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

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Outline

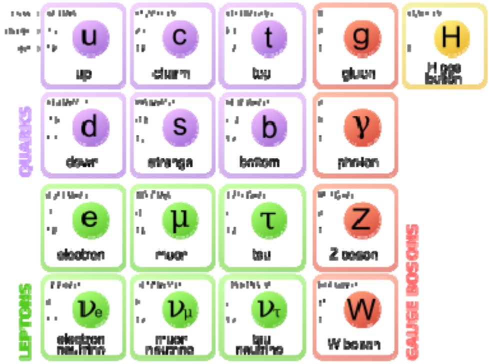
- Strong CP problem in the SM
- Axion dark matter
- mu-transition and stronger QCD in the early Universe
- Diluting inflationary axion fluctuations
- Summary

1. SM

The Standard Model of particle physics

Based on quantum field theory (special relativity + quantum mech.)

- Gauge sector: $SU(3)_c$ $SU(2)_L$ $U(1)_Y$ → gauge bosons
- Matter sector
  - quarks and leptons
  - 3 family: only mass difference
- Scalar sector: Higgs field
  - determines the vacuum structure of the SM



$$L = (\text{kinetic terms}) + (\text{gauge int's}) + (\text{Yukawa int's})$$

Some features of the SM

- Accidental global symmetries at the renormalizable level
  - $U(1)_B$ and $U(1)_L$
  - Explains why protons are stable, and why neutrinos are light.
- Flavor violation only through charged-current weak int's
  - Explains why FCNC effects are suppressed as experimentally measured

1. SM (3/3)

SM: very successful at energy scales below TeV, BUT

- Naturalness problems
  - Origin of EWSB: why <H>≠0, and why <H>~100 GeV << M_{Pl}?
  - Origin of flavor structure
  - Strong CP problem
- Dark matter, Dark energy
- Baryon asymmetry in the Universe
- Neutrino masses
- Why 3 gauge interactions? Grand unification?
- Cosmic inflation
- Quantum gravity, …

→ Requires new physics beyond the SM!

2. Axion solution to the strong CP problem

CP violation in the SM

C: charge conjugation (q → -q)
P: parity conversion (x → -x)

- CP violation if the Lagrangian involves a complex coupling which cannot be rotated away by any field redefinition.

e.g. Yukawa couplings in the SM

CP violation in the SM

- CP violation in the EW sector

  - CKM matrix: quark mixing matrix in association with weak int's

    Unitary tr to obtain mass eigenstates from $m_{u,d}=y_{u,d}\langle H\rangle$
    One CP violating phase: $\delta_{CKM}= 1.20\pm0.3$

  - PMNS matrix: lepton mixing matrix (massive neutrinos)

    One CP phase: δcp → the value is not well-known yet

- CP violation in strong interactions

  - One CP violating phase related with topological structure of QCD, anomaly, and instantons.

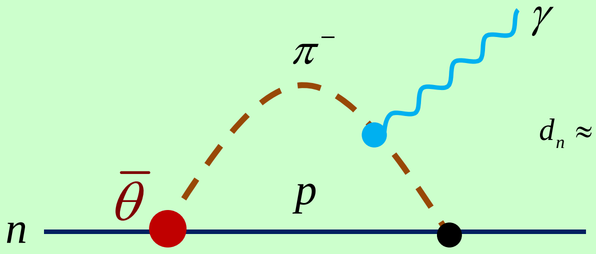
- CP violation in the electroweak and strong interactions

$$L_{\text{SM}} = y_q H\bar{q}q + \frac{\theta_{\text{QCD}}}{8\pi^2} G\tilde{G} + \cdots$$

CP violations

$$\begin{cases} \delta_{\text{CKM}} \sim \arg(y_q) \sim 1 \\ \bar{\theta} = \theta_{\text{QCD}} + \arg\det(y_q) \end{cases}$$

Experimental bound on the neutron EDM



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

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

- Strong CP problem: Why does QCD (almost) preserve CP?

Need some physical explanation!

Axion solution to the strong CP problem

Peccei and Quinn 1977

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

- the axion couples to gluons through

$$\frac{1}{8\pi^2}\frac{a}{f_a}G\tilde{G}$$

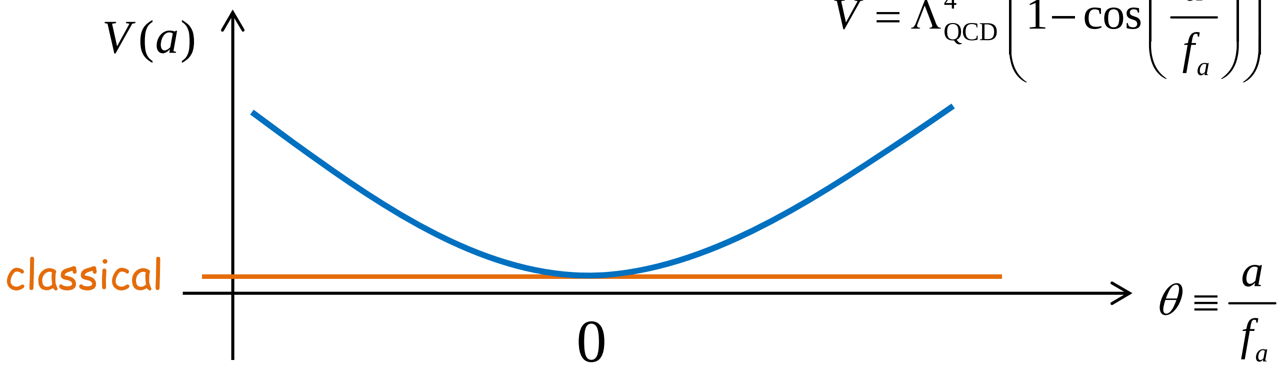
f_a: axion decay constant ~ (PQ symmetry breaking scale)

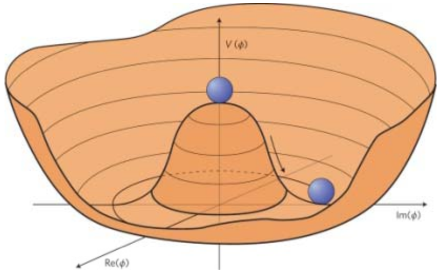
- QCD instantons explicitly break PQ, generating axion potential after QCD phase transition at Λ_{QCD} ~ 400 MeV.

Axion solution to the strong CP problem

- Axion potential

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





QCD instantons explicitly break PQ, generating axion potential.

- θ is dynamically cancelled,
  and thus QCD becomes CP conserving: $\bar{\theta} = \frac{\langle a \rangle}{f_a} = 0$

3. Axion dark matter

3. Axion DM (1/3)

Axion properties

determined by f_a ~ (PQ breaking scale)

- axion mass: $m_a \sim \frac{\Lambda_{\mathrm{QCD}}^2}{f_a} \sim 5\times10^{-6}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\mathrm{eV}$

- axion couplings to SM

axion-nucleon interaction

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

axion-photon interaction

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

➡

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

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

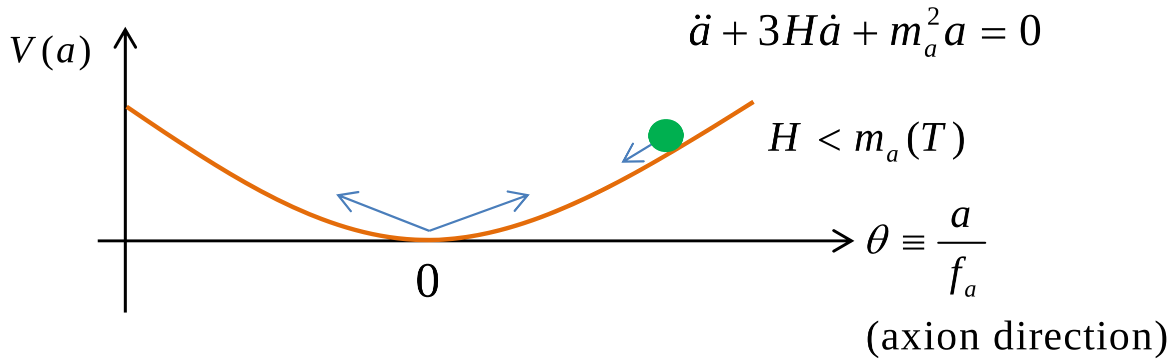
→ The axion is stable on a cosmological time scale, and so can explain the dark matter of the Universe.

3. Axion DM (2/3)

Axion dark matter

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

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



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

$$H < m_a(T)$$

$$\frac{\Omega_a}{\Omega_{\mathrm{DM}}} \sim 1.7 \times \theta_{\mathrm{mis}}^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.19}$$

θ_{mis}: initial misalignment angle of the axion

PQ extension of the SM

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

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

4. Cosmological constraints on axion dark matter

4. Constraints (1/2)

Possible scenarios depending on when PQ phase transition occurs

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

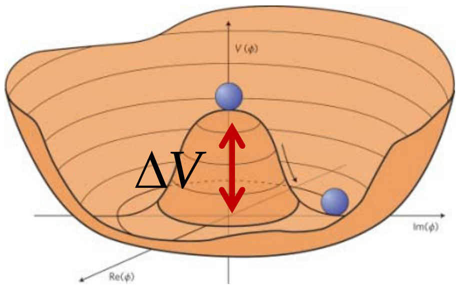
- Many patches with different axion initial value: $\langle\theta^2_{ini}\rangle=\pi^2/3$

- Axions are produced mainly by collapsing string-wall system ($N_{DW}=1$) + from coherent oscillations.

domain-wall (disc-like object surrounded by string): unstable

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

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



4. Constraints (2/3)

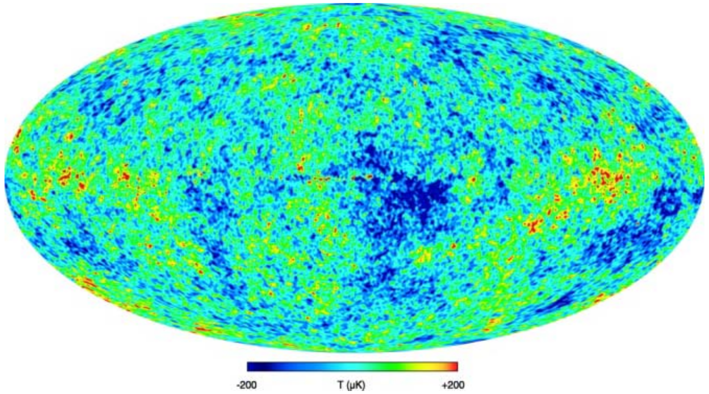
2. No PQ restoration during inflation and thereafter

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

Axenides et al 1983, Turner et al 1985, …

- They do not affect the total energy density during the primordial inflation.
- They turn into isocurvature density perturbations at the QCD phase transition.

- CMB observation



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

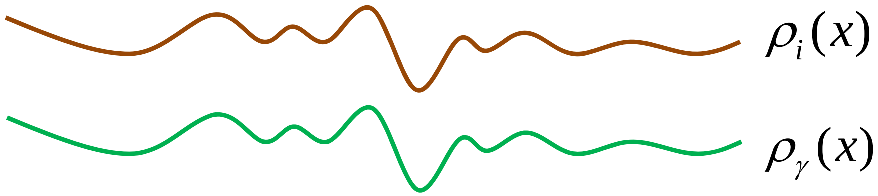
4. Constraints (3/3)

2. No PQ restoration during inflation and thereafter

- Single-field inflation generates adiabatic perturbations:

no perturbations in relative number densities of different species

Or high enough reheating temperature



→ consistent with the observations

- Isocurvature constraint on the axion DM

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

- **Axion density:** θ_{mis}($\gg\delta\theta$) uniform throughout the whole observable Universe

$$\frac{\Omega_a}{\Omega_{\text{DM}}} \sim 1.7\times\theta_{\text{mis}}^2\left(\frac{f_a(t_0)}{10^{12}\,\text{GeV}}\right)^{1.19} \leq 1 \;\rightarrow\; \text{large } f_a \text{ requires small } \theta_{\text{mis}}$$

5. Axion dark matter in the scenario with no PQ restoration

Questions

- What is the mechanism stabilizing the axion decay constant?

$$\frac{\Omega_a}{\Omega_{\mathrm{DM}}} \sim 1.7 \times \theta_{\mathrm{mis}}^2 \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}} \right)^{1.19}$$

- Can we suppress axion isocurvature perturbations?

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

- Axion fluctuation:

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

Planck results:
(tensor-to-scalar ratio) < 0.1
⇒ $H(t_I) < 10^{14}$ GeV

Questions

- Can we suppress axion isocurvature perturbations?
  - Evolution of the axion fluctuation from t_I to t_{QCD}:

$$\delta\theta \equiv \delta\theta(t_{\mathrm{QCD}}) = \gamma\delta\theta(t_I) = \gamma \frac{H(t_I)}{2\pi f_a(t_I)}$$

where $\gamma \lesssim 1$.

  - $f_a(t_I) \gg f_a(t_0)$ for $\theta_{mis} = O(1)$ and $\delta\theta \ll 1$

Validity of an effective theory: $f_a < M_{Pl}$

Weak gravity conjecture: gravitational interaction is the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa, 2007

$$\frac{1}{8\pi^2 f_a} aG\tilde{G} > O\left(\frac{1}{M_{Pl}}\right) aG\tilde{G}$$

→ $\gamma < 1$ can be important.

Scenario realizing $f_a(t_I) \gg f_a(t_0)$

- Supersymmetric axion models generating axion scales through competition between supersymmetric higher dim superpotential term and SUSY breaking effects

$$f_a(t_0) \sim \sqrt{m_{\text{SUSY}} M_{Pl}}$$

$$f_a(t_I) \sim \sqrt{H(t_I) M_{Pl}}$$

→ intermediate axion scale at present, while a Hubble-induced large axion scale during inflation.

- This type of axion models can be successfully embedded into string theory, where we can explain why global PQ symmetry is well protected from quantum gravity effects.

K. Choi, KSJ, M. S. Seo, 2014

Scenarios realizing $f_a(t_I) \gg f_a(t_0)$

- Isocurvature constraint

$$H(t_I) < 10^{14}\,\mathrm{GeV} \times \left(\frac{\gamma}{0.08}\right)^{-2} \left(\frac{\Omega_a}{\Omega_{\mathrm{DM}}}\right)^{-1} \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{0.8} \left(\frac{m_{\mathrm{SUSY}}}{1\mathrm{TeV}}\right)^{-1}$$

- An observable tensor-to-scalar ratio (0.1-0.01) in CMB can be compatible with the axion dark matter $\Omega_a = \Omega_{\mathrm{DM}}$, if the axion fluctuation experiences a mild suppression.

6. Diluting inflationary axion fluctuation by stronger QCD

6. Dilution mechanism (1/6)

We propose a simple way suppressing δθ through its cosmological evolution.

- Axions scales fixed by competition between supersymmetric higher dim superpotential and SUSY breaking effects

- mu-transition: Higgs mu-term generation through

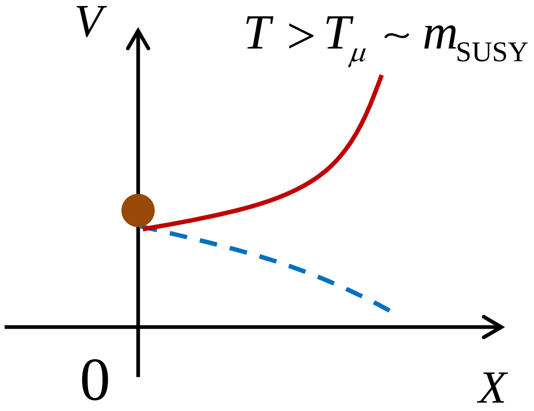
J.E. Kim and H. P. Nilles, 1984

$$W = \frac{X^2}{M_{Pl}} H_u H_d$$

Thermal effects make PQ-charged X evolve as

$$X(t \le t_\mu) = 0, \quad X(t > t_\mu) \sim \sqrt{m_{\text{SUSY}} M_{Pl}}$$

$$\Rightarrow \quad \mu(t \le t_\mu) = 0, \quad \mu(t > t_\mu) \sim m_{\text{SUSY}}$$



- With the mu-transition, the weak scale can experience unusual evolution because the H_uH_d flat direction (φ) has mass

$$m_\phi^2 = c_\phi H^2 + \xi_\phi m_{\mathrm{SUSY}}^2 + 2|\mu|^2$$

- Before the mu-transition (μ=0), negative c_φ and ξ_φ lead to

$$f_a(t_I) \sim \phi(t_I) \sim \sqrt{H(t_I) M_{Pl}}$$

$$f_a(t_I < t < t_\mu) \sim \phi(t_I < t < t_\mu) \sim \sqrt{m_{\mathrm{SUSY}} M_{Pl}}$$

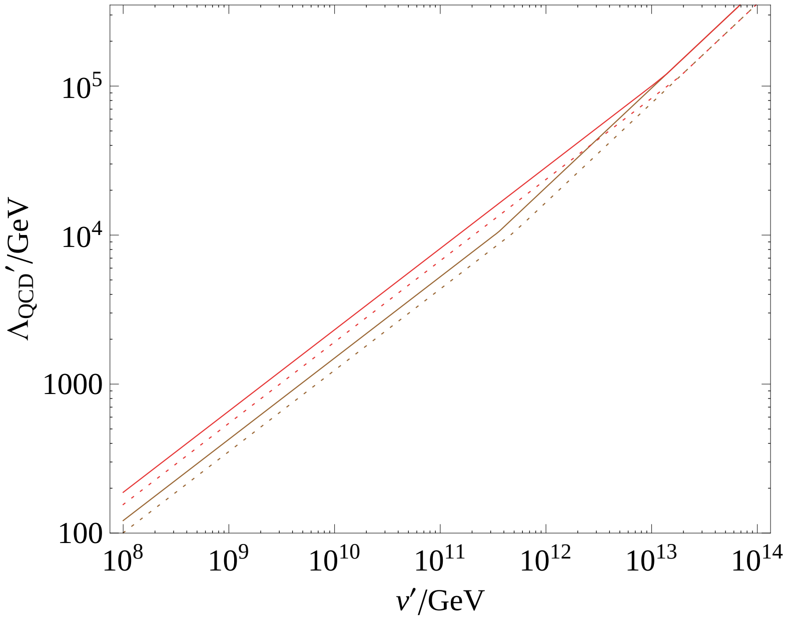
- After the mu-transition, $\mu = m_{\mathrm{SUSY}}$ and $m^2_\varphi > 0$

$$H_{u,d}(t_0) = O(100\mathrm{GeV})$$

$$f_a(t_0) \sim X(t_0) \sim \sqrt{m_{\mathrm{SUSY}} M_{Pl}}$$

Stronger QCD

- Large weak-scale before the mu-transition results in stronger QCD because the quarks become heavier:



(gluino mass before mu-transition), (tanβ at present)

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

→ The axion obtains a large mass for large Λ_{QCD}!

Suppression of $\delta\theta$

- The axion experiences a damped oscillation for $m_a(t) > H(t)$.

  Note: The axion mass is highly suppressed by thermal effects for $T \gg \Lambda_{QCD}$

- The axion fluctuation is diluted as

$$\delta\theta = \gamma \frac{H(t_I)}{2\pi f_a(t_I)} \approx \left(\frac{m_{\mathrm{SUSY}}}{\tilde{\Lambda}_{\mathrm{QCD}}} \right)^{3/2} \frac{H(t_I)}{2\pi f_a(t_I)}$$

if the axion mass is larger than H before the mu-transition:

$$\tilde{m}_a \approx 0.4\mathrm{MeV} \left(\frac{\tilde{f}_a}{10^{12}\,\mathrm{GeV}} \right)^{-1} \left(\frac{\tilde{\Lambda}_{\mathrm{QCD}}}{20\mathrm{TeV}} \right)^{2}, \quad H(t_\mu) \approx 0.2\mathrm{MeV} \left(\frac{\sqrt{V_0}}{1\mathrm{TeV} \times 10^{12}\,\mathrm{GeV}} \right)$$

Vacuum energy density $V_0 \sim m_{SUSY}^2 f_a(t_0)^2$ drives thermal inflation.

Lyth and Stewart, 1995

6. Dilution mechanism (5/6)

Upper bound on the inflationary Hubble scale consistent with the axion dark matter $\Omega_a = \Omega_{DM}$:

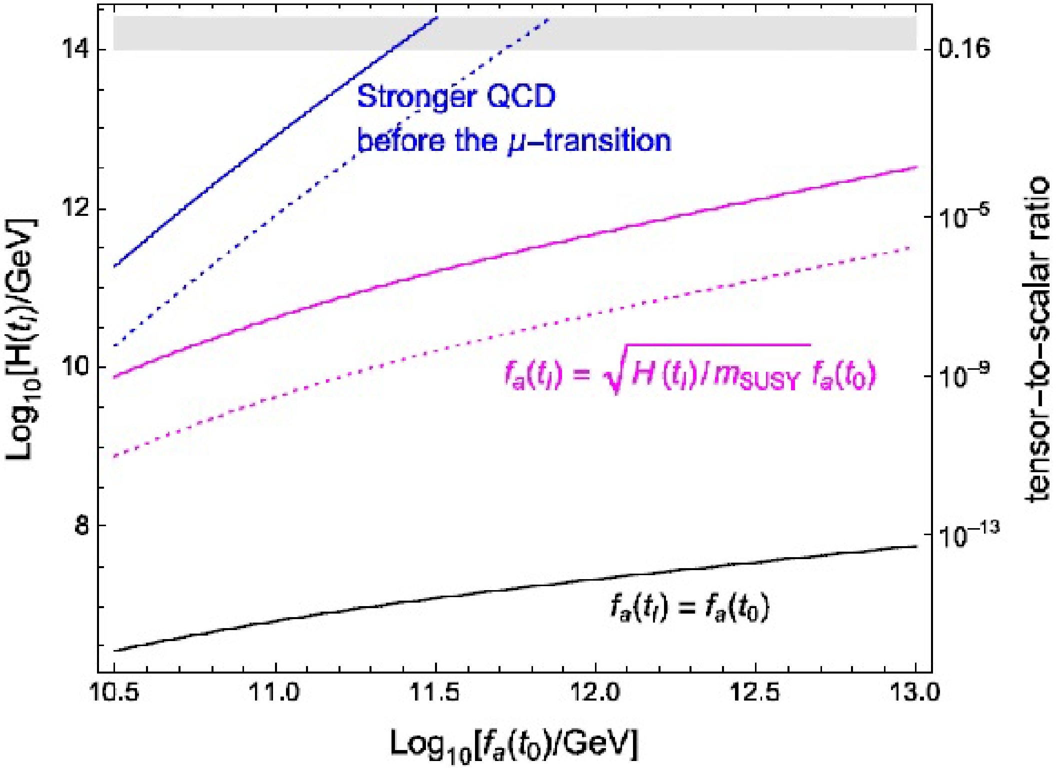


FIG. 1: Upper bound on the inflationary Hubble scale consistent with the axion dark matter, $\Omega_a = \Omega_{\mathrm{DM}}$. Here we have taken $m_{\tilde{g}} = 3$ TeV, $\tan\beta = 10$, and $T(t_\mu) = 1$ TeV. The shaded region is excluded by the Planck results. The black solid line is the constraint in the conventional scenario with $f_a(t_I) = f_a(t_0)$. The magenta lines are for the scenario with $f_a(t_I)/f_a(t_0) = \sqrt{H(t_I)/m_{\mathrm{SUSY}}}$, but without a stronger QCD. The blue lines are for our scheme which leads to a further suppression of $\delta\theta$ by the stronger QCD. The SUSY breaking mass has been taken $m_{\mathrm{SUSY}} = 1$ TeV for the solid lines and 10 TeV for the dotted lines.

6. Dilution mechanism (6/6)

Axion relic abundance

- The minimum of the axion potential induced by the stronger QCD is generally different from the minimum of the axion potential at present.

$$\theta_{\rm mis} = \left\langle \frac{a(t_\mu)}{f_a(t_\mu)} \right\rangle - \left\langle \frac{a(t_0)}{f_a(t_0)} \right\rangle = O(1)$$

Combined with an intermediate axion scale at present, it leads to $\Omega_a = \Omega_{DM}$ in a natural way.

7. Models implementing the suppression mechanism

Simple example

- Superpotential

$$W = (\text{MSSM Yukawa}) + \lambda Y \Phi \Phi^c$$

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

- PQ charged X and Y are responsible for mu-transition:

- Y obtains a thermal mass from the λ interaction, and is fixed at the origin until T drops below about m_{SUSY}.

- X is also trapped at the origin during this period because it has vanishing tadpole.

thermal inflation: diluting away unwanted relics (moduli, gravitino, ..)

number of *e*-foldings: $N \sim \frac{1}{4} \ln(M_{Pl} / m_{\text{SUSY}})$

7. Models (2/4)

- Before the mu-transition, κ_3 term stabilizes the H_uH_d and LH_u flat directions.

- After the mu-transition, the mu-term makes the flat directions non-tachyonic, and consequently H_u and H_d are stabilized near the weak scale while L is fixed at the origin.
  X and Y are fixed by κ_2 term.

- Axion misalignment angle is generally of O(1) because

  - the minimum of the axion potential induced by stronger QCD is determined by the phase of $\kappa_3 A_3$.
  - the minimum at present is determined by the phase of $B\mu$.

  → Axion can naturally account for the observed DM abundance.

7. Models (3/4)

The model can successfully realize the desired cosmological evolution of 3 relevant scales for m_{SUSY} between 1-10 TeV: the axion scale, the weak scale, and the QCD scale.

- Axion scale

$$f_a(t_I) \sim \sqrt{\frac{H(t_I)}{m_{\rm SUSY}}} \times f_a(t_0), \quad f_a(t_0) \sim \sqrt{m_{\rm SUSY} M_{Pl}}$$

- Weak scale

$$v(t < t_\mu) \sim f_a(t < t_\mu), \quad v(t_0) = O(100\mathrm{GeV})$$

- Stronger QCD before the mu-transition

$$\Lambda_{\rm QCD}(t_\mu) = (20\text{-}30)\ \mathrm{TeV}, \quad \Lambda_{\rm QCD}(t_0) \approx 400\ \mathrm{MeV}$$

Interesting issues (work in progress)

- To complete our scheme, we need a late-time baryogenesis.

  - The simple model offers an elegant mechanism to generate baryon asymmetry through the rolling flat direction LHu:

    Affleck-Dine leptogenesis

8. Summary

8. Summary

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

  → Well-motivated dark matter candidate!

- We have examined how to suppress axion isocurvature perturbations while producing the right amount of axion DM in a natural manner.

  - Axion scales are induced by SUSY breaking.

  - Intermediate phase transition to generate Higgs mu-term leads to a stronger QCD, providing further suppression of axion isocurvature perturbations.

Thank you!

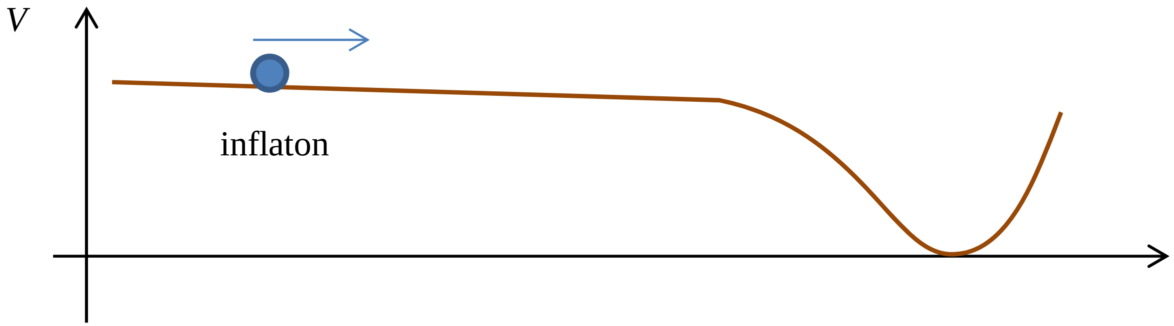
Backup

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:



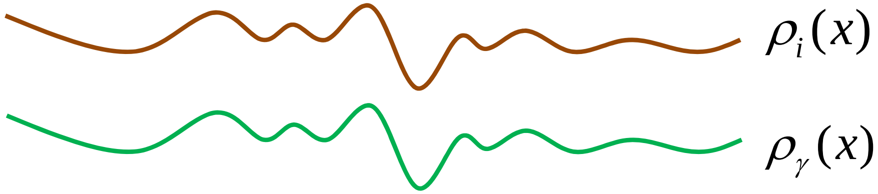
$$n_s \simeq 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2 ,$$

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

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



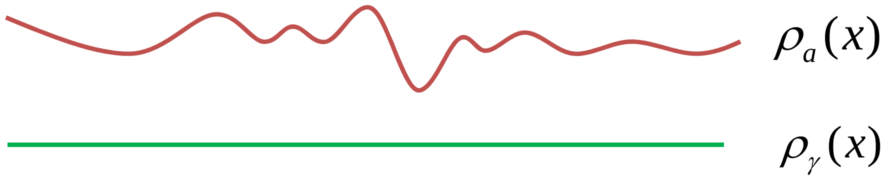
→ consistent with the observations

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

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

No PQ restoration during inflation and thereafter

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



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

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.