Hybrid inflation driven by QCD axion

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Based on 2204.XXXX in collaboration with Fuminobu Takahashi, Wen Yin

Introduction

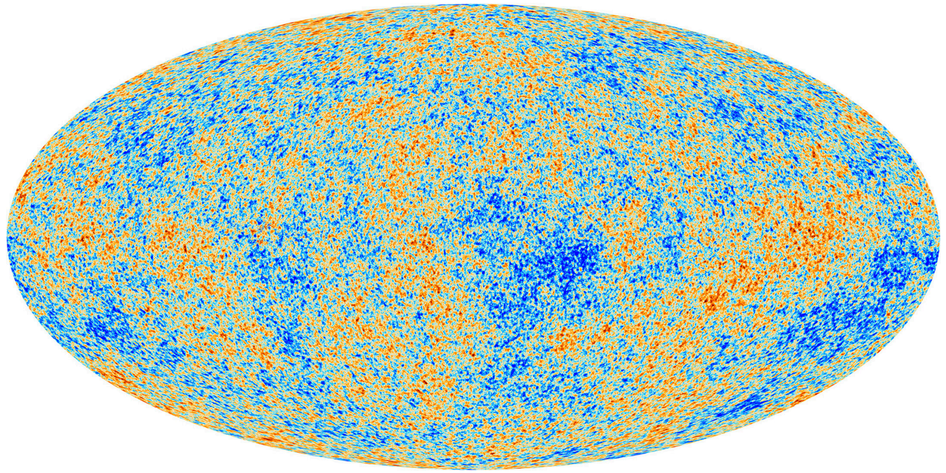
Inflation generates primordial density fluctuations that explain the CMB and large-scale structure.

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

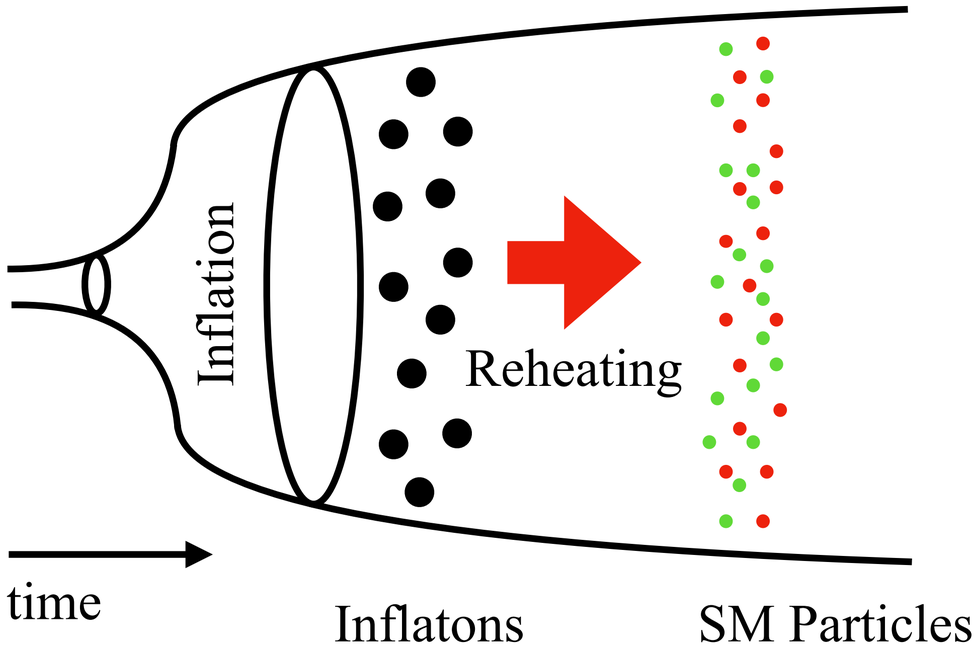
We consider a coupling to gluon Chern-Simons term:

$$\phi G\tilde{G} \quad (\phi : \text{inflaton}, G : \text{gluon field strength})$$

(e.g. ϕ can be taken as axion.)



ESA and the Planck Collaboration



QCD axion

- The QCD axion solves the strong CP problem.
- It is one of the candidates for Dark Matter.
- It is also coupled with the gluon Chern-Simons term:

$$\mathscr{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} \qquad (a : \text{QCD axion field}, f_a : \text{decay constant of } a)$$

▷The QCD axion can **mix** with the inflaton we consider.

During inflation, the inflaton is very light, so mixing with QCD axion could affect the evolution of both.

What we did

- We consider a scenario in which the QCD axion becomes a part of inflationary sector through the **mixing** with the inflaton.
- We show that if the energy scale of inflation is lower than the QCD scale, **hybrid inflation** is realized.
- **The initial misalignment angle of the QCD axion is determined by the inflationary dynamics.**

Potential in our inflation model

Let us take the potential to the inflaton ϕ and the QCD axion a:

$$V(a,\phi) = V_\phi(\phi) + V_a(\phi, a)$$

ϕ : inflaton field a : QCD axion field

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

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

$$\Rightarrow \quad V_a(a,\phi) = \chi_0 \left[1 - \cos\left(\frac{a}{f_a} - n_{mix}\frac{\phi}{f_\phi}\right)\right]$$

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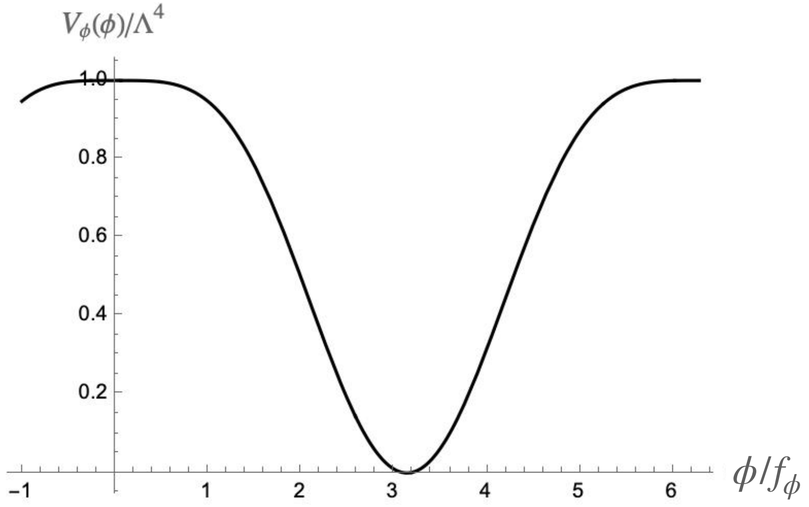
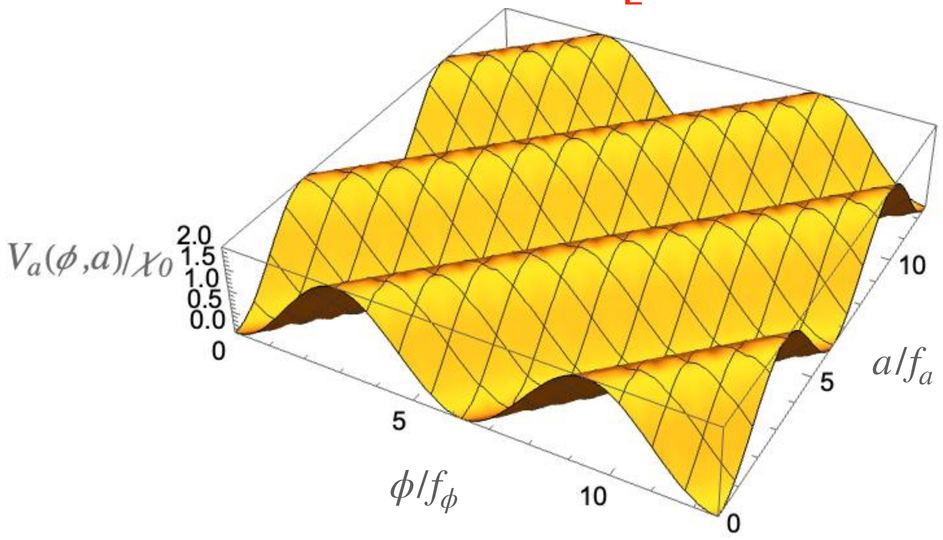
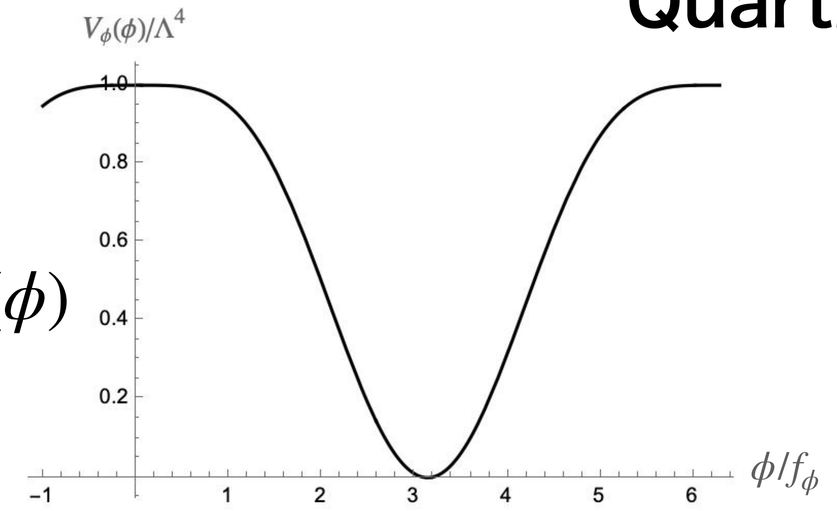




Quartic hilltop

$V_\phi(\phi)$



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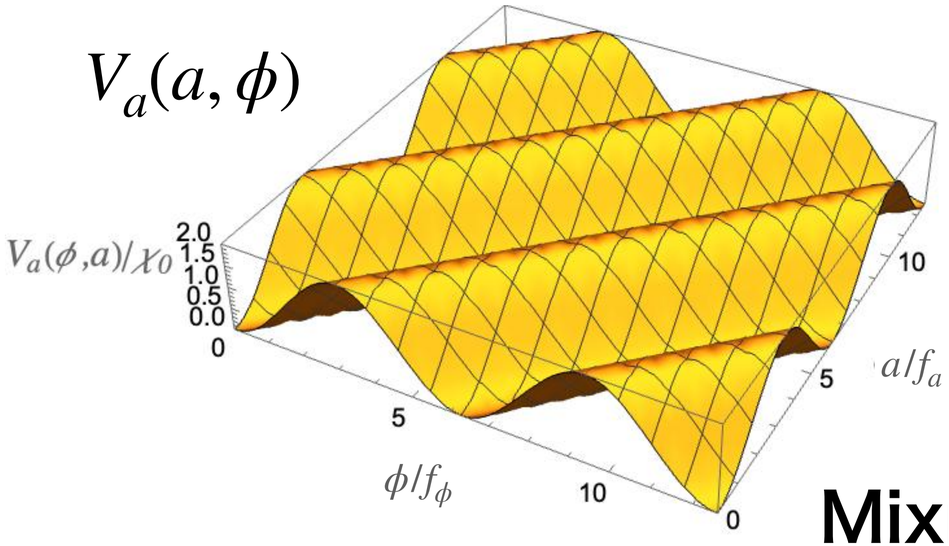
$V_a(a,\phi)$



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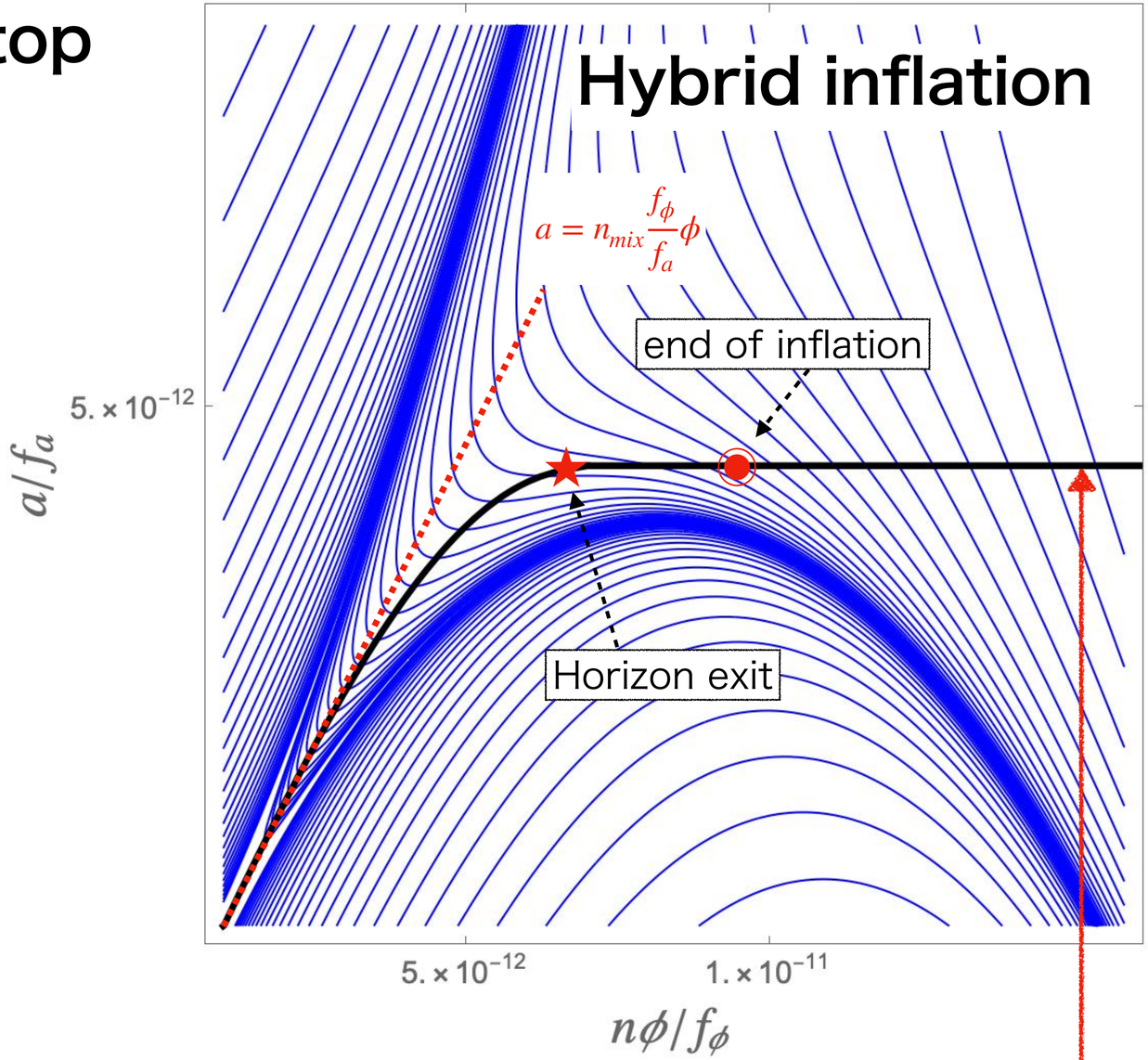
Mixing

Hybrid inflation



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

Estimated range of f_a in Hybrid QCD axion inflation

- $H_{inf} \lesssim \Lambda_{QCD}$

  We are interested in non-perturbative QCD effects.

  → $\Lambda \lesssim \sqrt{\Lambda_{QCD} M_{pl}} \sim 10^9\,\mathrm{GeV}$

- COBE normalization

  Quartic hilltop inflation : $V_{eff}(A_L) = \Lambda^4 - \lambda_{eff} A_L^4$

  From COBE normalization, $\lambda_{eff} = (\Lambda/f_a)^4 \sim 10^{-13}$

  → $f_a \sim 10^3 \Lambda$

- Mixing to be effective

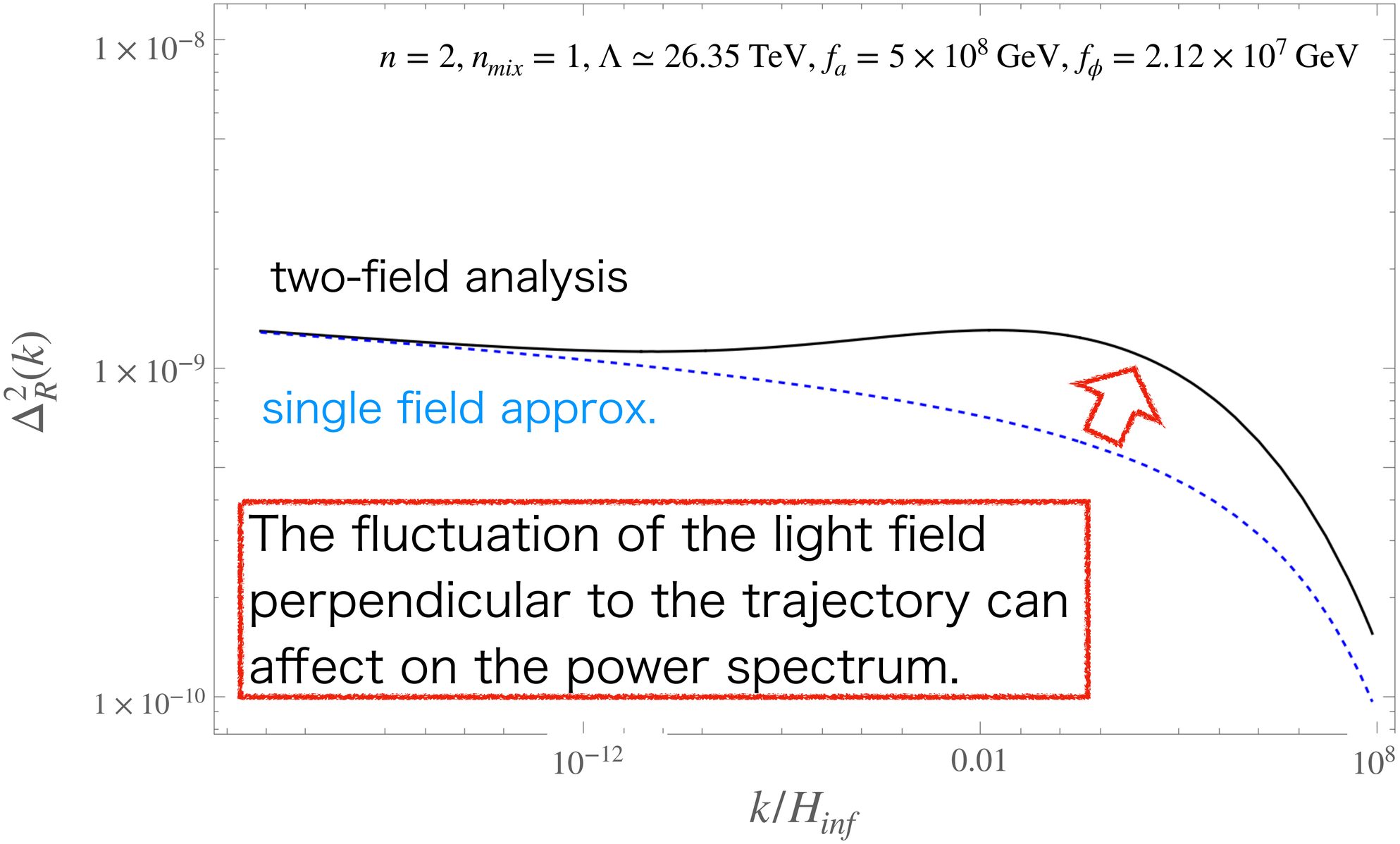
  To realize hybrid inflation, $M_H^2 \sim \chi_0/f_\phi^2 \gtrsim H_{inf}^2$

  → $\Lambda^2 f_\phi \lesssim 10^{17}\mathrm{GeV}^3$

Also, perturbative bound → $f_\phi \gtrsim 4\pi\Lambda$

We can estimate $f_a \sim 10^{8-9}\mathrm{GeV}$.

Power spectrum of curvature perturbations



Spectral index

measured spectral index

$n_s = 0.9647 \pm 0.0043$

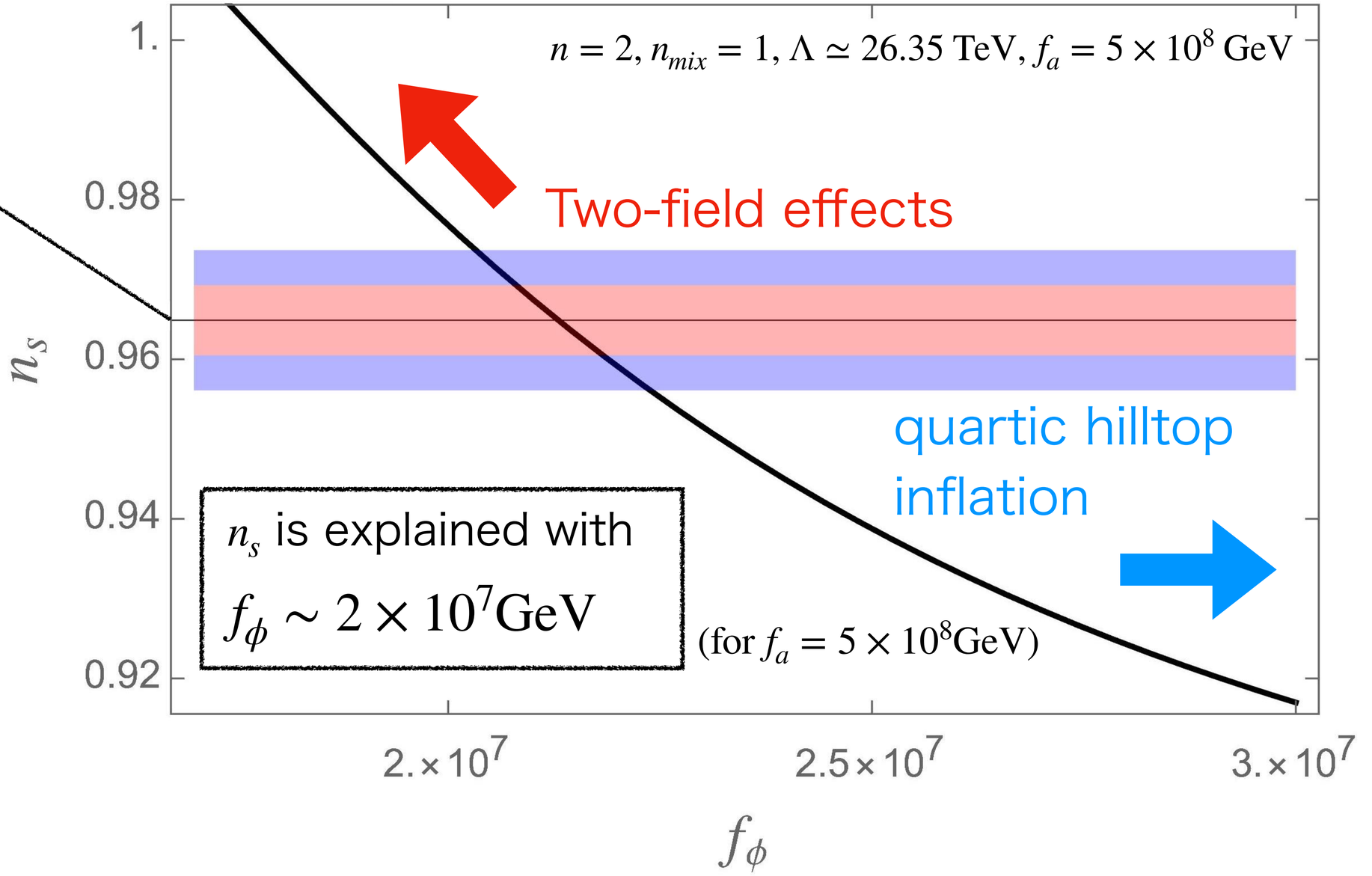
Planck 2018 collaboration

Typical cosmological parameters

$H_{inf} \simeq 0.2\text{eV}$

$N_* \simeq 28.5$

→ Low scale inflation



QCD axion abundance

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

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

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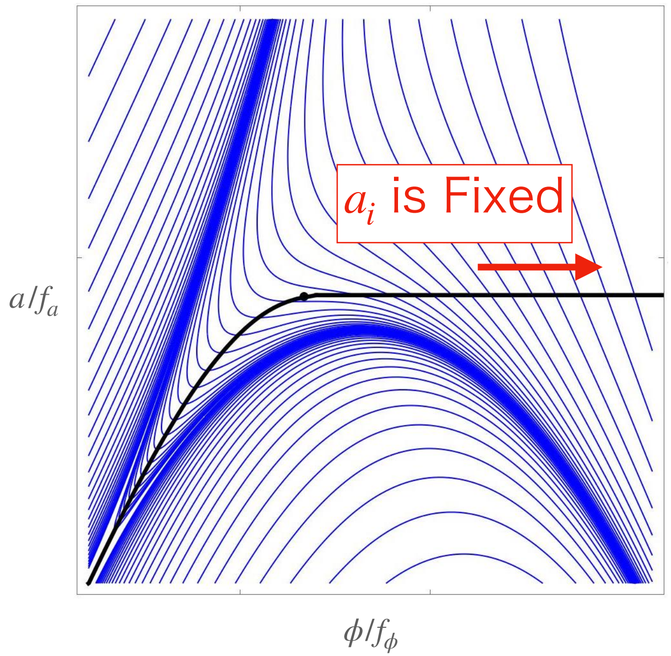
The initial value of the QCD axion a_i is fixed by the inflationary dynamics

→ **QCD axion abundance can be determined.**



e.g. $n = 2, n_{mix} = 1$

We have $\theta_i \simeq \pi$. If $f_a \sim 10^9\mathrm{GeV}$, the QCD axion explains all the dark matter.

Summary

- We showed that the hybrid inflation driven by the QCD axion can be realized due to the mixing between QCD axion and inflaton.
- The initial misalignment angle of the QCD axion θ_i is determined by this inflationary dynamics.

➡ QCD axion dark matter and inflation can be closely related!

- The heavy axion that is also the inflaton can be explored by experiments such as LHC.