

CMB constraints from WMAP and Planck on warm inflation models¹

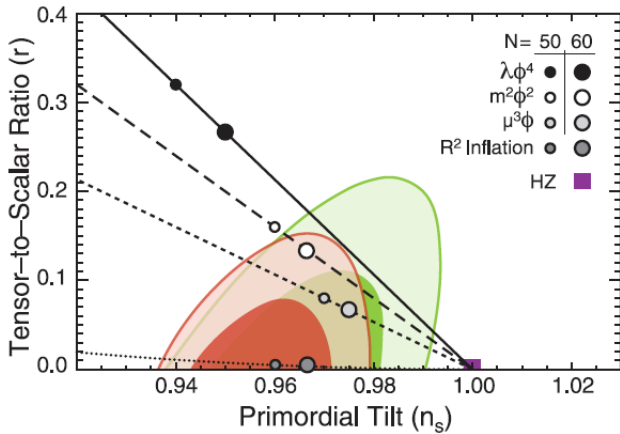
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¹ROR and L. A. da Silva, JCAP 03 (2013) 032;
S. Bartrum, M. Bastero-Gil, A. Berera, R. Cerezo, ROR and J. G. Rosa,
arXiv:1307.5868



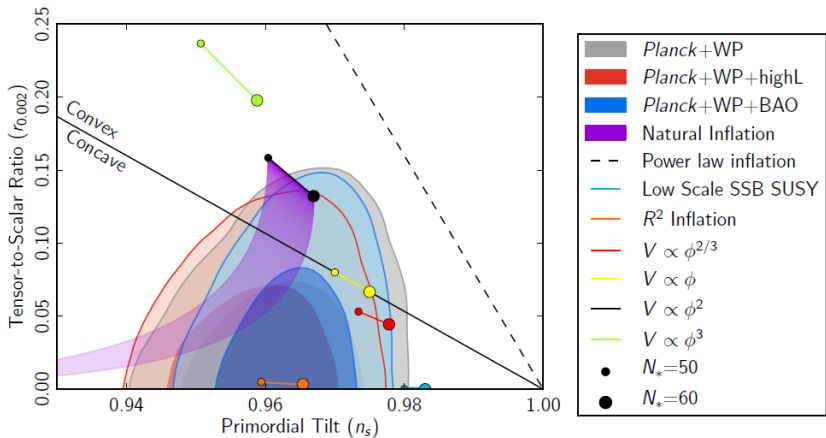


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Warm Inflation: how to built it²

Fully motivated (computed) from (renormalizable) QFT:

ϕ \longrightarrow χ, ψ_χ \longrightarrow ψ_σ, σ
inflaton heavy field light fermions or scalars

for example : $\mathcal{L}_I = -\frac{\lambda}{4}\phi^4 - \frac{1}{2}g_\chi^2\phi^2\chi^2 - g_\psi\phi\bar{\psi}_\chi\psi_\chi - h_\sigma M\chi\sigma^2 - h_\psi\chi\bar{\psi}_\sigma\psi_\sigma$

very same interactions found/needed in (p)reheating in cold inflation !

²For a review: Berera, Moss and ROR, Rep. Prog. Phys. **72**, 026901 (2009)

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- decouple the radiation from the inflaton
($m_\chi, m_{\psi_\chi} \gg T, m_{\sigma, \psi_\sigma} \ll T$)
- couplings between fields of order 0.1
- SUSY to reduce vacuum corrections, e.g., $W = g\Phi X^2 + hXY^2$
where Φ, X, Y are superfields.

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Let $\phi \equiv \phi(\mathbf{x}, t)$ and average out (integrate over) the other fields. This gives a stochastic (Langevin-like) system³,

$$\ddot{\phi}(\mathbf{x}, t) + 3H\dot{\phi}(\mathbf{x}, t) + \int d^4x' \Sigma_R(\mathbf{x}, \mathbf{x}') \phi(\mathbf{x}') + V_{,\phi} - \frac{1}{a^2} \nabla^2 \phi(\mathbf{x}, t) = \xi(\mathbf{x}, t).$$

The self-energy contribution is a dissipative term:

In the adiabatic approximation⁴, $\dot{\phi}/\phi, H, \dot{T}/T < \Gamma_x \approx h^2 m_x / (8\pi)$,

$$\int d^4x' \Sigma_R(\mathbf{x}, \mathbf{x}') \phi(\mathbf{x}') \approx \Upsilon \dot{\phi}(\mathbf{x}, t)$$

$$\ddot{\phi}(\mathbf{x}, t) + (3H + \Upsilon)\dot{\phi}(\mathbf{x}, t) + V_{,\phi} - \frac{1}{a^2} \nabla^2 \phi(\mathbf{x}, t) = \xi_T(\mathbf{x}, t).$$

$$\langle \xi_T(\mathbf{x}, t) \xi_T(\mathbf{x}', t') \rangle = a^{-3} \Upsilon T \delta(\mathbf{x} - \mathbf{x}') \delta(t - t')$$

³M. Gleiser and ROR, PRD50, 2441 (1994)

⁴A. Berera, I. G. Moss and ROR, PRD76, 083520 (2007)

Dissipation coefficient Υ :

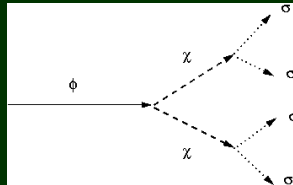
$\phi \rightarrow \sigma$, $\psi_\sigma \Rightarrow$ mediated by the excitation of the intermediate (catalyst) fields, χ , ψ_χ

Typically⁵ ($c + 2a - 2b = 1$):

$$\Upsilon = C_\phi \frac{T^c \phi^{2a}}{m_\chi^{2b}}$$

At low-T ($m_\chi, m_{\psi_\chi} \gg T$) (T-corrections to $V(\phi)$ are suppressed)
 \Rightarrow leading friction coefficient is:

$$\Upsilon \sim g^2 h^4 (T^3 / m_\chi^2)$$



By also integrating the quantum modes of the inflaton field and restricting to the long wavelength (classical) modes ⁶

$$\left[\frac{\partial^2}{\partial t^2} + (3H + \Upsilon) \frac{\partial}{\partial t} - e^{-2Ht} \nabla^2 \right] \Phi_c(\vec{x}, t) + \frac{\partial V(\Phi_c)}{\partial \Phi_c} = \xi_q(\vec{x}, t) + \xi_T(\vec{x}, t)$$

We have a spatial gradient term, a scale factor a , and stochastic thermal ξ_T and quantum ξ_q sources. The sources have a gaussian distributions with local correlation functions

⇒ Eq. for Φ_c is similar to a Langevin equation with quantum and thermal noise terms (stochastic process w/ gaussian noises).

Equation for the fluctuations:

$$\delta\ddot{\varphi}(\vec{k}, t) + (3H + \Upsilon)\delta\dot{\varphi}(\vec{k}, t) + V_{,\phi\phi}(\phi)\delta\varphi(\vec{k}, t) + a^{-2}k^2\delta\varphi(\vec{k}, t) = \xi_T(\vec{k}, t) + \xi_q(\vec{k}, t)$$

General solution expressed in terms of a Green function (analytical)

⁶ROR and L. A. da Silva, JCAP 03 (2013) 032

Thermal ξ_T and quantal ξ_q noises are uncorrelated (decoupled), so they give separated contributions to the power spectrum:

$$P_{\delta\varphi}(z) = \frac{k^3}{2\pi^2} \int \frac{d^3k'}{(2\pi)^3} \langle \delta\varphi(\mathbf{k}, z) \delta\varphi(\mathbf{k}', z) \rangle = P_{\delta\varphi}^{(\text{th})}(z) + P_{\delta\varphi}^{(\text{qu})}(z)$$

scalar curvature perturbation spectrum (at horizon crossing):

$$\Delta_{\mathcal{R}}^2 \simeq \left(\frac{H_*}{\dot{\phi}_*} \right)^2 \left(\frac{H_*}{2\pi} \right)^2 \left[1 + 2n_* + \frac{2\pi T_*}{H_*} \frac{\sqrt{3} Q_*}{\sqrt{3 + 4\pi Q_*}} \right], \quad Q = \frac{\Upsilon}{3H}$$

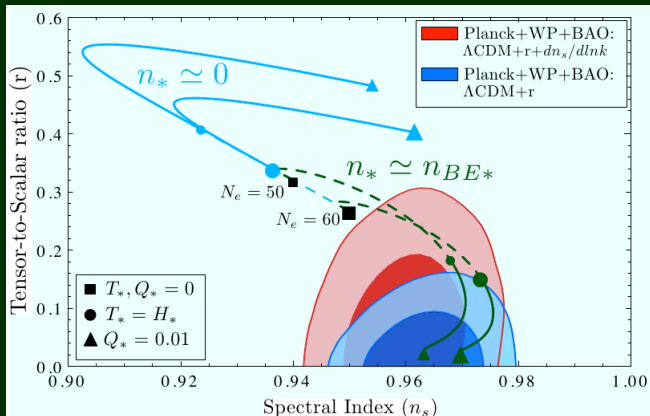
tensor-to-scalar ratio:

$$r \simeq \frac{8|n_t|}{1 + 2n_* + \kappa_*}, \quad \kappa_* = \frac{2\pi T_*}{H_*} \frac{\sqrt{3} Q_*}{\sqrt{3 + 4\pi Q_*}}$$

spectral index:

$$n_s - 1 \simeq 2\eta_* - 6\epsilon_* + \frac{2\kappa_*}{1 + \kappa_*} (7\epsilon_* - 4\eta_* + 5\sigma_*), \quad \sigma = M_{\text{pl}}^2 V' / (\phi V) < 1 + Q$$

Trajectories in the (n_s, r) plane for $\lambda\phi^4$ potential



black lines: nearly-thermal inflaton, $T_* \gtrsim H_*$

light blue lines: vanishing inflaton occupation numbers ($T_\phi = 0$)

dashed lines: $T_* \lesssim H_*$

$g_* = 228.75$ (MSSM)

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- Warm inflation \rightarrow dissipation mechanisms \rightarrow radiation production during inflation \rightarrow backreaction effect on the power spectrum
- Thermal radiation bath reconciles $\lambda\phi^4$ model with observations without the need of extra parameters (than those already required for reheating in conventional inflation) and completely in the context of renormalizable interactions
- Cosmological observables n_s , r , including running, f_{NL} , etc all compatible with Planck results (S. Bartrum, M. Bastero-Gil, A. Berera, R. Cerezo, ROR and J. G. Rosa, arXiv:1307.5868)