Level Crossing between QCD Axion and ALP

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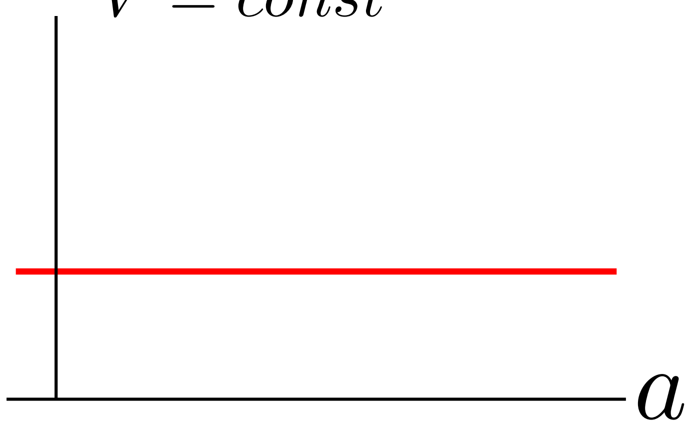
1505.07670
1510.06675

Axions

shift symmetry

$$a \to a + C$$

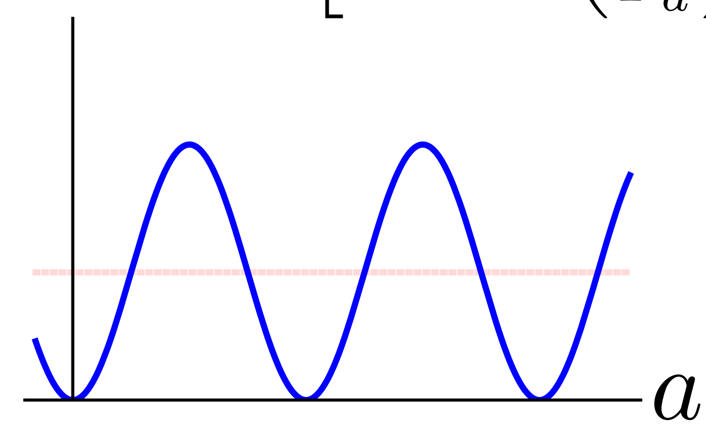
$$V = const$$



Non-perturbative effect

discrete shift symmetry

$$V \simeq \Lambda^4 \left[1 - \cos\left(\frac{a}{F_a}\right)\right]$$



- QCD axion (solves the strong CP)

$$a$$

$$\mathcal{L} \supset \frac{\theta}{32\pi^2} F\tilde{F}, \ |\theta| \lesssim 10^{-10}$$

- Axion Like Particles (e.g. String theory)

$$a_{\mathrm{H}}$$

Mixing

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

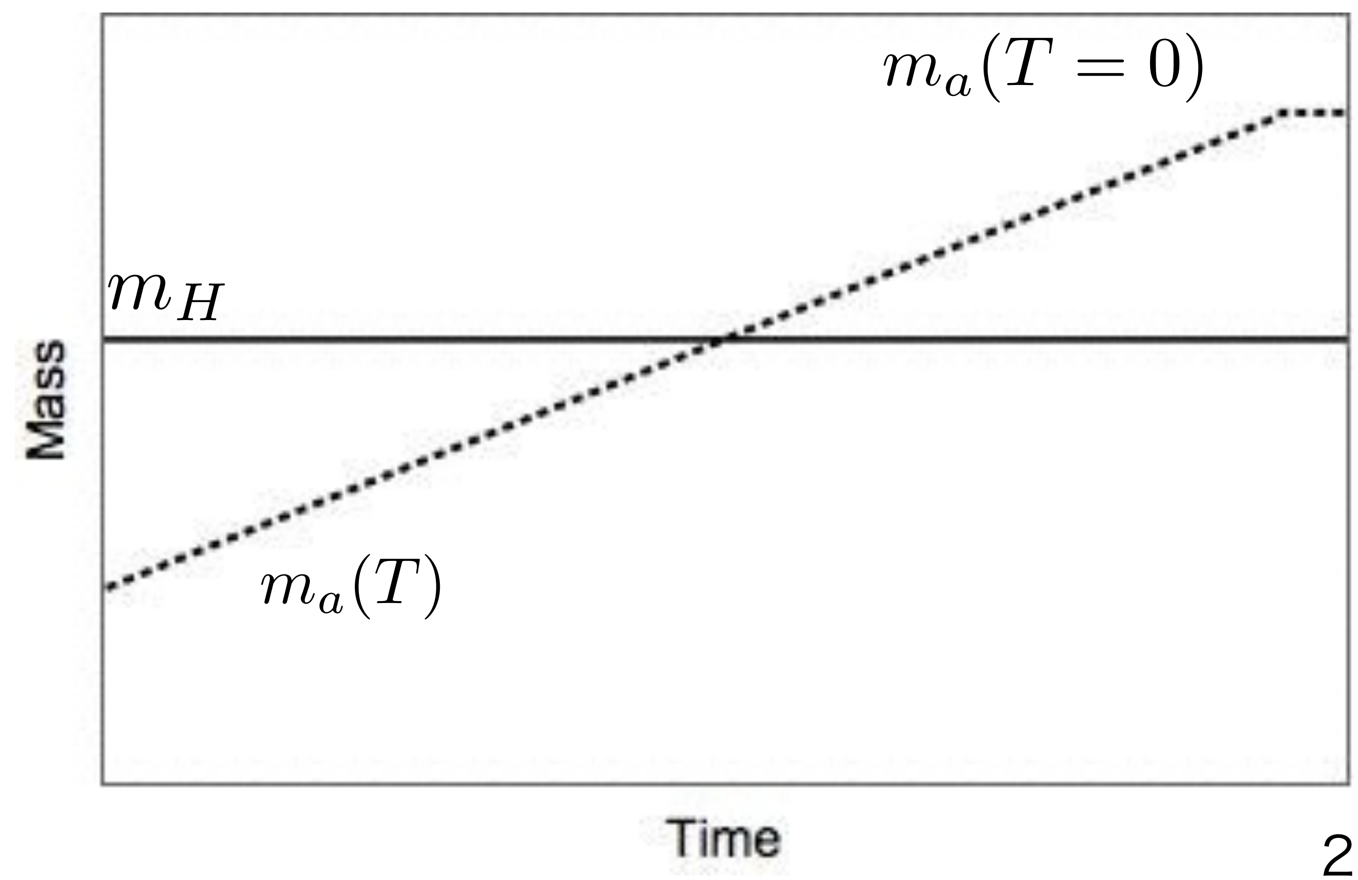
  temperature dependent

$$m_a(T) = \begin{cases} 4.05 \times 10^{-4}\, \frac{\Lambda_{\rm QCD}^2}{F_a} \left(\frac{T}{\Lambda_{\rm QCD}}\right)^{-3.34} & T > 0.26\Lambda_{\rm QCD} \\ 3.82 \times 10^{-2}\, \frac{\Lambda_{\rm QCD}^2}{F_a} & T < 0.26\Lambda_{\rm QCD} \end{cases}$$

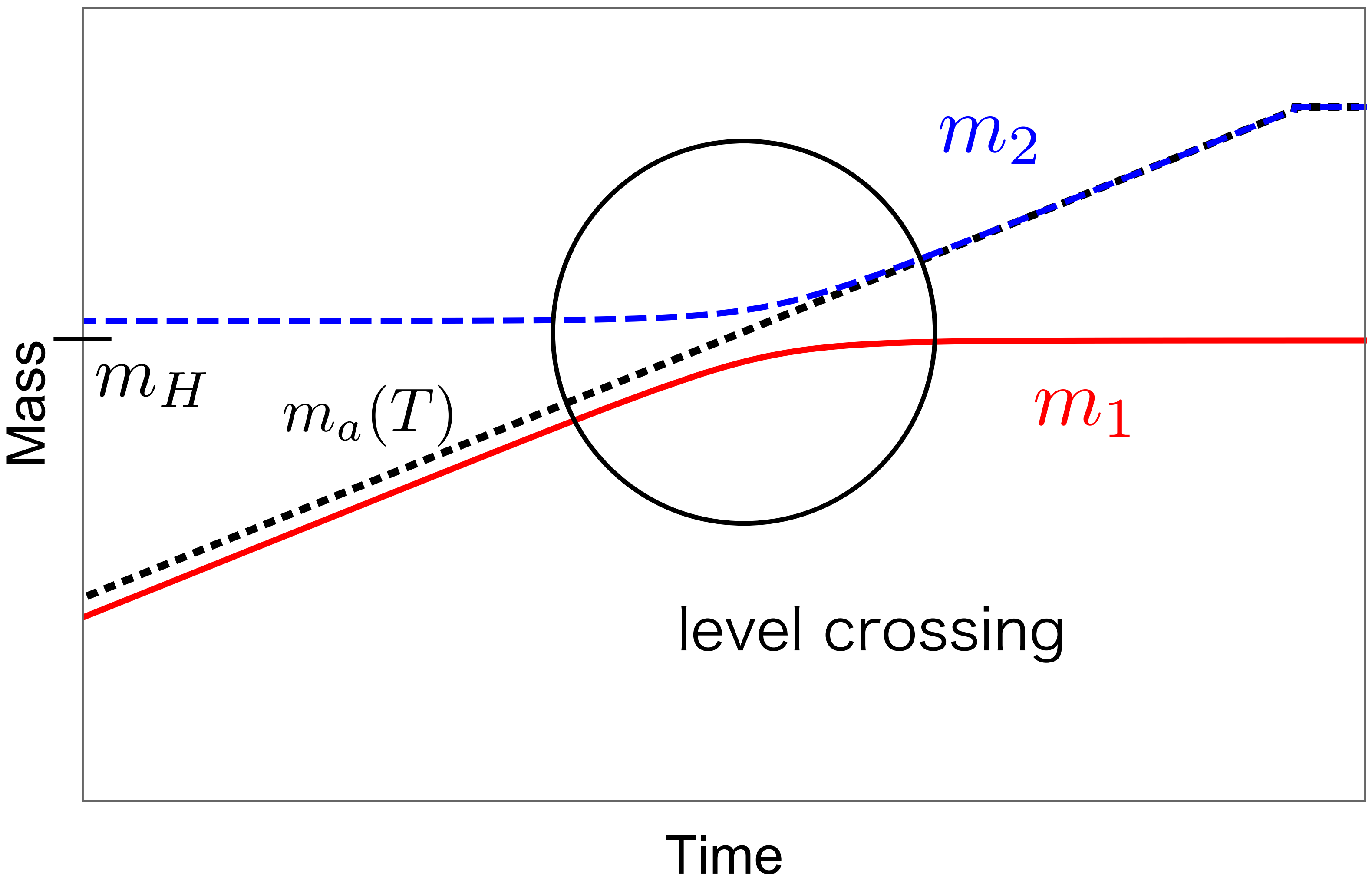
- $V_H = \Lambda_H^4 \left[1 - \cos\left(n_H \frac{a_H}{F_H} + n_a \frac{a}{F_a}\right)\right]$ $\quad m_H \equiv \frac{\Lambda_{\rm H}^2}{F_H/n_H}$

  mixing

$$m_H < m_a(T=0)$$



Level Crossing



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

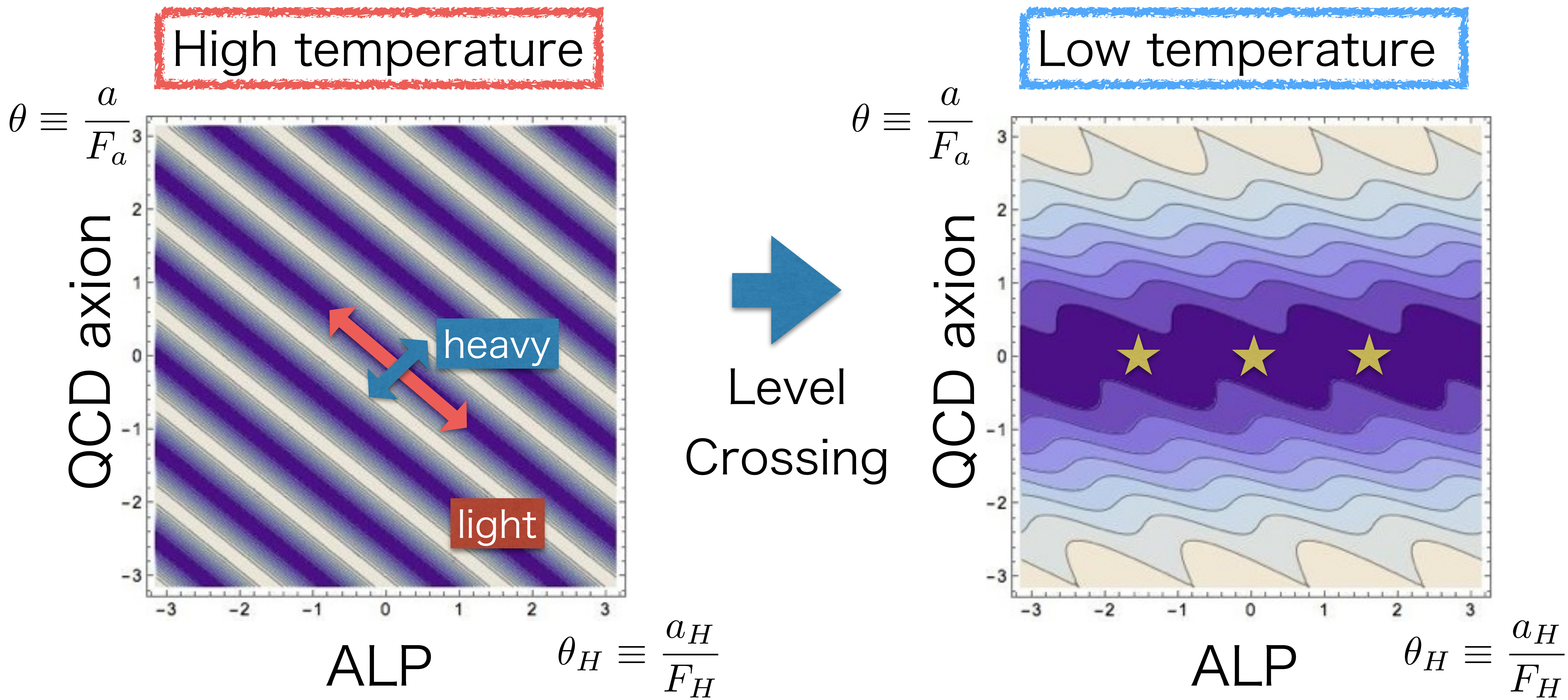
$$V_H = \Lambda_H^4 \left[1 - \cos\left(n_H \frac{a_H}{F_H} + n_a \frac{a}{F_a}\right)\right]$$

$$m_H < m_a(T=0)$$

➡ Level crossing takes place!

Hill, Ross, NPB 311, 253 (1988), Kitajima, Takahashi, 1411.2011

Time evolution of the potential



$$V_{\mathrm{QCD}} = m_a(T)^2 F_a^2 \left[1 - \cos\left(\frac{a}{F_a}\right)\right]$$

$$V_H = \Lambda_H^4 \left[1 - \cos\left(n_H \frac{a_H}{F_H} + n_a \frac{a}{F_a}\right)\right]$$

★ global minima

Timing of level crossing

(i) $H_{\rm lc} \ll H_{\rm osc}$

(The axion starts to oscillate well before the level crossing.)

➡ The potential changes adiabatically.

The resonant transition occurs like the MSW effect.

Kitajima, Takahashi, 1411.2011

(ii) $H_{\rm lc} \sim H_{\rm osc}$

➡ The adiabaticity is broken.

The axion exhibits non-trivial behavior!

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Axion roulette

Two conditions satisfied, the axion passes through many crests and troughs of the potential.

➡ Axion roulette!

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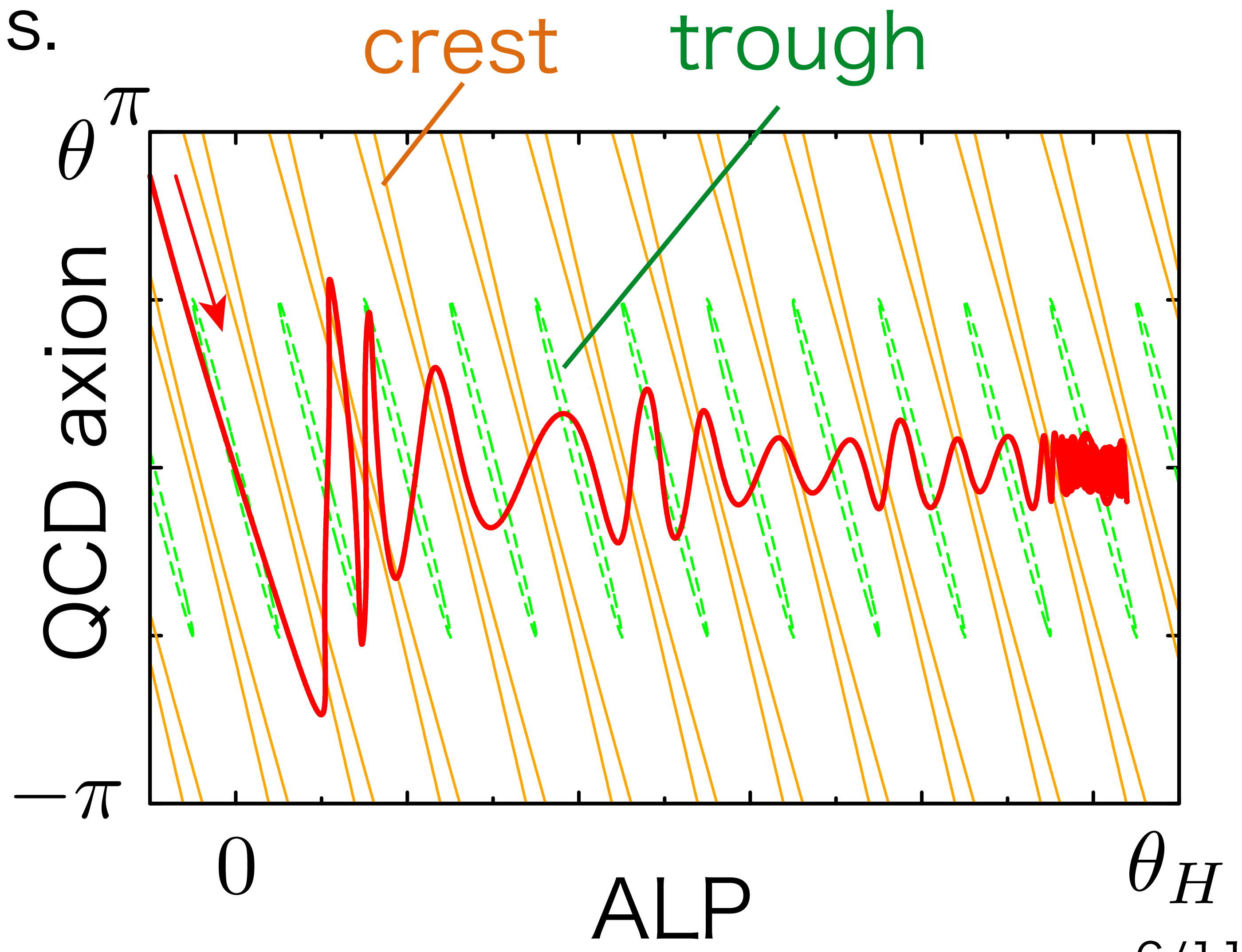
1.Kicked into different directions.

$$\frac{H_{\rm lc}}{H_{\rm osc}} = \mathcal{O}(0.1-1)$$

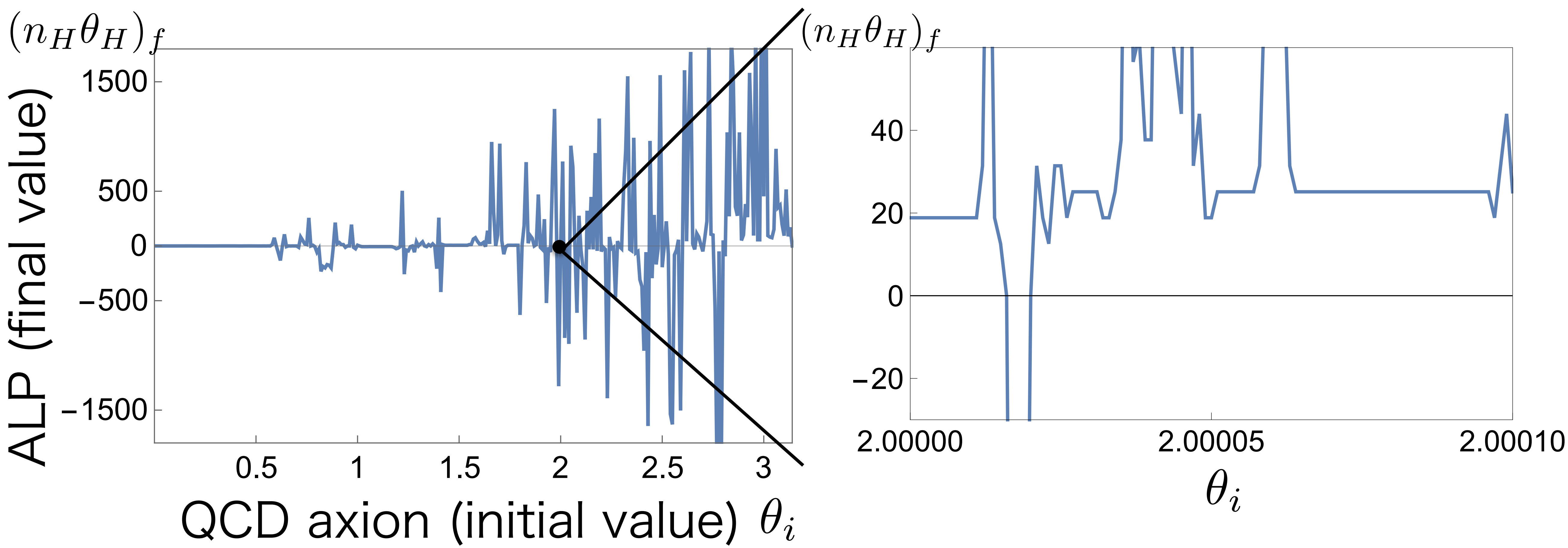
2.Initial energy is greater than the barrier.

$$\rho_{\rm osc} > \Lambda^4$$

@ oscillation



Numerical Results

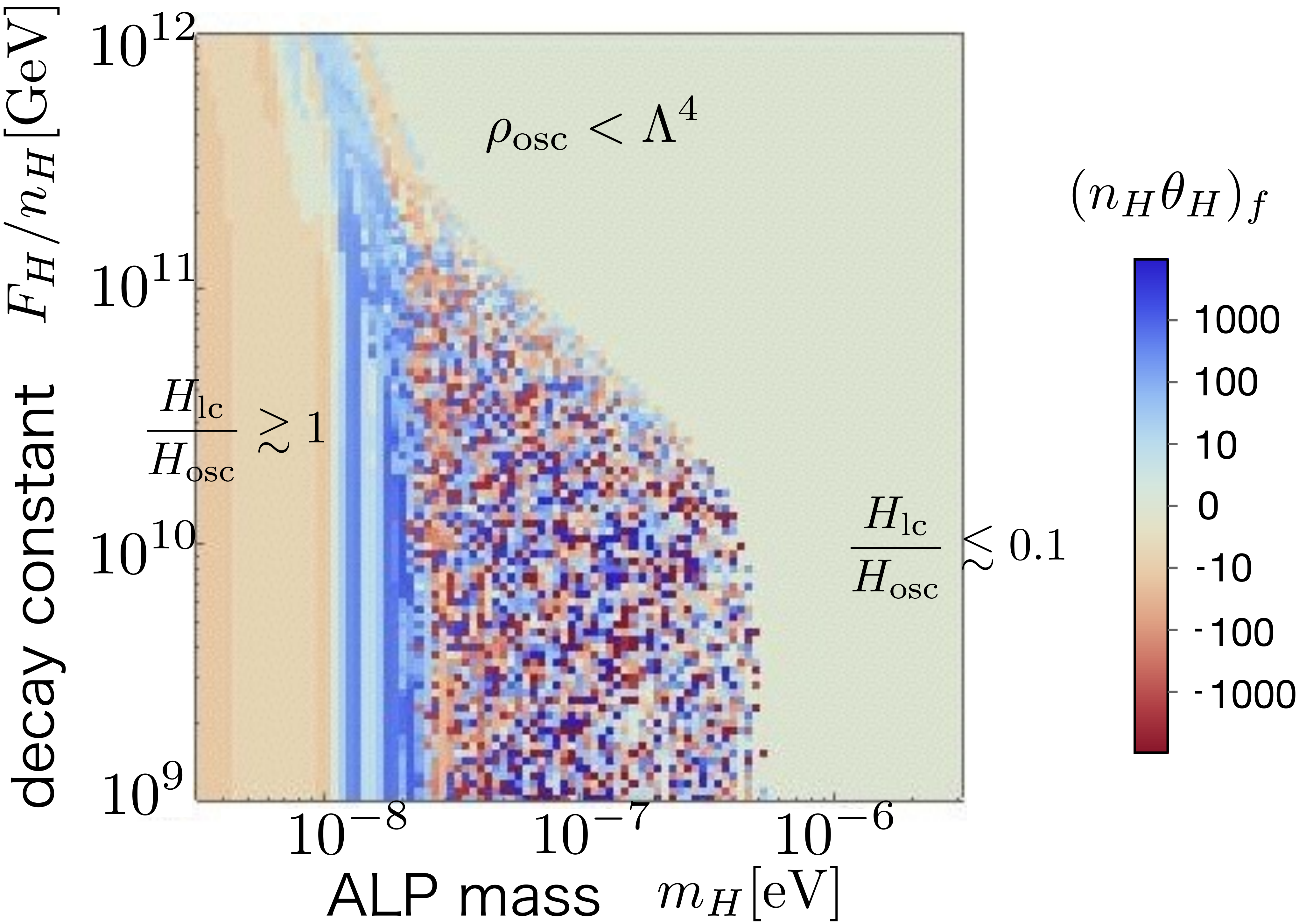


$$\theta_i = \frac{a_i}{F_a}$$

The final value is highly sensitive to θ_i .

The ALP takes different value even for $\delta\theta_i \sim 10^{-5}$.

Numerical Results



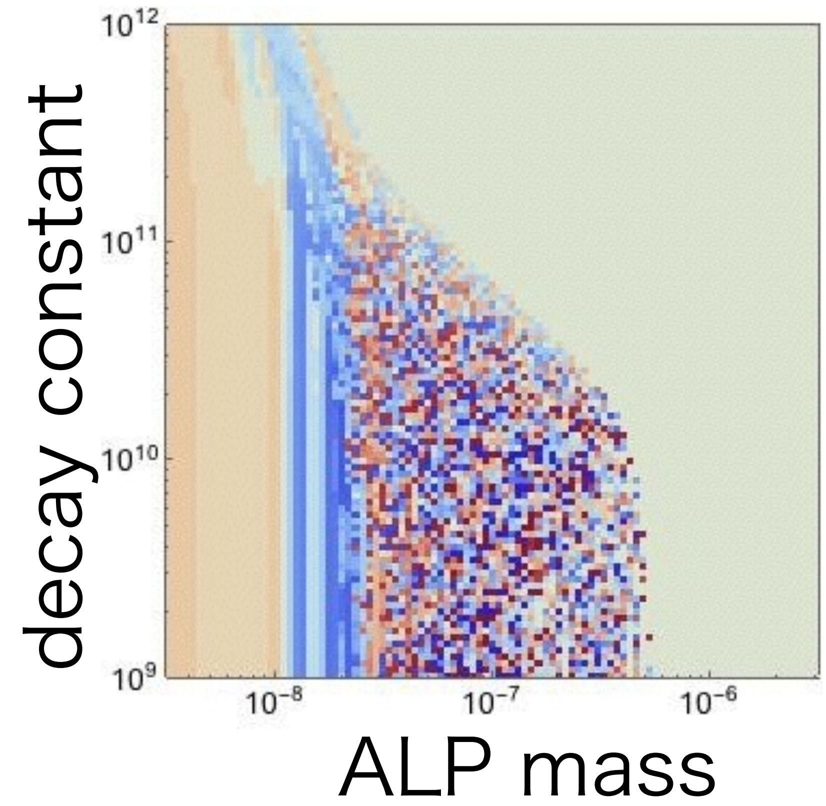
$$\frac{H_{\rm lc}}{H_{\rm osc}} = \mathcal{O}(0.1-1)$$
$$\rho_{\rm osc} > \Lambda^4$$

$$F_a = 10^{12}\,\text{GeV},\ \theta_i = 2.5,\ n_a = 5$$

Domain wall problem

If the axion roulette occurs, domain walls without cosmic strings are likely to be formed.

It is cosmologically problematic.



Solution 1

Diluting the domain wall by inflation.

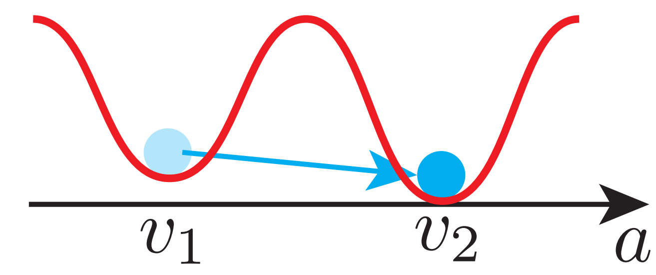
However, in our situation,..

It is unlikely that inflation continues until the QCD phase transition.

Domain wall problem

Solution 2

Introduce a bias term and makes the domain wall unstable.

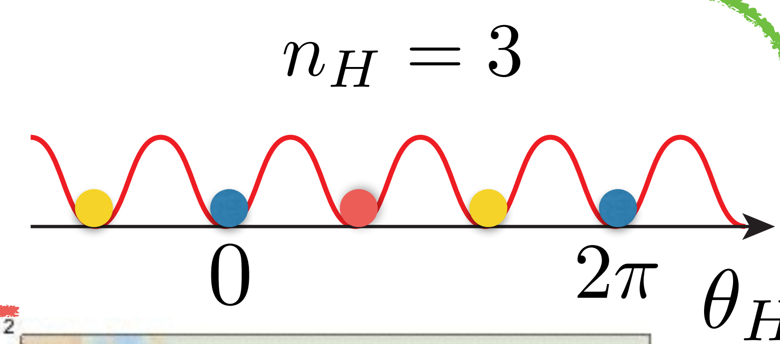


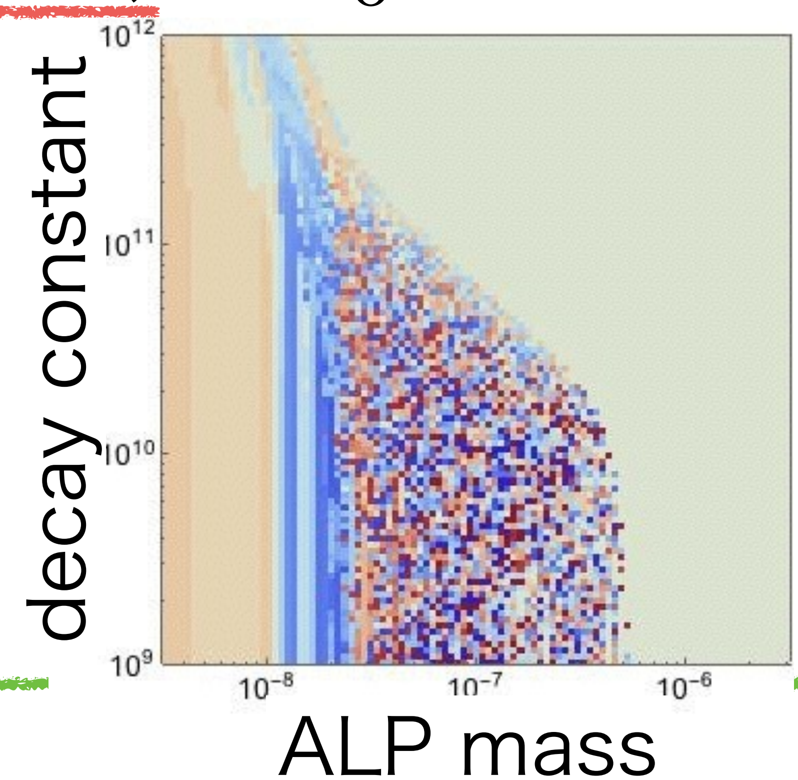
However, please note that..

- n_H determines identical minima.
- If the axion is trapped in identical minima, we cannot introduce bias.
- Bias can be introduced if

  $n_H \gg 1$ or

  the spatial variation of $(\theta_H)_f < 2\pi$.





Summary

- We studied level crossing between QCD axion and ALP.
- We found that the axion roulette occurs if the timing of level crossing is close to that of oscillation.
- We determined the parameter region where the axion roulette takes place.

$10^{-8}\mathrm{eV} \lesssim m_H \lesssim 5\times 10^{-7}\mathrm{eV},\ F_H/n_H \lesssim 10^{11}\mathrm{GeV}$ for $F_a = 10^{12}\mathrm{GeV}$

$10^{-7}\mathrm{eV} \lesssim m_H \lesssim 5\times 10^{-6}\mathrm{eV},\ F_H/n_H \lesssim 10^{9}\mathrm{GeV}$ for $F_a = 10^{10}\mathrm{GeV}$

- Stable domain wall is likely to be formed by the axion roulette.
- Bias can be introduced if $n_H \gg 1$ or the spatial variation of $(\theta_H)_f < 2\pi$.