

Observable Small-Scale Effects of Thermal Inflation

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Abstract

Thermal inflation, a brief low energy inflation after the primordial inflation, resolves the moduli problem in the context of supersymmetric cosmology. In the thermal inflation scenario, the primordial power spectrum is modestly redshifted on large scales, but suppressed by a factor of 1/50 on scales smaller than the horizon size at the beginning of thermal inflation. We compare the thermal inflation model with the warm dark matter and Λ CDM scenarios by studying CMB spectral distortions, halo abundances, and 21cm hydrogen lines.

Keywords: Thermal Inflation, Small Scale Structure, CMB Spectral Distortions, 21cm Hydrogen Lines

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1. MODULI PROBLEM

Moduli fields are generic in supersymmetric/string theories. They couple to matter with only gravitational strengths, and the decay rate is estimated by $\Gamma_\Phi \sim m_\Phi^3/M_{\text{Pl}}^2$, where m_Φ is the moduli mass and $M_{\text{Pl}} = 2.44 \times 10^{18}$ GeV is the reduce Planck mass. The lifetime of moduli is estimated by

$$\tau_\Phi \sim \tau_{\text{uni}} \left(\frac{100 \text{ MeV}}{m_\Phi} \right)^2 \quad (1)$$

where $\tau_{\text{uni}} \sim 4.3 \times 10^{17}$ sec is the age of universe.

When the energy scale of the universe is larger than the supersymmetry breaking scale, the moduli potential is the form of $V_\Phi \sim H^2 (\Phi - \Phi_1)^2$. As the universe expands, the energy scale of the universe decreases, and the moduli potential turns to its vacuum form of $V_\Phi \sim m_\Phi^2 (\Phi - \Phi_2)^2$. For $\Phi_0 \equiv |\Phi_1 - \Phi_2| \sim M_{\text{Pl}}$, the moduli would be oscillating with the Planckian amplitude. If the moduli decay out right after its oscillation, the entropy release is estimated to be

$$\frac{n_\Phi}{s} \sim \frac{\Phi_0^2}{10 M_{\text{Pl}}^{3/2} m_\Phi^{1/2}}. \quad (2)$$

This value remains constant unless there is no dramatic event with the moduli, and can be very large depending on the moduli mass.

The moduli problem is two-folded: (1) For $\tau_\Phi < \tau_{\text{uni}}$, the moduli decay might release a huge amount of entropy in the universe and dilute its contents. Hence, it could disturb the Big Bang Nucleosynthesis (BBN). (2) For $\tau_\Phi > \tau_{\text{uni}}$, the moduli might still be oscillating around the minimum, and the energy stored in the oscillations would overclose the universe.

2. THERMAL INFLATION

The moduli problem is discussed in the context of the gravity-mediated suersymmetry breaking model in the thermal inflation scenario [1, 2]. For $m_\phi \sim 1$ TeV, we estimate

$$\tau_\Phi \sim 10^{-12} \times \tau_{\text{uni}} \quad (3)$$

from Eq. (1) and

$$\frac{n_\Phi}{s} \sim 10^7 \quad (4)$$

from Eq. (2). The entropy release is so huge that it conflicts with the observational bounds for successful BBN, 10^{-14} to 10^{-12} [3].

In the thermal inflation scenario, the moduli problem is resolved by introducing a flaton field, a scalar field generated by a supersymmetric flat direction with considering thermal effects on it. The flaton potential becomes $V_\phi = V_0 + \frac{1}{2} (g^2 T^2 - m_\phi^2) \phi^2 + \dots$ around $\phi = 0$, where g is the thermal coupling, and T is the temperature of the universe. When the temperature is very high, the flaton is held at the origin. As the temperature decreases with the expansion of the universe, the vacuum energy V_0 drives the inflationary phase, and the pre-existing moduli can be diluted by $\Delta_{\text{TI}} \sim 10^{-12}$. In the scenario having successful Affleck-Dine baryogenesis, there can be found the additional dilution factor $\Delta_{\text{AD}} \sim 10^{-8}$. Hence, we can reduce the entropy release of Eq. (4)

sufficiently to the observational bounds. However, the moduli can be regenerated due to the misalignment of the potential at the end of thermal inflation by

$$\frac{n_\Phi}{s} \sim \frac{V_0 T_{\text{reh}}}{m_\Phi^2 M_{\text{Pl}}^2} \sim 10^{-14} \left(\frac{V_0^{1/4}}{10^8 \text{ GeV}} \right)^4 \left(\frac{T_{\text{reh}}}{\text{GeV}} \right) \quad (5)$$

where T_{reh} is the reheating temperature of the flaton. If the energy scale of thermal inflation is low enough, $V_0^{1/4} \lesssim 10^8 \text{ GeV}$, it would not conflict with the observational bounds for BBN.

3. POWER SPECTRUM OF THERMAL INFLATION

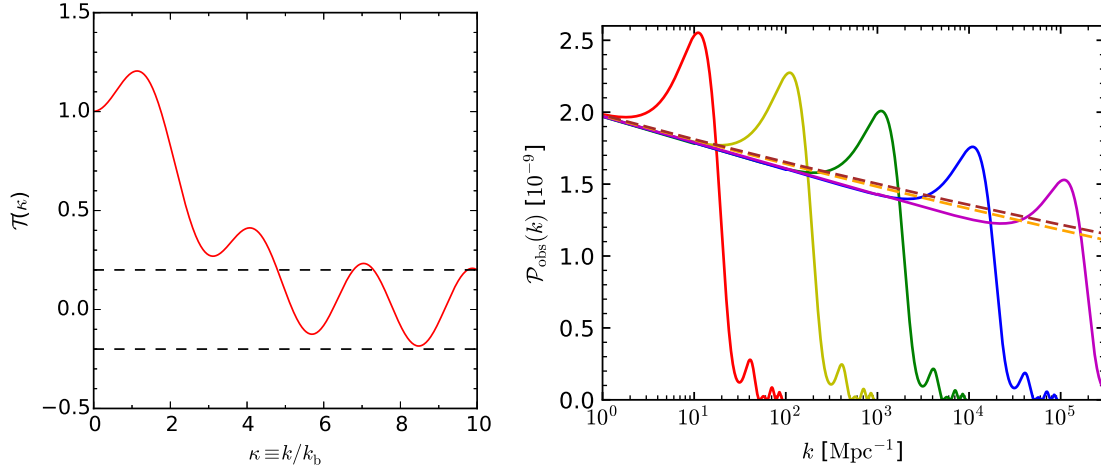


FIGURE 1: Left: The transfer function of thermal inflation of Eq. (6) (Credit: [4]). Right: The power spectrum of thermal inflation with $k_b/\text{Mpc}^{-1} = 10, 10^2, 10^3, 10^4, 10^5$. The dashed lines are the power spectra without thermal inflation. $\mathcal{N}_{\text{unknown}} = 0, -13, -\infty$ represent the amount of inflation between the beginning of the moduli domination and the end of the primordial inflation (Credit: [6]).

The outline of the thermal inflation scenario consists of the following five steps:

1. Primordial inflation produces the (nearly) scale-invariant power spectrum.
2. The moduli Φ dominates over the universe.
3. Thermal inflation gets started to resolve the moduli problem by the flaton ϕ with thermal effects on it.
4. The flaton oscillates around the its minimum and dominates over the universe.
5. As the inflaton decays out, it reheat the universe, and the radiation dominates over the universe.

In [4], we see that cosmological perturbations on large scales, corresponding to cosmic microwave background (CMB) or large scale structure (LSS) observations, remain preserving while perturbations on small scales are suppressed. At the step 1, the primordial power spectrum is given by $\frac{d \ln P_{\text{pri}}}{d \ln k} = -\frac{c}{\mathcal{N}}$, where c is a constant and $\mathcal{N} \equiv \ln \frac{k}{a_{\text{end}} H_{\text{end}}}$ is the amount of inflation from the ‘end’ of the primordial inflation. After the primordial inflation, there is an unknown era which is approximately described by the equation of state of a single component, $p = w\rho$ with $0 \leq w \leq 1/3$. Now we summarize the change of the primordial power spectrum from the step 2 to the step 4 of the above by a transfer function

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

where the characteristic scale k_b is estimated by

$$k_b \simeq 3 \times 10^3 \text{ Mpc}^{-1} \left(\frac{e^{20}}{e^{N_{\text{TI}}}} \right) \left(\frac{g_*(T_{\text{reh}})}{10^2} \right)^{1/12} \left(\frac{T_{\text{reh}}}{\text{GeV}} \right)^{1/3} \left(\frac{V_0^{1/4}}{10^7 \text{ GeV}} \right)^{2/3} \quad (7)$$

with the efolds during thermal inflation N_{TI} . In Eq. (7), $N_{\text{TI}} \sim 10$ to 15 is enough to resolve the moduli problem. However, there is no theoretical upper bound for N_{TI} , and if we include multiple thermal inflations, N_{TI} should get larger. Hence, N_{TI} can be larger as long as it is not consistent with the large scale observations such as CMB.

The resulting power spectrum is given by

$$P(k) = \mathcal{T}^2(k/k_b) \times P_{\text{pri}}(k) . \quad (8)$$

The transfer function of Eq. (6) is shown in the left panel of Figure 1 and the resulting power spectra of Eq. (8) are shown in the right of Figure 1. The crucial feature of the thermal inflation is that the power spectrum is suppressed by $1/50$ at $k \gtrsim k_b$. Hence, thermal inflation can be explored by cosmological or astrophysical observations on such small scales.

4. OBSERVATIONAL EFFECTS ON SMALL SCALES

The power spectrum of thermal inflation can be explored by the following three methods:

- CMB spectral distortion is generated by the dissipation of primordial density fluctuations due to the Silk damping of acoustic waves [5]. It is sensitive to the power spectrum on the scales $1 \text{ Mpc}^{-1} \lesssim k \lesssim 10^4 \text{ Mpc}^{-1}$ and can be used to probe the thermal inflation power spectrum. In the left panel of Figure 2, the spectral μ -distortion of thermal inflation falls well below the value of the standard Λ CDM scenario at $k_b \lesssim 10^3 \text{ Mpc}^{-1}$ [6].
- The suppression of the thermal inflation power spectrum gives a possible way of explaining the missing satellite problem [7]. The substructure of the galaxies can be useful in studying the thermal inflation cosmology compared to the warm dark matter scenario having the similar effects on small scales [8]. In [9], the halo mass function of N-body simulation of the thermal inflation scenario is distinguished from that of the warm dark matter and Λ CDM scenarios.
- The hydrogen 21-cm line background can be used to test the matter power spectrum of the thermal inflation scenario. In the right panel of Figure 2, the Square Kilometre Array (SKA) would be able to probe the differences of the hydrogen distributions between the thermal inflation, warm dark matter, and Λ CDM scenarios [8].

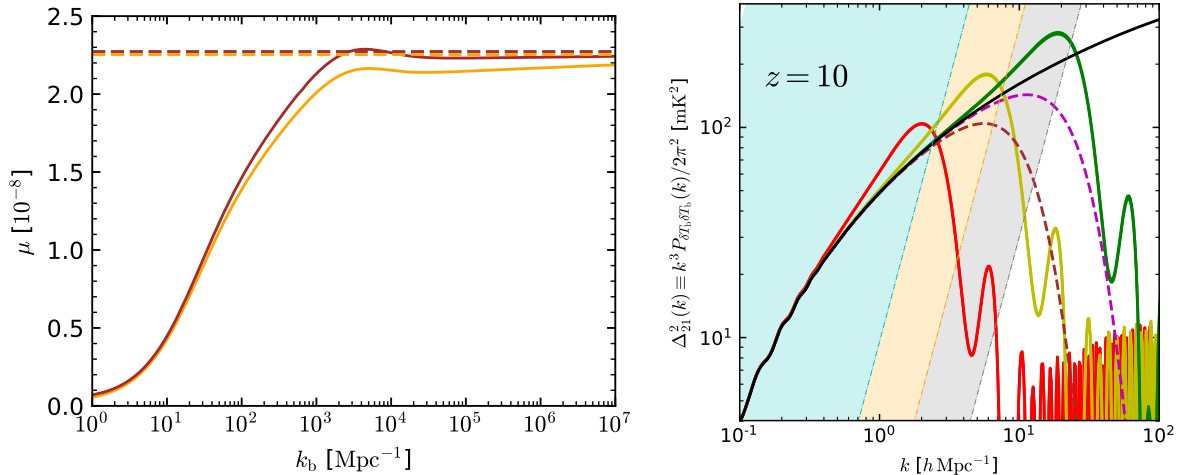


FIGURE 2: Left: CMB spectral μ -distortion with $\mathcal{N}_{\text{unknown}} = 0, -13, -\infty$ (Credit: [6]). Right: The 21-cm power spectra of thermal inflation ($k_b = 1 \text{ Mpc}^{-1}$ (red), 3 Mpc^{-1} (yellow), 5 Mpc^{-1} (green)), warm dark matter ($m_{\text{FD}} = 1 \text{ keV}$ (brown), 2 keV (magenta)), and Λ CDM (black) scenarios just before the epoch of reionization. The shaded regions imply the power spectra above the thermal noise from the modified SKA configuration with 100 deg^2 sky coverage. Exposure times are $10^3, 10^4,$ and 10^5 -hours in SKA1-LOW, and $10^2, 10^3,$ and 10^4 -hours in SKA2-LOW [10] (Credit: [8]).

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