Sep. 25 2019

Axion and Inflation

International workshop on
New Physics at the Low Energy Scales
NEPLES-2019@KIAS (Sep.23-27 2019)

Fumi Takahashi
(Tohoku)

Ryuji Daido, FT, Wen Yin, arXiv:1702.03284, JCAP 1705 (2017) 044 , FT, Wen Yin, Alan H. Guth, arXiv:1805.08763, Phys.Rev. D98 (2018) no.1, 015042 FT, Wen Yin, arXiv:1908.06071, to appear on JHEP

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QCD Axion Dark Matter and Low-scale Inflation

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Introduction

The axion DM is produced as coherent oscillations by the misalignment mechanism.

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

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

$$\Omega_a h^2 \simeq 0.12\, \theta_i^2 F(\theta, f_a) \left(\frac{f_a}{9 \times 10^{11}\, \mathrm{GeV}} \right)^{1.165}$$

↑ Anharmonic effect

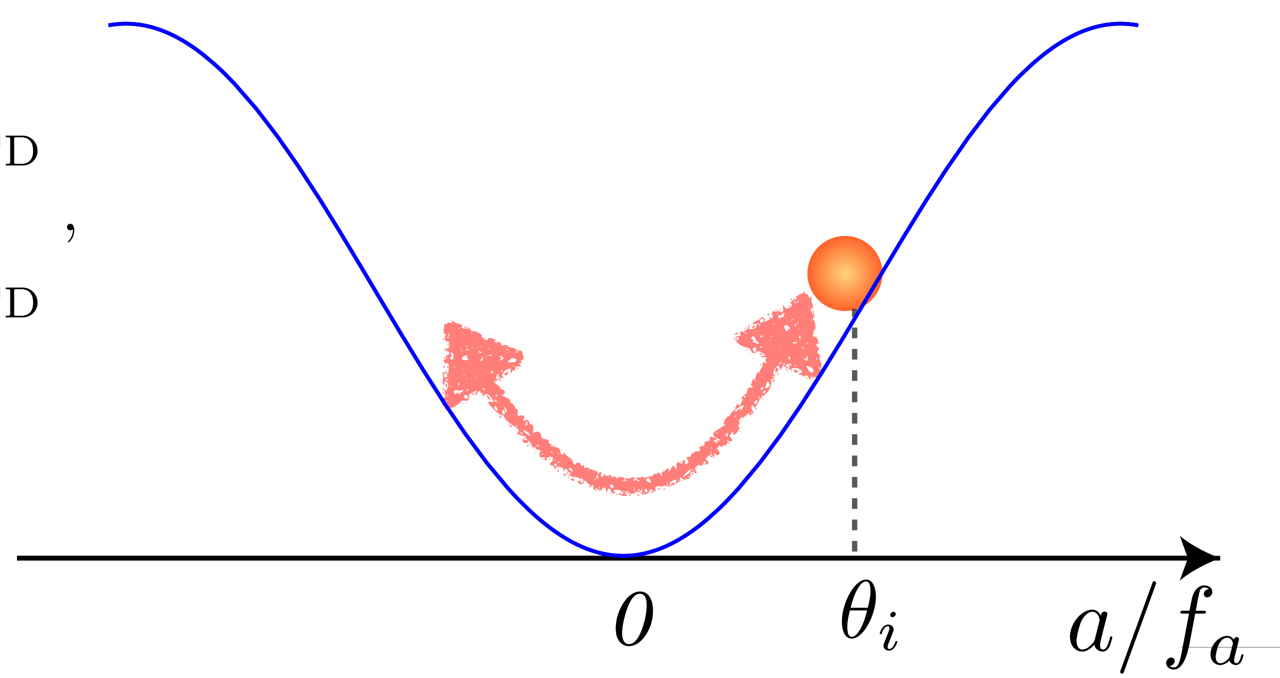
Bae, Huh, Kim `08, Wantz and Shellard, `10

Borsanyi et al., `16, Ballesteros et al `17

$$m_a(T) \simeq \begin{cases} \frac{\sqrt{\chi_0}}{f_a} \left(\frac{T_{\rm QCD}}{T} \right)^n & T \gtrsim T_{\rm QCD} \\ 5.7 \times 10^{-6} \left(\frac{10^{12}\mathrm{GeV}}{f_a} \right) \mathrm{eV} & T \lesssim T_{\rm QCD} \end{cases},$$

$n \simeq 4.08 \quad T_{\rm QCD} \simeq 153\mathrm{MeV}$

$\chi_0 \simeq (75.6\mathrm{MeV})^4$

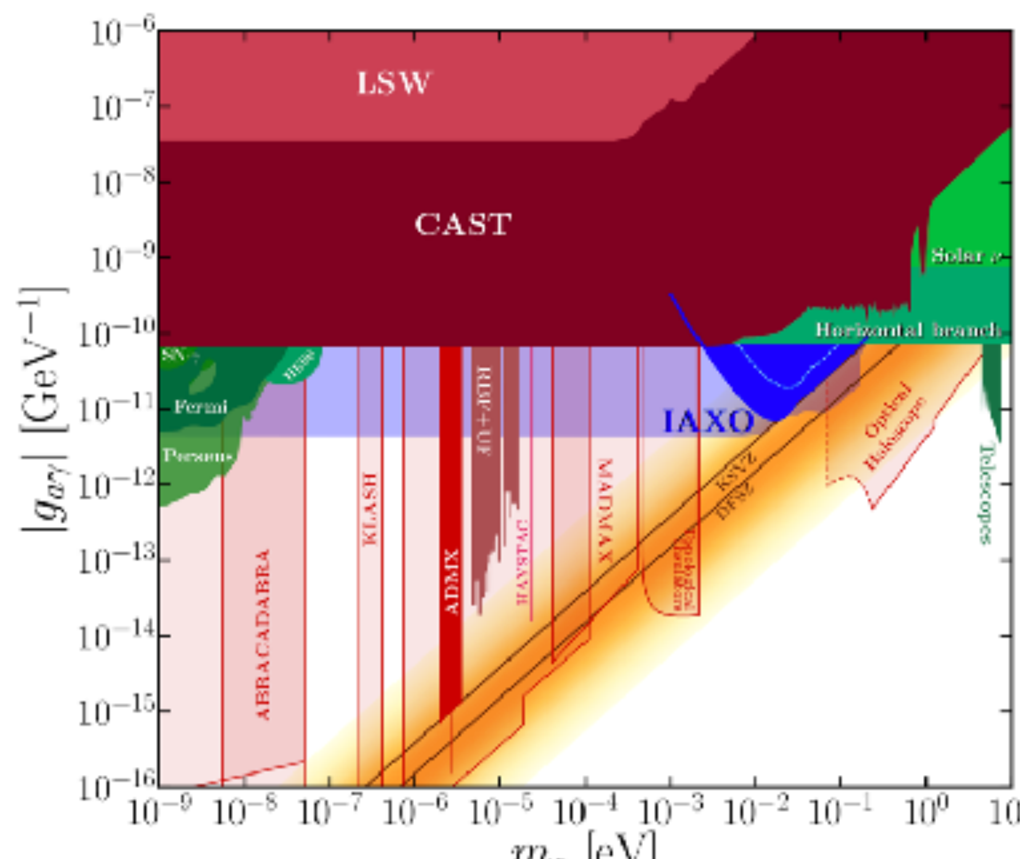


Classical axion window:

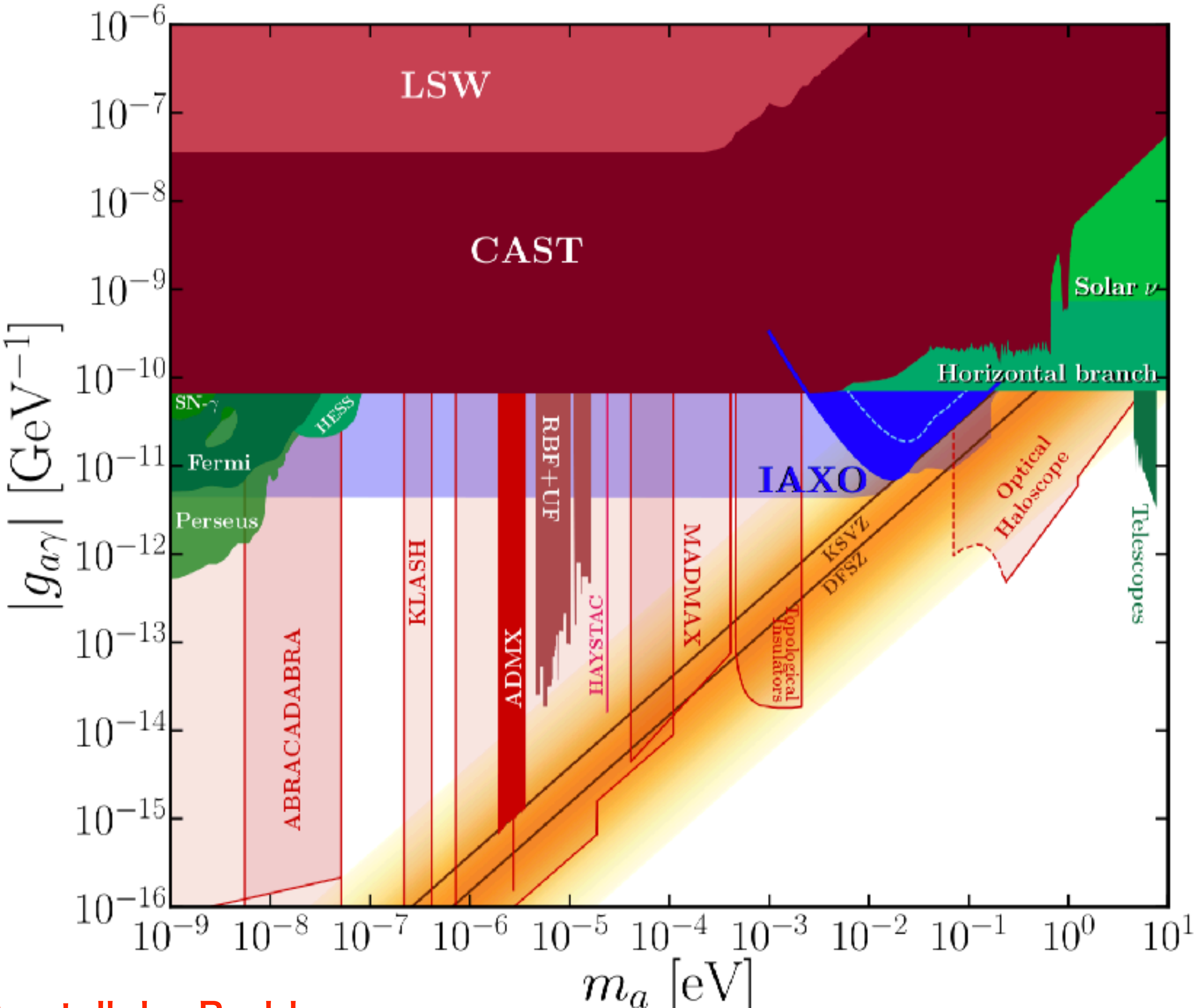
$$10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

Preskill, Wise, Wilczek `83, Abbott, Sikivie `83, Dine, Fischler `83
Mayle et al `88, Raffelt and Seckel `88, Turner 88.

For the initial angle $\theta_i \sim 1$, the observed DM is explained for $f_a \sim 10^{12}\,\mathrm{GeV}$ and $m_a \sim 10\,\mu\mathrm{eV}$

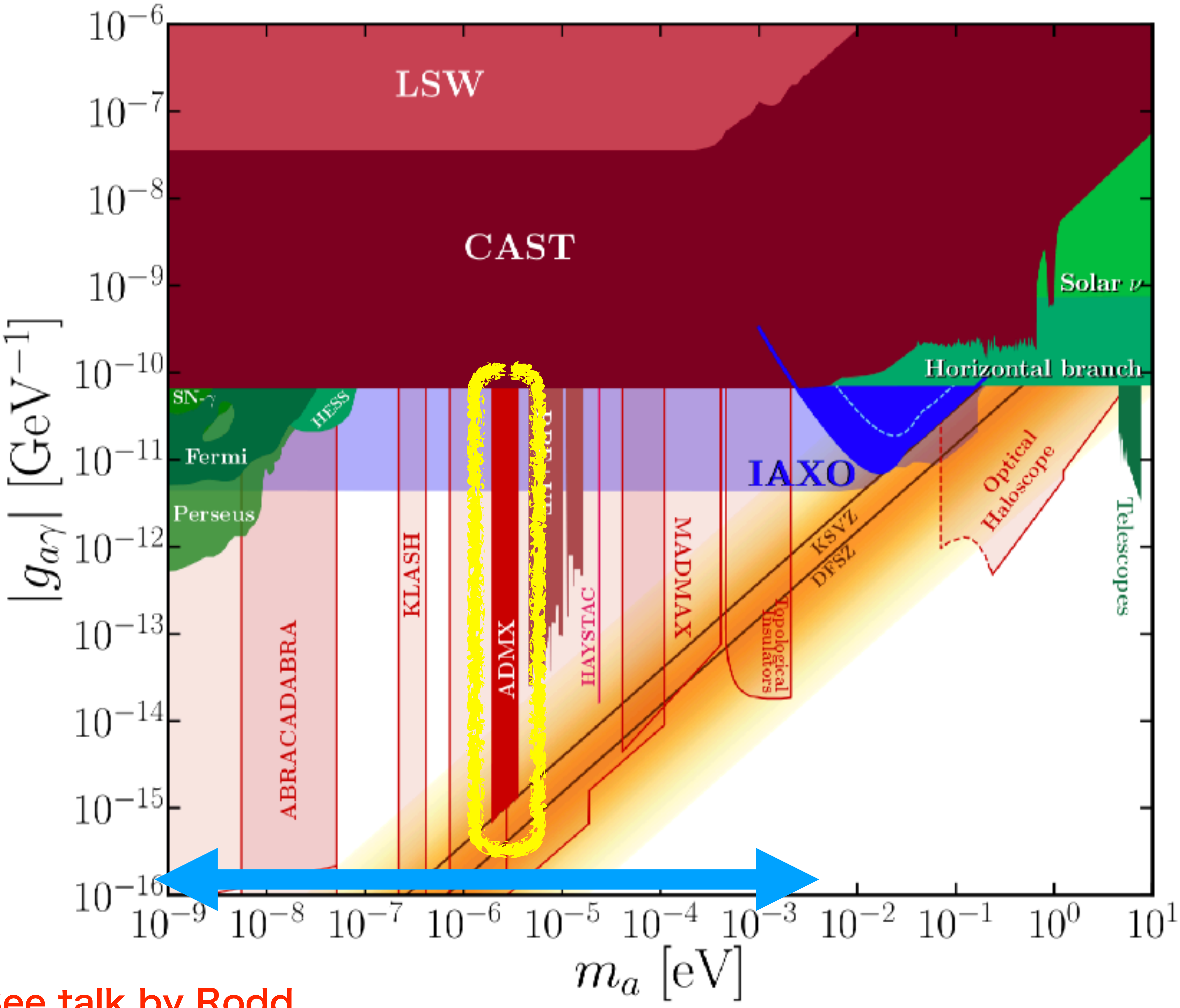


from Dafini et al ,1811.09290



See talk by Rodd

from Dafini et al ,1811.09290



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For the initial angle $\theta_i \sim 1$, the observed DM is explained for $f_a \sim 10^{12}\,\mathrm{GeV}$ and $m_a \sim 10\,\mu\mathrm{eV}$

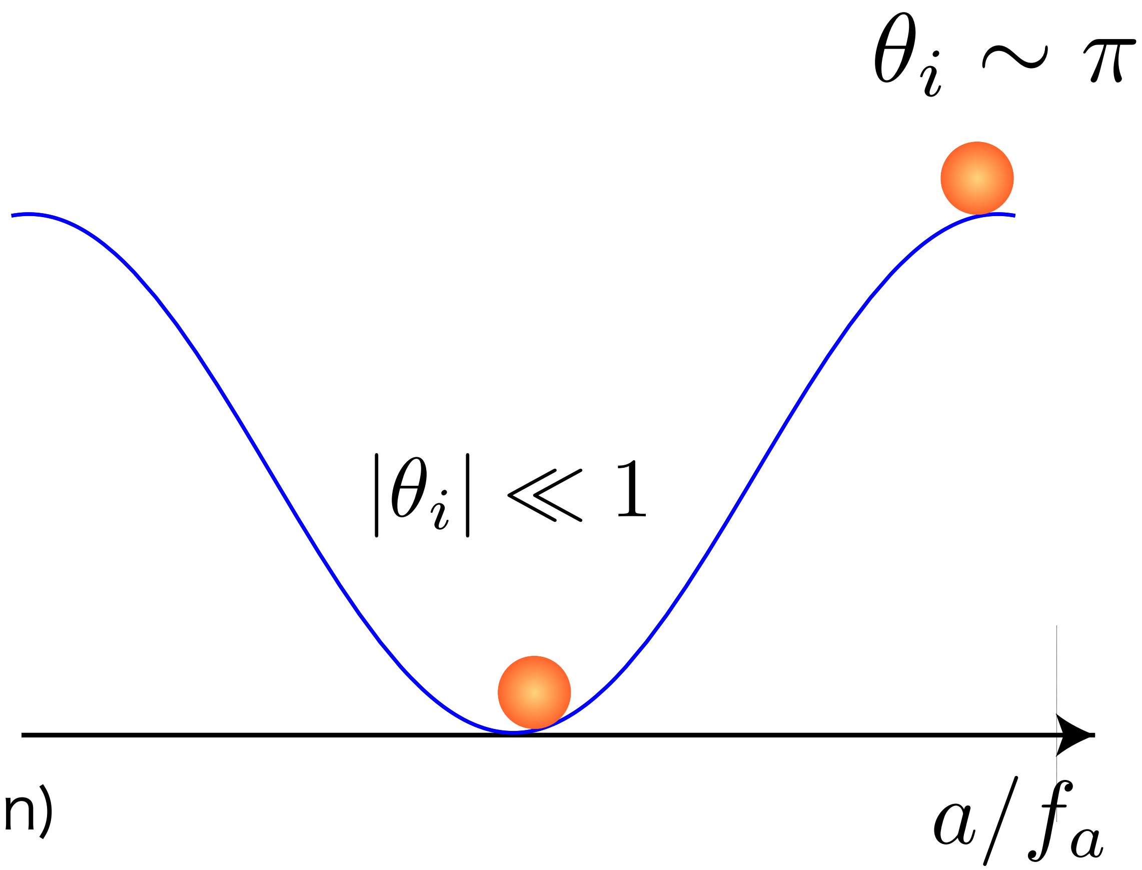
Otherwise, the initial angle needs to be tuned as

$|\theta_i| \ll 1$ for $f_a \gg 10^{12}\,\mathrm{GeV}$

$\theta_i \sim \pi$ for $f_a \ll 10^{12}\,\mathrm{GeV}$

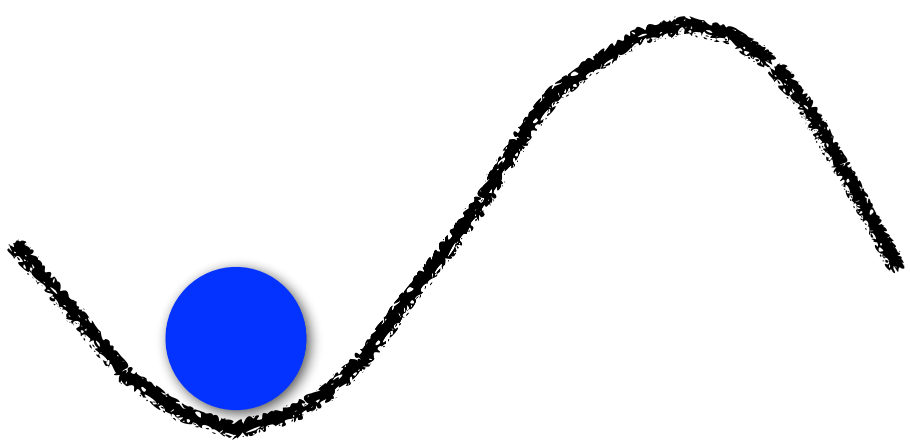
to explain DM.

(The PQ symmetry is assumed to be broken)



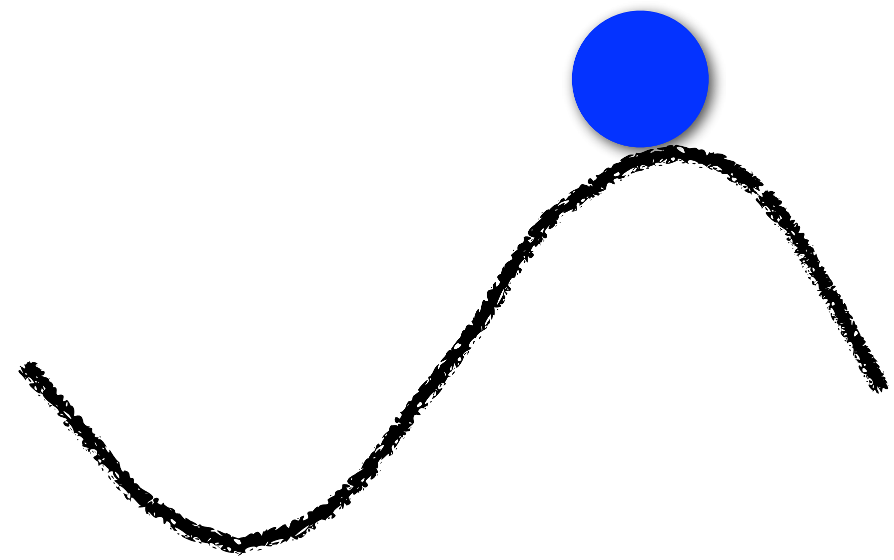
What we did:

We have shown that the initial angle $\theta_i \sim 0$ or π can be dynamically realized in certain low-scale inflation models.



$$|\theta_i| \ll 1$$

FT, Wen Yin, Alan H. Guth, arXiv:1805.08763

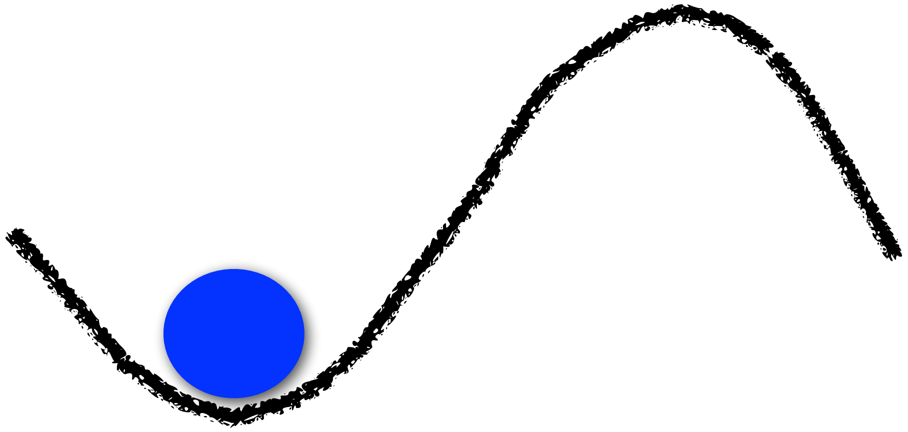


$$\theta_i \sim \pi$$

Ryuji Daido, FT, Wen Yin, arXiv:1702.03284, FT, Wen Yin, arXiv:1908.06071

Here we assume that the QCD scale remains the same during inflation. cf. Co, Gonzalez, and Harigaya 1812.11192,1812.11186.

For stronger QCD, see Dvali \`95, Banks and Dine \`97, K.Choi, H.B. Kim, J. E. Kim \`97, Jeong, FT \`13



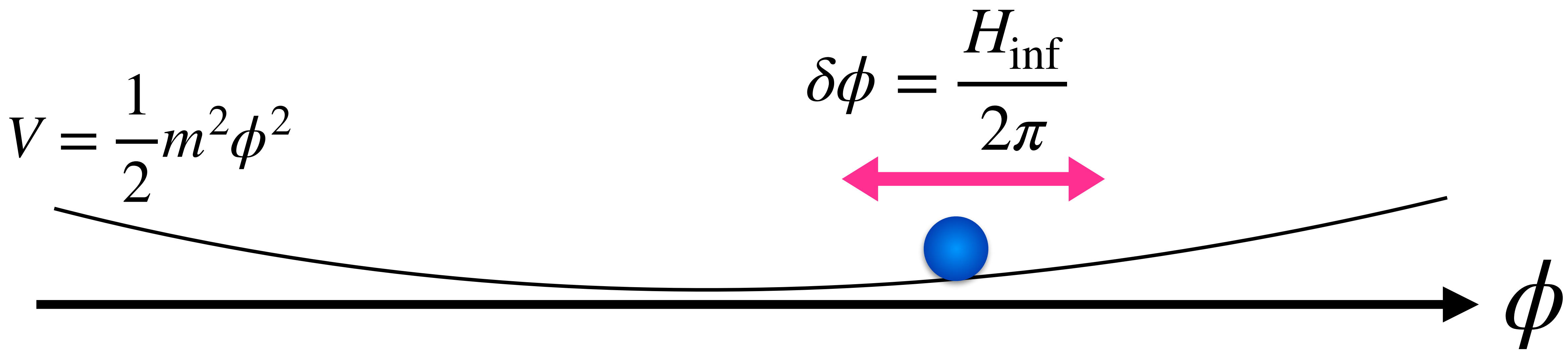
$$|\theta_i| \ll 1$$

Peter W. Graham, Adam Scherlis, 1805.07362,
FT, Wen Yin, Alan H. Guth, 1805.08763

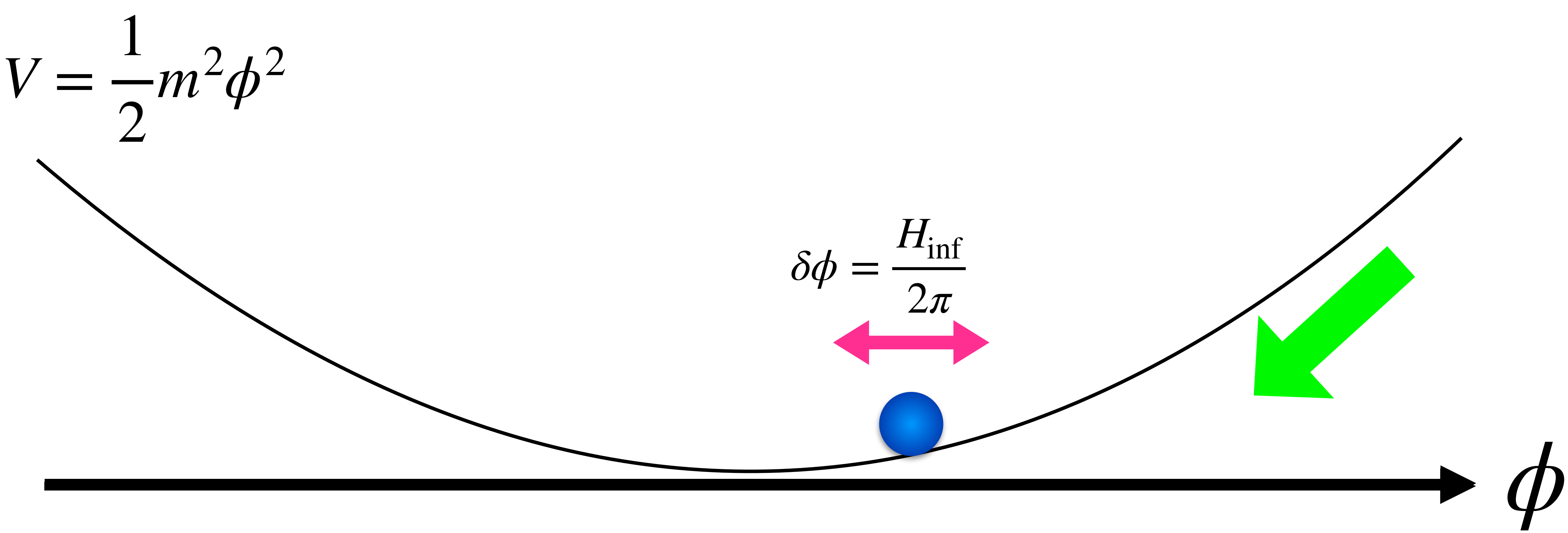
Consider a general light scalar during inflation with

$$m \ll H_{\rm inf}$$

Then, the scalar acquires a quantum fluctuation. Even if it initially sits near the minimum, it soon goes away due to the fluctuations.



However, this does not continue forever. In the end, quantum dissipation is balanced by the classical motion. If the inflation lasts sufficiently long, it reaches equilibrium.



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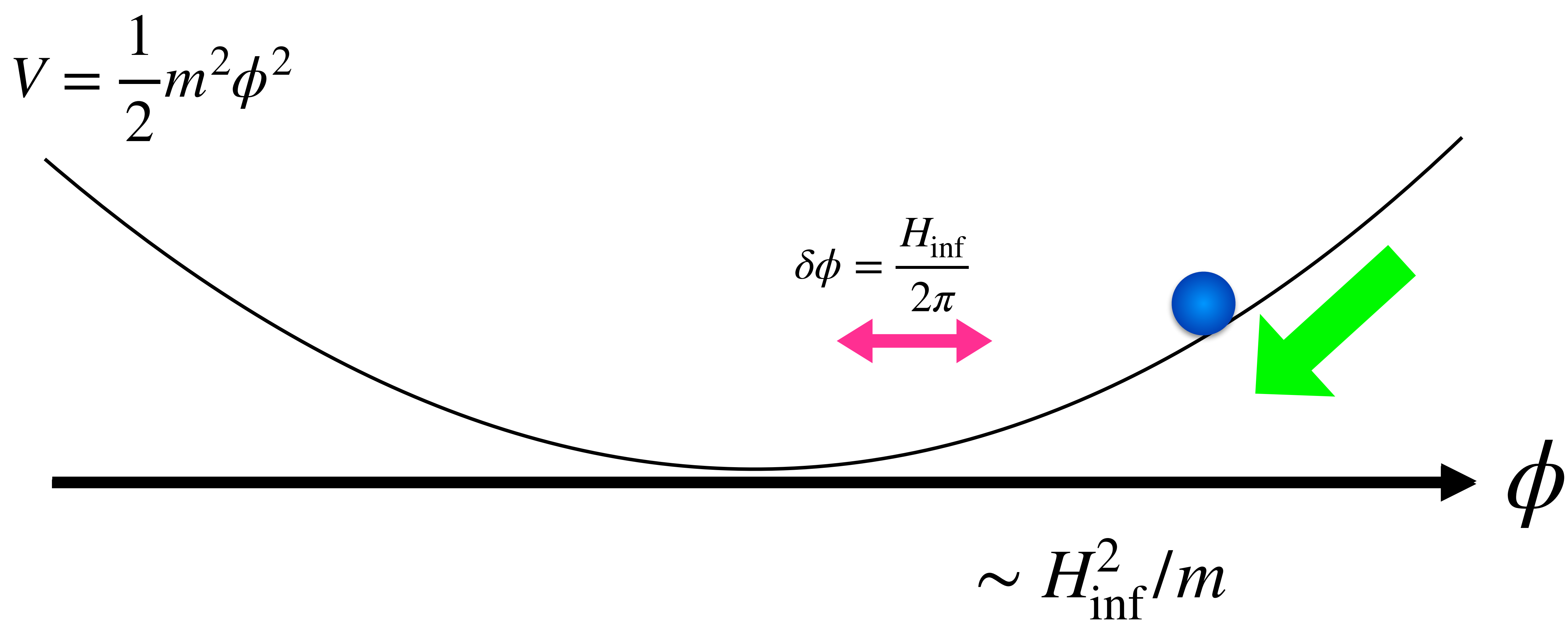

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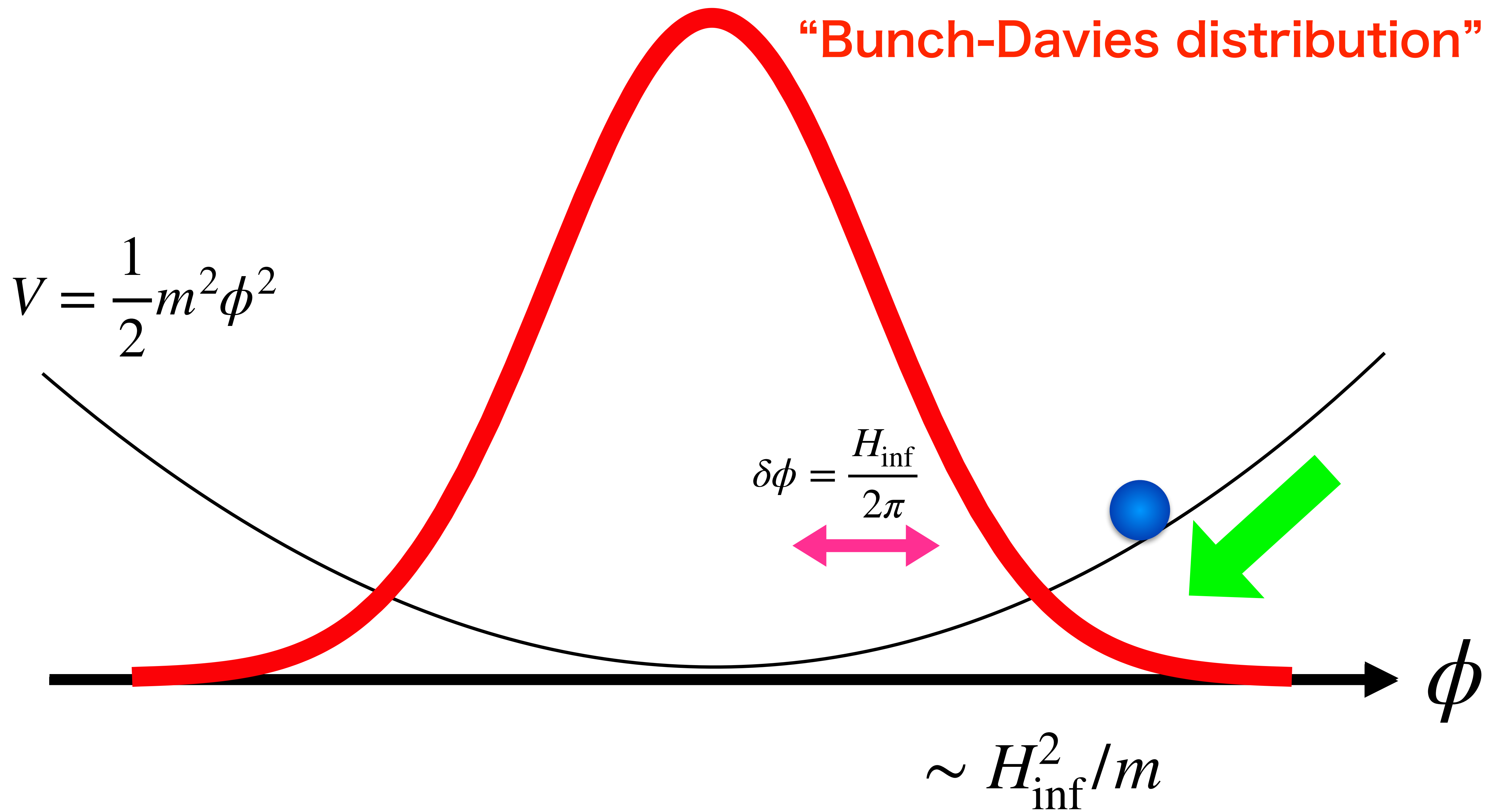


Bunch-Davies distribution

Bunch and Davies `78

The prob. distribution reaches equilibrium if the number of e-folds satisfies $N \gtrsim H_{\rm inf}^2/m^2$.

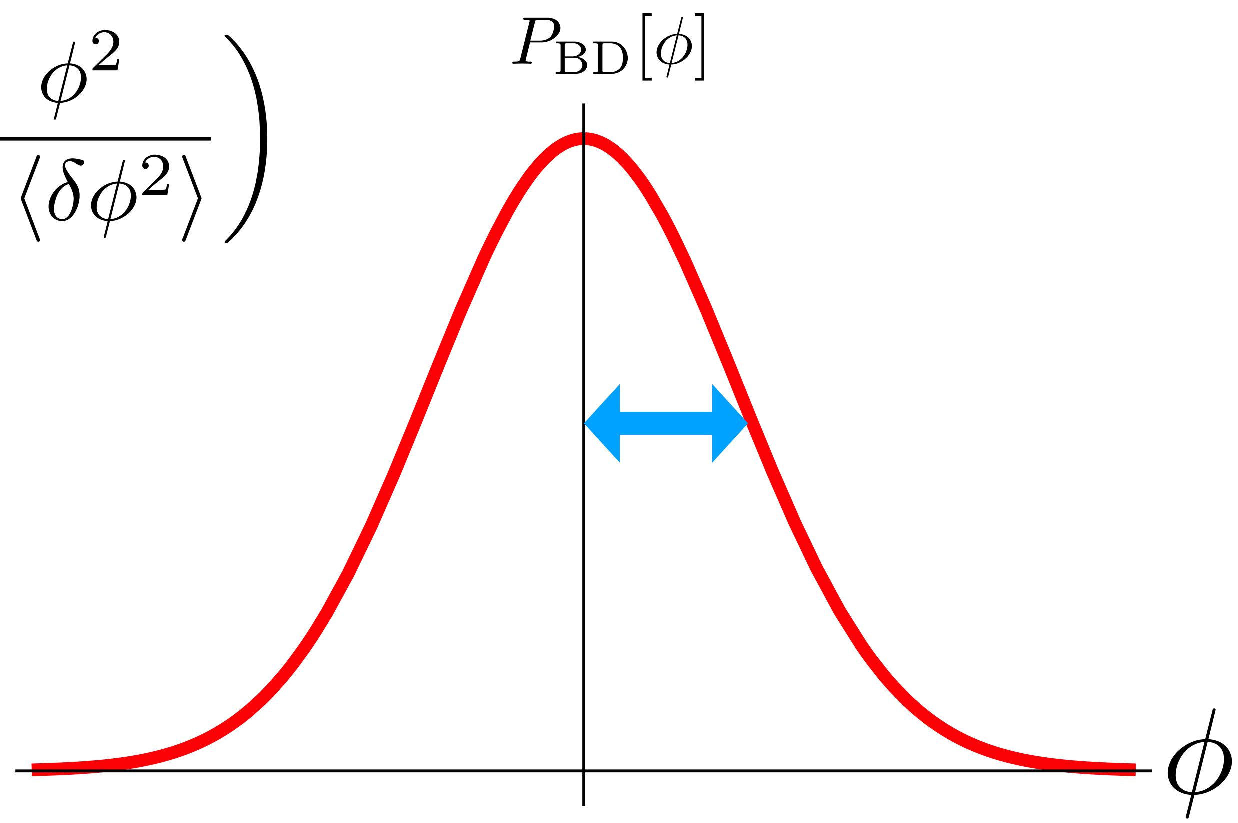
It is a Gaussian peaked at the potential min.

(The potential is assumed to be a quadratic one near the min.)

$$P_{\rm BD}[\phi] = \frac{1}{\sqrt{2\pi \langle \delta\phi^2 \rangle}} \exp\left(-\frac{\phi^2}{2\langle \delta\phi^2 \rangle}\right)$$

with

$$\sqrt{\langle \delta\phi^2 \rangle} = \sqrt{\frac{3}{8\pi^2}} \frac{H_{\rm inf}^2}{m}$$



A light scalar knows where its minimum is.

The QCD axion mass is temperature dependent.

$$m_a = m_a(T_{\rm inf}) \ \text{with} \ T_{\rm inf} = \frac{H_{\rm inf}}{2\pi}$$

: Gibbons-Hawking temperature

For $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$, the typical initial angle is

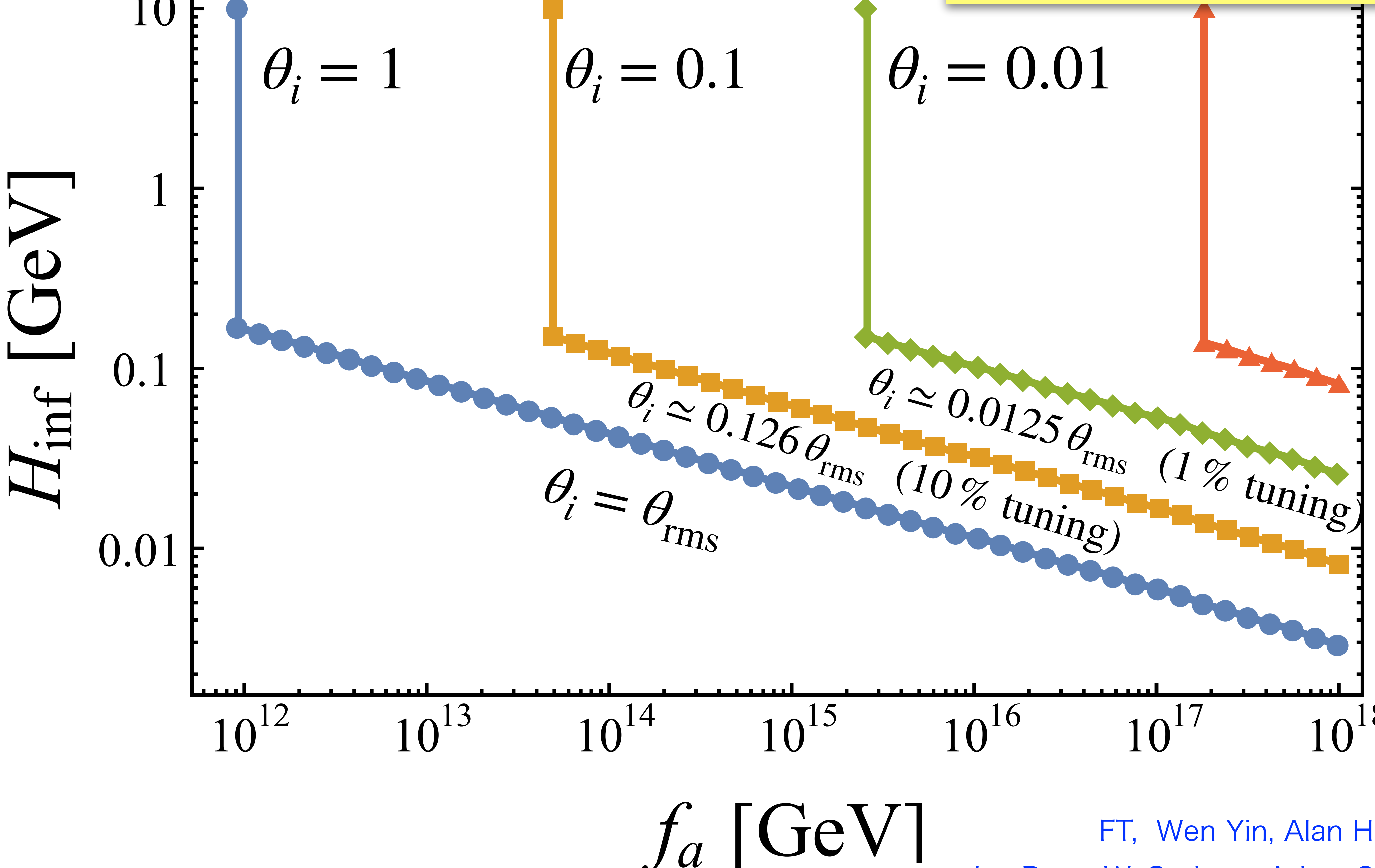
$$\theta_i \sim \frac{H_{\rm inf}^2}{m_a(T_{\rm inf}) f_a}$$

which can be much smaller than unity.

The upper bound of the QCD axion window can be relaxed if $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

Assumptions:

- Long inflation $N \gg H_{\rm inf}^2/m^2$
- No extra contribution to θ.



FT, Wen Yin, Alan H. Guth, 1805.08763

see also Peter W. Graham, Adam Scherlis, 1805.07362,

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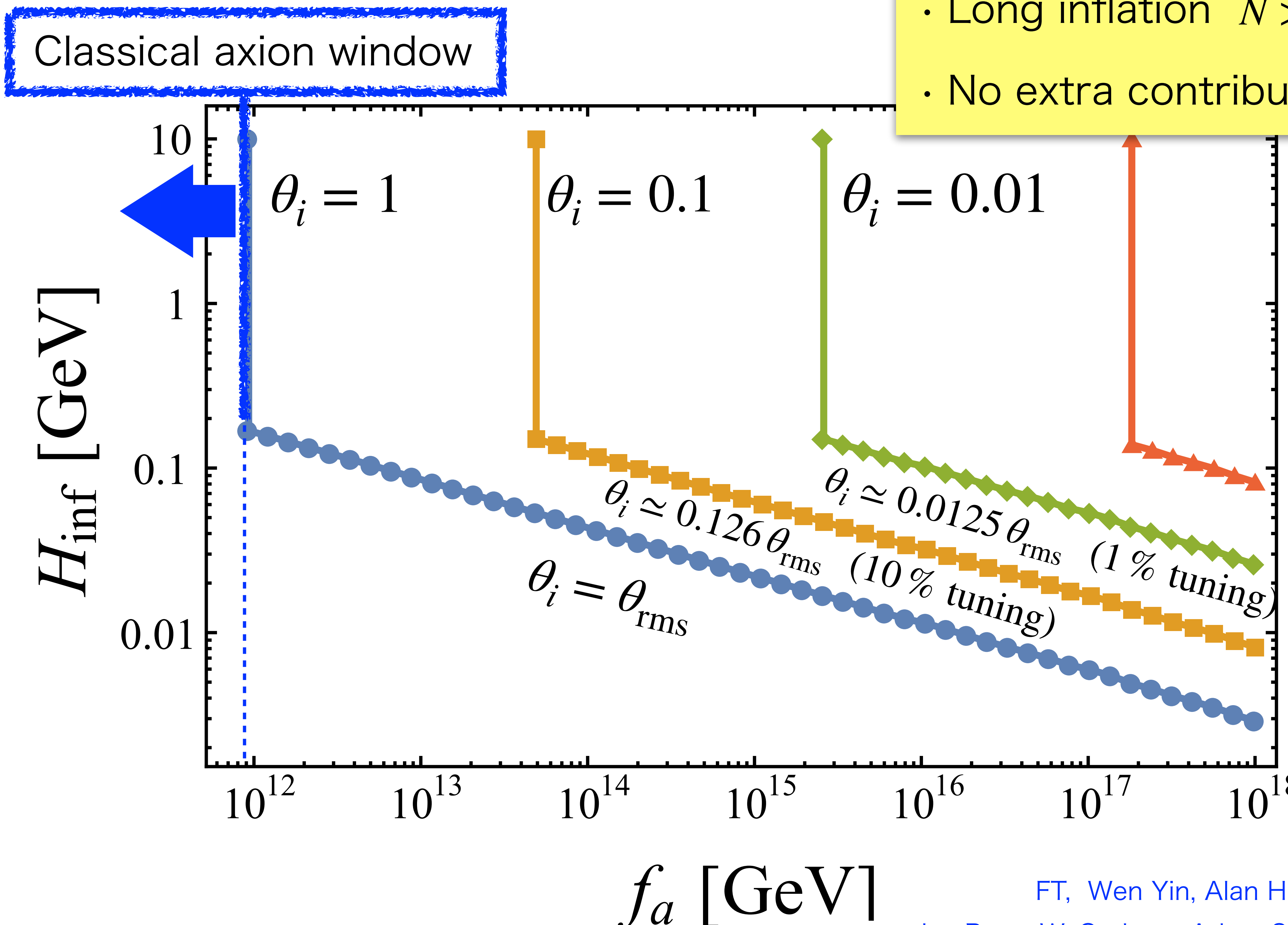

FT, Wen Yin, Alan H. Guth, 1805.08763

see also Peter W. Graham, Adam Scherlis, 1805.07362,

The upper bound of the QCD axion window can be relaxed if $H_{\inf} \lesssim \Lambda_{QCD}$.

Assumptions:

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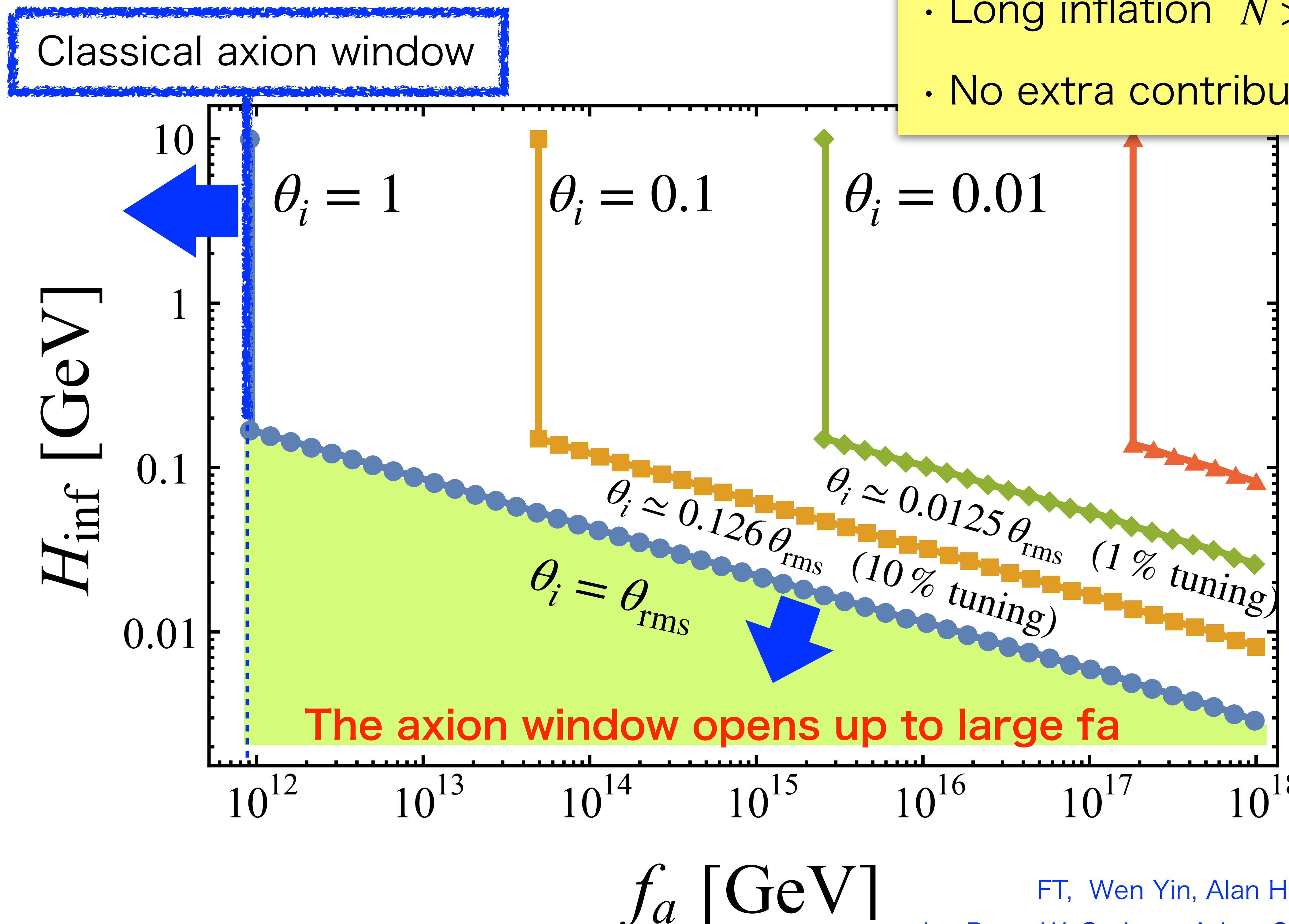
- No extra contribution to θ.



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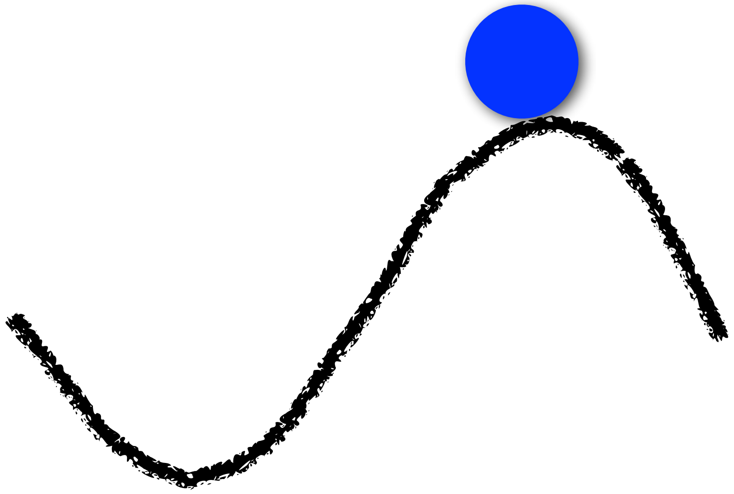


$$\theta_i \sim \pi$$

Ryuji Daido, FT, Wen Yin, 1702.03284,
FT and Wen Yin, 1903.00462,1908.06071

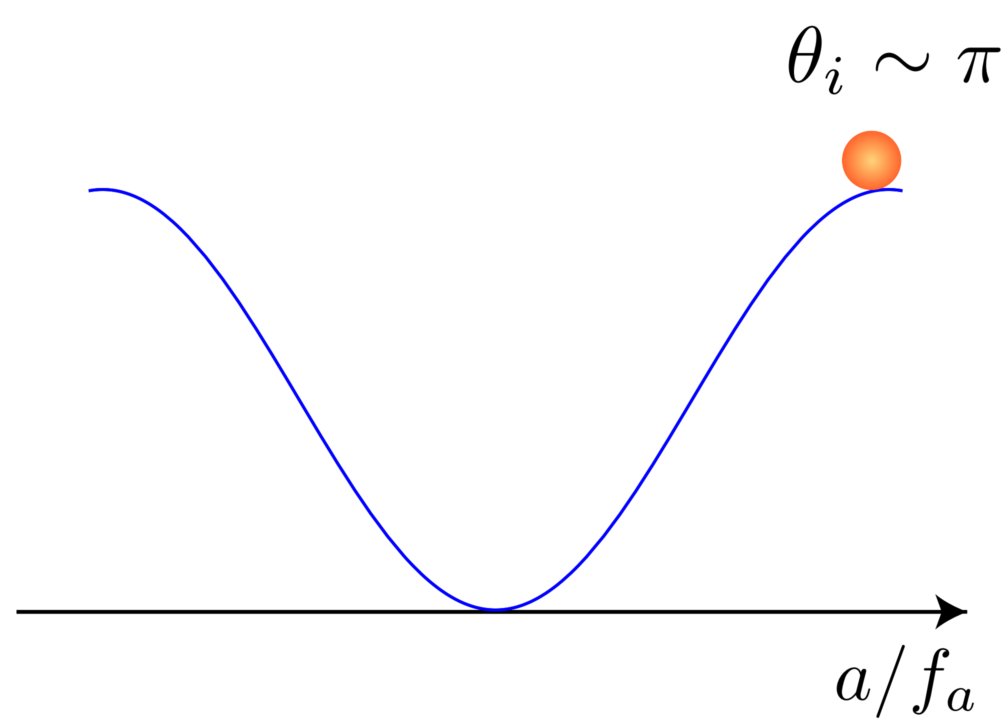
The axion abundance increases with the initial angle, and it diverges in the hilltop limit:

$$\Omega_a h^2 \simeq 0.12\,\theta_i^2 F(\theta, f_a) \left(\frac{f_a}{9 \times 10^{11}\,\mathrm{GeV}} \right)^{1.165}$$

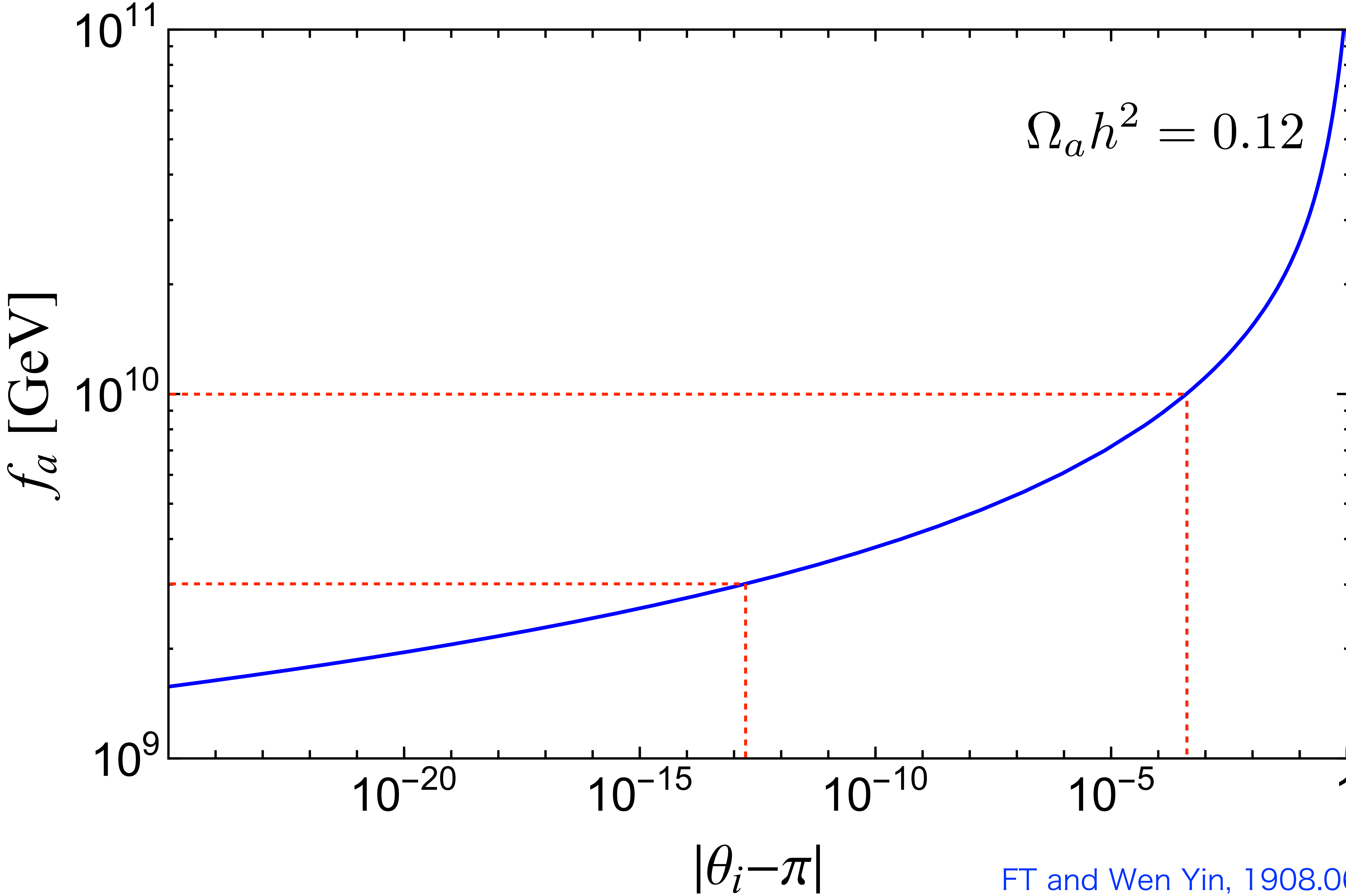
with $$F(\theta) \simeq \left[\log \left(\frac{e}{1 - \frac{\theta_i^2}{\pi^2}} \right) \right]^{1.165}.$$

Lyth `92, Bae, Huh, Kim `08, Visinelli and Gondolo, `09

Thus, the axion abundance becomes extremely sensitive to the initial deviation from π in this limit.



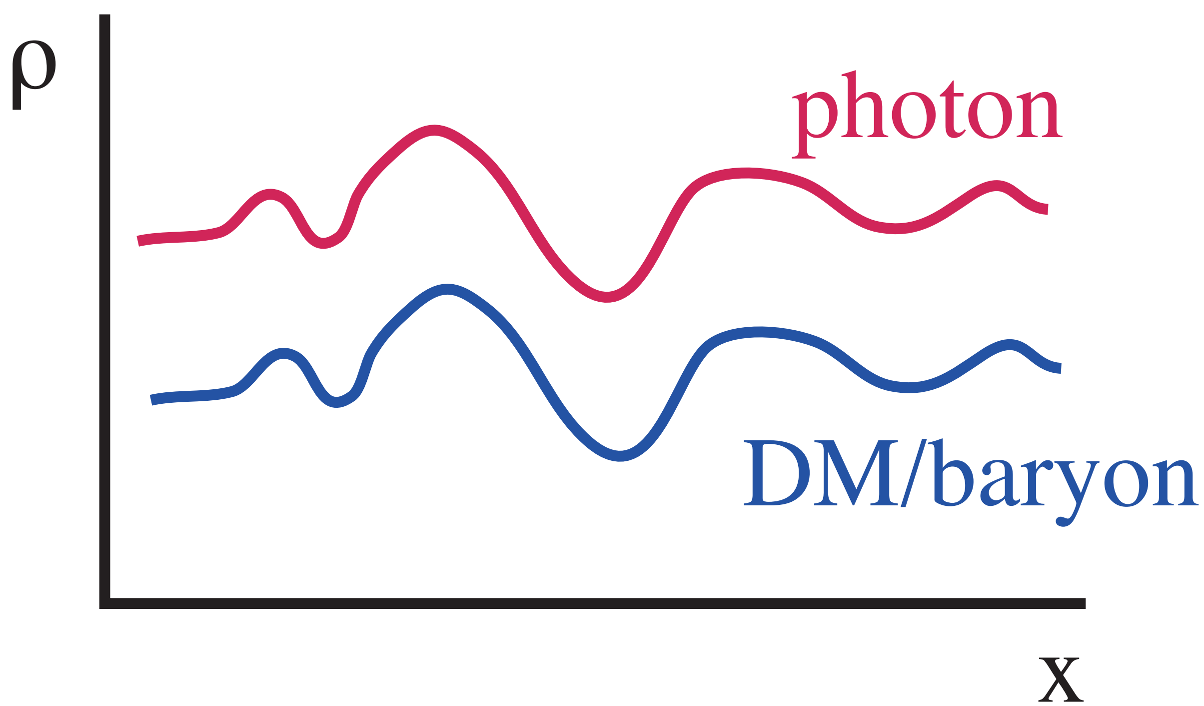
The decay constant and the initial angle



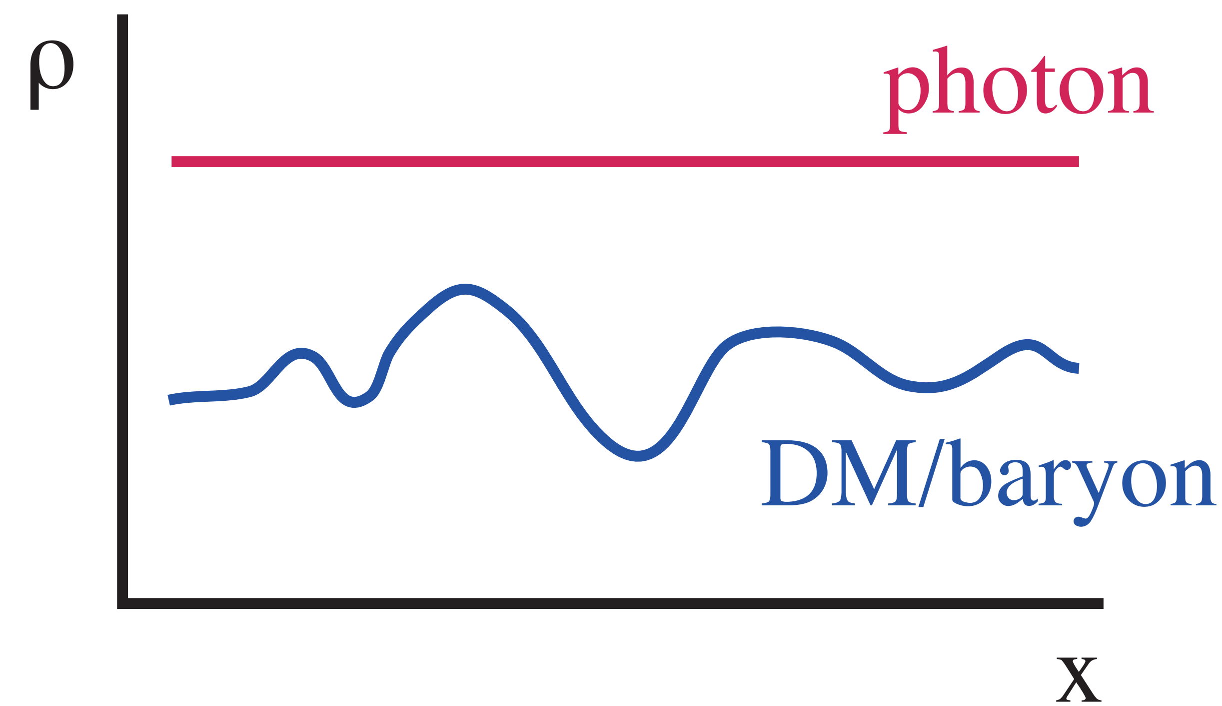
FT and Wen Yin, 1908.06071

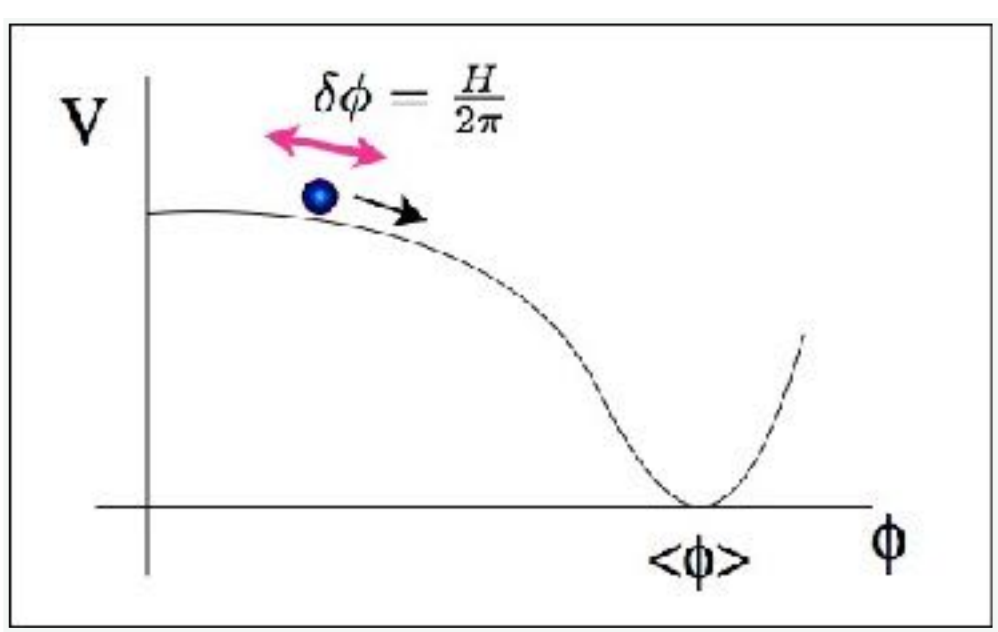
Axion isocurvature perturbations

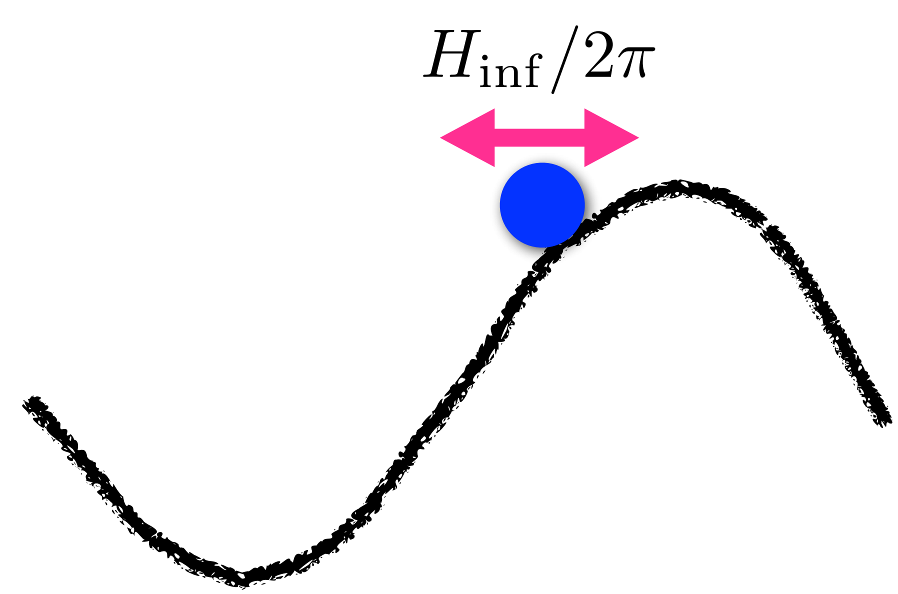
Adiabatic perturbation



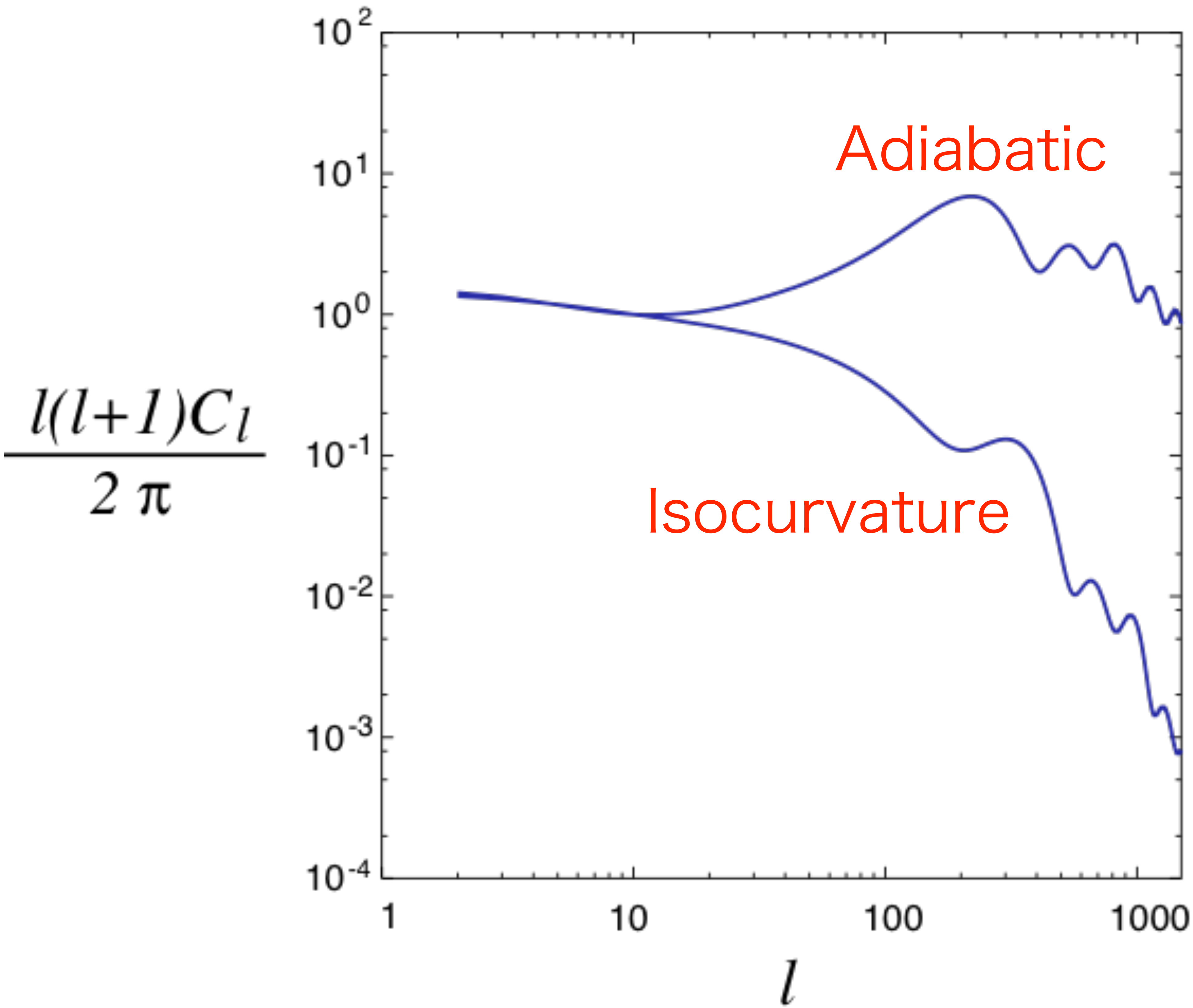
Isocurvature perturbation





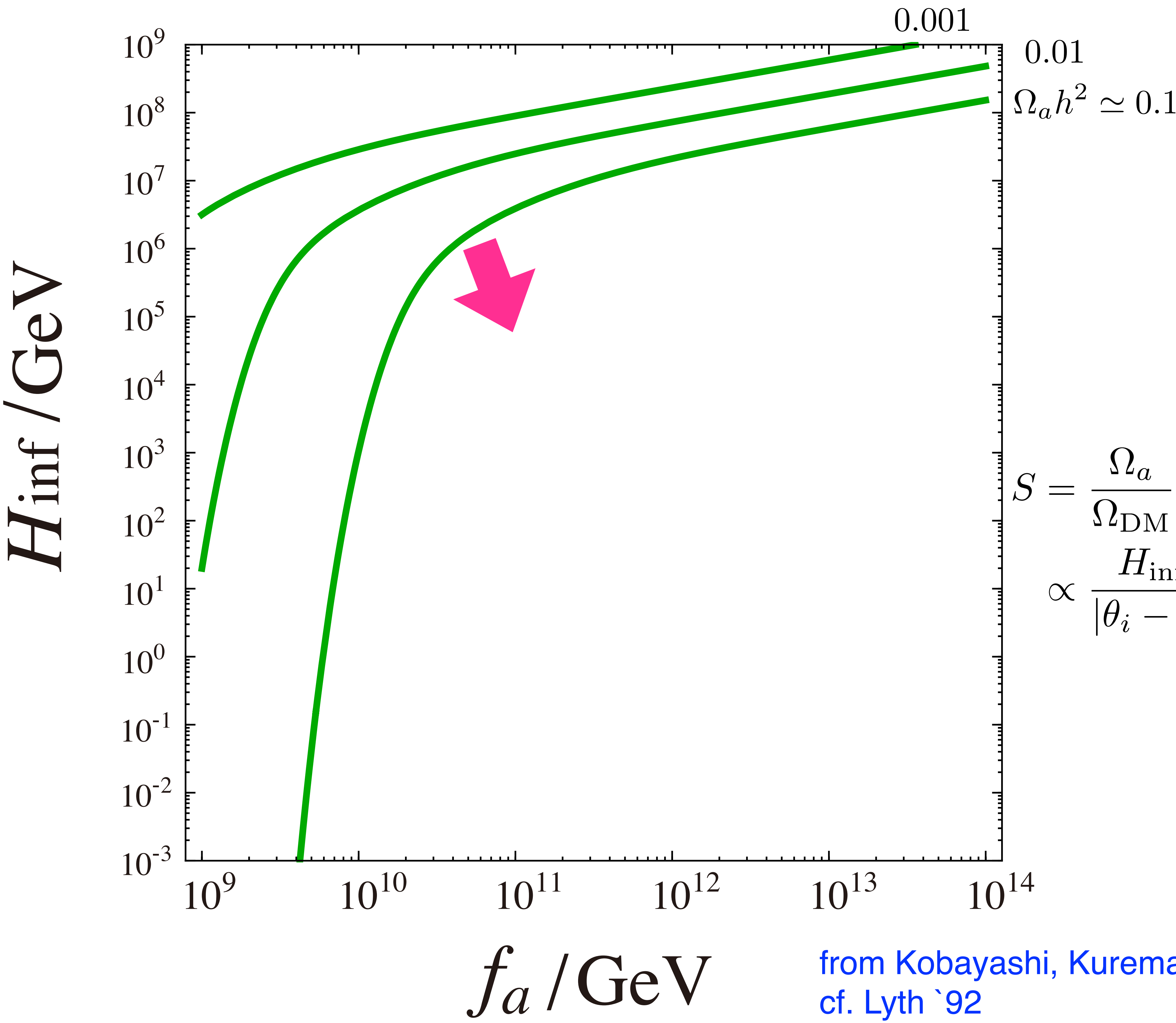


CMB angular power spectrum



(Taken from Kawasaki's slide)

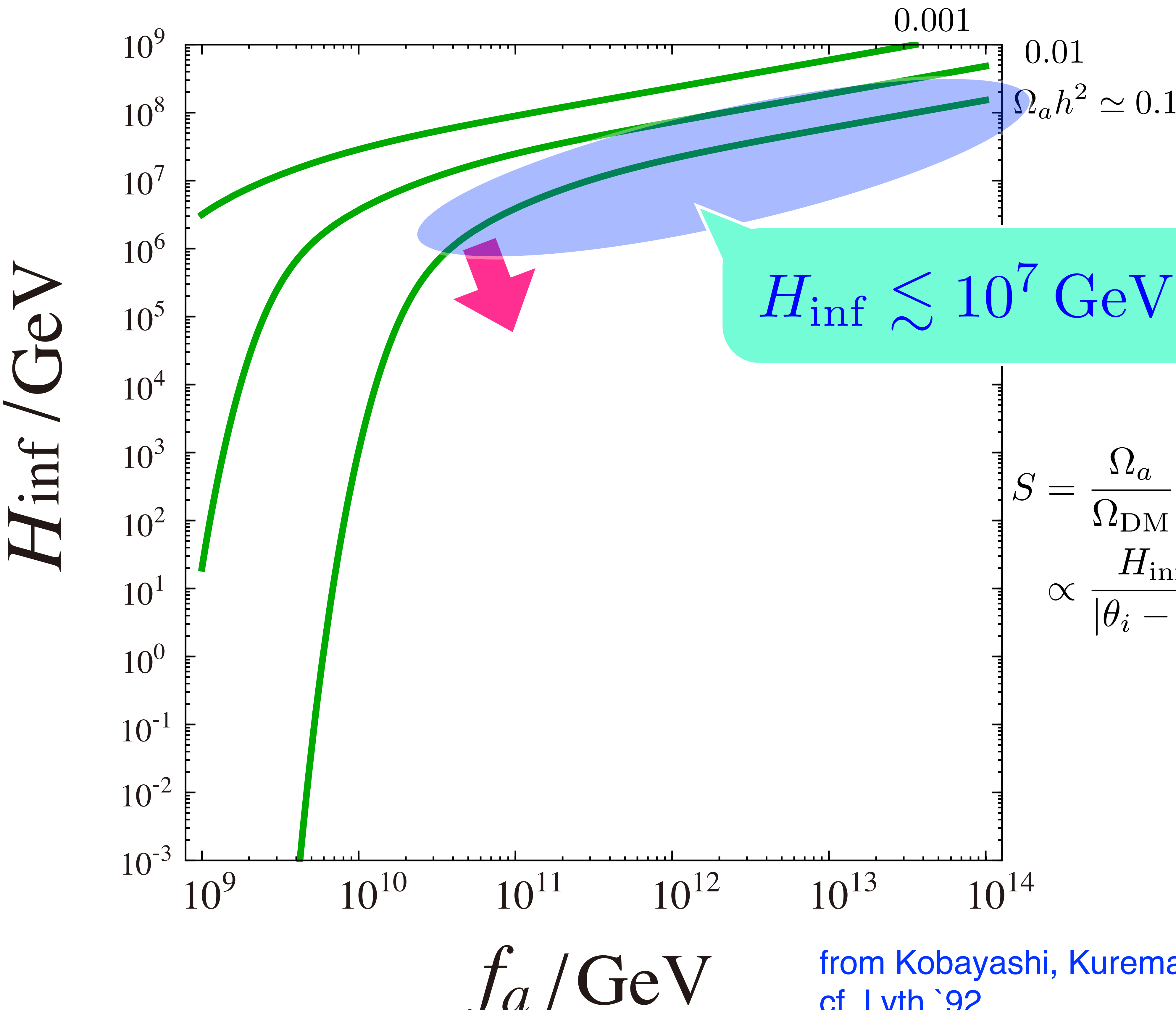
Isocurvature constraint on H_{inf}



$$S = \frac{\Omega_a}{\Omega_{\rm DM}} \frac{H_{\rm inf}}{2\pi f_a} \frac{\partial}{\partial \theta_i} \log\left[\Omega_a(\theta_i)\right]$$
$$\propto \frac{H_{\rm inf}}{|\theta_i - \pi|}$$

from Kobayashi, Kurematsu, FT, 1304.0922,
cf. Lyth `92

Isocurvature constraint on $H_{\rm inf}$



$H_{\rm inf} \lesssim 10^7\,{\rm GeV}$ **for** $\theta_i \sim 1$

$$S = \frac{\Omega_a}{\Omega_{\rm DM}} \frac{H_{\rm inf}}{2\pi f_a} \frac{\partial}{\partial \theta_i} \log\left[\Omega_a(\theta_i)\right]$$

$$\propto \frac{H_{\rm inf}}{|\theta_i - \pi|}$$

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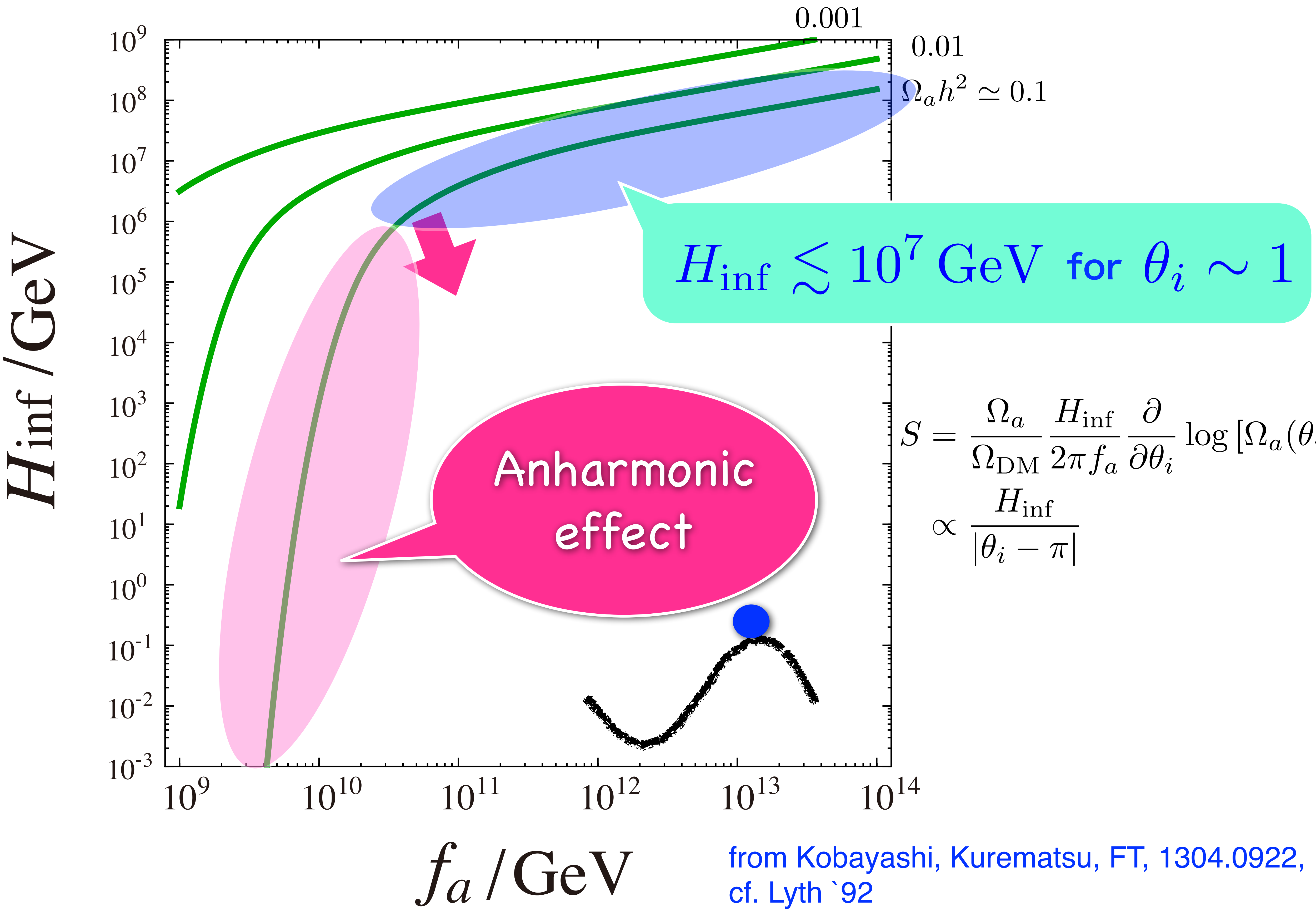

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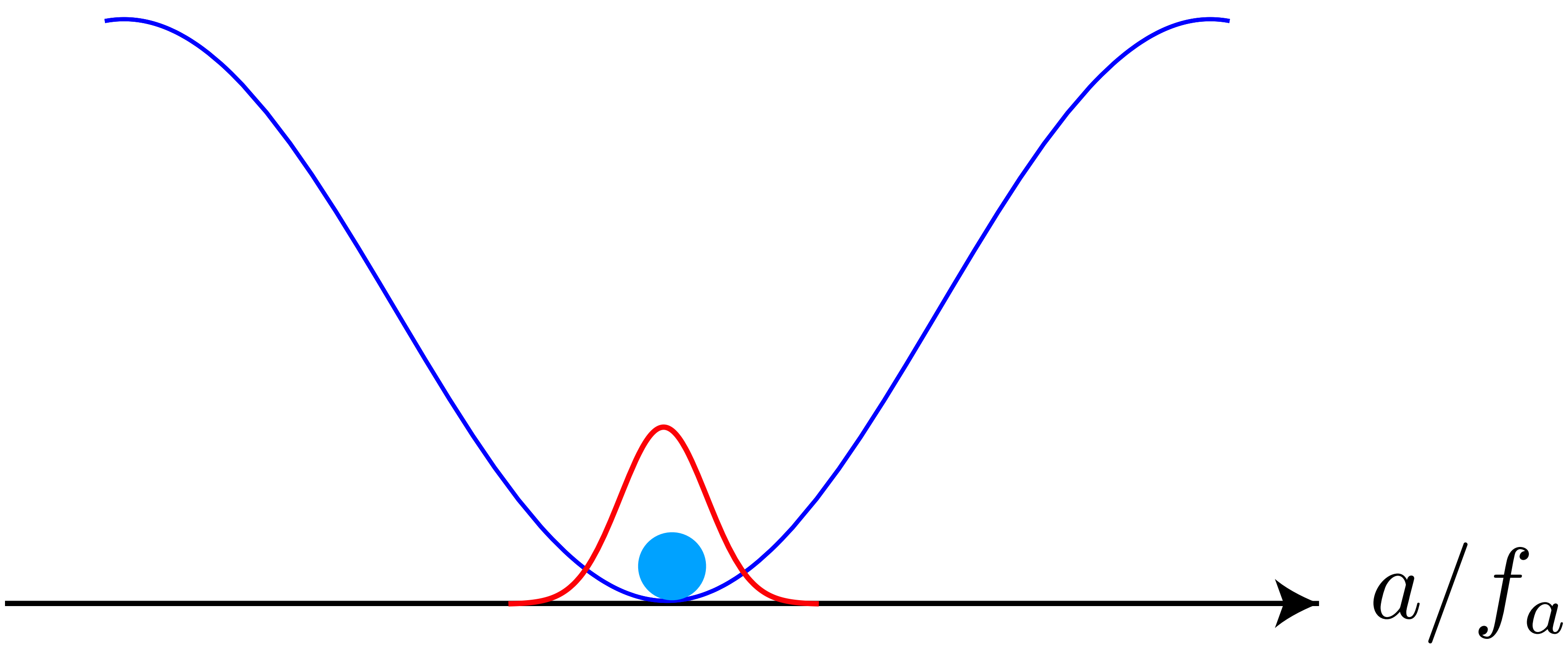
$$\propto \frac{H_{\rm inf}}{|\theta_i - \pi|}$$

from Kobayashi, Kurematsu, FT, 1304.0922, cf. Lyth `92

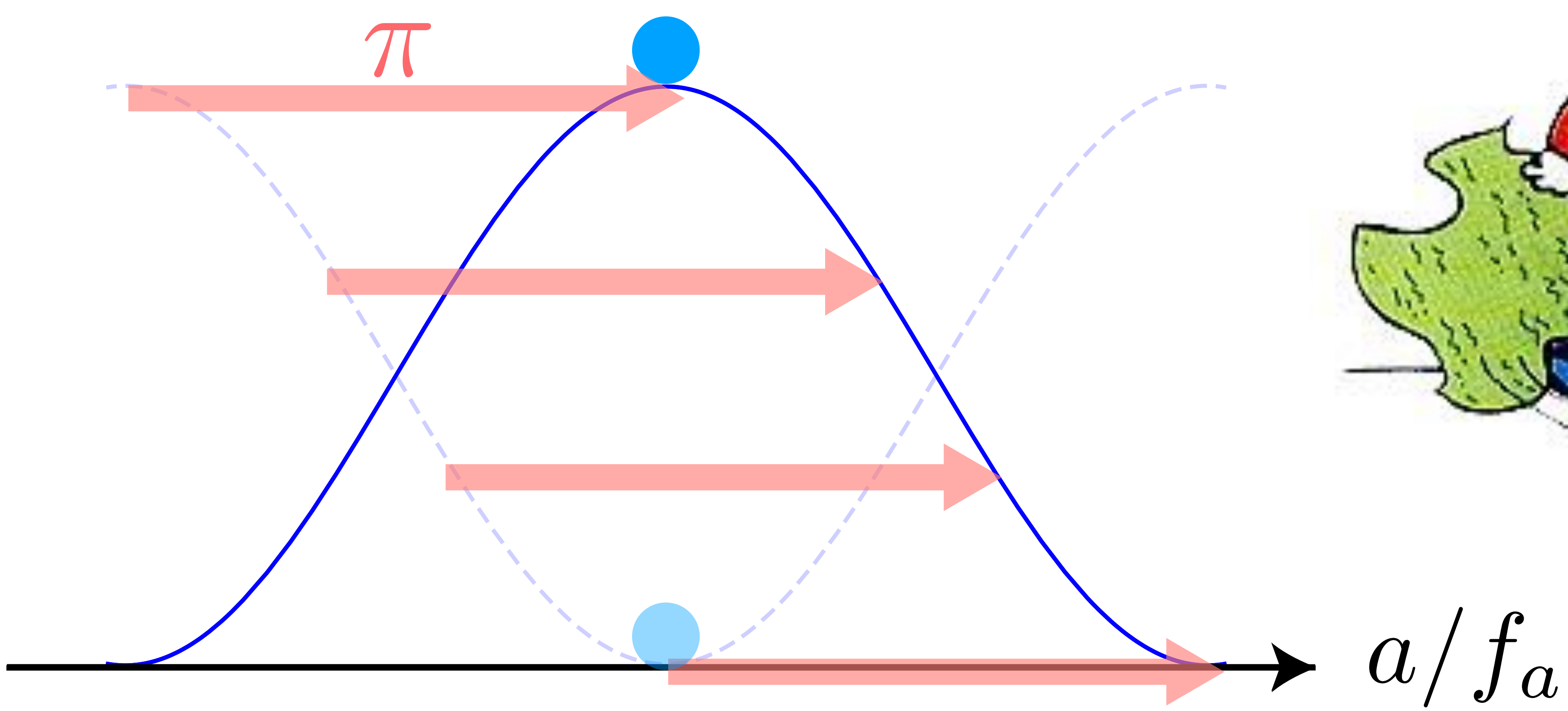
However, if the inflation scale is lower than the QCD scale, the axion will be likely near the minimum during inflation.



Then, how can we realize the hilltop initial condition?

Phase shift

The minimum turns into a maximum if the QCD axion potential abruptly receives a phase shift of π after (or during the end of) inflation.



Ryuji Daido, FT, Wen Yin, arXiv:1702.03284,1903.00462

This is possible if the QCD axion has a mixing with another heavy axion ϕ,

$$V(a,\phi) = \chi(T)\left[1 - \cos\left(\frac{\phi - \phi_{\min}}{f_\phi} + \frac{a}{f_a}\right)\right] + V_{\inf}(\phi)$$

with

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$$V(a,\phi) = \chi(T)\left[1-\cos\left(\frac{\phi-\phi_{\rm min}}{f_\phi}+\frac{a}{f_a}\right)\right] + V_{\rm inf}(\phi)$$

$$\frac{\phi-\phi_{\rm min}}{f_\phi} \sim \begin{cases} \pi & \text{during inflation} \\ 0 & \text{at present} \end{cases}$$

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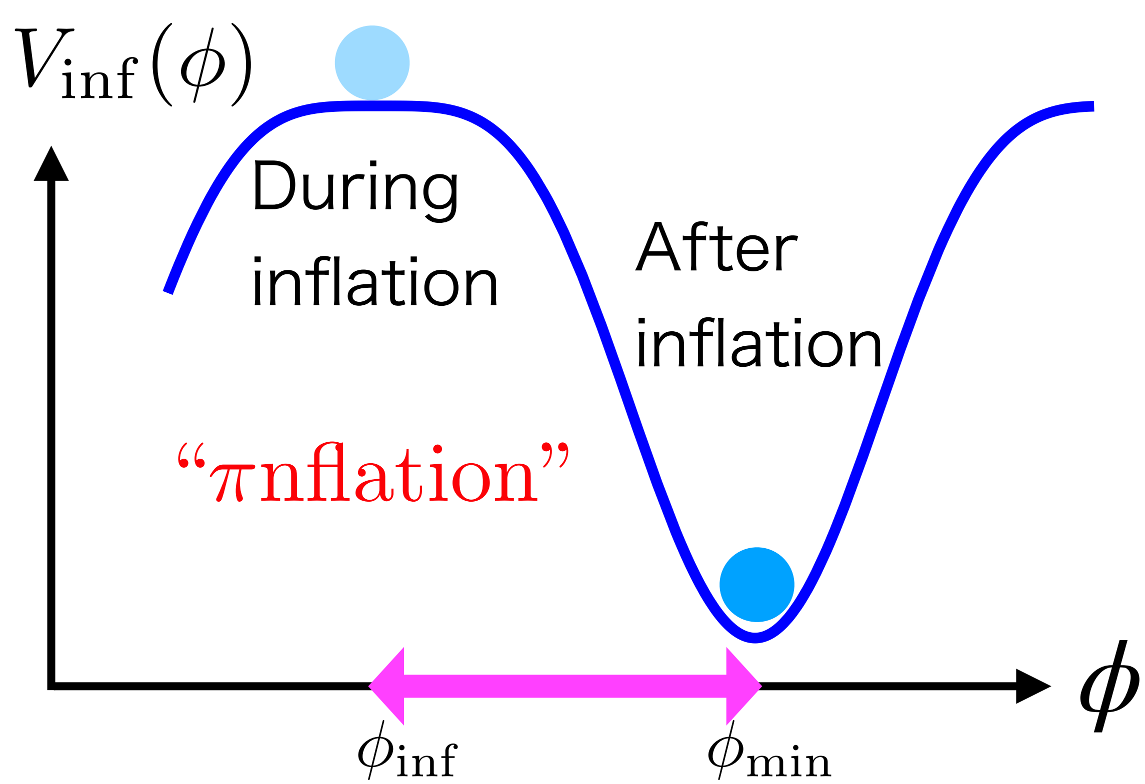

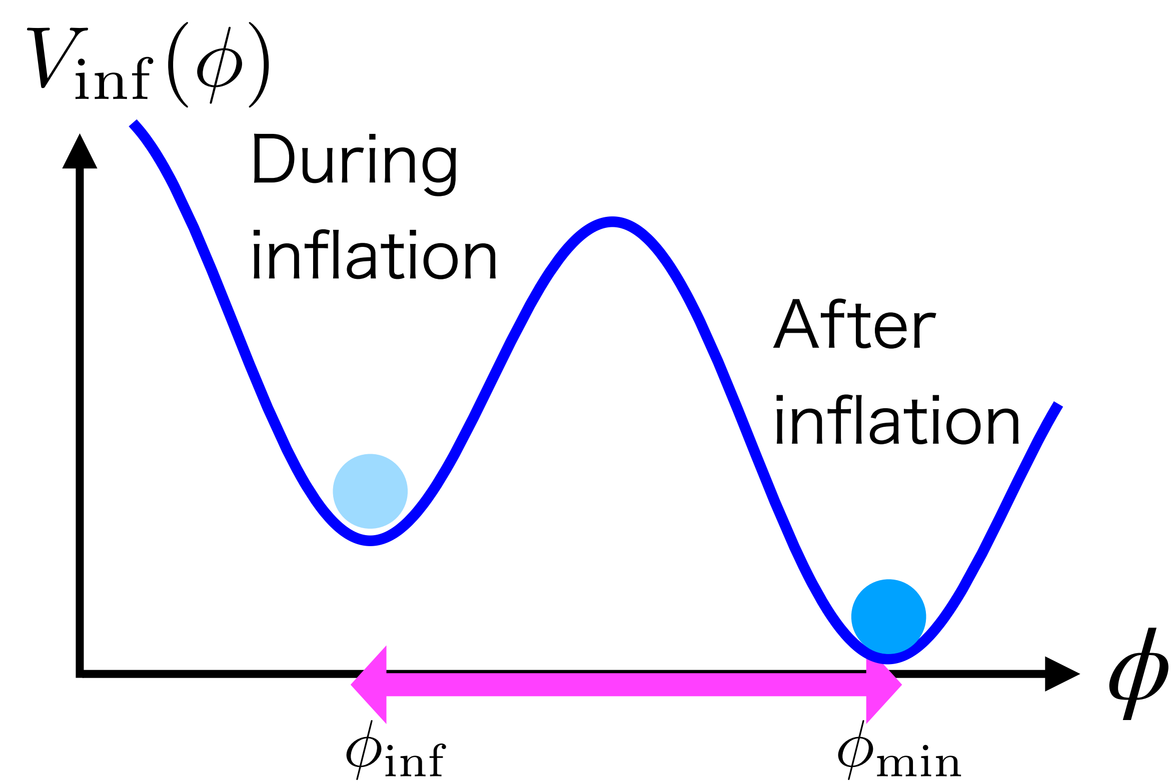

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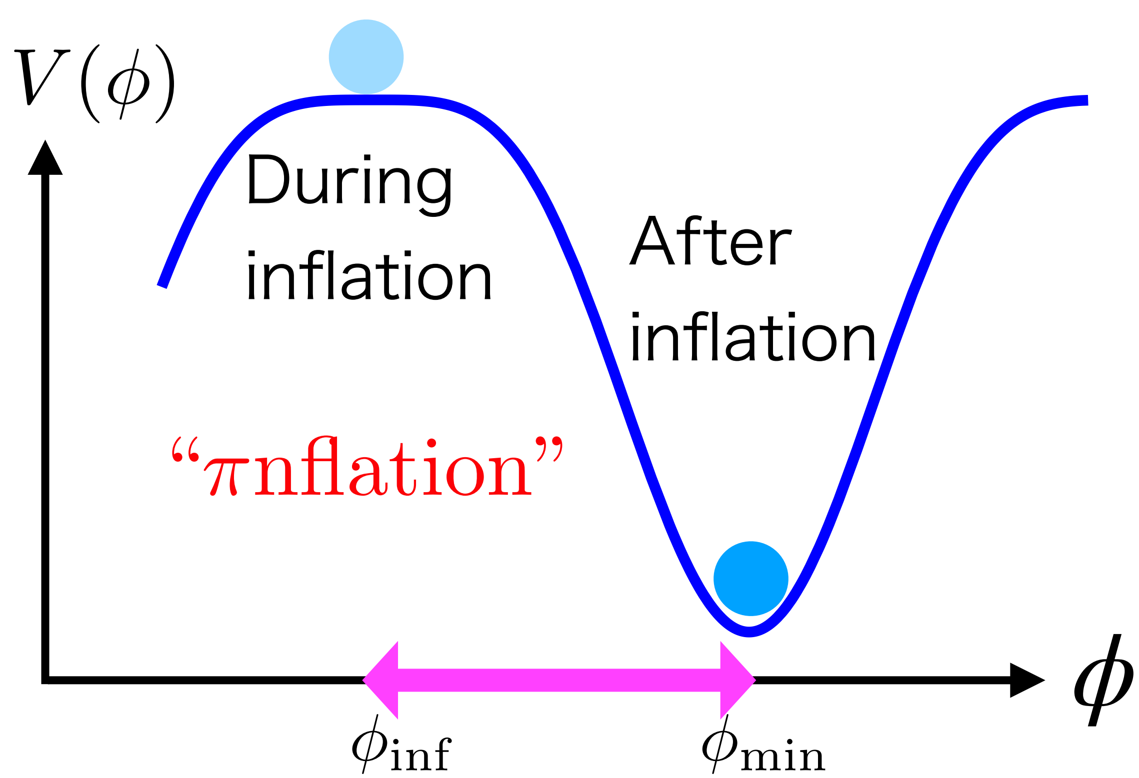
with

$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f_\phi}+\Theta\right) - \frac{\kappa}{n_{\rm inf}^2}\cos\left(n_{\rm inf}\frac{\phi}{f_\phi}\right)\right)$$



For $|\Theta| \ll 1$ and $|\kappa - 1| \ll 1$

$$V_{\rm inf}(\phi) \simeq V_0 - \lambda\phi^4 + \cdots$$

Quartic hilltop inflation

Czerny, FT `14

The axion field follows the Bunch-Davies distribution during inflation,

$$\left\langle \left(a - a_{\rm min}^{(\rm inf)}\right)^2 \right\rangle \simeq \frac{3H_{\rm inf}^4}{8\pi^2 m_a^2(T_{\rm inf})}.$$

After the phase shift of π , the initial angle becomes

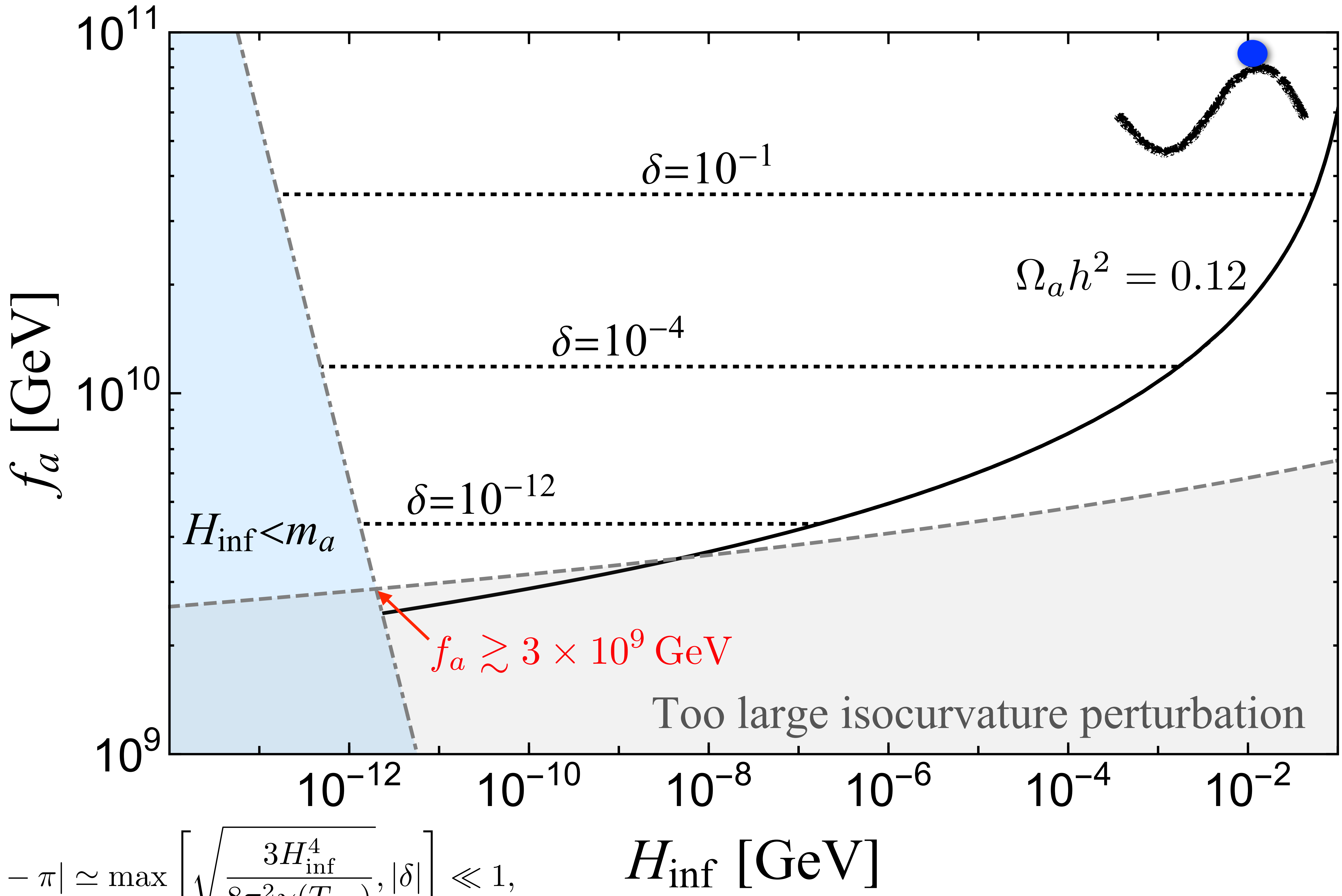
$$|\theta_i - \pi| \simeq \max\left[\sqrt{\frac{3H_{\rm inf}^4}{8\pi^2\chi(T_{\rm inf})}}, |\delta|\right] \ll 1,$$

where we assume $m_a(T_{\rm inf}) \ll H_{\rm inf}$.

This comes from the inflaton dynamics

$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f_\phi} + \Theta\right) - \frac{\kappa}{n_{\rm inf}^2}\cos\left(n_{\rm inf}\frac{\phi}{f_\phi}\right)\right)$$

Decay constant and H_{inf}

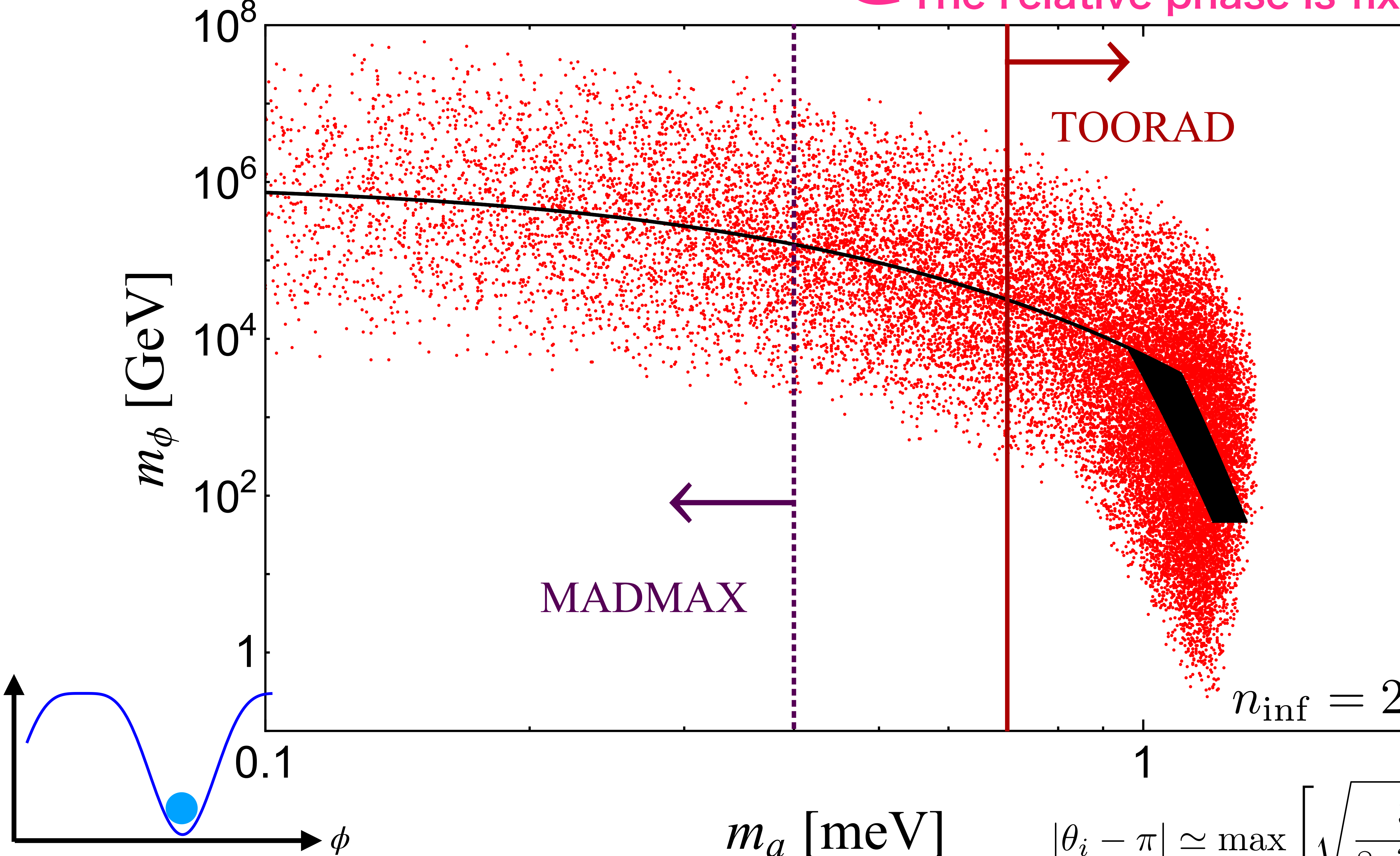


$$|\theta_i - \pi| \simeq \max\left[\sqrt{\frac{3H_{\rm inf}^4}{8\pi^2\chi(T_{\rm inf})}}, |\delta|\right] \ll 1,$$

Axion and inflaton masses

We adopt $V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f_\phi} + \Theta\right) - \frac{\kappa}{n_{\rm inf}^2}\cos\left(n_{\rm inf}\frac{\phi}{f_\phi}\right)\right)$ with $n_{\rm inf} = 2$

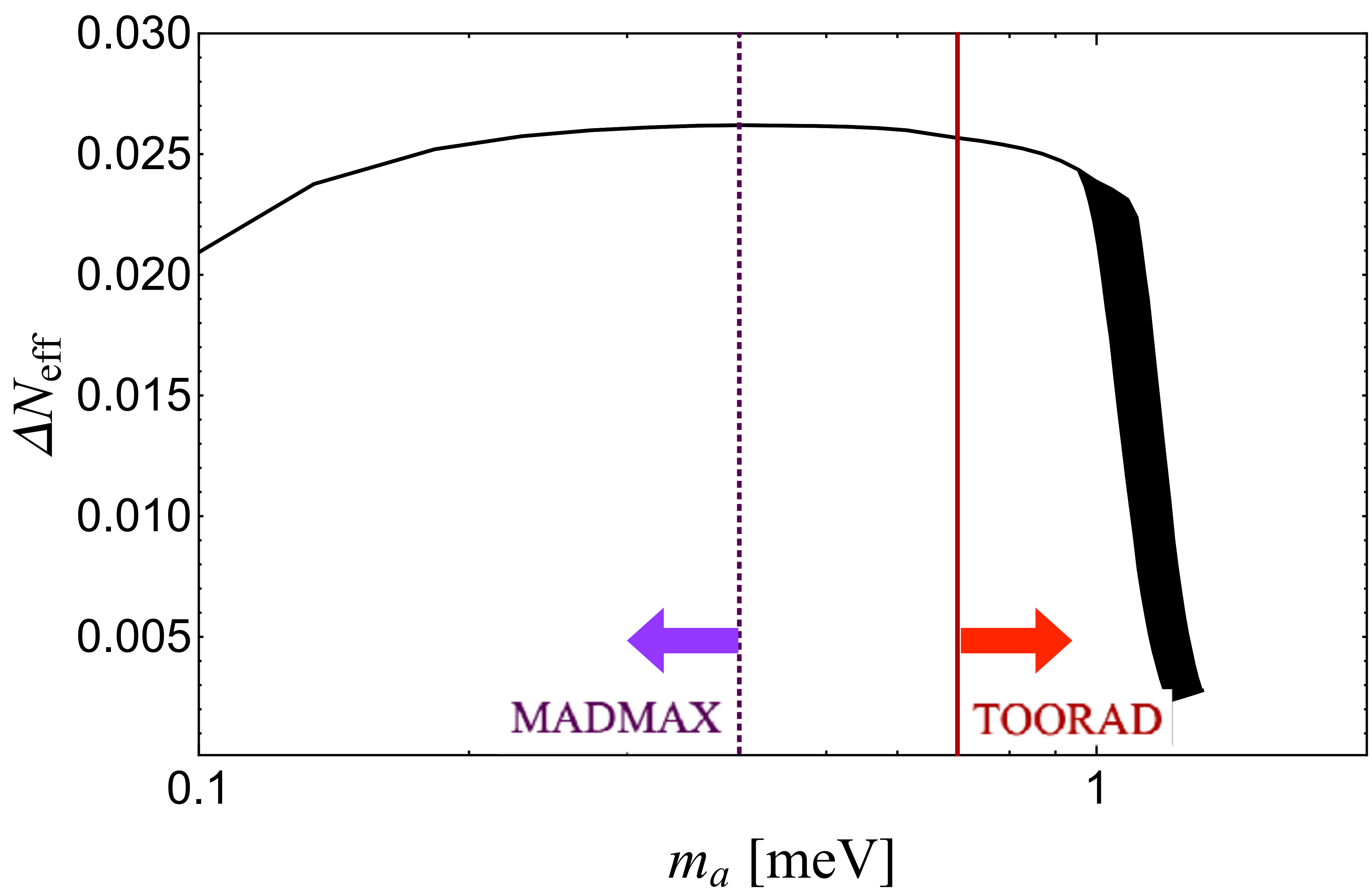
The relative phase is fixed by n_s.



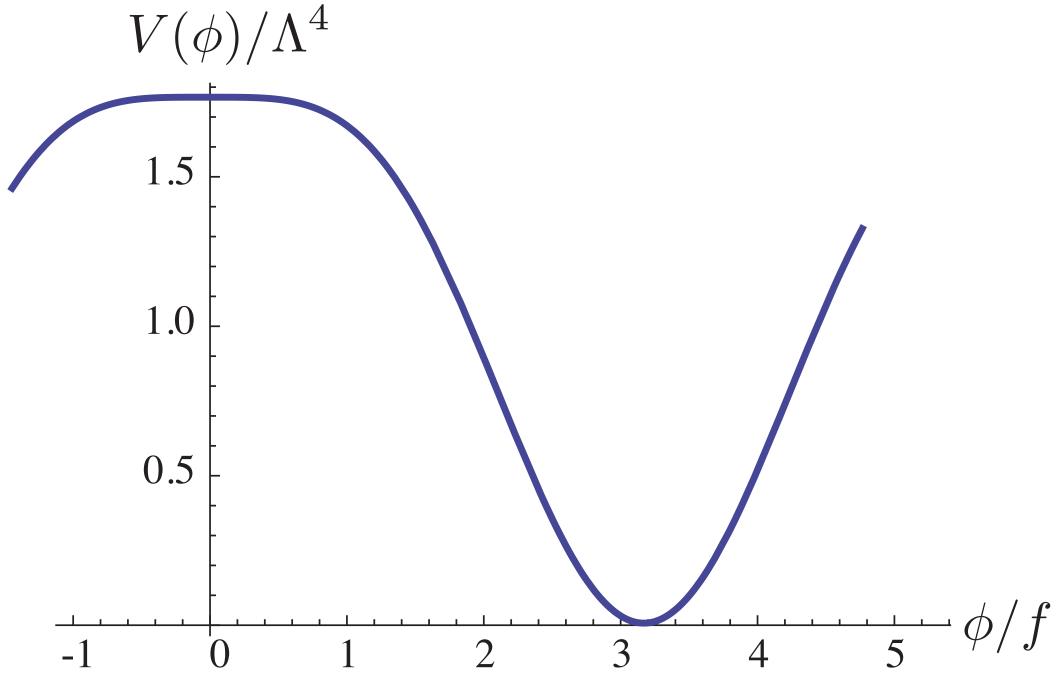
$$|\theta_i - \pi| \simeq \max\left[\sqrt{\frac{3H_{\rm inf}^4}{8\pi^2\chi(T_{\rm inf})}}, |\delta|\right]$$

Axion Dark Radiation

If the inflaton has Yukawa-like couplings to the SM fermions, the reheating is almost instantaneous, and axions are thermalized. $T_{\rm RH} \sim \sqrt{H_{\rm inf} M_{\rm pl}} \lesssim f_a$



Axion hilltop inflation



• Axion hilltop inflation

Czerny, FT 1401.5212,
Czerny, Higaki, FT 1403.0410, 1403.5883
Croon and Sanz, 1411.7809
FT, Yin, 1903.00462

Low-scale axion inflation can be realized with **at least two cosine terms**: *"Multi-natural inflation"*

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{\kappa}{n^2} \cos\left(\frac{n\phi}{f}\right)\right) + \text{const.}$$

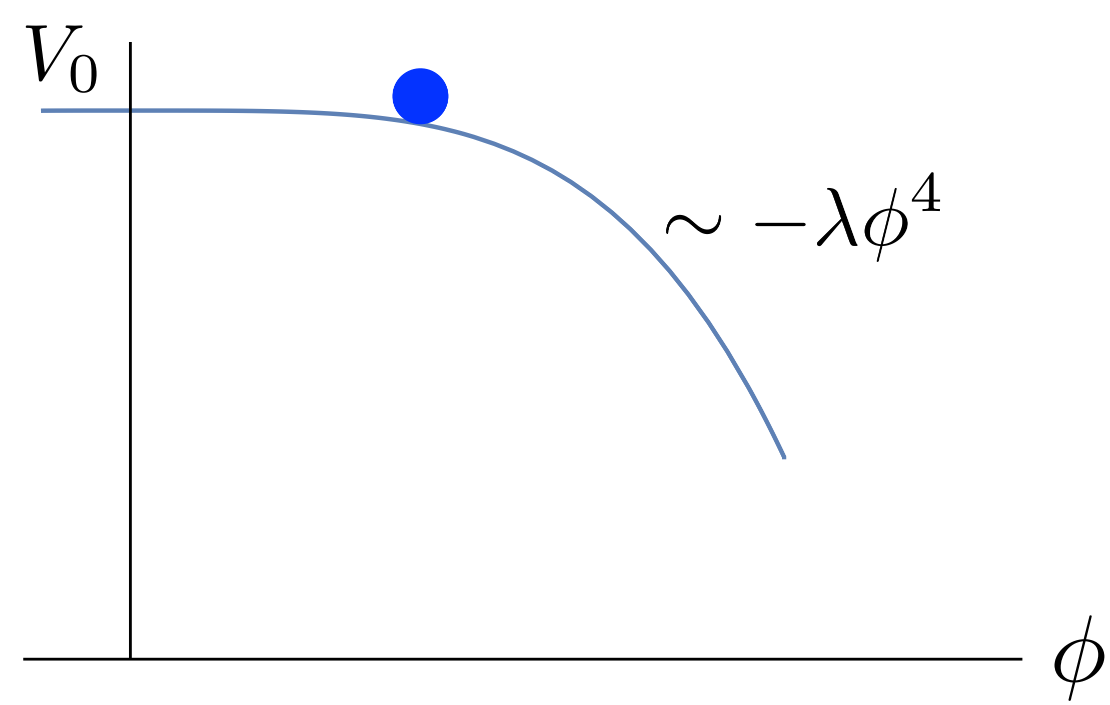
$$= V_0 - \lambda\phi^4 - \theta\frac{\Lambda^4}{f}\phi + (\kappa - 1)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots \quad \text{where} \quad \lambda \sim \frac{\Lambda^4}{f^4}$$

for $|\theta| \ll 1$ and $|\kappa - 1| \ll 1$

CMB normalization:

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$

independent of V_0



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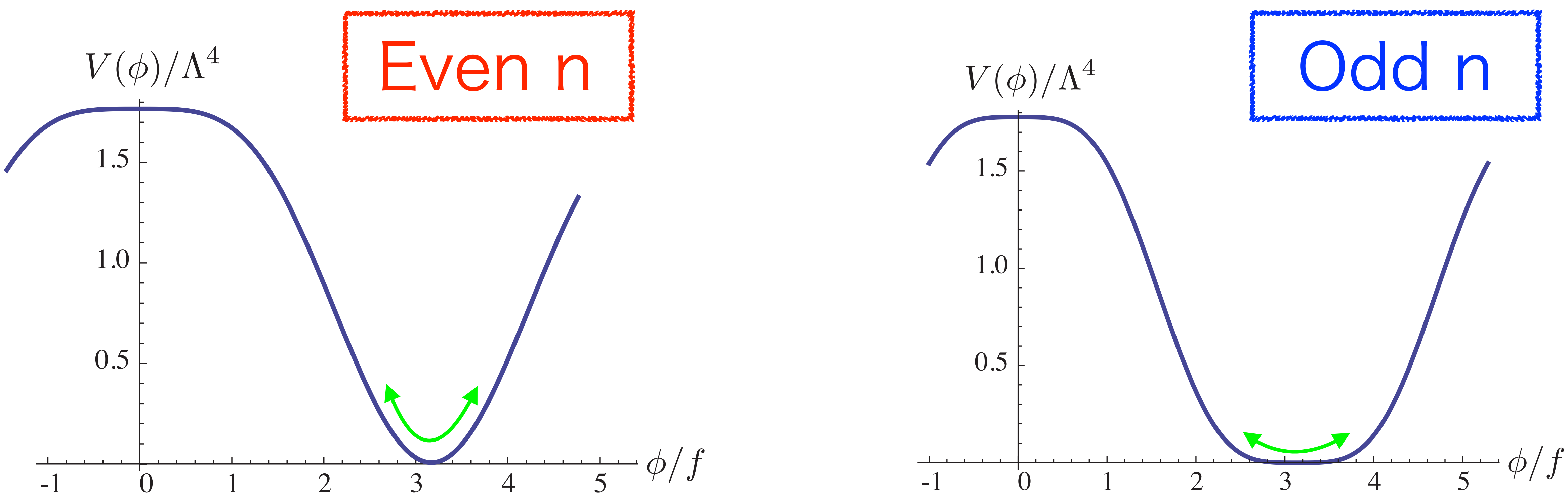
Low-scale axion inflation can be realized with **at least two cosine terms**: *"Multi-natural inflation"*

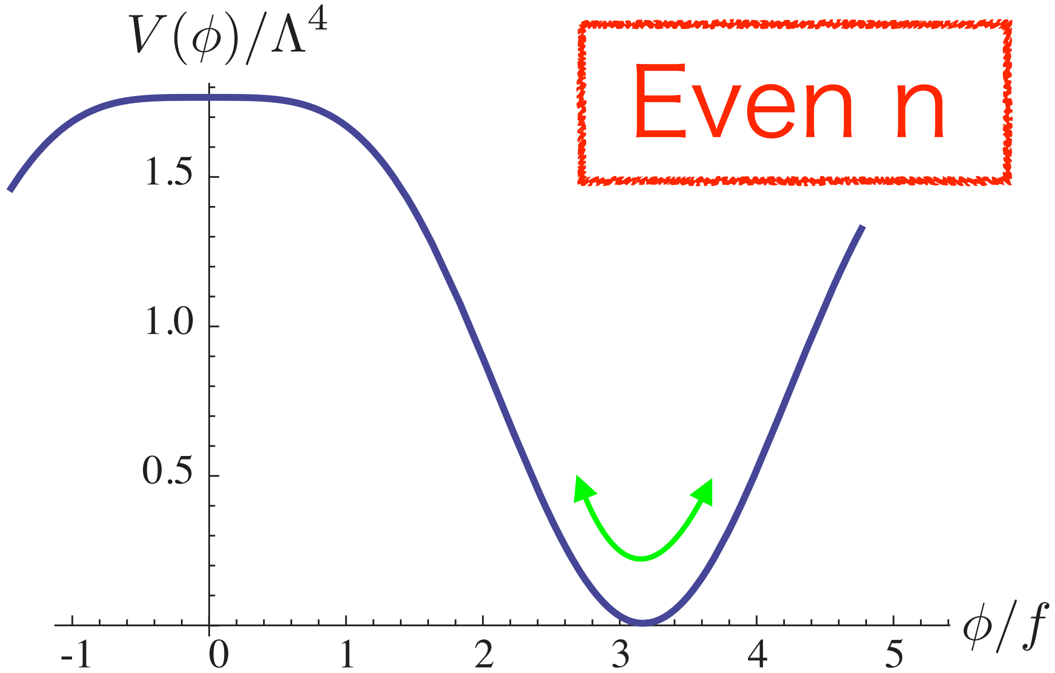
$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f}+\theta\right) - \frac{\kappa}{n^2}\cos\left(\frac{n\phi}{f}\right)\right) + {\rm const.}$$

The inflaton mass at the minimum, m_ϕ , depends on *n*.



$m_\phi \sim \Lambda^2/f$

$m_\phi \ll \Lambda^2/f$



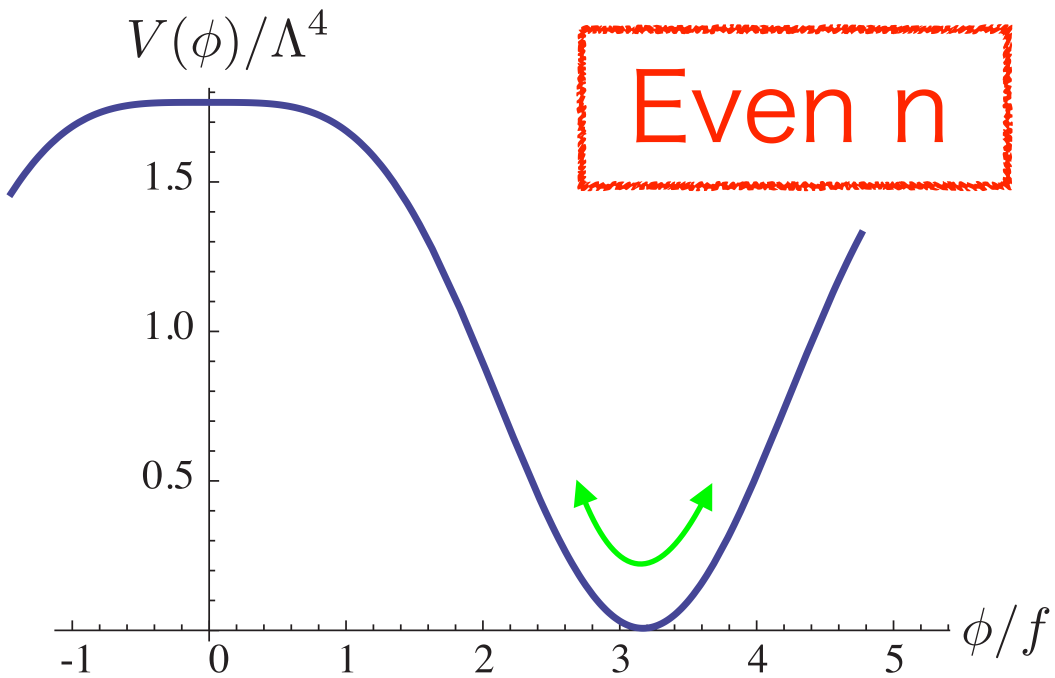
The potential is flat only around the potential maximum.

$$m_\phi \sim \frac{\Lambda^2}{f}$$

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$ **: CMB norm**

$$\Rightarrow \quad f \sim 10^6 m_\phi$$

Czerny, Higaki, FT 1403.0410, FT and Yin, 1903.00462



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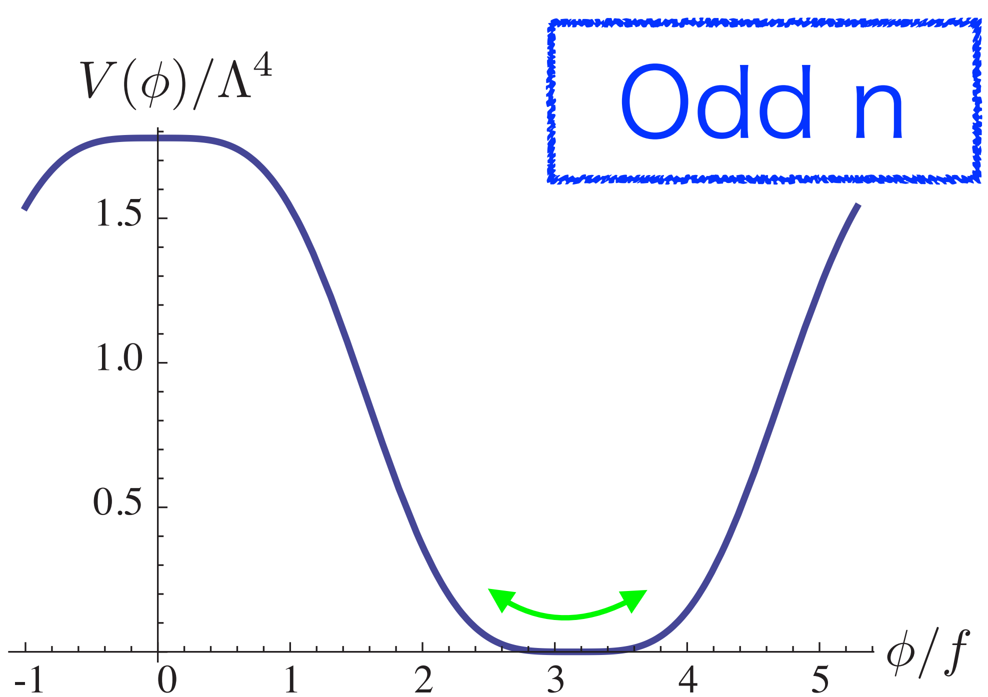

The potential is flat both around the maximum and minimum.

$$1 - n_s = -2M_p^2 \frac{V''}{V} \simeq \frac{2}{3}\frac{m_\phi^2}{H_{\rm inf}^2} \simeq 0.04$$

So $m_\phi \sim 0.1 H_{\rm inf} \sim 0.1 \dfrac{\Lambda^2}{M_p}$ **+ CMB norm.**

$$\Rightarrow \quad f \sim 10^3 \sqrt{m_\phi M_p}$$

Daido, FT, Yin, 1702.03284, 1710.11107

ALP mass and decay constant

In the case of the ALP coupled to photons

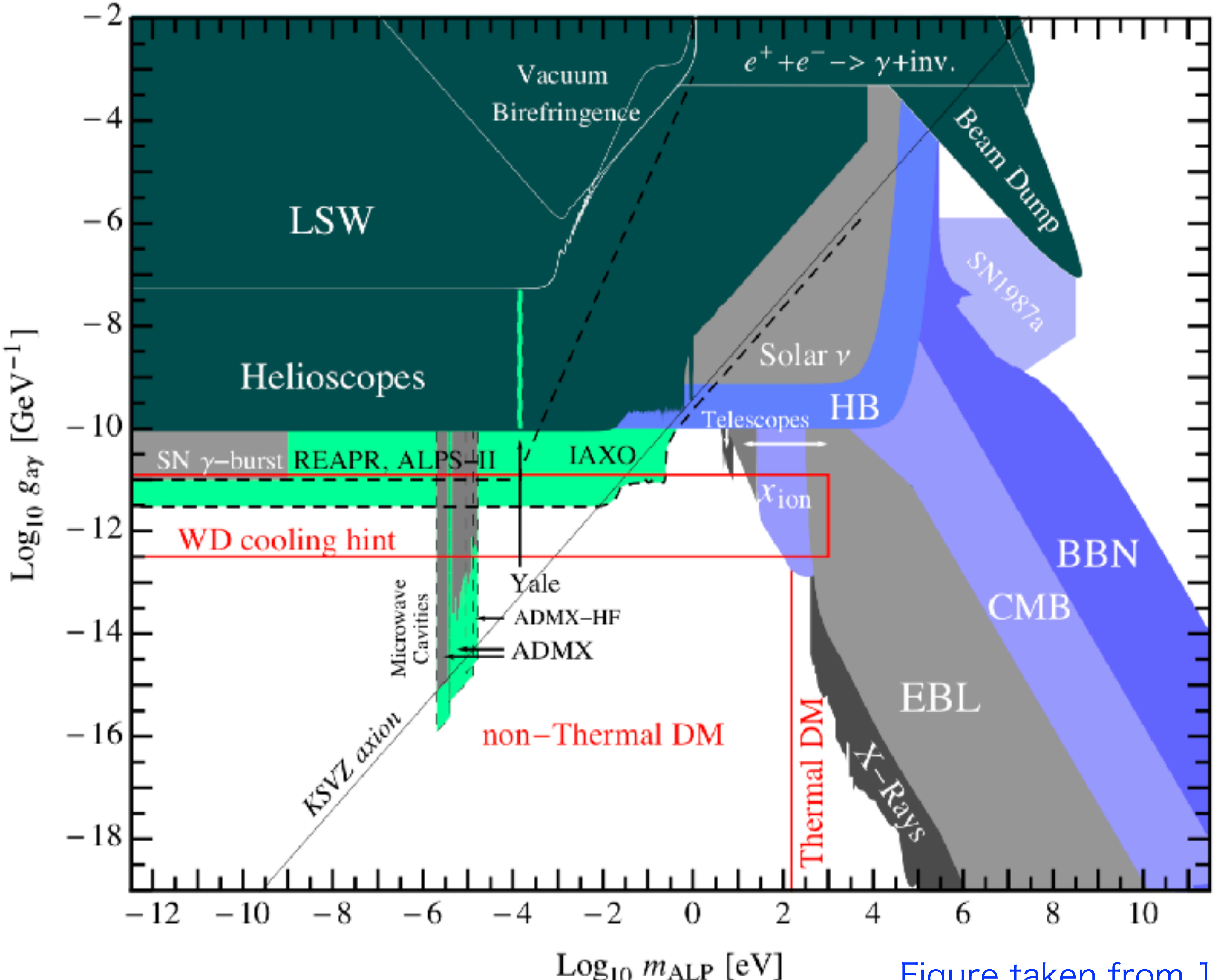

Figure taken from 1205.2671

ALP mass and decay constant

In the case of the ALP coupled to photons

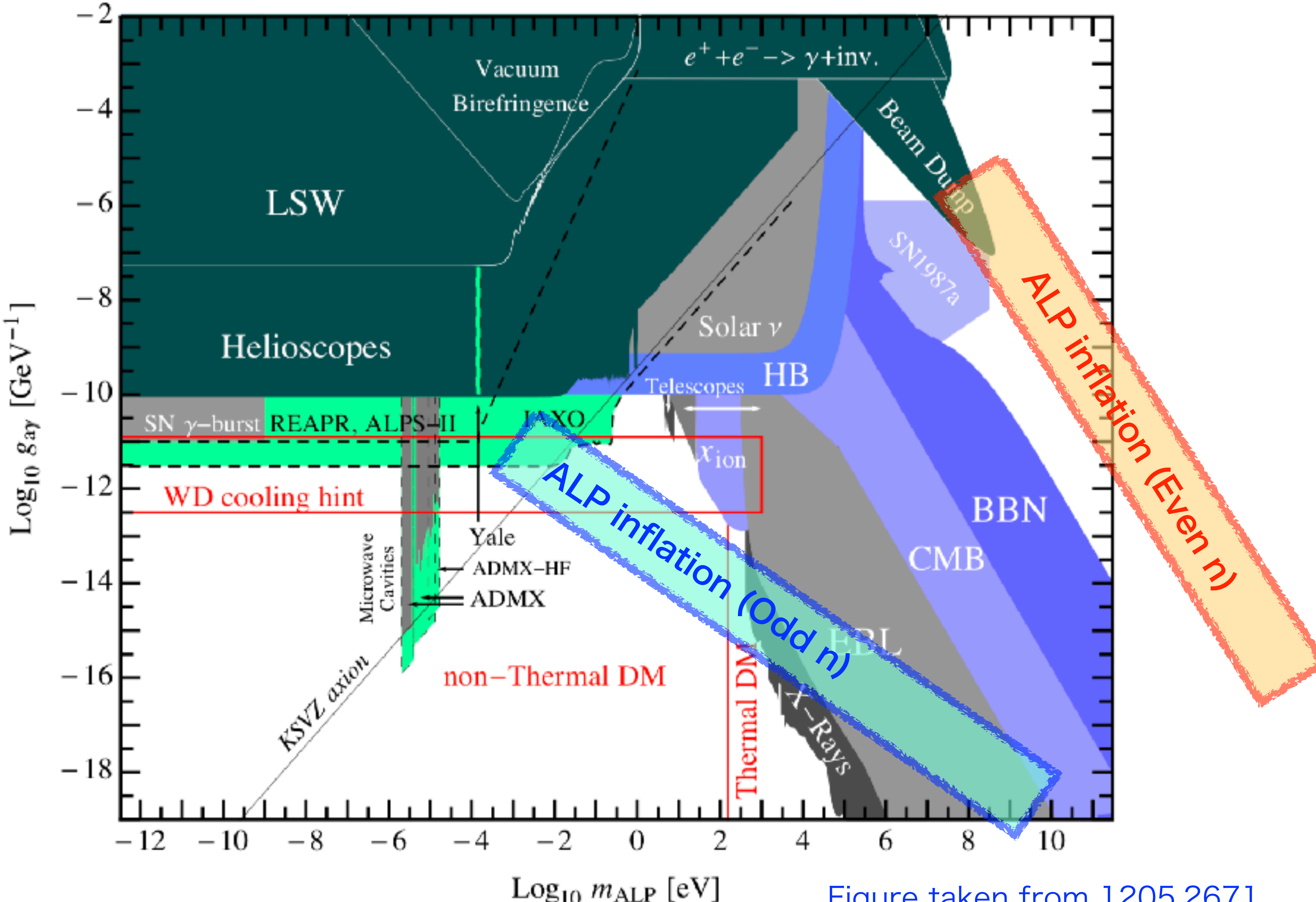

Figure taken from 1205.2671

ALP mass and decay constant

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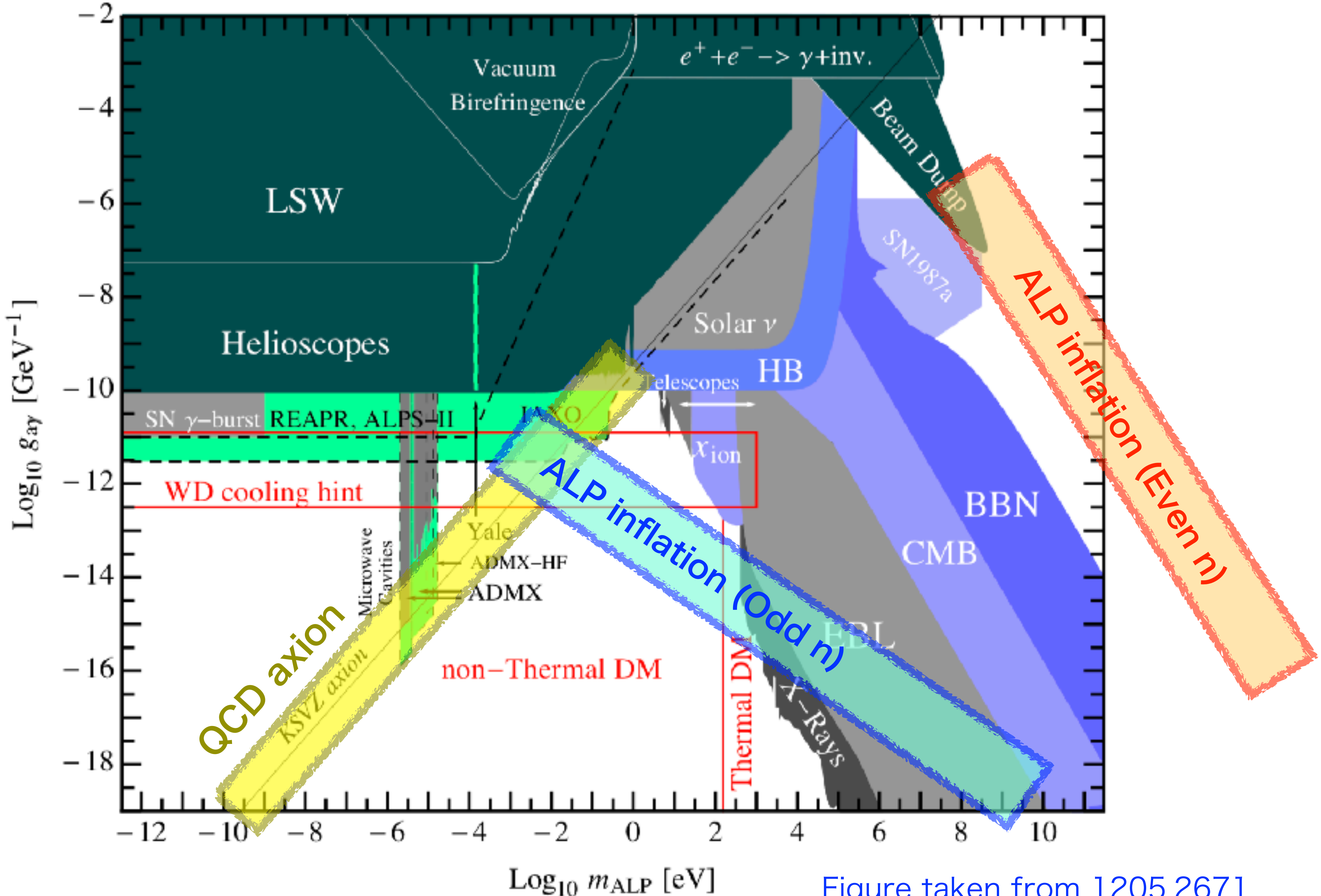
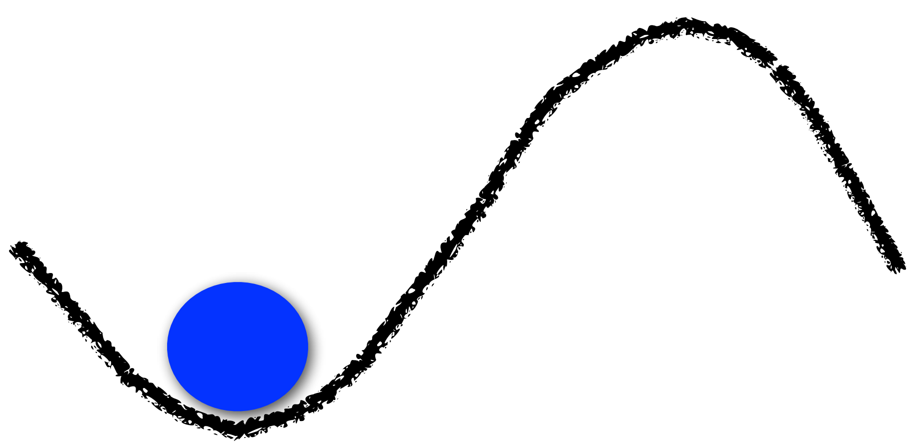


Figure taken from 1205.2671

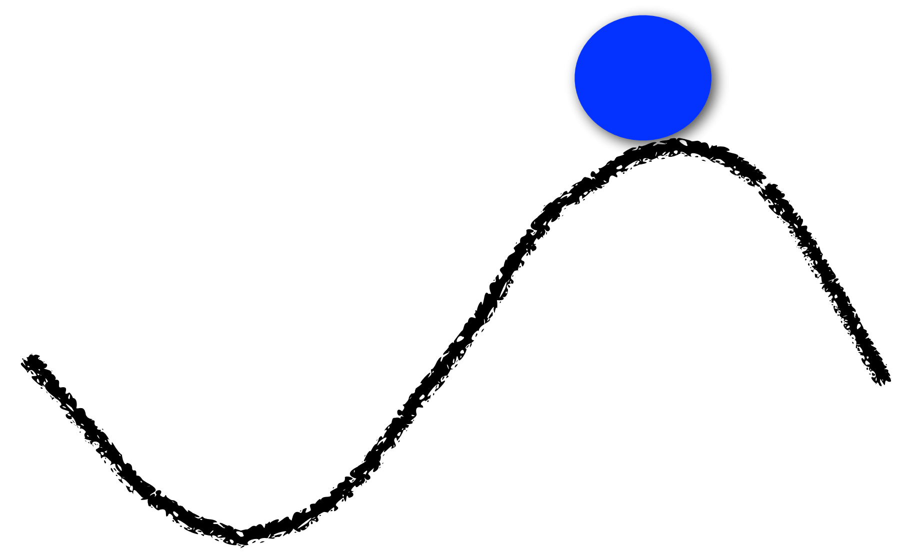
Conclusions

We have shown that the initial angle $\theta_i \sim 0 \text{ or } \pi$ of the QCD axion can be dynamically realized in low-scale inflation models.



$$|\theta_i| \ll 1$$

- Low-scale inflation $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$
- BD distribution $\theta_i \sim \dfrac{H_{\rm inf}^2}{m_a(T_{\rm inf}) f_a}$



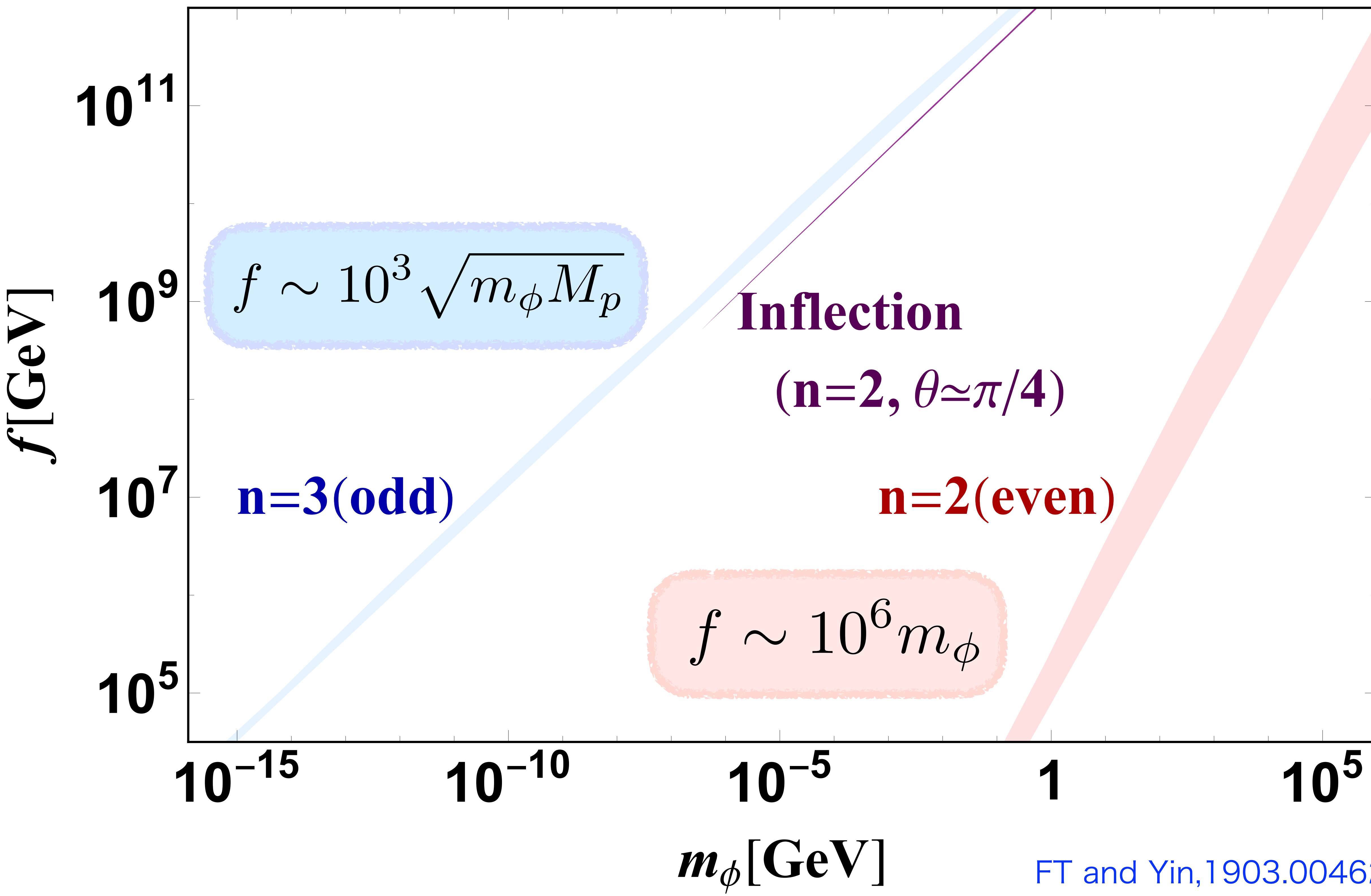
$$\theta_i \sim \pi$$

- \+ sudden phase shift of π via the mass mixing.
- "πnflation" = ALP inflation

Back-ups

ALP mass and decay constant

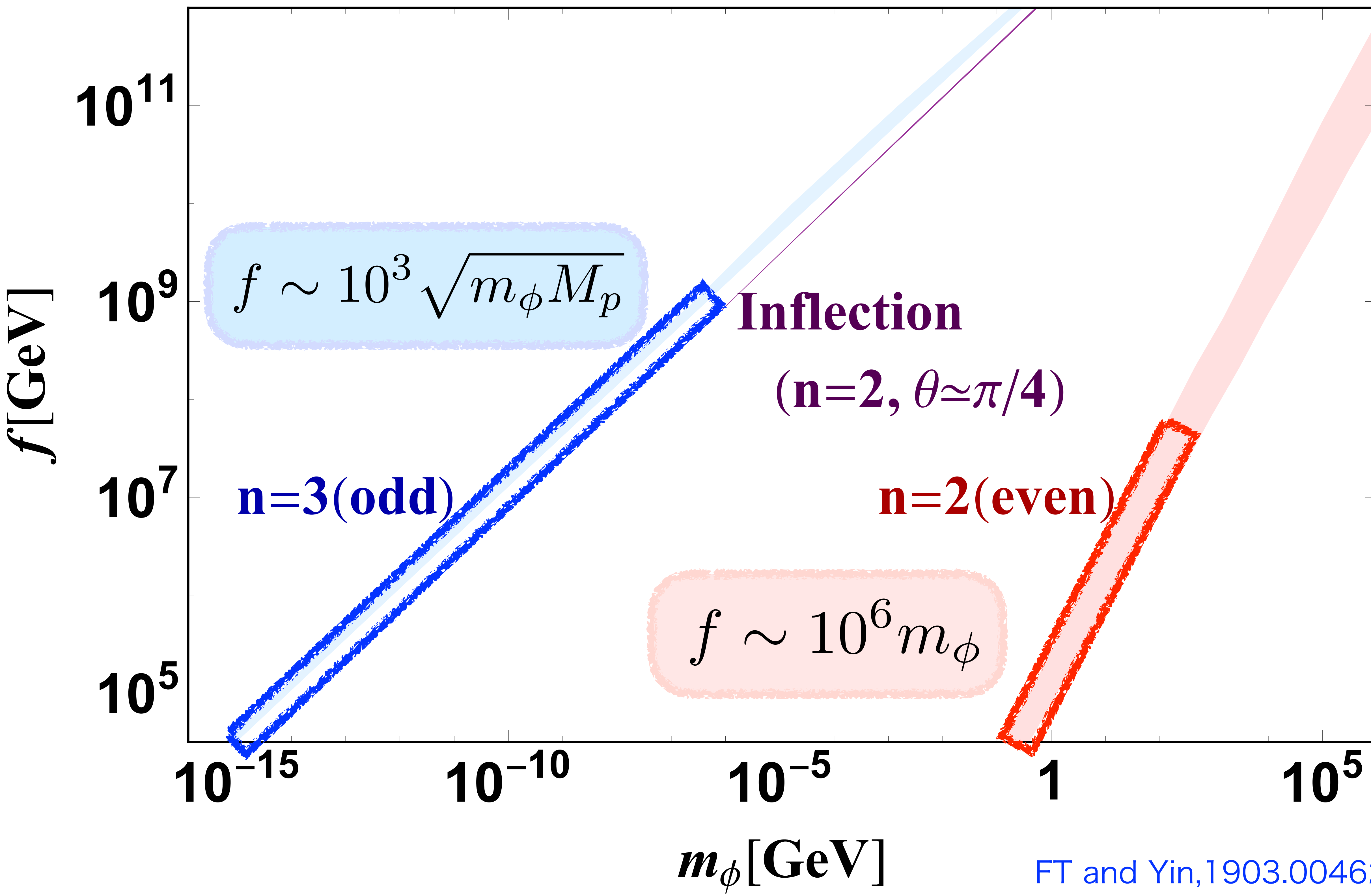
cf. $f \sim 10^{12}\,\mathrm{GeV}(m_a/6\,\mu\mathrm{eV})^{-1}$ for QCD axion



FT and Yin,1903.00462

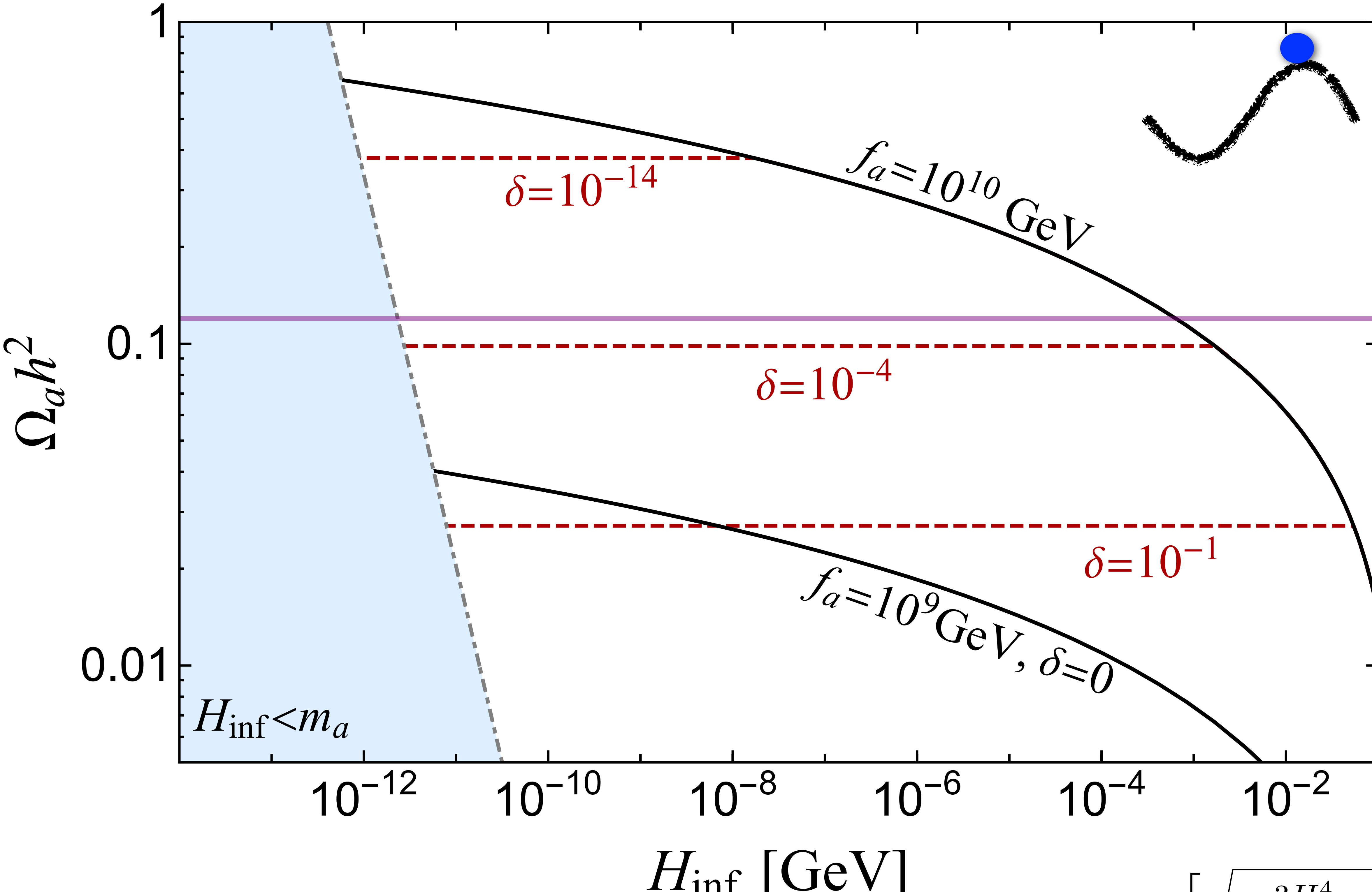
ALP mass and decay constant

cf. $f \sim 10^{12}\,\mathrm{GeV}(m_a/6\,\mu\mathrm{eV})^{-1}$ for QCD axion



FT and Yin,1903.00462

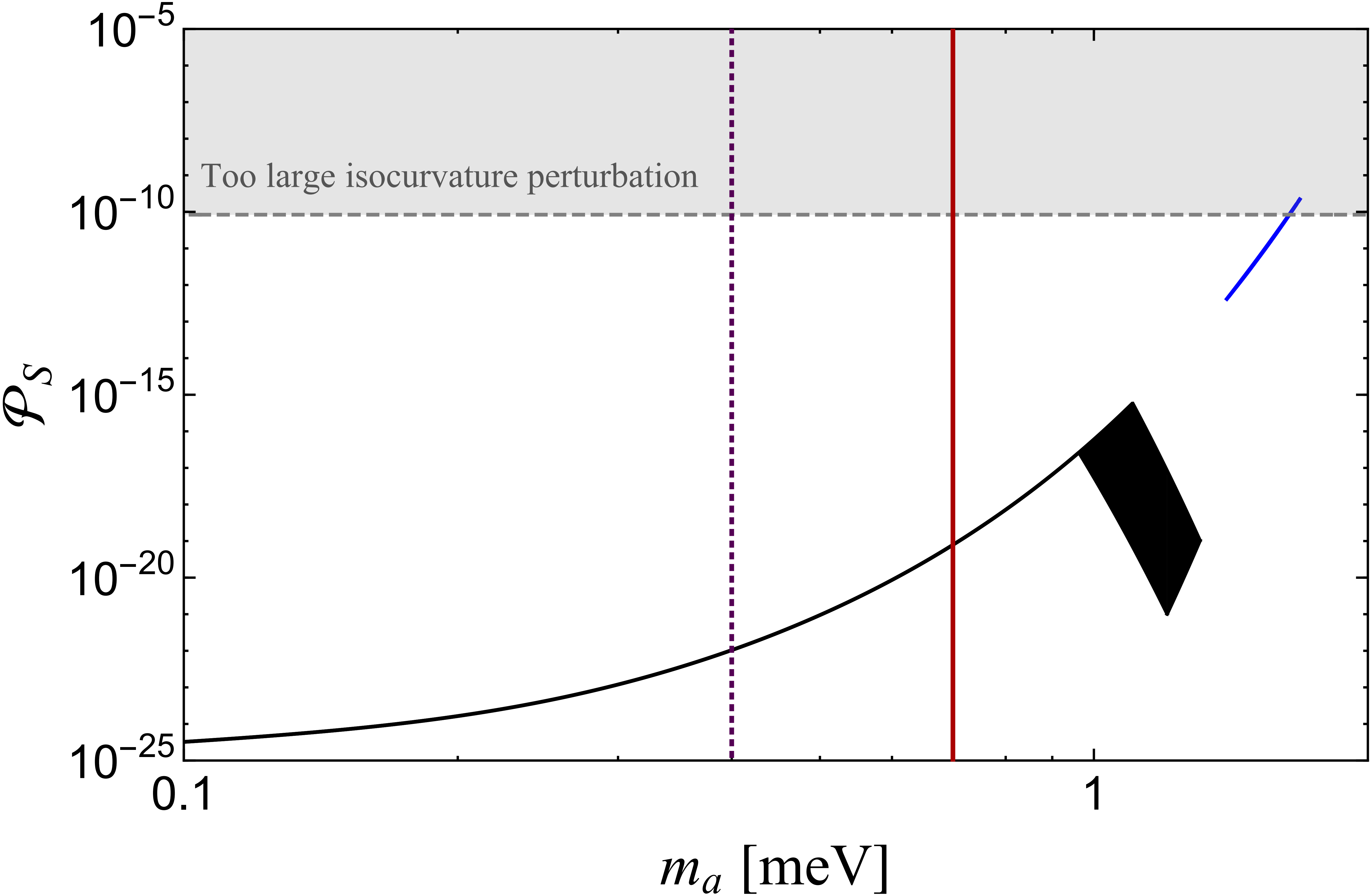
Axion abundance and H_{inf}



$$|\theta_i - \pi| \simeq \max\left[\sqrt{\frac{3H_{\rm inf}^4}{8\pi^2\chi(T_{\rm inf})}}, |\delta|\right] \ll 1,$$

Comparison with the paper by Co, Gonzalez, and Harigaya

Co, Gonzalez, and Harigaya	FT, Yin
CP symmetry in the (SUSY) Higgs & inflaton sector	Hilltop inflation with two cosine terms.
Phase shift of pi by the dynamics of Higgs and inflaton	Phase shift of pi by the inflaton
Stronger QCD in MSSM & heavy axion	QCD scale is unchanged and axion is light.
Axion stabilized by heavy mass	Bunch-Davies distribution
Suppressed isocurvature at CMB scales	Suppressed isocurvature at CMB scales, no DWs.



10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
Too large isocurvature perturbation
$\mathcal{P}_S$
0.1
1
m_a [meV]