Curvaton mechanism and its implications to (s)neutrino cosmology

Takeo Moroi (Tohoku)

Outline

1. Introduction
2. Curvaton Mechanism
3. A Possible Signal
4. Summary

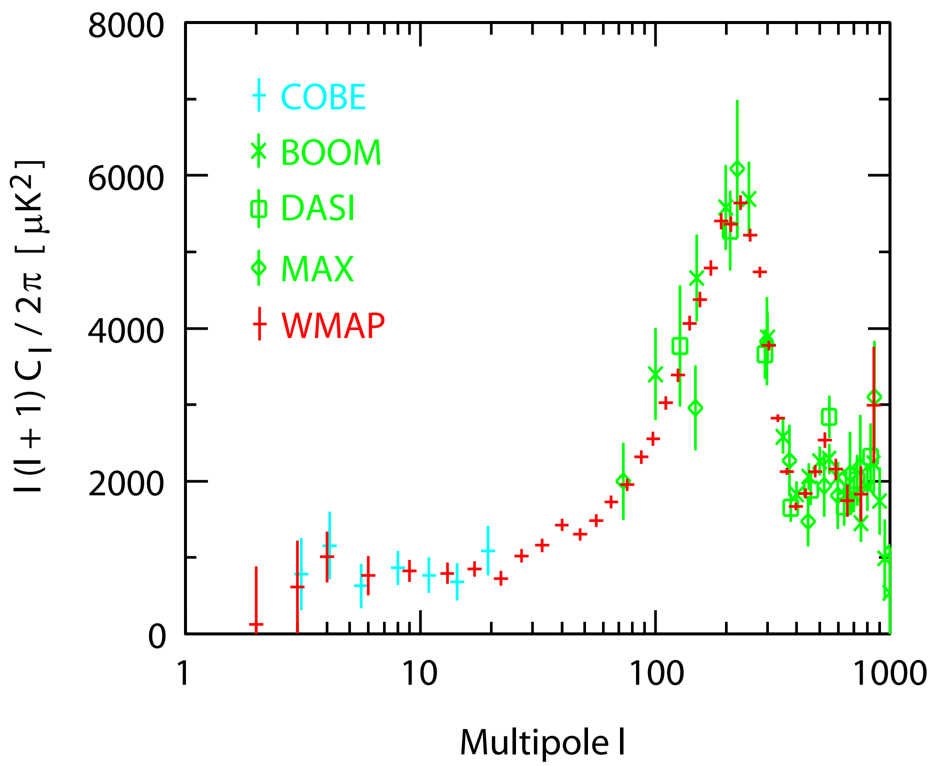
1. Introduction

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



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

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 ϕ (called "curvaton") generates density fluctuations
- Constraints on the inflaton potential is relaxed

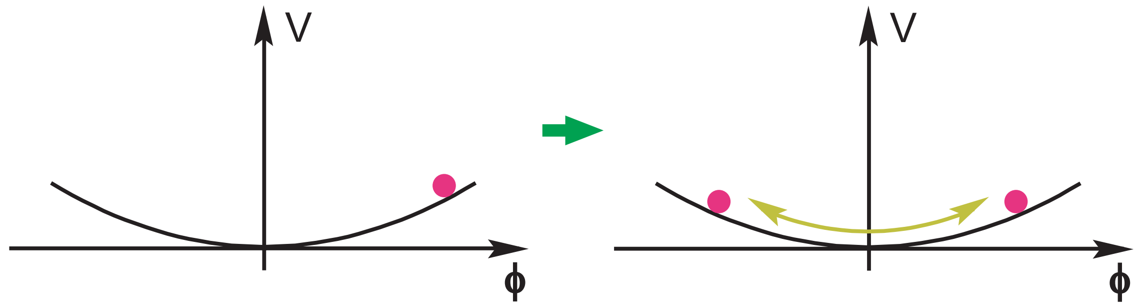
There are scalar fields whose condensation may dominate the universe at some epoch

- 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

$\Rightarrow$ If so, what happens?

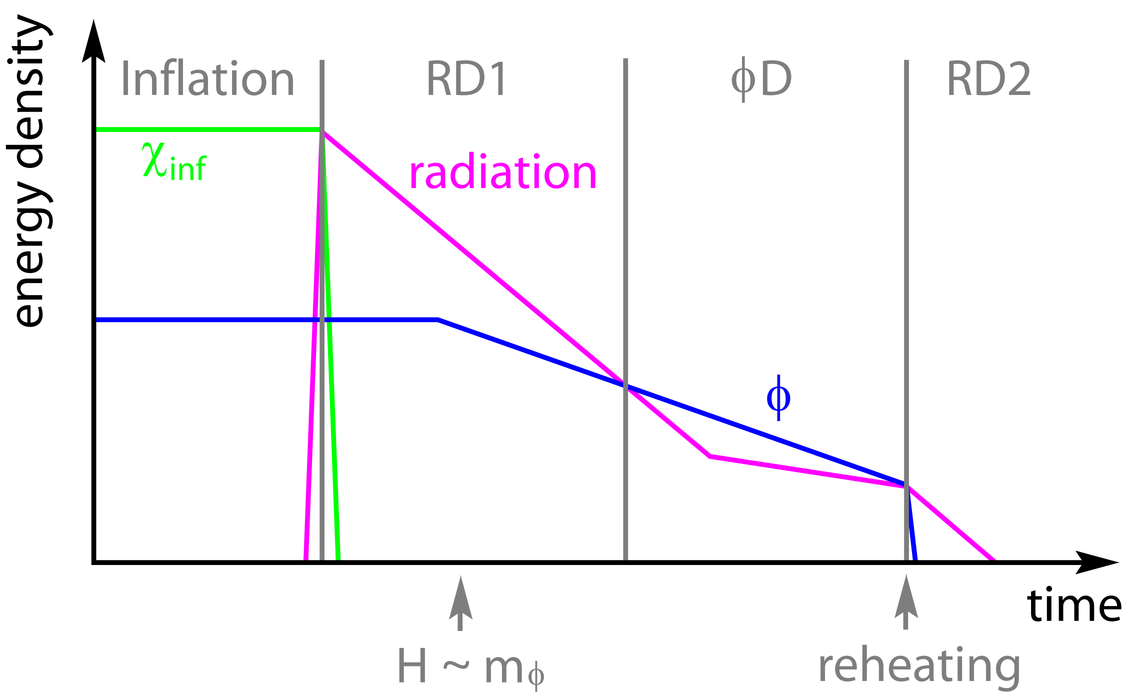
2. The Curvaton Scenario



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

   $\Rightarrow$ $\rho_\phi \propto a^{-3}$

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



$\Rightarrow$ CMB (and other components) we observe today originates from ϕ

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

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

$\delta\phi$ 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 $S_{\phi\chi}$

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

In the curvaton scenario, there are two sources of cosmic density fluctuations

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

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

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

$\Rightarrow$ As ϕ_{init} becomes smaller, the curvaton contribution becomes larger

$\Rightarrow$ Cosmic density fluctuations can be dominantly generated from $\delta\phi_{\mathrm{init}}$

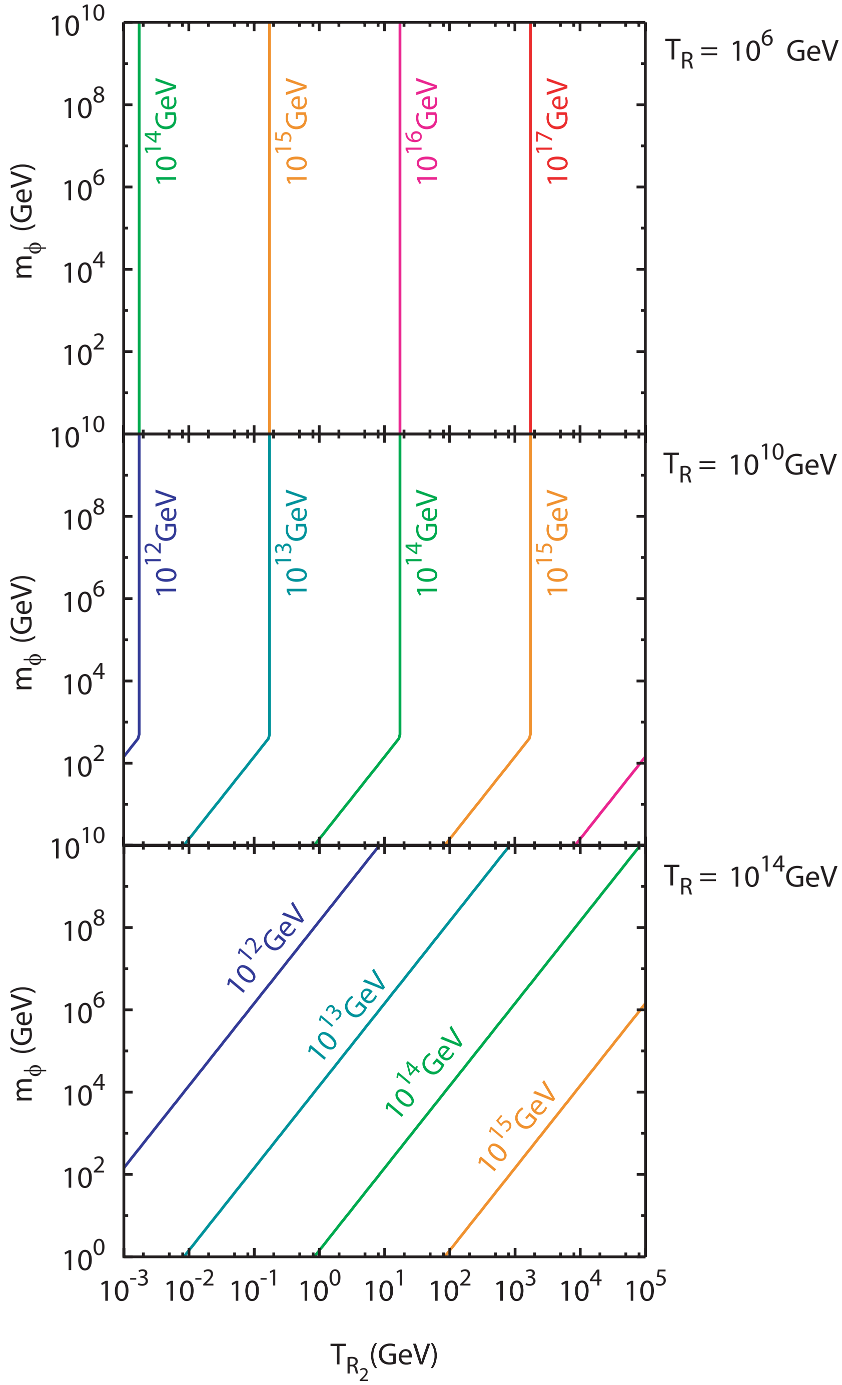
Shape of $C_l^{(\delta\phi)}$ is consistent with the WMAP result

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

Requirements on the initial value of ϕ

- ϕ_{init} should be small to make the curvaton contributions to the fluctuations dominant
- ϕ_{init} should be large enough to realize ϕD epoch

Lower bound on ϕ_{init} to realize ϕD epoch



In the curvaton scenario, constraints on the inflaton potential change

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

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

$$\Psi \propto k^{n-1} \sim (1/\mathrm{scale})^{n-1}$$

$\Rightarrow$ $n = 0.99 \pm 0.04$ (WMAP only)

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

$p = 2$: $n \simeq 0.96 \;\; \Rightarrow \;\; n \simeq 0.98$

$p = 4$: $n \simeq 0.95 \;\; \Rightarrow \;\; n \simeq 0.97$

$p = 6$: $n \simeq 0.94 \;\; \Rightarrow \;\; n \simeq 0.95$

For new inflation, change of n is more drastic

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

Requirements on the curvaton field:

- Flat potential to generate primordial fluctuation
  - $\Rightarrow$ No Hubble-induced mass term
- High enough reheating temperature ($T_{\mathrm{R}} \gtrsim 1$ MeV)

3. A Possible Signal: Entropy Fluctuations

Important check point in the curvaton scenario

Entropy fluctuations

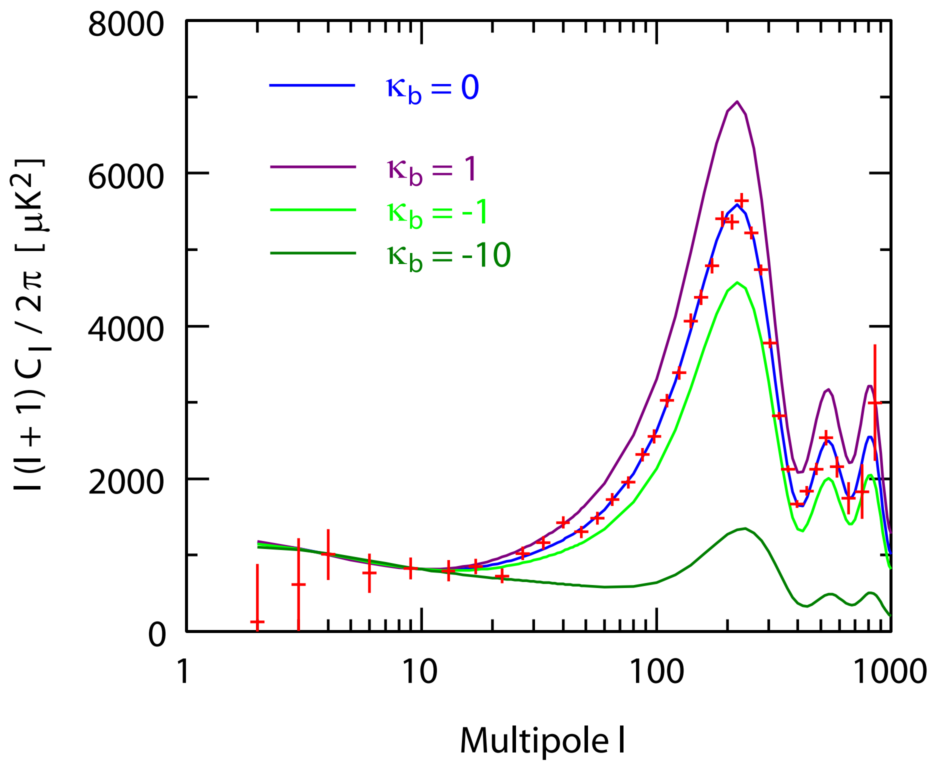
In simple inflationary scenarios, all the components in the universe are generated from decay products of inflaton

$\Rightarrow$ 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

$$S_{b\gamma} = \kappa_b \Psi_{\text{RD2}}$$



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 ϕ, 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
- $\cdots$

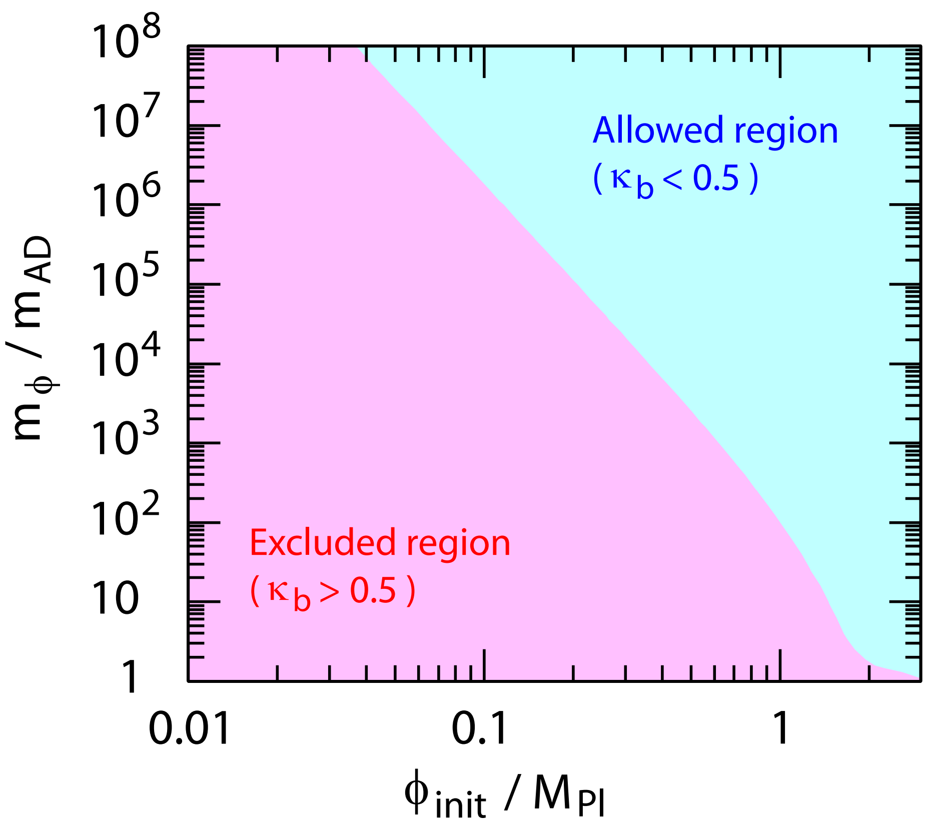
If a heavy modulus field (with $m_\phi \sim 100$ TeV) plays the role of the curvaton, $T_{\rm RD2} \sim 1 - 10$ MeV

$\Rightarrow$ 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 $m_{\rm AD}$

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

- $H \sim m_{\rm AD}$ in RD1 $\Rightarrow \kappa_b \neq 0$
- $H \sim m_{\rm AD}$ in ϕD $\Rightarrow \kappa_b \sim 0$



$\kappa_b \lesssim 0.5$ (from the WMAP)

$\Rightarrow$ $\phi_{\rm init} \sim M_{\rm Pl}$ or $m_\phi \gg m_{\rm AD}$
[Ikegami & Moroi]

Another possibility: Baryogenesis with the curvaton

$\Rightarrow$ 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

$\Rightarrow$ 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 ϕD epoch is realized, some fraction of the radiation originates from the inflaton

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

$\Rightarrow$ Small but non-vanishing κ_b may arise

$$\kappa_b = -\frac{9}{2}\frac{1 - f_{\gamma_{\tilde{N}}}}{f_{\gamma_{\tilde{N}}}}$$

$f_{\gamma_{\tilde{N}}}$: 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

  $\Rightarrow$ For example, Affleck-Dine field cannot play the role of curvaton

- In other case, sizable entropy fluctuation may be generated

  $\Rightarrow$ 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