기초과학연구원
Institute for Basic Science

Diluting the inflationary axion fluctuation by a stronger QCD in the early Universe

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K. Choi, E. J. Chun, S. H. Im, and K. S. Jeong

Sang Hui Im (CTPU/IBS)
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Outline

- Axion Dark Matter vs. High Scale Inflation
- Stronger QCD phase in the early Universe
- An example of model
- Summary

Axion Dark Matter

- PQ breaking *after* inflation

✓ Axionic strings and domain walls are generated.
✓ Axion DM is mainly given by annihilation of them.

$$\frac{\Omega_a}{\Omega_{\rm DM}} \simeq (5 \pm 2) \times \left(\frac{f_a(t_0)}{10^{11}{\rm GeV}} \right)^{1.19}$$

Hiramatsu, Kawasaki, Saikawa, Sekiguchi (2012)

But, it requires $N_{\rm DW} = \left| \sum_i 2 q_{\psi_i} {\rm Tr}(T_a^2(\psi_i)) \right| = 1$

(Axion Domain Wall problem)

Axion Dark Matter

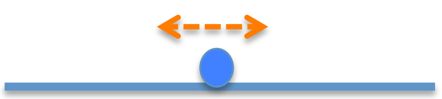
- PQ breaking *before/during* inflation

✓ No domain wall problem
✓ Axion DM is given by coherent oscillation of the axion field.

$$\frac{\Omega_a}{\Omega_{\rm DM}} \simeq 1.7\,\theta_{\rm mis}^2 \left(\frac{f_a(t_0)}{10^{12}\,{\rm GeV}}\right)^{1.19}$$

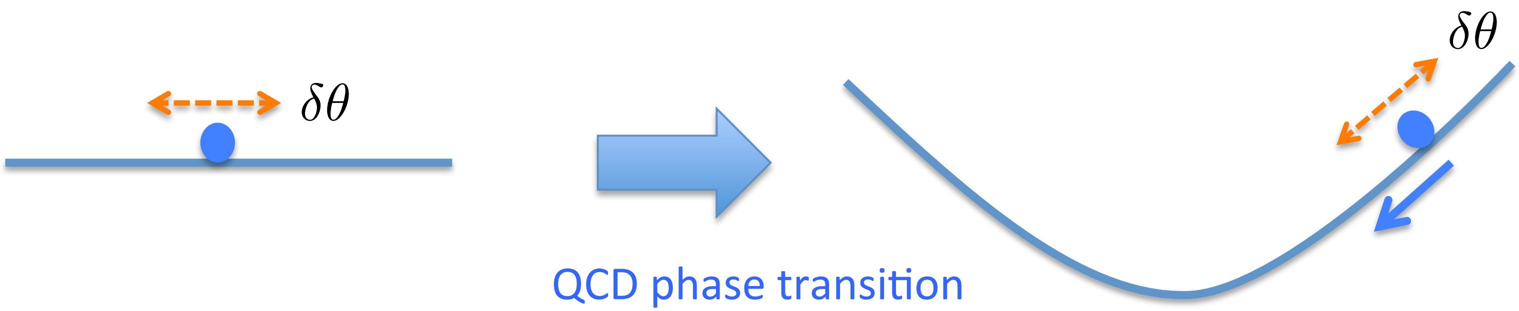
But, the axion field gets quantum fluctuation during inflation.

$$\delta\theta = \frac{H(t_I)}{2\pi f_a(t_I)}$$



Axion isocurvature perturbation

- The primordial axion quantum fluctuations turn into axion DM density perturbation after QCD phase transition.



$$\frac{\Omega_a}{\Omega_{\rm DM}} \simeq 1.7(\theta_0^2 + \delta\theta^2)\left(\frac{f_a(t_0)}{10^{12}{\rm GeV}}\right)^{1.19}$$

- This must generate the "isocurvature mode" of CMB perturbation.

$$\left(\frac{\delta T}{T}\right)_{\rm iso} \simeq \frac{4}{5}\left(\frac{\Omega_a}{\Omega_{\rm DM}}\right)\frac{\delta\theta}{\theta_{\rm mis}} < 3.8\times 10^{-6}$$

Planck Collaboration (2014)

Tension with *High* scale inflation

- If axion is a major component of DM in the Universe, the axion field fluctuations must be very small.

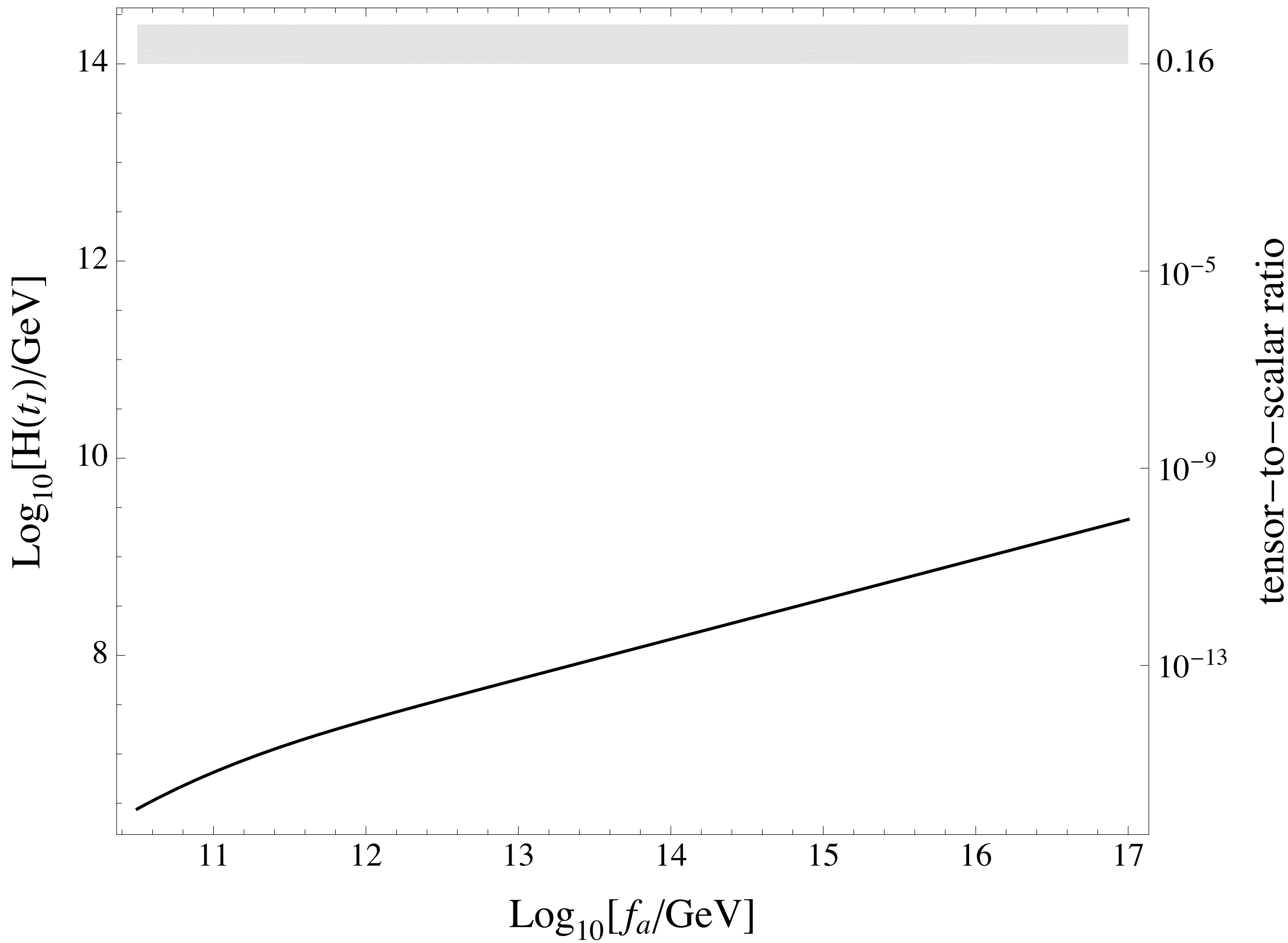
$$\left(\frac{\delta T}{T}\right)_{\rm iso} \simeq \frac{4}{5}\left(\frac{\Omega_a}{\Omega_{\rm DM}}\right)\frac{\delta\theta}{\theta_{\rm mis}} < 3.8\times 10^{-6} \quad \Longrightarrow \quad \frac{\delta\theta}{\theta_{\rm mis}} \lesssim 10^{-5}$$

$$\Omega_a \simeq \Omega_{\rm DM}$$

- This means that the primordial inflationary Hubble scale should be so suppressed compared to the axion scale at the inflationary epoch.

$$\delta\theta = \frac{H(t_I)}{2\pi f_a(t_I)} \quad \Longrightarrow \quad \boxed{H(t_I) \lesssim 10^{-5}\,\theta_{\rm mis}\, f_a(t_I)}$$

Upper bound on the inflation scale for $\Omega_a = \Omega_{DM}$ in the conventional scenario



Suppressing the axion field fluctuation : A stronger QCD in the early Universe

- If the QCD confinement scale Λ'_{QCD} in the early Universe was high enough compared to Λ_{QCD} of the present Universe, there can be an epoch in which

$$m_a(t) \sim \frac{\Lambda'^2_{\rm QCD}}{f_a(t)} > H(t)$$

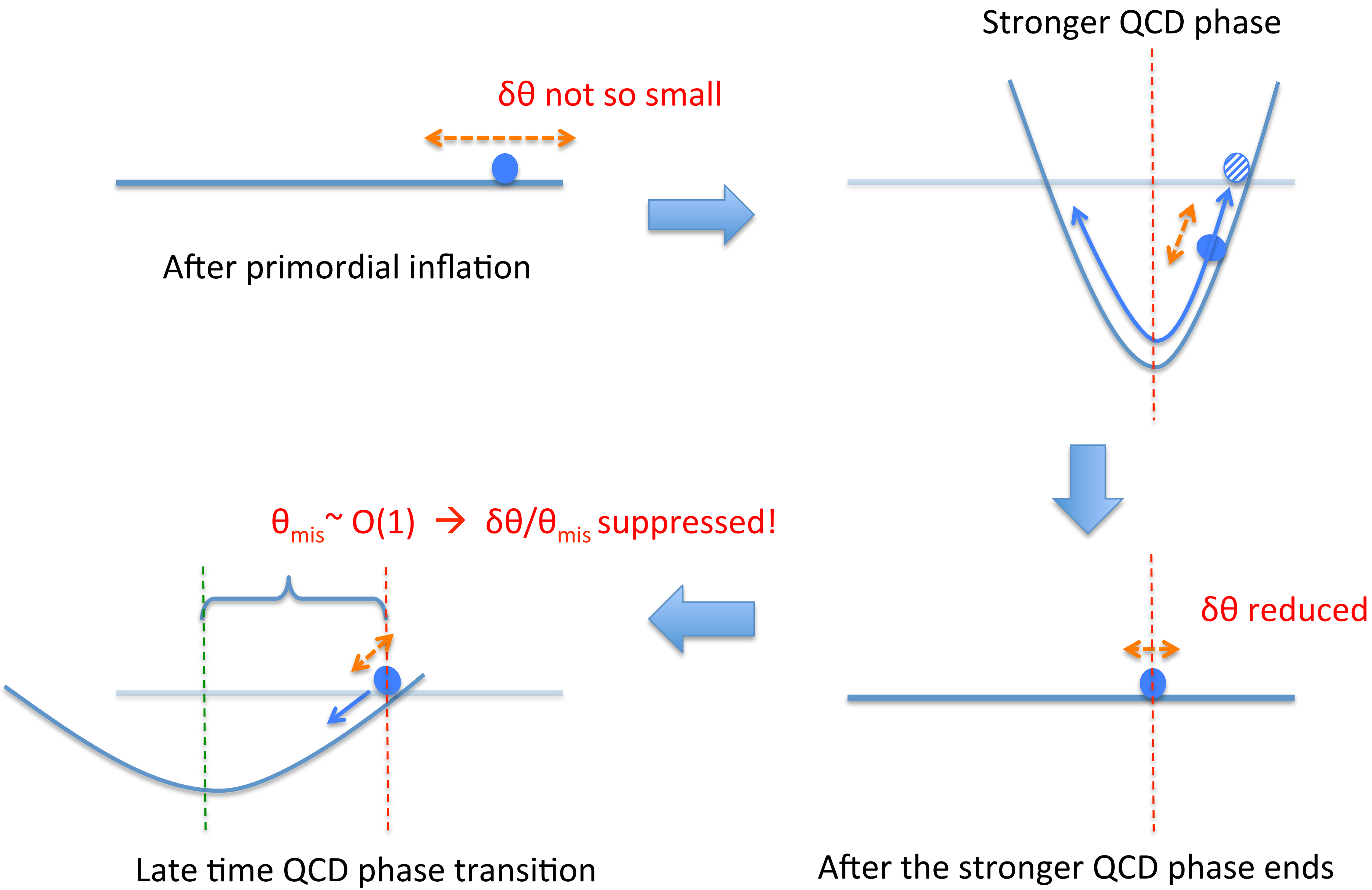
- During the epoch, the axion field undergoes *damped* coherent oscillation toward the minimum of its potential.

$$\ddot{a} + 3H(t)\dot{a} + m_a^2(t)a = 0 \quad \Rightarrow \quad |a(t)| \sim (a_0 + \delta a_0)\left(\frac{R(t_i)}{R(t)}\right)^{3/2}$$

- If this period is long enough, then the axion field fluctuation δa can be significantly reduced, though the ratio $\delta a/\langle a\rangle = \delta\theta/\theta_{mis}$ is still *unchanged.*

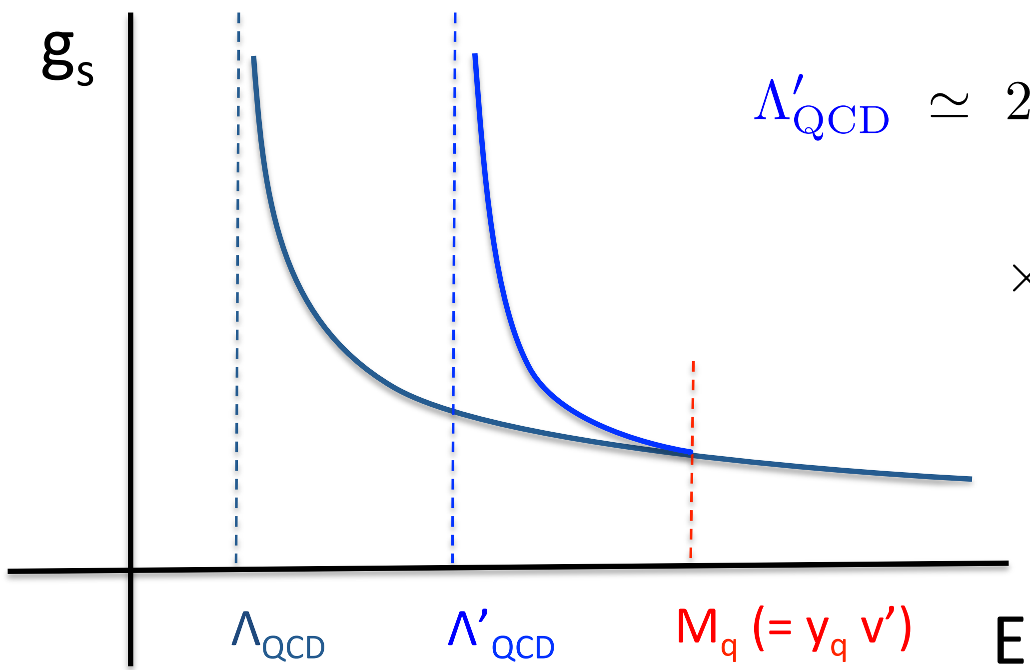
- But *if the axion potential minimum of the present Universe is displaced from the stronger QCD phase's one*, θ_{mis} becomes O(1) while $\delta\theta$ remains reduced.
  → $\delta\theta/\theta_{mis}$ suppressed!

Schematic picture



Stronger QCD by large Higgs VEV

- A temporal stronger QCD phase in the early Universe can arise if the Higgs field has *temporarily* large vacuum expectation value so that quarks become heavy during the time.
- Heavy quarks make the QCD coupling run faster, and so QCD confinement scale becomes large.



$$\Lambda'_{\rm QCD} \simeq 23\,{\rm TeV}\left(\frac{v'}{10^{12}\,{\rm GeV}}\right)^{6/11} \times \left(\frac{m_{\tilde{g}}}{3\,{\rm TeV}}\right)^{2/11}\left(\frac{\tan\beta}{10}\right)^{3/11}$$

Large Higgs VEV along flat directions

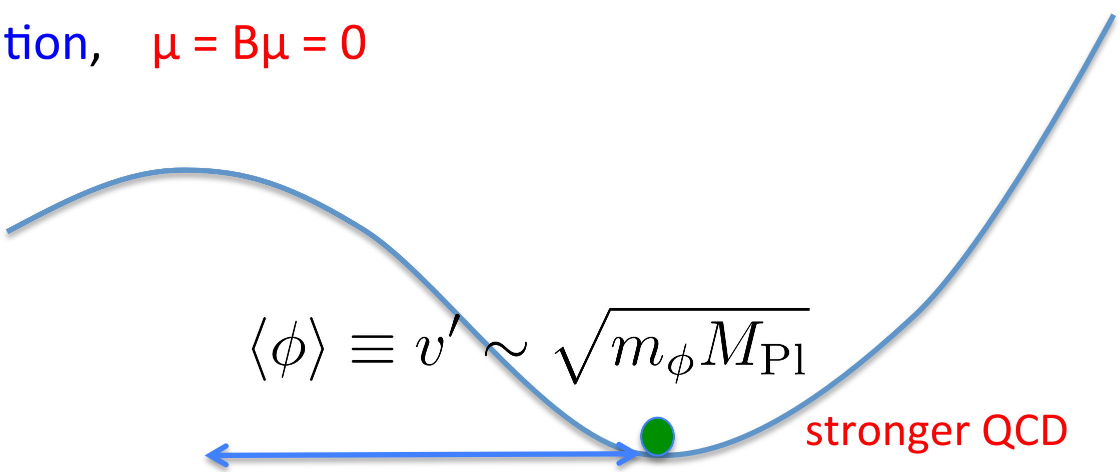
- *Temporarily* large Higgs VEV in the early Universe is plausibly realized in supersymmetric theories because of the existence of Higgs flat directions.

$$V(\phi) = m_\phi^2|\phi|^2 - \left(A_\phi \frac{\phi^4}{M_{\rm Pl}} + {\rm h.c.}\right) + \frac{|\phi|^6}{M_{\rm Pl}^2} + 2|\mu|^2|\phi|^2 - (B\mu\phi^2 + {\rm h.c.})$$

$$\phi^2 \equiv H_u H_d$$

D-flat direction

- We assume that $m_\phi^2 < 0$ and μ-term is *dynamically generated* at the time of so-called "μ-transition".
- *Before* μ-transition, μ = Bμ = 0



$$\langle\phi\rangle \equiv v' \sim \sqrt{m_\phi M_{\rm Pl}}$$

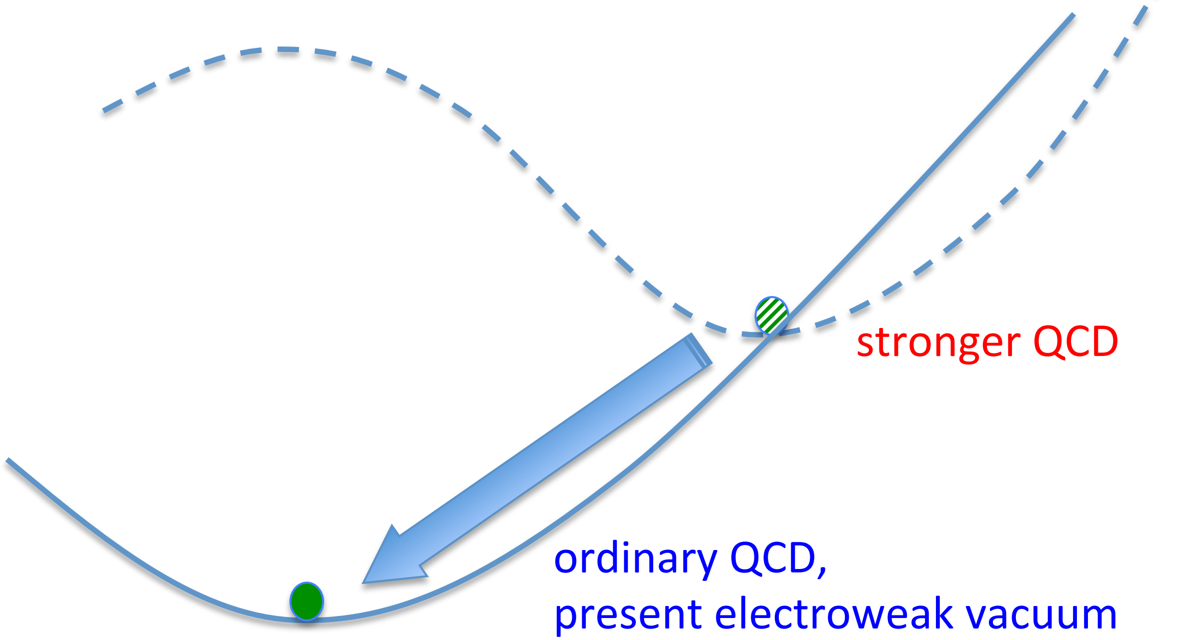
Large Higgs VEV along flat directions

$$V(\phi) = m_\phi^2|\phi|^2 - \left(A_\phi \frac{\phi^4}{M_{\rm Pl}} + {\rm h.c.}\right) + \frac{|\phi|^6}{M_{\rm Pl}^2} + 2|\mu|^2|\phi|^2 - (B\mu\phi^2 + {\rm h.c.})$$

$\phi^2 \equiv H_u H_d$

D-flat direction

- *After* μ-transition, non-zero μ and Bμ are generated so that $m_\phi^2 + 2|\mu|^2 > 2B\mu$.
- Arg(Bμ) *changes the position of the axion potential minimum* of the present Universe compared to the stronger QCD phase (→ $\theta_{mis} \sim O(1)$).



An example of model

$$W = (\text{MSSM Yukawa terms}) + \lambda Y \Phi \Phi^c$$
$$+ \kappa_1 \frac{X^2}{M_{Pl}} H_u H_d + \kappa_2 \frac{XY^3}{M_{Pl}} + \kappa_3 \frac{(H_u H_d)(LH_u)}{M_{Pl}}$$

thermal mass ($|\lambda|^2 T^2/8$) to Y

→ μ Kim, Nilles (1984)

> 0 < 0

$$V_1 = m_X^2 |X|^2 + \left(m_Y^2 + \frac{1}{8}|\lambda|^2 T^2 \right) |Y|^2 + \left(\frac{\kappa_2 A_2}{M_{Pl}} XY^3 + \text{h.c.} \right)$$
$$+ \frac{|\kappa_2|^2}{M_{Pl}^2} \left(|Y|^6 + 9|X|^2|Y|^4 \right)$$

"μ-transition"

- $\frac{1}{8}|\lambda|^2 T^2 > |m_Y^2|$ $(T > T_c \sim m_Y)$ $\rightarrow$ $\langle X \rangle = \langle Y \rangle = 0$ $\rightarrow$ $\mu = 0$
- $\frac{1}{8}|\lambda|^2 T^2 < |m_Y^2|$ $(T < T_c)$ $\rightarrow$ $\langle X \rangle \sim \langle Y \rangle \sim \sqrt{m_{\rm SUSY} M_{\rm Pl}}$ $\rightarrow$ $\mu \sim m_{\rm SUSY}$

$$W = (\text{MSSM Yukawa terms}) + \lambda Y \Phi \Phi^c + \kappa_1 \frac{X^2}{M_{Pl}} H_u H_d + \kappa_2 \frac{XY^3}{M_{Pl}} + \kappa_3 \frac{(H_u H_d)(L H_u)}{M_{Pl}}$$

- Higgs flat direction (F & D flat)

$$H_d^T = (\phi_d, 0), \quad L^T = (\phi_\ell, 0),$$
$$H_u^T = (0, \sqrt{|\phi_d|^2 + |\phi_\ell|^2}),$$

< 0 $\quad$ < 0

$$V_2 = (m_{\phi_d}^2 + 2|\mu|^2)|\phi_d|^2 + (m_{\phi_\ell}^2 + |\mu|^2)|\phi_\ell|^2 + \left(B\mu\phi_d \sqrt{\sum |\phi_i|^2} + \frac{\kappa_3 A_3 \phi_d \phi_\ell}{M_{\rm Pl}} \left(\sum |\phi_i|^2\right) + \text{h.c.} \right) + \frac{|\kappa_3|^2}{M_{\rm Pl}^2} \left(\sum |\phi_i|^2\right) \left(|\phi_d|^4 + 4|\phi_d \phi_\ell|^2 + |\phi_\ell|^4 \right)$$

Before μ-transition ($T > T_c$), $\mu = B\mu = 0, \quad \phi_d \sim \phi_\ell \sim \sqrt{m_{\rm SUSY} M_{\rm Pl}}$ stronger QCD

After μ-transition ($T < T_c$), $\mu \sim \sqrt{B\mu} \sim m_{\rm SUSY}, \quad \phi_d \sim m_Z, \quad \phi_\ell = 0$

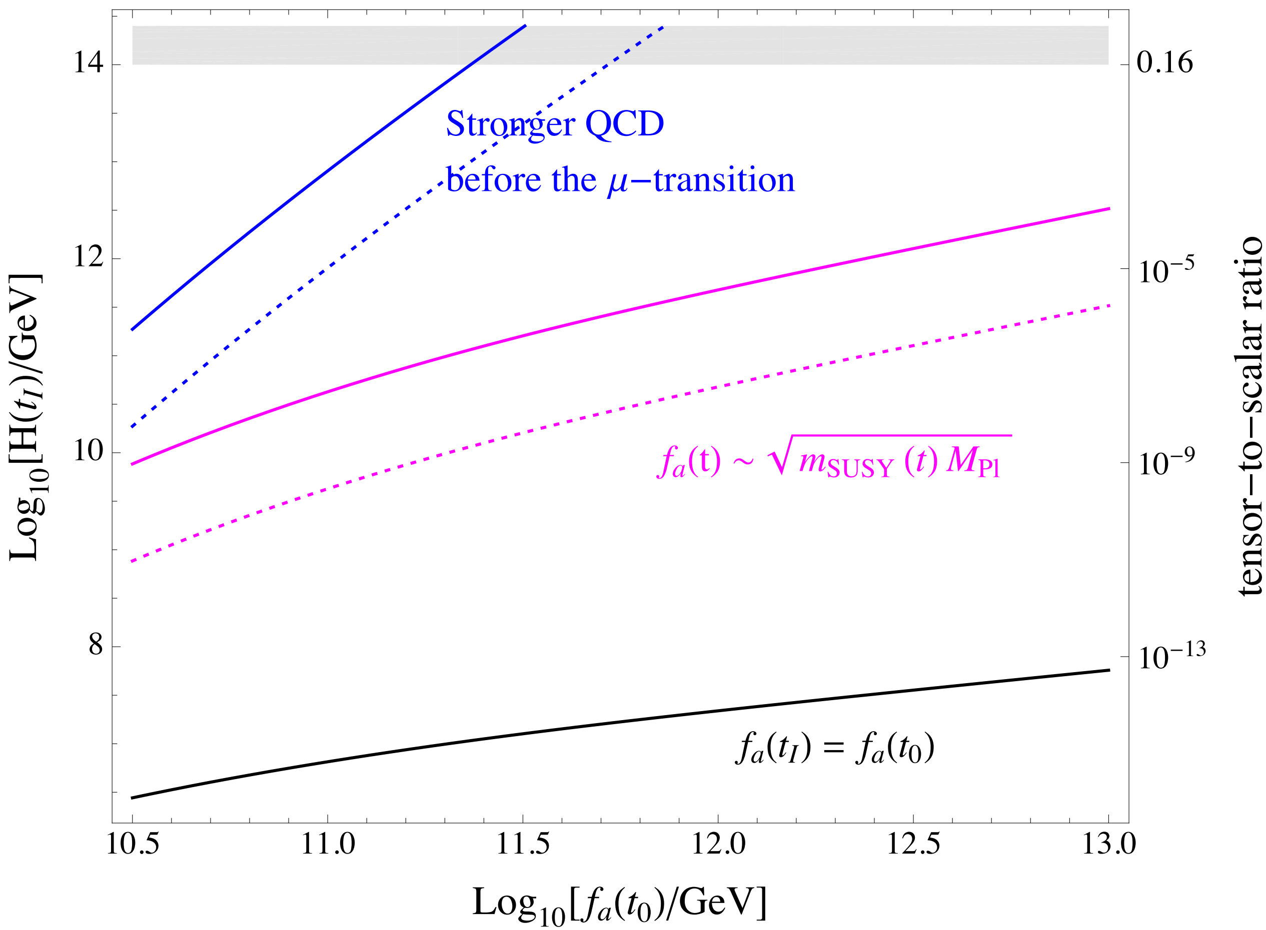
ordinary QCD,
present electroweak vacuum

Total damping over the stronger QCD phase

- Axion gets a large enough mass during $T_c < T < \Lambda'_{QCD}$ so that $m_a > H$.
- Then its amplitude and fluctuation get suppressed during its coherent oscillation.

$$\left(\frac{R(t_i)}{R(t_i + \Delta t)}\right)^{3/2} \approx \left(\frac{T_c}{\Lambda'_{\rm QCD}}\right)^{3/2} \sim \mathcal{O}(10^{-2} - 10^{-3})$$

Upper bound on the inflation scale for $\Omega_a = \Omega_{DM}$



- Solid : $m_{SUSY}(t_0)$ = 1 TeV
- Dashed : $m_{SUSY}(t_0)$ = 10 TeV

- T_c = 1 TeV
- M_{gluino}= 3 TeV, tan β=10

Summary

- If one allows $N_{DW} > 1$ and assumes that axion explains the dominant part of DM in the Universe, high scale inflation ($> 10^{10}$ GeV) conflicts with the axion isocurvature constraint in the conventional scenario.

- If there exists a stronger QCD phase in the early Universe by temporarily large Higgs VEV, axion undergoes damped coherent oscillation while reducing its fluctuation.

- Together with the reduced fluctuation, the displacement of the axion potential minimum after μ-transition suppresses the axion isocurvature perturbation.

- This allows that even the current Planck upper bound value (10^{14} GeV) on the inflationary Hubble scale is compatible with the axion DM.