# CONSTRAINING WARM INFLATION WITH CMB OBSERVATIONS

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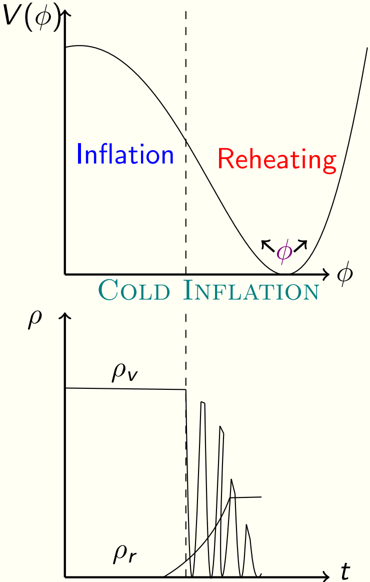
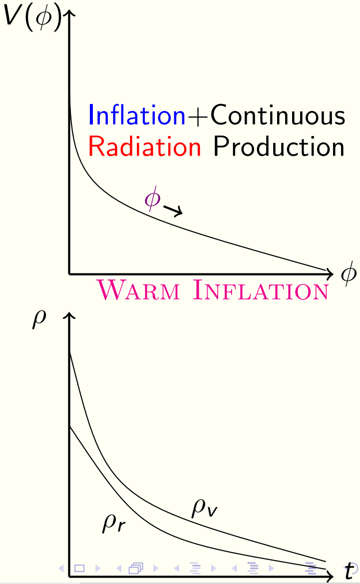
# Presentation Outline


1. MOTIVATION
2. THEORY
3. ANALYSIS
4. CONCLUSION
5. REFERENCES

# Warm vs Cold Inflation



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# Warm Inflation

- Dissipation of inflaton ($\phi$) energy => Dissipative term : $\Upsilon$
- Radiation is produced through friction and continuously replenish through the inflaton field decay.

$$\boxed{\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_{,\phi} = 0} \qquad \boxed{\dot{\rho}_r + 4H\rho_r = \Upsilon\,\dot{\phi}^2}$$

- Inflaton is a pNGB from a broken gauge symmetry (inspired by the Little Higgs Mechanism).
- Quartic potential $\boxed{V(\phi) = \lambda\phi^4}$ is tested in the linear dissipation regime $\boxed{\Upsilon = C_T T}$.

$$\boxed{\rho_r = \frac{\pi^2}{30} g_* T^4 = C_R T^4}$$

- $\boxed{Q = \Upsilon/3H}$

# Power Spectrum

- $Q_e$ and $\phi_e$ can be computed from:

$$\frac{Q_e^3}{(1+Q_e)} = \frac{C_T^4}{2^4 \times 3^5 \times C_R\lambda}$$

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

- $Q(k)$ is determined from:

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

- Scalar power spectrum is given as:

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

- The tensor spectrum is defined to be:

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

# Model Parameters

- Model parameters: $C_T$, $\lambda$, $g_*$.
- No. of e-folds ($N_e(k)$) is defined as:

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

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

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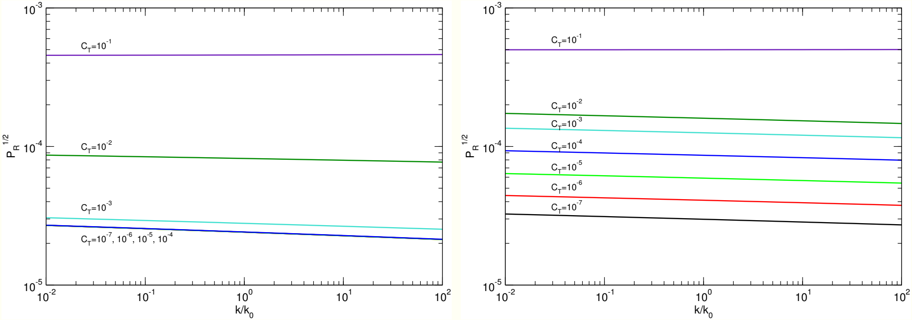
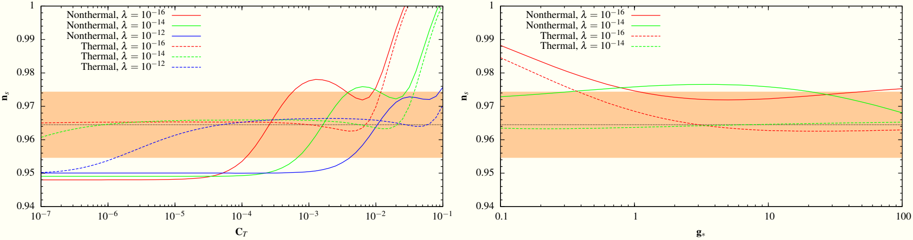
$$N(k) = 56.02 - \ln\frac{k}{k_0} + \ln\frac{V_k^{1/2}}{V_{end}^{1/2}} + \ln\frac{V_{end}^{1/4}}{10^{16}\,\mathrm{GeV}}$$

# Scalar Power Spectrum



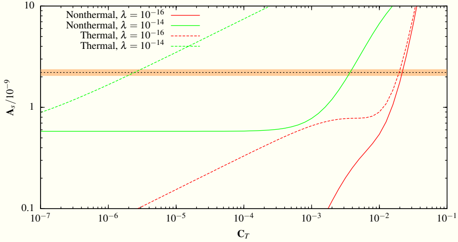

Primordial spectrum as a function of $k/k_0$, for different values of the parameter $C_T = 10^{-7}, 10^{-6}, ...10^{-1}$ and for fixed $\lambda = 10^{-14}$, $g_* = 12.5$. LHS is for a non-thermal inflaton, i.e, $\mathcal{N}_* = 0$ and RHS is for a thermal inflation, i.e., $\mathcal{N}_* \neq 0$.

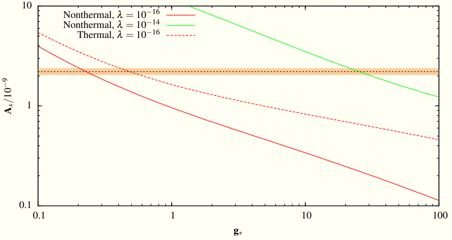
# Background Dependence




Spectral index ($n_s$) as a function of $C_T$ with $g_* = 12.5$ in LHS and as a function of $g_*$ with $C_T = 0.004$ in RHS. The solid lines are for $\mathcal{N}_* = 0$ and the dashed lines are for $\mathcal{N}_* \neq 0$.

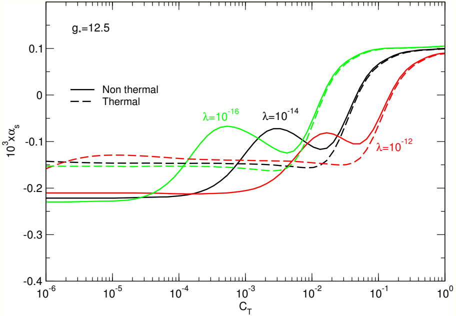
# Background Dependence

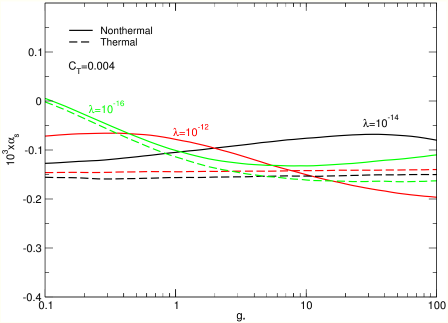



Amplitude of spectrum ($A_s$) as a function of $C_T$ with $g_* = 12.5$ in LHS and as a function of $g_*$ with $C_T = 0.004$ in RHS for different values of $\lambda$ as indicated in the plot. The solid lines are for $\mathcal{N}_* = 0$ and dashed lines are for $\mathcal{N}_* \neq 0$.

# Background Dependence




Running of the spectral index $(\alpha)$ as a function of $C_T$ with $g_* = 12.5$ in LHS, and as a function of $g_*$ with $C_T = 0.004$ in RHS, for different values of $\lambda$ as indicated in the plot. The solid lines are for $\mathcal{N}_* = 0$ and dashed lines are for $\mathcal{N}_* \neq 0$.

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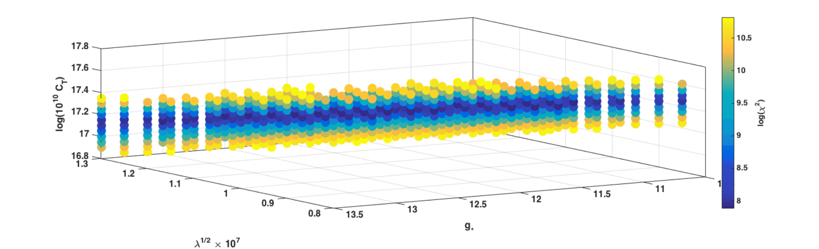
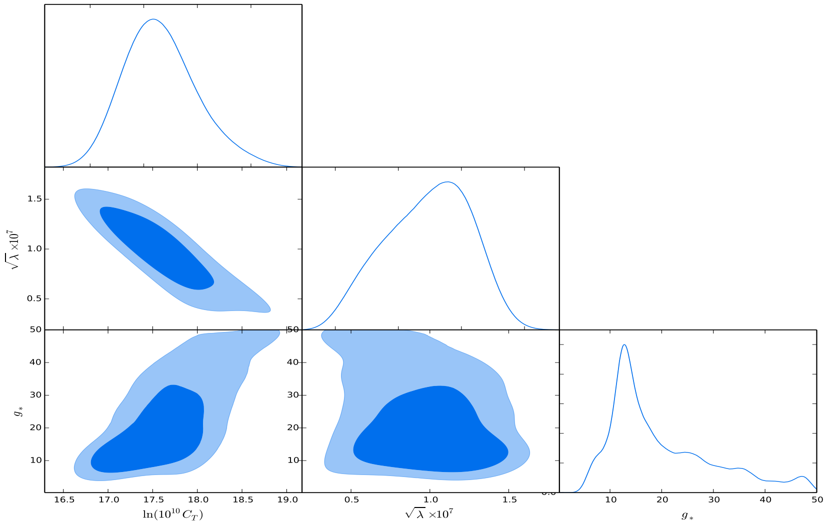
# MCMC METHODOLOGY

- MCMC is performed using COSMOMC package coupled with CAMB.
- Slow mixing an bad convergence in COSMOMC due to multimodality in the theory.

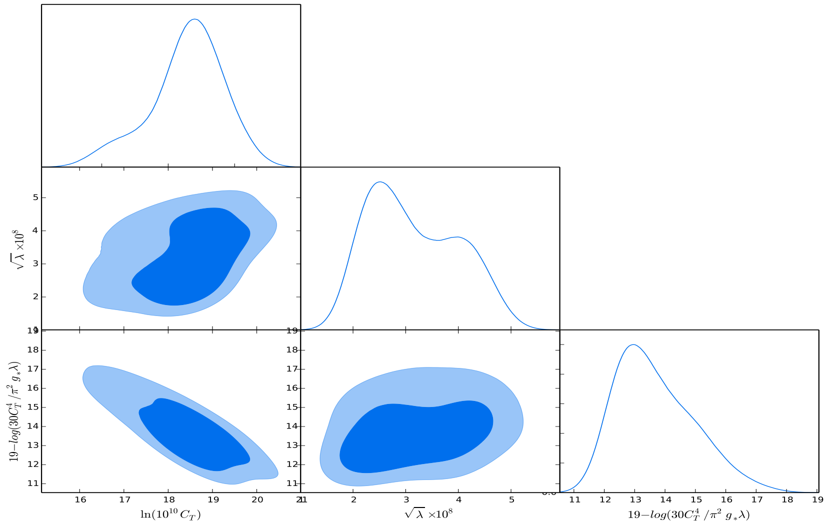



- Increase the temperature of the chains and changing the standard Metropolis-Hastings algorithm to Wang-Landau algorithm.
- In thermal case, hierarchical centering is employed to solve convoluted multimodality.

# Non-Thermal Case ($N_* = 0$)



# Thermal Case ($N_* \neq 0$)



# Results

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

| Warm Inflation | | | | | Cold Inflation | | |
|---|---|---|---|---|---|---|---|
| | $\mathcal{N}_* = 0$ | | $\mathcal{N}_* \neq 0$ | | | $\Lambda CDM + r$ | |
| parameters | mean value | $1\sigma$ | mean value | $1\sigma$ | parameters | mean value | $1\sigma$ |
| $\Omega_b h^2$ | 0.02233 | 0.00022 | 0.02224 | 0.00019 | $\Omega_b h^2$ | 0.02224 | 0.00017 |
| $\Omega_c h^2$ | 0.1178 | 0.0015 | 0.1194 | 0.0013 | $\Omega_c h^2$ | 0.1192 | 0.0016 |
| $100\theta_{MC}$ | 1.04097 | 0.00046 | 1.04088 | 0.00038 | $100\theta_{MC}$ | 1.04085 | 0.00034 |
| $\tau$ | 0.077 | 0.019 | 0.068 | 0.021 | $\tau$ | 0.064 | 0.018 |
| $C_T$ | 0.0043 | 0.0018 | 0.0104 | 0.0077 | $\ln(A_s \times 10^{10})$ | 3.06 | 0.031 |
| $\lambda$ | $9.77\times10^{-15}$ | $5.41\times10^{-15}$ | $9.74\times10^{-16}$ | $6.78\times10^{-16}$ | $n_s$ | 0.966 | 0.0052 |
| $g_*$ | 20.03 | 10.39 | 139.91 | 487.98 | $r$ | $< 0.07$ | |

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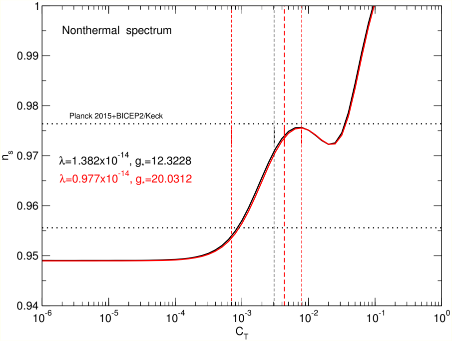
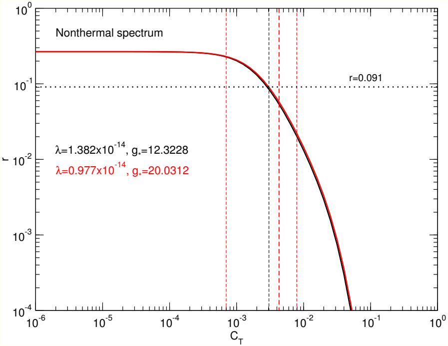
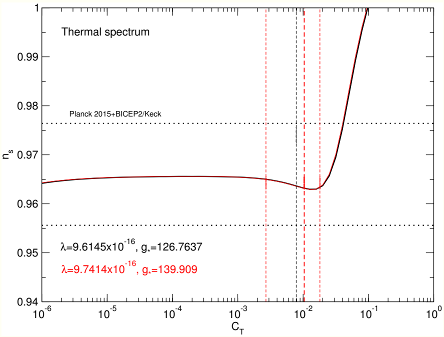
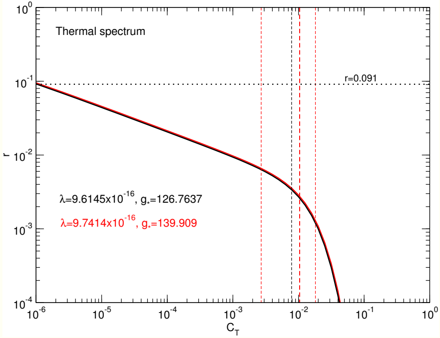



The predictions for the spectral index and tensor-to-scalar ratio for the best-fit and mean value of parameters for non-thermal case($N_* = 0$).

# Thermal Case($N_* \neq 0$)




The predictions for the spectral index and tensor-to-scalar ratio for the best-fit and mean value of parameters for thermal case($N_* \neq 0$).

# Discussions

- No reheating is required in warm inflation => Warm exit to the radiation dominated universe.
- Model parameters are kept free and a statistical simulation is carried out to constrain the parameters and inflationary observables.
- The difficulties related to the MCMC simulations are dealt with more sophisticated statistical tweaks.
- Non-thermal case $(N_* = 0)$: Spectral index is within the observational bounds but the tensor-to-scalar ratio is close to the upper bound.
- Thermal case $(N_* \neq 0)$: tensor-to-scalar ratio is well within the observational bound.

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- A. Berera and L. -Z. Fang, Phys. Rev. Lett. 74, 1912 (1995) [astro-ph/9501024]. A. Berera, Phys. Rev. Lett. 75, 3218 (1995) [astro-ph/9509049].
- M. Bastero-Gil, A. Berera, I. G. Moss and R. O. Ramos, JCAP 1405 (2014) 004 [arXiv:1401.1149 [astro-ph.CO]].
- M. Bastero-Gil, A. Berera and R. O. Ramos, JCAP 1109, 033 (2011) [arXiv:1008.1929 [hep-ph]]; M. Bastero-Gil, A. Berera, R. O. Ramos and J. G. Rosa, JCAP 1301, 016 (2013) [arXiv:1207.0445 [hep-ph]].
- S. Bartrum, M. Bastero-Gil, A. Berera, R. Cerezo, R. O. Ramos and J. G. Rosa, Phys. Lett. B 732, 116 (2014) [arXiv:1307.5868 [hep-ph]].
- M. Bastero-Gil, A. Berera, R. O. Ramos and J. G. Rosa, Phys. Rev. Lett. 117 (2016) no.15, 151301 [arXiv:1604.08838 [hep-ph]].


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- M. Bastero-Gil, A. Berera, I. G. Moss and R. O. Ramos, JCAP 1405 (2014) 004 [arXiv:1401.1149 [astro-ph.CO]].
- M. Bastero-Gil, A. Berera and R. O. Ramos, JCAP 1109, 033 (2011) [arXiv:1008.1929 [hep-ph]]; M. Bastero-Gil, A. Berera, R. O. Ramos and J. G. Rosa, JCAP 1301, 016 (2013) [arXiv:1207.0445 [hep-ph]].
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# Thank You !!