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Axion Window and Low-Scale Inflation

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IHEP at CAS

(Moving to KAIST from Sep)

In collaboration with

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1. Introduction

The QCD axion, a pseudo-NGB, is a promising solution to strong CP problem and a candidate of dark matter.

Classical axion window:

$$4 \times 10^8 \, \mathrm{GeV} \lesssim f_a \lesssim 10^{12} \, \mathrm{GeV},$$

Focus Point

SN1987a

Axion abundance for $\theta_* = O(1)$.

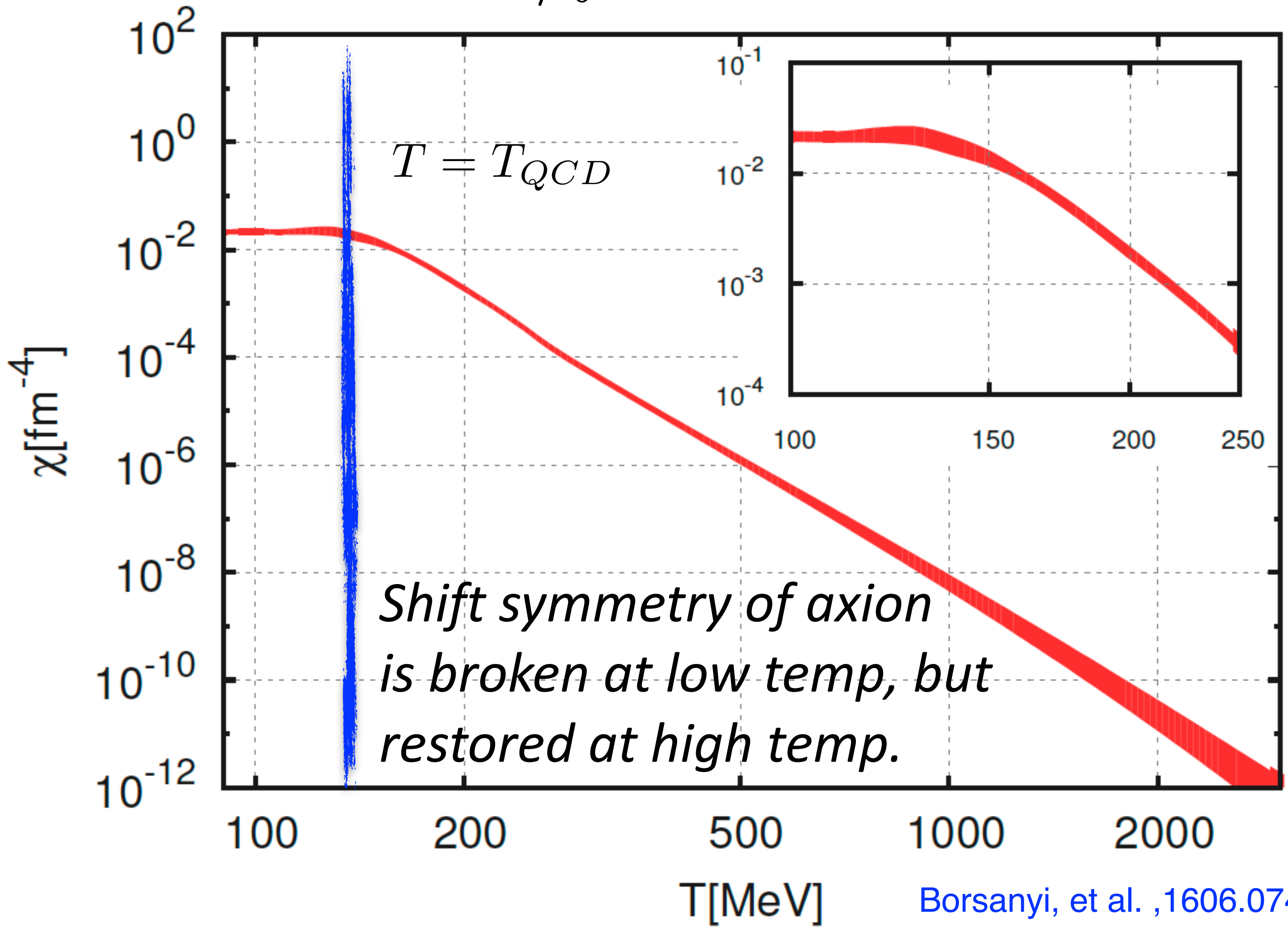
For comparison, the axion from GUT models or string theory has

$$f = O(10^{15-17}) \ \mathrm{GeV}$$

QCD axion potential

$$V(\theta) \supset \chi(T)\cos(\theta) \sim \frac{\chi(T)}{f_a^2} a^2$$

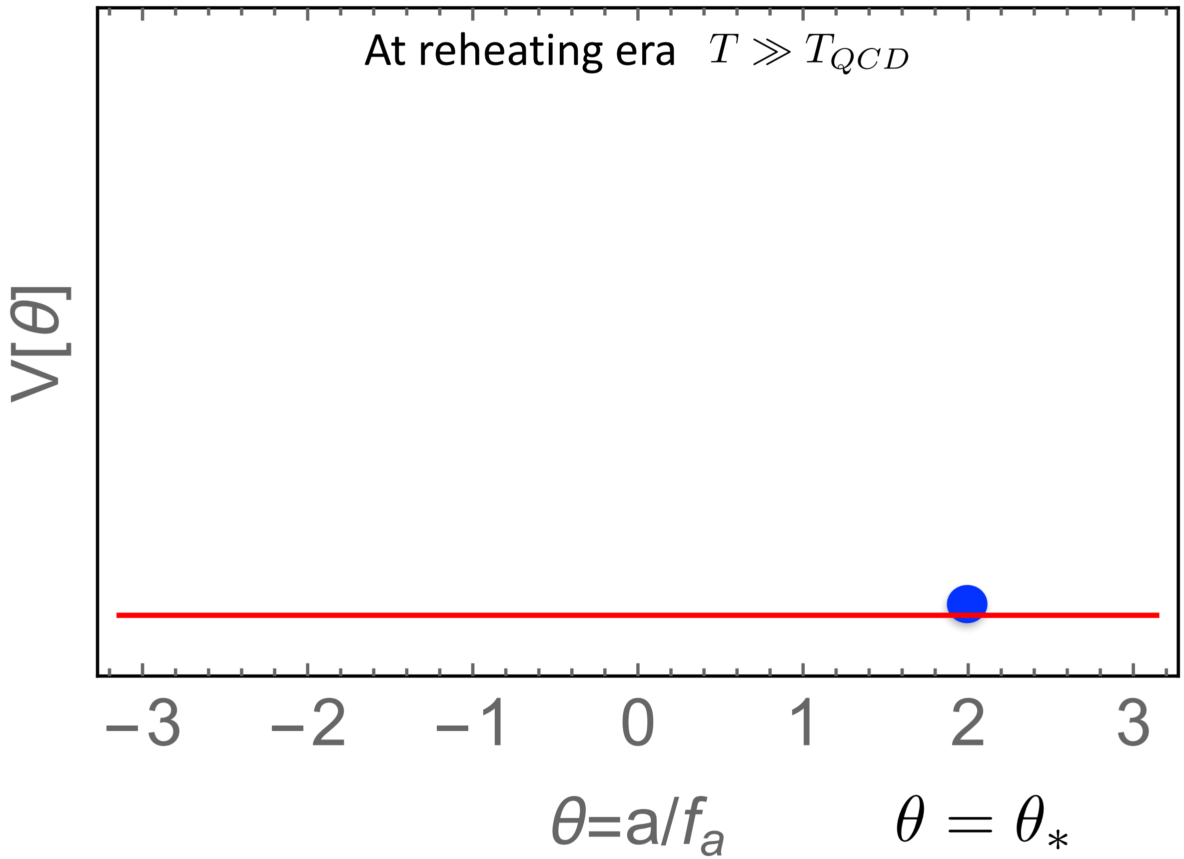
$\theta \equiv a/f_a$ the zero mode is the strong CP phase.



Borsanyi, et al. ,1606.07494

Axion abundance

The early Universe is hot. Axion has shift sym.
It is natural to have initial value $\theta_* = O(1)$.



Axion starts oscillate about the CP conserving minimum at $T \sim T_{QCD}$.

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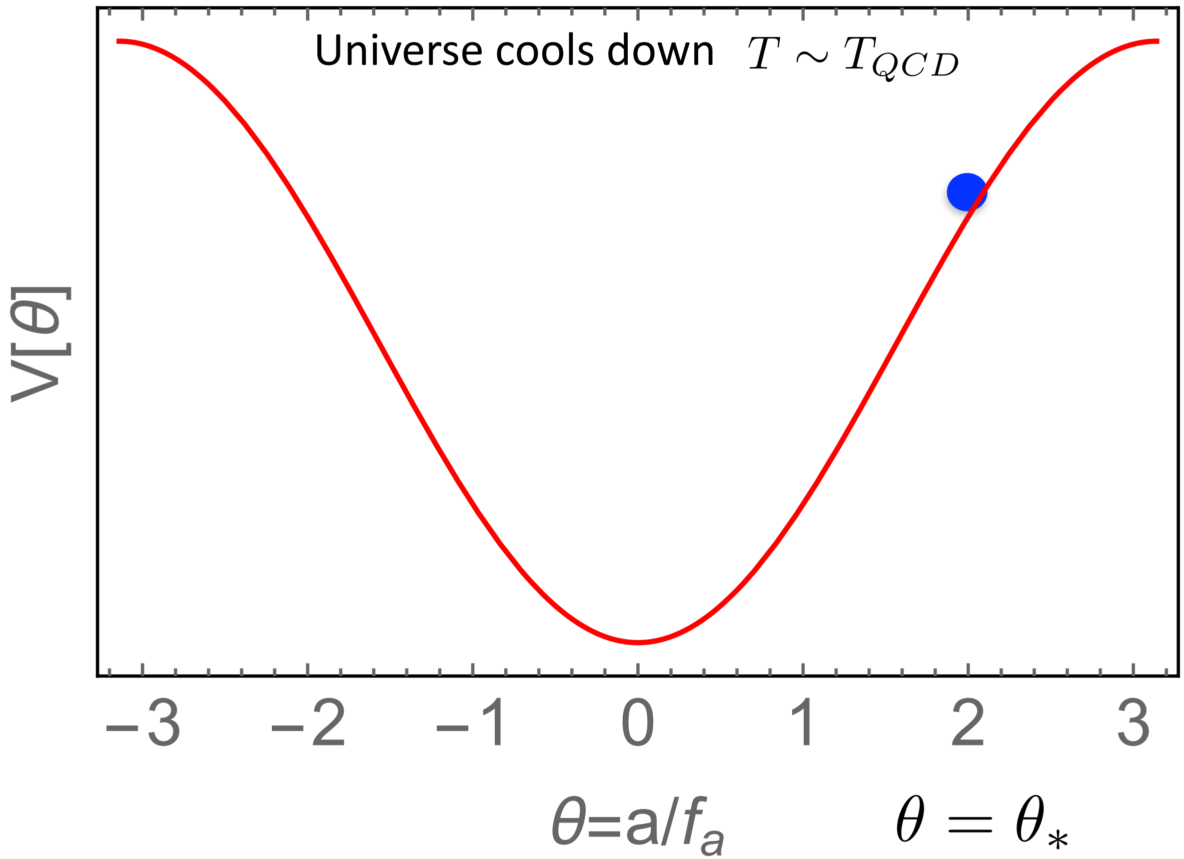

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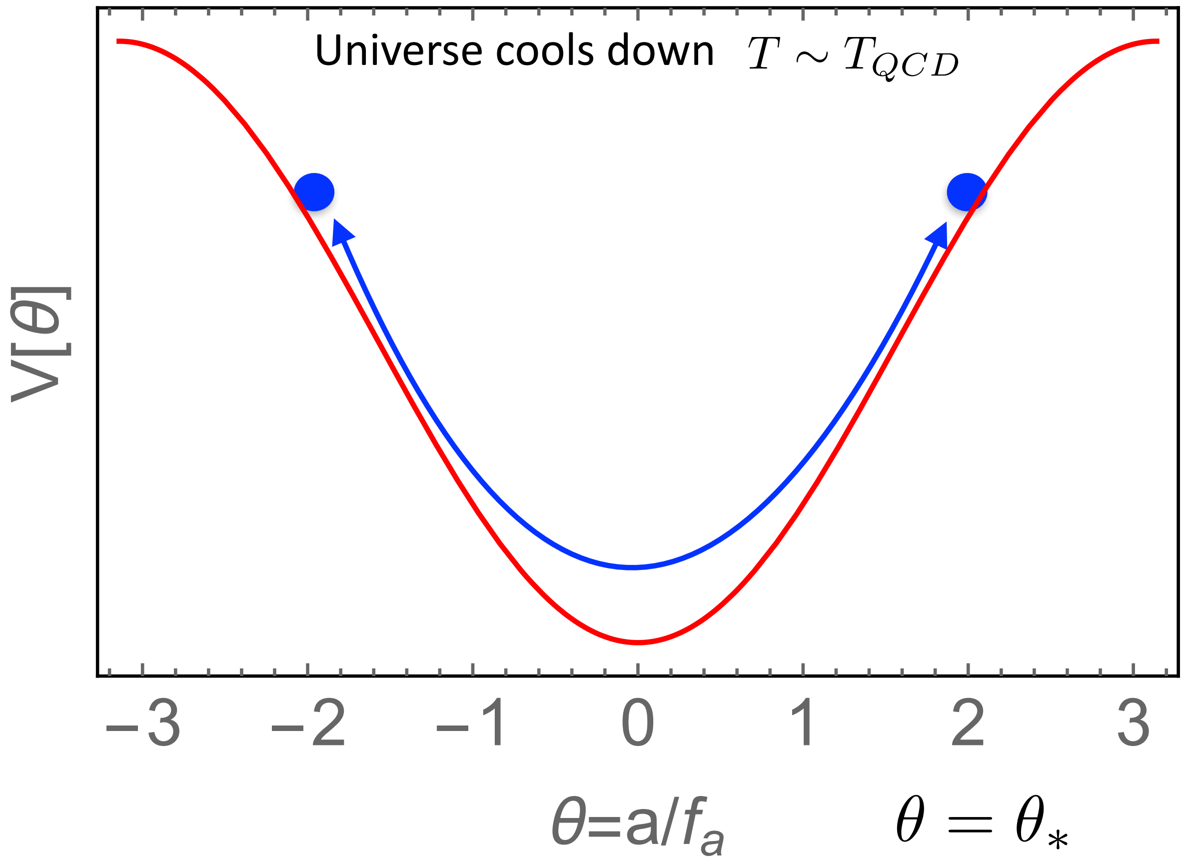

Axion starts oscillate about the CP conserving minimum at $T \sim T_{QCD}$.

Axion abundance

Coherent oscillation contributes to matter density of Universe

$$\Omega_a h^2 \simeq 0.1\ \theta_*^2 \left(\frac{f_a}{10^{12} GeV} \right)^{1.17}$$

Matter abundance sets $f_a \lesssim 10^{12}\mathrm{GeV}$ for $\theta_* = O(1)$, otherwise axion is overproduced.

For larger f_a (e.g. $\sim 10^{15-17} GeV$)

*Tuning $\theta_* \ll O(1)$ with anthropic principle.

Linde, 91; Wilczek,0408167; Tegmark, et al. 0511774.

Entropy production: Dine, Fischler 82; Steinhardt, Turner, 83; etc.Lazarides, et al, 90; Kawasaki, et al.,9510461; Kawasaki, Takahashi, 0410158; Abundance transfer: Kitajima, Takahashi, 1411.2011; Daido et al, 1505.07670, 1510.06675;Kitajima et al. 1711.06590; Agrawal, et al. 1708.05008; Witten effect: Kawasaki et al. 1511.05030; 1708.06047;

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*Reducing $\theta_* \ll O(1)$ from axion dynamics during low-scale inflation.

Graham, Scherlis, 1805.07362, Takahashi, WY, and Guth, 1805.08763

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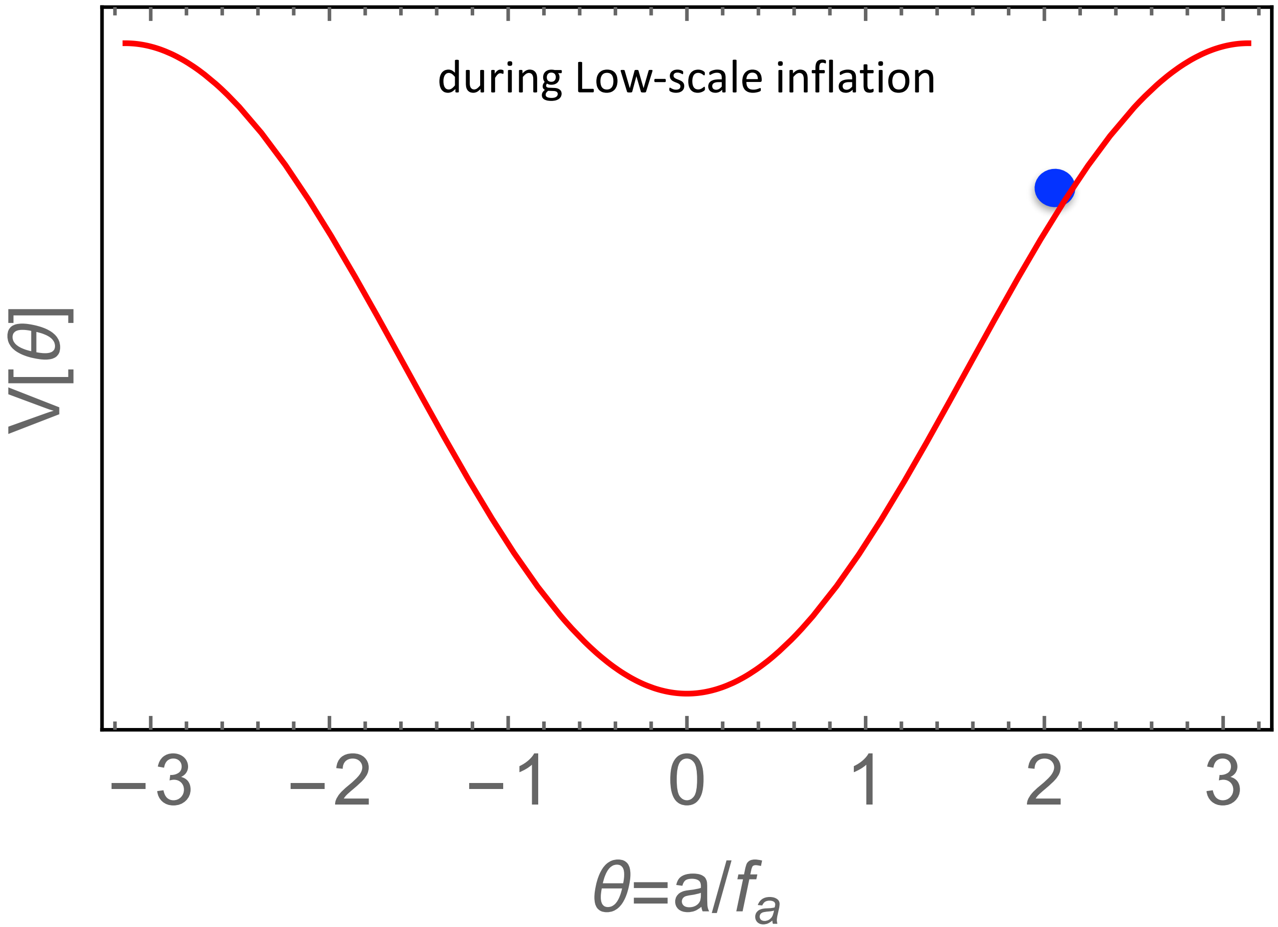
2. Low-scale inflation and Axion

During inflation temperature exists:

$$T_{\rm inf} = \frac{H_{\rm inf}}{2\pi}$$ Gibbons, Hawking, 77

Axion gets potential for $T_{\rm inf} < T_{\rm QCD}$.



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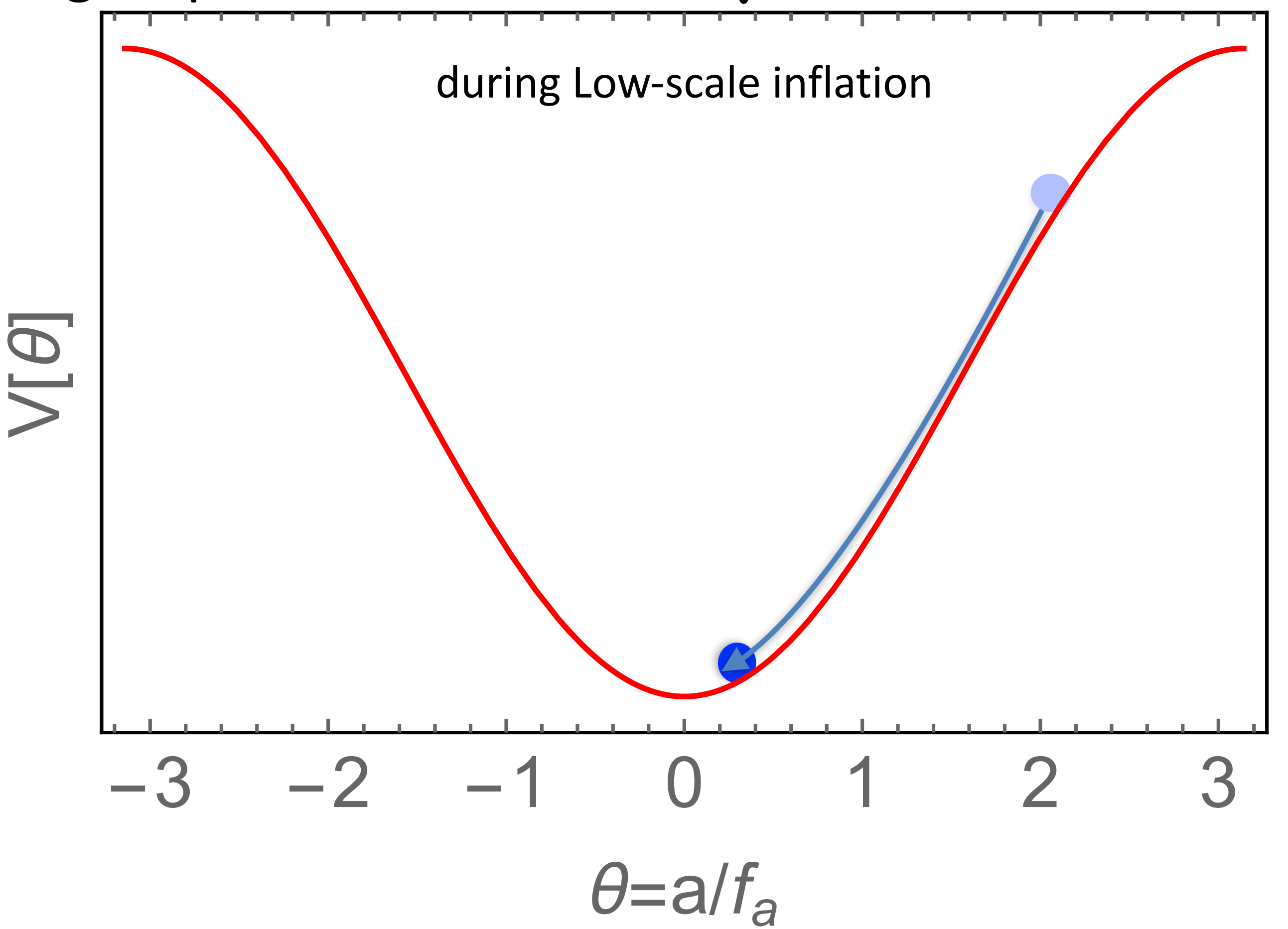
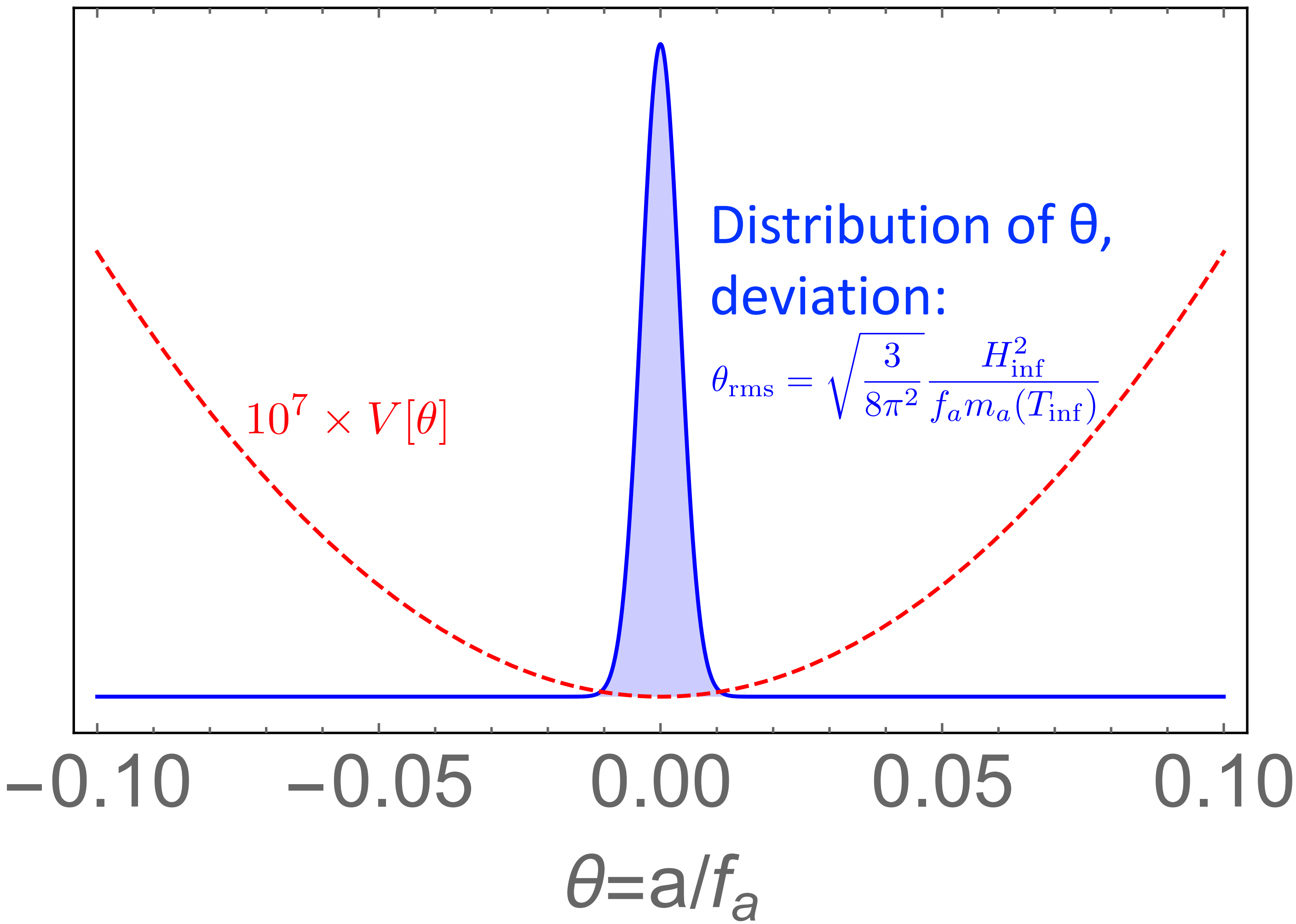


Axion during Inflation

For long enough inflation, the classical force gets into equilibrium with quantum diffusion.

θ follows Bunch-Davies Distribution Bunch Davies, 78



Axion after Inflation

After inflation, at 1σ level,

$$|\theta_*| \lesssim \sqrt{\frac{3}{8\pi^2}} \frac{H_{\rm inf}^2}{f_a m_a(T_{\rm inf})} \simeq 0.0034 \left(\frac{H_{\rm inf}}{10{\rm MeV}} \right)^2 .$$

Much smaller than O(1).

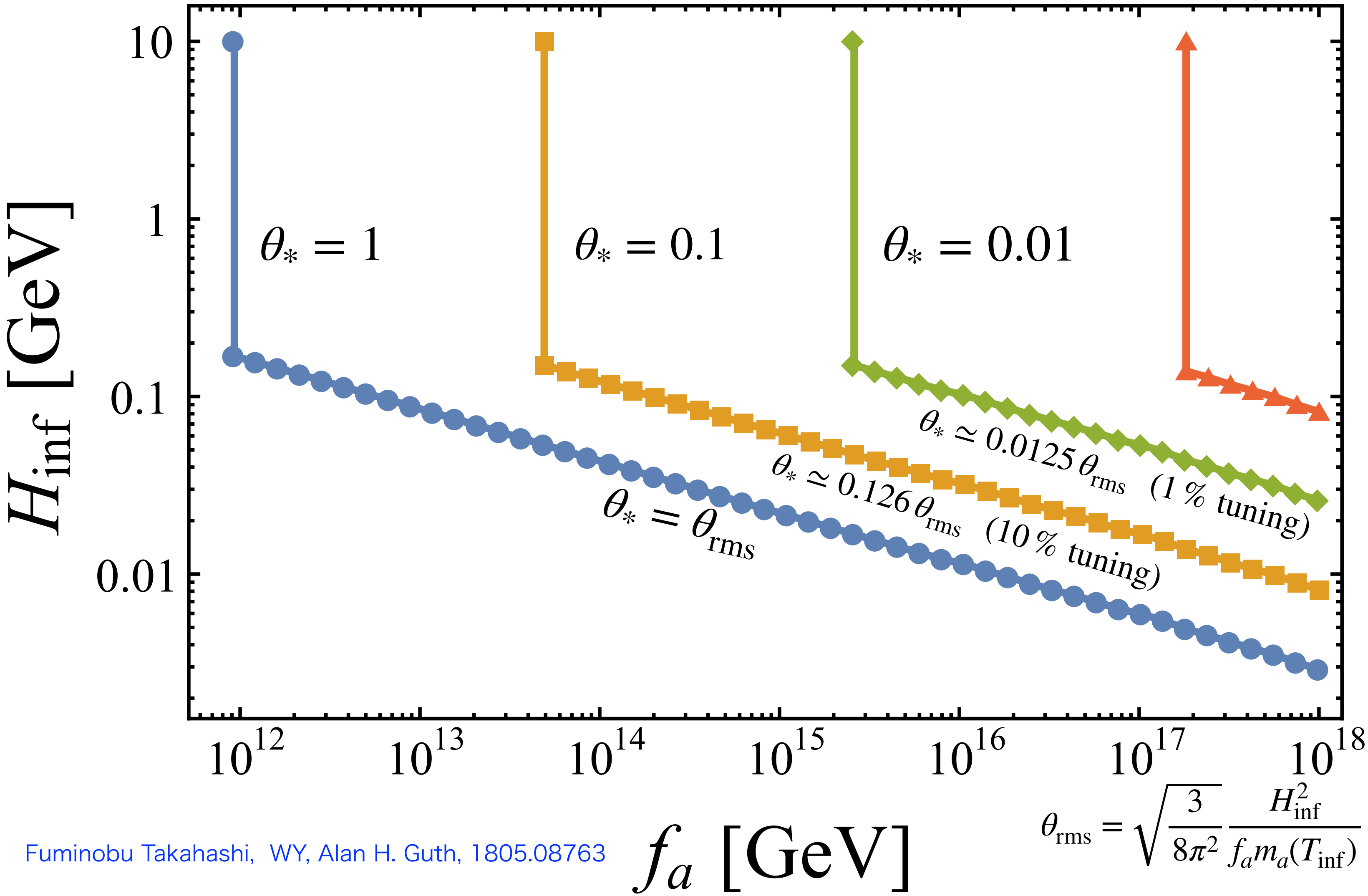
Inflaton decays to heat the Universe and the axion potential vanishes.

$|\theta|$ remains to be small. (Assuming no light degrees contributing to strong CP phase.)

Therefore, the abundance is highly suppressed,

$$\Omega_a h^2 \simeq 0.1\ \theta_*^2 \left(\frac{f_a}{10^{12} GeV} \right)^{1.17}$$ with $\theta_* \ll O(1)$

Upper bound of QCD axion window can be relaxed in low-scale inflation.



$$\theta_{\rm rms} = \sqrt{\frac{3}{8\pi^2}\frac{H_{\rm inf}^2}{f_a m_a(T_{\rm inf})}}$$

Fuminobu Takahashi, WY, Alan H. Guth, 1805.08763

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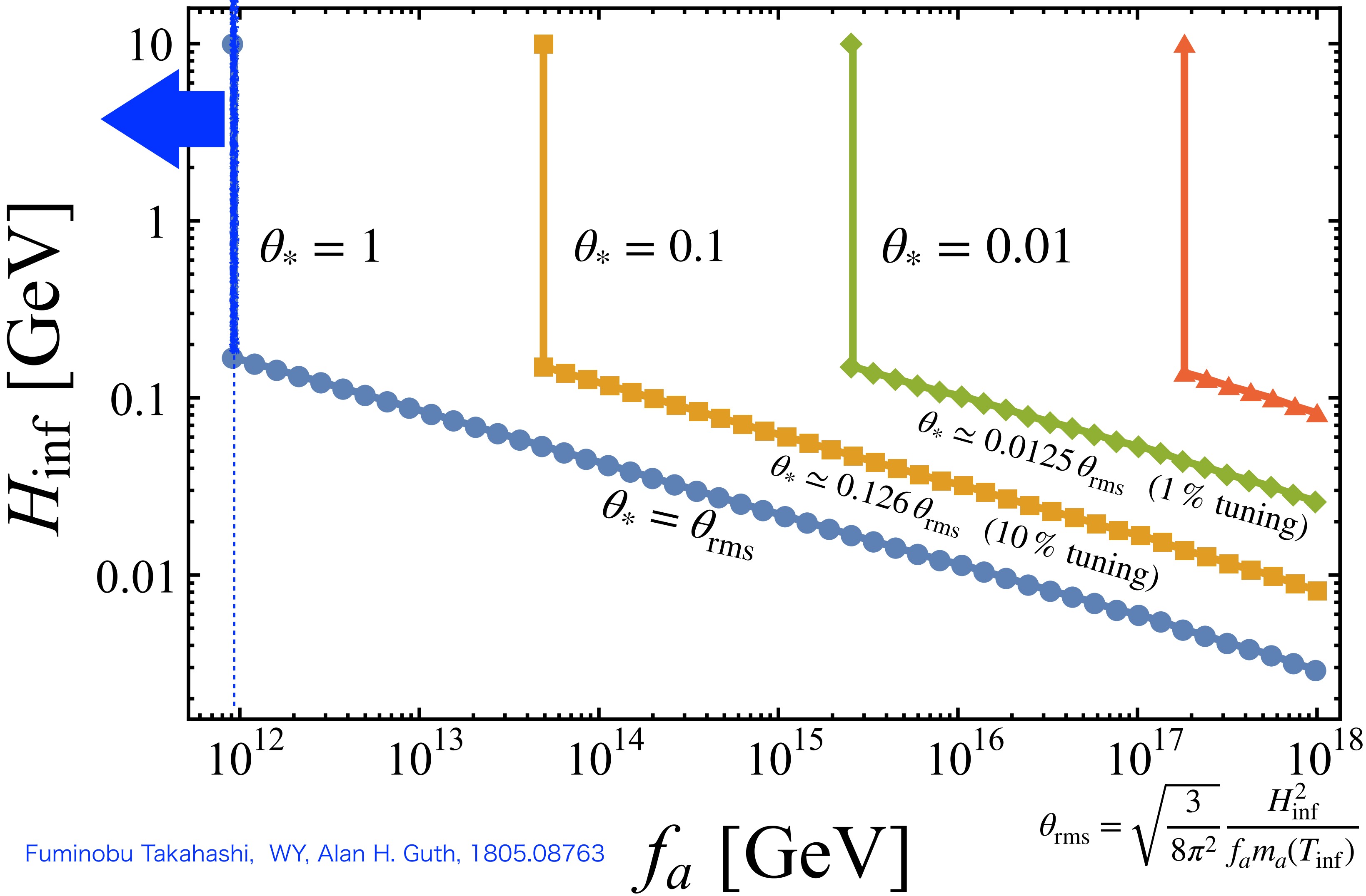
Conventional axion window, $f_a \lesssim 10^{12}\,\mathrm{GeV}$



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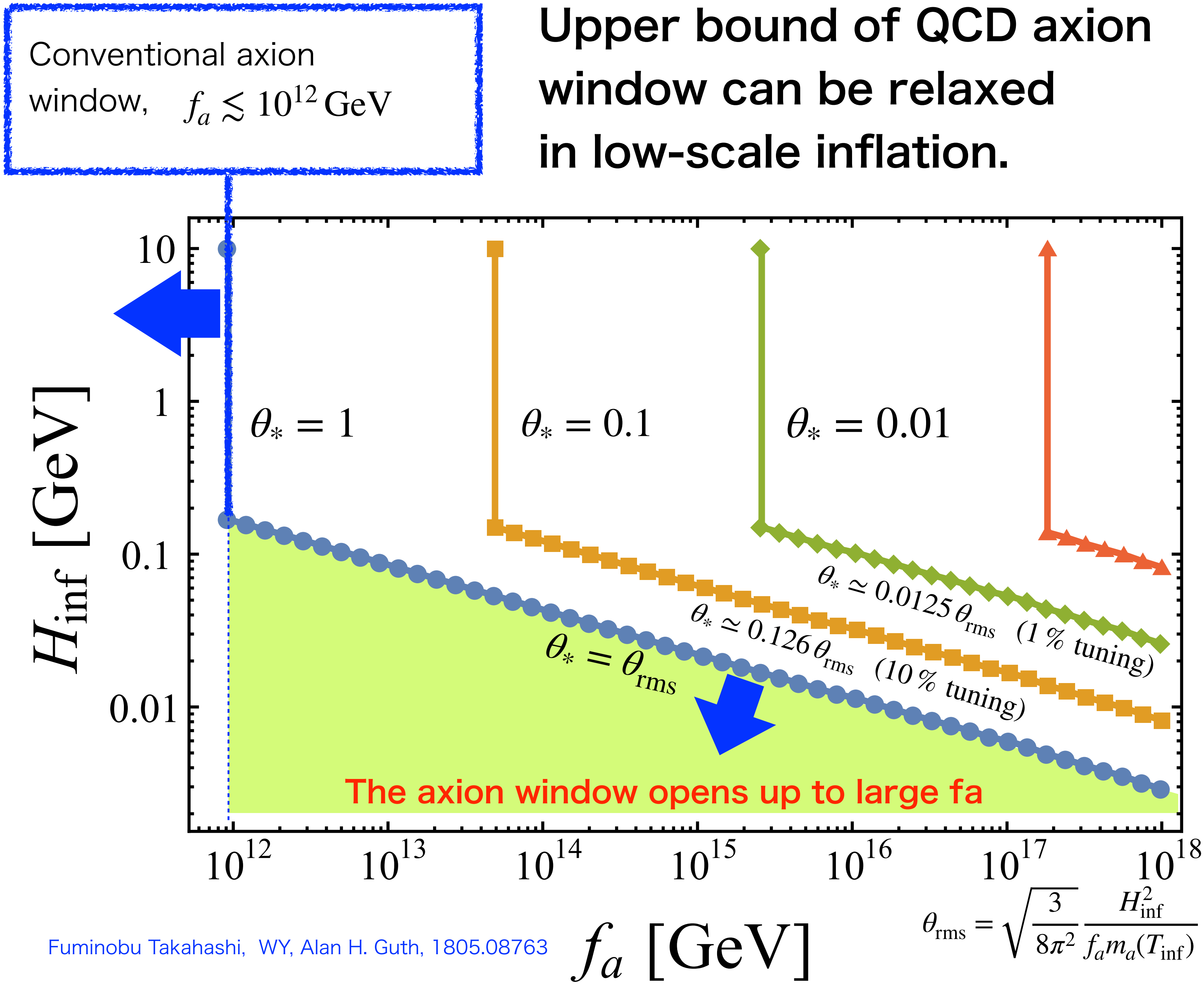

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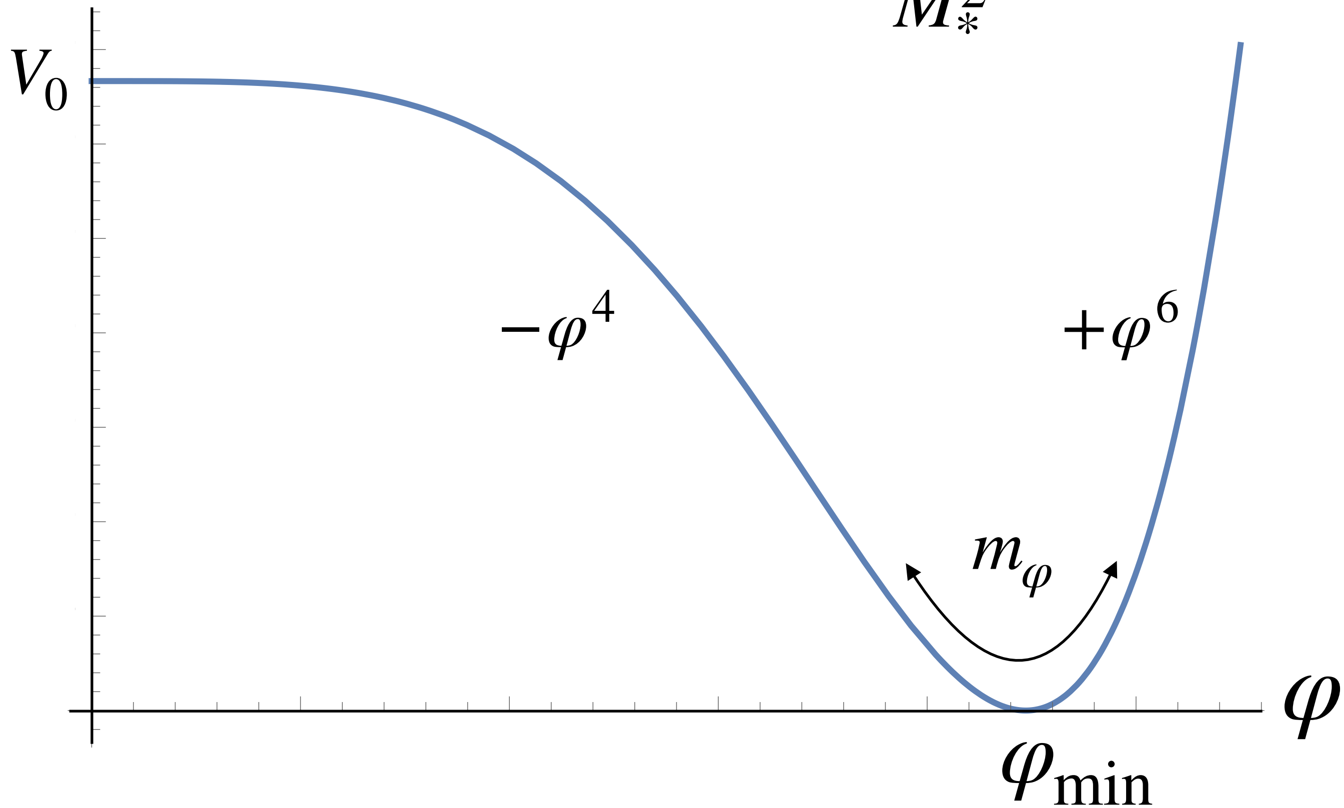
3. Low-scale inflation model with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$

$$V(\varphi) = V_0 - \kappa\varphi^4 + \lambda\frac{\varphi^6}{M_*^2}$$



$$H_{\rm inf} \sim 100\,{\rm MeV}, \quad m_\varphi \sim 10^6\,{\rm GeV}, \quad \varphi_{\rm min} \sim 10^{12}\,{\rm GeV}$$

Fuminobu Takahashi, WY, Alan H. Guth, 1805.08763

Spectral index $n_s \simeq 0.96$ can be realized by including either a linear term or Coleman-Weinberg correction.

Nakayama, Takahashi, 1108.0070,
Takahashi 1308.4212

Successful reheating is possible

We introduce a coupling to right-handed neutrinos,

$$\mathscr{L} = y_{N_i} \varphi \, \bar{\nu}^c_{Ri} \nu_{Ri}$$

with $y_N \sim 10^{-7}$.

The decay rate is $\Gamma_\varphi = \sum \frac{y_{N_i}^2}{8\pi} m_\varphi$ if kinematically allowed.

$$T_R \sim \left(\frac{90}{\pi^2 g_*} \right)^{\frac{1}{4}} \sqrt{M_{\rm pl} \Gamma_\varphi}$$

$$\simeq O(10) \mathrm{TeV} \left(\frac{106.75}{g_*} \right)^{\frac{1}{4}} \left(\frac{y_N}{10^{-7}} \right) \left(\frac{m_\varphi}{10^6 \mathrm{GeV}} \right)^{\frac{1}{2}} \left(\frac{N_R^{\rm eff}}{2} \right)^{1/2}$$

cf. Even Inflation with $H_{\rm inf} = O(1)\,\mathrm{eV}$ is possible. In this case the reheating proceeds through thermal dissipation. “ALP miracle”, Daido, Takahashi, WY, 1702.03284, 1710.11107

Summary

The QCD axion window is opened up to
$f_a \sim M_{\rm pl}$ for inflation with $H_{\rm inf} < \Lambda_{\rm QCD}$.

- Axion abundance follows Bunch-Davies distribution.

- QCD scale inflation with successful reheating is possible.

Backup

Reheating Temperature

Boltzmann Equation:

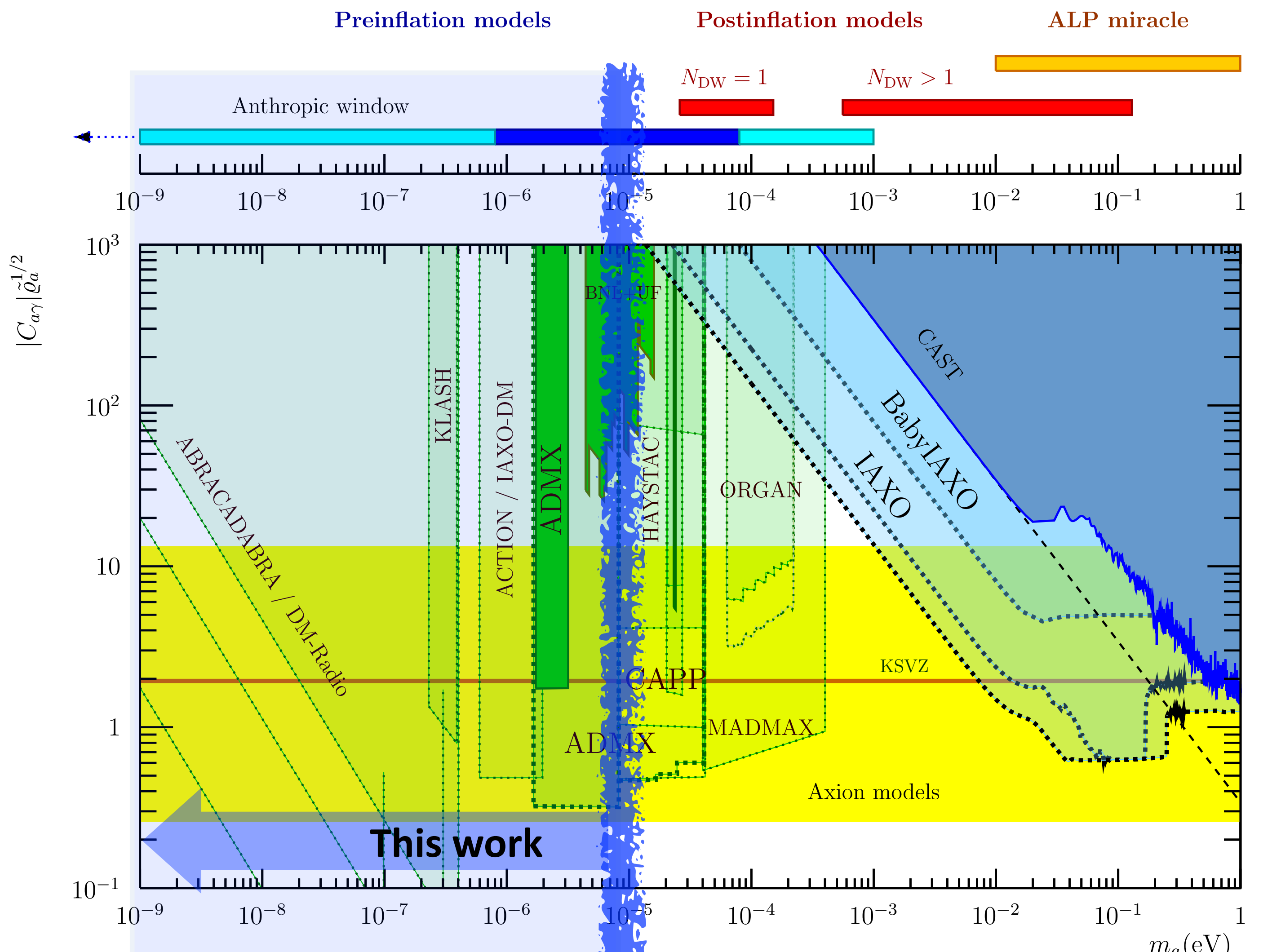
$$\frac{d\rho_r}{dt} = -4H\rho_r + \Gamma_\varphi \rho_\varphi,$$
$$\frac{d\rho_\varphi}{dt} = -3H\rho_\varphi - \Gamma_\varphi \rho_\varphi.$$

The reheating temperature is calculated as

$$T_R \simeq 0.64 \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{M_{\rm pl}\Gamma_\varphi}$$
$$\simeq 10 \text{ TeV} \left(\frac{106.75}{g_*}\right)^{\frac{1}{4}} \left(\frac{y_N}{10^{-7}}\right) \left(\frac{m_\varphi}{5\times 10^5 \text{ GeV}}\right)^{\frac{1}{2}} \left(\frac{N_R^{\rm eff}}{2}\right)^{1/2},$$

This is much larger than the weak scale and one can have resonant leptogenesis
Pilaftsis,9702393; Buchmuller, Plumacher, 9710460; Pilaftsis, Underwood, 0309342; 0506107; Anisimov, et al., 0511248; Garny, et al., 1112.6428

or electroweak baryogenesis.



Irastorza, Redondo,1801.08127

If axion DM is found to have certain mass, the inflation scale is predicted.