Constraints on axion in high scale inflation

arXiv:1404.3880, K. Choi, KSJ and M. S. Seo

work in progress: K, Choi, E. J. Chun, KSJ and S. H. Lim

Kwang Sik JEONG

IBS Center for Theoretical Physics of the Universe

ibs Institute for Basic Science

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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,
…

1. PQ extension of the SM (2/7)

Strong CP problem

The strong interactions can generate CP violation via

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

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

$$d_n \simeq 3\times 10^{-16} \times \theta \; e \cdot cm$$

experimental bound on neutron EDM

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

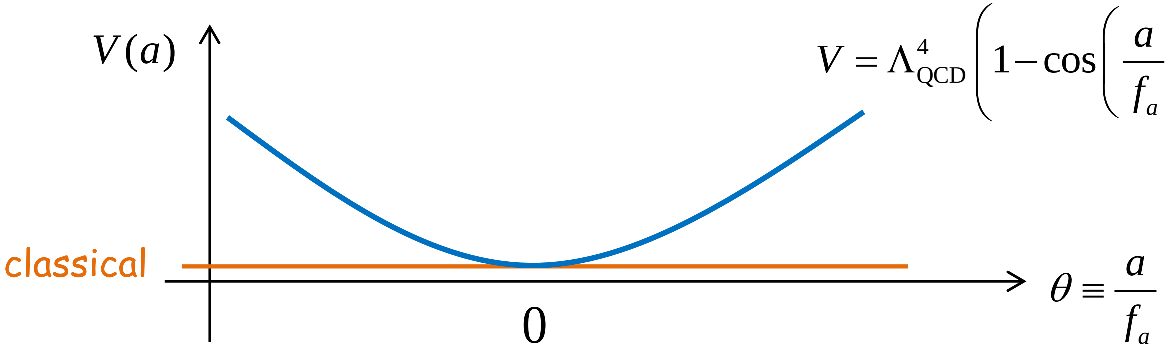
→ Need some physical explanation for the absence of CP violation in the strong interactions.

1. PQ extension of the SM (3/7)

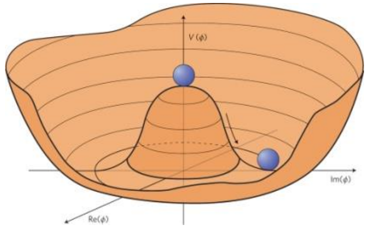
Axion solution to the strong CP problem

Peccei and Quinn 1977

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



$$V = \Lambda_{\rm QCD}^4 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$



QCD instantons explicitly break PQ, generating axion potential.

- θ is dynamically cancelled, and QCD becomes CP conserving.

1. PQ extension of the SM (4/7)

Axion physics: determined by f_a ~ (PQ breaking scale)

- Axion mass: $m_a \simeq 5\times10^{-6}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\mathrm{eV}$
- Axion couplings to SM

axion-nucleon interaction	axion-photon interaction
$g_{aNN} \simeq 10^{-12}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$	$g_{a\gamma\gamma} \simeq 10^{-15}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\mathrm{GeV}^{-1}$

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

$$f_a > 4\times10^{8}\,\mathrm{GeV}$$

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

1. PQ extension of the SM (5/7)

PQ extension of the SM

- KSVZ models (hadronic axion model): PQ charged heavy quarks
- DFSZ models: PQ charged Higgs bilinear H_1H_2

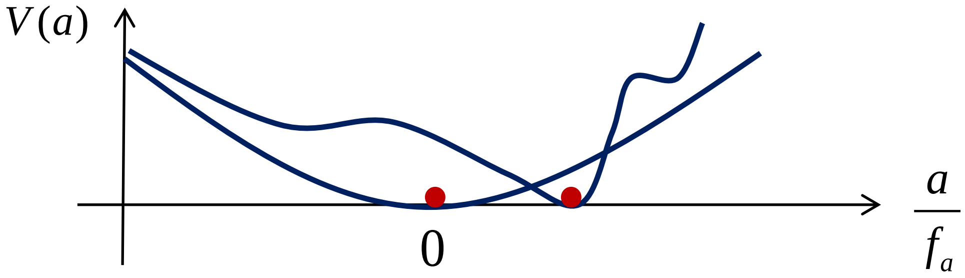
PQ extension naturally explains why the strong interaction does not break CP, and provides a good dark matter candidate- the QCD axion.

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).



1. PQ extension of the SM (7/7)

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.

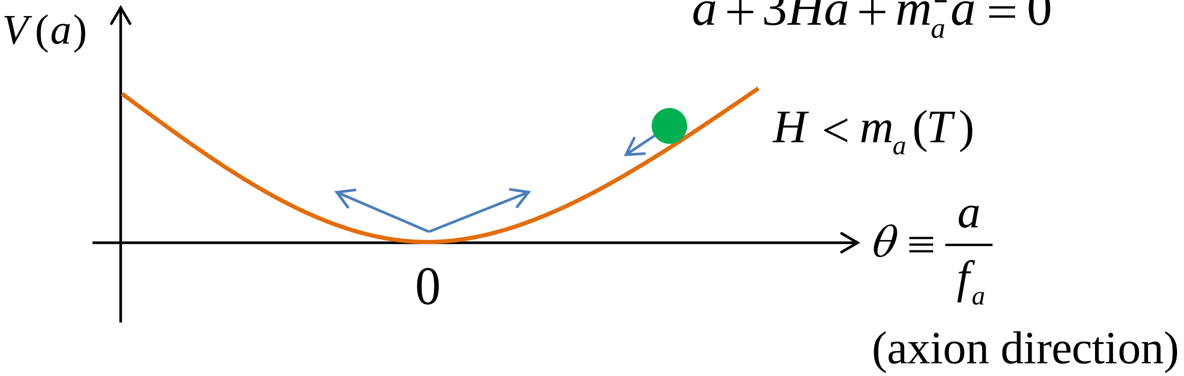
Axion dark matter

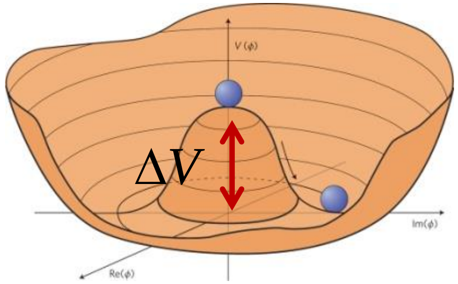
2. Axion DM (1/9)

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.

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$





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

2. Axion DM (2/9)

Axion relic abundance

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

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

from topological defects

production by misalignment mechanism

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

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

Numerical simulation
Hiramatsu, Kawasaki, Saikawa, Sekiguchi, 2012

2. Axion DM (3/9)

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:

$$N_{\rm eff} = 3.046 + \Delta N_{\rm eff}$$

(=0.61+-0.30)

2. Axion DM (4/9)

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

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

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.

2. Axion DM (5/9)

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: $\langle\theta^2_{ini}\rangle=\pi^2/3$
- Axions are produced by collapsing string-wall system as well as from coherent oscillations:

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

2. Axion DM (6/9)

2. No PQ restoration during inflation and thereafter

There is no domain-wall problem.

- Axion relic abundance

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

θ_{ini} : uniform at classical level throughout the whole observable Universe.

Large f_a requires small θ_{ini}:

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

- Axion fluctuations during inflation

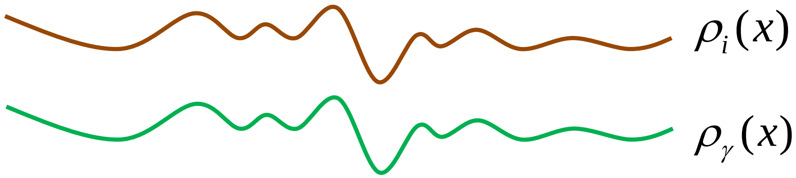
$$\delta a = \frac{H_I}{2\pi}$$ (H_I: expansion rate during inflation)

2. Axion DM (7/9)

2. No PQ restoration during inflation and thereafter

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

Or high enough reheating temperature



→ consistent with the observations

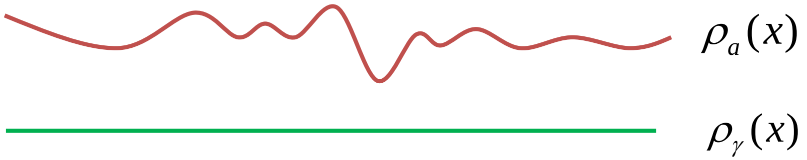
$$\frac{\delta T}{T} \sim 10^{-5}, \quad T = 2.725K$$

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

2. Axion DM (8/9)

2. No PQ restoration during inflation and thereafter

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



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

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

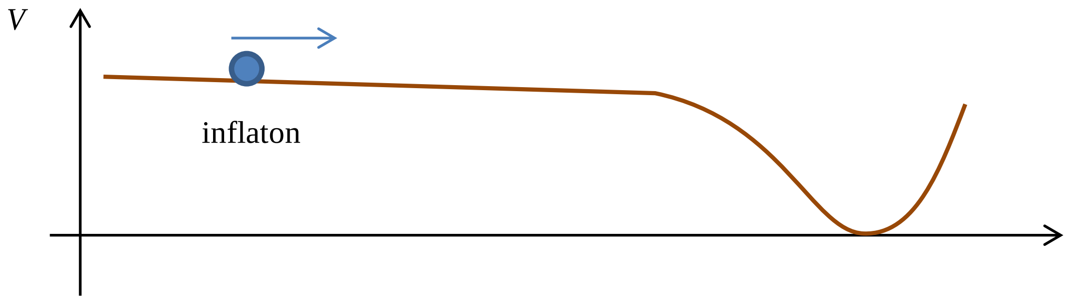
3. Axion with high scale inflation (1/8)

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:



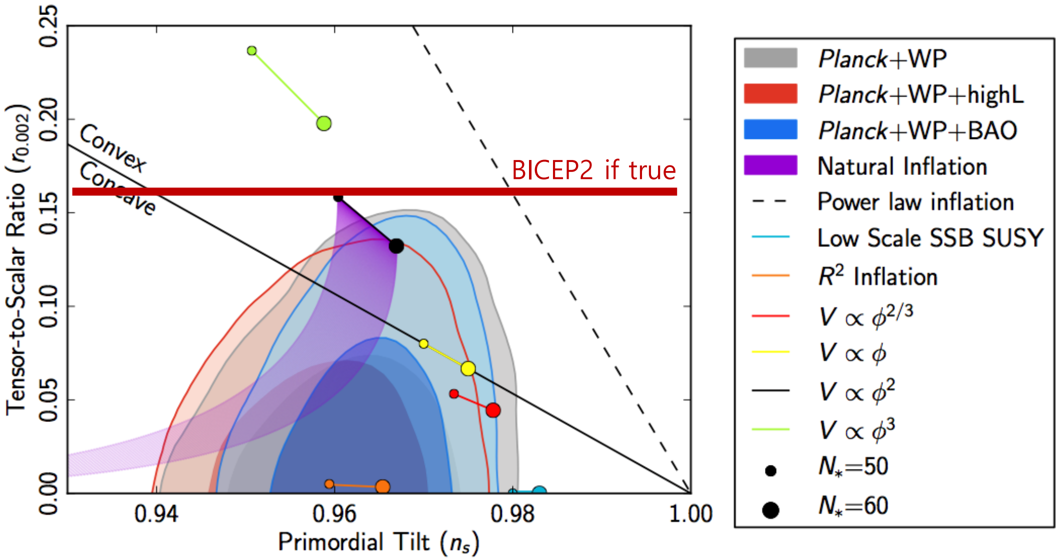
$$n_s \simeq 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2,$$

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

3. Axion with high scale inflation (2/8)

Inflation

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



On-going and planned experiments can probe r down to 10^{-2}.

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

3. Axion with high scale inflation (3/8)

Cosmological constraints on the axion

- Relic abundance: Ω_a = function of m_a, $f_a(t_0)$, and θ_{ini}
- Axon 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 $\underbrace{\Omega_a/\Omega_{DM}, f_a(t_0)}_{\text{present}}$, $\underbrace{f_a(t_I), H_I}_{\text{inflation epoch}}$.

In this talk we consider a generic situation with

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

relaxing the isocurvature constraint

3. Axion with high scale inflation (4/8)

Cosmological constraints on the axion

- Relic abundance

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

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

- Isocurvature perturbations

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

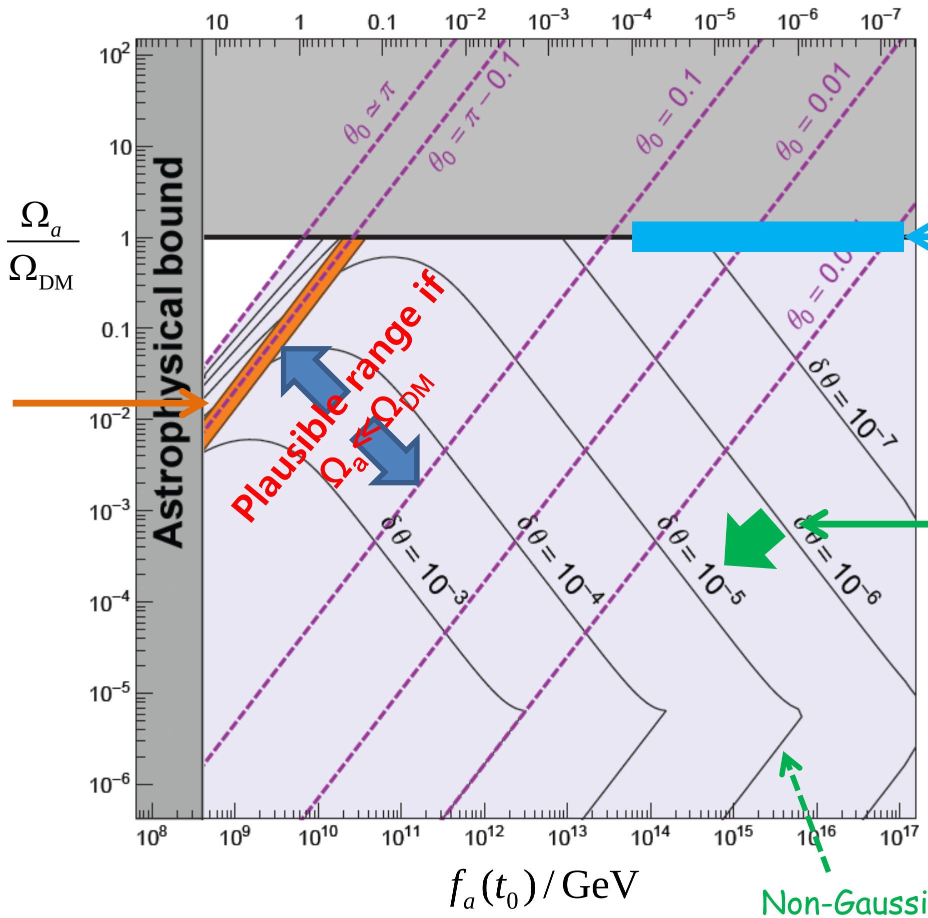
with the curvature perturbation power spectrum $P_\xi \simeq 2.2\times 10^{-9}$

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

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

3. Axion with high scale inflation (5/8)

Constraints on Ω_a and $f_a(t_0)$ for a generic situation



PQ restoration during inflation or reheating

Anthropic axion DM

Linde 1988; Tegmark et al 2006; Feivogel 2008

Isocurvature constraints

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

Non-Gaussianity

Choi, KSJ, Seo 2014

QCD axion in high scale inflation

- High scale inflation with $r \sim 10^{-3 \sim -1}$ ($H_I \sim 10^{13-14}$ GeV)

  e.g. chaotic inflation models generally give $r \sim 0.1$.

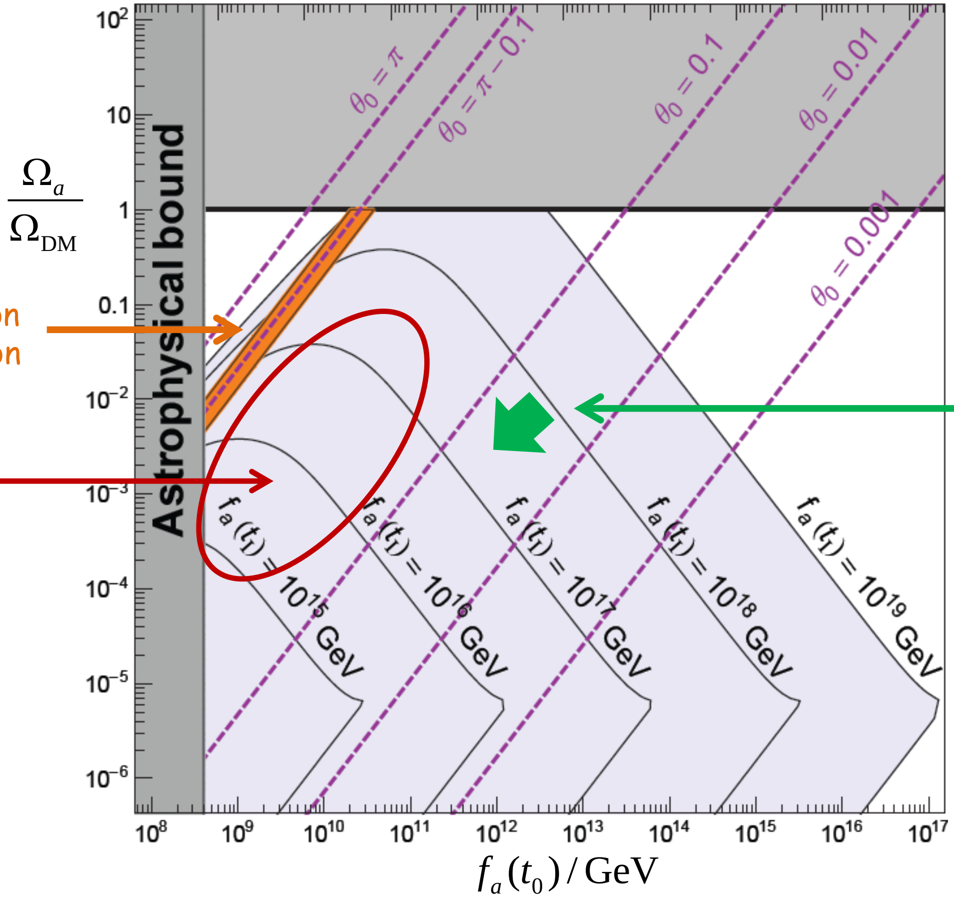
- Axion fluctuations are suppressed if $f_a(t_I)$ is large.

  $f_a(t_I)$ ~ VEV of ϕ 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. $\frac{|\phi|^2}{M_{Pl}^2} \times (\text{inflaton sector})$

3. Axion with high scale inflation (7/8)

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



PQ restoration
during inflation
or reheating

Plausible region
for $f_a(t_I)$ smaller
than M_{Pl}.

Isocurvature constraints

$$\delta\theta = \frac{10^{14}\,\mathrm{GeV}}{2\pi f_a(t_I)}$$

Choi, KSJ, Seo 2014
See also,
T. Higaki, KSJ, F. Takahashi 2014
E. J. Chun 2014

3. Axion with high scale inflation (8/8)

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

4. String theoretic QCD axion (1/9)

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: $F = T + (T\text{-independent})$

T= modulus-axon superfield
Re(T): volume, a_{st}=Im(T): stringy axion

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

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

It can be well protected from quantum gravity.

4. String theoretic QCD axion (2/9)

Stringy axion

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

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

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

Choi, Kim, 1985; Svrcek, Witten 2006

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

- f_{st} does not change much during and after inflation:

Isocurvature constraint is quite severe in high scale inflation.

4. String theoretic QCD axion (3/9)

Intermediate axion decay constant

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

D-term includes Fayet-Illopoulos (FI) term

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

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

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

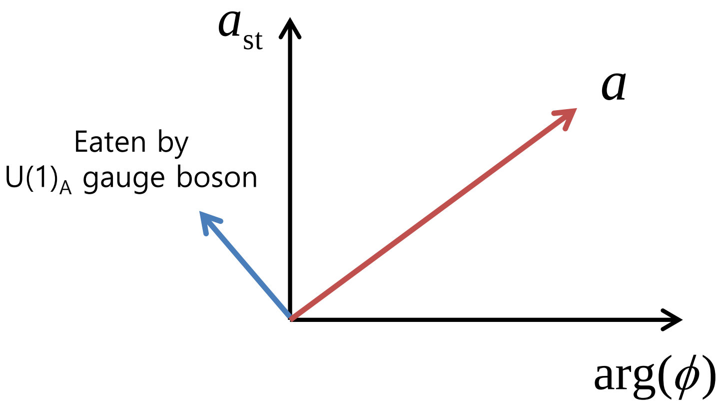
Intermediate axion decay constant

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

- 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 = one combination of two massless directions



axion decay constant

$$f_a = \min\left(f_{\text{st}} \propto \langle \mathrm{Re}(T) \rangle, \langle \phi \rangle \right)$$

4. String theoretic QCD axion (5/9)

Intermediate axion decay constant

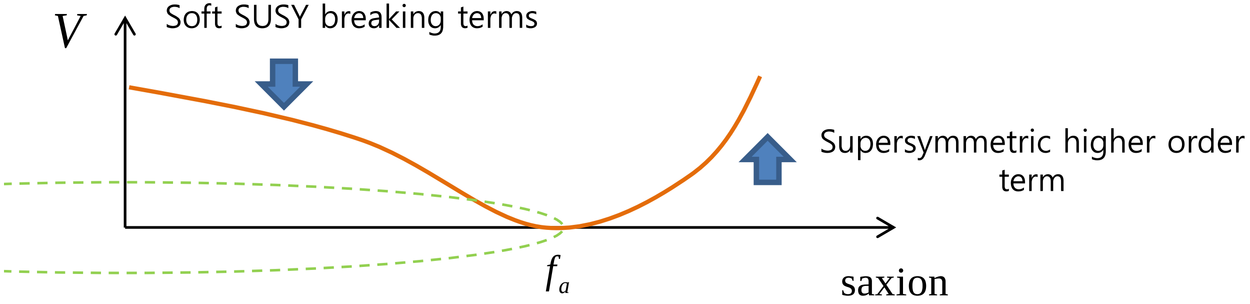
- $f_a \sim \langle\phi\rangle \ll M_{Pl}$ is obtained in compactified string models involving anomalous $U(1)_A$ with vanishing FI-term.
  - Realized in Type II string models with D-branes and heterotic string models with U(1) YM bundles.
  - axion scale is generated by SUSY breaking effect (D-term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

4. String theoretic QCD axion (6/9)

Intermediate axion decay constant

- How to stabilize the saxion ~ the D-flat direction (mostly ϕ)

Interplay between supersymmetric higher order term and SUSY breaking



Axion decay constant

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

4. String theoretic QCD axion (7/9)

Axion scales during and after inflation

- 4D effective SUGRA analysis
  - U(1)$_A$ and PQ sector

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

M. Kawasaki, M. Yamaguchi, T. Yanagida 2000

  - SUSY breaking and Inflation sector (SUSY chaotic inflation)

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

Z: SUSY breaking in the present Universe
X: SUSY breaking during inflation
Im(Φ): Inflaton

  - Couplings between two sectors

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

4. String theoretic QCD axion (8/9)

Axion scales during and after inflation

- D-term domination is generic!

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

Either ϕ_1 or ϕ_2 necessarily gets tachyonic both during and after inflation.

→ PQ symmetry remains broken from the inflationary epoch!

- Axion scales
  - Implications on SUSY breaking scale

$$f_a \sim \left(D_A M_{Pl}^n\right)^{1/(n+1)}$$: 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.

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

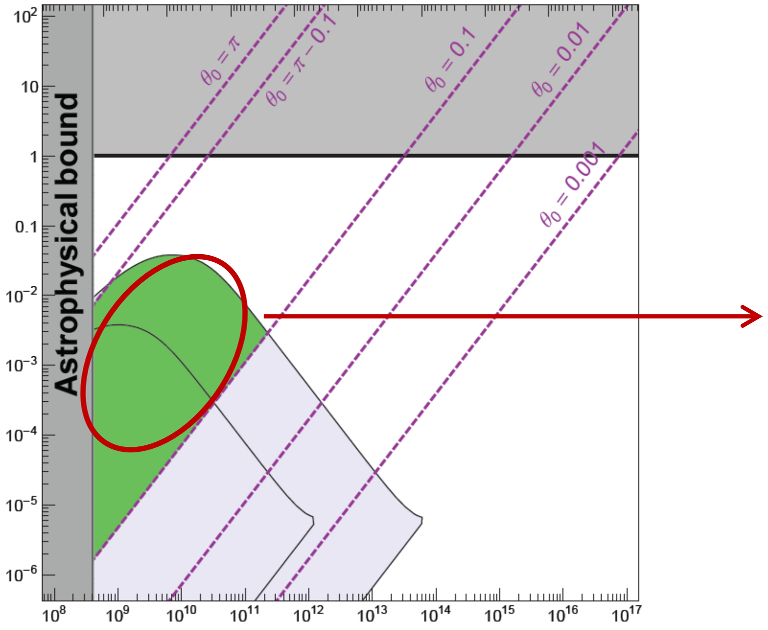
Choi, KSJ, Seo 2014
E. J. Chun 2014

4. String theoretic QCD axion (9/9)

String theoretic QCD axion with high scale inflation

$$f_a(t_I) = \min\left(f_{st}, \langle\phi\rangle\right) \le 10^{17}\,\mathrm{GeV}$$

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



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

$$\boxed{\begin{aligned} f_a(t_0) &= 10^{9-11}\,\mathrm{GeV} \\ f_a(t_I) &= 10^{15-17}\,\mathrm{GeV} \end{aligned}} \qquad \boxed{\frac{\Omega_a}{\Omega_{\mathrm{DM}}} \le O(0.1)}$$

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.