Hybrid inflation with QCD axion Dark Matter

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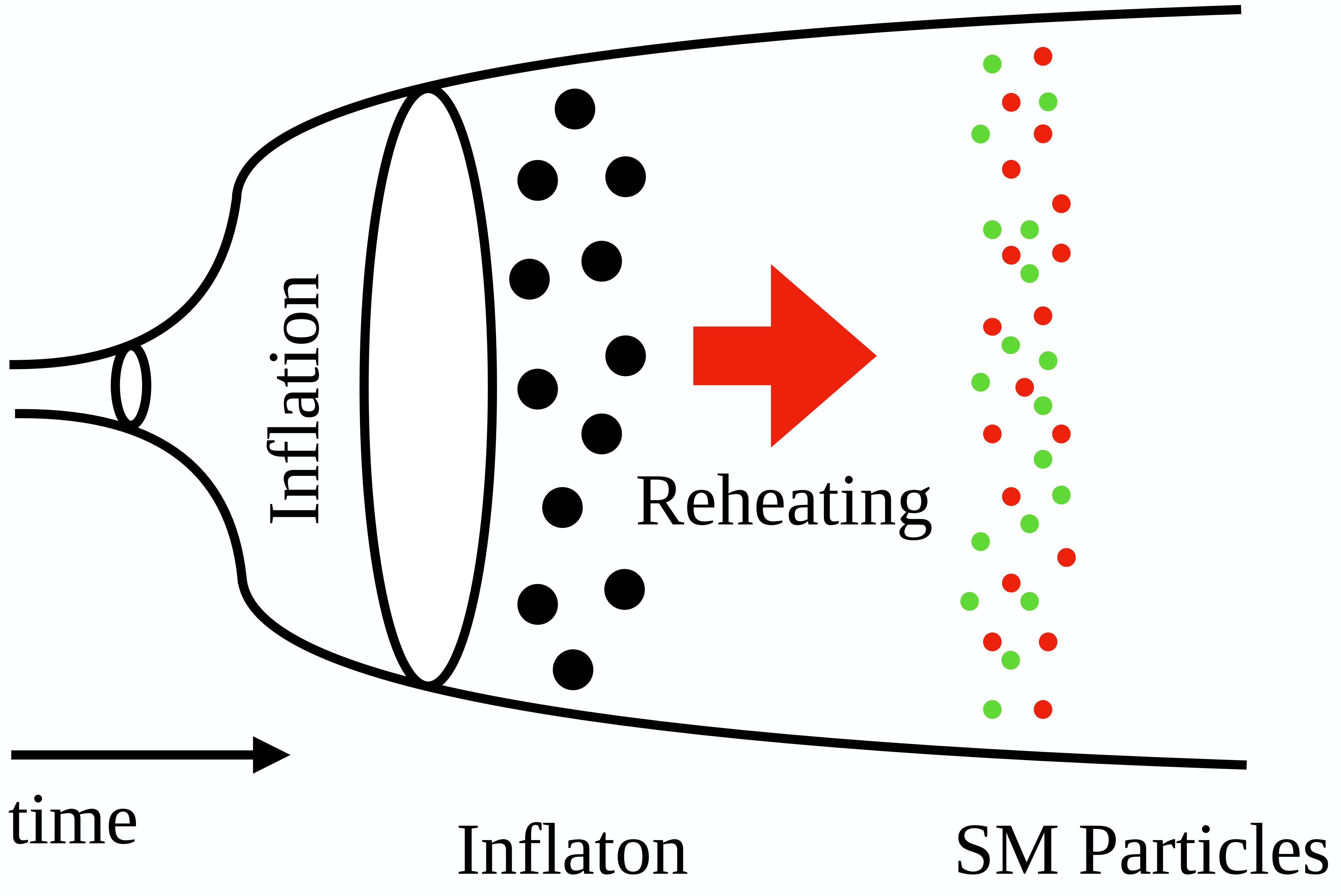
Based on JCAP 12 (2023) 039 in collaboration with Fuminobu Takahashi, Wen Yin

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**:

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

✓ This is a natural possibility if the inflaton ϕ is an axion.

Introduction

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

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

Peccei, Quinn 1977; Weinberg, Wilczek 1978

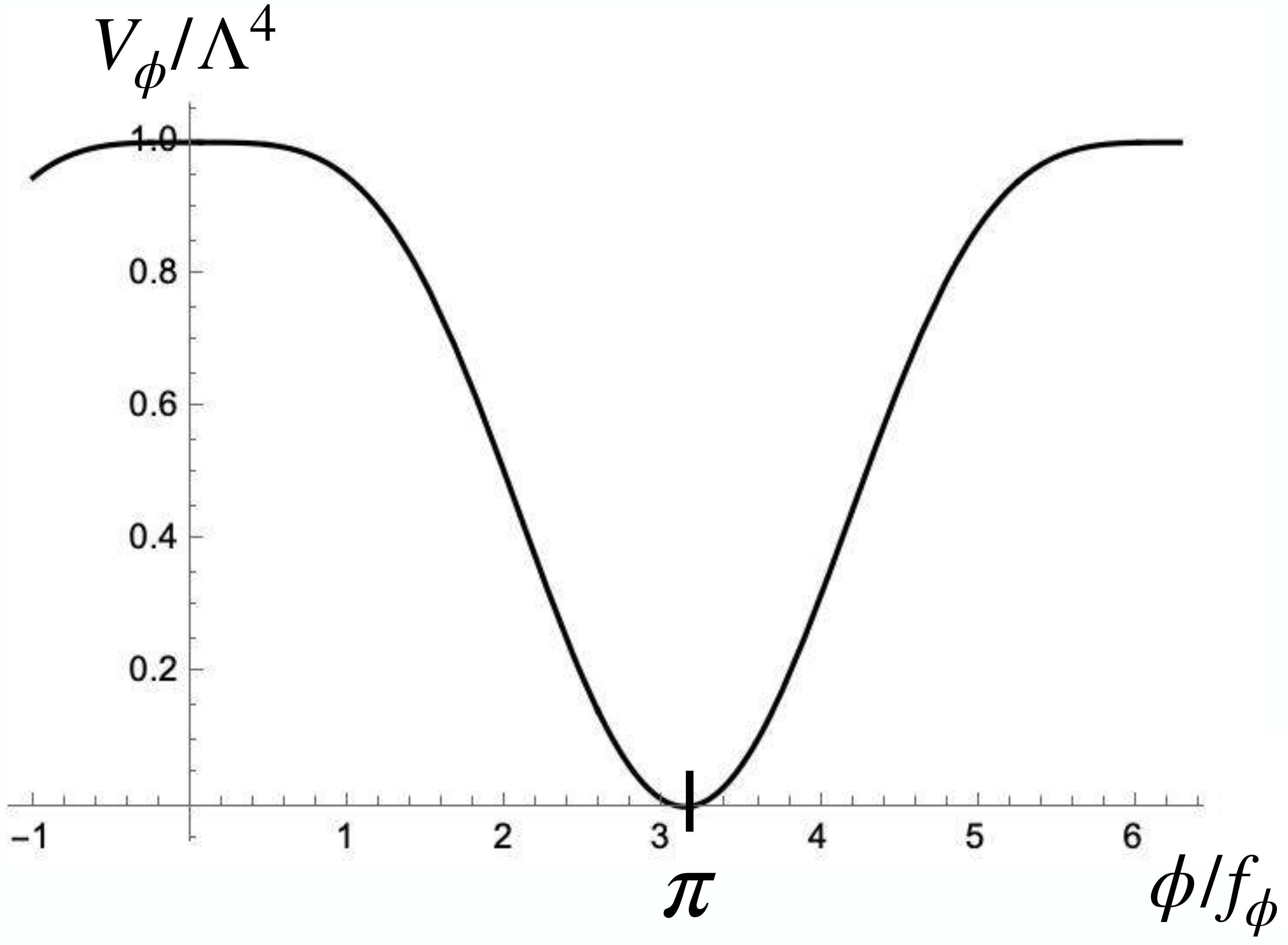
$$aG\tilde{G} \qquad (a : \text{QCD axion})$$

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

✔ **Mixing with QCD axion could affect the evolution of both.**

Hilltop Potential for ALP

Let us introduce an axion-like particle (ALP), which has its own potential $V_\phi(\phi)$ with a periodicity of $2\pi f_\phi$.



Let us adopt a model with two cosine terms

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

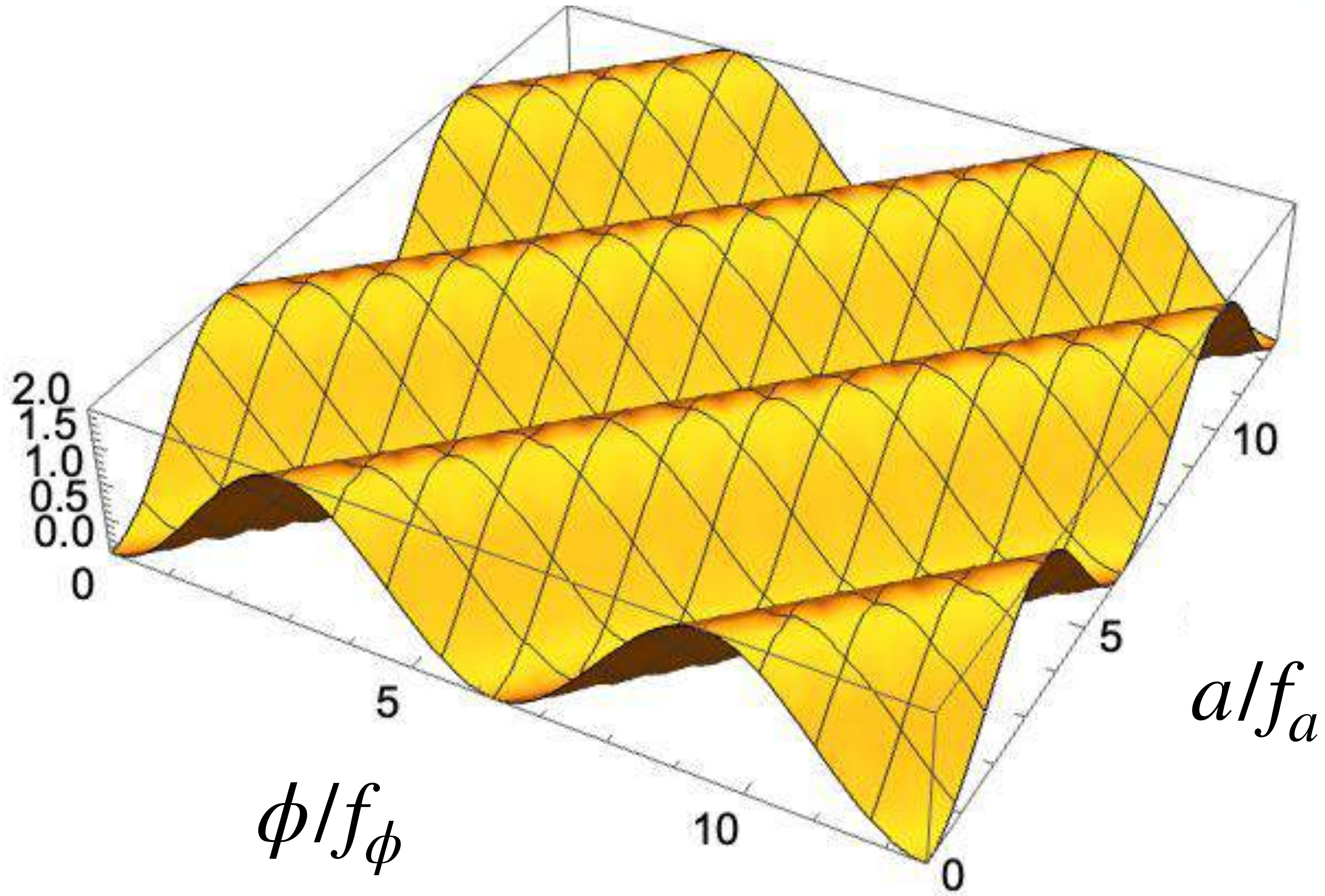
Czerny, Takahashi 1401.5212

for the successful inflation.

QCD Potential

The ALP ϕ is coupled to gluons in a similar to the QCD axion a:

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



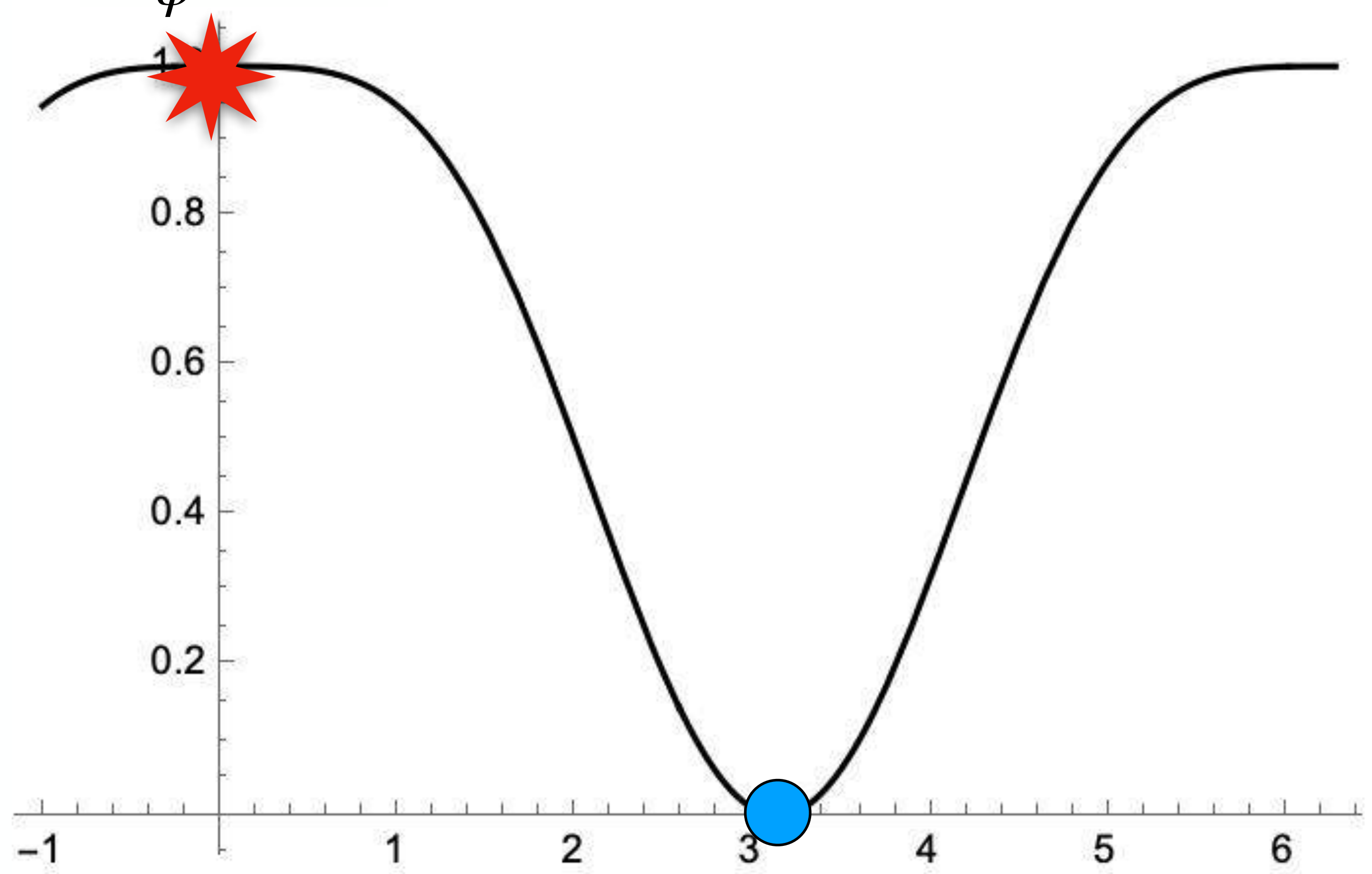
This leads to the QCD potential,

$$V_{\rm QCD}(a,\phi) = \chi(T)\left[1 - \cos\left(\frac{a}{f_a} - n_{mix}\frac{\phi}{f_\phi}\right)\right], \quad \chi(T) = \begin{cases} \chi_0 \sim (75.6\text{MeV})^4 & T \lesssim \Lambda_{\rm QCD} \\ \chi_0 (T_{\rm QCD}/T)^{8.16} & T \gtrsim \Lambda_{\rm QCD} \end{cases}$$

Borsanyi, et al. 1606.07494

where $\chi(T)$ is the topological susceptibility.

Total Potential



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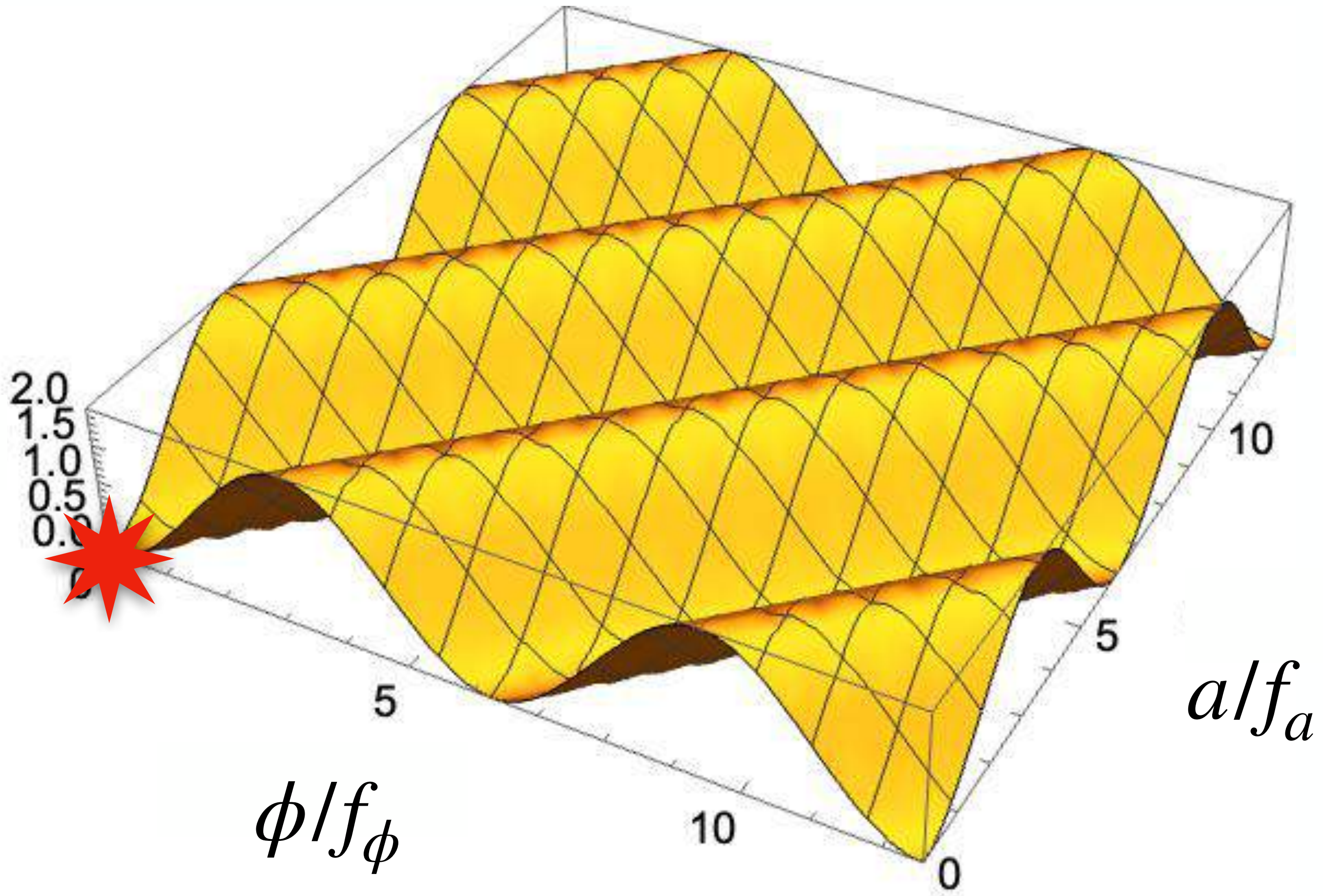
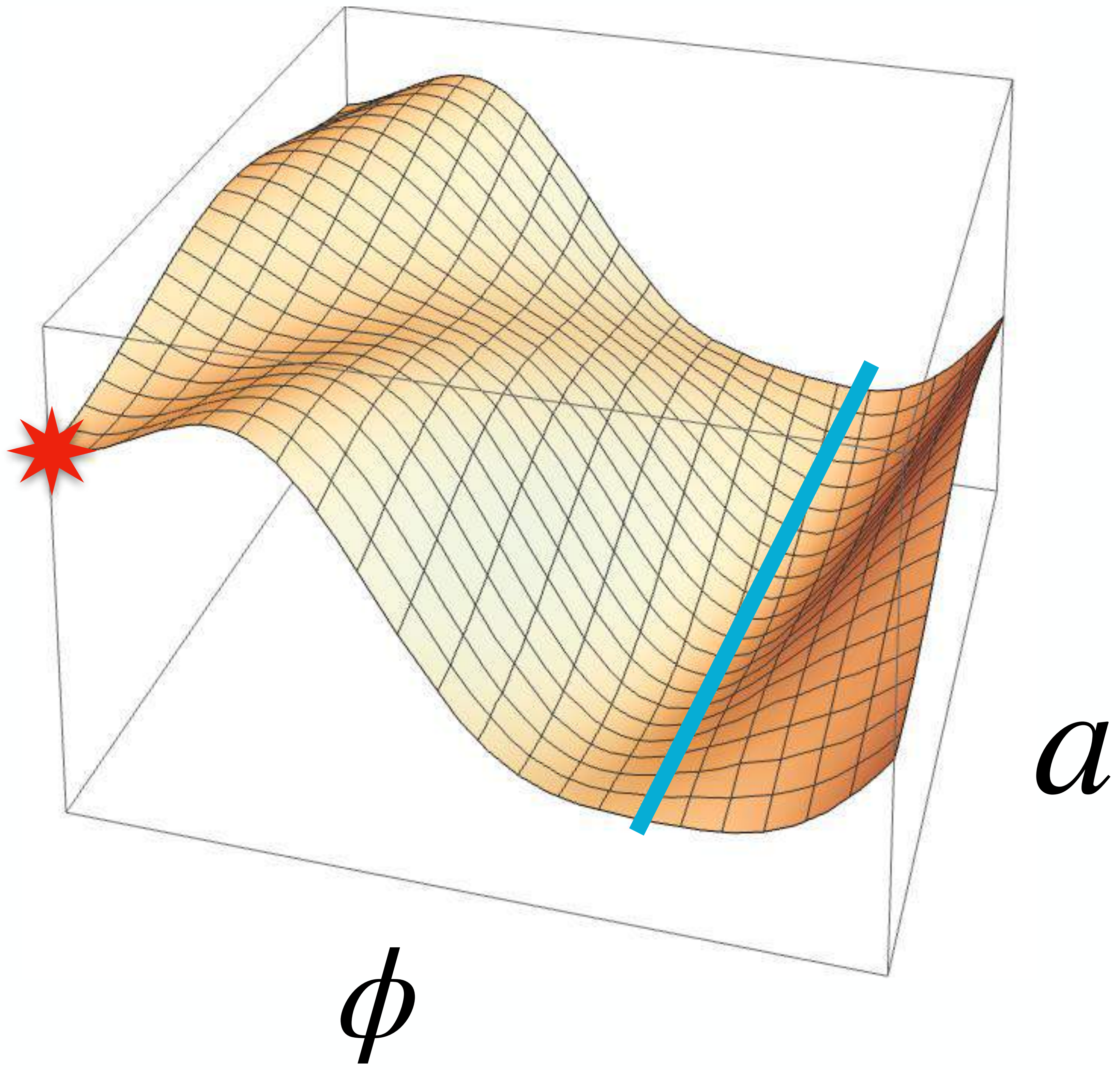


$$V(a,\phi) = V_\phi(\phi) + V_{\rm QCD}(a,\phi)$$

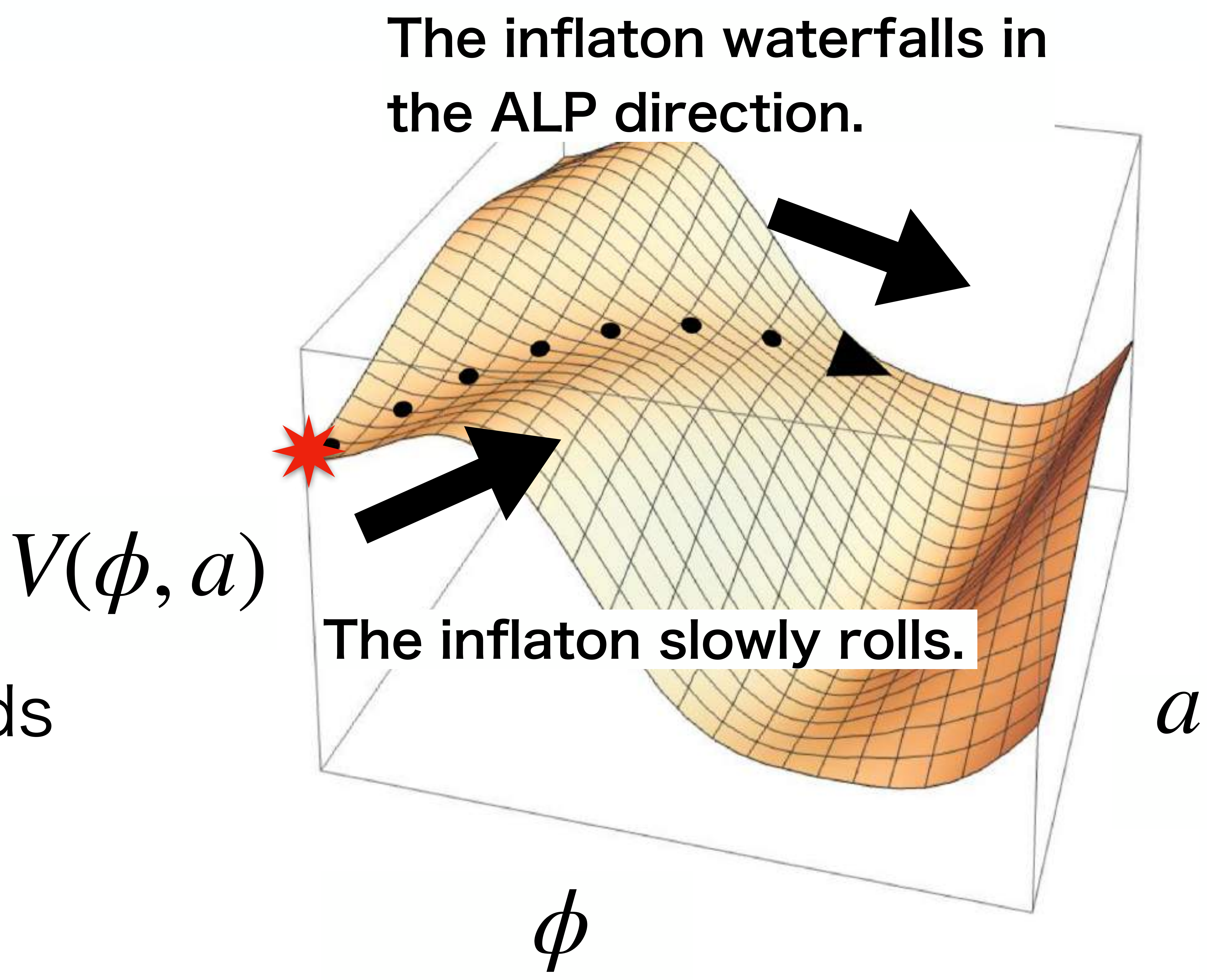
$=\ V(a,\phi)$



The total potential

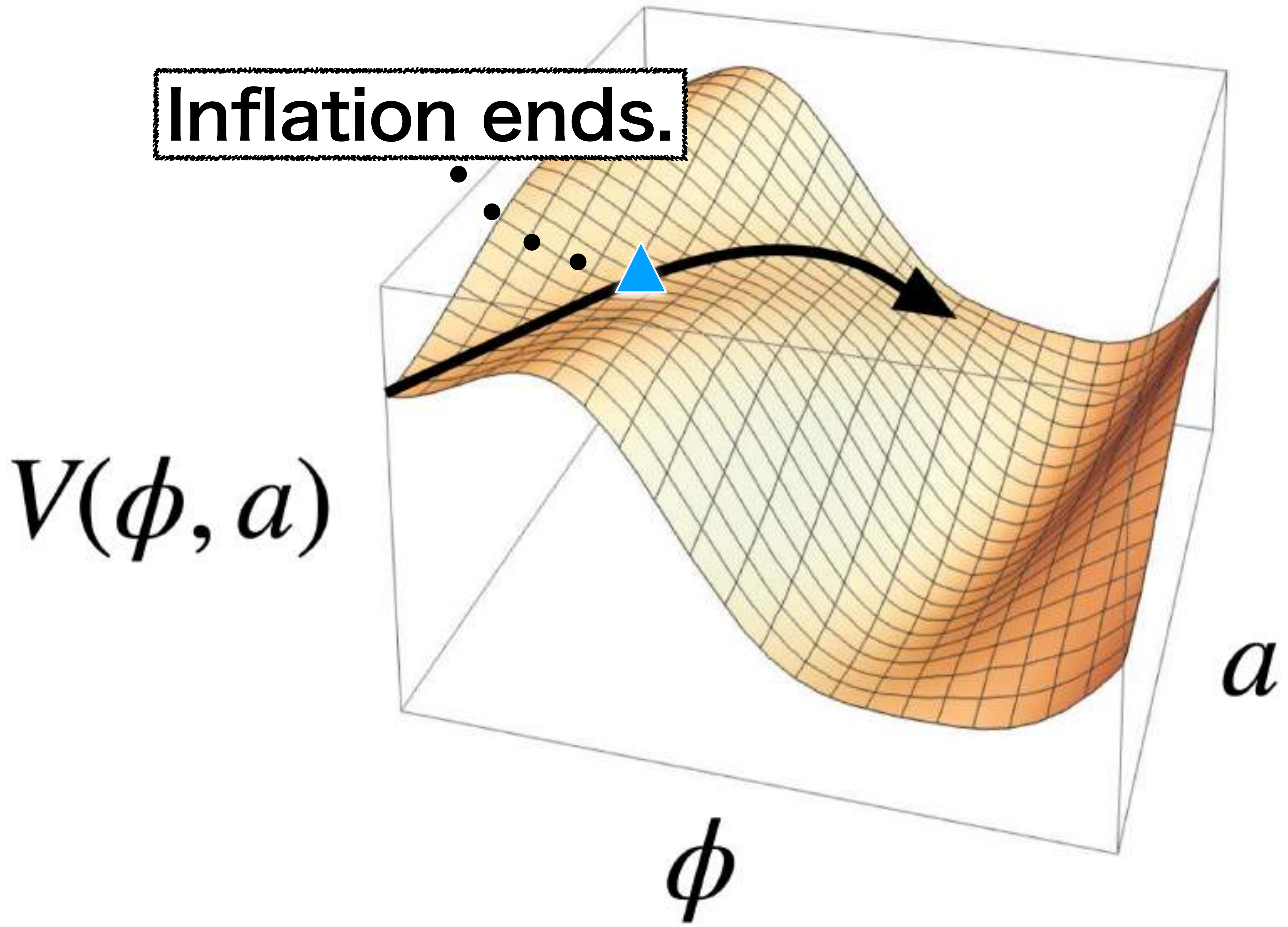
The inflationary dynamics

- ✔ In the early stage, the inflaton slowly rolls along $a = n_{\rm mix}\dfrac{f_a}{f_\phi}\phi$.
- ✔ After that, the trajectory bends to the ALP direction.



Regime classification

We can consider three scenario.



Single-field regime

The inflation ends before the waterfall by the ALP field.

Instantaneous waterfall regime

The inflation ends at the moment the ALP ϕ waterfalls.

Prolonged waterfall regime

The inflation continues for a while after the inflaton path changes.

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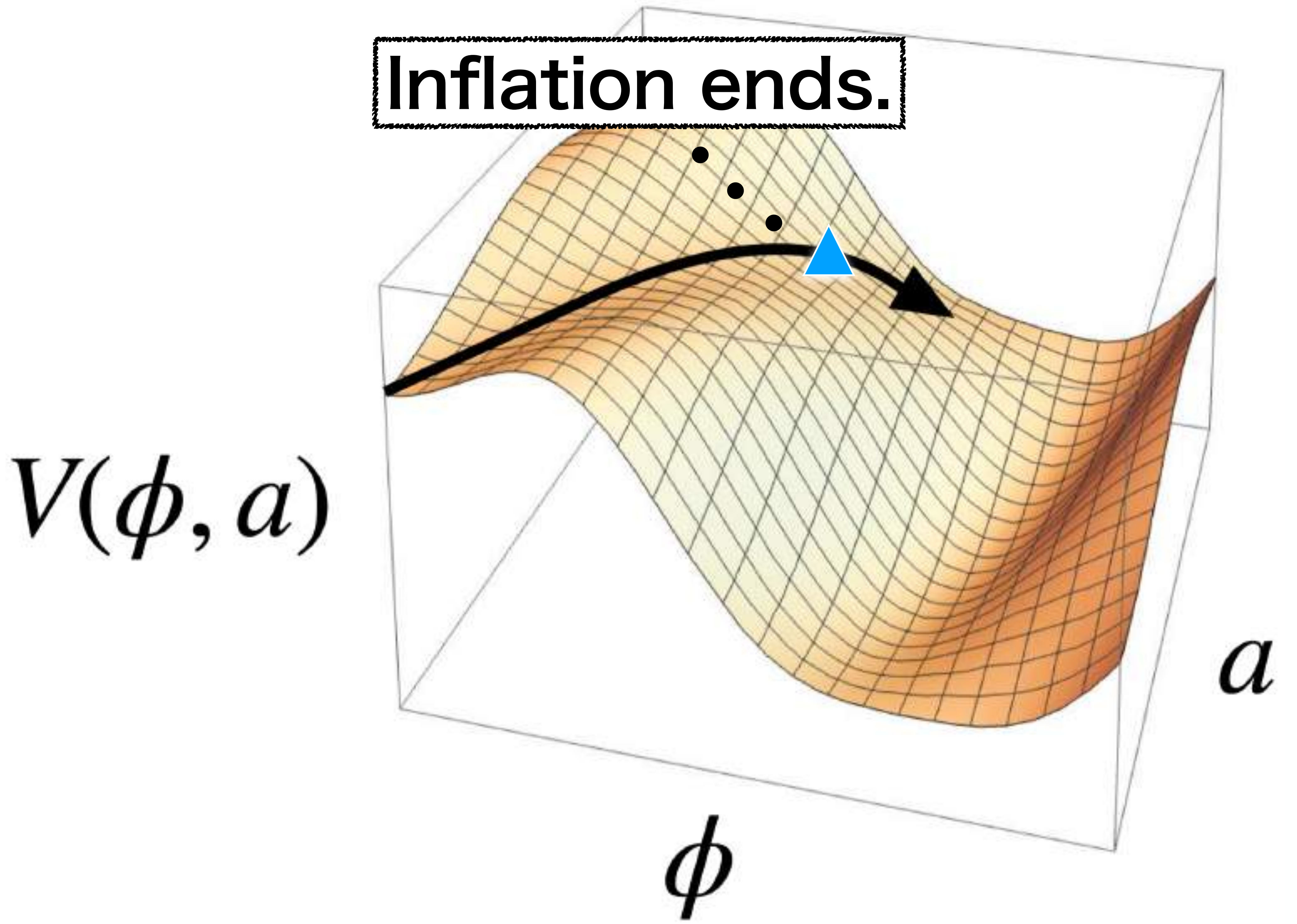

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Prolonged waterfall regime

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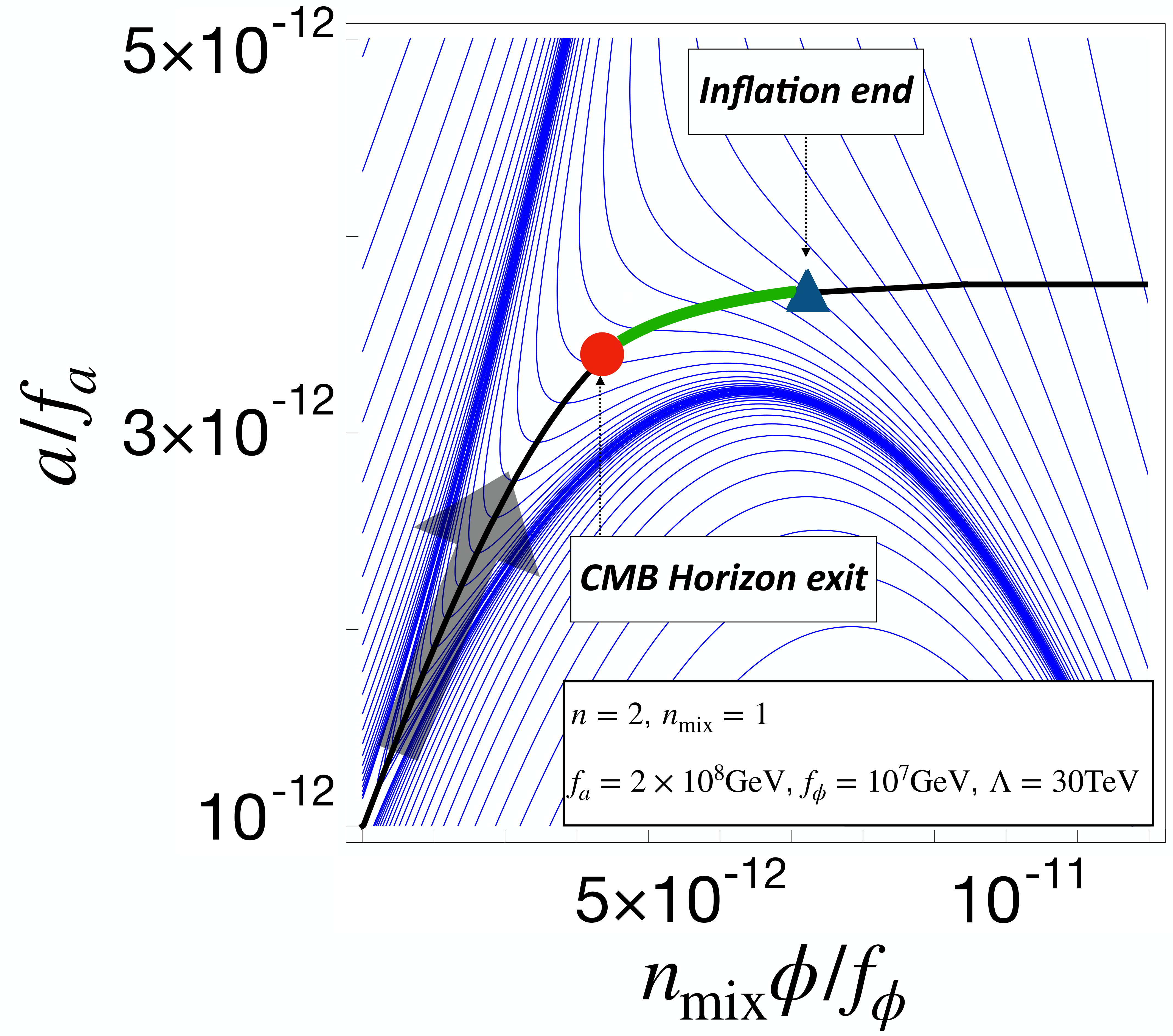
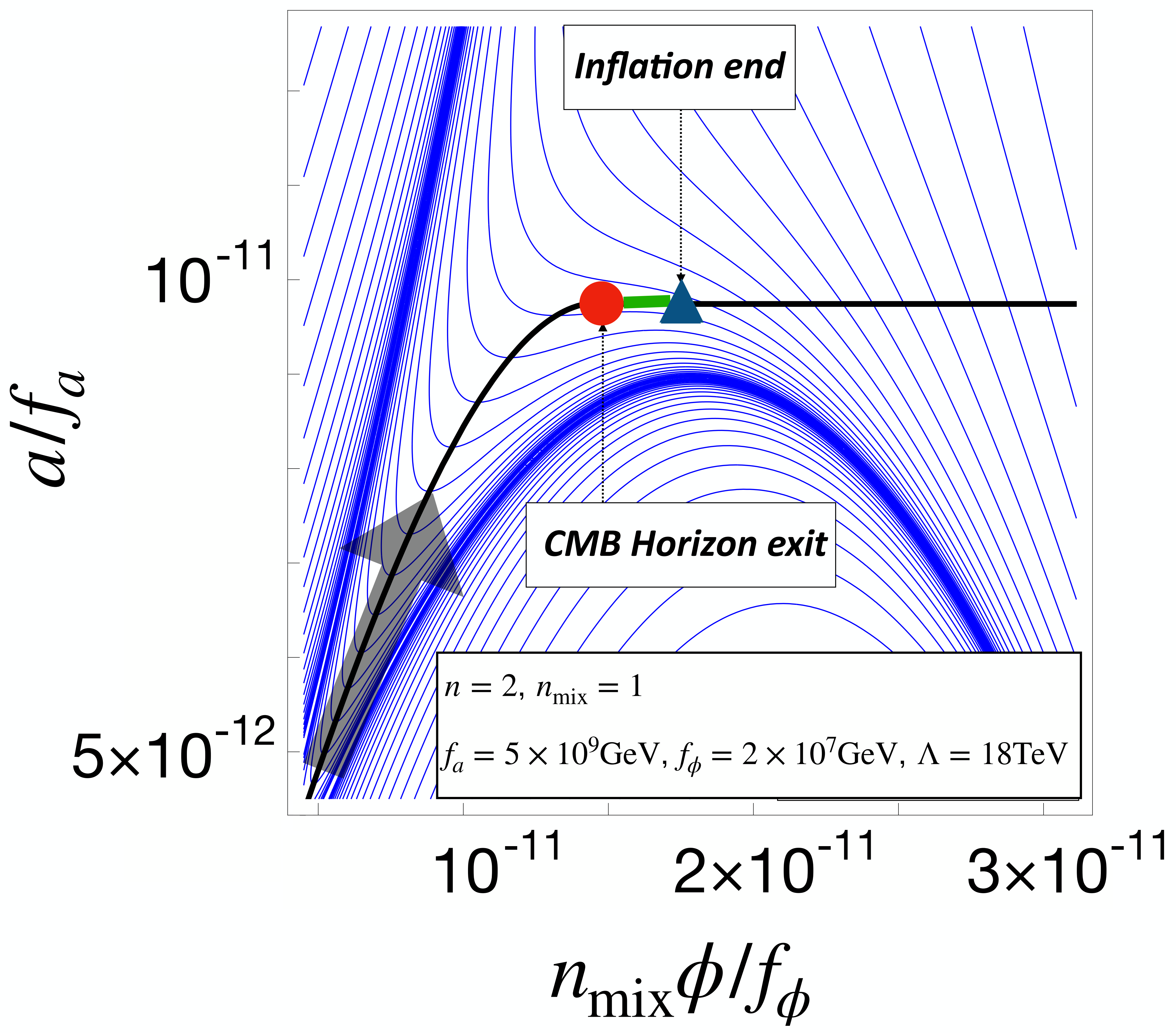
Trajectory during inflation



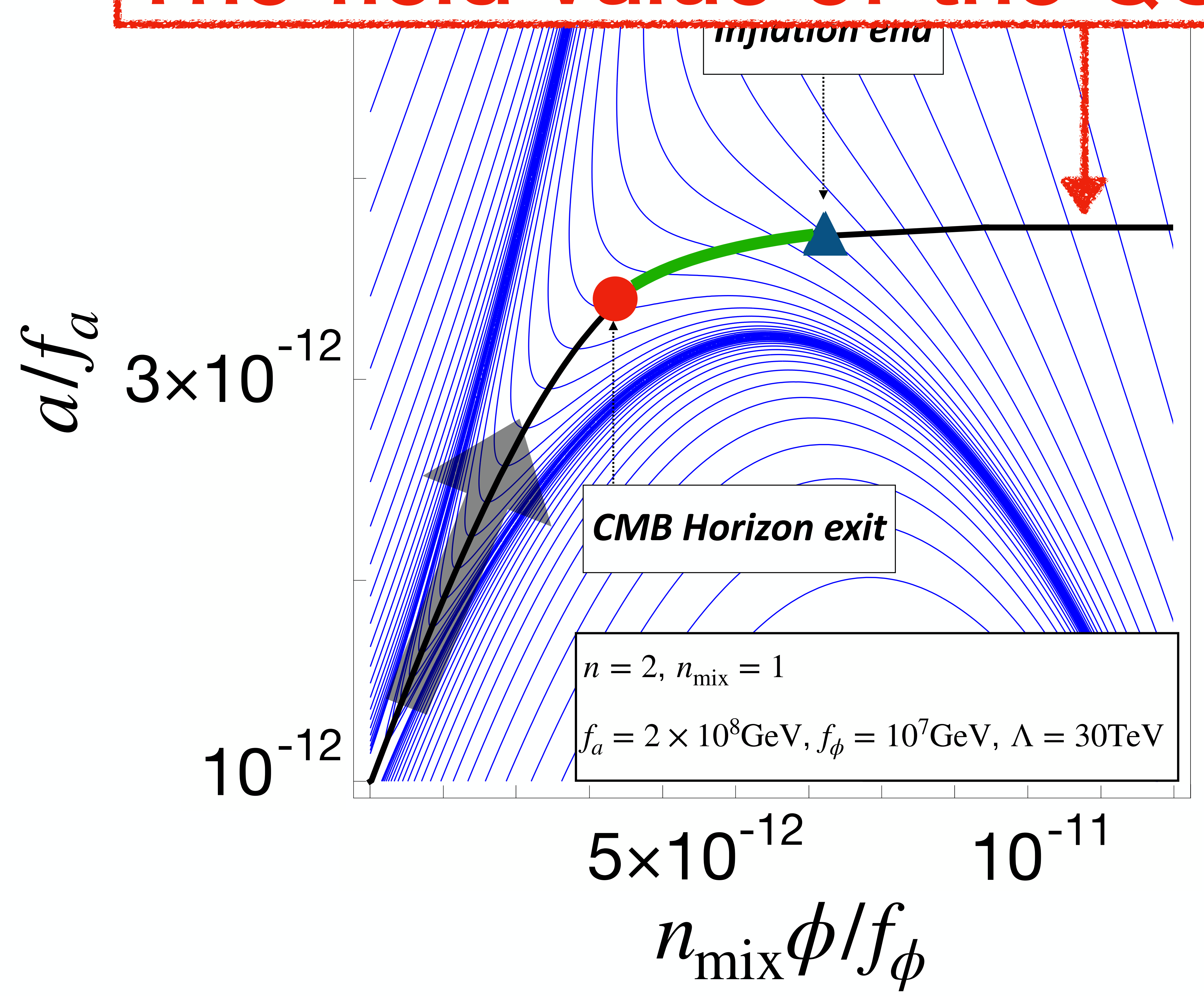
Inst. waterfall regime



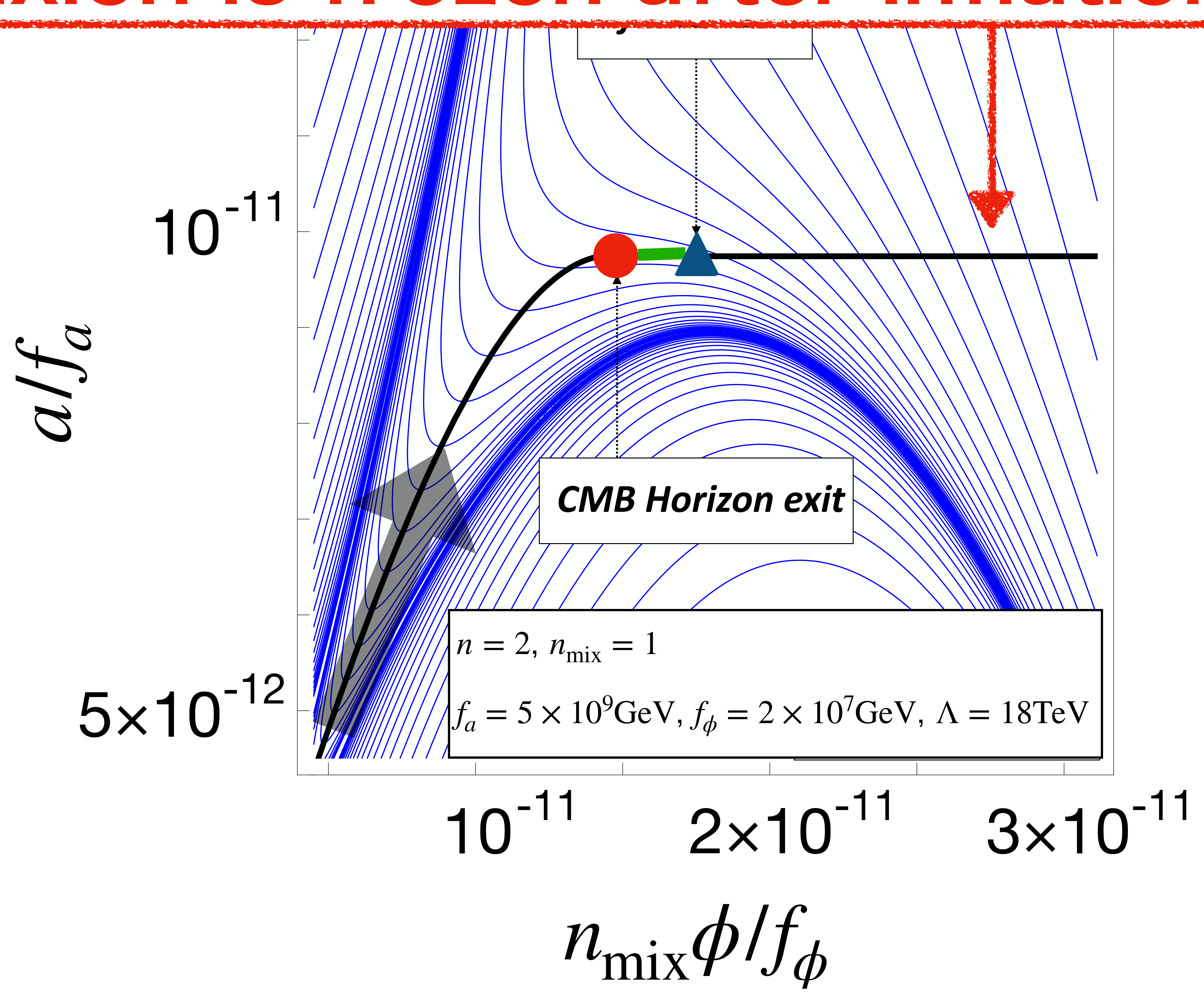
Prolonged waterfall regime

Trajectory during inflation

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



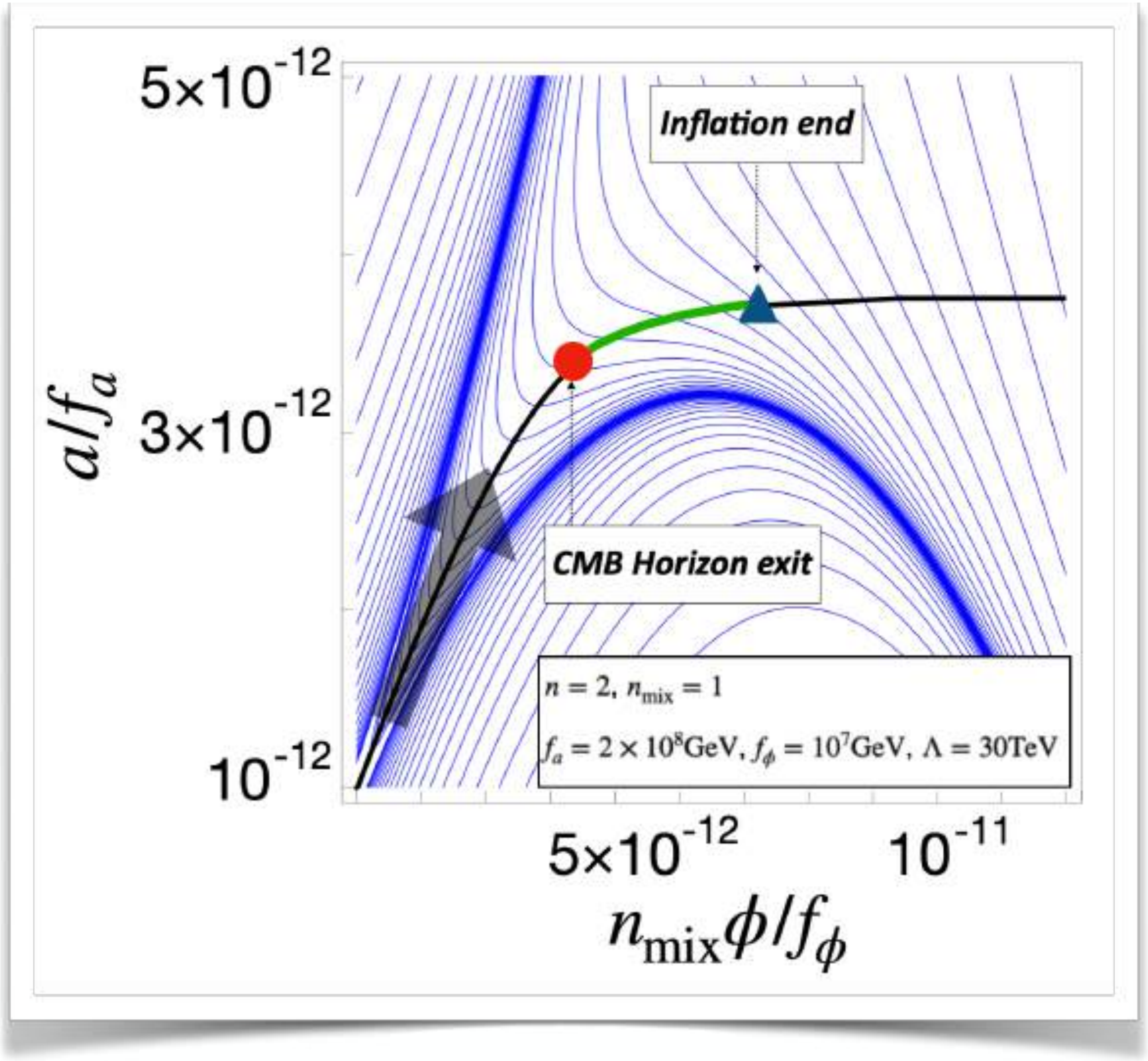
Inst. waterfall regime

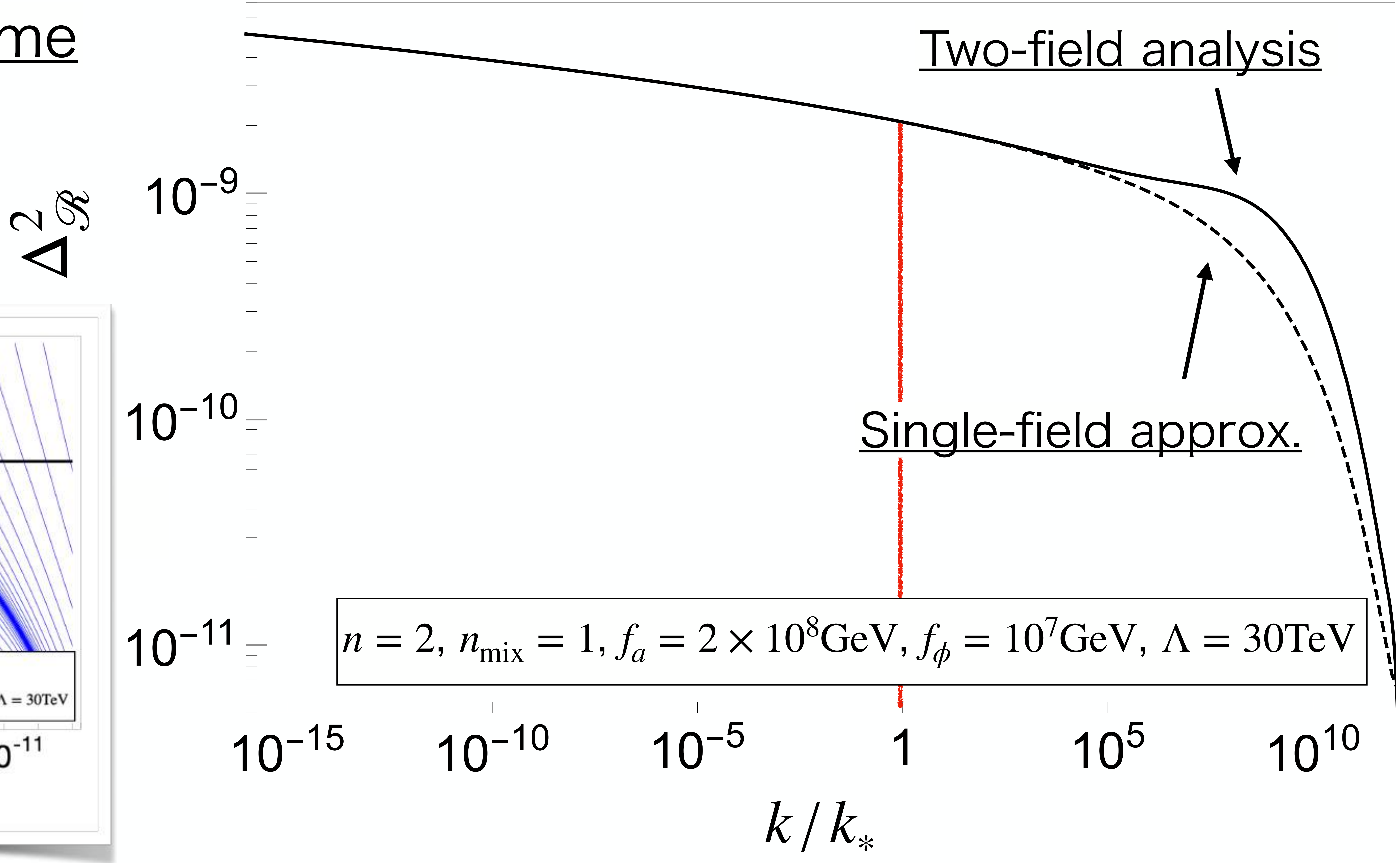


Prolonged waterfall regime

Power spectrum of curvature perturbation

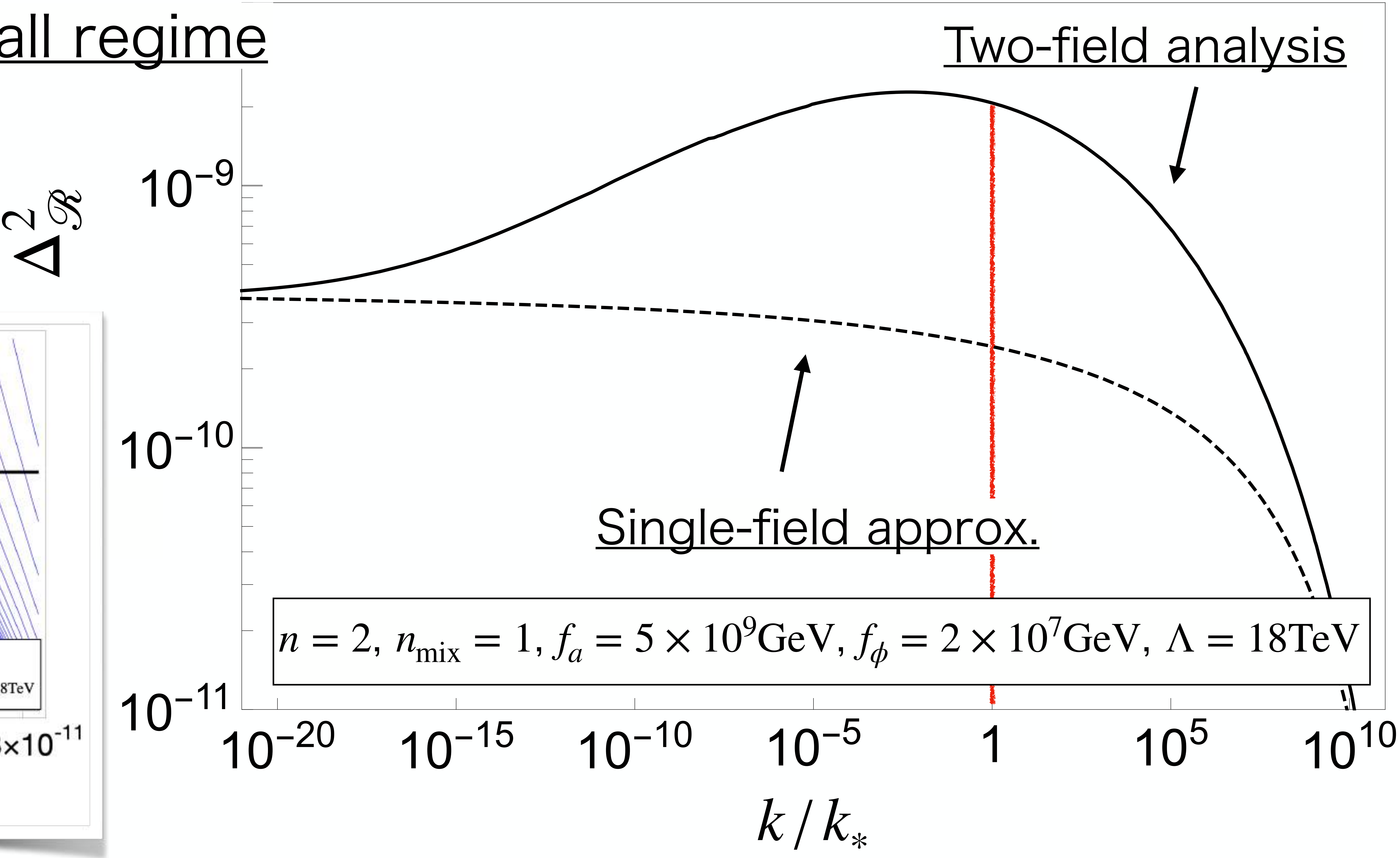
Inst. waterfall regime

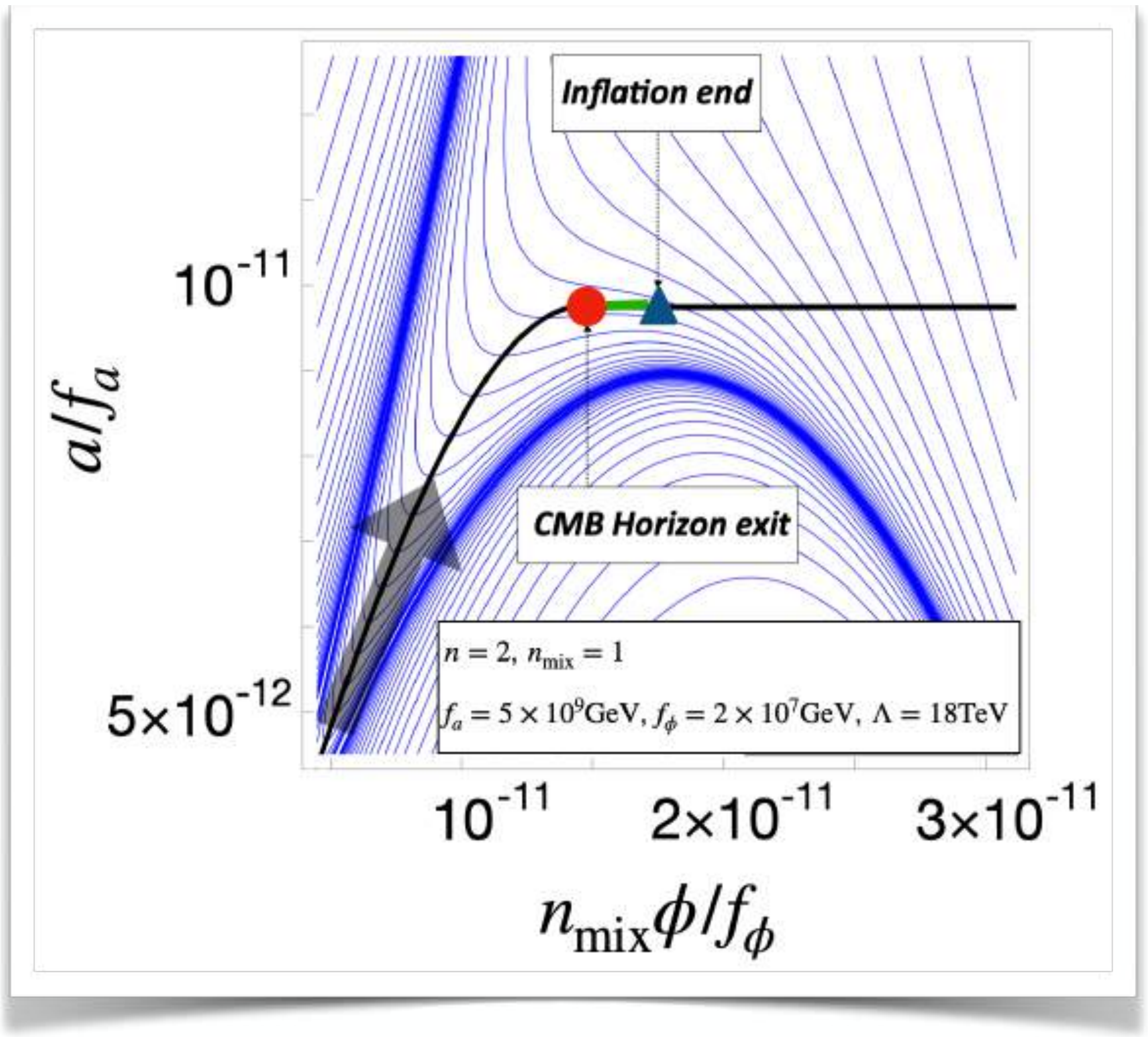




Power spectrum of curvature perturbation

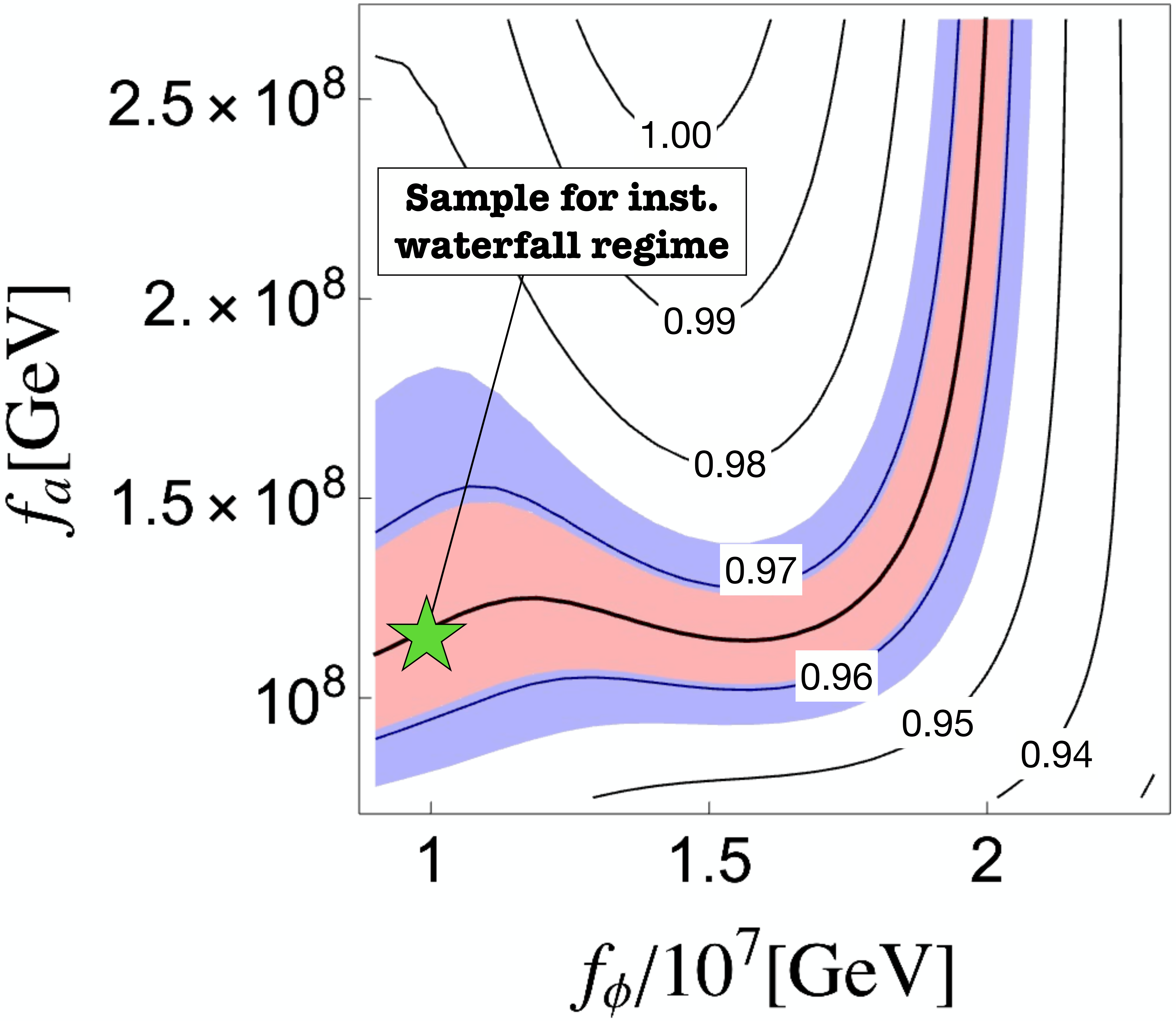
Prolonged waterfall regime

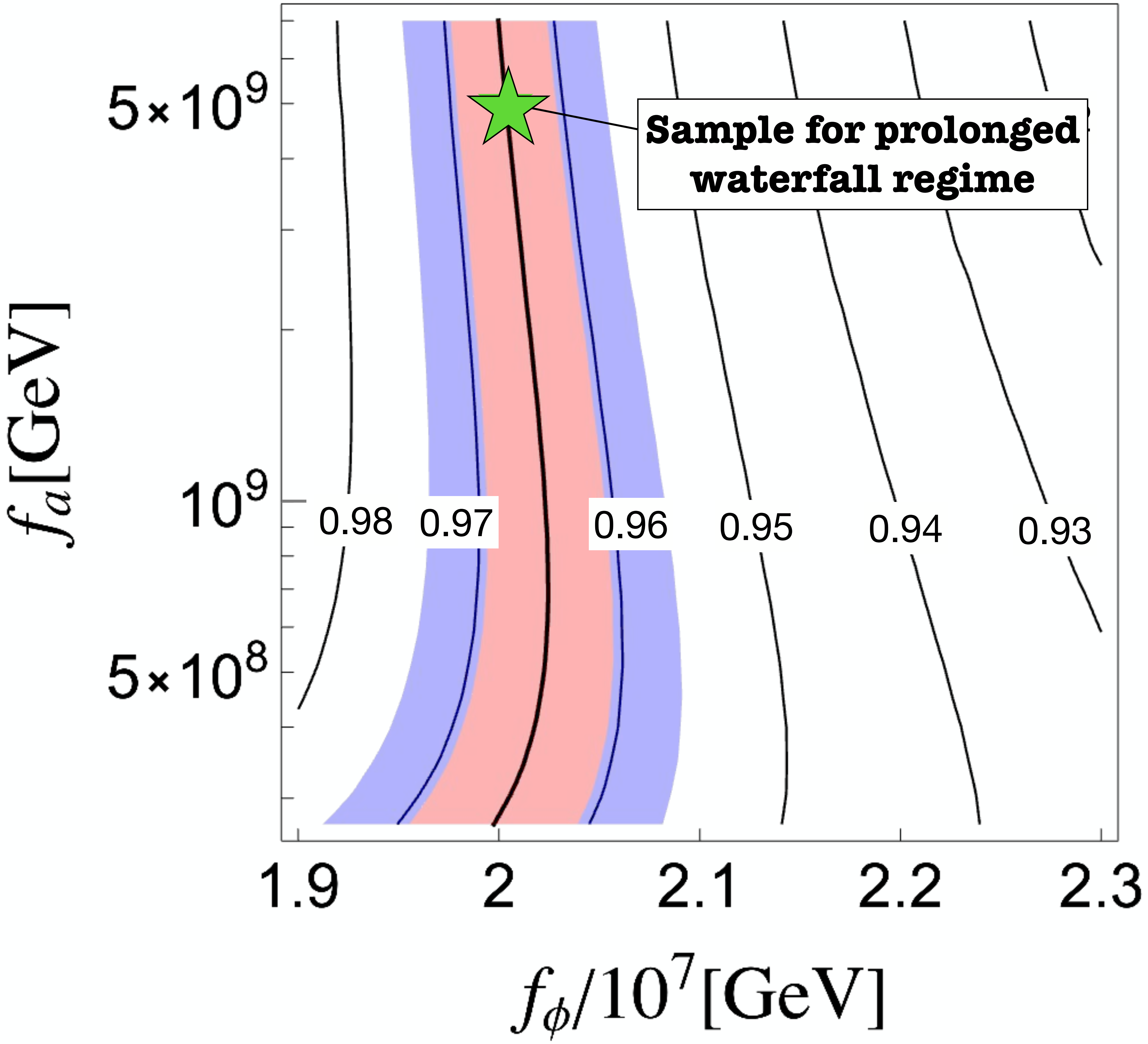




Spectral index

$$n_s \equiv 1 + \left.\frac{d \ln \Delta^2_{\mathscr{R}}(k)}{d \ln k}\right|_{k=k_*} = 0.9647 \pm 0.0043$$





The dynamics after inflation

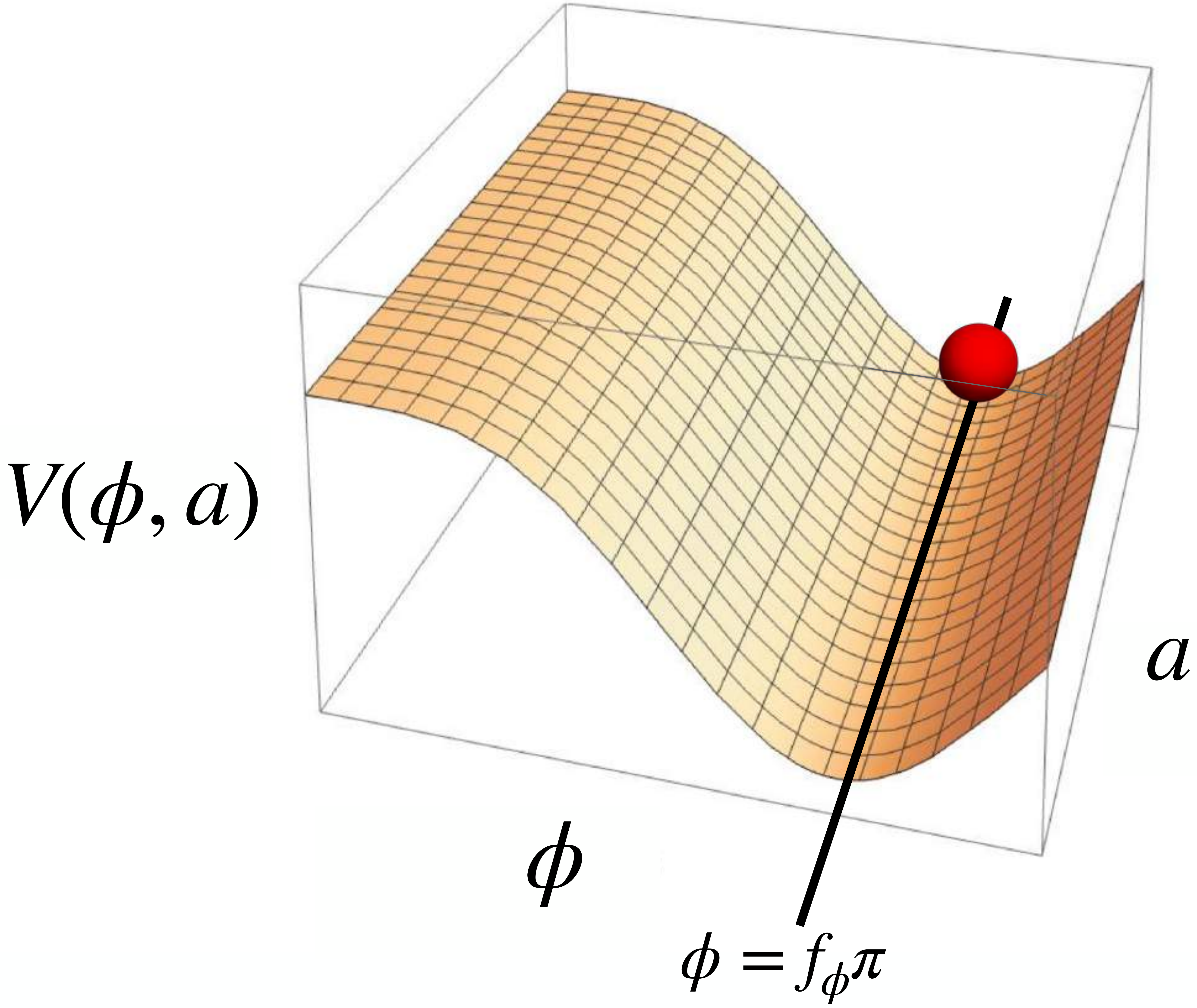
Interaction

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

Reheating temperature

$$T_{\rm re} \approx \left(\frac{g_* \pi^2}{30}\right)^{-1/4} \quad V_0^{1/4} \approx \mathcal{O}(10)\mathrm{TeV}$$

✔ The QCD potential vanishes immediately after inflation.



Misalignment mechanism

Preskill, Wise, Wilczek 1983;
Abbot, Sikivie 1983;
Fischler 1983

Before QCD phase transition

Misalignment mechanism

After QCD phase transition

Preskill, Wise, Wilczek 1983;
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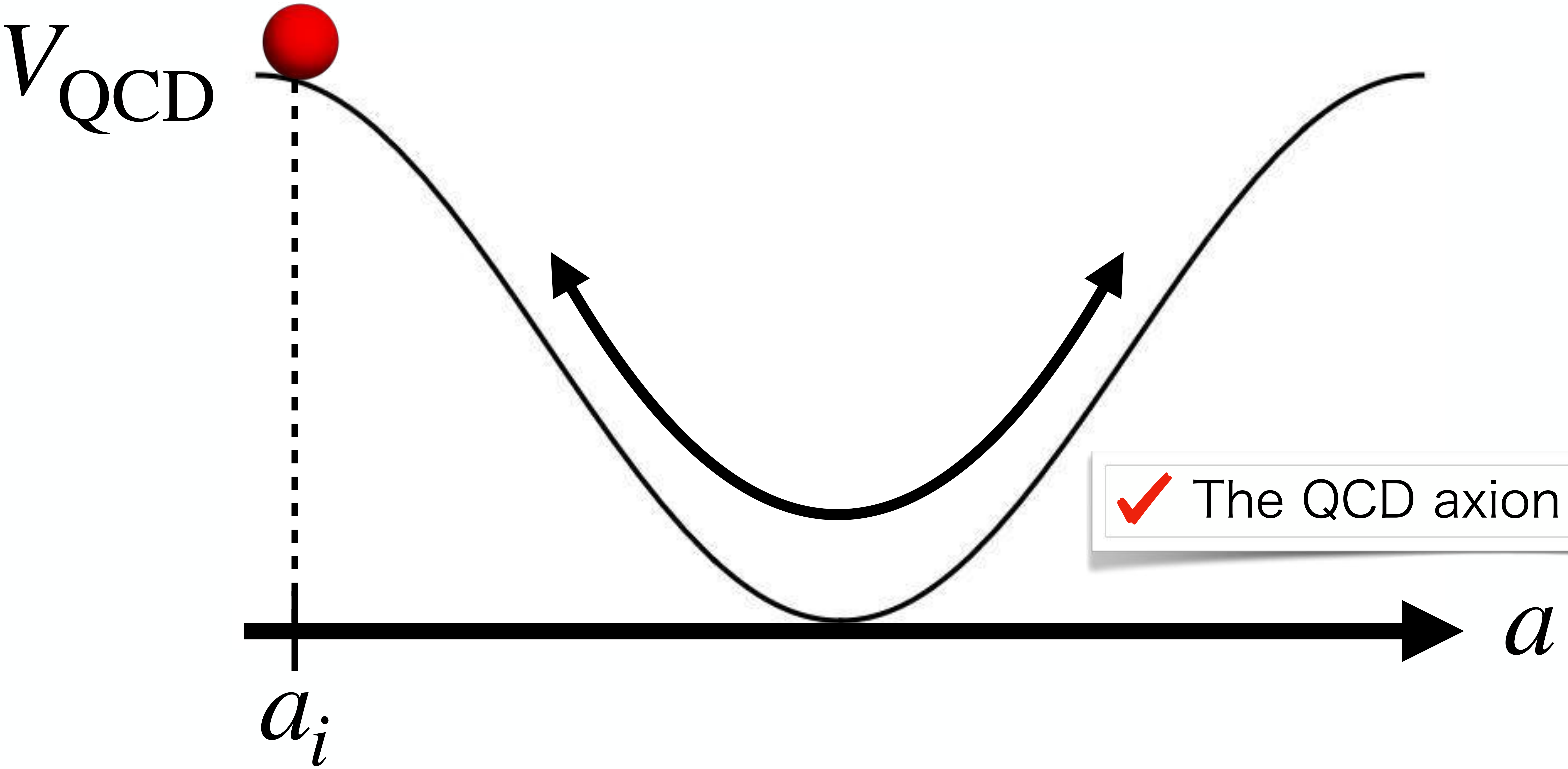


✔ The QCD axion a can be **DM**.

QCD axion abundance

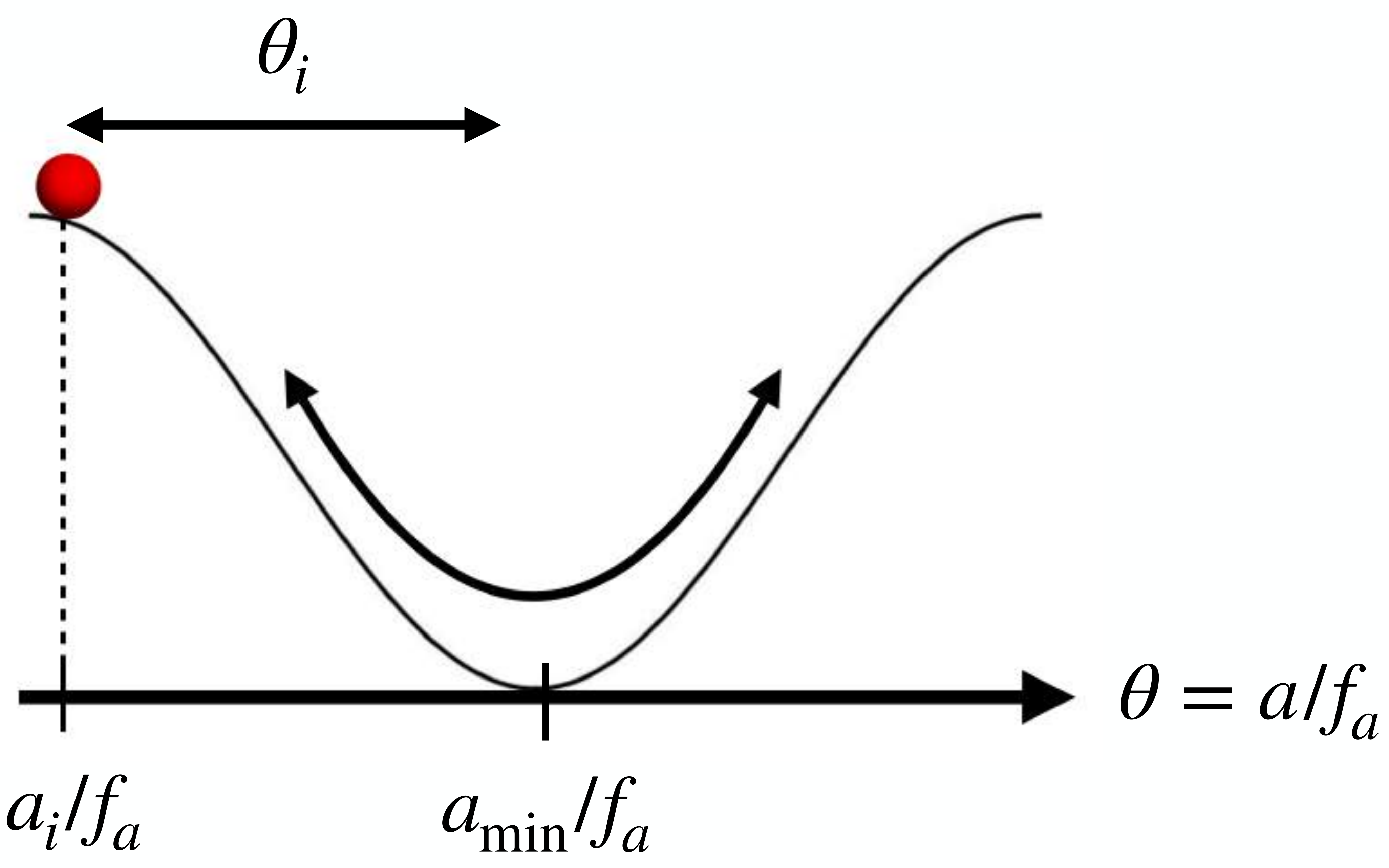
The QCD axion abundance is generated through the misalignment mechanism. Bae, Huh, Kim 0806.0497; Visinelli, Gondolo 0903.4377; Ballesteros, Redondo, Ringwald, Tamarit 1610.01639

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

The function $F(\theta_i)$ is given by

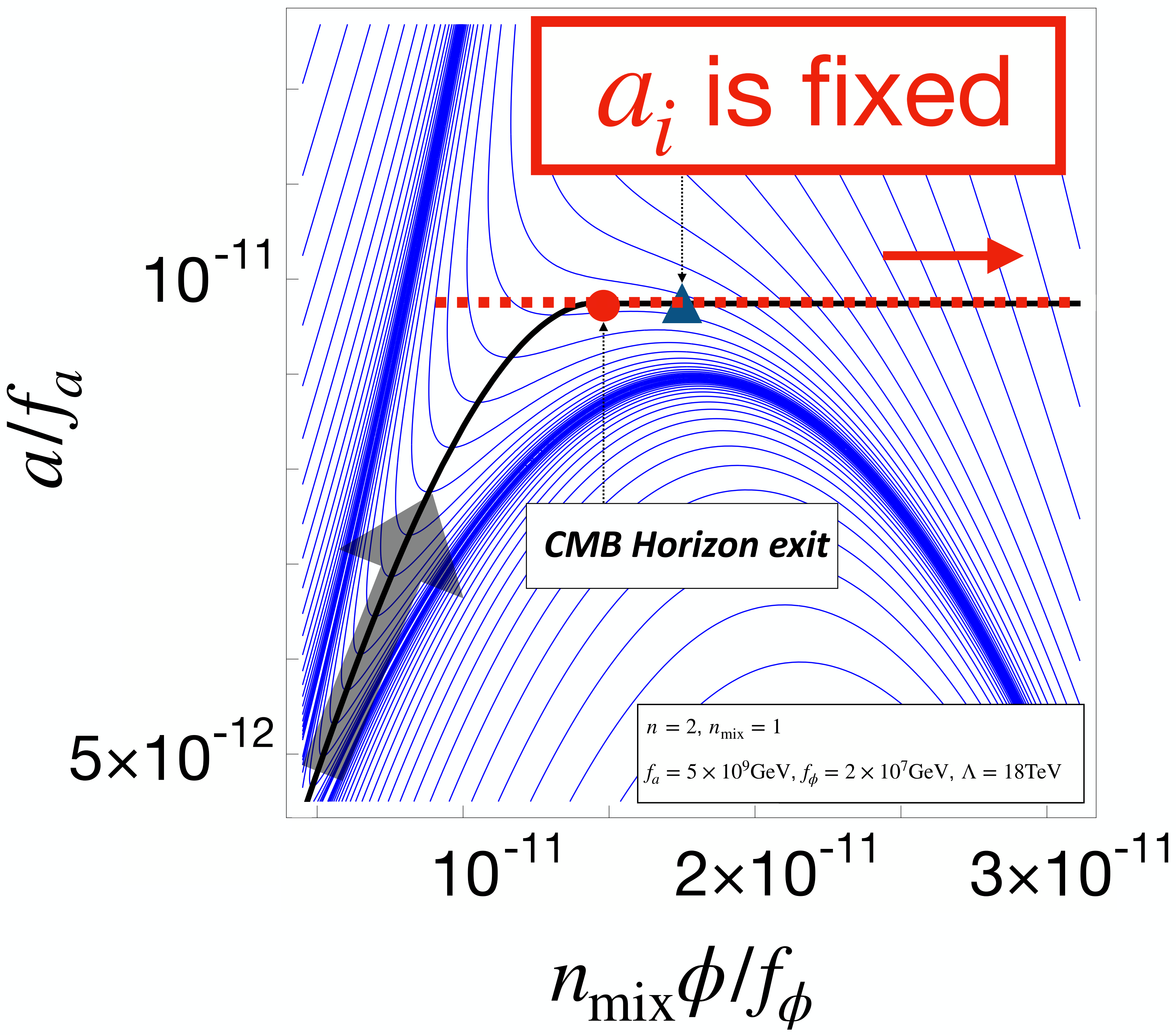
$$F(\theta_i) = \left[\ln\left(\frac{e}{1-\theta_i^2/\pi^2}\right)\right]^{1.17}$$

Visinelli, Gondolo 0903.4377



QCD axion abundance

θ_i is usually a free parameter. However, in our model, the initial value of the QCD axion a_i is determined by the inflationary dynamics.



<u>In this case</u>

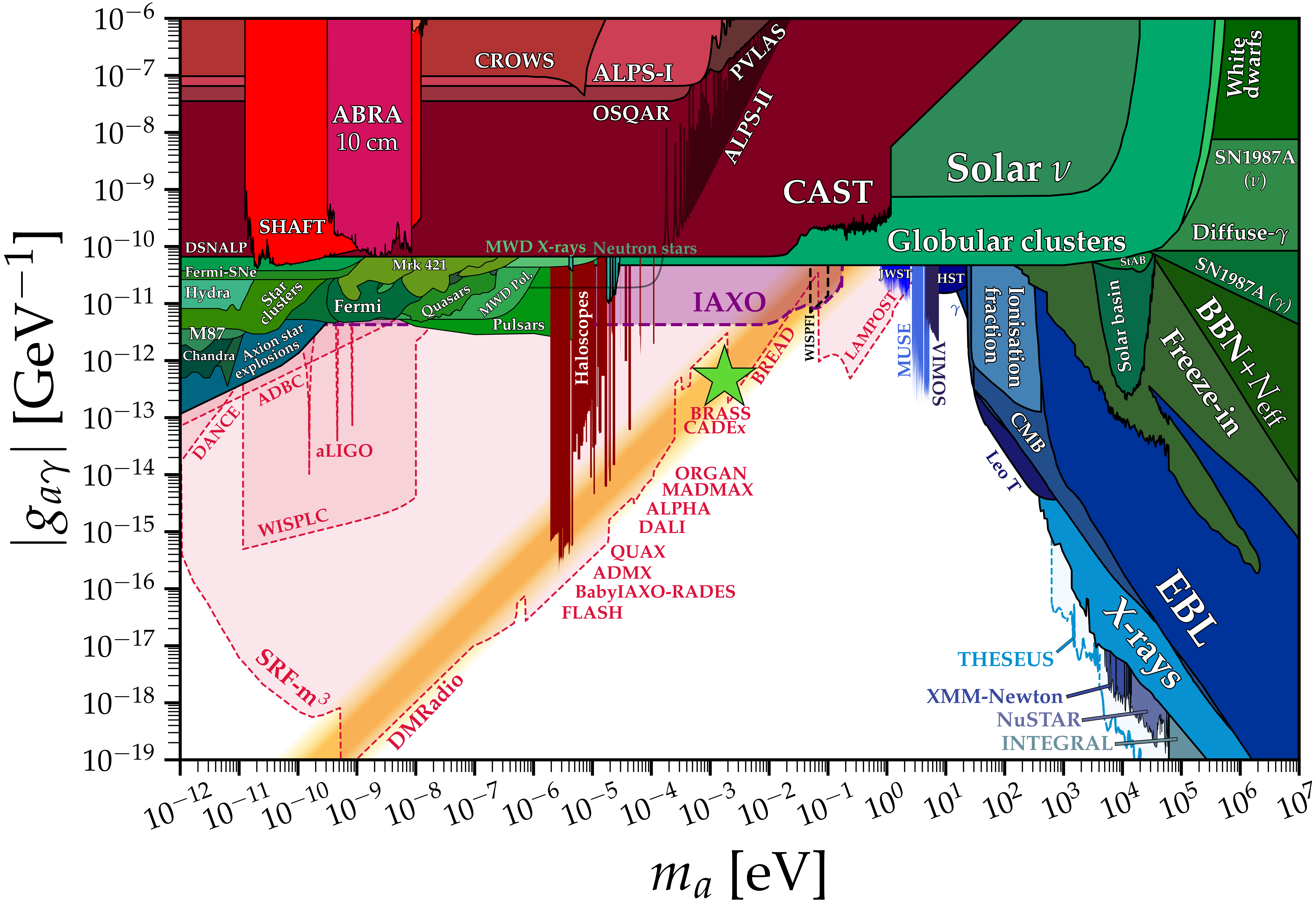
$$a_{\rm min}/f_a = \pi,\ a_i/f_a \sim 10^{-11} \ \Rightarrow\ \theta_i \sim \pi$$

The oscillation starts near hilltop.

If $f_a = 5\times10^9\,{\rm GeV}$, **the QCD axion becomes the DM.**

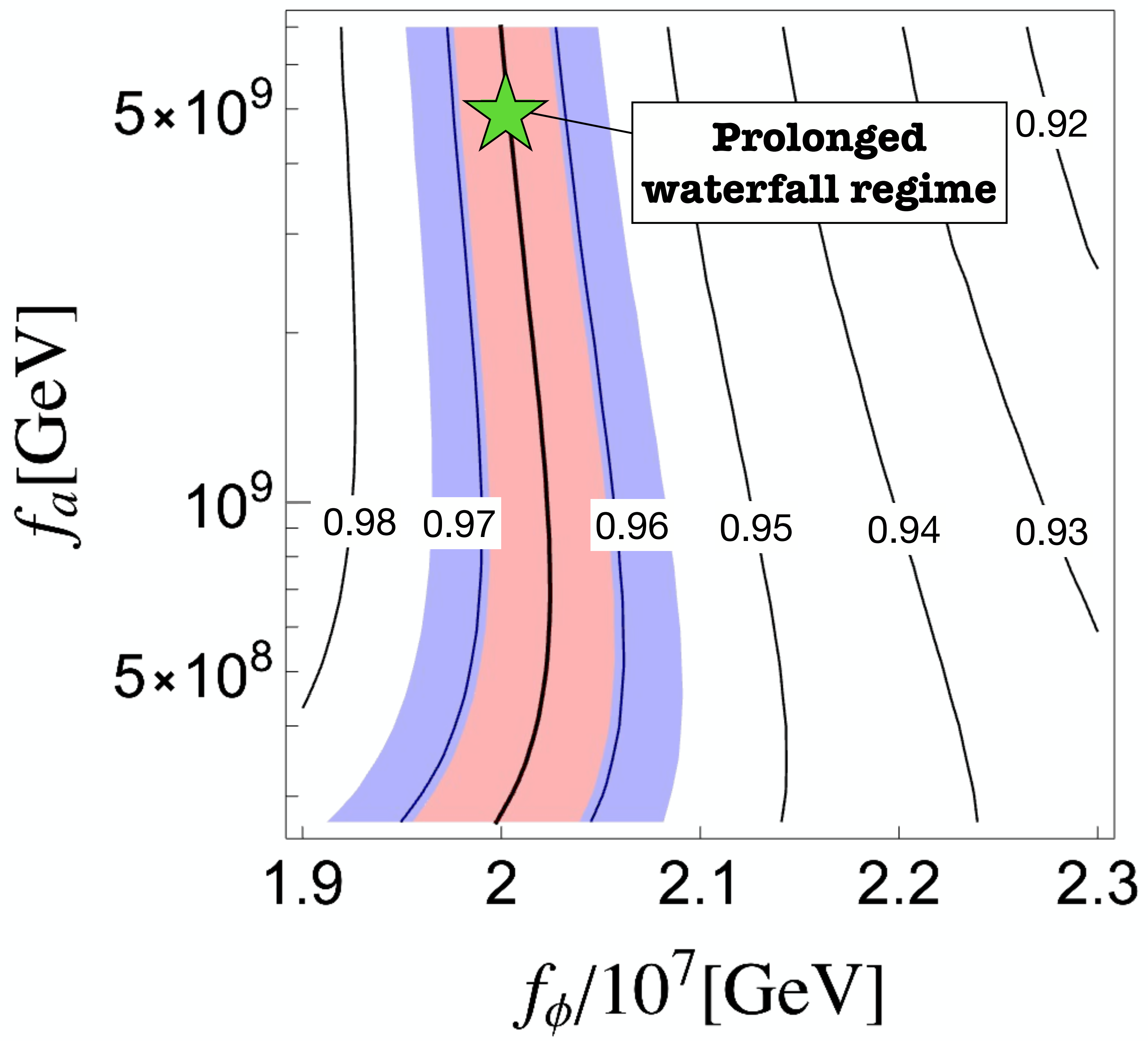
QCD axion searches

https://cajohare.github.io/AxionLimits/



Axion- photon coupling

$$L = \frac{1}{4} g_{a\gamma} a F \tilde{F}$$



Summary

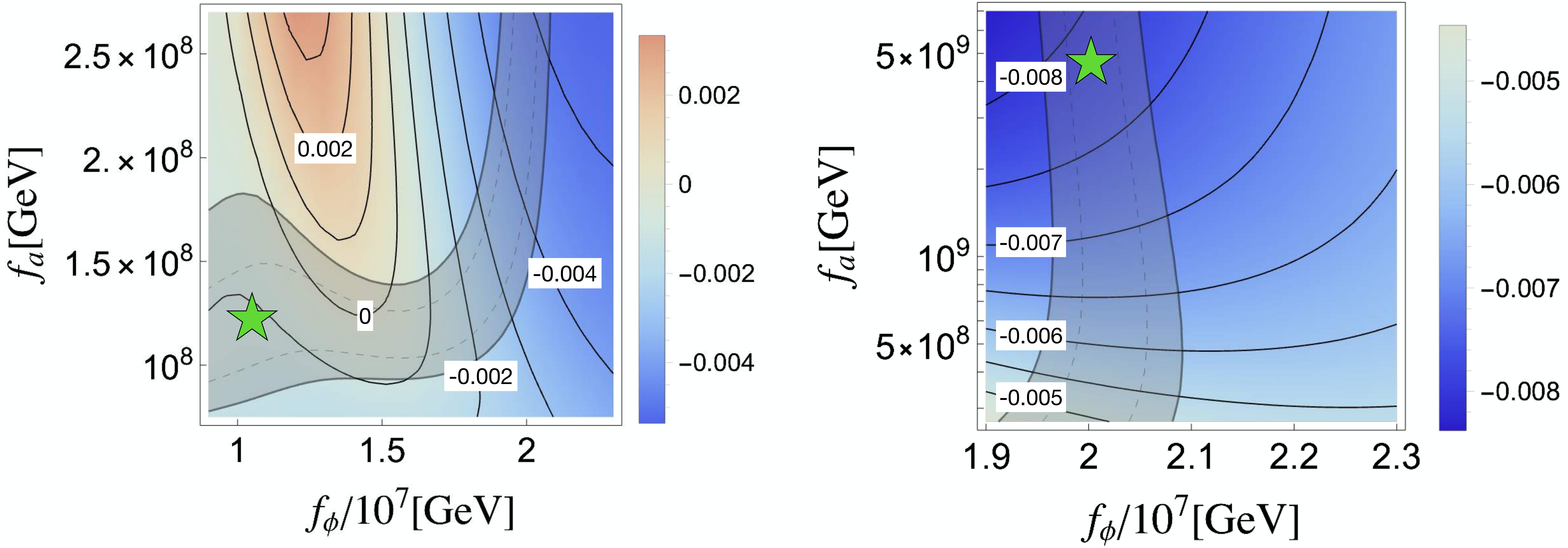
- We have shown that the hybrid inflation driven by the QCD axion can explain the CMB.
- QCD axion DM and inflation can be closely related in our inflationary model.
- This scenario can be probed by the axion direct search experiments and future CMB experiments.
- Also, the ALP may be probed by future accelerator experiments.

Back up

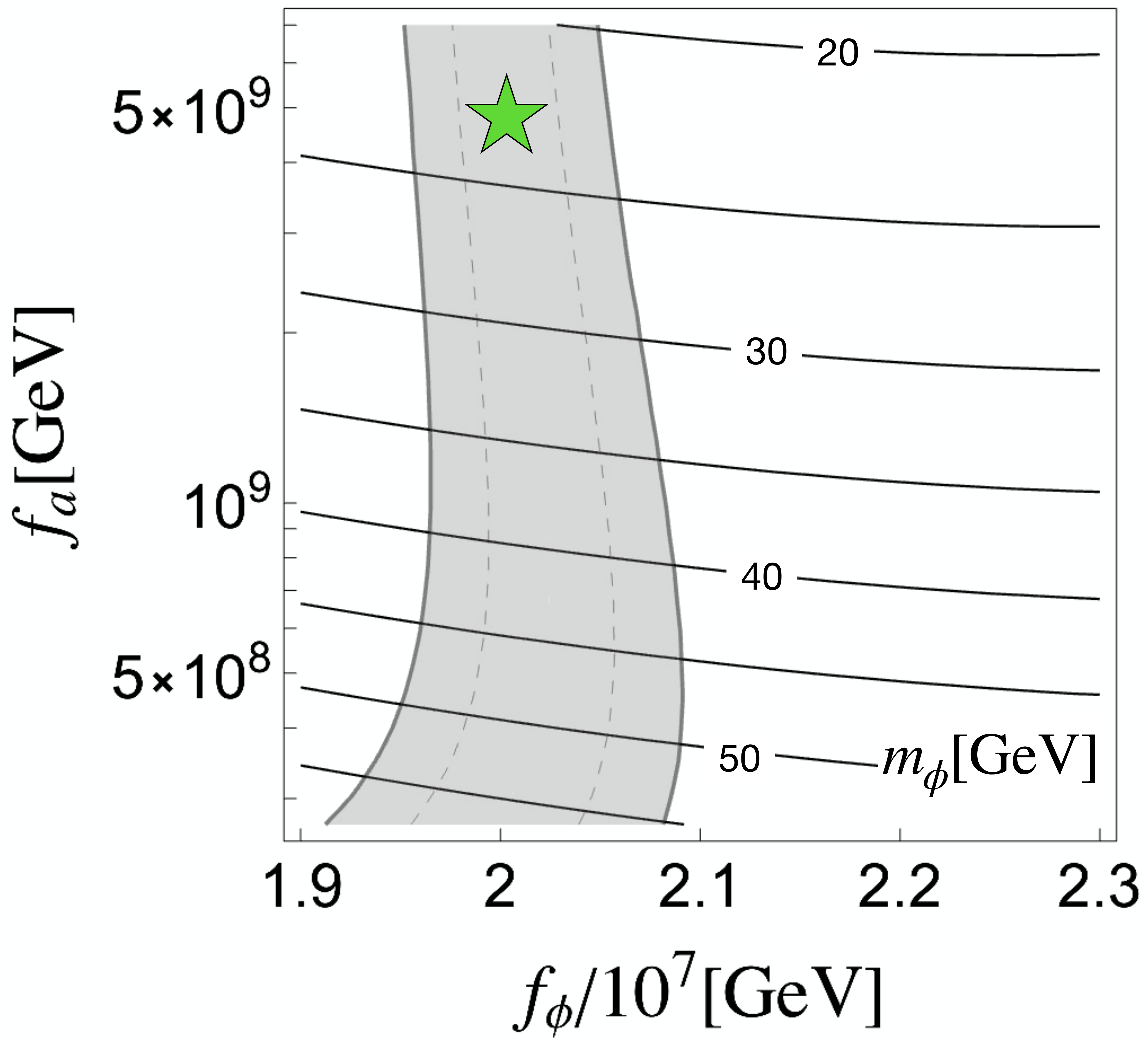
Running of spectral index

Planck 2018 collaboration

The observed running of spectral index $\left.\frac{dn_s}{d\ln k}\right|_{k=k_*} = -0.0045 \pm 0.0067$



Possible experimental searches for ALP



For $n = \mathrm{even}$, we have

$$m_\phi^2 = \left.\frac{d^2V_\phi}{d\phi^2}\right|_{\phi=f_\phi\pi} \qquad \therefore m_\phi = \frac{\sqrt{2}\Lambda^2}{f_\phi}.$$

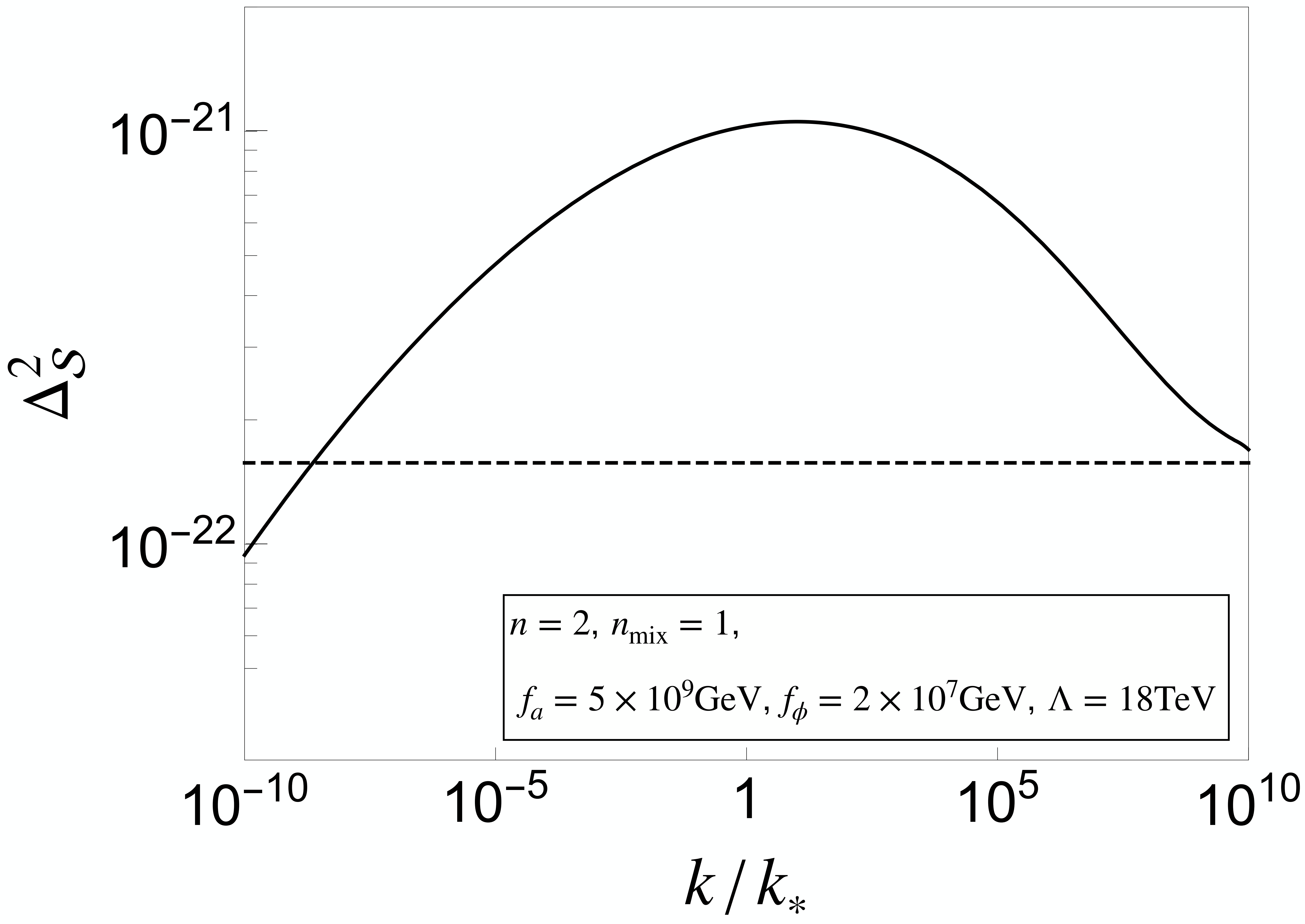
The production rate of the ALP ϕ

$$R \sim 10^{-20} I \left(\frac{2\times10^7\mathrm{GeV}}{f_\phi}\right)^2 \frac{(30\mathrm{GeV})^2}{s}\left(\frac{m_\phi}{25\mathrm{GeV}}\right)^2$$

The decay length of ϕ with energy E_{ALP}

$$l_{\mathrm{decay}} \sim 10\mathrm{m}\left(\frac{E_{\mathrm{ALP}}}{1\mathrm{TeV}}\right)\left(\frac{f_\phi}{2\times10^7\mathrm{GeV}}\right)^2\left(\frac{25\mathrm{GeV}}{m_\phi}\right)^3$$

Isocurvature perturbation



The isocurvature perturbation is defined as follows:

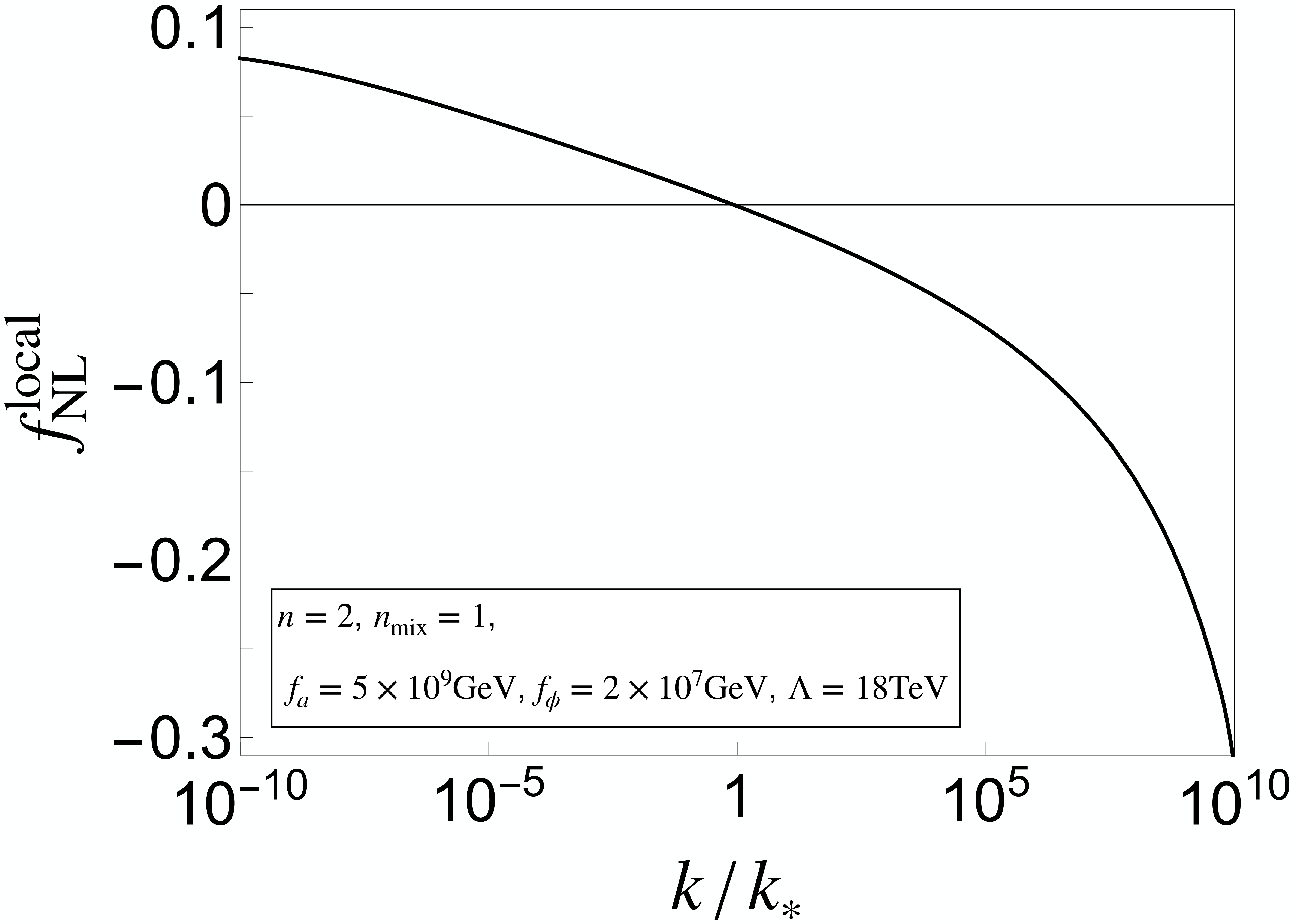
$$\mathcal{S} \equiv \frac{\delta\Omega_a}{\Omega_{\rm DM}} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} \sim \left.\frac{\delta\Omega_a}{\Omega_{\rm DM}}\right|_{\delta\rho_\gamma \simeq 0}$$

,where

$$\left.\delta\Omega_a\right|_{\delta\rho_\gamma\simeq 0} = \frac{\partial\Omega_a}{\partial\theta_i}\delta\theta_i = \frac{\partial\Omega_a}{\partial\theta_i}\frac{\delta a}{f_a}.$$

It is too small to be observed.

Non-Gaussianity



The definition of local non-Gaussianity is

$$-\frac{6}{5} f_{\rm NL}^{\rm local} = \frac{B_{\mathscr{R}}^{\rm local}(k_1,k_2,k_3)}{P_{\mathscr{R}}(k_1)P_{\mathscr{R}}(k_2) + (\text{k cyclic perms})},$$

where where $B_{\mathscr{R}}^{\rm local}$ is the bispectrum of local non-Gaussianity.

<u>CMB observation</u>

$$f_{NL}^{\rm local} = 0.9 \pm 5.1$$

Planck 2018 collaboration