Warm inflation and its observational consequences

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Observatório Nacional

Overview

1. Cosmic inflation in two slides
2. Warm inflation
3. Connection with observations
4. Comparing dissipative coefficients
5. Forecasts for future CMB data
6. Final remarks

Cosmic inflation in two slides

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Horizon problem solved | Flatness problem solved

The main candidate for realizing this is a scalar field dubbed *inflaton*, represented as ϕ, and follows the following equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0, \tag{1}$$

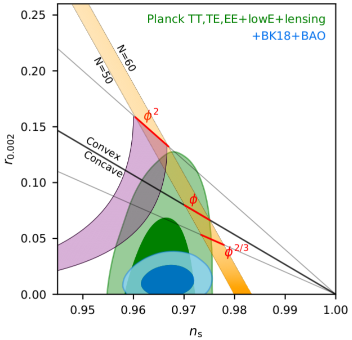
in which $V(\phi)$ is the scalar potential that dictates the dynamics of the field:

- $V(\phi)$ needs to be flat enough, so H varies slowly, and $\ddot{a} > 0$;
- This is the so-called *slow-roll* regime, which ends whenever the potential breaks this flatness condition, thereby ending inflation;
- Observables like n_s and r can be derived from the slow-roll conditions, and compared with data.

Cosmic inflation in two slides

The slow-roll inflation seems to be a viable scenario according to data!

1. $n_s < 1$ is compatible with predictions from different models;
2. Tensor perturbations generated during inflation are very small;
3. However, a large number of models are possible (dozens of $V(\phi)$).



P.A R. Ade et al.; PRL 127 (2021) 15, 151301

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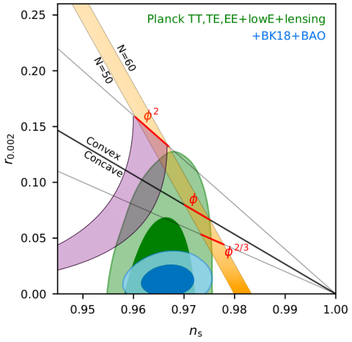

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Future data might be able to solve the mentioned issues (more on that later!)

Warm inflation

The idea consists on considering the importance of couplings of radiation fields to the inflaton through a dissipative term in the field eq. of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon\dot{\phi} + V_{,\phi} = 0, \tag{2}$$

A. Berera; Phys.Rev.Lett. 75 (1995) 3218-3221

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- One can define the dissipation ratio $Q \equiv \frac{\Upsilon}{3H}$, which determines the weak ($Q < 1$) and strong ($Q > 1$) dissipative regimes;
- In both regimes, effective dissipation leads to a radiation-dominated universe by the end of inflation (no need for reheating);
- Υ carries the microphysics of the model, being derived from SUSY, extensions to the Standard Model, and even within the Standard Model.

Warm inflation

Let's see quickly a successful realization of warm inflation. In the **Warm Little Inflaton** scenario, the scalar field is coupled to only two other intermediate fields, where:

$$\mathcal{L}_{\phi\psi} = -gM\cos(\phi/M)\bar{\psi}_1\psi_1 - gM\sin(\phi/M)\bar{\psi}_2\psi_2, \tag{3}$$

corresponds to a direct coupling of the inflaton with light fermions with masses $m_1, m_2 \leq gM$, M being the symmetry breaking VEV:

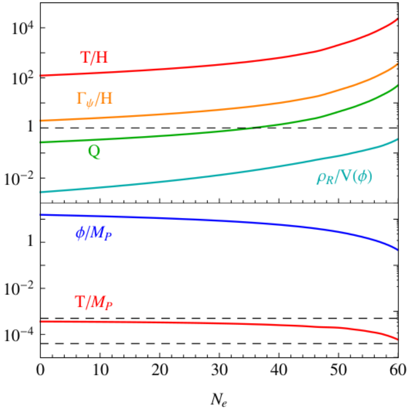
- In this scenario, thermal corrections to the potential are suppressed;
- The dissipation coefficient is approximated as a simple linear function of the temperature $\Upsilon = C_T T$;
- C_T is a constant dependent on the coupling strength of the field, in a way that it is possible to connect the microphysics with observations.

M. Bastero Gil, A. Berera, R. O. Ramos, J. G. Rosa; Phys.Rev.Lett. 117 (2016) 15, 151301

Warm inflation

For a potential $V(\phi) = \lambda\phi^4$

1. T/H is comfortably above unity;
2. Q transits from a weak regime to a strong dissipative regime;
3. The ratio $\rho_R/V(\phi)$ is almost one by the end of inflation.



Connection with observations

The main ingredients for a warm inflation scenario are a potential function $V(\phi)$ and a dissipative coefficient Υ. How do we connect this with observable quantities?

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We do this in the same manner as in the cold inflationary picture, with some changes:

1. The slow-roll parameter ϵ is redefined as:

$$\epsilon = \frac{\epsilon_V}{1+Q}, \quad \epsilon_V = \frac{M_p^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2; \tag{4}$$

2. Due to the interaction terms, the scalar power spectrum changes as well:

$$\Delta^2_{\mathcal{R}}(k_\star) = \mathcal{P}_{\mathcal{R},c}\left(1 + 2n_{BE,\star} + \frac{2\sqrt{3}\pi Q_\star}{\sqrt{3+4\pi Q_\star}}\frac{T_\star}{H_\star}\right)G(Q_\star), \tag{5}$$

where $\mathcal{P}_{\mathcal{R},c} \equiv \left(\frac{H_\star^2}{2\pi\dot{\phi}_\star}\right)^2$ and $n_{BE,\star} = \frac{1}{e^{H_\star/T_\star}-1}$. $G(Q_\star)$ is determined numerically, dependent on both $V(\phi)$ and Υ.

Connection with observations

The computation of these extra terms allows one to estimate the impact on cosmological observables, and comparison with current constraints on both n_s and r as well.

One of the first works in this direction appeared some years ago:

Constraining Warm Inflation with CMB data

Mar Bastero-Gil,[a] **Sukannya Bhattacharya,**[b,c] **Koushik Dutta**[b,c] **Mayukh Raj Gangopadhyay**[b]

JCAP 02 (2018) 054

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Here, they consider a quartic potential $V(\phi) = \lambda\phi^4$ and a linear dependence on the temperature for Υ.

Connection with observations

Specifically, the dissipation coefficient takes the form

$$\Upsilon = C_T T, \quad C_T \simeq \frac{3g^2/h^2}{1 - 0.34 \ln h}, \tag{6}$$

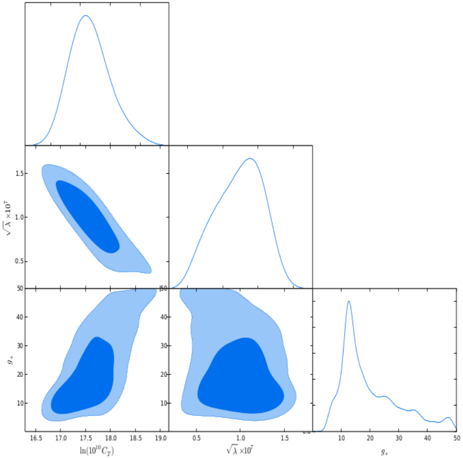
so the constant C_T has a direct connection with the couplings to the inflaton. In their analysis, the additional parameters in the analysis are:

$$(\lambda, C_T, g_\star), \tag{7}$$

which are sampled through an MCMC method, using *Planck* 2015+BICEP/Keck Array data.

Connection with observations

1. CMB data is able to restrict the parameter space of the model, linking properties of the couplings to the inflaton with observations;
2. C_T has a best-fit value of $C_T \sim 0.003$, resulting in a dissipative ratio of $Q_\star \sim 0.031$;
3. As for the inflationary parameters, they have found $n_s = 0.9709$, $r = 0.09$.



Connection with observations

Studies for other forms of Υ were also made at the same time, for instance, for $\Upsilon \propto \frac{T^3}{\phi^2}$:

Revisiting CMB constraints on Warm Inflation

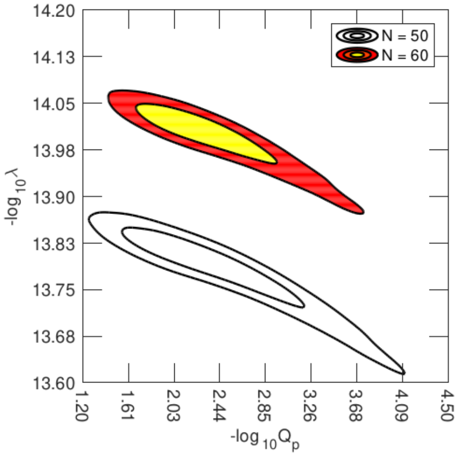
Richa Arya,[a] Arnab Dasgupta,[a] Gaurav Goswami,[b] Jayanti Prasad,[c] Raghavan Rangarajan[a]

JCAP 02 (2018) 043

for the same quartic potential. In their approach, direct constraints on the ratio $Q_\star$ are obtained.

Connection with observations

1. We note a clear correlation between $Q_\star$ and λ from the potential;
2. $Q_\star$ is constrained as $Q_\star \sim 0.004$, also favoring a weak dissipative regime;
3. This is compatible with a value of n_s also compatible with the *Planck* data, being $n_s \sim 0.968$.



Comparing dissipative coefficients

Now, we have seen that consistent constraints can be obtained on these models, specially on the dissipative ratio Q. On the other hand, can we use current data to actually distinguish these models observationally?

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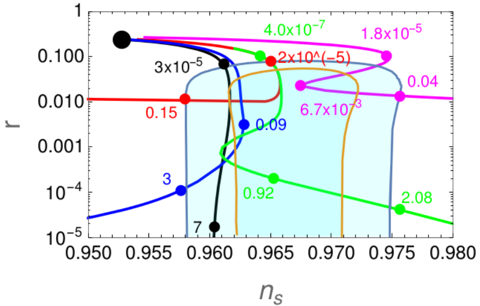
For a given $V(\phi)$, different Υ give very distinct behaviors for n_s and r, so one is able to do that:

M. Motaharfar, V. Kamali, R. O. Ramos; Phys.Rev.D 99 (2019) 6, 063513



Comparing dissipative coefficients

It is then instructive to look at the current restrictions on these models. Considering the following forms of Υ:

$$\boxed{\Upsilon \propto T^3/\phi^2, \quad \Upsilon \propto T, \quad \Upsilon \propto \phi^2/T, \quad \Upsilon \propto H}$$

for a quartic potential $V(\phi) = \lambda\phi^4/4$, we are able to improve the restrictions on the dissipative ratio $Q_\star$ **FBMS, R. de Souza, J. S. Alcaniz; JCAP 10 (2024) 071**:

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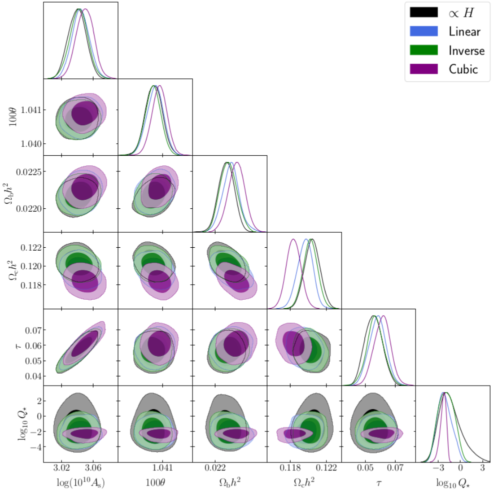
	Cubic coefficient	Linear coefficient	Inverse coefficient	$\propto H$ coefficient
Parameter	mean	mean	mean	mean
	PR4+BK18			
$\Omega_b h^2$	0.02230 ± 0.00012	0.02222 ± 0.00012	0.02218 ± 0.00011	0.02215 ± 0.00011
$\Omega_c h^2$	0.11839 ± 0.00080	0.11964 ± 0.00087	0.12021 ± 0.00077	0.12042 ± 0.00084
100θ	1.04091 ± 0.00024	1.04077 ± 0.00025	1.04071 ± 0.00024	1.04073 ± 0.00026
τ	0.0608 ± 0.0059	0.0580 ± 0.0057	0.0563 ± 0.0056	0.0555 ± 0.0058
$\ln(10^{10} A_s)$	3.049 ± 0.012	3.044 ± 0.011	3.041 ± 0.012	3.040 ± 0.011
$\log_{10} Q_\star$	$-2.32^{+0.50}_{-0.33}$	$-2.11^{+0.80}_{-1.2}$	$-1.9^{+1.1}_{-1.2}$	$-1.4^{+1.1}_{-1.7}$
H_0^* [Km/s/Mpc]	67.87 ± 0.37	$67.31^{+0.37}_{-0.41}$	67.06 ± 0.35	66.98 ± 0.37
χ^2_{min}	31124.3	31124.7	31126.2	31127.3
$\ln B$	-4.133	-0.779	-1.656	-2.187

Comparing dissipative coefficients

1. The cubic model is better restricted on $Q_\star$;
2. A weak dissipative regime is preferred overall, even for models where $Q_\star > 1$ is allowed;
3. The linear $\Upsilon \propto T$ model is preferred statistically.



Forecasts for future CMB data

It is possible to compare different models with current data, but what is expected from the next generation of CMB experiments?

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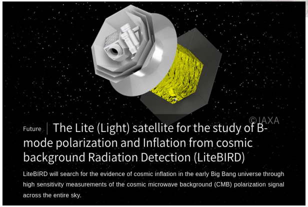
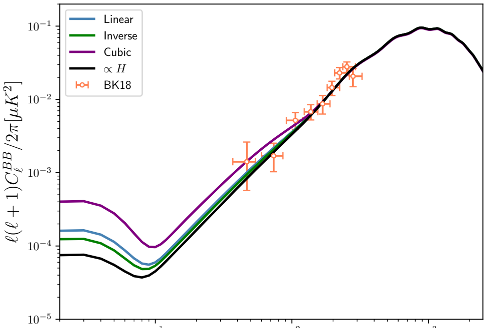


Forecasts for future CMB data

A discussion of this was done recently

FBMS, G. Rodrigues, R. de Souza, J. S. Alcaniz, JCAP 03 (2025) 062

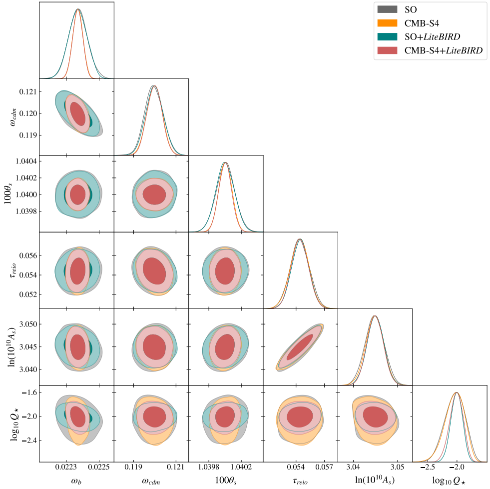
1. We parametrize the primordial power spectra for each model;
2. The forecast implementation on MontePython is used, where we also include the effect of delensing of the B-mode CMB spectrum;



Forecasts for future CMB data

Cubic model ($\Upsilon \propto T^3/\phi^2$)

1. Both CMB-S4 and Simons Observatory improve the uncertainties by at least a factor of two;
2. The combination with *LiteBIRD* decrease the errors on $\log_{10} Q_\star$ by a factor of around **four**;



Forecasts for future CMB data

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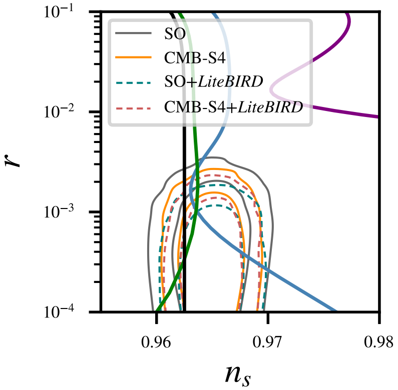
1. Both CMB-S4 and Simons Observatory improve the uncertainties by at least a factor of two;
2. The combination with *LiteBIRD* decrease the errors on $\log_{10} Q_\star$ by a factor of around **four**;
3. Comparison with a ΛCDM+r forecast shows that even at the level of the $n_s - r$ plane, models can be excluded.



Final remarks

- Warm inflation is now a serious candidate for a reasonable description of the very early universe, with a solid theoretical foundation;
- The connection with cosmological observables makes this scenario testable with current and future data;
- Even with the added complexity, we can expect to distinguish the different dissipative regimes with the new information from the CMB.

Thank You!