

# Constraints on axion in high scale inflation

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## Outline

1. Peccei-Quinn extension of the SM
2. QCD axion dark matter
3. QCD axion in high scale inflation
4. String theoretic realization of the QCD axion
5. Summary

# Introduction

## Standard Model

- The Higgs boson, the last missing piece of the SM, has been discovered. So far there is no direct hint for new physics beyond the SM.

- Many reasons to consider new physics beyond the SM.

Naturalness: gauge hierarchy, strong CP problem

Unknown components: dark energy, dark matter

Neutrino mass

Inflation

Baryon asymmetry of the Universe,

...

## Strong CP problem

The strong interactions can generate CP violation via

$$\frac{\theta_{\text{QCD}}}{16\pi^2} G\tilde{G} + (y_{\text{quark}} H\bar{q}_L q_R + \text{h.c.})$$

However, no neutron electric dipole moment (EDM) has been found:

experimental bound on neutron EDM

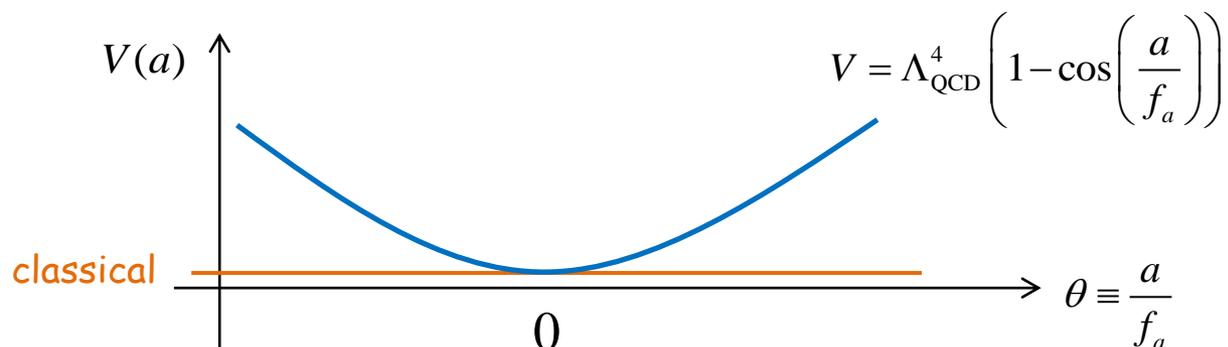
$$\theta = \left| \theta_{\text{QCD}} + \arg \det(y_{\text{quark}}) \right| < 10^{-11}$$

→ Need physical explanation for the absence of CP violation in the strong interactions.

## Axion solution to the strong CP problem

Peccei and Quinn 1997

- Make  $\theta$  dynamical by introducing global U(1) symmetry s.t.
  - spontaneously broken: **axion** (NG boson)
  - **anomalous under QCD**



QCD instantons explicitly break PQ, generating axion potential.

- $\theta$  is dynamically cancelled, and QCD becomes CP conserving.

**Axion physics:** determined by  $f_a \sim$  (PQ breaking scale)

- **Axion mass:**  $m_a \sim 5 \times 10^{-6} \left( \frac{10^{12} \text{ GeV}}{f_a} \right) \text{ eV}$

- **Axion couplings to SM**

axion-nucleon interaction

$$g_{aNN} \sim 10^{-12} \left( \frac{10^{12} \text{ GeV}}{f_a} \right)$$

axion-photon interaction

$$g_{a\gamma\gamma} \sim 10^{-15} \left( \frac{10^{12} \text{ GeV}}{f_a} \right) \text{ GeV}^{-1}$$

To avoid the astrophysical constraints (axion emission from neutron stars, and supernovae),

Talk by Georg Raffelt, also see talk by Alexandre Payez

$$f_a > 4 \times 10^8 \text{ GeV}$$

→ The axion is stable on a cosmological time scale, and so can explain the dark matter of the Universe.

## On-going axion experiments

- Axion Dark Matter eXperiment (ADMX)

Talk by Gray Rybka

- Center for Axion and Precision Physics (CAPP), IBS

Talk by Yannis Semertzidis

## PQ extension of the SM

- KSVZ models (hadronic axion model): PQ charged heavy quarks
- DFSZ models: PQ charged Higgs bilinear  $H_1 H_2$

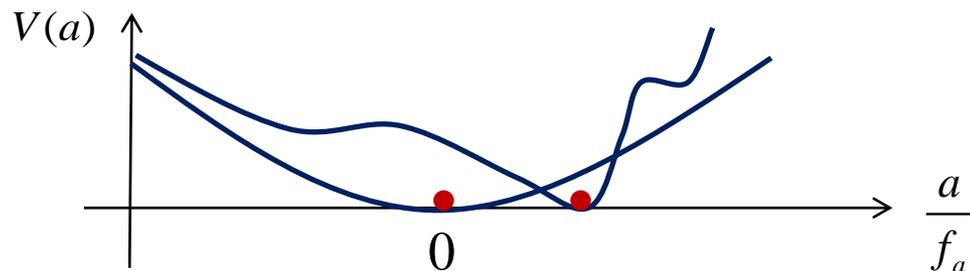
The QCD axion provides a natural solution to the strong CP problem, and is a good dark matter candidate.

## Important theoretical questions

- What is the origin of the PQ symmetry?

Global symmetries are generally broken by UV physics such as quantum gravity effects.

For the axion solution to work, other explicit PQ breaking should be highly suppressed (at present).



## Important theoretical questions

- Which physics determines the axion decay constant  $f_a$ , the scale of PQ breaking?

Connection to other new physics beyond the SM: SUSY breaking, string compactification, ... ?

To address these questions, we need to rely on the fundamental theory accommodating quantum gravity (string theory).

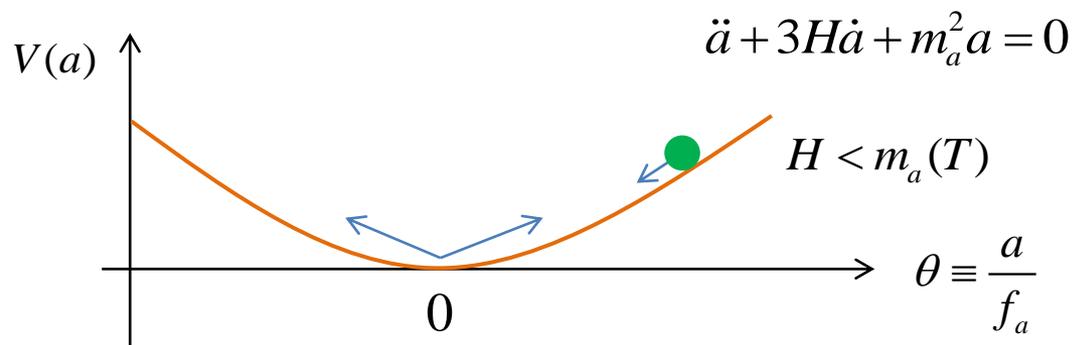
We will return to this issue soon.

See also talk by Jihn E. Kim

Axion dark matter

## Axion production

Axions are produced by coherent oscillations of misaligned axion field when  $H$  becomes comparable to the axion mass, and behave like non-relativistic particles.



Axions are produced also from topological defects (strings and walls) if spontaneous PQ breaking occurs after inflation.

## Axion relic abundance

The axion necessarily contributes to cold dark matter if it dynamically solves the strong CP problem.

$$\Omega_a \sim 0.2 \left( \theta_{\text{ini}}^2 + r_{\text{defect}} \right) \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}$$

↑ production by misalignment mechanism  
↑ from topological defects

$\theta_{\text{ini}}$ : initial misalignment angle of the axion

$r_{\text{defect}}$  (efficient factor)  $\sim 40$ - $120$  for  $N_{\text{DW}}=1$ , if PQ is restored in the early Universe

Numerical simulation  
 Hiramatsu, Kawasaki, Saikawa, Sekiguchi, 2012

### Axion contribution to hot dark matter

KSJ, M. Kawasaki, F. Takahashi, 2014

- Axions can be produced from the decay of heavy particles, e.g. radial component of PQ field, string moduli:  
**very model-dependent**
- Effective number of neutrino species:

$$N_{\text{eff}} = 3.046 + \Delta N_{\text{eff}} \\ (=0.61 \pm 0.30)$$

Axion abundance depends on when PQ transition occurs.

### Contribution to the potential of PQ fields in the early Universe

- Hubble-induced mass squared term: either sign

$$\Delta V_{\text{inflation}} \sim \pm H_I^2 |\phi|^2$$

- Thermal potential

$$\Delta V_{\text{thermal}} \sim (\lambda + y^2) T^2 |\phi|^2$$

for PQ field having  $\lambda|\phi|^4$  and  $y\phi Q^c Q$ , if the radial component sits at  $|\phi| < T_R$  after inflation ends.

Need to know the potential of PQ fields during inflation.

## Possible scenarios

### 1. PQ symmetry breaking occurs after inflation

- Need  $N_{DW}=1$  to avoid overclosure of the Universe  
→ severely constraining axion models
- Many patches with different axion initial value:  $\langle \theta_{ini}^2 \rangle = \pi^2/3$
- Axions are produced by collapsing string-wall system as well as from coherent oscillations:

$$\Omega_a \leq \Omega_{DM} \Rightarrow 10^9 \text{ GeV} \leq f_a \leq (2-4) \times 10^{10} \text{ GeV}$$

## 2. No PQ restoration during inflation and thereafter

There is no domain-wall problem.

### - Axion relic abundance

$$\Omega_a \sim 0.2 \times \theta_{\text{ini}}^2 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}$$

$\theta_{\text{ini}}$ : uniform at classical level throughout the whole observable Universe.

Large  $f_a$  requires small  $\theta_{\text{ini}}$ :

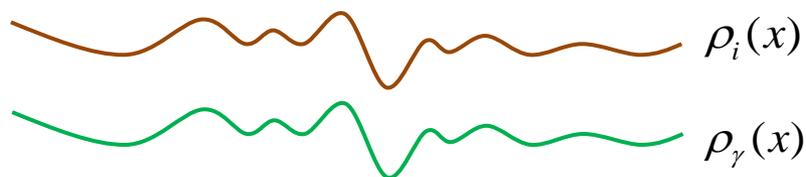
Anthropic argument is applicable if the axion is the main component of dark matter.

### - Axion fluctuations during inflation

$$\delta a = \frac{H_I}{2\pi} \quad (H_I: \text{expansion rate during inflation})$$

## 2. No PQ restoration during inflation and thereafter

- Single-field inflation generates **adiabatic perturbations**:  
no perturbations in the relative number densities of different species



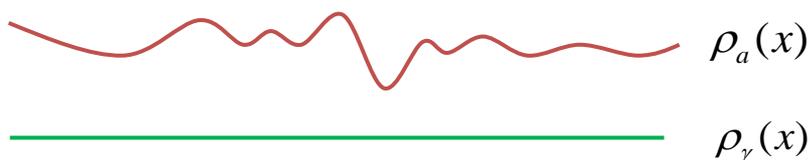
→ consistent with the observations

$$\frac{\delta T}{T} \sim 10^{-5}, \quad T = 2.725K$$

- Axion fluctuations are produced during inflation, but do not affect the total energy density.

## 2. No PQ restoration during inflation and thereafter

- Axion fluctuations turn into **isocurvature density perturbations** at QCD phase transition, and there appears non-Gaussianity.



$$\left. \frac{\delta T}{T} \right|_{\text{iso}} \sim \frac{\delta \rho_a}{\rho_{\text{DM}}} \propto \delta \theta$$

Axenides, Brandenberger, Turner, 1983;

Seckel, Turner 1985; Linde 1985; Fox, Pierce, Thomas 2004, ...

The axion is a DM candidate with isocurvature perturbations, and so is constrained from the observed CMB spectrum.

### 3. Non-trivial axion cosmology

Temporarily-enhanced explicit PQ breaking in the early Universe  
(during or after inflation)

→ can make the axion heavy, or make domain walls ( $N_{DW} > 1$ )  
unstable

e.g. Dine, Anisimov 2004; Higaki, KSJ, Takahashi 2014

KSJ, Takahashi 2013; Barr, Kim 2014

c.f. Folkerts, Germani, Redondo 2013

Late-time entropy production, after the QCD phase transition  
but before the primordial nucleosynthesis

→ can dilute the axion abundance

In this talk we do not consider these possibilities.

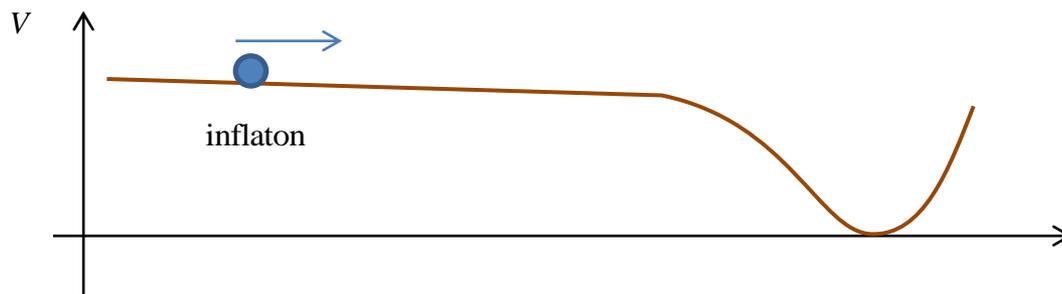
QCD axion in high scale inflation

## Inflation

- can explain the initial conditions required for the Universe to evolve to its current state in the Big Bang theory.
- generates density perturbations that give rise to the cosmic structures.

### Slow-roll inflation

Important observables are the spectral index and tensor-to-scalar ratio:

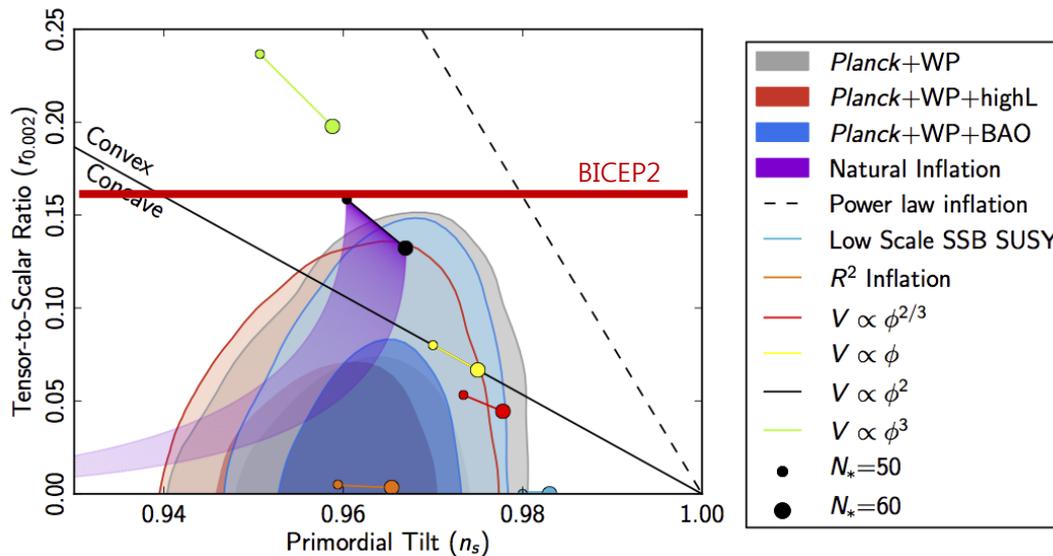


$$n_s \approx 1 + 2 \frac{V''}{V} - 3 \left( \frac{V'}{V} \right)^2,$$

$$r = \frac{A_t}{A_s} \approx 8 \left( \frac{V'}{V} \right)^2$$

## Inflation

- Tensor modes (primordial gravitational waves):  $r \approx 0.16 \times \left( \frac{H_I}{10^{14} \text{ GeV}} \right)^2$



On-going and planned experiments can probe  $r$  down to  $10^{-3}$ .

If discovered, high scale inflation with  $H_I = 10^{13-14} \text{ GeV}$

## Cosmological constraints on the axion

- Relic abundance:  $\Omega_a$  = function of  $m_a$ ,  $f_a(t_0)$ , and  $\theta_{ini}$
- Axion isocurvature modes

If the axion exists in the inflation epoch, it acquires

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

Constraints depend on  $\frac{\Omega_a}{\Omega_{DM}}$ ,  $f_a(t_0)$ ,  $f_a(t_I)$ ,  $H_I$ .

present
inflation epoch

In this talk we consider a generic situation with

$$\frac{\Omega_a}{\Omega_{DM}} \leq 1 \quad \text{and} \quad f_a(t_I) = \begin{cases} 0 \\ \sim f_a(t_0) \\ \gg f_a(t_0) \end{cases}$$

relaxing the isocurvature constraint

## Cosmological constraints on the axion

- Relic abundance

$$\text{PQ restoration: } \frac{\Omega_a}{\Omega_{\text{DM}}} \approx 4.5 \times \left( \frac{f_a(t_0)}{10^{11} \text{ GeV}} \right)^{1.19}$$

$$\text{No PQ restoration: } \frac{\Omega_a}{\Omega_{\text{DM}}} \approx 0.11 \times (\theta_0^2 + \delta\theta^2) \left( \frac{f_a(t_0)}{10^{11} \text{ GeV}} \right)^{1.19}$$

- Isocurvature perturbations

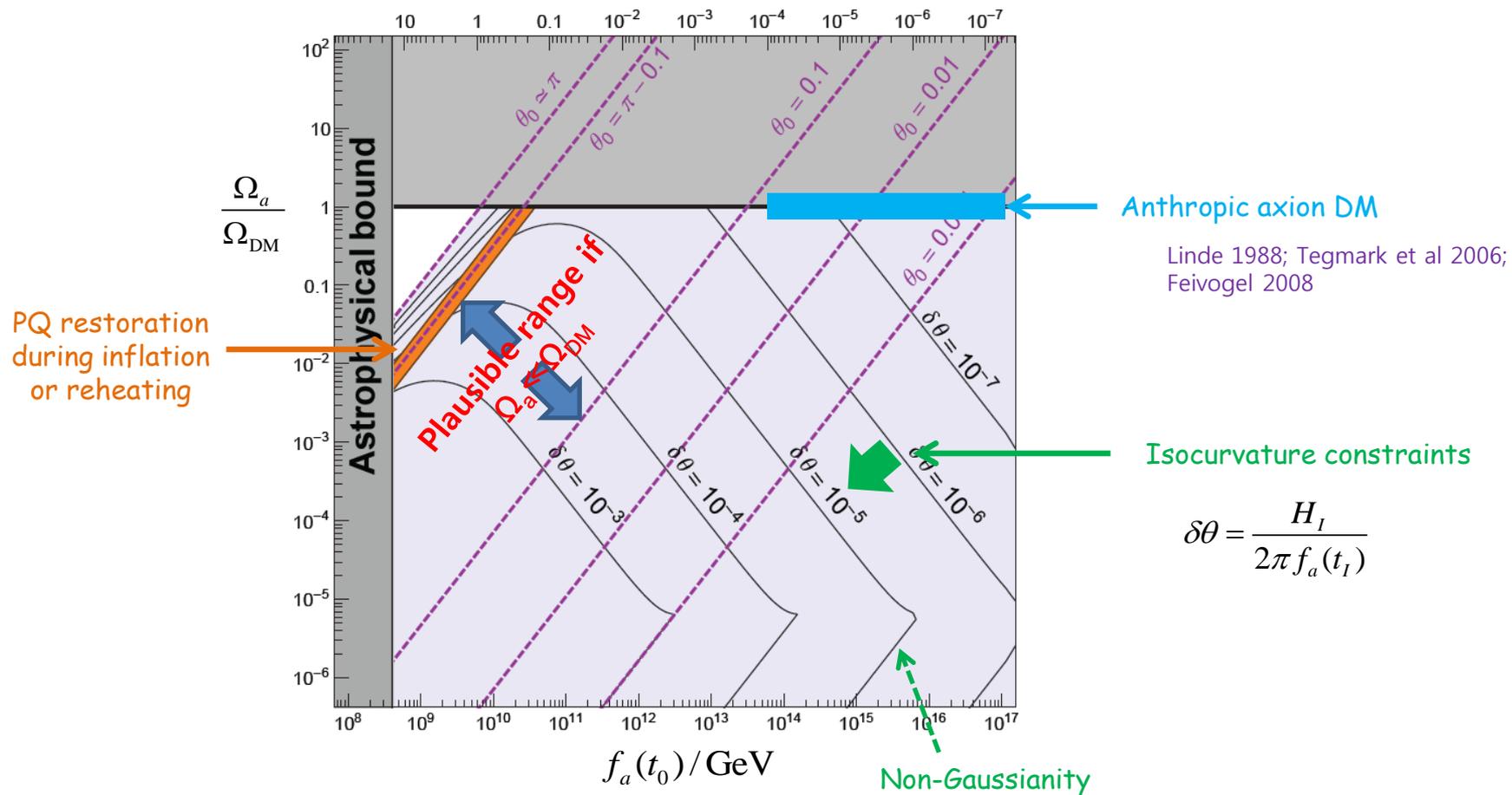
$$P_s \approx 0.44 \times \left( \frac{\Omega_a}{\Omega_{\text{DM}}} \right) \left( \frac{f_a(t_0)}{10^{11} \text{ GeV}} \right)^{1.19} \delta\theta^2 < 0.041 P_\xi$$

with the curvature perturbation power spectrum  $P_\xi \approx 2.2 \times 10^{-9}$

$$\frac{\Omega_a}{\Omega_{\text{DM}}} < 0.9 \times \left( \frac{H_I}{10^{14} \text{ GeV}} \right)^{-2} \left( \frac{f_a(t_I)}{10^{18} \text{ GeV}} \right)^2$$

Note: anharmonic effects become important when the axion sits near the hilltop after inflation ends.

# Constraints on $\Omega_a$ and $f_a(t_0)$ for a generic situation



#### QCD axion in high scale inflation

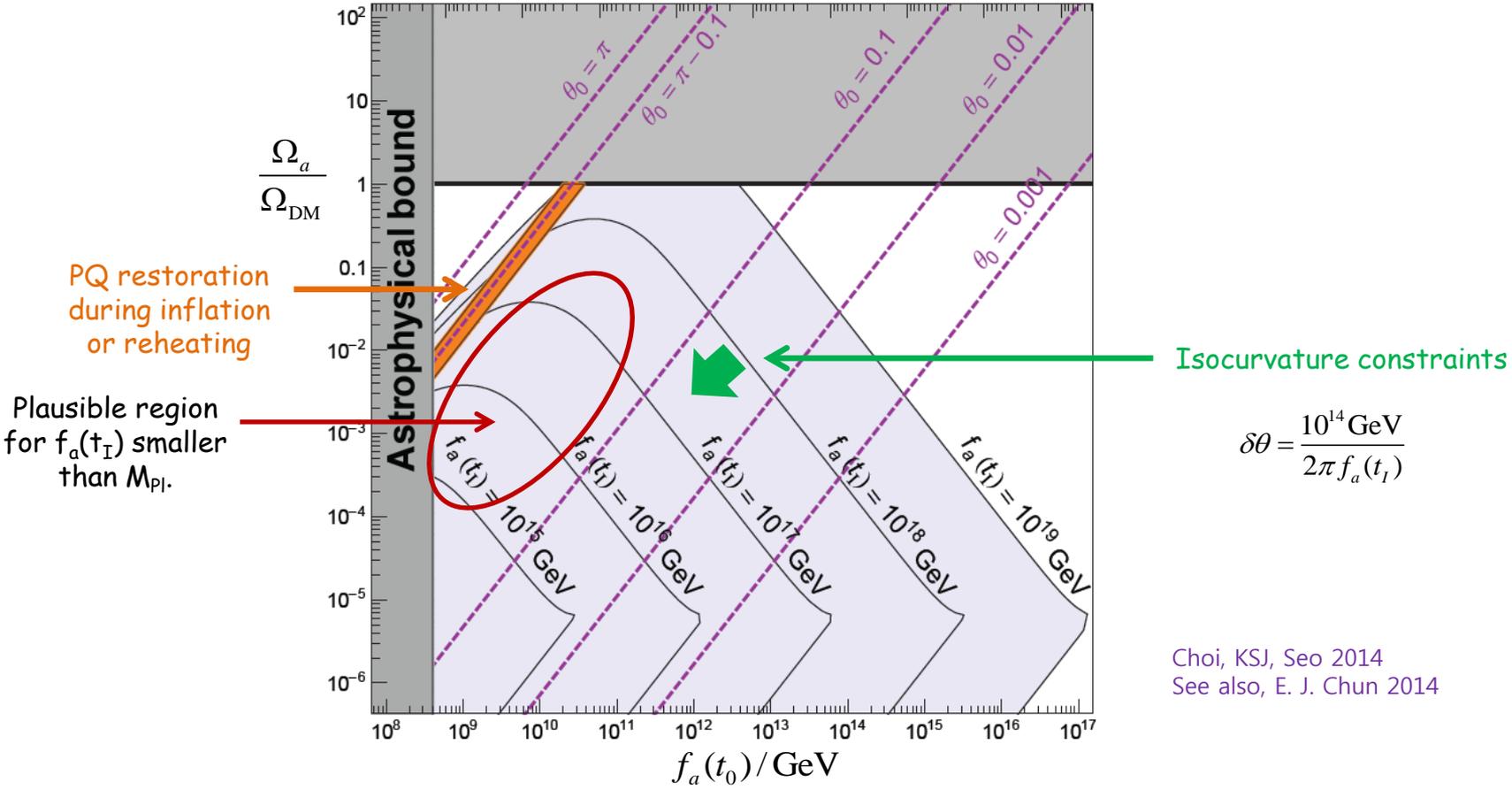
- High scale inflation with  $r \sim 10^{-3 \sim -1}$  ( $H_I \sim 10^{13-14} \text{ GeV}$ )  
e.g. chaotic inflation models generally give  $r \sim 0.1$ .
- Axion fluctuations are suppressed if  $f_a(t_I)$  is large.

$f_a(t_I) \sim \text{VEV of } \phi \text{ during inflation}$

- The effective theory is valid at  $\phi \ll M_{Pl}$ .
- If  $\phi(t_I) \gg M_{Pl}$ , Planck-suppressed operators would spoil the inflation dynamics.

e.g.  $\frac{|\phi|^2}{M_{Pl}^2} \times (\text{inflaton sector})$

# Constraints for $H_I=10^{14}$ GeV



Choi, KSJ, Seo 2014  
See also, E. J. Chun 2014

## Cosmological consequences of axion

Depend on where the PQ fields are stabilized during inflation:

- PQ symmetry restoration?
  - PQ symmetry breaking at a different scale than at present?
- If then, how large scale it can be?

Important to know ♦ UV origin of the PQ symmetry,  
and ♦ Physical mechanism determining  $f_a$ .

Realization of the QCD axion in string theory

### Stringy axion

String theory includes a variety of higher-dim anti-symmetric tensor gauge fields: zero modes behave like axions in the 4-dim effective theory:

Kaehler potential:  $K = K(T + T^*)$

Gauge kinetic function:  $F = T + \dots$

$T$  = modulus-axon superfield

$\text{Re}(T)$ : volume,  $a_{\text{st}} = \text{Im}(T)$ : stringy axion



Perturbative shift symmetry  $U(1)_{\text{shift}}$  from higher-dim **gauge symmetry**

$\text{Im}(T) \rightarrow \text{Im}(T) + \text{constant}$

It can be well protected from quantum gravity.

## Stringy axion

- $a_{st}$  can be identified as the QCD axion:

$$L_{eff} = \frac{1}{4\sqrt{\partial_T^2 K} \times M_{Pl}} a_{st} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$\Rightarrow f_{st} = \frac{\sqrt{\partial_T^2 K}}{8\pi^2} M_{Pl} \sim 10^{15-17} \text{ GeV}$$

Choi, Kim, 1985; Svrcek, Witten 2006

for most of compactification models with a compactification scale higher than  $10^{16} \text{ GeV}$  (GUT scale).

- $f_{st}$  does not change much during and after inflation:  
Isocurvature constraint is quite severe in high scale inflation.

## Intermediate axion decay constant

Possible in a generalized scheme with anomalous  $U(1)_A$  gauge symmetry where  $a_{st}$  implements the Green-Schwarz mechanism of anomaly cancellation.

D-term includes Fayet-Iliopoulos (FI) term

$$\xi_{FI} = \frac{\sum q_i \text{Tr}(T_a^2(\phi_i))}{8\pi^2} \times \partial_T K$$

To cancel the FI term (D-flat condition), there should be  $U(1)_A$  charged matter field  $\phi$ :

$$V_D = \left( \xi_{FI} - q|\phi|^2 \right)^2$$

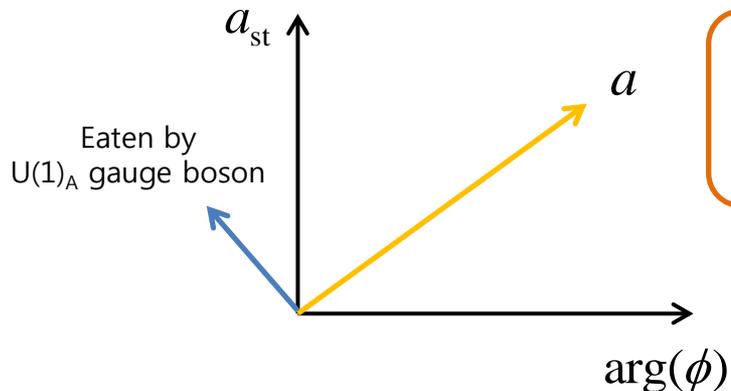
## Intermediate axion decay constant

$$U(1)_{\text{shift}} + U(1)_{\phi}$$

- anomalous  $U(1)_A$  gauge symmetry
- global  $U(1)$  symmetry: valid in perturbation theory

↓  
can be identified as PQ symmetry solving the strong CP problem

### ◆ QCD axion



axion decay constant

$$f_a = \min(f_{\text{st}}, \langle \phi \rangle)$$

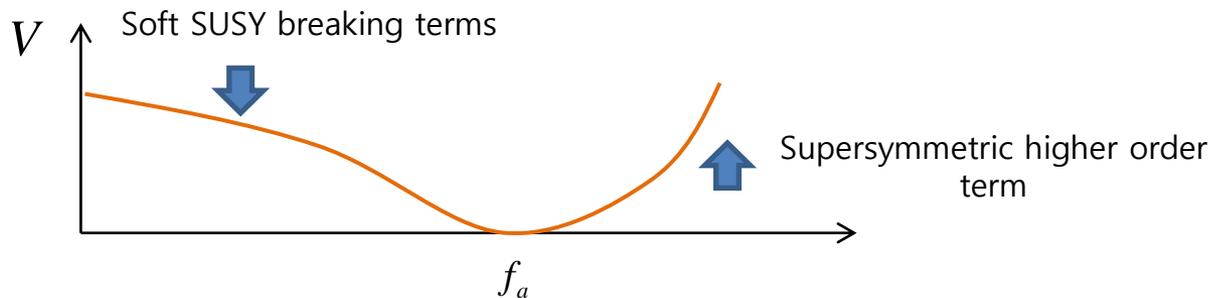
## Intermediate axion decay constant

- $f_a \sim \langle \phi \rangle \ll M_{\text{pl}}$  is obtained in compactified string models involving anomalous  $U(1)_A$  with vanishing FI-term.
  - Realized in Type II string models with D-branes and heterotic string models with  $U(1)$  YM bundles.
  - axion scale is generated by SUSY breaking effect (D-term stabilization)
  - Compactification scale close to  $M_{\text{pl}}$  as needed for GUT and high scale inflation.

## Intermediate axion decay constant

- How to stabilize the D-flat direction (mostly  $\phi$ )

Interplay between supersymmetric higher order term and SUSY breaking



## Axion decay constant

$$f_a = \left( m_{\text{SUSY}} M_{\text{Pl}}^n \right)^{1/(n+1)}, \quad (n \geq 0)$$

## Axion scales during and after inflation

- 4D effective SUGRA analysis

- U(1)<sub>A</sub> and PQ sector

$$K_1 = \frac{M_{Pl}^2}{2} (T + T^* - 2\tau_0 - \delta_{GS} V_A)^2 + \phi_i^* e^{-q_i V_A} \phi_i, \quad W_1 = \lambda \frac{\phi_1^{n+2} \phi_2}{M_{Pl}^n}$$

- SUSY breaking and Inflation sector (SUSY chaotic inflation)

$$K_2 = |Z|^2 + (\Phi + \Phi^*)^2 + |X|^2, \quad W_2 = \omega_0 + M^2 Z + \mu \Phi X$$

Z: SUSY breaking in the present Universe

X: SUSY breaking during inflation

Im(Φ): Inflaton

- Couplings between two sectors

$$\Delta K = (k|Z|^2 + \kappa|X|^2) (T + T^* - 2\tau_0 - \delta_{GS} V_A) + \frac{k_i |Z|^2 + \kappa_i |X|^2}{M_{Pl}^2} \phi_i^* e^{-q_i V_A} \phi_i$$

## Axion scales during and after inflation

- **D-term domination is generic.**

$$D_A \approx \frac{1}{\delta_{GS}} \left( k \frac{|F^Z|^2}{M_{Pl}^2} + \kappa \frac{|F^X|^2}{M_{Pl}^2} \right) \sim 8\pi^2 (m_{3/2}^2 + H_I^2)$$

Either  $\phi_1$  or  $\phi_2$  gets tachyonic both during and after inflation.  
 → PQ symmetry remains broken from the inflationary epoch.

- Axion scales

- Implications on SUSY breaking scale

$$f_a \sim (D_A M_{Pl}^n)^{1/(n+1)} : \text{axion scale SUSY (n=0), low scale SUSY (n=1)}$$

- Naturally leads to  $f_a(t_I) \gg f_a(t_0)$  in high scale inflation.

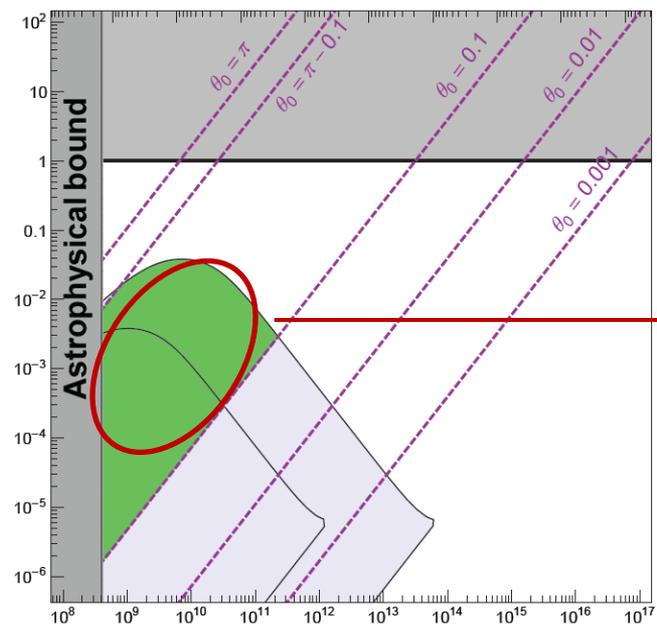
$$\frac{f_a(t_I)}{f_a(t_0)} \sim \frac{m_{3/2}}{H_I} \text{ for } n=0, \text{ and } \sqrt{\frac{m_{3/2}}{H_I}} \text{ for } n=1$$

Choi, KSJ, Seo 2014  
 E. J. Chun 2014

## String theoretic QCD axion with high scale inflation

$$f_a(t_I) = \min(f_{st}, \langle \phi \rangle) \leq 10^{17} \text{ GeV}$$

$$f_a(t_0) = \left( m_{\text{SUSY}} M_{\text{Pl}}^n \right)^{1/(n+1)}$$



The most probable region compatible with high scale inflation  $H_I \sim 10^{14} \text{ GeV}$ :

$f_a(t_0) = 10^{9-11} \text{ GeV}$ $f_a(t_I) = 10^{15-17} \text{ GeV}$	$\frac{\Omega_a}{\Omega_{\text{DM}}} \leq O(0.1)$
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## Summary

**High scale inflation:** the isocurvature perturbation bound puts a severe constraint on the QCD axion.

**String compactification models with anomalous U(1) gauge symmetry**

- explain the origin of the PQ symmetry, which needs to be protected from quantum gravity effects
- realizes an intermediate axion decay constant, while making connection between SUSY breaking scale and axion scale.
- D-term domination leads to that PQ symmetry remains broken during and after inflation
- The isocurvature constraint is naturally relaxed because the scheme results in  $f_a(t_I) \gg f_a(t_0)$  in high scale inflation.