Hybrid Inflation driven by the QCD axion

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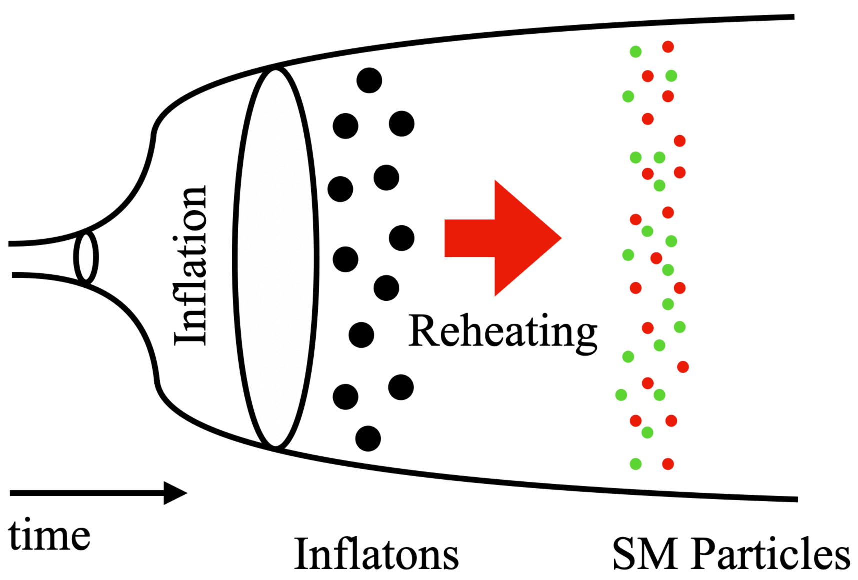
1. Introduction

To achieve a successful reheating after inflation, the inflaton must interact with Standard Model particles.



We consider a coupling to **gluon Chern-Simons term**:

$\phi G\tilde{G}$. (ϕ : inflaton, G : gluon field strength)

This is a natural possibility if ϕ is an axion.

The QCD axion is needed to solve the Strong CP problem through the coupling with gluons as

$aG\tilde{G}$. (a : QCD axion)

✔ **The QCD axion can mix with the inflaton** if the Hubble parameter below the QCD scale.

✔ It is one of the candidates for Dark Matter(DM).

2. Setup in our model

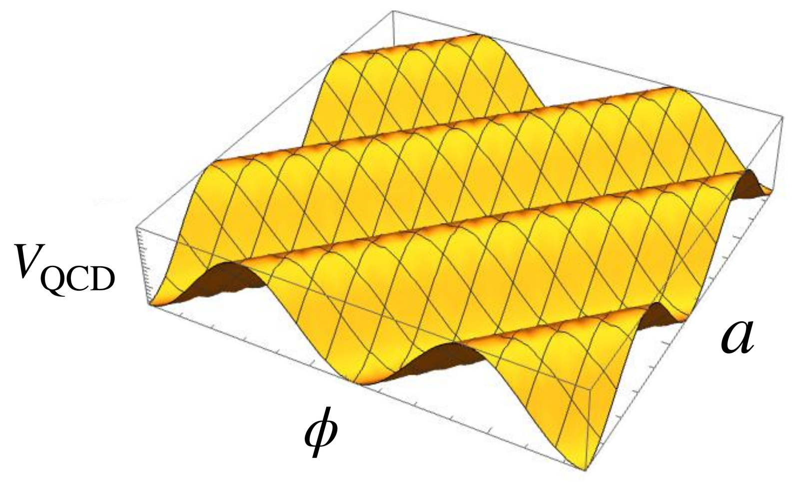
Let us introduce an Axion-Like Particle (ALP) ϕ, which is coupled to gluons in the similar way to the QCD axion a,

$$\mathscr{L} \supset \frac{\alpha_{st}}{8\pi}\left(\frac{a}{f_a} - n_{mix}\frac{\phi}{f_\phi}\right)G\tilde{G},$$

where n_{mix} is an integer.

Through this coupling, they acquire the QCD potential :

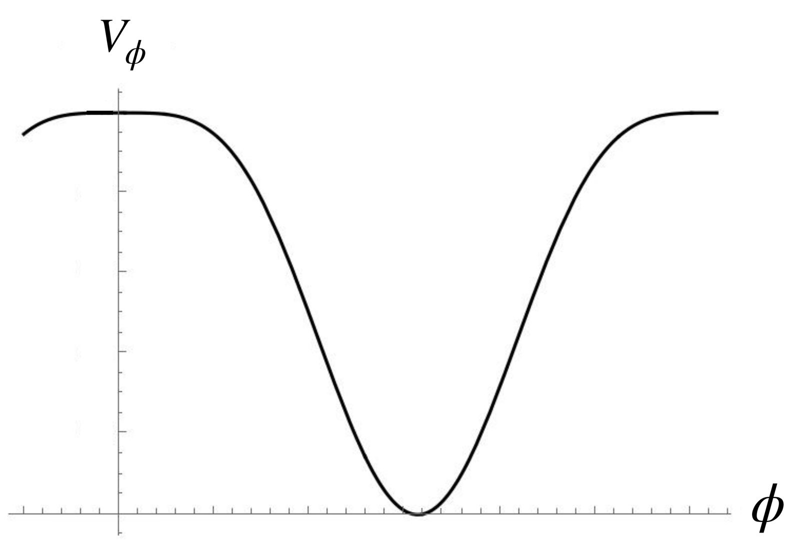
$$V_{\rm QCD}(a,\phi) = \chi_0\left[1-\cos\left(\frac{a}{f_a} - n_{mix}\frac{\phi}{f_\phi}\right)\right],$$



where $\chi_0 \simeq (75.6{\rm MeV})^4$.

We also consider that the ALP has its own potential with a periodicity of $2\pi f_\phi$:

$V_\phi(\phi) = V_\phi(\phi + 2\pi f_\phi)$.



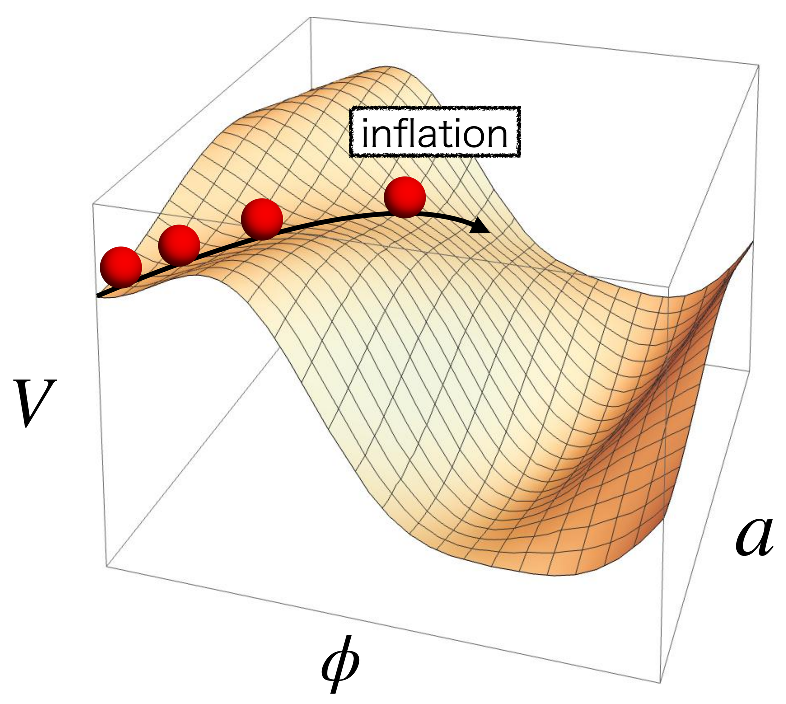
We focus on

$$V_\phi(\phi) = \Lambda^4\left[\cos\left(\frac{\phi}{f_\phi}\right) - \frac{1}{n^2}\cos\left(n\frac{\phi}{f_\phi}\right)\right] + {\rm const.},$$

where $n(>1)$ is an even integer.

Then, the total potential is given by

$V(a,\phi) = V_{\rm QCD}(a,\phi) + V_\phi(\phi)$.



3. Calculation Results

Hubble parameter
$H_{\rm inf} \approx 0.1{\rm eV} < \Lambda_{\rm QCD}$

We find the following parameters:

$$f_a = 5\times10^9{\rm GeV},\ f_\phi \approx 2\times10^7{\rm GeV},\ \Lambda\approx 18{\rm TeV},\ n=2,\ n_{\rm mix}=1,$$

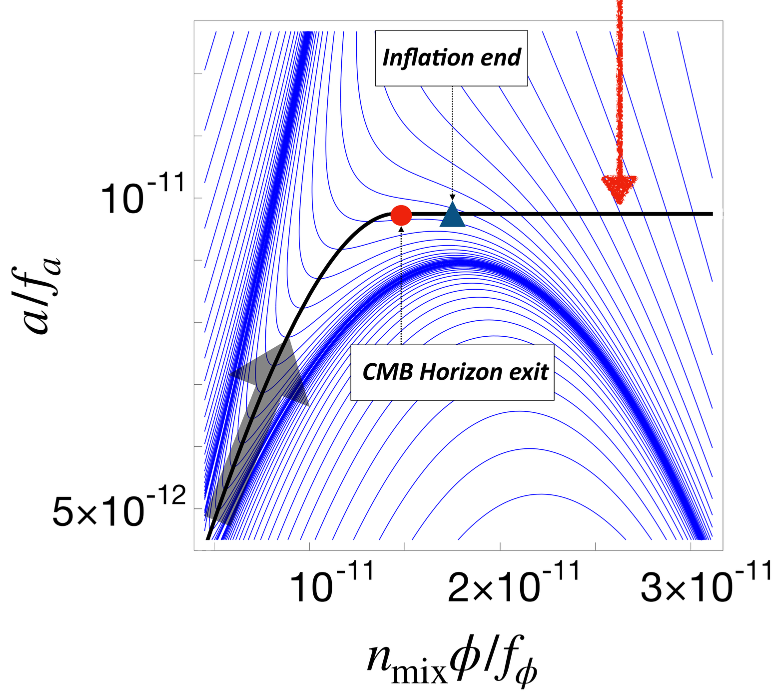
which are consistent with the CMB observations.

This parameter set also explain the QCD axion DM.

Inflationary dynamics

Trajectory

The field value of the QCD axion is frozen after inflation.



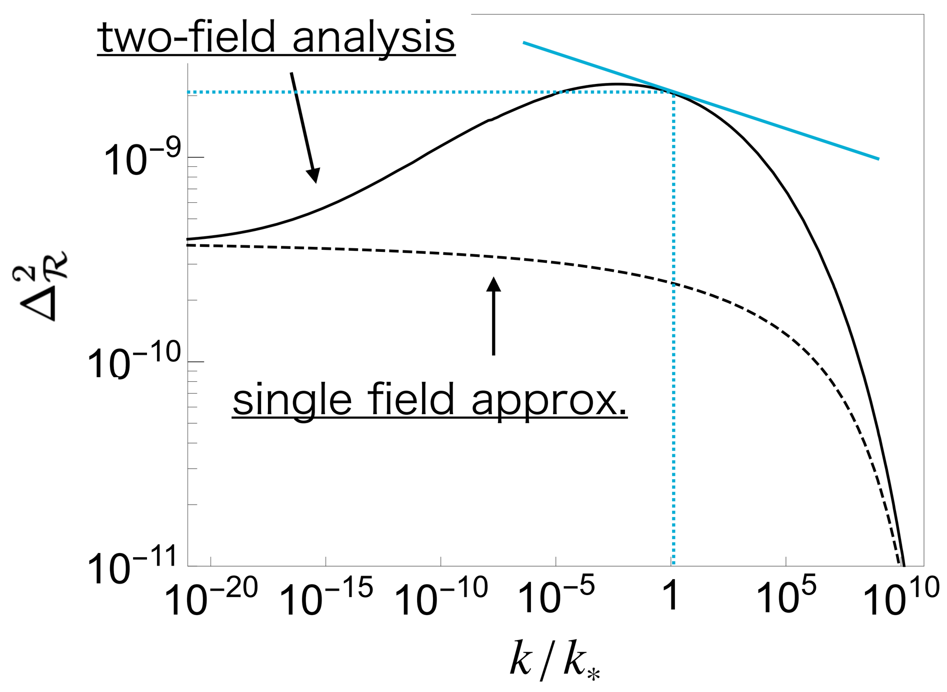
- The QCD axion drives the inflation at an early stage.
- Both mass eigenvalues are lighter than $H_{\rm inf}$.

⇩

We need to consider the two-field effect.

🔍 We numerically calculate the time evolution of the both fluctuations.

Power spectrum of curvature perturbation



CMB normalization is

$\Delta^2_{\mathcal{R}}(k_*) \simeq 2.1\times10^{-9}$.

The observed spectral index is

$n_s(k_*) \simeq 0.965$.

- The fluctuations of both scalars affect on the power spectrum.
- This result can successfully explain the CMB data!

QCD axion abundance and DM

The QCD axion abundance generated by the misalignment mechanism is given by

a_i is fixed!

$$\Omega_a h^2 \simeq 0.0092 F(\theta_i)\theta_i^2\left(\frac{f_a}{10^{11}{\rm GeV}}\right)^{1.17},\ \theta_i \equiv \frac{|a_i - a_{\rm min}|}{f_a},$$

where the function $F(\theta_i)$ is

$$F(\theta_i) \equiv \left[\log\left(\frac{e}{1-\theta_i^2/\pi^2}\right)\right]^{1.17},$$

In this case, $f_a = 5\times10^9{\rm GeV}$, $a_{\rm min} = \pi$, and $\theta_i \sim \pi - 10^{-11}$.

So, we can estimate the QCD axion abundance: $\Omega_a h^2 \sim 0.12$.

➡ **The QCD axion explains all DM!**

Summary

- Through the detailed analysis of the two axion fields, we have identified the viable parameters and shown that the QCD axion can be not only the inflaton but also DM.
- This scenario can be probed in the axion direct search experiments such as IAXO, and in future CMB and BAO experiments.
- Also, The ALP ϕ may probed by future accelerator experiments.
- Interestingly, we can solve the quality problem of Peccei-Quinn symmetry by the requirement of successful inflation and the axion DM bound.