

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

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Summary

High reheating temperature without axion domain walls

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High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

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Summary

- QCD has $\bar{\theta}G\tilde{G}$ (violates CP). However, $\bar{\theta} < 10^{-10}$ (by neutron EDM).
- Anomalous $U(1)_{PQ}$ promotes $\bar{\theta} \rightarrow a(x)$, the **axion** field.
- Strong dynamics makes $\langle a(x) \rangle \rightarrow 0$.
- Vafa-Witten theorem also ensures $\bar{\theta} \rightarrow 0$ if it is dynamical.

The QCD axion

Many axion models, KSVZ, DFSZ, etc.
Phenomenologically,

$$\mathcal{L} \supset \frac{1}{2} (\partial a)^2 + \frac{1}{32\pi^2} N_{\text{DW}} \frac{a}{f_a} G \tilde{G} + \frac{\partial a}{f_a} \cdot (\dots) + \underbrace{\delta V}_{\text{explicit breaking}}$$

$$\rightarrow \frac{1}{2} (\partial a)^2 + \underbrace{\frac{1}{2} m_a^2 a^2}_{\text{Non-perturbative}} + \frac{\partial a}{f_a} \cdot (\dots)$$

- N_{DW} is the domain wall number.
- f_a is usually called decay constant.
- δV causes the **axion quality problem**.
- The axion mass is given by

$$m_a \simeq 6 \mu\text{eV} \times \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

The QCD axion

High reheating temperature without axion domain walls

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Introduction

Cosmology

Always Broken

Summary

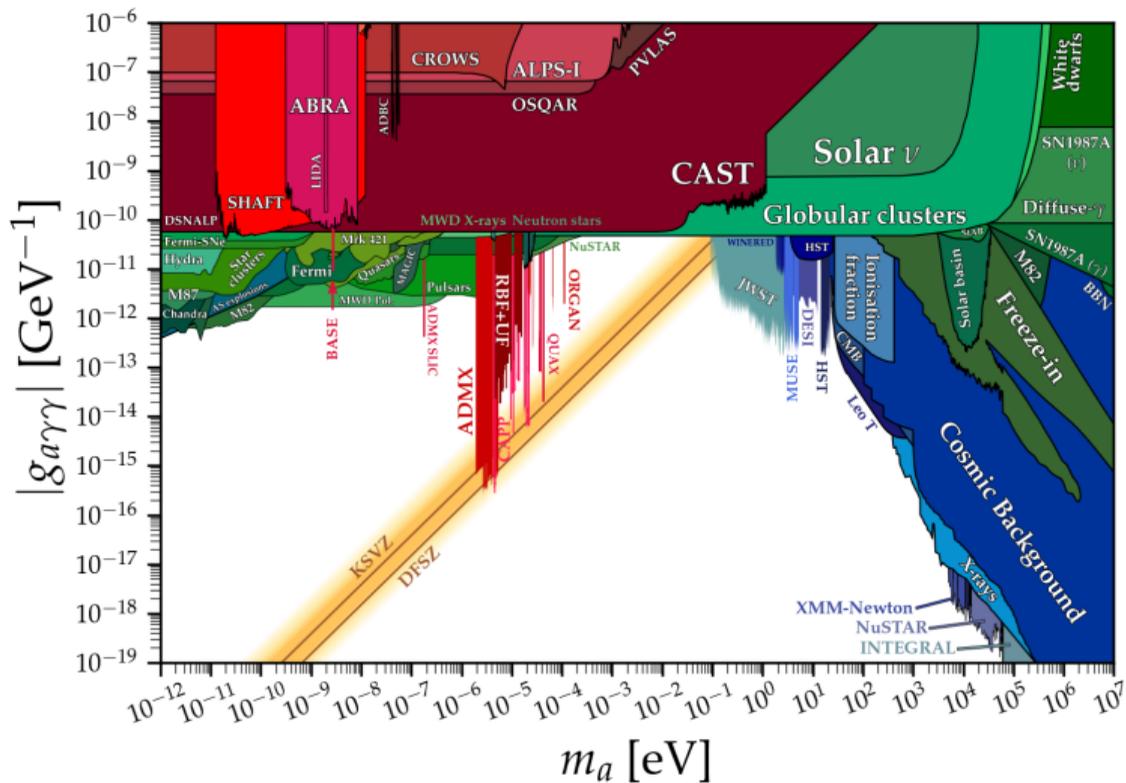


Figure: From AxionLimits.

The axion mass is obtained by expanding the potential around its minimum. If the quality is ensured, the potential is in the form

$$V(a) = \Lambda^4 \left[1 - \cos \left(\frac{N_{\text{DW}} a}{f_a} \right) \right].$$

The decay constant f_a , defines the periodicity of the axion field under the shift symmetry.

$$a \rightarrow a + \alpha f_a, \quad a + 2\pi f_a \sim a$$

The instanton effect Λ breaks the shift symmetry.

So, N_{DW} determines the number of degenerate vacua.

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

Shift symmetry is originated from a $U(1)_{PQ}$. Peccei and Quinn (1977)

The PQ symmetry is spontaneously broken by a PQ scalar $\langle \phi \rangle = v_{PQ}$.

The decay constant f_a is determined by PQ scale,

$$f_a \propto v_{PQ}$$

High reheating
temperature
without axion
domain walls

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Introduction

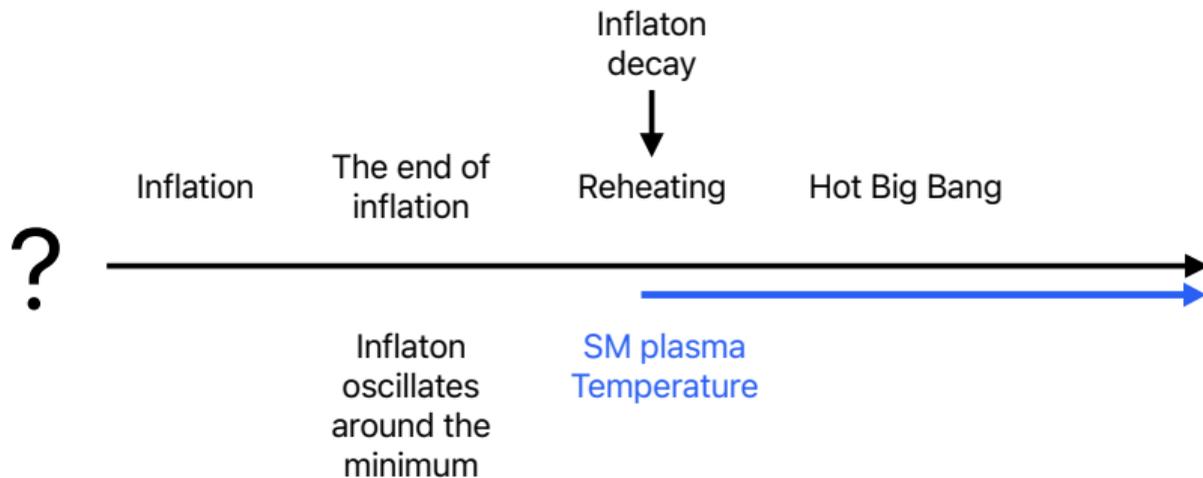
Cosmology

Post-inflation

Pre-inflation

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Summary



T_R , reheating temperature, describes the hot big bang starting temperature.

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

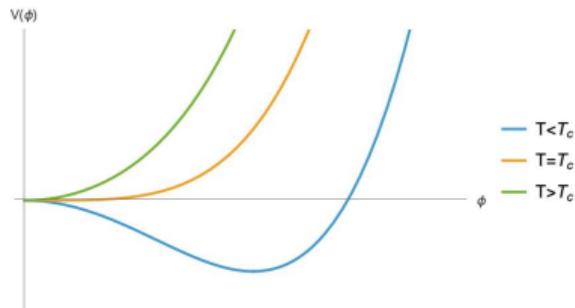
Post-inflation

Pre-inflation

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Summary

Consider $f_a < T_R$:



When SM plasma formed, thermal effects will restore the PQ symmetry.
Just like EW symmetry.

Here $T_c \sim f_a$.

Defect formation

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temperature
without axion
domain walls

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Introduction

Cosmology

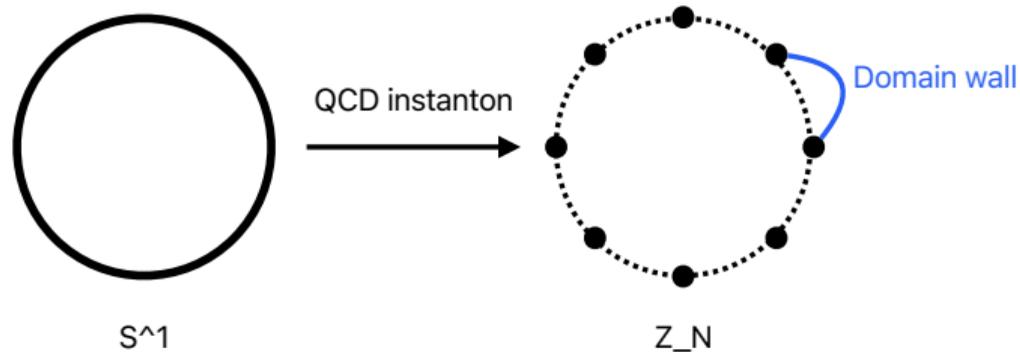
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Pre-inflation

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Summary

The universe expands, T becomes smaller. PQ symmetry broken again.



Domain wall forms. → domain wall problem

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temperature
without axion
domain walls

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Introduction

Cosmology

Post-inflation

Pre-inflation

Always Broken

Summary

Consider $f_a > T_R$:

Inflation leads to $a(x) \rightarrow a_i$ after inflation.

The PQ symmetry is never restored by SM temperature.

Fluctuations from inflation remain, $\langle \delta a^2 \rangle \simeq H_{\text{inf}}^2 / 2\pi$.

So one has

$$\theta_{i,\text{eff}}^2 = (a/f_a)^2 + (H_{\text{inf}}/2\pi f_{\text{inf}})^2$$

The CMB power spectrum constrain such fluctuations by

$$\mathcal{P}_{S_c} = \left(\frac{\delta\Omega_a}{\Omega_c} \right)^2 \simeq 1.4 \times \theta_{i,\text{eff}}^2 \left(\frac{H_{\text{inf}}}{2\pi f_{\text{inf}}} \right)^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{2.38} < 10^{-11}$$

For $f_a = 10^{12} \text{ GeV}$, one has $H_{\text{inf}} < 10^8 \text{ GeV}$. **Isocurvature problem**

Any way out?

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without axion
domain walls

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High reheating temperature is good for theories like leptogenesis.

Usually, T_R is limited by the H_{inf} from above.

How can we have High reheating temperature without **domain wall problem** and **isocurvature problems**?

Any way out?

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Post-inflation

Pre-inflation

Always Broken

Summary



A symmetry nonrestoration mechanism!

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temperature
without axion
domain walls

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Introduction

Cosmology

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Summary

Consider a scalar ϕ in the high temperature limit.

Suppose we have another scalar s couple to it through $\lambda_{\phi s} \phi^2 s^2$, we have

$$V^\beta \supset \lambda_{\phi s} \phi^2 T^2 + \dots$$

So, if $\lambda_{\phi s} < 0$, it protects the broken phase.

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temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

If we succeed in protects the broken phase against the T_R ,
the axion is just in pre-inflation scenario, which has isocurvature problem.

If we succeed in protects the broken phase against the T_R ,
the axion is just in pre-inflation scenario, which has isocurvature problem.

Not if $f_{\text{inf}} \gg f_a$ (Linde's (1991)).

Recall,

$$\mathcal{P}_{S_c} = \left(\frac{\delta\Omega_a}{\Omega_c} \right)^2 \simeq 1.4 \times \theta_{i,\text{eff}}^2 \left(\frac{H_{\text{inf}}}{2\pi f_{\text{inf}}} \right)^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{2.38} < 10^{-11}$$

The parametric production

Schematic realization of avoid parametric production

Kasuya, Kawasaki, Yanagida (1997),

Kawasaki, Sonomoto (2018),

Kawasaki, Sonomoto, Yanagida (2018)

High reheating
temperature
without axion
domain walls

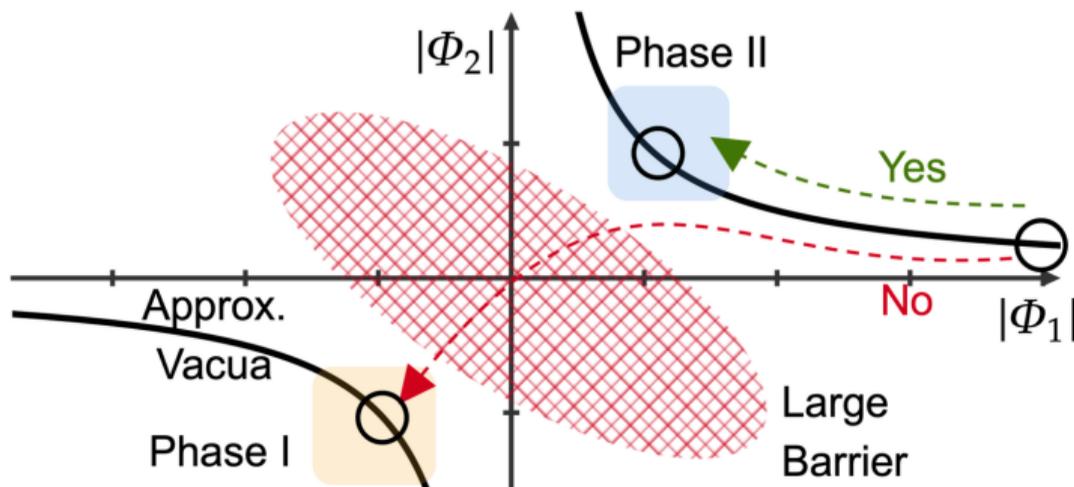
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Introduction

Cosmology

Always Broken

Summary



High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

During inflation, the PQ fields stabilize at large field values, leads to $f_{\text{inf}} \gg f_a$.

After inflation, the PQ fields starts to rolling towards its global minimum, which eventually gives f_a .

The existence of the flat direction suppresses the parametric production of axion. When reheating completed, thermal correction will not restore the PQ symmetry thanks to the additional scalar s .

Suppose that axion is originated from two complex scalar field, $\Phi_+(+1)$ and $\Phi_-(-1)$.

$$V_0 = \lambda |\Phi_+ \Phi_- - v^2|^2 + m_+^2 |\Phi_+|^2 + m_-^2 |\Phi_-|^2 + \lambda_{\phi_s} s^2 (\Phi_+ \Phi_- + \text{c.c.})$$

In the limit of $m_{\pm} \rightarrow 0$ and $\lambda_{\phi_s} \rightarrow 0$, flat direction is $\Phi_+ \Phi_- = v^2$.

$$\Phi_+ = \frac{\Phi_1 + \Phi_2}{\sqrt{2}}, \quad \Phi_- = \frac{\Phi_1^* - \Phi_2^*}{\sqrt{2}}$$

$$\Phi_1 = \frac{\phi}{\sqrt{2}} e^{ia/v_{\text{PQ}}}, \quad \Phi_2 = \frac{\xi + i\eta}{\sqrt{2}} e^{ia/v_{\text{PQ}}},$$

a is the axion and $\{\phi, \eta, \xi\}$ are three PQ scalars, $v_{\text{PQ}} = \sqrt{\langle \phi \rangle^2 + \langle \xi \rangle^2 + \langle \eta \rangle^2}$.

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

$$\begin{aligned} V_0 = & -\frac{1}{2}\mu_\phi^2\phi^2 + \frac{1}{2}\mu_\xi^2\xi^2 + \frac{1}{2}\mu_\eta^2\eta^2 \\ & + \frac{\lambda}{8}(\eta^2\phi^2 - \phi^2\xi^2 + \eta^2\xi^2) + \frac{\lambda}{16}(\phi^4 + \xi^4 + \eta^4) \\ & + \frac{\lambda_{\phi s}}{2}s^2\phi^2 - \frac{\lambda_{\phi s}}{2}s^2(\xi^2 + \eta^2) \\ & + y_j\phi\bar{\psi}_j\psi_j + \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4, \end{aligned}$$

The thermal potential

High reheating
temperature
without axion
domain walls

Yu-Cheng QIU

Introduction

Cosmology

Always Broken

Summary

$$V_{\text{eff}}(\phi, \xi, \eta, s, T) = V_0 + V_1 + \dots ,$$

$$V_1 = \sum_{i=\phi, \xi, \eta, s, \psi_j} \frac{n_i T}{2} \sum_{n=-\infty}^{\infty} \int \frac{d^3 \vec{k}}{(2\pi)^3} \log \left[\vec{k}^2 + \omega_n^2 + m_i^2(\phi, \xi, \eta, s) + \Pi_i(T) \right] ,$$

$$m_\phi^2 = -\mu_\phi^2 + \lambda_{\phi s} s^2 + \frac{3\lambda}{4} \phi^2 - \frac{\lambda}{4} \xi^2 + \frac{\lambda}{4} \eta^2 , \quad \Pi_\phi = \left(\sum_j \frac{y_j^2}{2} + \frac{\lambda}{16} + N_s \frac{\lambda_{\phi s}}{12} \right) T^2 ,$$

$$m_\xi^2 = \mu_\xi^2 - \lambda_{\phi s} s^2 - \frac{\lambda}{4} \phi^2 + \frac{3\lambda}{4} \xi^2 + \frac{\lambda}{4} \eta^2 , \quad \Pi_\xi = \left(\frac{\lambda}{16} - N_s \frac{\lambda_{\phi s}}{12} \right) T^2 ,$$

$$m_\eta^2 = \mu_\eta^2 - \lambda_{\phi s} s^2 + \frac{\lambda}{4} \phi^2 + \frac{\lambda}{4} \xi^2 + \frac{3\lambda}{4} \eta^2 , \quad \Pi_\eta = \left(\frac{5\lambda}{48} - N_s \frac{\lambda_{\phi s}}{12} \right) T^2 ,$$

$$m_s^2 = \mu_s^2 + 3\lambda_s s^2 + \lambda_{\phi s} \phi^2 - \lambda_{\phi s} (\xi^2 + \eta^2) , \quad \Pi_s = \left((N_s + 2) \frac{\lambda_s}{12} - \frac{\lambda_{\phi s}}{12} \right) T^2 ,$$

$$m_{\psi_j}^2 = y_j^2 \phi^2 .$$

The thermal potential

High reheating
temperature
without axion
domain walls

Yu-Cheng QIU

Introduction

Cosmology

Always Broken

Summary

$$V_1 = V_1^{(0)} + V_1^\beta + V_{\text{daisy}}$$

$$V_1^{(0)} = \sum_{i=\phi,\xi,\eta,s,\psi_j} \frac{n_i m_i^4}{64\pi^2} \left(\log \frac{m_i^2}{m_{0i}^2} - \frac{3}{2} \right),$$

$$V_1^\beta = \sum_{i=\phi,\xi,\eta,s} \frac{n_i T^4}{2\pi^2} J_b \left(\frac{m_i^2}{T^2} \right) + \sum_{j=1}^{N_\psi} \frac{n_{\psi_j} T^4}{2\pi^2} J_f \left(\frac{m_i^2}{T^2} \right),$$

$$V_{\text{daisy}} = \sum_{i=\phi,\xi,\eta,s} \frac{n_i T}{12\pi} \left[m_i^3 - (m_i^2 + \Pi_i)^{3/2} \right],$$

The parameter space

High reheating
temperature
without axion
domain walls

Yu-Cheng QIU

Introduction

Cosmology

Always Broken

Summary

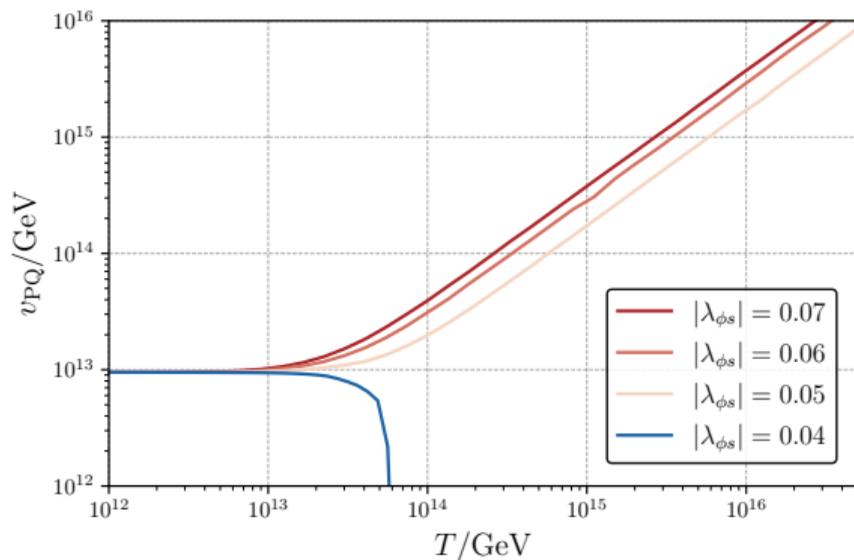


Figure: The PQ scale v_{PQ} against temperature T . Here we take $f_a = 10^{12}$ GeV, $\lambda = 0.03$, $m_{\psi} = 10^{11}$ GeV, $\mu_s = 4 \times 10^{12}$ GeV, $\mu_{\xi} = \mu_{\eta} = 2 \times 10^{12}$ GeV, $\lambda_s = 0.8$, $N_s = 1$ and $N_{DW} = N_{\psi} = 10$.

The parameter space

High reheating
temperature
without axion
domain walls

Yu-Cheng QIU

Introduction

Cosmology

Always Broken

Summary

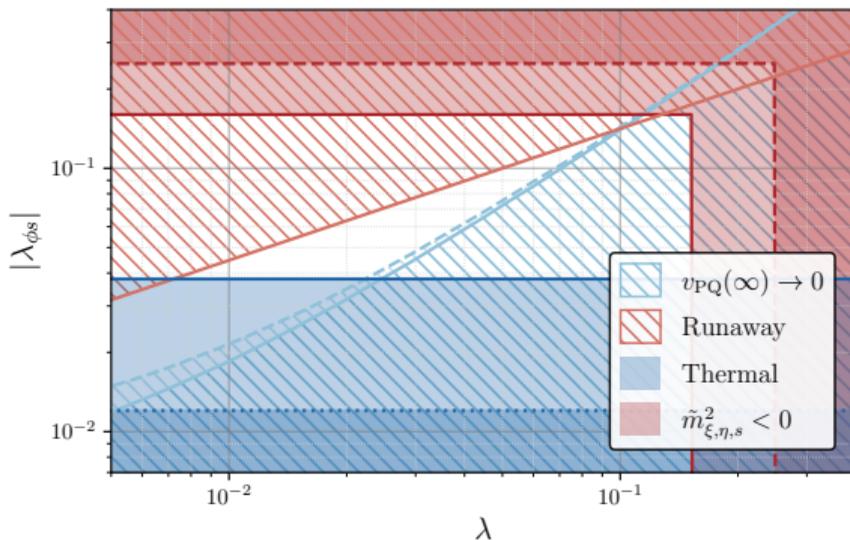


Figure: The runaway region is where $|\lambda_{\phi_s}| > \sqrt{\lambda_s \lambda} / 2$. The $v_{\text{PQ}}(\infty) \rightarrow 0$ indicates a failed protection. The $\tilde{m}_{\xi, \eta, s}^2 < 0$ region indicates the instability of expected vacuum solution. The solid (dashed) lines are limits under $f_a = 10^{12}$ (8×10^{11}) GeV. The thermal bounds (blue shaded region) are where s does not have thermal contact with PQ fields; the solid (dotted) line is obtained under $T_R = 10^{15}$ (10^{14}) GeV.

High reheating
temperature
without axion
domain walls

Yu-Cheng QIU

Introduction

Cosmology

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Summary

- Low reheating temperature gives pre-inflation axion, which usually has isocurvature problem.
- High reheating temperature gives post-inflation axion, which usually has domain wall problem.
- Our model allow high reheating temperature and free from both problems.

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

- SUSY?
- detailed Reheating?
- ...

High reheating
temperature
without axion
domain walls

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Introduction

Cosmology

Always Broken

Summary

Thank You!

High reheating
temperature
without axion
domain walls

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