

# CMB constraints from WMAP and Planck on warm inflation models<sup>1</sup>

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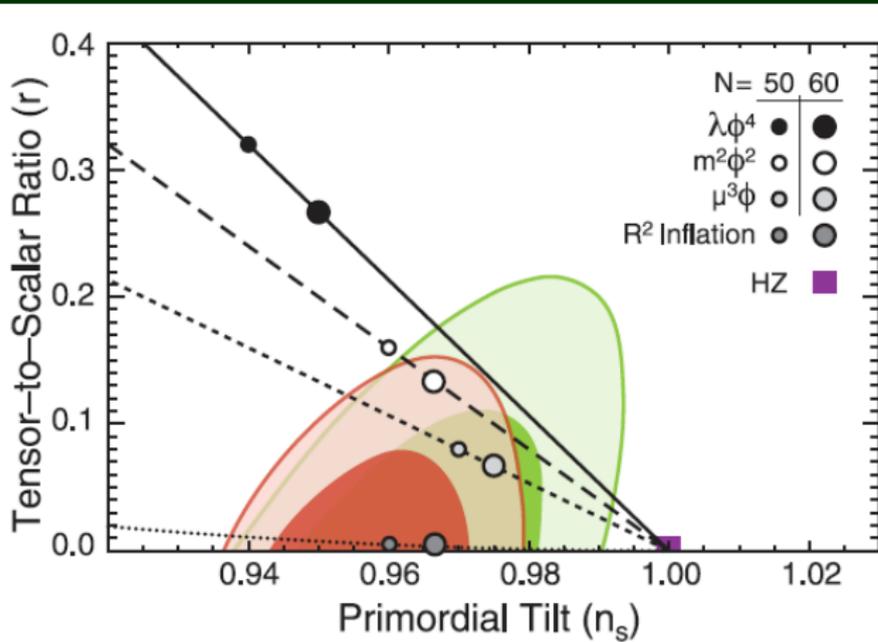
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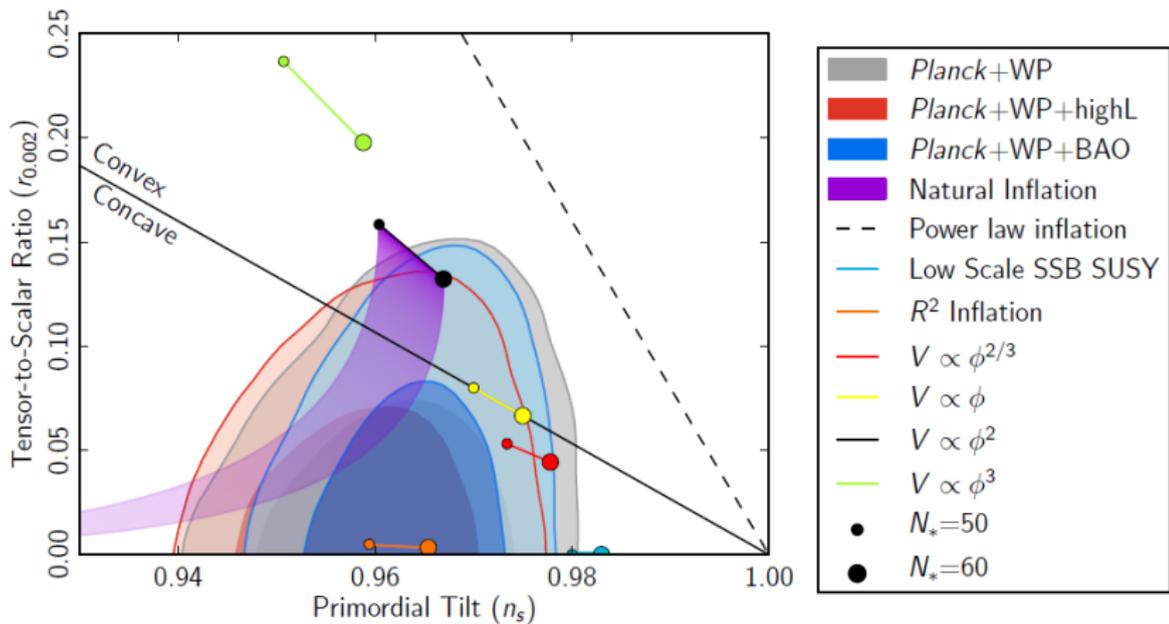
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<sup>1</sup>ROR and L. A. da Silva, JCAP 03 (2013) 032;  
S. Bartrum, M. Bastero-Gil, A. Berera, R. Cerezo, ROR and J. G. Rosa,  
arXiv:1307.5868





**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 it<sup>2</sup>

Fully motivated (computed) from (renormalizable) QFT:

$\phi$   $\longrightarrow$   $\chi, \psi_\chi$   $\longrightarrow$   $\psi_\sigma, \sigma$   
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 !

<sup>2</sup>For 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  $\Phi, X, Y$  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) system<sup>3</sup>,

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

The self-energy contribution is a dissipative term:

In the adiabatic approximation<sup>4</sup>,  $\dot{\phi}/\phi, H, \dot{T}/T < \Gamma_x \approx h^2 m_x / (8\pi)$ ,

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

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

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

<sup>3</sup>M. Gleiser and ROR, PRD50, 2441 (1994)

<sup>4</sup>A. Berera, I. G. Moss and ROR, PRD76, 083520 (2007)

Dissipation coefficient  $\Upsilon$ :

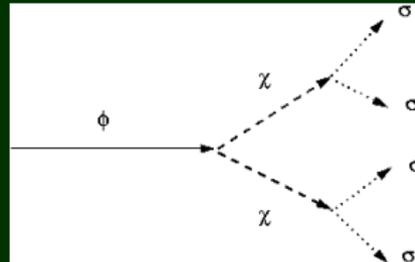
$\phi \rightarrow \sigma$ ,  $\psi_\sigma \Rightarrow$  mediated by the excitation of the intermediate (catalyst) fields,  $\chi$ ,  $\psi_\chi$

Typically<sup>5</sup> ( $c + 2a - 2b = 1$ ):

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

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 <sup>6</sup>

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

We have a spatial gradient term, a scale factor  $a$ , and stochastic thermal  $\xi_T$  and quantum  $\xi_q$  sources. The sources have a gaussian distributions with local correlation functions

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

Equation for the fluctuations:

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

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

<sup>6</sup>ROR and L. A. da Silva, JCAP 03 (2013) 032

Thermal  $\xi_T$  and quantal  $\xi_q$  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):

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

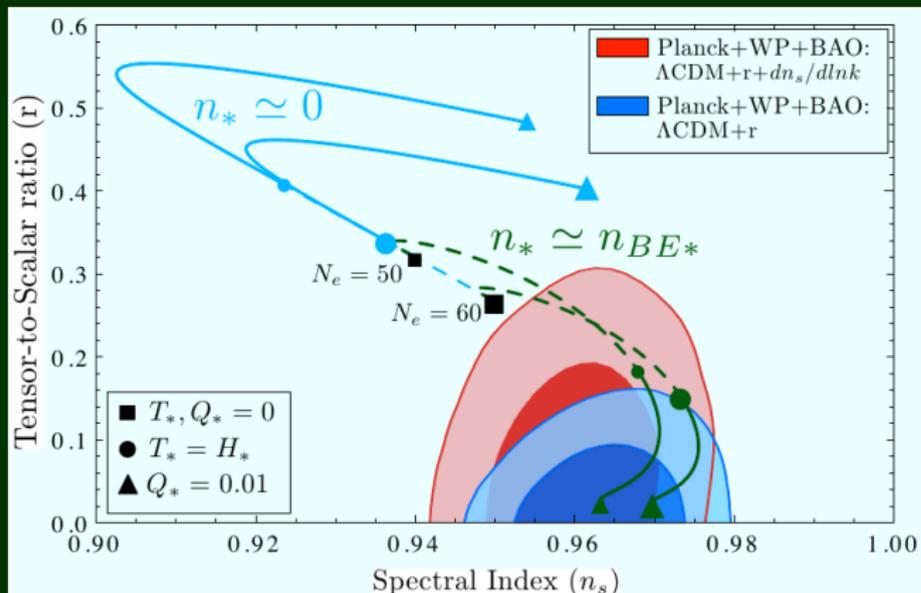
tensor-to-scalar ratio:

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

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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- 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)