Curvaton mechanism and its implications to (s)neutrino cosmology

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Outline

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1. Introduction

One of the important issues in cosmology

Origin of the cosmic density fluctuations

Our universe:

- Almost homogeneous and isotropic at large scale
- There are various structures at small scale
- CMB has anisotropy

\[
\langle \Delta T(\vec{x}, \vec{\gamma})\Delta T(\vec{x}, \vec{\gamma}') \rangle_{\vec{x}} = \frac{1}{4\pi} \sum_l (2l + 1) C_l P_l(\hat{\gamma} \cdot \hat{\gamma}')
\]

\(C_l\): CMB anisotropy at angular scale \(\theta \simeq \pi/l\)
The conventional origin of the density fluctuations

Primordial fluctuation of the inflaton

Today, I will discuss another possibility

Curvaton mechanism
[Enqvist & Sloth; Lyth & Wands; Moroi & Takahashi]

- Primordial fluctuation of a scalar field \( \phi \) (called “curvaton”) generates density fluctuations
- Constraints on the inflaton potential is relaxed

There are scalar fields whose condensation may dominate the universe at some epoch

- Right-handed sneutrino
- Cosmological moduli fields
- Affleck-Dine field
- Flat directions in SUSY models
- Pseudo-NG boson
- \( \cdots \)

If these fields acquire primordial fluctuation, it also becomes the source of cosmic density fluctuations

\[ \Rightarrow \text{If so, what happens?} \]
2. The Curvaton Scenario

1. In the early universe, $\phi \neq 0$
2. $\phi$ starts to oscillate as the universe expands
   \[ \Rightarrow \rho_\phi \propto a^{-3} \]
   \[ \Rightarrow \rho_\phi \text{ takes over } \rho_{\text{rad}} \text{ at some epoch} \]
3. The $\phi$ field decays and reheats the universe

\[ \Rightarrow \text{CMB (and other components) we observe today originates from } \phi \]
During inflation, $\phi$ acquires fluctuation if $m_\phi \ll H_{\text{inf}}$

\[
\delta \phi(k) \approx \frac{H_{\text{inf}}}{2\pi}
\]

$\delta \phi$ produces cosmic density fluctuations:

- $ds^2 = (1 + 2\Psi)dt^2 - a^2(1 + 2\Phi)d\vec{x}^2$
- $T = T_{\text{CMB}} + \Delta T$
- $\cdots$

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

\[
\Rightarrow \Psi = \Psi^{(\text{inf})} + \Psi^{(\delta \phi)}
\]

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

\[
\Rightarrow \Delta T = \Delta T^{(\text{inf})} + \Delta T^{(\delta \phi)}
\]

with $\Delta T^{(\text{inf})} \propto \delta \chi_{\text{inf}}$ and $\Delta T^{(\delta \phi)} \propto \delta \phi_{\text{init}}$

Inflaton contribution ($\Psi^{(\text{inf})}$, $\Delta T^{(\text{inf})}$ $\cdots$)

- Same as the usual case

Curvaton contribution ($\Psi^{(\delta \phi)}$, $\Delta T^{(\delta \phi)}$ $\cdots$)

- All fluctuations from $\delta \phi_{\text{init}}$ are proportional to $S_{\phi \chi}$

\[
S_{\phi \chi} = \left[ \frac{\delta \rho_{\phi}}{\rho_{\phi}} \right]_{\text{init}} = \frac{2\delta \phi_{\text{init}}}{\phi_{\text{init}}}
\]
In the curvaton scenario, there are two sources of cosmic density fluctuations

\[ \Psi_{\text{RD2}}^{{(\inf)}}(k) = \frac{2}{3} \left[ \frac{3H_{\text{inf}}^2}{V_{\text{inf}}} \delta \chi_{\text{inf}} \right]_{k=aH} = \frac{2}{3} \left[ \frac{3H_{\text{inf}}^2}{V_{\text{inf}}} \times \frac{H_{\text{inf}}}{2\pi} \right]_{k=aH} \]

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

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

\( \Rightarrow \) As \( \phi_{\text{init}} \) becomes smaller, the curvaton contribution becomes larger

\( \Rightarrow \) Cosmic density fluctuations can be dominantly generated from \( \delta \phi_{\text{init}} \)

Shape of \( C_l^{(\delta \phi)} \) is consistent with the WMAP result

\( \Psi^{(\delta \phi)} \) becomes (almost) scale invariant if \( H_{\text{inf}} \) does not change much during inflation

Requirements on the initial value of \( \phi \)

- \( \phi_{\text{init}} \) should be small to make the curvaton contributions to the fluctuations dominant
- \( \phi_{\text{init}} \) should be large enough to realize \( \phi^D \) epoch
Lower bound on $\phi_{\text{init}}$ to realize $\phi_D$ epoch

![Graph showing lower bounds on $m_\phi$ for different $T_R$ values. The graph has logarithmic scales on both axes and includes straight lines representing different $m_\phi$ values at $10^{12}, 10^{13}, 10^{14}, 10^{15}, 10^{16}, 10^{17}$ GeV. The $T_R$ values are $10^6, 10^{10}, 10^{14}$ GeV.](image-url)
In the curvaton scenario, constraints on the inflaton potential change

- Energy scale of the inflation
- Scale-dependence of the primordial fluctuations

Scale dependences of $\Psi^{(\text{inf})}$ and $\Psi^{(\delta \phi)}$ are different!

\[ \Psi \propto k^{n-1} \sim (1/\text{scale})^{n-1} \]
\[ \Rightarrow n = 0.99 \pm 0.04 \text{ (WMAP only)} \]

Spectral index $n$ for chaotic inflation with $V \propto \chi^p$

\begin{align*}
  p = 2: & \quad n \simeq 0.96 \quad \Rightarrow \quad n \simeq 0.98 \\
  p = 4: & \quad n \simeq 0.95 \quad \Rightarrow \quad n \simeq 0.97 \\
  p = 6: & \quad n \simeq 0.94 \quad \Rightarrow \quad n \simeq 0.95
\end{align*}

For new inflation, change of $n$ is more drastic

\[ \Rightarrow \text{Observational constraints on the inflaton potential can be relaxed!} \]

Requirements on the curvaton field:

- Flat potential to generate primordial fluctuation
  \[ \Rightarrow \text{No Hubble-induced mass term} \]
- High enough reheating temperature ($T_R \gtrsim 1 \text{ MeV}$)
3. A Possible Signal: Entropy Fluctuations

Important check point in the curvaton scenario

Entropy fluctuations

In simple inflationary scenarios, all the components in the universe are generated from decay products of inflaton

⇒ No fluctuation in the entropies (i.e., the density fluctuations become adiabatic)

\[ S_{b\gamma} \equiv \frac{\delta(n_b/n_\gamma)}{n_b/n_\gamma} = 0, \quad S_{c\gamma} \equiv \frac{\delta(n_c/n_\gamma)}{n_c/n_\gamma} = 0 \]

Effect of (correlated) entropy fluctuations

\[ S_{b\gamma} = \kappa_b \Psi_{RD2} \]
Too large entropy fluctuations are inconsistent with the observation

⇒ With the WMAP data, $|\kappa_b| \leq 0.5$

If the baryon-asymmetry or the CDM does not originate from $\phi$, entropy fluctuation may be generated

- Constraints on the scenario
- Unique signal of the curvaton mechanism

Curvaton mechanism lowers the reheating temperature

⇒ In order not to overproduce the gravitino after inflation, low reheating temperature is preferred

⇒ Baryogenesis may become difficult

Possible mechanism of baryogenesis

- Leptogenesis
  [Fukugita & Yamagida]
- Affleck-Dine mechanism
- ...
If a heavy modulus field (with $m_\phi \sim 100 \text{ TeV}$) plays the role of the curvaton, $T_{RD2} \sim 1 - 10 \text{ MeV}$

⇒ The best scenario for the baryogenesis is (probably) the Affleck-Dine mechanism

Affleck-Dine field starts to move when $H$ becomes comparable to its mass $m_{AD}$

⇒ $S_{b\gamma}^{(\delta \phi)}$ depends when $H \sim m_{AD}$ is realized

- $H \sim m_{AD}$ in RD1 ⇒ $\kappa_b \neq 0$
- $H \sim m_{AD}$ in $\phi D$ ⇒ $\kappa_b \sim 0$

$k_b \lesssim 0.5$ (from the WMAP)

⇒ $\phi_{init} \sim M_{Pl}$ or $m_\phi \gg m_{AD}$

[Ikegami & Moroi]
Another possibility: Baryogenesis with the curvaton

⇒ Right-handed sneutrino $\tilde{N}$ as the curvaton

Baryon-number asymmetry is generated when the right-handed sneutrino decays

[Murayama, Suzuki, Yanagida & Yokoyama]

Right-handed sneutrino becomes the origin of the cosmic density fluctuations as well as the baryon asymmetry

⇒ In the simplest case, $\kappa_b = 0$

One interesting possibility:

Contamination of the photon from the inflaton

[Moroi & Murayama]

If $\tilde{N}$ decays soon after the $\phi D$ epoch is realized, some fraction of the radiation originates from the inflaton

⇒ Baryon asymmetry inherits fluctuation from $\tilde{N}$

⇒ Small but non-vanishing $\kappa_b$ may arise

$$\kappa_b = -\frac{9}{2} \left( 1 - \frac{f_{\gamma\tilde{N}}}{f_{\gamma\tilde{N}}} \right)$$

$f_{\gamma\tilde{N}}$: fraction of the photon from $\tilde{N}$

$\kappa_b \sim O(0.1)$ is possible, which may provide detectable signals at future measurements of the CMB anisotropy
4. 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

Why curvaton?

- Constraints on the inflation can be relaxed
- There are various scalar fields which may once dominate the universe

In the curvaton scenario, (correlated) entropy fluctuations may be generated

- In some case, entropy fluctuation becomes too large
  ⇒ For example, Affleck-Dine field cannot play the role of curvaton
- In other case, sizable entropy fluctuation may be generated
  ⇒ Some signal may be found in the future measurements of the CMB power spectrum
- Right-handed sneutrinos are interesting and well-motivated candidates of the curvaton