High Reheating Temperature without Axion Domain Walls

based on arXiv: 2509.24812

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Content

Post-inflation PQ breaking and DWs

Why high reheating temperature (and small axion decay constant)?

- high reheating temperature $T_R \to$ favored by leptogenesis [Fukugita, Yanagida (1986)...]
- small axion decay constant (at current) $f_a \to$ detectability [Irastorza et. al.(2018), Irastorza(2022), Caputo et. al.(2024)...]

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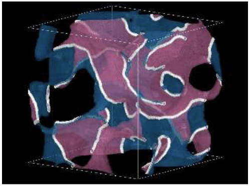

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$f_a \ll T_R$ ("post-inflation")

$N_{DW} = 2$ (domain walls take over)

Solutions?

- PQ breaking bias terms [Vilenkin (1981), Sikivie (1982), Gelmini et. al. (1989)...] $\rightarrow$ fine-tuning?

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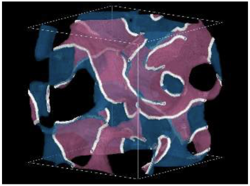

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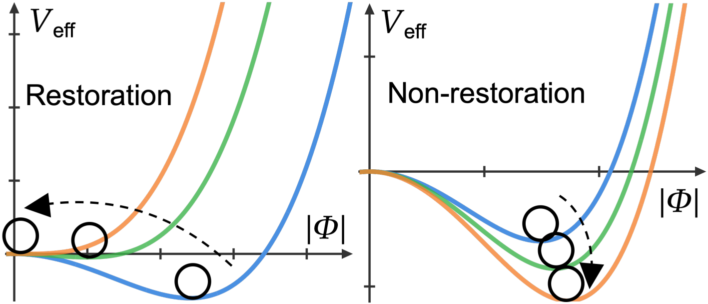
  $\rightarrow$ fine-tuning?
- symmetry non-restoration [Dvali et. al. (1995, 1996)...]

Symmetry non-restoration

$$V^{\beta}(|\Phi|) = c_2|\Phi|^2T^2 + \mathcal{O}(T^3)$$

$c_2 > 0$ $c_2 < 0$



Non-restoration can be realized by additional scalar(s) coupled to PQ field(s)

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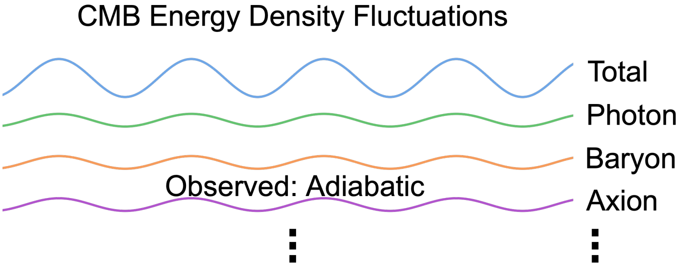
Problem during inflation

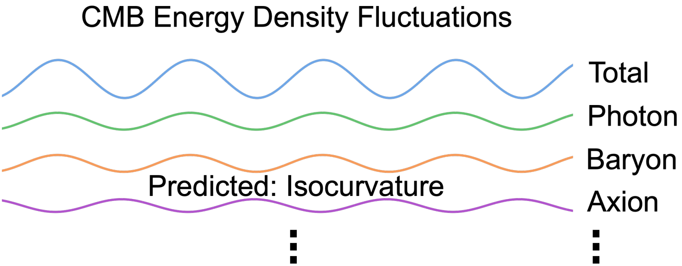


Fluctuations are spatially in phase (CMB anisotropy obervations e.g. WMAP and Planck)

$$\alpha_c \equiv \frac{\mathcal{P}_{S_c}}{\mathcal{P}_\zeta + \mathcal{P}_{S_c}} < 0.033$$

- $\mathcal{P}_\zeta \simeq 2 \times 10^{-9}$: curvature pert. power spectrum
- $\mathcal{P}_{S_c}$: isocurvature pert. power spectrum

Problem during inflation

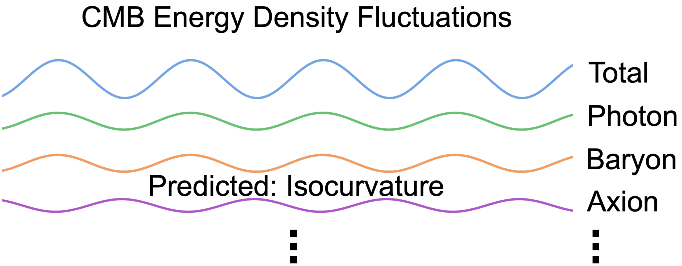


PQ field(s) develop uncorrelated phase(s) $\delta\theta \sim H_{\rm inf}/(2\pi f_a)$ during inflation.

$$\mathcal{P}_{S_c} = \left(\frac{\delta\Omega_a}{\Omega_c}\right)^2 \simeq 1.4 \times (\theta^2 + \delta\theta^2)\left(\frac{H_{\rm inf}}{2\pi f_a}\right)^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{2.38}$$

$f_a \sim 10^{12}\mathrm{GeV} \rightarrow H_{\rm inf} \lesssim 10^8\mathrm{GeV}$... Unavoidable if PQ was already broken before inflation.

Solution to the isocurvature problem



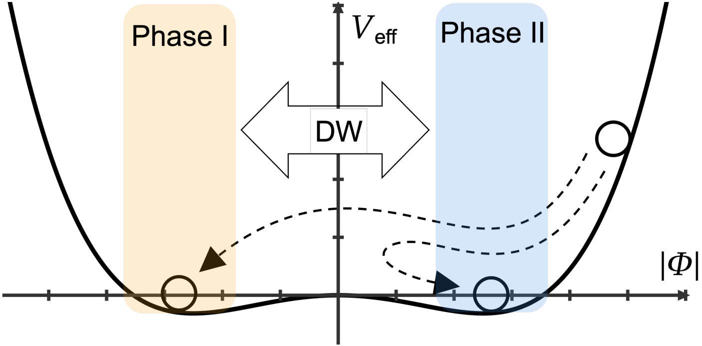
If PQ field(s) had a much larger VEV during inflation [Linde (1991)]... $\delta\theta \sim H_{\rm inf}/(2\pi f_{\rm inf})$ during inflation

$$\mathcal{P}_{S_c} = \left(\frac{\delta\Omega_a}{\Omega_c}\right)^2 \simeq 1.4 \times (\theta^2 + \delta\theta^2)\left(\frac{H_{\rm inf}}{2\pi f_{\rm inf}}\right)^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{2.38}$$

Isocurvature perturbation is suppressed, as $f_a \sim 10^{12}\mathrm{GeV}, f_{\rm inf} \sim 0.1 M_{\rm Pl} \to H_{\rm inf} \lesssim 10^{14}\mathrm{GeV}$

Problem in the reheating epoch

Parametric resonance induced topological defects production



Potential for spontaneously breaking $U(1)_{PQ}$

Solution to parametric resonance

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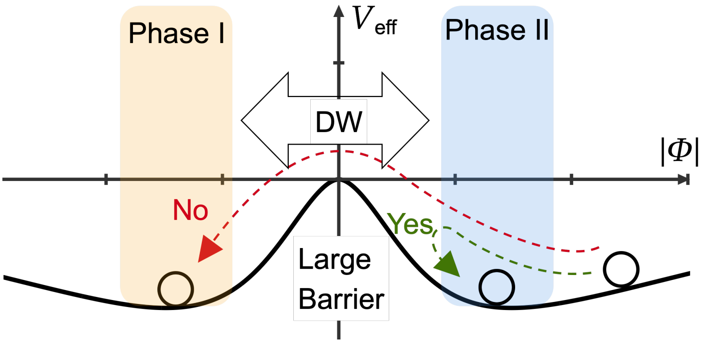
How to control the parametric resonance to avoid transitions to different vacua?

- A large potential barrier



Any natural realization?

Solution to parametric resonance

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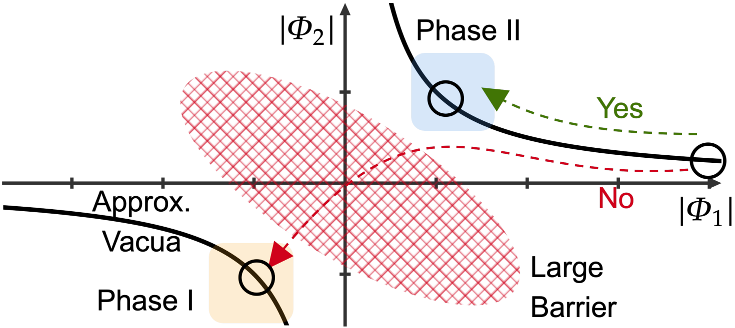
Schematic realization of the large potential barrier [Kasuya, Kawasaki, Yanagida(1997), Kawasaki, Sonomoto(2018), Kawasaki, Sonomoto, Yanagida(2018)]



$$V_0 \supset \lambda \left|\Phi_1\Phi_2 - v^2\right|^2 + m_1^2\left|\Phi_1\right|^2 + m_2^2\left|\Phi_2\right|^2$$

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The model

In the KSVZ framework,

$$
\begin{aligned}
V_0 = & \lambda \left| \Phi_+ \Phi_- - v^2 \right|^2 \\
& + m_+^2 \left| \Phi_+ \right|^2 + m_-^2 \left| \Phi_- \right|^2 \\
& + \lambda_{\phi s} s^2 \left(\Phi_+ \Phi_- + \text{c.c.} \right) \\
& + \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 \\
& + y(\Phi_+ + \Phi_-^*) \bar{\psi} \psi
\end{aligned}
$$

- Φ: PQ fields
- s: scalar singlet
- ψ: KSVZ quarks

Unzip axion

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

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

- a: axion
- ϕ, ξ, η: real scalars
- $v_{PQ} = \sqrt{\langle \phi \rangle^2 + \langle \xi \rangle^2 + \langle \eta \rangle^2}$
- $(v_{PQ})_{\rm inf} \sim 0.1 M_{\rm Pl}$ due to (negative) Hubble induced mass

Thermal masses at high-temperature

PQ fields - scalar singlet coupling highlighted

$$V_0 \supset \frac{\lambda_{\phi s}}{2} s^2 \phi^2 - \frac{\lambda_{\phi s}}{2} s^2 \left(\xi^2 + \eta^2\right)$$

$$V_{\rm eff}(\phi, \xi, \eta, s, T) = V_0 + V_1^\beta + \cdots$$

Leading order finite temperature correction

$$V_1(T)^\beta = \sum_{i=\phi,\xi,\eta,s,\psi_j} \frac{n_i T}{2} \sum_{n=-\infty}^{\infty} \int \frac{d^3\vec{k}}{(2\pi)^3}$$

$$\times \log\left[\vec{k}^2 + \omega_n^2 + m_i^2(\phi, \xi, \eta, s) + \Pi_i(T)\right]$$

Debye mass (finite temperature mass shifts)

$$\Pi_\phi = \left(\sum_j \frac{y_j^2}{2} + \frac{\lambda}{16} + N_s \frac{\lambda_{\phi s}}{12}\right) T^2 ,$$

$$\Pi_\xi = \left(\frac{\lambda}{16} - N_s \frac{\lambda_{\phi s}}{12}\right) T^2 ,$$

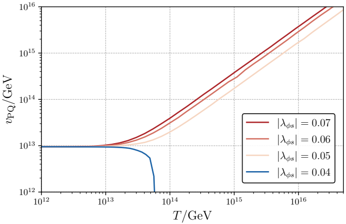
$$\Pi_\eta = \left(\frac{5\lambda}{48} - N_s \frac{\lambda_{\phi s}}{12}\right) T^2 ,$$

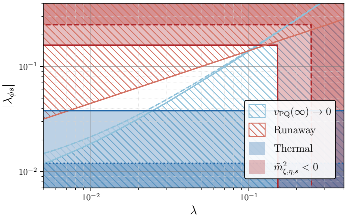
$$\Pi_s = \left((N_s + 2)\frac{\lambda_s}{12} - \frac{\lambda_{\phi s}}{12}\right) T^2$$

For $\lambda_{\phi s} < 0$ and proper N_s, $\Pi_\phi < 0$ can be realized

Parameter spaces

The parameter space opens up in the presence of one scalar singlet





- $f_a = 10^{12}$GeV
- $\lambda = 0.03$, $\lambda_s = 0.8$
- $\mu_s = 4 \times 10^{12}$GeV, $\mu_\xi = \mu_\eta = 2 \times 10^{12}$GeV, $m_\psi = 10^{11}$GeV
- $N_s = 1$, $N_{DW} = N_\psi = 10$

Summary

- **small** f_a and **large** T_R without the domain wall problem
- **one** extra scalar singlet
  - PQ symmetry retains unbroken through entire the thermal history
- **two** PQ scalars with large VEVs during inflation
  - suppress isocurvature perturbation
  - avoid parametric resonance production of topological defects

Thank you for your attention