init}}} \times \frac{H_{\text{inf}}}{2\pi}\right]_{k=aH}$$

Density fluctuations from $\delta\phi_{\text{init}}$ is (almost) scale-invariant

H_{inf} is almost constant during inflation in many class of models

Since $\delta\chi_{\text{inf}}$ and $\delta\phi$ are uncorrelated: $C_l = C_l^{(\text{inf})} + C_l^{(\delta\phi)}$

$$C_l^{(\text{inf})} \sim O[(\Psi^{(\text{inf})}_{\text{RD2}})^2], \qquad C_l^{(\delta\phi)} \sim O[(\Psi^{(\delta\phi)}_{\text{RD2}})^2]$$

$\Psi^{(\delta\phi)}$ is proportional to $\phi_{\rm init}^{-1}$

$\Rightarrow$ As $\phi_{\rm init}$ becomes smaller, all the cosmic density fluctuations are generated from the curvaton

$\Rightarrow$ Then, C_l is also dominated by the curvaton contribution

Implication of the curvaton scenario

- Scale-invariant density fluctuations can be easily obtained
- Size of the cosmic density fluctuation is not directly related to parameters in inflaton potential

$\Rightarrow$ Observational constraints on the inflaton potential can be relaxed

Any scalar field ϕ can be the curvaton if:

- ϕ has non-vanishing initial amplitude to realize the ϕD epoch
- ϕ acquires primordial fluctuation
- ϕ has large enough decay rate to realize $T_{\rm RD2} \gtrsim 1$ MeV

3. Curvatons in Supersymmetric Models

SUSY plays important roles in curvaton scenarios

- SUSY guarantees the flatness of the curvaton potential
- There are many well-motivated candidates of the curvaton in SUSY models

Curvaton candidates in SUSY models

- F- and D-flat directions
- Affleck-Dine field (?)
- Cosmological moduli fields

  $\Rightarrow$ Takahashi's talk

- Right-handed sneutrino
- $\cdots$

In some supersymmetric curvaton models, sizable entropy fluctuation is generated in baryon and/or CDM

- Large entropy fluctuation is inconsistent with observations

  $\Rightarrow$ Constraints on curvatons in SUSY models

- Size and properties of the entropy fluctuation depend on the model

Case with F- and D-flat direction as a curvaton

$$V = m_\phi^2 \left[1 + K \log \frac{|\phi|^2}{M_{\text{Pl}}^2} \right] |\phi|^2$$

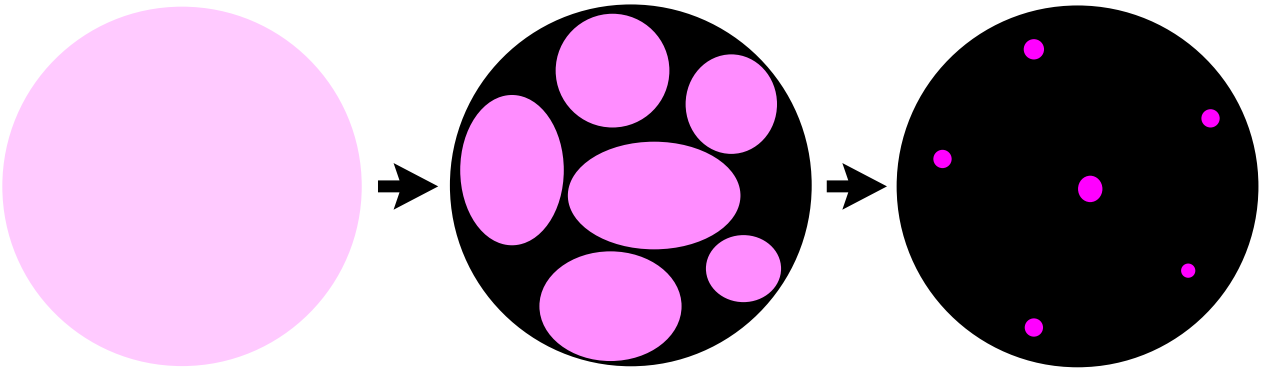
We assume $m_\phi \sim O(100 \text{ GeV})$

K parameterizes the renormalization-group effects

M_{Pl}: Reduced Planck scale

If $K < 0$, instability band arises

$\Rightarrow$ Q-ball formation occurs
[Kusenko; Kusenko & Shaposhnikov; Enqvist & McDonald; Kasuya & Kawasaki]



Detailed thermal history depends on whether Q-balls are formed or not

- For the case without Q-ball formation, the curvaton scenario is the same as the discussion so far
- If Q-balls are formed, we should worry about the entropy perturbation

Thermal history with Q-ball formation

1. Q-balls are formed when ϕ starts to move
$$|Q_{\rm init}| \sim 10^{-4} \left(\frac{\phi_{\rm init}}{m_\phi}\right)^2$$
2. Q-ball dominates the universe at some epoch
3. Q-balls decay and reheat the universe
$$T_{\rm RD2} \sim 1 \text{ MeV} \times \left(\frac{|K|}{0.03}\right)^{-1/2} \left(\frac{\phi_{\rm init}}{M_{\rm Pl}}\right)^{-1}$$

If $\phi_{\rm init} \gtrsim 10^{-3} M_{\rm Pl}$, $T_{\rm RD2}$ becomes lower than the freeze-out temperature of the LSP (i.e., the lightest neutralino)

⇒ LSPs are emitted when the Q-balls decay

⇒ Relic abundance of the LSP is non-thermally determined

At the decay of the Q-ball, the pair-annihilation of the LSP proceeds until $n_{\rm LSP}\langle\sigma v\rangle \sim H \sim T_{\rm RD2}^2/M_{\rm Pl}$
[Moroi & Randall; Fujii & Hamaguchi]

$$\frac{n_{\rm LSP}}{n_\gamma} \sim \frac{1}{T_{\rm RD2} M_{\rm Pl} \langle\sigma v\rangle}$$

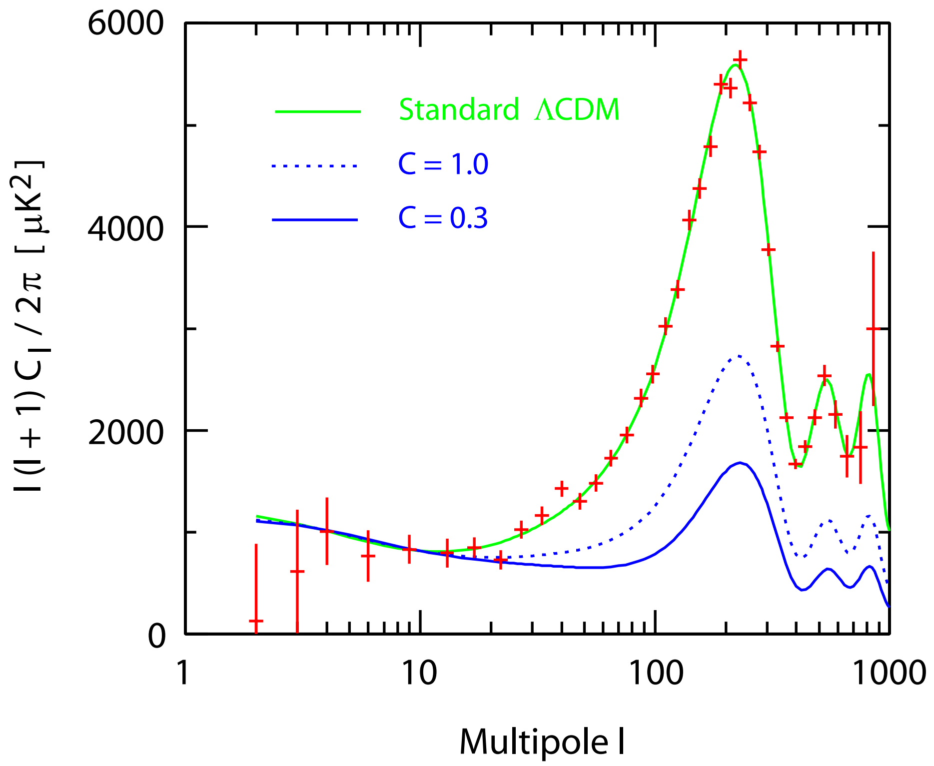
If $\phi_{\rm init}$ has fluctuation, $T_{\rm RD2}$ also fluctuates

⇒ Non-zero entropy fluctuation, if the LSP is the CDM
$$S_{c\gamma}^{(\delta\phi)} = \frac{\delta(n_{\rm LSP}/n_\gamma)}{(n_{\rm LSP}/n_\gamma)} = \frac{\delta\phi_{\rm init}}{\phi_{\rm init}}$$

Correlated mixture of adiabatic and entropy fluctuations is generated

$$\Psi_{\mathrm{RD2}}^{(\delta\phi)} \simeq \left(-\frac{4}{9} - C\right) \frac{\delta\phi_{\mathrm{init}}}{\phi_{\mathrm{init}}}, \qquad S_{c\gamma}^{(\delta\phi)} = \frac{\delta\phi_{\mathrm{init}}}{\phi_{\mathrm{init}}}$$

$C \sim O(0.1)$: From the fluctuation of the decay rate [Dvali, Gruzinov & Zaldarriaga; Enqvist, Mazumdar & Postma; Matarrese & Riotto]



With Q-ball formation, non-thermal production of the CDM induces too large entropy fluctuation

- T_{RD2} should be higher than the freeze-out temperature of the LSP
- This constraint does not apply if the CDM is not the LSP or if $K > 0$

4. An Application: Case of D-term Inflation

Model: U(1) SUSY YM with FI D-term
[Haylo; Binetruy & Dvali]

Particle content: $S(0)$, $\bar{Q}(-1)$ and $Q(+1)$

Superpotential: $W = \lambda S \bar{Q} Q$

Scalar potential:

$$V = \lambda^2 \left(|S\bar{Q}|^2 + |SQ|^2 + |\bar{Q}Q|^2 \right) + \frac{1}{2} g^2 \left(-|\bar{Q}|^2 + |Q|^2 - \xi \right)^2$$

True minimum:

$$S = 0, \quad \bar{Q} = 0, \quad Q = \sqrt{\xi}$$

Quasi flat direction exists (which is used as an inflaton)

$$S \to \infty, \quad \bar{Q} = 0, \quad Q = 0$$

Taking account of the gauge coupling running, the flat direction is slightly lifted:

$$V(S) = \frac{1}{2} g^2 \xi^2 \Rightarrow \frac{1}{2} \left[g^2 + \frac{1}{4\pi^2} g^4 \log \frac{S}{S_0} \right] \xi^2$$

If S has large enough amplitude, inflation occurs

- $S \gtrsim g M_{\mathrm{Pl}} / 2\pi$: Slow-roll condition
- $S \gtrsim g \xi^{1/2} / \lambda$: Stability of the potential of Q

D-term inflation starts with the symmetric phase of U(1), while ends at the broken phase

⇒ D-term inflation generates cosmic string, which may significantly change the shape of C_l
[Jeannerot; Lyth & Riotto]

In this case, C_l has two sources:

$$C_l = C_l^{(\mathrm{inf})} + C_l^{(\mathrm{str})}$$

Cosmic-string contribution $C_l^{(\mathrm{str})}$ does not have oscillatory behavior

⇒ C_l becomes inconsistent with the WMAP result if $C_l^{(\mathrm{str})}$ becomes comparable to $C_l^{(\mathrm{inf})}$

For $\lambda \gtrsim O(10^{-4} - 10^{-5})$, inflation ends with the break-down of slow-roll condition

- $C_l^{(\mathrm{inf})} \propto \xi^2$ (since $\Psi_{\mathrm{RD2}}^{(\mathrm{inf})} \sim \xi / M_{\mathrm{Pl}}^2$)
- $C_l^{(\mathrm{str})} \propto \mu^2 \propto \xi^2$ (with $\mu = 2\pi\xi$ being string tension)

Size of $C_l^{(\mathrm{str})}$ given in the literatures:
[Allen et al.; Contaldi, Hindmarsh & Magueijo; Albrecht, Battye & Robinson; Pogosian & Vachaspati; Copeland, Magueijo & Steer; Landriau & Shellard]

$$C_{10}^{(\mathrm{str})} / C_{10}^{(\mathrm{inf})} \sim O(1)$$

⇒ C_l from a simple D-term inflation model is inconsistent with the WMAP result

Caveat: $C_l^{(\mathrm{inf})}$ can be enhanced if λ is small

If λ is small, instability condition breaks down first

For a consistent scenario of D-term inflation

- $\lambda \lesssim O(10^{-4} - 10^{-5})$
  [Endo, Kawasaki & Moroi; Kallosh & Linde]
- $\lambda \gtrsim O(10^{-4} - 10^{-5})$ with curvaton

D-term inflation with $\lambda \sim 1$ is possible with curvaton

With curvaton, effects of the cosmic string can be reduced

Total angular power spectrum: $C_l = C_l^{(\mathrm{inf})} + C_l^{(\mathrm{str})} + C_l^{(\delta\phi)}$

- $C_l^{(\mathrm{inf})}$ and $C_l^{(\mathrm{str})}$ are proportional to ξ^2/M_{Pl}^2
- $C_l^{(\delta\phi)}$ is proportional to $[\Psi^{(\delta\phi)}]^2 \sim \xi^2/\phi_{\mathrm{init}}^2$

Thus, the total angular power spectrum becomes well consistent with the WMAP observation if:

- ξ is small enough to suppress $C_l^{(\mathrm{str})}$

  $\Rightarrow \ \xi^{1/2} \lesssim 10^{-3} M_{\mathrm{Pl}}$

- ϕ_{init} has proper size to obtain $\Psi_{\mathrm{RD2}}^{(\delta\phi)} \simeq 2 \times 10^{-5}$

  $\Rightarrow \ \phi_{\mathrm{init}} \simeq 10^2 \times g\xi/M_{\mathrm{Pl}}$

5. Summary

Today, I discussed the curvaton mechanism

- All the cosmic density fluctuations are from primordial fluctuation of the "curvaton" field
- Late-decaying scalar condensation is required

Merits of the curvaton mechanism

- Constraints on the inflation can be relaxed
- It may be also applied to the case of pre-big-bang and the ekpyrotic scenarios

In SUSY models, entropy fluctuation may be dangerous

- If a F- and D-flat direction is the curvaton, Q-ball may be formed

  $\Rightarrow$ CDM may be non-thermally produced, and the entropy perturbation may become too large

- If the Affleck-Dine field is the curvaton, baryonic entropy fluctuation becomes too large [Enqvist, Kasuya & Mazumdar; Hamaguchi, Kawasaki, Moroi & Takahashi]
- In general, in SUSY models, curvaton should be a complex scalar field

  $\Rightarrow$ Entropy between two scalars may exist

Lower bound on ϕ_{init} to realize the ϕD epoch