Axion dark matter in high scale inflation

T. Higaki, KSJ, F. Takahashi 2014, K. Choi, KSJ, M. S. Seo 2014
K. Choi, E. J. Chun, KSJ, S. H. Im, in preparation

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Outline

1. Axion dark matter
2. Cosmological constraints
3. Axion in high scale inflation
4. Summary

1. Axion dark matter

1. Axion (1/4)

QCD axion

Peccei and Quinn 1977

NG boson associated with spontaneously broken U(1)$_{PQ}$ symmetry which is anomalous under QCD

- The axion couples to gluons through $\frac{1}{8\pi^2}\frac{a}{f_a}G\tilde{G}$

  f$_a$: axion decay constant ~ PQ symmetry breaking scale

- QCD instantons explicitly break PQ, generating axion potential:

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

The axion obtains mass, and is stabilized at the origin.

1. Axion (2/4)

QCD axion

- CP violation in the electroweak and strong interactions

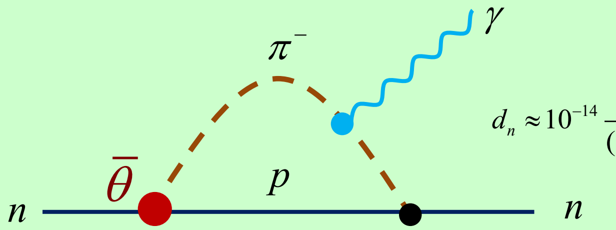
$$\frac{\theta_{\rm QCD}}{8\pi^2} G\tilde{(}$$

CP violation

$$\delta_{\rm CKM} \sim \qquad \sim$$

$$\bar{\theta} = \theta_{\rm QCD} + \arg\det(y_q)$$

Experimental bound on the neutron EDM



$$d_n \approx 10^{-14} \frac{m_u m_d}{(m_u + m_d) m_s} \bar{\theta}\ e \cdot cm$$

$$|\bar{\theta}| < 10^{-11} \rightarrow \text{Strong CP problem}$$

- The axion makes the strong interaction CP conserving.

$$\bar{\theta} = \frac{\langle a \rangle}{f_a}$$ → Natural solution to the strong CP problem

1. Axion (3/4)

Axion properties

determined by f_a ~ (PQ breaking scale)

- axion mass: $m_a \sim \frac{\Lambda^2}{f_a} \sim \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\mathrm{eV}$

- axion couplings to SM

axion-nucleon interaction

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

axion-photon interaction

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

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.

Axion detection
- See the talk by Yannis Semertzidis

1. Axion (4/4)

Axion dark matter

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

axions produced by misaligned axion field:

$$\Omega_a \sim \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

θ_{ini}: initial misalignment angle of the axion

See also the talk by Fuminobu Takahashi

- Axion contribution to hot dark matter (dark radiation)
  - Axions can be produced from the decay of heavy particles, e.g. radial component of PQ field, string moduli.

2. Cosmological constraints on axion dark matter

2. Constraints (1/4)

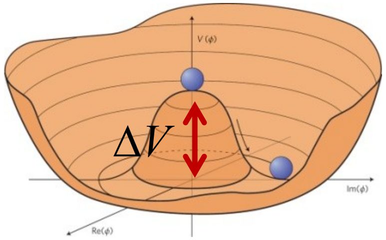
Possible scenarios

1. PQ symmetry breaking occurs after inflation

- Need $N_{DW}=1$ (number of degenerate vacua) to avoid overclosure of the Universe
  → severe constraint on 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 ($N_{DW}=1$) as well as from coherent oscillations:

$$\Omega_a \le \Omega_{\mathrm{DM}} \Rightarrow 4\times10^{8}\,\mathrm{GeV} \le f_a \le (2-4)\times10^{10}\,\mathrm{GeV}$$

Numerical simulation
- Hiramatsu, Kawasaki, Saikawa, Sekiguchi, 2012



2. Constraints (2/4)

2. No PQ restoration during inflation and thereafter

- There is no domain-wall problem.
- Axion acquires quantum fluctuations during inflation.

Axenides et al 1983, Turner et al 1985, ...

They turn into isocurvature density perturbations at QCD phase transition: constraints from the observed CMB spectrum

- Axion relic abundance

$$\Omega_a \sim \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \leq \Omega_{\mathrm{DM}}, \quad \theta_{ini} = \theta_0 + \delta\theta = \theta_0 + \frac{H_I}{2\pi f_a(t_I)}$$

θ_0: uniform throughout the whole observable Universe

- Large f_a requires small θ_{ini}:

Anthropic argument is applicable if $\Omega_a \sim \Omega_{\mathrm{DM}}$.

Constraints on the axion in high scale inflation

$$r \simeq \left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2$$

- High scale inflation with $H_I \sim 10^{13\text{-}14}$ GeV

  tensor-to-scalar ratio of the CMB fluctuations: $r \sim 10^{-3\sim-1}$

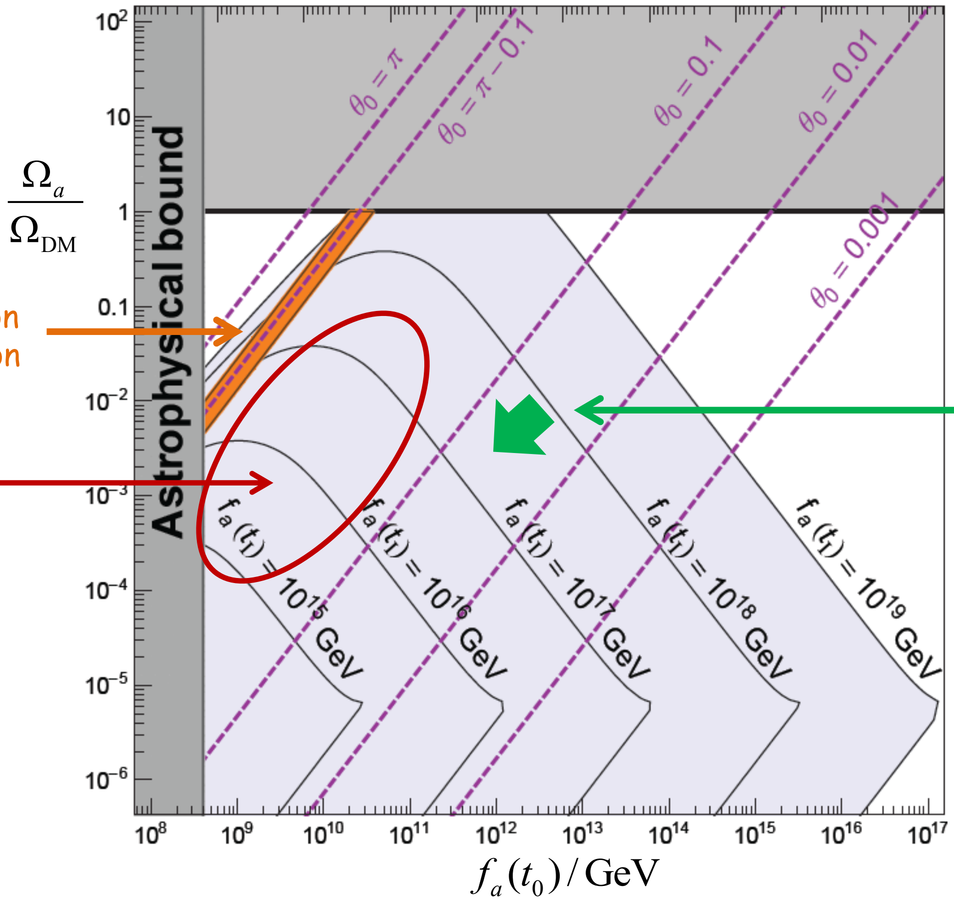
  (within the reach of future experiments) Planck bound: $r<0.10$

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

- $f_a(t_I)$ is generally different from $f_a(t_0)$ because PQ scalars get additional contributions from the inflation sector.

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

Constraints for $H_I=10^{14}$ GeV in the standard axion cosmology



PQ restoration
during inflation
or reheating

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

Axion provides a
fraction of DM.

Isocurvature constraints

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

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

3. Axion dark matter in high scale inflation

3. Axion in high scale inflation (1/9)

Can the axion explain the total dark matter abundance in high scale inflation scenarios?

- PQ restoration in the early Universe
  $\Omega_a \sim \Omega_{DM}$ requires $N_{DW}=1$ and $f_a \sim (2\text{-}4)\cdot 10^{10}$ GeV
- Let us consider the case where PQ symmetry is broken during inflation: no domain-wall problem, but isocurvature constraint

  - $\Omega_a \sim \Omega_{DM}$ for large $f_a(t_I)$ (e.g. $\sim M_{Pl}$ for $H_I=10^{14}$ GeV), and $f_a(t_0)$ in a limited range.
  - Temporarily-enhanced explicit PQ breaking during inflation can suppress isocurvature perturbation

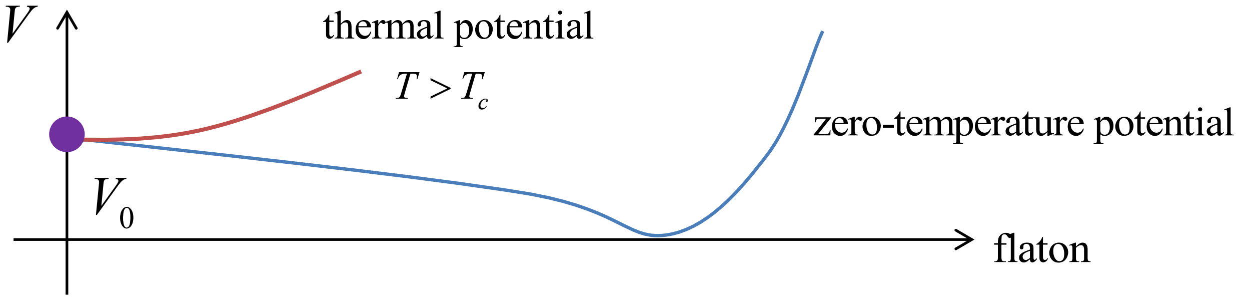
e.g. Dine, Anisimov 2004; Higaki, KSJ, Takahashi 2014
KSJ, Takahashi 2013; Barr, Kim 2014
c.f. Folkerts, Germani, Redondo 2013

Washing away axion quantum fluctuations by thermal inflation

- **Thermal inflation**

Lyth, Stewart 1995

A flaton couples to thermal bath, and is trapped at the origin:



→ vacuum domination for $V_0 \sim$ $_{\text{on}} > T^4$

- The Hubble parameter during TI is small:

$$H_{\text{TI}} = \frac{1}{M_{Pl}}\left(\frac{V_0}{3}\right)^{1/2} \sim \qquad \text{GeV}\left(\frac{m_{\text{flaton}}}{10^3\,\text{GeV}}\right)\left(\frac{v_{\text{flaton}}}{10^{10}\,\text{GeV}}\right)$$

3. Axion in high scale inflation (3/9)

- TI dilutes away unwanted relics (moduli, gravitinos, …)

  number of e-foldings: $N_{\mathrm{TI}} \sim$ [illegible] $_{l} / m_{\mathrm{flaton}})$

- If the axion mass is larger than H_{TI}, the axion settles down at the minimum of the potential.

  $$m_a(t_{\mathrm{TI}}) > H_{\mathrm{TI}}$$

  → effectively eliminates the primordial axion fluctuations

- After thermal inflation ends, axions are produced by the misalignment mechanism with initial position depending on the involved CP phases of the model.

  → axion dark matter is free from the isocurvature constraint!

Stronger QCD during thermal inflation

- If the Higgs VEV increases, the quarks become heavier, making the strong coupling run faster at low energy scales.

→ QCD scale increases with the Higgs VEV.

→ If the Higgs field has a large VEV, axion can get a large mass.

- We consider the supersymmetric SM, which possesses flat directions involving the Higgs fields H_u and H_d.

QCD scale and axion mass during TI depend on

$$v_{\rm TI} = \langle | H_u^0 | \rangle_{\rm TI}, \quad \tan\beta_{\rm TI} = \frac{\langle | H_u^0 | \rangle_{\rm TI}}{\langle | H_d^0 | \rangle_{\rm TI}}, \quad m_{\tilde{g}} \quad \text{(gluino mass during TI)}$$

Stronger QCD during thermal inflation

- **Case 1:** $\Lambda_{\mathrm{QCD}}(t_{\mathrm{TI}}) < m_{\tilde{q}} \quad 10^{-5} v_{\mathrm{TI}}$

  The quarks/squarks have large SUSY masses.

$$\Lambda_{\mathrm{QCD}}(t_{\mathrm{TI}}) \simeq \qquad \mathrm{GeV}\left(\frac{m_{\tilde{q}}}{3\mathrm{TeV}}\right)^{2/11}\left(\frac{v_{TI}}{5\times10^{11}\mathrm{GeV}}\right)^{6/11}\left(\frac{\tan\beta/\tan\beta_{\mathrm{TI}}}{10}\right)^{3/11}$$

$$m_a \approx \frac{\Lambda^2_{\mathrm{QCD}}(t_{\mathrm{TI}})}{f_a(t_{\mathrm{TI}})}$$

- **Case 2:** $m_{\tilde{q}} \quad \Lambda_{\mathrm{QCD}}(t_{\mathrm{TI}}) < 10^{-5} v_{\mathrm{TI}}$

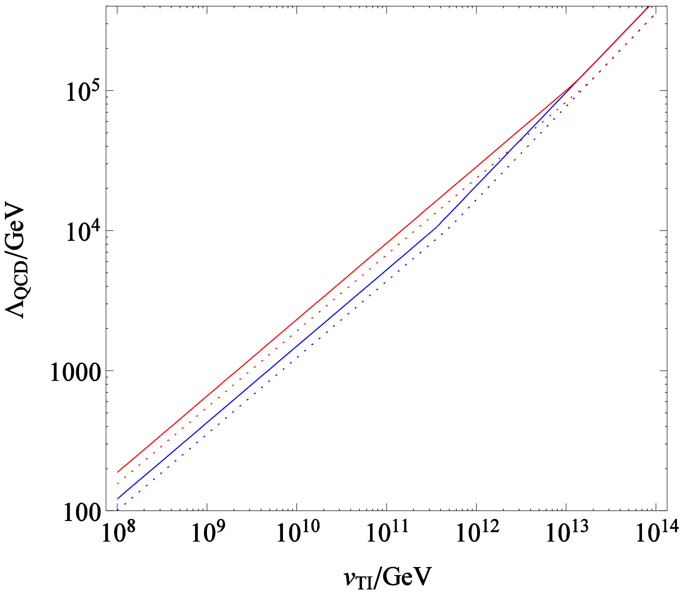
  The quarks/squarks have large SUSY masses.

$$\Lambda_{\mathrm{QCD}}(t_{\mathrm{TI}}) \simeq \qquad \mathrm{GeV}\left(\frac{v_{TI}}{5\times10^{11}\mathrm{GeV}}\right)^{2/3}\left(\frac{\tan\beta/\tan\beta_{\mathrm{TI}}}{10}\right)^{1/3}$$

$$m_a \approx \left(\frac{m_{\tilde{q}}}{\Lambda_{\mathrm{QCD}}(t_{\mathrm{TI}})}\right)^{1/2}\frac{\Lambda^2_{\mathrm{QCD}}(t_{\mathrm{TI}})}{f_a(t_{\mathrm{TI}})}$$

Stronger QCD during thermal inflation

- QCD scale during TI in the MSSM



c.f. Stronger QCD during primordial inflation to suppress axion isocurvature perturbations

- KSJ, Takahashi 2013

Gluino mass (at present) = 1 TeV (blue), 10 TeV (red)

$\tan\beta / \tan\beta_{TI}$ =10 for solid lines, and =5 for dashed lines

Thermal inflation and heavy axion

- Model: How to obtain large Higgs VEVs during TI?

  - Higgsino μ-term from the flaton VEV (Kim-Nilles mechanism)

$$W = \frac{\phi^2}{\Lambda} H_u H_d \quad (\Lambda:\ \text{effective cutoff scale})$$

  - Flat direction involving the Higgs fields (H_uH_d, H_uL)
    - · Tachyonic when the μ-term is turned off, i.e. during TI.
    - · Stabilization by the competition between supersymmetric high dim operator and SUSY breaking effects

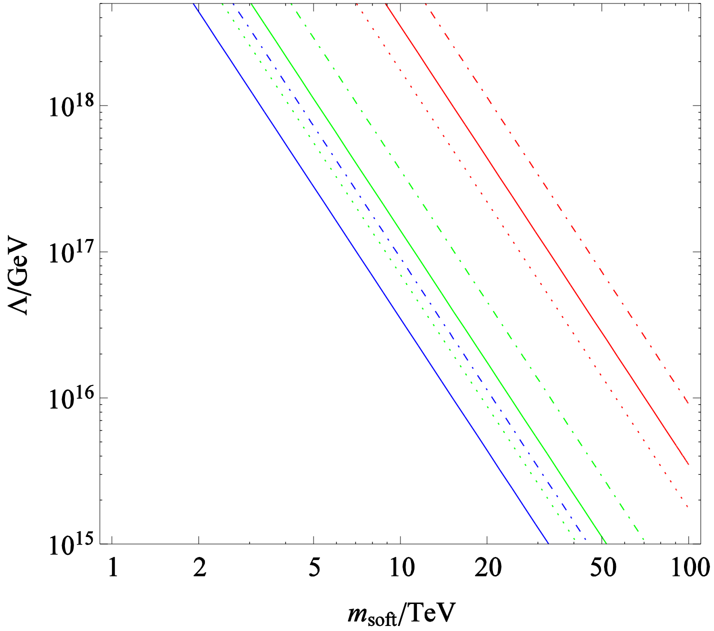
  - Axion decay constant fixed by the competition between supersymmetric high dim operator and SUSY breaking effects

Thermal inflation and heavy axion

Higgs VEV and axion decay constant during TI:

$$v_{TI} \sim \qquad\qquad \sim \qquad \sim$$

Ratio between the axion mass and the Hubble parameter during TI



$$m_a(t_{TI})\big/H_{TI} = 1(\text{red}),\ 5(\text{green}),\ 10(\text{blue})$$

Solid: $\dfrac{\tan\beta}{\tan\beta_{TI}} = 10,\ m_{\tilde{}}\qquad \mathrm{TeV}$

Dotted: $\dfrac{\tan\beta}{\tan\beta_{TI}} = 5,\ m_{\tilde{}}\qquad \mathrm{TeV}$

Dotdashed: $\dfrac{\tan\beta}{\tan\beta_{TI}} = 10,\ m_{\tilde{}}\qquad \mathrm{TeV}$

3. Axion in high scale inflation (9/9)

Possible models

- PQ singlet flaton

$$W=\frac{\phi^2}{\Lambda}H_uH_d+\lambda\phi\Psi\Psi^c+\frac{\phi^4}{\Lambda}+\left[S\Phi\Phi^c+\frac{SS'^3}{\Lambda}\right]+\left[\frac{1}{\Lambda}(H_uH_d)^2,\ \text{or}\ \frac{1}{\Lambda}(H_uL)^2,\ \text{or}\ \frac{1}{\Lambda}(H_uH_d)(H_uL)\right]+\ldots$$

  - Effective μ-term by the Kim-Nilles mechanism
  - Flaton thermal mass due to λ
  - Dim 4 op's to stabilize flaton, PQ scalars, flat directions

- Thermal inflation by the PQ sector

$$W=\frac{S^2}{\Lambda}H_uH_d+\lambda S\Psi\Psi^c+\frac{SS'^3}{\Lambda}+\frac{1}{\Lambda}(H_uH_d)(H_uL)+\ldots$$

- Axion misalignment after TI

~ (phase of B-term of H_uH_d) – (phase of A-term of dim 4 op.)

5. Summary

4. Summary

- The axion naturally solves the strong CP problem, and contributes to dark matter of the Universe.

→ Well-motivated dark matter candidate!

- In the conventional scenario with $m_a \ll H$ above Λ_{QCD} and no PQ restoration in the early Universe, axion dark matter is in conflict with high scale inflation.
- Thermal inflation can dilute away primordial axion fluctuations as well as unwanted relics such as moduli and gravitinos.

  This is achieved by stronger QCD during thermal inflation.

Thank you!