TOHOKU UNIVERSITY

Dark Matter in Axion Landscape

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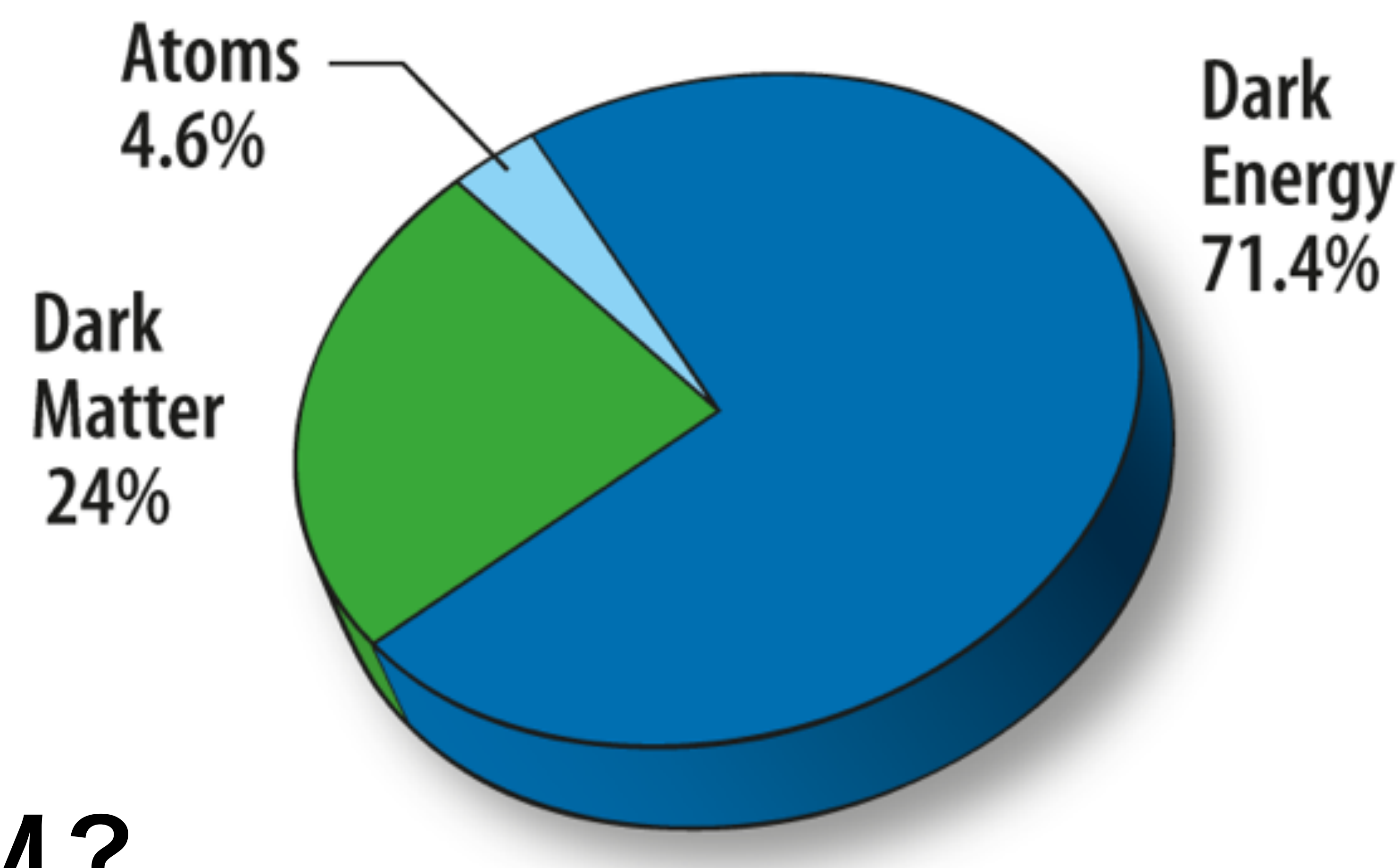
1608.04092

Introduction

The presence of Dark Matter (DM) has been confirmed by astrophysical and cosmological observations.

$$\Omega_{\rm DM} h^2 \simeq 0.12$$

Planck Collaboration 1502.01589



TODAY

What is DM ?

What we know

1. Cold

2. Long lifetime

   (light mass? very weak interaction? symmetry?)

3. Abundance

   $$\Omega_{\rm DM} h^2 \simeq 0.12$$

Known DM candidates

WIMP | Sterile neutrino
SIMP | Topological defects
Q-ball | Axion

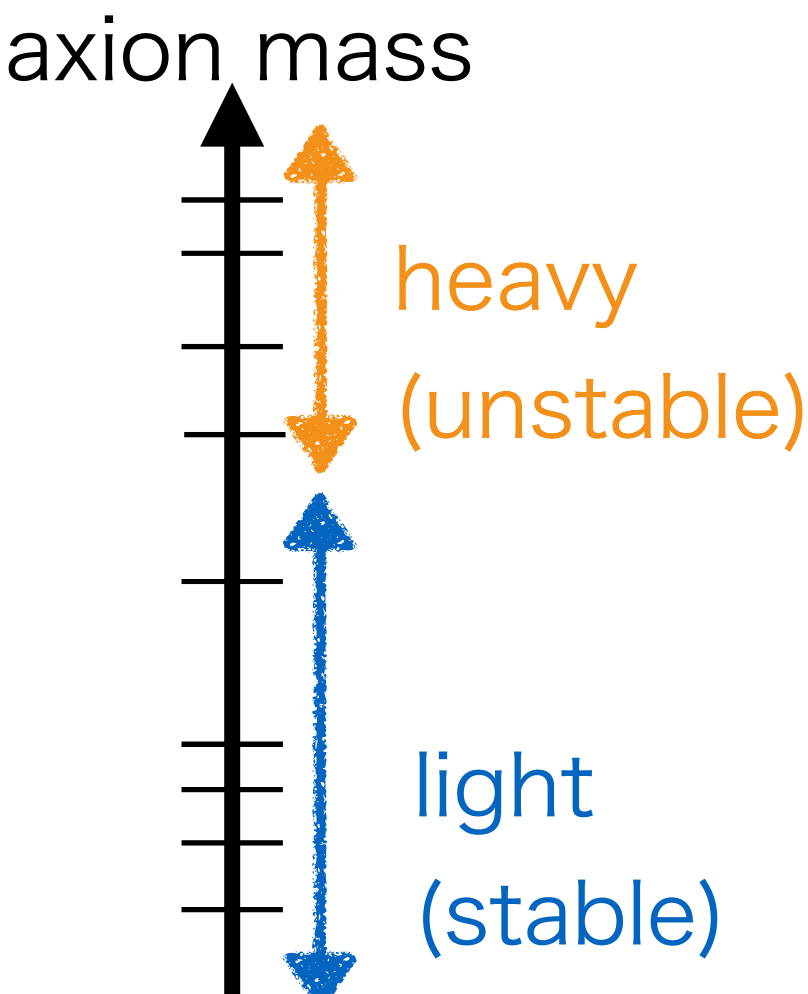
and so on..

Axion

In the string theory, there appear many axions in the conpactification of the extra dimensions. $f \sim 10^{15-16}\,\mathrm{GeV}$

Shift symmetry
$a_i \to a_i + C$

massless at perturbative level, but massive at non-pertubative level



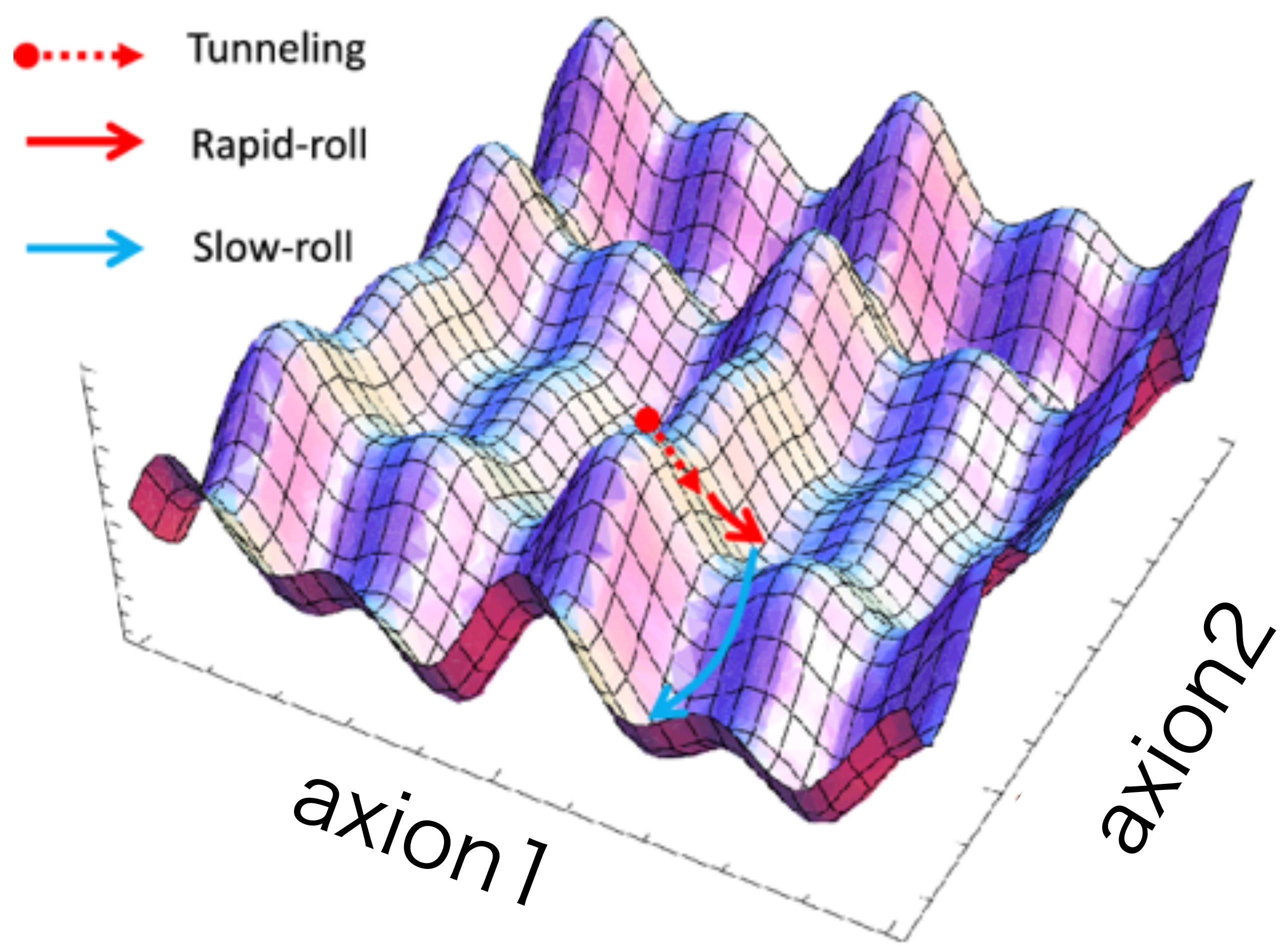
a lot of axions $\sim$ **Axiverse**
S. Dimopoulos et al. 0905.4720

The masses of axions range over many orders of magnitude.

Axion

If there are many axions and symmetry breaking terms, the potential may be quite complicated.

$$V(\phi_\alpha) = \sum_{i=1}^{N_S} \Lambda_i^4 \left[1 - \cos\left(\sum_{\alpha=1}^{N_A} n_{i\alpha}\frac{\phi_\alpha}{f_\alpha} + \delta_i\right)\right] + C$$



Axion Landscape

Higaki, Takahashi 1404.6923, 1409.8409

cf.

Aligned natural inflation

Kim, Nilles, Peloso, 0409138

Multi natural inflation

Czerny, Takahashi 1401.5212

Outline

1. Introduction

2. Axion dark matter

3. Axion Dynamics
in flat-bottomed potential

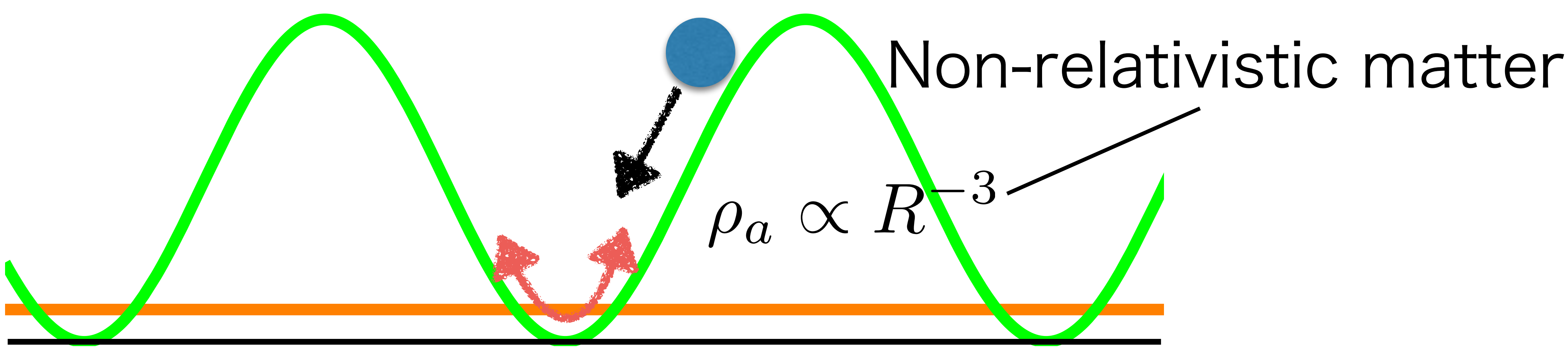
4. Summary

Axion Dark Matter

The axions acquire periodic potential by non-perturbative effects such as instanton.

Shift symmetry $a \to a + C$ ➡ Discrete shift symmetry $a \to a + 2\pi f$

$$V(a) \simeq \Lambda^4 \left[1 - \cos\left(\frac{a}{f}\right)\right] \simeq \frac{1}{2} m^2 a^2$$

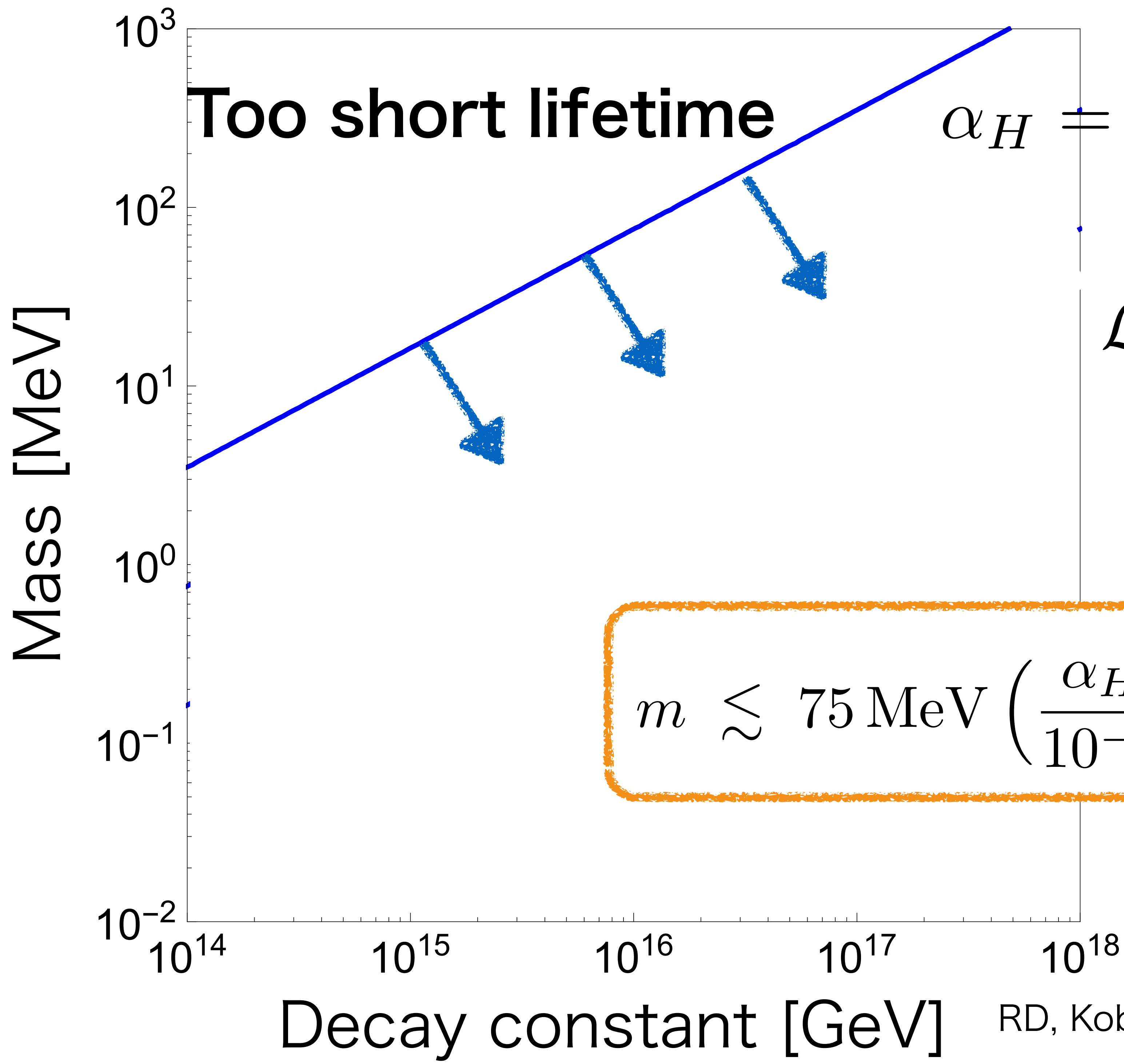


Light axion can be dark matter !

Mass and Lifetime

The lifetime of DM should be longer than 97 Gyr.

Enqvist, Nadathur, Sekiguchi, Takahashi 1505.05511



$$\alpha_H = 10^{-2}$$

$$\mathcal{L} \supset \frac{\alpha_H a}{4\pi f} F_{H,\mu\nu} \tilde{F}_H^{\mu\nu}$$

$$m \lesssim 75\,\mathrm{MeV} \left(\frac{\alpha_H}{10^{-2}}\right)^{-\frac{2}{3}} \left(\frac{f}{10^{16}\,\mathrm{GeV}}\right)^{\frac{2}{3}}$$

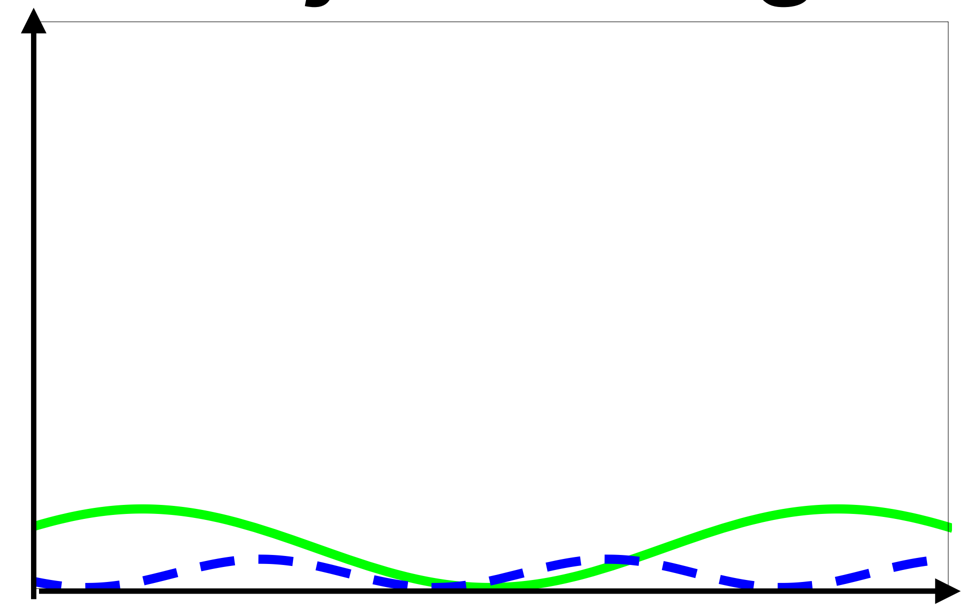
RD, Kobayashi, Takahashi 1608.04092

How to realize a light mass

Case1. Suppressing all the symmetry breakings

$m \sim 10^{-17}\,\mathrm{eV}$

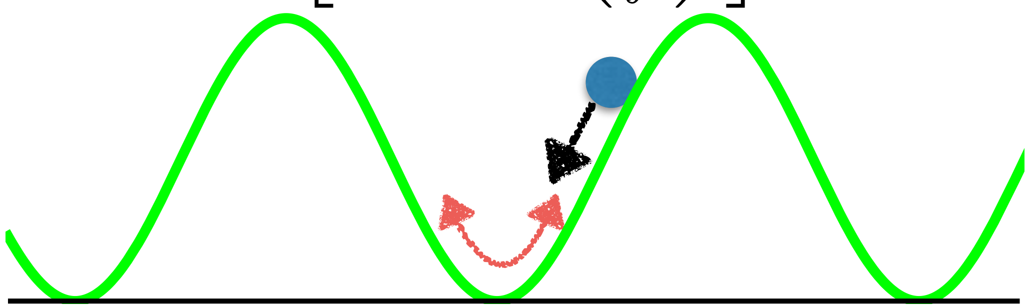
in general



Axion Abundance

If the potential is approximated by a single cosine term, the axion abundance is given by

$$V(a) \simeq \Lambda^4 \left[1 - \cos\left(\frac{a}{f}\right)\right] \simeq \frac{1}{2} m^2 a^2$$



$$\rho_a \propto R^{-3}$$

$$\Omega_a h^2 \simeq 0.2\, \theta_{\rm osc}^2 \left(\frac{m}{10^{-17}\,{\rm eV}}\right)^{1/2} \left(\frac{f}{10^{16}\,{\rm GeV}}\right)^2$$

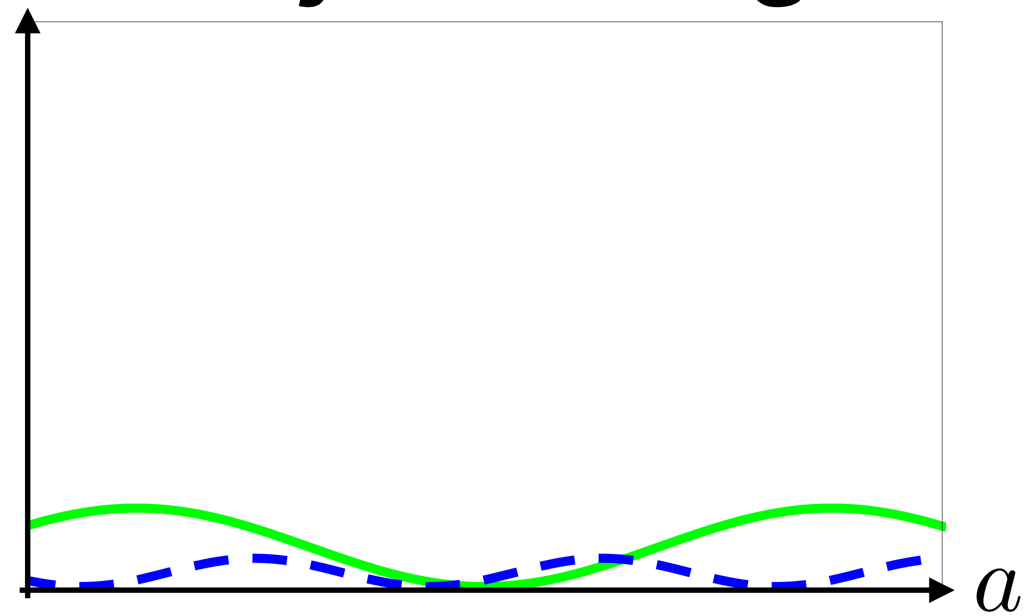
In order to explain all the DM abundance, the axion should be ultralight ($m \sim 10^{-17}\,{\rm eV}$) and so, it is completely stable!

How to realize a light mass

Case1. Suppressing all the symmetry breakings

$$m \sim 10^{-17}\,\mathrm{eV}$$

in general



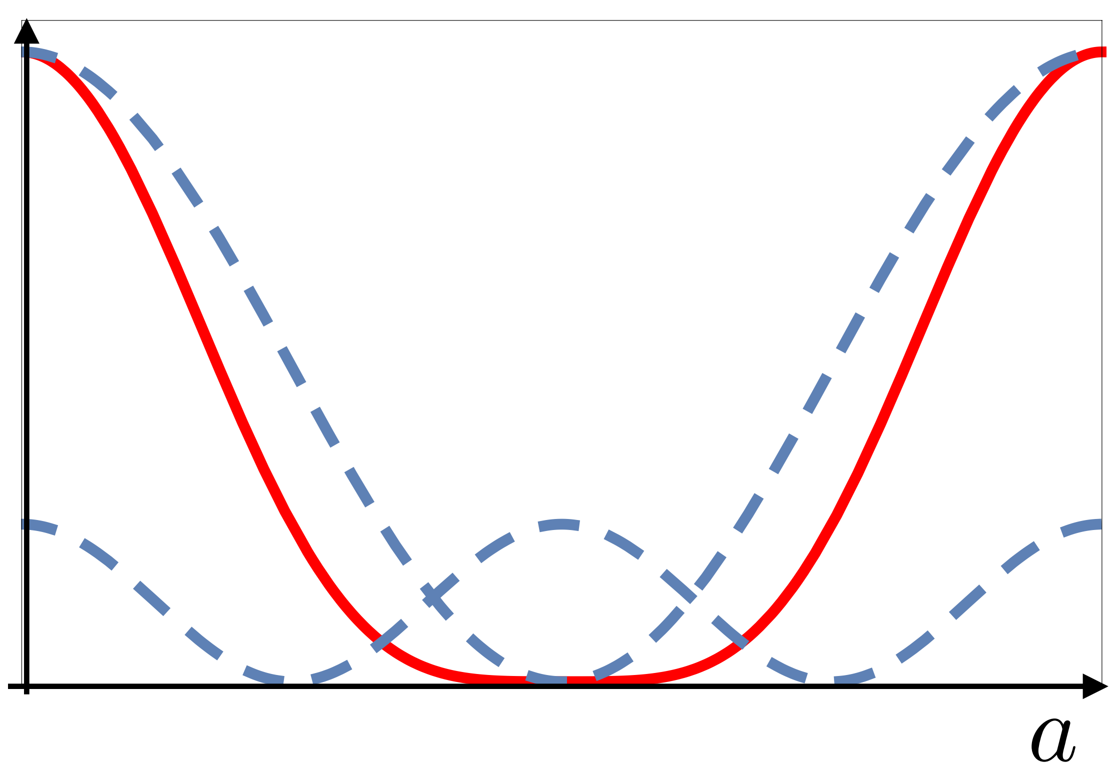
Case2. Cancellation among symmetry breaking terms

The mass can be small even if the curvatures of each potential is large.

➡ Flat-bottomed potential

cf. Inflation based on elliptic function

Higaki, Takahashi 1501.02354



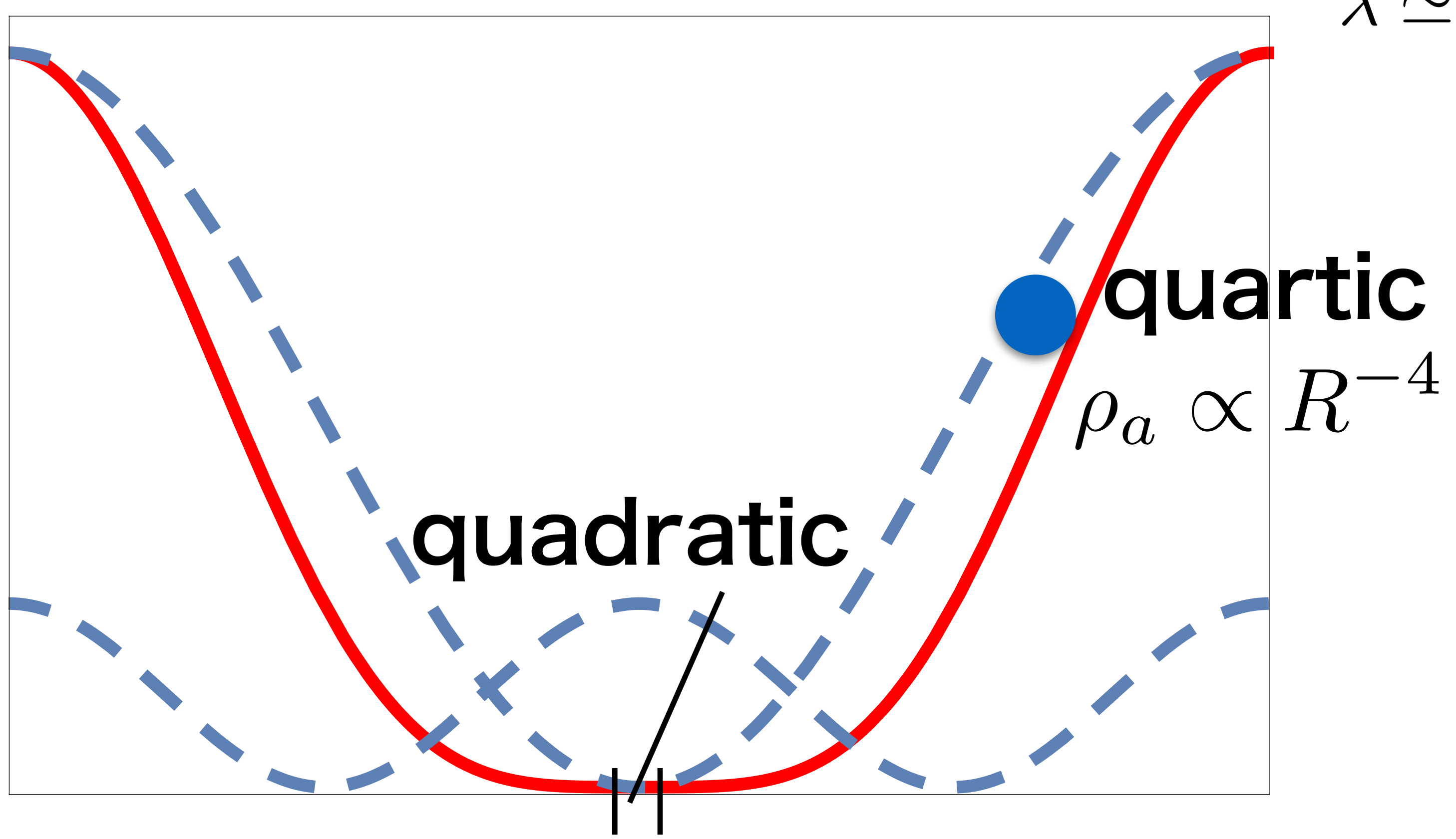
Flat-bottomed Potential

To be concrete, we consider minimal setup

$$V(a) = \Lambda_1^4\left[1-\cos\left(n_1\frac{a}{f}\right)\right] + \Lambda_2^4\left[1-\cos\left(n_2\frac{a}{f}+\delta\right)\right] + C \qquad M_i \equiv \frac{n_i\Lambda_i^2}{f}$$

$$\Rightarrow \quad V(a) \simeq \frac{m^2}{2}a^2 + \frac{\lambda}{4!}a^4 \qquad m^2 \equiv M_1^2 - M_2^2$$

$$\lambda \simeq (n_2^2 - n_1^2)\frac{M_1^2}{f^2}$$



The abundance and the isocurvature perturbation are modified drastically !

Outline

1. Introduction

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3. Axion Dynamics in flat-bottomed potential

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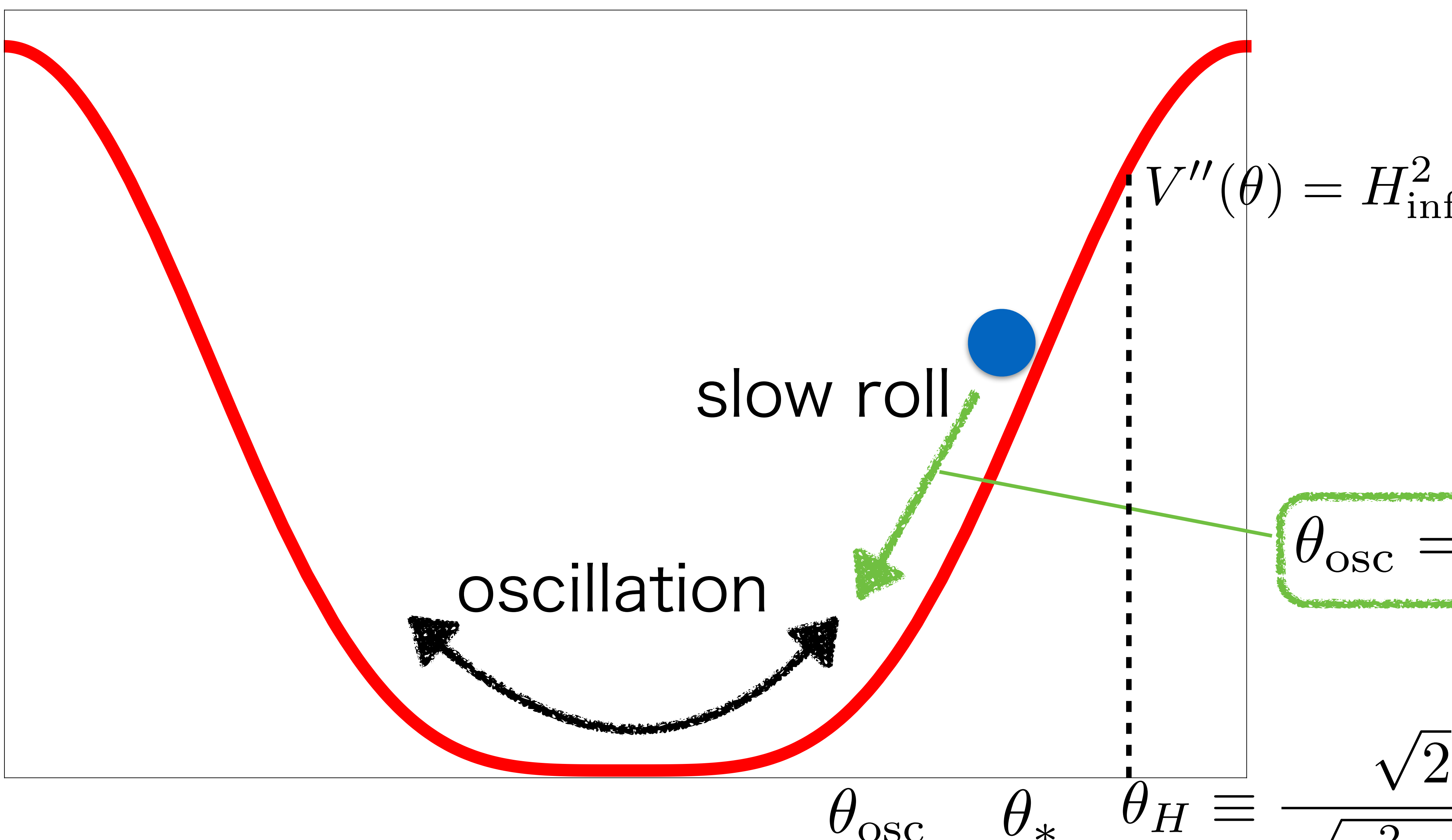
Axion Dynamics

When axion (θ) starts to oscillate is essential to estimate the abundance and the isocurvature perturbation.

$$\theta \equiv \frac{a}{f}$$



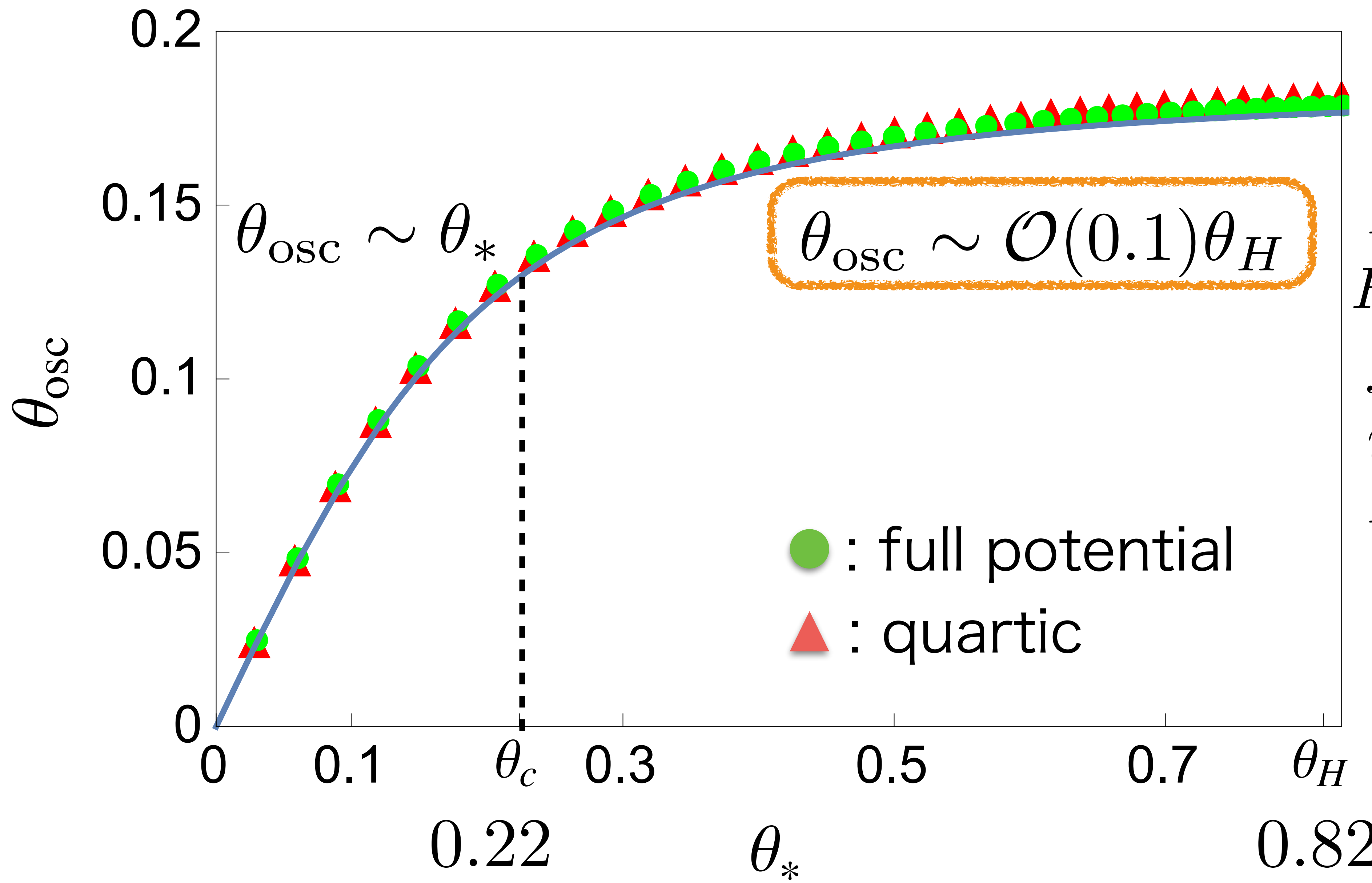
$$\theta_{\rm osc} = \theta_{\rm osc}(\theta_*)$$

$$\theta_H \equiv \frac{\sqrt{2}}{\sqrt{n_2^2 - n_1^2}} \frac{M_i}{H_{\rm inf}}$$

Axion Dynamics

$$\theta_{\rm osc} \simeq \sqrt{\frac{2}{3}} \frac{\theta_*}{\sqrt{1+\left(\frac{\theta_*}{\theta_c}\right)^2}}$$

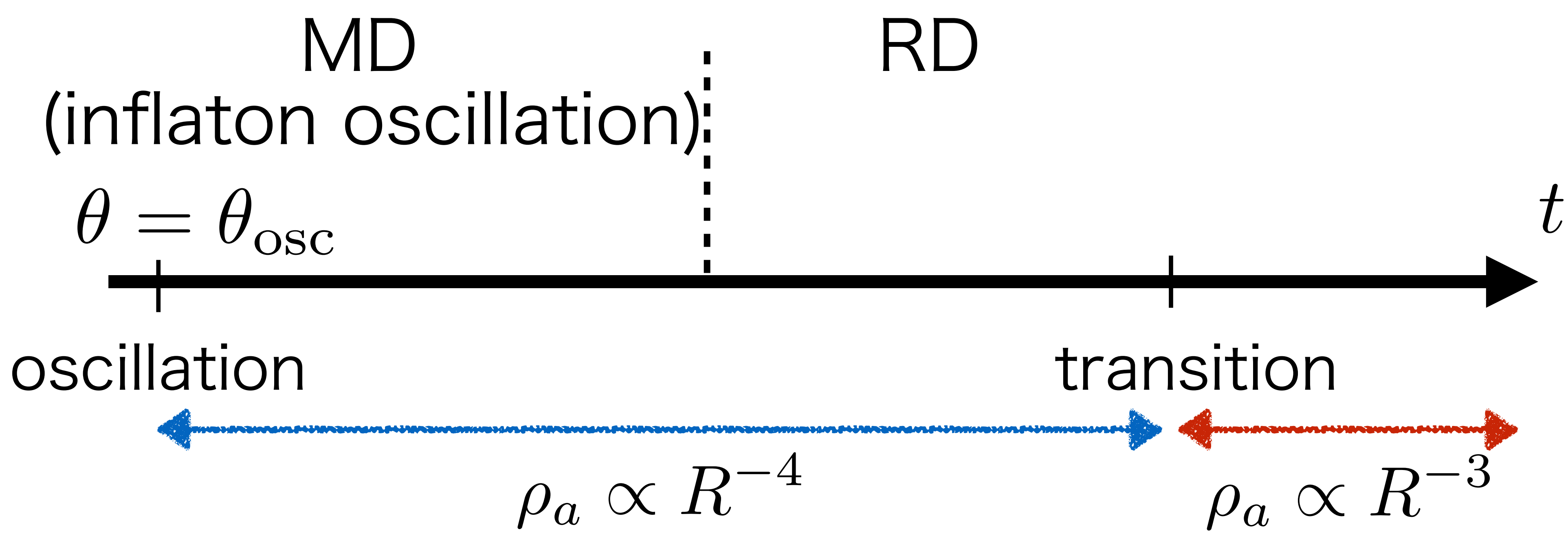
$$\theta_c \equiv \frac{3}{\sqrt{2N_*}}\theta_H \sim \mathcal{O}(0.1)\theta_H$$



$M_i = 10^{12}$ GeV
$H_{\rm inf} = 10^{12}$ GeV
$f = 10^{16}$ GeV
$n_1 = 1 \quad n_2 = 2$
$N_* = 60$

Axion Abundance

Assuming that the axion starts to oscillate before reheating, the abundance is given as follows.



$$\Omega_a h^2 \simeq \frac{0.3}{n_2^2 - n_1^2} \left(\frac{\theta_{\rm osc}}{0.1\theta_H}\right) \left(\frac{m}{100\,{\rm MeV}}\right) \left(\frac{f}{10^{16}\,{\rm GeV}}\right)^2 \left(\frac{T_{\rm reh}}{10^{10}\,{\rm GeV}}\right) \times \left(\frac{M_1}{10^{12}\,{\rm GeV}}\right)^{-2} \left(\frac{H_{\rm inf}}{10^{12}\,{\rm GeV}}\right)$$

cf. $m \sim 10^{-17}\,{\rm eV}$

The axion mass can be 100 MeV !

Isocurvature perturbation

During inflation the axion acquires quantum fluctuations which result in axionic isocurvature perturbations.

The isocurvature perturbation is tightly constrained.

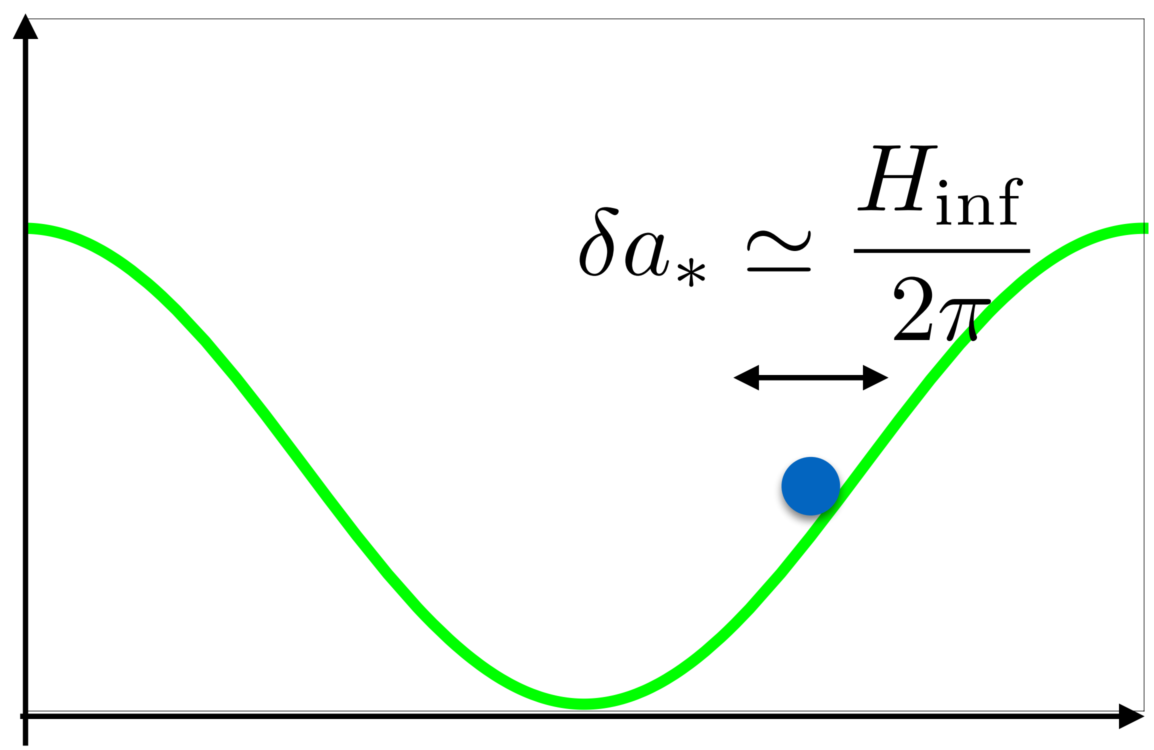
$$\mathcal{P}_S \lesssim 0.04\mathcal{P}_R = 8.7 \times 10^{-11}$$

$$\mathcal{P}_S = (r_a \, \Delta_{a,S})^2$$

$$r_a = \frac{\Omega_a}{\Omega_{\rm DM}}$$

$$\Delta_{a,S} = \frac{\partial \ln \Omega_a}{\partial \theta_*} \frac{\delta a_*}{f} \simeq \frac{\partial \ln \Omega_a}{\partial \theta_*} \frac{H_{\rm inf}}{2\pi f}$$

Kawasaki, Kurematsu, Takahashi, 1304.0922



Isocurvature perturbation

single cosine $\Omega_a \propto \theta_{\rm osc}^2 \propto \theta_*^2$

$$\Delta_{a,S}^2 = \left(\frac{H_{\rm inf}}{\pi f \theta_*}\right)^2 \simeq 1 \times 10^{-9} \frac{1}{\theta_*^2} \left(\frac{H_{\rm inf}}{10^{12}\,{\rm GeV}}\right)^2 \left(\frac{f}{10^{16}\,{\rm GeV}}\right)^{-2}$$

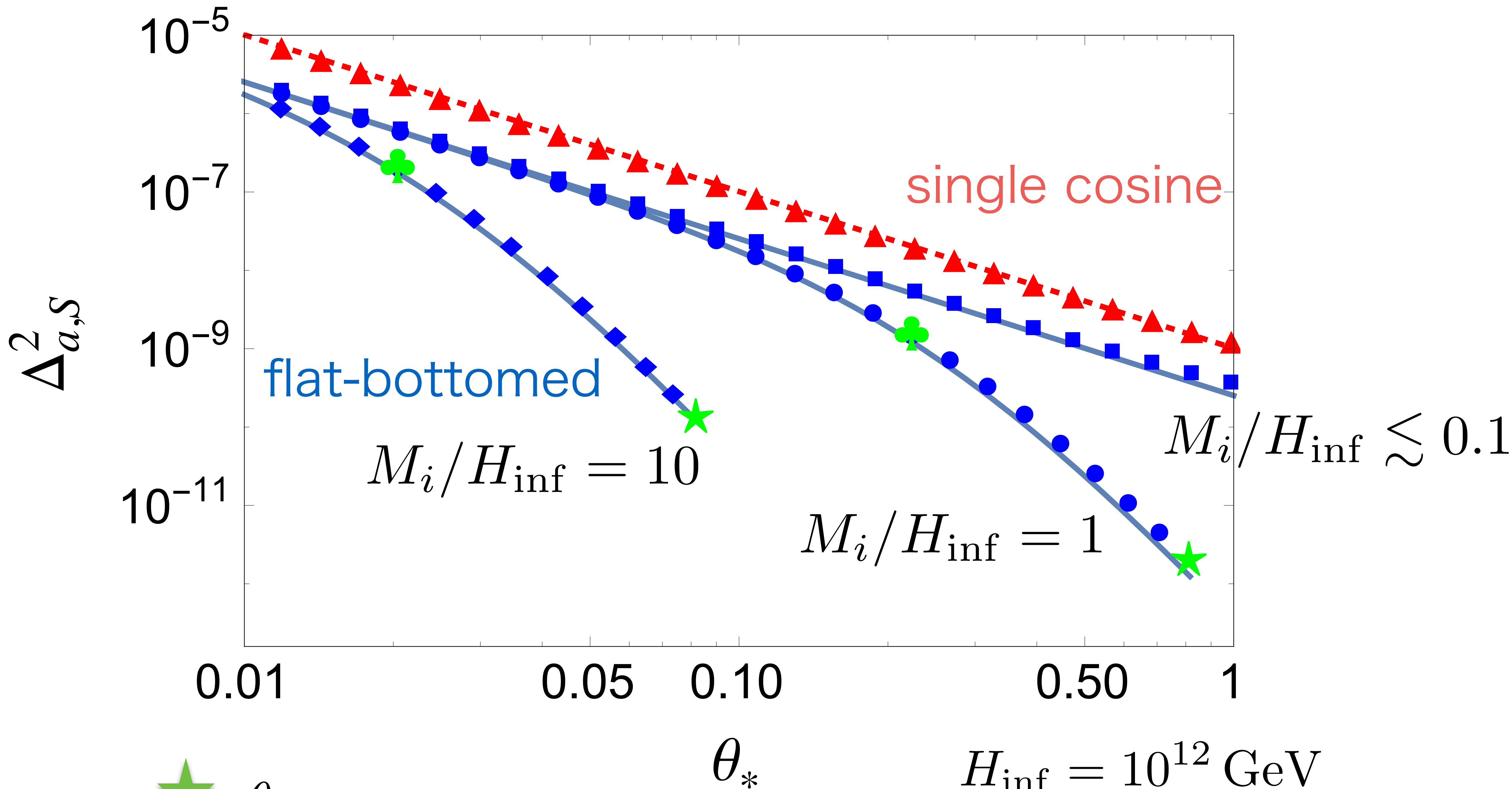
flat-bottomed $\Omega_a \propto \theta_{\rm osc}$

$$\Delta_{a,S}^2 = \left(\left(\frac{1}{\theta_*} - \frac{\theta_*/\theta_c^2}{1+(\theta_*/\theta_c)^2}\right)\frac{H_{\rm inf}}{2\pi f}\right)^2$$

$$\simeq 2.5 \times 10^{-10} \frac{1}{\theta_*^2} \left(\frac{1}{1+(\theta_*/\theta_c)^2}\right)^2 \left(\frac{H_{\rm inf}}{10^{12}\,{\rm GeV}}\right)^2 \left(\frac{f}{10^{16}\,{\rm GeV}}\right)^{-2}$$

The isocurvature perturbation can be suppressed by at most a few orders of magnitude !

Results



★: θ_H

$H_{\rm inf} = 10^{12}$ GeV
$f = 10^{16}$ GeV
$n_1 = 1 \quad n_2 = 2$
$N_* = 60$

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Summary

- If many axions in the nature, one (some) of them may be DM.
- To this end, the axion must be sufficiently light.
- There are two ways to realize a light mass.

①suppressing all the symmetry breaking terms

➡ $m \sim 10^{-17}\,\mathrm{eV}$

②cancellation among the symmetry breaking terms

➡ **flat-bottomed potential**

- In the latter case, the abundance and the isocurvature perturbation are significantly suppressed, and the axion mass 100 MeV is possible