Relaxing the Cosmological Moduli Problem by low-scale inflation

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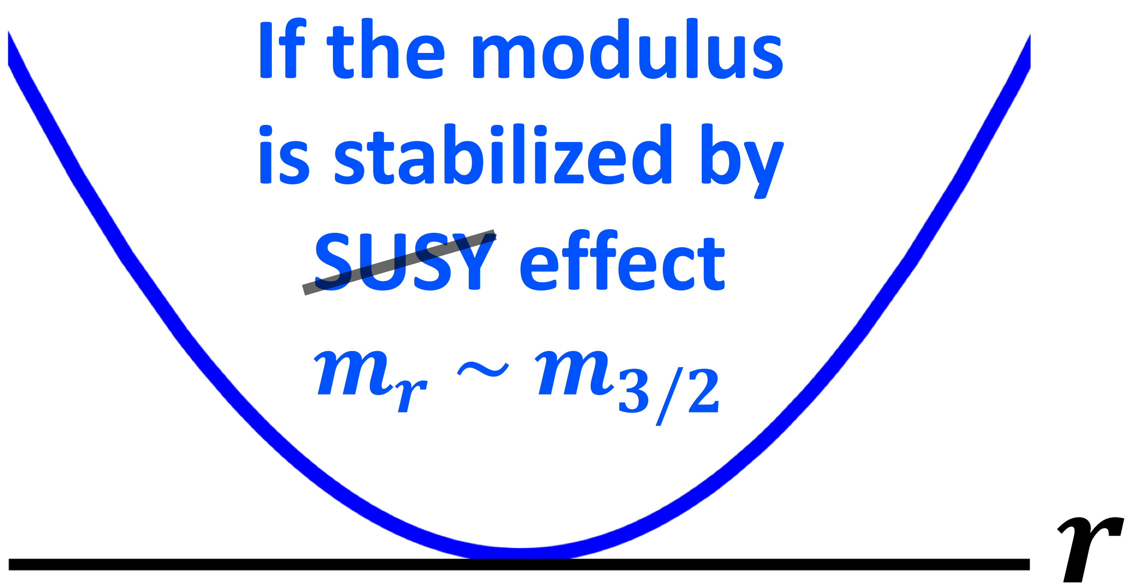
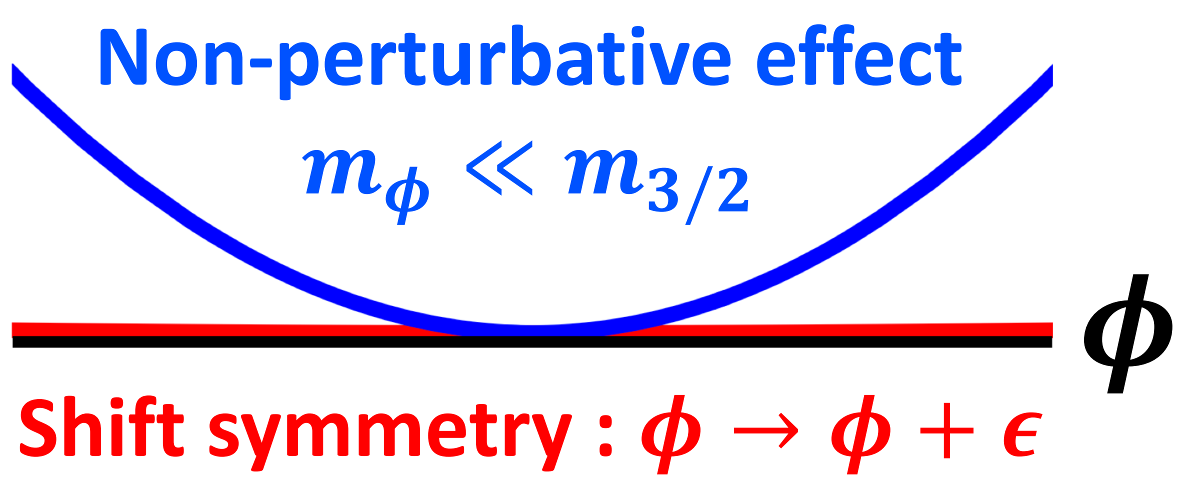
Modulus field

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

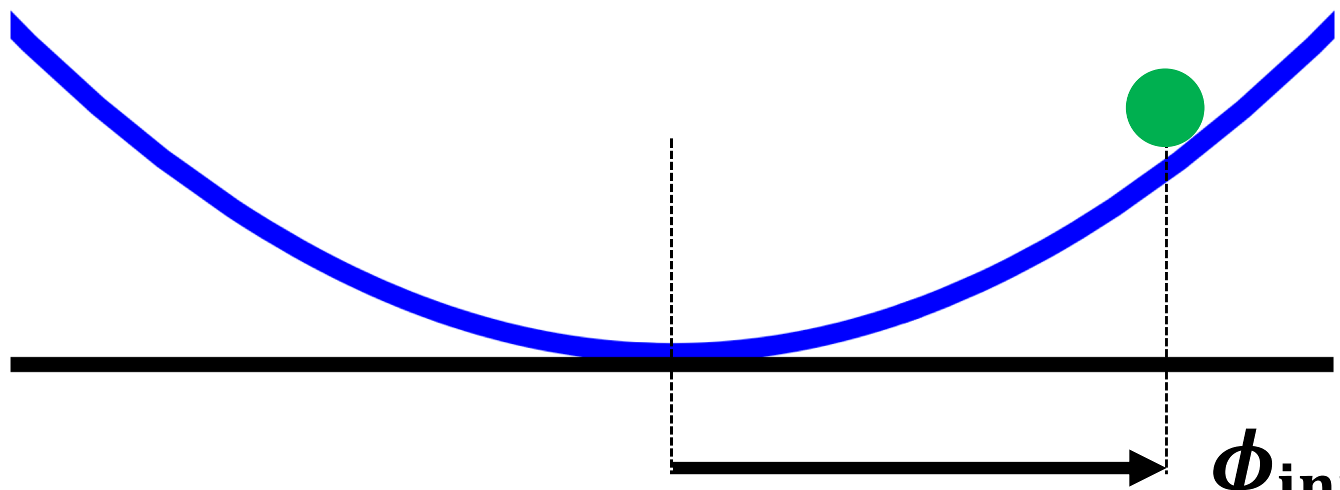
$$X = r + i\phi \quad \text{Axion}$$





Dynamics of modulus field

- After inflation ends



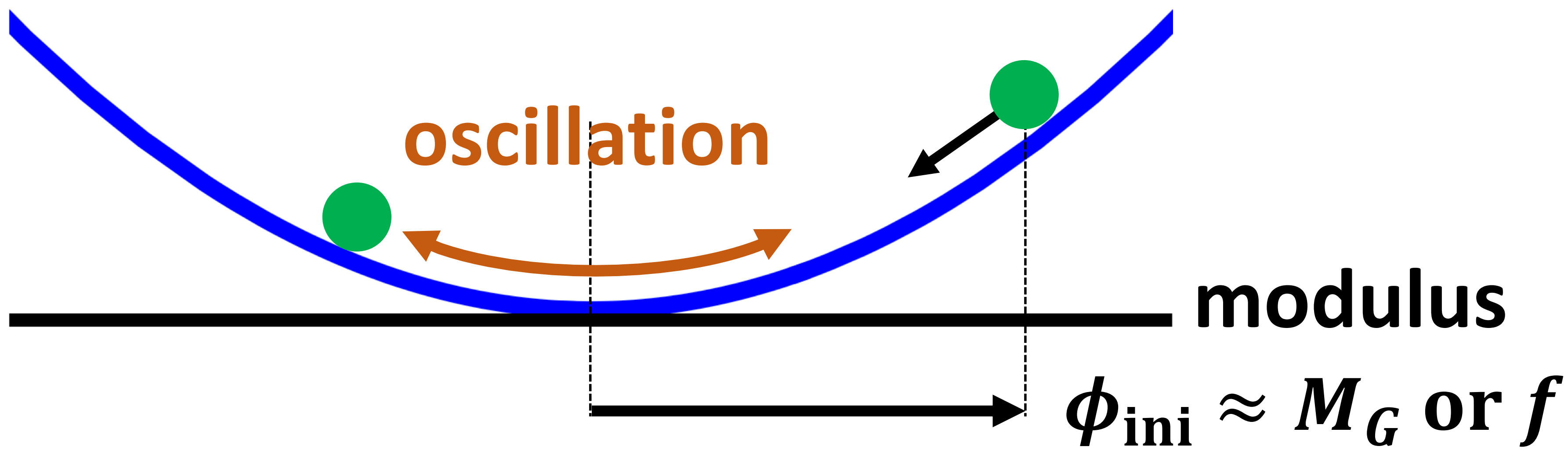
$H = H(t)$: Hubble parameter

m : modulus mass

Dynamics of modulus field

- After inflation ends

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



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

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

$$\Omega_\phi h^2 = \frac{\rho_{\phi,\,\mathrm{ini}}}{\rho_c} \frac{s_0}{s} h^2 \simeq \begin{cases} 3.0 \times 10^{10} \left(\frac{g_{\star,\mathrm{osc}}}{106.75}\right)^{-1/4} \left(\frac{m_\phi}{0.1\,\mathrm{GeV}}\right)^{1/2} \left(\frac{\phi_{\mathrm{ini}}}{10^{16}\,\mathrm{GeV}}\right)^2 & \Gamma_{\mathrm{inf}} > m_\phi \\ 2.5 \times 10 \left(\frac{T_{\mathrm{RH}}}{20\,\mathrm{MeV}}\right) \left(\frac{\phi_{\mathrm{ini}}}{10^{16}\,\mathrm{GeV}}\right)^2 & \Gamma_{\mathrm{inf}} < m_\phi \end{cases}$$

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

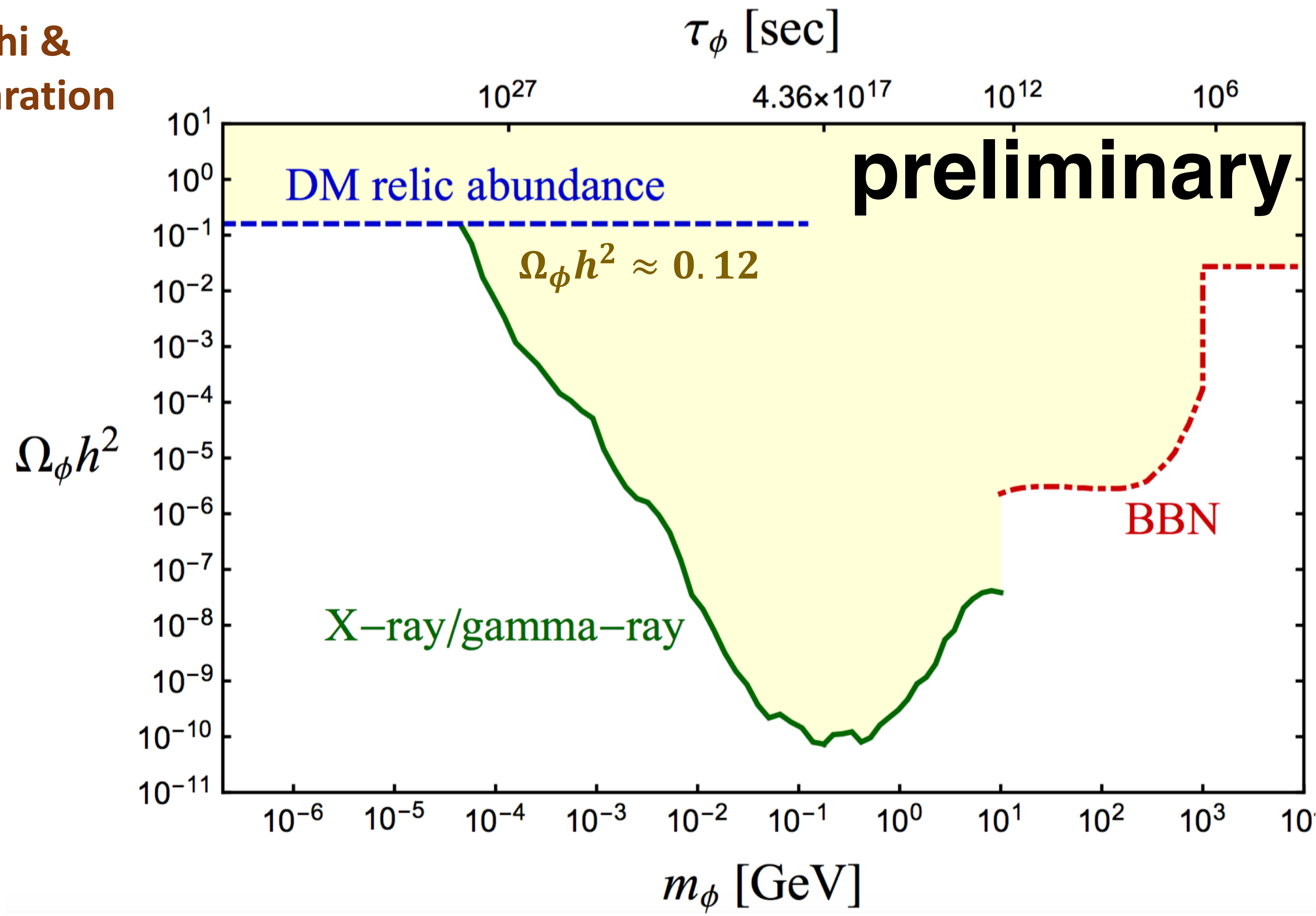
Cosmological moduli problem

- **If the modulus is stable on a cosmological scale.**
  - ✓ **Its abundance may exceed the observed DM density.**
- **If the modulus is unstable and can decay into photons.**
  - ✓ **It may spoil the success of big bang nucleosynthesis (BBN) due to the photo-dissociation of the light elements.**
  - ✓ **It may overproduce X-ray or gamma-ray fluxes.**

→ **moduli problem in cosmology**

Astrophysical & cosmological constraints

SYH, F. Takahashi &
Y. Wen in preparation



Simple solutions to moduli problem

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

  → dilutes baryon asymmetry

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

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

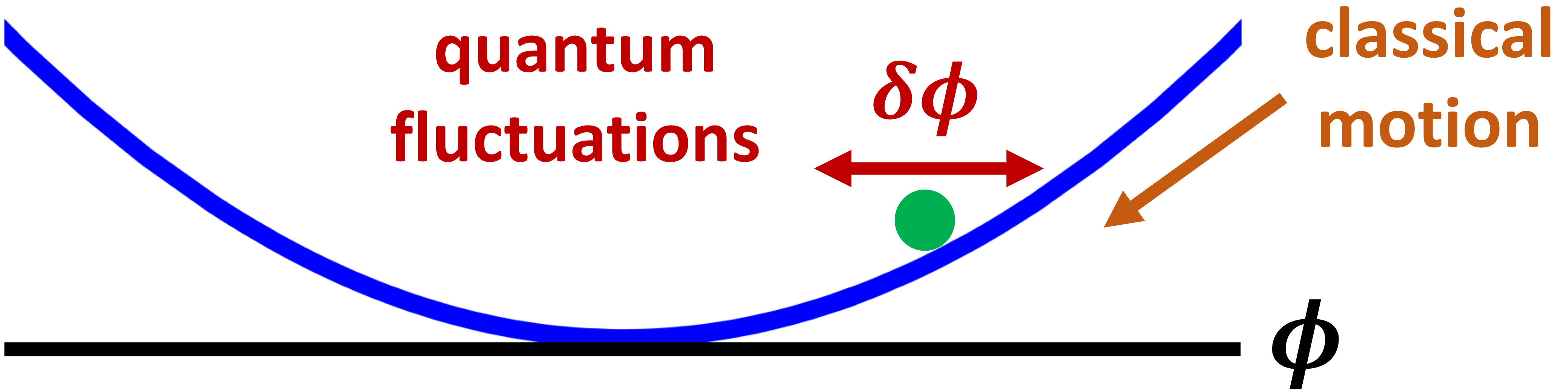
- Bunch-Davies distribution

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

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

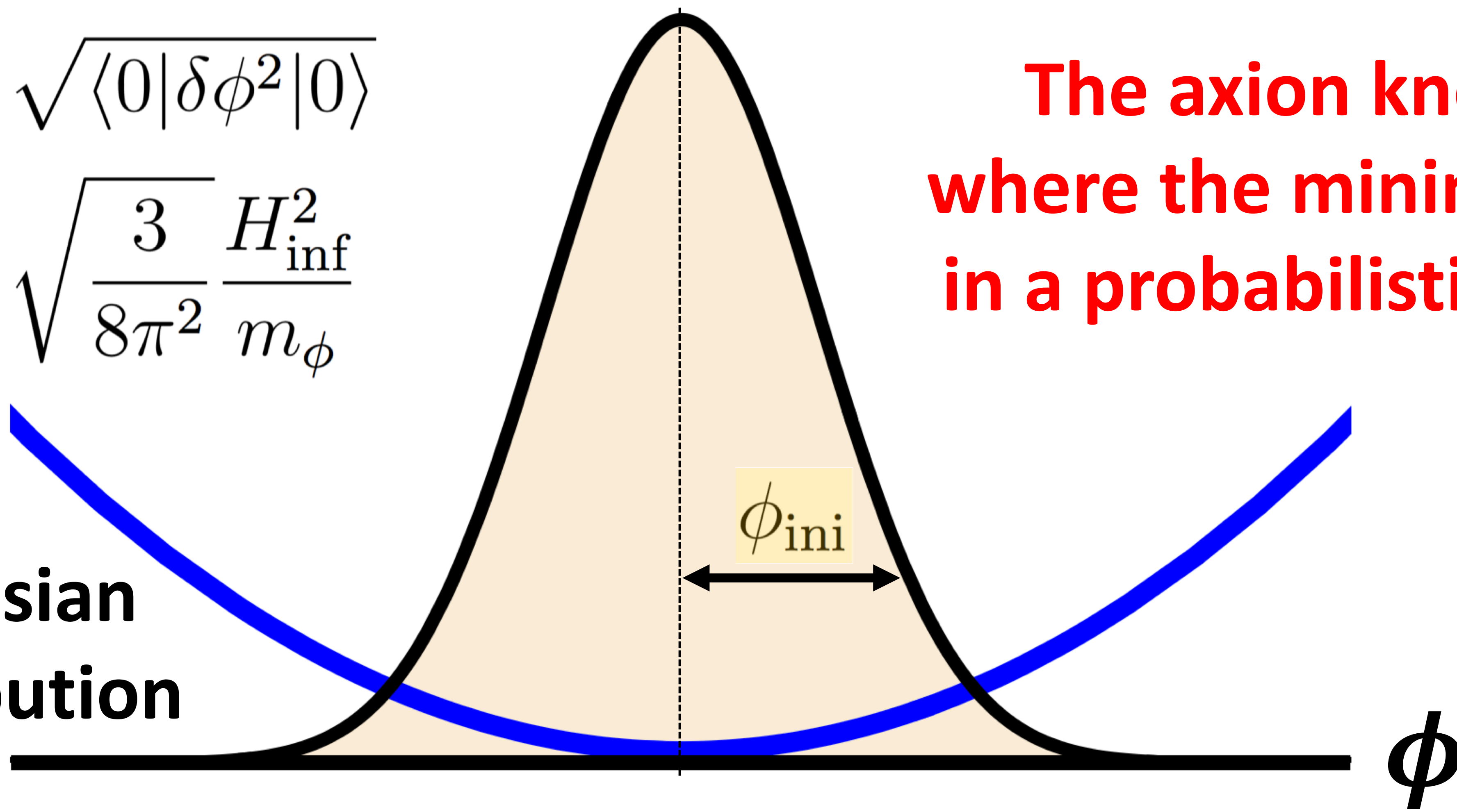
Bunch & Davies `78

quantum fluctuations ⟷ classical motion

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

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

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



Gaussian distribution

The axion abundance with the BD distribution

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

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

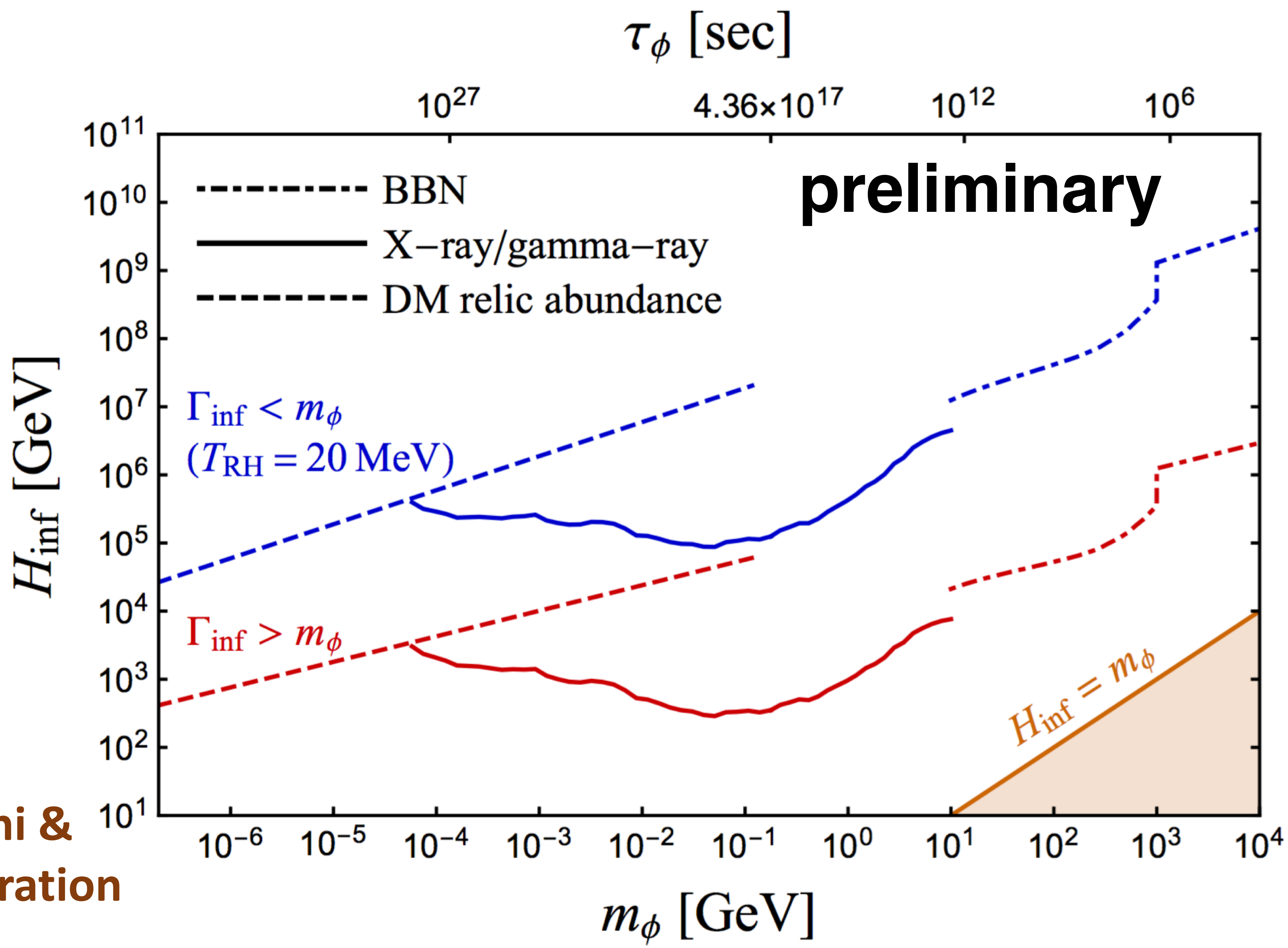
$H(t_{\rm osc}) \approx m_\phi$

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

$$\Omega_\phi h^2 \simeq \begin{cases} 1.1\times 10^{-20}\,{\rm GeV}\left(\frac{g_{\star,\rm osc}}{106.75}\right)^{-1/4}\left(\frac{m_\phi}{0.1\,{\rm GeV}}\right)^{-3/2}\left(\frac{H_{\rm inf}}{\rm GeV}\right)^4 & \Gamma_{\rm inf} > m_\phi \\ 9.6\times 10^{-31}\,{\rm GeV}\left(\frac{T_{\rm RH}}{20\,{\rm MeV}}\right)\left(\frac{m_\phi}{0.1\,{\rm GeV}}\right)^{-2}\left(\frac{H_{\rm inf}}{\rm GeV}\right)^4 & \Gamma_{\rm inf} < m_\phi \end{cases}$$

Suppress Ω_ϕ by low inflation scale

Upper bound on H_{inf} for solving the moduli problem



SYH, F. Takahashi & Y. Wen in preparation

Summary

- **We have shown that the cosmological moduli problem can be significantly relaxed by low-scale inflation even if the Hubble parameter during inflation is much bigger than the scalar mass. This is because the value of the scalar field follows the BD distribution if the inflation lasted sufficiently long.**
- **The axionic moduli problem is solved at m_ϕ = 0.1 GeV for $H_{\rm inf}$ < 100 GeV, where the X-ray bound is the tightest because the axion lifetime is equal to the present age of the universe.**