

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

Arxiv 1505.00306 (Accepted in PLB)
K. Choi, E. J. Chun, S. H. Im, and K. S. Jeong

Sang Hui Im (CTPU/IBS)
2015 Aug 20, IBS-KASI Joint workshop

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.

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

Hiramatsu, Kawasaki, Saikawa, Sekiguchi (2012)

But, it requires

$$N_{\text{DW}} = \left| \sum_i 2q_{\psi_i} \text{Tr}(T_a^2(\psi_i)) \right| = 1$$

(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.

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

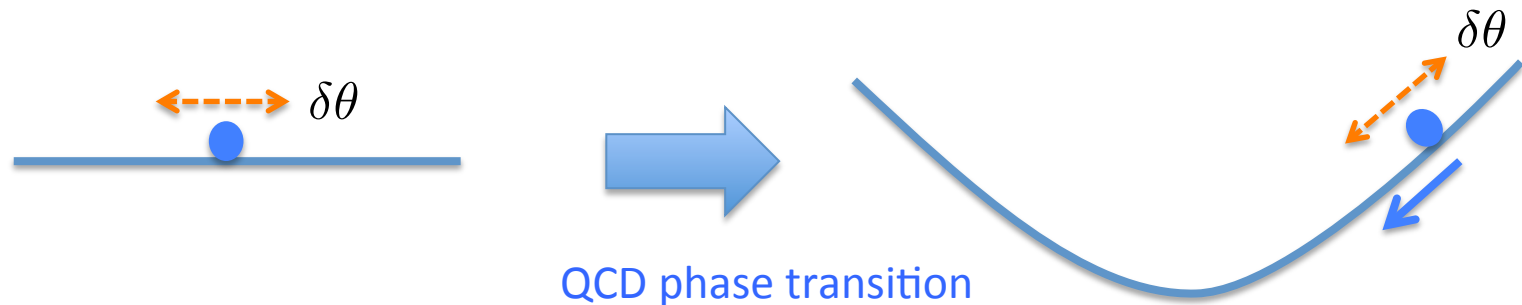
But, the axion field gets quantum fluctuation during inflation.

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



Axion isocurvature perturbation

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



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

- This must generate the “isocurvature mode” of CMB perturbation.

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

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.

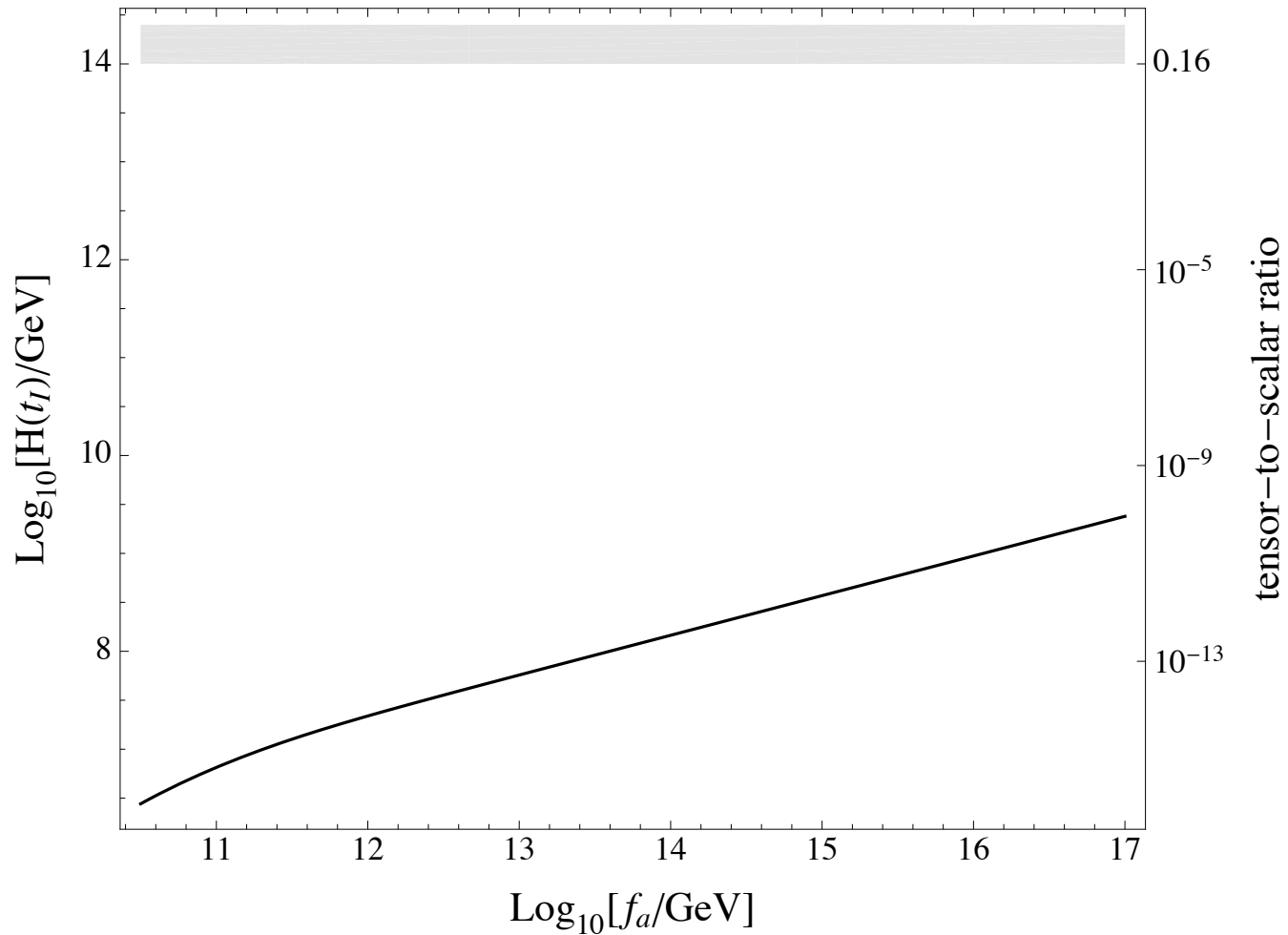
$$\left(\frac{\delta T}{T}\right)_{\text{iso}} \simeq \frac{4}{5} \left(\frac{\Omega_a}{\Omega_{\text{DM}}}\right) \frac{\delta\theta}{\theta_{\text{mis}}} < 3.8 \times 10^{-6} \quad \Rightarrow \quad \frac{\delta\theta}{\theta_{\text{mis}}} \lesssim 10^{-5}$$

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

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

$$\delta\theta = \frac{H(t_I)}{2\pi f_a(t_I)} \quad \Rightarrow \quad H(t_I) \lesssim 10^{-5} \theta_{\text{mis}} f_a(t_I)$$

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

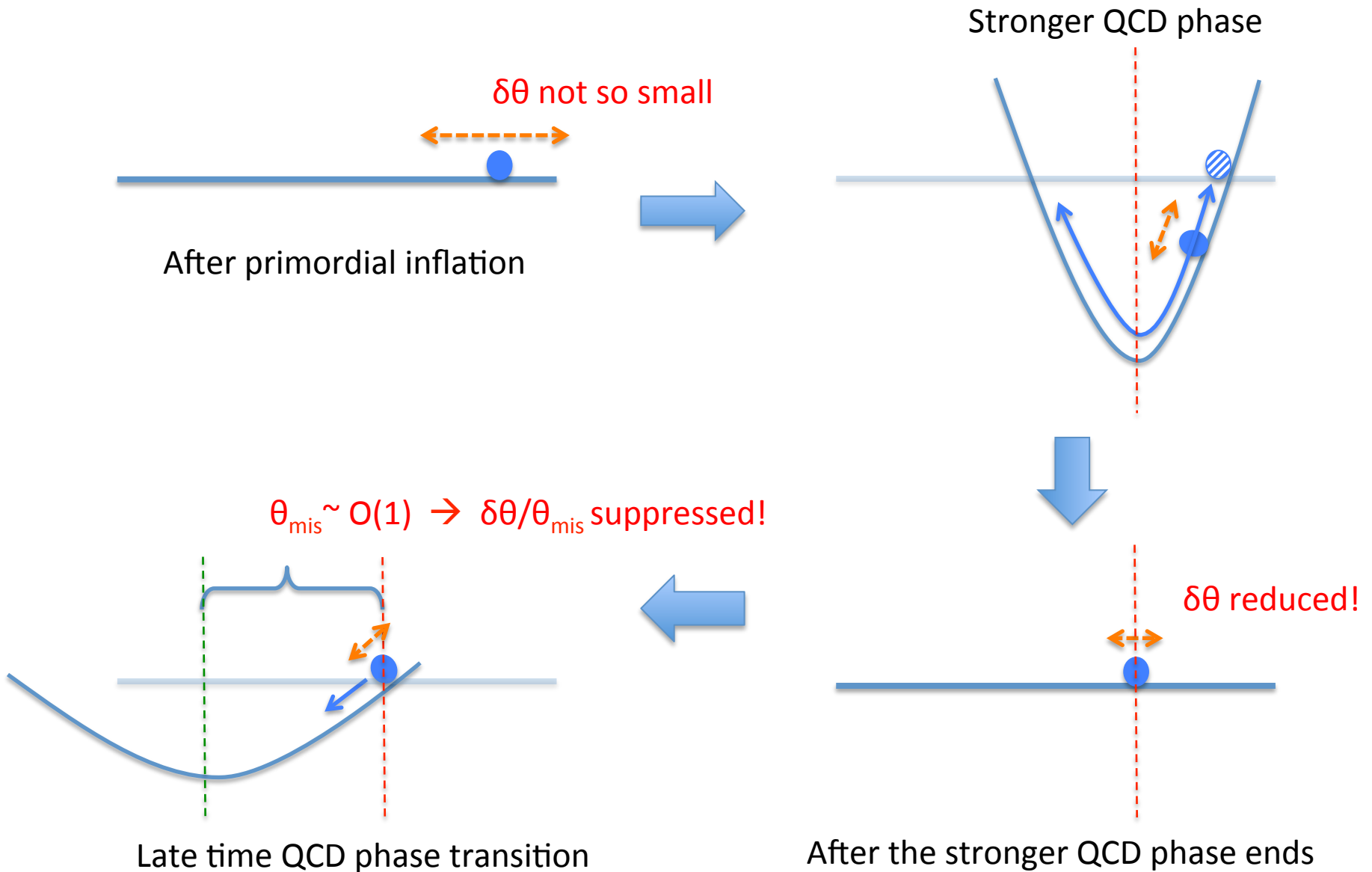
$$m_a(t) \sim \frac{\Lambda'^2_{\text{QCD}}}{f_a(t)} > H(t)$$

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

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

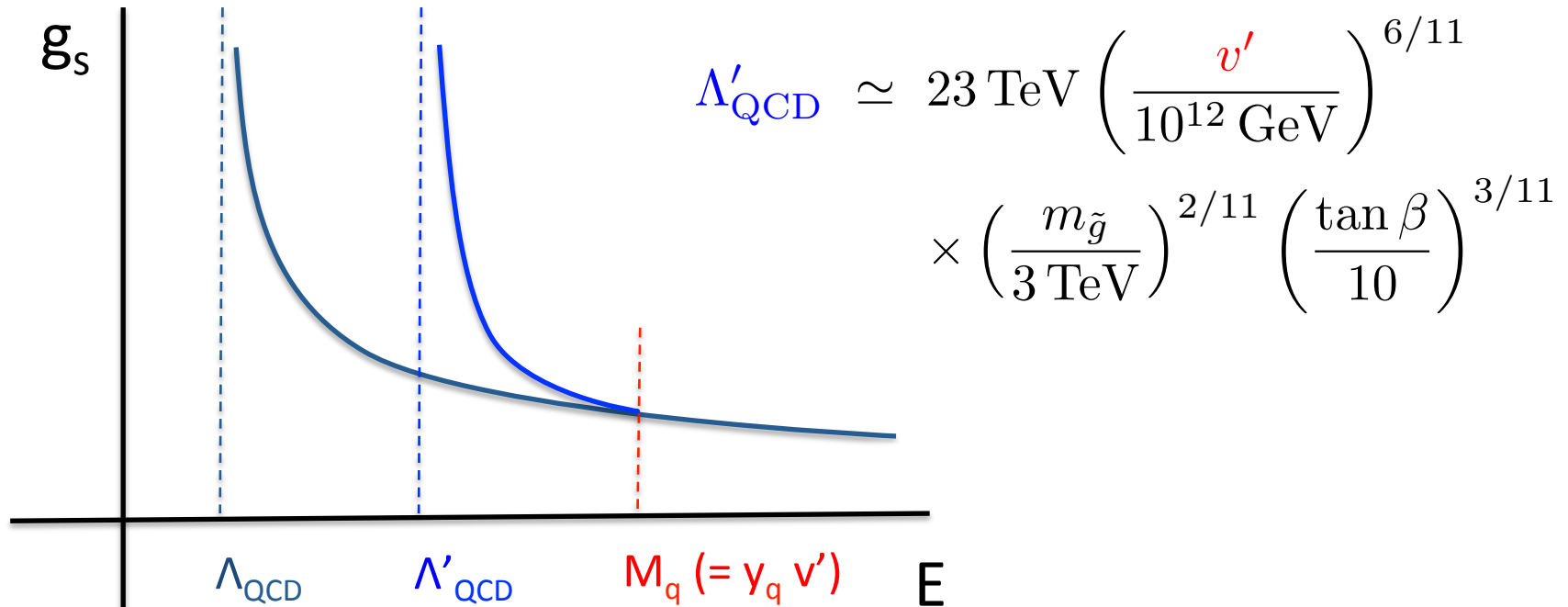
- If this period is long enough, then the axion field fluctuation δa can be significantly reduced, though the ratio $\delta a / \langle a \rangle = \delta \theta / \theta_{\text{mis}}$ is still *unchanged*.
- But if the axion potential minimum of the present Universe is displaced from the stronger QCD phase's one, θ_{mis} becomes $O(1)$ while $\delta \theta$ remains reduced.
 $\rightarrow \delta \theta / \theta_{\text{mis}}$ 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.



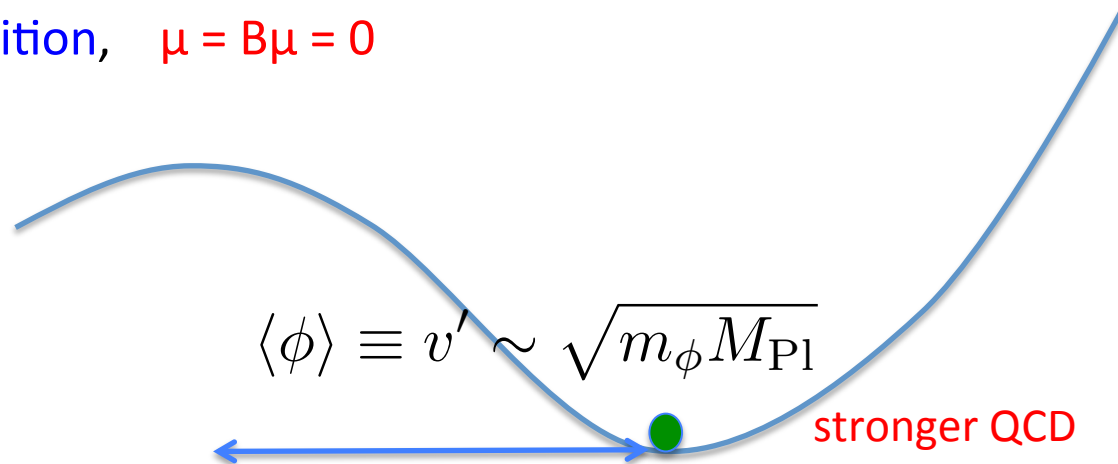
Large Higgs VEV along flat directions

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

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

$\phi^2 \equiv H_u H_d$
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, $\mu = B\mu = 0$

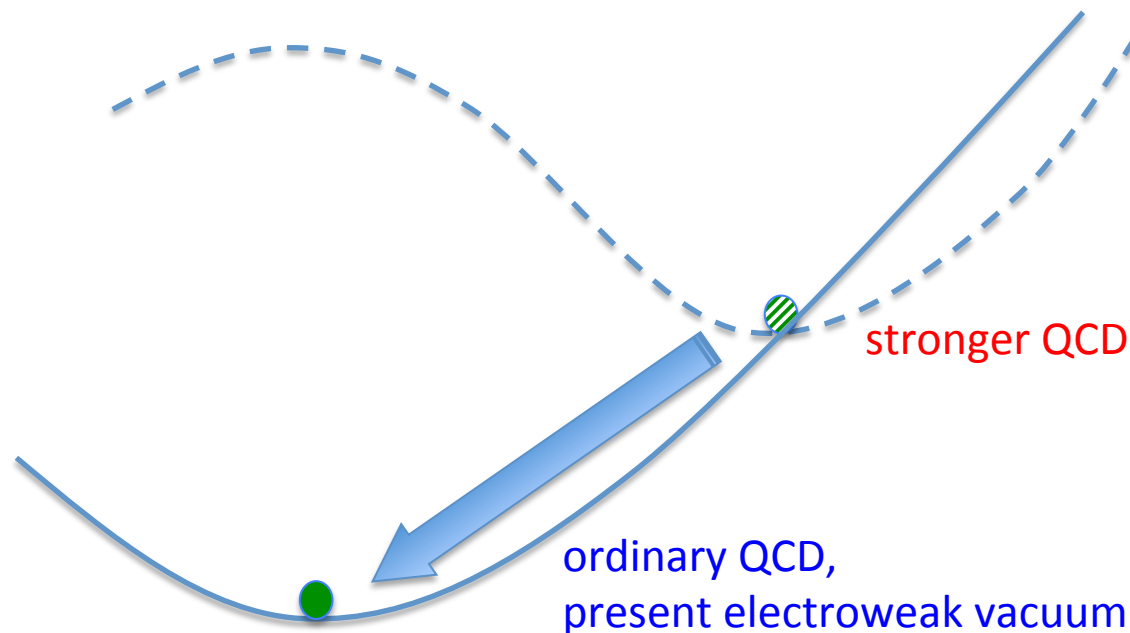


Large Higgs VEV along flat directions

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

$\phi^2 \equiv H_u H_d$
D-flat direction

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



An example of model

$$W = (\text{MSSM Yukawa terms}) + \lambda Y \Phi \Phi^c \text{ thermal mass } (|\lambda|^2 T^2/8) \text{ to } Y$$

$$+ \kappa_1 \frac{X^2}{M_{Pl}} H_u H_d + \kappa_2 \frac{XY^3}{M_{Pl}} + \kappa_3 \frac{(H_u H_d)(L H_u)}{M_{Pl}}$$

→ μ Kim, Nilles (1984)

$$V_1 = \overset{>0}{m_X^2} |X|^2 + \left(\overset{<0}{m_Y^2} + \frac{1}{8} |\lambda|^2 T^2 \right) |Y|^2 + \left(\frac{\kappa_2 A_2}{M_{Pl}} XY^3 + \text{h.c.} \right)$$

$$+ \frac{|\kappa_2|^2}{M_{Pl}^2} (|Y|^6 + 9|X|^2 |Y|^4)$$

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

“ μ -transition”

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

- Higgs flat direction (F & D flat) $H_d^T = (\phi_d, 0), \quad L^T = (\phi_\ell, 0),$
 $H_u^T = (0, \sqrt{|\phi_d|^2 + |\phi_\ell|^2}),$



$$V_2 = (\overset{<0}{\textcircled{m_{\phi_d}^2}} + 2|\mu|^2)|\phi_d|^2 + (\overset{<0}{\textcircled{m_{\phi_\ell}^2}} + |\mu|^2)|\phi_\ell|^2 \\ + \left(B\mu\phi_d\sqrt{\sum|\phi_i|^2} + \frac{\kappa_3 A_3 \phi_d \phi_\ell}{M_{Pl}} \left(\sum|\phi_i|^2 \right) + \text{h.c.} \right) \\ + \frac{|\kappa_3|^2}{M_{Pl}^2} \left(\sum|\phi_i|^2 \right) (|\phi_d|^4 + 4|\phi_d \phi_\ell|^2 + |\phi_\ell|^4)$$

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

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

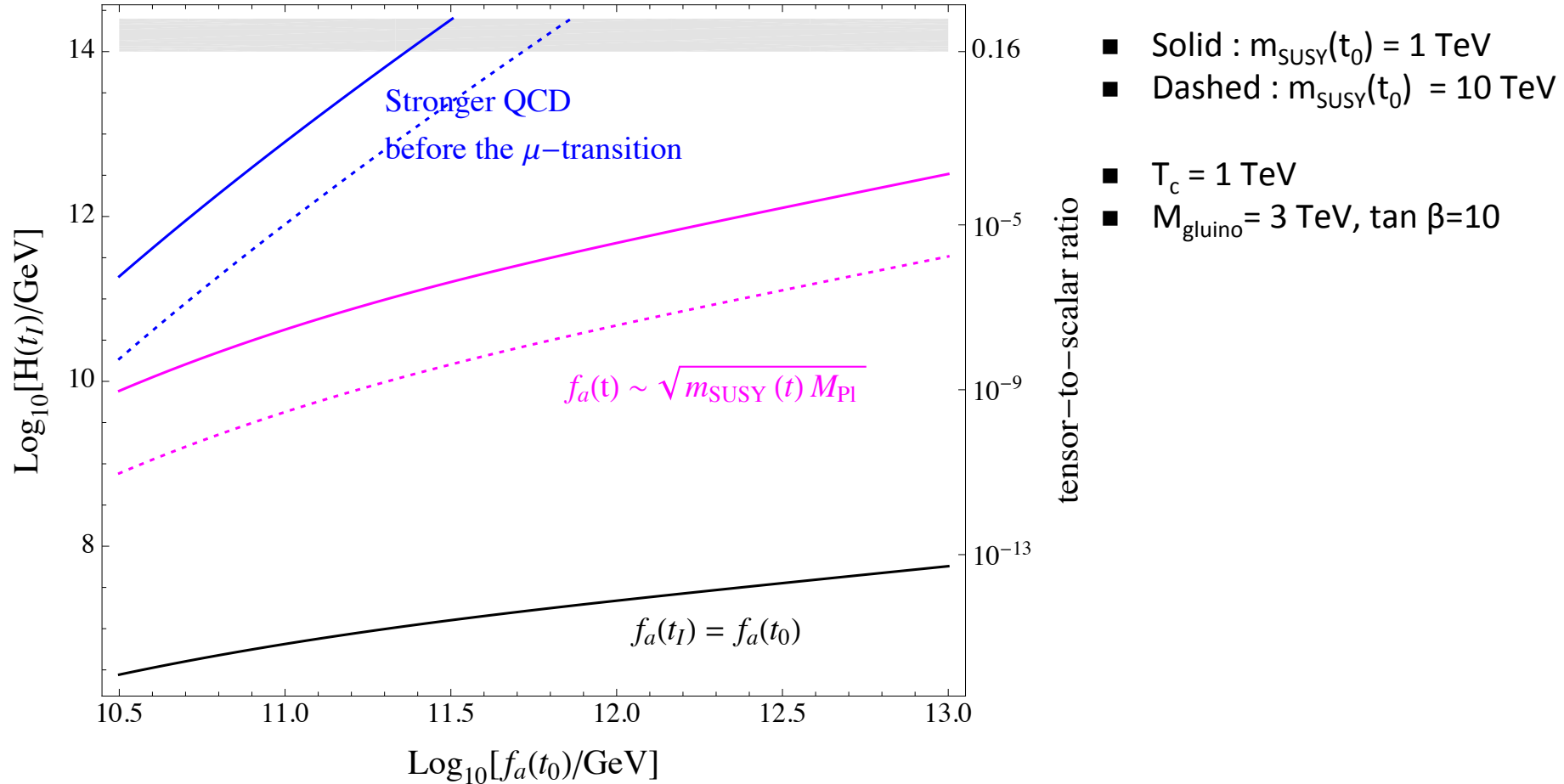
ordinary QCD,
present electroweak vacuum

Total damping over the stronger QCD phase

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

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

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



Summary

- If one allows $N_{\text{DW}} > 1$ 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.