Planck inflation constraints: search for features in the power spectrum

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on behalf of the Planck Collaboration

A smooth primordial power spectrum?

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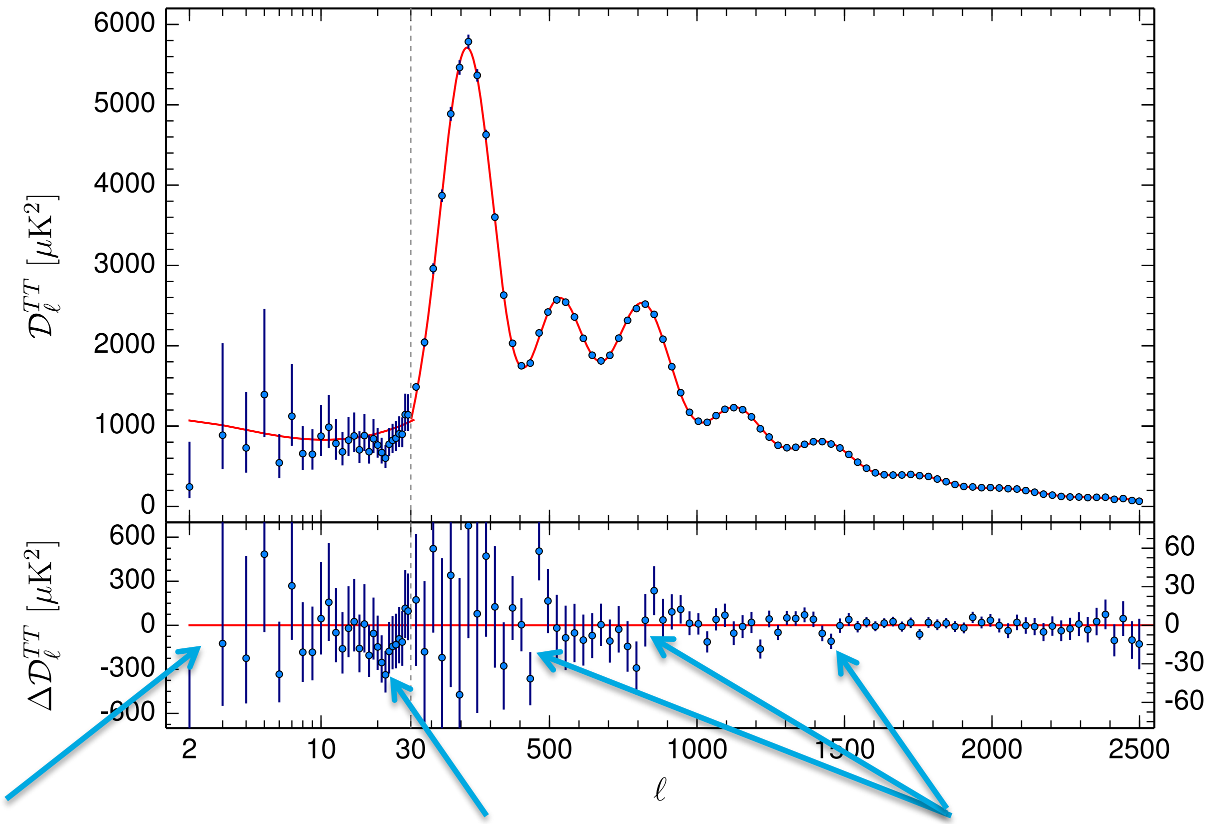
Natural scatter or signs of new physics?



large angle deficit ell = 20-30 feature other features

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Features in the primordial spectrum

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- Standard slow-roll inflation

  → almost scale-invariant spectrum of scalar perturbations
  (i.e., power-law, small running)

- Deviations from almost-scale invariance ("features") can be caused by:
  - Non-standard initial conditions (curvature, matter, kinetic energy of inflaton)
  - Non-Bunch-Davies vacuum
  - Features in the inflaton potential
  - Multi-field dynamics
  - …

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Bottom-up vs. top-down

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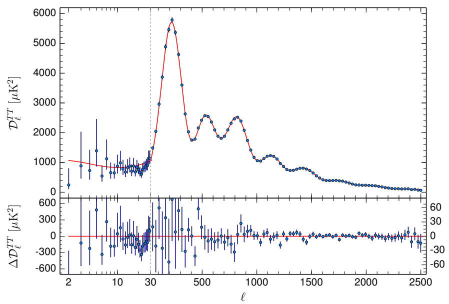
Inflation

$$\mathcal{P}_{\mathcal{R}}(k)$$

Convolution with
transfer functions



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Inflation

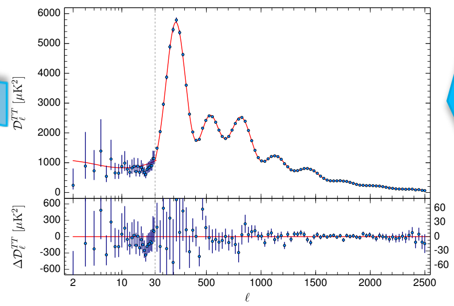
$$\mathcal{P}_{\mathcal{R}}(k)$$

"Bottom-up"

- Reconstruct shape of primordial power spectrum from measurement of the CMB angular power spectrum
- Planck 2014: three different reconstruction approaches

"Top-down"

- Fit a specific physical features model or parameterised features spectrum to the data
- Planck 2014: four different parameterised features models [plus axion monodromy case study]



Method 1: penalised likelihood reconstruction

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- Consider deviations from power-law spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{(0)}(k)\left[1 + f(k)\right]$$

- Take discrete *f*(*k*), interpolate with B-splines
- Add a likelihood penalty

$$\mathbf{f}^T \mathbf{R}(\lambda,\alpha)\mathbf{f} = \lambda \int \mathrm{d}\kappa \left(\frac{\partial^2 f(\kappa)}{\partial \kappa^2}\right)^2 + \alpha \int_{-\infty}^{\kappa_{\min}} \mathrm{d}\kappa\, f^2(\kappa) + \alpha \int_{\kappa_{\max}}^{+\infty} \mathrm{d}\kappa\, f^2(\kappa)$$

suppresses small structures

drive f(k) to zero at the largest and smallest scales

- Maximise penalised likelihood with respect to $f_i(k)$, h, $\Omega_b h^2$, $\Omega_c h^2$
- Extra degrees of freedom* = N_{bins} - 2

* with respect to a power-law spectrum

Method 1: penalised likelihood reconstruction

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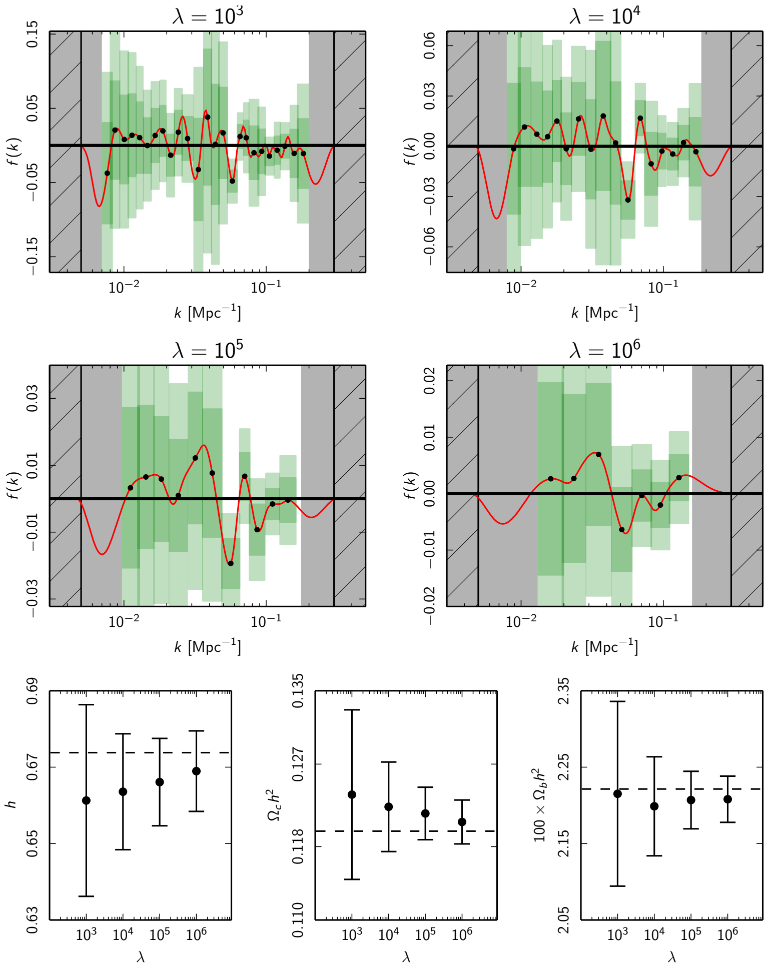
Temperature data



Deviation from power-law for different smoothness penalties

- The deviation from power-law is constrained to be within a few per cent
- The feature at ell≈1800 reported in 2013 papers no longer present (improved understanding of 4K cooler systematics)
- Inclusion of polarisation data increases resolution and reduces scatter

Cosmological parameter values are remarkably stable under changes to primordial spectrum

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Method 1: penalised likelihood reconstruction

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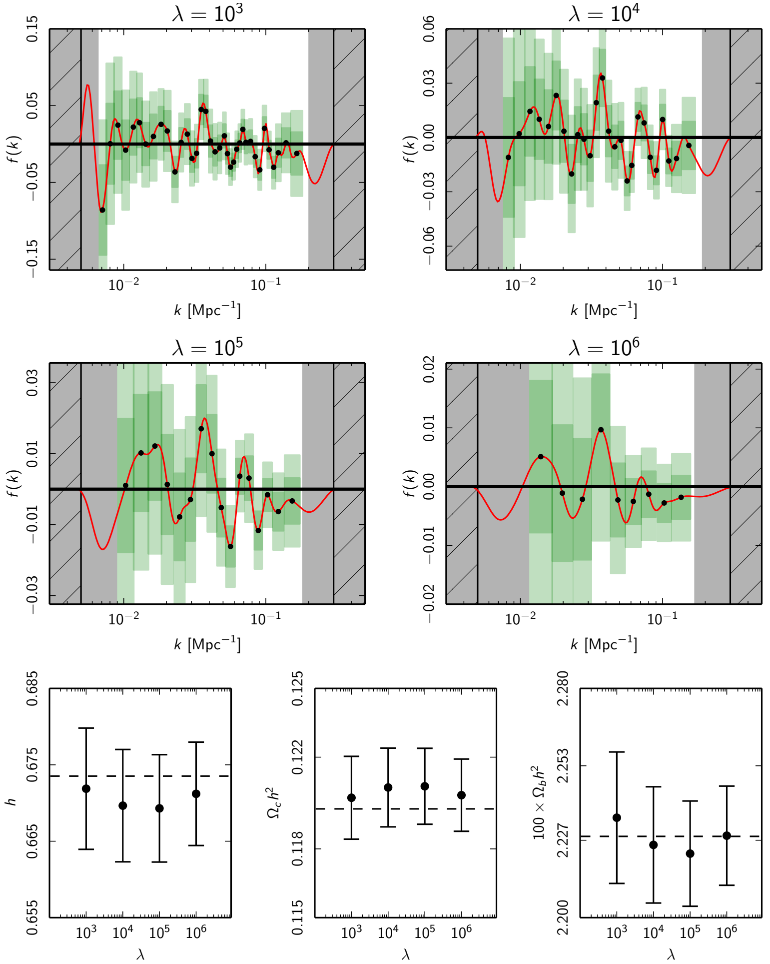
Temperature+polarisation data



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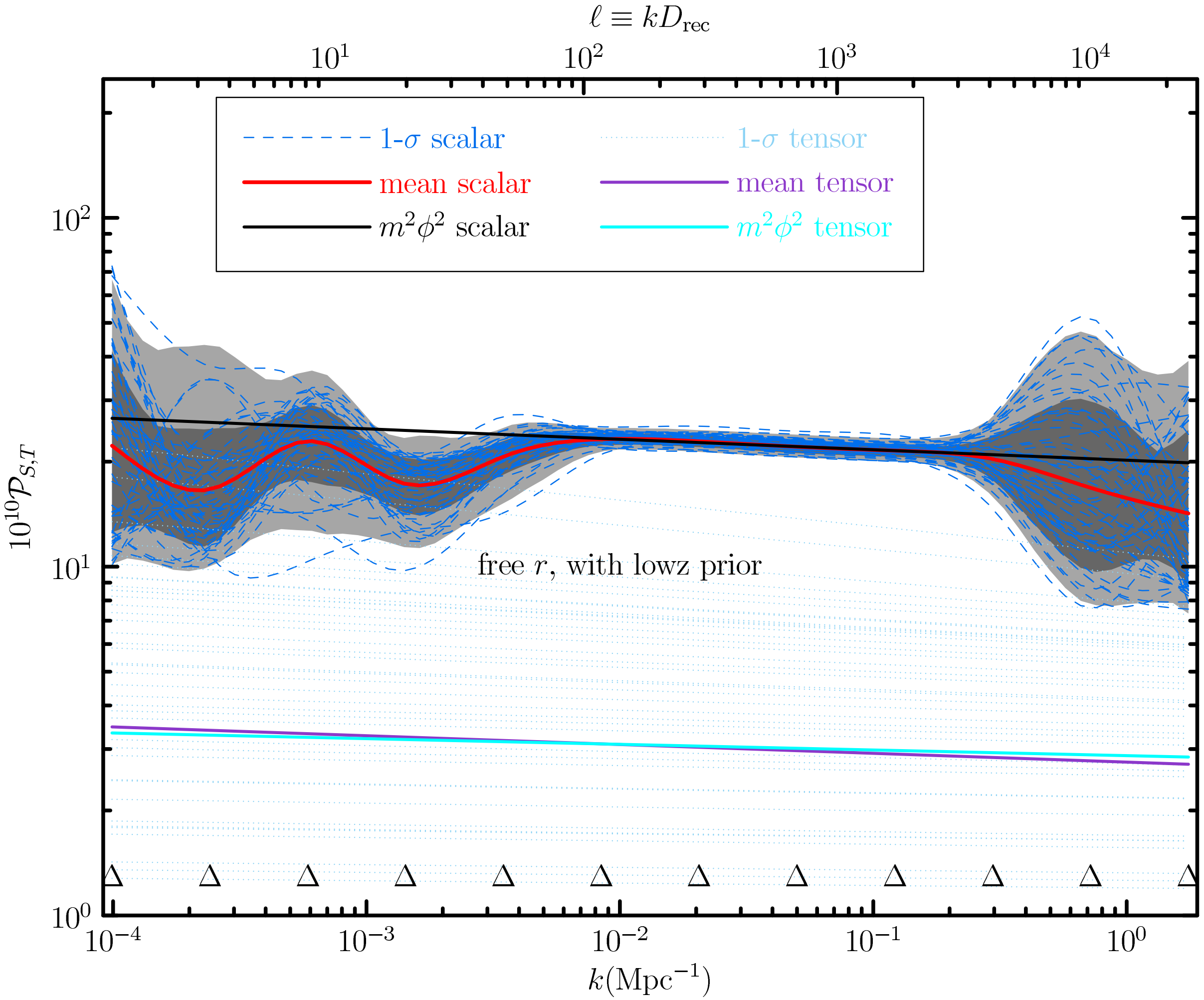
Method 2: Bayesian reconstruction with cubic splines on fixed knots

- Primordial power spectrum taken as cubic spline interpolation between fixed logarithmically spaced knots
- Extra degrees of freedom = N_{knots} - 2
- Bayesian method
- MCMC analysis, varying $P_i(k)$, tensor amplitude (assumed to be power-law), cosmological and foreground parameters
- Using slow-roll relations, can also reconstruct inflaton potential $V(\phi)$

Method 2: Bayesian reconstruction with cubic splines on fixed knots



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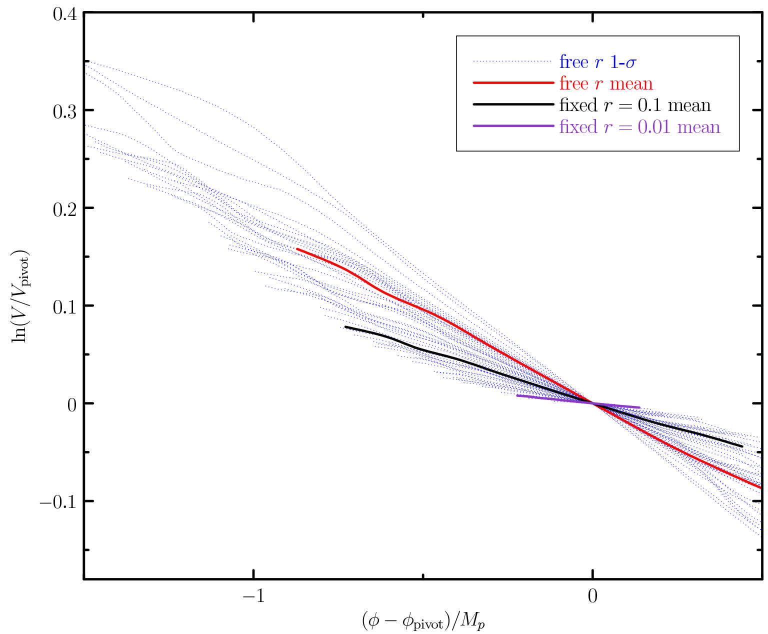
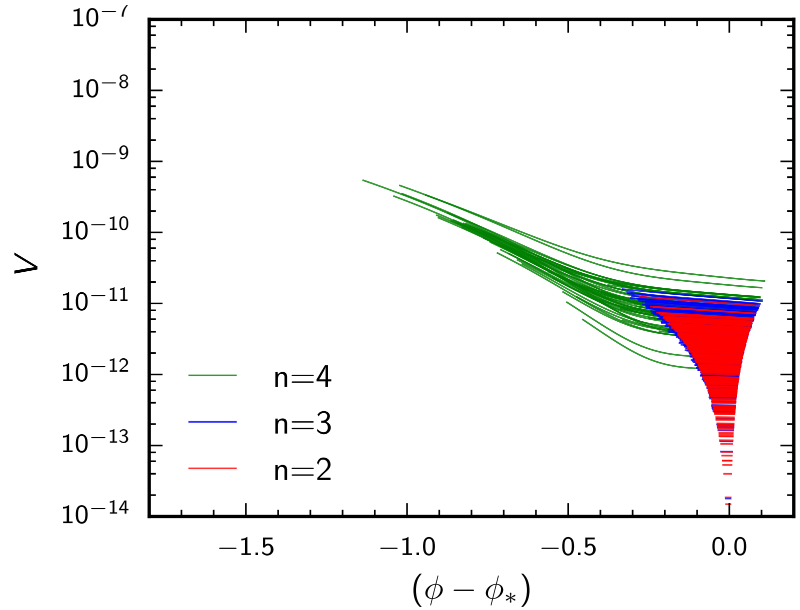
Method 2:
Bayesian reconstruction with cubic splines on fixed knots



Corresponding reconstructed inflaton potentials



Compare with Bayesian reconstruction of potential using n-th order polynomial expansion of $V(\phi)$

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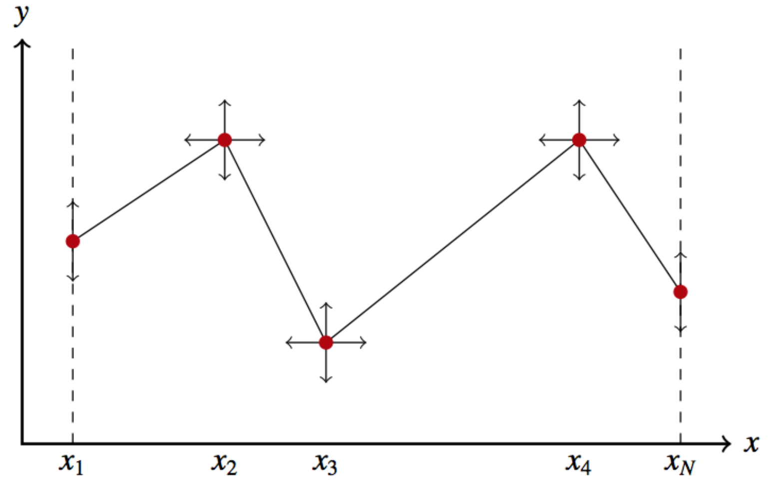
Method 3: Bayesian reconstruction with linear splines and variable knot positions

- Primordial power spectrum taken as linear interpolation between knots with variable positions
- Bayesian method
- Varying all primordial, cosmological and foreground parameters, using PolyChord sampler (nested sampling)
- Use Bayesian evidence to decide how many knots to add
- Extra degrees of freedom = 2 N_{knots}



Method 3: Bayesian reconstruction with linear splines and variable knot positions

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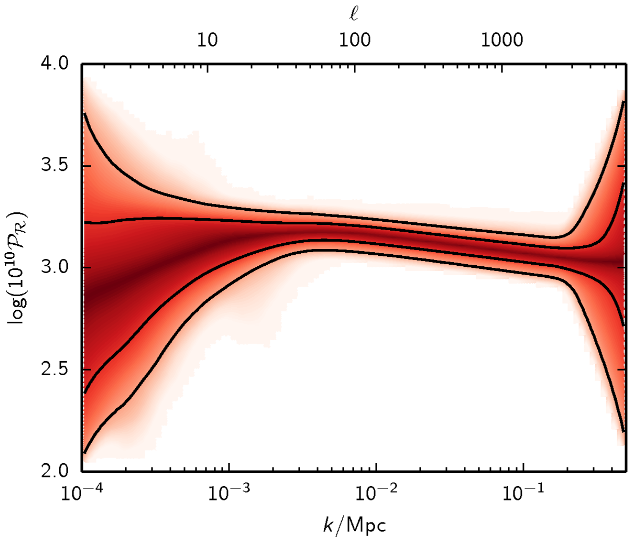
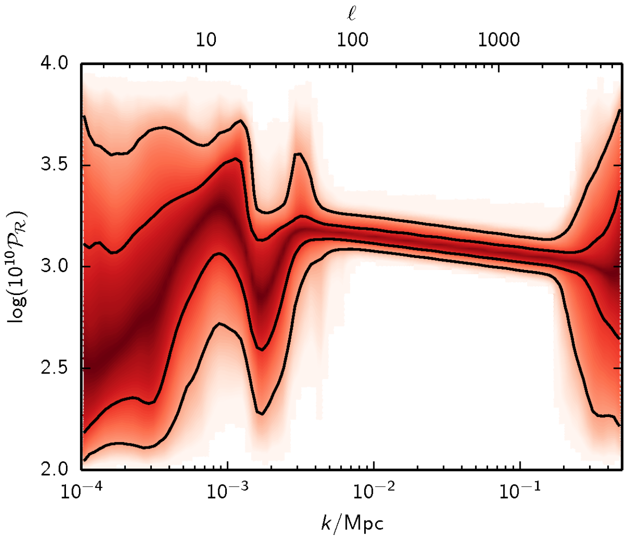
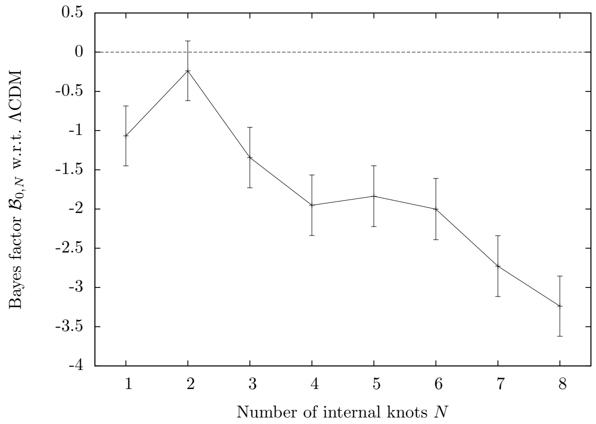
2 knots



8 knots



Bayesian evidence vs. number of knots



- Bayesian evidence does not favour the introduction of extra knots

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Search for parameterised features

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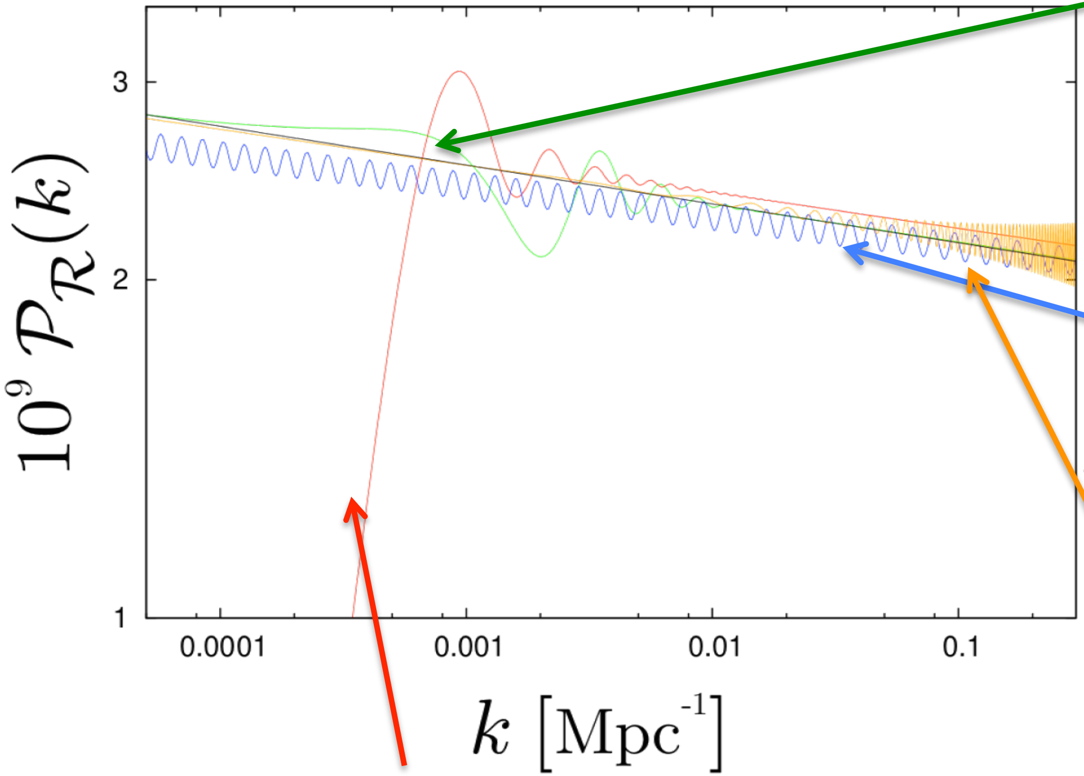
Temperature data best-fit power spectra



Step model
(step in inflaton potential)

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Log oscillation model
(e.g., non-BD vacuum, axion monodromy)

$$\mathcal{P}_{\mathcal{R}}^{\mathrm{log}}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\mathrm{log}}\cos\left(\omega_{\mathrm{log}}\ln\left(\frac{k}{k_*}\right) + \varphi_{\mathrm{log}}\right)\right]$$

Linear oscillation model
(e.g., boundary EFT)

$$\mathcal{P}_{\mathcal{R}}^{\mathrm{lin}}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\mathrm{lin}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{lin}}}\cos\left(\omega_{\mathrm{lin}}\frac{k}{k_*} + \varphi_{\mathrm{lin}}\right)\right]$$

Cutoff model
(inflation starts from kinetic stage)

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Search for parameterised features

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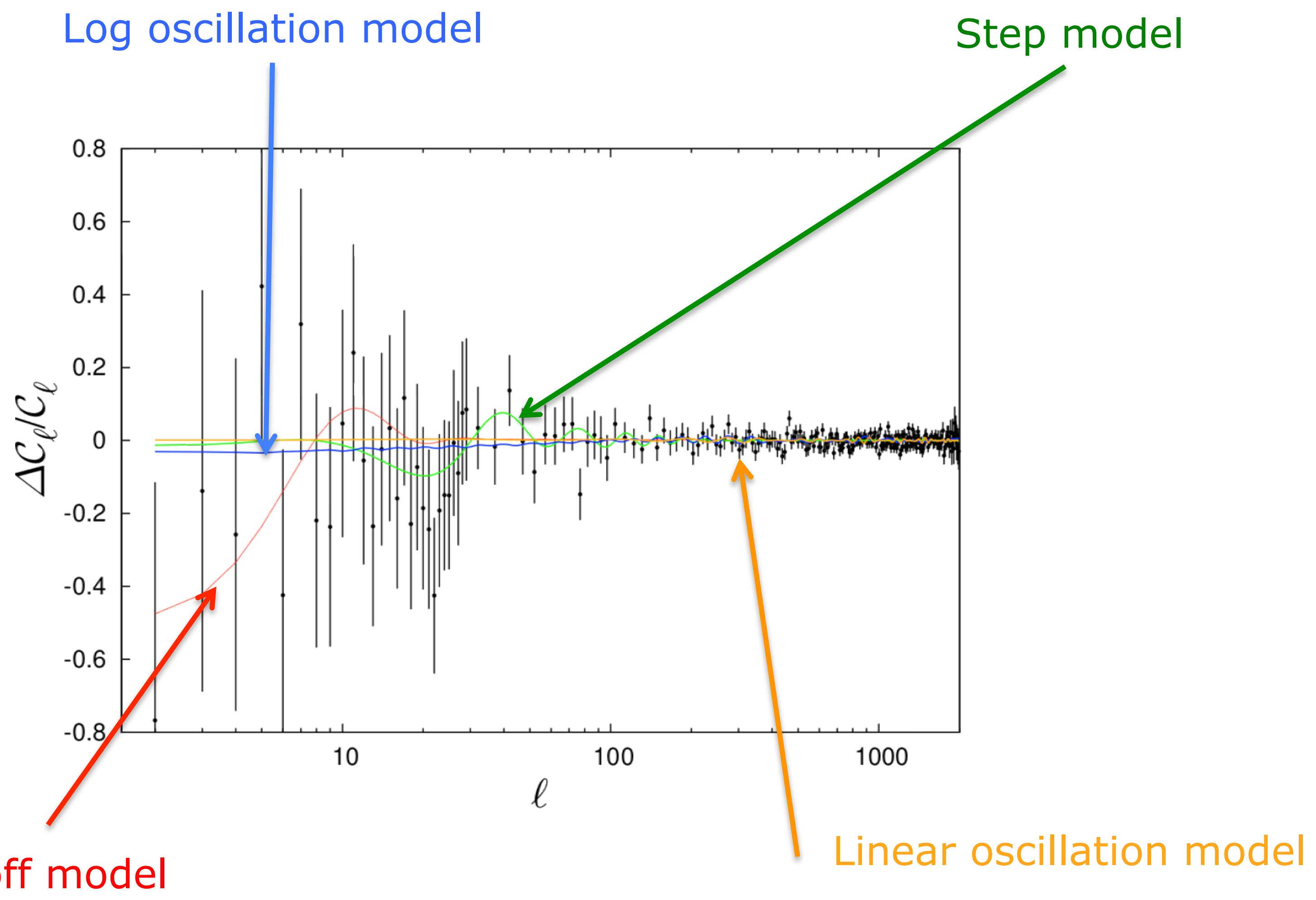

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Search for parameterised features: Bayesian analysis

"What are the relative probabilities of the features models compared to power-law ΛCDM?"

- Compute Bayesian evidences with MultiNest, varying primordial and other cosmological parameters (foregrounds fixed)

Search for parameterised features: Bayesian analysis

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"What are the relative probabilities of the features models compared to power-law ΛCDM?"

cutoff
(1 extra parameter)

	T	T+E
$\Delta\chi^2$	-2.1	-1.8
ln B_{01}	0.8	0.2

step
(3 extra parameters)

	T	T+E
$\Delta\chi^2$	-8.2	-6.6
ln B_{01}	0.1	-0.3

Caveat:
Bayes factors are prior dependent!

log oscillations
(3 extra parameters)

	T	T+E
$\Delta\chi^2$	-9.2	-9.3
ln B_{01}	1.3	0.6

linear oscillations
(4 extra parameters)

	T	T+E
$\Delta\chi^2$	-7.3	-11.1
ln B_{01}	0.9	0.4

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Search for parameterised features: frequentist analysis

"What would be the typical improvement in the fit if the underlying model was power-law ΛCDM?"

- Simulate Planck-like power spectra, using the power-law ΛCDM best-fit as fiducial model
- For each simulated data set:
  - Find power-law ΛCDM best-fit effective χ^2 and parameters
  - Find features models best-fit effective χ^2 (varying only primordial parameters, other cosmological parameters fixed to their respective best-fit values)
  - Evaluate effective $\Delta\chi^2$ (conservative, i.e., underestimates the maximum obtainable value)
- Compare distribution of simulated effective $\Delta\chi^2$ with observed effective $\Delta\chi^2$

Search for parameterised features: frequentist analysis

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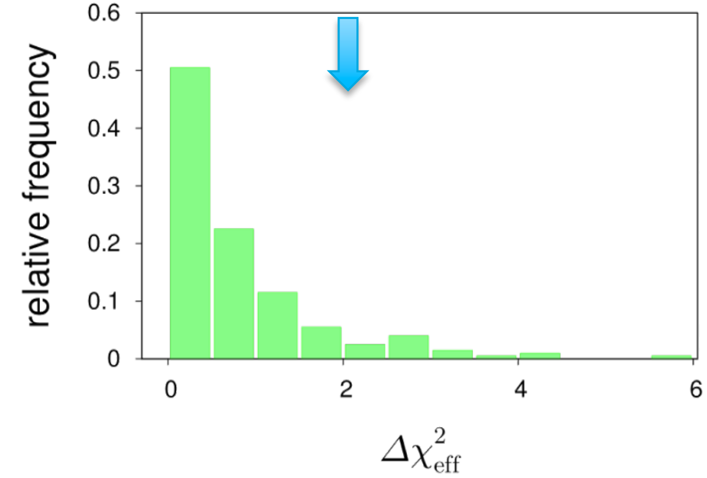
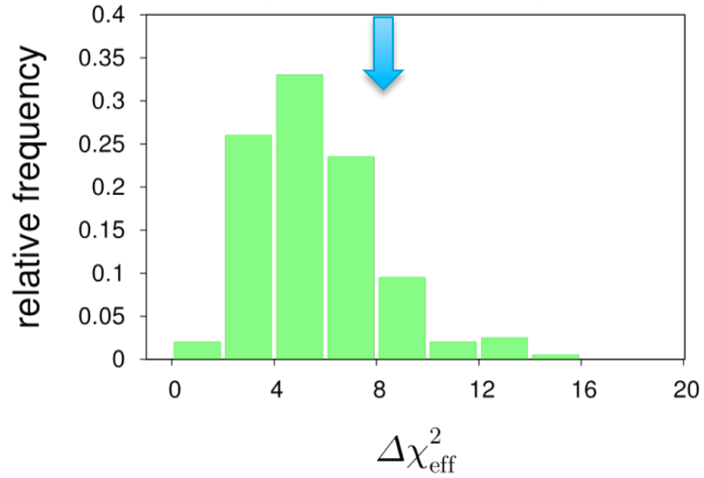
cutoff

(1 extra parameter)



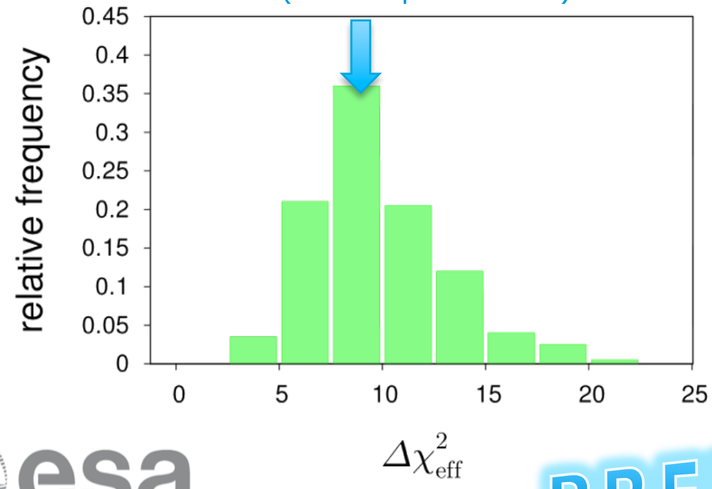
step

(3 extra parameters)



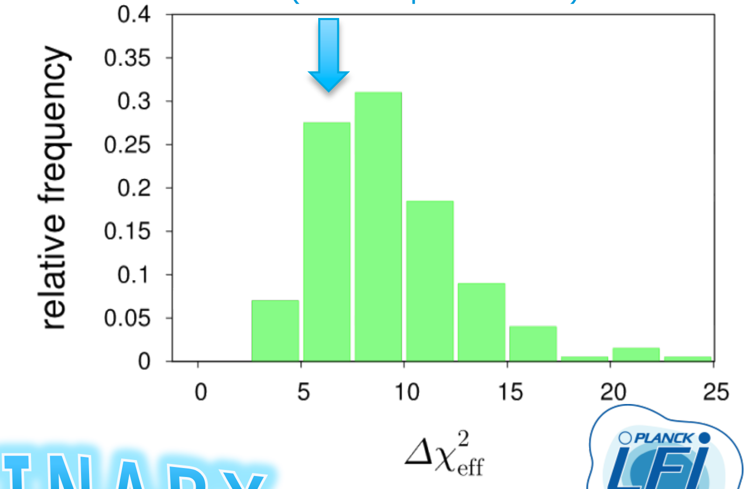
log oscillations

(3 extra parameters)



linear oscillations

(4 extra parameters)



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Conclusions

- Planck data are consistent with a smooth, power-law primordial spectrum as generically predicted by the simplest models of inflation
- Particularly strong constraints on features for wavenumbers $0.008\ \mathrm{Mpc}^{-1} < k < 0.2\ \mathrm{Mpc}^{-1}$
- Different ways of reconstructing the primordial power spectrum from Planck data yield results in agreement with each other
- Observed features at large scales could in principle be explained by (inflationary) models predicting features in the primordial spectrum, but no strong statistical evidence

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.