Saxion Cosmology Revisited

– Trapping and Dissipation –

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Refs:

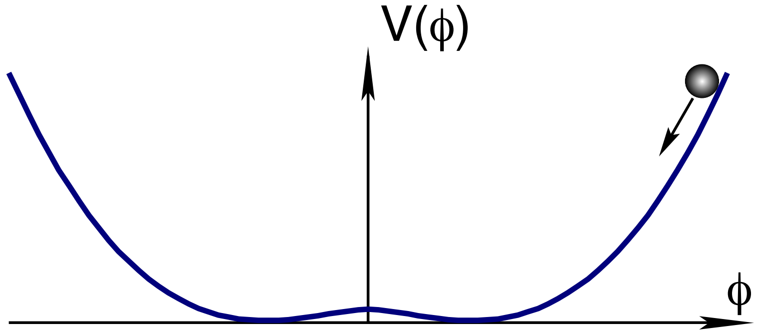
TM and Takimoto, PLB718 ('12) 105

TM, Mukaida, Nakayama and Takimoto, JHEP 1306 ('13) 040

SUSY13, August, 2013

1. Introduction

What is the fate of (cosmological) scalar-field oscillation?



1. If the cosmic expansion is fast enough:

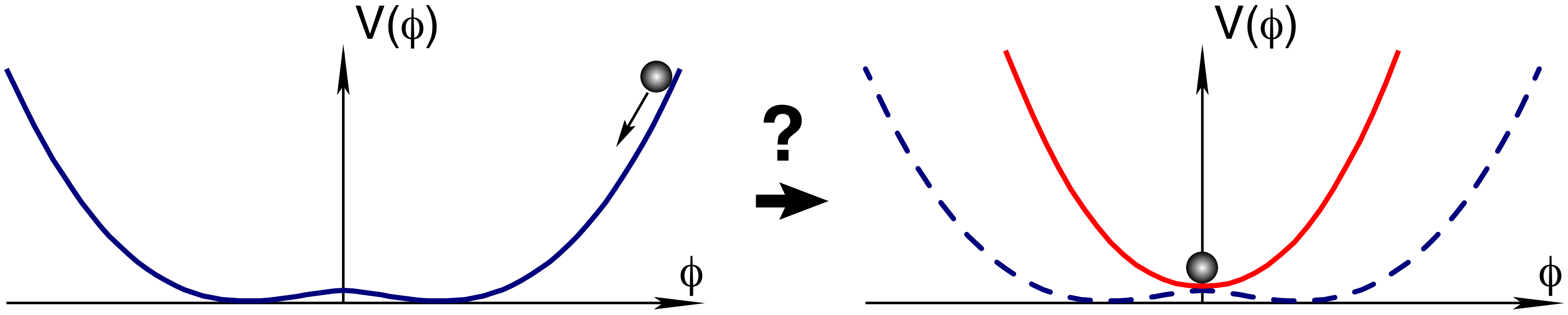
   $\Rightarrow$ Amplitude decreases with Hubble friction

   $\Rightarrow$ It may eventually decay

2. Dissipation may be faster than the expansion rate:

   $\Rightarrow$ Energy density of the scalar oscillation is quickly converted to that of radiation

Does the trapping happen?



$\Rightarrow$ The evolution of the scalar field depends on the model

$\Rightarrow$ Here, I consider a well-motivated candidate: saxion ϕ

$$\mathcal{A} = \frac{1}{\sqrt{2}}(\phi + ia) + \sqrt{2}\tilde{a}\theta + F\text{-term: Axion multiplet}$$

In the early universe, colored particles exist in thermal bath

$\Rightarrow$ They affect the evolution of saxion

$\Rightarrow$ Trapping may happen in large fraction of parameter space

2. Saxion: Basic Properties

Interaction of the saxion with PQ quarks (Q & $\bar{Q}$)

[Kim; Shifman, Vainshtein & Zakharov]

$$\mathcal{L} = \lambda \int d^2\theta \mathcal{A}\bar{Q}Q + \text{h.c.} + \cdots$$

$$\mathcal{A} = \frac{1}{\sqrt{2}}(\phi + ia) + \sqrt{2}\tilde{a}\theta + F\text{-term: Axion multiplet}$$

Interaction (after integrating out PQ quarks):

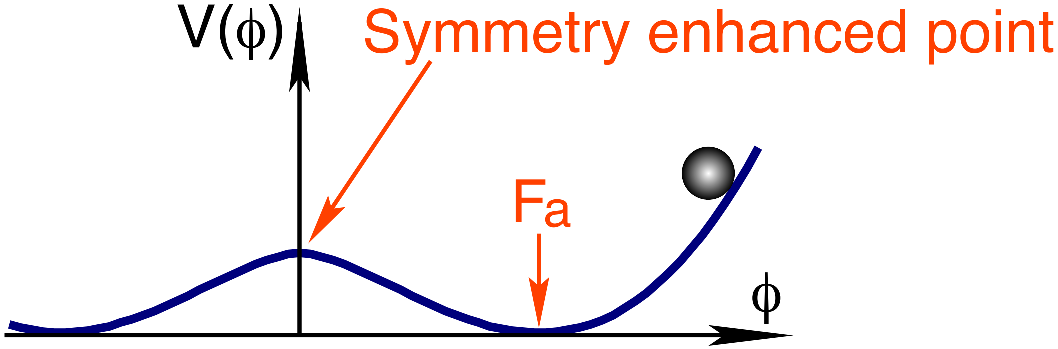
$$\mathcal{L}_{\text{int}} = \frac{\alpha_s}{8\pi F_a} a G^{(a)}_{\mu\nu}\tilde{G}^{(a)\mu\nu} + \frac{\alpha_s}{8\pi F_a}\phi G^{(a)}_{\mu\nu}G^{(a)\mu\nu} + \cdots$$

Saxion potential is lifted by the effect of SUSY breaking

$\Rightarrow$ Here, I consider the case where the PQ symmetry breaking is via the SUSY breaking

Saxion potential (for this talk):

[Asaka & Yamaguchi; Abe, TM & Yamaguchi]



$$V(\phi) \sim \begin{cases} -m_0^2\phi^2 & : \ \phi \ll F_a \\ +m_\infty^2\phi^2 & : \ \phi \gg F_a \end{cases}$$

- $V(\phi)$ is lifted by the SUGRA effect at $\phi \gg F_a$
- Negative curvature at $\phi \sim 0$ can be due to RG or gauge-mediation effects

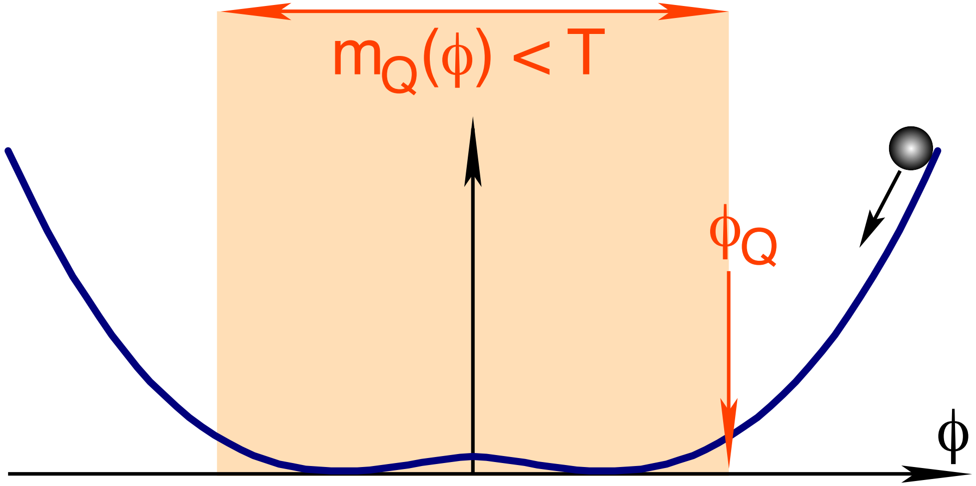
  [Arkani-Hamed, Giudice, Luty & Rattazzi]

PQ (s)quarks become massless at $\phi = 0$

$\Rightarrow$ Significant particle production may occur when $\phi \sim 0$

3. Saxion in Thermal Bath

1. PQ (s)quarks may be effectively produced when $\phi \sim 0$



$$\phi_Q \sim \frac{T}{\lambda}$$

Scattering (because gluons are abundant in thermal bath)

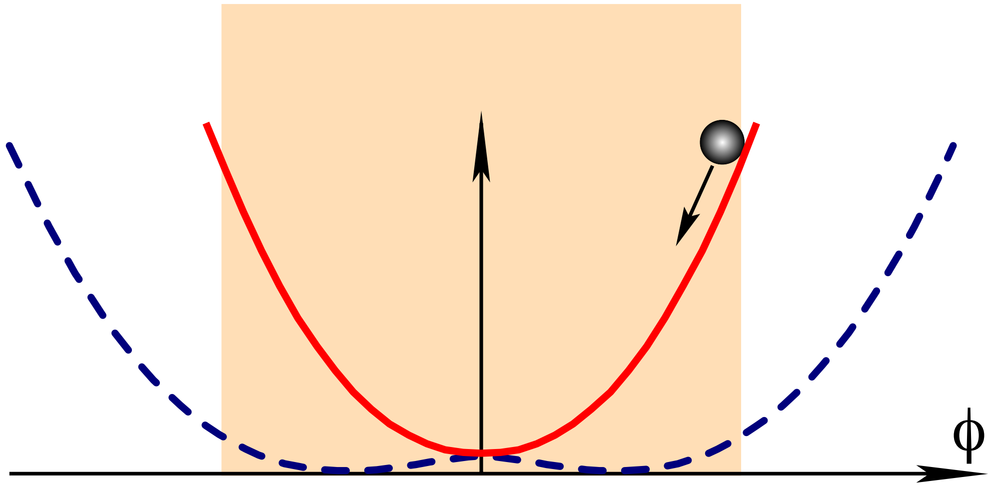
- This process is important if $\phi \sim 0$ is realized long enough
- $gg \to \bar{Q}Q,\ \tilde{Q}^\dagger\tilde{Q},\ \cdots$

Non-perturbative production

[Kofman, Linde & Starobinsky; Tkachev]

- This process is important if adiabaticity breaks down

2. Deformation of the saxion potential



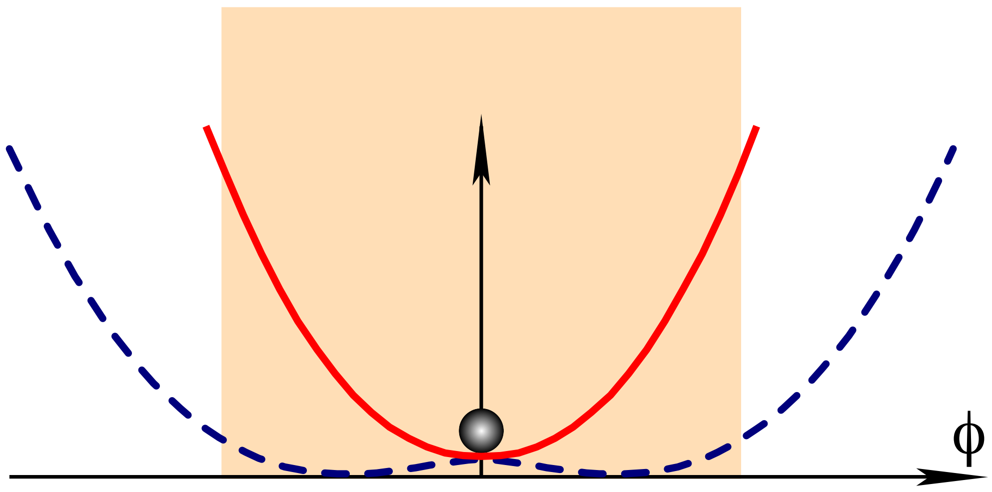
Because there are PQ (s)quarks in the environment:

$$\mathcal{L}_{\text{int}} \sim -\lambda^2 \tilde{Q}^\dagger \tilde{Q} \phi^2 \quad \Rightarrow \quad V_T \sim \lambda^2 \langle \tilde{Q}^\dagger \tilde{Q} \rangle \phi^2$$

$\phi = 0$ may become the minimum of the potential:

- $V(\phi \sim 0) \sim \lambda^2 T^2 \phi^2$, if Q is thermalized
- $V(\phi \gtrsim \phi_Q) \sim m_Q(\phi) n_Q \sim \lambda n_Q |\phi|$, if Q lives long enough
  [Kofman, Linde, Liu, Maloney, McAllister & Silverstein]

3. Dissipation of the energy density of ϕ



Dissipation via the interaction with thermal bath

[Bastero-Gil, Berera & Ramos; Mukaida & Nakayama]

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\Gamma_{\text{diss}}\dot{\phi} \quad \text{with} \quad \Gamma_{\text{diss}} \sim \alpha_s \lambda^2 T \ (\text{when } m_\phi \lesssim T)$$

Decay and/or pair annihilation of PQ quarks

Because the "mass" of Q depends on ϕ, the energy density of ϕ may be reduced by the decay of Q

4. An Example

The evolution of ϕ depends on:

- Initial amplitude ϕ_{init}
- Reheating temperature T_{R}
- Interaction of PQ quarks (lifetime, annihilation rates, $\cdots$)
- $\cdots$

Let us consider the case where:

- ϕ_{init} is large: $\phi_{\mathrm{init}} \sim M_{\mathrm{Pl}}$
- PQ quarks are long-lived
- T_{R} is relatively high

Saxion starts to oscillate when $H \sim m_\infty$

$$\Rightarrow T_{\mathrm{osc}} \sim m_\infty^{1/4} M_{\mathrm{Pl}}^{1/4} T_{\mathrm{R}}^{1/2} \sim 10^{10}\ \mathrm{GeV} \times \left(\frac{m_\infty}{1\ \mathrm{TeV}}\right)^{1/4} \left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right)^{1/2}$$

$\Rightarrow$ Time to pass through $m_Q(\phi) \lesssim T_{\mathrm{osc}}$: $\delta t \sim \frac{\phi_Q}{\dot{\phi}} \sim \frac{T_{\mathrm{osc}}}{\lambda m_\infty \phi_{\mathrm{init}}}$

$\Rightarrow$ Production rate of Q: $\Gamma_{\mathrm{th}}^{Q} \sim \sigma_{gg \to \bar{Q}Q} T_{\mathrm{osc}}^3 \sim \alpha_s^2 T_{\mathrm{osc}}$

Efficiency of PQ-quark production:

$$d_Q \equiv \Gamma_{\mathrm{th}}^{Q} \delta t \sim O(10^{-2}) \times \lambda^{-1} \left(\frac{m_\infty}{1\ \mathrm{TeV}}\right)^{-1/2} \left(\frac{\phi_{\mathrm{init}}}{M_{\mathrm{Pl}}}\right)^{-1} \left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right)$$

Even if $d_Q < 1$, PQ (s)quark production is significant

$$\Rightarrow n_Q \sim d_Q T_{\mathrm{osc}}^3$$

The saxion potential after Q-production (for $d_Q < 1$)

$$V_{\text{eff}}(\phi) \sim \begin{cases} (d_Q \lambda^2 T_{\text{osc}}^2 - m_0^2)\phi^2 & : \quad \phi \lesssim \phi_Q \\ \lambda n_Q |\phi| & : \quad \phi \gtrsim \phi_Q \end{cases}$$

$\phi = 0$ becomes the minimum of $V_{\text{eff}}(\phi)$, if $d_Q \lambda^2 T_{\text{osc}}^2 > m_0^2$

$$T_{\text{R}} \gtrsim 10^{-4}\ \text{GeV} \times \left(\frac{1}{\min(d_Q, 1)}\right) \left(\frac{m_0/\lambda}{1\ \text{TeV}}\right)^2 \left(\frac{m_\infty}{1\ \text{TeV}}\right)^{-1/2}$$

Dissipation rate (when $m_Q(\phi) \lesssim T$): $\Gamma_{\text{diss}} \sim \alpha_s \lambda^2 T$

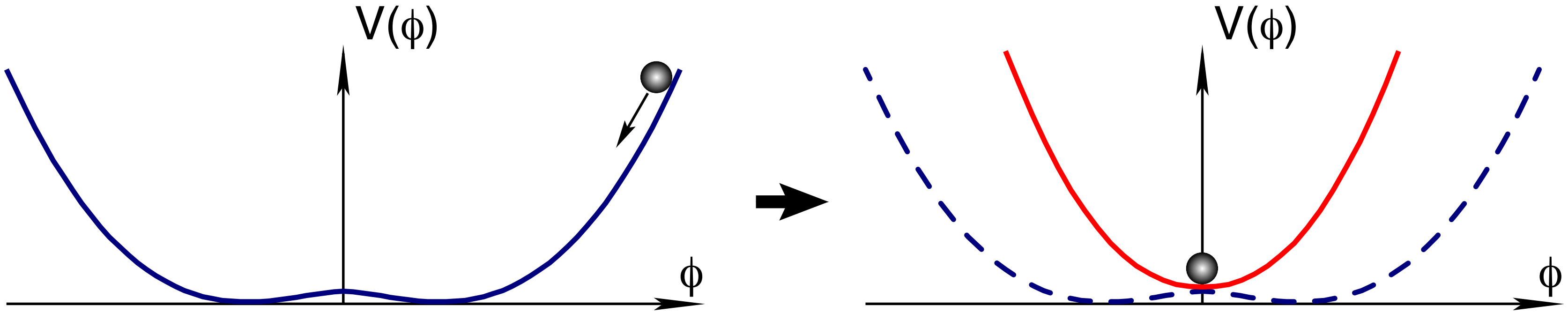
$\Rightarrow$ Saxion oscillation loses its energy

Saxion is likely to be thermally trapped at $\phi = 0$

5. Summary

I discussed the evolution of the saxion oscillation

$\Rightarrow$ Saxion can be easily trapped at $\phi = 0$ even if its initial amplitude is large



Production of PQ (s)quarks at $\phi \sim 0$ is important

- Thermal scattering; non-perturbative production

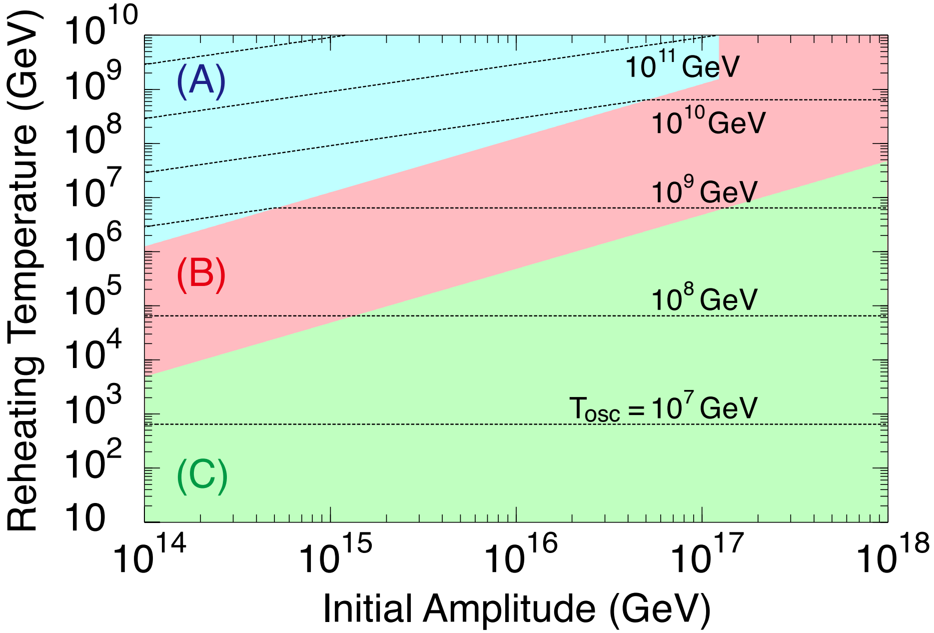
Dissipation (energy-loss) of the oscillation is often effective

- Thermal dissipation; decay and annihilation of PQ quarks

Cosmology with saxion may be significantly changed

Backups

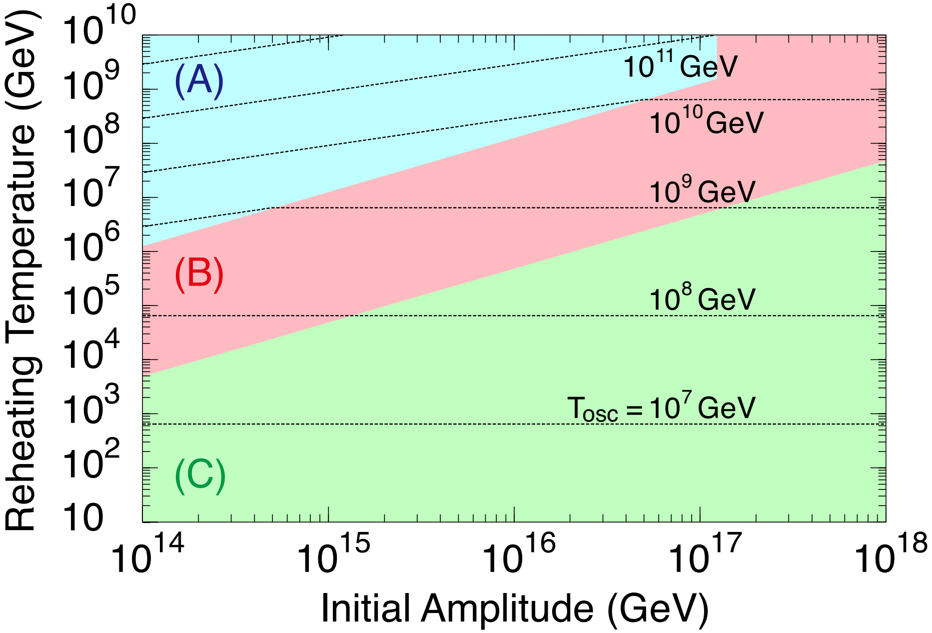
Other cases (with $\lambda = 0.05$, $m_\infty = 1$ GeV):



- Case (A)
  - ϕ starts to oscillate with thermal-log potential
  - Condition for trapping:

$$T_{\mathrm{R}} \gtrsim 10^3\ \text{GeV} \times \left(\frac{m_0/\lambda}{1\ \text{TeV}} \right)^2$$

Other cases (with $\lambda = 0.05$, $m_\infty = 1$ GeV):



- Case (C)
  - Non-perturbative particle production is effective
  - Energy-loss: pair annihilation