Axion/Saxion Cosmology Revisited

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Based on
Nakamura, Okumura, MY, PRD77 ('08)
and
Work in Progress

1. Introduction

Fine Tuning Problems of Particle Physics

- Smallness of electroweak scale
- Smallness of Strong CP phase
- And others

Strong CP problem

Why is the strong CP phase so small?

$$\mathcal{L}_{\bar{\Theta}} = \frac{g_3^2}{64\pi^2}\bar{\Theta}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

EDM measurements give constraint: $\Theta < 10^{-9}$

Solutions

- Vanishing up quark mass (unlikely?)
- Spontaneous CP violation
- Peccei-Quinn Symmetry (axion)

At present, the PQ symmetry is the most plausible solution.

PQ solution

Global U(1) PQ symmetry with $SU(3)_C$ anomaly

U(1) PQ spontaneously broken at scale f_a

→NG boson = Axion a

$$\mathcal{L} = \frac{g_3^2}{64\pi^2}\left(\bar{\Theta} + \frac{a}{f_a}\right)\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

Θ becomes dynamical. QCD dynamics makes this effective Θ zero at vacuum.

→ No Strong CP violation

Naturalness of Electroweak Scale

Why is EW scale much smaller than Planck scale?

How is EW scale stable against radiative corrections?

Many ideas/models have been proposed.

Supersymmetry: a promising solution

Marriage of PQ Sym. and SUSY

1) Axion (Goldstone boson) has superpartners

- Scalar partner: saxion
- Fermionic partner: axino

Exact SUSY →

- (complex) axion potential is flat
- Axion/Saxion/Axino are degenerate in mass

SUSY breaking →

- Generation of saxion potential
- Saxion and Axino acquire masses

2) Bonus: A solution to the mu problem

superpotential contains $W=\mu H_1 H_2$,
How can we make μ of EW scale?

Kim-Nilles '84

Assign PQ charge as

X (-1): PQ field, $H_1(+1)$ $H_2(+1)$

→ $H_1 H_2$ term forbidden in superpotential

$X^2/M\, H_1 H_2$ allowed

→ $\mu= f_a{}^2/M$, $B=O(m_{3/2})$

If PQ scale is in an intermediate scale and M is close to Planck scale, mu becomes correct order.

Remark)

Abe-Moroi-MY 01

Nakamura et al 08

Workable mechanism in gravity mediation.

A more complicated set-up based on PQ sym. can account for mu problem in anomaly mediaton/mirage mediaton (heavy gravitino)

In this talk.....

- I want to proceed one step further.

- Consider cosmological behavior of saxion/axion fields.
- Focus on the case the saxion has large initial value at early stage of universe evolution.
- Derive constraints on expansion rate during inflation.

2. *Saxion Potentials*

Model 1: multi field model

X(1), Y(-1), Z(0)

superpotential W=Z(XY—f²)

SUSY condition

$$\frac{\partial W}{\partial X} = ZY = 0 \quad \frac{\partial W}{\partial Y} = ZX = 0 \quad \frac{\partial W}{\partial Z} = XY - f^2 = 0$$

→ Z=0, XY=f^2 fixed, but one direction X/Y undetermined

SUSY breaking effect generates potential for this direction

$$V = m_x^2 |X|^2 + m_y^2 |Y|^2$$

For comparable soft masses, axion decay const $f_a \sim f$

Model 2: one field model

Gauge mediation: Asaka-MY 98
Anomaly mediation: Abe-Moroi-MY 01
Mirage mediation: Nakamura-Okumura-MY 08

saxion potential

= tree level + radiative corrections (Coleman-Weinberg)

$\leftarrow$ Yukawa + Gauge interaction

Axion decay constant is determined dynamically.

In the case of mirage mediation:

Nakamura-Okumura-MY 08

S (-2) : axion multiplet

Q(+1): new vector-like quarks

Q'(+1):

X (0): moduli

superpotential:

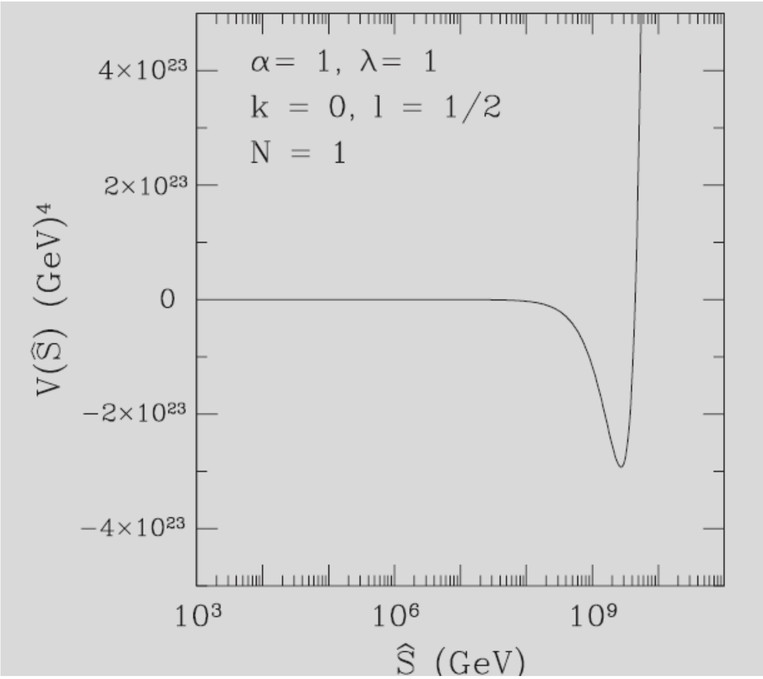
$$W=\lambda\ SQQ'$$

scalar potential

$$\mathcal{L} = \int d^4\theta (X + X^\dagger)^k Z_S\left(\sqrt{\frac{\hat{S}^\dagger \hat{S}}{\Phi^\dagger \Phi}}, X + X^\dagger\right)|\hat{S}|^2$$

$$V(|\hat{S}|) \simeq \left\{k\left|\frac{F_X}{2X_R}\right|^2 - \frac{1}{4}\frac{\partial^2 \ln Z_S}{\partial(\ln|\hat{S}|)^2}|F_\Phi|^2 + \frac{1}{2}\left(\frac{\partial^2 \ln Z_S}{\partial X \partial \ln|\hat{S}|} F_\Phi{}^\dagger F_X + \text{H.c.}\right)\right\}|\hat{S}|^2 = m_S^2 |\hat{S}|^2$$

$$-\frac{1}{4}\frac{\partial^2 \ln Z_S}{\partial(\ln|\hat{S}|)^2}|F_\Phi|^2 \simeq -\left(\frac{1}{16\pi^2}\right)^2 \times N[16 g_3^2(S) - 5(5N+2) \times \lambda^2(S)]\lambda^2(S)|F_\Phi|^2,$$



In the following, we will mainly consider the single field case (model 2). But some of the results can apply to the multi field case (model 1) as well.

3. Cosmological behavior of Saxion/Axion potential

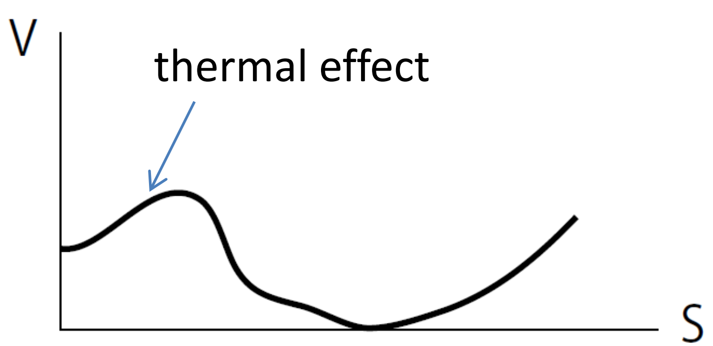
Thermal effects

Axion multiplet couples to thermal bath through

$$W = \lambda\, SQQ'$$

For $\lambda S < T$, Q and Q' are in thermal bath and S receives thermal effects to potential.

For $\lambda S > T$, Q and Q' become massive and no longer in thermal bath



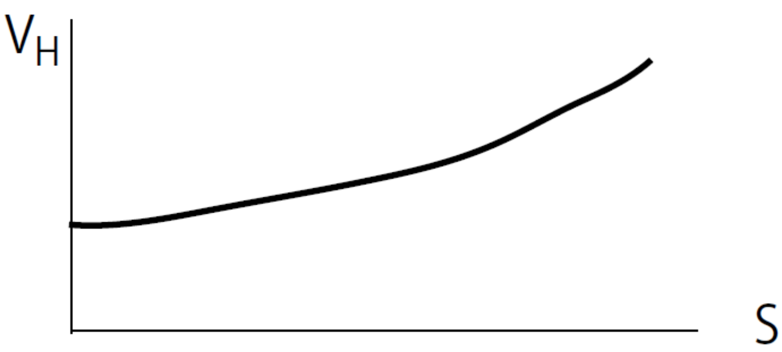
Potential during inflation

-- sensitive to the coupling between PQ field and inflaton

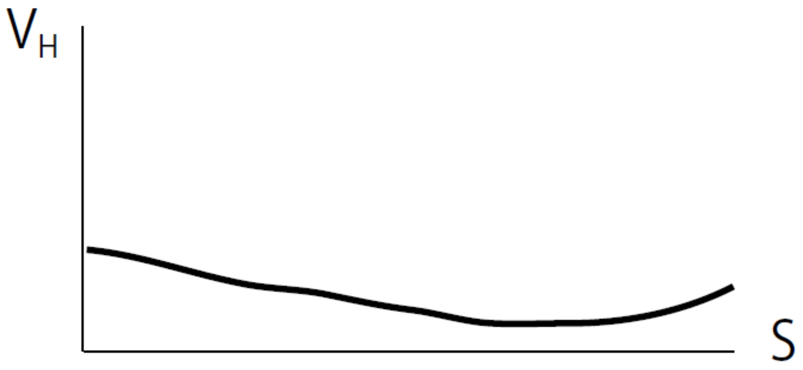
In particular, PQ field may get either positive or negative (or vanishing) Hubble mass contribution.

Typically there are the following two cases.

Case a) positive Hubble mass ^2

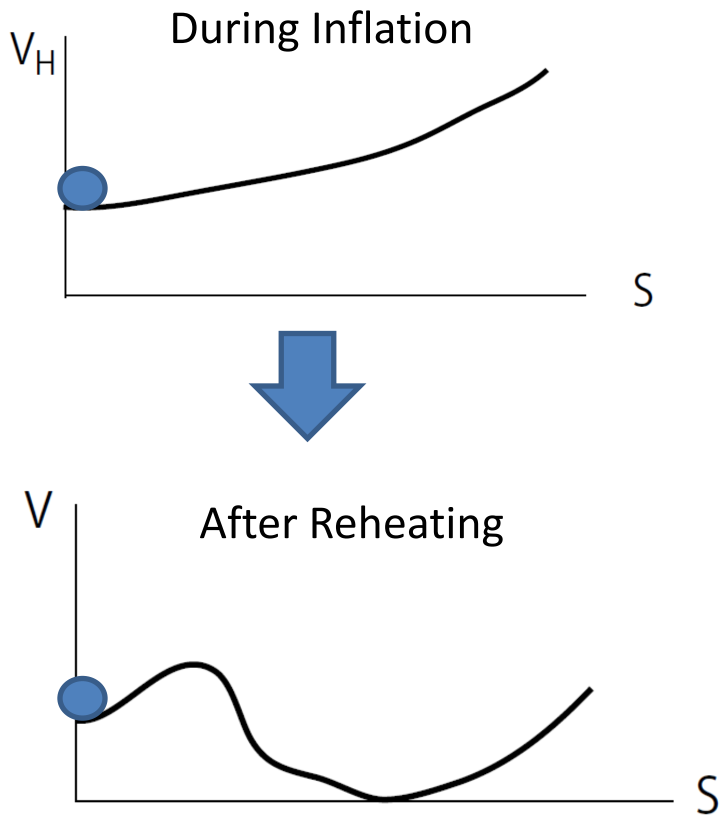


Case b) negative Hubble mass^2



Cosmological Evolution of Saxion field

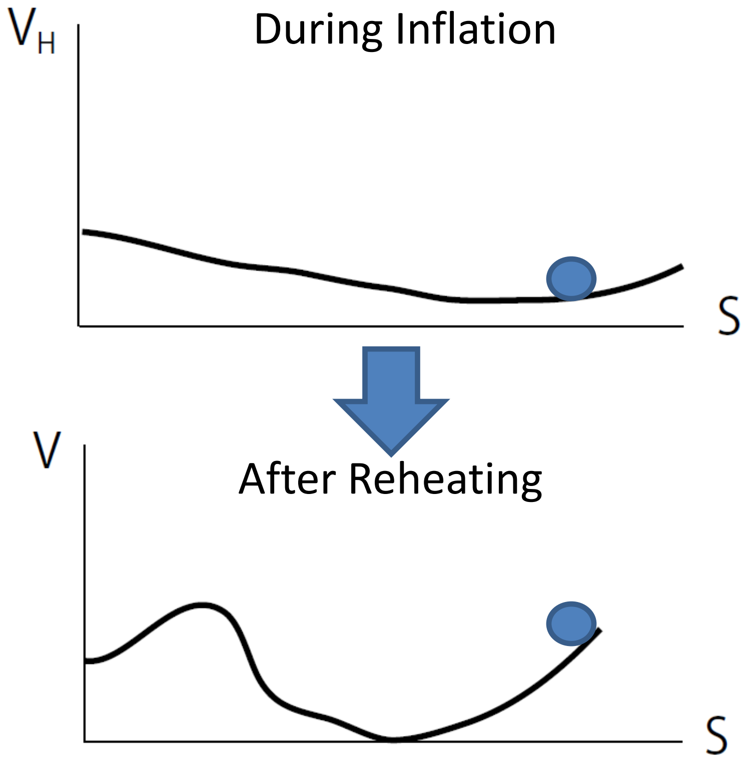
Case a)



Saxion is trapped at origin due to thermal effect.
Thermal inflation occurs.

Saxion tends to decay into axion pair.
Saxion decay would give axion dominated universe.
→ cosmologically disfavored.

Case b)



During inflation, the saxion is displaced far from origin. Typically it is around Planck scale.

Then, saxion oscillates with large initial amplitude.

In the following, we consider this case.

Saxion with large initial amplitude

Saxion obeys damped coherent oscillation with large initial amplitude

1) Can saxion settle down into one single vacuum?
(domain wall problem)

2) Is isocurvature perturbation of axion suppressed enough?

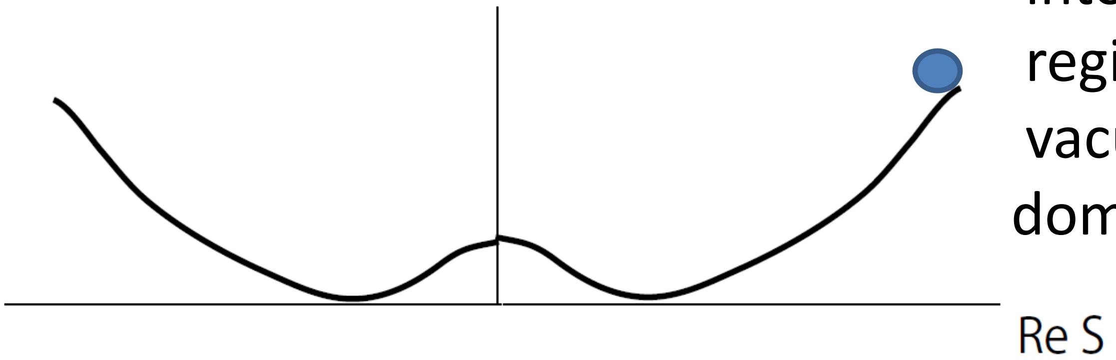
Domain wall problem

Anomaly coefficient N>1

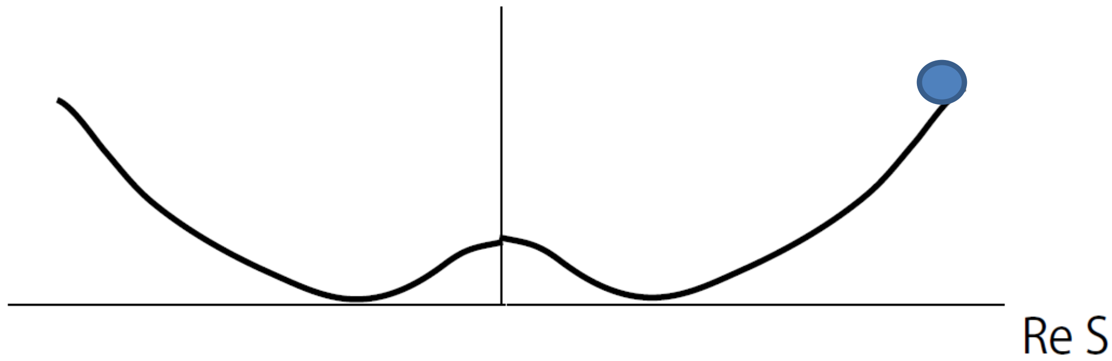
→ N degenerate vacua

→ Afraid of domain wall production

Ex. N=2 case



Potential looks double well.
If some region of universe falls into one vacuum and other region falls into the other vacuum, then
domain wall will form.



Saxion starts moving at a position much higher than the potential barrier at the origin.

It gradually loses energy due to friction from expansion of universe.

So it oscillates many times before it settles down one vacuum.

If initial condition of the saxion is uniform in the whole universe, then classical equation of motion determines the saxion motion completely.

However, we expect fluctuation of the initial value of the saxion due to the quantum fluctuation during de Sitter expansion.

Condition that the whole universe settles down one vacuum

Nakamura-MY, in prepartion
See also Kasuya-Kawasaki-Yanagida ‘97

Estimate:

Energy loss of one oscillation $\Delta\rho \sim H\rho\Delta t \sim \frac{H}{m_s}\rho$

The saxion settles down in one vacuum if
the energy fluctuation is smaller the energy loss of one oscillation at the critical point where the saxion energy is equal to its potential barrier.

$$\frac{\delta\rho}{\rho} \sim \frac{\delta s_{in}}{s_{in}} < \frac{H}{m_s} \sim f_a/M_{Pl}$$

Furthermore, we expect $\delta S_{in} \sim \frac{H_I}{2\pi}$

So we obtain the constraint on Hubble constant during inflation

$$\frac{H_I}{2\pi} < f_a \frac{S_{in}}{M_{Pl}}$$

Constraint from Isocurvature Fluctuation

Axion is known to make contribution to isocurvature fluctuation.

Usual estimate: $\delta_{iso} \sim \frac{H_I}{2\pi f_a}$

→ severe bound on the Hubble during inflation.

In the case where PQ field has large value during inflation, the above estimate is modified as $\delta_{iso} \sim \frac{H_I}{2\pi S_{in}}$ Linde '91

Observation: (isocurvature fluctuation) <0.3 (total fluctuation)

→

$$\frac{H_I}{2\pi} < 10^{-5}\, S_{in}$$

Constraints on Hubble during inflation

Nakamura-MY, in preparation

Domain Wall Problem:

$$\frac{H_I}{2\pi} < 10^{12}\mathrm{GeV}\,\frac{f_a}{10^{12}\mathrm{GeV}}\,\frac{S_{in}}{M_{Pl}}$$

Isocurvature Fluctuation:

$$\frac{H_I}{2\pi} < 10^{13}\mathrm{GeV}\,\frac{S_{in}}{M_{Pl}}$$

Rather mild constraints on Hubble expansion rate during inflation

These constraints can apply to the multi field case as well.

4. Saxion Decay

Saxion decay: model dependent

Key Point: saxion decay into axion pair

$$\Gamma(s \to 2a) \simeq \frac{f^2}{64\pi}\frac{m_s^3}{F_a^2} \qquad f = \sum_i q_i^3 v_i^2 / F_a^2$$

For f=O(1), saxion dominantly decays to axions.
In fact, this is the case in one field axion model.

With large initial value of saxion field, saxion oscillation dominates energy density of the universe. Then

Saxion dcay → Axion dominated universe ????

A natural solution in mirage mediation

Nakamura
-Okumura-MY 08

Moduli decay dilutes axions produced this way.

Mass Spectrum: little hierarchy

moduli: 10^6 GeV

gravitiono: 10^4 GeV

sparticles: 10^2 GeV

Choi-Falkowski-Nilles
-Olechowski 05
Endo-MY-Yoshioka 05
Choi-Jeong-Okumura 05

Moduli, instead of saxion, dominates energy density of universe.

Moduli decay reheats the universe with SM thermal bath, diluting axions generated at saxion decay.

5. Axino dark matter

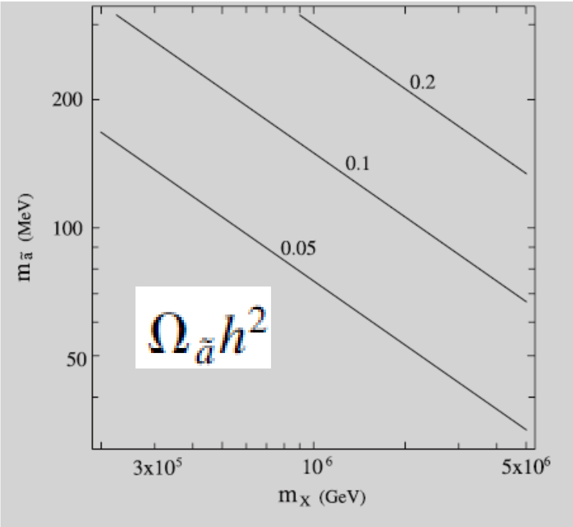
Nakamura -Okumura-MY 08

Dark matter candidates in SUSY Axion model
- Axion
- LSP (model dependent)

In axionic extension of mirage mediation, the axino becomes LSP.
Axino production: through the following decay chain

moduli → gravitino → neutralino → axino

Axino with mass ~100 MeV gives correct relic density.



Summary

- Axion models in supersymmetry was considered.
- Cosmological behavior of saxion field was discussed.
- Obtained constraints on expansion rate during inflation.

  ← domain wall problem

  ← isocurvature perturbation