Consistency of Warm Inflation Models and Constraints from Planck[1]

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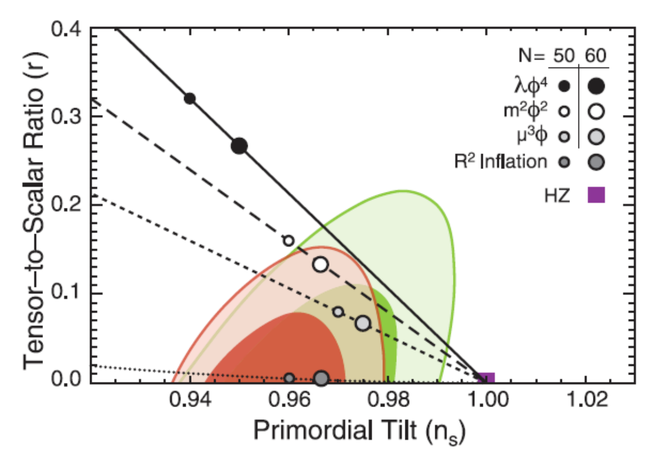
[1] ROR and L. A. da Silva, JCAP 03 (2013) 032;
S. Bartrum, M. Bastero-Gil, A. Berera, R. Cerezo, ROR and J. G. Rosa, arXiv:1307.5868

WMAP 9yrs



0.4
0.3
0.2
0.1
0.0
Tensor–to–Scalar Ratio (r)
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
R^2 Inflation
HZ

Planck

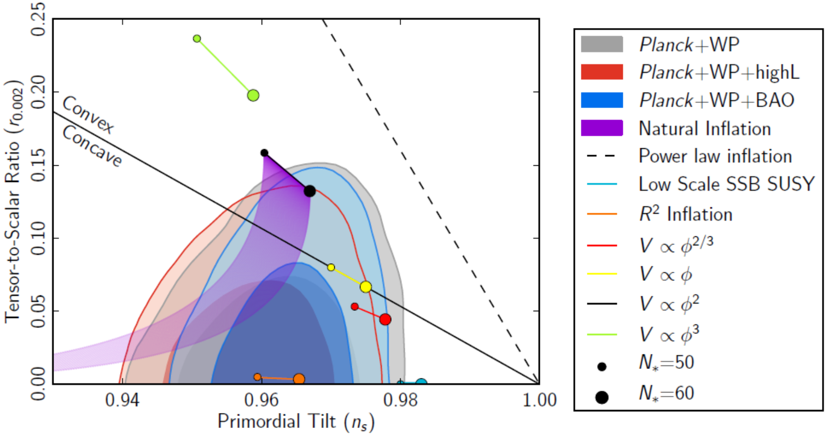


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Warm Inflation: how to built it[2]

Fully motivated (computed) from (renormalizable) QFT:

$$\begin{array}{ccccc} \phi & \longrightarrow & \chi, \psi_\chi & \longrightarrow & \psi_\sigma, \sigma \\ \text{inflaton} & & \text{heavy field} & & \text{light fermions or scalars} \end{array}$$

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 !

[2] 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 Φ, X, Y are superfields.

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Let $\phi \equiv \phi(x,t)$ and average out (integrate over) the other fields. This gives a stochastic (Langevin-like) system[3],

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

The self-energy contribution is a dissipative term:

In the adiabatic approximation [4], $\dot{\phi}/\phi, H, \dot{T}/T < \Gamma_\chi \approx h^2 m_\chi/(8\pi)$,

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

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

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

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

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

Dissipation coefficient Υ:

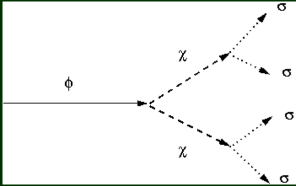
$\phi \to \sigma,\ \psi_\sigma \Rightarrow$ mediated by the excitation of the intermediate (catalyst) fields, $\chi,\ \psi_\chi$

Typically[5] ($c + 2a - 2b = 1$):

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

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

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



[5] M. Basteiro-Gil, A. Berera, ROR, JCAP 09 (2011) 033

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

$\Rightarrow$ 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:

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

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

[6] ROR 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:

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

scalar curvature perturbation spectrum (at horizon crossing):

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

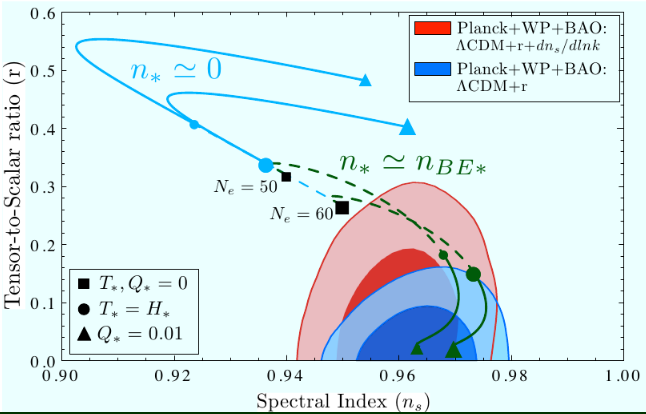
tensor-to-scalar ratio:

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

spectral index:

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

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)