TOHOKU UNIVERSITY

QCD Axion Dark Matter in the presence of Peccei-Quinn symmetry breaking

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Chung-Ang University Beyond the Standard Model Workshop

Fumi Takahashi (Tohoku)

Based on 2201.00681 with Kwang Sik Jeong, Shota Nakagawa, and Kohei Matsukawa

1. Introduction

The strong CP problem

Why is the strong CP-violating effect so small?

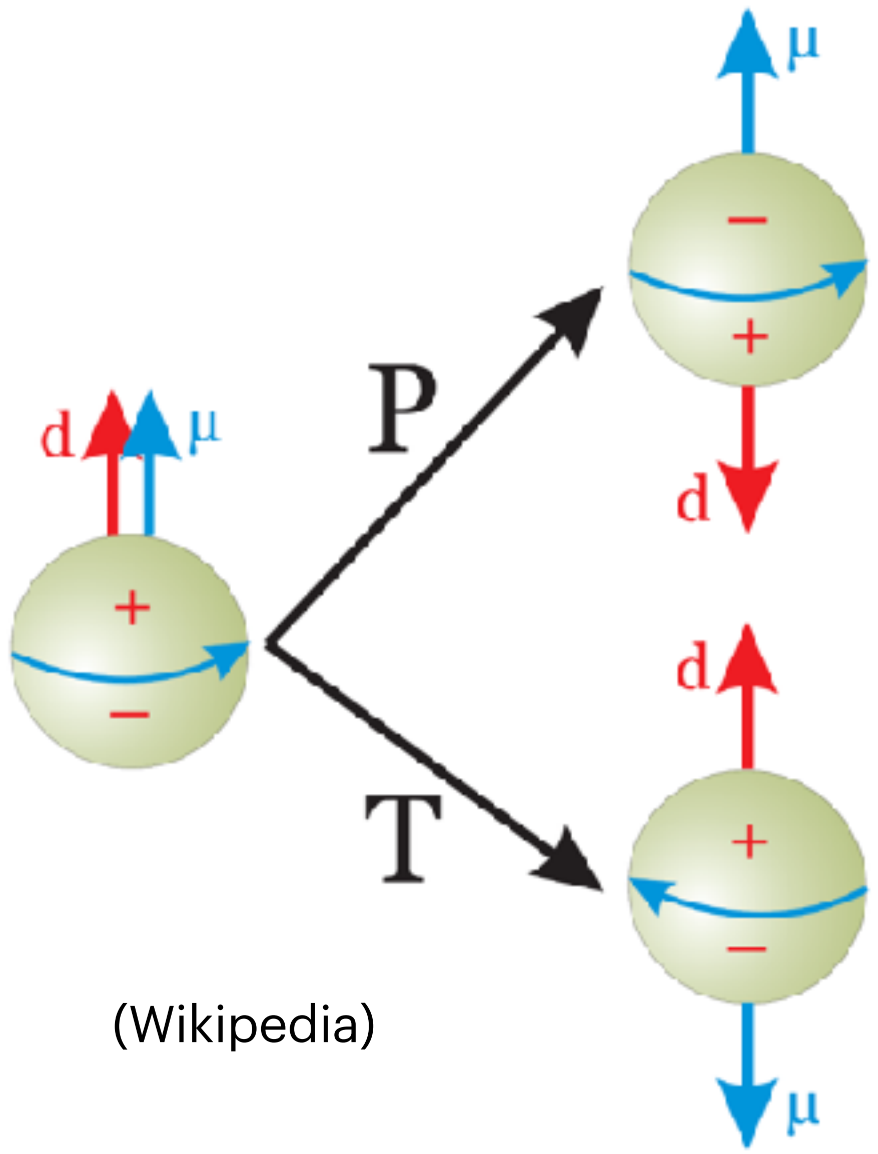
- nEDM bound on the θ-parameter:

$$|d_n| < 1.8 \times 10^{-26}\, e \cdot \mathrm{cm} \;\text{(90\%CL)} \quad \Rightarrow \quad |\bar{\theta}| \lesssim \mathcal{O}(10^{-10})$$

Abel et al, 2001.11966

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \qquad \bar{\theta} \equiv \theta - \arg\det\left(M_u M_d\right)$$

$\not{P}$, $\not{CP}$



(Wikipedia)

The QCD axion dynamically solves the strong CP problem!

Peccei, Quinn `77, Weinberg `78, Wilczek `78

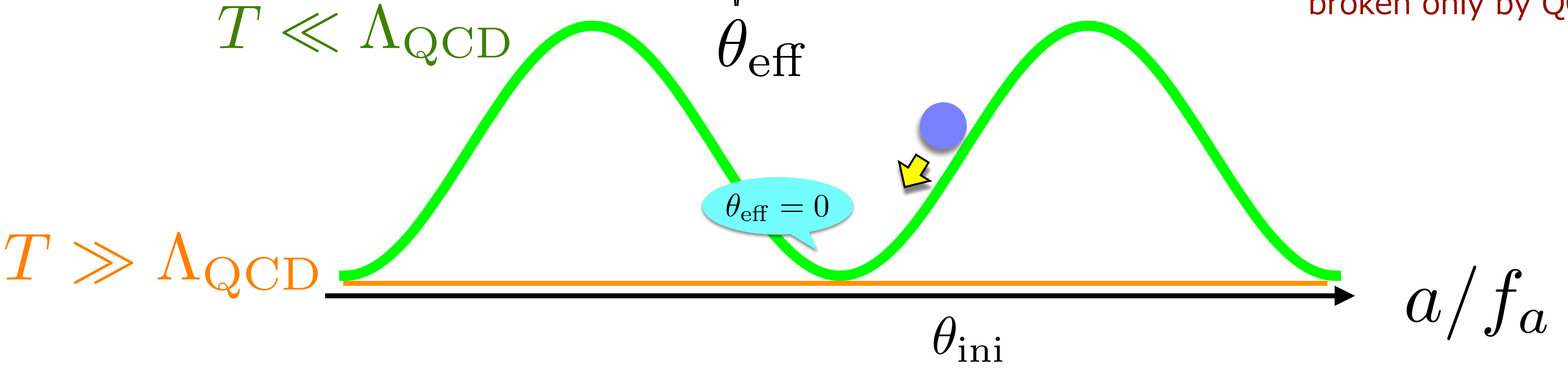
The Peccei-Quinn (PQ) mechanism

Peccei, Quinn `77, Weinberg `78, Wilczek `78

In the PQ mechanism, the axion dynamically zeroes out the strong CP phase.

$$\mathcal{L}_\theta = \underbrace{\left(\theta + \frac{a}{f_a}\right)}_{\theta_{\rm eff}} \frac{g_s^2}{32\pi^2} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

PQ symmetry assumed to be broken only by QCD



Axion mass (at T=0): $m_{a,0} \simeq 6\,\mu{\rm eV}\left(\frac{f_a}{10^{12}{\rm GeV}}\right)^{-1}$

Axion Dark Matter

The axion starts to oscillate about the CP-conserving minimum, and the oscillation energy becomes dark matter. "Misalignment mechanism"

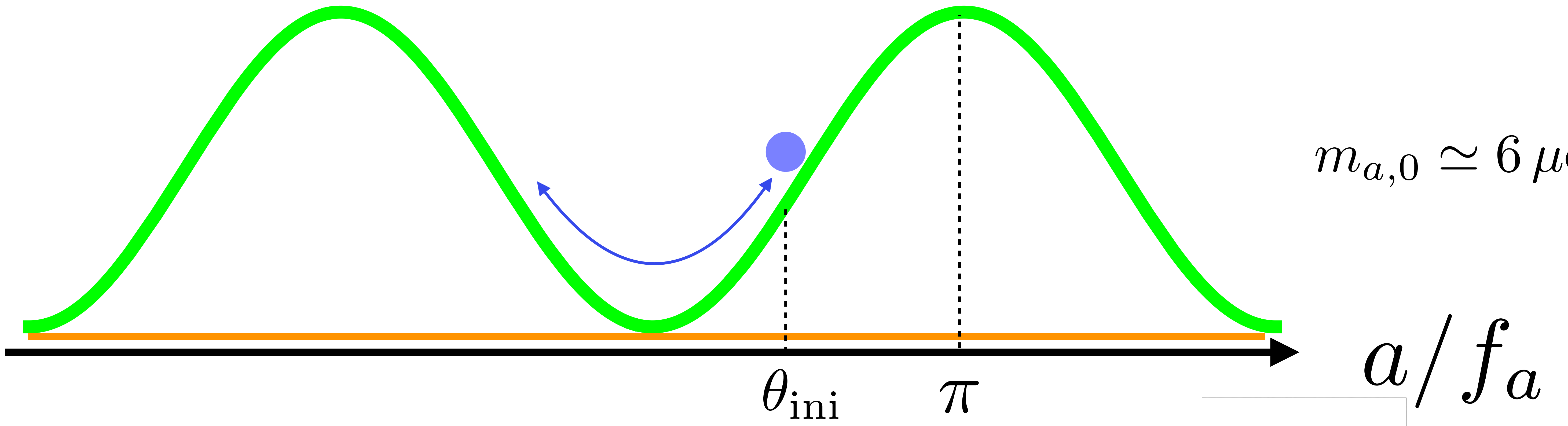
Preskill, Wise, Wilczek `83, Abbott, Sikivie, `83, Dine, Fischler, `83

$$\Omega_a h^2 \simeq 0.14\, \theta_{\rm ini}^2 F(\theta_{\rm ini}) \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^{1.17}$$

Ballesteros et al, 1610.01639

The anharmonic effect: $F(\theta_{\rm ini}) = \left[\ln \left(\frac{e}{1-\theta_{\rm ini}^2/\pi^2} \right) \right]^{1.17}$

Lyth `92, Bae, Huh and Kim 0806.0497, Visinelli and Gondolo 0903.4377



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(Classical) axion window:

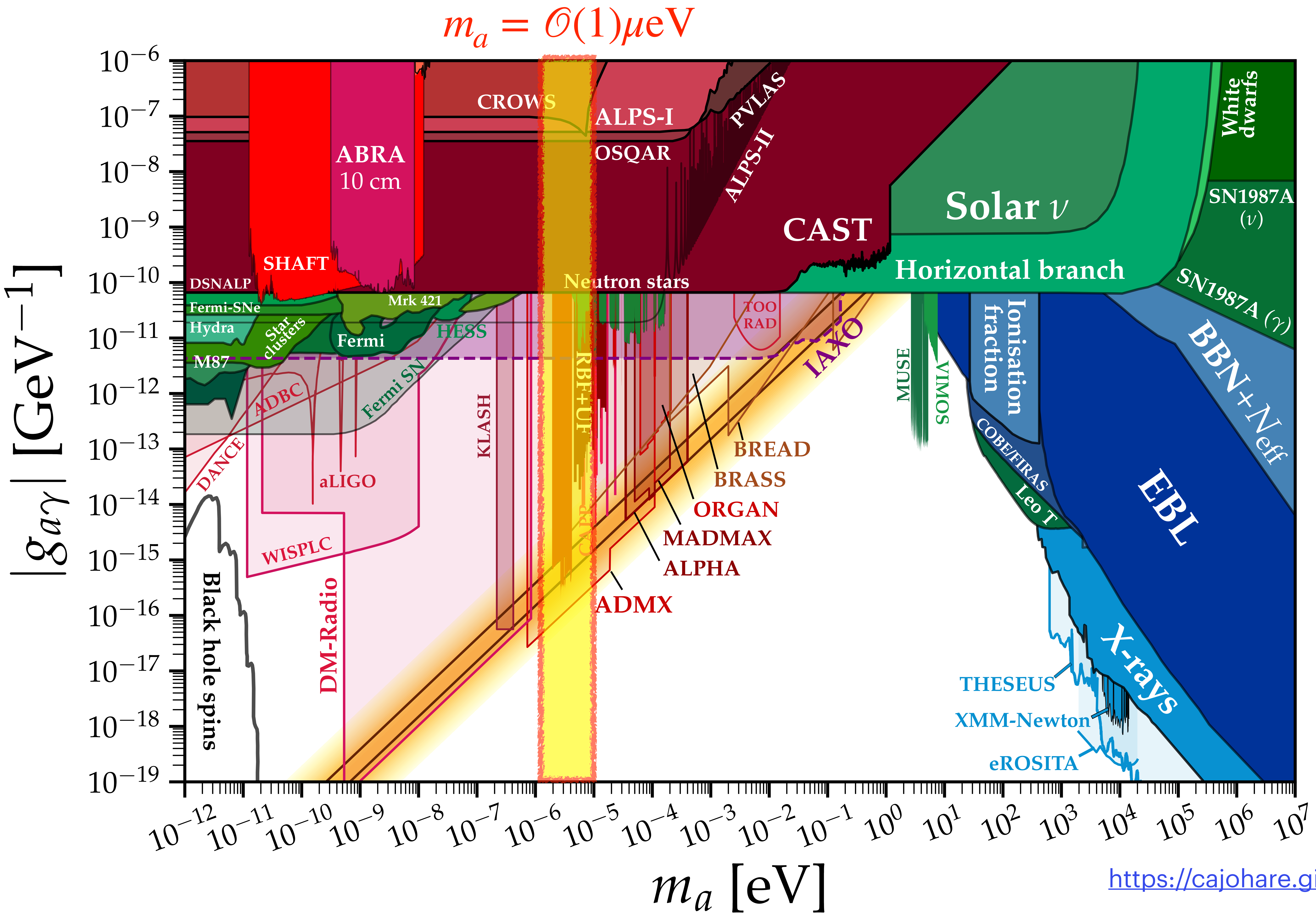
$$10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

i.e. $\mathcal{O}(1)\mu\mathrm{eV} \lesssim m_a \lesssim \mathcal{O}(10)\,\mathrm{meV}$

The lower bound comes from cooling arguments of e.g. neutron stars.

Leinson 1405.6873, 1909.03941, Hamaguchi et al 1806.07151, Bushmann et al 2111.09892.

Searching for axion dark matter



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

How can we produce axion dark matter heavier or lighter than μeV?

How to produce axion DM heavier or lighter than μeV?

- $m_a \ll \mu\mathrm{eV}$

  Fine-tune the initial angle, $|\theta_{\rm ini}| \ll 1$.

  e.g. $\theta_{\rm ini} = \mathcal{O}(10^{-3})$ for $f_a = 10^{16-17}\,\mathrm{GeV}$

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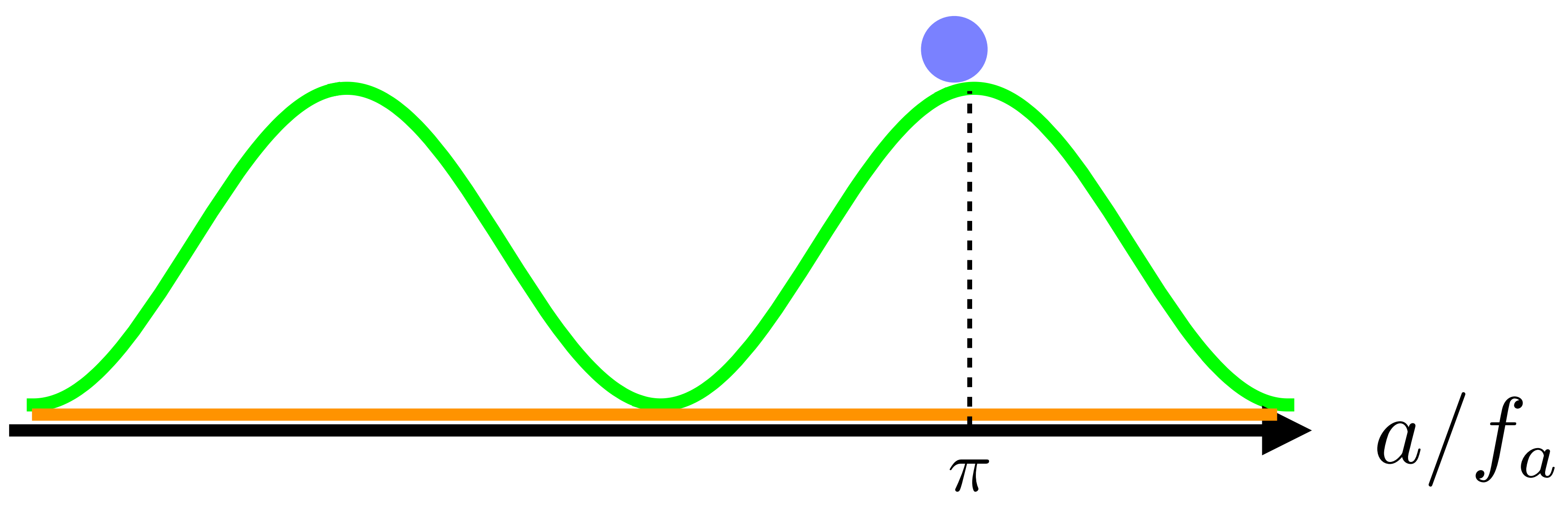
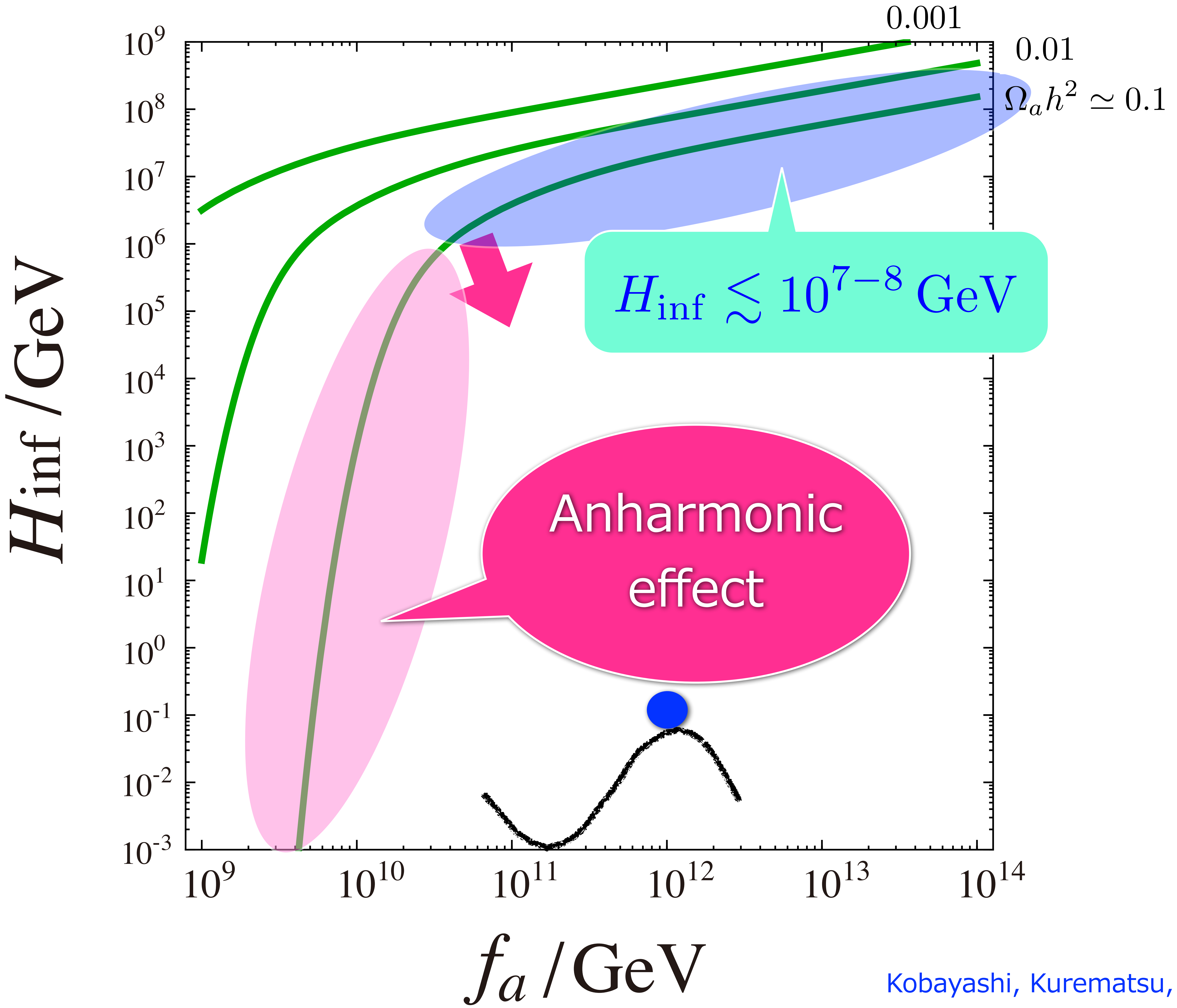


FT, Yin 1702.03284 ,1908.06071, Co, Gonzalez, and Harigaya 1812.11192

However, the enhancement is only logarithmic, and the isocurvature perturbation and non-Gaussianity get extremely enhanced. Lyth `90, Kobayashi, Kurematsu, FT, 1304.0922



Kobayashi, Kurematsu, FT, 1304.0922

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cf. see Peter W. Graham, Adam Scherlis, 1805.07362, FT, Wen Yin, Alan H. Guth, 1805.08763 for stochastic dynamics

$$\Omega_a h^2 \simeq 0.14\,\theta_{\rm ini}^2 F(\theta_{\rm ini}) \left(\frac{f_a}{10^{12}\text{GeV}}\right)^{1.17}$$

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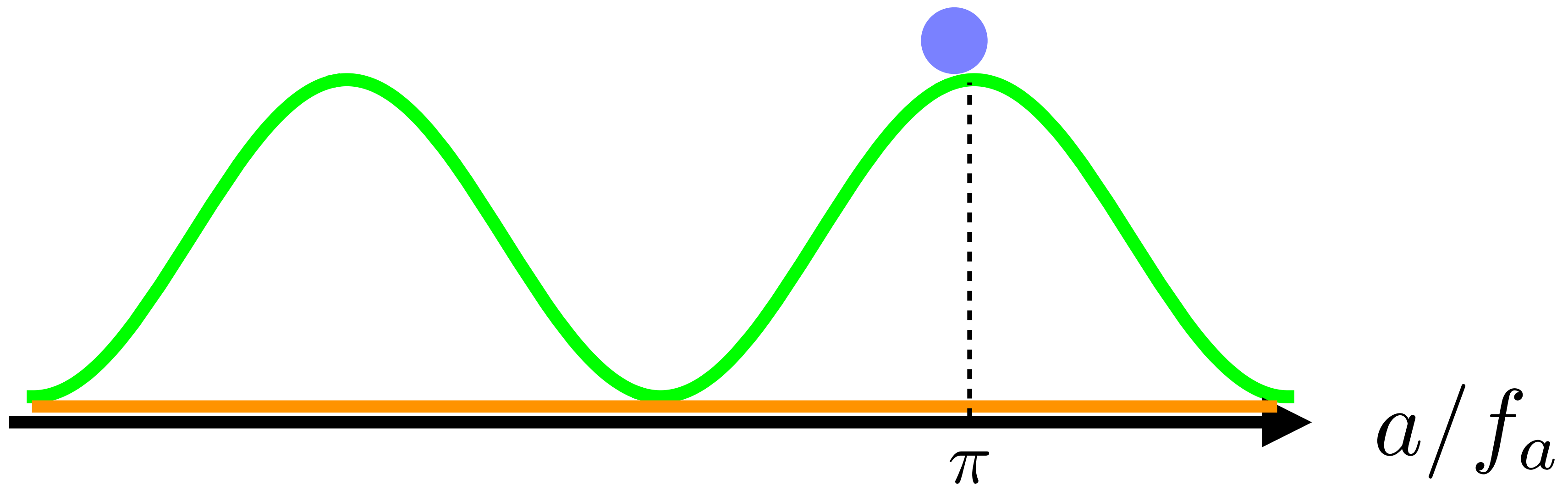

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Decays of topological defects (domain walls and cosmic strings)

$f_a = \mathcal{O}(10^{10})\,\text{GeV}$?

Hiramatsu et al 1012.5502, Hiramatsu, Kawasaki, Saikawa, Sekiguchi, 1202.5851, Kawasaki, Saikawa, Sekiguchi, 1412.0789, Gorghetto, Hardy and Villadoro, 1806.04677, 2007.04990, Klaer, Moore, 1708.07521, Vaquero, Redondo and Stadler, 1809.09241, Buschmann, Foster and Safdi 1906.00967, Hindmarsh et al, 1908.03522, 2102.07723, Buschmann et al, 2108.05368, Dine 2111.10942, and more..

In fact, the string-wall evolution may depend on the UV completion:

e.g. clockwork axion model

See also Sikivie `86, Kim, Nilles, Peloso hep-ph/0409138, Choi, Kim, Yun 1404.6209, Higaki, FT 1404.6923, Harigaya and Ibe, 1407.4893, Choi and Im, 1511.00132, Kaplan and Rattzzi, 1511.01827, Giudice and McCullough 1610.07962

Consider *N* complex scalars with *N* U(1) symmetries.

$$V = \sum_{i=1}^{N} \left(-m_i^2|\Phi_i|^2 + \lambda_i|\Phi_i|^4\right) + \sum_{i=1}^{N-1} \epsilon \left(\Phi_i \Phi_{i+1}^3 + \text{h.c.}\right)$$

$\Rightarrow$

$$f_a \sim 3^N f$$

- Phase transition takes place at lower $T \sim f \ll f_a$
- Strings and walls form complicated network

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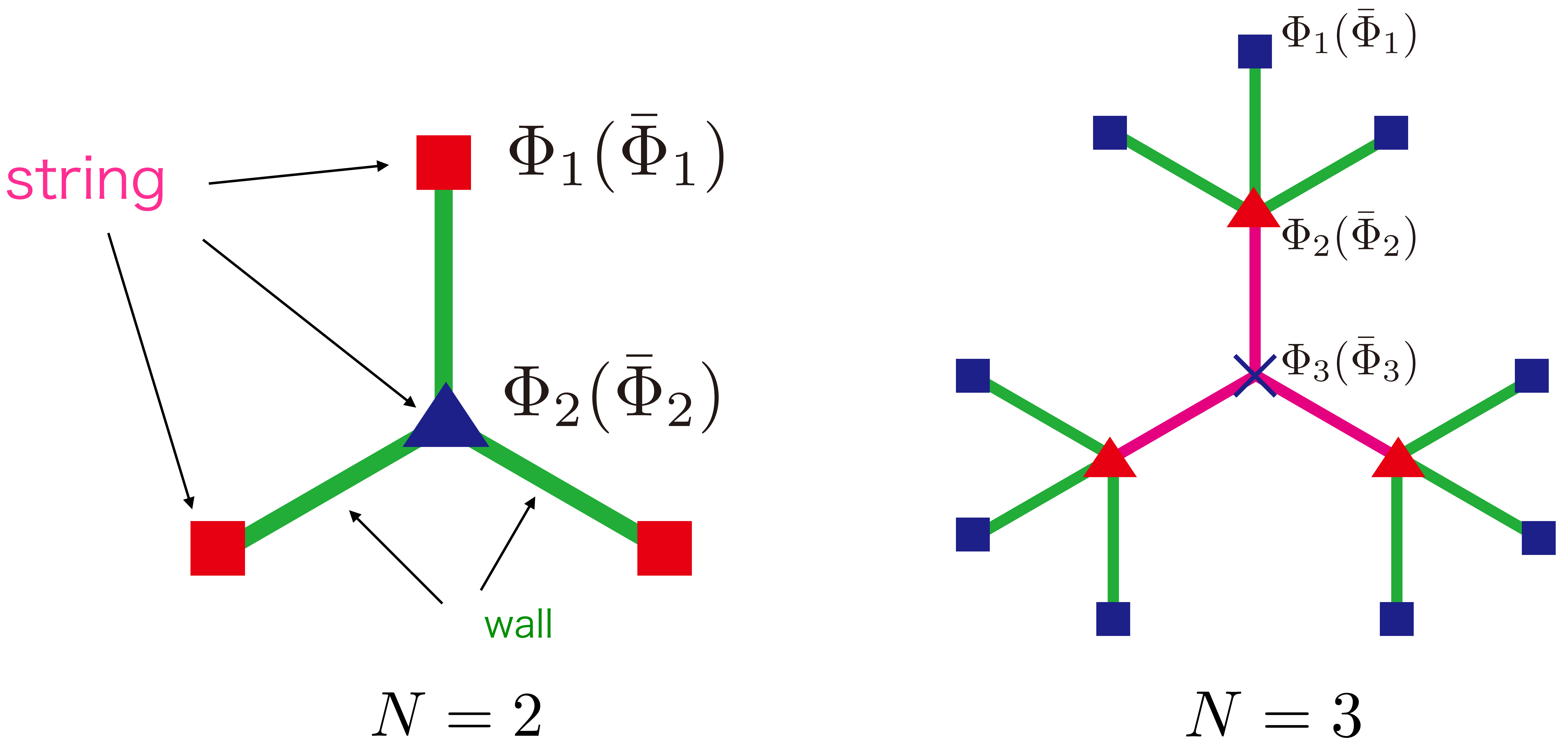

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

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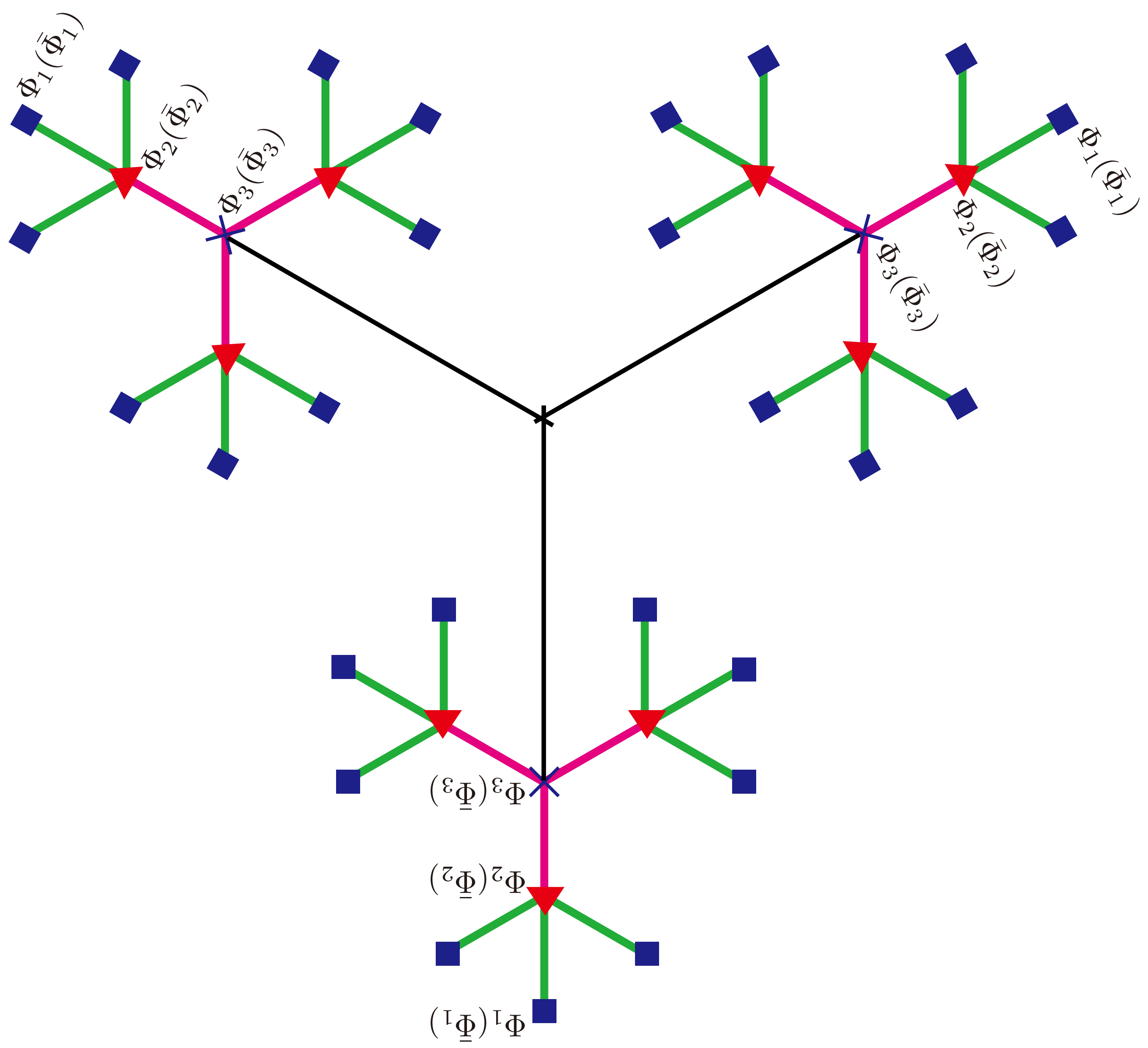
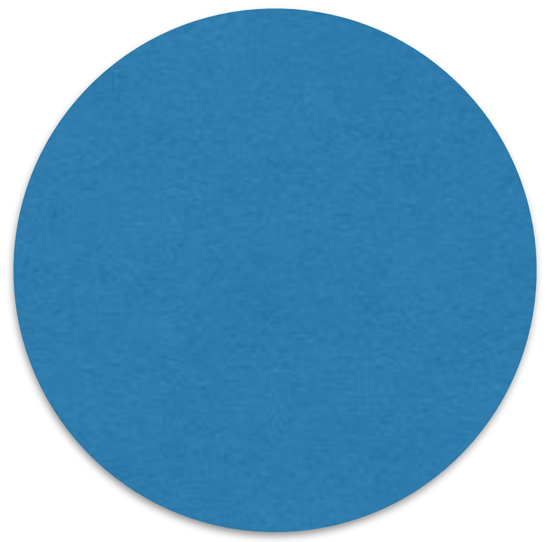


$\simeq$



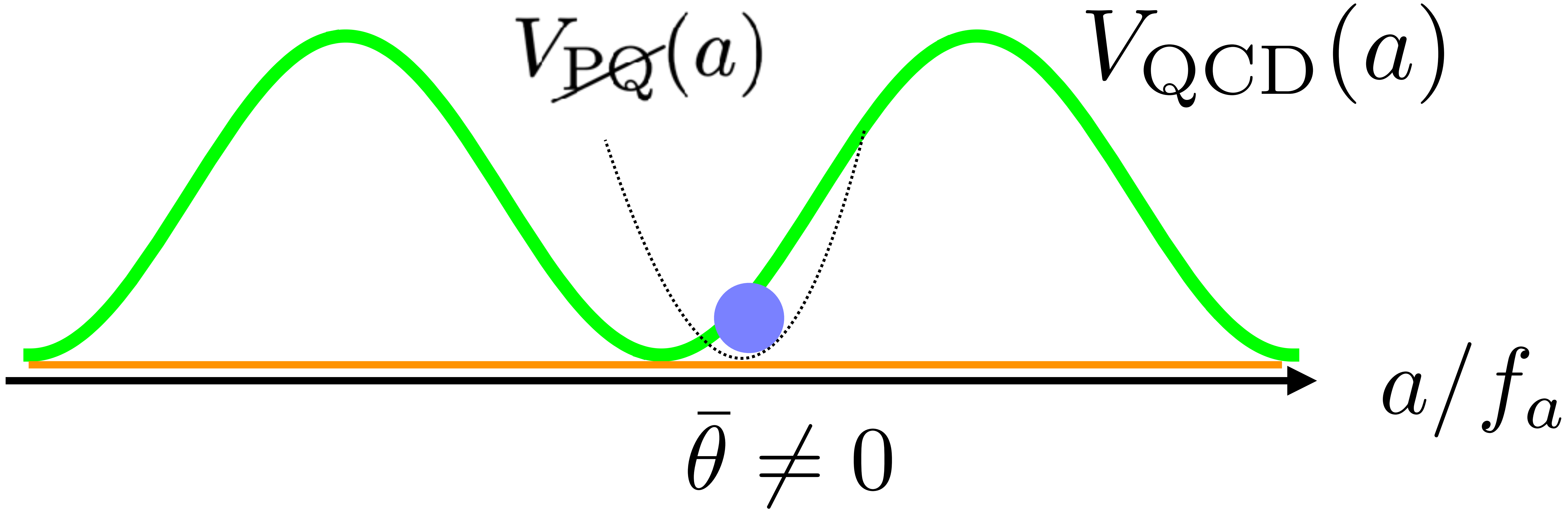
$$\mu_{\rm eff} \simeq \pi(3^{2(N-1)} f_1^2 + \cdots + 3^2 f_{N-1}^2 + f_N^2) \ln\left(\frac{R}{\delta}\right) = \pi f_a^2 \ln\left(\frac{R}{\delta}\right)$$

However, it is unclear if such isolated string bundles are actually formed. If not, the collapse of the complicate string-wall network may produce more axions and nHz GWs.

Higaki, Jeong, Kitajima, Sekiguchi, FT, 1606.05552

Quality of the PQ symmetry

In the PQ mechanism, the PQ symmetry is assumed to be broken only by QCD. Other PQ symmetry breaking terms must be suppressed.



$$|\bar{\theta}| \lesssim \mathcal{O}(10^{-10})$$

N.B. if the extra PQ breaking is effectively time-dependent, its size can be larger in the early Universe.

e.g. larger f_a in the early universe, the Witten effect, mirror SM sectors, etc.

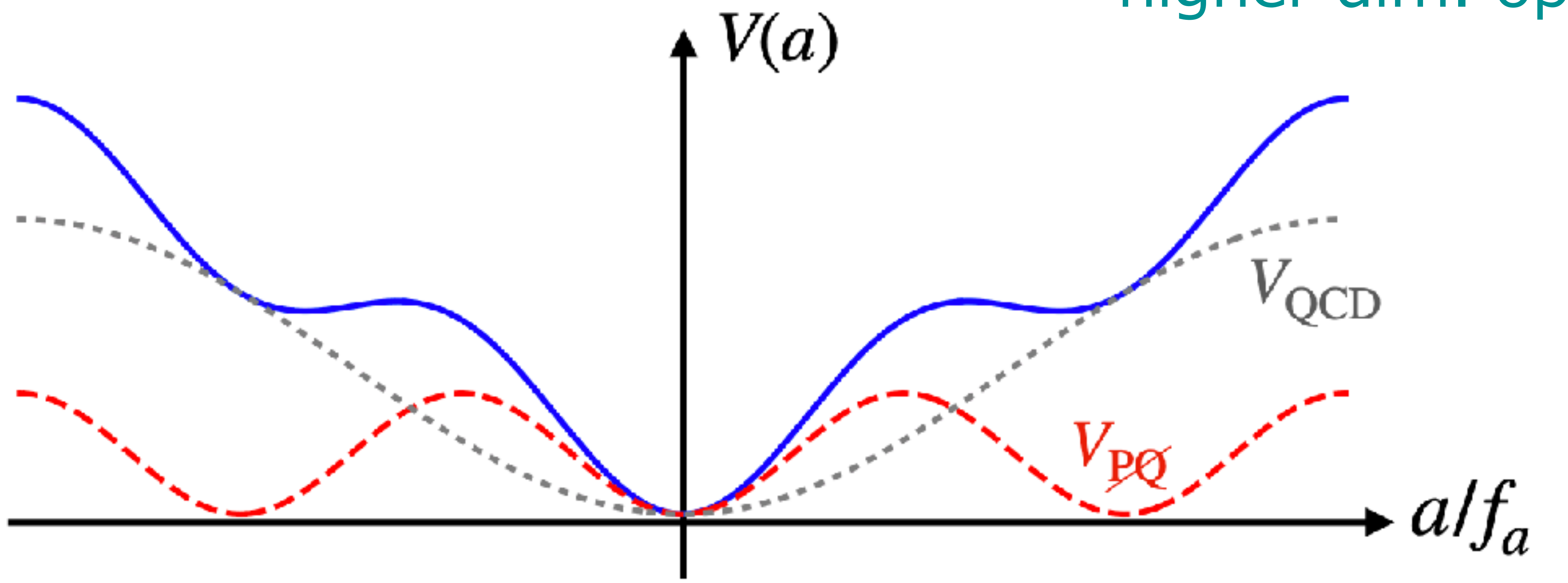
S^{n+4}/M^n $\qquad$ $m_a^2 \propto n_M$

Dine, Anisimov hep-ph/0405256, Higaki, Jeong, FT, 1403.4186, Barr and J.E.Kim, 1407.4311, FT and Yamada 1507.06387, Kawasaki, FT, Yamada 1511.05030, 1708.06047, Nomura, Rajendran, Sanches, 1511.06347, Nakagawa, FT, Yamada 2012.13592, Di Luzio et al 2102.01082

What we did in 2201.00681:

We study the cosmological effect of the (time-independent) extra PQ breaking term on the QCD axion DM.

e.g. hidden non-Abelian gauge sym, higher dim. operator of the PQ scalar.



We find that the axion abundance can be enhanced or reduced, depending on the initial condition. In particular, the axion can explain DM for any f_a, if a mild tuning is allowed.

cf. Higaki, Jeong, Kitajima, and FT, 1603.02090
"Quality of the Peccei-Quinn symmetry in the Aligned QCD Axion and Cosmological Implications"

2. Experimental limits on explicit PQ breaking

In the usual scenario, the axion acquires a potential from QCD as

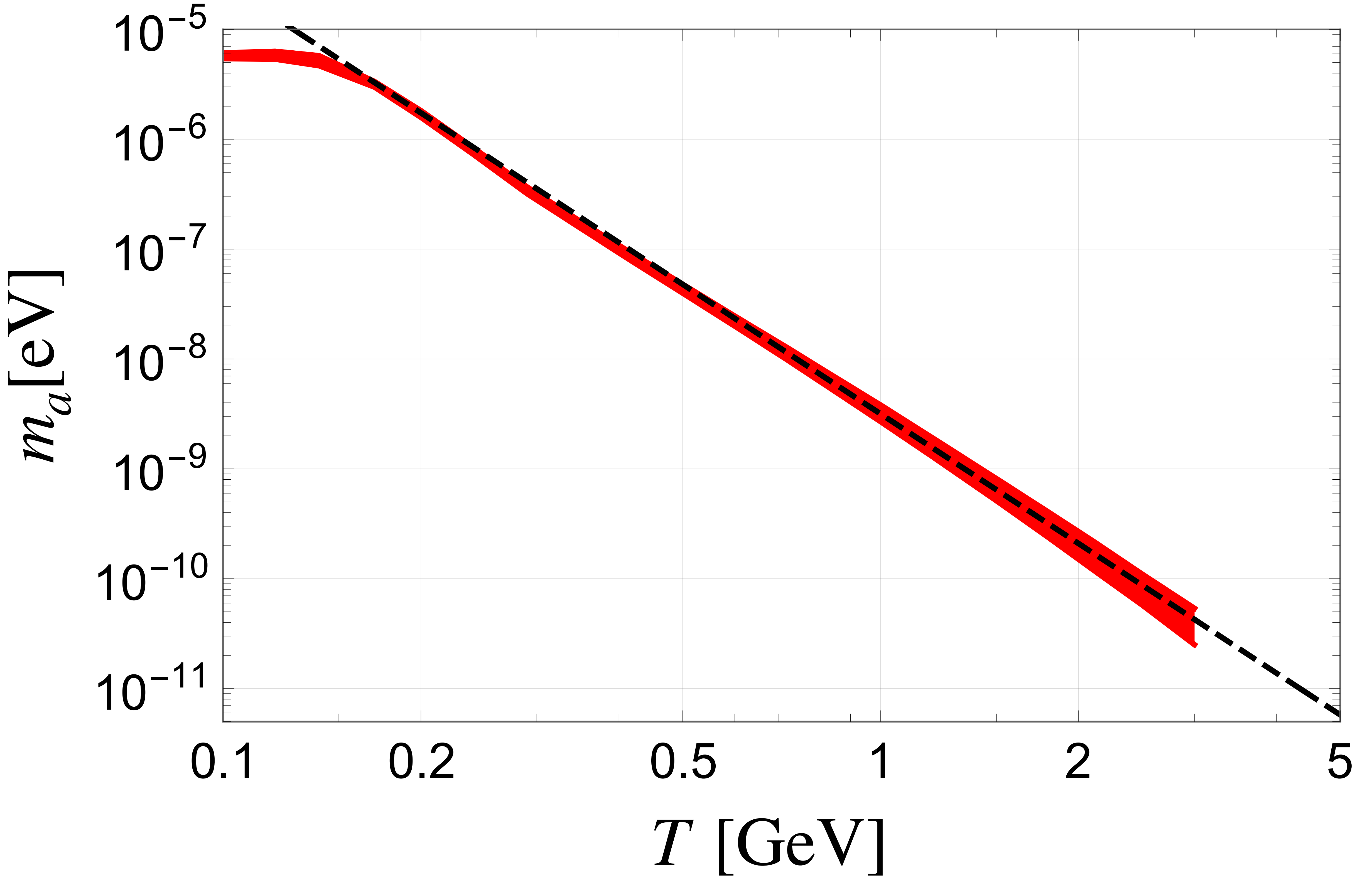
$$V_{\rm QCD}(a) = m_a^2(T) f_a^2 \left(1 - \cos\frac{a}{f_a}\right)$$

with

$$m_a(T) \simeq \begin{cases} m_{a,0}\left(\dfrac{T}{\Lambda_{\rm QCD}}\right)^{-\tilde{b}} & \text{for } T > \Lambda_{\rm QCD} \\ m_{a,0} & \text{for } T < \Lambda_{\rm QCD} \end{cases}$$

$$m_{a,0} \simeq 6\,\mu{\rm eV}\left(\frac{f_a}{10^{12}{\rm GeV}}\right)^{-1}$$

$$\Lambda_{\rm QCD} = 150{\rm MeV}, \quad \tilde{b} = 3.92$$



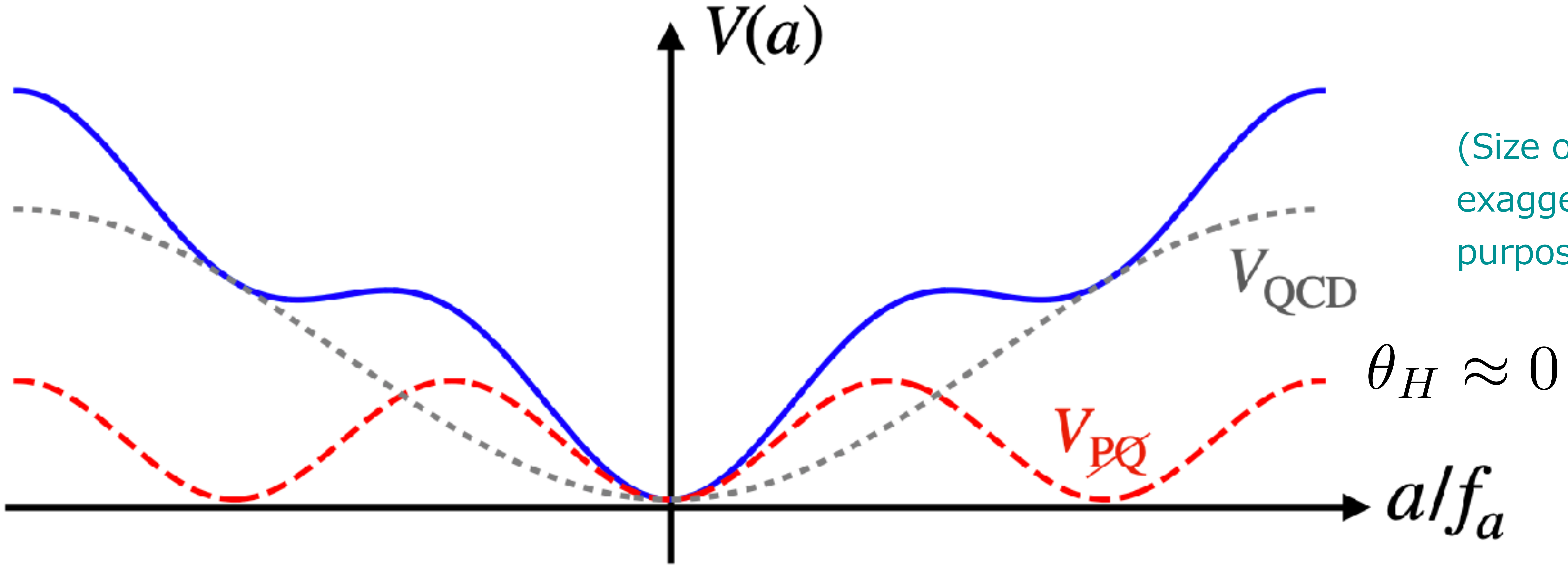
Borsanyi et al, 1606.07494

Now we introduce the extra PQ breaking term,

$$V_{\not{\mathrm{PQ}}}(a) = \Lambda_H^4 \left[1 - \cos\left(N\left(\frac{a}{f_a} - \theta_H\right)\right)\right]$$

with the relative height $r \equiv \Lambda_H/\sqrt{m_{a,0} f_a}$ and relative phase θ_H.

The total axion potential is $V(a) = V_{\mathrm{QCD}}(a) + V_{\not{\mathrm{PQ}}}(a)$



(Size of the PQ breaking is exaggerated for illustration purposes.)

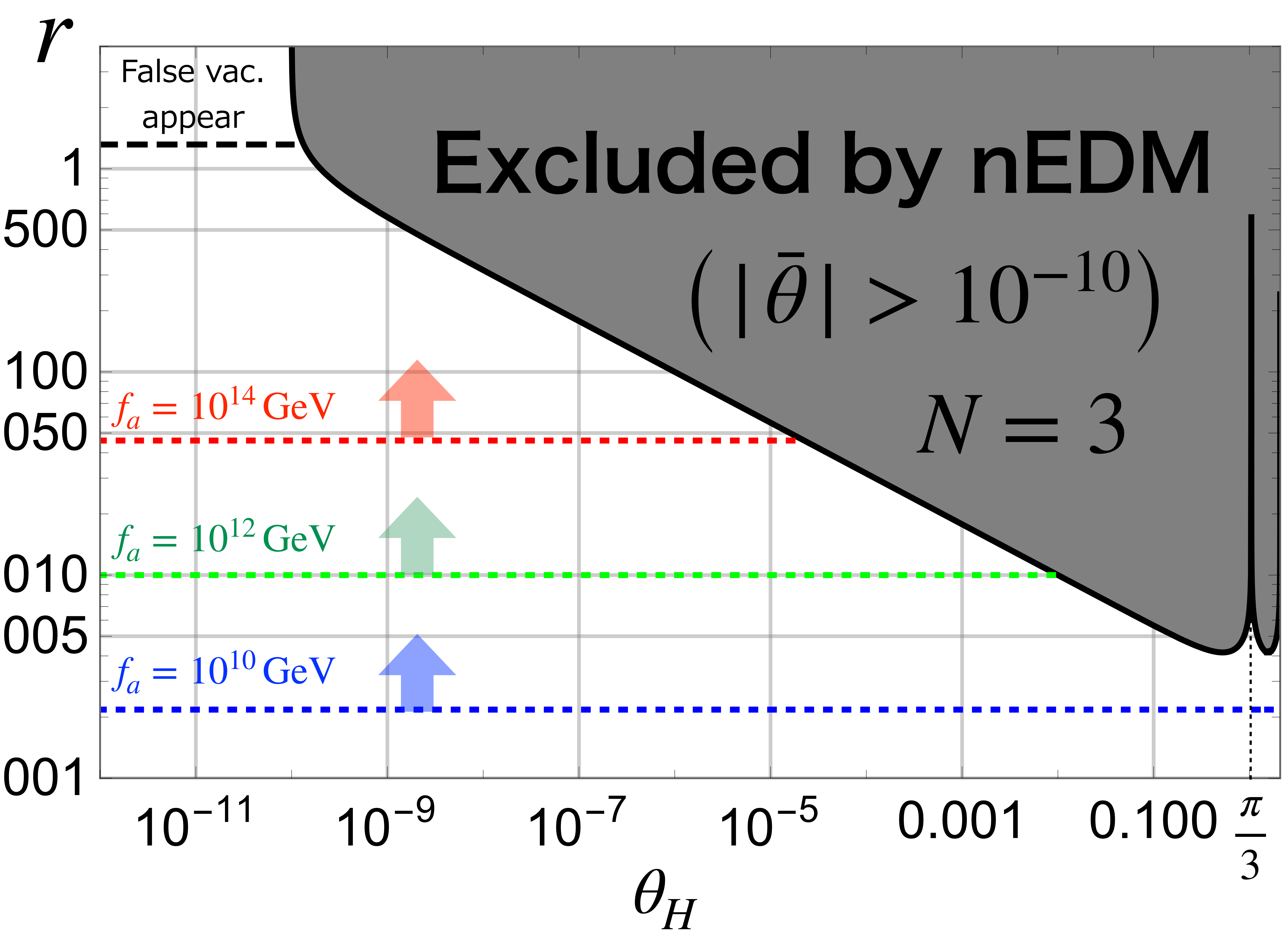
The nEDM bound on the PQ breaking

$$|\bar{\theta}| \lesssim 10^{-10}$$

$$r \equiv \frac{\Lambda_H}{\sqrt{m_{a,0} f_a}} \lesssim \left| \frac{10^{-10}}{N \sin(N(10^{-10} - \theta_H))} \right|^{1/4}$$

Here we set $N = 3$.

The axion first starts to oscillate due to $V_{\not{PQ}}$ in the region above the dotted line for each f_a.



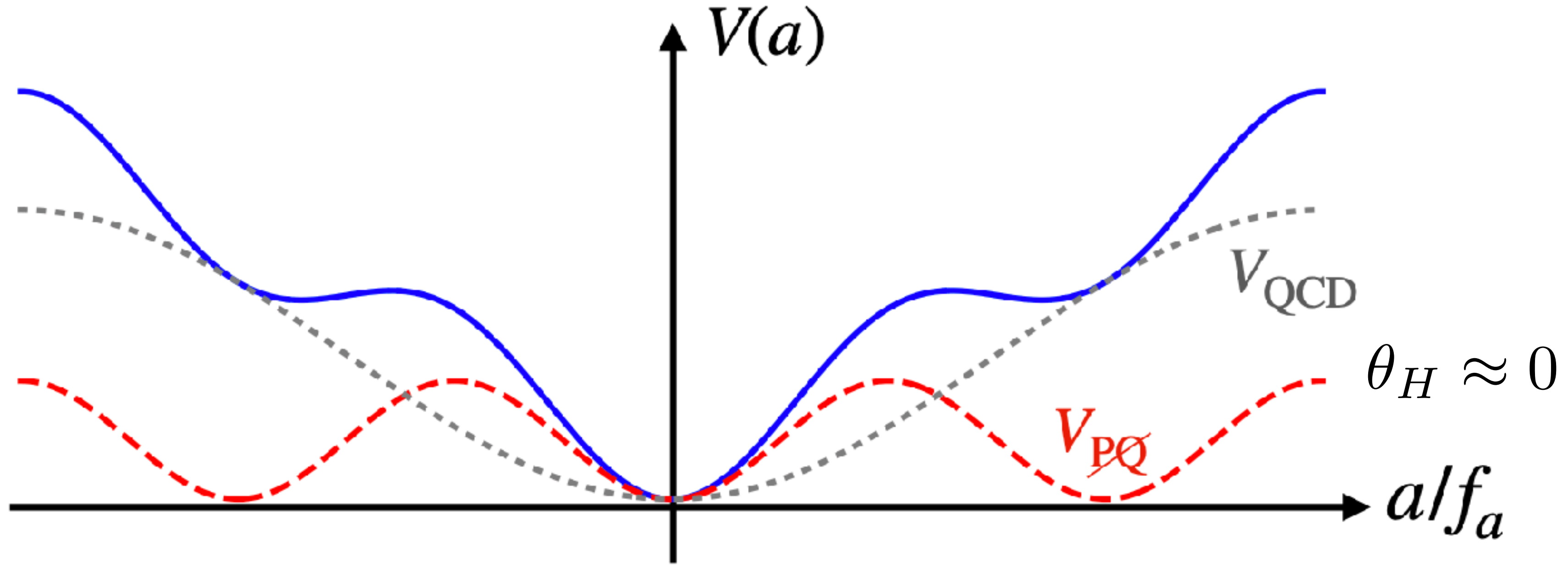
3. Axion abundance

We assume the axion first starts to oscillate about one of the minima of $V_{\not{PQ}}$, i.e.

$$T_{\rm osc} \gtrsim T_{\rm osc}^{\rm (conv)}$$

$$V''_{\rm QCD} \sim H^2(T) \quad \Rightarrow \quad T_{\rm osc}^{\rm (conv)} \simeq 1.1 \text{ GeV} \left(\frac{g_*}{80}\right)^{-0.084} \left(\frac{f_a}{10^{12} \text{ GeV}}\right)^{-0.17}$$

$$V''_{\not{PQ}} \sim H^2(T) \quad \Rightarrow \quad T_{\rm osc} \simeq 0.91 \text{ GeV} \left(\frac{g_*}{80}\right)^{-1/4} \left(\frac{N r^2}{3 \times 10^{-4}}\right)^{1/2} \left(\frac{f_a}{10^{12} \text{ GeV}}\right)^{-1/2}$$



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$$T_{\text{osc}} \gtrsim T_{\text{osc}}^{(\text{conv})}$$

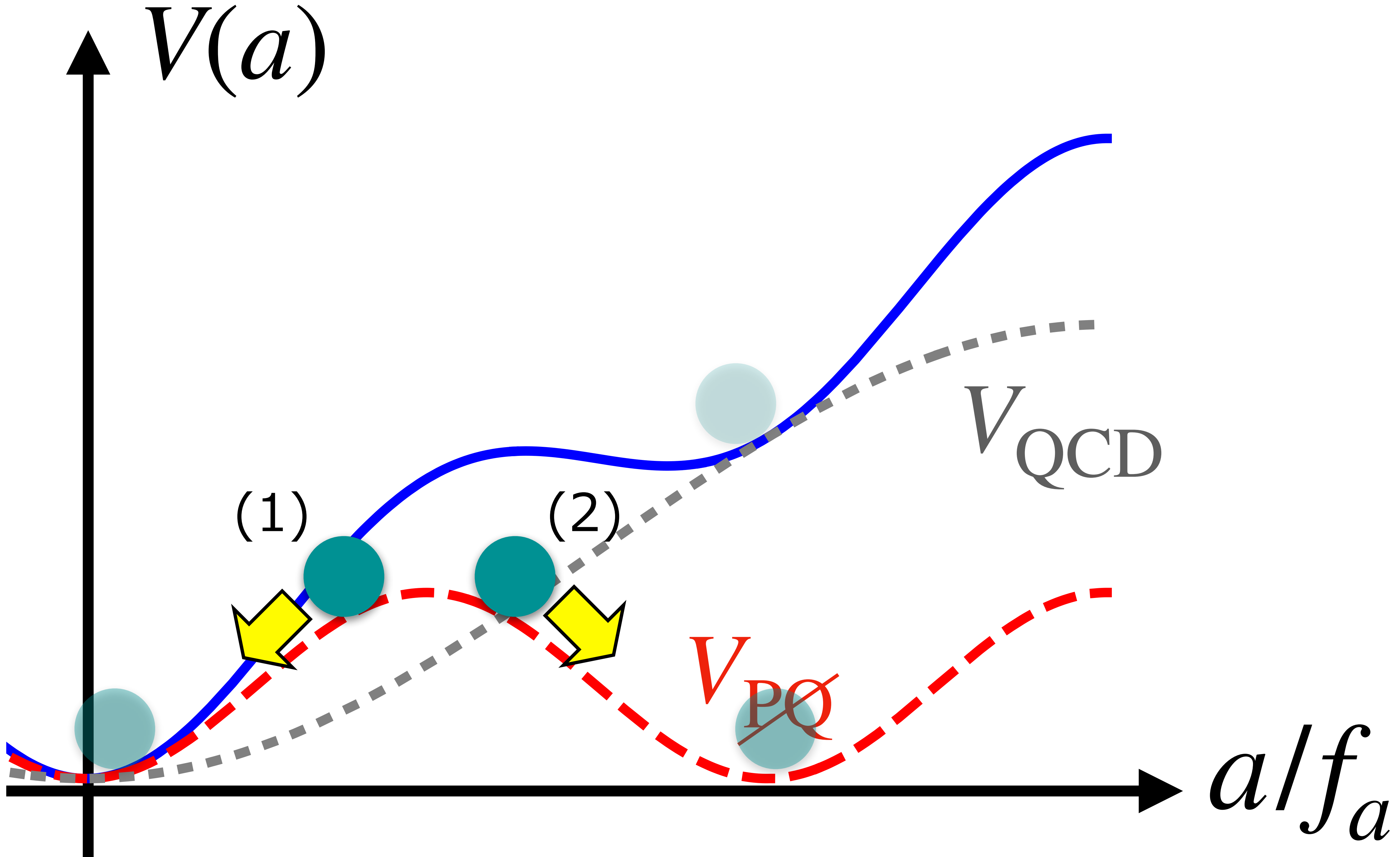
The axion dynamics can be categorized into two types:

(1) Smooth-shift regime

$$|\theta_{\text{ini}} - \theta_H| < \pi/N$$

(2) Trapping regime

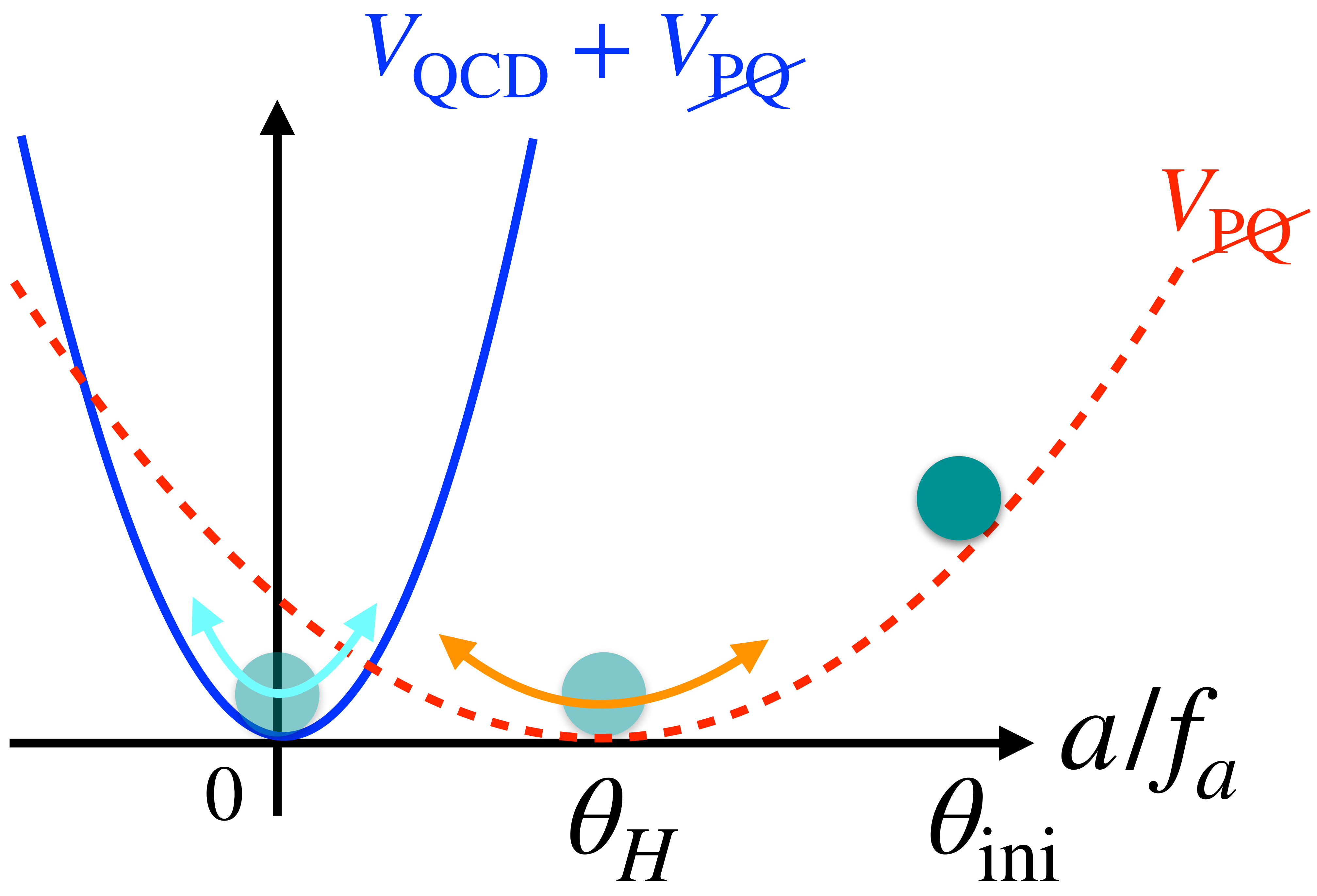
$$|\theta_{\text{ini}} - \theta_H| > \pi/N$$



(1) Smooth-shift regime: $|\theta_{\rm ini} - \theta_H| < \pi/N$

The axion first starts to oscillate about a minimum close to the origin.

The minimum gradually moves to the origin, but no particle production takes place if $V'' \gg H^2$.



"Adiabatic suppression mechanism"

Linde hep-th/9601083, Nakayama, FT, Yanagida 1109.2073

$$\Omega_a^{\rm (smth)} h^2 \simeq 5.0 \times 10^{-3} \left(\frac{g_*(T_{\rm osc})}{80}\right)^{-\frac{1}{4}} (\theta_{\rm ini} - \theta_H)^2 F_1(\theta_{\rm ini}) \left(\frac{N r^2}{3 \times 10^{-2}}\right)^{-\frac{1}{2}} \left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{\frac{3}{2}}$$

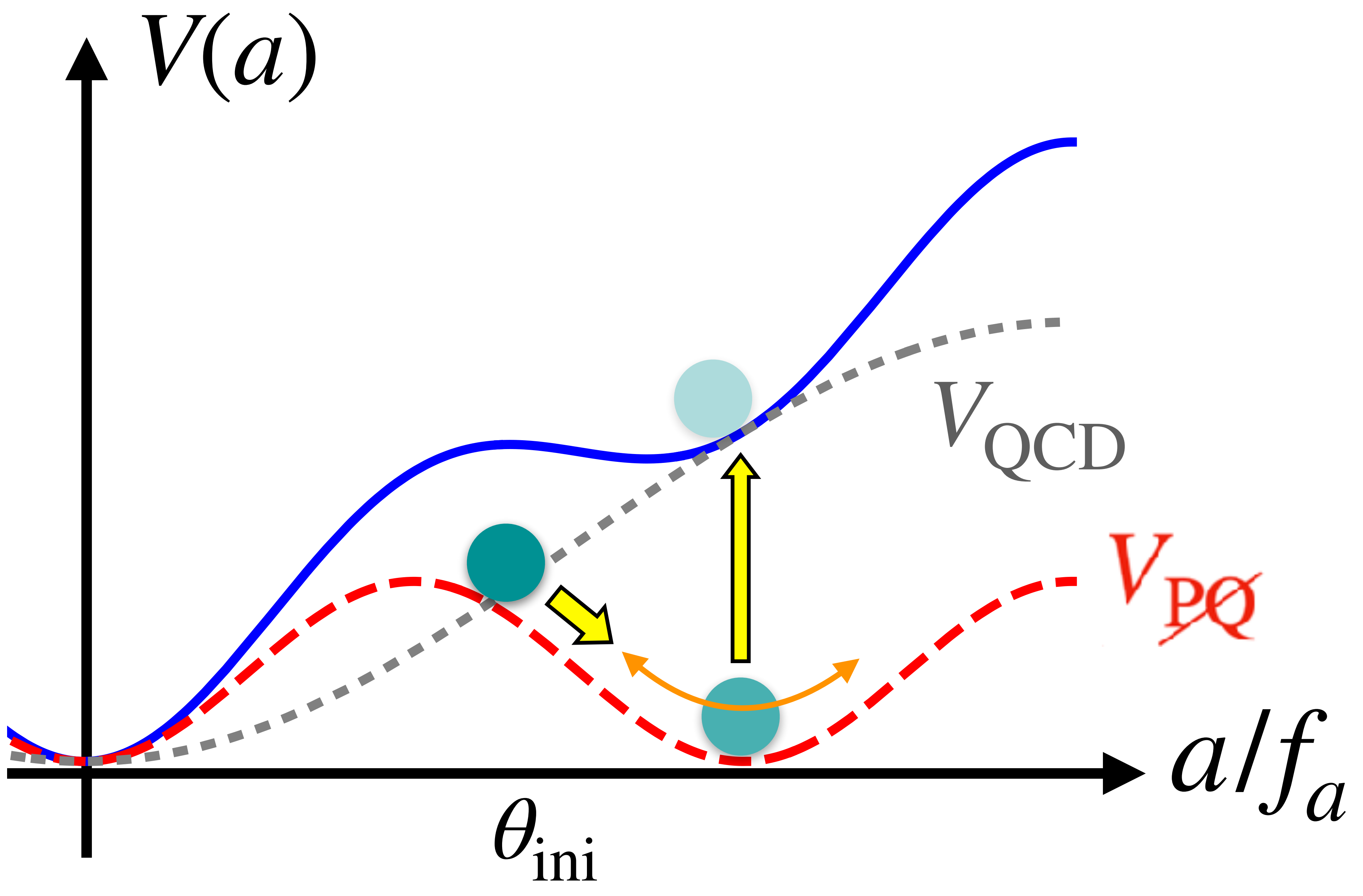
with $F_1(\theta_{\rm ini}) = \left[\ln\left(\frac{e}{1 - (\theta_{\rm ini} - \theta_H)^2/(\pi/N)^2}\right)\right]^{3/2}$

The abundance is reduced w.r.t. the conventional scenario.

cf. The adiabatic suppression by the Witten effect: Kawasaki, FT, Yamada 1511.05030, 1708.06047, Nakagawa, FT, Yamada 2012.13592

(2) Trapping regime: $|\theta_{\rm ini} - \theta_H| > \pi/N$

The axion gets trapped in a false vacuum until $V_{\rm QCD}$ becomes large, and then it starts to oscillate again about the origin.



$$T_{\rm osc2} \sim 0.4 \left(\frac{Nr^4}{3\times 10^{-4}}\right)^{-0.13} {\rm GeV}$$

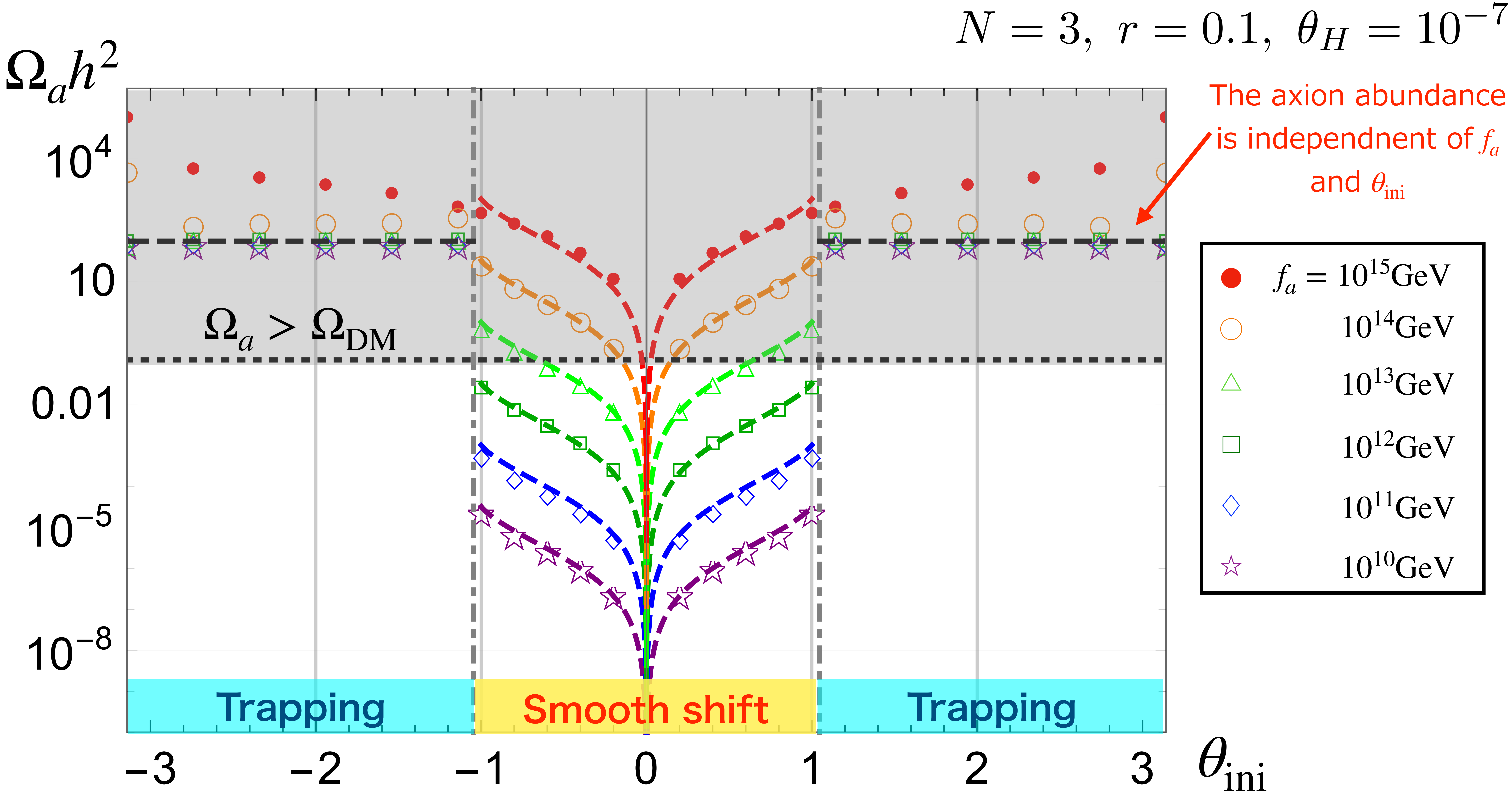
$$\Omega_a^{(\rm trap)} h^2 \simeq 0.25\, \theta_{\rm osc2}^2 \left(\frac{g_*(T_{\rm osc2})}{60}\right)^{-1} \left(\frac{Nr^4}{10^{-6}}\right)^{0.88}.$$

$$\theta_{\rm osc2} \sim (2k-1)\pi/N$$

The axion abundance is independent of f_a and $\theta_{\rm ini}$, and thus, the axion can explain DM for any f_a!

Higaki, Jeong, Kitajima, and FT, 1603.02090

The dependence of Ω_a on $\theta_{\rm ini}$ and f_a



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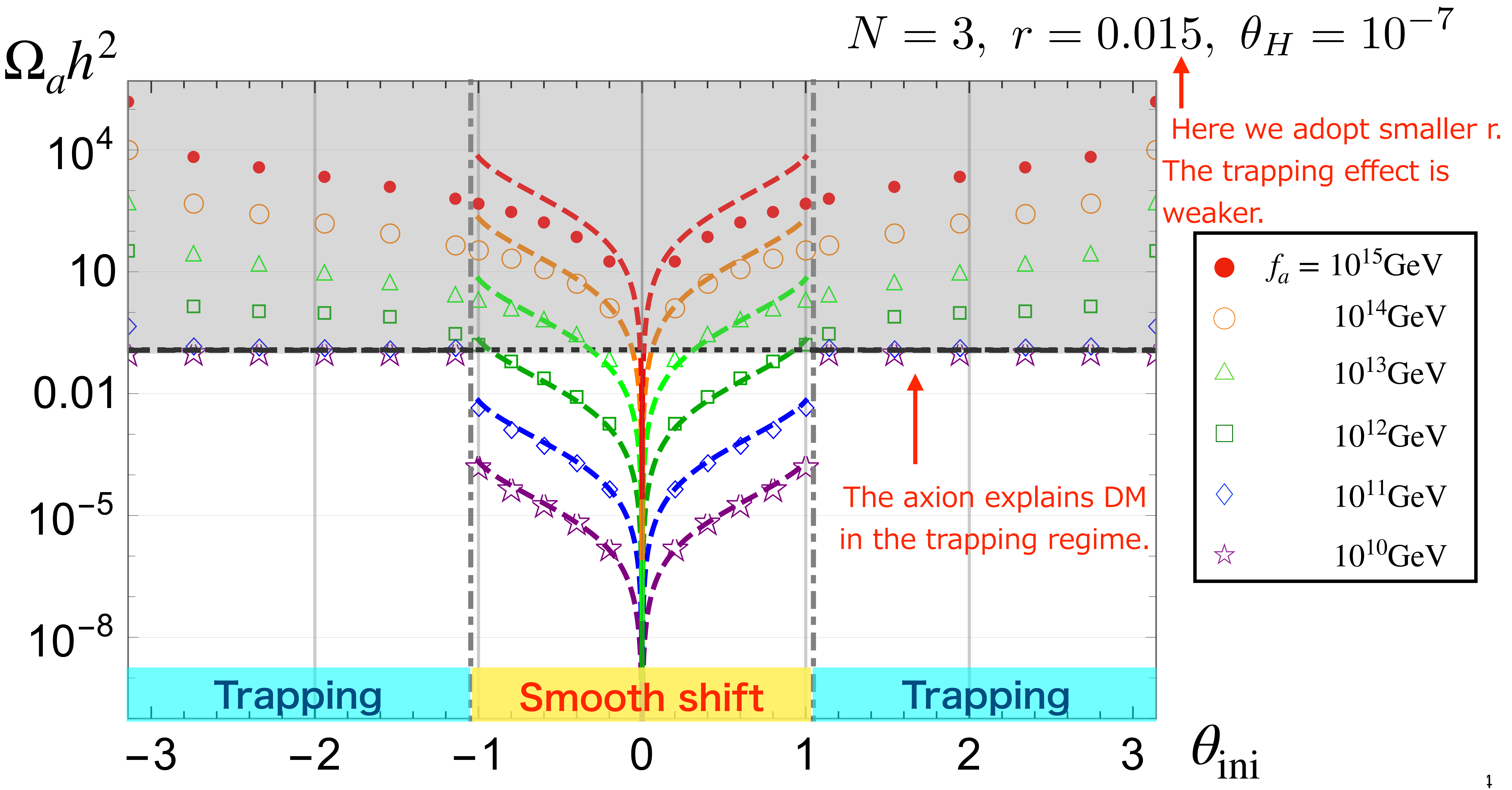
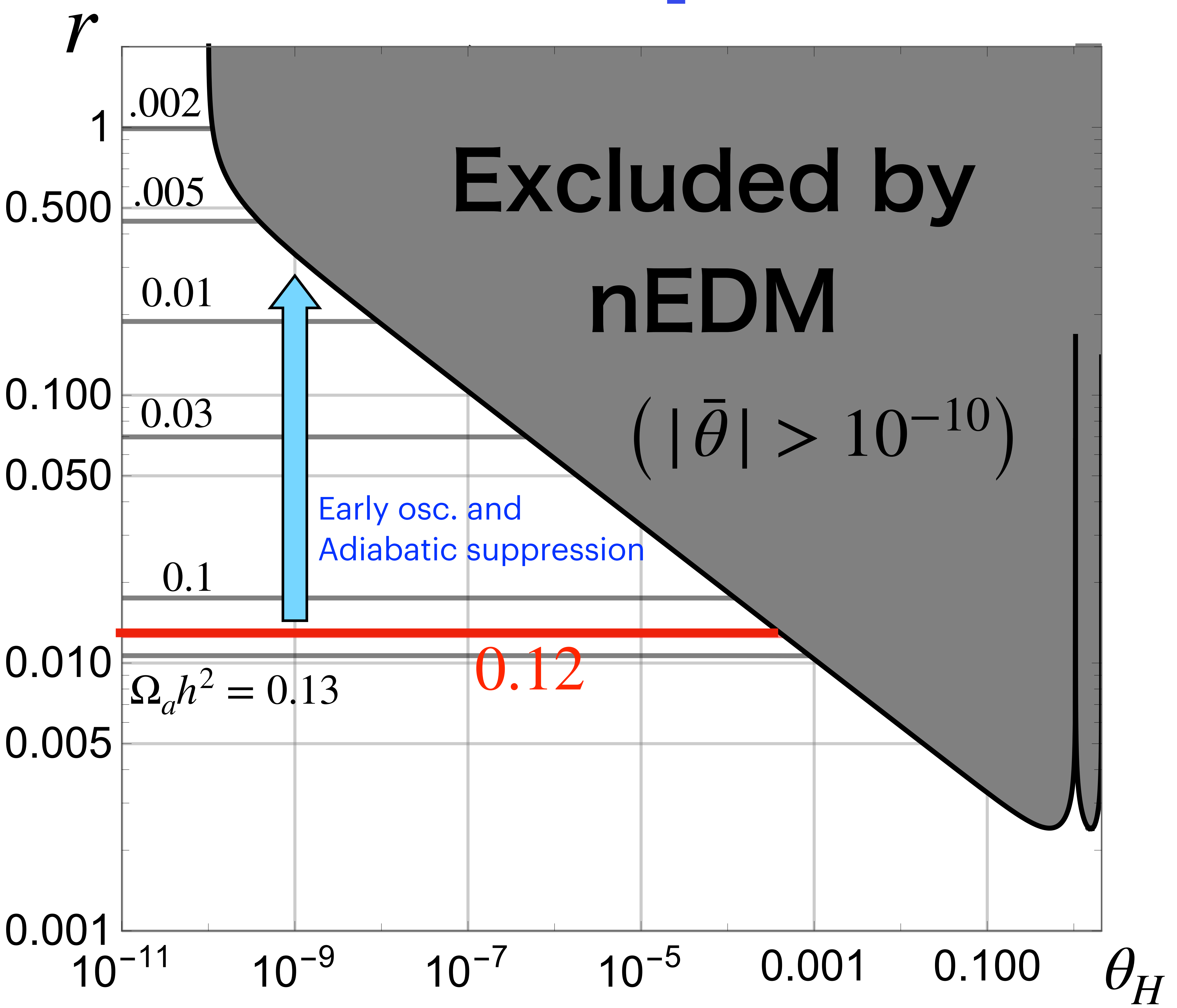
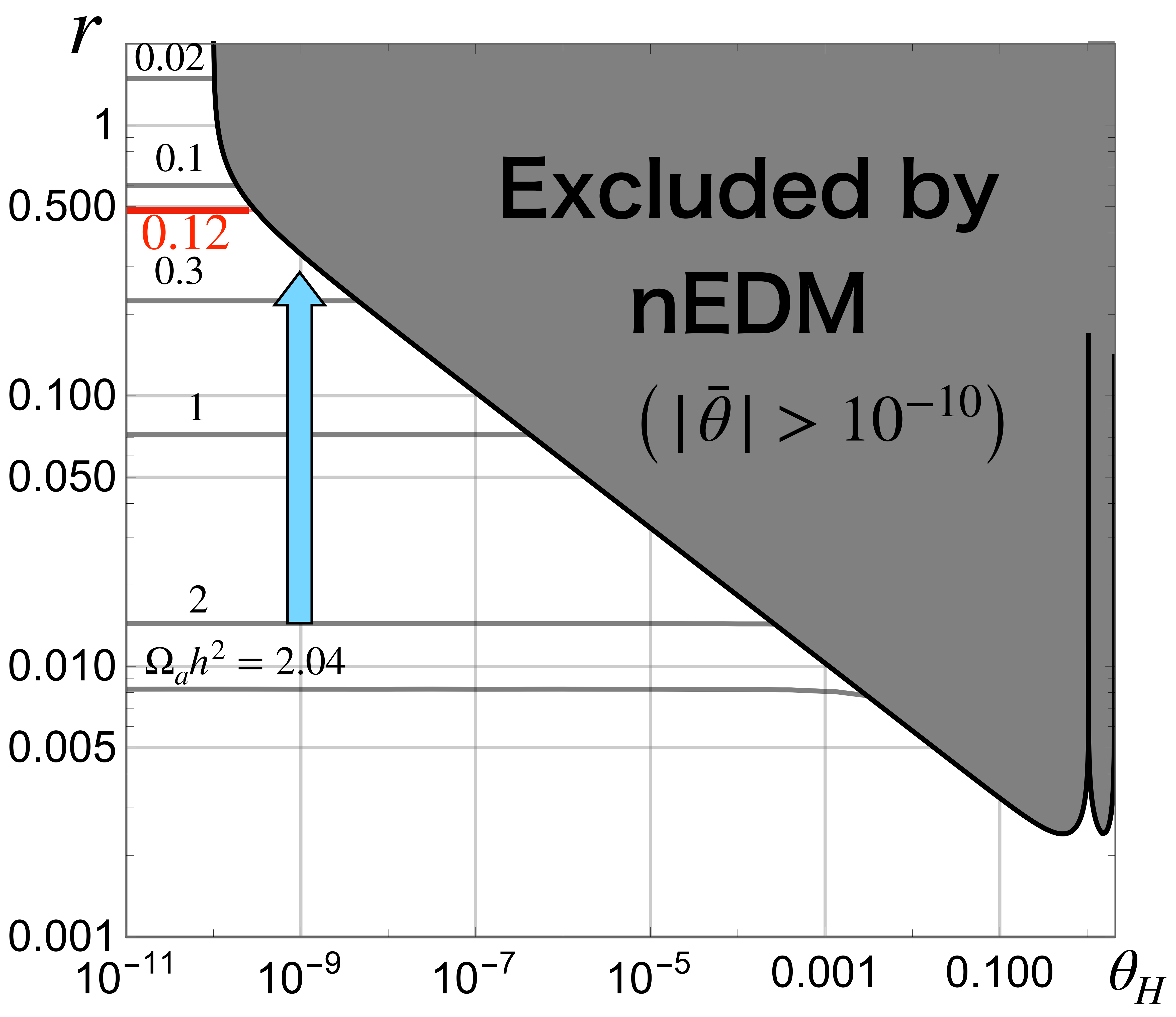


The dependence of Ω_a on $\theta_{\rm H}$ and r

[smooth-shift regime: $\theta_{\rm ini} = 1$]



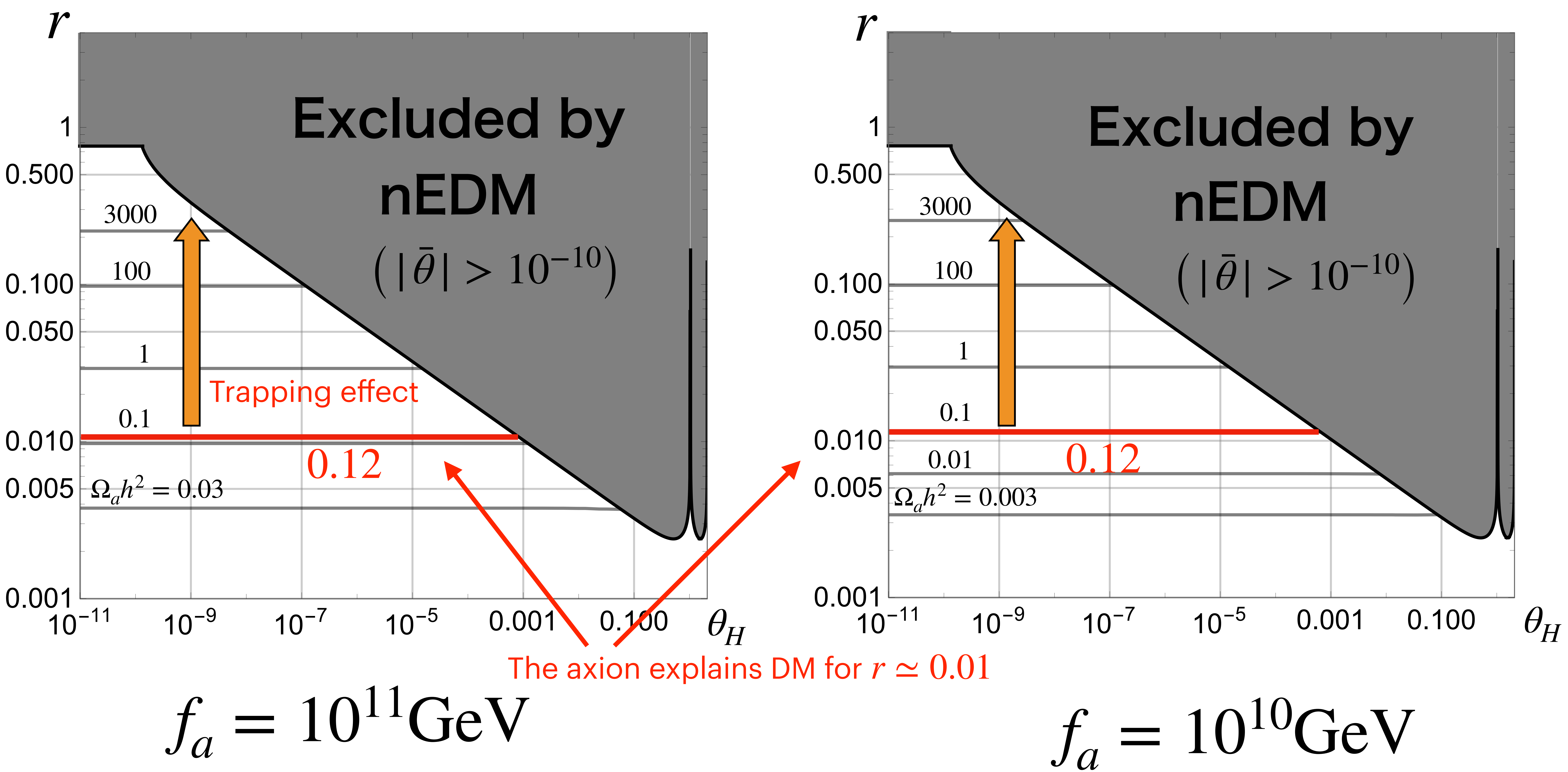
$f_a = 10^{12}$GeV



$f_a = 10^{13}$GeV

The dependence of Ω_a on $\theta_{\rm H}$ and r

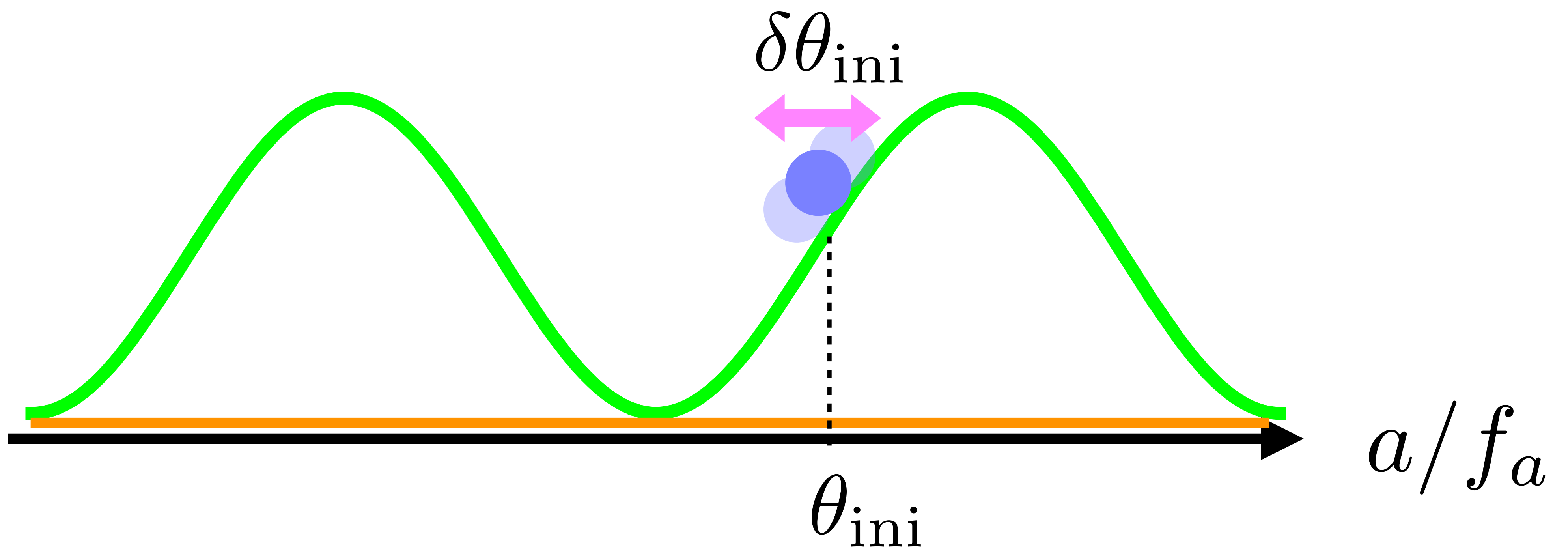
[Trapping regime: $\theta_{\rm ini} = 1.5$]



4. Axion isocurvature perturbations

In the pre-inflationary scenario, the axion acquires quantum fluctuations during inflation,

$$\delta a_{\rm ini} = \frac{H_{\rm inf}}{2\pi} \quad \text{i.e.,} \quad \delta\theta_{\rm ini} = \frac{H_{\rm inf}}{2\pi f_a}$$



leading to the CDM isocurvature perturbation,

$$\Delta_S^2 \simeq \left(\frac{\Omega_a}{\Omega_{\rm DM}}\frac{\partial \ln \Omega_a}{\partial \theta_{\rm ini}}\frac{H_{\rm inf}}{2\pi f_a}\right)^2 = \left(\frac{\partial \ln \Omega_a}{\partial \theta_{\rm ini}}\frac{H_{\rm inf}}{2\pi f_a}\right)^2 < 8.3\times 10^{-11}$$

Planck `18

if $\Omega_{\rm DM} = \Omega_a$

(1) Smooth-shift regime

$$\Delta_S^2 \simeq \left(\frac{\Omega_a}{\Omega_{\rm DM}} \frac{\partial \ln \Omega_a}{\partial \theta_{\rm ini}} \frac{H_{\rm inf}}{2\pi f_a} \right)^2 \simeq \left(\frac{2}{\theta_{\rm ini}} \frac{H_{\rm inf}}{2\pi f_a} \right)^2$$

$\Omega_{\rm DM} = \Omega_a \propto \theta_{\rm ini}^2$

The decay constant f_a becomes larger w.r.t. the conventional case, since the axion abundance is suppressed.

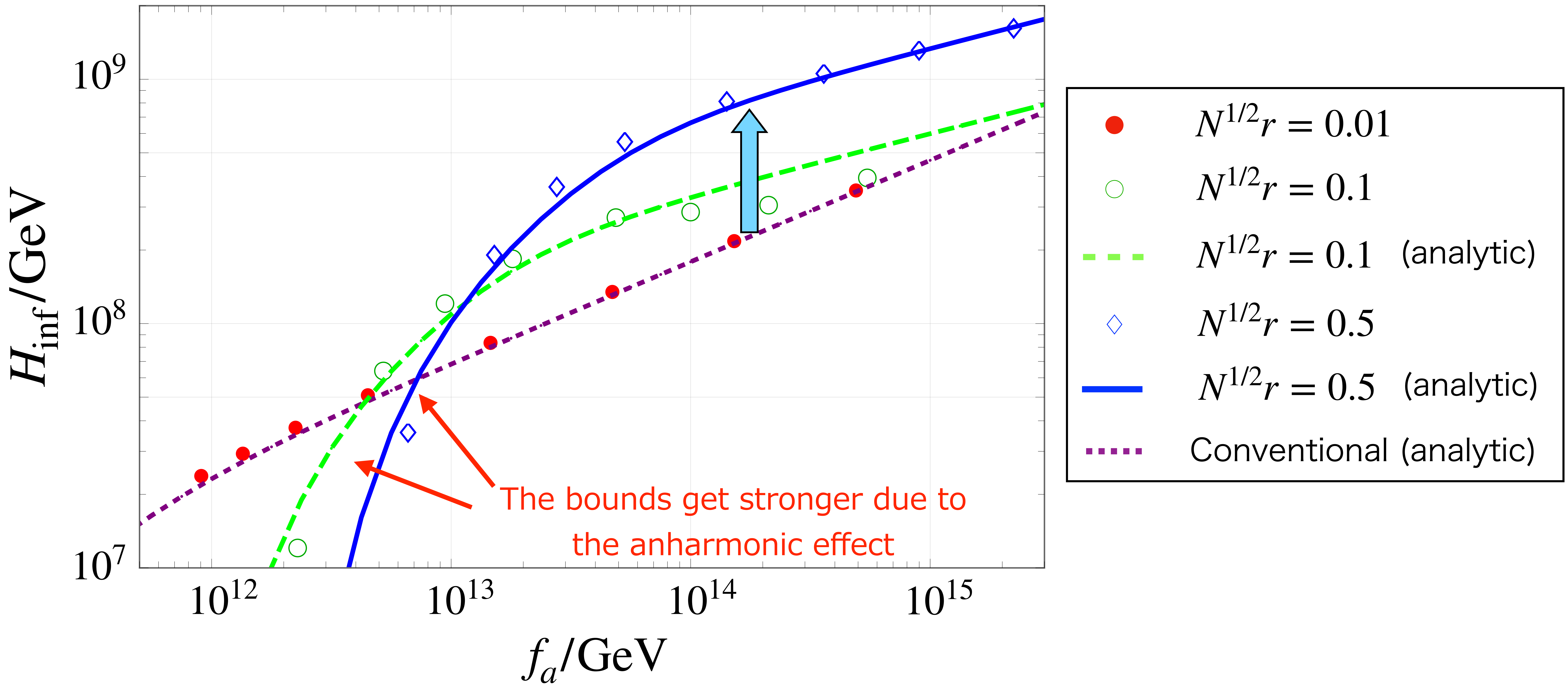
(2) Trapping regime

The axion abundance is insensitive to $\theta_{\rm ini}$, and so, the isocurvature perturbation is suppressed.

In both cases, the axion isocurvature bound is relaxed.

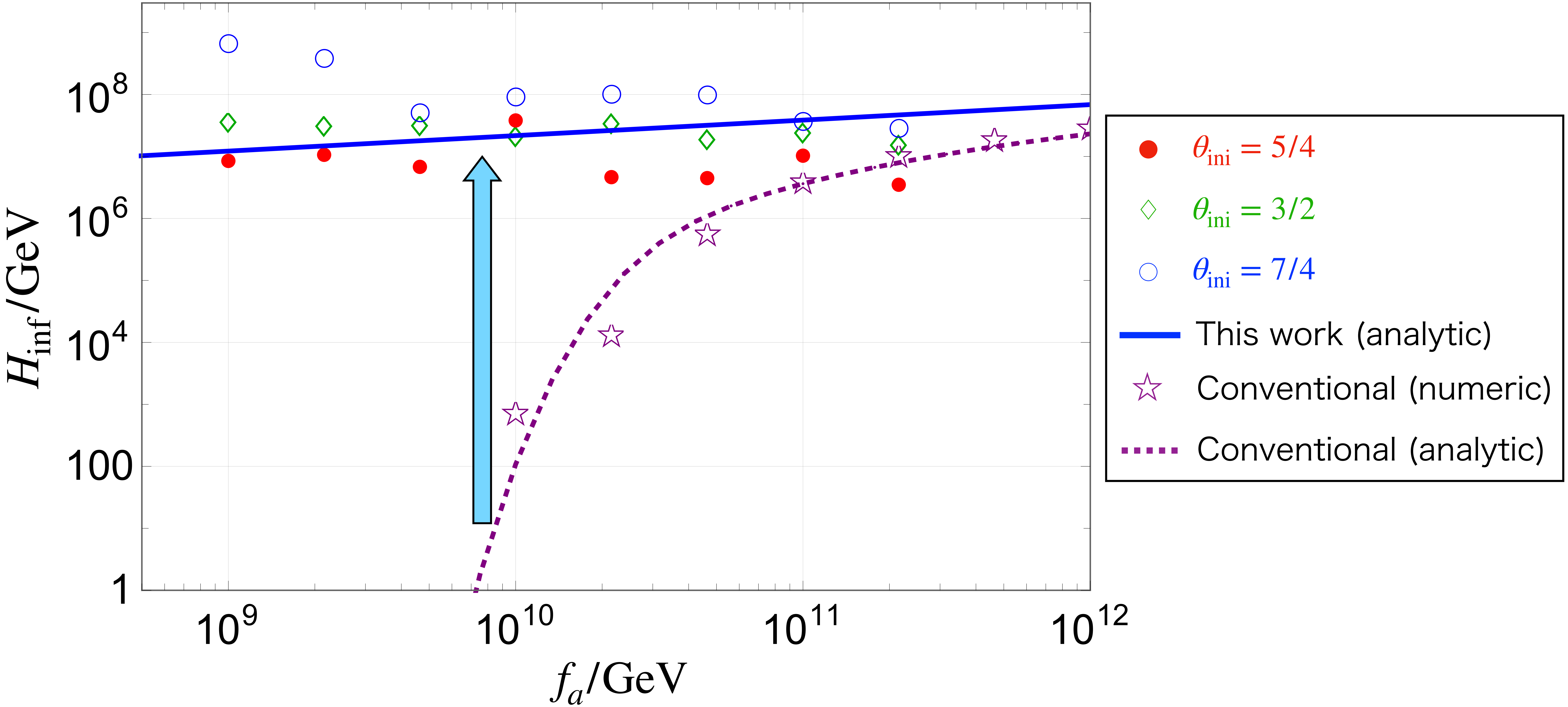
Isocurvature limits on $H_{\rm inf}$

[smooth-shift regime: $N = 3,\ \theta_H = 0,\ \Omega_a = \Omega_{\rm DM}$]



Isocurvature limits on $H_{\rm inf}$

[trapping regime: $N = 3,\ \theta_H = 0,\ \Omega_a = \Omega_{\rm DM}$]

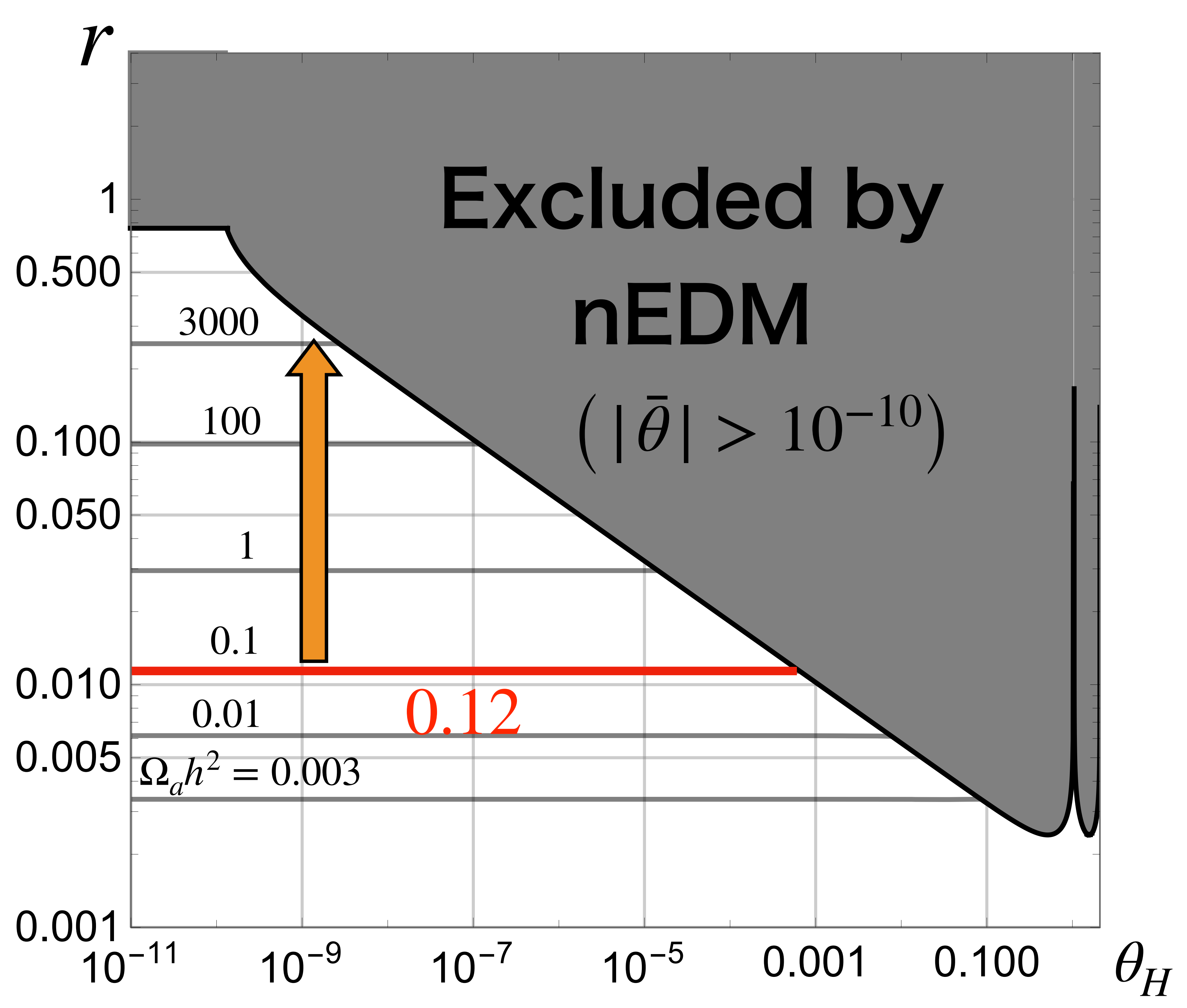


5. Summary

- We have found that, in the presence of the extra PQ breaking, the axion abundance can be either reduced or enhanced, depending on the initial position.

- In particular, the axion can explain DM for arbitrarily small f_a if it gets trapped in a false vacuum [cf. 1603.02090].

- The axion isocurvature bound is relaxed.



$f_a = 10^{10}\mathrm{GeV}$