Relaxing the Cosmological Moduli Problem by Low-scale Inflation

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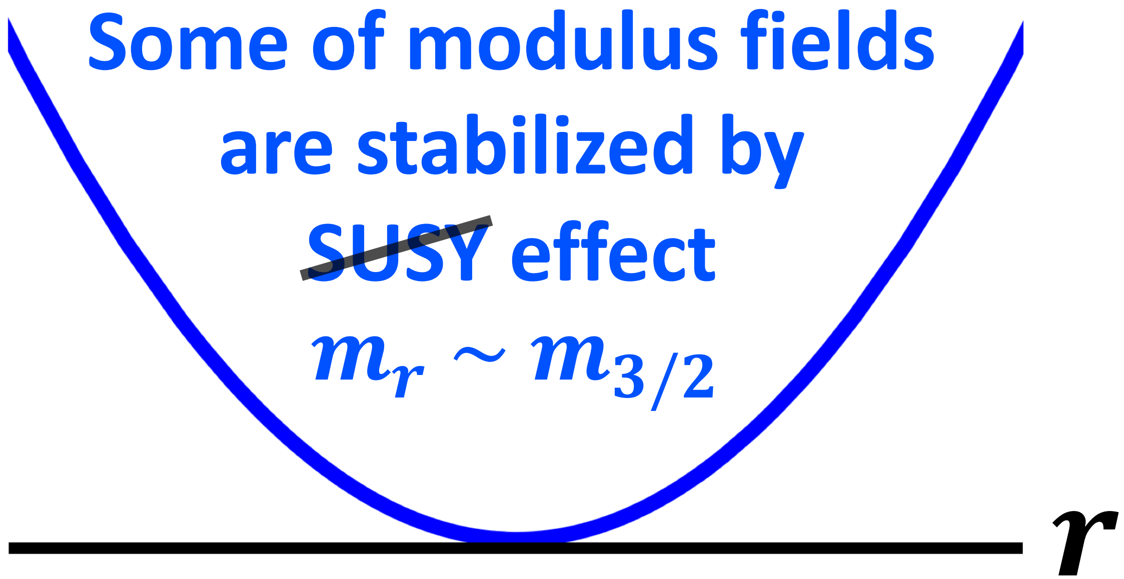
14 May 2019, 2 day mini-workshop : Axion Cosmology
Resonant instabilities in cosmology
and their observational consequences

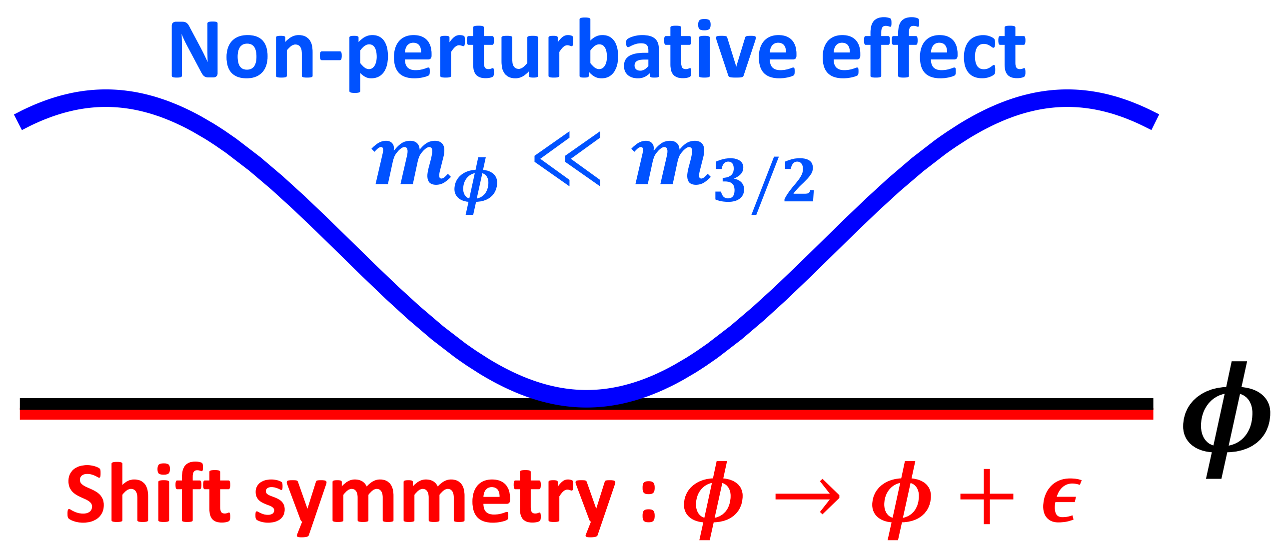
Introduction

Modulus Field

- String theory predicts many light scalar moduli fields through compactification.
- In SUSY, a modulus forms a chiral supermultiplet, X.

$$X = r + i\phi \quad \text{Axion}$$



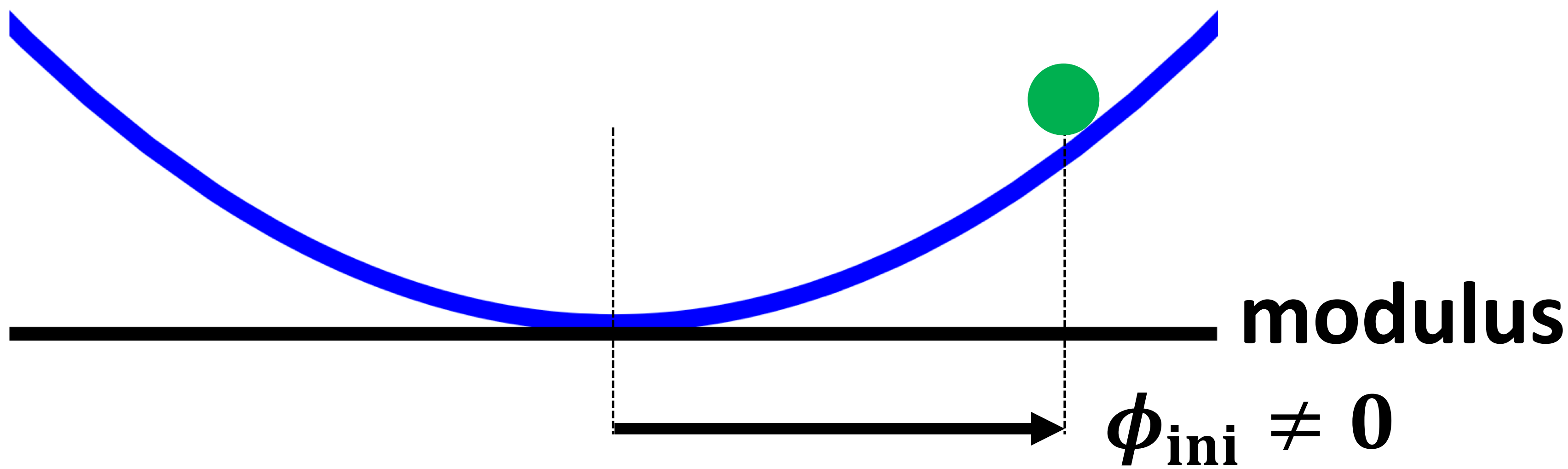


Dynamics of Modulus Field

- **After inflation ends**

$H(t) \gg m$

modulus is frozen by Hubble friction



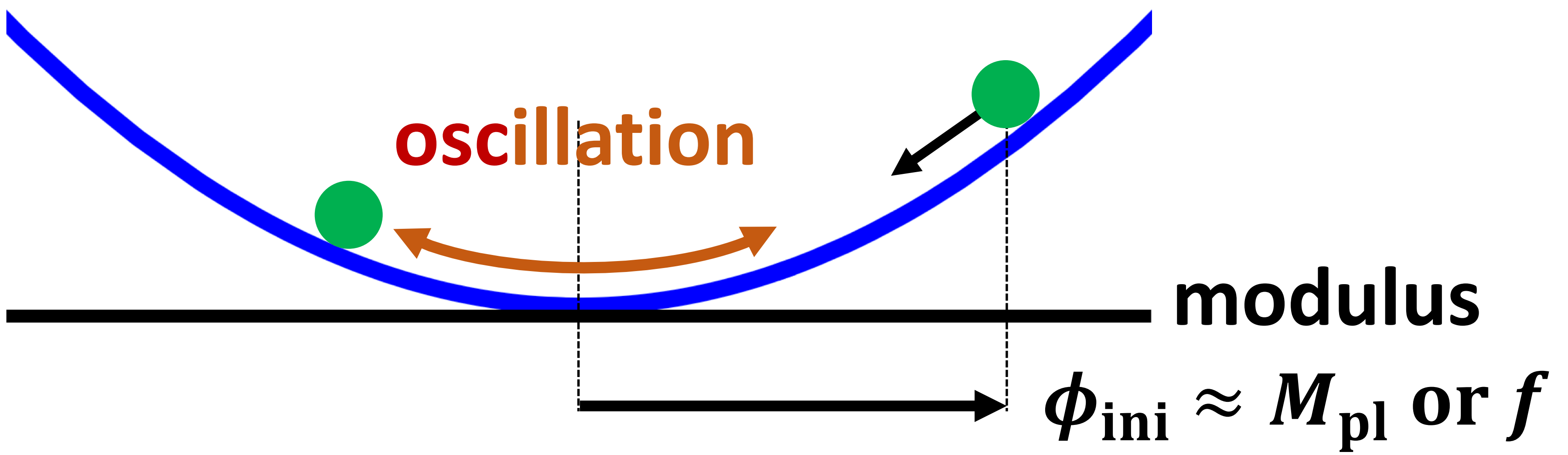
$H(t)$: Hubble parameter

m : modulus mass

Dynamics of Modulus Field

- After inflation ends

$$H(t_{\rm osc}) \approx m$$



$$\rho_{\rm mod} \approx m^2 M_{\rm pl}^2 \ \text{or}\ m^2 f^2$$

The energy density of modulus may dominate the Universe.

Moduli Abundance

- We consider only one (string) axion ϕ with a potential

$$V(\phi) \simeq \frac{1}{2} m_\phi^2 \phi^2$$

- At $H(t_{osc}) \approx m_\phi$ ⟶ $\rho_{\phi,\,\mathrm{ini}} \simeq \frac{1}{2} m_\phi^2 \phi_{\mathrm{ini}}^2$

$$\Omega_\phi^{\mathrm{stable}} h^2 \simeq 3.3 \times 10^{11} \left(\frac{g_{\star,\mathrm{osc}}}{106.75} \right)^{-1/4} \left(\frac{m_\phi}{0.1\,\mathrm{GeV}} \right)^{1/2} \left(\frac{\phi_{\mathrm{ini}}}{10^{16}\,\mathrm{GeV}} \right)^2 \quad \text{for } \Gamma_{\mathrm{inf}} > m_\phi$$

The axion abundance Ω_ϕ can be suppressed if ϕ_{ini} is sufficiently small.

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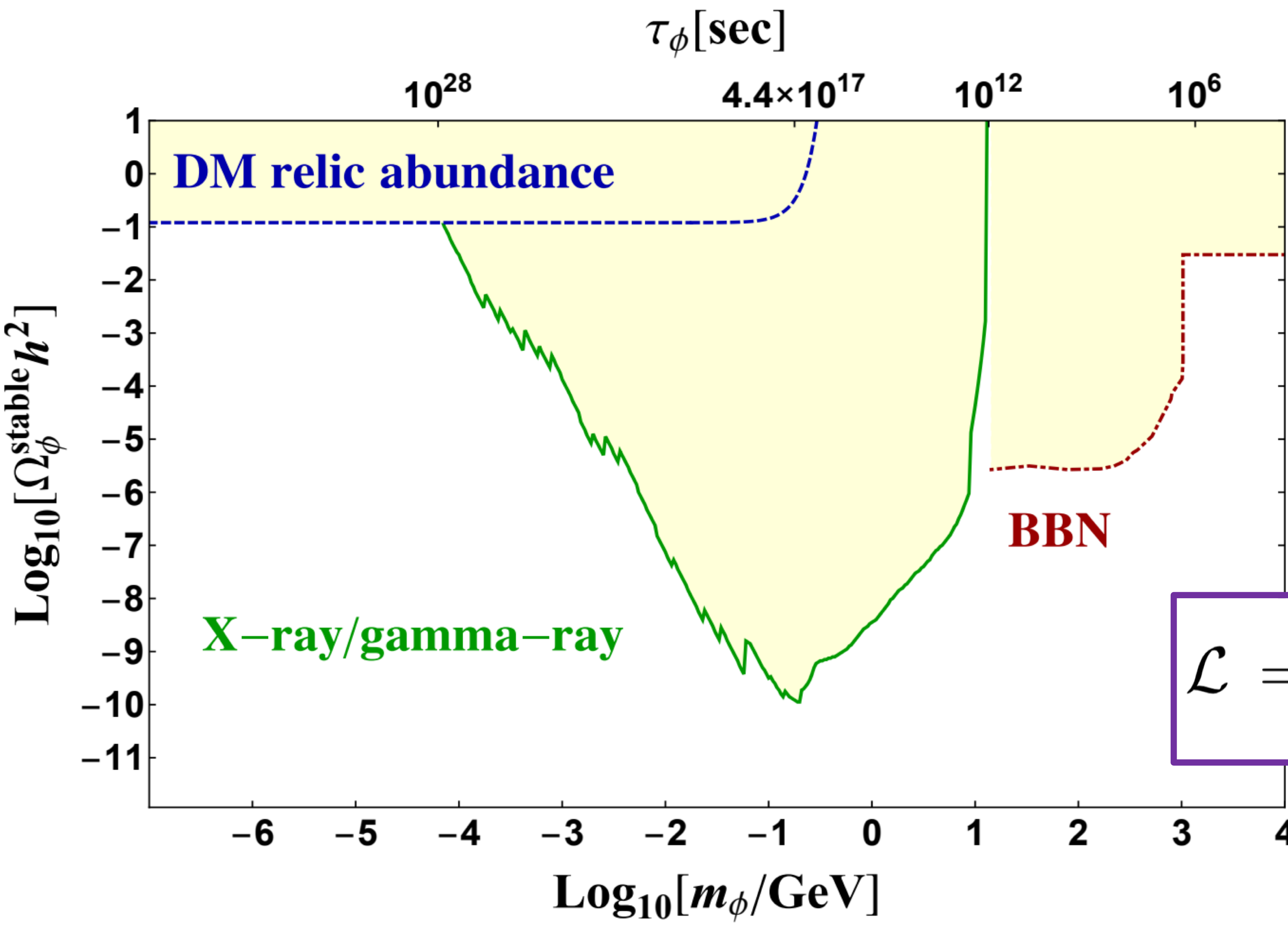
  - ✓ It may overproduce X-ray or gamma-ray fluxes.

Astrophysical & Cosmological Constraints



$$\mathcal{L} = \frac{\alpha}{4\pi}\frac{\phi}{f_\phi}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

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⟶ **moduli problems in cosmology**

Simple Solutions to Moduli Problem

- Entropy production (e.g. thermal inflation) — Yamamoto '86 Lyth & Stewart '96

  → It may also dilute pre-existing baryon asymmetry

- Adiabatic suppression → It is not so efficient — Linde '96, K. Nakayama et al. 2011

- Very low scale inflation with $H_{\rm inf} \ll m_\phi$ — Randall & Thomas '95

- Bunch-Davies (BD) distribution — S.Y.H, Takahashi & Wen 2019

  $m_\phi \ll H_{\rm inf}$

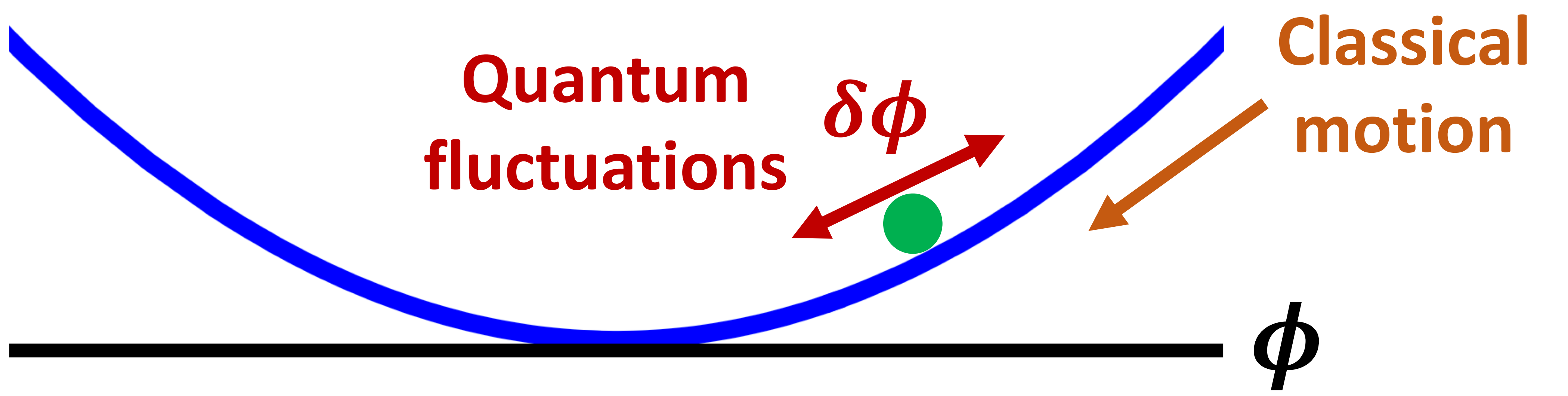
  [cf. Graham & Scherlis (1805.07362) and Takahashi, Wen & Guth (1805.08763) applied to the QCD axion]

What we did

Bunch-Davies Distribution

Bunch & Davies `78

- Suppose that the axion already acquires its mass (or potential) during inflation.
- The quantum diffusion prevents the axion from falling into the potential minimum.



Bunch-Davies Distribution

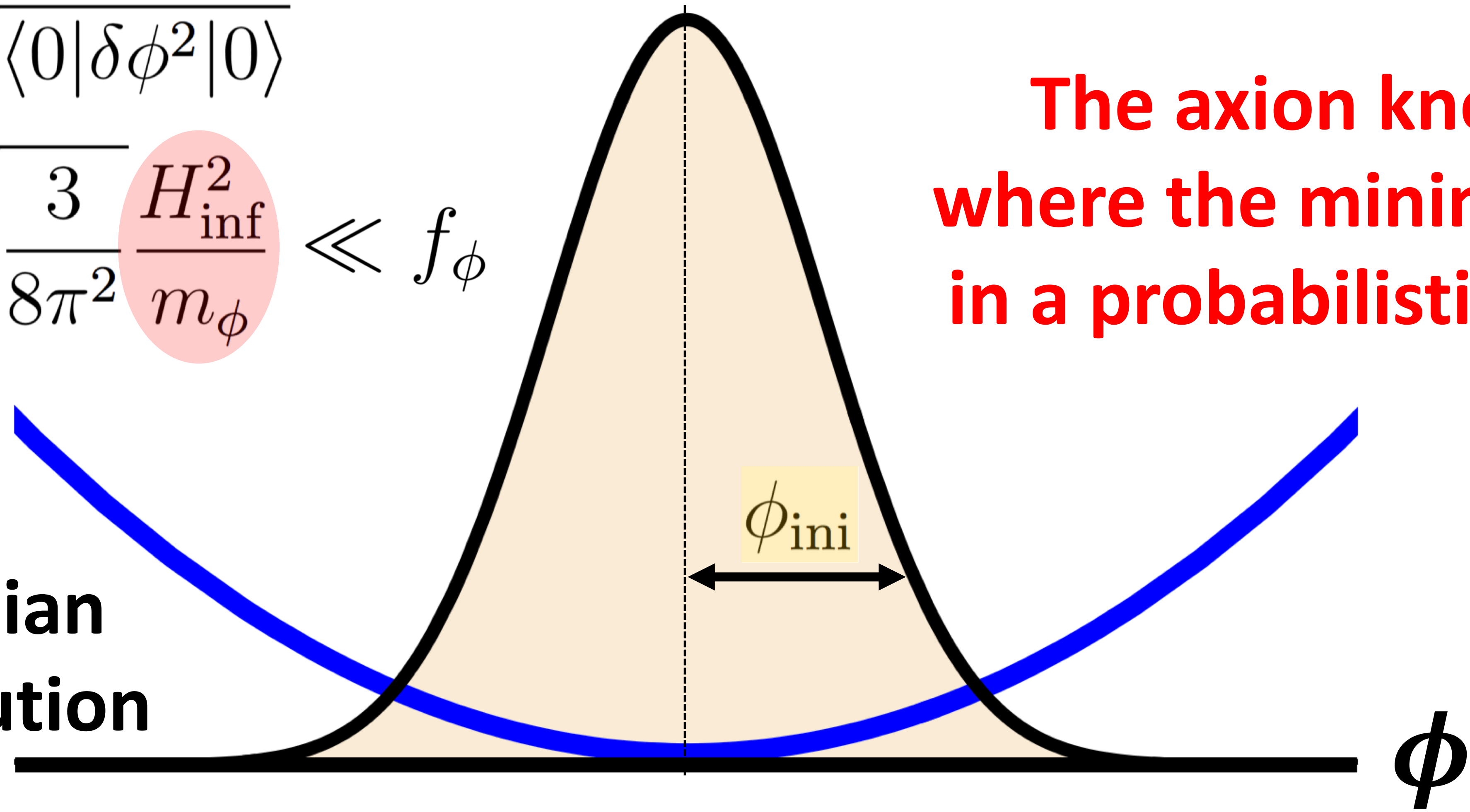
Bunch & Davies `78

Quantum fluctuations ⟷ **Classical motion**

$$\phi_{\rm ini} \simeq \sqrt{\langle 0|\delta\phi^2|0\rangle}$$

$$\simeq \sqrt{\frac{3}{8\pi^2}\frac{H_{\rm inf}^2}{m_\phi}} \ll f_\phi$$

The axion knows where the minimum is in a probabilistic way.



Bunch-Davies Distribution

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- **In order to reach the BD distribution, we also assume that the inflation lasts sufficiently long (a large number of e-folds).**

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- In order to reach the BD distribution, we also assume that the inflation lasts sufficiently long (a large number of e-folds).

- Such a long period of inflation can be realized by eternal inflation, a situation where the inflation never ends globally but it only ends locally.

A.D. Linde '86
A.H. Guth 2007

The Axion Abundance with the BD Distribution

- **The energy density of the axion with BD distribution**

$$\phi_{\rm ini} \simeq \sqrt{\frac{3}{8\pi^2}\frac{H_{\rm inf}^2}{m_\phi}} \;\Rightarrow\; \rho_{\phi,\,{\rm ini}} \simeq \frac{3}{16\pi^2}H_{\rm inf}^4$$

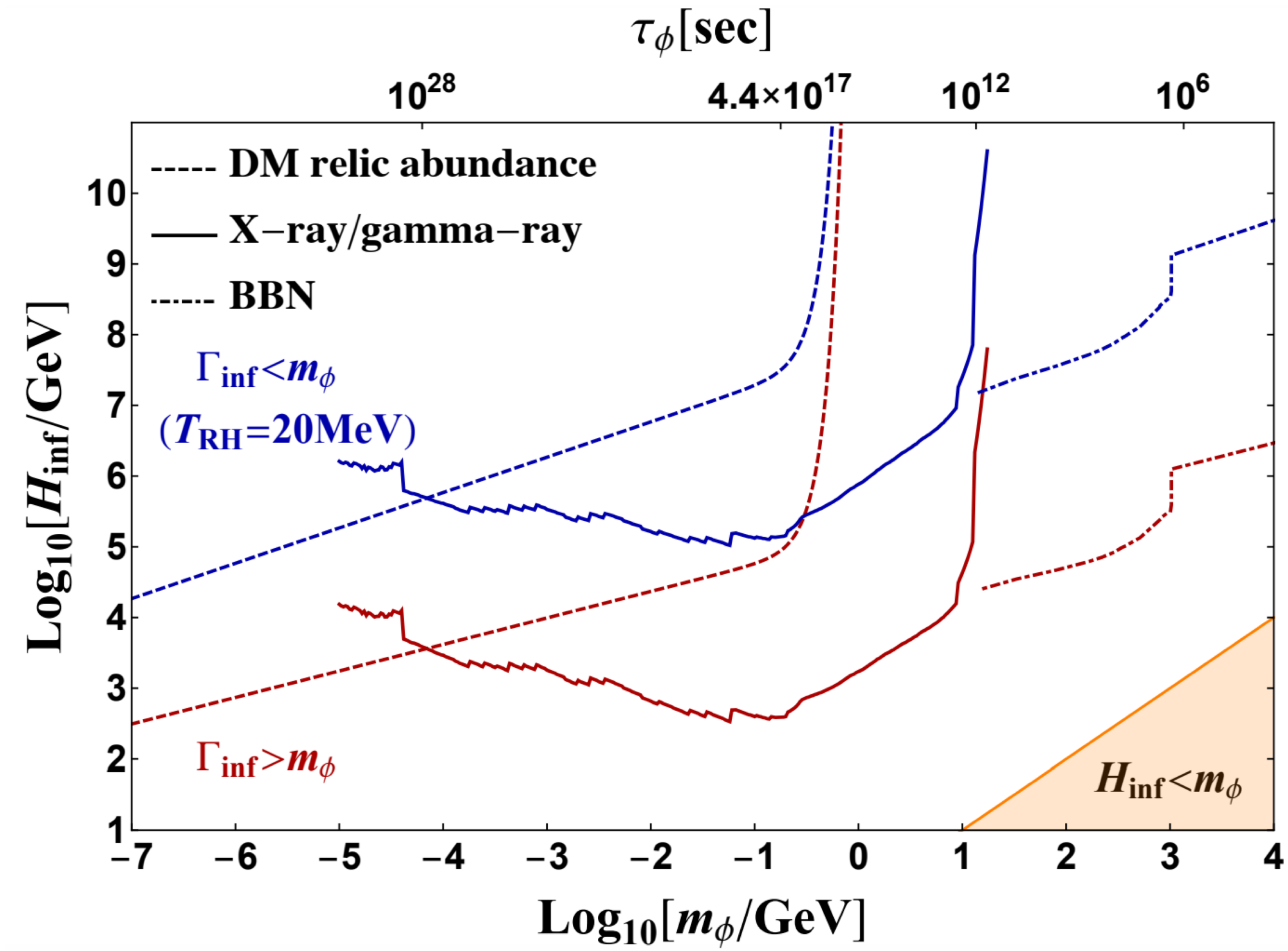
$H(t_{\rm osc}) \approx m_\phi$

- **The axionic moduli problem is relaxed if** $H_{\rm inf} \ll \sqrt{m_\phi f_\phi}$.

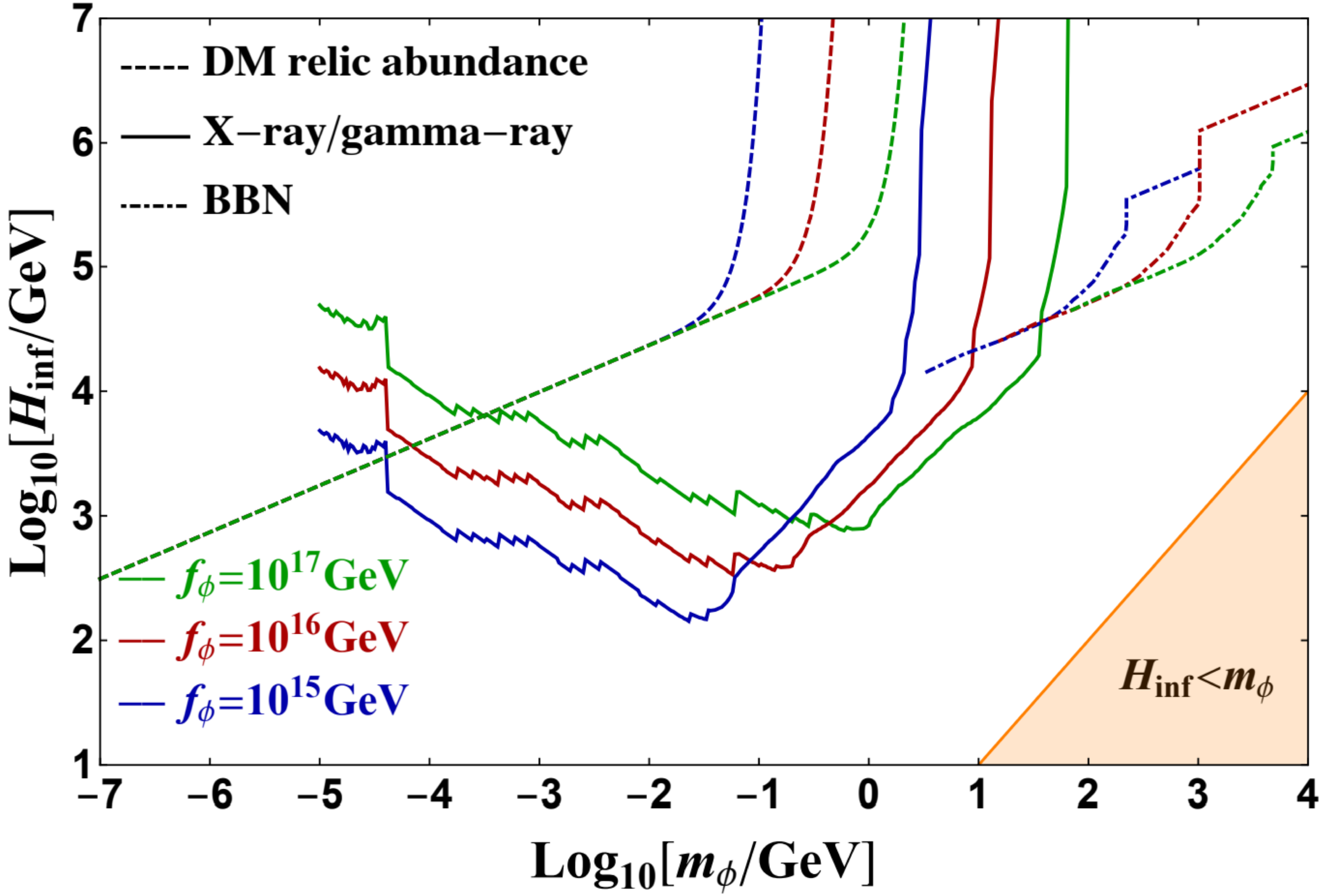
$$\Omega_\phi^{\rm stable}h^2 \simeq 1.3\times 10^{-20}\left(\frac{g_{\star,{\rm osc}}}{106.75}\right)^{-1/4}\left(\frac{m_\phi}{0.1\,{\rm GeV}}\right)^{-3/2}\left(\frac{H_{\rm inf}}{\rm GeV}\right)^4 \quad {\rm for}\;\; \Gamma_{\rm inf} > m_\phi$$

One can suppress Ω_ϕ by low inflation scale

Upper Bound on H_{inf} for Solving CMP

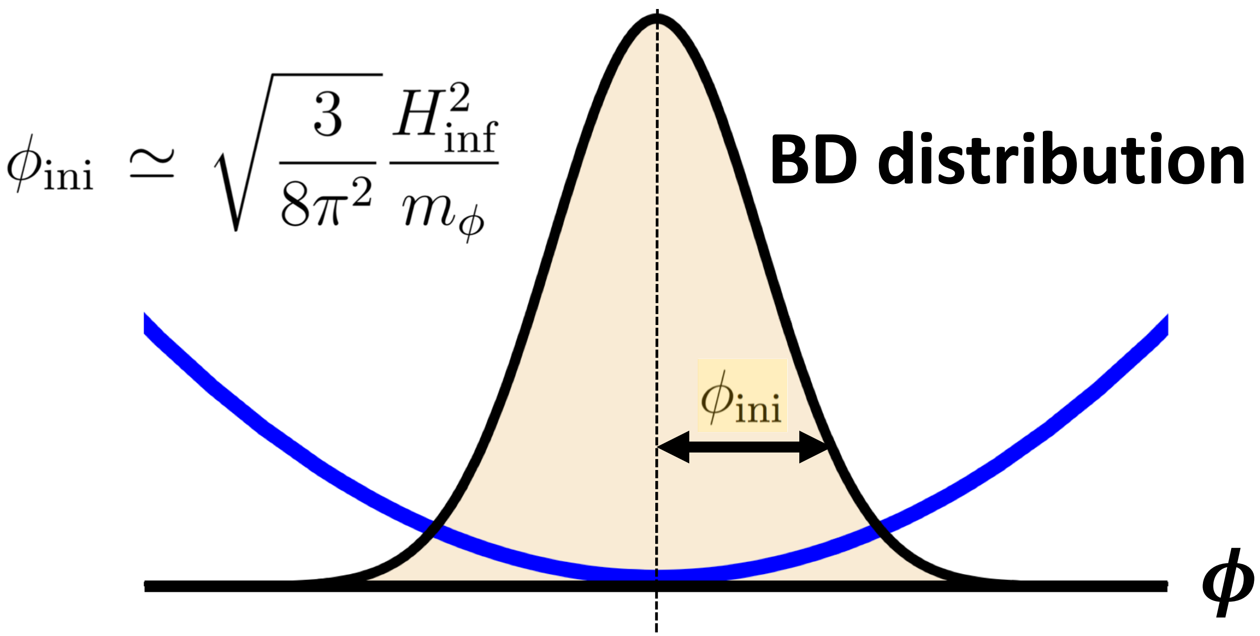


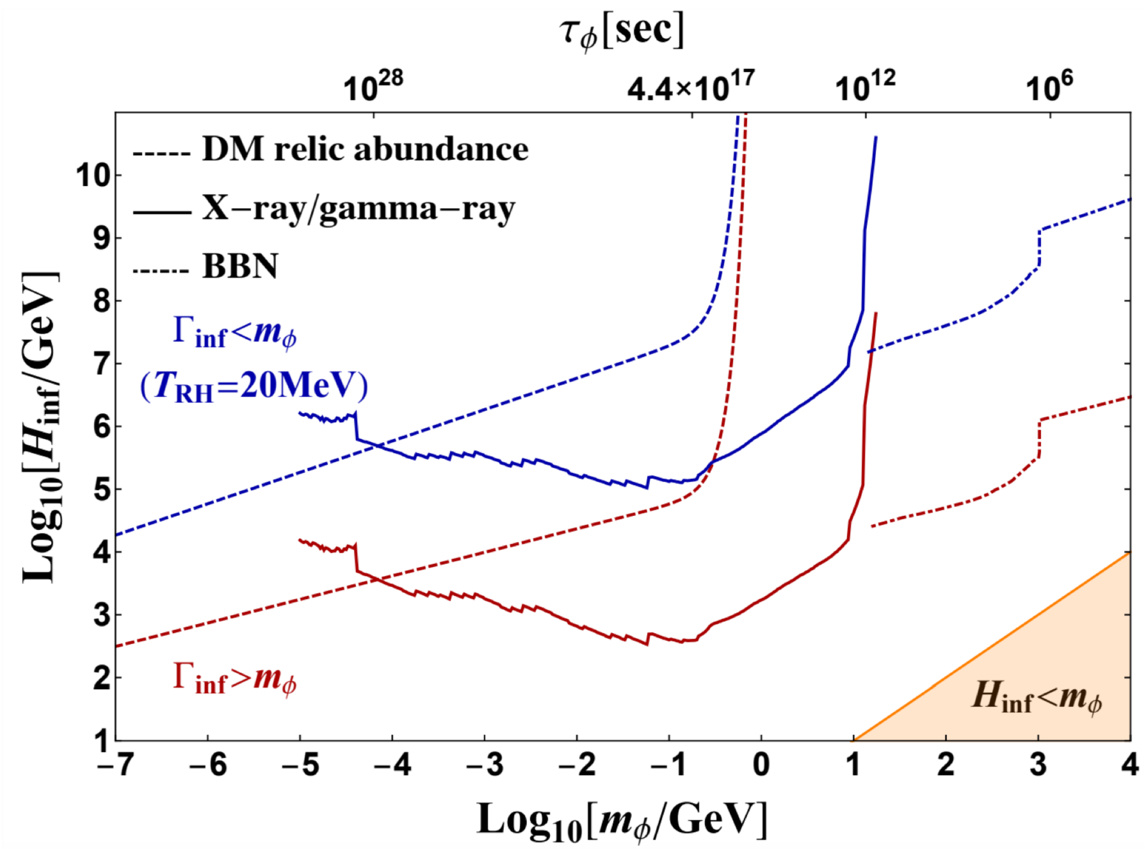
Upper Bound on $H_{\rm inf}$ with Different f_ϕ



Summary

- We have shown that the CMP can be significantly relaxed by low-scale inflation even $m_\phi \ll H_{\rm inf}$. This is because the value of the scalar field follows the BD distribution if the inflation lasted sufficiently long.





Back up

Upper Bound on H_{inf} for lower axion masses