Extra Peccei-Quinn symmetry breaking effects on QCD axion dark matter

素粒子現象論研究会2022

Mar. 17th, 2023

中川　翔太

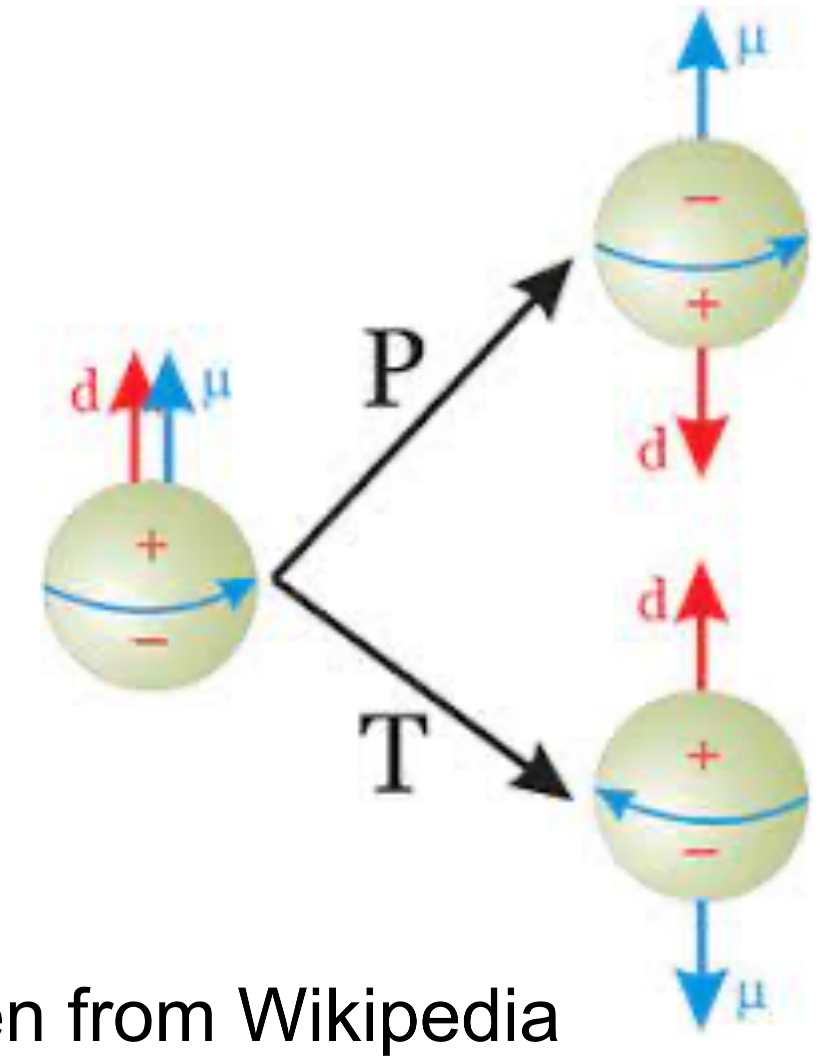
(Tohoku U. → T. D. Lee Institute)

JCAP 03 (2022) 026 [2201.00681] with K. S. Jeong, K. Matsukawa, and F. Takahashi

1. Introduction

Strong CP problem

The CP violation in QCD induces the neutron electric dipole moment (nEDM).



Taken from Wikipedia

$$-\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + (\bar{q}_L M_q q_R + \text{h.c.})$$

M_q : (complex) quark mass matrix

$$\Rightarrow \quad |d_n| \simeq 1.2 \times 10^{-16} |\bar{\theta}| e \text{ cm} \qquad \bar{\theta} \equiv \theta + \arg(\det M_q)$$

Pospelov and Ritz hep-ph/9908508

$$< 1.8 \times 10^{-26} e \text{ cm}$$ (90%C.L.) $\Leftrightarrow |\bar{\theta}| \lesssim 10^{-10}$

Abel et al, 2001.11966

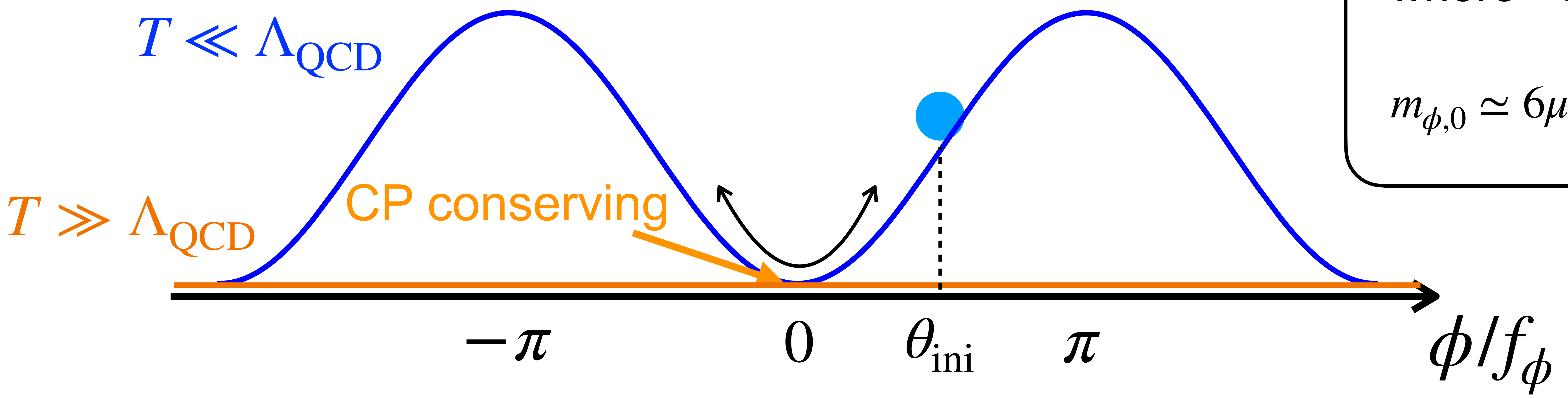
Why is $\bar{\theta}$ so small?

Peccei-Quinn (PQ) mechanism

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

The theta parameter is promoted to a dynamical field, QCD axion ϕ.

$$-\mathcal{L} \supset \left(\bar{\theta} + \frac{\phi}{f_\phi}\right) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$



Axion mass

$$m_\phi(T) \simeq m_{\phi,0} \left(\frac{T}{\Lambda_{\mathrm{QCD}}}\right)^{-b} \quad (T \gg \Lambda_{\mathrm{QCD}})$$

where $b = 3.92,\ \Lambda_{\mathrm{QCD}} = 0.15\mathrm{GeV},$

$$m_{\phi,0} \simeq 6\mu\mathrm{eV} \left(\frac{f_\phi}{10^{12}\mathrm{GeV}}\right)^{-1} \quad (T \ll \Lambda_{\mathrm{QCD}})$$

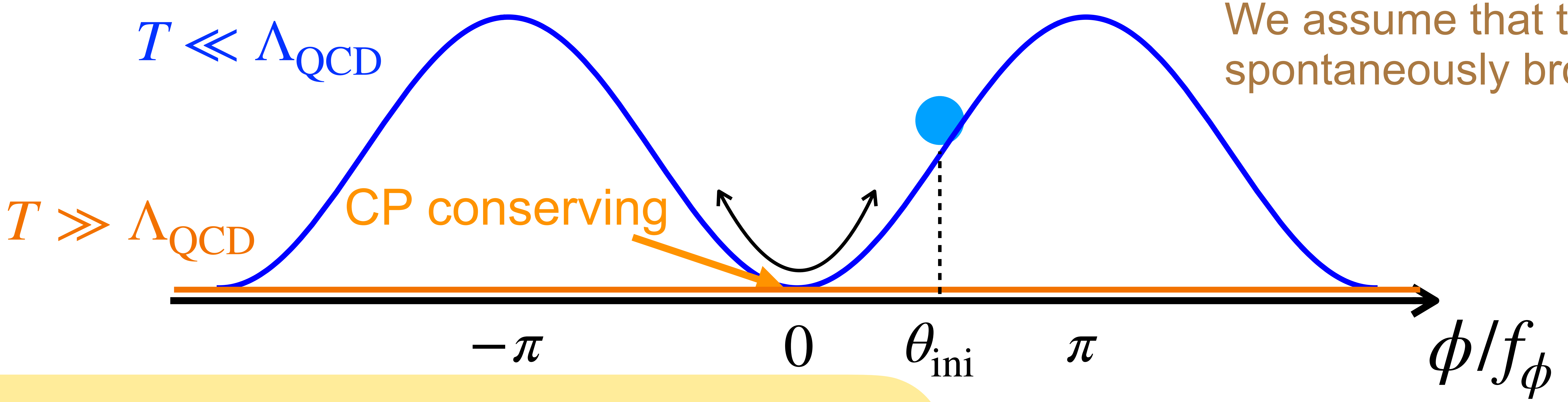
Borsanyi, et al. 1606.07494
Gorghetto and Villadoro, 1812.01008

The Strong CP problem can be dynamically solved !

Misalignment mechanism

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

The oscillation energy contributes to the DM abundance.



We assume that the PQ symmetry is spontaneously broken during inflation.

Axion abundance

$$\Omega_\phi h^2 \simeq 0.14\theta_{ini}^2 F(\theta_{ini}) \left(\frac{f_\phi}{10^{12}\mathrm{GeV}} \right)^{1.17}$$

Ballesteros et al, 1610.01639

Anharmonic factor

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

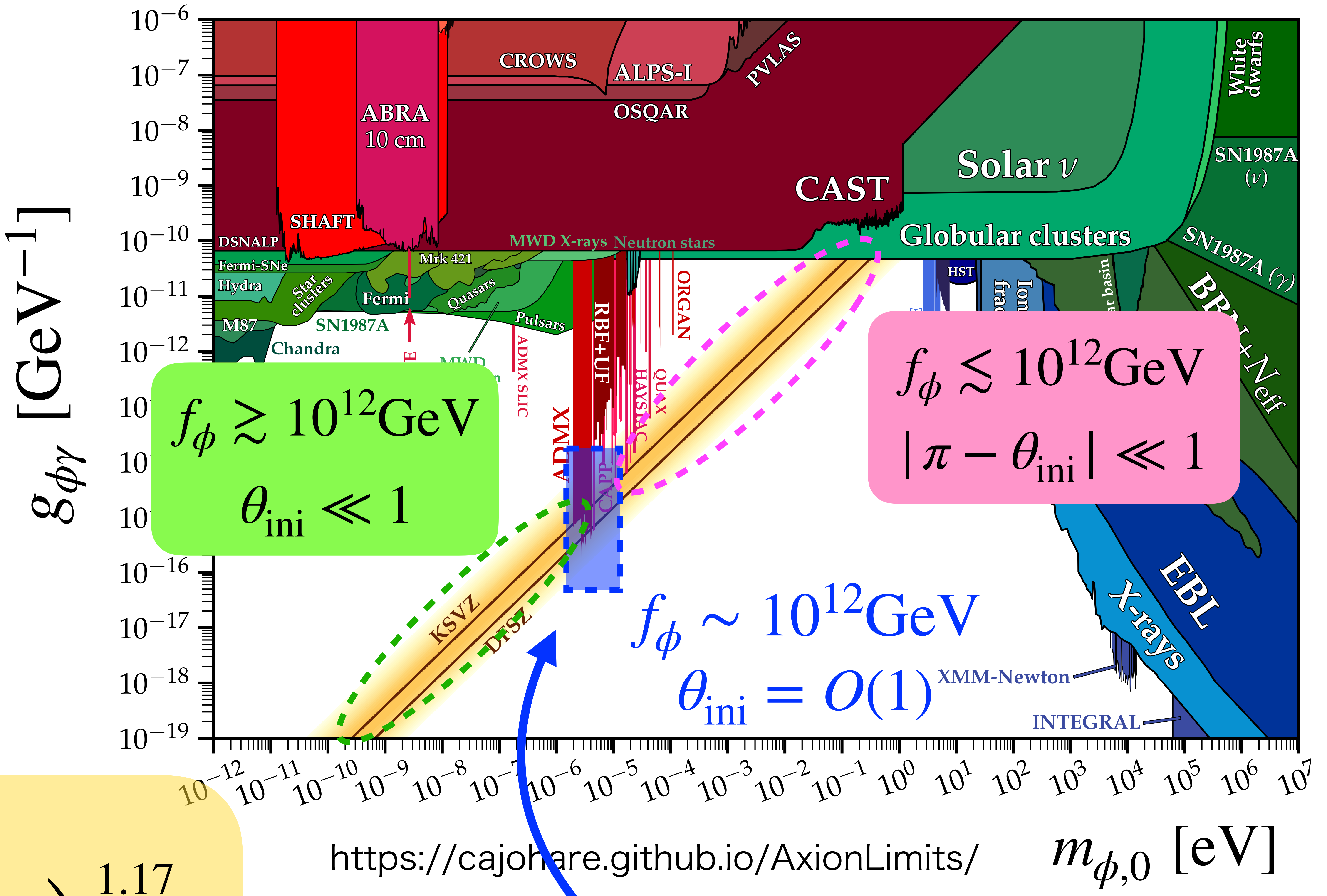
Lyth `92, Bae, Huh and Kim 0806.0497,
Visinelli and Gondolo 0903.4377

The DM abundance can be explained for $f_\phi \simeq 10^{12}\mathrm{GeV}$ and $\theta_{ini} \sim 1$.

The current constraints on axion-photon coupling

$$\mathcal{L} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

where $$g_{\phi\gamma} = \frac{c_\gamma \alpha}{2\pi f_\phi}$$



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

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e.g. stochastic axion scenario

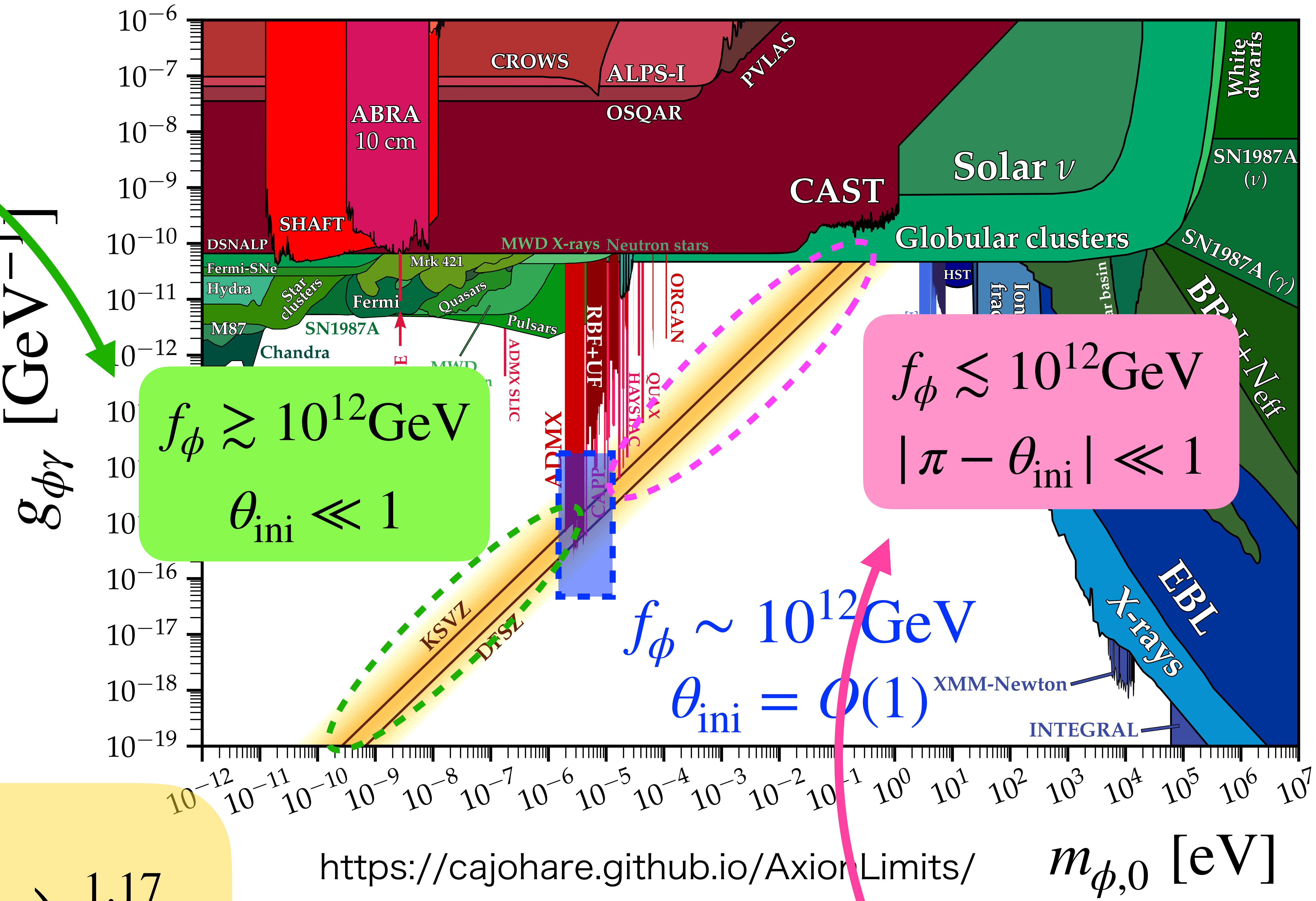
$$\sqrt{\langle \theta_{\rm ini}^2 \rangle} \sim H_{\rm inf}^2 / m_\phi f_\phi$$

Graham, Scherlis, 1805.07362. Takahashi, Yin, Guth, 1805.08763. **SN**, Takahashi, Yin, 2002.12195 for ALP

cf. energy dissipation

Papageorgiou, Quilez, & Schmitz, 2206.01129.
Choi, Im, Kim, & Seong, 2206.01462.

In prep. w/ Jeong+



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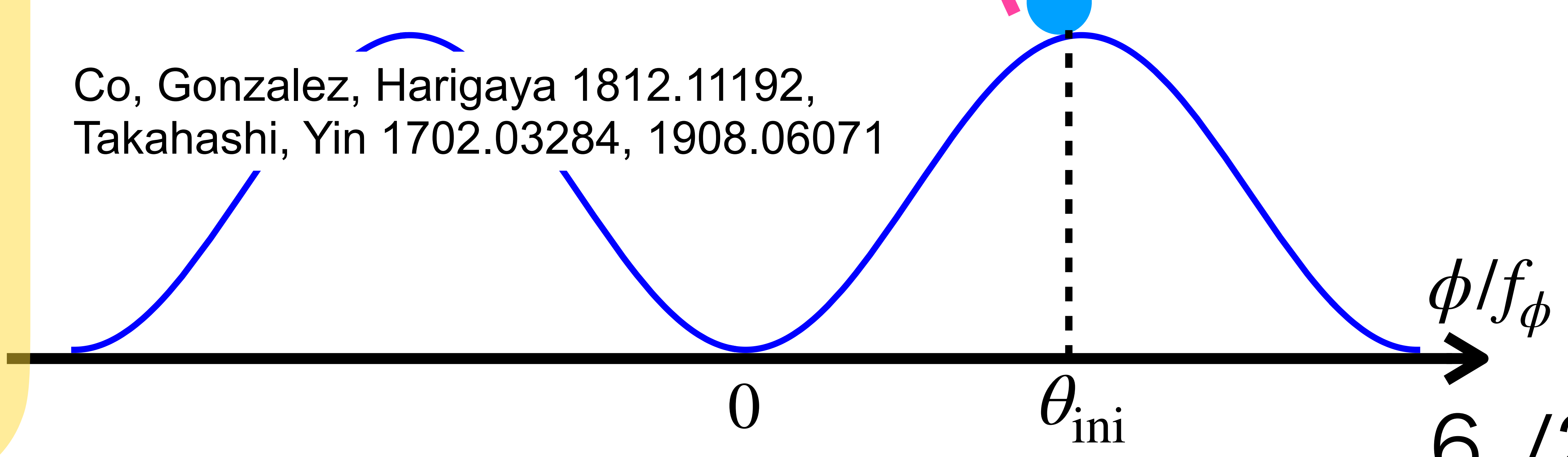
Anharmonic effect

Co, Gonzalez, Harigaya 1812.11192,
Takahashi, Yin 1702.03284, 1908.06071

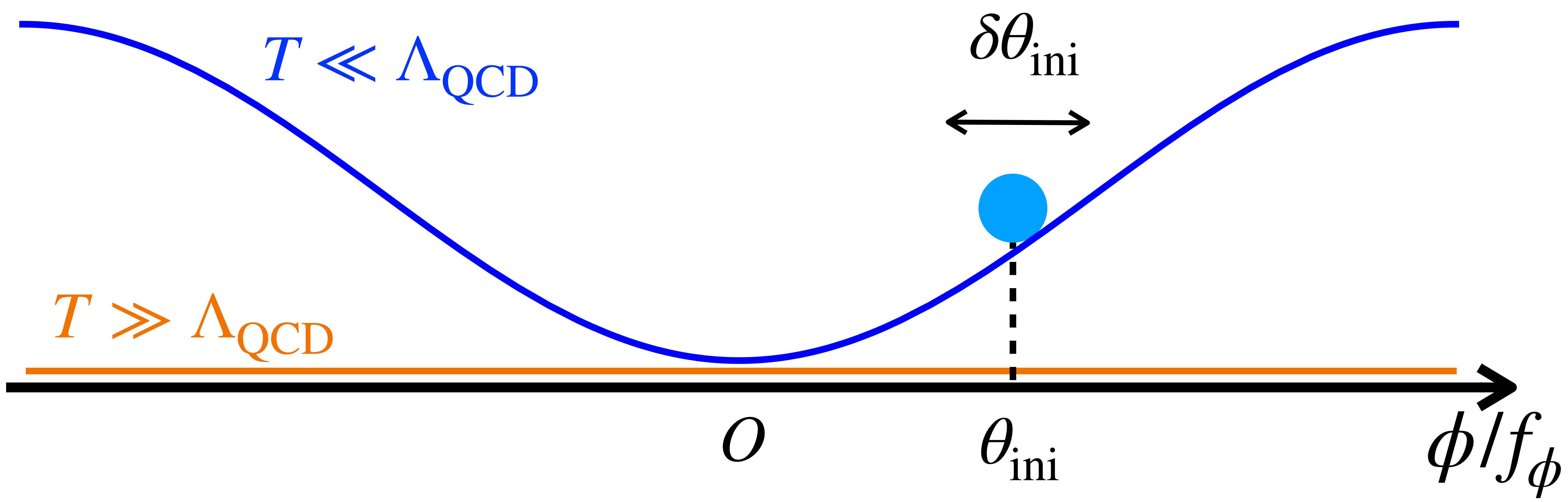


Isocurvature perturbations

The axion acquires quantum fluctuation during inflation.

$$\delta\theta_{\rm ini} = \frac{H_{\rm inf}}{2\pi f_\phi}$$

$$\rightarrow \frac{\delta\rho_\phi}{\rho_\phi} \sim \frac{2\delta\theta_{\rm ini}}{\theta_{\rm ini}}$$

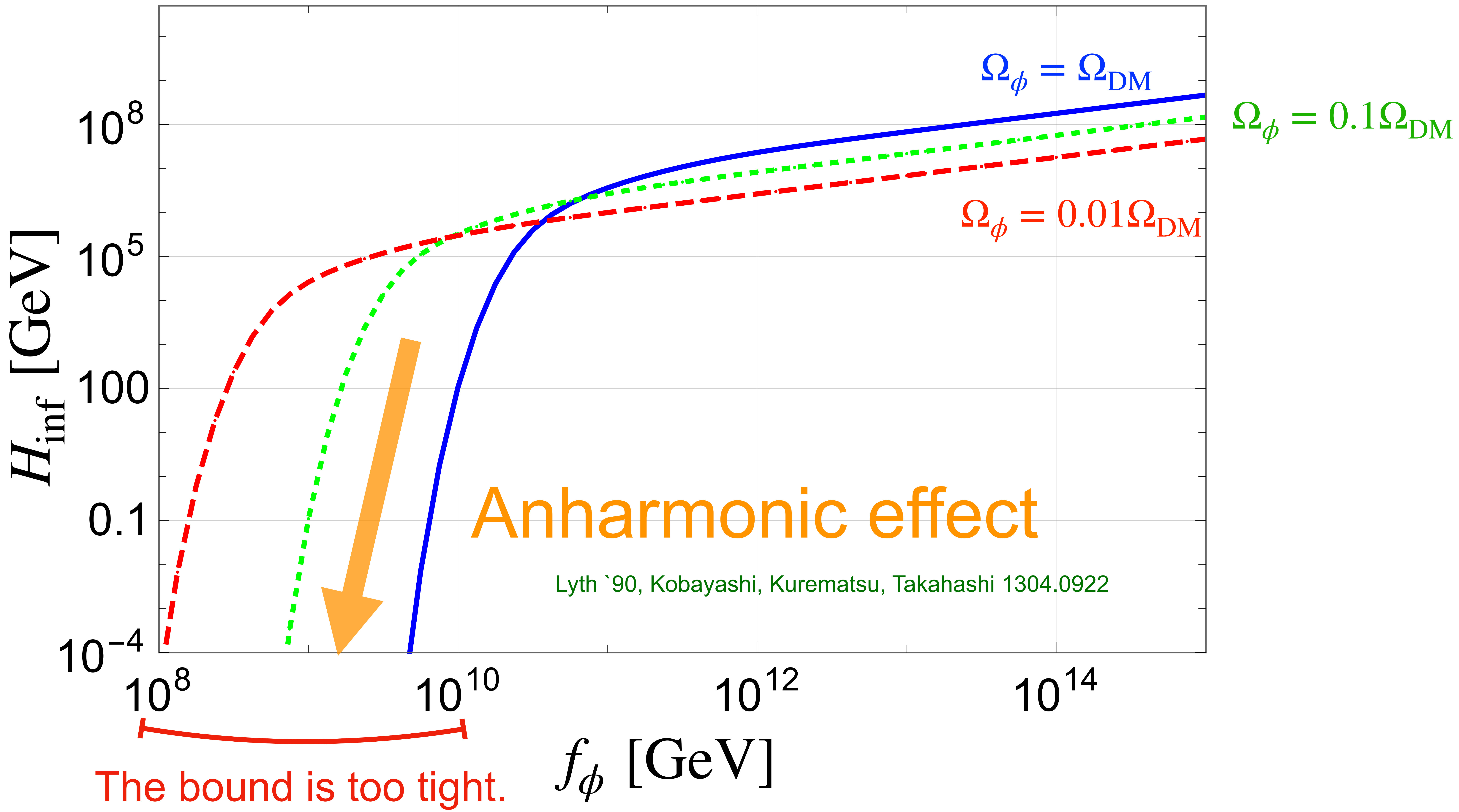


It leaves an imprint on the CMB spectrum.

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

Planck Collaboration

Isocurvature bound on $H_{\rm inf}$



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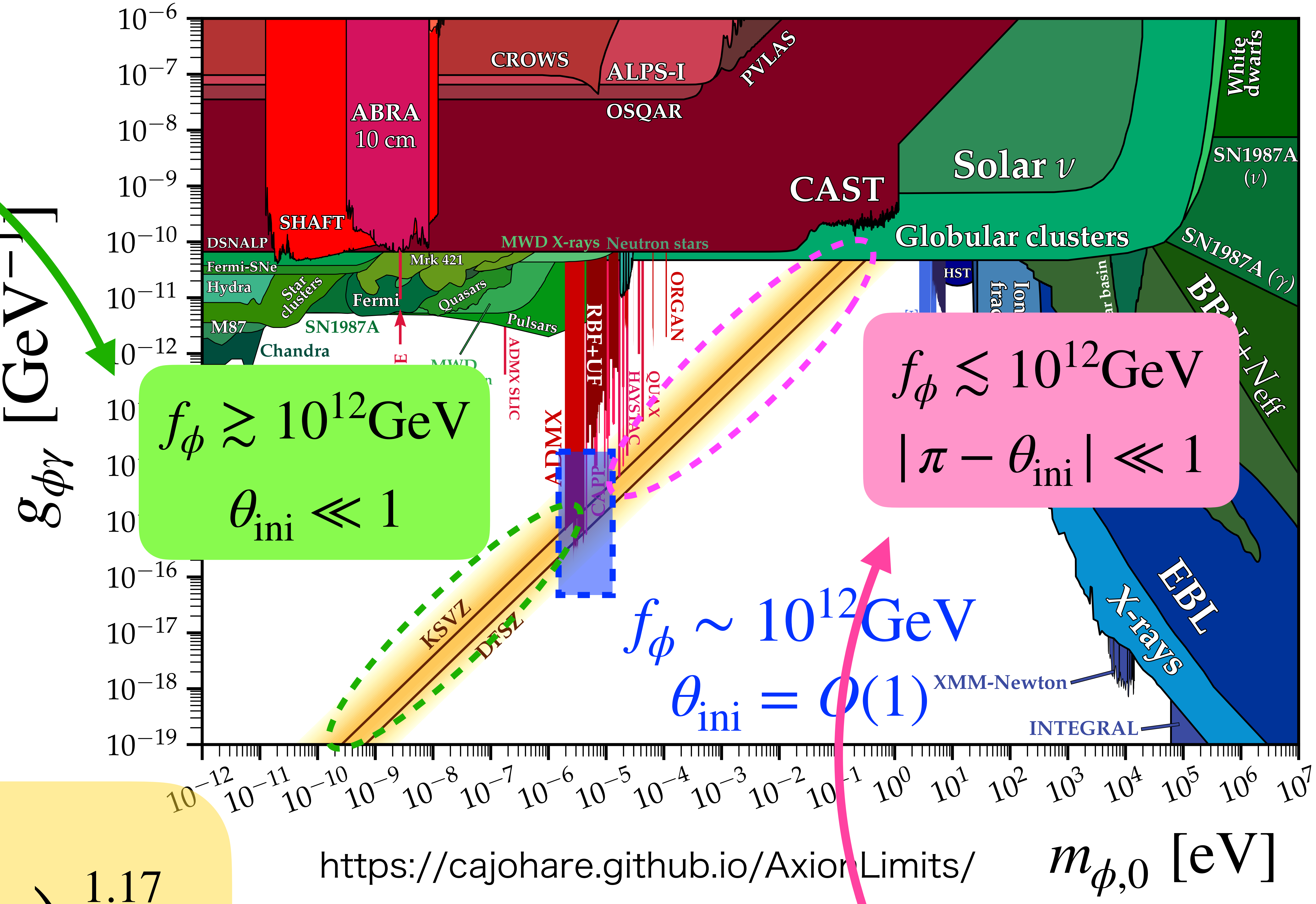
In prep. w/ Jeong+



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

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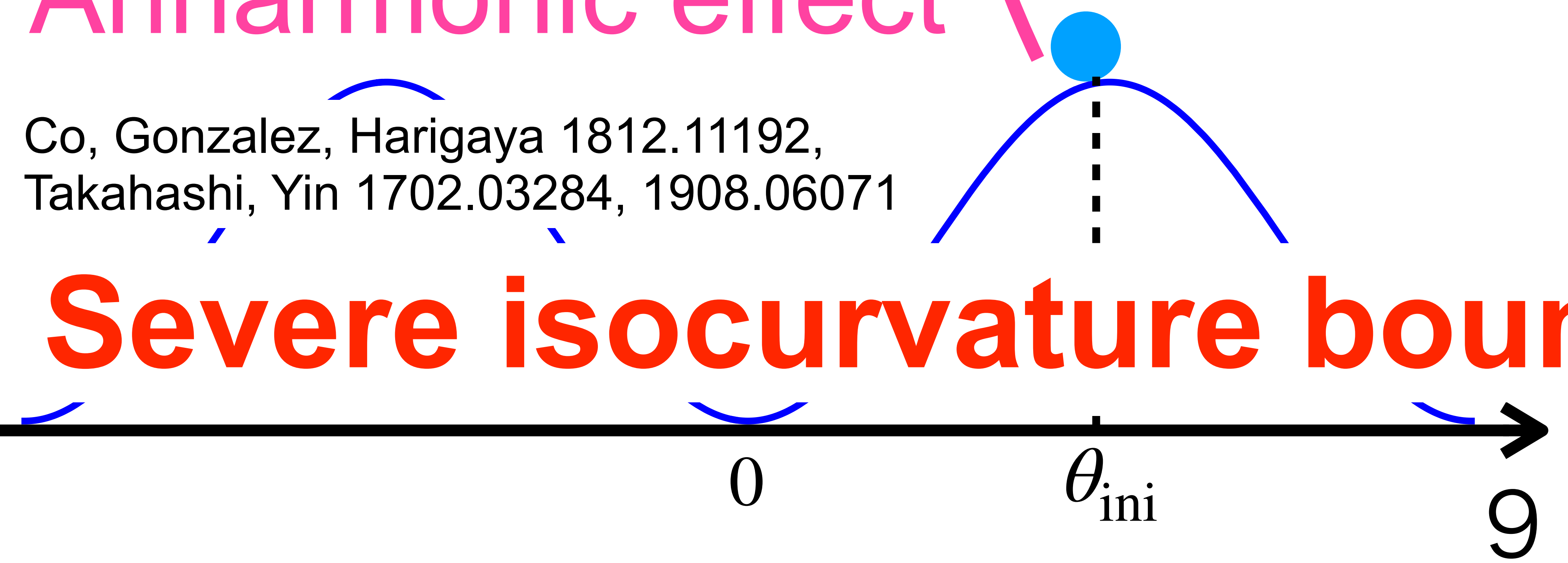
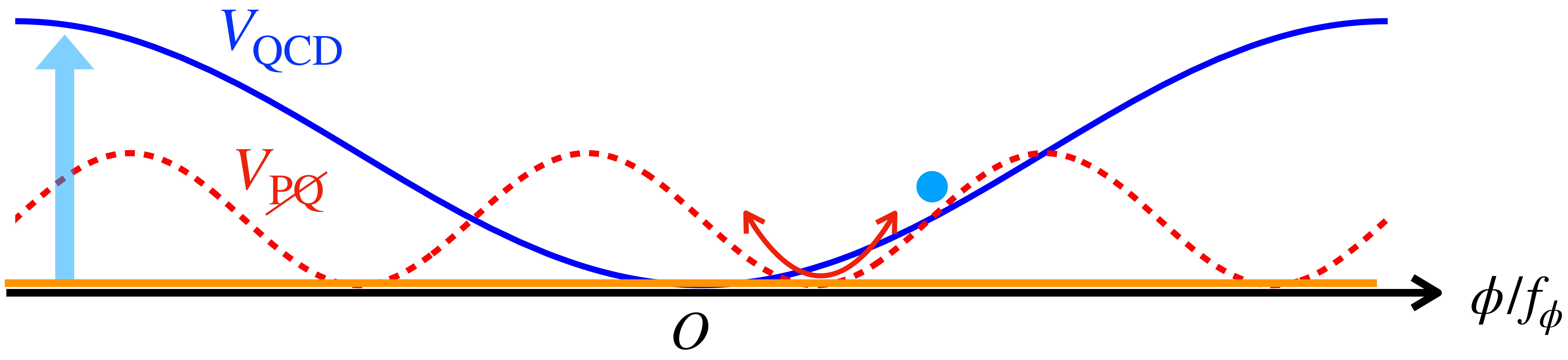
Co, Gonzalez, Harigaya 1812.11192, Takahashi, Yin 1702.03284, 1908.06071



Severe isocurvature bound

Any global symmetry is believed to be explicitly broken.

Hawking '75, Kallosh, Linde, Linde, Suskind hep-th/9502069,
Harlow and Ooguri 1810.05337, Yonekura 2011.11868



The nEDM bound $|\bar\theta| \lesssim 10^{-10}$ requires the extra potential to be highly suppressed. PQ quality problem In prep. w/ Nakai+

However, the axion can be temporarily trapped by extra PQ symmetry breaking in the very early universe.

The extra PQ breaking effects can alter the axion dynamics !

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2. Experimental bounds on extra PQ breaking
3. Axion abundance
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2. Experimental bounds on extra $\not{P}\not{Q}$

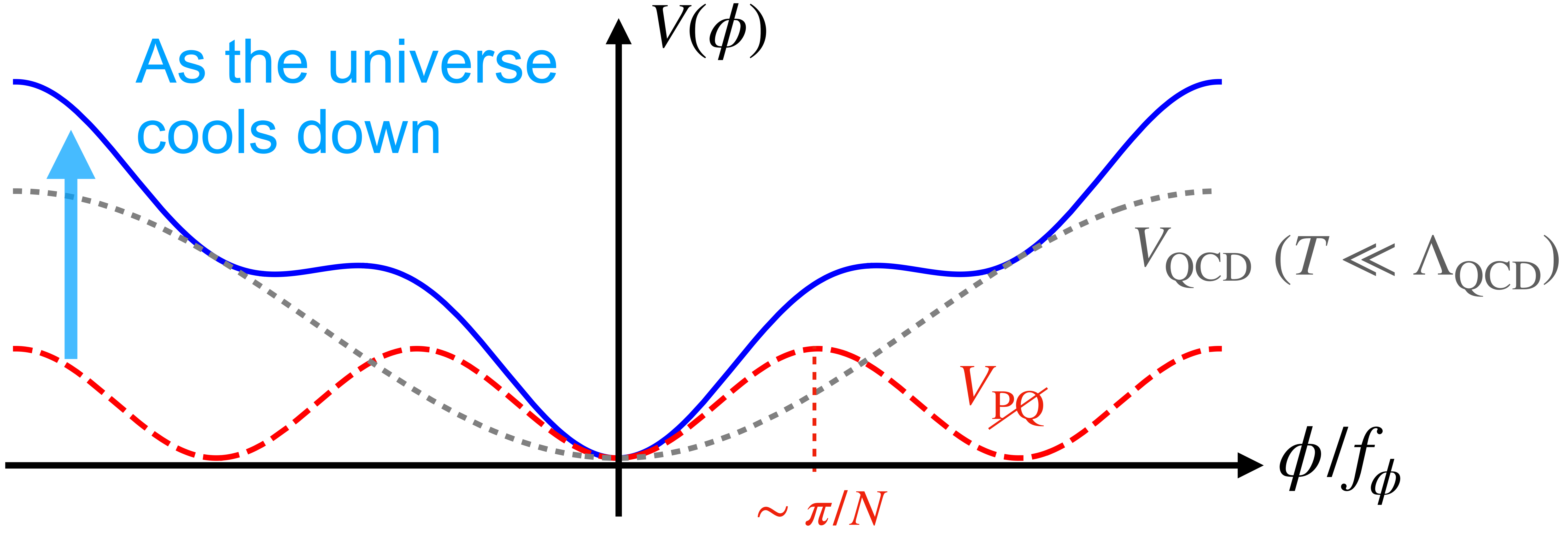
Jeong, Matsukawa, **SN**, Takahashi 2101. 00681

We consider the following potential.

Axion potential

$$V(\phi) = V_{\rm QCD}(\phi) + V_{\not{P}\not{Q}}(\phi)$$

where $V_{\rm QCD}(\phi) = m_\phi^2(T) f_\phi^2 \left(1 - \cos\frac{\phi}{f_\phi}\right)$ $\quad V_{\not{P}\not{Q}} = \Lambda_H^4 \left[1 - \cos\left(N\left(\frac{\phi}{f_\phi} - \theta_H\right)\right)\right]$



nEDM bound

The extra potential $V_{\not{PQ}}$ is parametrized by the following two:

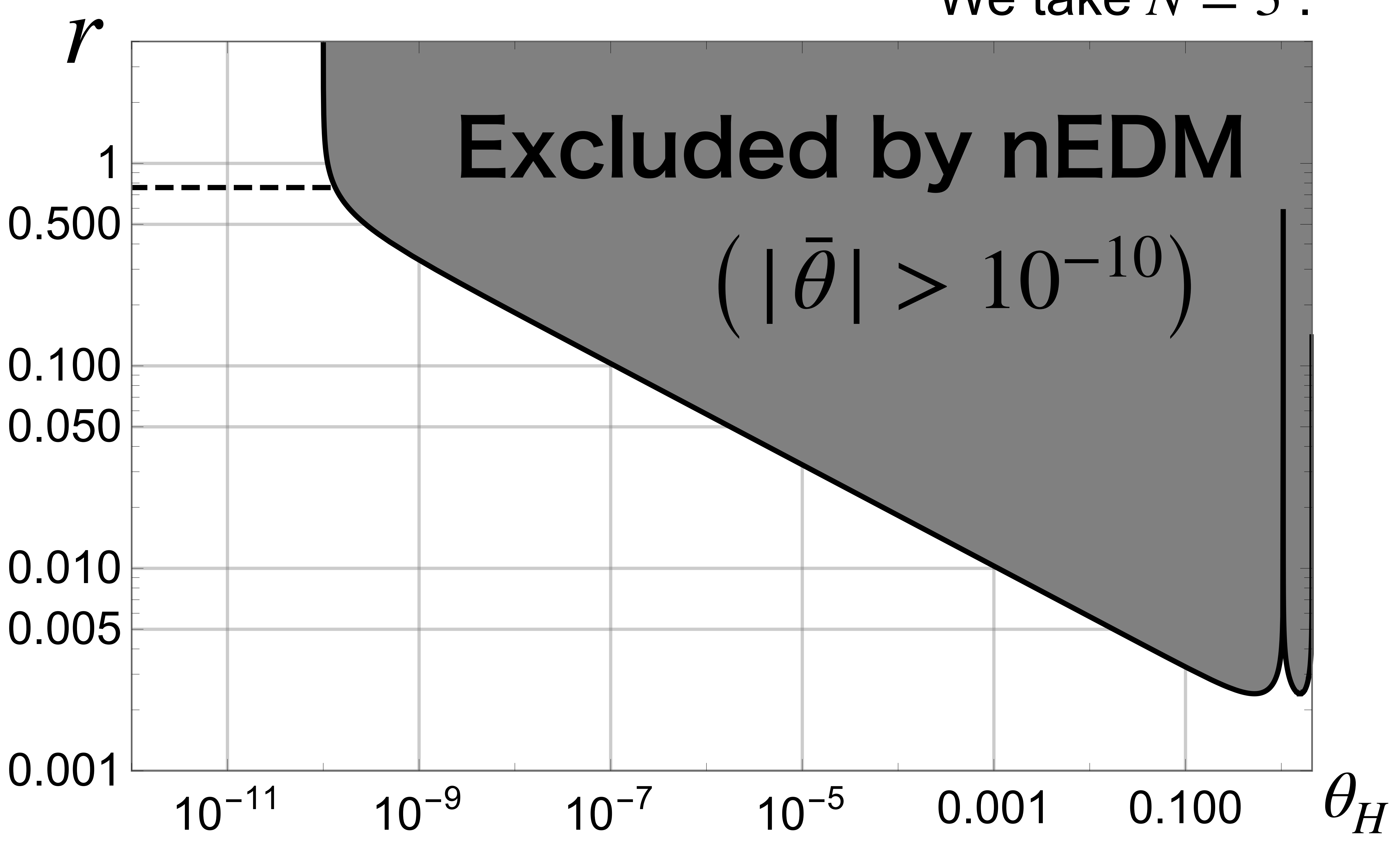
・Relative height : $r \equiv \Lambda_H / \sqrt{m_{\phi,0} f_\phi}$

・Relative phase : θ_H

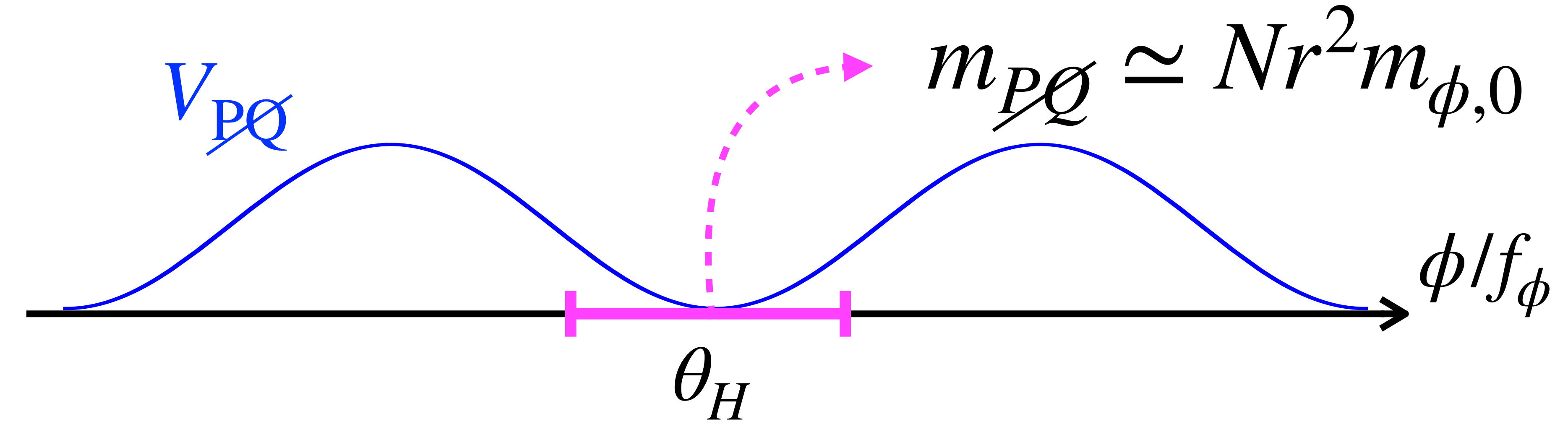
nEDM bound : $|\bar{\theta}| \lesssim 10^{-10}$

$$\rightarrow \quad r \lesssim \left| \frac{10^{-10}}{N \sin(N(10^{-10} - \theta_H))} \right|^{1/4}$$

We take $N = 3$.



3. Axion abundance



The dynamics becomes nontrivial when the axion starts to oscillate by the extra potential.

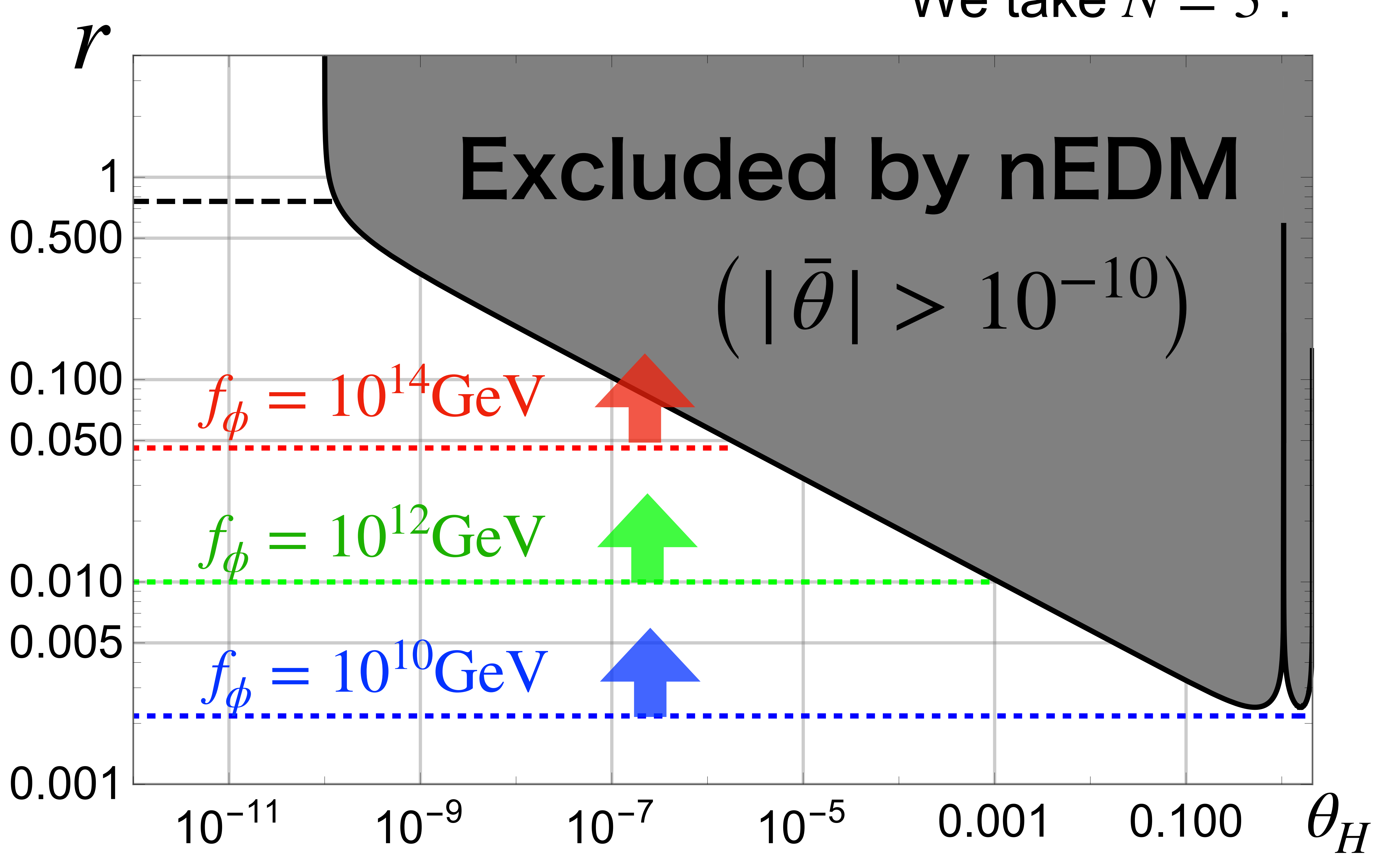
Strong trapping condition :

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

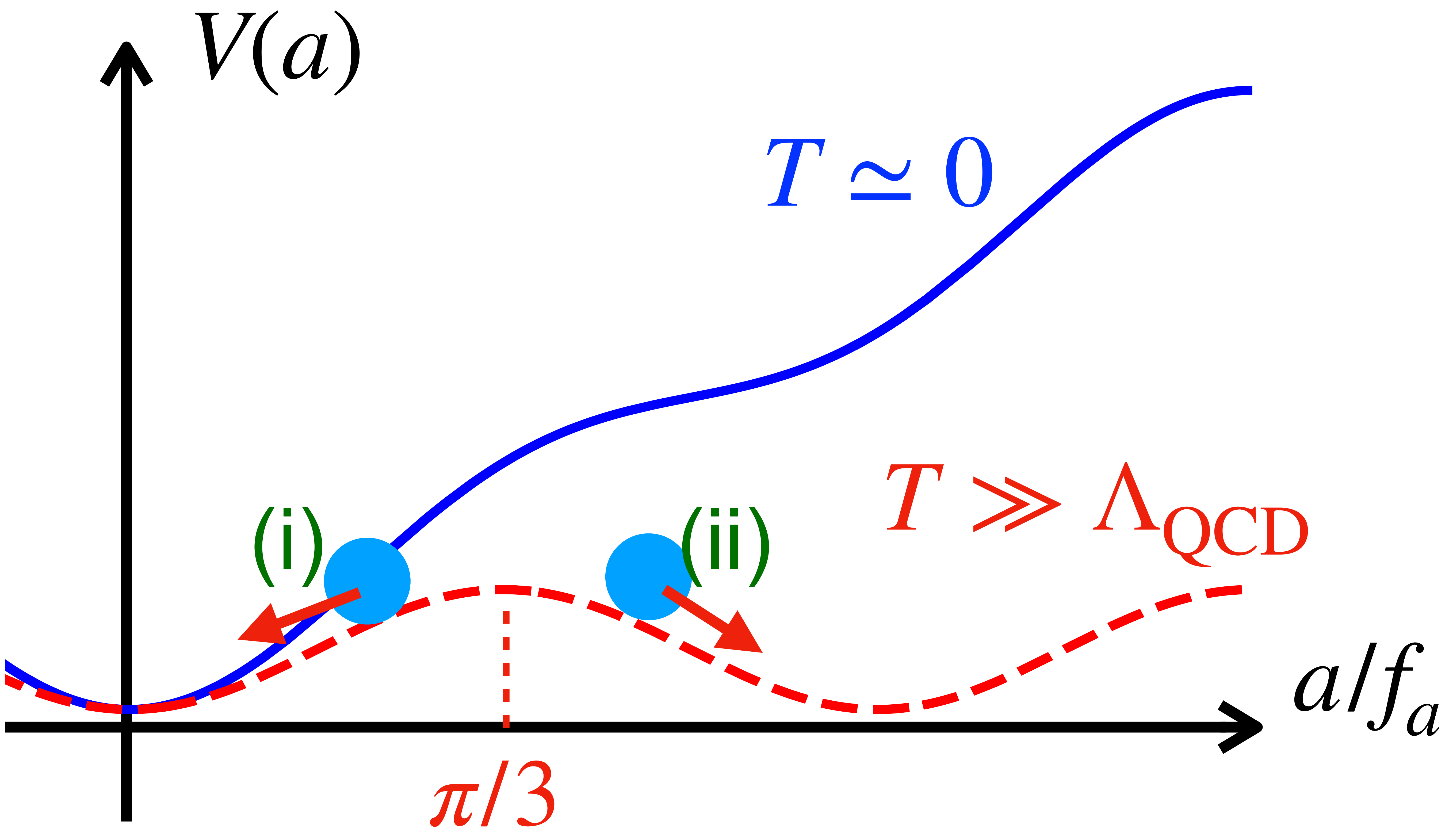
$m_{\not{PQ}} \simeq H$ $\quad\quad$ $m_\phi(T_{\rm osc}^{\rm (conv)}) \simeq H$

$$N r^2 \gtrsim 3.0 \times 10^{-4} \left(\frac{g_*(T_{\rm osc})}{80}\right)^{0.33} \left(\frac{f_\phi}{10^{12}\ {\rm GeV}}\right)^{0.66}$$

We take $N = 3$.



Under the condition, $T_{\rm osc} > T_{\rm osc}^{\rm (conv)}$, the axion dynamics can be divided into two cases.



(i) Smooth shift regime

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

(ii) Trapped regime

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

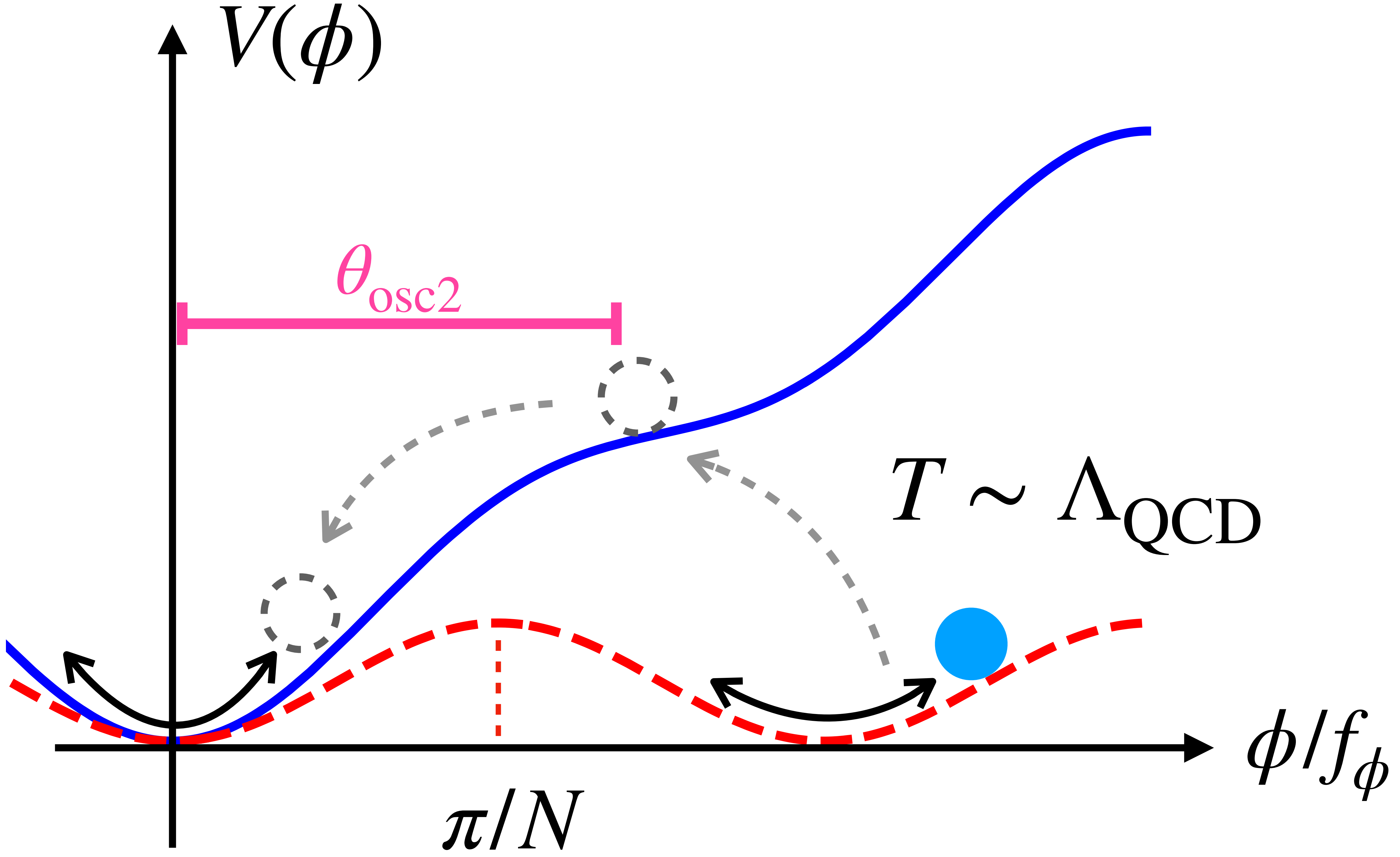
Here we assume $N = 3$.

cf) Trapped misalignment
Di Luzio, Gavela, Quilez, and Ringwald, 2102.01082.
Higaki, Jeong, Kitajima, and Takahashi, 1603.02090.

(ii) Trapped regime $(|\theta_{\rm ini} - \theta_H| > \pi/N)$

• The axion is temporarily trapped around the wrong minimum until $T \sim \Lambda_{\rm QCD}$.

• The wrong minimum disappears, and then the axion starts to oscillate about the origin.



$$\Rightarrow \quad T_{\rm osc2} \sim 0.4 \text{ GeV} \left(\frac{N r^4}{3 \times 10^{-4}}\right)^{-0.13}$$

It is independent of f_ϕ .

• The amplitude is almost independent of $\theta_{\rm ini}$.

(ii) Trapped regime $(|\theta_{\rm ini} - \theta_H| > \pi/N)$

- Oscillation amplitude $\theta_{\rm osc2} \sim \pi/N$
- Oscillation timing $T_{\rm osc2} \sim 0.4\ {\rm GeV} \left(\frac{Nr^4}{3\times 10^{-4}}\right)^{-0.13}$

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

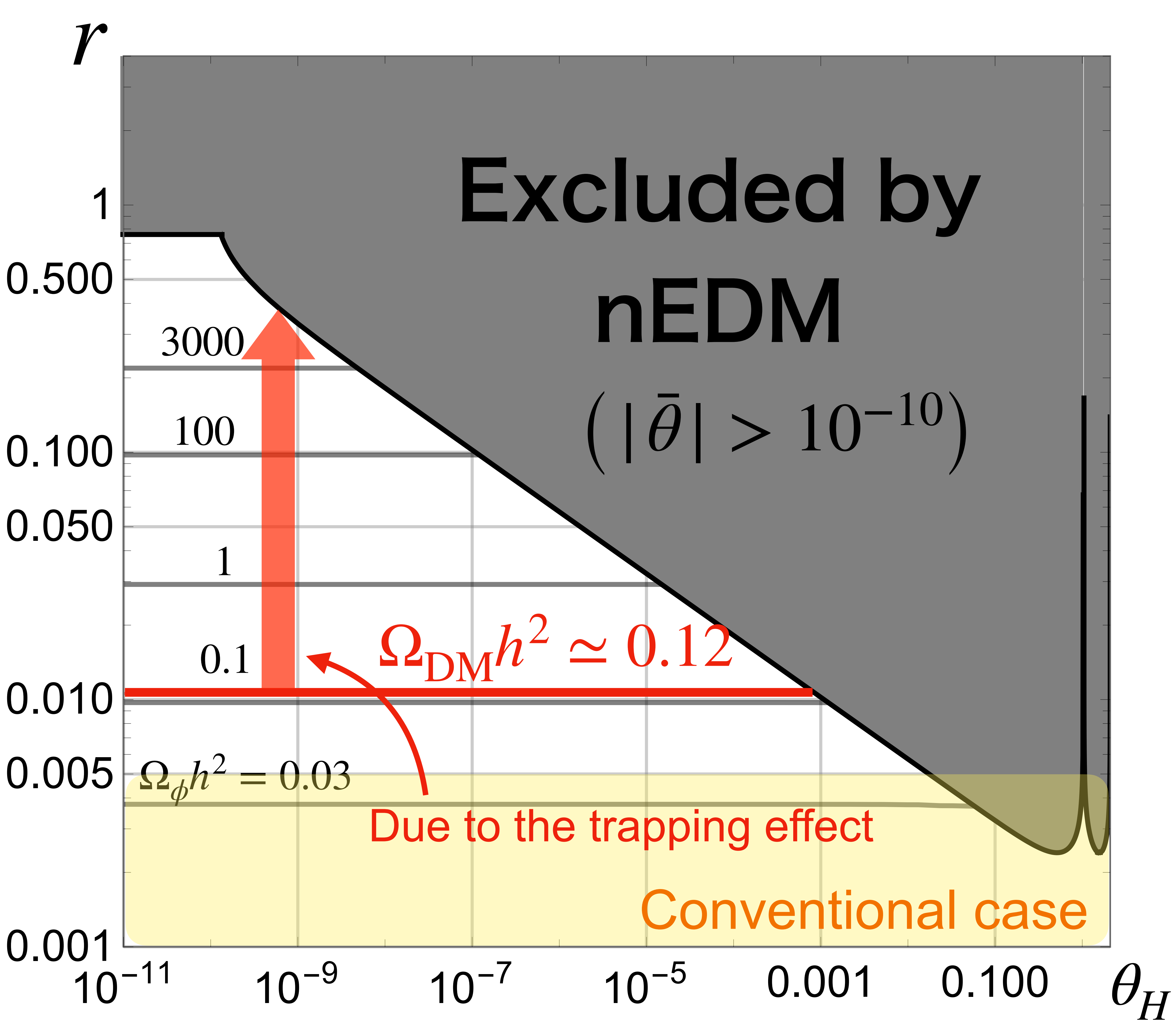
For stronger trapping, the potential height is higher and the oscillation is delayed.

DM can be explained for arbitrary (small) f_ϕ and $\theta_{\rm ini}\ (>\pi/N)$ if $r \sim 0.01$.

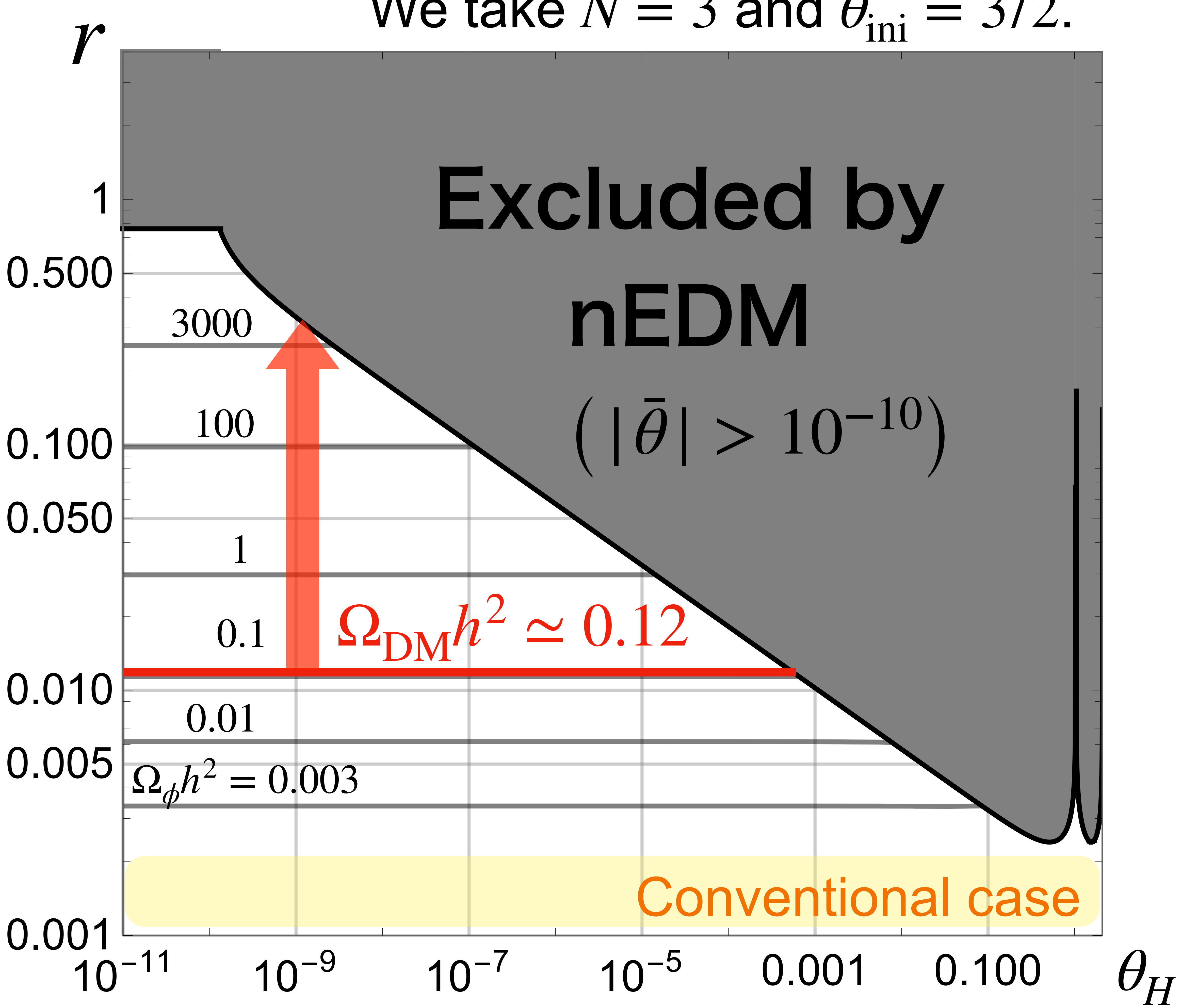
$\Omega_\phi h^2$ as a function of θ_H and r

Jeong, Matsukawa, **SN**, Takahashi 2101. 00681

We take $N = 3$ and $\theta_{\rm ini} = 3/2$.



$f_\phi = 10^{11}\mathrm{GeV}$



$f_\phi = 10^{10}\mathrm{GeV}$

DM can be explained for $f_\phi \lesssim 10^{11}\mathrm{GeV}$, if $r \sim 0.01$.

4. Isocurvature bounds

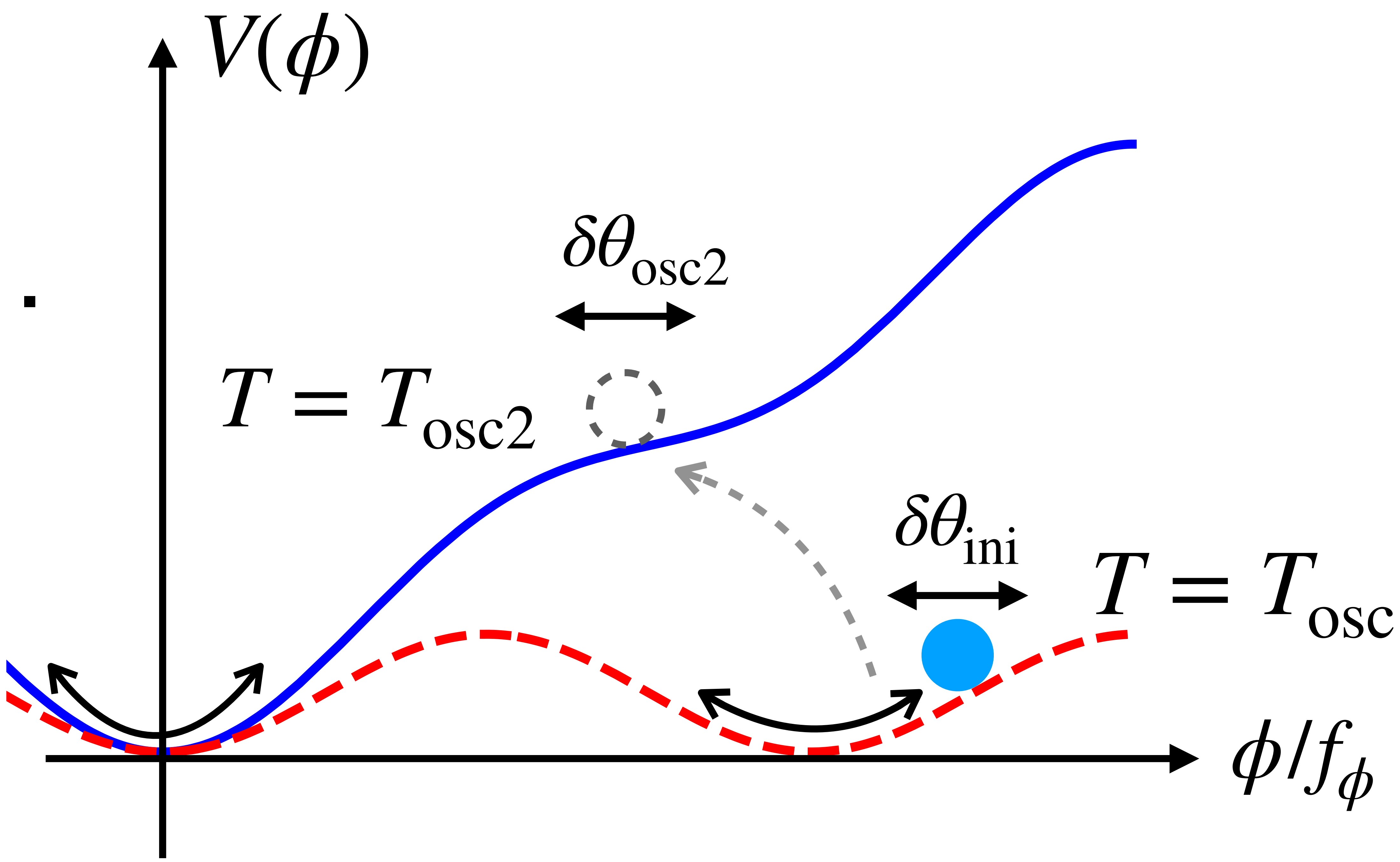
In the trapped regime, we need more careful estimate because the abundance does not depend on $\theta_{\rm ini}$ so much.

$$\Delta_S^2 \simeq \left(\frac{\Omega_\phi}{\Omega_{\rm DM}} \underbrace{\frac{\partial \ln \Omega_\phi}{\partial \theta_{\rm ini}}}_{\sim 0} \frac{H_{\rm inf}}{2\pi f_\phi} \right)^2$$

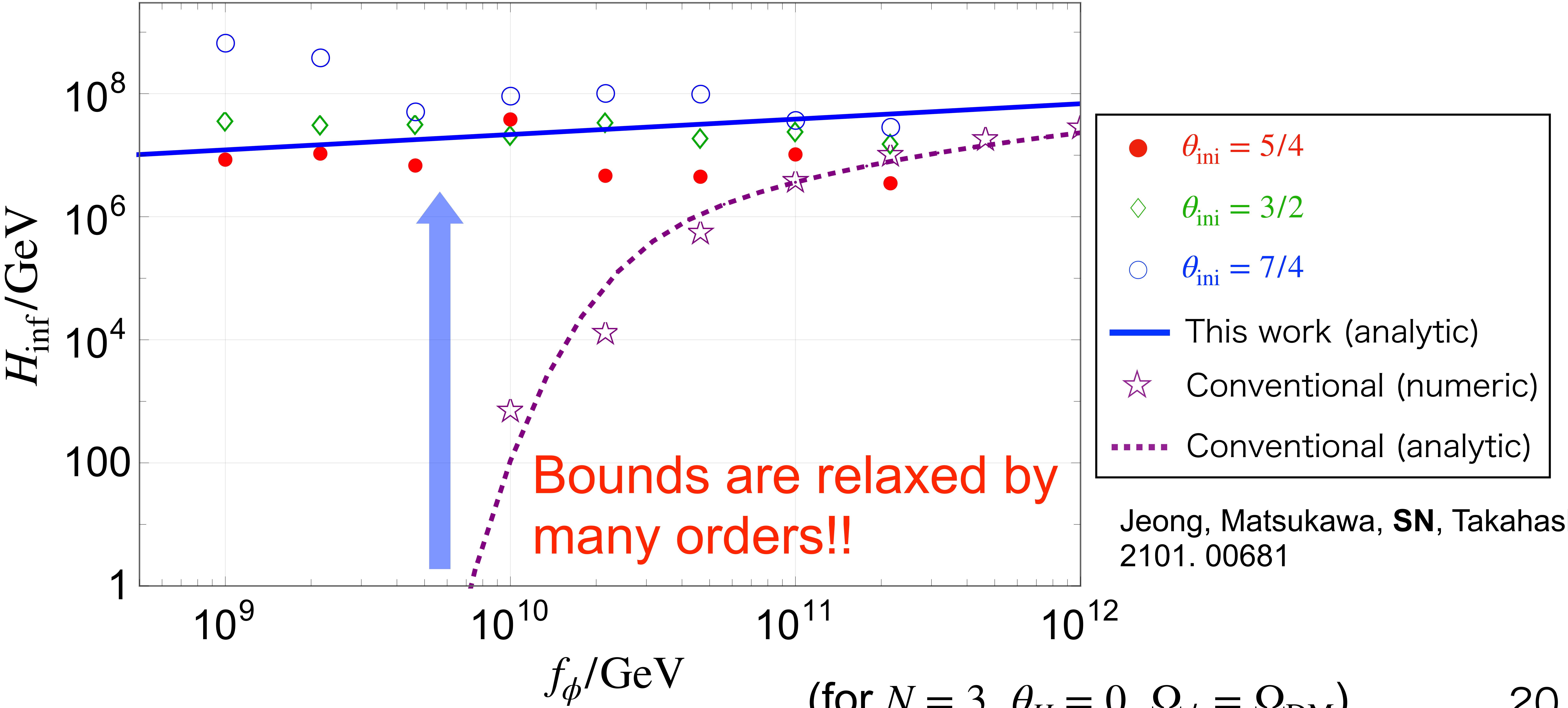
The axionic fluctuation is redshifted after the axion oscillation, $\delta\phi \propto a^{-3/2}$.

$$\delta\theta_{\rm osc2} \simeq \left(\frac{a_{\rm osc}}{a_{\rm osc2}}\right)^{3/2} \delta\theta_{\rm ini} \simeq \left(\frac{T_{\rm osc2}}{T_{\rm osc}}\right)^{3/2} \delta\theta_{\rm ini} \propto r^{-\frac{8}{b}-4}$$

$$\Rightarrow \Delta_S^2 \simeq \left(R_\phi \frac{\partial \ln \Omega_\phi}{\partial \theta_{\rm osc2}} \underline{\left(\frac{T_{\rm osc2}}{T_{\rm osc}}\right)^{\frac{3}{2}}} \frac{H_{\rm inf}}{2\pi f_\phi} \right)^2.$$



Isocurvature bounds on H_{inf}



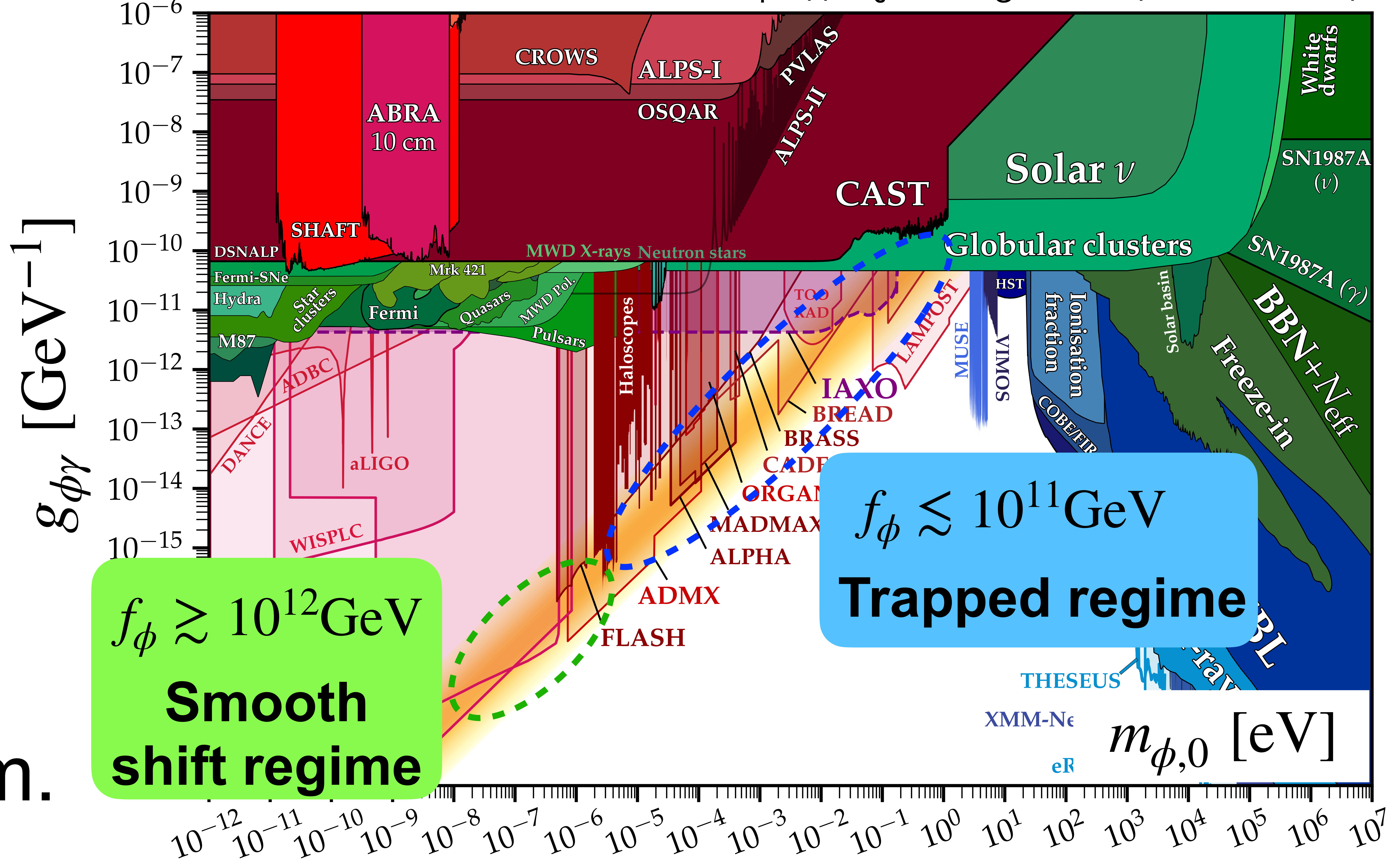
Jeong, Matsukawa, **SN**, Takahashi
2101. 00681

(for $N = 3$, $\theta_H = 0$, $\Omega_\phi = \Omega_{\mathrm{DM}}$)

5. Summary

- We studied the effects of extra PQ symmetry breaking on the QCD axion DM.
- $\Omega_\phi h^2$ increases with r.
- DM can be explained for arbitrary $f_\phi \lesssim 10^{11}\mathrm{GeV}$ if taken $r \sim 0.01$.
- No isocurvature problem.

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



For your interest

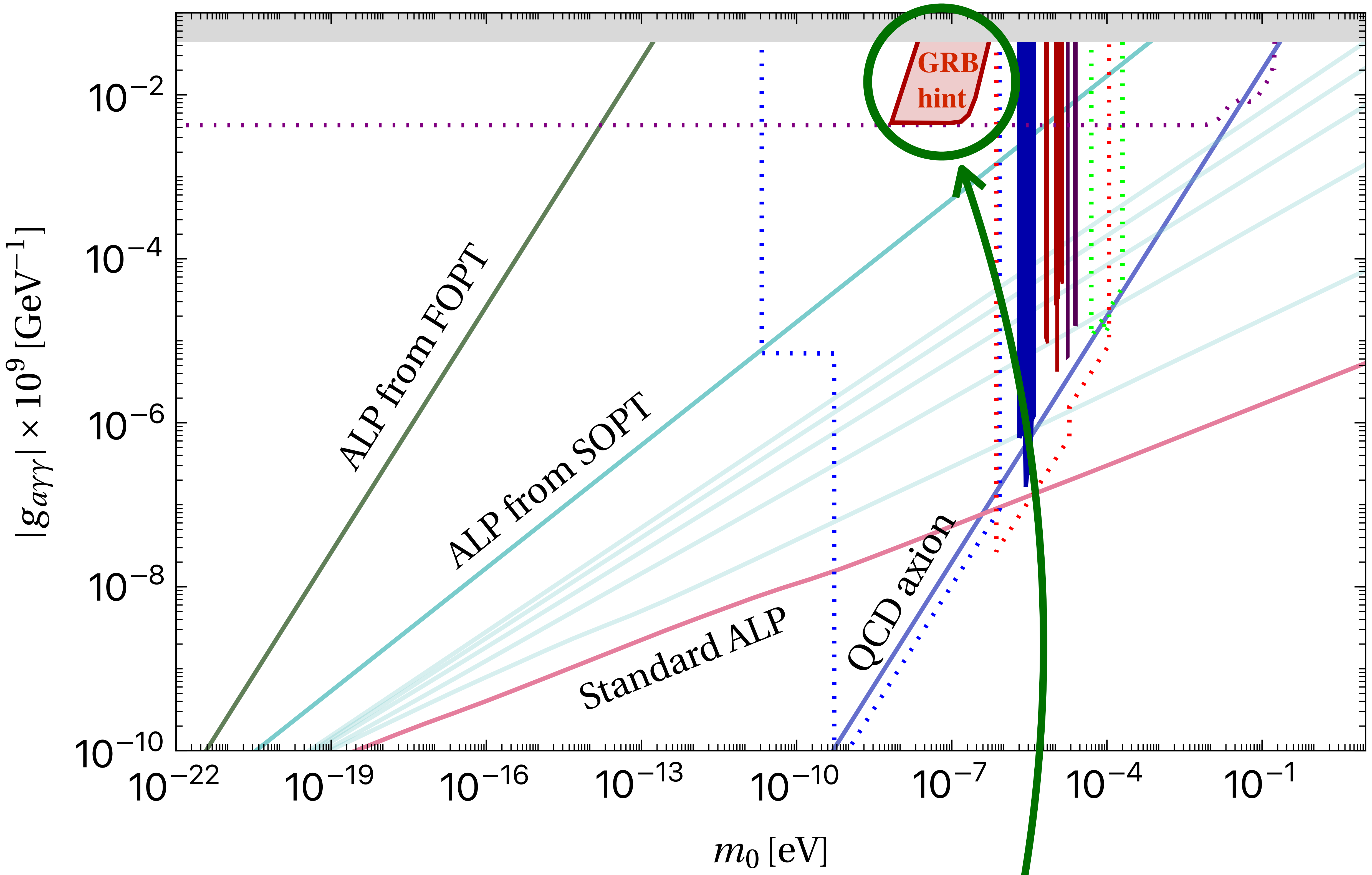
物理学会春季大会

3/24 (金) 11:00~11:15

「１次相転移に伴うアクシオン暗黒物質」

PLB 839 (2023) 137824 [2210.10022]

SN, F. Takahashi, M. Yamada, and W. Yin



High energy photon
from GRB221009A

Thanks.