Cosmic Inflation: Warm or Cold?

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Chennai, 05.03.2019

Presentation Outline

Guth's Diary!!

"Historical motivation for inflation arose largely on philosophical ground."

- A. Linde

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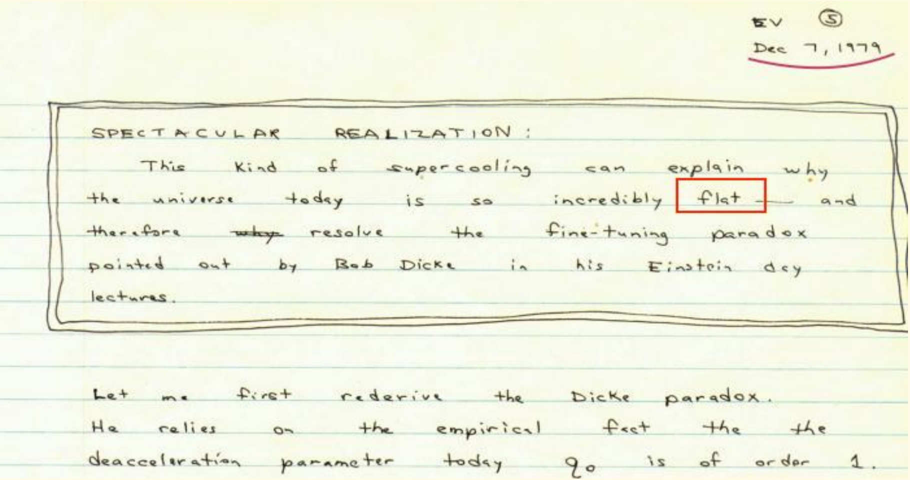

EV (5)

Dec 7, 1979

SPECTACULAR REALIZATION:

This kind of supercooling can explain why the universe today is so incredibly flat — and therefore ~~why~~ resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

Let me first rederive the Dicke paradox. He relies on the empirical fact the the deacceleration parameter today q_0 is of order 1.

Flatness Problem

- Why our universe is almost perfectly flat? This is also known as the age problem...
- Friedmann equation: $\boxed{|1-\Omega^{-1}|\rho a^2 = \frac{-3k}{8\pi G}}$

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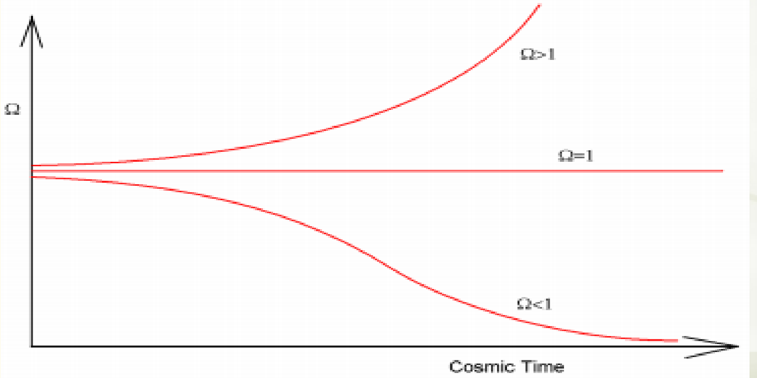
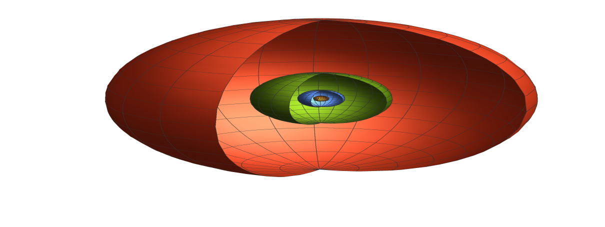


Solving Flatness Problem



$$\boxed{\ddot{a} > 0}$$

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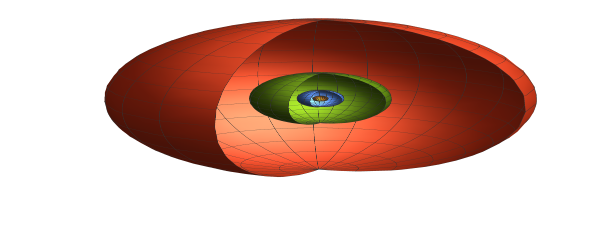

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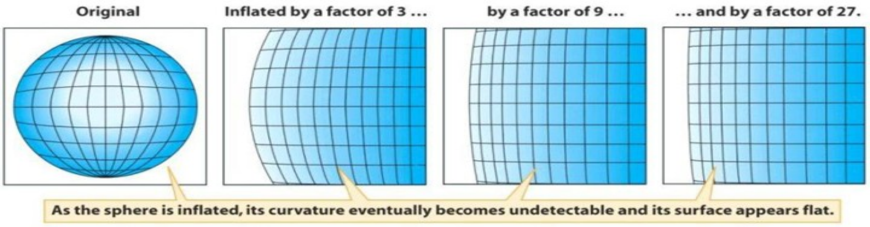
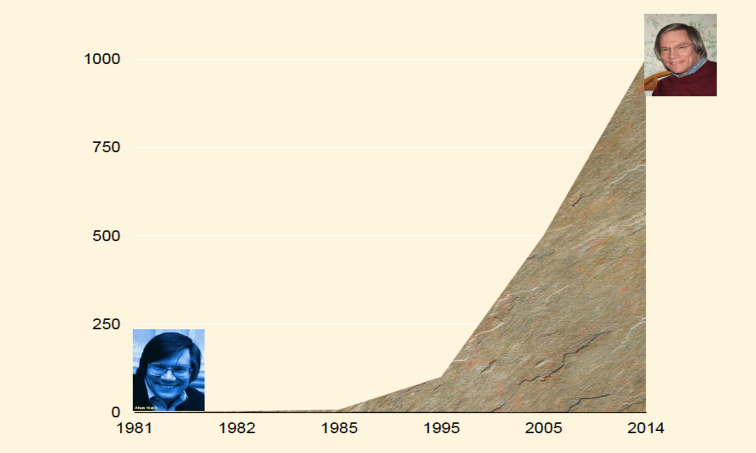


Inflation Models!!



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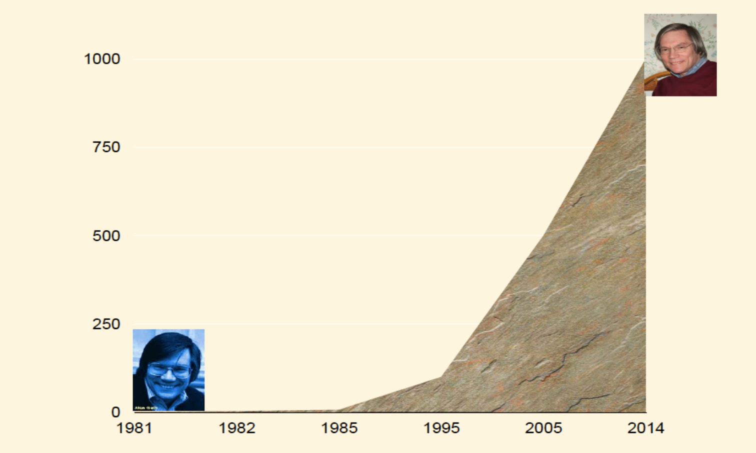
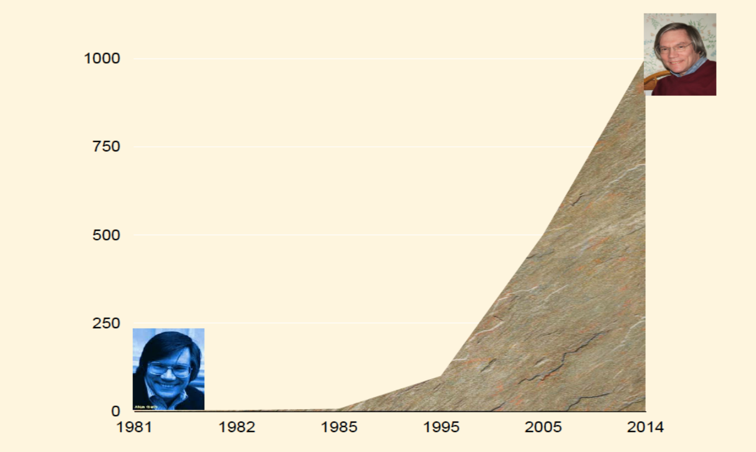


Another Inflation!!

Inflation Models!!



Another Inflation!!

Only two dynamical realization ⇒ Warm or Cold!!

Presentation Outline

Cold Inflation

- $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$ Scale Factor Eqn.
- $$\dot{\rho} = -3H(\rho + p)$$ Energy Conservation Eqn.
- $$\ddot{a} > 0 \Rightarrow p < -\rho/3$$ Scalar Fields.
- $$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2(t)}\nabla^2\phi - \frac{\partial V}{\partial \phi} = 0$$ G.R version of K-G Eqn.
- $$\rho_R \sim \rho_{RI} Exp[-4\sqrt{8\pi G V_0/3}t]$$ Radiation Decay Eqn.
- $$a_f/a_i = Exp[N_e] => T(t) = T_i(a_i/a(t))$$ Supercold Universe.

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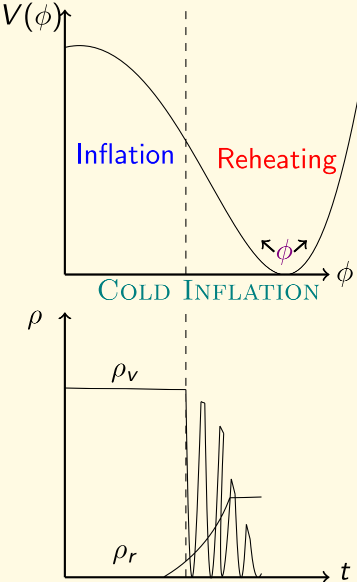
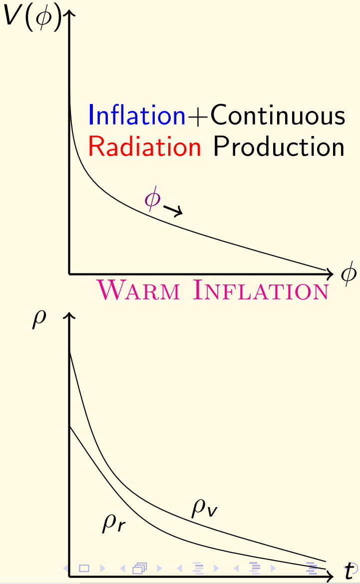
Inflation $\rightarrow$ Cold Universe $\rightarrow$ Reheating $\rightarrow$ Radiation Domination...

Warm vs Cold Inflation





Warm Inflation

- $\ddot{\phi} + (3H + \Upsilon)\dot{\phi} - \frac{1}{a^2(t)}\nabla^2\phi + V_{,\phi} = \zeta$ — W.I. Equivalent Form.
- $\dot{\rho}_V = -\Upsilon\dot{\phi}^2$ — Potential Energy Dissipation.
- $\dot{\rho}_r = -4H\rho_r + \Upsilon\,\dot{\phi}^2$ — Radiation Energy Eqn.
- $\rho_R \sim \frac{C}{4H} + (\rho_{R0} - \frac{C}{4H})e^{-4Ht}$ — For Constant Dissipation.

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Inflation + Reheating → Radiation Domination...

A. Berera and L. -Z. Fang, Phys. Rev. Lett. 74, 1912 (1995),

A. Berera, Phys. Rev. Lett. 75, 3218 (1995).

Warm vs Cold Inflation

- Vacuum Energy ($E_V \equiv \rho_V^{1/4}$), Radiation Energy ($E_R \equiv \rho_R^{1/4}$),
- Hubble Scale (H), Inflaton mass ($m \equiv V(\phi)''$),
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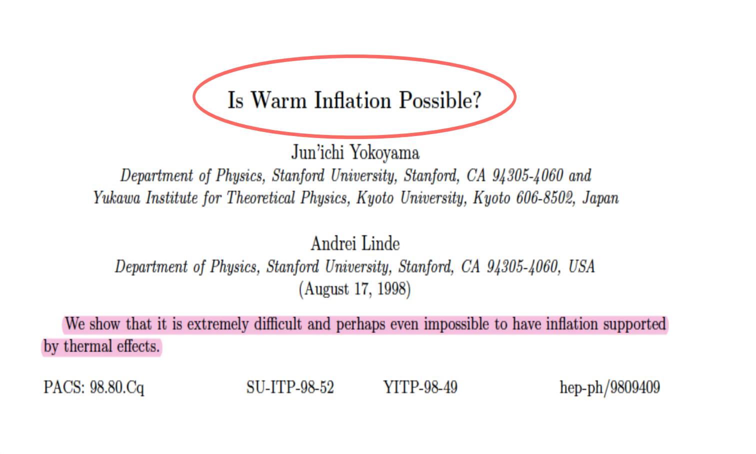
Cold Inflation	Warm Inflation
$E_V > E_R$	$E_V > E_R$
$H > m$	$max(\Upsilon, H) > m$
$m > E_R$	$E_R > m$
$H >> \Upsilon$	$\Upsilon > 3H$ (Strong) $\Upsilon < 3H$ (Weak)

Barring The Fact..



Is Warm Inflation Possible?

Jun'ichi Yokoyama
Department of Physics, Stanford University, Stanford, CA 94305-4060 and
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(August 17, 1998)

We show that it is extremely difficult and perhaps even impossible to have inflation supported by thermal effects.

PACS: 98.80.Cq SU-ITP-98-52 YITP-98-49 hep-ph/9809409

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$$g\phi\psi\overline{\psi} => m_\psi = g\phi, \quad m_\phi \sim gT$$

Way Out:

- Brane-world Scenario:
  - Inflaton is indirectly coupled to light DOF through heavy mediator fields.
  - Thermal mass corrections are exponentially suppressed and dissipation coefficient is suppressed only by power of $T/M_m \leqslant 1$.
  - Requires large multiplicity of mediator fields to sustain thermal bath for $50-60$ e-folds.
- Little Warm Inflation:
  - Inflaton is a pNGB from a broken gauge symmetry.
  - Fermion masses remain light during inflation for an arbitrary inflaton value provided the thermal bath temperature follows some conditions.
  - Quadratic divergences and thermal mass corrections cancels thus not ruining the slow roll for prolonged time.

M. Bastero-Gil, A. Berera, R. O. Ramos and J. G. Rosa, Phys. Rev. Lett. 117 (2016) no.15.

Presentation Outline

Quartic Little Warm Inflation

- $V(\phi) = \lambda\phi^4$ — Quartic Potential.
- $\Upsilon = C_T T$ — Linear Dissipation Regime
- $\rho_r = \frac{\pi^2}{30} g_* T^4 = C_R T^4$ — Radiation Energy Density.
- $Q = \Upsilon / 3H$ — Dissipative Ratio.
- $4\rho_R \simeq 3Q(\dot{\phi})^2$ — SRA Regime.

Power Spectrum

- Q_e can be computed from:

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

- Scalar power spectrum is given as:

$$P_R = \left(\frac{H_*}{\dot{\phi}_*}\right)^2\left(\frac{H_*}{2\pi}\right)^2\left[\frac{T_*}{H_*}\frac{2\pi Q_*}{\sqrt{1+4\pi Q_*/3}} + 1 + 2N_*\right]$$

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

- The tensor spectrum is defined to be:

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

Bastero-Gil, Bhattacharya, Dutta, MRG [JCAP 1802 (2018) NO.02, 054]

Model Parameters

- Model parameters: C_T, λ, 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 $N_e(k)$.

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

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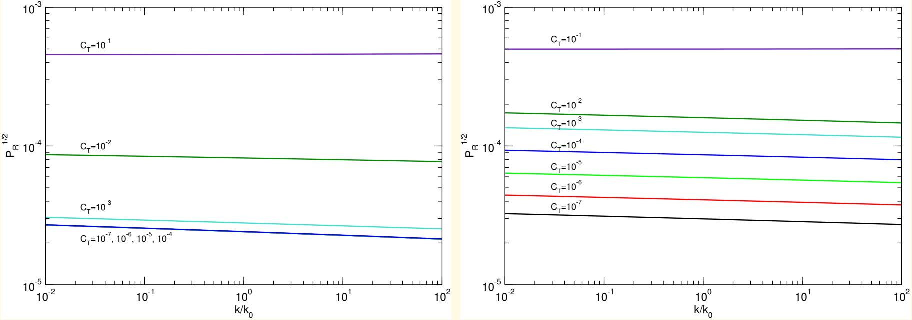
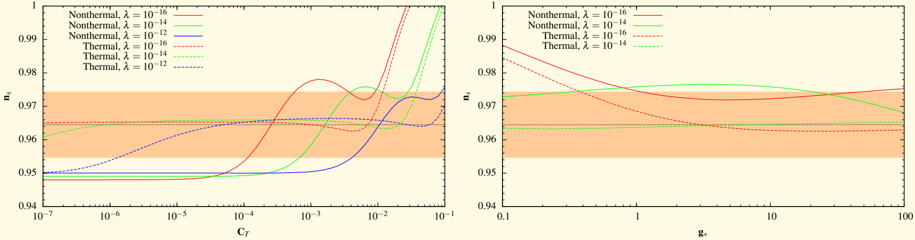
Scalar Power Spectrum



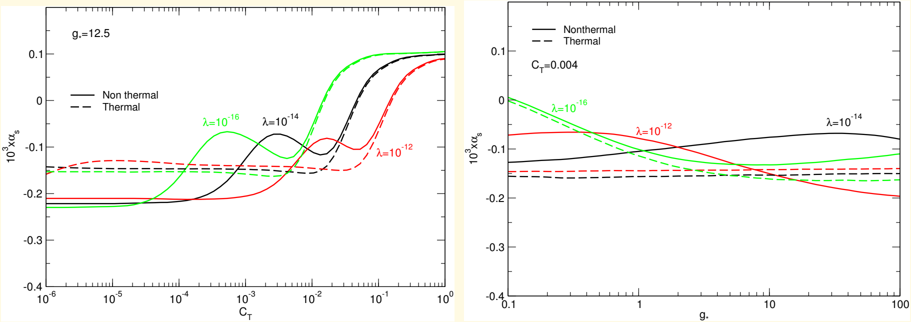
Primordial spectrum as a function of k/k_0, for different values of the parameter $C_T = 10^{-7}, 10^{-6}, ...10^{-1}$ and for fixed $\lambda = 10^{-14}$, $g_* = 12.5$. LHS is for a non-thermal inflaton, i.e, $\mathcal{N}_* = 0$ and RHS is for a thermal inflation, i.e., $\mathcal{N}_* \neq 0$.

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

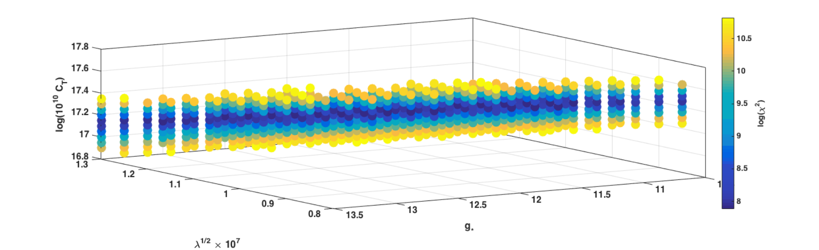


Running of the spectral index (α) as a function of C_T with $g_* = 12.5$ in LHS, and as a function of g_* with $C_T = 0.004$ in RHS, for different values of λ as indicated in the plot. The solid lines are for $\mathcal{N}_* = 0$ and dashed lines are for $\mathcal{N}_* \neq 0$.

Presentation Outline

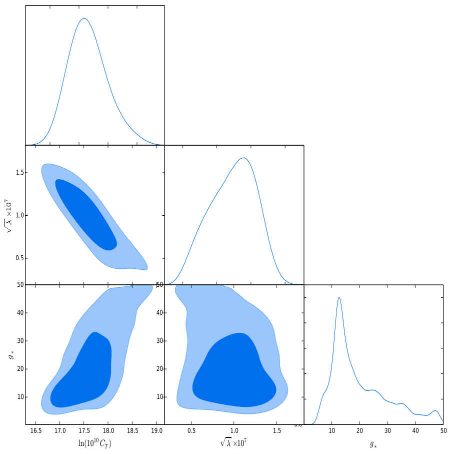
MCMC Methodology

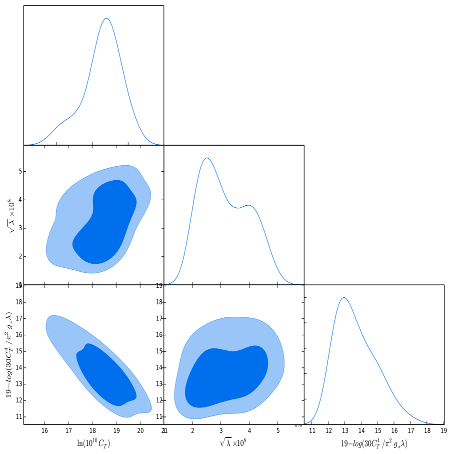
- MCMC is performed using CosmoMC package coupled with CAMB.
- Slow mixing an bad convergence in CosmoMC due to multimodality in the theory.



- 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.

MCMC Simulations





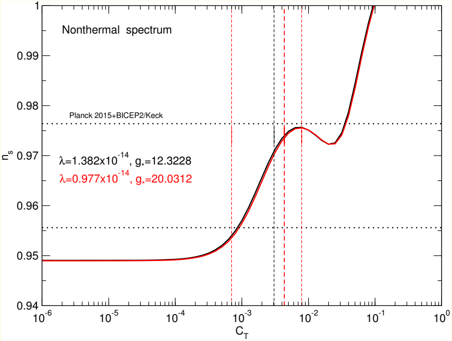
Results

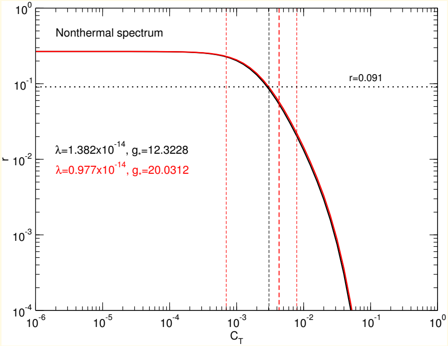
Constraints on cosmological parameters for non-thermal and thermal case compared with $\Lambda CDM + r$ using Planck 2015+BICEP2/Keck Array observations.

Warm Inflation					Cold Inflation		
	$\mathcal{N}_* = 0$		$\mathcal{N}_* \neq 0$			$\Lambda CDM + r$	
parameters	mean value	1σ	mean value	1σ	parameters	mean value	1σ
$\Omega_b h^2$	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
τ	0.077	0.019	0.068	0.021	τ	0.064	0.018
C_T	0.0043	0.0018	0.0104	0.0077	$\ln(A_s \times 10^{10})$	3.06	0.031
λ	9.77×10^{-15}	5.41×10^{-15}	9.74×10^{-16}	6.78×10^{-16}	n_s	0.966	0.0052
g_*	20.03	10.39	139.91	487.98	r	< 0.07	

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

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





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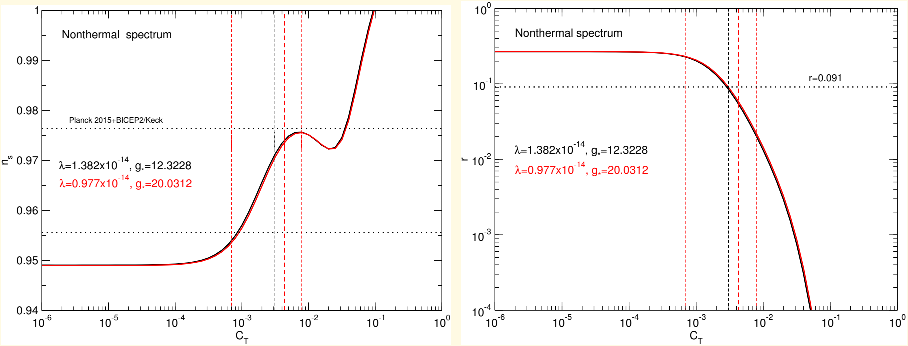
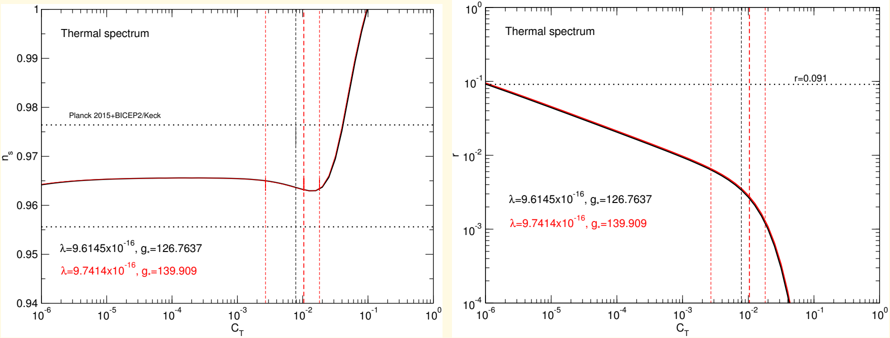


Standard cold quartic inflation, $n_s = 1 - \frac{6}{3+2N}$ and $r = \frac{32}{3+2N}$

For, $N = 60$, $n_s = 0.95122$ and $r = 0.2602$

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($N_* \neq 0$).

Presentation Outline

Swampland Criterion Fiasco!!

- Swampland criterions states:

1. $$\frac{|\Delta\phi|}{M_{pl}} \leqslant \Delta$$

2. $$\left|\frac{V_\phi}{V}\right| \geqslant \frac{c}{M_{pl}}$$

G. Obied et. al. arXiv:1806.08362 [hep-th].

- None of the single field slow roll cold inflation in standard scenario can survive if these conjectures are true!!

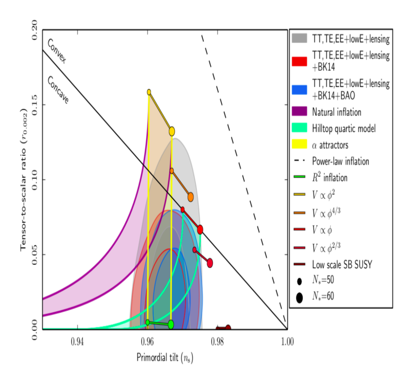
$$\epsilon_V := \frac{M_{pl}^2}{2}\left(\frac{V_\phi}{V}\right)^2 < 1$$

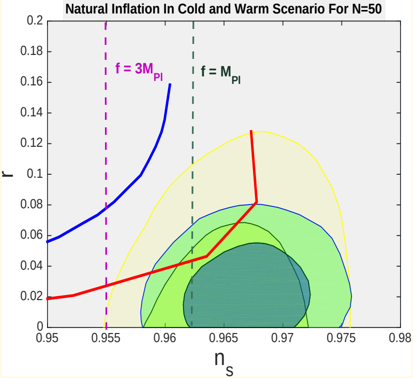
- Warm inflation might survive as the slow roll condition $\Rightarrow$

$$\epsilon_\phi < 1 + Q\,, \qquad \eta_\phi < (1 + Q)$$

Warm Natural Inflation

- Natural inflation is disfavoured by Planck18 + BK14 data with a Bayes factor $lnB = -4.2$.





MRG, Mathews, Nguyen, Suh [In Preparation]

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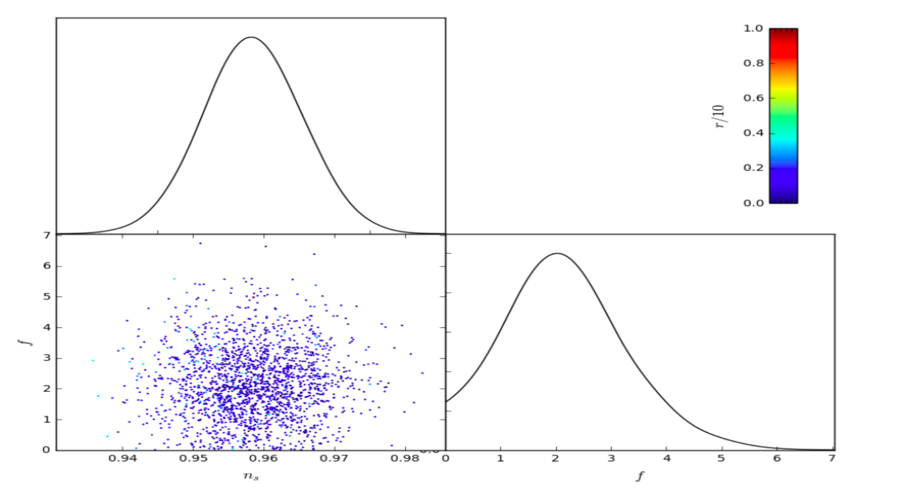

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Conclusions

- No reheating is required in warm inflation => Warm exit to the radiation dominated universe.
- Thermal case $(N_* \neq 0)$: tensor-to-scalar ratio is well within the observational bound.
- Bispectrum features are different in cold and warm inflation.
- Warm Little Inflaton as DM? Work in Progress with A. Naskar
- Future observations will lead us to distinguish these features.

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- Future observations will lead us to distinguish these features.

"To me, the accidental Universe idea is scientifically meaningless because it explains nothing and predicts nothing. " -Steinhardt

Extra

- $$\phi_1 = \frac{M}{\sqrt{2}} e^{i\phi/M}, \qquad \phi_2 = \frac{M}{\sqrt{2}} e^{i\phi/M}$$
- $$-\mathcal{L}_{\phi\psi} = \frac{g}{\sqrt{2}}(\phi_1 + \phi_2)\ \bar{\psi}_{1L}\psi_{1R} - i\frac{g}{\sqrt{2}}(\phi_1 - \phi_2)\ \bar{\psi}_{2L}\psi_{2R}$$
- $$-\mathcal{L}_{\phi\psi} = gM\ cos(\phi/M)\ \bar{\psi}_1\psi_1 + gM\ sin(\phi/M)\ \bar{\psi}_2\psi_2$$
- $$\sum_{\phi}(0) = g^2[-cos(2\phi/M) + cos(2\phi/M)]\ I_T = 0$$