Small-scale Features of Thermal Inflation Cosmology

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The Moduli Problem

Moduli fields are generic in supersymmetric/string theories.

They couple to matter with gravitational strength.

The decay rate is estimated by $\Gamma_\Phi \sim N \frac{m_\Phi^3}{M_{Pl}^2}$

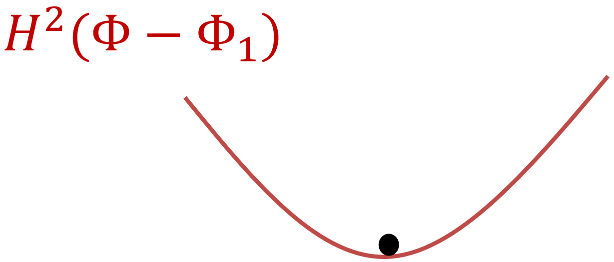
where N is the number of decay channels

We can compare the lifetime of moduli and the age of universe:

$$\tau_\Phi \sim \tau_{\text{uni}} \left(\frac{100\text{MeV}}{m_\Phi} \right)^3$$

The Moduli Problem

The moduli fields can oscillate around the minimum with the Planckian amplitude.



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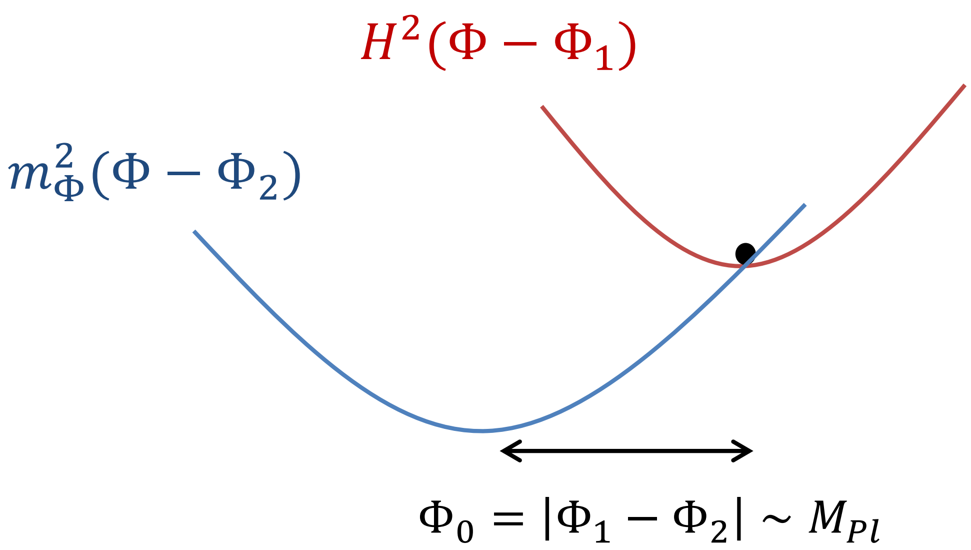

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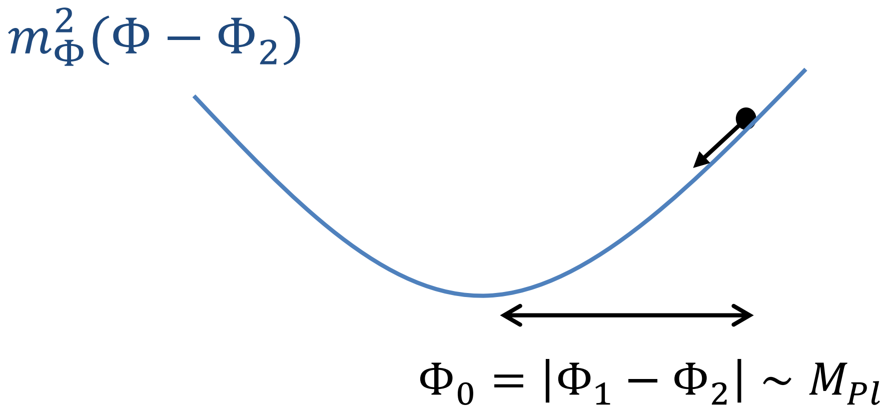

The energy density of the moduli field is $\rho_\Phi \sim \dfrac{1}{2} m_\Phi^2 \Phi_0^2$

The Moduli Problem

If the moduli decay out right after its domination, the entropy release is estimated by

$$\rho_\Phi \sim \frac{1}{2} m_\Phi^2 \Phi_0^2$$

$$n_\Phi = \frac{\rho_\Phi}{m_\Phi}$$

$$\rho_\Phi = \frac{\pi^2}{30} g_* T_\Phi^4$$

$$s = \frac{2\pi^2}{45} g_{*S} T_\Phi^3$$

$$\frac{n_\Phi}{s} \sim \frac{\Phi_0^2}{10\, M_{Pl}^{3/2} m_\Phi^{1/2}}$$

The Moduli Problem

1. If the lifetime of moduli is smaller than the age of our universe, their decay might release a very large amount of entropy in the universe and dilute its contents.

2. If their lifetime is larger than the age of the universe, they might presently still be oscillating around their minimum and the energy stored in these oscillations may overclose the universe.

The Moduli Problem

In Gravity-Mediated SUSY Breaking Scenario: $m_\Phi \sim 1\ \mathrm{TeV}$

The moduli fields decay out very early:

$$\tau_\Phi \sim 10^{-12} \times \tau_{\mathrm{uni}}$$

The entropy release is huge enough to disturb BBN:

$$\frac{n_\Phi}{s} \sim 10^{7}$$

Lyth, Stewart (1995)

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$$\frac{n_\Phi}{s} \sim 10^{7} \gg 10^{-12}$$

How can we save BBN?

Lyth, Stewart (1995)

Thermal Inflation Scenario

1. Primordial inflation produces the scale-invariant power spectrum.

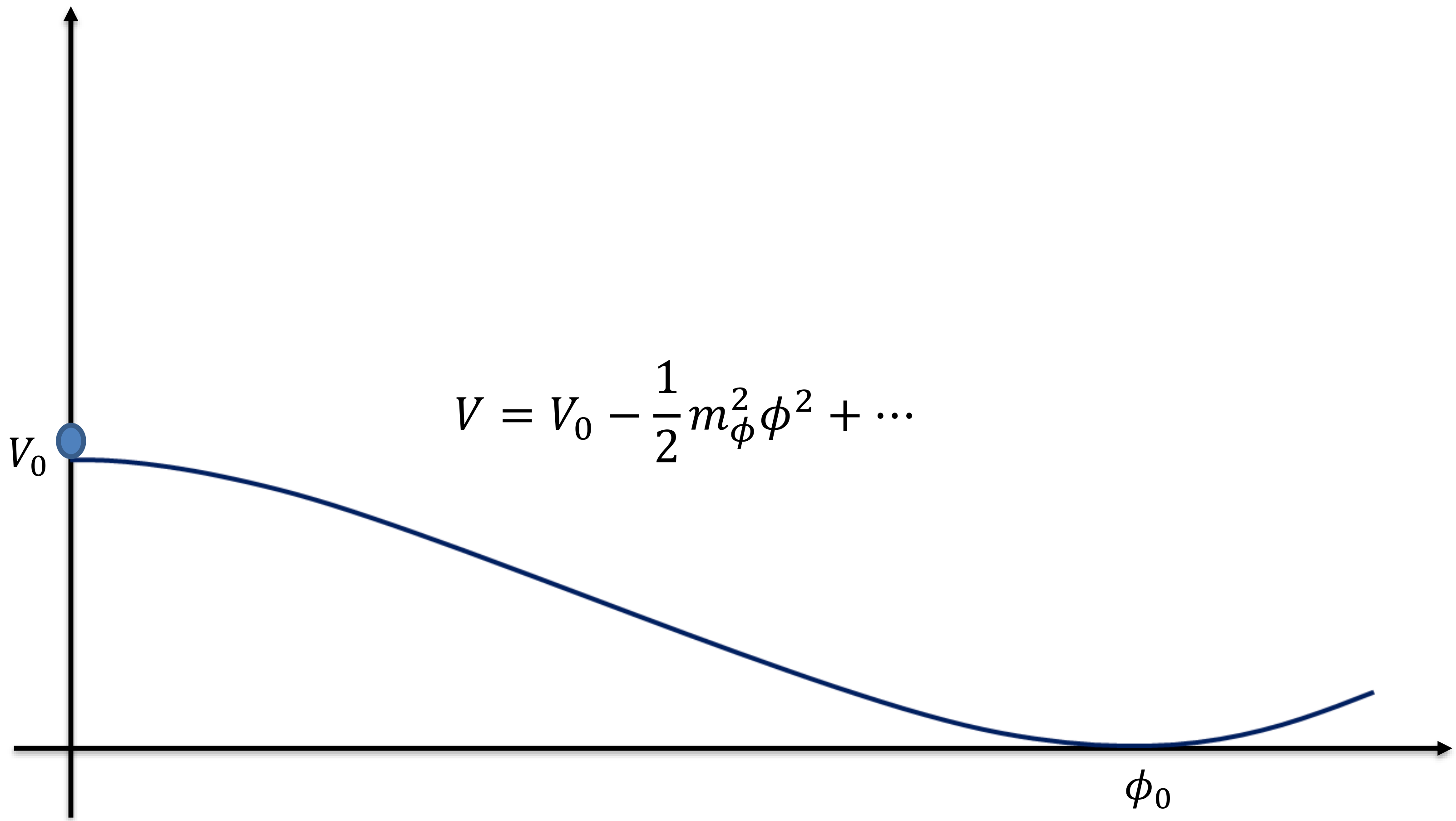
2. The moduli dominates over the universe.

3. Thermal inflation gets started to resolve the moduli problem by introducing so-called “flaton”.

4. The “flaton” dominates over the universe.

5. As the inflaton decays out, they reheat the universe and the radiation dominates over the universe.

Thermal Inflation Scenario



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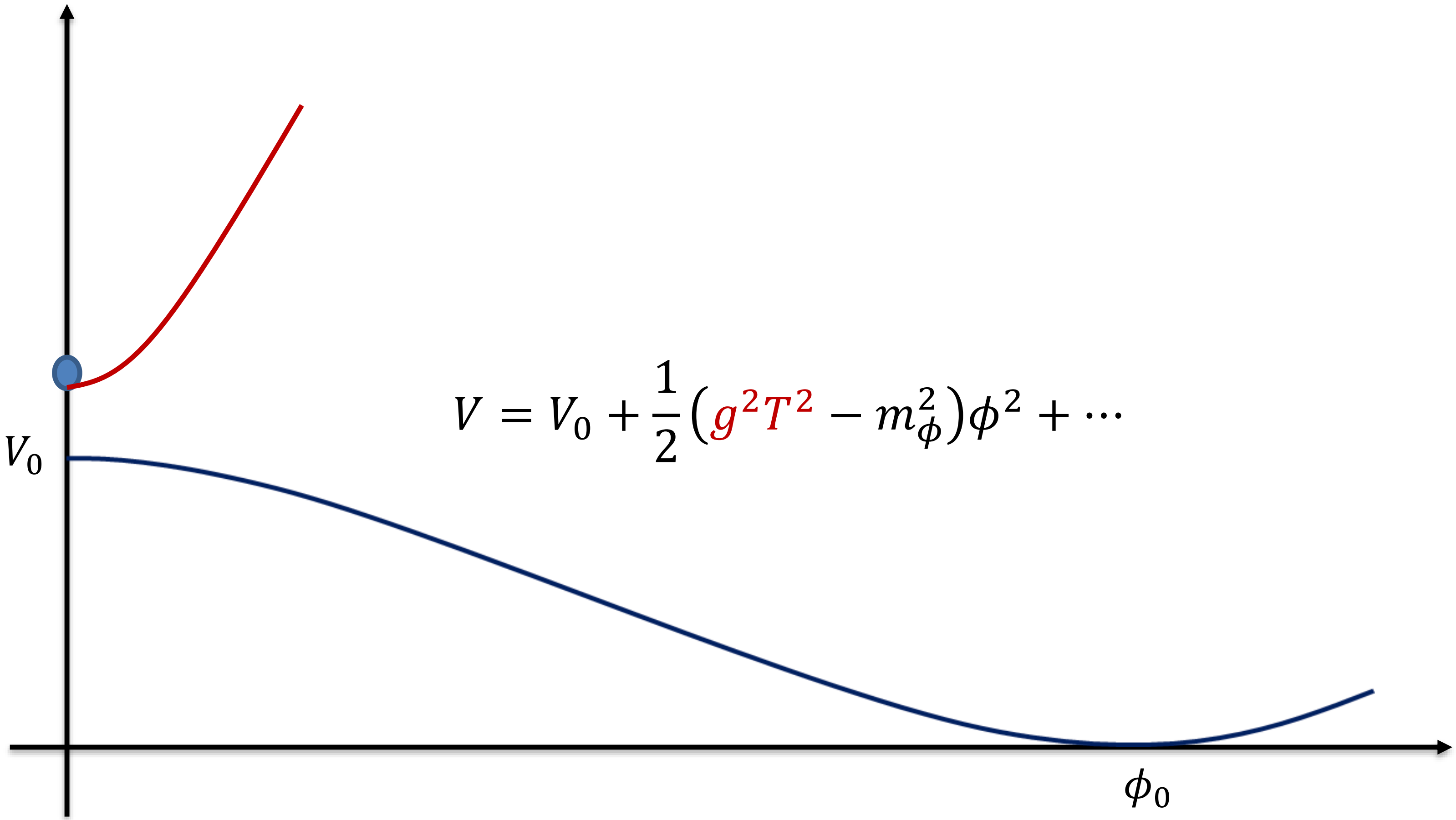
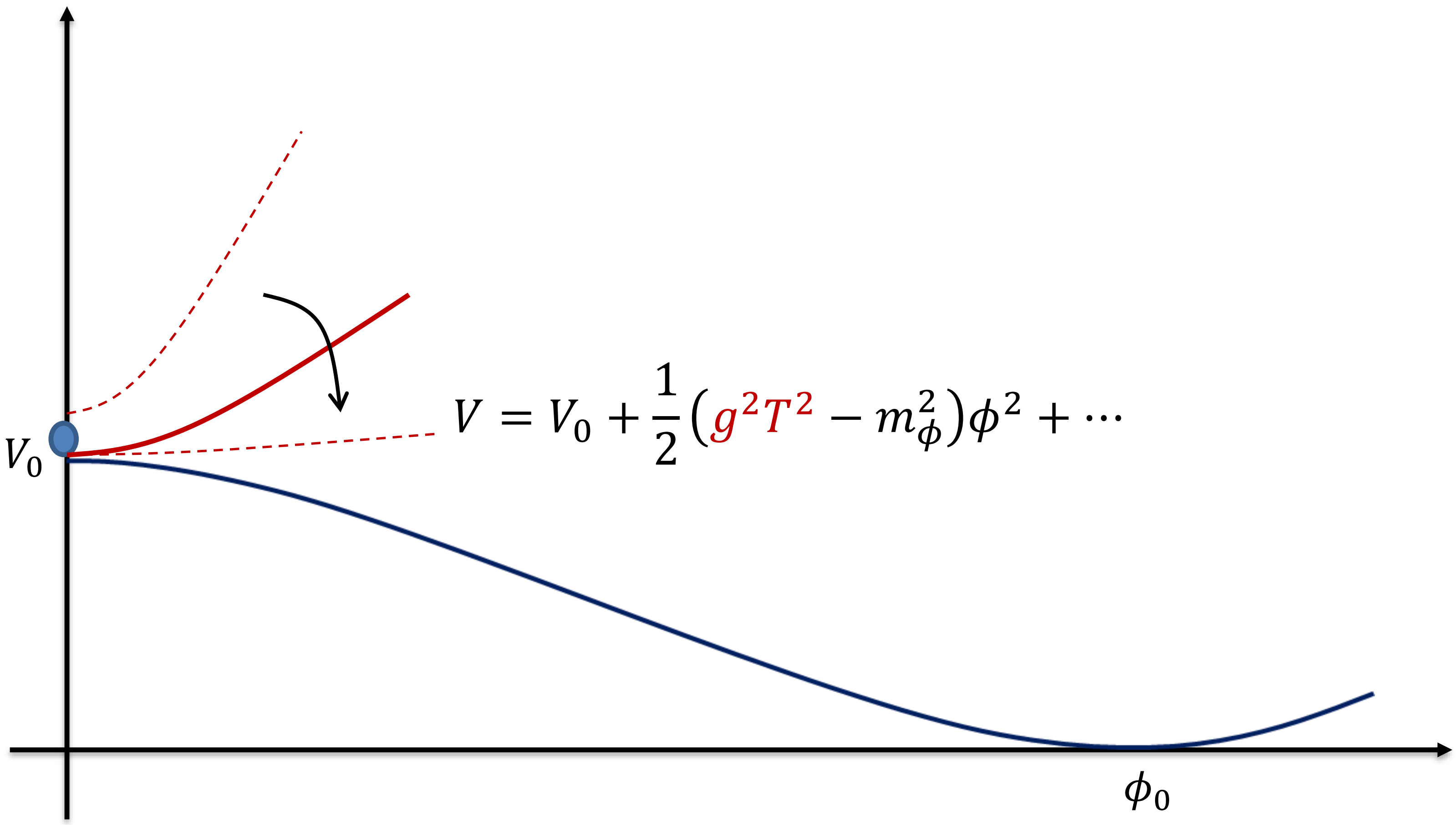


$$V = V_0 + \frac{1}{2}\left(g^2 T^2 - m_\phi^2\right)\phi^2 + \cdots$$

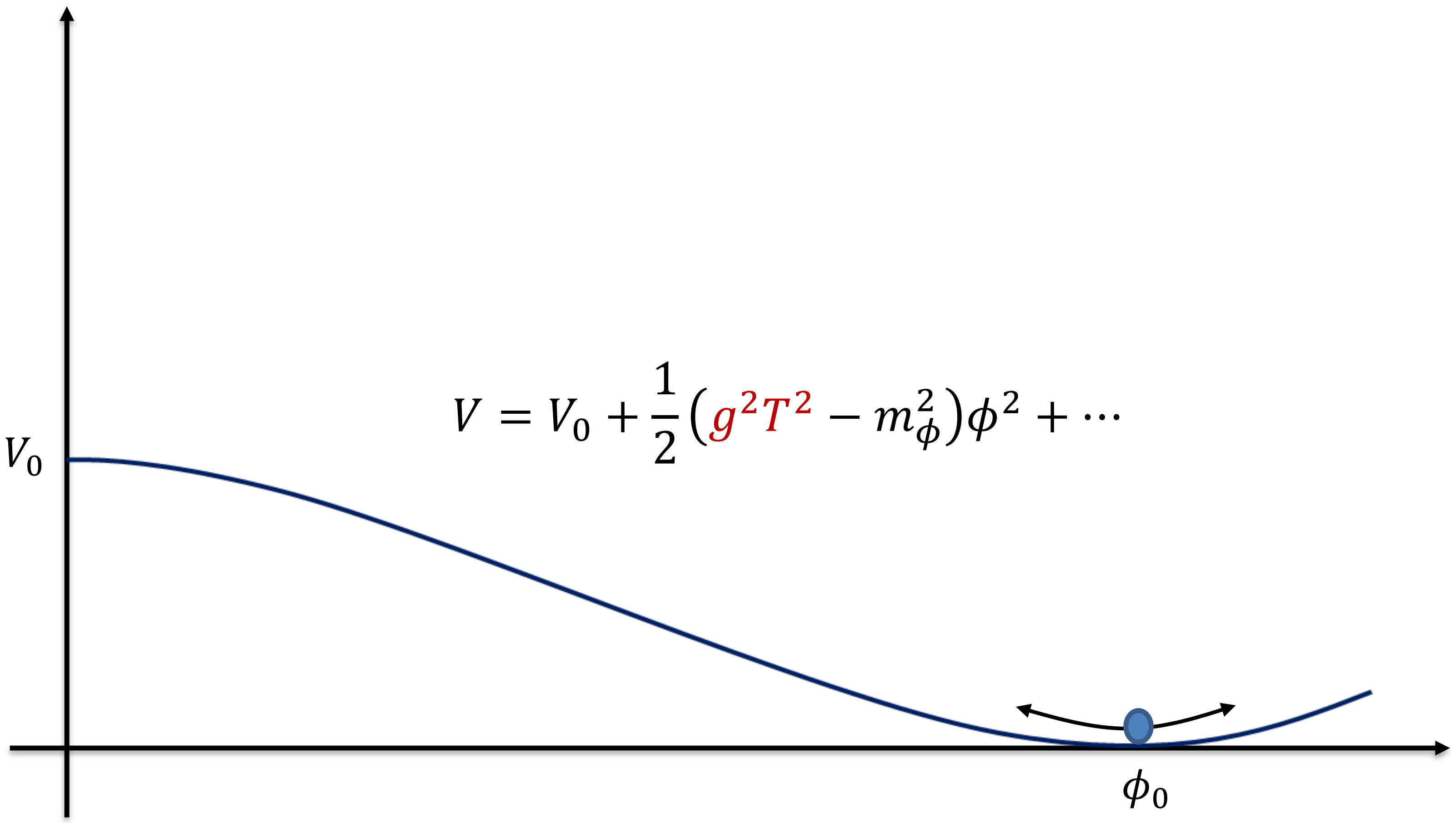
$T > \frac{V_0^{1/2}}{g}$: ϕ is trapped at the origin.

Thermal Inflation Scenario



$\frac{V_0^{1/2}}{g} > T > \frac{m_\phi}{g}$: V_0 drives inflation to dilute the moduli.

Thermal Inflation Scenario



$\frac{m_\phi}{g} > T$: ϕ rolls away to the vev and produces radiation domination.

Thermal Inflation Scenario

1. Thermal inflation can dilute the pre-existing moduli.

$$\frac{n_\Phi}{s} \sim \frac{g_{*s}(T_c)T_c^3 T_d M_{Pl}^{1/2}}{V_0 m_\Phi^{1/2}} \sim 10^{-13}\left(\frac{10^8\,\mathrm{GeV}}{V_0^{1/4}}\right)^4$$

For thermal inflation model cooperating with Affleck-Dine leptogenesis, we could get the additional dilution factor $\Delta_{\mathrm{AD}} \sim 10^{-8}$.

Thermal Inflation Scenario

2. The moduli may be re-generated at the end of thermal inflation due to a slight change of the moduli potential:

$$\frac{n_\Phi}{s} \sim \frac{V_0 T_d}{m_\Phi^3 M_{Pl}^2} \sim 10^{-14} \left(\frac{V_0^{1/4}}{10^8 \mathrm{GeV}} \right)^4$$

∴ By 1 and 2, the moduli problem is resolved by thermal inflation.

Thermal Inflation Scenario

3. The e-folds during thermal inflation is

$$N_{\mathrm{TI}} \sim \ln \frac{T_b}{T_c} \sim 10$$

to resolve the moduli problem.

The perturbations from primordial inflation are preserved on large scales but *not on small scales*.

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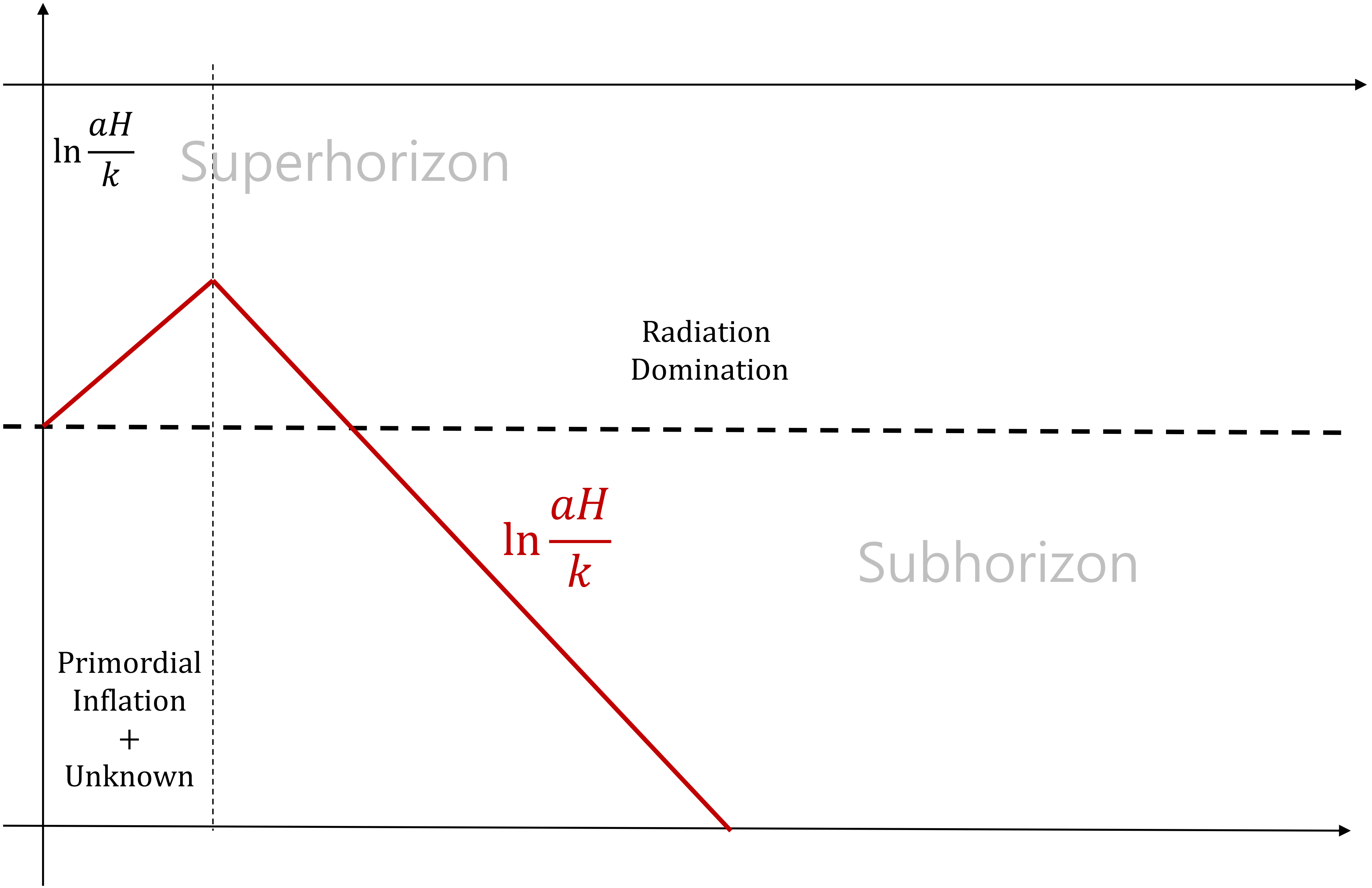
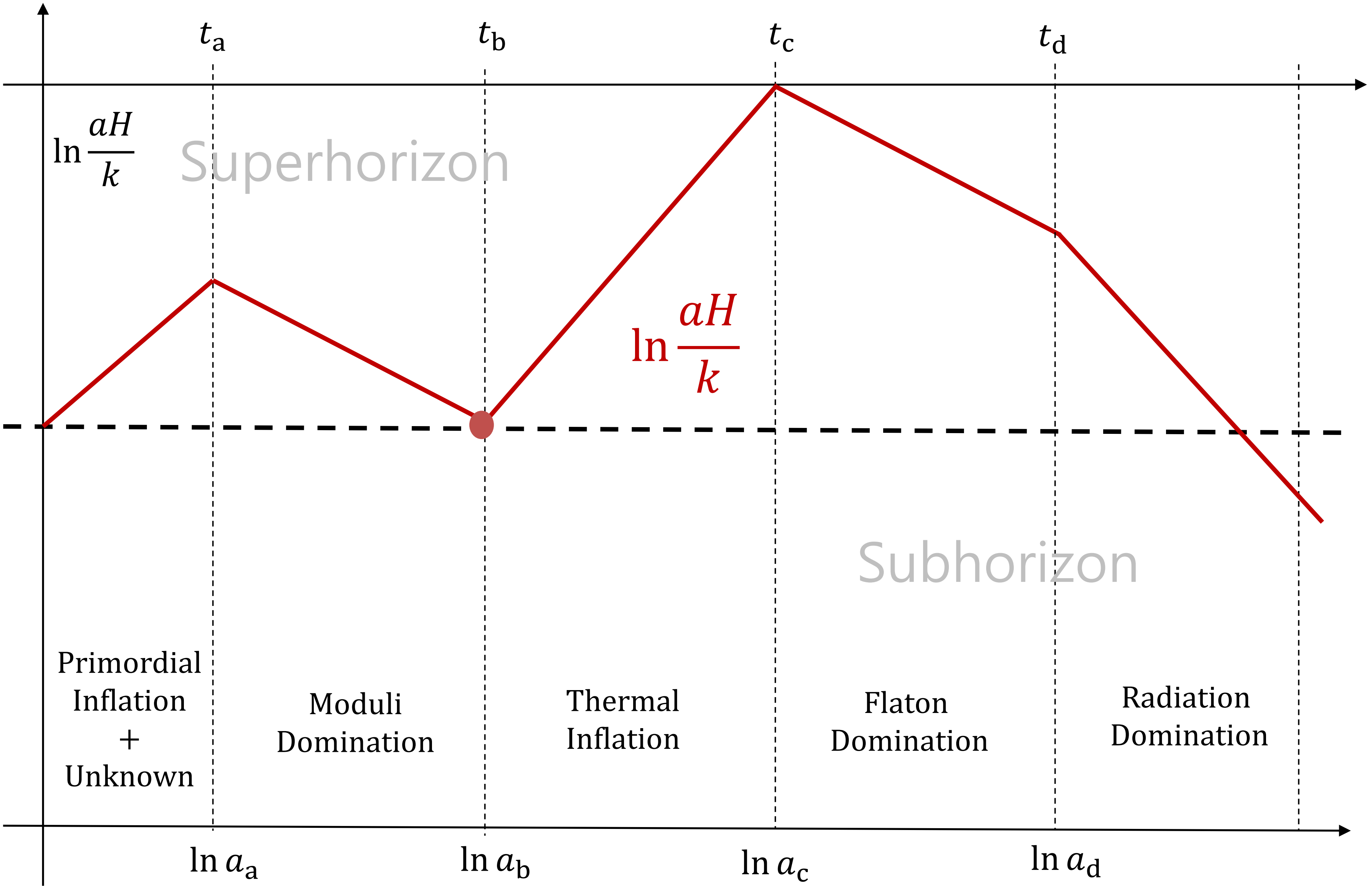
Can we probe thermal inflation by these small scale effects?

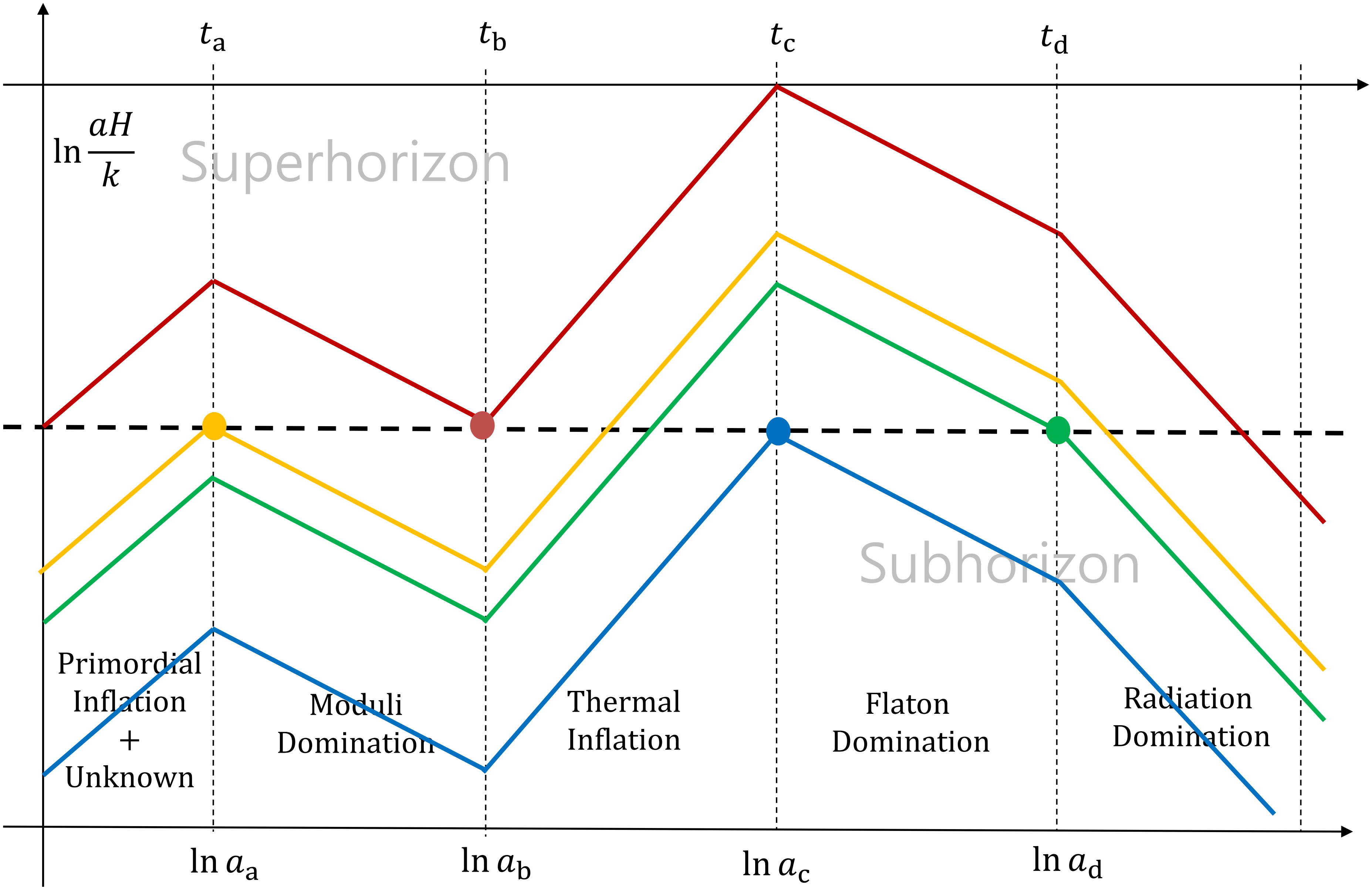
Standard Inflation Scenario



Thermal Inflation Scenario



Characteristic Scales



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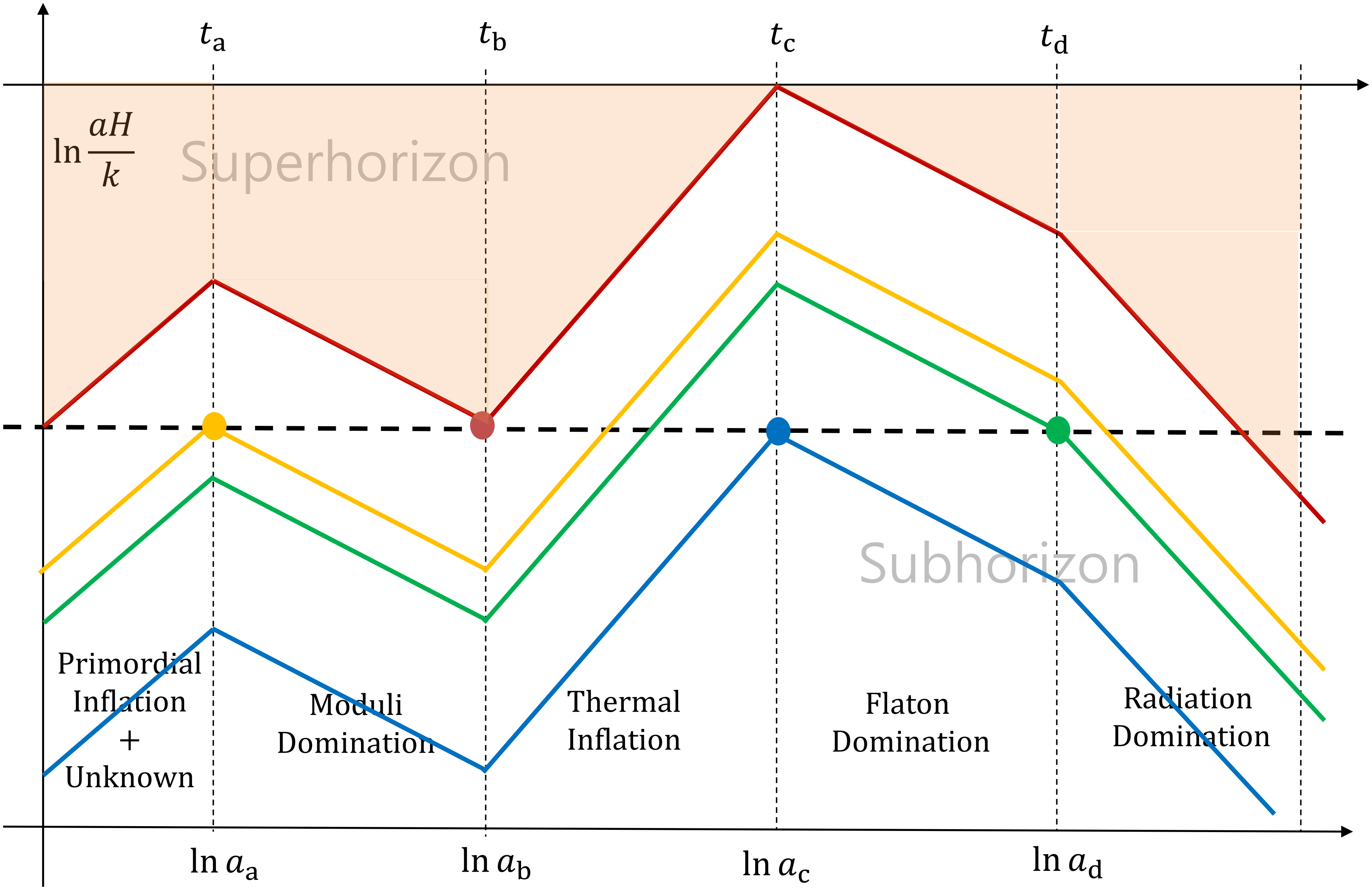

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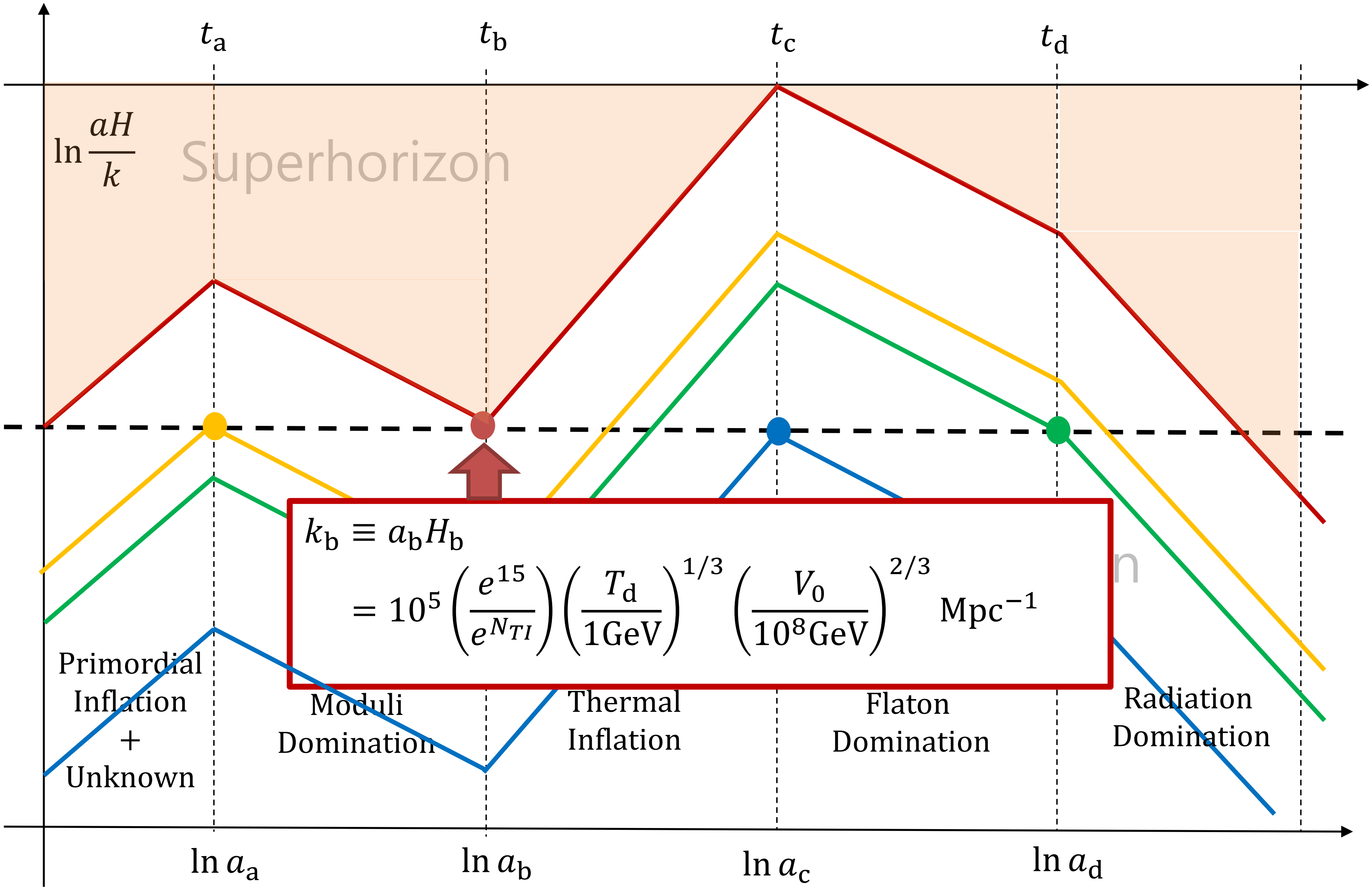

$$k_b \equiv a_b H_b$$
$$= 10^5 \left(\frac{e^{15}}{e^{N_{TI}}}\right) \left(\frac{T_d}{1\text{GeV}}\right)^{1/3} \left(\frac{V_0}{10^8\text{GeV}}\right)^{2/3} \text{Mpc}^{-1}$$

Power Spectrum of Thermal Inflation Scenario

$$P(k) = P_{\mathrm{pri}}(k) \times \mathcal{T}(k)^2$$

1. The largest characteristic scale is

$$k_{\mathrm{b}} = 10^5 \left(\frac{e^{15}}{e^{N_{\mathrm{TI}}}}\right) \left(\frac{T_{\mathrm{d}}}{1\mathrm{GeV}}\right)^{1/3} \left(\frac{V_0}{10^8\mathrm{GeV}}\right)^{2/3} \mathrm{Mpc}^{-1}$$

- $N_{\mathrm{TI}} \sim 10$ is enough to resolve the moduli problem.
- Multiple thermal inflation can be possible.
- There is no theoretical upper bound for N_{TI}.

Power Spectrum of Thermal Inflation Scenario

$$P(k) = P_{\text{pri}}(k) \times \mathcal{T}(k)^2$$

2. For the primordial power spectrum, we assume a simple inflation model of

$$\frac{d \ln P_{\text{pri}}}{d \ln k} = -\frac{c}{\mathcal{N}} + \mathcal{O}\left(\frac{1}{\mathcal{N}^2}\right)$$

$$\mathcal{N} = \ln \frac{a_e H_e}{aH}\bigg|_{aH=k} = \ln \frac{k_e}{k}$$

with $H_e \leq 2 \times 10^{14} \text{GeV}$

Power Spectrum of Thermal Inflation Scenario

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2. For the primordial power spectrum, we assume a simple inflation model of

$$P_{\mathrm{pri}}(k) = A_* \left(1 - \frac{1}{\mathcal{N}_{*e}} \ln \frac{k}{k_*}\right)^{(1-n_*)\mathcal{N}_{*e}}$$

$$\begin{cases} k_* = 0.05\mathrm{Mpc}^{-1} \\ A_* = 2.21 \times 10^{-9} \\ n_* = 0.96 \end{cases}$$

With TI: $13 \leq \mathcal{N}_{*e} \leq 32$

Without TI: $44 \leq \mathcal{N}_{*e} \leq 57$

Power Spectrum of Thermal Inflation Scenario

$$P(k) = P_{\mathrm{pri}}(k) \times \mathcal{T}(k)^2$$

3. We could find the transfer function

$$\mathcal{T}(k) = \cos\left[\frac{k}{k_{\mathrm{b}}}\int_0^\infty \frac{d\alpha}{\sqrt{\alpha(2+\alpha^3)}}\right] + 6\frac{k}{k_{\mathrm{b}}}\int_0^\infty \frac{d\gamma}{\gamma^3}\int_0^\gamma d\beta\left(\frac{\beta}{2+\beta^3}\right)^{\frac{3}{2}} \sin\left[\frac{k}{k_{\mathrm{b}}}\int_\gamma^\infty \frac{d\alpha}{\sqrt{\alpha(2+\alpha^3)}}\right]$$

Hong, Lee, Lee, Stewart, Zoe (2015)

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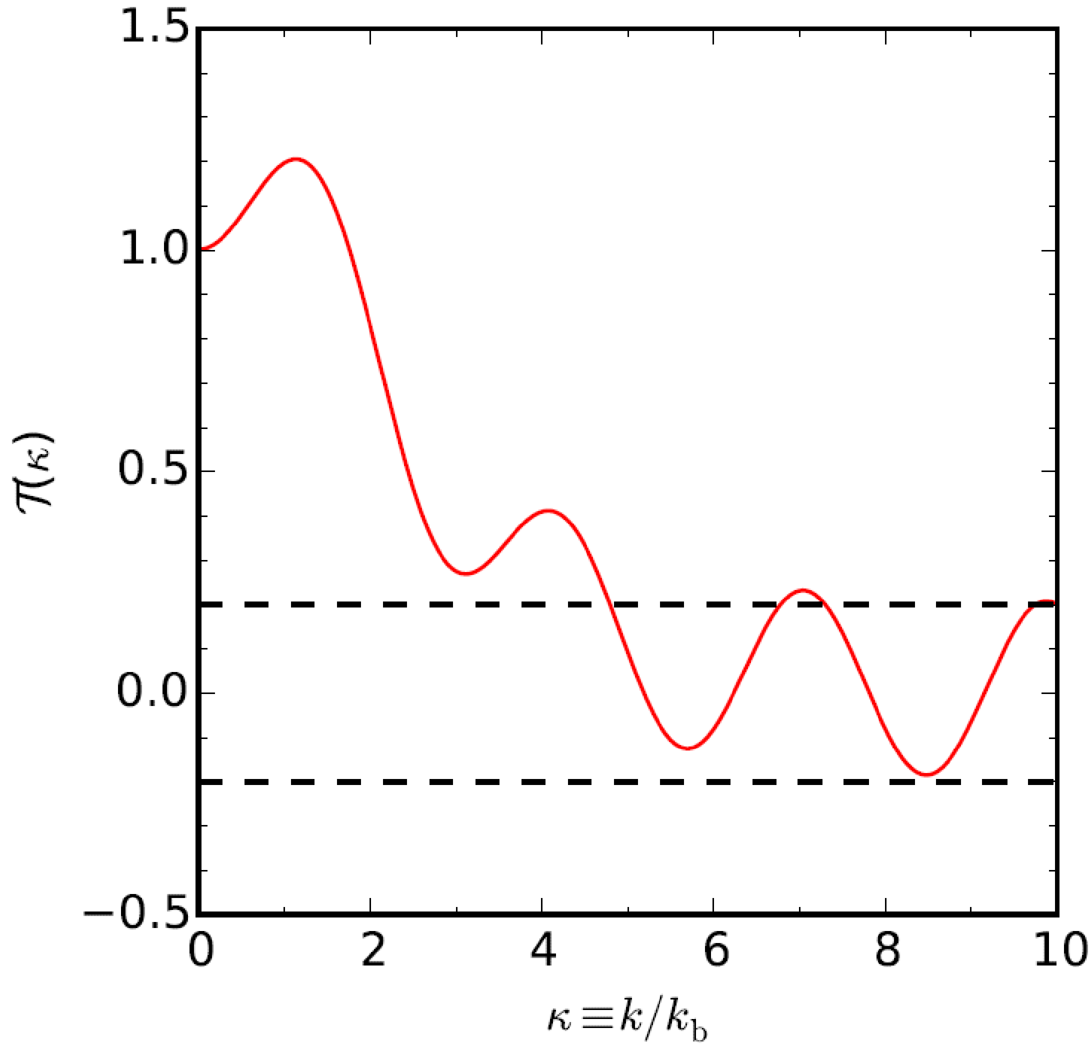

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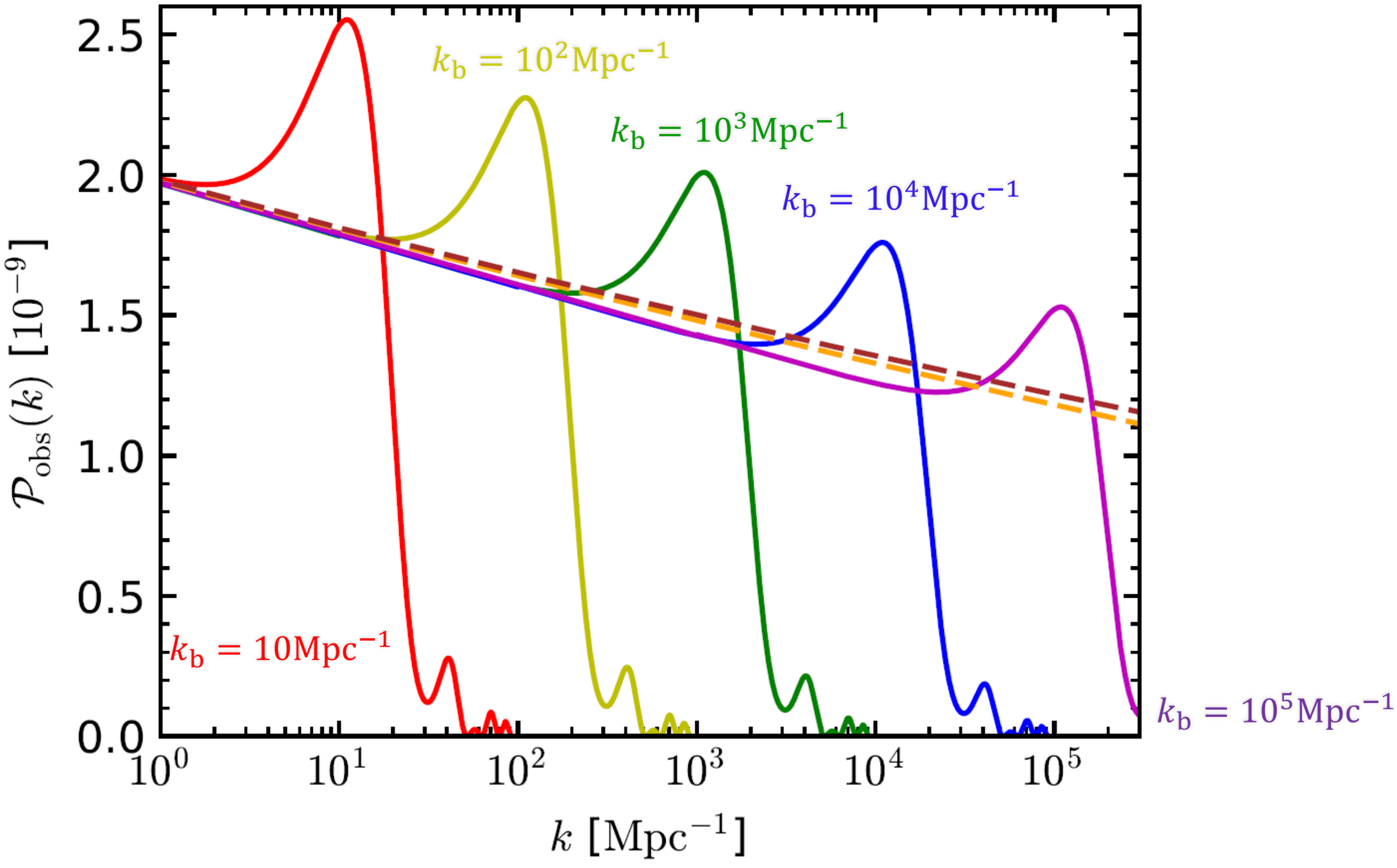
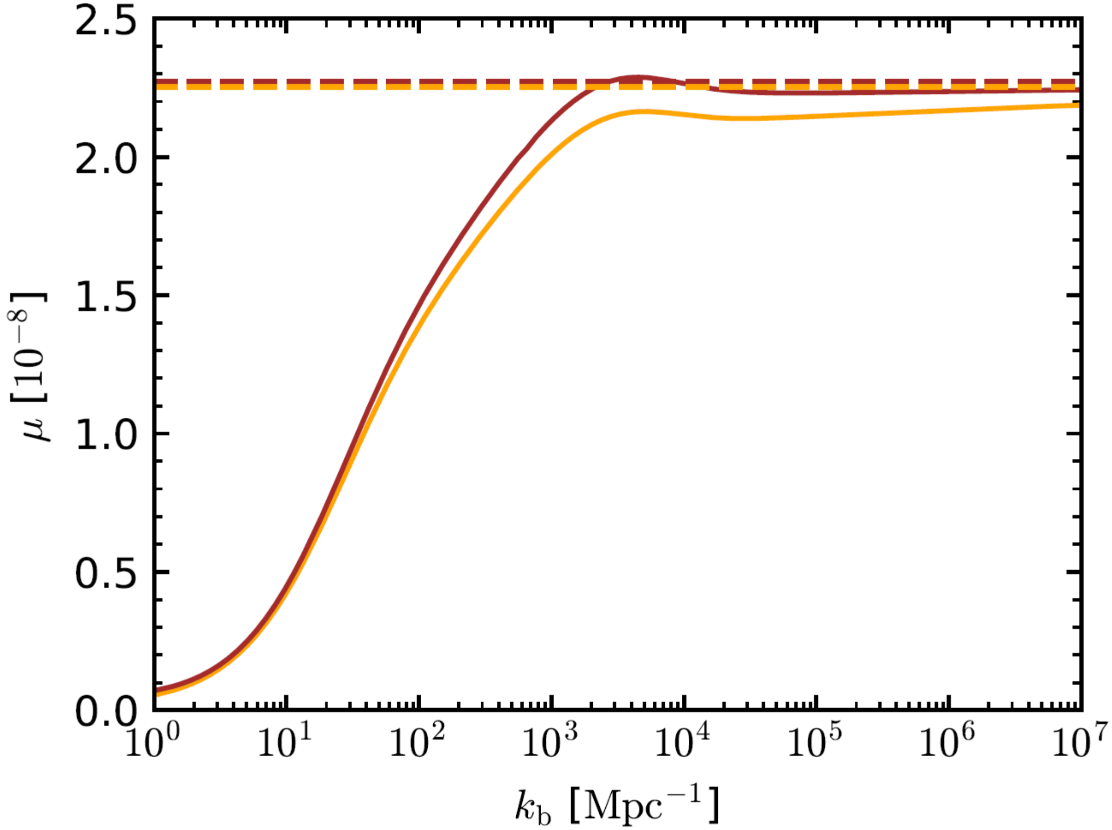


The power spectrum is suppressed by a factor $1/100$ at $k > k_b$

Hong, Zoe, Ahn (2017)

CMB μ-distortion Constraints on Thermal Inflation



$$k_\mathrm{b} = 10^5 \left(\frac{e^{15}}{e^{N_\mathrm{TI}}}\right)\left(\frac{T_\mathrm{d}}{1\mathrm{GeV}}\right)^{1/3}\left(\frac{V_0}{10^8\mathrm{GeV}}\right)^{2/3} \mathrm{Mpc}^{-1}$$

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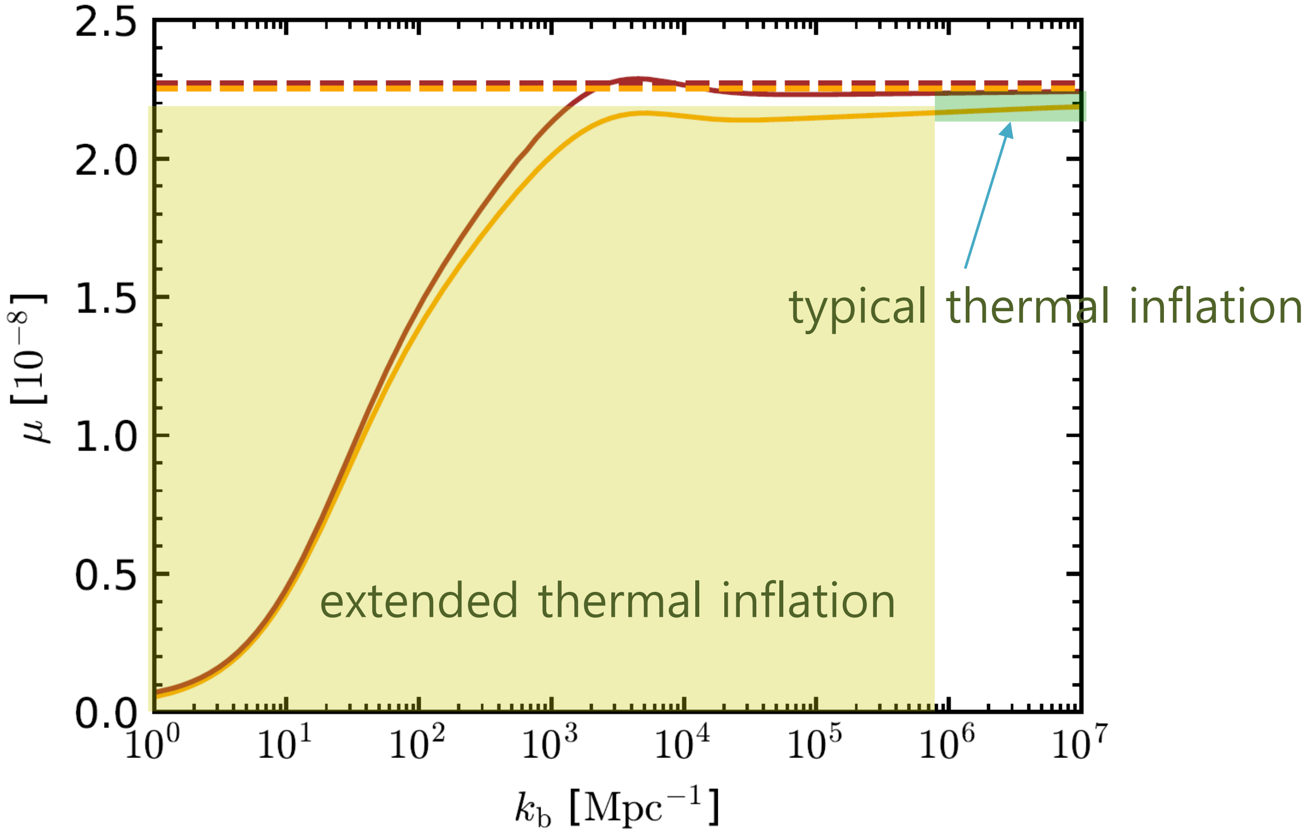

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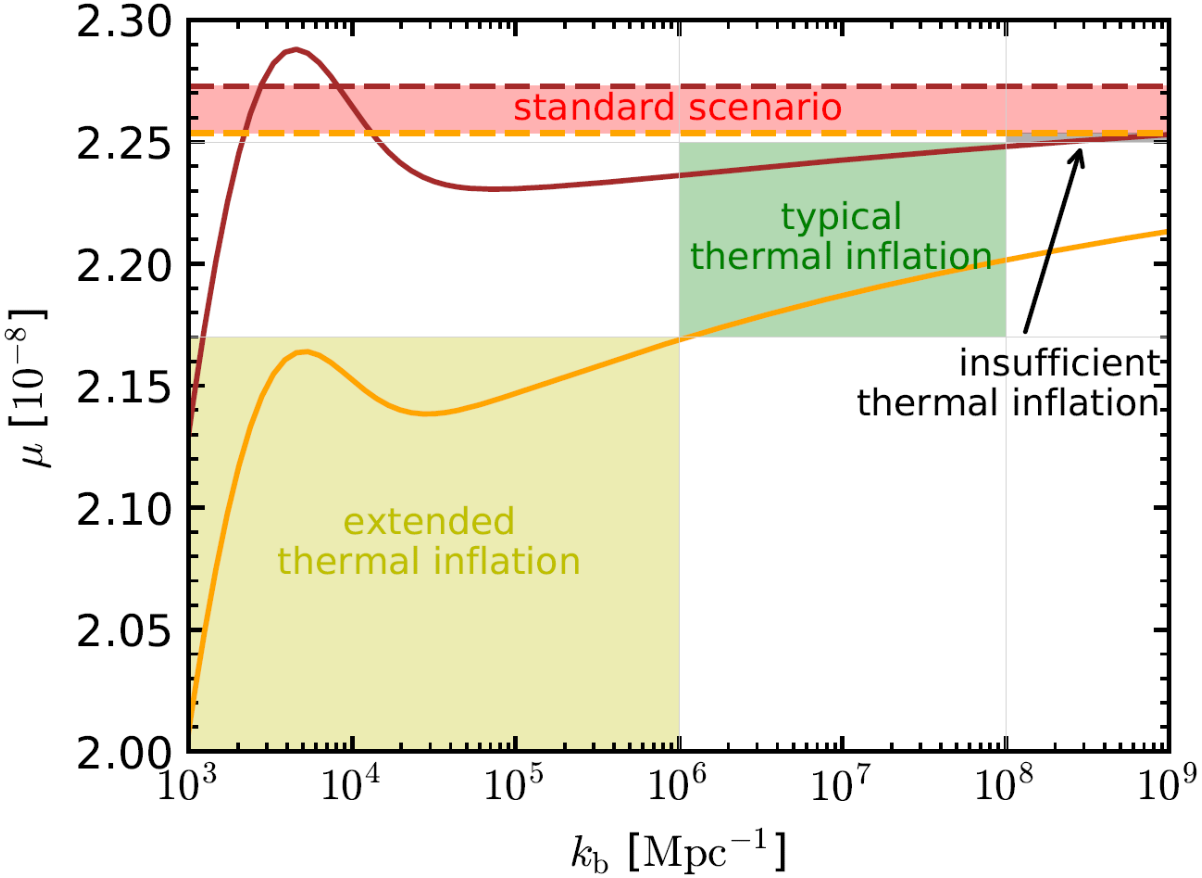

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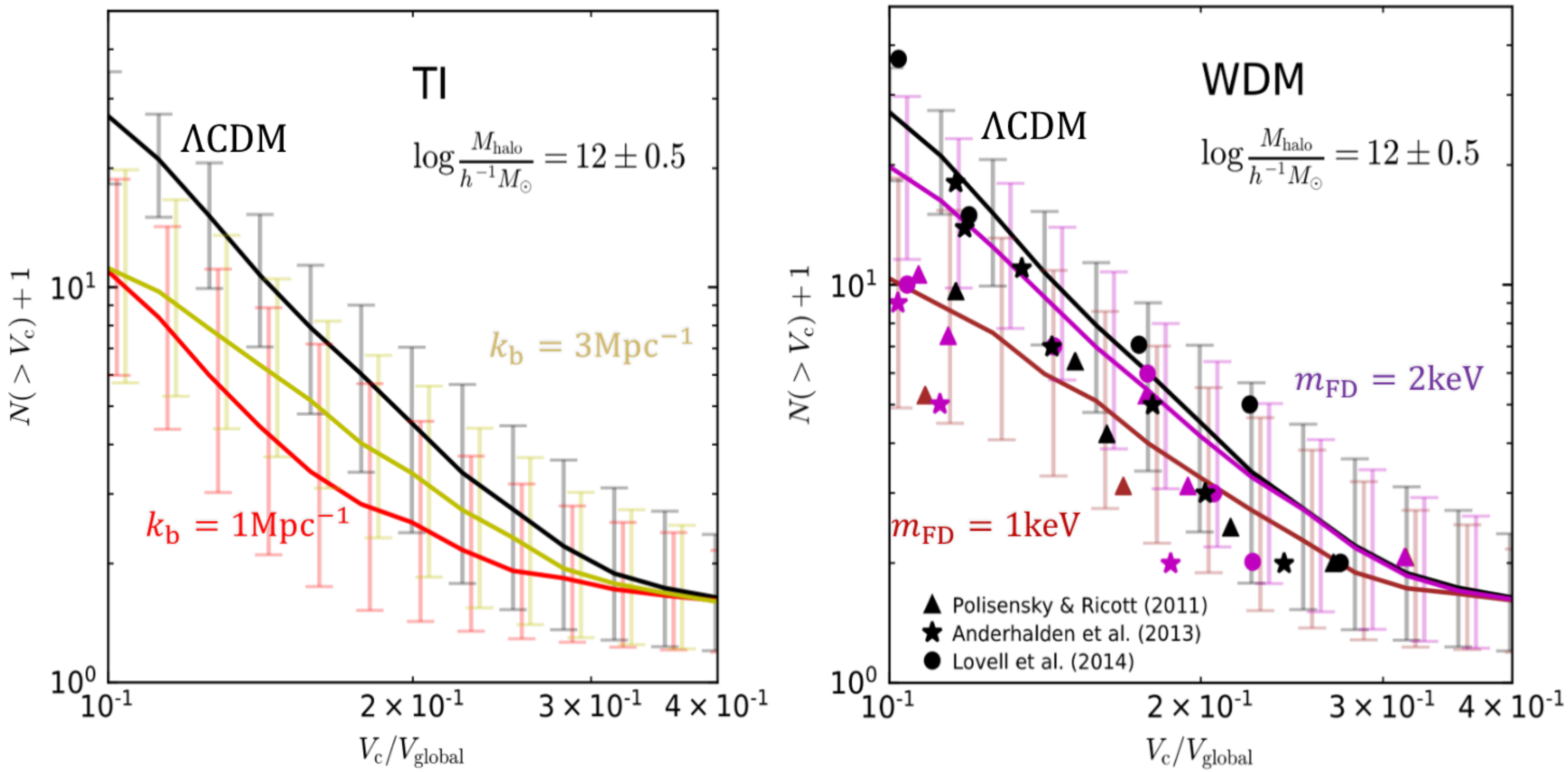
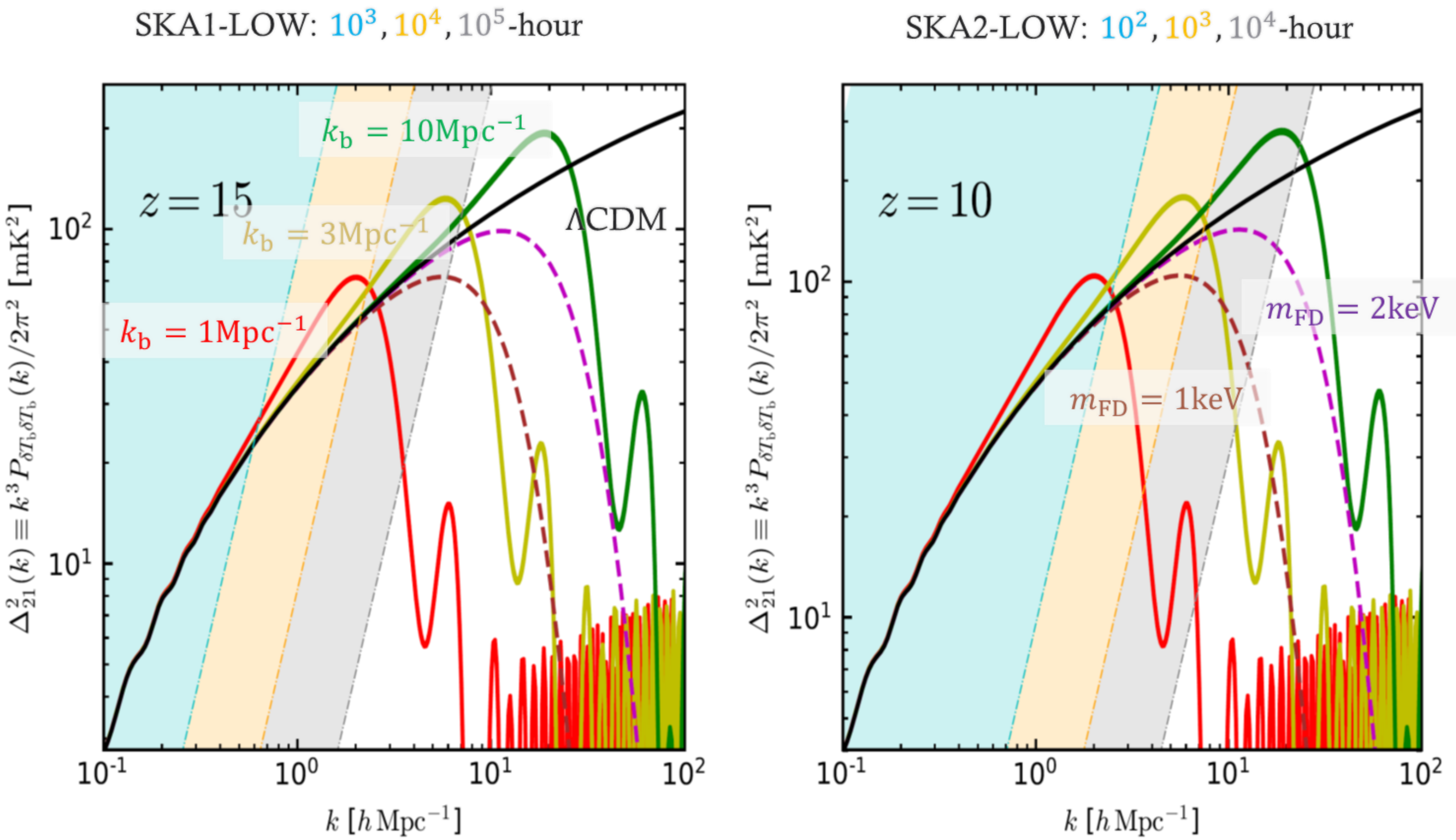
Satellite Galaxy Abundance



Satellite galaxy abundance inside the Milky Way may constrain thermal inflation scenario with $k_b \leq 3\mathrm{Mpc}^{-1}$, while it may be confused with warm dark matter scenario with $m_{\rm FD} \leq$ 2keV by satellite galaxy abundance alone.

Hong, Zoe, Ahn (2017)

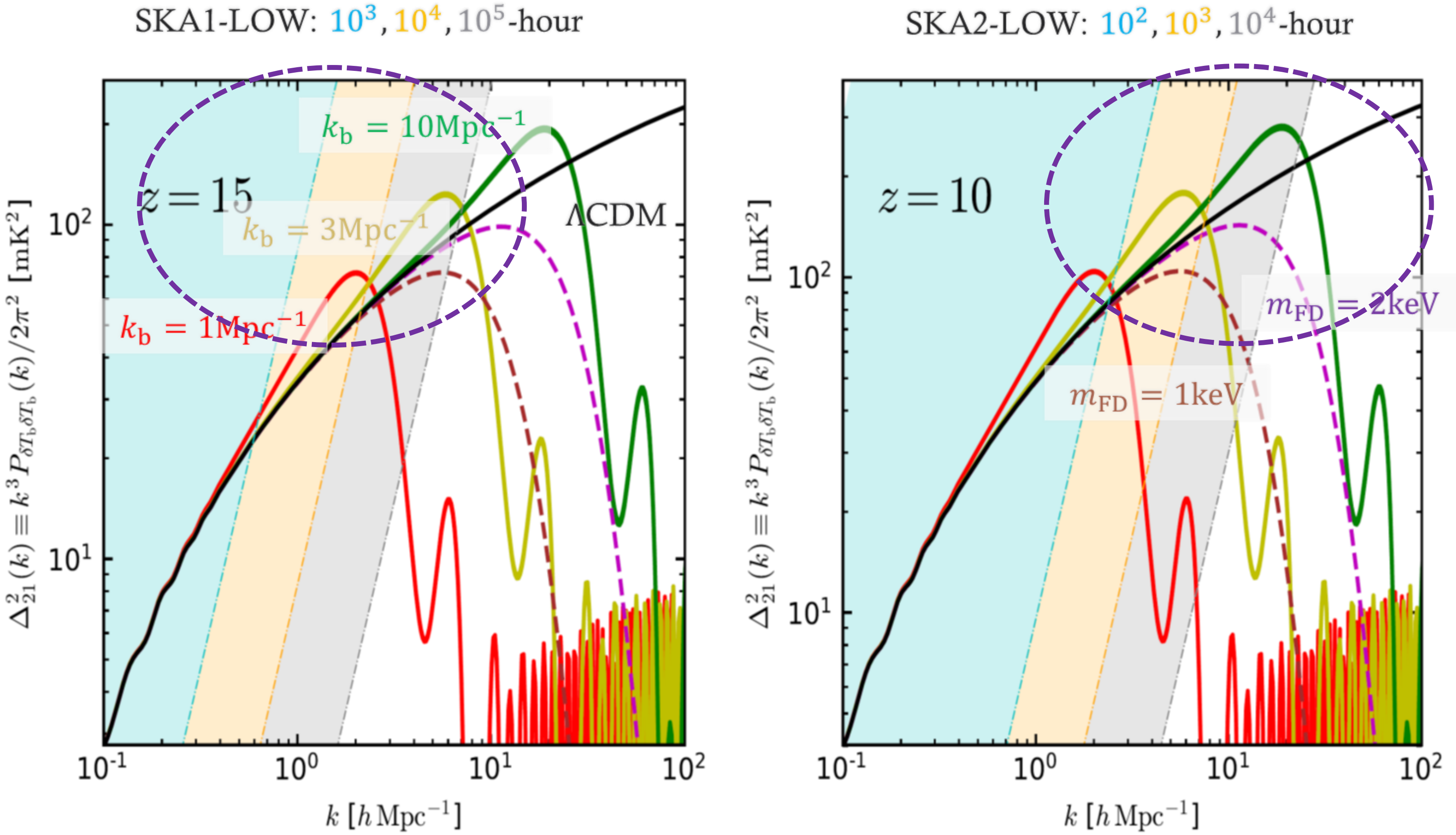
21cm Power Spectrum



21cm power spectrum before the epoch of reionization with *SKA* may constrain thermal inflation scenario with $k_b \leq 10\mathrm{Mpc}^{-1}$ without confusion with warm dark matter scenario.

Hong, Zoe, Ahn (2017)

21cm Power Spectrum



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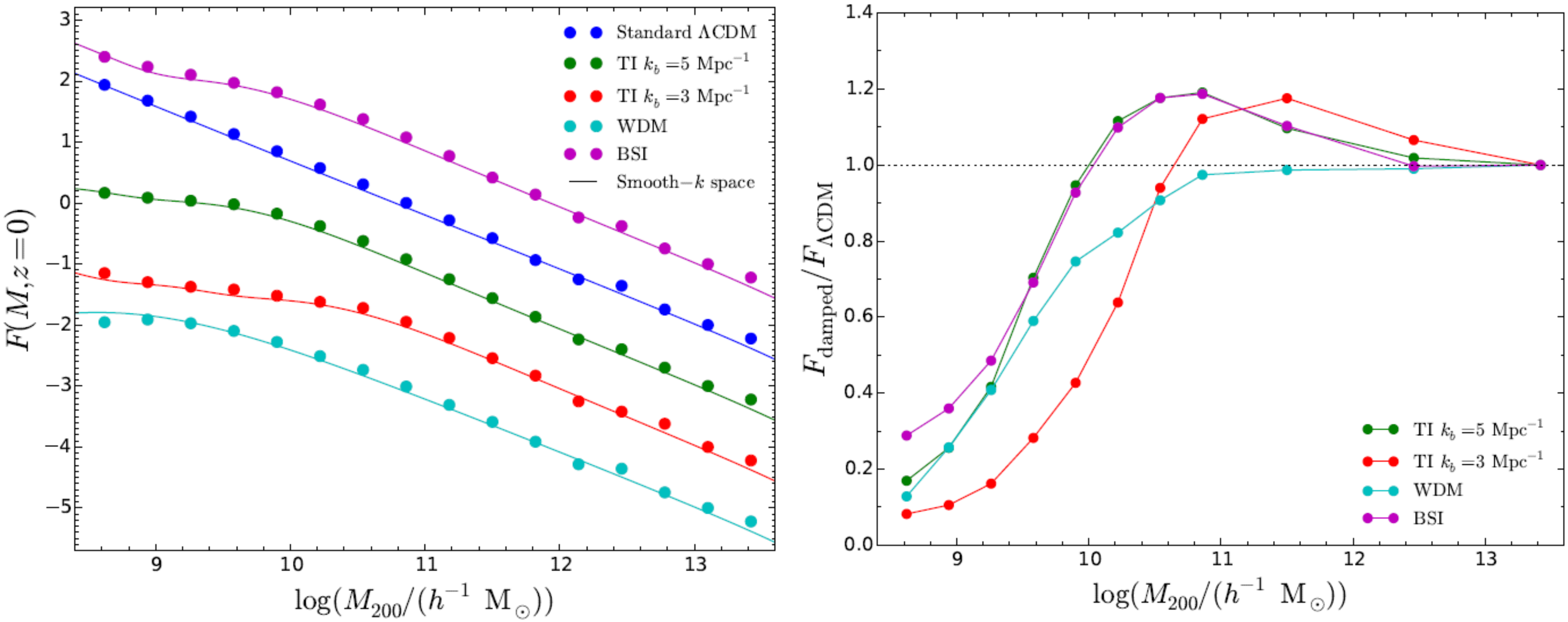
Hong, Zoe, Ahn (2017)

Halo Mass Function by N-body Simulations



The non-linear power spectrum at low redshifts in TI is enhanced with respect to that in ΛCDM while the non-linear power spectra in WDM have less power than that in ΛCDM.

Leo, Baugh, Li, Pascoli (2018)

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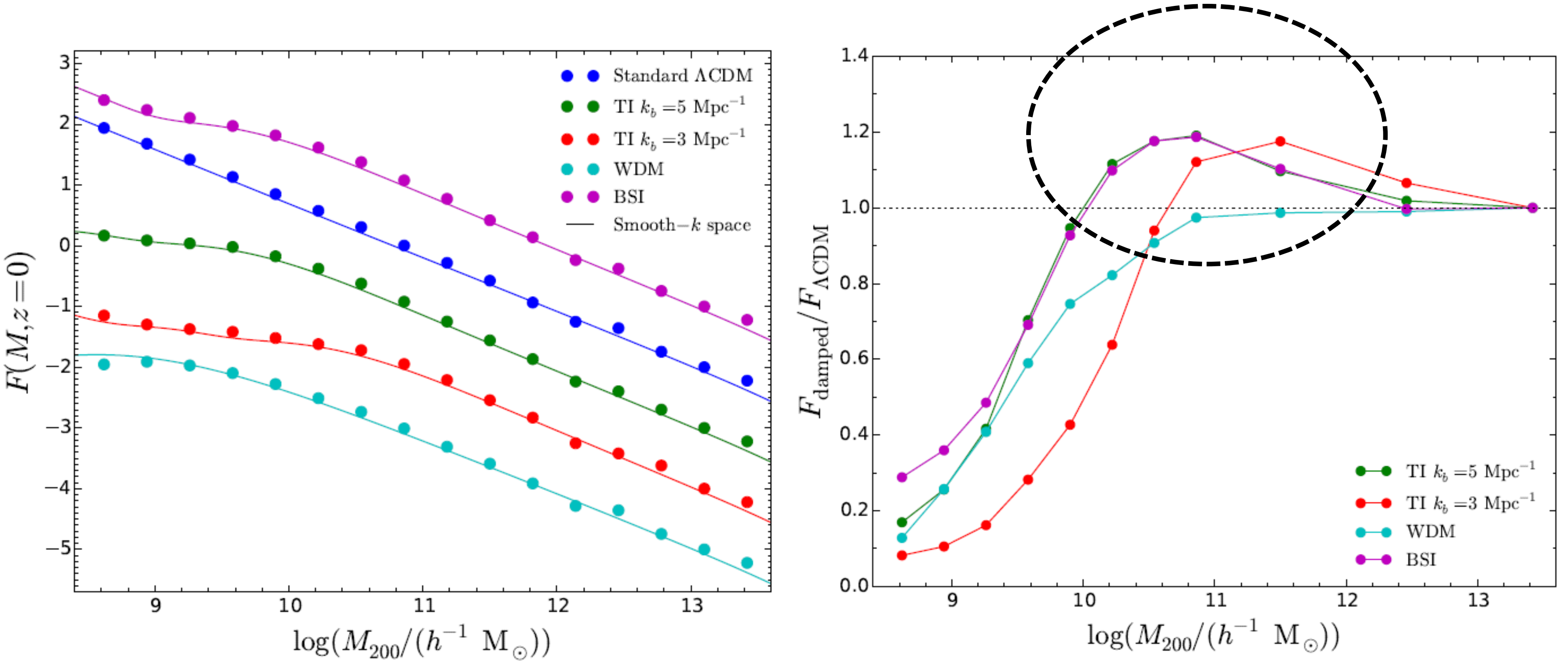

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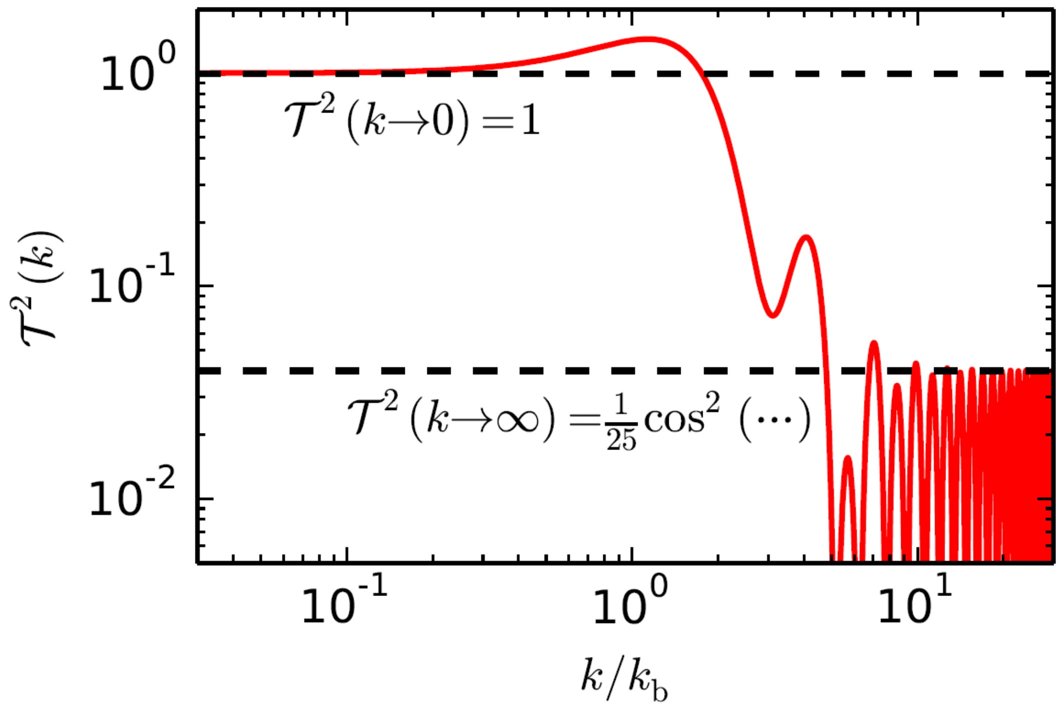
Discussion



✓ For *typical thermal inflation* ($k_b \sim 10^2\mathrm{Mpc}^{-1}$), only CMB spectral distortion may be working.

✓ For *extended thermal inflation* ($k_b \leq 5\mathrm{Mpc}^{-1}$), small scale observations inclduing the substructure, 21cm lines and halo mass seem to be working, but the observabilities are still questionable.