

Cosmic perturbations and baryon asymmetry from a rotating field

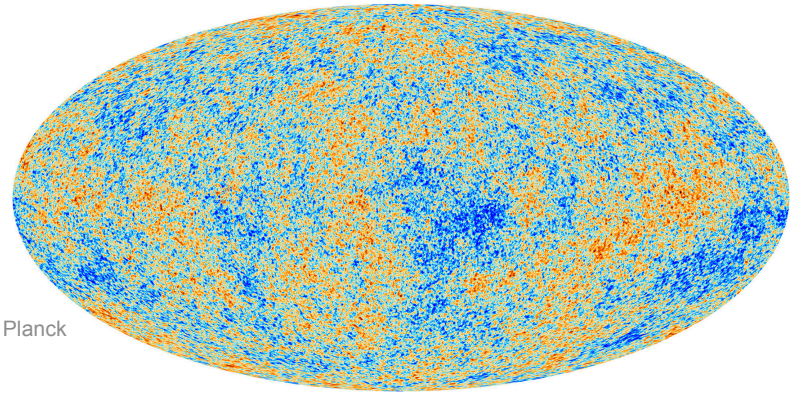
Taegyu Lee

arXiv:26xx.xxxx

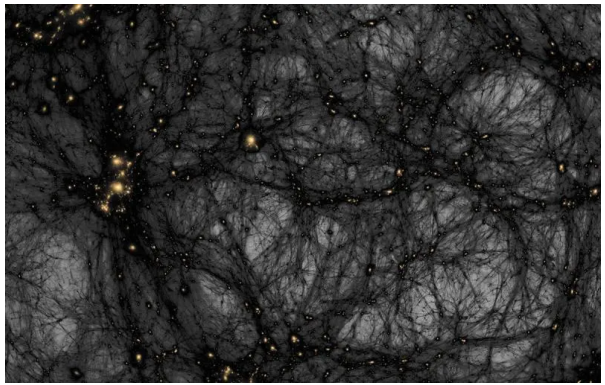
Collaboration with Raymond Co, Keisuke Harigaya, and Aaron Pierce

INDIANA UNIVERSITY BLOOMINGTON

Questions about the Universe



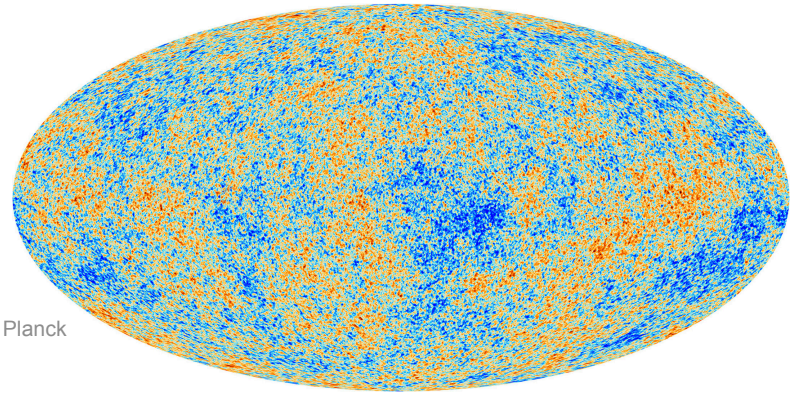
Planck



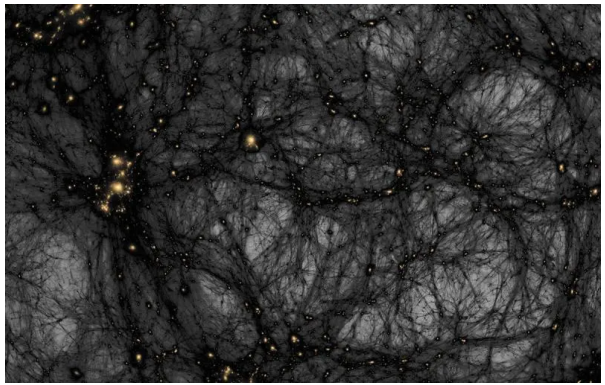
NASA

Source: Planck 2018

Questions about the Universe



Planck



NASA

Baryon asymmetry

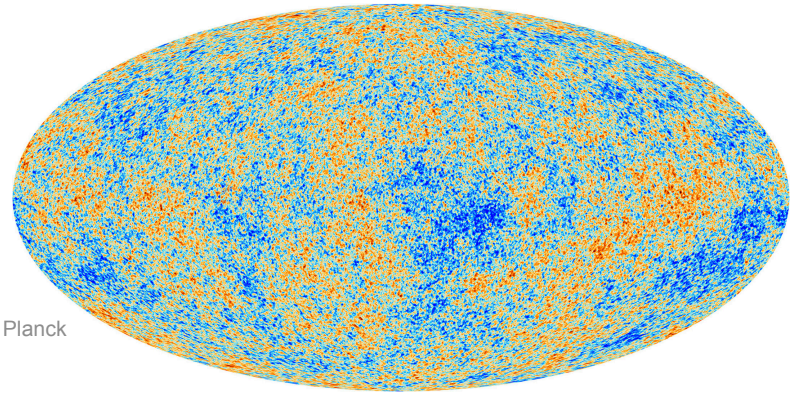
The question of why the Universe is dominantly made of matter than antimatter.

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11}$$

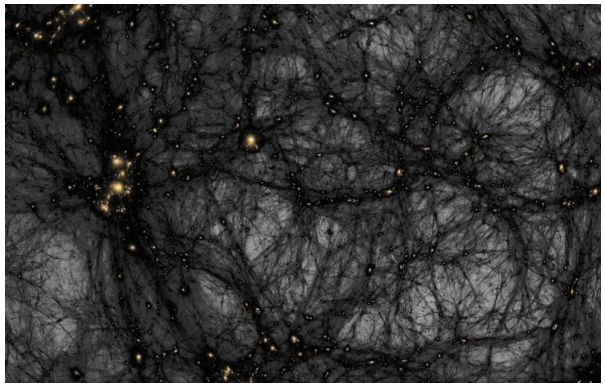
(s = entropy density)

Source: Planck 2018

Questions about the Universe



Planck



NASA

Baryon asymmetry

The question of why the Universe is dominantly made of matter than antimatter.

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11}$$

(s = entropy density)

Cosmic perturbation

The question of why the primordial fluctuations are adiabatic with observed spectral index (n_s).

$$P_\zeta(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1} \qquad n_s = 0.965 \pm 0.004$$

Source: Planck 2018

Affleck Dine mechanism

I. Affleck and M. Dine (Nucl. Phys. B 249 (1985) 361–380)

$$V(\phi) = \frac{|\phi|^{2N-2}}{M^{2N-6}} + m_\phi^2 |\phi|^2 - H^2 |\phi|^2 + \left(\frac{A}{M^{N-3}} \phi^N + \text{h.c.} \right) \qquad (N > 3) \qquad \phi = \frac{1}{\sqrt{2}} S e^{i\theta}$$

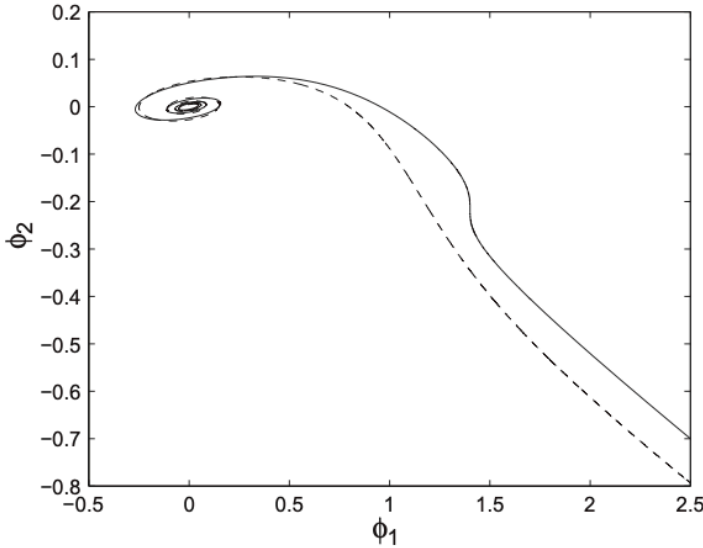
1. During inflation, MSSM flat direction (ϕ) obtains large initial field value due to the Hubble induced mass

* Flat direction is a direction where the scalar potential vanishes at renormalizable level

2. After inflation, CP violating A-term gives a kick in the angular direction

3. The charge stored in the condensate produces baryon number

$$n_\theta = i(\dot{\phi}^* \phi - \phi^* \dot{\phi})$$



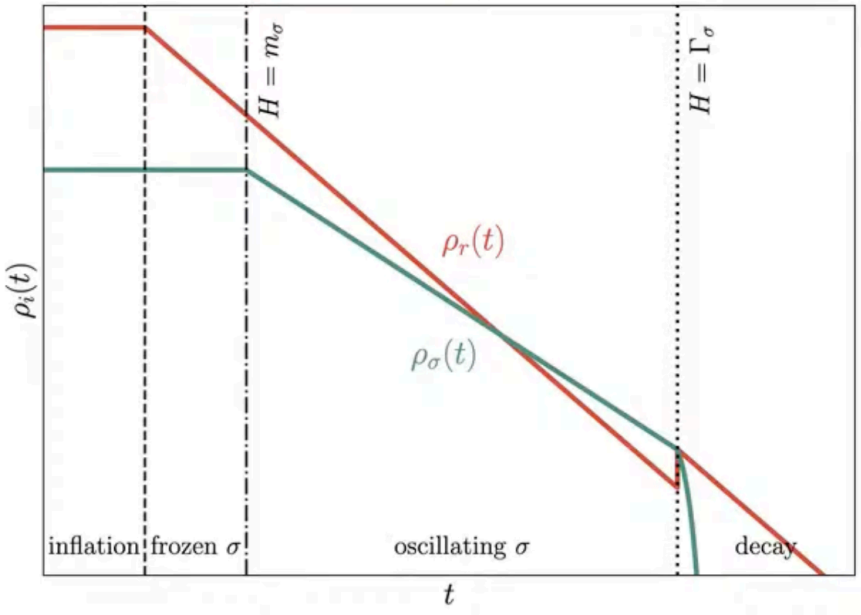
R. Allahverdi and A. Mazumdar (Nucl. Phys. B 249 (1985) 361–380)

Curvaton

D. H. Lyth and D. Wands (arXiv:0110002)
K. Enqvist and M. S. Sloth (arXiv:0109214)
N. Bartolo and A. R. Liddle (arXiv:0203076)

Inflaton is only responsible for inflation and primordial fluctuations are produced from curvaton.

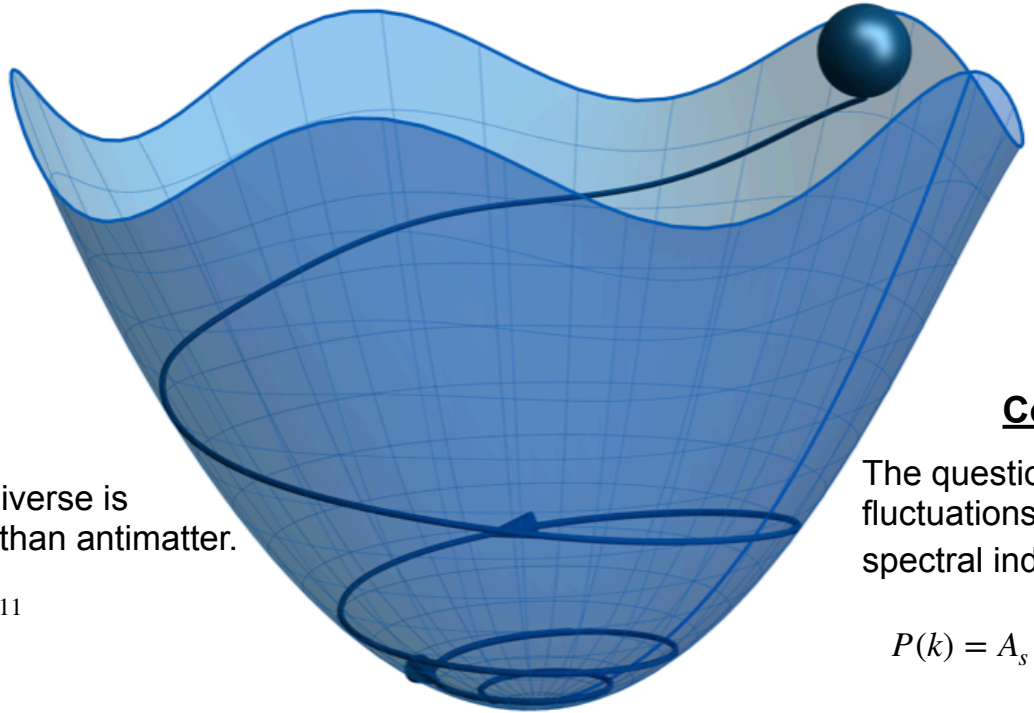
Curvaton dominates the energy density of the universe and then decays to produce primordial perturbation



$$f_{\rm NL}^{\rm local} = \frac{5}{4r} - \frac{5}{3} - \frac{6r}{5} \qquad \left(r = \frac{3\rho_\sigma}{4\rho_r + 3\rho_\sigma} \right)$$

Takuya Okawa's talk slides

Can one scalar field answer two questions



Baryon asymmetry

The question of why the Universe is dominantly made of matter than antimatter.

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11}$$

Cosmic perturbation

The question of why the primordial fluctuations are adiabatic with observed spectral index (n_s).

$$P(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \qquad n_s = 0.965 \pm 0.004$$

Why this is non-trivial

Baryon isocurvature

Source: Planck 2018

If the baryon yield depends on components other than curvaton, it can lead to large baryon isocurvature

$$\frac{P_{S_b}}{P_\zeta} = \beta_{b,\mathrm{iso}} \lesssim 0.027$$

Observed spectral index

Generally, fine tuning in the potential is needed to match observed spectral index

$$P(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \qquad n_s = 0.965 \pm 0.004$$

* In a given model, $n_s - 1 \simeq \frac{2}{3}\frac{V''}{H^2}$. But due to the Hubble induced mass, generically we expect $V'' \sim \mathcal{O}(H^2)$

Cosmological history

$$V(\phi) = \frac{|\phi|^{2N-2}}{M^{2N-6}} + m_\phi^2 |\phi|^2 + m_T^2 |\phi|^2 - H^2 |\phi|^2 + \left(\frac{A}{M^{N-4}} \phi^N + \text{h.c.} \right)$$

$m_\phi = m_0$ SUSY breaking scale

$$\phi = \frac{1}{\sqrt{2}} S e^{i\theta}$$

$(N > 3)$

1. During inflation, MSSM flat direction (ϕ) obtains large initial field value due to the negative Hubble induced mass

2. After inflation, CP violating A-term gives a kick in the angular direction

Cosmological history

$$V(\phi) = \frac{|\phi|^{2N-2}}{M^{2N-6}} + m_\phi^2 |\phi|^2 + m_T^2 |\phi|^2 - H^2 |\phi|^2 + \left(\frac{A}{M^{N-4}} \phi^N + \text{h.c.} \right)$$

$m_\phi = m_0$ SUSY breaking scale

$$\phi = \frac{1}{\sqrt{2}} S e^{i\theta}$$

$$(N > 3)$$

1. During inflation, MSSM flat direction (ϕ) obtains large initial field value due to the negative Hubble induced mass

2. After inflation, CP violating A-term gives a kick in the angular direction

Angular direction (θ) serves as a curvaton

Cosmological history

$$V(\phi) = \frac{|\phi|^{2N-2}}{M^{2N-6}} + m_\phi^2 |\phi|^2 + m_T^2 |\phi|^2 - H^2 |\phi|^2 + \left(\frac{A}{M^{N-4}} \phi^N + \text{h.c.} \right)$$

$m_\phi = m_0$ SUSY breaking scale

$$\phi = \frac{1}{\sqrt{2}} S e^{i\theta}$$

$$(N > 3)$$

1. During inflation, MSSM flat direction (ϕ) obtains large initial field value due to the negative Hubble induced mass

2. After inflation, CP violating A-term gives a kick in the angular direction

Angular direction (θ) serves as a curvaton

1. If radial mode also produces curvature perturbation it can lead to large baryon isocurvature

Cosmological history

$$V(\phi) = \frac{|\phi|^{2N-2}}{M^{2N-6}} + m_\phi^2 |\phi|^2 + m_T^2 |\phi|^2 - H^2 |\phi|^2 + \left(\frac{A}{M^{N-4}} \phi^N + \text{h.c.} \right)$$

$m_\phi = m_0$ SUSY breaking scale

$$\phi = \frac{1}{\sqrt{2}} S e^{i\theta}$$

$(N > 3)$

1. During inflation, MSSM flat direction (ϕ) obtains large initial field value due to the negative Hubble induced mass

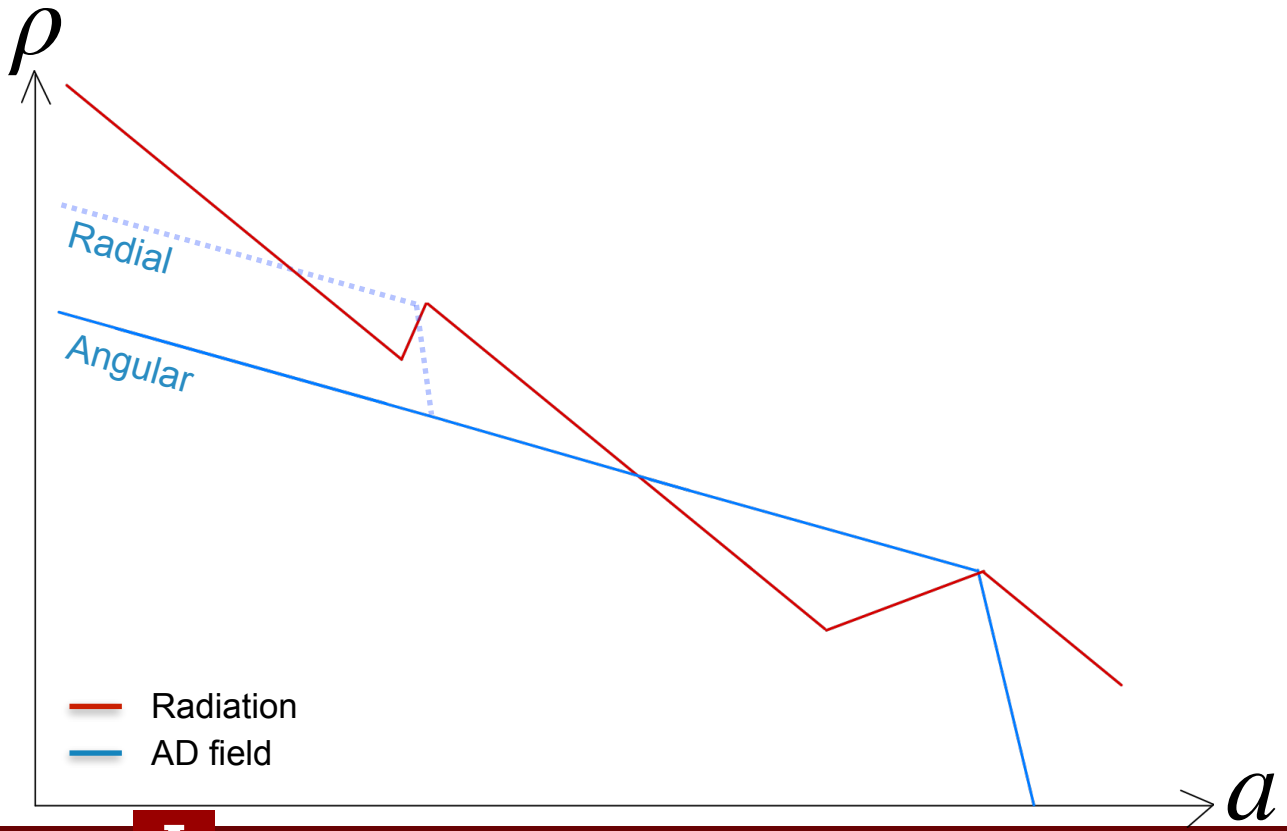
2. After inflation, CP violating A-term gives a kick in the angular direction

Angular direction (θ) serves as a curvaton

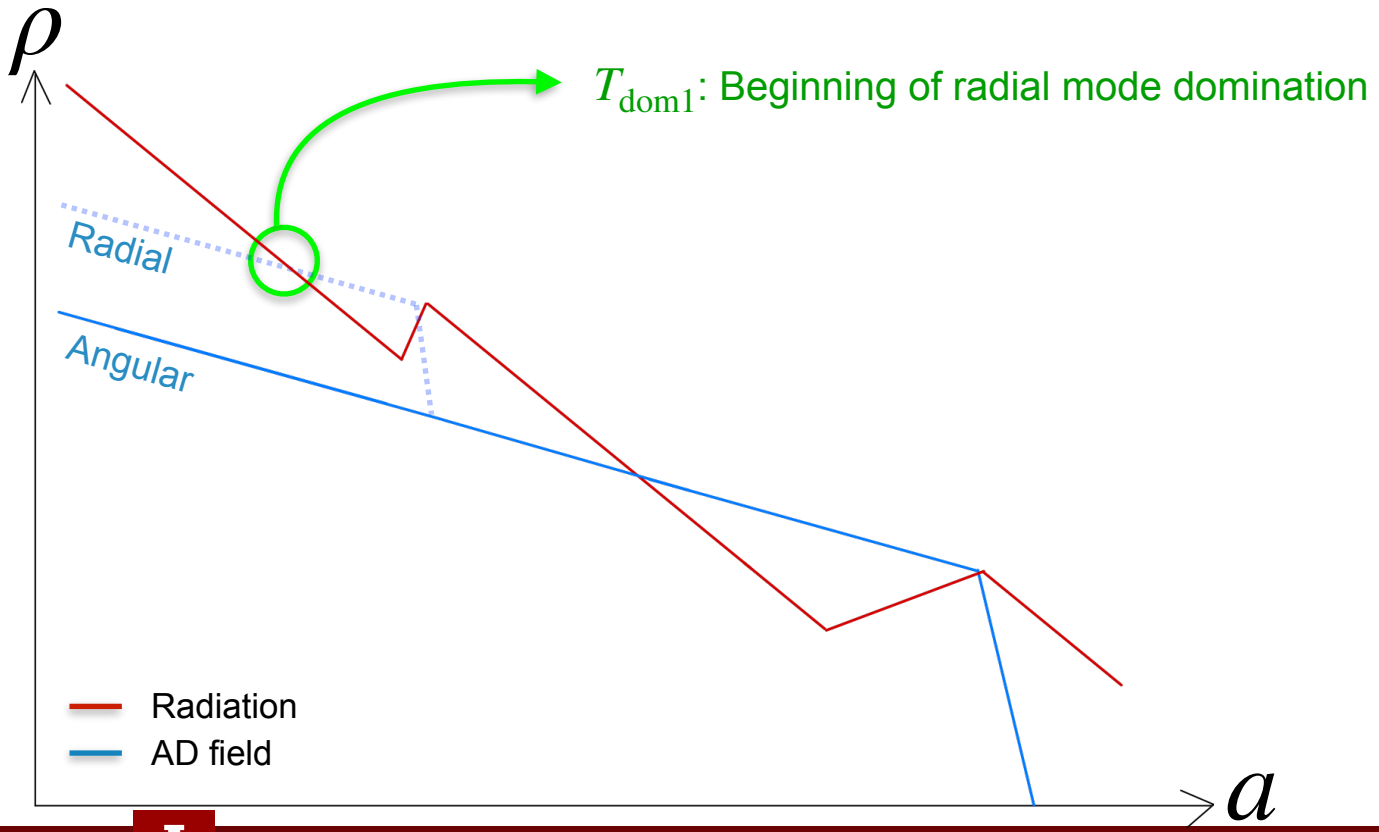
1. If radial mode also produces curvature perturbation it can lead to large baryon isocurvature

2. Angular mode is light during inflation which can lead to observable $f_{\rm NL}$

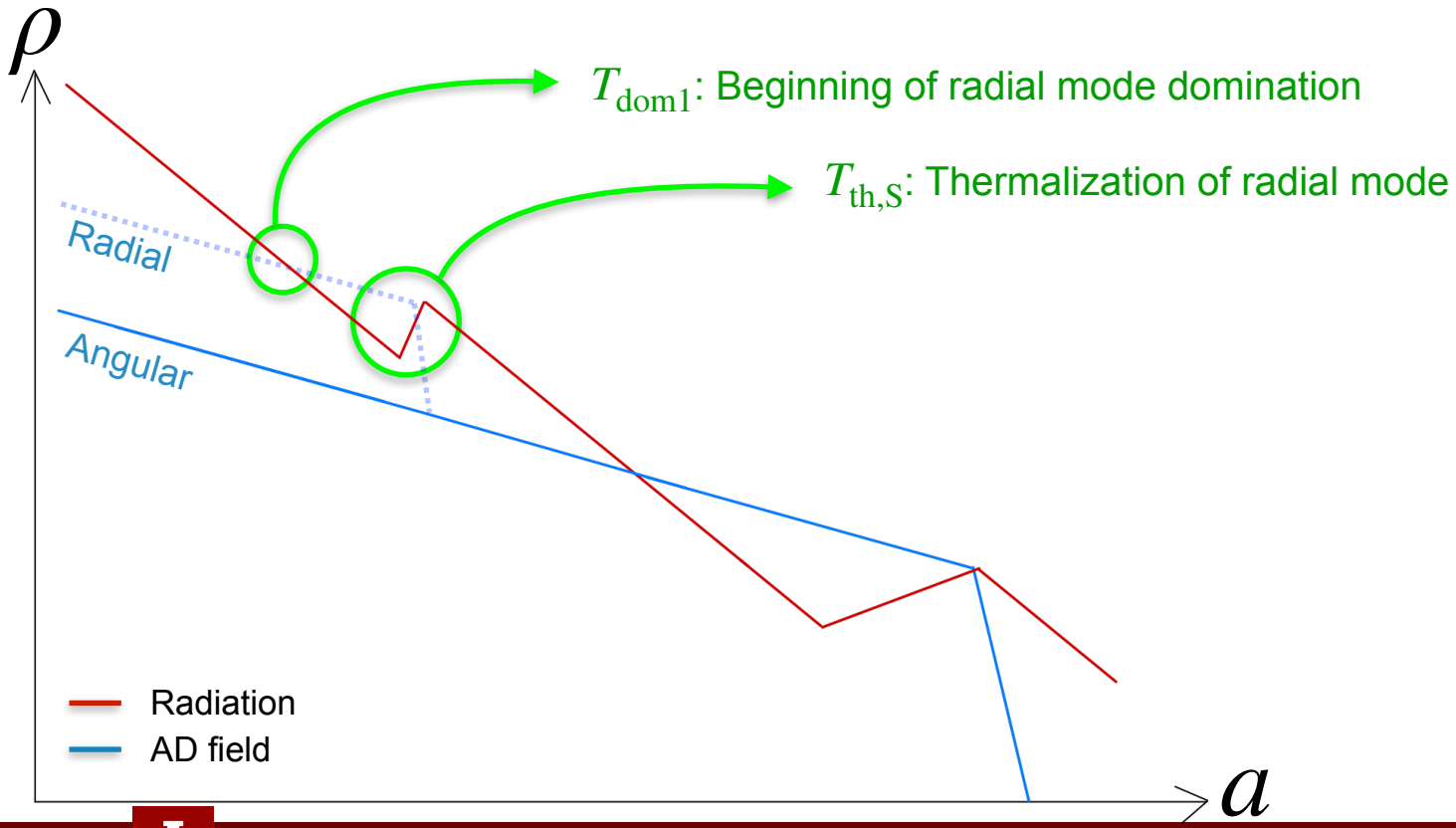
Cosmological history



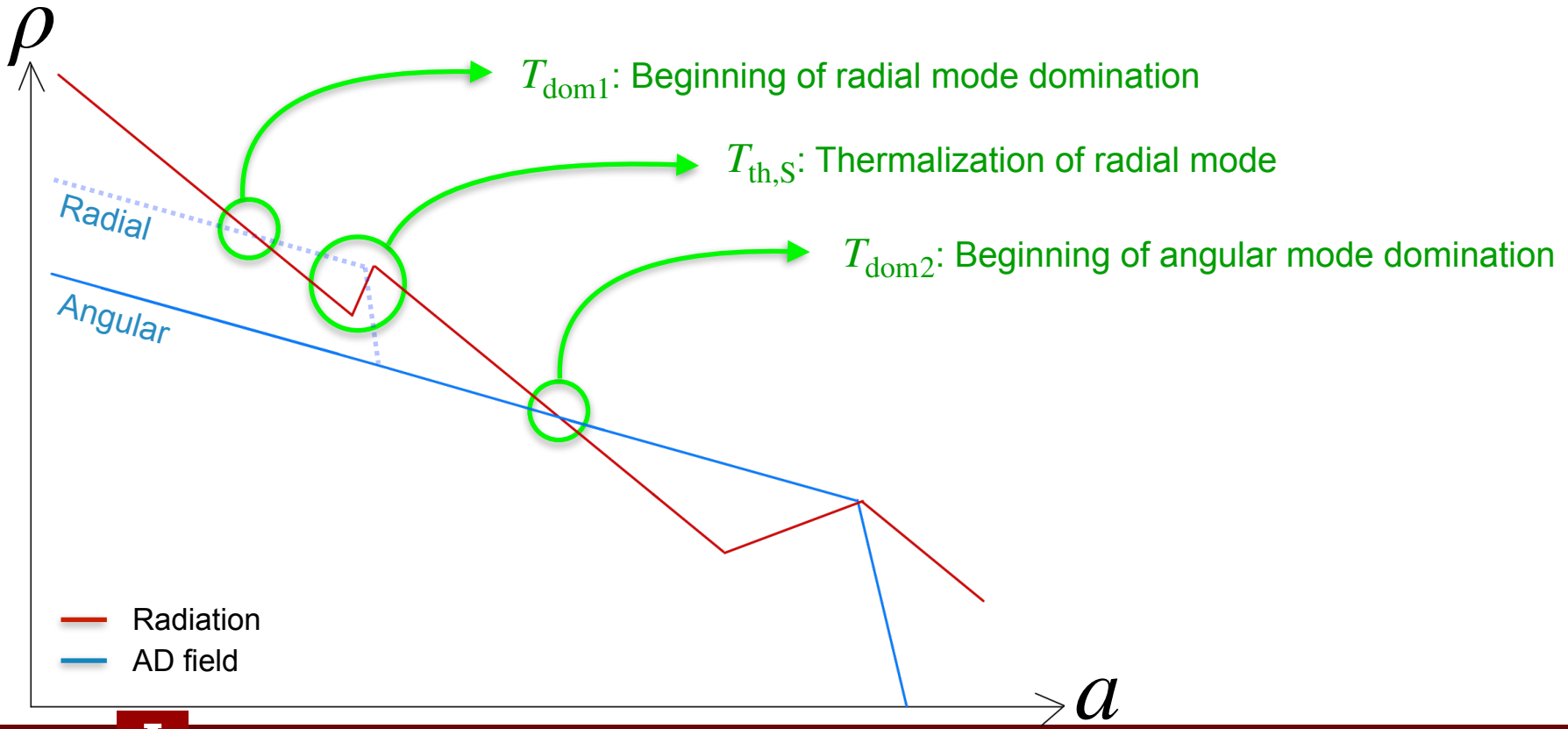
Cosmological history



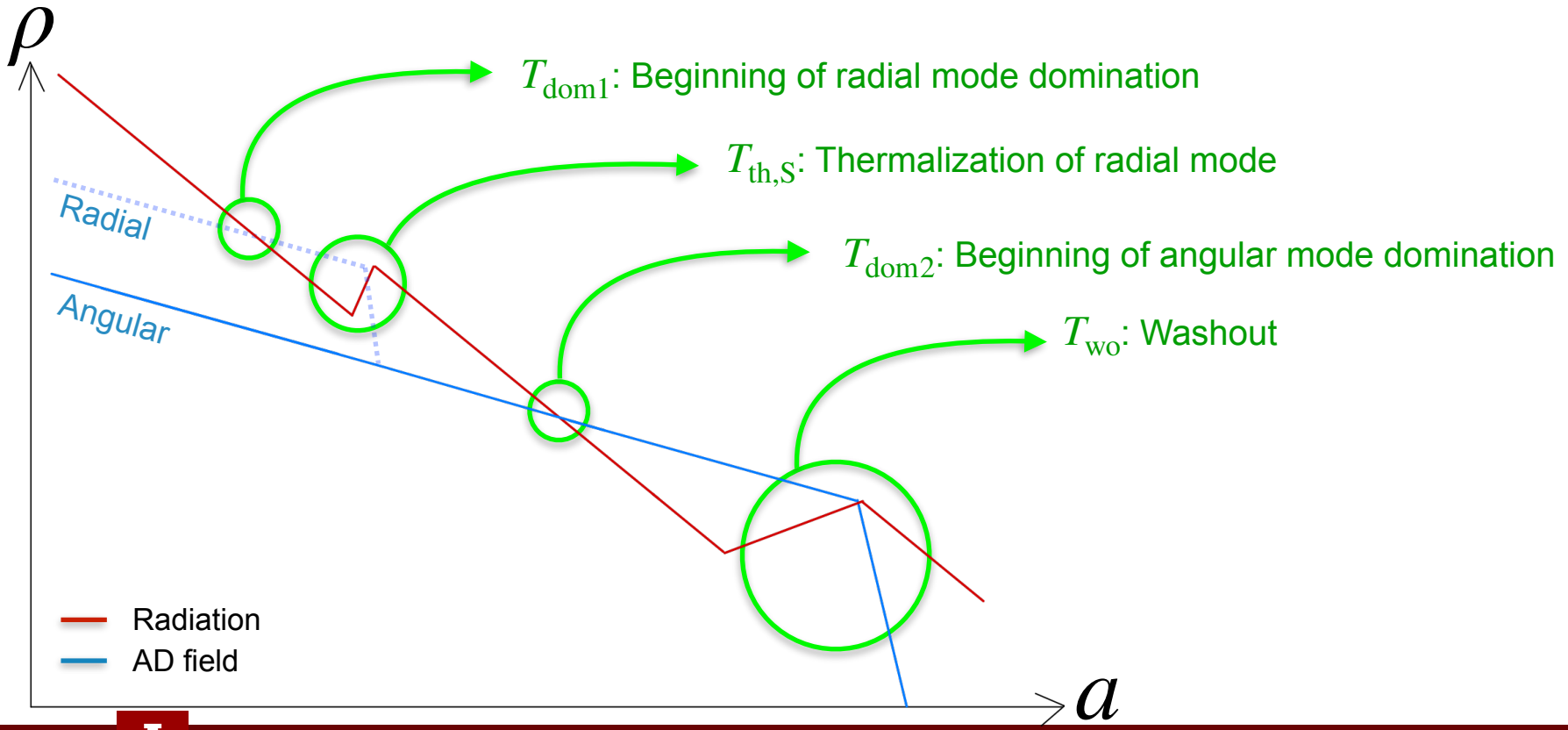
Cosmological history



Cosmological history



Cosmological history



Model setup

MSSM flat direction: $(U_i^c)^R(U_j^c)^G(D_m^c)^B E_n^c$

$i \neq j, m, n$ are generational indices

This flat direction breaks $SU(3)_c$ and $U(1)_Y$ for the large field value. Also leads to several chiral super fields with large mass that is proportional to the coupling (κ) and the field value ($m \sim \kappa\phi$)

Model setup

MSSM flat direction: $(U_i^c)^R(U_j^c)^G(D_m^c)^B E_n^c$ $i \neq j, m, n$ are generational indices

This flat direction breaks $SU(3)_c$ and $U(1)_Y$ for the large field value. Also leads to several chiral super fields with large mass that is proportional to the coupling (κ) and the field value ($m \sim \kappa\phi$)

The super fields that become heavy

α, β, γ are color indices

1. Gauge: G, B, and nine linear combination of $(U_i^c)^\alpha$, $(U_j^c)^\beta$, $(D_m^c)^\gamma$, E_n^c $\quad m_g \sim g\phi$
2. Up type: H_u, $y_{u,i}Q_i^R + y_{u,j}Q_j^G$ $\quad m_1 \sim \sqrt{y_{u,i}^2 + y_{u,j}^2}\phi$
3. Down type: H_d, $y_{d,m}Q_m^B + y_{l,n}L_n$ $\quad m_2 \sim \sqrt{y_{d,m}^2 + y_{l,n}^2}\phi$

Model setup

MSSM flat direction: $(U_i^c)^R(U_j^c)^G(D_m^c)^B E_n^c$ $i \neq j, m, n$ are generational indices

To washout the charge and reheat the universe, we need to break all the symmetries that are carried by the flat direction

Symmetry	Process that breaks the symmetry
Flavor	Squark mixing or CKM mixing and slepton mixing
Chiral	Yukawa interaction
Peccei-Quinn	μ or $B\mu$ term
R	Gaugino mass
Color	Exchange of SU(3) gauge field

Model setup

MSSM flat direction: $(U_i^c)^R(U_j^c)^G(D_m^c)^B E_n^c$ $i \neq j, m, n$ are generational indices

To washout the charge and reheat the universe, we need to break all the symmetries that are carried by the flat direction

Symmetry	Process that breaks the symmetry
Flavor	Squark mixing or CKM mixing and slepton mixing
Chiral	Yukawa interaction
Peccei-Quinn	μ or $B\mu$ term
R	Gaugino mass
Color	Exchange of SU(3) gauge field

The process with the smallest rate to reach equilibrium determines the onset of charge washout and reheating, thereby generating curvature perturbations.

Baryon asymmetry : right handed neutrino

$$W = y_N L H_u N$$

Baryon asymmetry : right handed neutrino

$$W = y_N L H_u N$$

Generation of baryon number is dominated by the decay of H_u since it remains heavy

Baryon asymmetry : right handed neutrino

$$W = y_N L H_u N$$

Generation of baryon number is dominated by the decay of H_u since it remains heavy

In the present of EW sphaleron, $H_u \to L + N$ can generate baryon number

Baryon asymmetry : right handed neutrino

$$W = y_N L H_u N$$

Generation of baryon number is dominated by the decay of H_u since it remains heavy

In the present of EW sphaleron, $H_u \to L + N$ can generate baryon number

$$\Gamma_B \propto \frac{\mu_{H_u}}{T} \times \left(m_1 T\right)^{3/2} e^{-m_1/T} \times y_N^2 m_1 \qquad \left(y_N^2 = \frac{m_\nu m_N}{v_u^2}\right)$$

Due to the Boltzmann suppression, the baryon asymmetry is dominantly produced near the end of washout when the universe is effectively described only by AD field

Baryon asymmetry : right handed neutrino

$$W = y_N L H_u N$$

Generation of baryon number is dominated by the decay of H_u since it remains heavy

In the present of EW sphaleron, $H_u \to L + N$ can generate baryon number

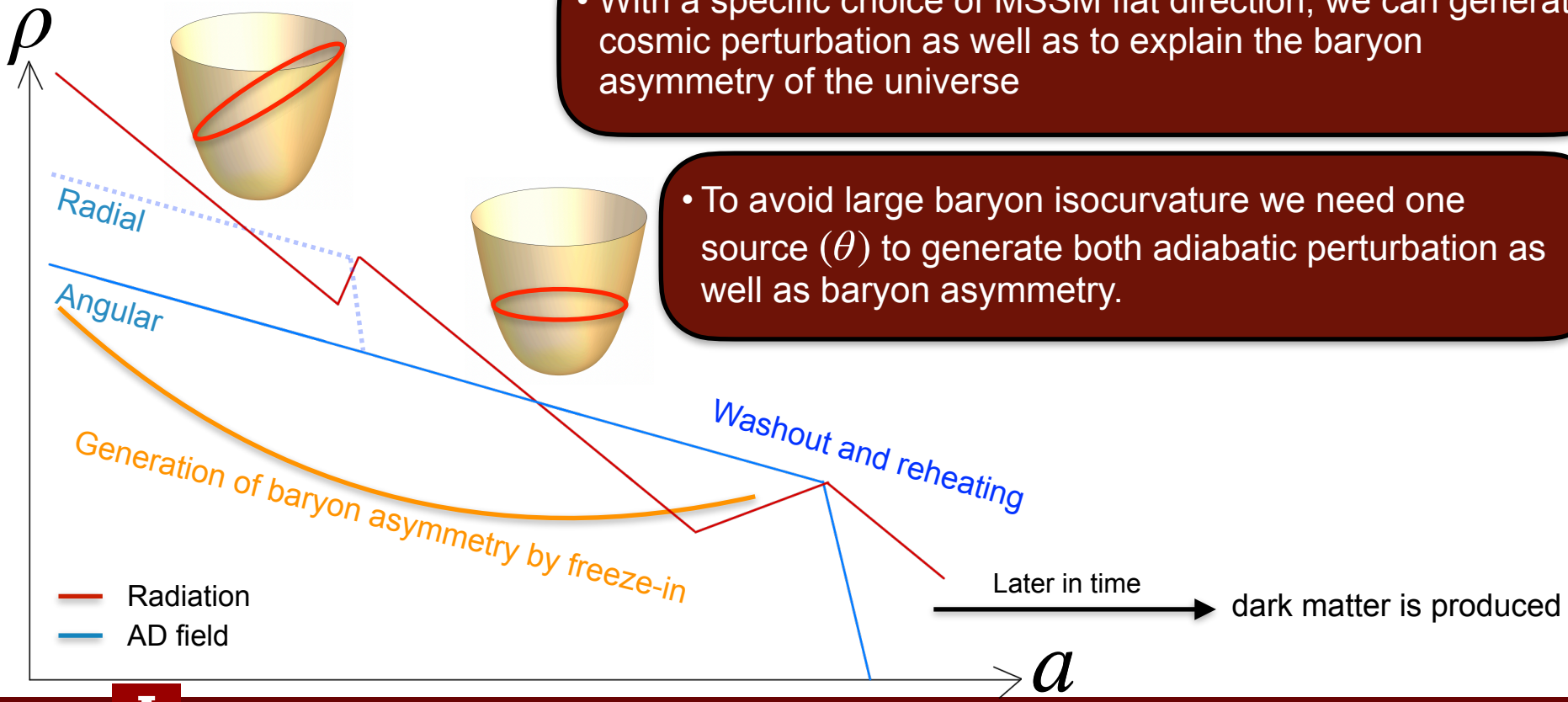
$$\Gamma_B \propto \frac{\mu_{H_u}}{T} \times \left(m_1 T\right)^{3/2} e^{-m_1/T} \times y_N^2 m_1 \qquad \left(y_N^2 = \frac{m_\nu m_N}{v_u^2}\right)$$

Due to the Boltzmann suppression, the baryon asymmetry is dominantly produced near the end of washout when the universe is effectively described only by AD field

→ Suppressed baryon isocurvature

Summary

- With a specific choice of MSSM flat direction, we can generate cosmic perturbation as well as to explain the baryon asymmetry of the universe
- To avoid large baryon isocurvature we need one source (θ) to generate both adiabatic perturbation as well as baryon asymmetry.



Backup slides

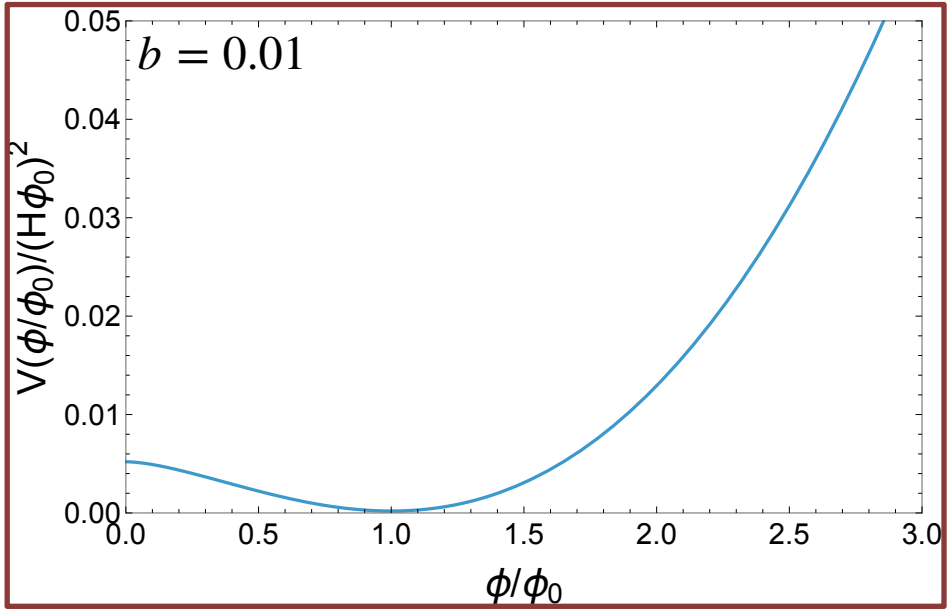
Spectral Index

$$V(\phi) = cH^2\phi^2 + bH^2\phi^2 \log\left(\frac{\phi}{M}\right) = bH^2\phi^2\left[\log\left(\frac{\phi}{\phi_0}\right) - 1\right]$$

$$\phi_0 = M\exp\left(-\frac{1}{2} - \frac{c}{b}\right)$$

$b \sim \mathcal{O}(0.01)$ that can originate from loop factor

$$n_s - 1 \simeq \frac{2}{3}\frac{V''}{H^2} = \frac{4}{3}b\left[1 + \log\left(\frac{\phi}{\phi_0}\right)\right]$$



Chiral Plasma Instability

- Chiral Plasma Instability (CPI)

  The motion in the angular direction can generate helical magnetic field of $U(1)_Y$.

  The decaying helical hypermagnetic field after the EW phase transition can source baryon asymmetry

  1. This flat direction breaks $SU(3)_c$ and $U(1)_Y$ leading to no CPI problem until near washout when $\phi < T$.

  * If CPI is effective, the charge in the condensate can be stored in helical magnetic field which later produces baryon asymmetry that is much larger than the observed value

Q-ball

- Q-ball formation

  When the potential is flatter than the quadratic, it can lead to formation of non-topological defect.

  Once Q-balls decay, it can generate extra-curvature perturbation which can lead to large Baryon isocurvature

If one of the up type squark is from third generation, the zero temperature potential obtains positive log correction avoiding Q-ball production.