Oscillating Affleck-Dine condensate and its cosmological implication

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FH, Kawasaki, arXiv:1706.08659

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Introduction

- Our universe is **baryon asymmetric**

to explains the abundances of light elements by **Big Bang Nucleosynthesis**,

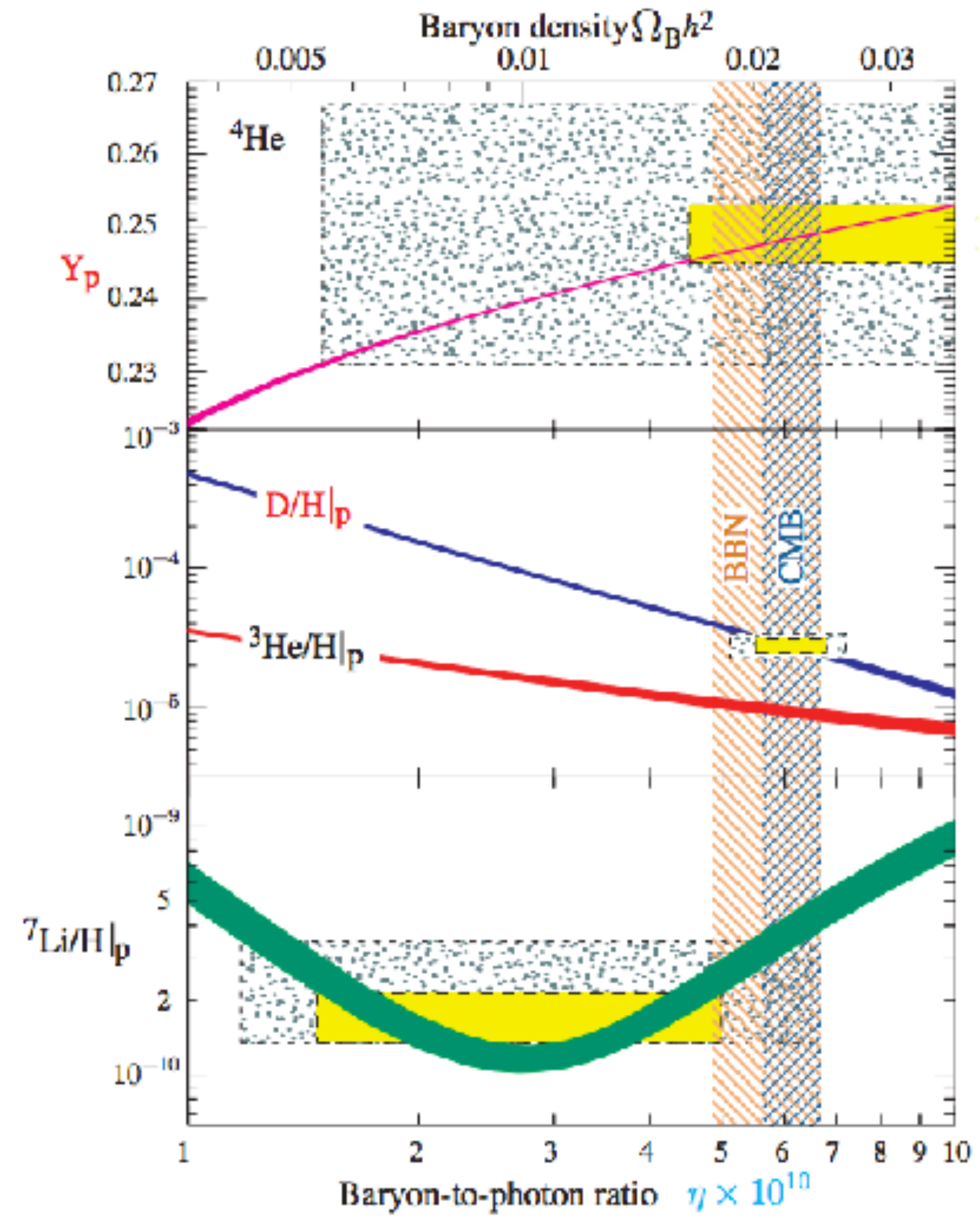
$$\frac{n_B}{s} = (6-8) \times 10^{-11}$$

is required, which is consistent with the observation of **Cosmic Microwave Background**

- We need a mechanism to produce the baryon asymmetry **after inflation**

⬇

Baryogenesis



…Which scenario?

[Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.]

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. **Affleck-Dine (AD) baryogenesis.** 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Affleck-Dine (AD) baryogenesis

- described by the scalar dynamics in **minimally supersymmetric standard model (MSSM)**
- very **efficient** production of the baryon asymmetry
- Q-ball **dark matter**

Affleck-Dine Baryogenesis

[Affleck, Dine, 85 Dine, Randall, Thomas, 96]

Scalar Potential

- MSSM $\supset$ flat directions AD-fields: Φ with B♯ (B-L♯)

  → massless for renormalizable level

  non-renormalizable superpotential for AD field is

$$W_{\rm AD} = \frac{\lambda}{nM^{n-3}}\Phi^n, \quad (n \geq 4)$$

M : cut-off, λ : coupling constant,

- In the presence of SUSY breaking sector, its scalar potential is cast as

SUSY breaking term SUSY term

$$V_{\rm AD}(\phi,\phi^*) = (m_\phi^2 - cH^2)|\phi|^2 + \left(a_m \frac{\lambda m_{3/2}\phi^n}{nM^{n-3}} + {\rm h.c.}\right) + \frac{\lambda^2|\phi|^{2n-2}}{M^{2n-6}},$$

$(\Phi|_{\theta=0} = \phi)$

soft mass Hubble ind. mass A-term: ~~$U_B(1)$~~

Assumption: $c > 0$

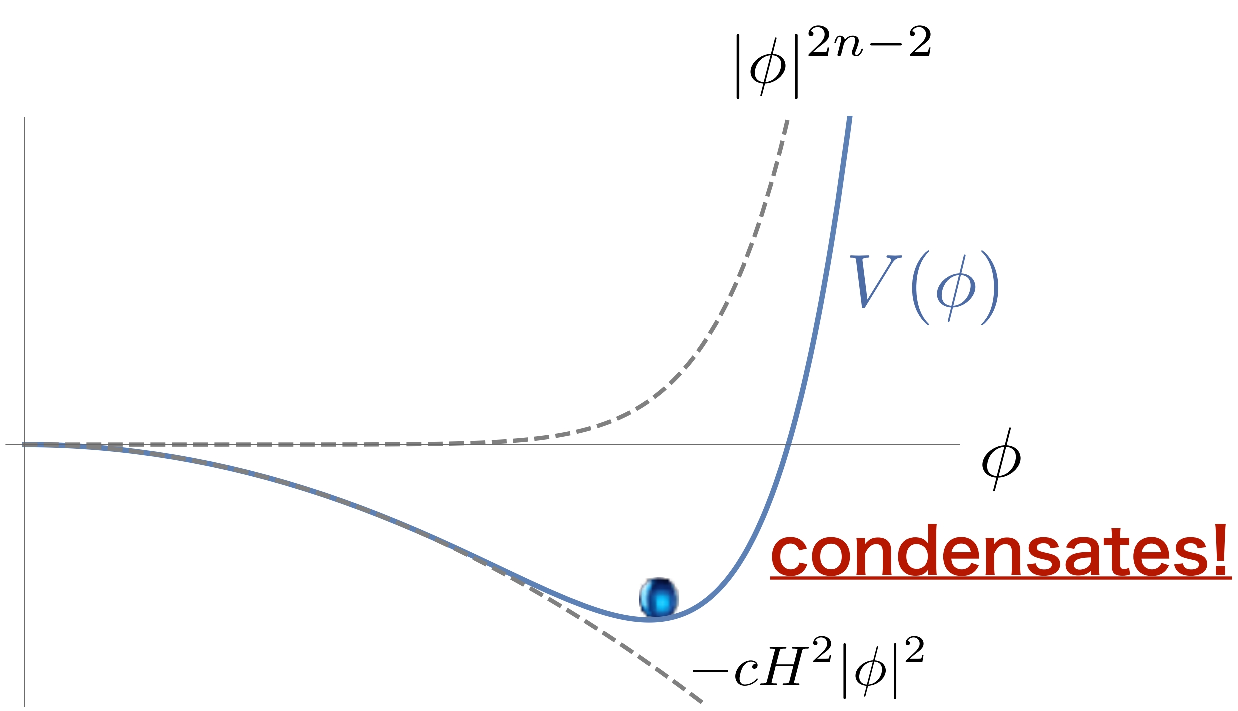
Scalar Dynamics

$$cH > m_\phi$$

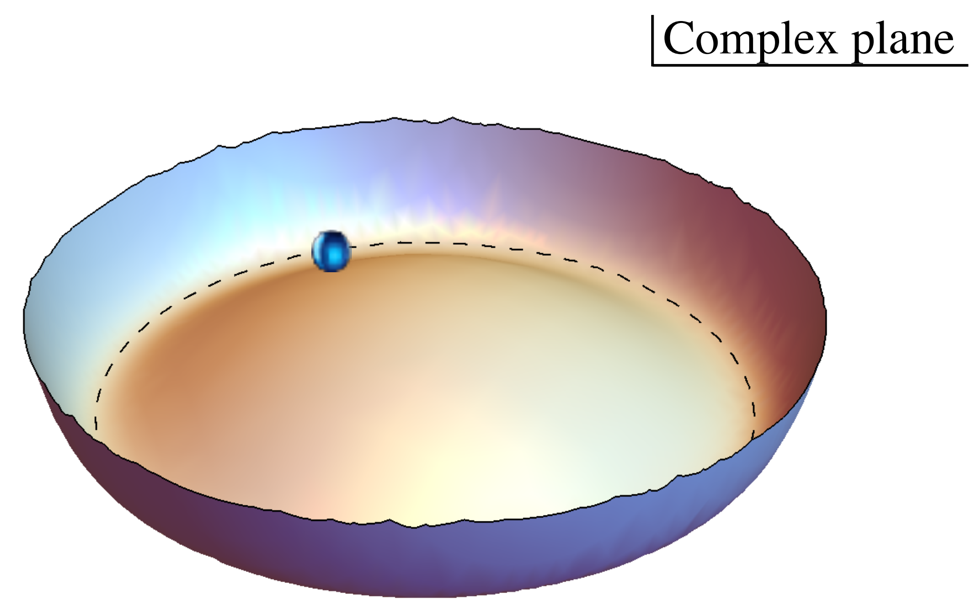
$(\theta = \arg\phi)$

$$V_{\rm AD}(\phi,\phi^*) = (m_\phi^2 - cH^2)|\phi|^2 + \left(a_m \frac{\lambda m_{3/2}\phi^n}{nM^{n-3}} + {\rm h.c.}\right) + \frac{\lambda^2|\phi|^{2n-2}}{M^{2n-6}},$$

negative mass!



$$\langle|\phi(t)|\rangle \sim (M^{n-3}H(t)\sqrt{c}/\lambda)^{1/(n-2)}$$



$\langle\theta\rangle \sim \theta_i$ (∵Hubble friction)

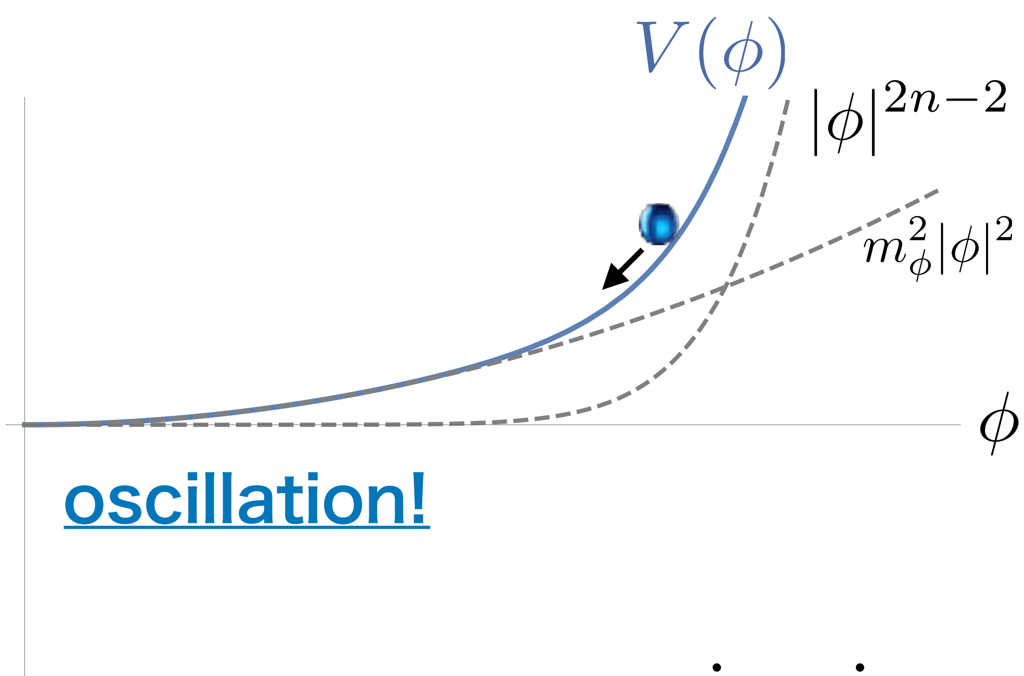
Scalar Dynamics

$$cH < m_\phi$$

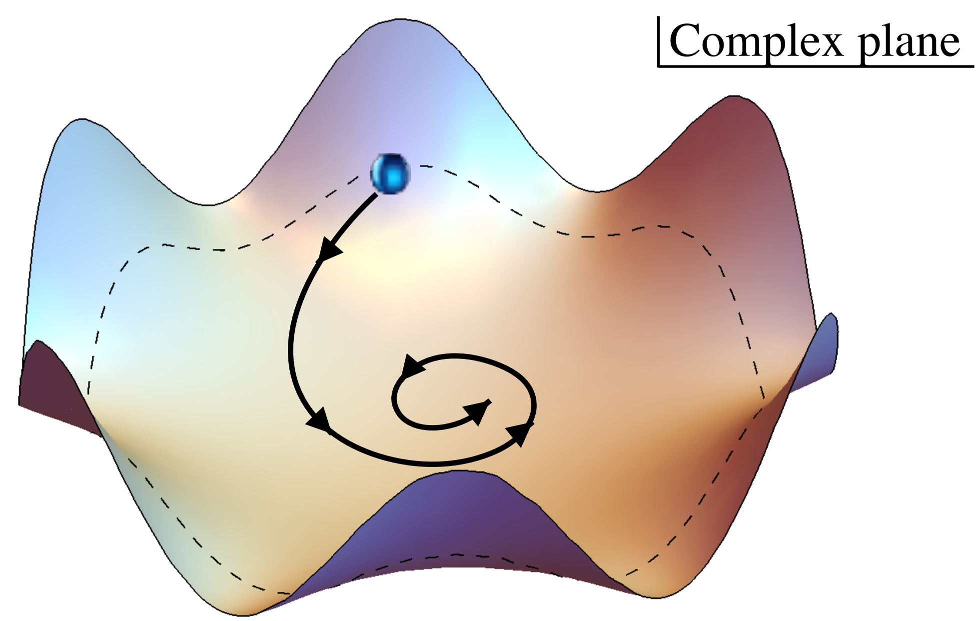
$$V_{\rm AD}(\phi,\phi^*) = (m_\phi^2 - cH^2)|\phi|^2 + \left(a_m \frac{\lambda m_{3/2}\phi^n}{nM^{n-3}} + \text{h.c.}\right) + \frac{\lambda^2|\phi|^{2n-2}}{M^{2n-6}},$$

positive mass!

A-term: $U_B(1)$ $\sim \sin n\theta$



oscillation!



rotation in the complex plane!

$$n_B = i(\phi^*\dot\phi - \dot\phi^*\phi) \sim \dot\theta|\phi|^2$$

B♯ generation!

Predicted baryon asymmetry

$$\frac{n_B}{s}$$

$$= 1.1 \times 10^{-11} \lambda^{-1} \left(\frac{T_R}{10^{8.5}\mathrm{GeV}} \right) \left(\frac{m_{3/2}}{1\mathrm{TeV}} \right) \left(\frac{m_\phi}{1\mathrm{TeV}} \right)^{-1} \qquad (n = 4)$$

$$= 4.6 \times 10^{-11} \lambda^{-1/2} \left(\frac{T_R}{10\mathrm{GeV}} \right) \left(\frac{m_{3/2}}{1\mathrm{TeV}} \right) \left(\frac{m_\phi}{1\mathrm{TeV}} \right)^{-3/2} \qquad (n = 6)$$

Successful generation of the baryon asymmetry!

is ADBG possible

in

high-scale inflation?

$$\parallel$$

$$H_{\rm inf} \simeq 10^{13} {\rm GeV}$$

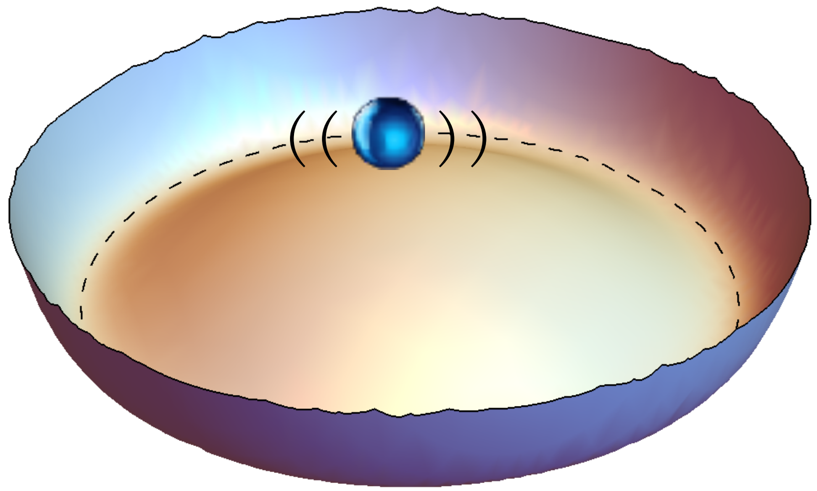
Issues of ADBG
in high-scale inflation scenario

- Constraint on baryonic isocurvature
  [K. Enqvist, J. McDonald (1999)]

- Finite temperature effect
  [A. Anisimov, M. Dine (2000)]

Constraint from baryonic isocurvature

[K. Enqvist, J. McDonald (1999)]



phase direction of AD field has
a quantum fluctuations during inflation

$$|\delta\theta_i| \simeq \frac{\sqrt{2}H_I}{2\pi\phi_I}$$

→AD predicts baryonic isocurvature perturbation:

$$\frac{\delta Y_B}{Y_B} \simeq \cot(n\theta_i)\delta\theta_i \qquad (\because Y_B \propto \sin(n\theta_i))$$

- Since the density perturbations of the CMB are predominantly adiabatic, the baryonic isocurvature perturbation is tightly constrained as

$$\frac{\delta Y_B}{Y_B} < 5.0 \times 10^{-5} \ \text{(CMB)}$$

→

$$\lambda \lesssim \begin{cases} 4.2 \times 10^{-4} \left(\frac{H_{\rm inf}}{10^{13}\,{\rm GeV}}\right)^{-1} & \text{for} \quad n = 4 \\ 1.2 \times 10^{-2} \left(\frac{H_{\rm inf}}{10^{13}\,{\rm GeV}}\right)^{-3} & \text{for} \quad n = 6, \end{cases}$$

upper bound on λ
→lower bound on Y_B

Issues of ADBG in high-scale inflation scenario

- Constraint on baryonic isocurvature
  [K. Enqvist, J. McDonald (1999)]

- Finite temperature effect
  [A. Anisimov, M. Dine (2000)]

Finite temperature effects

High-scale inflation predict the higher reheating temperature:

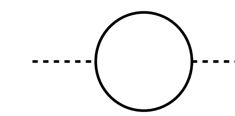
$$T_R \sim 10^9\,\mathrm{GeV}$$ for M_p-suppressed decay

→Thermal potential for AD field can dominate the dynamics

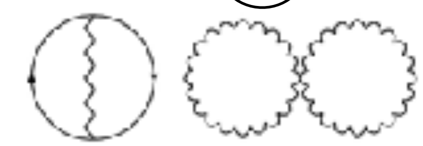
($\because \phi \supset$ squark, sleptons, Higgs)

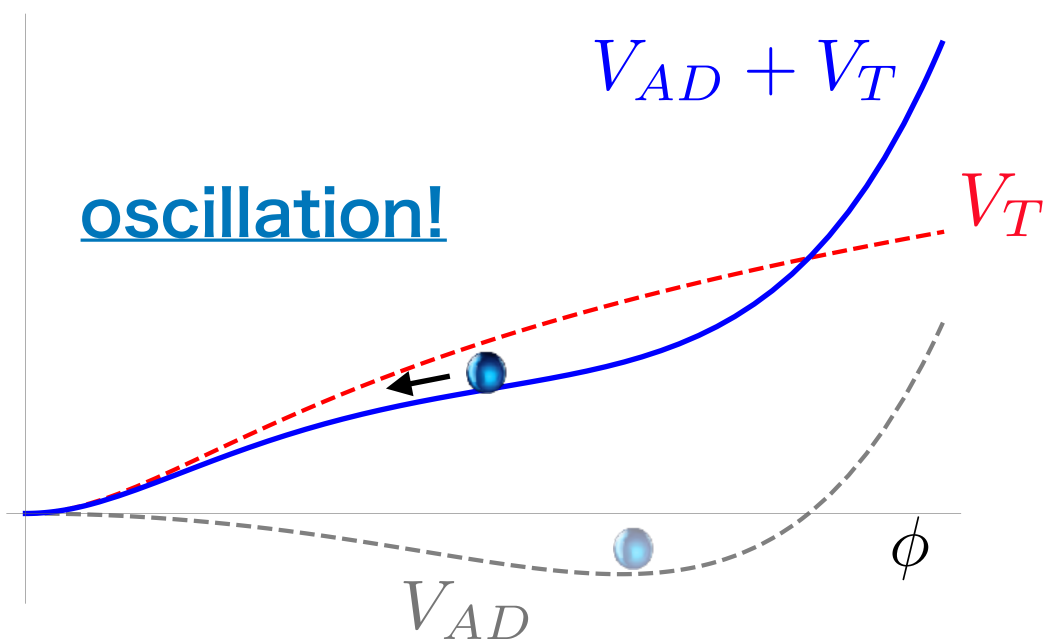
$$V_T(\phi) = \begin{cases} c_k f_k^2 T^2 |\phi|^2, & f_k|\phi| \lesssim T, \\ a_g \alpha_s^2 T^4 \ln\left(\frac{|\phi|^2}{T^2}\right), & |\phi| \gtrsim T. \end{cases}$$

:1-loop (thermal mass)



:2-loop (thermal log)



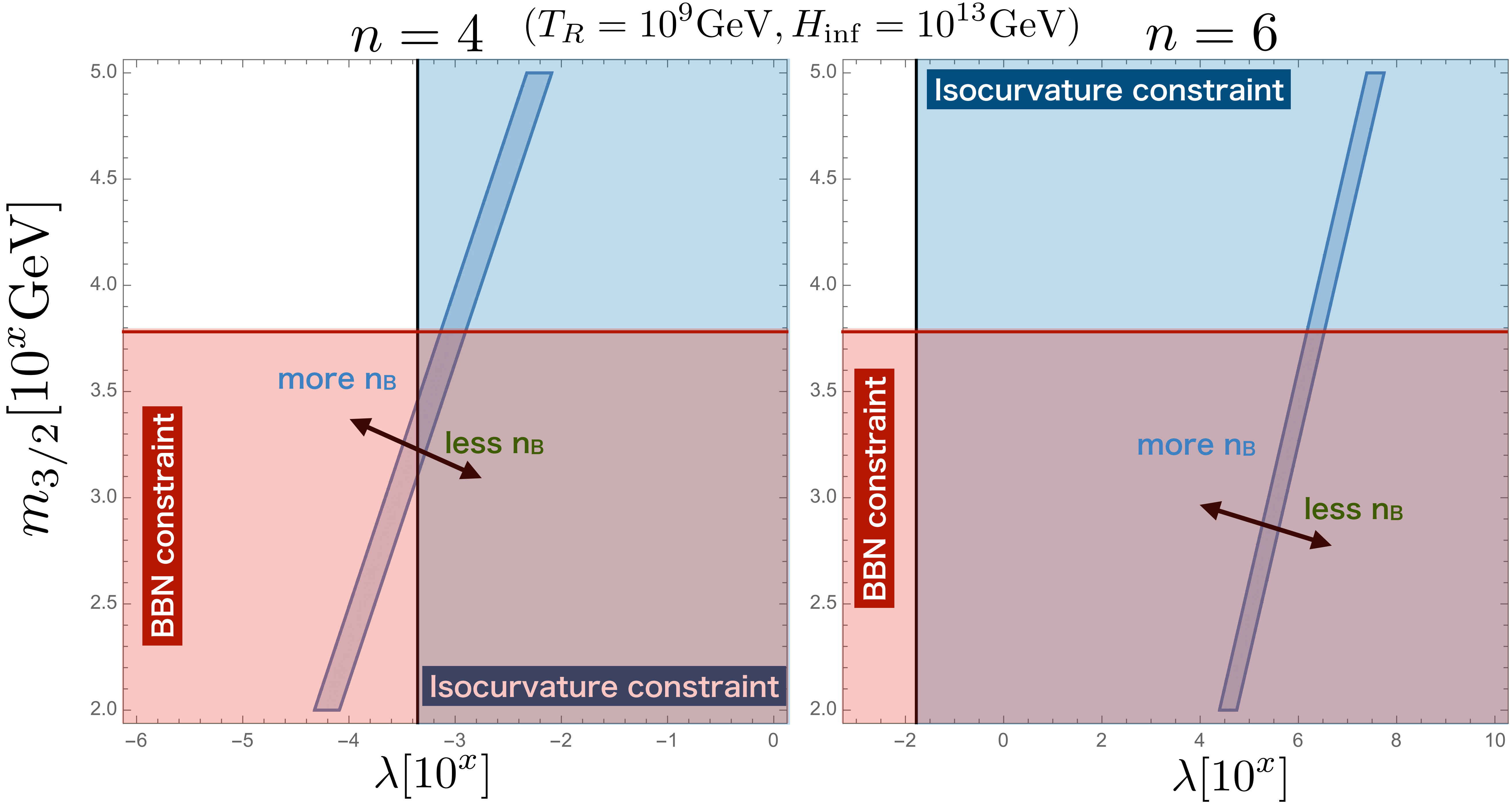


Thermal potential could destabilize the AD condensate before H ~ m_ϕ

→ Early Oscillation

ADBG in high-scale inflation

$(T_R = 10^9\mathrm{GeV}, H_{\rm inf} = 10^{13}\mathrm{GeV})$



BBN constraint for gravitino mass $m_{3/2} > 6\mathrm{TeV}$ for $T_R = 10^9\mathrm{GeV}$

[M, Kawasaki, K. Kohri, T. Moroi, and A. Yotsuyanagi (2008)]

nB is overproduced by thermal effect & isocurvature constraint…

Issues of ADBG in high-scale inflation scenario

- Constraint on baryonic isocurvature

  [K. Enqvist, J. McDonald (1999)]

- Finite temperature effect

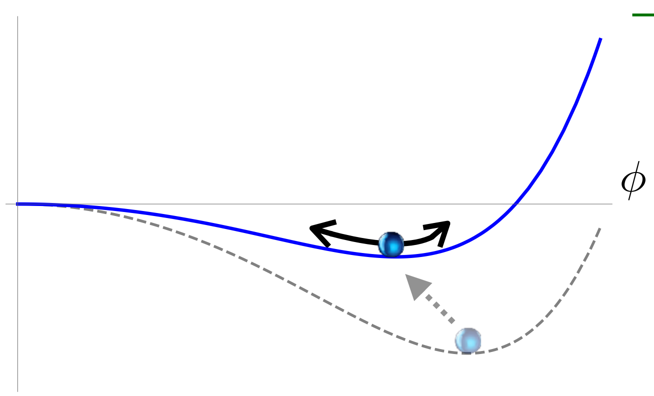
  [A. Anisimov, M. Dine (2000)]

Solution!

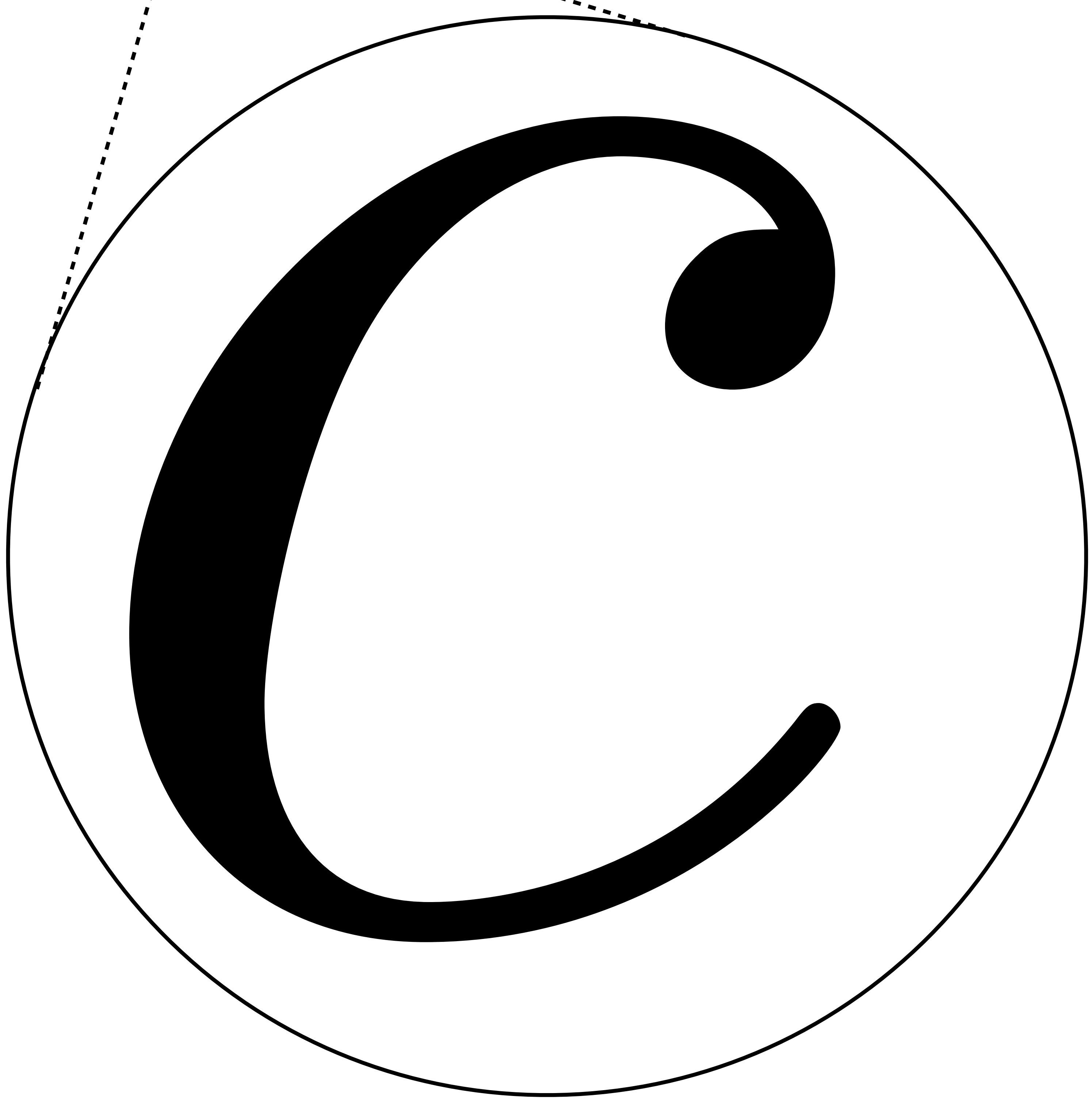
- Oscillation of the AD <u>condensate</u>

  →**Effective in multi-superfield inflation**

  [FH, Kawasaki, arXiv:1706.08659]



$$V_{\mathrm{AD}}(\phi,\phi^*) = (m_\phi^2 - cH^2)|\phi|^2 + \left(a_m \frac{\lambda m_{3/2}\phi^n}{nM^{n-3}} + \mathrm{h.c.}\right) + \frac{\lambda^2|\phi|^{2n-2}}{M^{2n-6}},$$



Inflation in supergravity

- Model with *Stabilizer* field and *shift-symmetry*

[Kawasaki, Yamaguchi, Yanagida, 2000]
[Kallosh, Linde, 2010]

$$K = \frac{1}{2}(I - \bar{I})^2 + |S|^2 - \frac{|S|^4}{\Lambda^2}$$

$$W = Sf(I) \qquad \Lambda \ll 1$$

$$\langle S \rangle \sim 0 \Rightarrow \langle W \rangle \sim 0$$

$$K \not\ni \mathrm{Re}\phi$$

during inflation $\quad |F_S|^2 \simeq |f(I)|^2 = V_{\rm inf} \quad |F_I|^2 \simeq 0$

after inflation $\quad |F_S|^2 \simeq |f(I)|^2 = V_{\rm inf} \quad |F_I|^2 \simeq \dot{I}^2$

Inflation energy is provided by ~~SUSY~~ of S

Hubble induced mass in stabilizer model

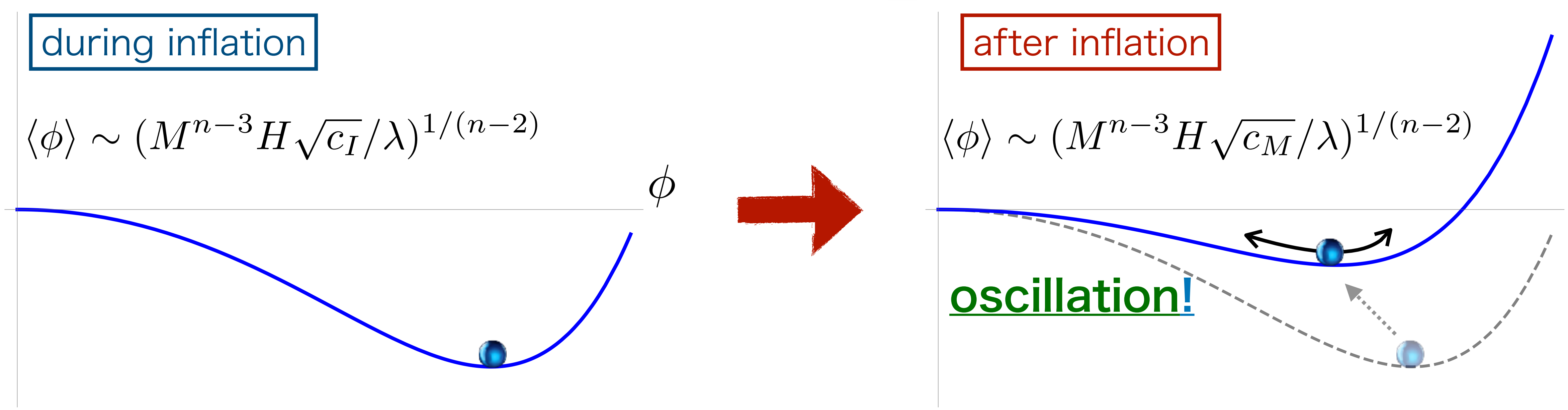
$$K_{\rm mix} = \frac{c_1}{M_p^2}|\Phi|^2\frac{(I-\bar{I})^2}{2} + \frac{c_2}{M_p^2}|\Phi|^2|S|^2$$

(with virial Th.)

$$c = \begin{cases} c_I \equiv 3(c_2 - 1) & \text{(during inflation)} \leftarrow F_S \\ c_M \equiv \frac{3}{2}(c_1 + c_2 - 1) & \text{(after Inflation)} \leftarrow F_I \ \& \ F_S \end{cases}$$

$$V_{AD}(\phi) \supset -cH^2|\phi|^2 + \frac{\lambda^2}{M^{2n-6}}|\phi|^{2n-2}$$

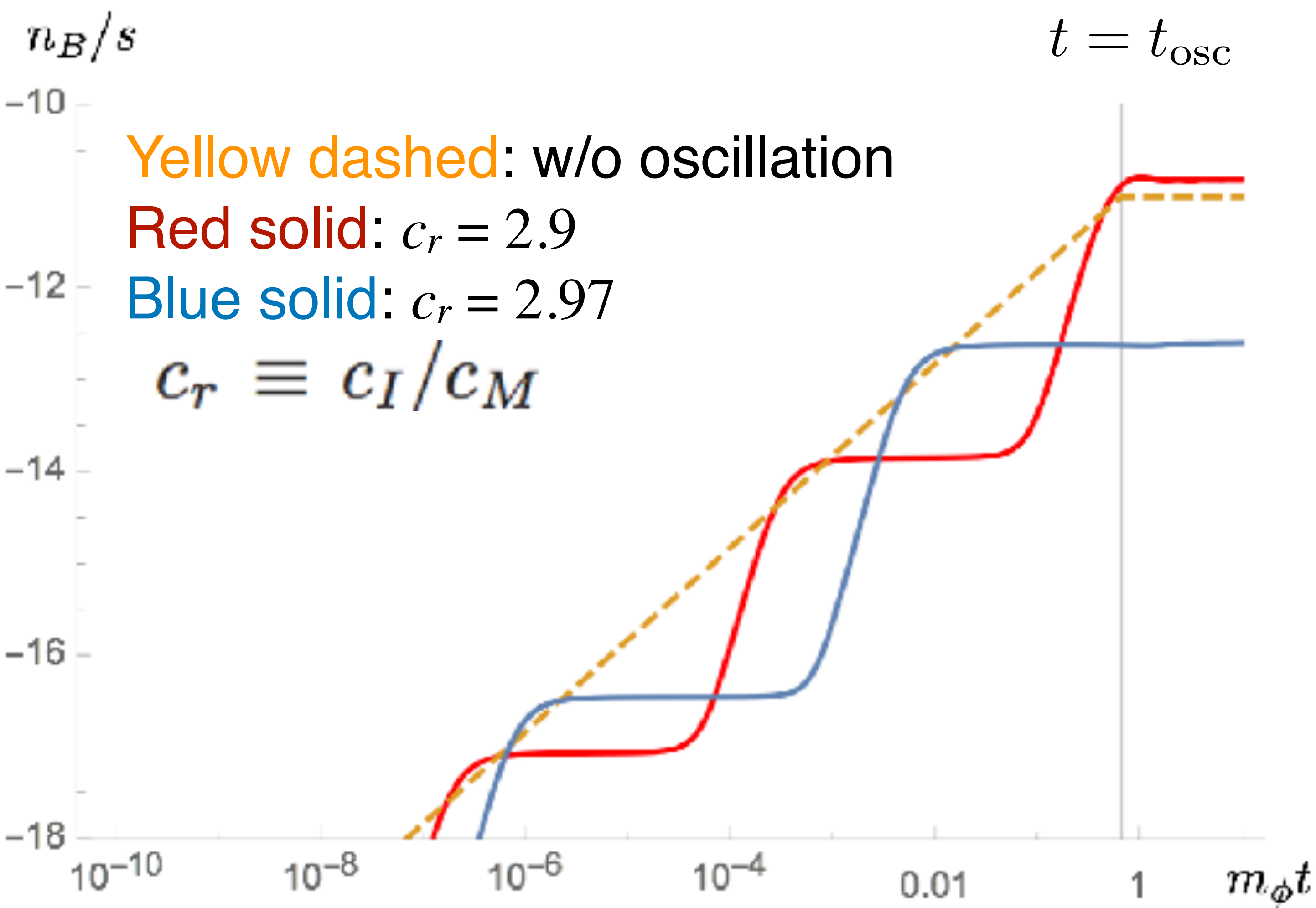
Vacuum moves after inflation!

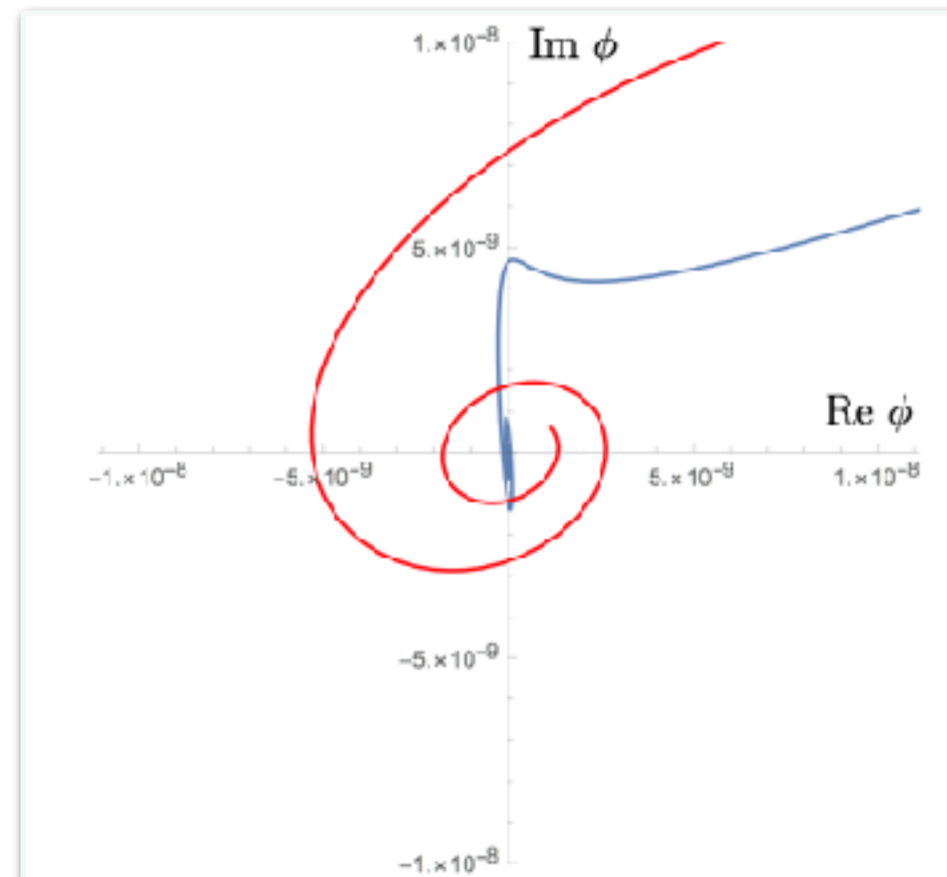


Radial direction receives a kick at the end of the inflation!

→AD condensate Oscillates after inflation

Effect on baryon asymmetry ($n = 4$)





$$n_B = i(\phi^* \dot{\phi} - \dot{\phi}^* \phi) \sim \dot{\theta} |\phi|^2$$

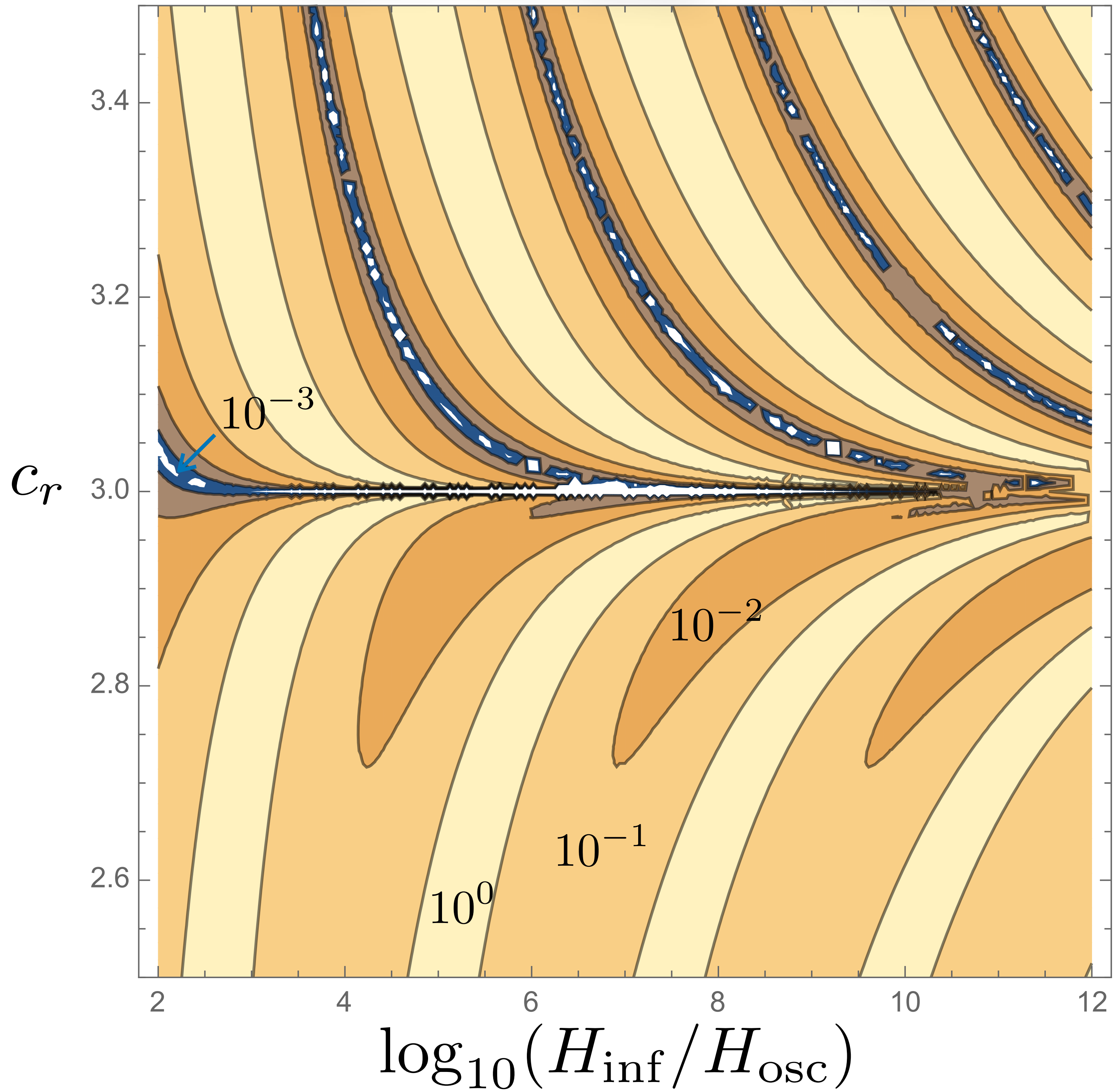
affected by the oscillation

n/s is fixed at $t_{\rm osc}$

Suppression is determined by c_r & $t_{\rm osc}$

Baryon asymmetry suppression ($n = 4$)

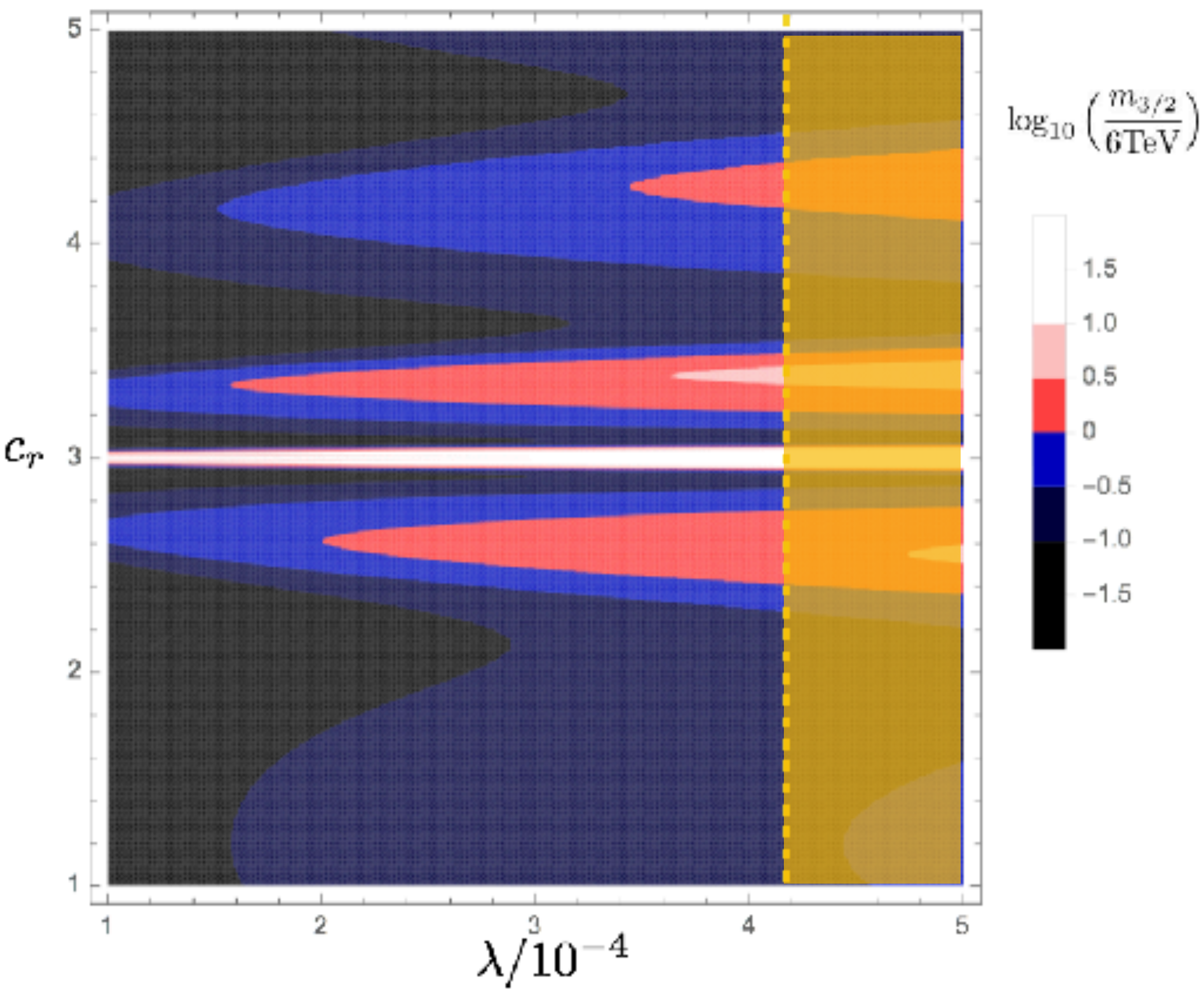
$$\left.\frac{n_B(\text{w/ osc.})}{n_B(\text{w/o osc.})}\right|_{t=t_{\rm osc}} = \frac{\phi(t_{\rm osc})^2}{\langle\phi(t_{\rm osc})\rangle^2}$$



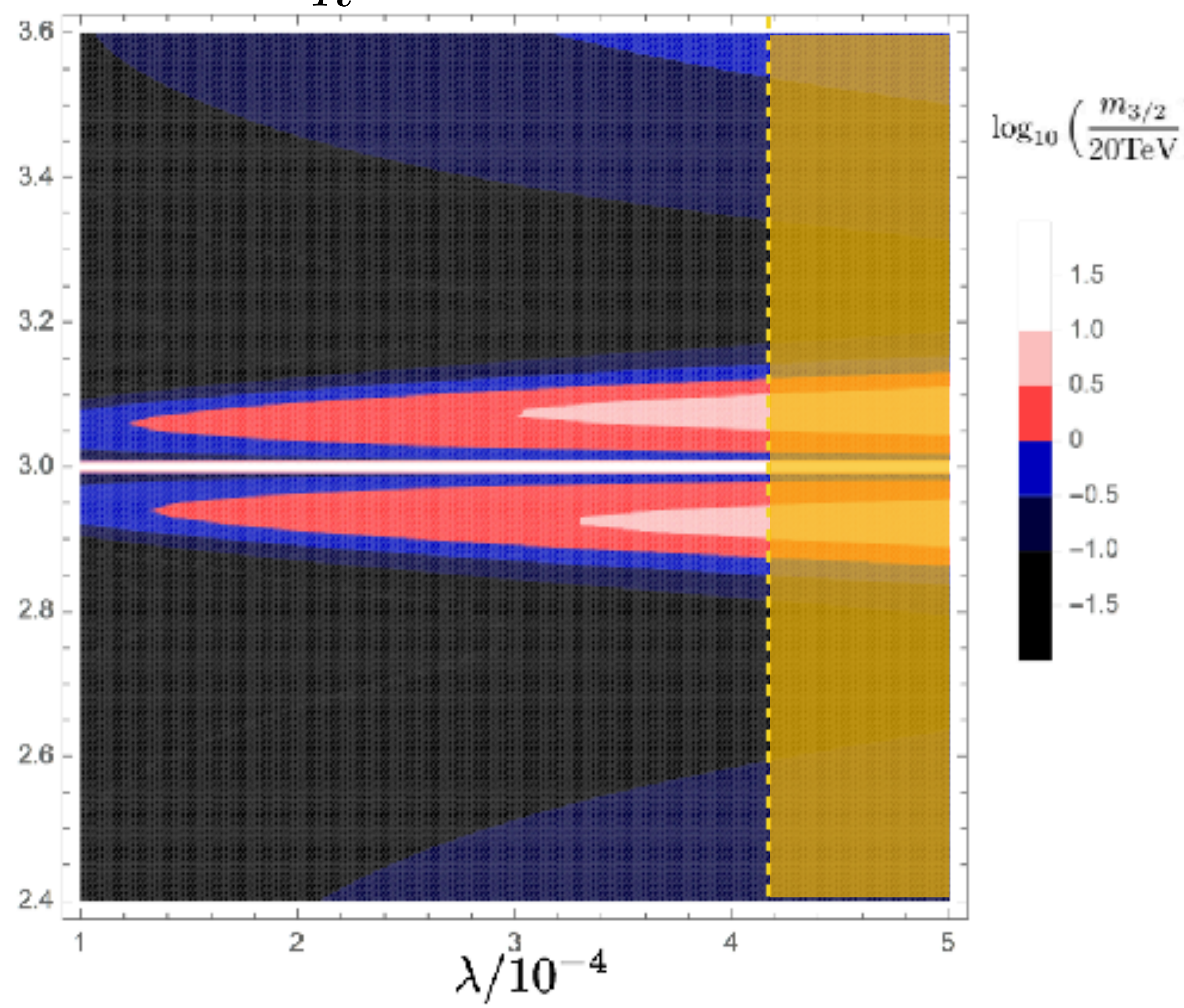
- There can be O(1-0.1)% suppressions for $c_r \sim 3$
- The choice $c_r = 3$ is unstable solution where ϕ approaches the origin with infinite time
- For $c_r > 3$, ϕ begins to oscillate around the origin just after inflation

ADBG in high scale-inflation ($n = 4$)

$T_R = 10^9 \mathrm{GeV}$



$T_R = 10^{10} \mathrm{GeV}$



Blue region: Excluded by BBN
Red region: Consistent with BBN
Yellow shade: Constraint from isocurvature

ADBG in high-scale inflation becomes workable

by 10% tuning of O(1) constant c

Summary

- In the high-scale inflation scenario, isocurvature constraint and finite temperature effect lead overproduction of the baryon asymmetry.
- Inflation model with Stabilizer induce the oscillation of the AD condensate after inflation.
- The oscillation could suppress the resultant baryon asymmetry for O(0.1-1)%.
- In n = 4 scenario, this effect is significant and baryon asymmetry is consistently produced even in high-scale inflation regime.

Thank you very much!