Constraining Warm Inflation with CMB observations

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(work in prep.)

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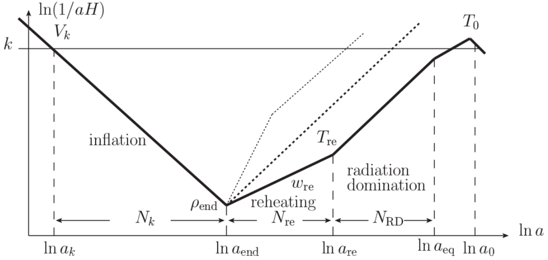
- Slow Roll inflation $\Longrightarrow$ (p)Reheating $\Longrightarrow$ Radiation Domination : Cold Inflation.



- Inflaton energy density $\Longrightarrow$ Radiation Energy during inflation: Warm Inflation
- Inflation can naturally occur at a finite temperature $T > H$ that is sustained by dissipative effects.

Background Theory

- Dissipation of inflation (ϕ) energy $\Longrightarrow$ Dissipative term : Υ.
- Slow-Roll Inflation with friction.
- ρ_R is produced, and continuously replenished by decay of the inflaton field.

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} + \frac{dV}{d\phi} = 0 \tag{1}$$

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2 \tag{2}$$

- Relativistic degree of freedom present during inflation.
- Similar approach as Little Higgs mechanism $\Longrightarrow$ Inflaton is a pNGB from a broken gauge symmetry[1].
- Dissipation coefficient linear in T; quartic potential.

$$\rho_R = \frac{\pi^2}{30} g_* T^4 = C_R T^4 \tag{3}$$

$$\Upsilon = C_T T \tag{4}$$

$$V(\phi) = \lambda\phi^4 \tag{5}$$

- $Q = \frac{\Upsilon}{3H}$

[1] arXiv:1604.08838

Power Spectrum

- Q_e and ϕ_e can be determined as:

$$\frac{Q_e^3}{1+Q_e} = \frac{C_T^4}{48C_R \times \lambda} \tag{6}$$

$$Q^3(1+Q)^2 = \frac{4}{9}\left(\frac{C_T^4}{C_R\lambda}\right)\left(\frac{m_P}{\phi}\right)^6 \tag{7}$$

- $Q(k)$ can be found as following:

$$\frac{dQ}{dN_e} \simeq \frac{Q}{3+5Q}\left(6\epsilon_\phi - 2\eta_\phi\right) \tag{8}$$

- Scalar Power Spectrum[2]

$$P_{\mathcal{R}} = \frac{C_T^4}{4\pi^2 \times 36C_R} Q_*^{-3}\left[\frac{3Q_*}{C_T}\frac{2\pi Q_*}{\sqrt{1+4\pi Q_*/3}} + 1 + 2\mathcal{N}_*\right] \tag{9}$$

- $1 + 2\mathcal{N}_*$: thermal contribution. $\mathcal{N}_* = n_{BE}(a_* H_*) = (e^{H_*/T_*} - 1)^{-1}$.
- Q_e (eq. 6) + ϕ_e (eq. 7) + numerically solving for Q_* (eq. 8)
- Tensor Power Spectrum:

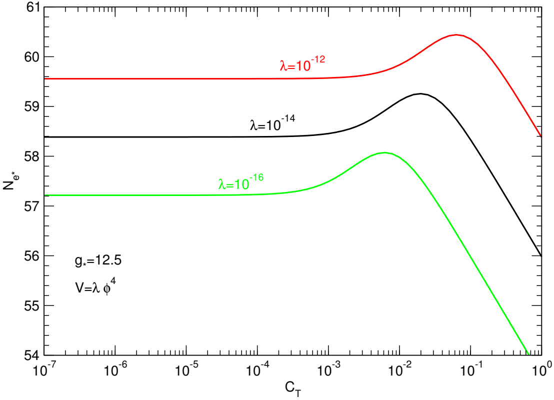
$$P_T = 8\left(\frac{H_*}{2\pi m_p}\right)^2 = \frac{8\lambda^{1/3}}{4\pi^2}\left(\frac{4C_T^4}{9C_R}\right)^{2/3}\frac{1}{Q_*^2(1+Q_*)^{2/3}} \tag{10}$$

[2] arXiv:1302.3544, 1401.1149

- Model parameters :C_T, λ, g_*.
- N_e is known as a function of the wavenumbers $k \Rightarrow P_{\mathcal{R}}(k)$.

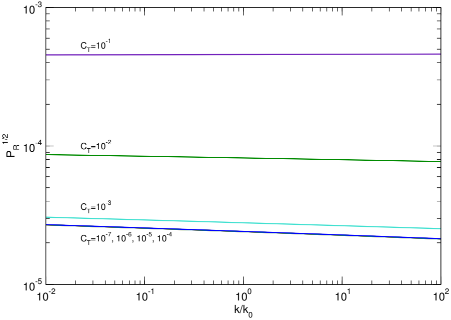
$$N_e(k) = 56.12 - \ln\frac{k}{k_0} + \frac{1}{3(1+\tilde{w})}\ln\frac{2}{3} + \ln\frac{V_k^{1/4}}{V_{end}^{1/4}} + \frac{1-3\tilde{w}}{3(1+\tilde{w})}\ln\frac{\rho_{RH}^{1/4}}{V_{end}^{1/4}} + \ln\frac{V_k^{1/4}}{10^{16}\,\mathrm{GeV}} \quad (11)$$

- $\tilde{w} = 1/3$ reduces expression for $N_e(k)$.

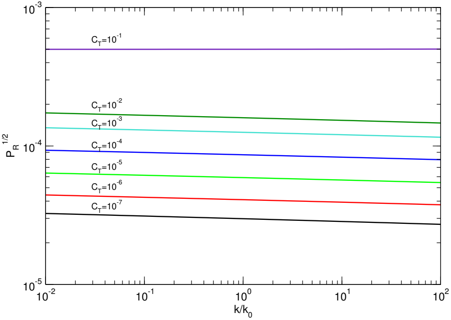


Scalar Power spectrum

Non-thermal Case



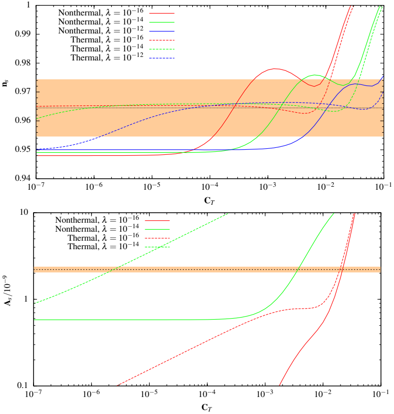
Thermal Case



Dependences from Background

$$P_{\mathcal{R}}(k) = P_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s-1} = A_s\left(\frac{k}{k_0}\right)^{n_s-1} \quad (12)$$

$g_* = 12.5$



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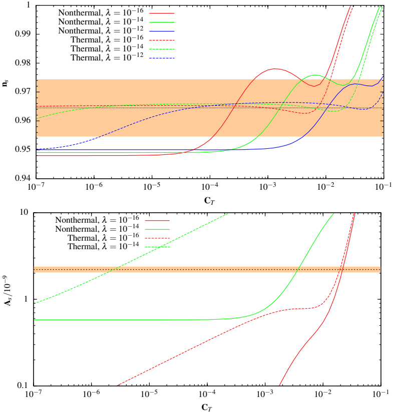
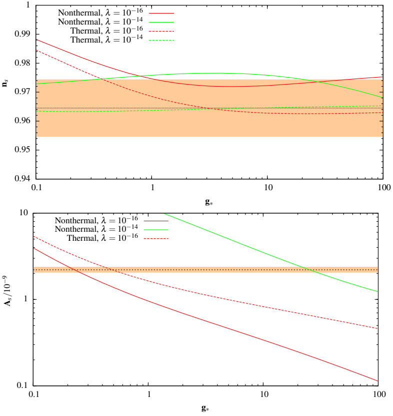


$C_T = 0.004$



MCMC Methodology

- MCMC runs done with *CosmoMC*.

$$C_l = \int d(lnk) P_R(k) T_l^2(k) \tag{13}$$

- Given $P_{\mathcal{R}}(k)$, compares C_l's to minimise χ^2 and parameters of the theory are constrained.

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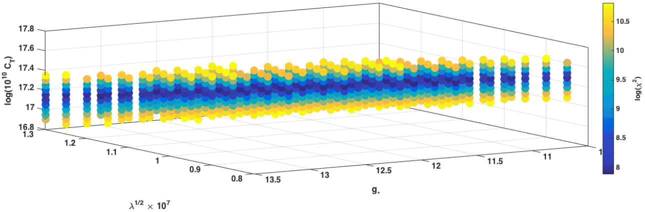
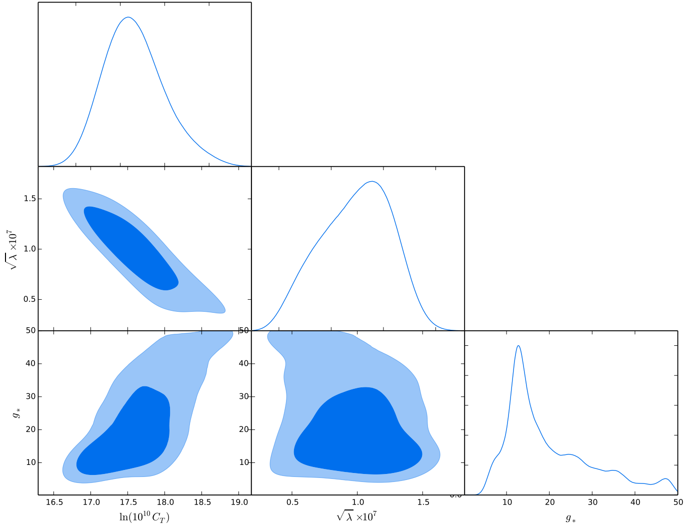


- Slow mixing and bad convergence in CosmoMC.
- Posterior probability distribution has multiple peaks and long tails.
- Increase the temperature of the Chains in the Metropolis-Hastings algorithm.

Results: $\mathcal{N}_* = 0$

Planck TT+TE+EE + lowP +lensing +BKPlanck



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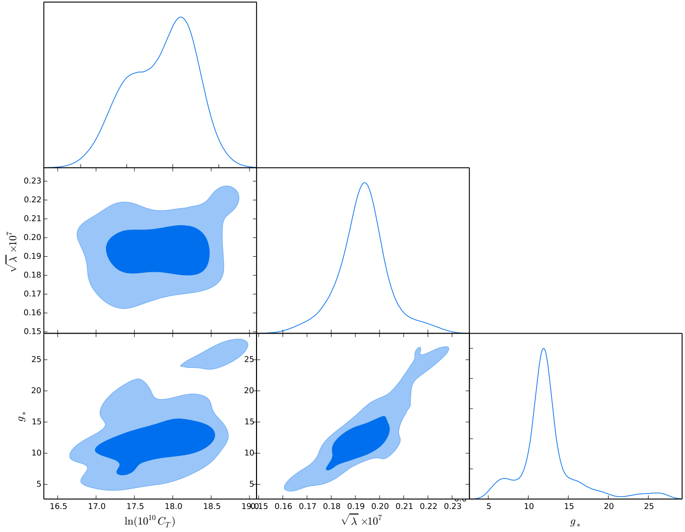


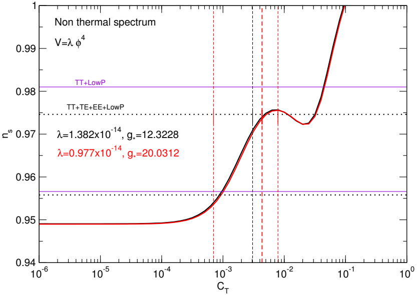
Results Combined

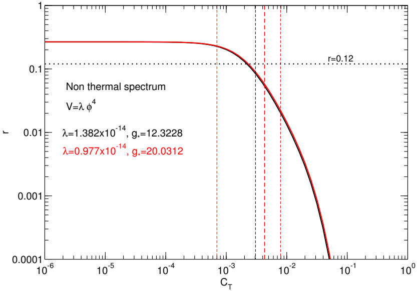
Table : Constraints on cosmological parameters for non-thermal and thermal case compared with $\Lambda CDM + r$. Data used: Planck 2015+BICEP2/Keck Array.

	$\mathcal{N}_* = 0$		$\mathcal{N}_* \neq 0$			$\Lambda CDM + r$	
	$\chi^2/dof = 423.27$		$\chi^2/dof = 425.37$			$\chi^2/dof = 421.87$	
parameters	mean value	1σ	mean value	1σ	parameters	mean value	1σ
$\Omega_b h^2$	0.02232	0.00021	0.02224	0.00018	$\Omega_b h^2$	0.02223	0.00017
$\Omega_c h^2$	0.1178	0.0015	0.1193	0.0016	$\Omega_c h^2$	0.1193	0.0016
$100\theta_{MC}$	1.04097	0.00045	1.04084	0.00041	$100\theta_{MC}$	1.04083	0.00033
τ	0.077	0.019	0.063	0.017	τ	0.062	0.017
$ln(C_T \times 10^{10})$	17.59	0.42	17.68	0.67	$ln(A_s \times 10^{10})$	3.057	0.031
$\sqrt{\lambda} \times 10^7$	0.99	0.27	0.19	0.014	n_s	0.9656	0.0051
g_*	20.03	10.39	14.68	4.5	r	0.051	0.022

Discussions

- $\mathcal{N}_* = 0$: The marginalised mean values: $\lambda = 0.97 \times 10^{-14}$, $C_T = 0.0043$, $g_* = 20$.
- Best fit values: $\lambda = 1.38 \times 10^{-14}$, $C_T = 0.00304$, $g_* = 12.32$.

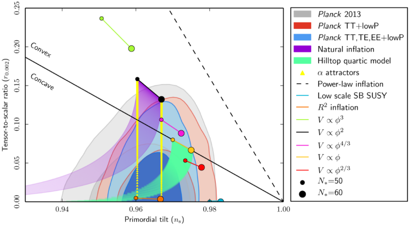




- $N_e = 58.2$ for mean values of the model parameters.
- $\mathcal{N}_* \neq 0$: mean values of model parameters give: $n_s = 0.96298$, $r = 0.00189$.

Results

- $\mathcal{N}_* = 0$: $n_s \simeq 0.972$, $r \simeq 0.05$.
- $\mathcal{N}_* \neq 0$: $n_s \simeq 0.963$, $r \simeq 0.002$.



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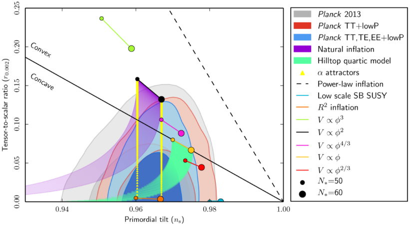

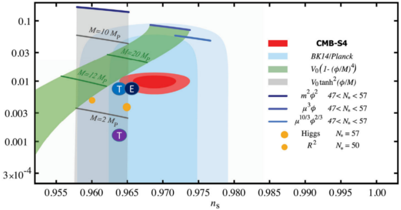

Conclusion

- Avoiding extra parameterisation for reheating. Warm exit to Radiation Domination $\implies e-$folds are constrained.
- Quantitative study of warm inflation with inflaton (pNGB) coupled with light degrees of freedom (light fermions) is done.
- Parameters of the theory C_T, λ, g_* are constrained using observations.
- Non-thermal case: Spectral index (n_s) : within observational bounds.
- Non-thermal case: Tensor-to-scalar ratio (r): close to the upper bound.
- Thermal case: better r expected.
- Ongoing work on thermal warm inflation case.

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