Mainly based on Phys. Rev. D 98, 015042 [1805.08763]

QCD axion dark matter and inflation scale

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In collaboration with
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Introduction: phenomenology of Axion

The QCD axion is not only a promising solution to strong CP problem, but also a candidate of dark matter (DM).

$$\mathscr{L} = \mathscr{L}_{\rm SM}|_{\theta_{\rm CP}=0} + \underbrace{\frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon}}_{\text{strong CP term}} + \underbrace{f_a^2(\partial\theta)^2}_{\text{Kinetic term}}$$

θ: QCD axion, f_a : decay constant

Shift symmetry @ $T \gg T_{\rm QCD}$: $V(\theta) \sim 0$

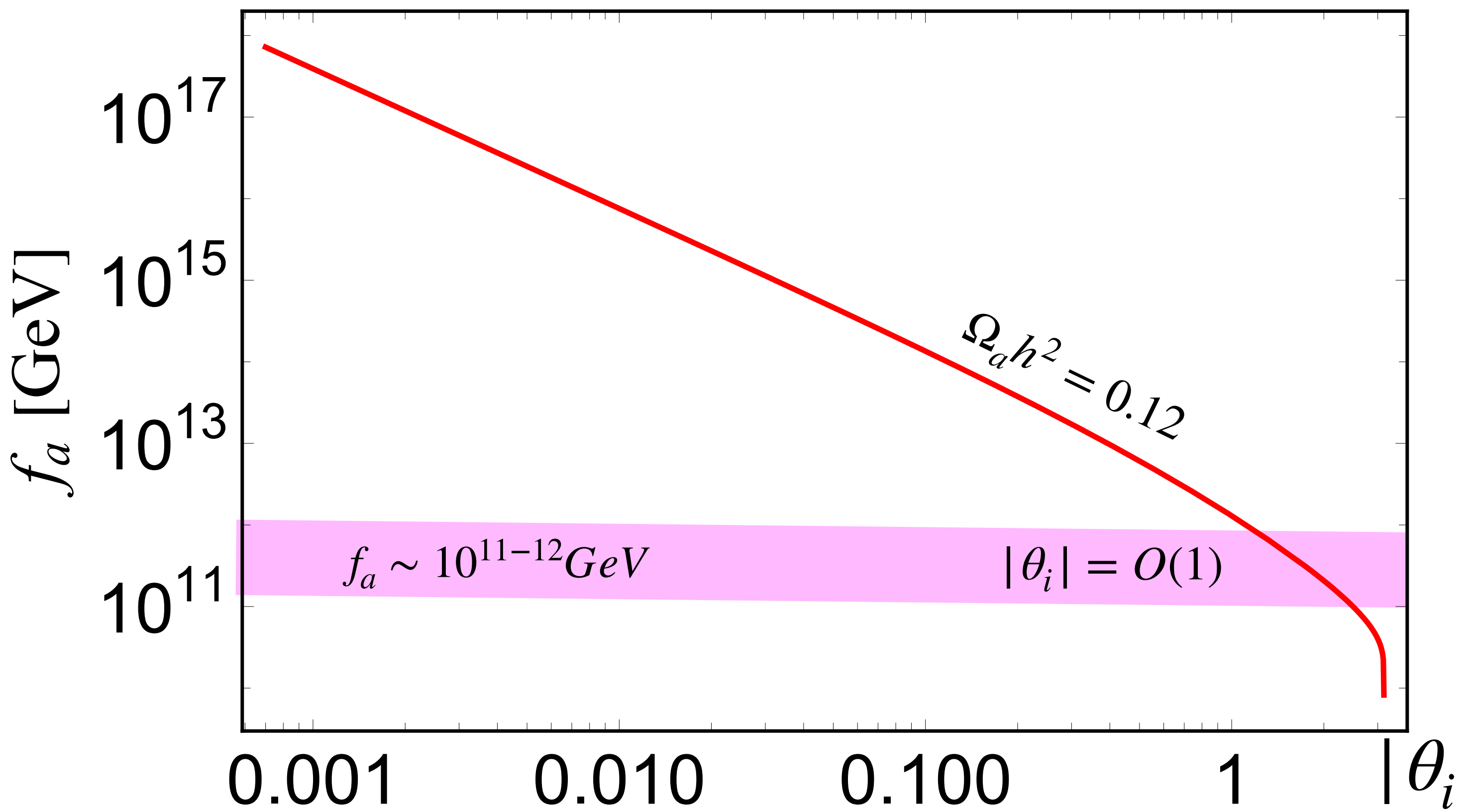
No shift symmetry@ $T \ll T_{\rm QCD}$: $V(\theta) \sim \chi(1 - \cos[\theta])$

Peccei, Quinn, 77; Weinberg, 78; Wilczek, 78;
Kim, 79; Shifman, Vainstein, Zakharov, 80; (See also Zhitnitsky, 80; Dine, Fischler, Srednicki 81;)

“Natural” prediction of axion DM

The axion abundance is obtained Ballesteros et al, 1610.01639

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



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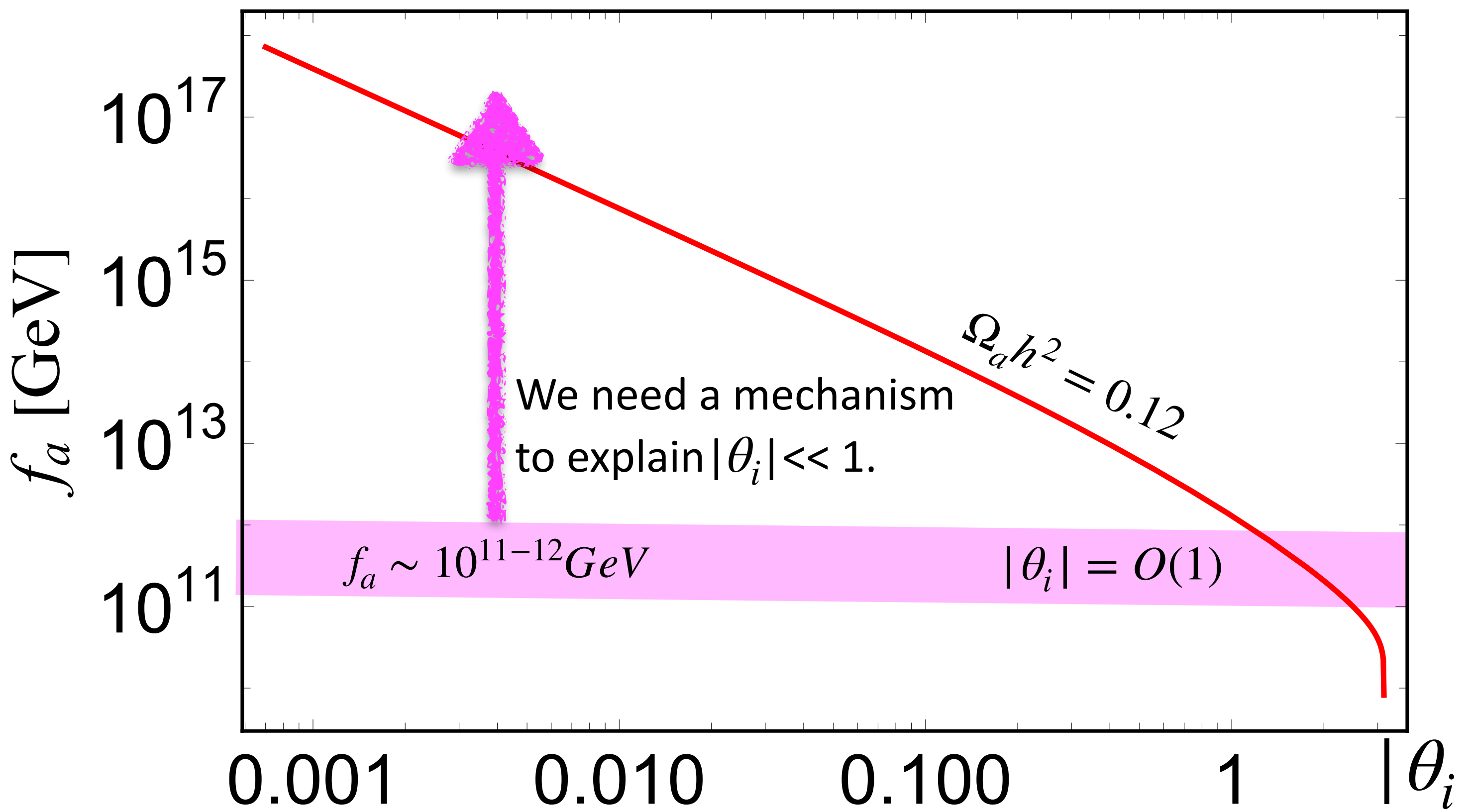
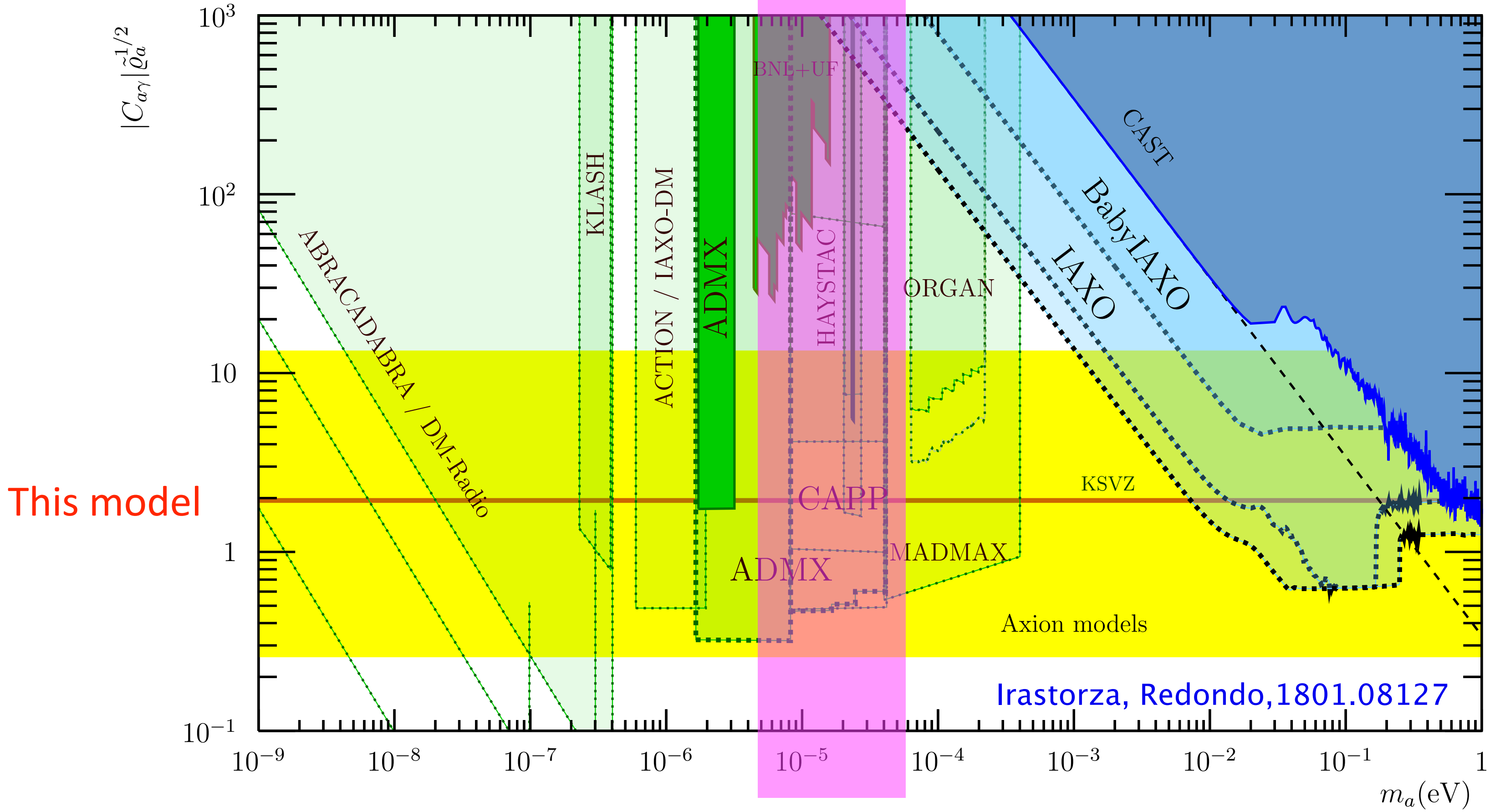


Phenomenology of Axion

Axion DM can be tested in near future.

Most of testable range is out of the “natural” prediction…

$f_a \sim 10^{11-12} GeV$



(IAXO does not assume axion as the DM.)

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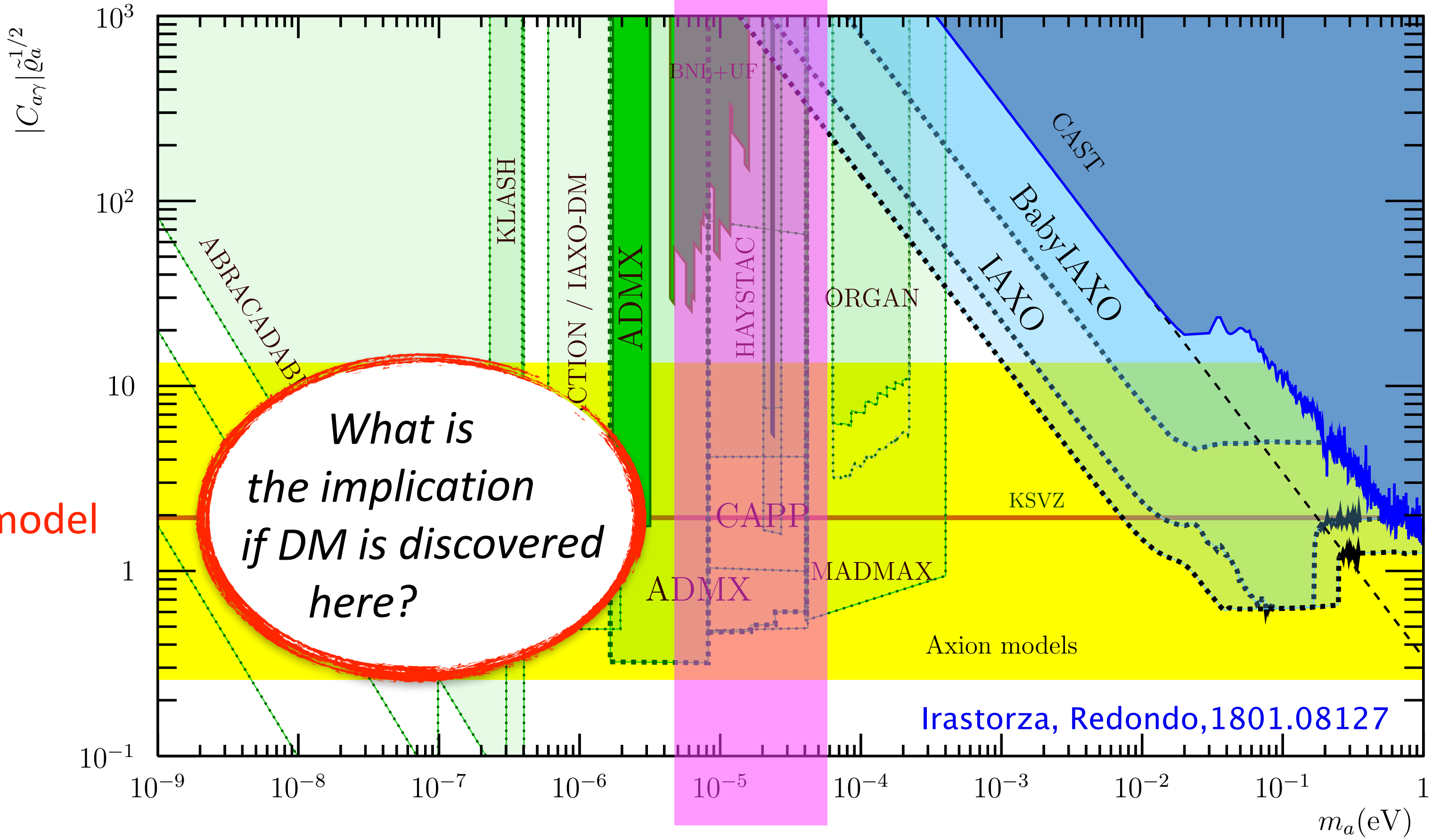
This model



See also Manuel Buen-Abad's talk.

(IAXO does not assume axion as the DM.)

What I will be talking about

Takahashi, WY, and Guth 1805.08763

The QCD axion DM naturally predicts

$$f_a \sim 10^{12-18} GeV$$

if inflation scale $\lesssim 10^8\,\mathrm{GeV}$ equivalently $H_{\mathrm{inf}} \lesssim \Lambda_{\mathrm{QCD}}$

and inflation lasts long enough.

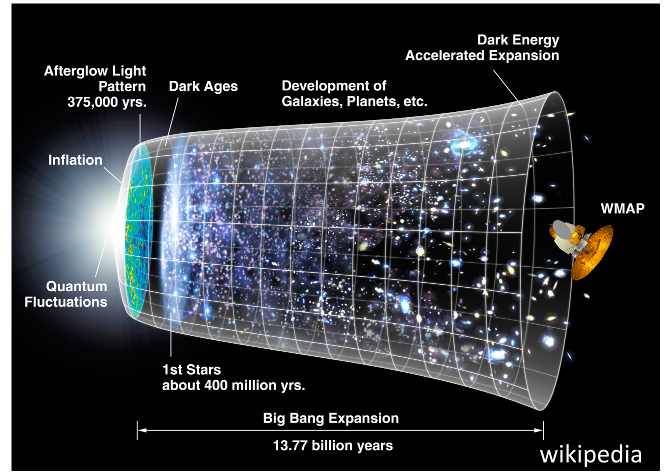
* No isocurvature/domain-wall problem.
* No new particles required.
* DM mass $\leftrightarrow$ inflation scale.

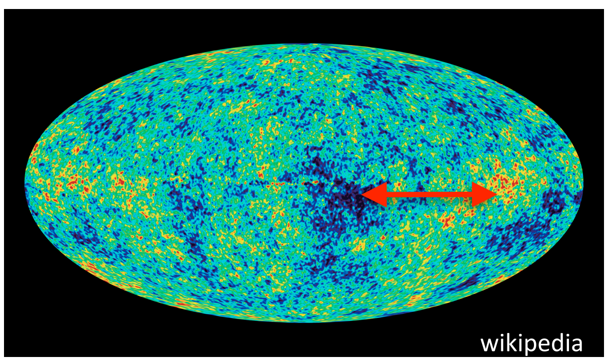
2. Low-scale inflation and QCD axion DM

A.Guth, 1980; K.Sato, 1980; A.Starobinsky, 1980; Kazanas, 1980; A.Linde, 1981; Albrecht, Steinhardt, 1981;

The Universe experienced an exponential expansion $a \propto \exp[H_{\rm inf} t]$

Inflation solves horizon and flatness problems.





Quantum fluctuation during inflation has been observed in CMB.

Existence of inflation is rigid!

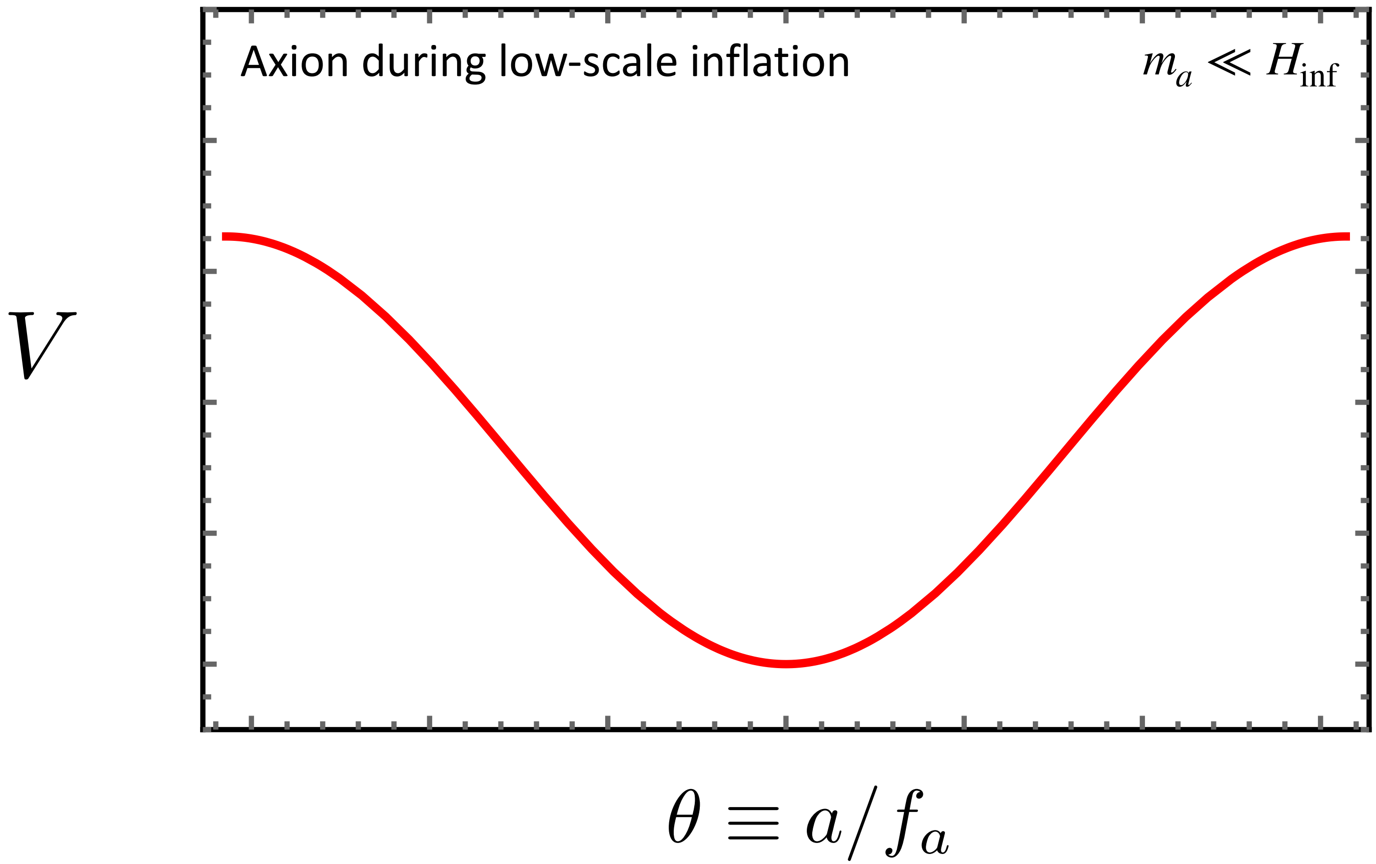
But $H_{\rm inf}$ *is still undetermined from observations.*

Axion during inflation

During inflation temperature exists:

$$T_{\rm inf} = \frac{H_{\rm inf}}{2\pi} \propto \frac{\sqrt{V_{\rm inf}}}{M_{\rm pl}}$$ Gibbons, Hawking, 77

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



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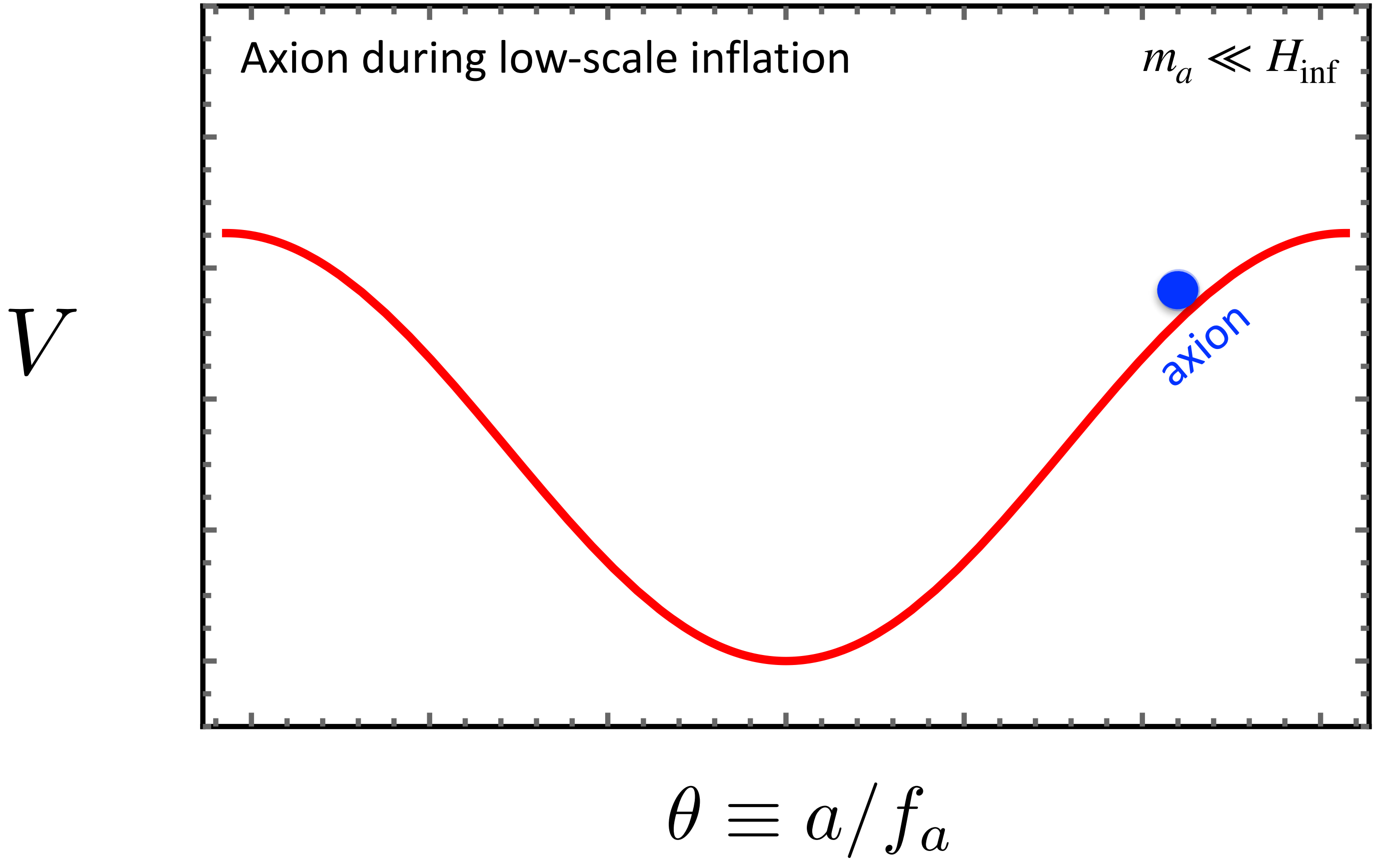

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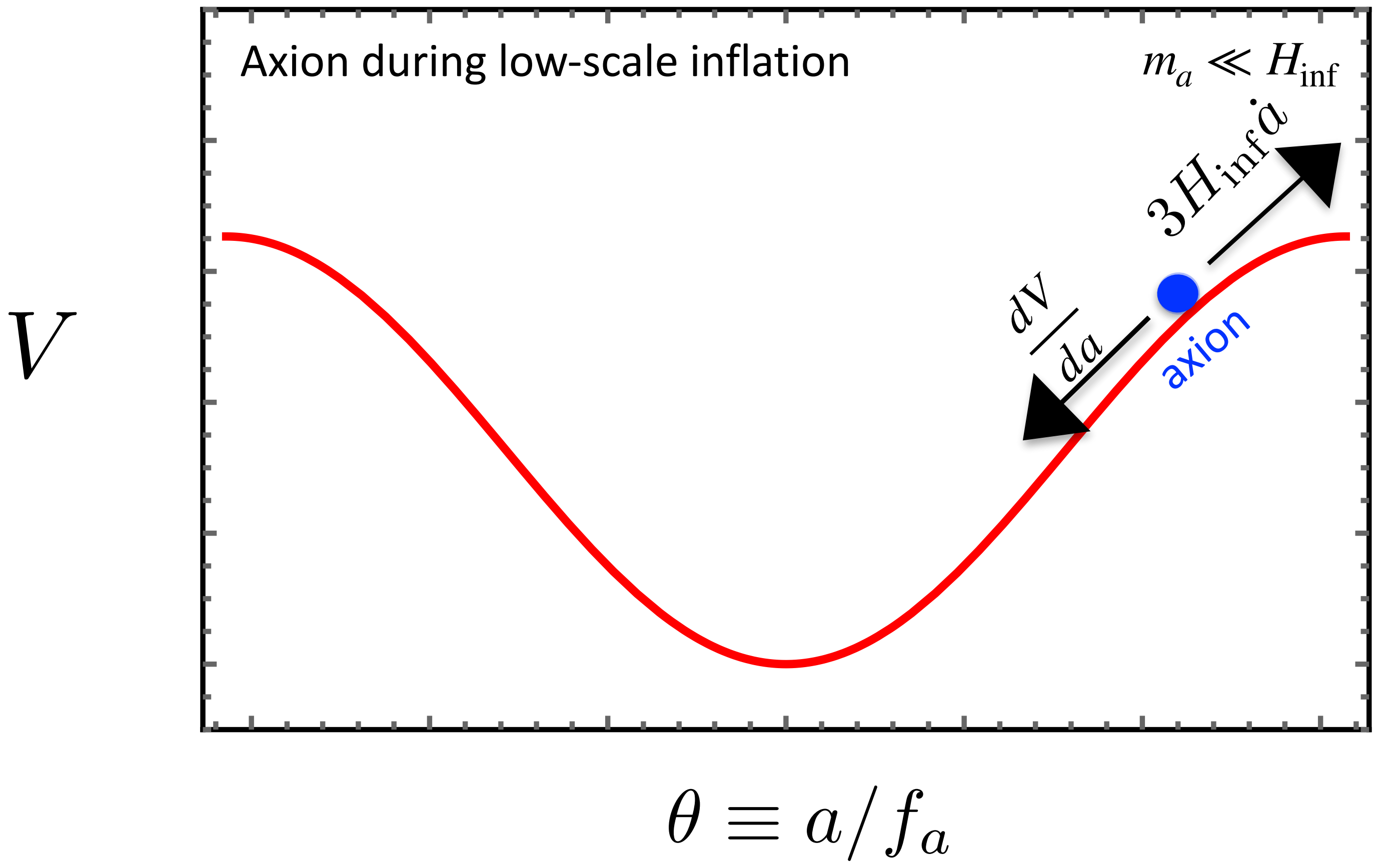

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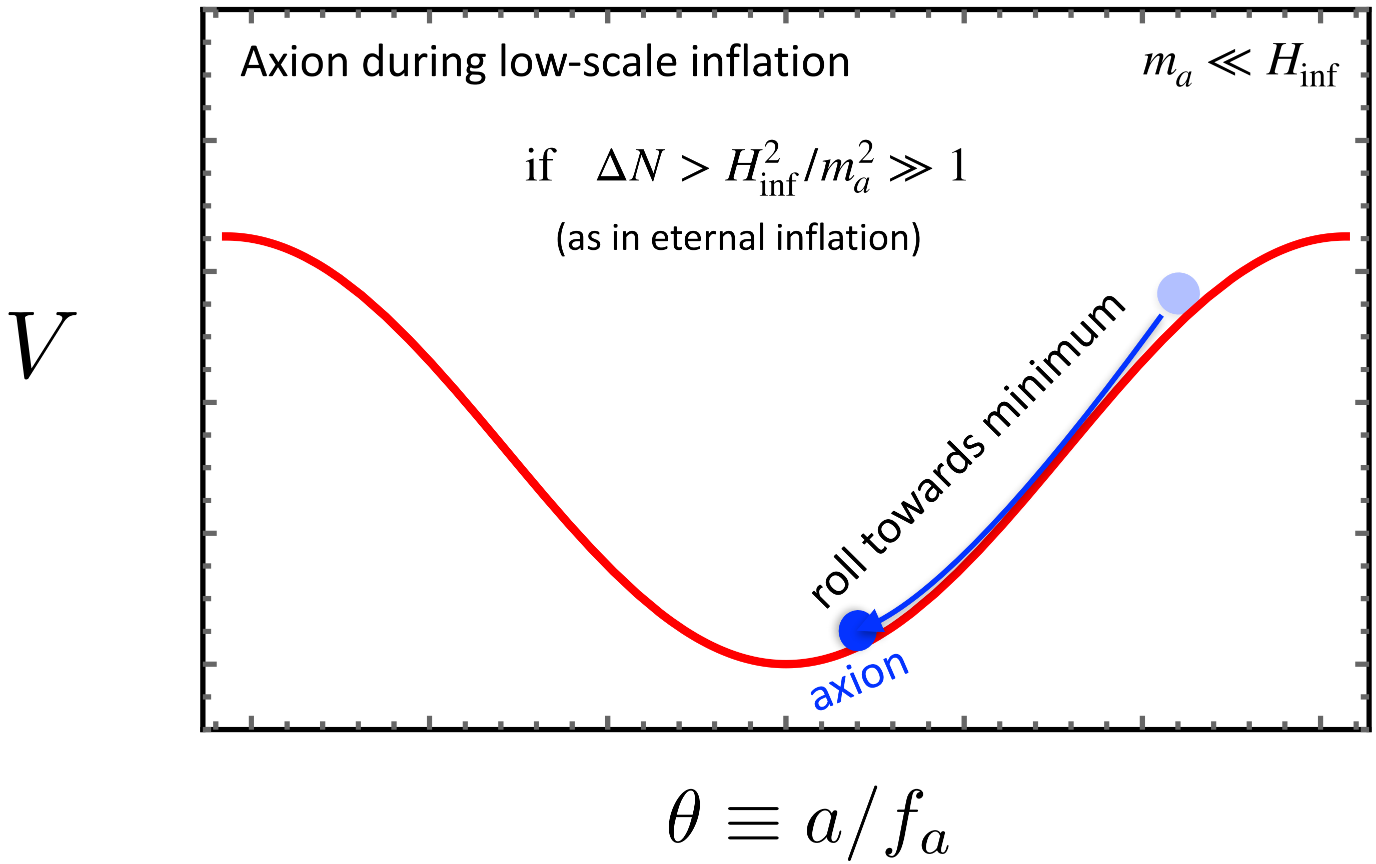
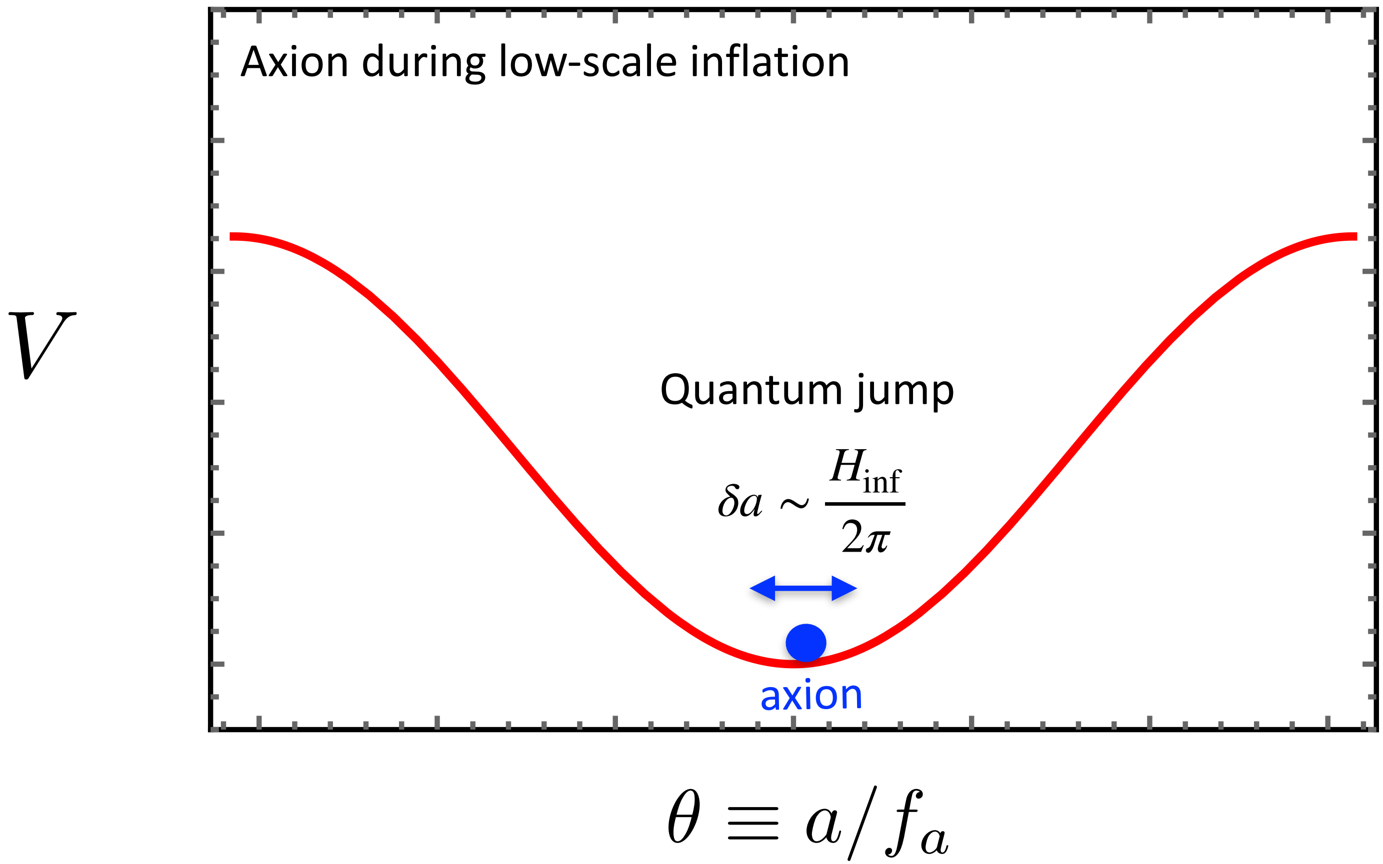


Axion during inflation

Quantum diffusion prevents the axion from falling into the potential minimum.



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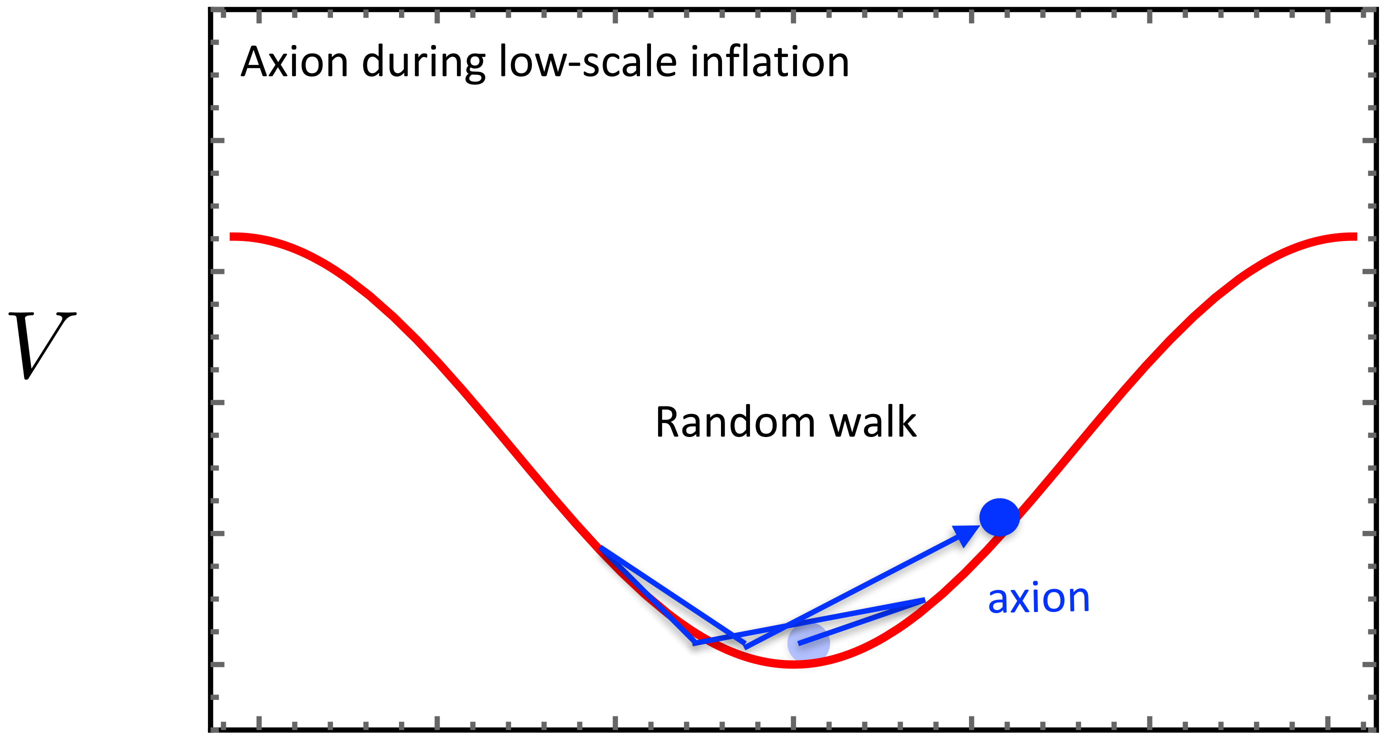


$$\theta \equiv a/f_a$$

Equilibrium of classical motion and quantum diffusion

Classical motion: $\Delta a^{\mathrm{classical}} \sim N_{\mathrm{eq}} \times \frac{m_a^2}{H_{\mathrm{inf}}^2} a$

$N_{\mathrm{eq}} \sim \frac{H_{\mathrm{inf}}^2}{m_a^2}$

Accumulated jumps (random walk): $\Delta a^{\mathrm{quantum}} \sim \sqrt{N_{\mathrm{eq}}} \times \frac{H_{\mathrm{inf}}}{2\pi}$

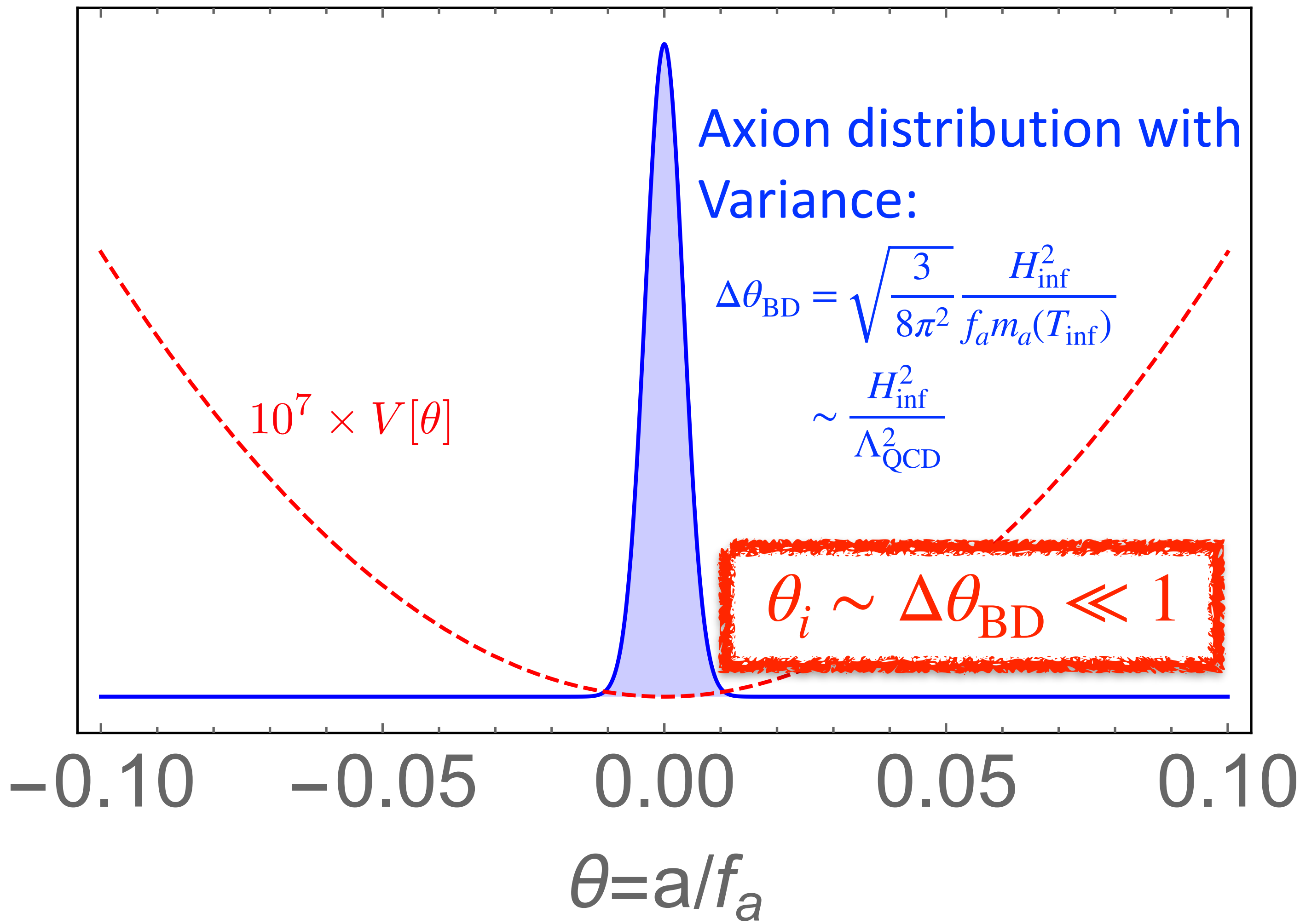
$$\sqrt{\langle a^2 \rangle} \propto \frac{H_{\mathrm{inf}}^2}{m_a}$$

Axion during inflation

For $N \gg H_{\rm inf}^2/m_a^2$, the classical motion gets into equilibrium with quantum diffusion.

Bunch Davies, 78

θ follows an equilibrium distribution in Bunch-Davies vacuum

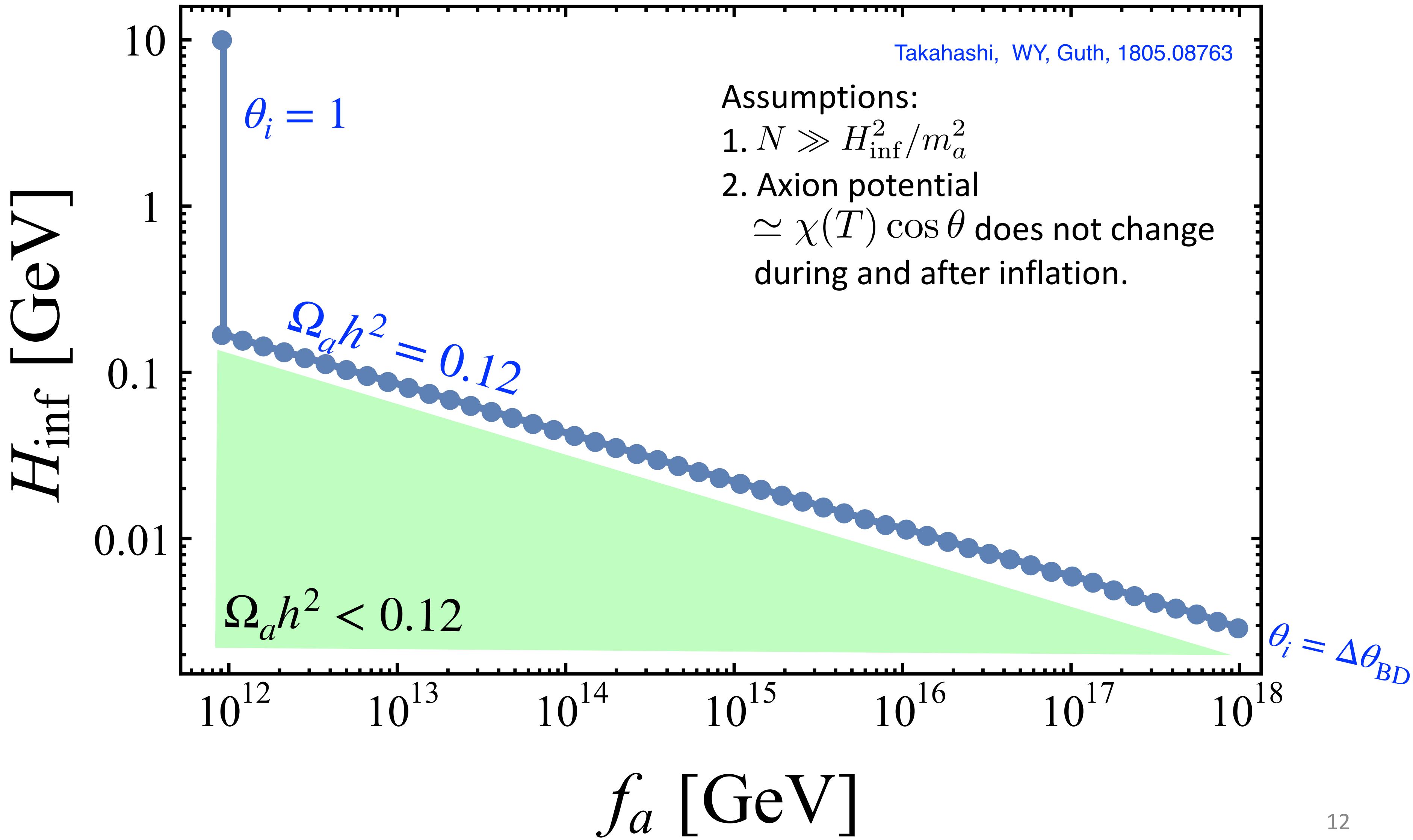


The QCD axion DM can be naturally explained with $f_a \sim 10^{12-18} GeV$

in low-scale inflation with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

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

See also stochastic ALP DM with quadratic potential Ho,Takahashi, WY, 1901.01240, Marsh, WY, 1912.08188
quartic potential Nakagawa, Takahashi, WY, 2002.12195



Conclusions

With long enough inflation with $H_{\rm inf} < \Lambda_{\rm QCD}$
the dominant QCD axion DM can be naturally realized with

$$f_a \sim 10^{12-18} GeV.$$

The axion DM mass can be a probe of low inflation scale.

*With Higgs excursion the inflation scale can be higher $H_{\rm inf} \lesssim 10 TeV$
"Higgs false vacuum inflation" Matsui, Takahashi, WY, 2001.04464

*(ALP) Inflaton-axion mixing can lead to heavier axion DM with

$$10^9 GeV < f_a < 10^{11} GeV.$$

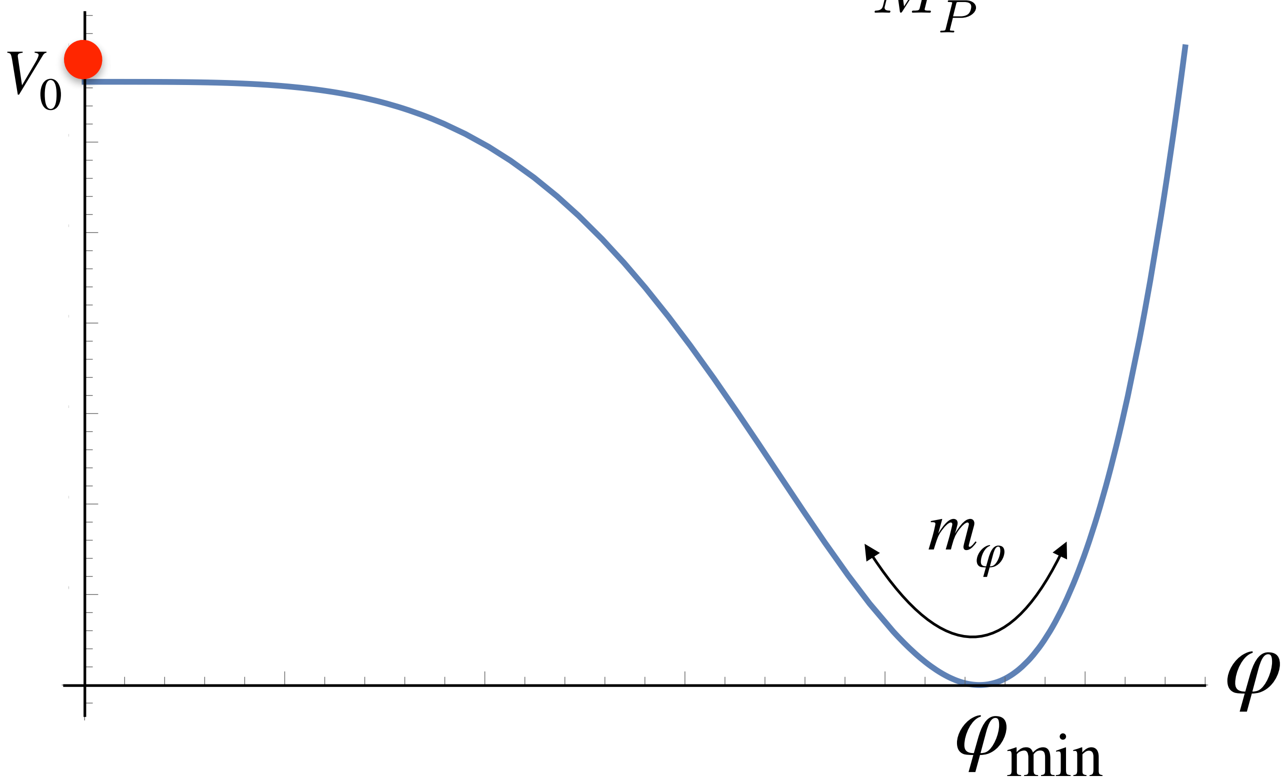
"πnflation" Takahashi, WY, 1908.06071, Daido, Takahashi, WY, 1702.03284

See also Jacob Leedom's talk.

backup

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

$$V = V_0 - \kappa\varphi^4 + \lambda\frac{\varphi^6}{M_P^2}$$



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

Takahashi, WY, Guth, 1805.08763

Spectral index $n_s \simeq 0.96$ can be obtained by introducing a linear term or Coleman-Weinberg correction (with SUSY.)

Nakayama, Takahashi, 1108.0070, Takahashi 1308.4212

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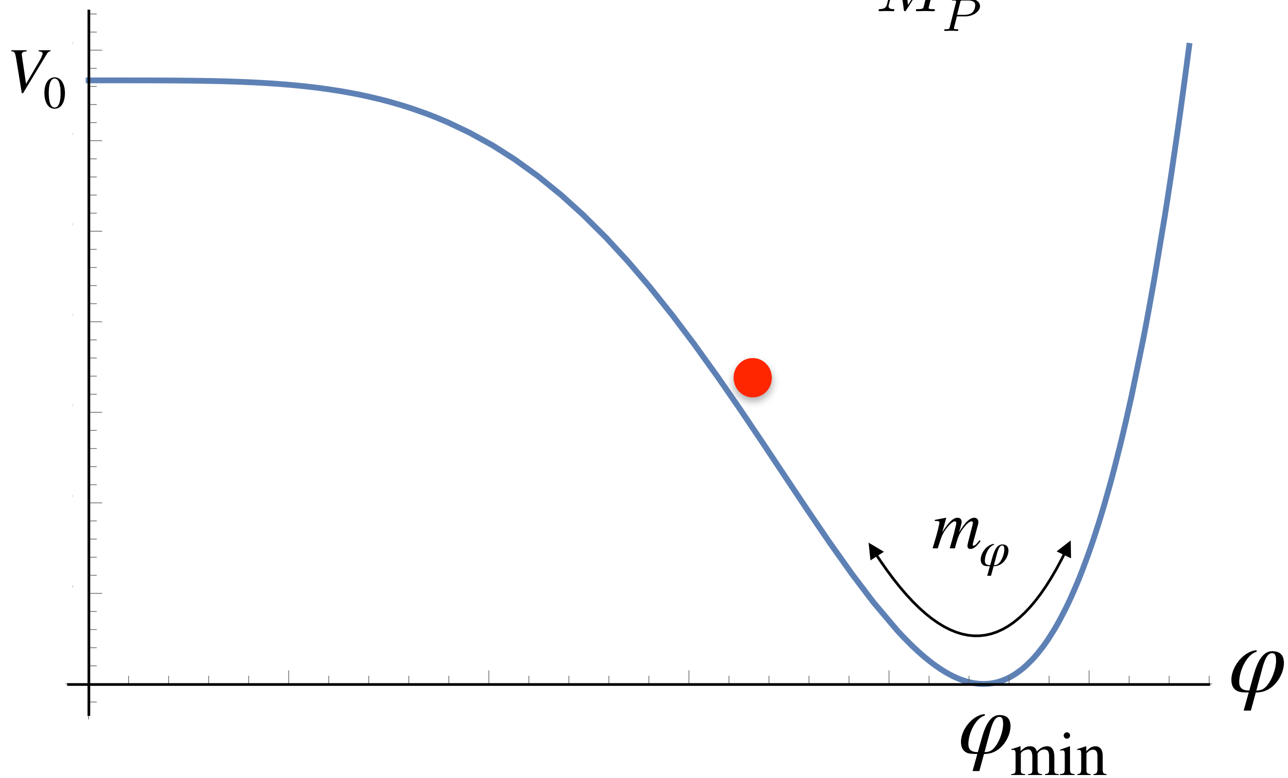

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Successful reheating is possible

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.

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

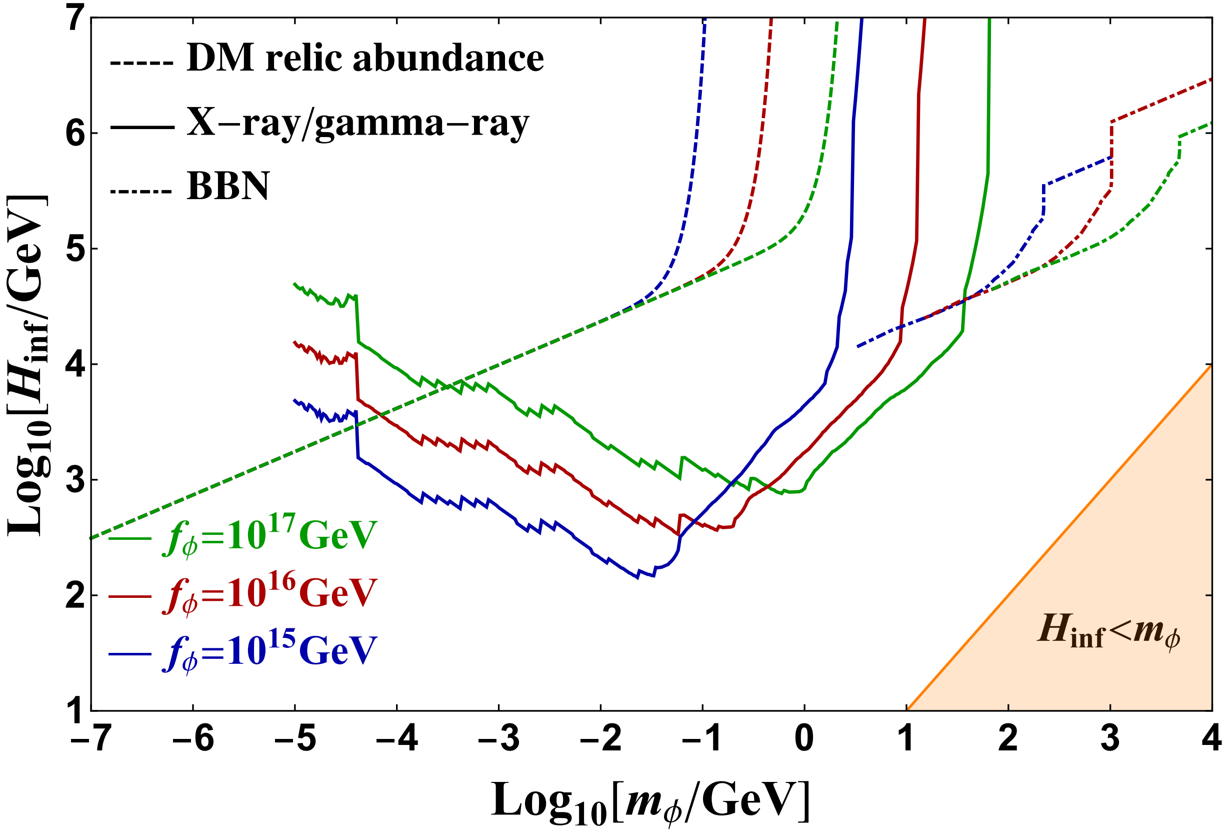
$$\simeq O(10)\mathrm{TeV} \left(\frac{106.75}{g_*}\right)^{\frac{1}{4}} \left(\frac{y_N}{10^{-7}}\right) \left(\frac{m_\varphi}{10^6 \mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{N_R^{\rm eff}}{2}\right)^{1/2}$$

cf. Inflation with $H_{\rm inf} \lesssim O(\mathrm{eV})$ is possible. In this case the reheating proceeds through thermal dissipation.

"ALP miracle", Daido, Takahashi, WY, 1702.03284, 1710.11107,
"Big bang on earth" Takahashi, WY 1902.00462

The moduli problem can be alleviated due to (not too) low-scale inflation. (Quadratic term)

Shu-Yu Ho, Fuminobu Takahashi, and WY 1901.01240



Assumption:

$N \gg H_{\rm inf}^2/m_\phi^2$

minima do not change during and after inflation

Data taken from

X(gamma)-ray:

Essig, et al. 1309.4091;

BBN:

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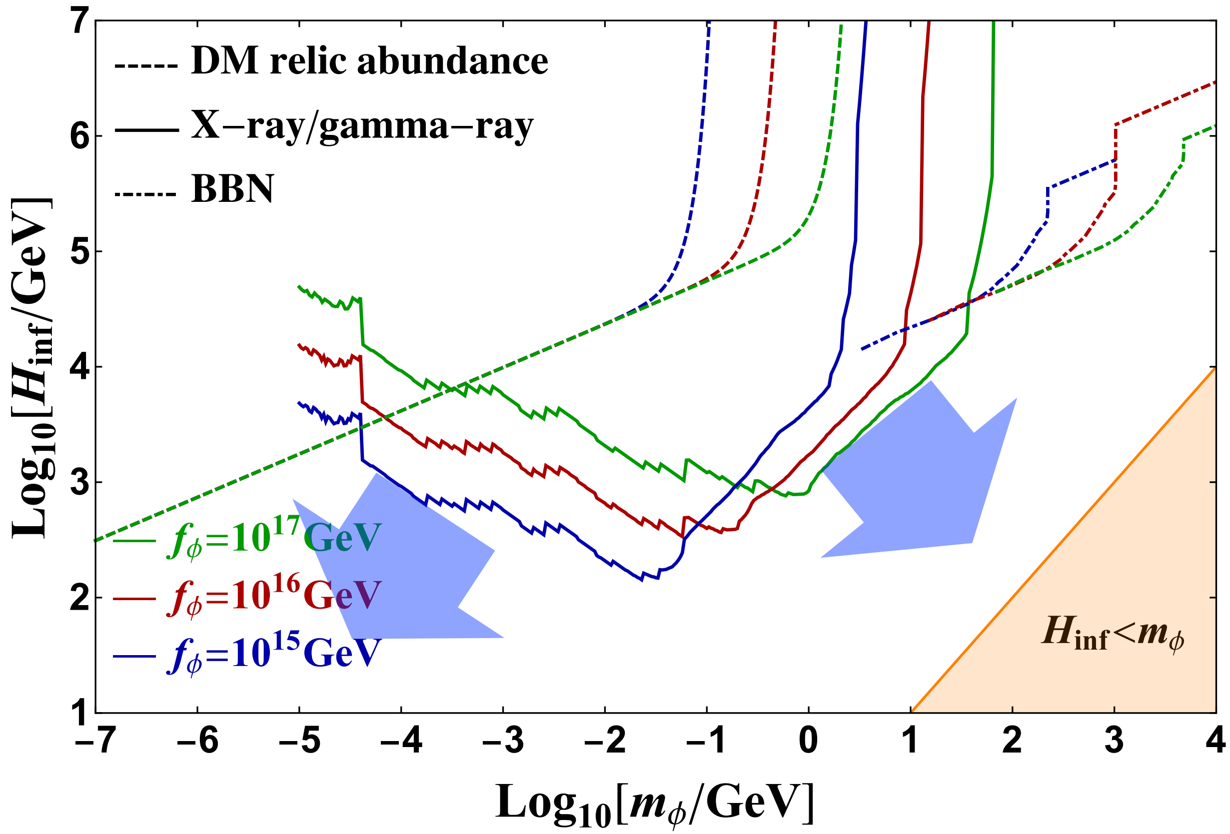

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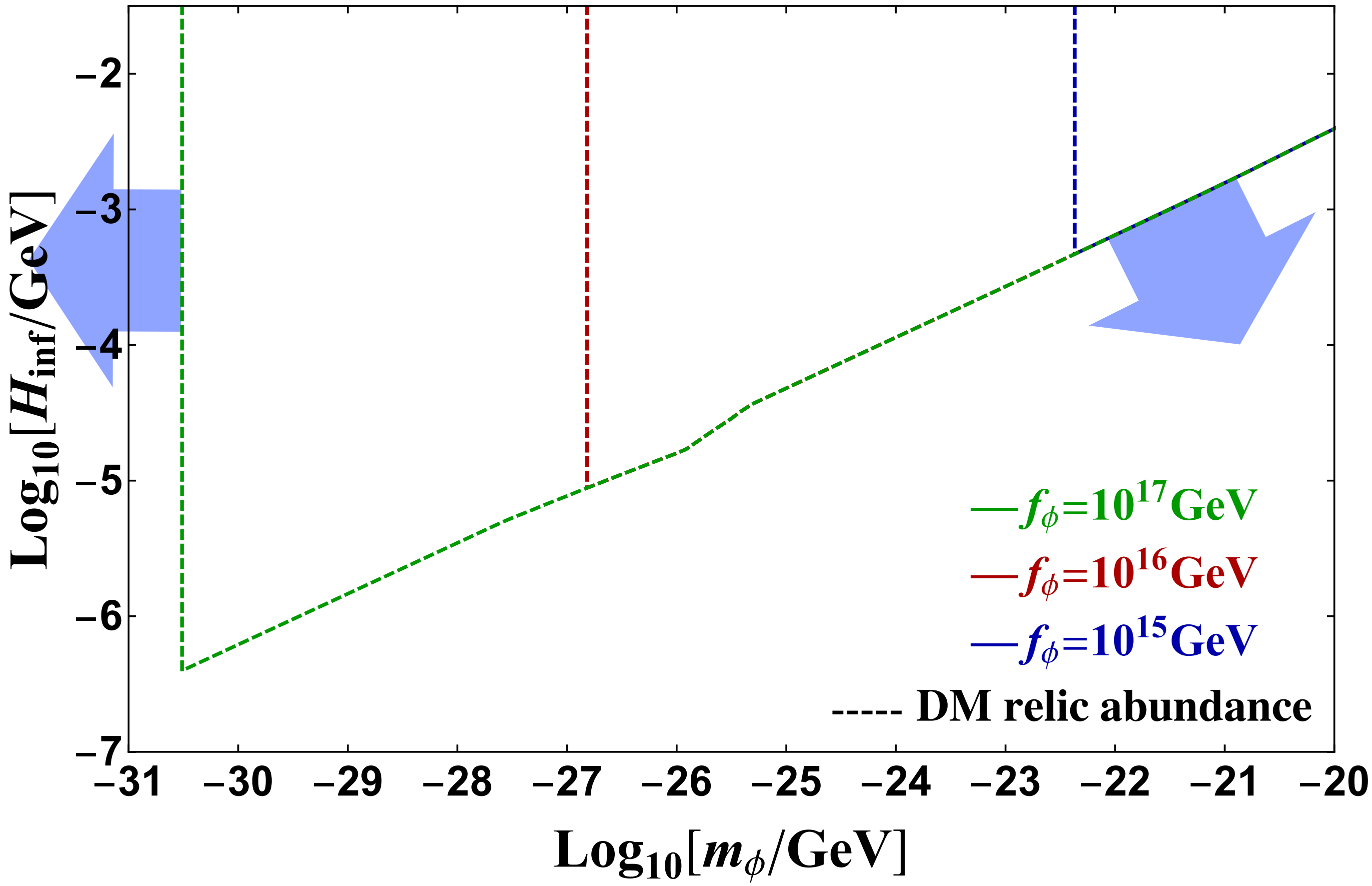
No moduli problem for the string axions

if $H_{\rm inf} \lesssim O({\rm keV})$ **[** $\rho_{\rm inf}^{1/4} \lesssim O(1){\rm PeV}$ **].**



Inflation with $H_{\rm inf} \lesssim O({\rm eV})$ is possible with successful reheating through thermal dissipation, and can be tested.

"ALP miracle", Daido, Takahashi, WY, 1702.03284, 1710.11107,
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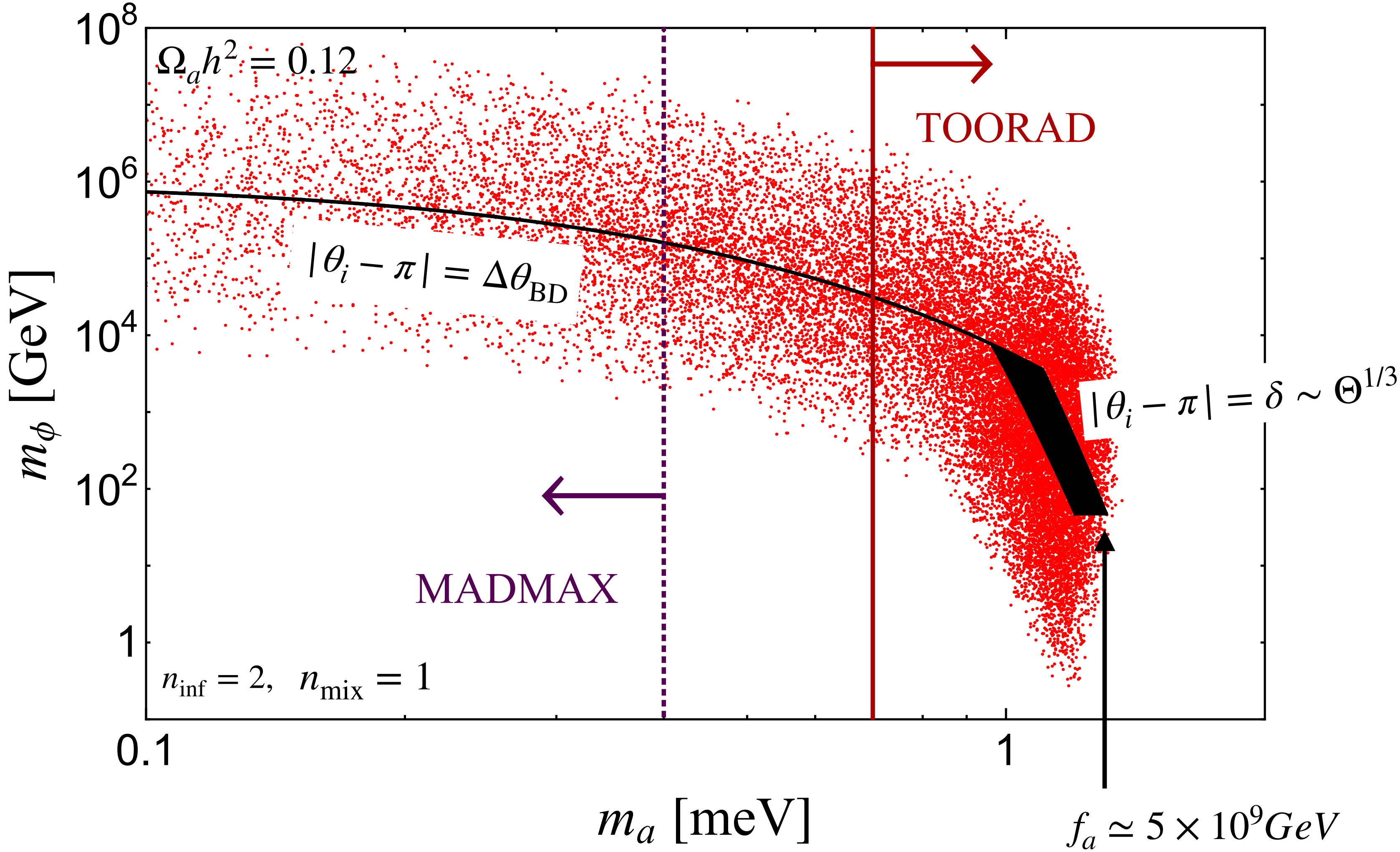
ALP πnflation with hilltop axion DM

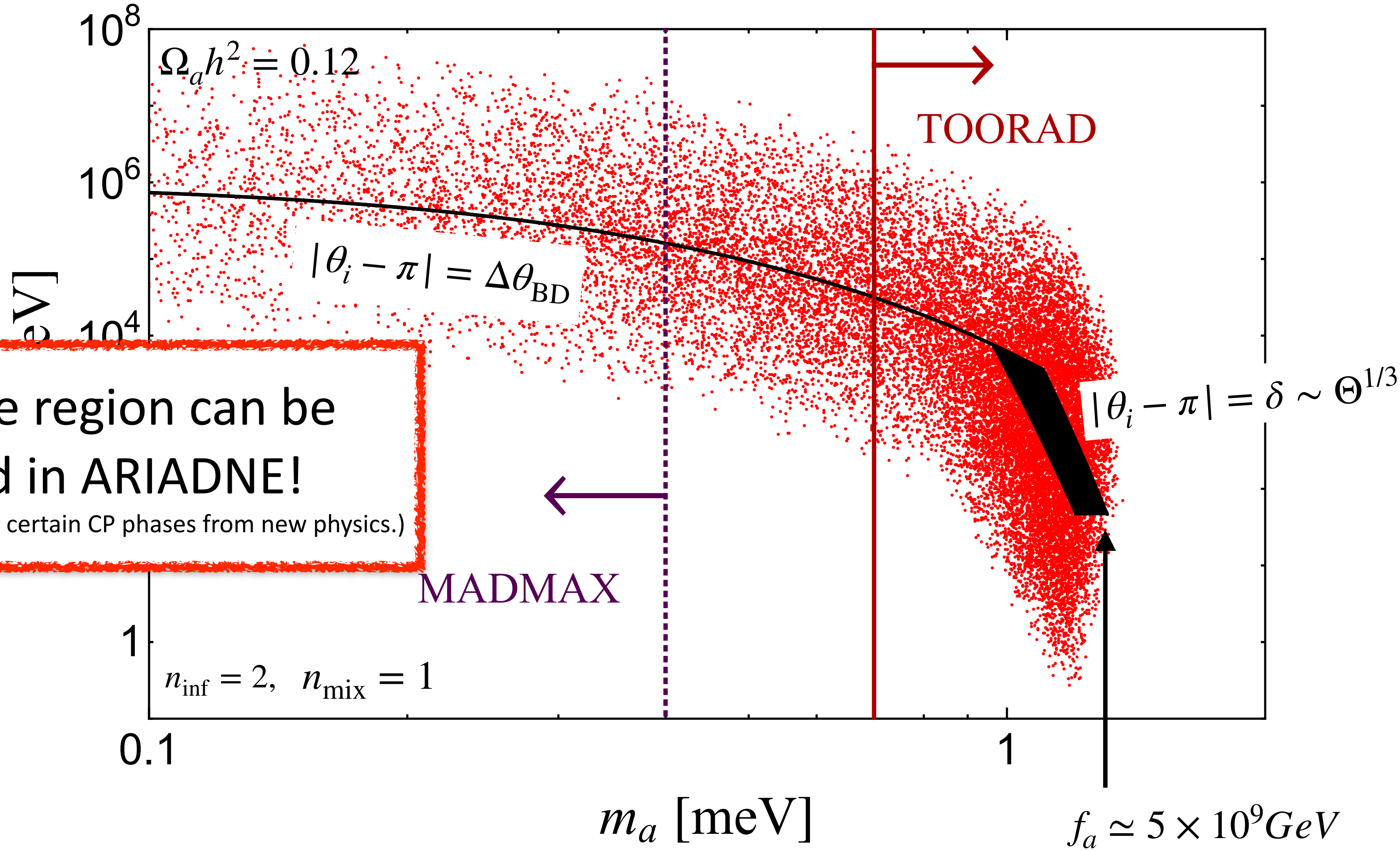
Takahashi, WY, 1908.06071,



$f_a \simeq 5 \times 10^9 GeV$

ALP πnflation with hilltop axion DM

Takahashi, WY, 1908.06071,

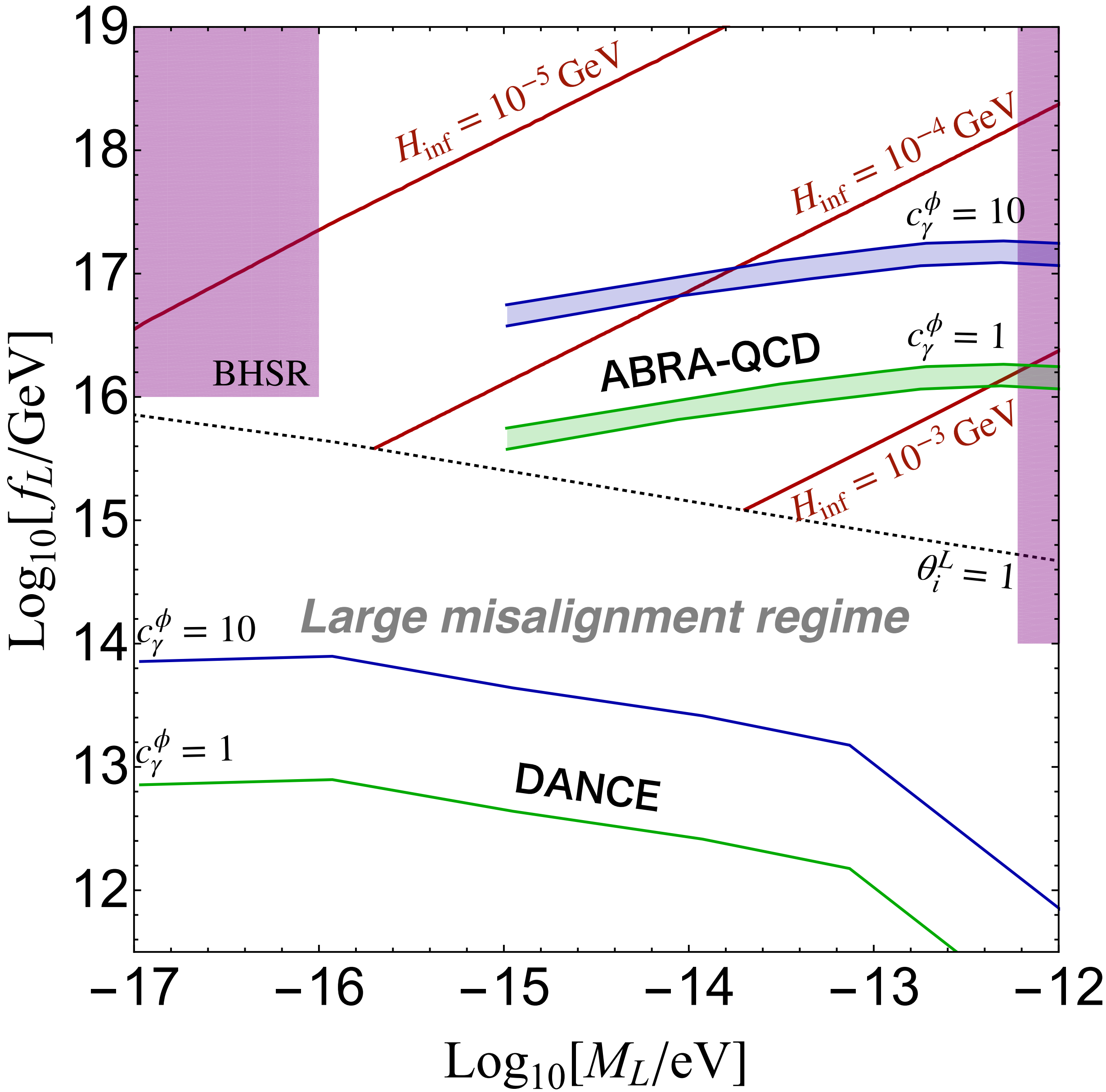


Whole region can be tested in ARIADNE!

(If there are certain CP phases from new physics.)

Opening 1Hz axion window

Marsh, WY, 1912.08188



Stochastic ALP DM with flat bottom

Nakagawa, Takahashi, WY, 2002.12195