First CMB constraints on the inflationary reheating temperature

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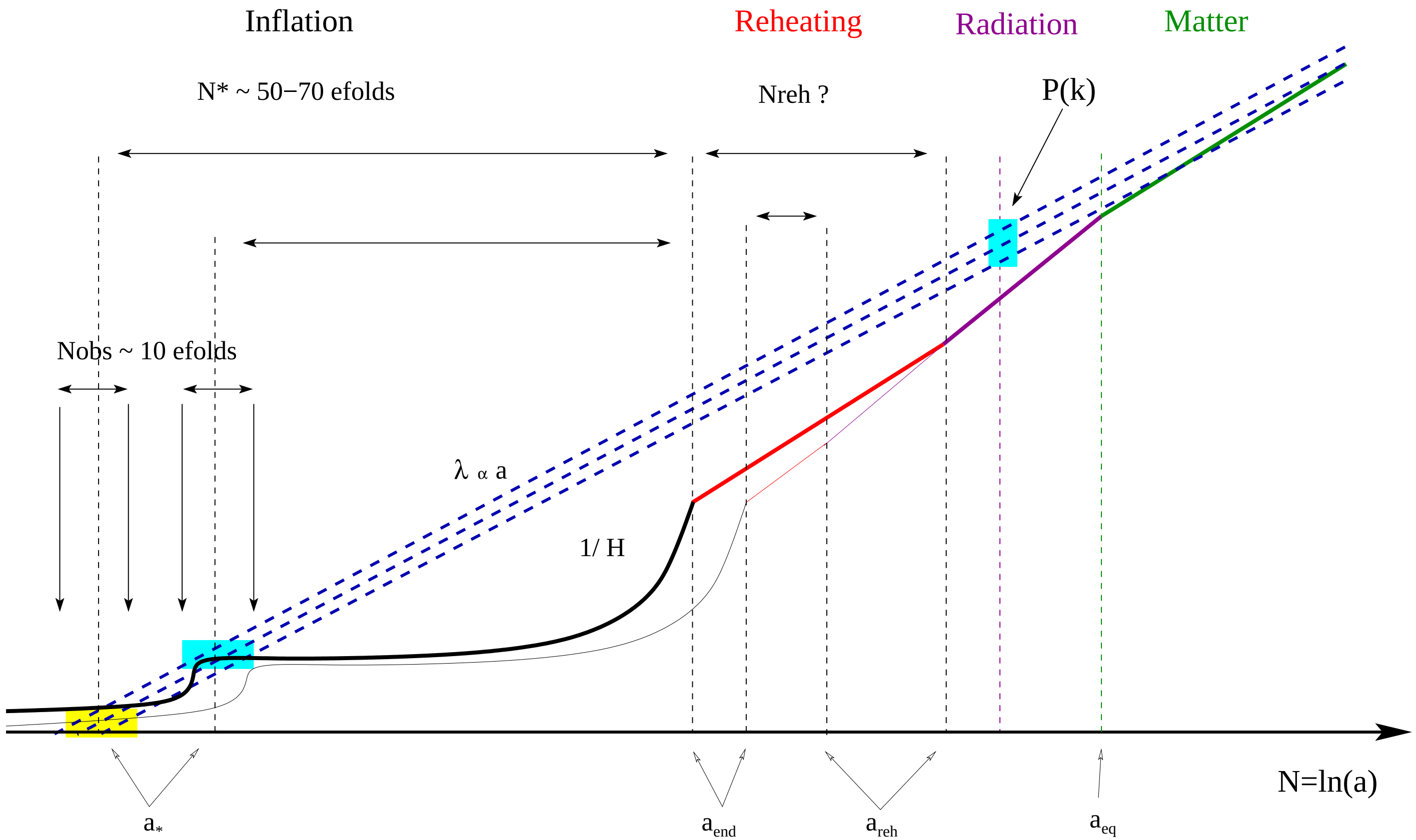
Tokyo, 27/09/2010

Outline

J. Martin and CR: `arXiv:1004.5525`
J. Martin, CR and R. Trotta: `arXiv:1009.4157`

Cosmological perturbations of inflationary origin



- CMB and LSS sourced by ζ (curvature) and h (tensor)

$$\mathcal{P}_\zeta(k) = \frac{k^3}{2\pi^2}\left|\zeta_{\boldsymbol{k}}\right|^2, \qquad \mathcal{P}_h = \frac{2k^3}{\pi^2}\left|h_{\boldsymbol{k}}\right|^2$$

Example: single field inflation

- Makes predictions for the primordial power spectra
  - Knowing $V(\phi)$ + FLRW gives $\phi(N)$ (background)
  - Knowing $\phi(N)$ gives the evolution of $\mu_{\boldsymbol{k}} \equiv a\sqrt{2}\dot{\phi}\zeta_{\boldsymbol{k}}$

$$\dot{\phi} \equiv \frac{\mathrm{d}\phi}{\mathrm{d}N} \quad \Rightarrow \ddot{\mu}_{\boldsymbol{k}} + \left(1 - \frac{1}{2}\dot{\phi}^2\right)\dot{\mu}_{\boldsymbol{k}} + \frac{1}{H^2}\left[\left(\frac{k}{a}\right)^2 - \frac{(a\dot{\phi})''}{a^3\dot{\phi}}\right]\mu_{\boldsymbol{k}} = 0$$

  - $\zeta_{\boldsymbol{k}}$ is conserved after Hubble exit $\Rightarrow \mathcal{P}_\zeta$
- What is the actual value of k/a?
  - The one we are interested in today in Mpc^{-1}

$$\frac{k}{a} = \frac{k}{a_0}(1 + z_{\mathrm{end}})e^{N_{\mathrm{end}} - N}$$

  - Depends on a background quantity: $z_{\mathrm{end}} =$?!

Hidding z_{end} behind a pivot

- Pick up a particular scale $k_*/a_0 = 0.05\,\text{Mpc}^{-1}$

$$\frac{k}{k_*} = \frac{k/a_0}{0.05\,\text{Mpc}^{-1}}$$

- Expand the power spectra around the pivot: ex slow-roll

$$\mathcal{P}_\zeta(k) = \frac{H_*^2}{8\pi^2 M_{\text{Pl}}^2 \epsilon_{1*}}\left[1 - 2\left(C+1\right)\epsilon_{1*} - C\epsilon_{2*} - \left(2\epsilon_{1*} + \epsilon_{2*}\right)\ln\frac{k}{k_*}\right]$$

- All "*" quantities are evaluated at N_* such that: $k_* = a(N_*)H(N_*)$

$$\frac{k_*}{a_0} = \frac{e^{N_* - N_{\text{end}}} H(N*)}{1 + z_{\text{end}}}$$

  - Solving for N_* requires z_{end}

- Inflationary predictions $\Leftarrow z_{\text{end}} \Leftarrow$ reheating model

The reheating parameter R_{rad}

- For instantaneous transitions: $\mathrm{inf} \to \mathrm{reh} \to \mathrm{rad} \to \mathrm{mat}$

$$1 + z_{\mathrm{end}} = (1 + z_{\mathrm{eq}}) \left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{eq}}}\right)^{1/4} \frac{a_{\mathrm{reh}}}{a_{\mathrm{end}}} = \left(\frac{\rho_{\mathrm{end}}}{\rho_{\mathrm{r}_0}}\right)^{1/4} \frac{1}{R_{\mathrm{rad}}}$$

$$R_{\mathrm{rad}} \equiv \frac{a_{\mathrm{end}}}{a_{\mathrm{reh}}} \left(\frac{\rho_{\mathrm{end}}}{\rho_{\mathrm{reh}}}\right)^{1/4}$$

- Quantifies deviations from a radiation-like reheating era
  - In terms of reheating duration: $\Delta N \equiv N_{\mathrm{reh}} - N_{\mathrm{end}}$

$$\overline{w}_{\mathrm{reh}} \equiv \frac{1}{\Delta N} \int_{N_{\mathrm{end}}}^{N_{\mathrm{reh}}} \frac{P(n)}{\rho(n)} \mathrm{d}n \quad \Rightarrow \quad \ln R_{\mathrm{rad}} = \frac{\Delta N}{4} \left(-1 + 3\overline{w}_{\mathrm{reh}}\right)$$

  - In terms of energy densities

$$\ln R_{\mathrm{rad}} = \frac{1 - 3\overline{w}_{\mathrm{reh}}}{12 + 12\overline{w}_{\mathrm{reh}}} \ln \left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right)$$

Reheating consistent predictions for massive inflation

- Slow-roll trajectory for $V(\phi) = m^2\phi^2$

$$\phi^2(N) \simeq \phi^2_{\mathrm{end}} - 4(N_{\mathrm{end}} - N), \quad \phi^2_{\mathrm{end}} = 2, \quad \epsilon_1 = \frac{2}{\phi^2}, \quad \epsilon_2 = \frac{4}{\phi^2}$$

- Solving the pivot crossing for $\Delta N_* = N_{\mathrm{end}} - N_*$
  - Friedmann–Lemaître: $\rho_{\mathrm{end}}(\Delta N_*) = \dfrac{3}{2}\dfrac{V_{\mathrm{end}}}{V_*} \times 3H^2_*(3 - \epsilon_{1*})$
  - For a given R_{rad}, ΔN_* solution of the transcendental equation

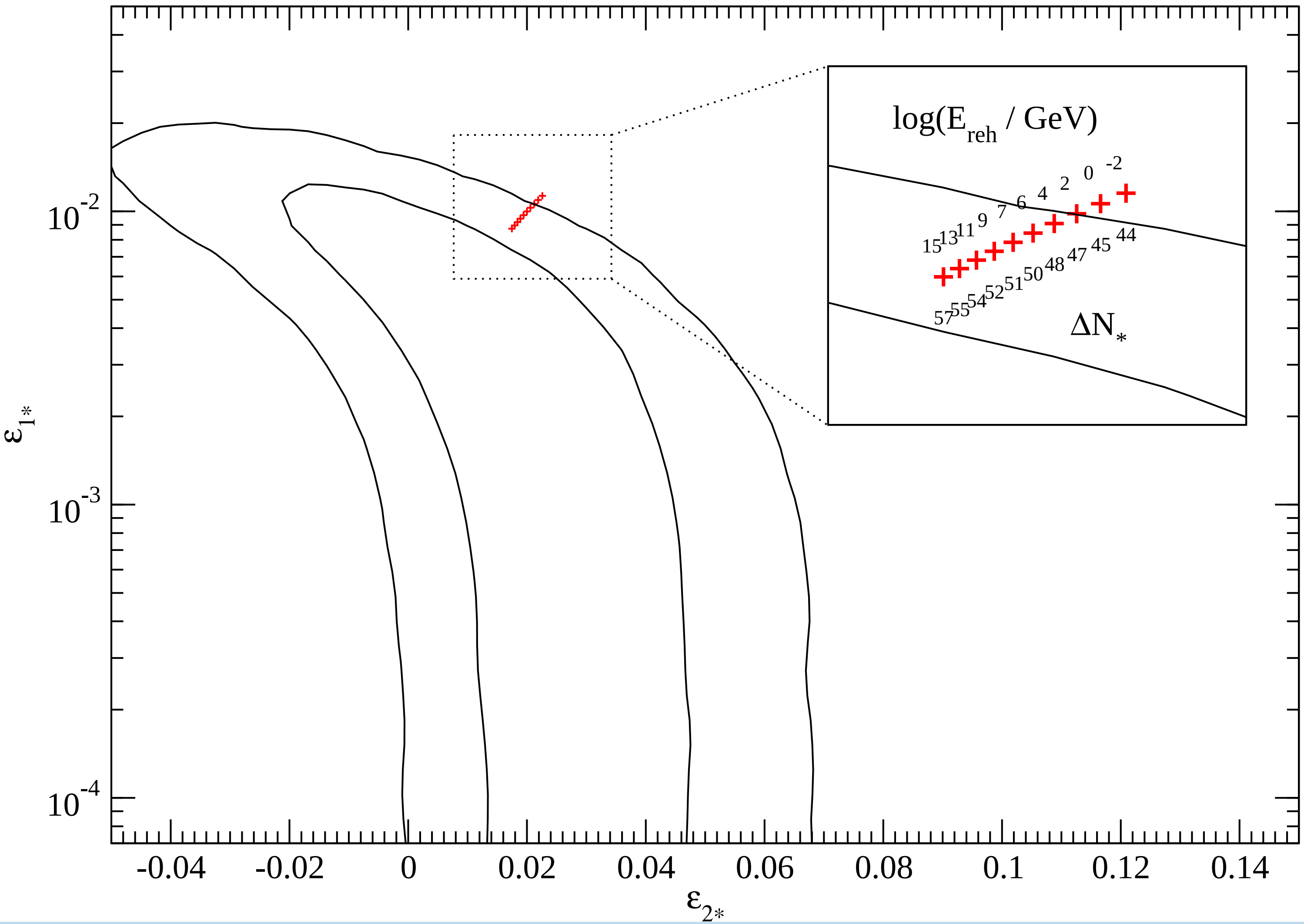
$$\Delta N_* - \frac{1}{4}\ln(8\pi^2 P_*) + \frac{1}{4}\ln\left(\frac{3}{\epsilon_{1*}}\frac{V_{\mathrm{end}}}{V_*}\frac{3-\epsilon_{1*}}{3-\epsilon_{1\mathrm{end}}}\right) = \ln R_{\mathrm{rad}} - \ln\left(\frac{k_*/a_0}{\rho_{\mathrm{r}0}^{1/4}}\right)$$

  - Particular case $\overline{w}_{\mathrm{reh}} = 0$ (parametric oscillations)

$$\ln R_{\mathrm{rad}} = \frac{1}{12}\ln\left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right)$$

CMB and slow-roll parameters

- Massive inflation with $\overline{w}_{\rm reh} = 0$



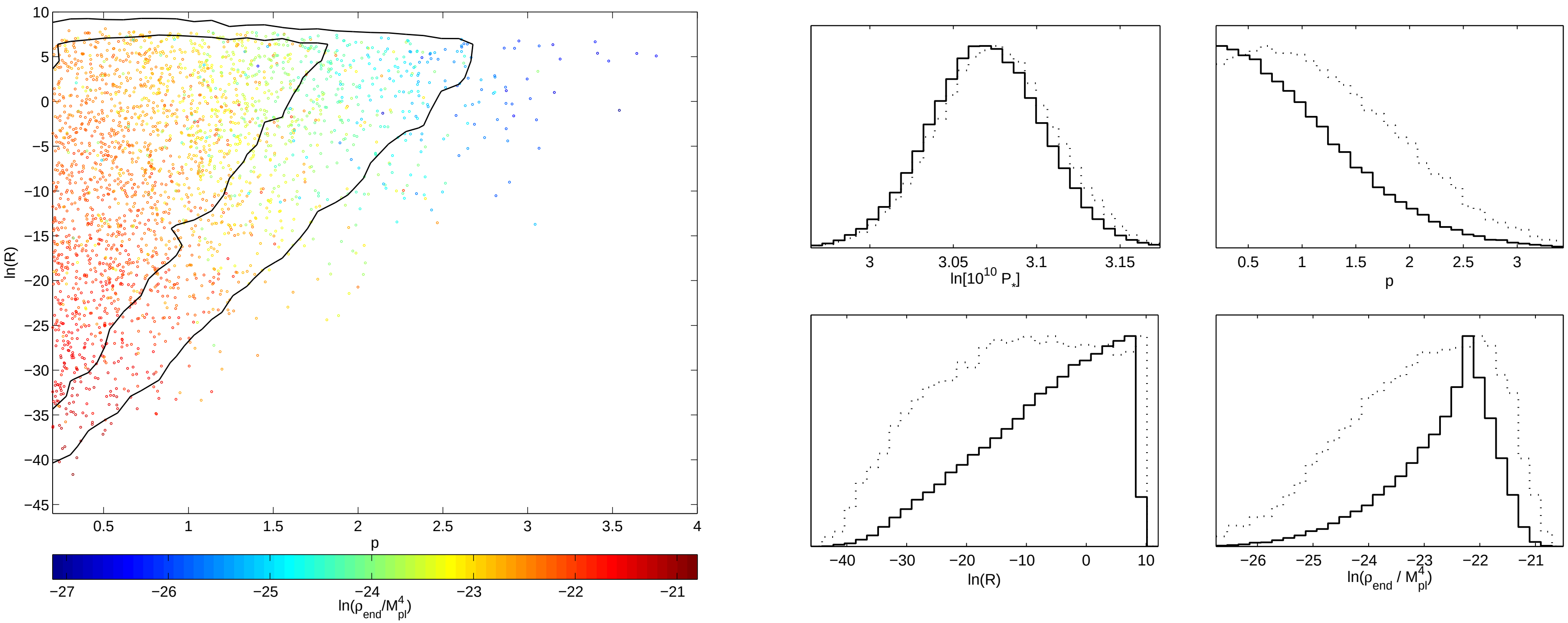
Inferring reheating from CMB data

- General reheating (no assumptions on $\overline{w}_{\mathrm{reh}}$)
  - Occurs after inflation and before BBN: $\rho_{\mathrm{nuc}} \leq \rho_{\mathrm{reh}} \leq \rho_{\mathrm{end}}$
  - GR energy conditions: $-1/3 < \overline{w}_{\mathrm{reh}} \leq 1$.
- $\forall$ inflationary model $V(\phi)$
  - Numerical integration background + linear perturbations
  - Computes the power spectra (`FieldInf`)
  - Evolves the cosmological perturbations (`CAMB`)
  - MCMC data analysis (`CosmoMC`) + evidence (`MultiNest`)
- Inflationary cosmological parameters
  - Usual cosmo params + potential parameters -1 (normalisation)
  - Amplitude of the scalar perturbations: P_*
  - Rescaled reheating parameter $R \equiv R_{\mathrm{rad}} \rho_{\mathrm{end}}^{1/4}$

WMAP7 constraints on large field reheating

- Large field models $V(\phi) \propto \phi^p$ with priors

$$0.2 < p < 5, \quad \rho_{\rm end} < 1, \quad -46 < \ln R < 15 + \frac{1}{3} \ln \rho_{\rm end}$$

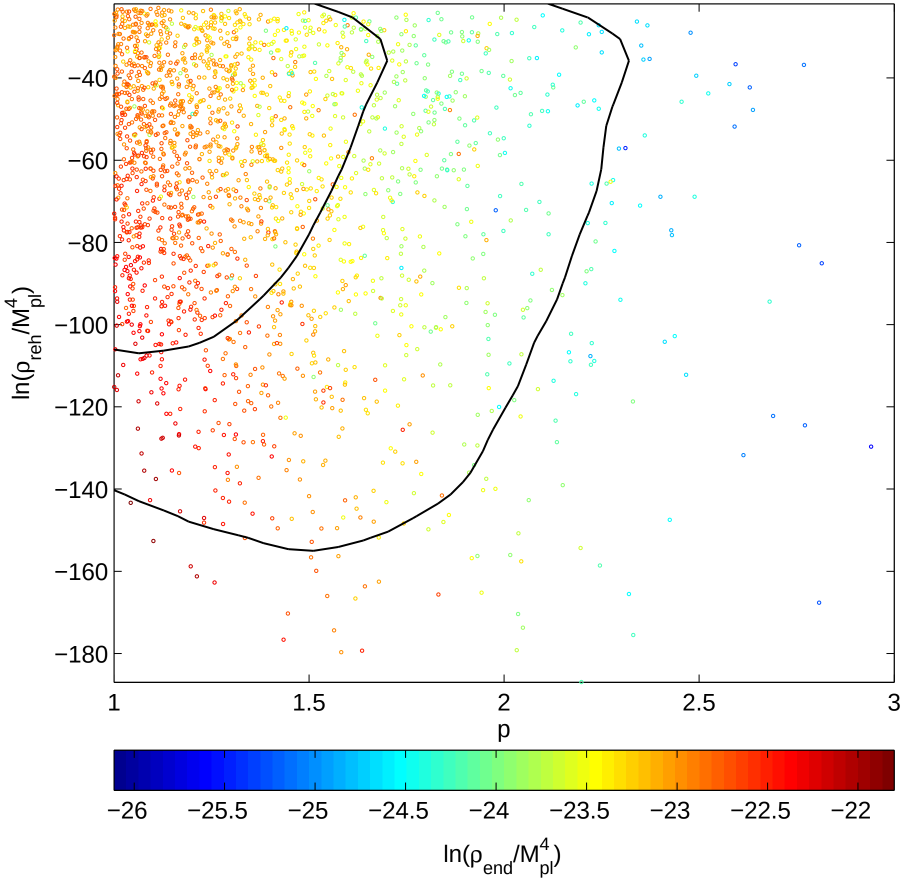


- Posteriors at 95% of confidence level

$$\ln R > -28.9, \quad p < 2.2, \quad 4.4 \times 10^{15} \mathrm{GeV} < \rho_{\rm end}^{1/4} < 1.2 \times 10^{16} \mathrm{GeV}$$

The reheating temperature

- CMB is sensitive to $R_{\rm rad}$ (or R) only
  - Inferring $\rho_{\rm reh}$ requires extra-assumptions
  - Parametric oscillations in $V(\phi) \propto \phi^p \Rightarrow \overline{w}_{\rm reh} = \dfrac{p-2}{p+2}$



- New posteriors: at 95% CL

$$\rho_{\rm reh}^{1/4} > 17.3\,\mathrm{TeV}$$

Conclusion

- New approach of CMB data analysis to test inflationary models
  - Goes behond slow-roll or power law functional forms for $P(k)$
  - Directly infers the inflationary "physical parameters"
- Reheating model with R_{rad} (role similar to τ)
  - Does not have small effects (ΔN_*)
  - No longer a nuisance: constrained by WMAP7, also for SF

$$\ln R > -23.1 \quad \Rightarrow \quad \begin{cases} \rho_{\mathrm{reh}}^{1/4} > 390\,\mathrm{GeV} & (\overline{w}_{\mathrm{reh}} = -0.2) \\ \rho_{\mathrm{reh}}^{1/4} > 890\,\mathrm{TeV} & (\overline{w}_{\mathrm{reh}} = -0.3) \end{cases}$$

- Application to Bayesian evidence
  - Comparison SF/LF for WMAP7 $3:1$

Bayesian evidence for LF and SF