Suppressing isocurvature fluctuations of QCD axion DM

arXiv:1304.8131 KSJ and F. Takahashi

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Outline

- Axion solution to the strong CP problem
- Axion dark matter and isocurvature fluctuations
- Mechanism to relax the isocurvature constraint on inflation
- Summary

Talk by T. Davidek

Finally, the Higgs boson has been discovered, but so far with no direct hint for new physics beyond the SM. It looks just like the SM Higgs boson.

However, many reasons to consider new physics beyond the SM:

- Naturalness
  - Gauge hierarchy problem
  - Strong CP problem
- Unknown components such as dark energy and dark matter
- …

- Strong CP problem

In SM, the QCD interaction can generate CP violation through the coupling,

$$\frac{\bar{\theta}}{16\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}.$$

This contributes to the neutron EDM, and the experimental bound on neutron EDM requires

$$\left|\bar{\theta}\right| < 10^{-10}.$$

Why is the CP violating angle so tiny?

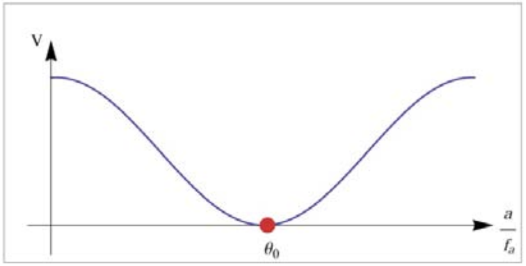
- Axion solution to the strong CP problem

The idea is to replace the CP violation phase in QCD by a dynamical field, the axion, transforming as a → a + (constant) under $U(1)_{PQ}$.

Peccei and Quinn (1977)

$$\bar{\theta} \to \frac{a}{f_a}$$

PQ is explicitly broken by QCD instantons, and consequently an axion potential is generated:



dynamical relaxation

$$m_a^2 \sim \frac{m_q \Lambda_{\mathrm{QCD}}^3}{f_a^2}$$

in the presence of a light quark with $m_q < \Lambda_{\mathrm{QCD}}$

- Axion dark matter

It is stable on a cosmological time scale.

The axion starts to oscillate with amplitude $a_i = f_a \theta_i$ when $H \sim m_a$. The axion energy density produced from the misalignment is

$$\Omega_a h^2 \approx 0.2 \theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.184},$$

$f_a > 10^9$ GeV to avoid astrophysical constraints; axion emission from neutron stars and supernovae.

The axion can explain both a tiny CP violation in QCD and the dark matter of the Universe.

However, there are difficulties yet.

- Isocurvature fluctuations of axion DM

The axion potential remains flat until the Universe cools down to $T \sim \Lambda_{QCD}$ and the QCD phase transition occurs.

If the (massless) axion is present during inflation, it has quantum fluctuations:

$$\delta a \simeq \frac{H_{\inf}}{2\pi}, \text{ where } a = f_a \theta$$

As this contributes to the axion misalignment, axion fluctuations produced during inflation result in isocurvature CMB fluctuations.

The observed CMB spectrum severely constrains the isocurvature fluctuations:

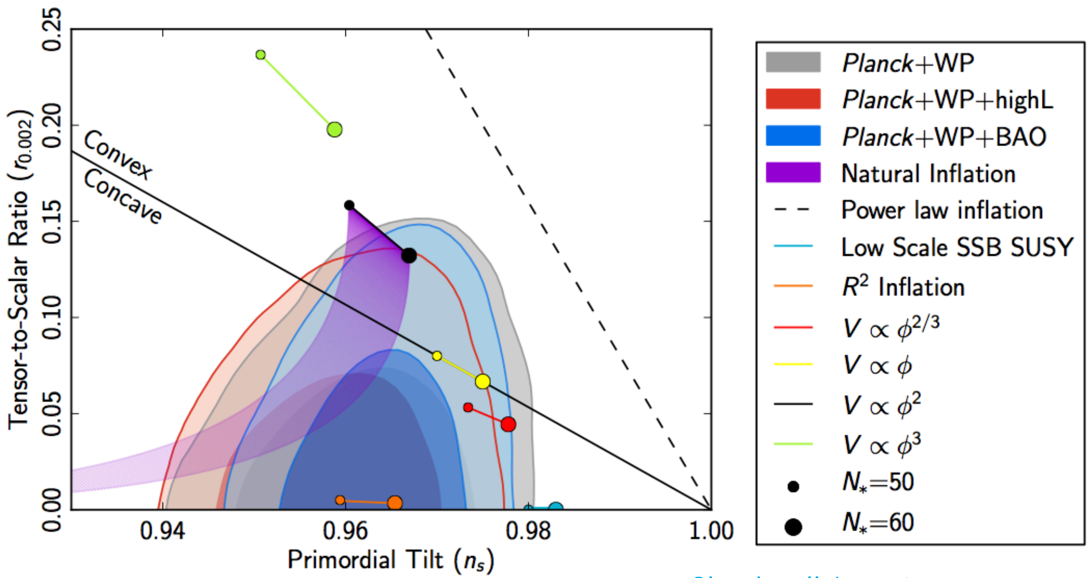
$$\frac{(\delta T/T)^2_{\text{isocurvature}}}{(\delta T/T)^2_{\text{adiabatic}}} < 0.041 \text{ (95\% C.L.)} \Rightarrow \boxed{H_{\text{inf}} \leq 1.13\times 10^7\,\text{GeV}\left(\frac{\Omega_a}{\Omega_{\text{DM}}}\right)^{-1}\left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^{0.408}}$$

Thus high scale inflation models with H_{inf}>10^{10} GeV are in conflict with axion DM.

▪ Inflation

Talk by F. Couchot

In the slow-roll inflation scenario, important observables are the spectral index and the tensor-to-scalar ratio:



$$\begin{cases} n_s \approx 1 + 2\dfrac{V''}{V} - 3\left(\dfrac{V'}{V}\right)^2, \\ r = \dfrac{A_t}{A_s} \approx 8\left(\dfrac{V'}{V}\right)^2. \end{cases}$$

Planck collaborations, 1303.5082

Inflation models with V''>0 do not fit well the observations.

The Planck constraint on r corresponds to an upper bound on the inflation scale:

$$r \approx \frac{1}{A_s}\frac{2}{\pi^2}\left(\frac{H_{\rm inf}}{M_{Pl}}\right)^2 \simeq 0.12\times\left(\frac{H_{\rm inf}}{0.9\times10^{14}\,{\rm GeV}}\right)^2 \quad\Rightarrow\quad r<0.12 \text{ requires } H_{\rm inf}<10^{14}\,{\rm GeV}$$

The sensitivity of the Planck is about 0.05.

Now the question is:

- Is the axion DM excluded if the tensor mode (gravitational waves) is observed, i.e. if H_{inf}~$10^{13\text{-}14}$ GeV?
- Can we make the axion DM viable in high scale (>10^{10} GeV) inflation scenarios?
  If possible, how large can the inflation scale be?

Let us discuss how to suppress the isocurvature fluctuations of axion DM and relax the bound on inflation scale.

The axion appears after PQ breaking. Thus isocurvature constraint can be avoided if PQ is restored during or after inflation.

However, in this case, topological defects such as cosmic strings and domain walls ($N_{DW}\neq1$) are generated, and will overclose the Universe. (for $N_{DW}=1$, we need f_a smaller than about 10^{10} GeV.)

Hitamatsu, Kawasaki, Saikawa, Sekiguchi (2012)

Here we assume,

- PQ symmetry is not restored in the early Universe,
- the axion accounts for the observed dark matter of Universe.

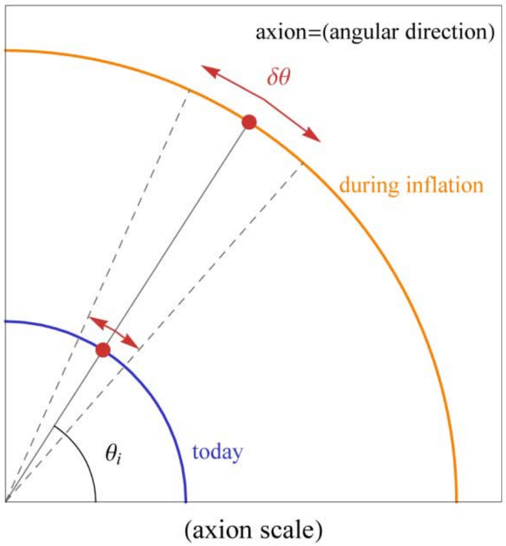
There are several ways to avoid the isocurvature bound on H_{inf}.

1. Larger axion decay constant during inflation.
2. Strong QCD during inflation.

▪ Large axion scale during inflation

Linde (1991)

If the value of f_a during inflation is larger than the present one, axion fluctuations are suppressed:



axion fluctuation: $\delta a \simeq \left(\frac{f_a}{f_a|_{\text{inflation}}} \right) \frac{H_{\text{inf}}}{2\pi}$

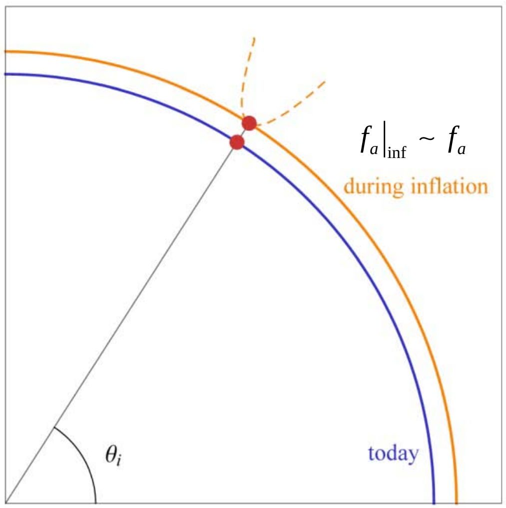
$H_{inf}=10^{13\text{-}14}$ GeV is allowed for f_a close to the Planck scale.

c.f. non-minimal coupling to gravity (canonical normalization)

Folkerts, Germani, Redondo, 1304.7270

- Strong QCD during inflation

The potential for the axion is generated during inflation if the QCD confines at a high energy scale. If it makes the axion heavier than H_{inf}, the axion field is fixed at the minimum.



(axion scale)

$m_a > H_{\text{inf}}$

$\rightarrow$ quantum fluctuations at superhorizon scales are significantly suppressed.

misalignment : $\theta_i = \theta_{\text{inf}} - \theta_0$

The constraint on H_{inf} can be relaxed if QCD becomes strong enough during inflation.

Dvali (1995), Banks and Dine (1996)

A stronger QCD in the early Universe was considered to suppress the initial misalignment, in theories where the gauge coupling is fixed by the VEV of some scalar field (e.g. dilaton, string moduli).

- QCD becomes stronger during inflation if the moduli take a smaller value than the present one.

Choi, Kim, Kim (1996)

However it is non-trivial to achieve $m_a > H_{inf}$ for $f_a > 10^{12}$ GeV due to the small quark mass. In addition one should explain how the moduli are stabilized during inflation.

Here we present an interesting model where the isocurvature constraint on the inflation scale is relaxed by providing a large mass to the axion.

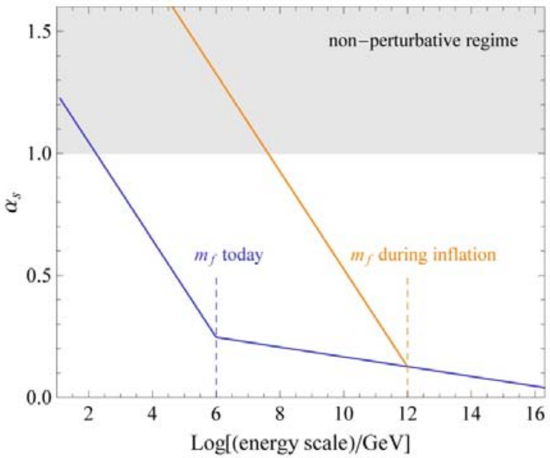
Important issues are

- how to raise the QCD scale to a high value,
- how to stabilize the axion decay constant,

during the inflationary epoch.

- QCD scale

The QCD confines at a higher scale if one makes a quark heavier, since the coupling runs faster at scales below the quark mass:



$$(\text{QCD scale}) \propto \left(\frac{m_f}{M_{\text{GUT}}}\right)^{1/\beta}$$

for colored fermion with $m_f \bar{f}f$,

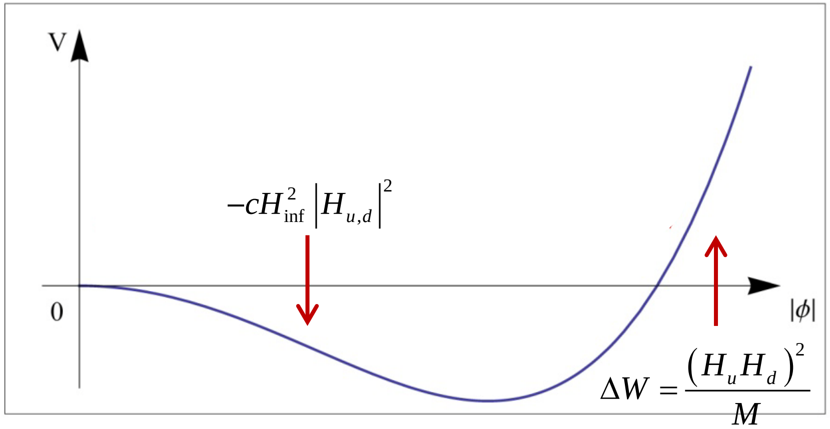
where $\beta > 0$ is the beta function coefficient at scales below m_f.

SM quarks obtain masses from Higgs VEV, and thus the QCD scale will be raised if the Higgs field takes a large value during inflation.

This is naturally realized within the supersymmetric SM because it possesses flat-directions involving the Higgs fields.

Let us take the H_uH_d flat direction.

If the Higgs doublets are not charged under PQ, the H_uH_d flat direction is naturally fixed at a large value during inflation:



H_uH_d flat direction is fixed at

$$\langle H_{u,d}^0 \rangle \approx \sqrt{H_{\inf} M}$$

as a result of the competition between Hubble-induced tachyonic mass and higher-order superpotential term.

- Stronger QCD during inflation

The QCD scale is raised when the Higgs takes a large field value, because the SM quarks obtain larger masses.

Similar effect occurs in the presence of extra PQ-singlet quarks that couple to $H_u H_d$:

$$W = \left(M_\Psi + \frac{H_u H_d}{M'} \right) \Psi \Psi^c, \text{ where } \Psi + \Psi^c \text{ are } 5 + \bar{5} \text{ of SU(5).}$$

The SM and additional quarks obtain large masses from the Higgs VEV during inflation, and the QCD confines at a scale:

$$\Lambda_h \simeq 1.3 \times 10^7 \,\mathrm{GeV} \left(\frac{M_{\mathrm{GUT}}}{M_\Psi} \right)^{N_\Psi / 9},$$

for $M' \sim M_{GUT}$. Here we used $g_{GUT}{}^2 \approx 0.5$ in MSSM, and have taken into account the hierarchy in SM quark masses.

On the other hand, we need PQ quarks in order for the axion to couple to the QCD anomaly:

$W = S\Phi\Phi^c$ where $\Phi + \Phi^c$ are $5 + \overline{5}$ of SU(5), and carry PQ charges.

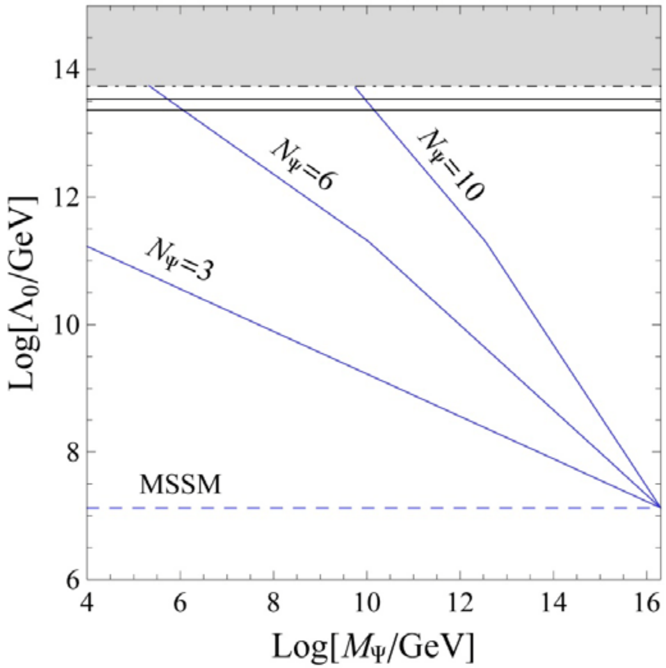
But, PQ quarks play no role in raising QCD scale since their masses are the same ($\sim f_a$) during and after inflation.

Perturbativity constraint

The total number of 5+5bar is constrained by the requirement that the GUT gauge coupling be below the perturbativity bound:

$$\Lambda_h < 2.7\times 10^{14}\,\mathrm{GeV}\left(\frac{f_a}{M_{\mathrm{GUT}}}\right)^{N_\Phi/9}$$

QCD scale for the H_uH_d flat direction stabilized around M_{GUT}



$$\begin{cases} \text{upper black line: } f_a = 10^{14}\,\text{GeV},\ N_\Phi = 1 \\ \text{lower black line: } f_a = 10^{12}\,\text{GeV},\ N_\Phi = 1 \end{cases}$$

$M_\Psi =$ (mass of PQ singlet quarks at present)

- ## Axion potential during inflation

An axion potential is generated through non-perturbative effect (gluino condensation at Λ_0) and supersymmetry breaking (dominant contribution from the Higgs F-term):

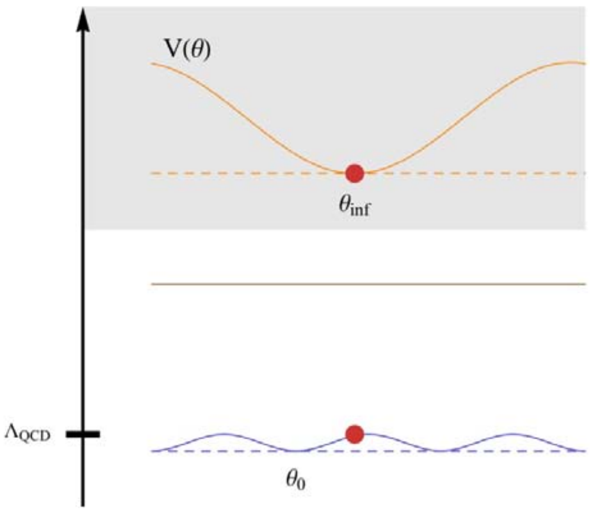
$$\text{massive axion: } m_a^2 = \frac{\hat{c} H_{\inf} \Lambda_0^3}{f_a^2}$$

$\hat{c}$ measures how strongly the Higgs fields couple to the inflaton, and is generally order unity.

for $f_a > \Lambda_0 > H_{inf}$, to avoid a significant modification of the saxion potential by the NP effect, and to make gluinos not decouple at a scale above Λ_0 (gauge mediation from Higgs loops).

- Inflation scale

To be fixed at the minimum during inflation, the axion should obtain a mass larger than the inflation scale:



$$m_a > H_{\rm inf}$$

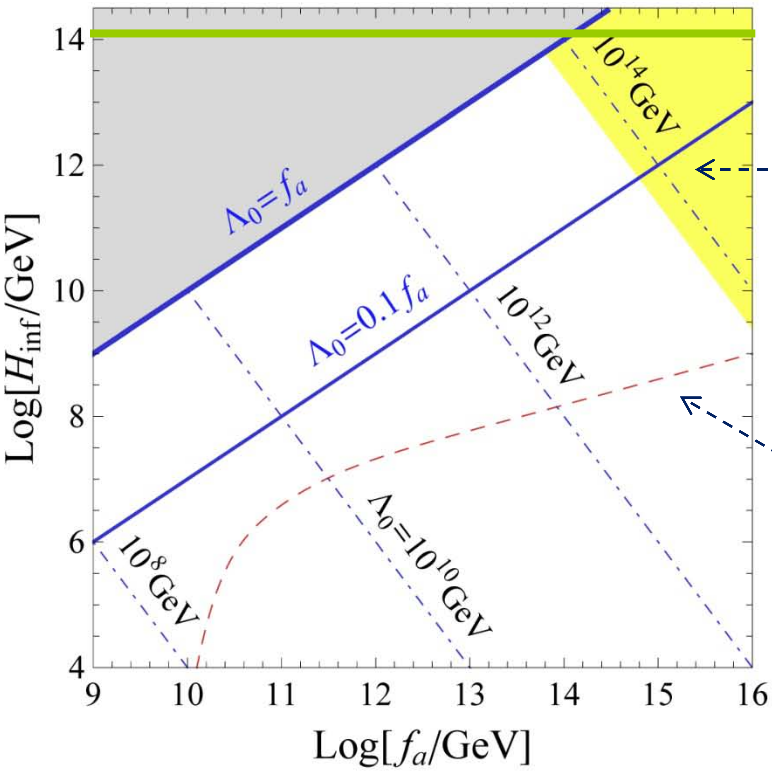
$$\Rightarrow H_{\rm inf} < 10^{12}\,{\rm GeV} \times \hat{c} \times \left(\frac{\Lambda_0}{f_a}\right)^3 \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)$$

The isocurvature constraint is significantly relaxed compared to the conventional scenario for a QCD scale close to f_a.

The minimum of potential during inflation is different from the QCD vacuum at present because it receives various contributions, e.g. phases of Higgs fields, and extra quark mass.

Thus axions are produced by the misalignment mechanism.

Suppression of the axion DM isocurvature perturbation



$$m_a^2 = \frac{\hat{c} H_{\rm inf} \Lambda_0^3}{f_a^2}$$

for the case with $\hat{c} = 1$

The isocurvature constraint on the inflation scale from axion DM can be significantly relaxed compared to the conventional scenario.

High scale inflation scenarios, for instance, with an inflation scale around $10^{13\text{-}14}$ GeV can be consistent with the axion DM for a QCD scale close to f_a and $\hat{c}$ around 1-10.

(Planck bound on tensor-to-scalar ratio requires $H_{inf}<10^{14}$ GeV.)

- Saxion stabilization

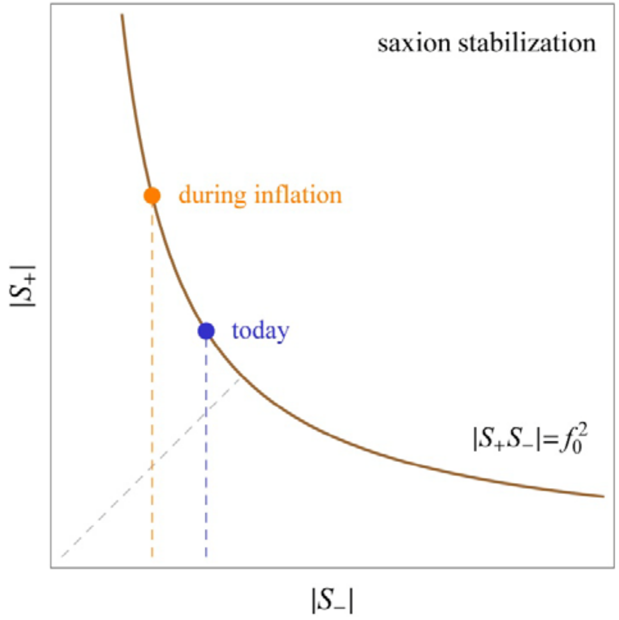
The axion scale is determined by the saxion VEV, and so far we have assumed that the axion scale does not change much.

One simple example is when the saxion is given by an F-flat direction of two PQ scalars:

$$\Delta W = \Sigma(S_+S_- - f_0^2)$$

and non-tachyonic Hubble-induced masses for $S_\pm$

For $H_{\text{inf}} < f_0$, we have $f_a \approx f_0$ as long as S_+ and S_- feel supersymmetry breaking with similar strength.



Possible to have $f_a|_{\text{inflation}} \approx f_a|_{\text{today}}$.

In general, the saxion potential is modified during inflation even for $H_{inf} < f_a$. However this does not spoil the suppression mechanism as long as the minimum lies at a large enough saxion value.

One may consider a case where f_a is around 10^{12} GeV at present, but it has a value around $10^{13\text{-}15}$ GeV during inflation. Then,

- the observed DM is explained for $|\theta_i| \sim 1$,
- high scale inflation with H_{inf} around $10^{13\text{-}14}$ GeV can be allowed.

Let me summarize.

- The QCD axion not only provides a natural solution to the strong CP problem, but also is a good DM candidate.

  However the inflation scale is constrained by isocurvature fluctuations of the axion DM.

- Isocurvature bound on the inflation scale can be significantly relaxed if the QCD confines at a high energy scale during inflation so that the axion becomes massive.

- The suppression mechanism works well if the Higgs scalar has a large field value during inflation, and the supersymmetric SM is a natural framework for this.

  High scale inflation scenarios can be compatible with axion DM.