Axion dark matter and inflation scale

Wen Yin (Tohoku University)

Mainly based on 1805.08763

In collaboration with
Fuminobu Takahashi, and Alan Guth

July 29th 2021 @ workshop on very light DM 2021

Introduction

Parameter region of QCD Axion DM

Peccei, Quinn, 77; Weinberg, 78; Wilczek, 78;

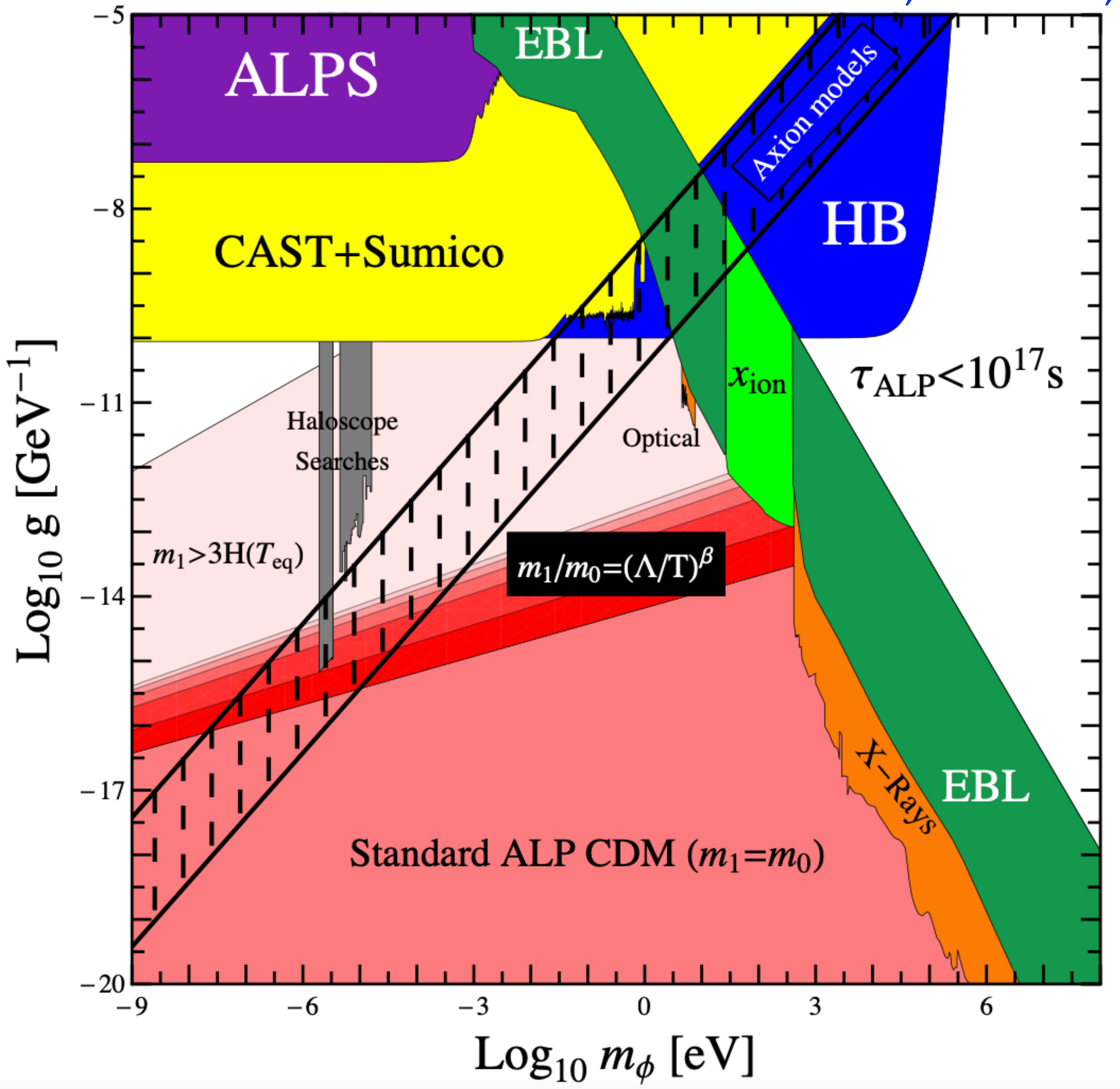
QCD axion may be fully tested in the near future by assuming the axion is dominant DM.

How to produce the axion abundance in the early Universe?

See Joerg's talk on youtube.

Arias et al,1201.5902;

Irastorza, Redondo,1801.08127



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I focus on **Preinflation model:** see UV model for also Kim, 79; Shifman, Vainstein, Zakharov, 80; Zhitnitsky, 80; Dine, Fischler, Srednicki '81;

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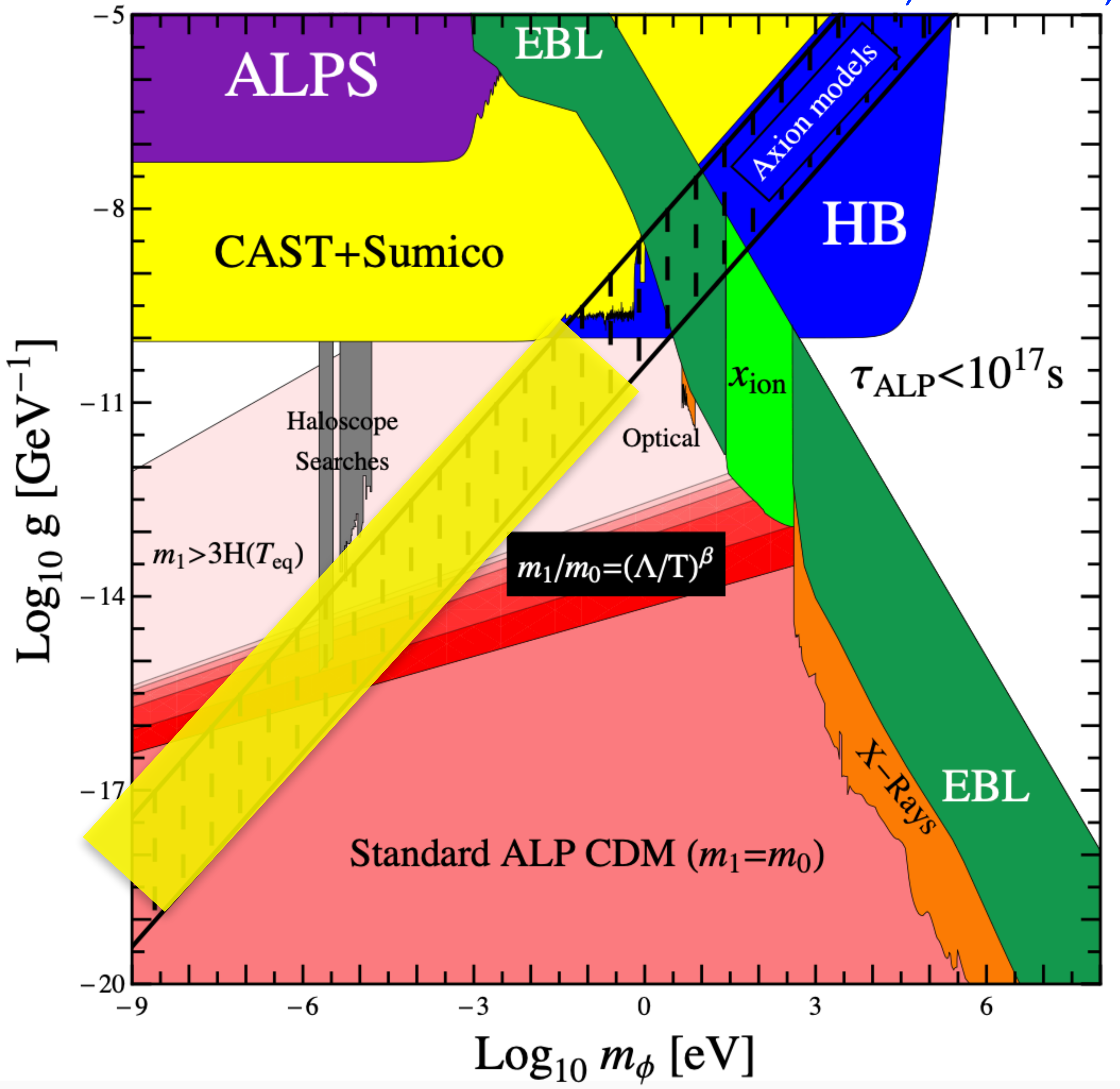

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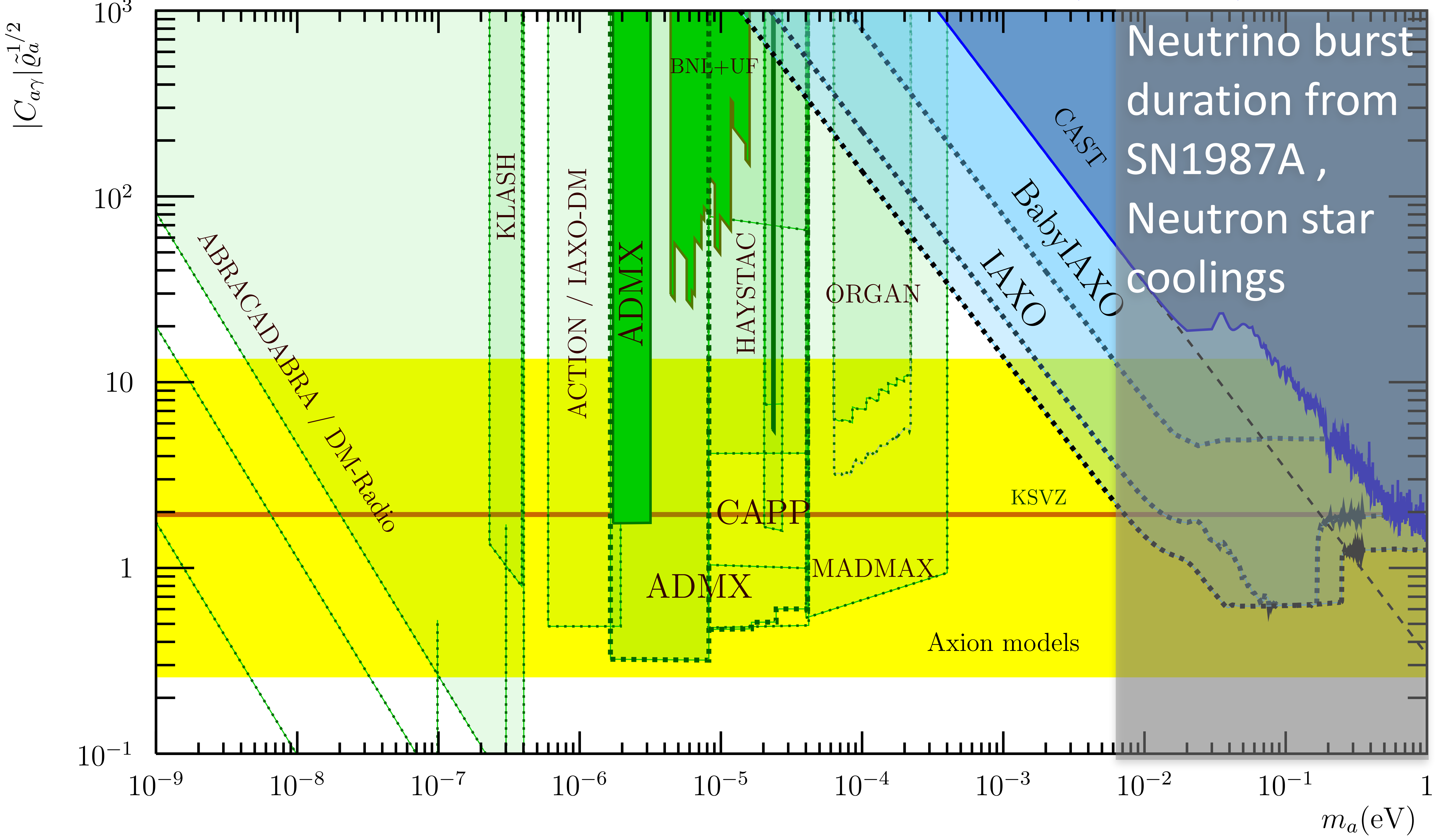

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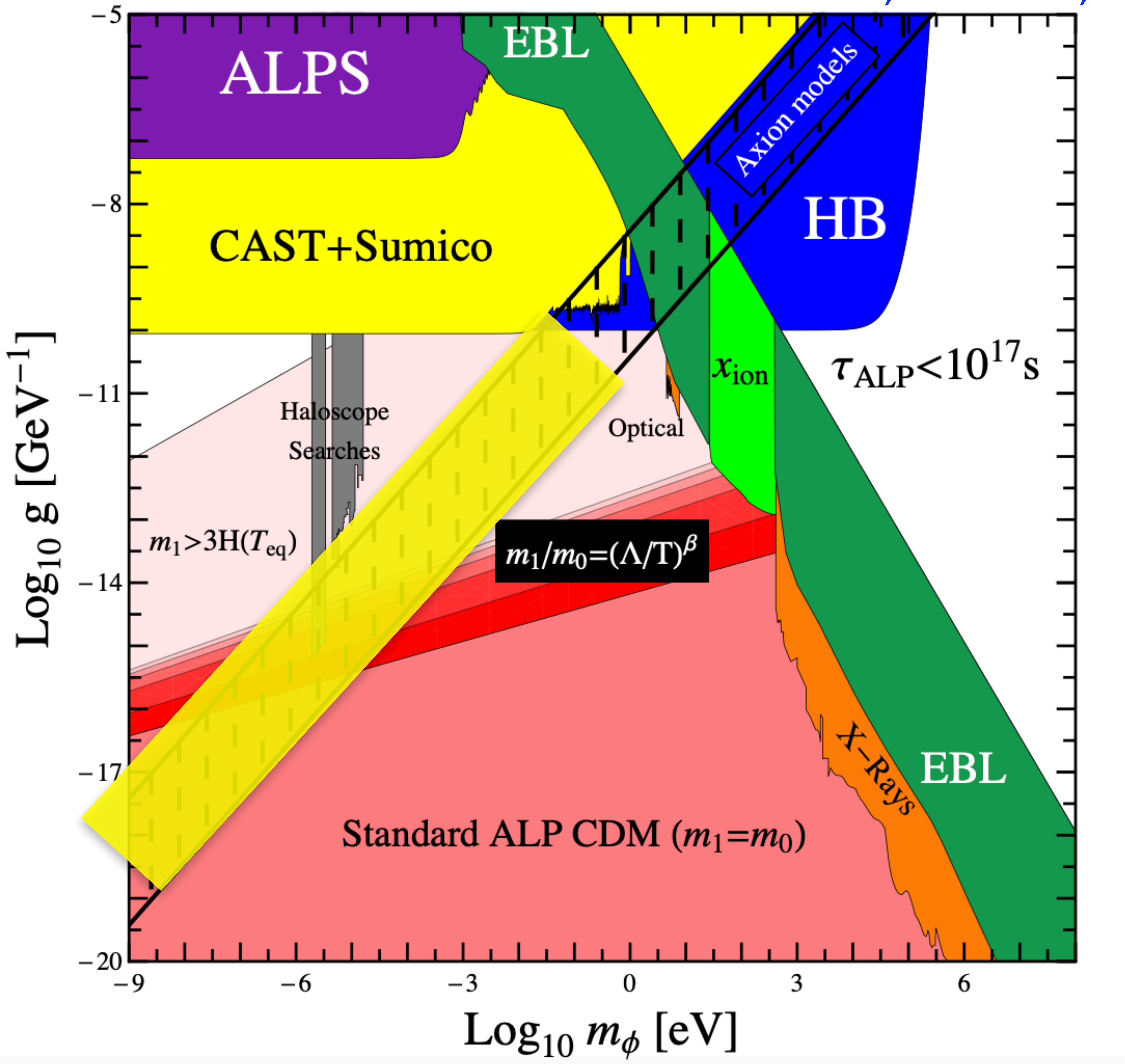

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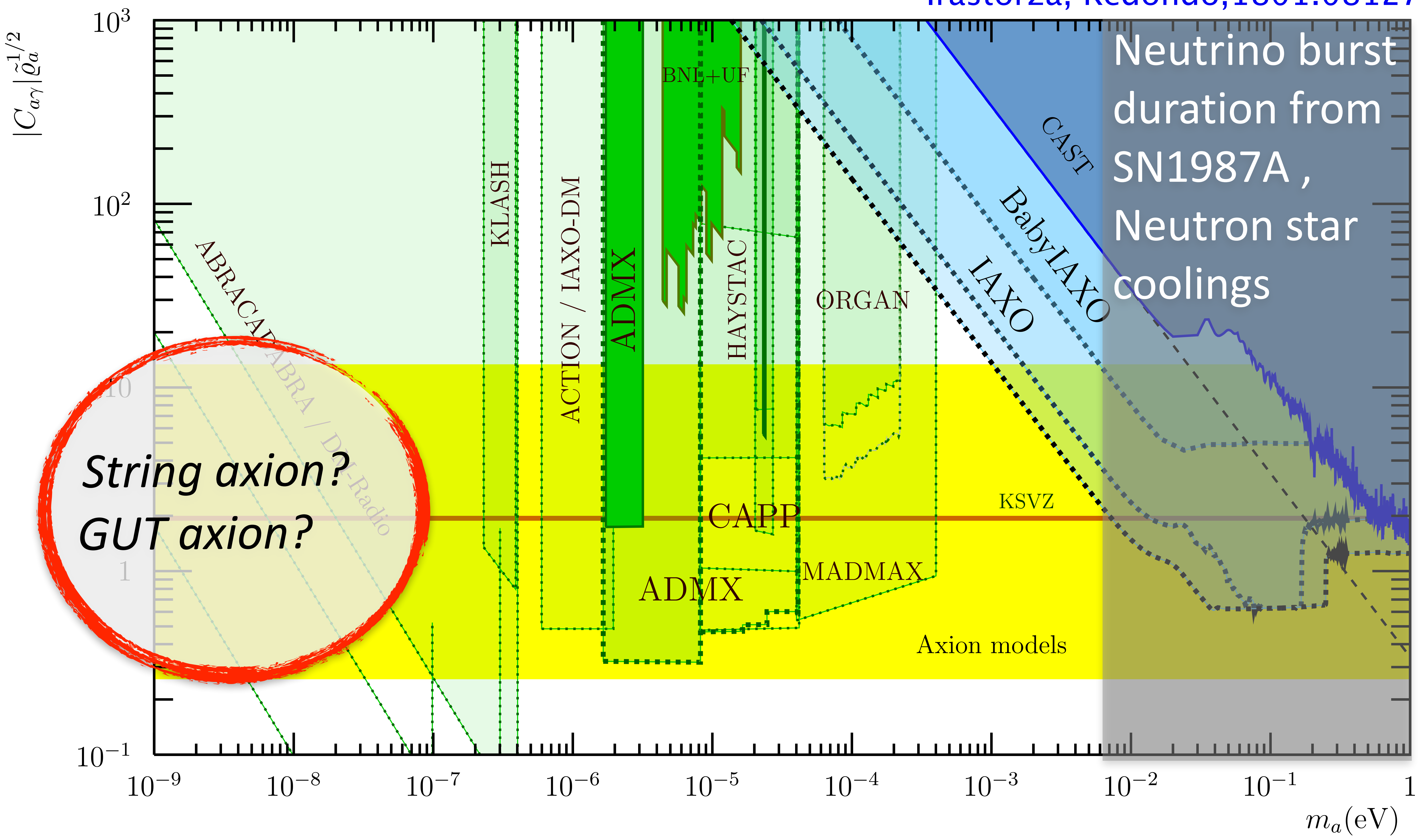

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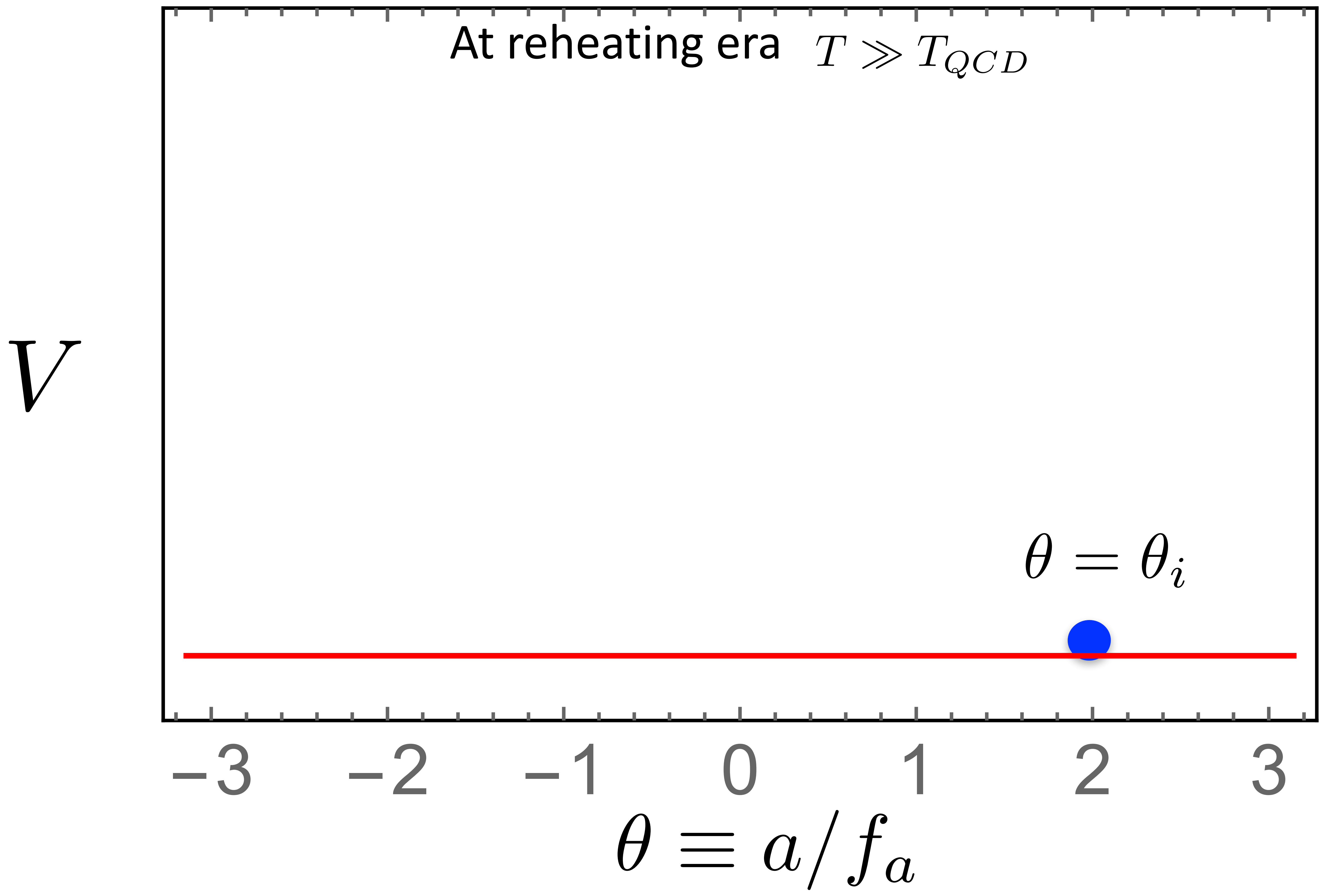

See also anthropic principle:
Linde, 91;Wilczek,0408167; Tegmark, et al. 0511774.

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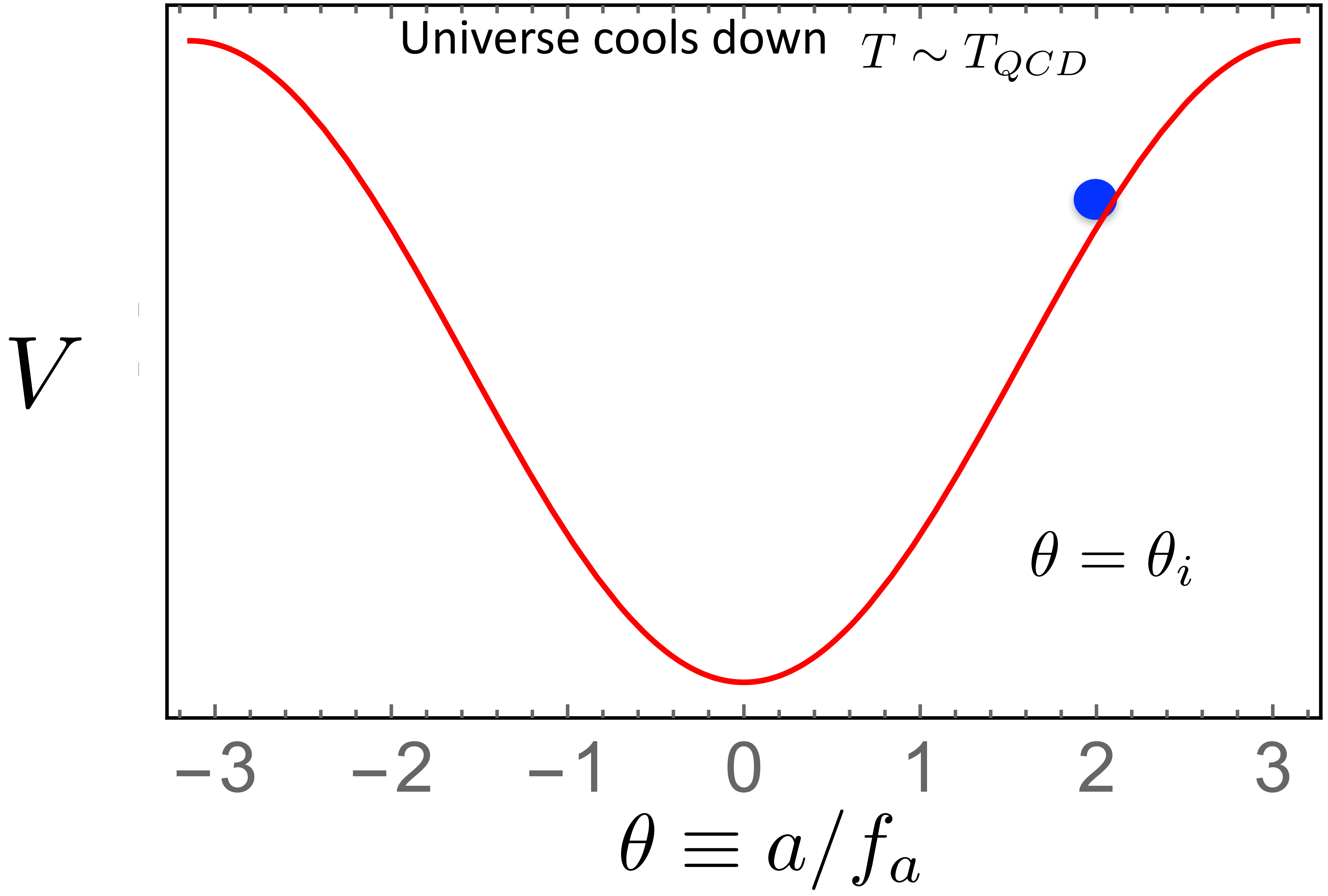

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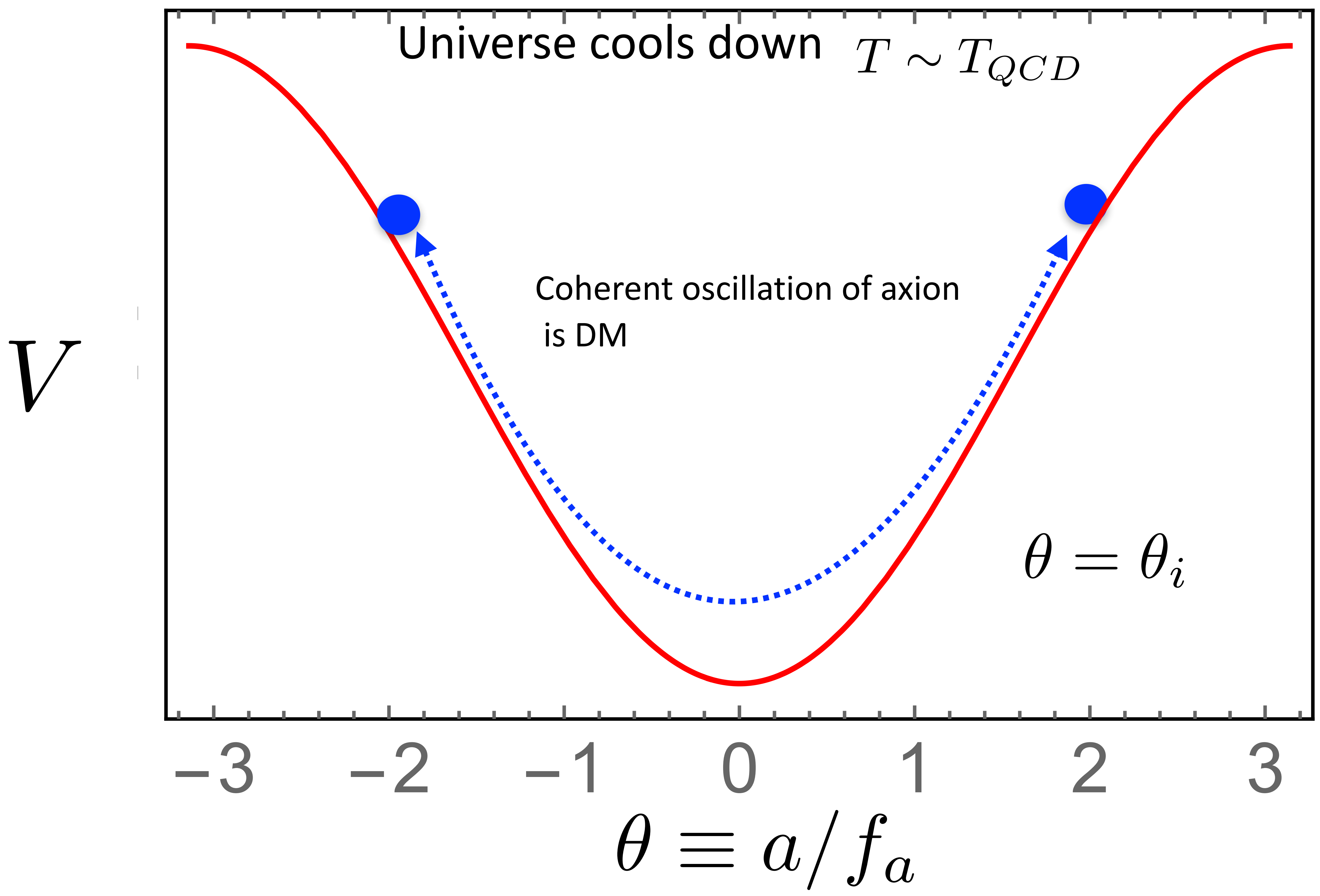

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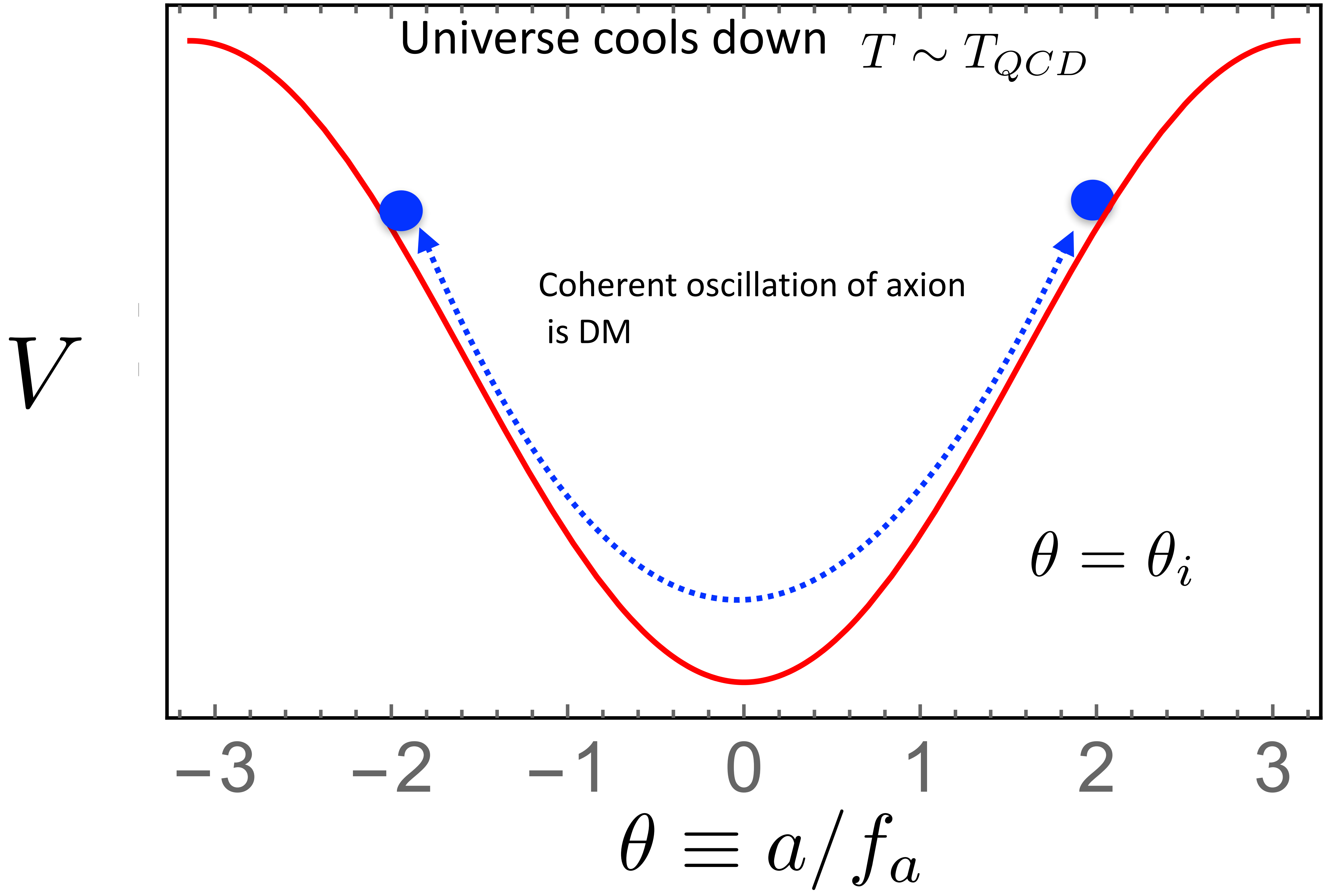
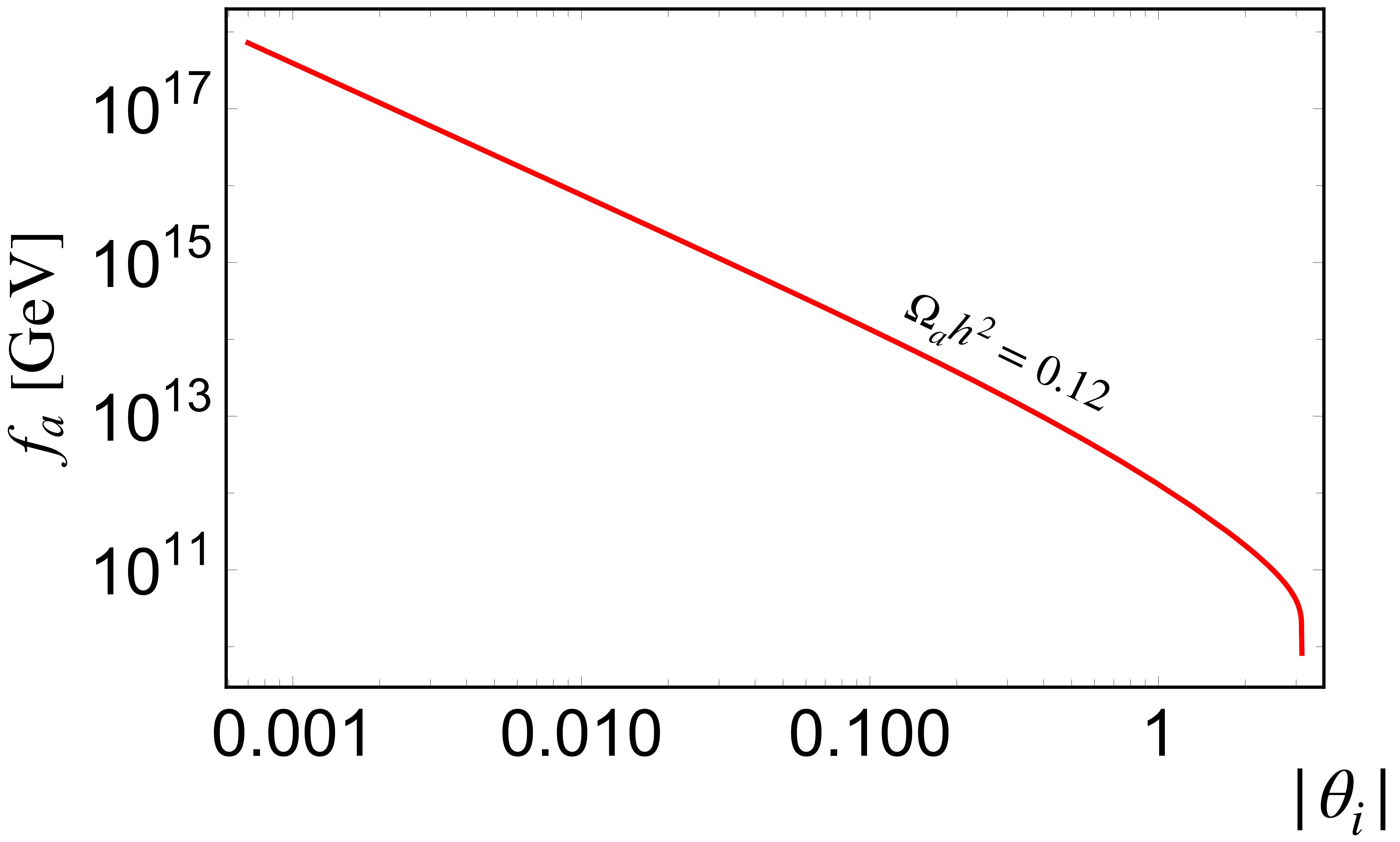


To explain the DM abundance we need



Bae et al, 0806.0497; Visinelli, Gondolo, 0903.4377; Ballesteros et al, 1610.01639, for making the figure.

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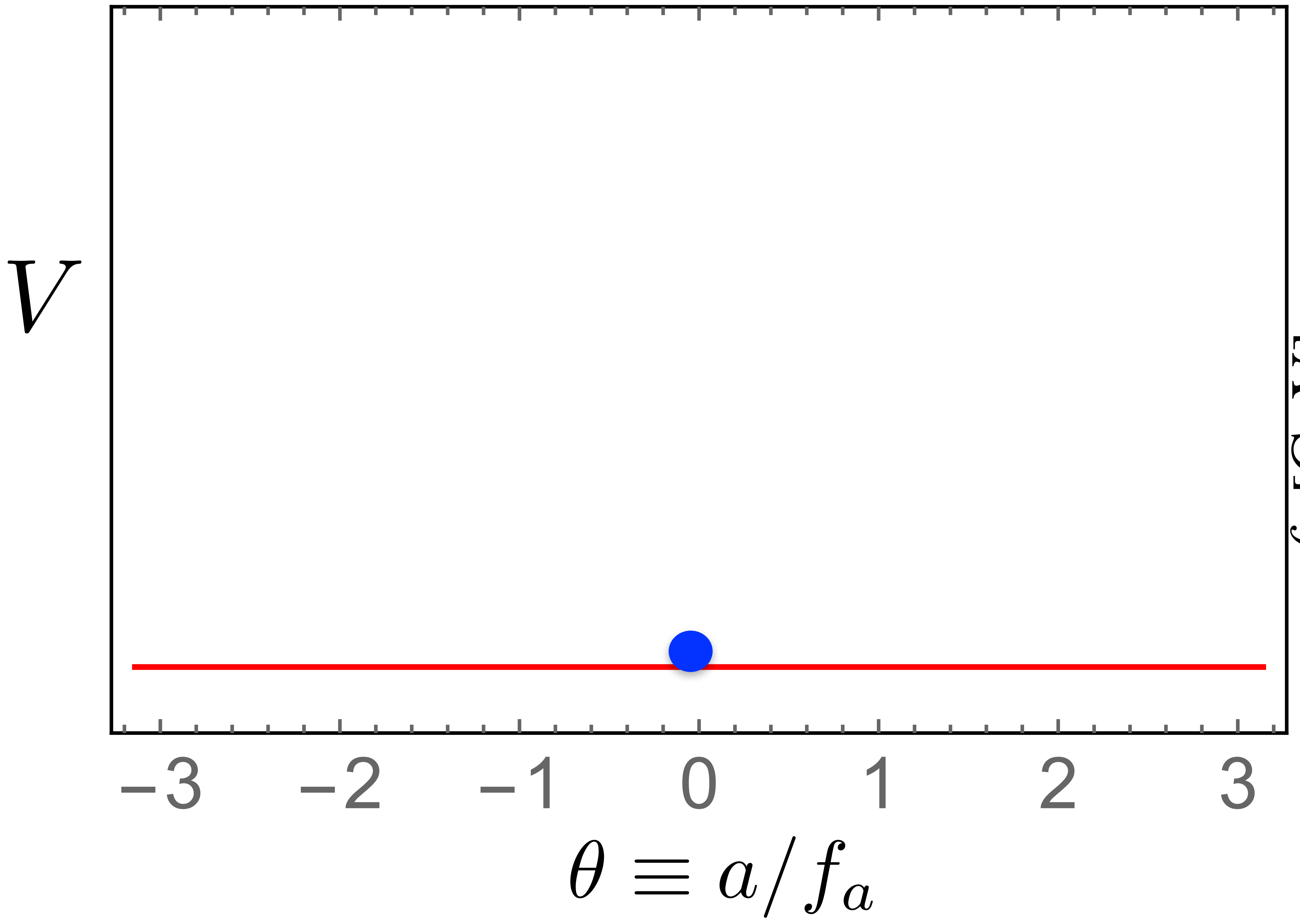
Axion distribution during high-scale inflation $(H_{\rm inf} \gg \Lambda_{QCD})$ and isocurvature problem

During inflation, light scalar field undergoes random walk due to the de-sitter space dynamics.

$$\langle (a - a_0)^2 \rangle \sim \Delta N_{\rm efold} \frac{H_{\rm inf}^2}{4\pi^2}$$



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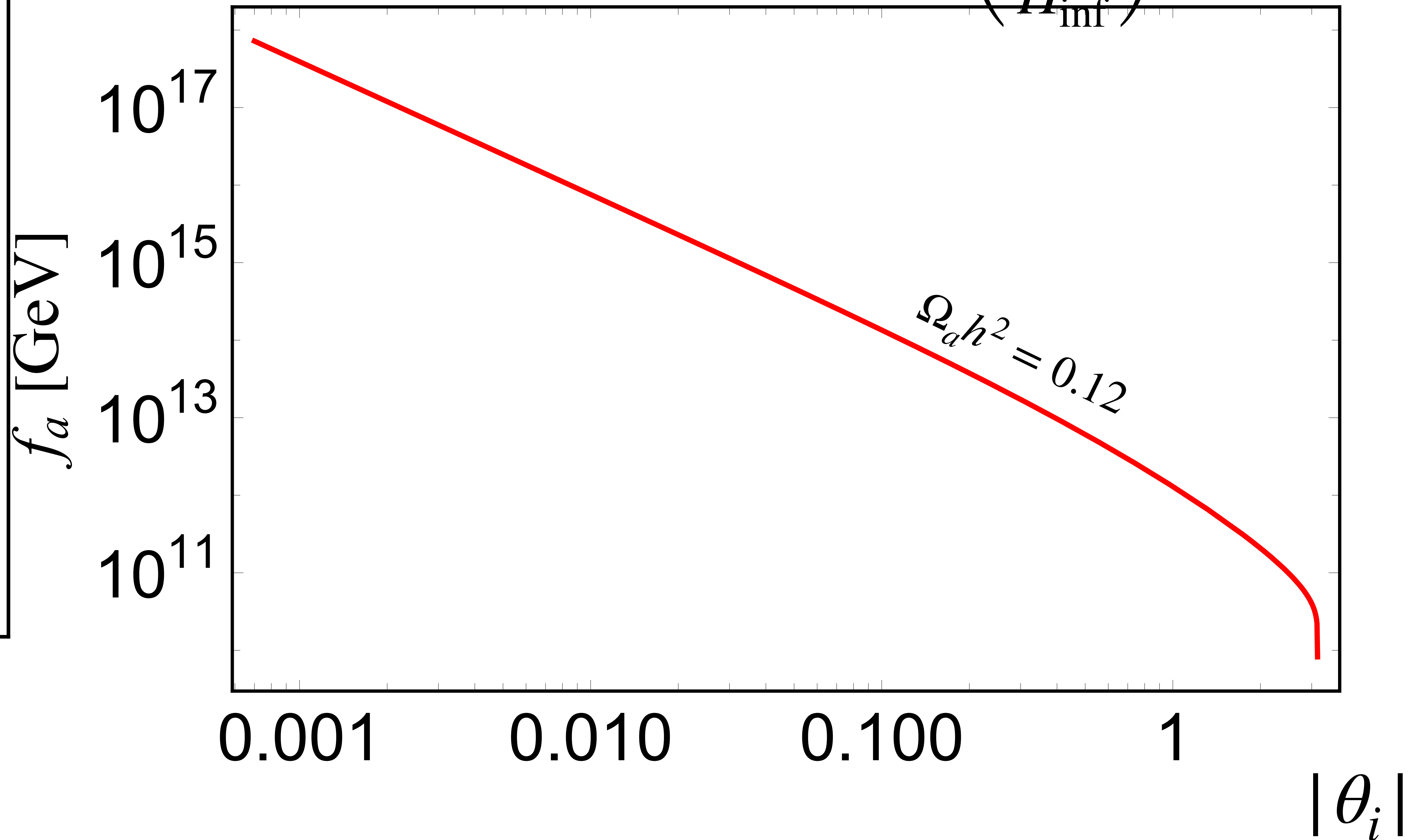

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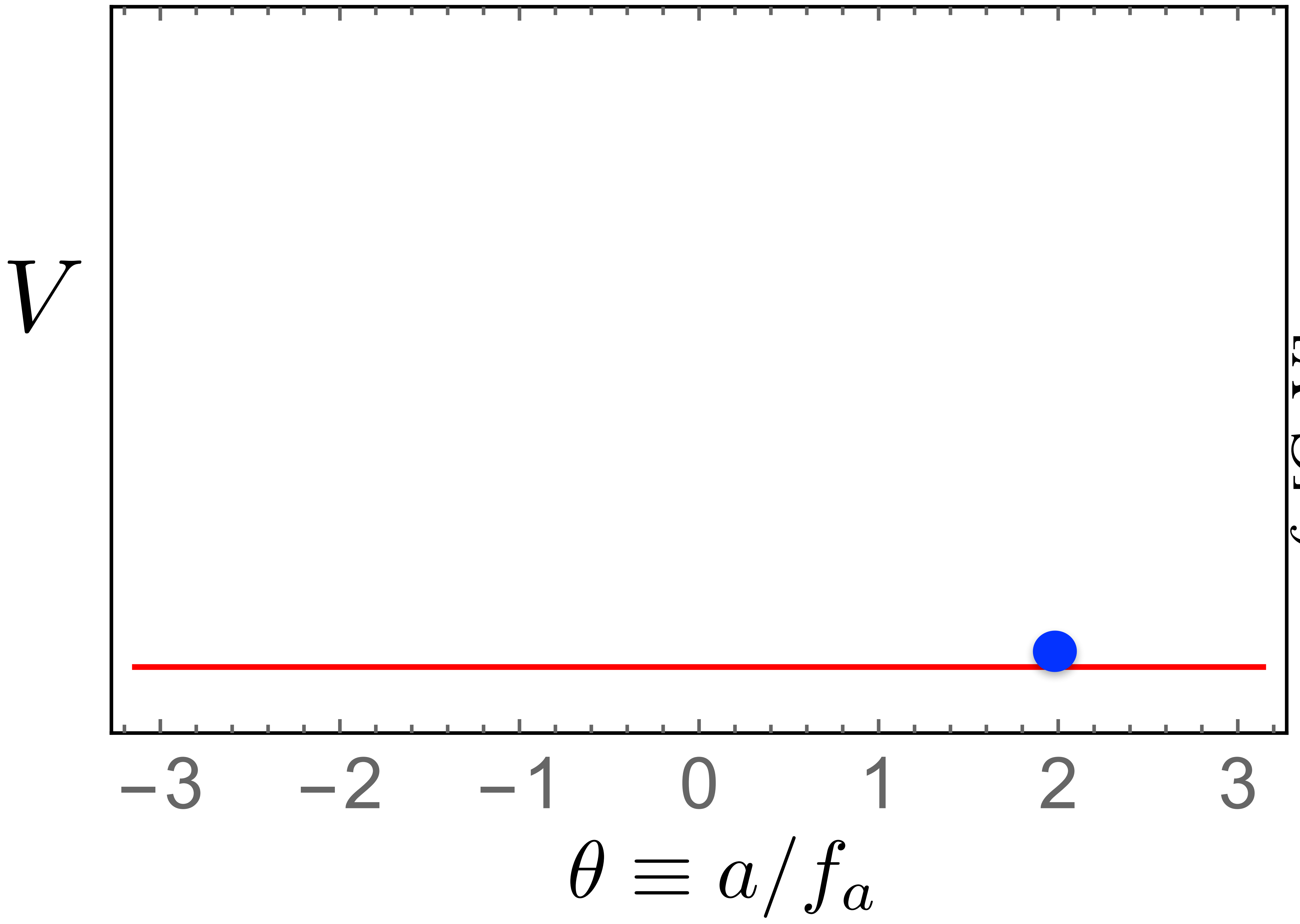

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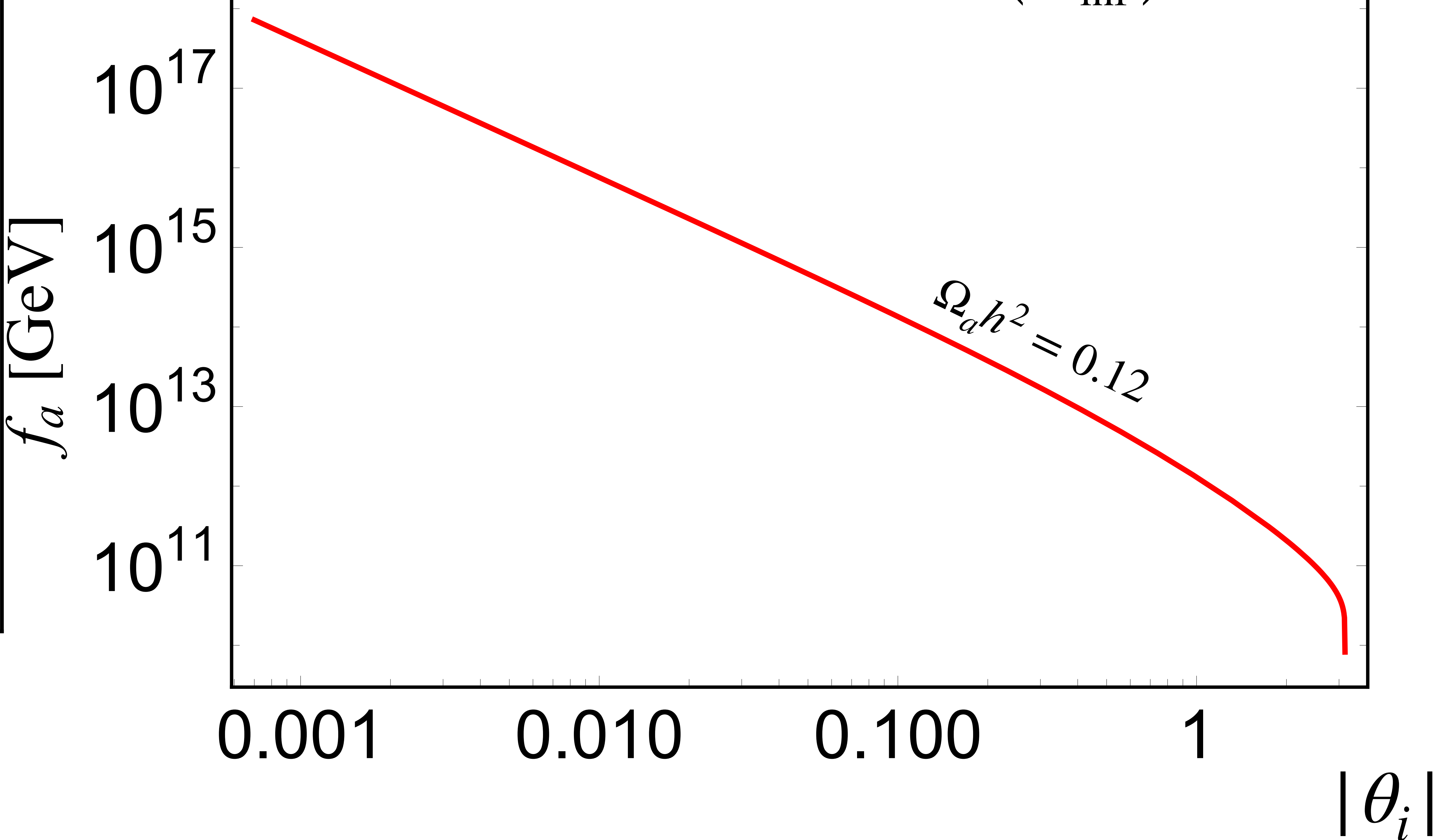

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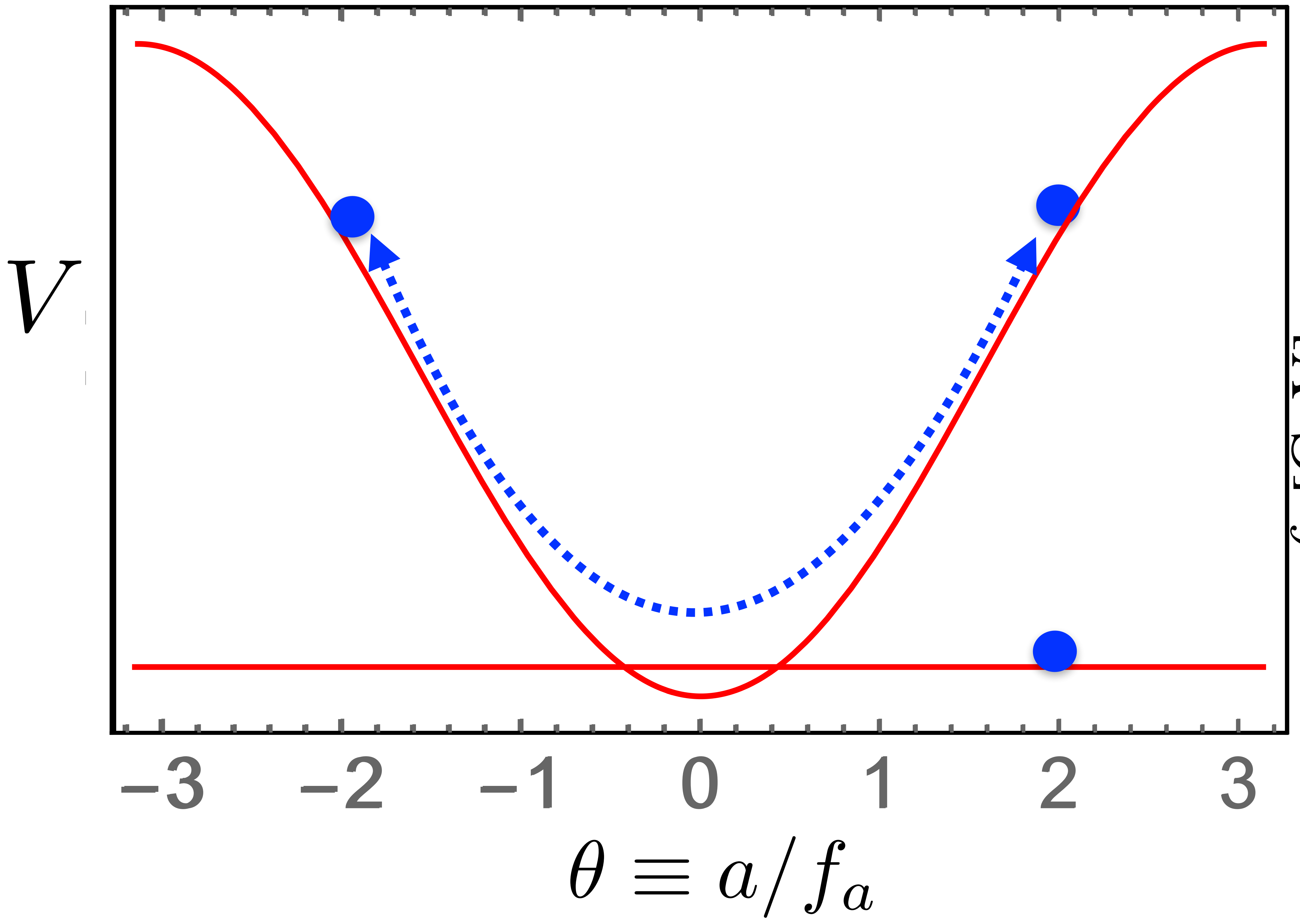

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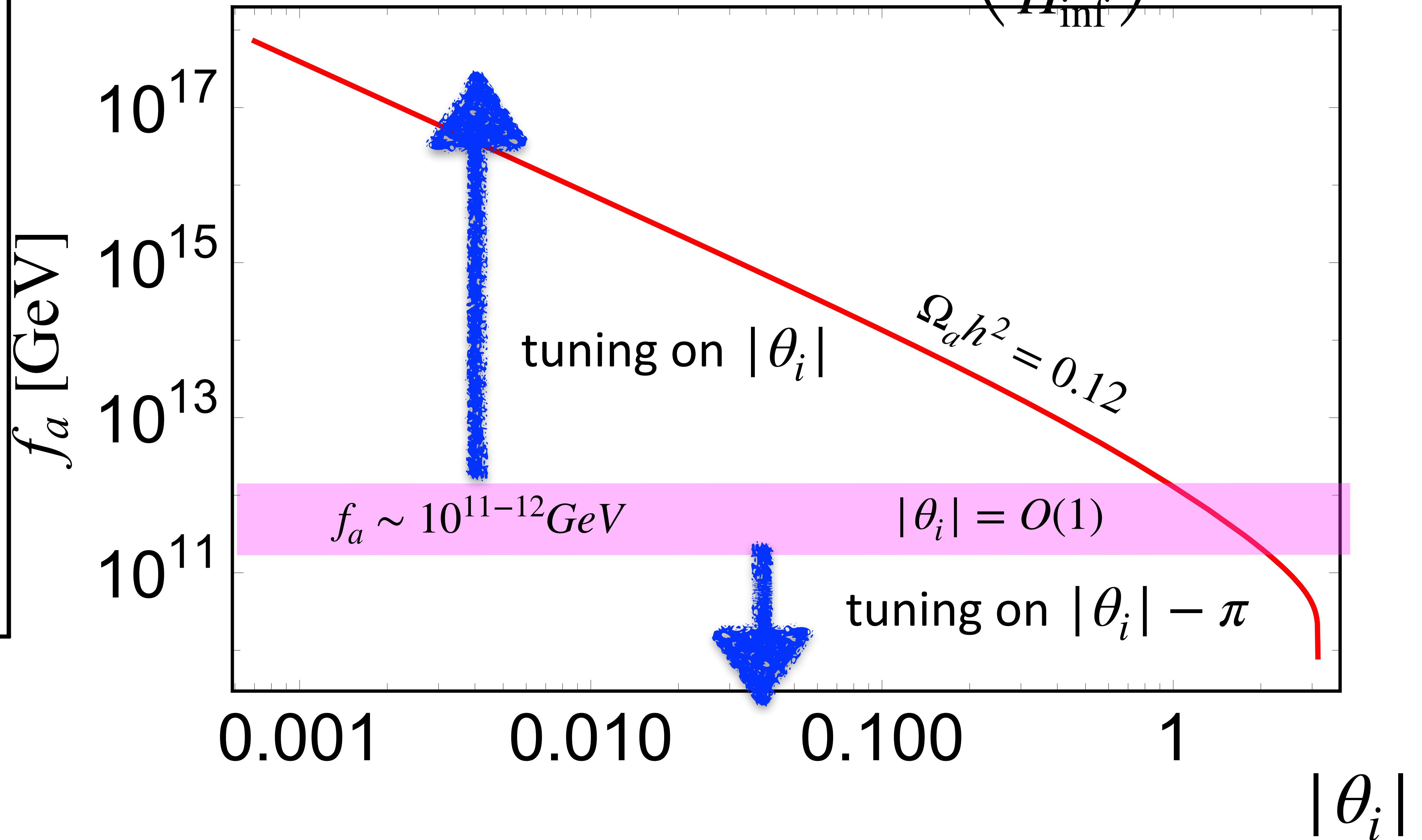

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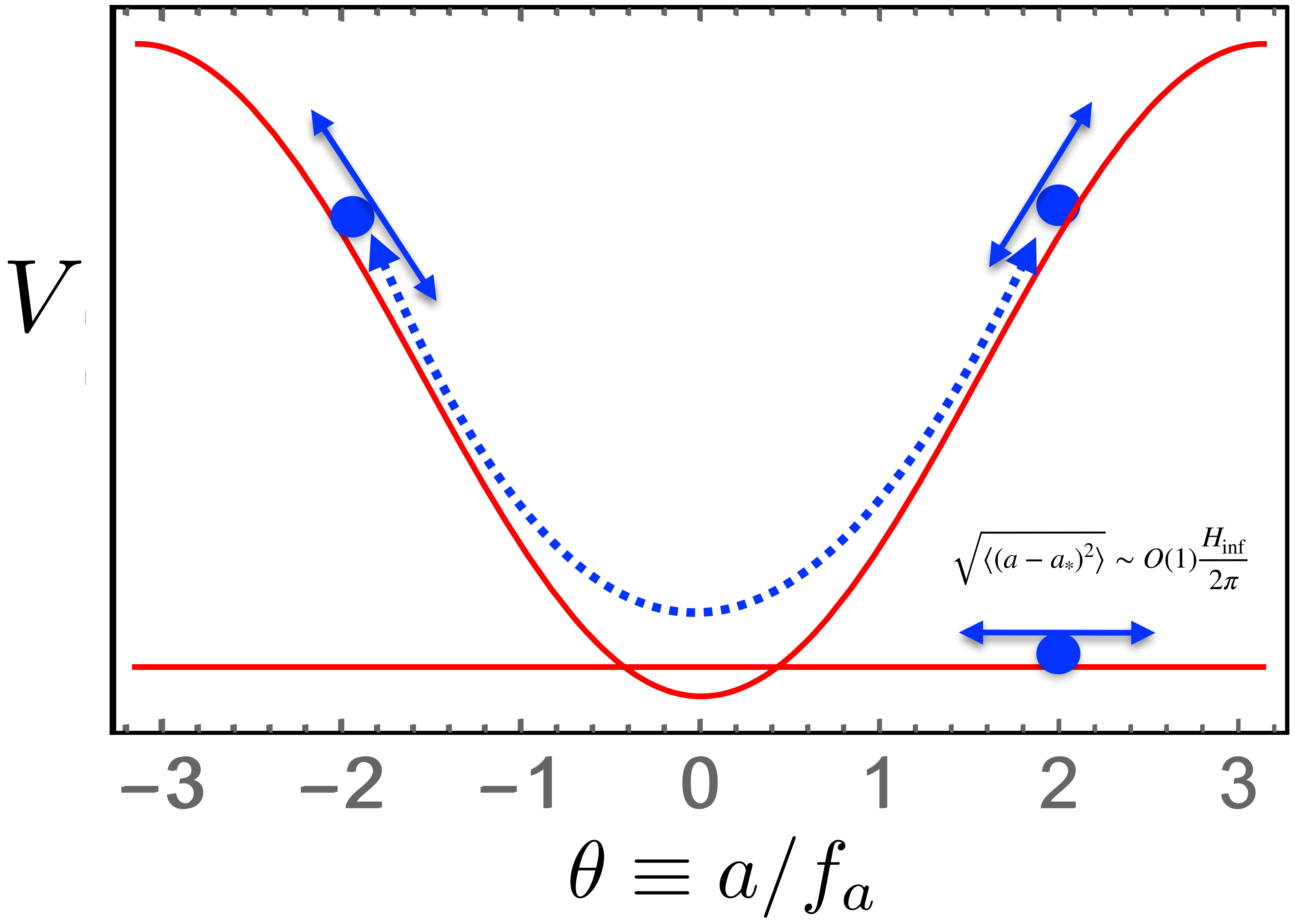

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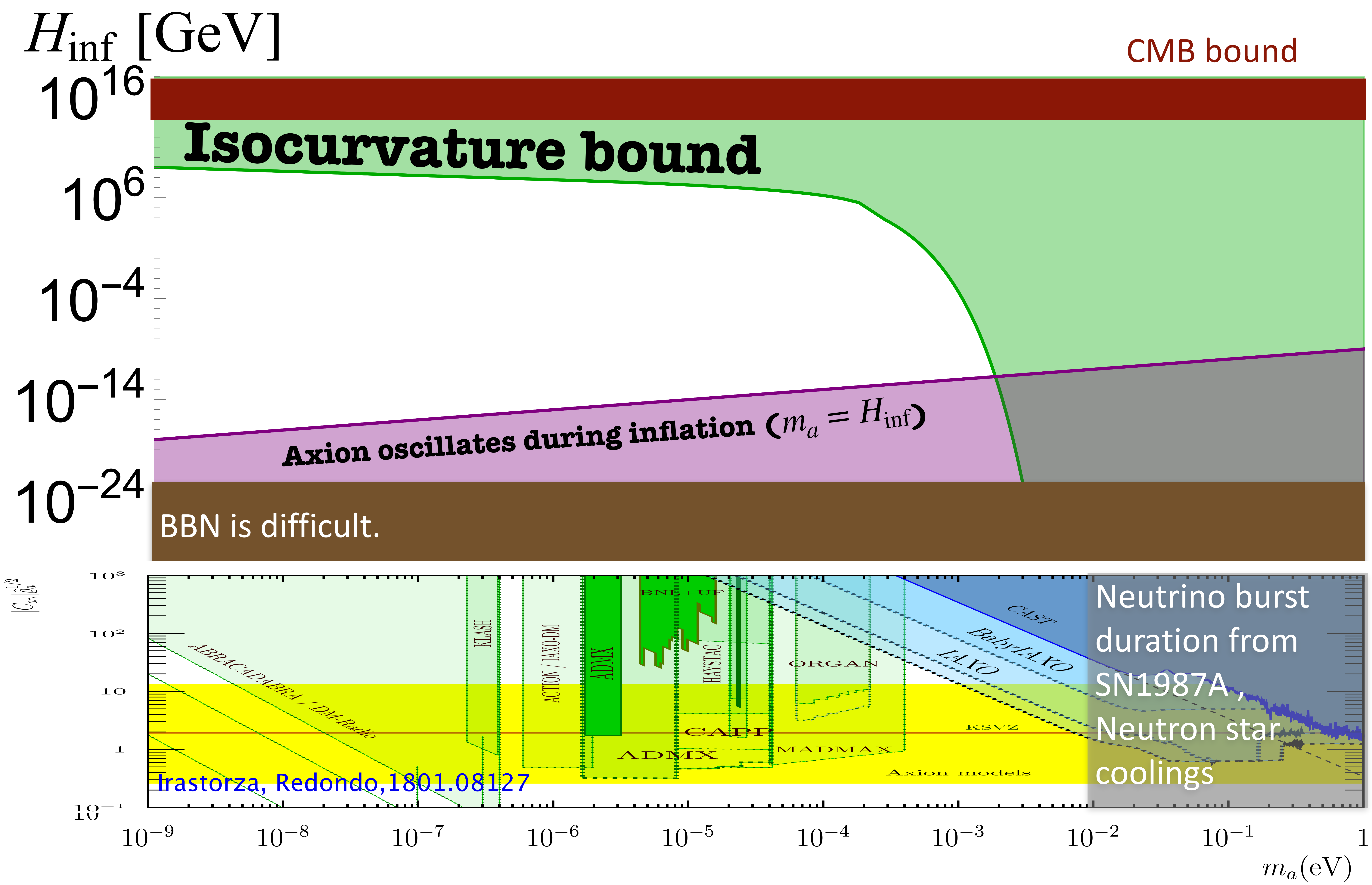
- In last few $\Delta N_{\rm efold} = O(1)$, diffusion predicts isocurvature perturbation.

e.g. Lyth, 1992;Marsh, 1510.07633;

- $H_{\rm inf}$ has an upper-limit to satisfy the isocurvature bound.

Upper bound of $H_{\rm inf}$ with axion DM from misalignment

Kobayashi, et al, 1304.0922 and Planck 2018, 1807.06211 are referred to make the figure.



- Misalignment QCD axion DM in the preinflation models predicts **low inflation scale.**

- Comment: for relatively heavy axion, other mechanisms may work, e.g. Moroi WY 2011.09475. In general by introducing other d.o.f., isogurvature bound can be relaxed.

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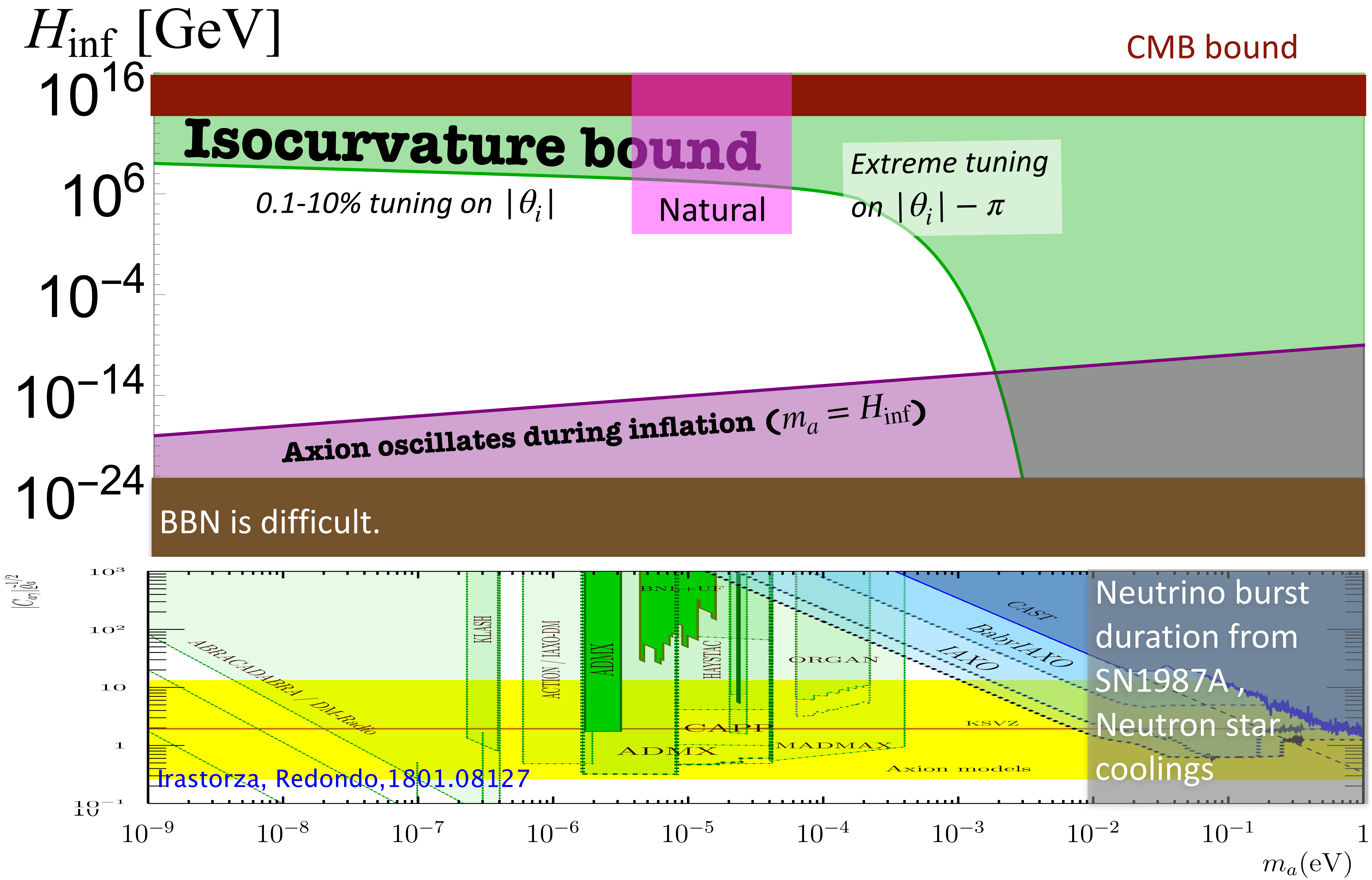

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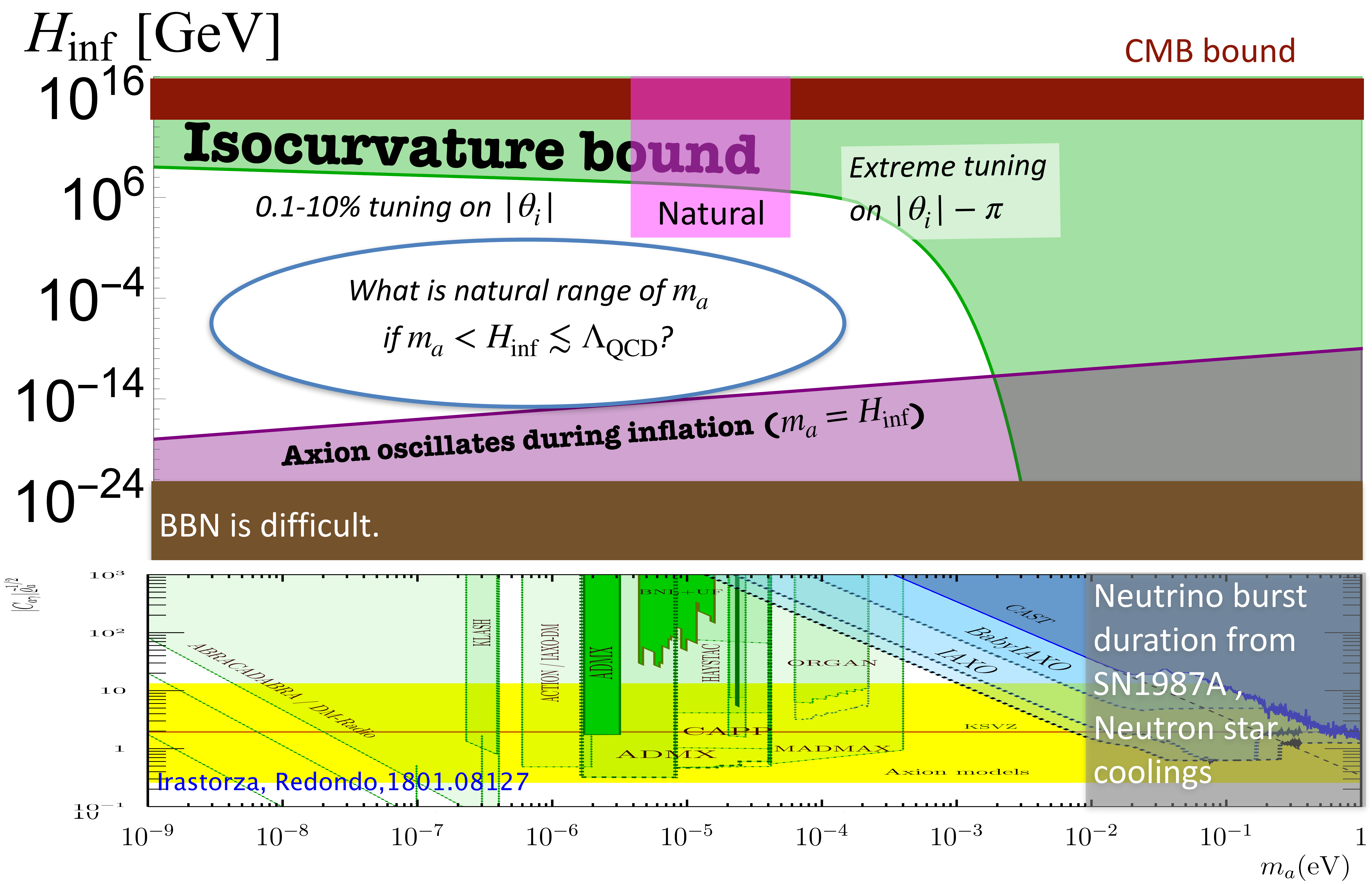

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What I will be talking about

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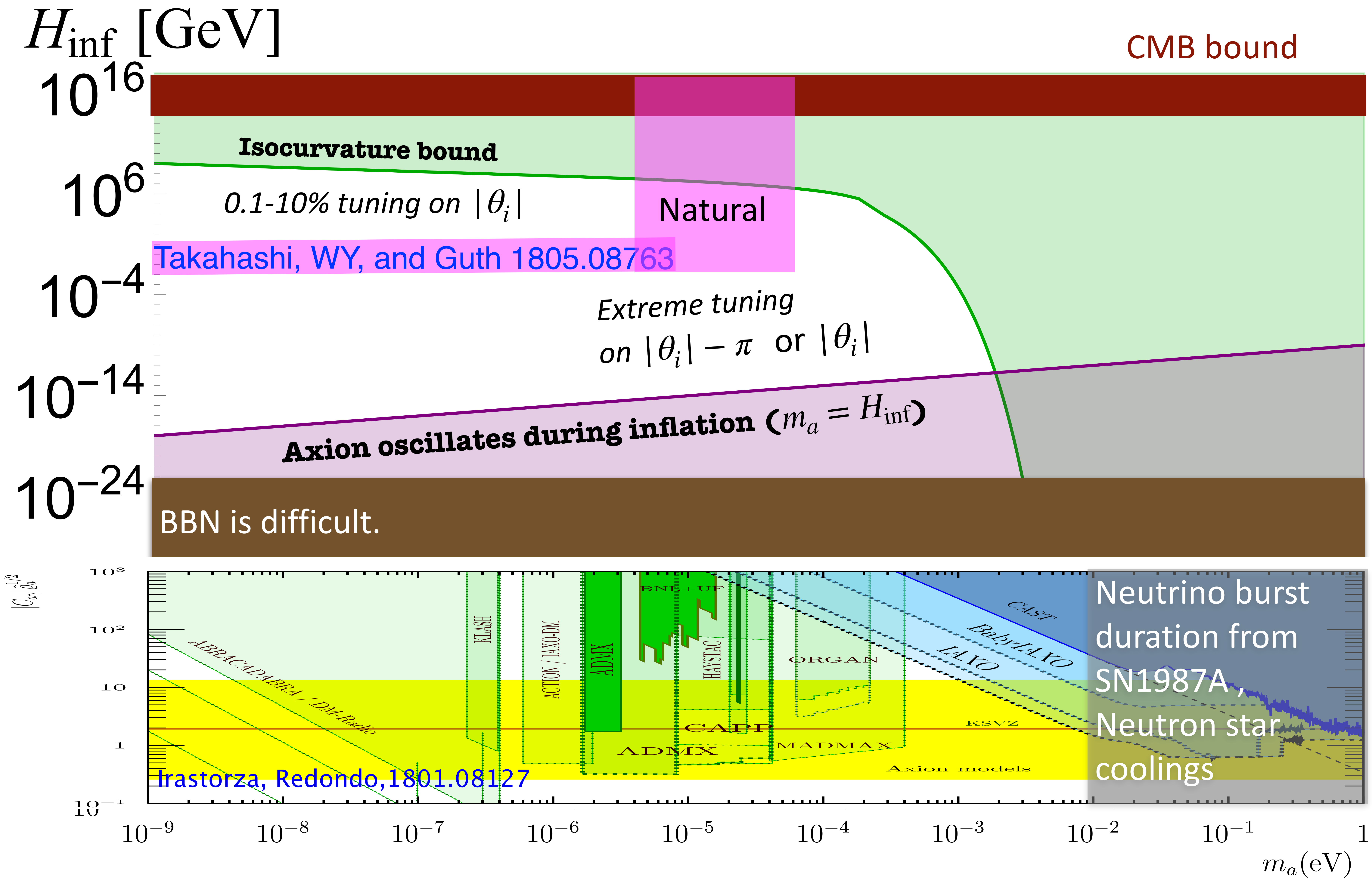

Takahashi, WY, and Guth 1805.08763

Assumptions: preinflation models +long inflation+no inflaton-axion mixing.

- **When inflation has $H_{\rm inf} \sim 0.1\text{GeV}$, tuning is highly alleviated.**
- **Detecting axion DM may be a new window to probe inflation scale.**

QCD axion dark matter with $H_{\rm inf} \lesssim \Lambda_{QCD}$

Axion during inflation with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$

During inflation temperature exists:

$$T_{\rm inf} = \frac{H_{\rm inf}}{2\pi} \propto \frac{\sqrt{V_{\rm inf}}}{M_{\rm pl}}$$ Gibbons, Hawking, 77

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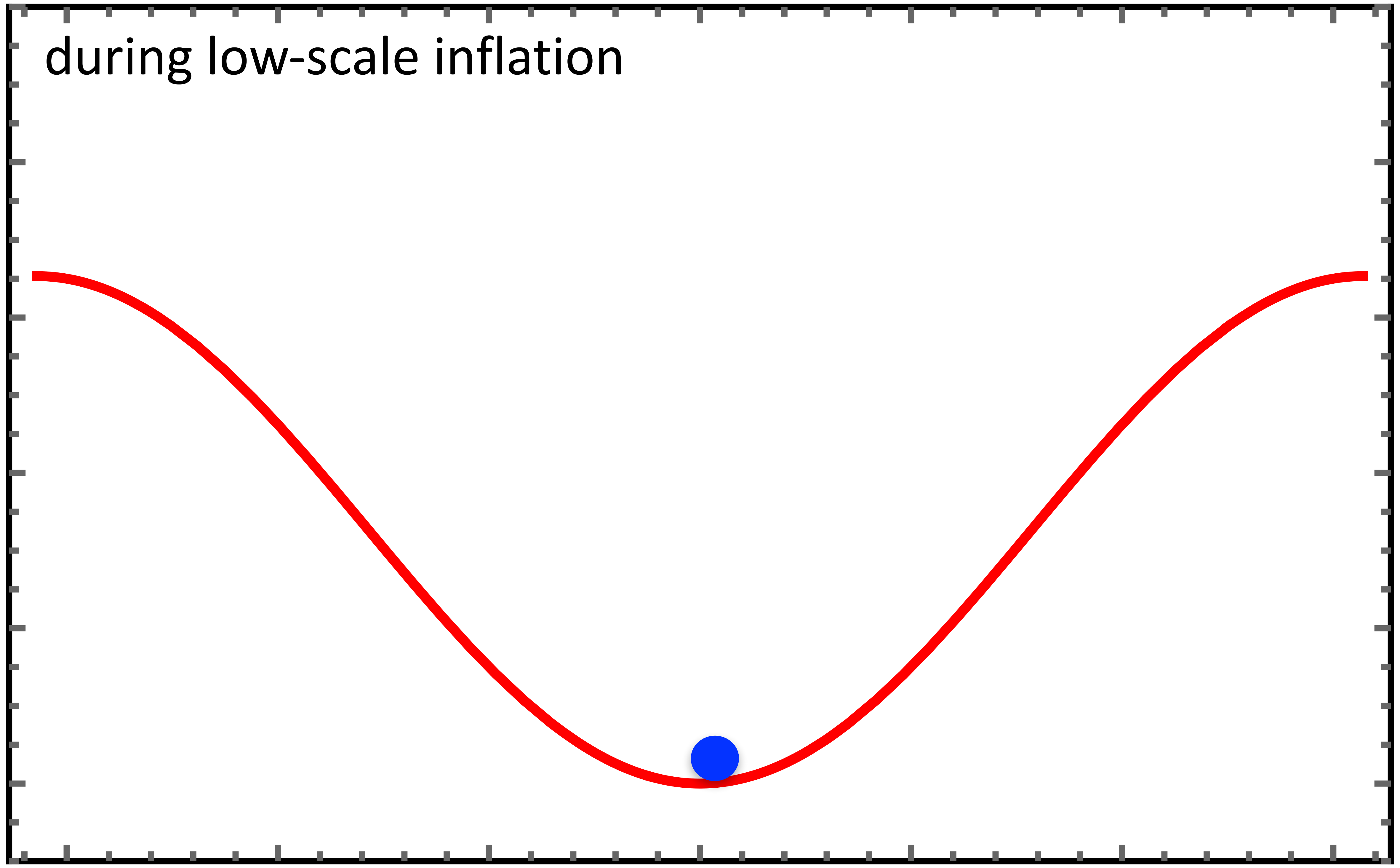
V



$\theta \equiv a/f_a$

- **Classical motion vs quantum diffusion**
- Equilibrium is biased to $\theta = 0$, a la the atmosphere surrounding Earth.

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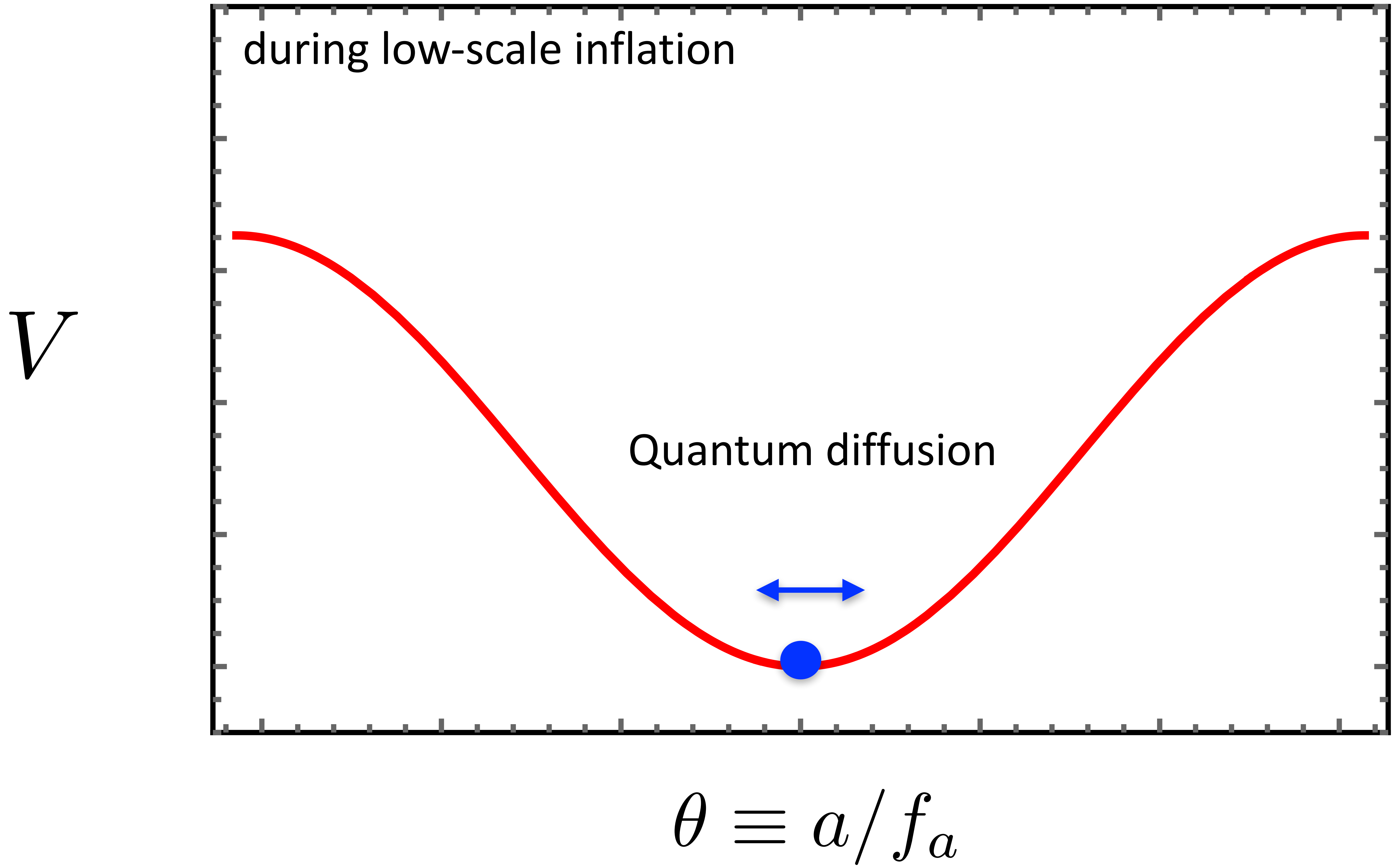

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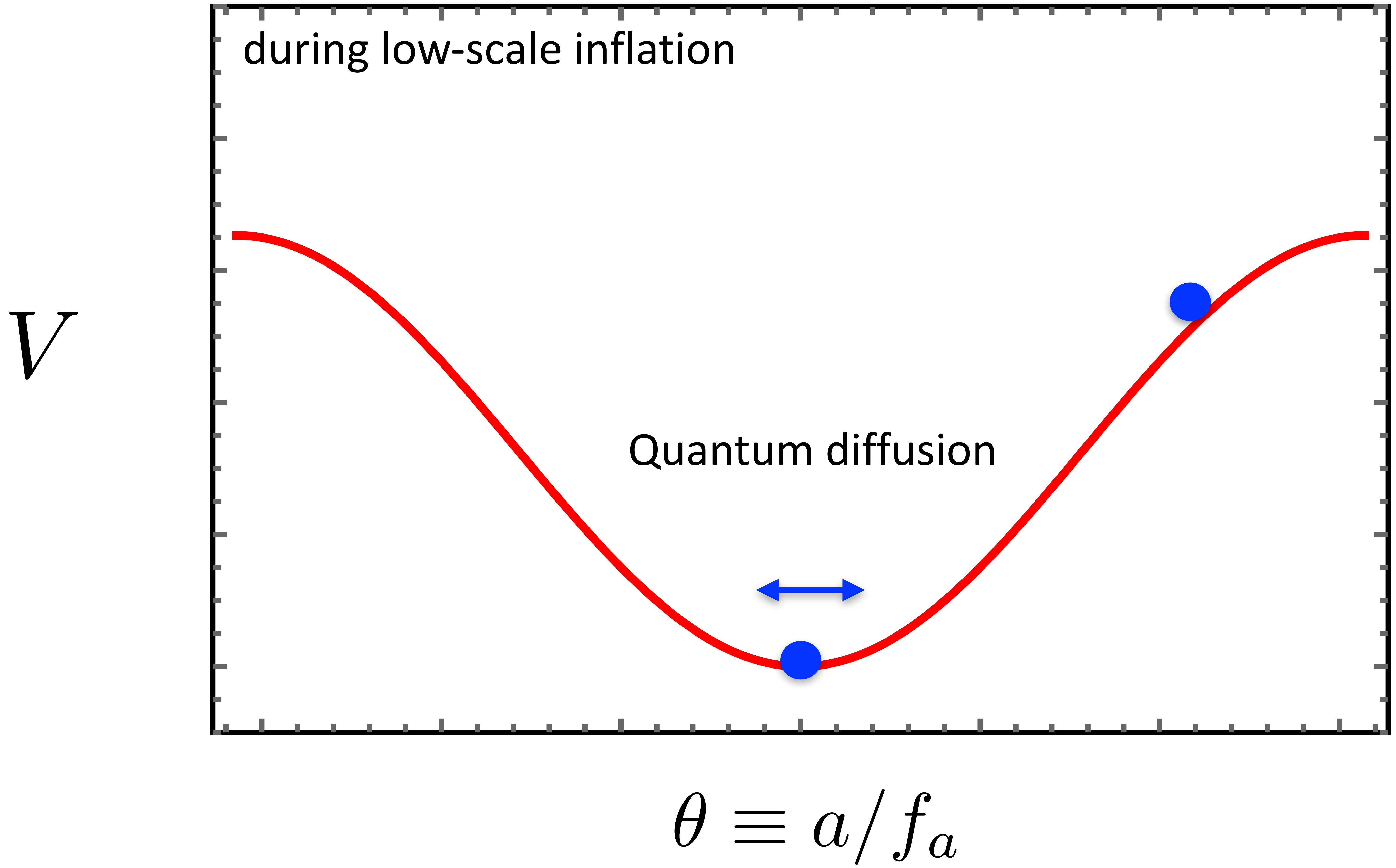

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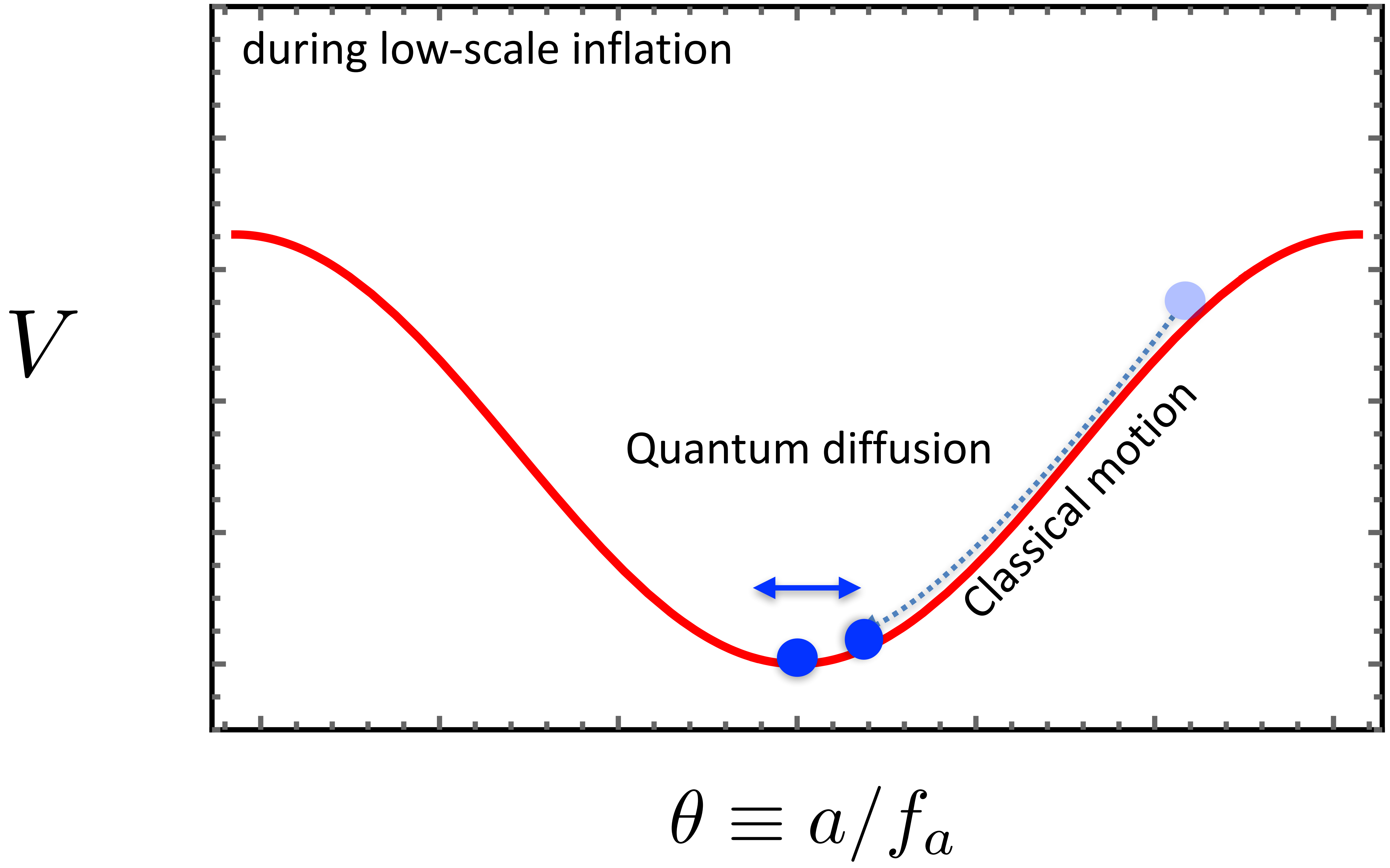

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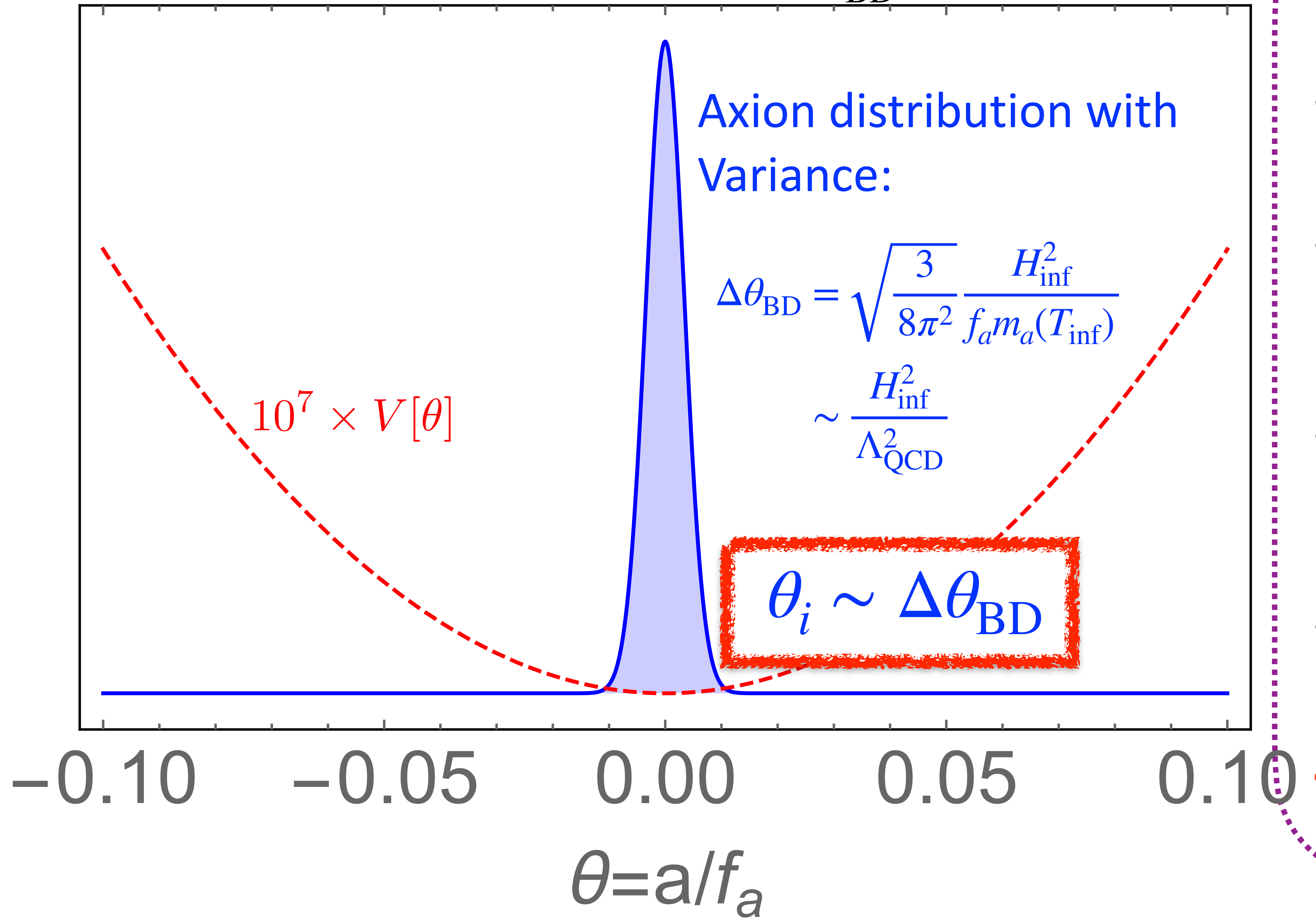
Equilibrium distribution during inflation

$$P[\theta_i] \propto \exp[-\frac{\theta_i^2}{2\Delta\theta_{\rm BD}^2}]$$



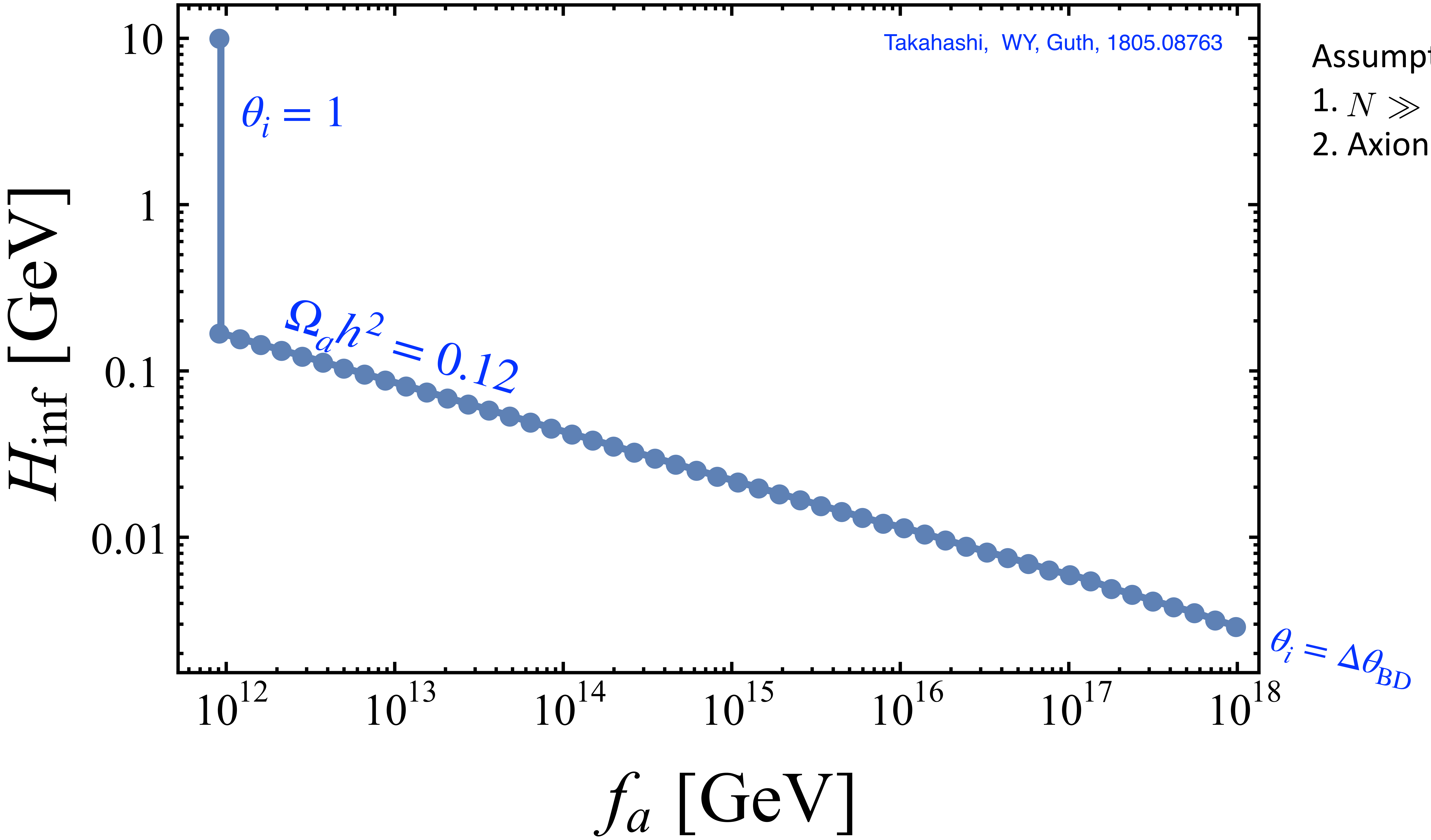
- Light scalar during inflation approaches to equilibrium distribution.

  Bunch Davies, 78

- The equilibrium is independent from initial condition.
- Long inflation is required but very long inflation is predicted in most of inflation models.
- This distribution is robust for axion since ``PQ" or shift symmetry forbids any Hubble induced terms.
- Central value is CP conserving unless axion-inflaton mixing.
- **Typical $|\theta_i| \ll 1$ is natural if** $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

The QCD axion DM can be naturally explained with $f_a \sim 10^{12-18} GeV$ in low-scale inflation with $H_{\rm inf} \sim \Lambda_{\rm QCD}$.

Graham, Scherlis, 1805.07362,
Takahashi, WY, Guth, 1805.08763



Assumptions:

1. $N \gg H_{\rm inf}^2/m_a^2$
2. Axion does not mix with inflaton.

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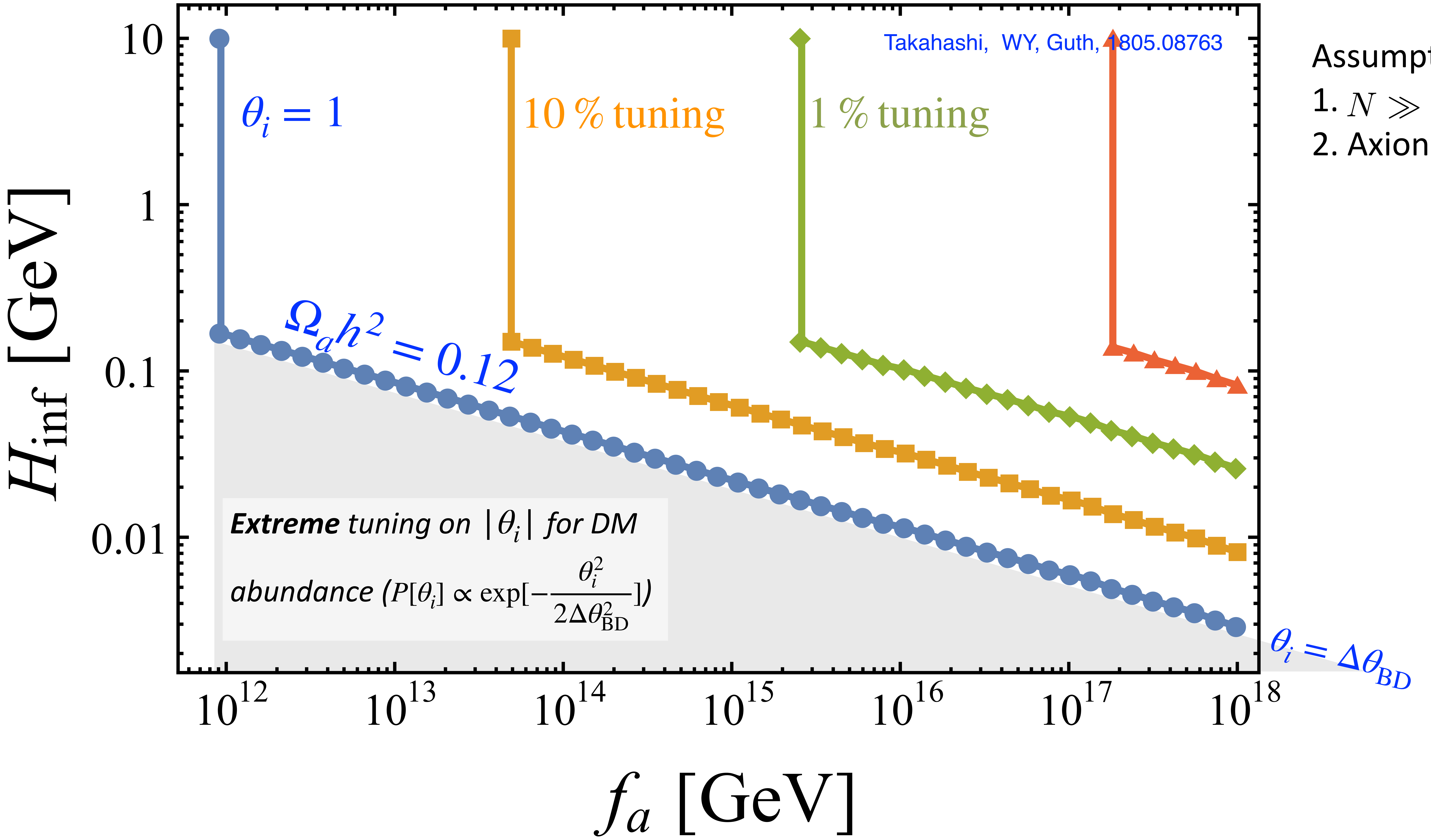

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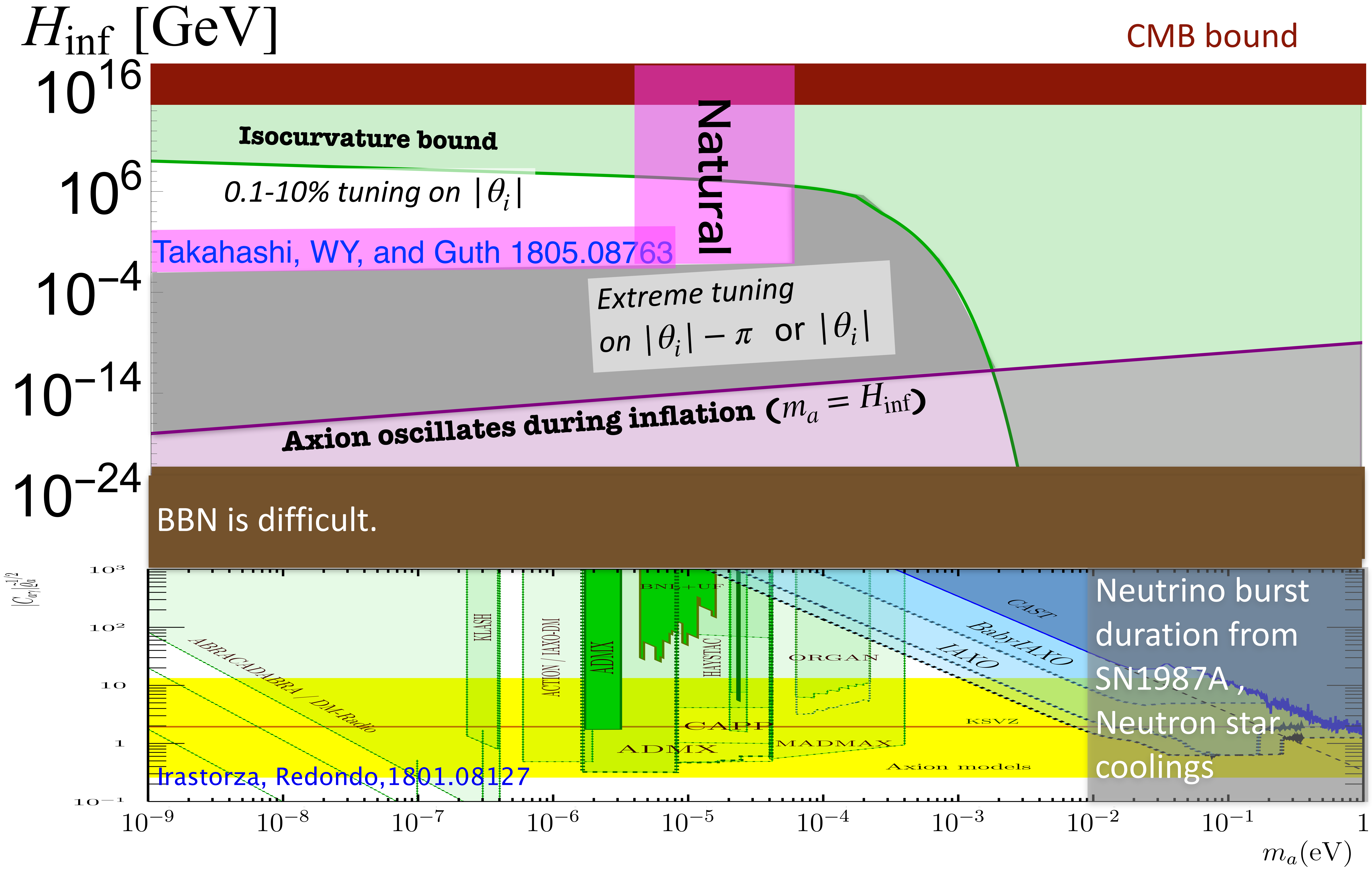

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See also stochastic ALP DM

Ho, Takahashi, and WY 1901.01240;
Marsh, WY, 1912.08188;
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Backups

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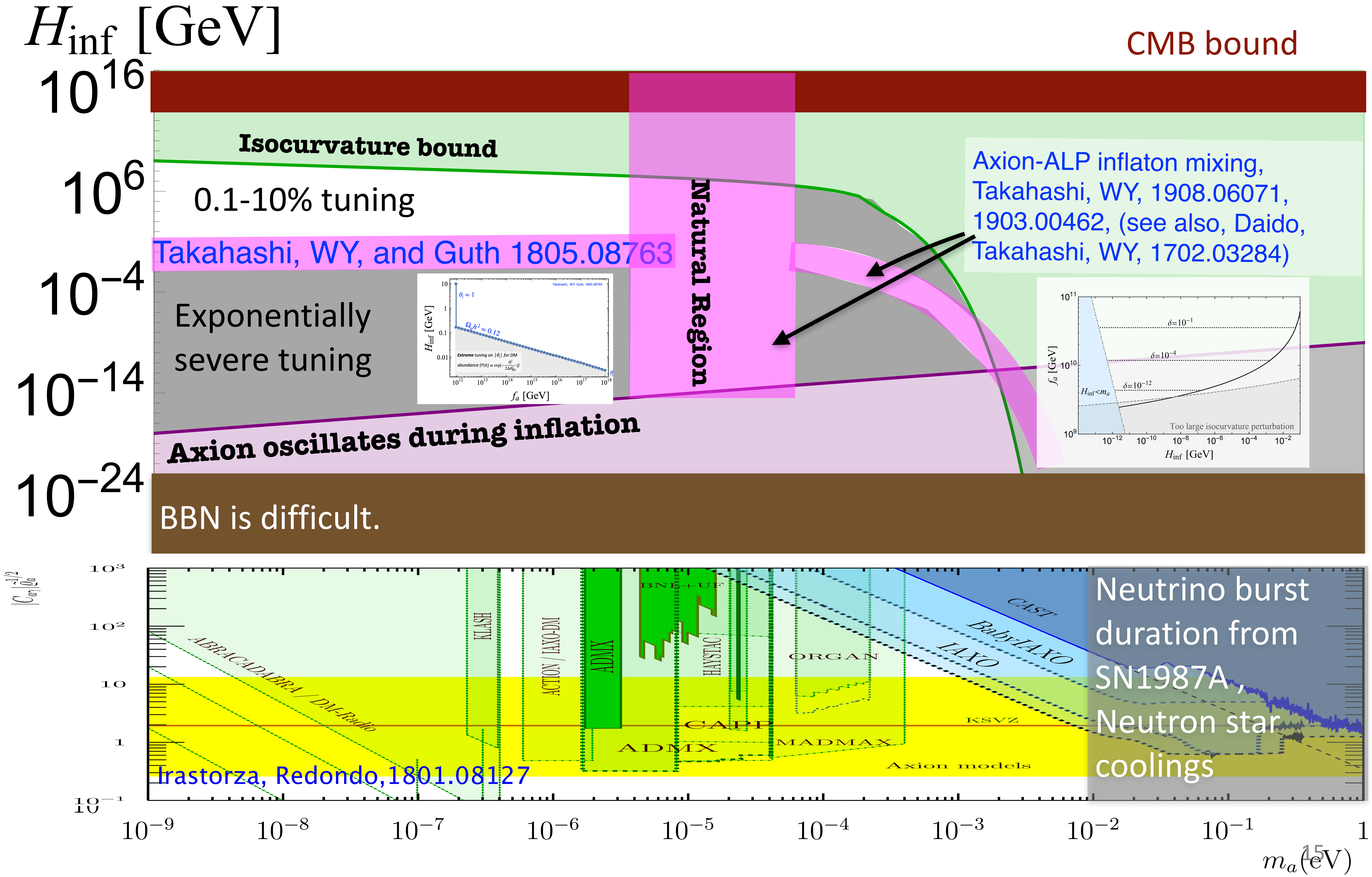

Assumptions: preinflation models +long inflation.

- **When inflation has $H_{\rm inf} \sim 0.1{\rm GeV}$, tuning is highly alleviated.**
- **If axion DM is discovered, we can say quite a few things on inflation.**

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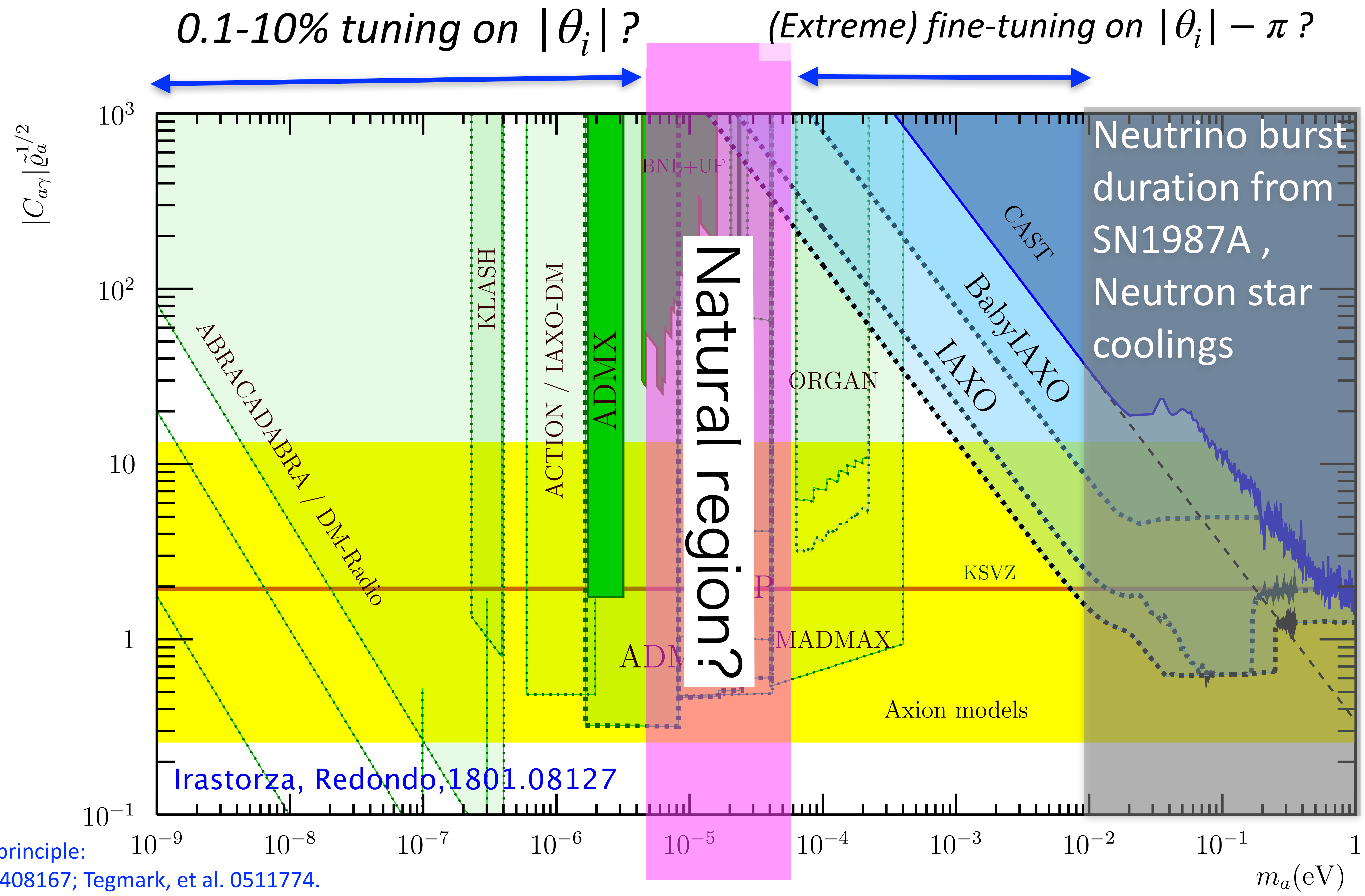
Misalignment mechanism and Axion DM



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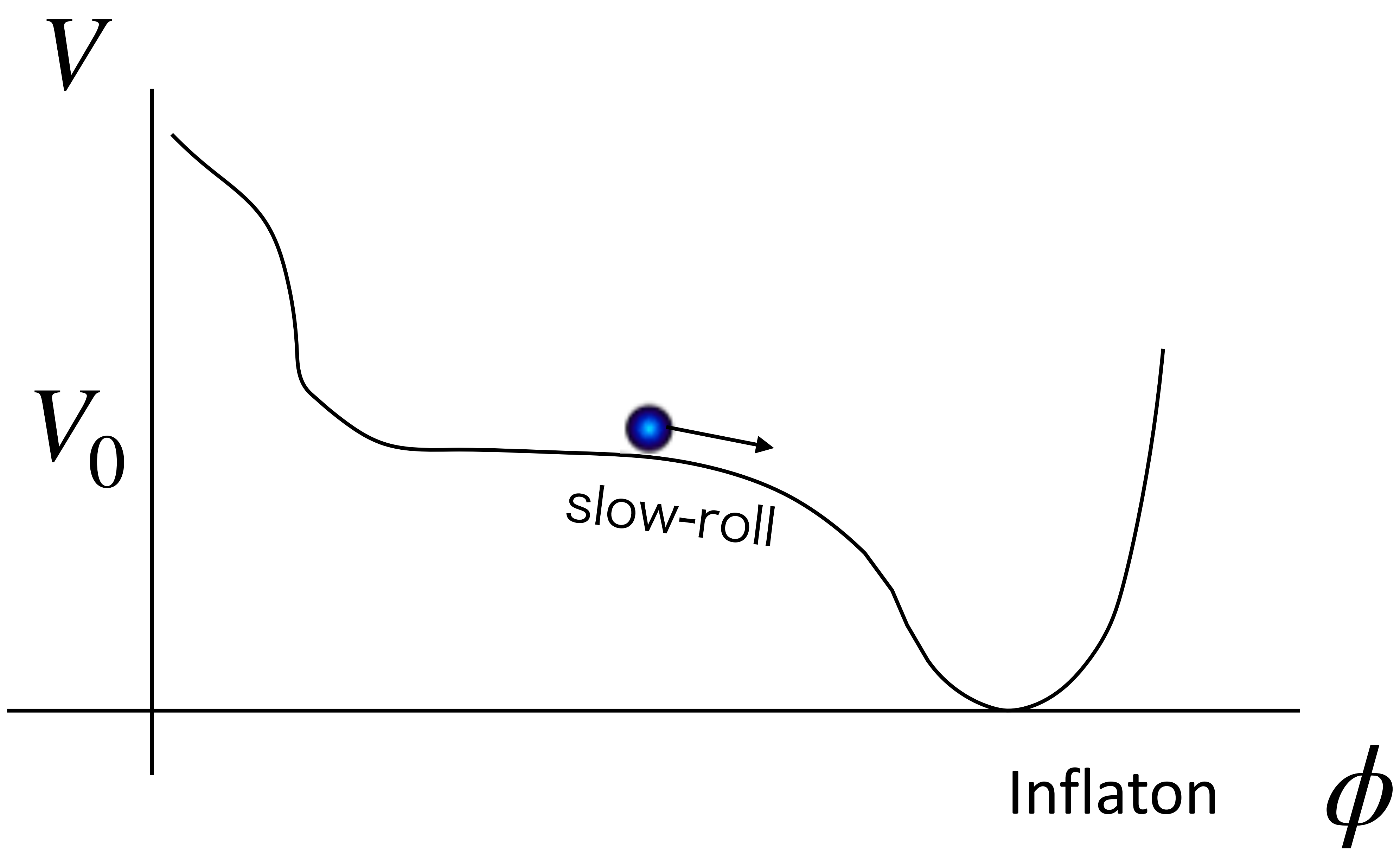
Since abundance depends on initial-condition, we need to study beginning of Universe.

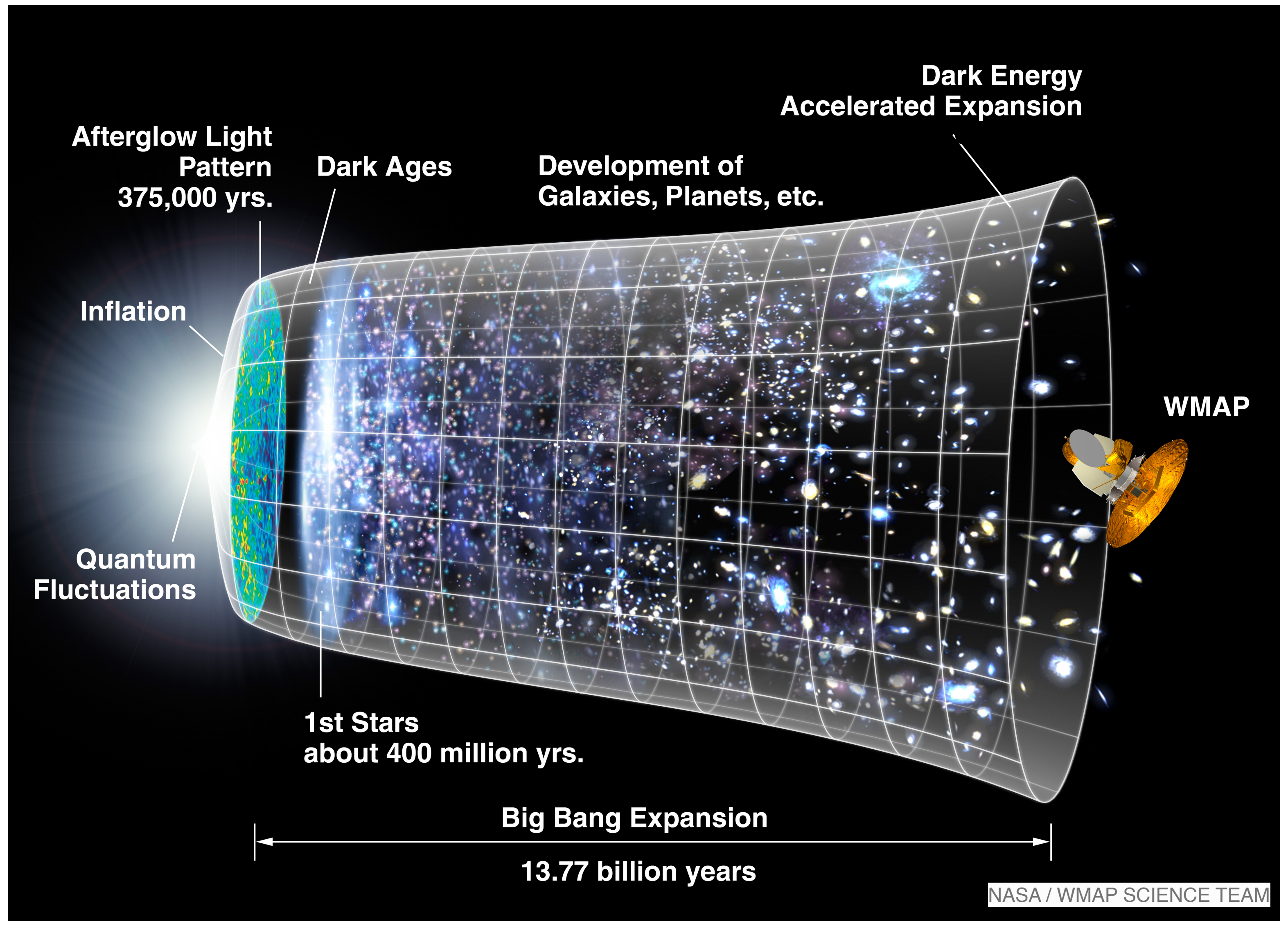
Inflationary cosmology

A.Guth, 1980; K.Sato, 1980; A.Starobinsky, 1980; Kazanas, 1980; A.Linde, 1981; Albrecht, Steinhardt, 1981;

Much before the thermal history, there was inflation.

Inflation solves horizon and flatness problems.





- Slow-roll inflation is plausible.
- The inflationary quantum fluctuation of inflaton field seems to be discovered.
- $H_{\rm inf} \lesssim 10^{14} GeV$ from CMB data
  Planck 2018, 1807.06211

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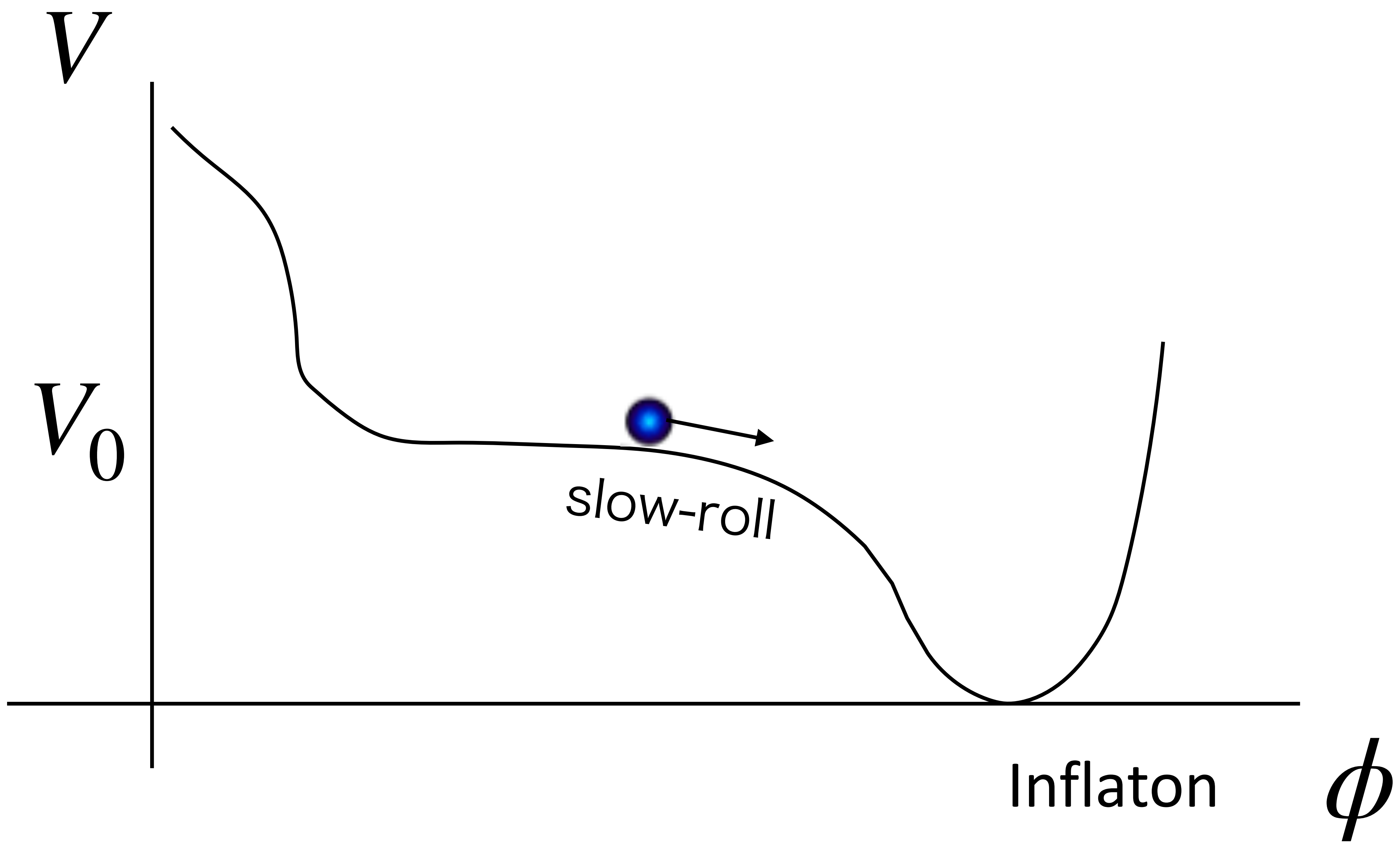

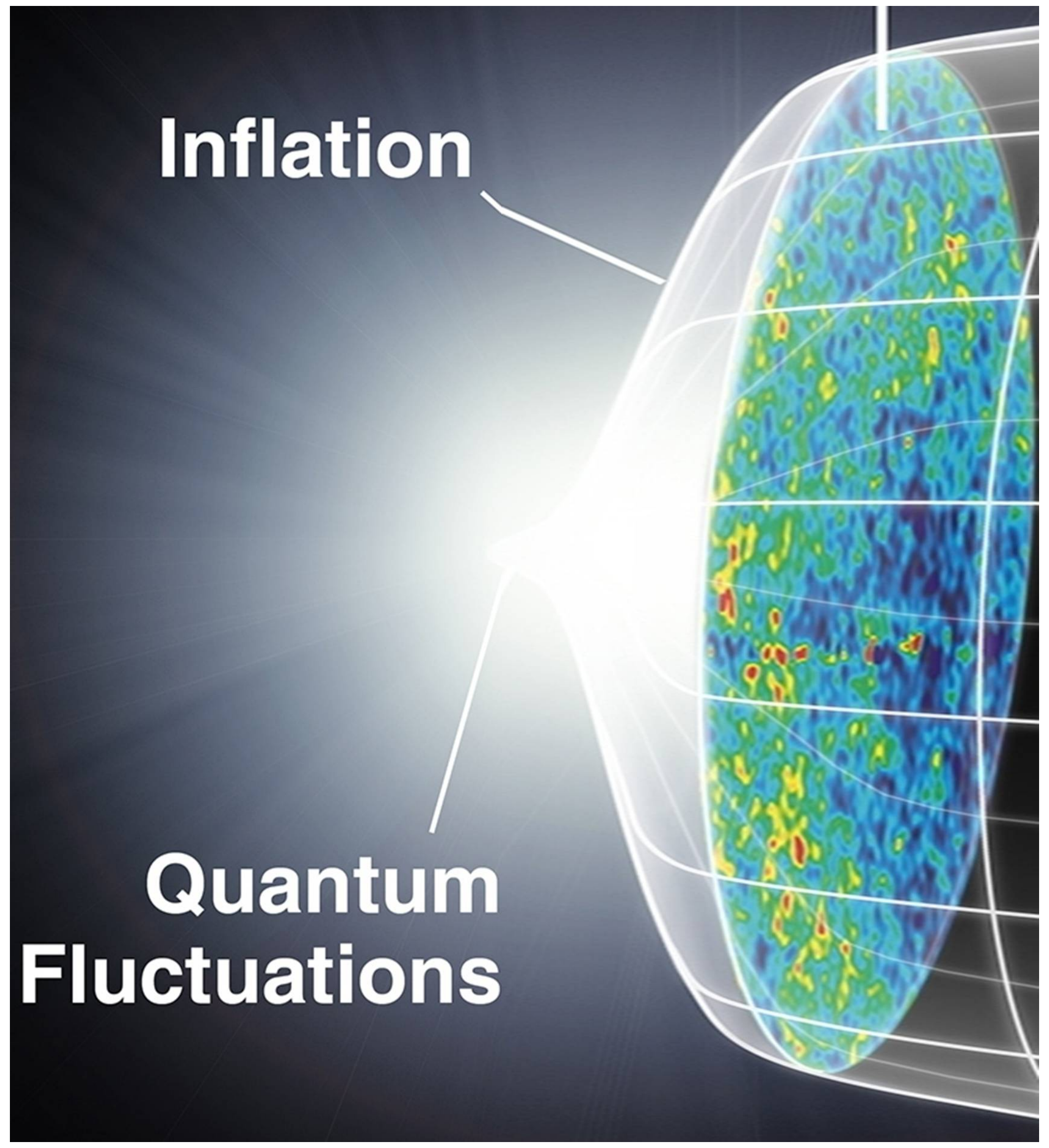

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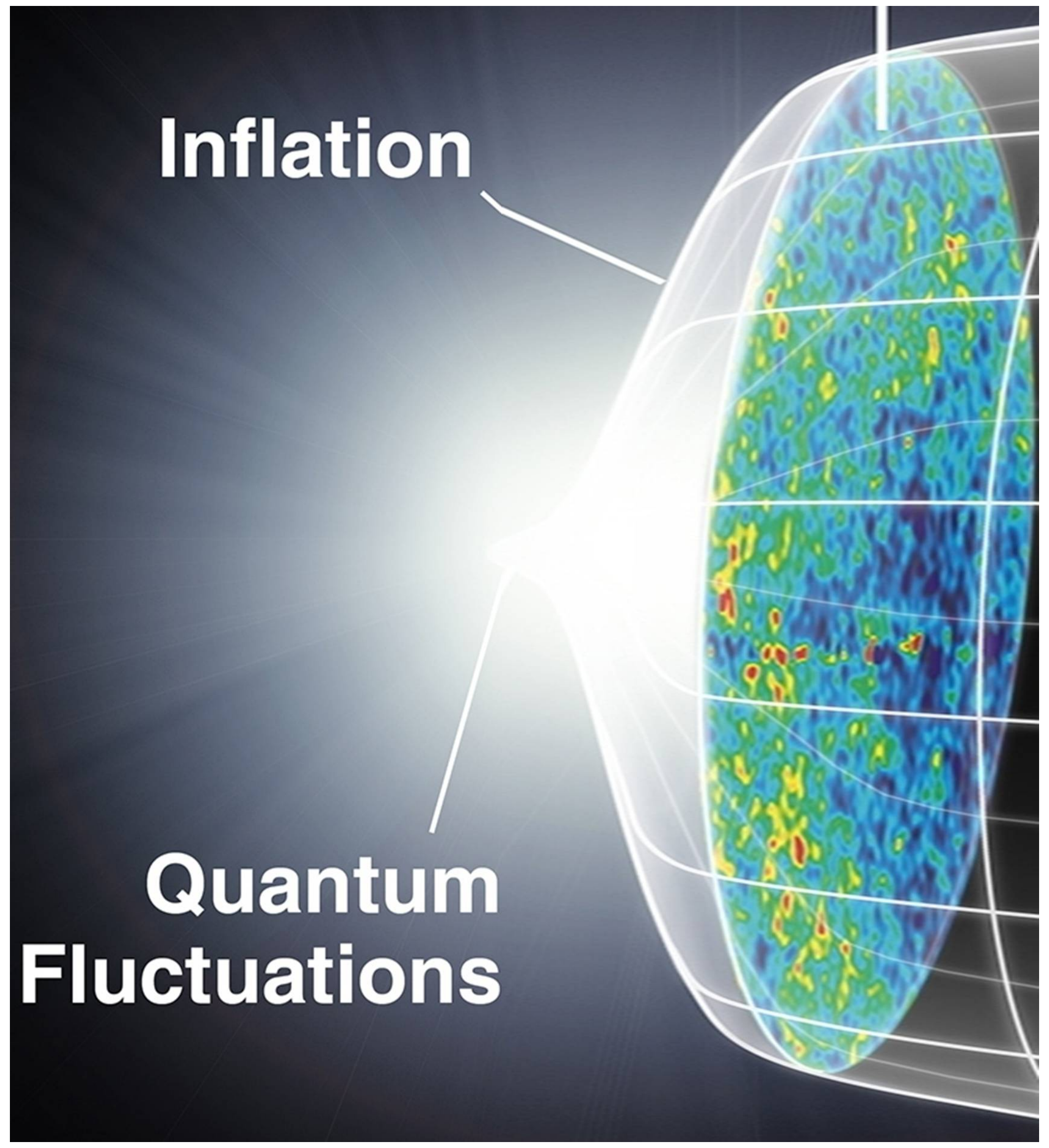

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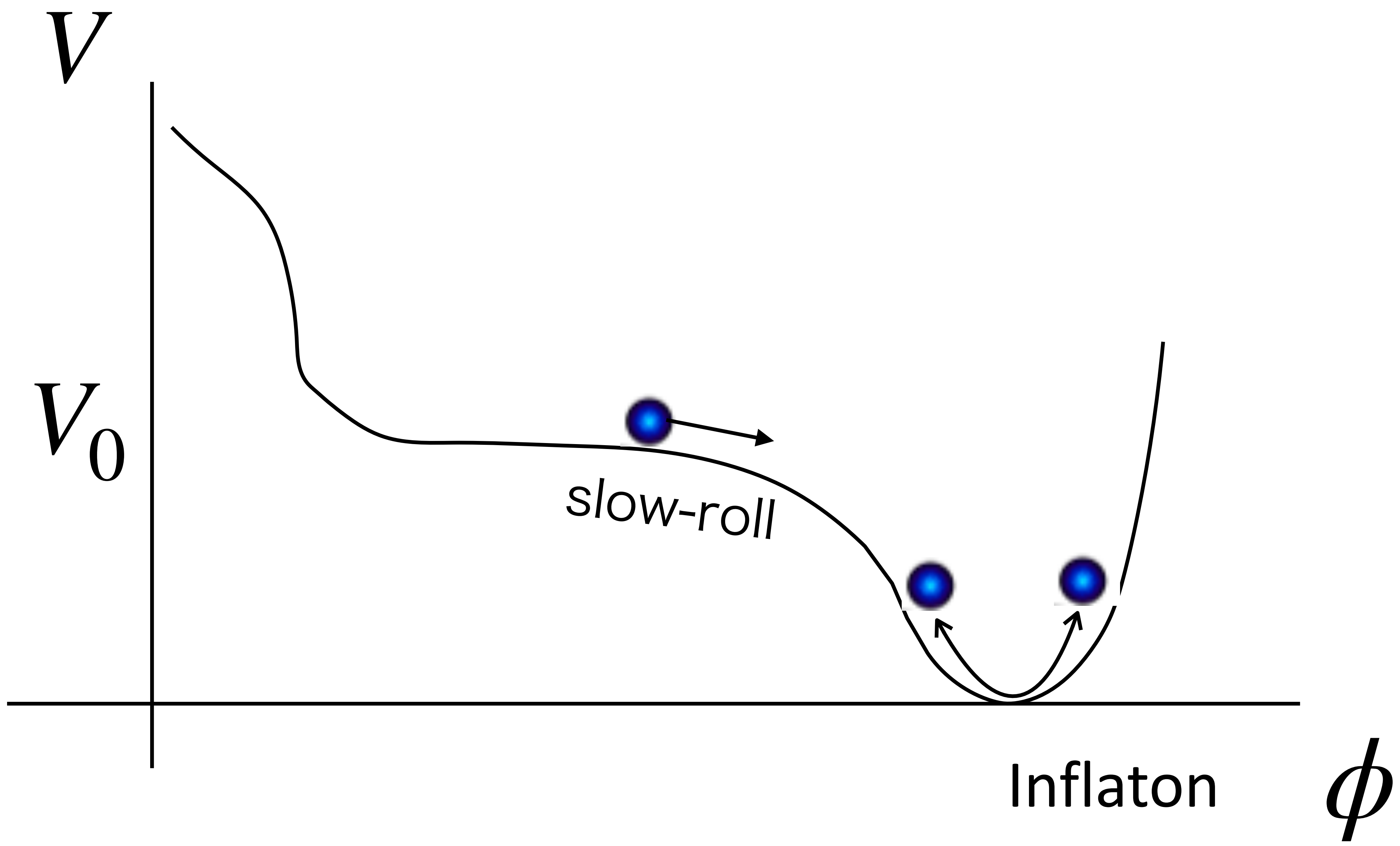

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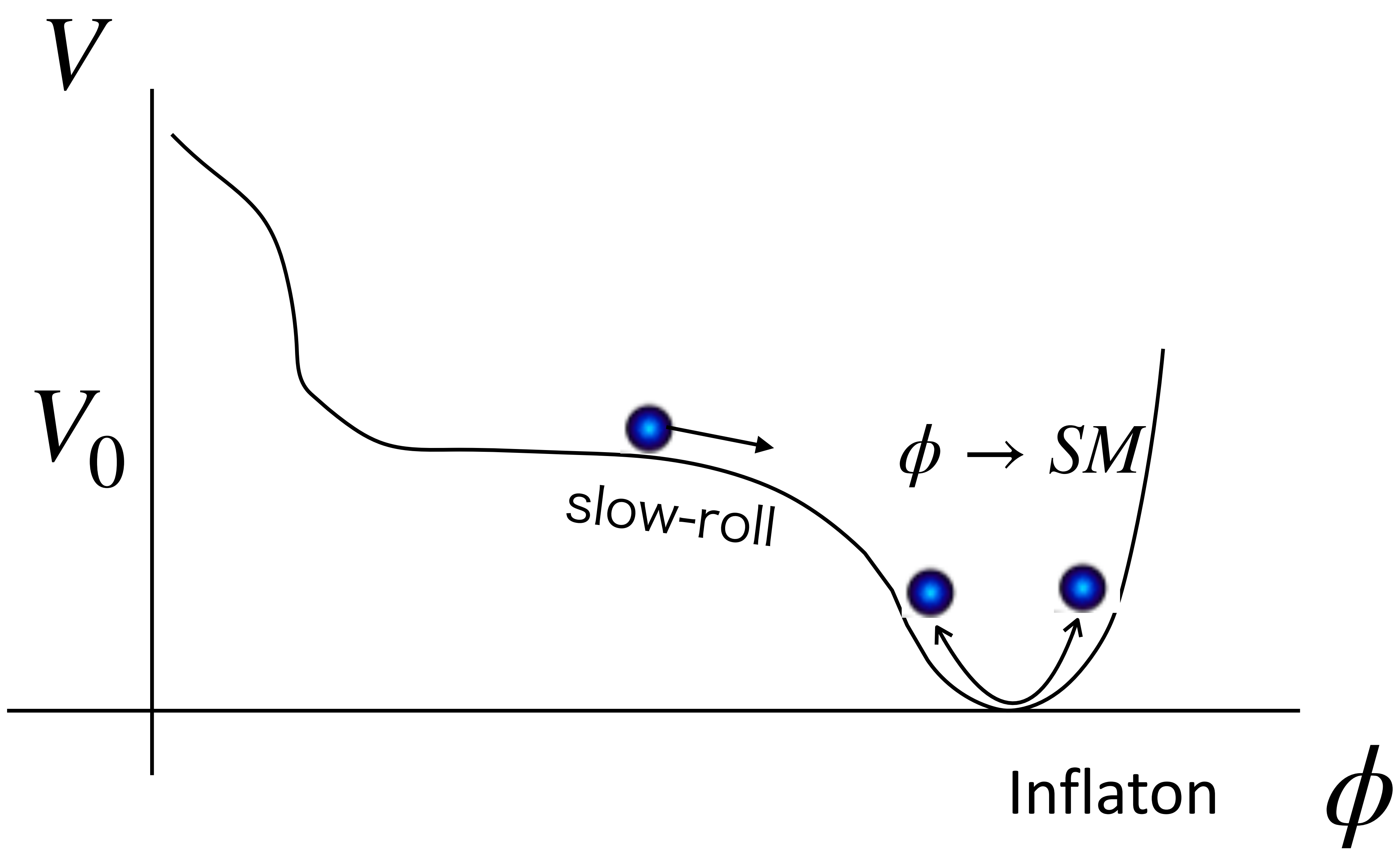

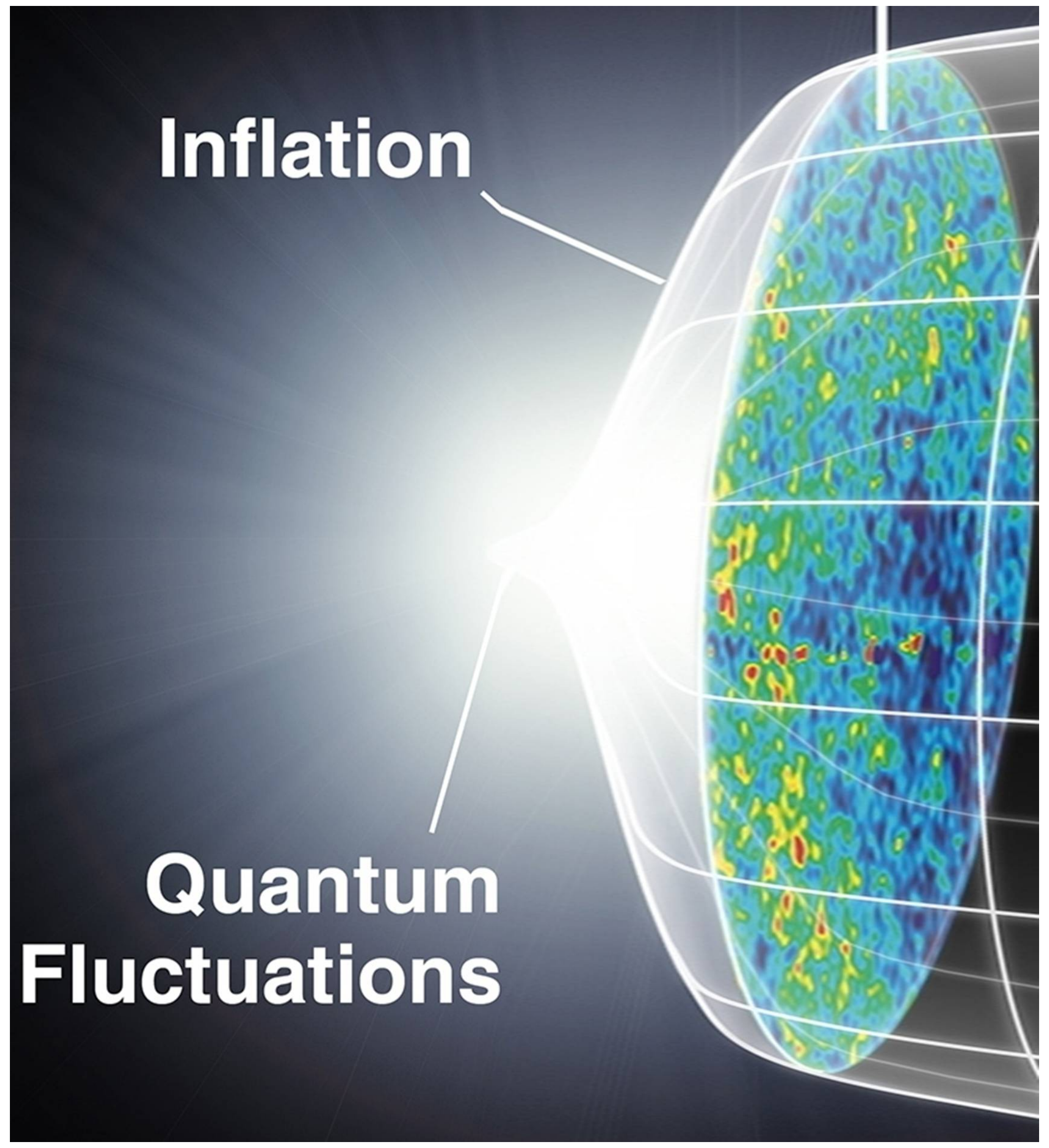

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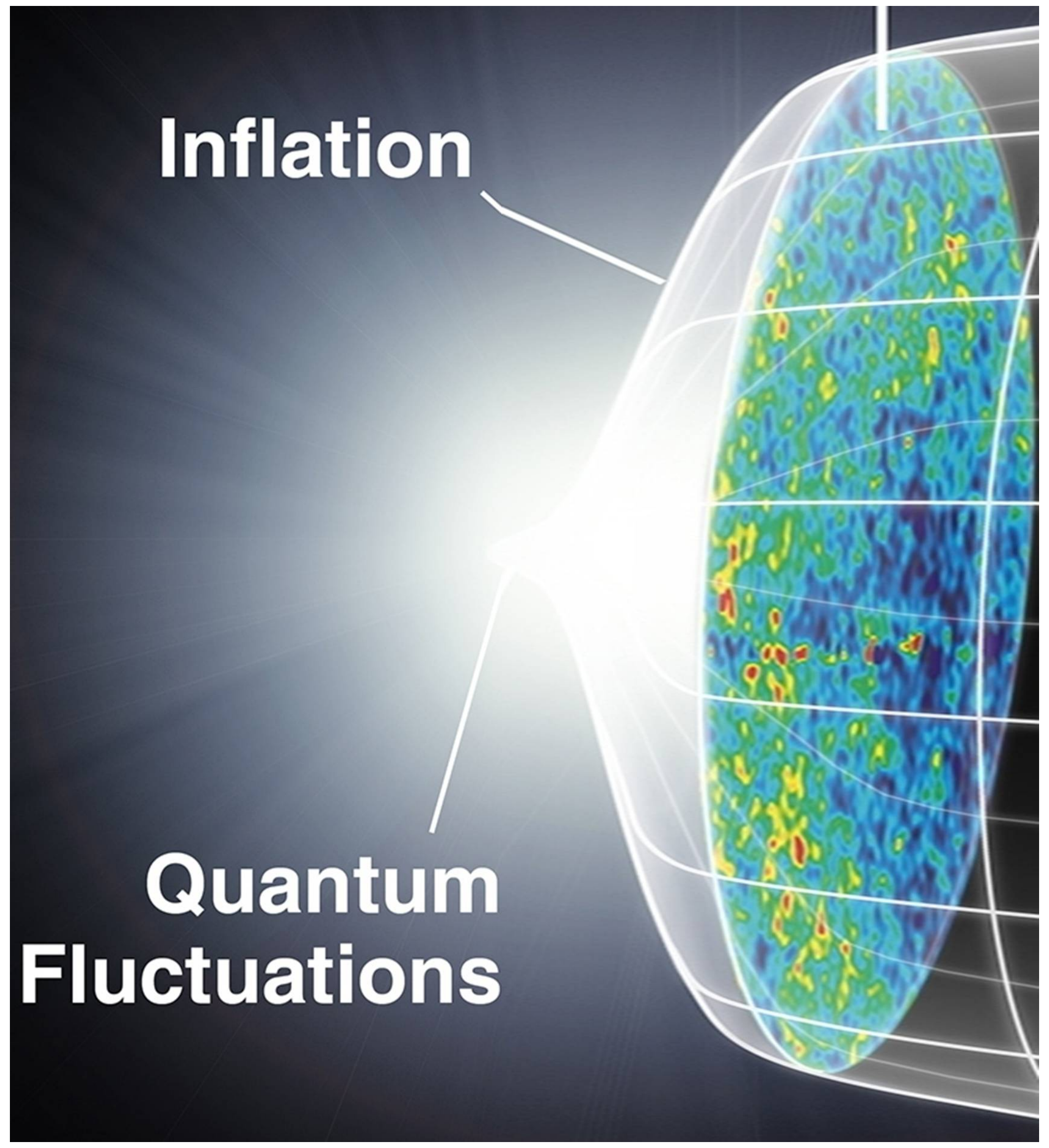
  Planck 2018, 1807.06211

Inflationary cosmology

A.Guth, 1980; K.Sato, 1980; A.Starobinsky, 1980; Kazanas, 1980; A.Linde, 1981; Albrecht, Steinhardt, 1981;

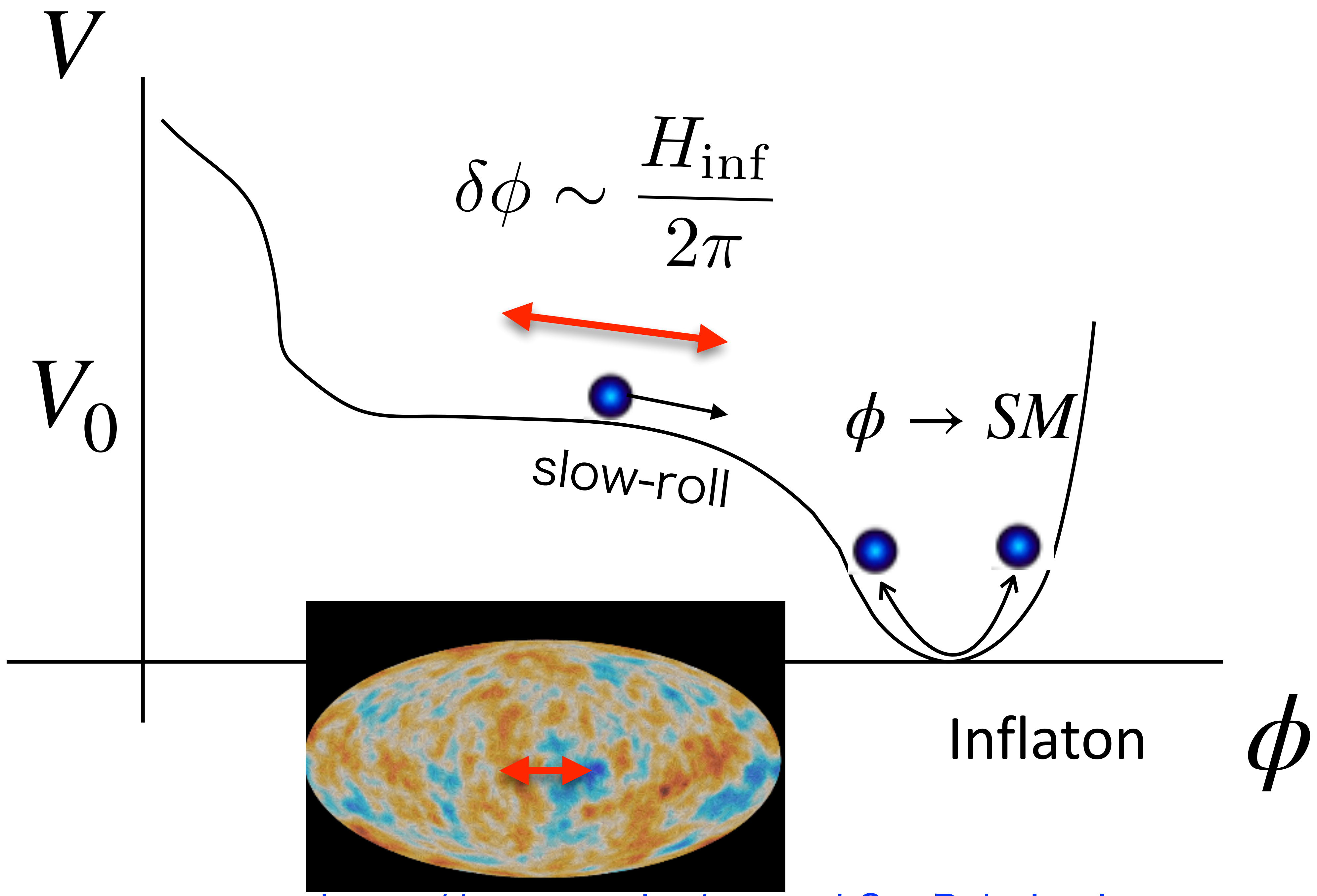
Much before the thermal history, there was inflation.

Inflation solves horizon and flatness problems.



$$a \propto \exp[\frac{V_0^{1/2}}{\sqrt{3}M_{\rm pl}} t]$$

NASA / WMAP SCIENCE TEAM



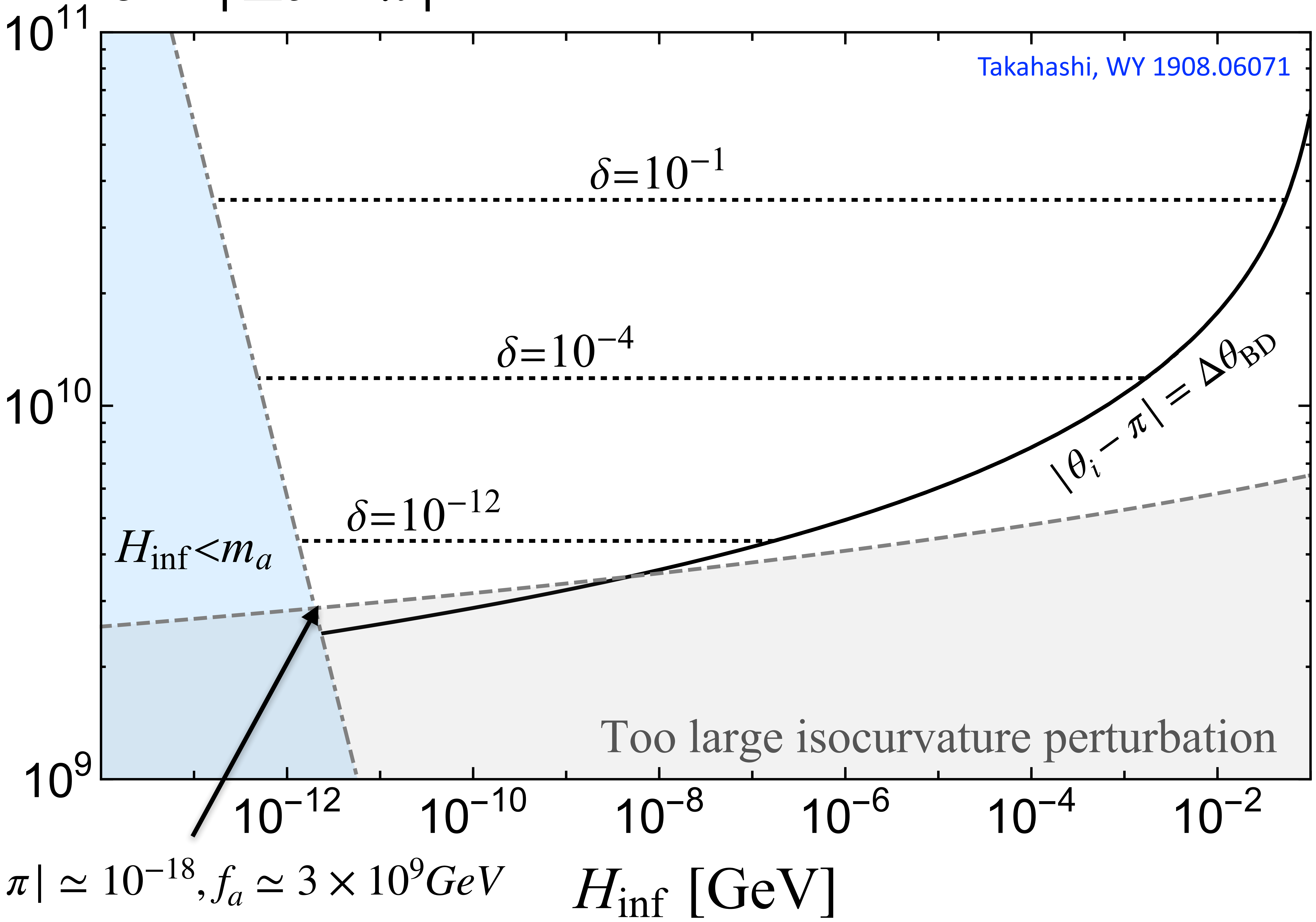
https://www.esa.int/esearch?q=Polarisation

- Slow-roll inflation is plausible.
- The inflationary quantum fluctuation of inflaton field seems to be discovered.
- $H_{\rm inf} \lesssim 10^{14} GeV$ from CMB data
  Planck 2018, 1807.06211

Some related topics

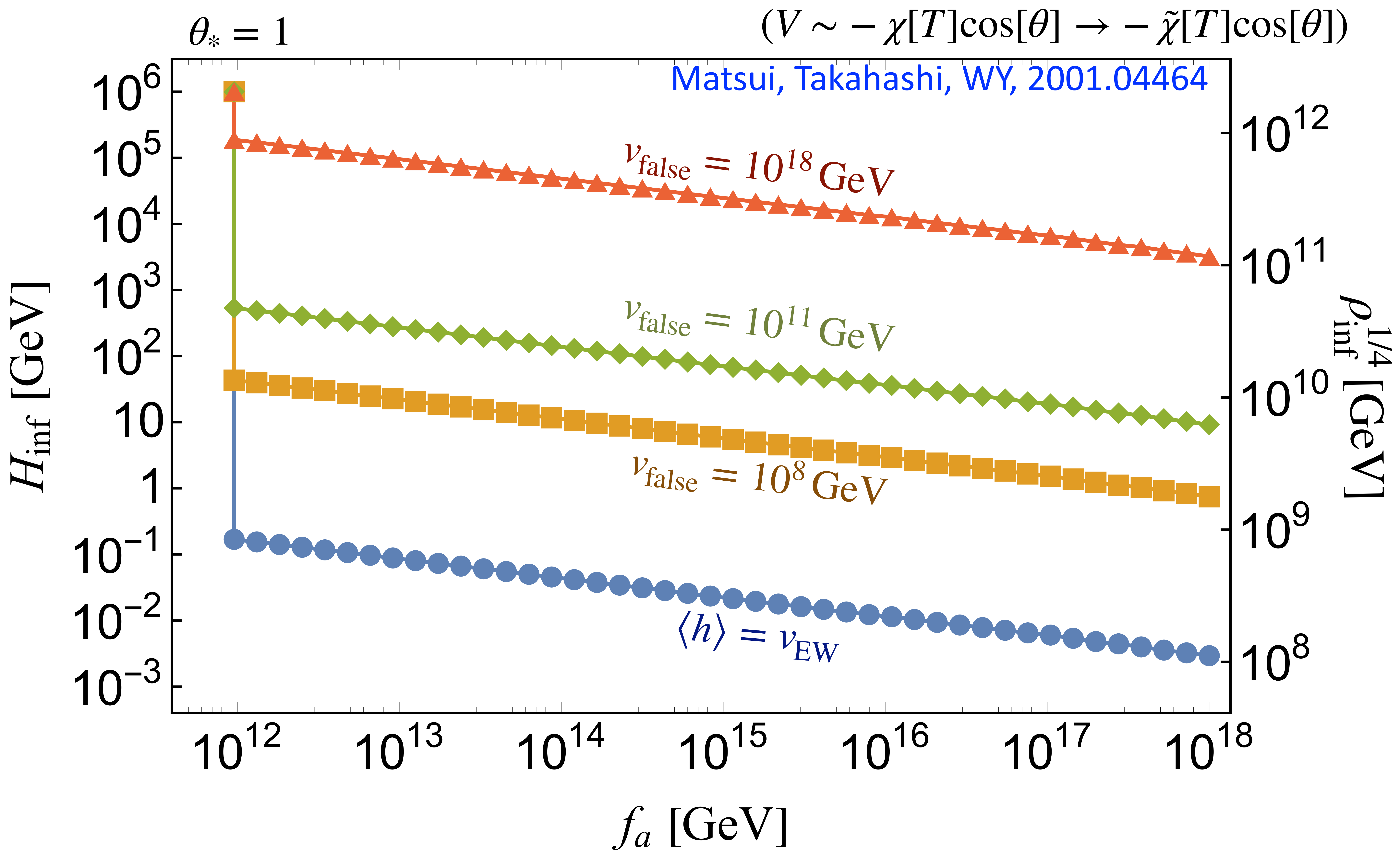
Axion DM can be possible with $f_a \simeq 10^{9-11} GeV$
which is consistent with the isocurvature constraint.

$\delta = |\Delta\theta - \pi|$



$|\theta_i - \pi| \simeq 10^{-18}, f_a \simeq 3\times 10^9 GeV$

Higgs false vacuum inflation open the axion window.

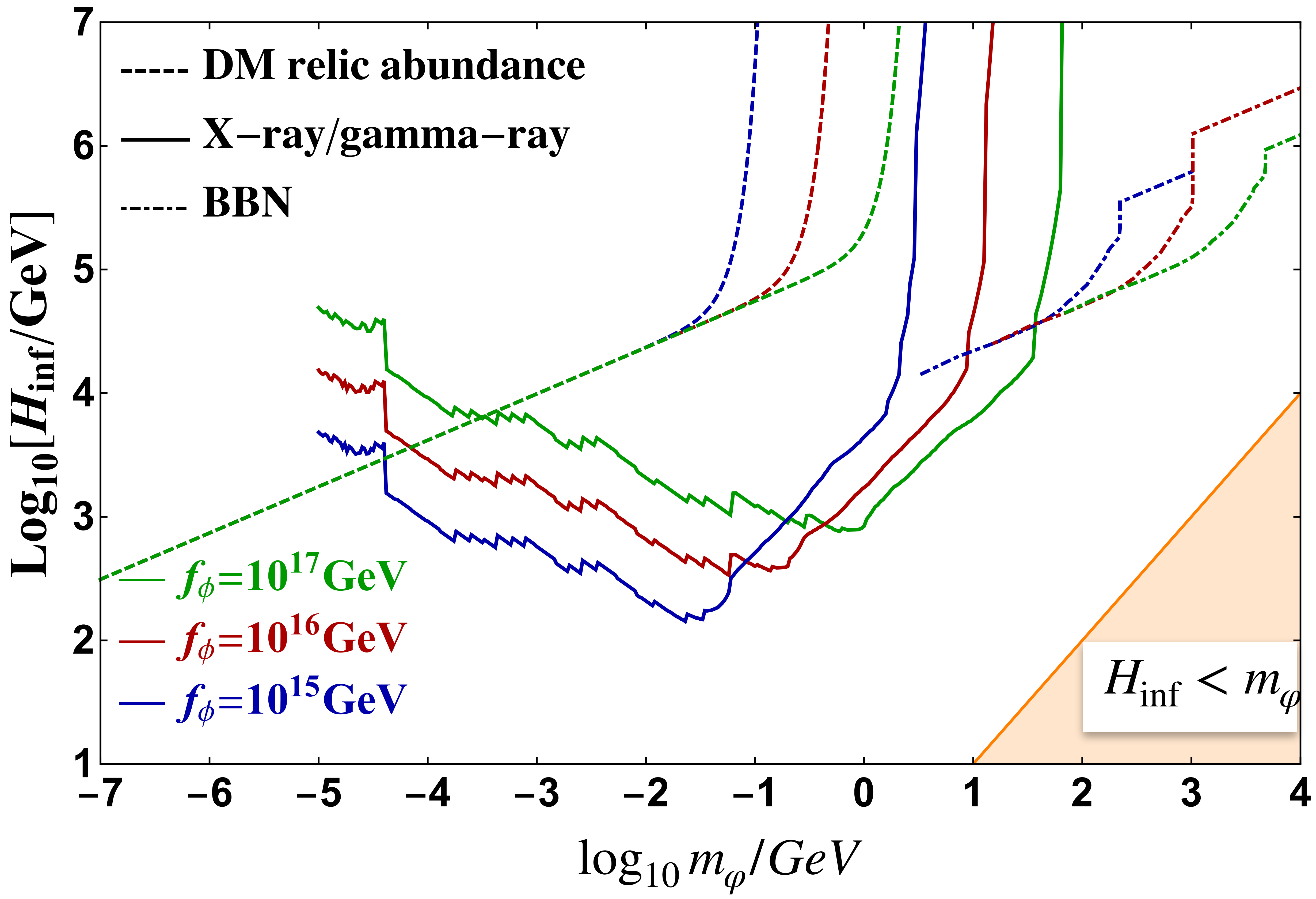


See also Refs. Dvali:1995ce,Banks:1996ea,Choi:1996fs,Jeong:2013xta,Co:2018mho, for stronger QCD with SUSY flat direction of Higgs potential.

Axion-like particle (string axion) φ and low scale inflation

The moduli problem for axion-like particle can be alleviated due to (not too) low-scale inflation.

Shu-Yu Ho, Fuminobu Takahashi, and WY 1901.01240



Assumption:

$N \gg H_{\rm inf}^2/m_\phi^2$

minima do not change during and after inflation

Data taken from
X(gamma)-ray:
Essig, et al. 1309.4091;
BBN:
Kawasaki, et al. 1709.01211;

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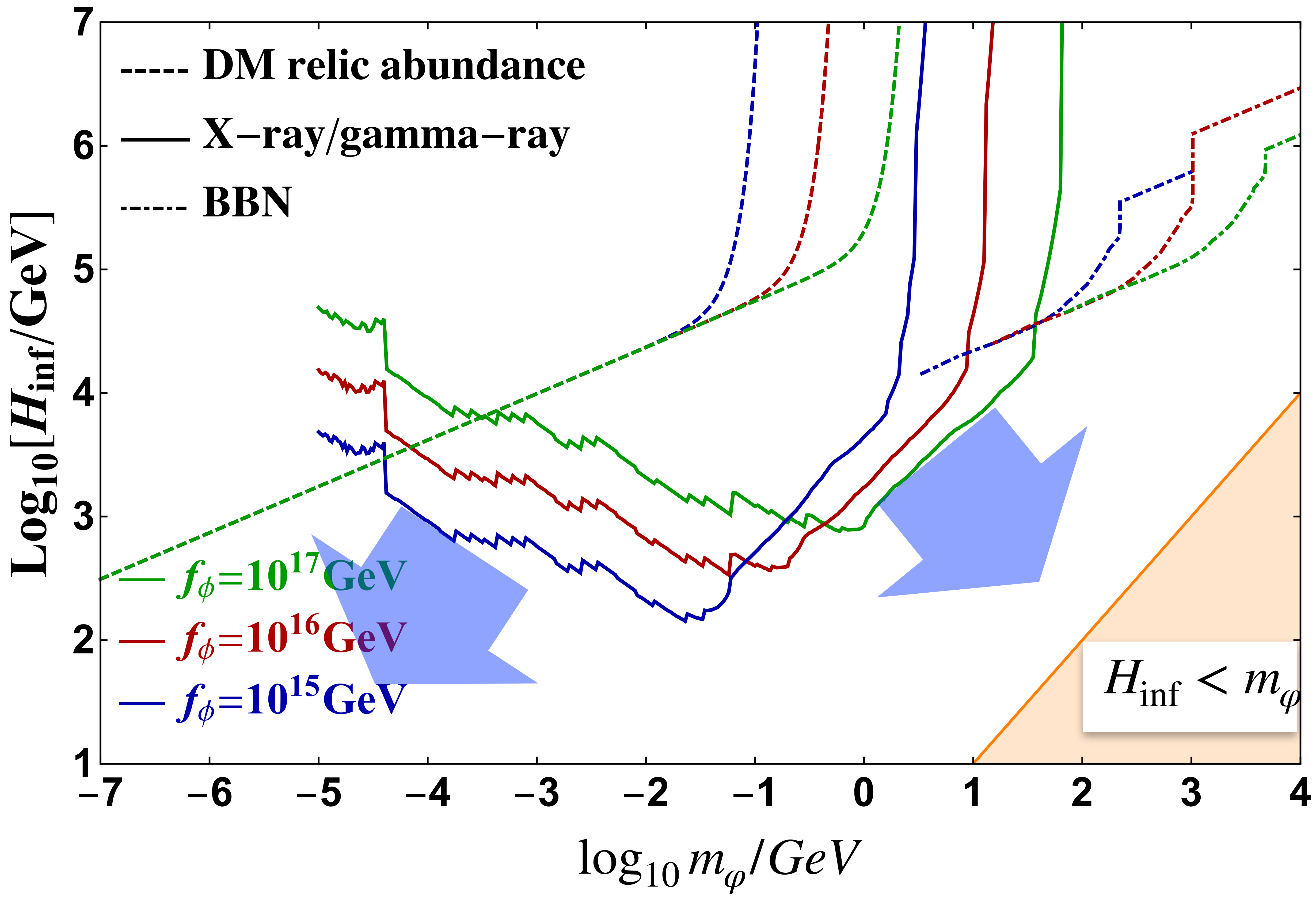

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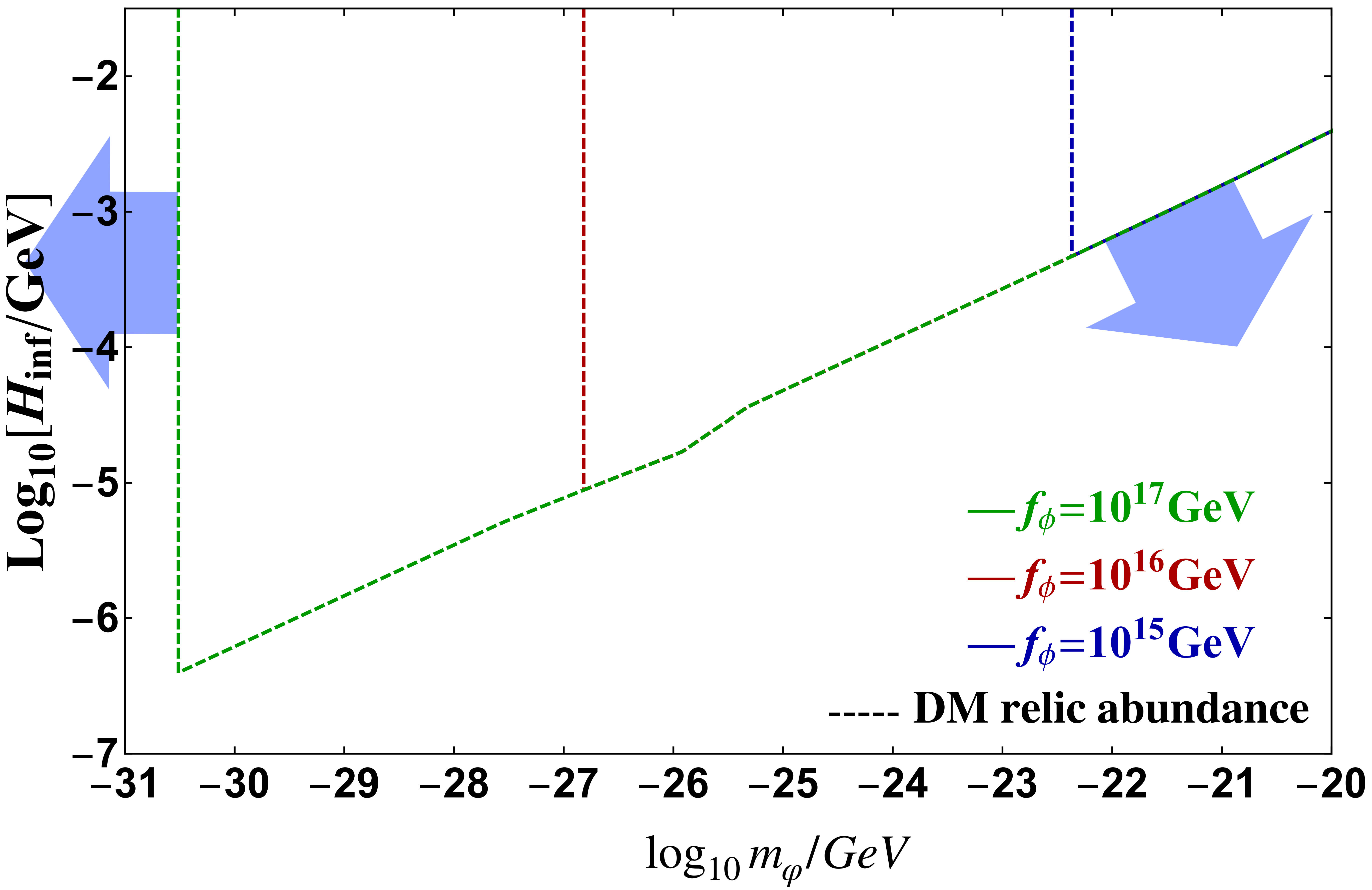
No moduli problem if $H_{\rm inf} < O(1)keV \ll m_{3/2}$.

$$\rho_{\rm inf}^{1/4} \lesssim O(1)\mathrm{PeV}$$



Inflation with $H_{\rm inf} \lesssim O(\mathrm{eV})$ is possible with successful reheating through thermal dissipation, and can be tested.

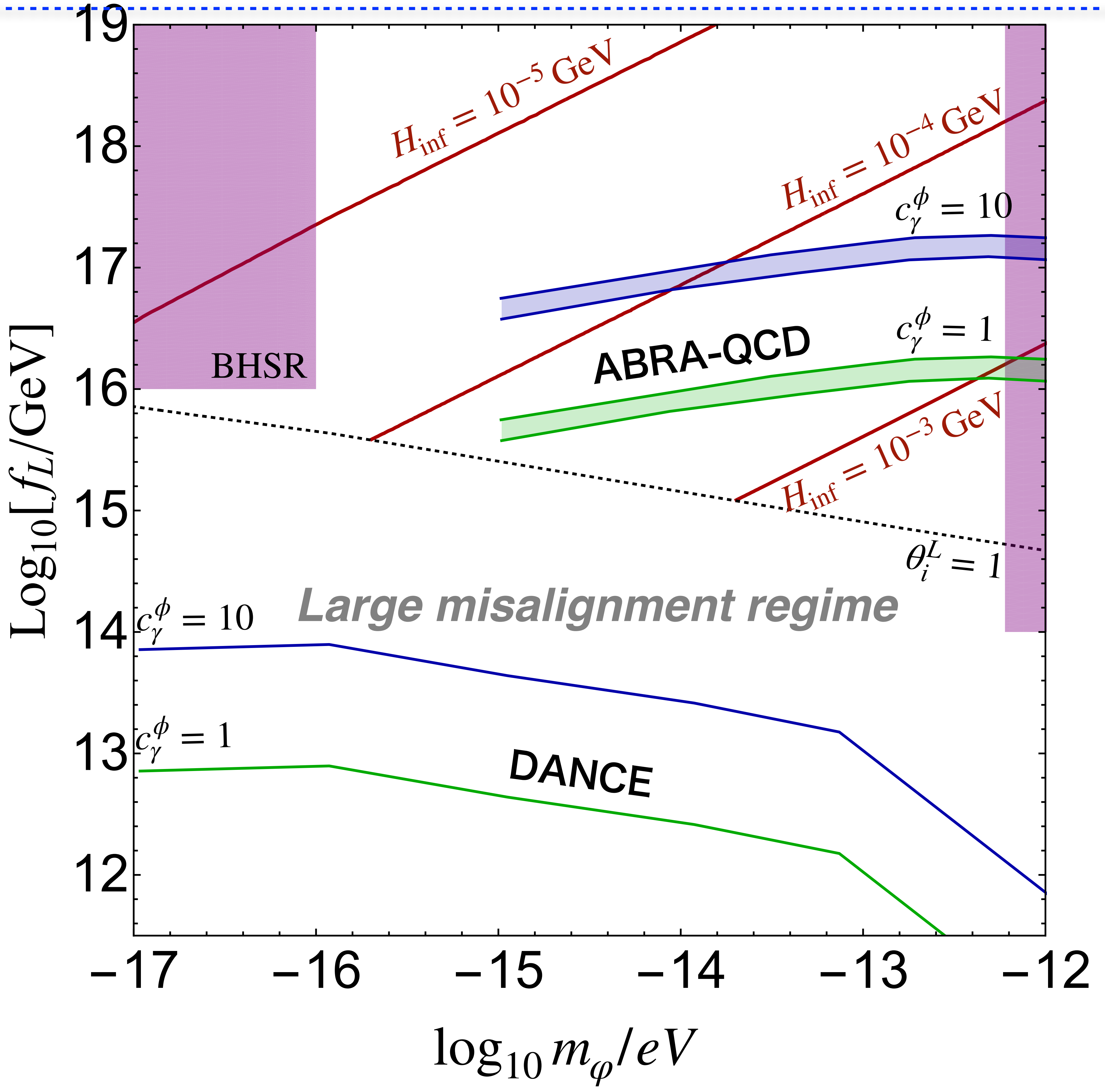
"ALP miracle", Daido, Takahashi, WY, 1702.03284, 1710.11107,
"Big bang on earth", Takahashi, WY 1902.00462.

Opening 1Hz axion window

Marsh, WY, 1912.08188

$10^{-15} eV \sim$ 1Hz axion may be predicted from M-theory Acharya et al 1004.5138.

If no coupling to gluon,



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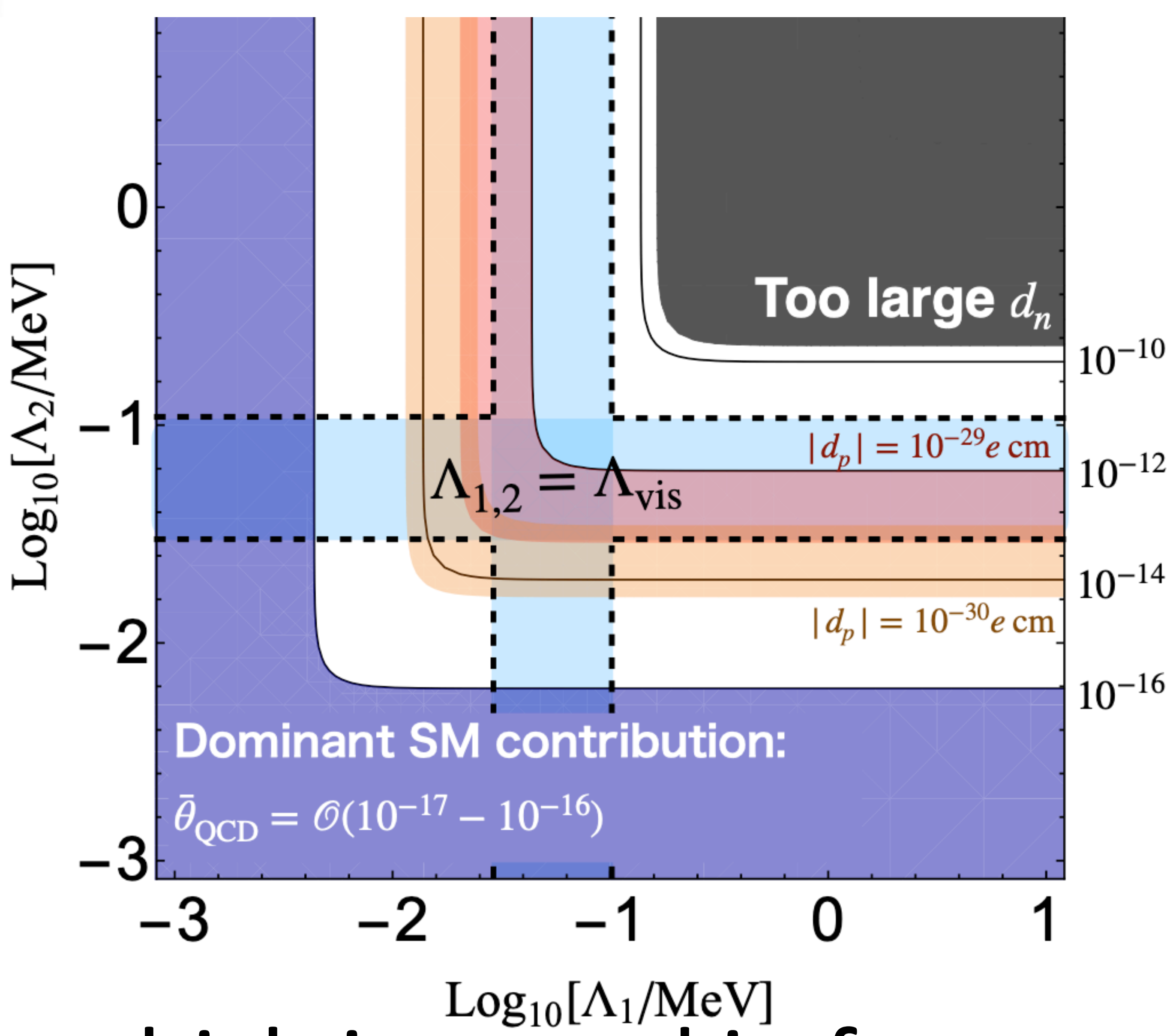
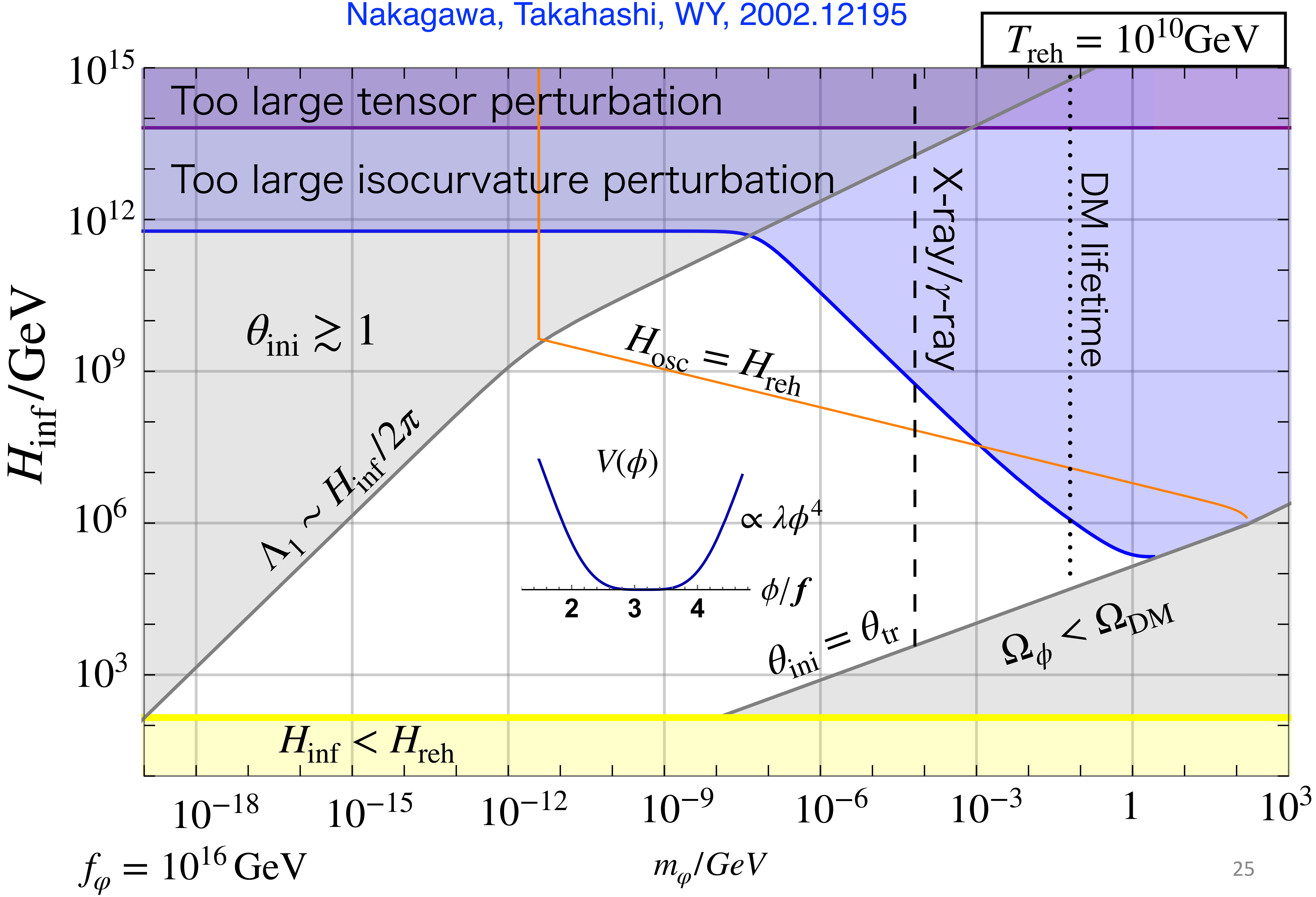


which is tested in future storage ring experiment. Anastassopoulos et al, 1502.04317

Stochastic ALP DM with flat bottom (or flat hilltop see the ref)

Nakagawa, Takahashi, WY, 2002.12195



• Axion hilltop inflation

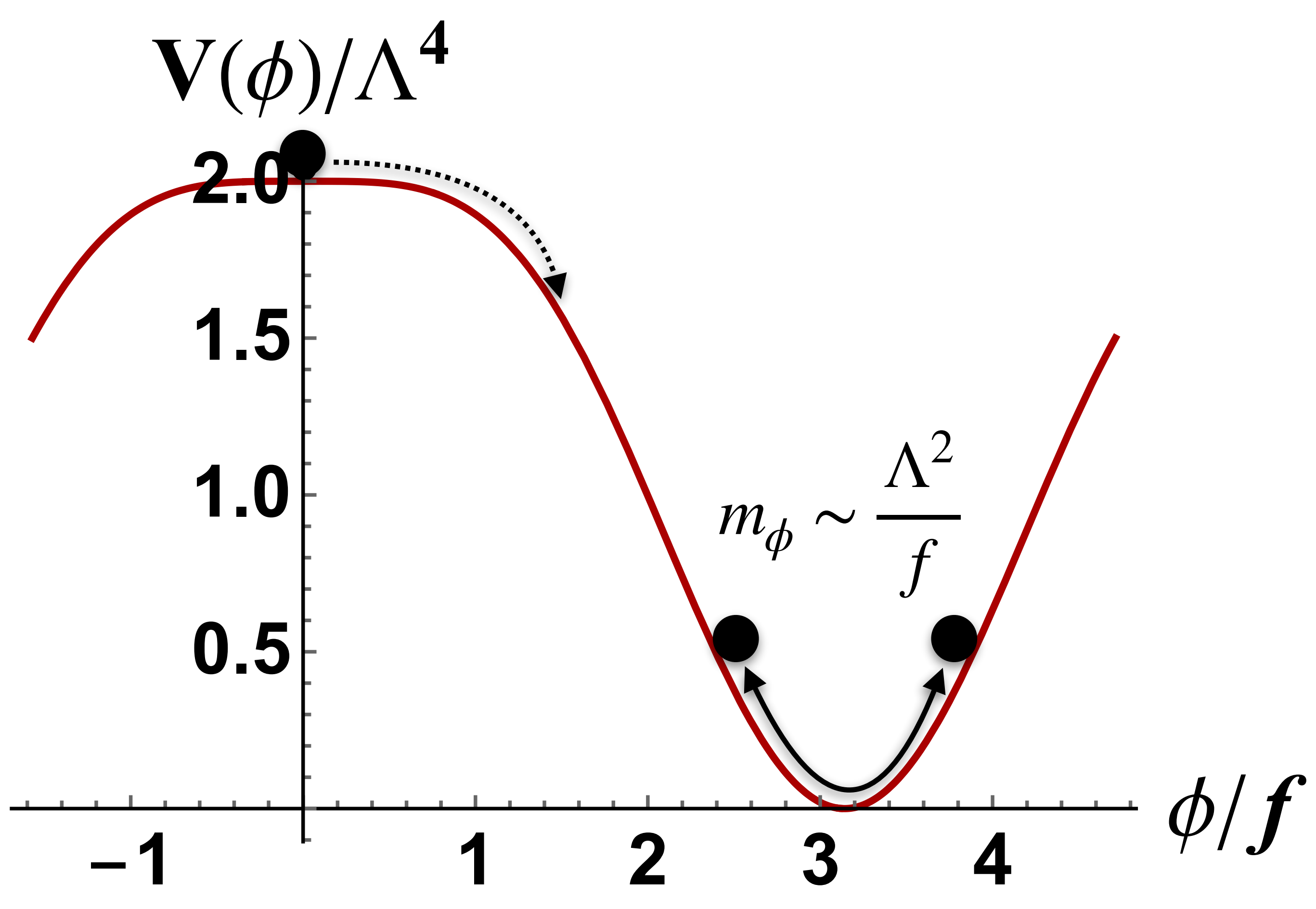
Czerny, Takahashi 1401.5212,
Czerny, Higaki, Takahashi 1403.0410, 1403.5883
Croon and Sanz, 1411.7809
Daido, Takahashi, and WY 1702.03284, 1710.11107
Takahashi and WY, 1903.00462

Axion hilltop inflation can be realized with (at least) two cosine terms: "*Multi-natural inflation*"

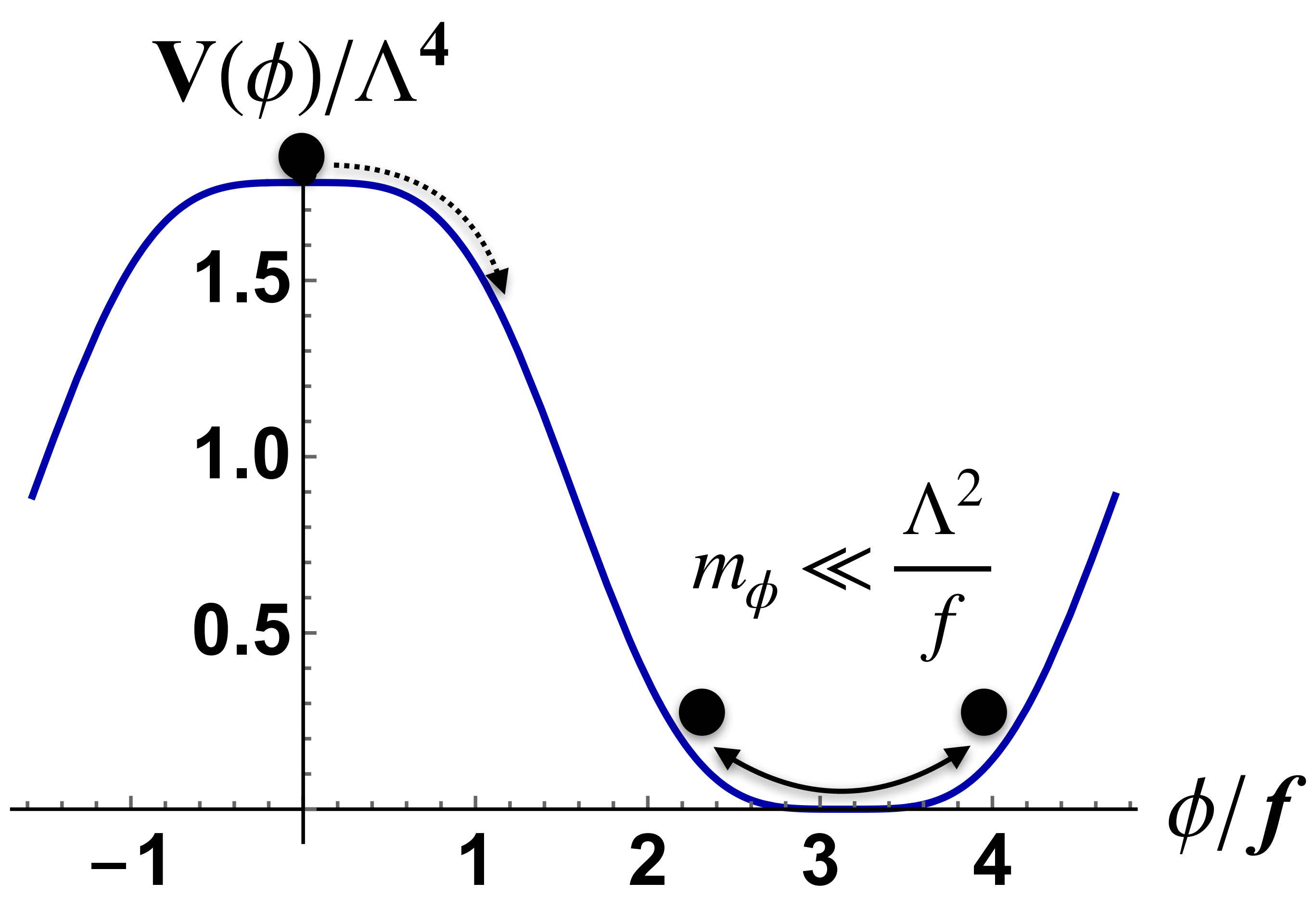
$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f}+\theta\right) - \frac{\kappa}{n^2}\cos\left(\frac{n\phi}{f}\right)\right) + \text{const.} \quad f \ll M_{pl}$$

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

The inflaton masses depend on the parity of n.



Even n

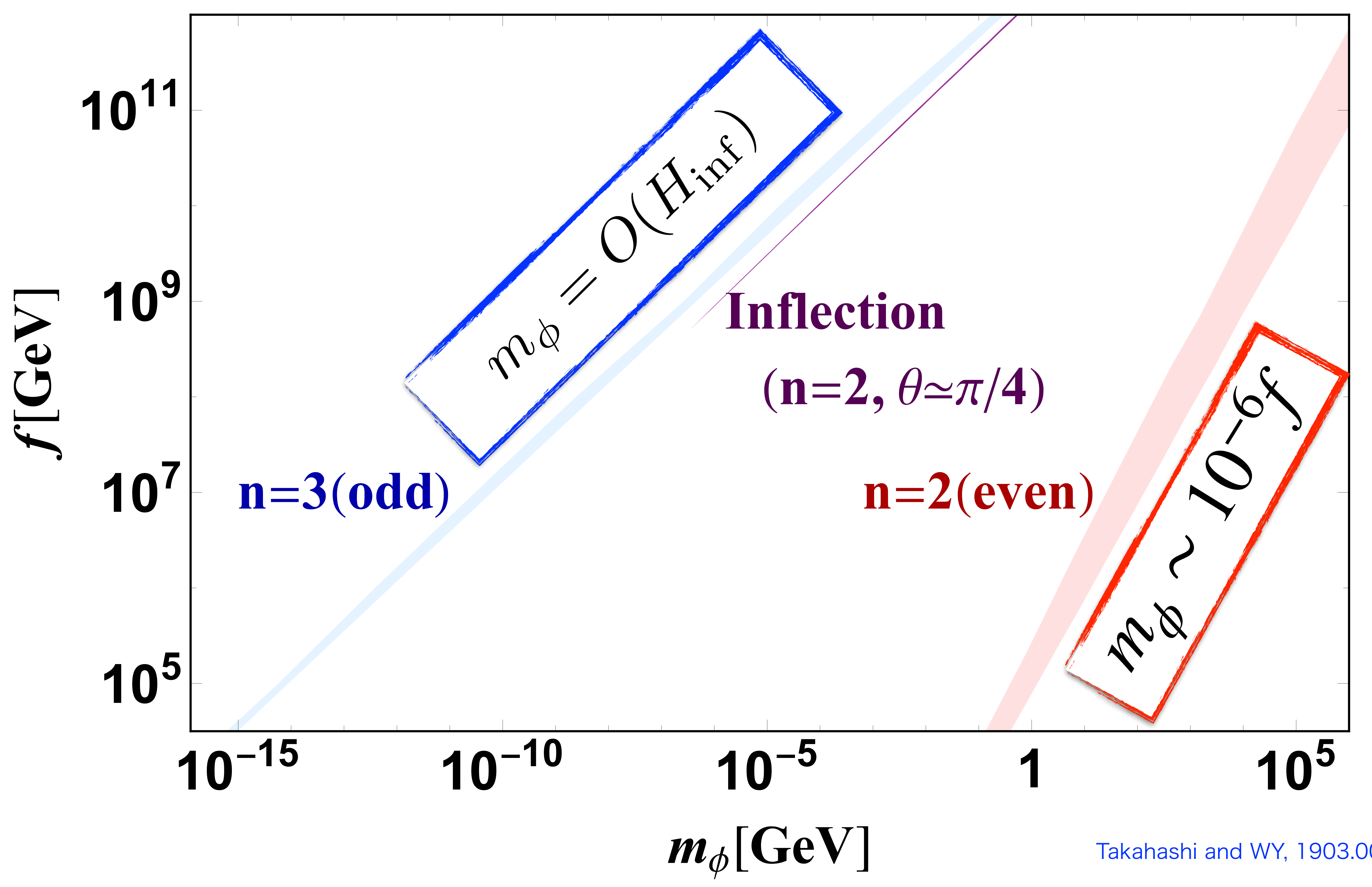


Odd n

• Viable parameter region for inflation

CMB data explained in 2 sigma level

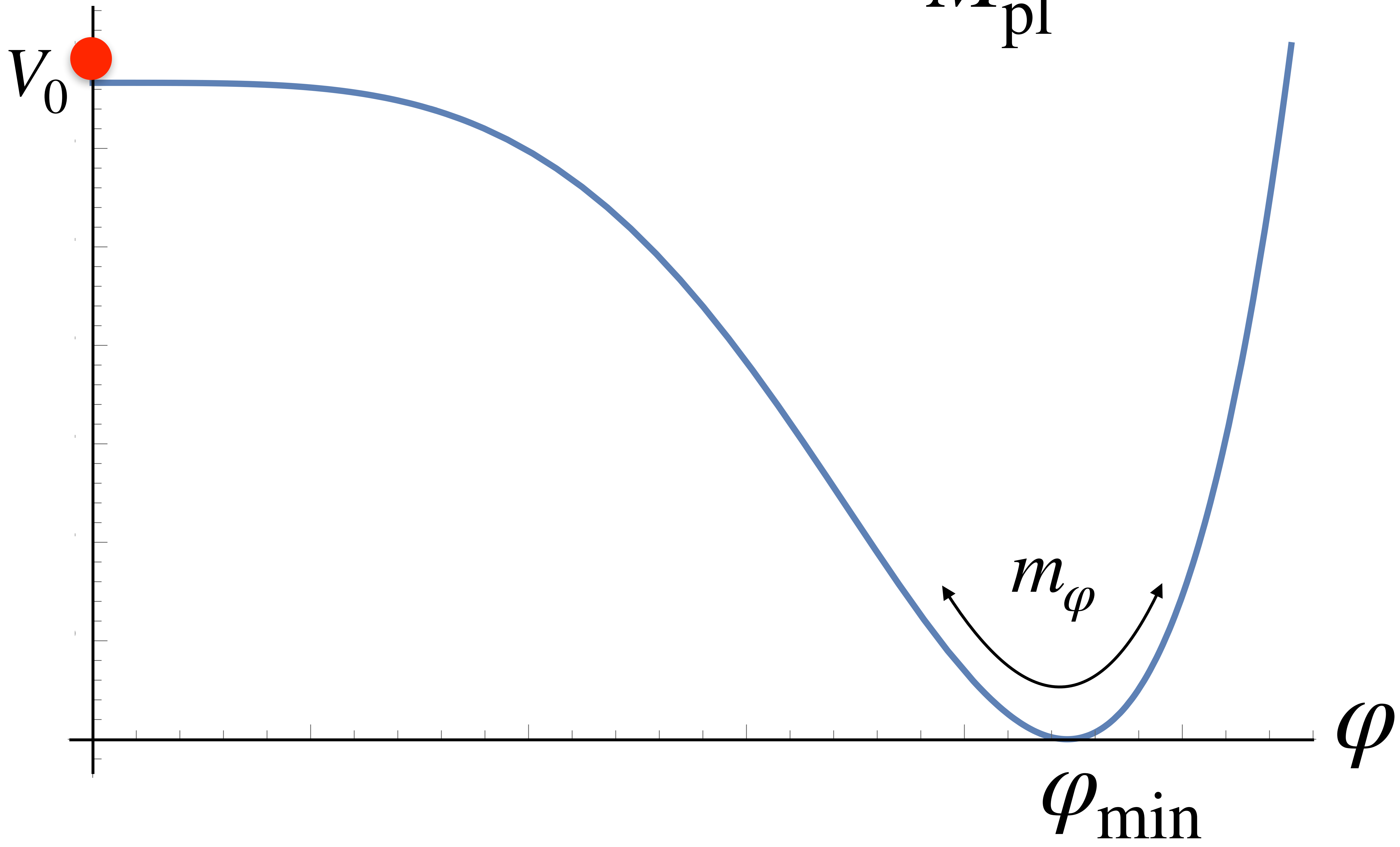
(runnings of spectral index are taken into account)



Takahashi and WY, 1903.00462

3. Low-scale inflation model with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$

$$V = V_0 - \lambda\varphi^4 + c\frac{\varphi^6}{M_{\rm pl}^2}$$



$$H_{\rm inf} \sim 10\,{\rm MeV}, \quad m_\varphi \sim 10^6\,{\rm GeV}, \quad \varphi_{\rm min} \sim 10^{12}\,{\rm GeV}$$

Takahashi, WY, Guth, 1805.08763

Spectral index $n_s \simeq 0.96$ can be obtained by introducing a linear term or Coleman-Weinberg correction (with SUSY.)

Nakayama, Takahashi, 1108.0070, Takahashi 1308.4212

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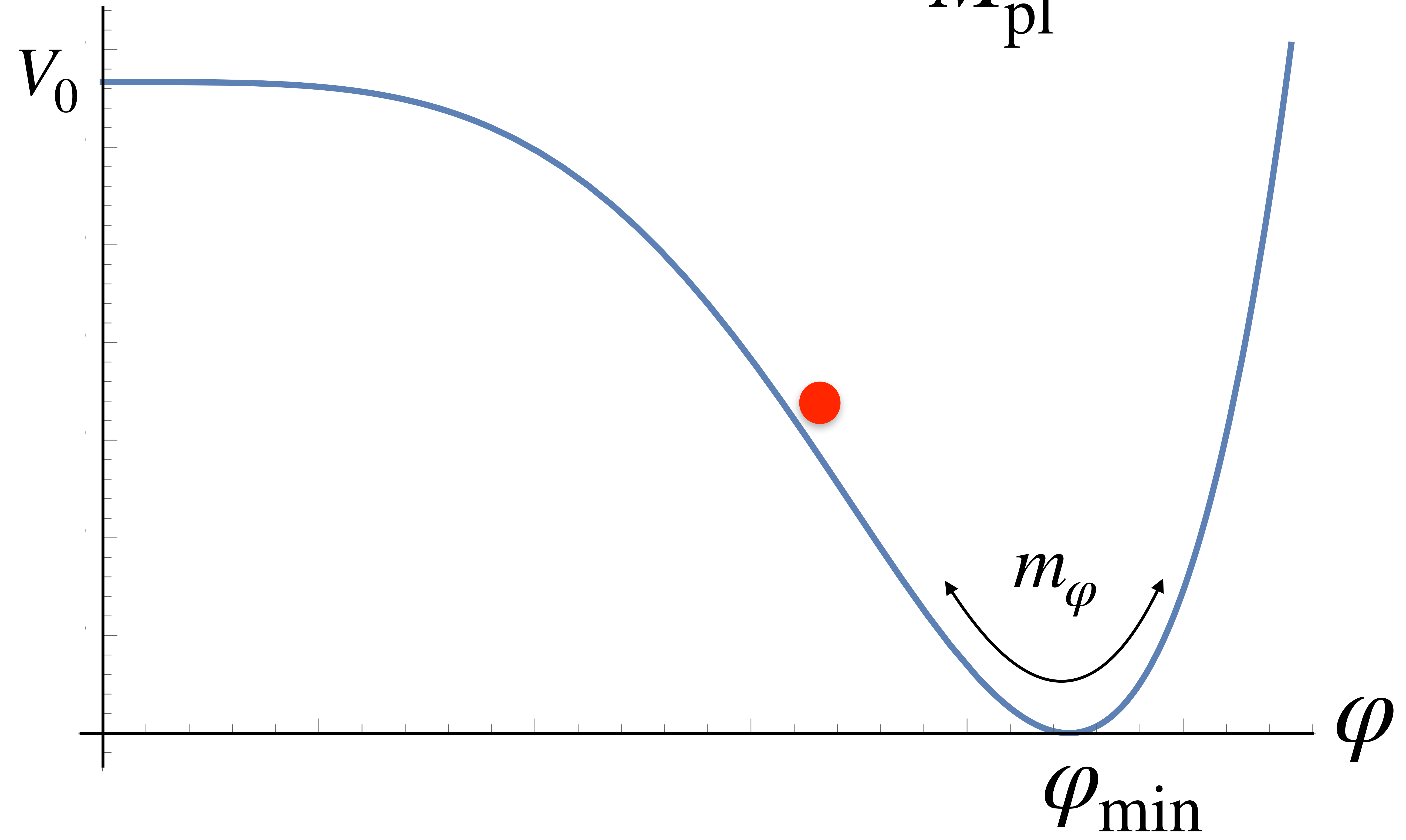

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Successful reheating is possible

We introduce a coupling to right-handed neutrinos,

$$\mathscr{L} = y_{N_i} \varphi\, \bar{\nu}^c_{Ri} \nu_{Ri}$$

with $y_N \sim 10^{-7}$.

The decay rate is $\Gamma_\varphi = \sum \frac{y_{N_i}^2}{8\pi} m_\varphi$ if kinematically allowed.

$$T_R \sim \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{M_{\rm pl}\Gamma_\varphi}$$

$$\simeq O(10)\mathrm{TeV} \left(\frac{106.75}{g_*}\right)^{\frac{1}{4}} \left(\frac{y_N}{10^{-7}}\right) \left(\frac{m_\varphi}{10^6\mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{N_R^{\rm eff}}{2}\right)^{1/2}$$

cf. Inflation with $H_{\rm inf} \lesssim O(\mathrm{eV})$ is possible. In this case the reheating proceeds through thermal dissipation.

"ALP miracle", Daido, Takahashi, WY, 1702.03284, 1710.11107,
"Big bang on earth" Takahashi, WY 1902.00462