The hunt for features in the primordial power spectrum

Jan Hamann

Sydney Institute for Astronomy, The University of Sydney

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Daejeon

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planck

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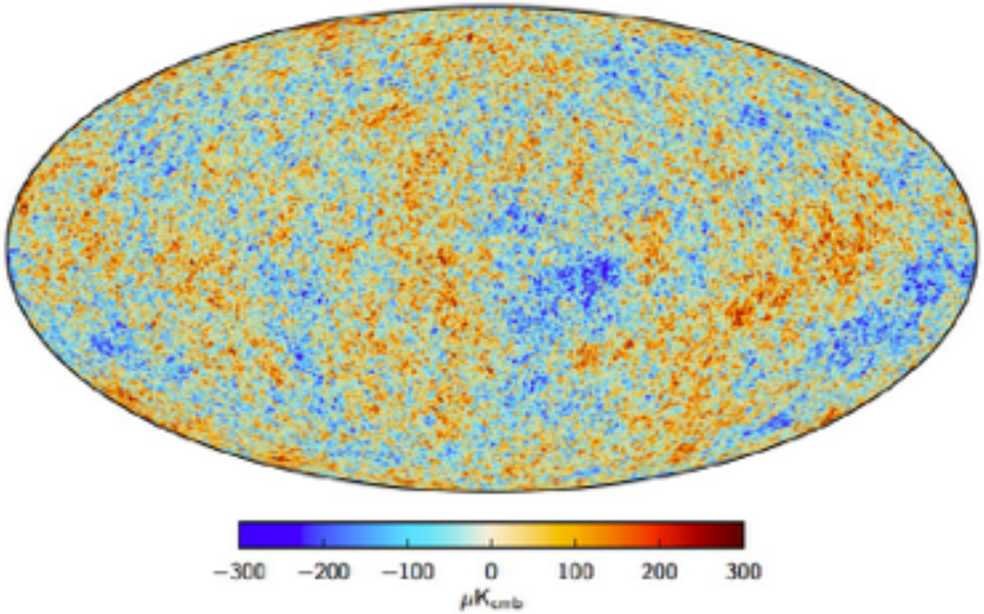
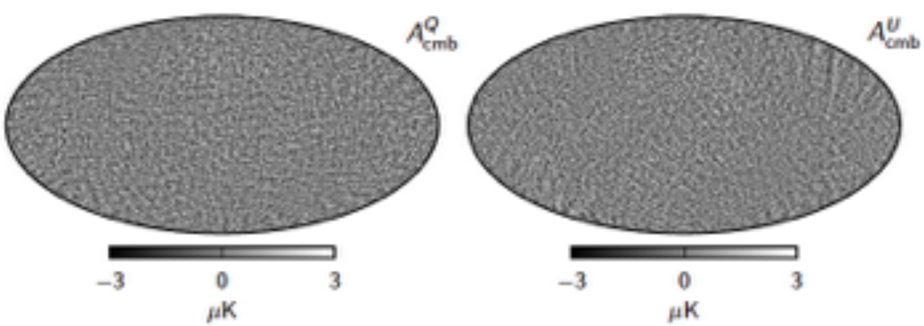
Planck has measured the Cosmic Microwave Background's …

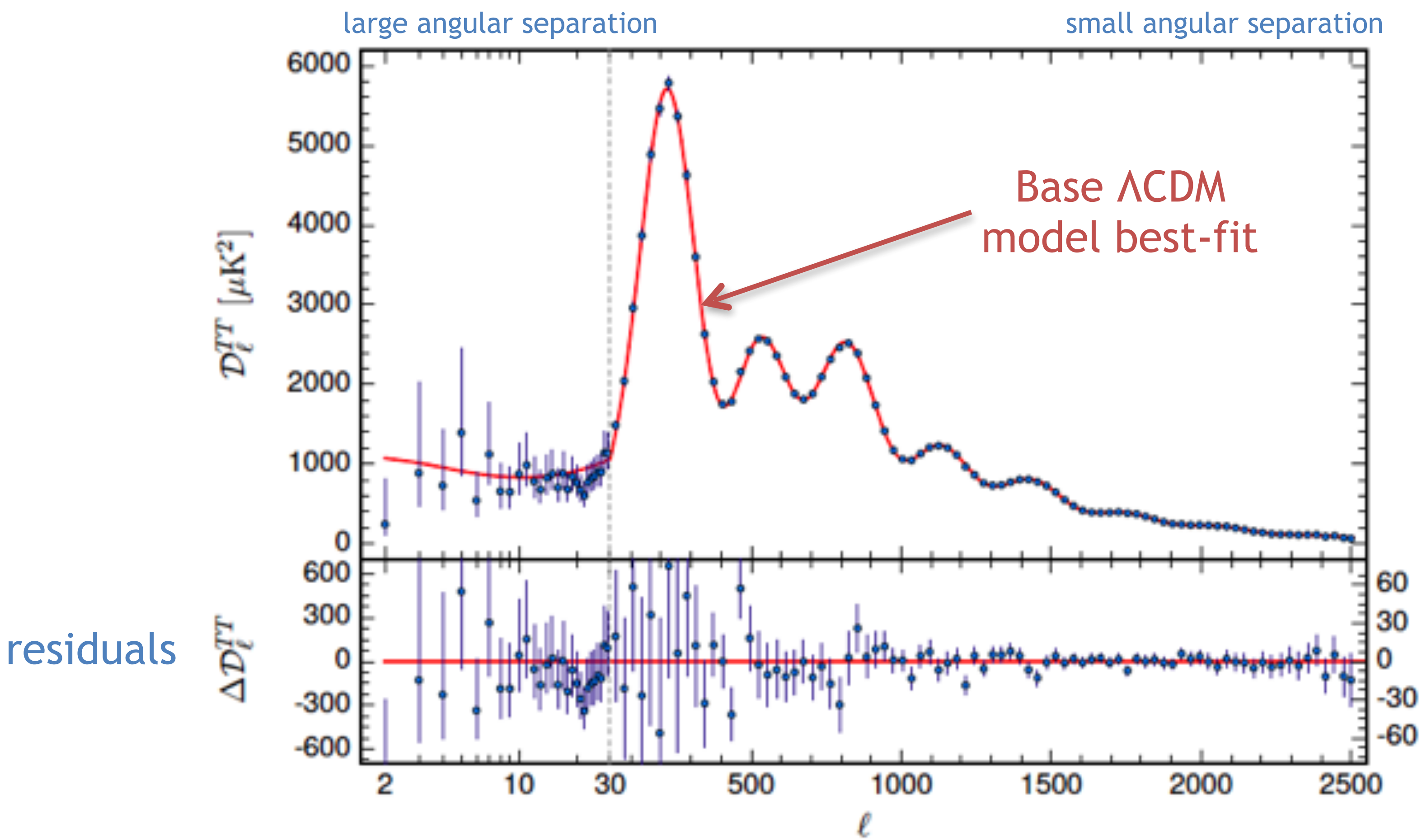
… temperature anisotropies …



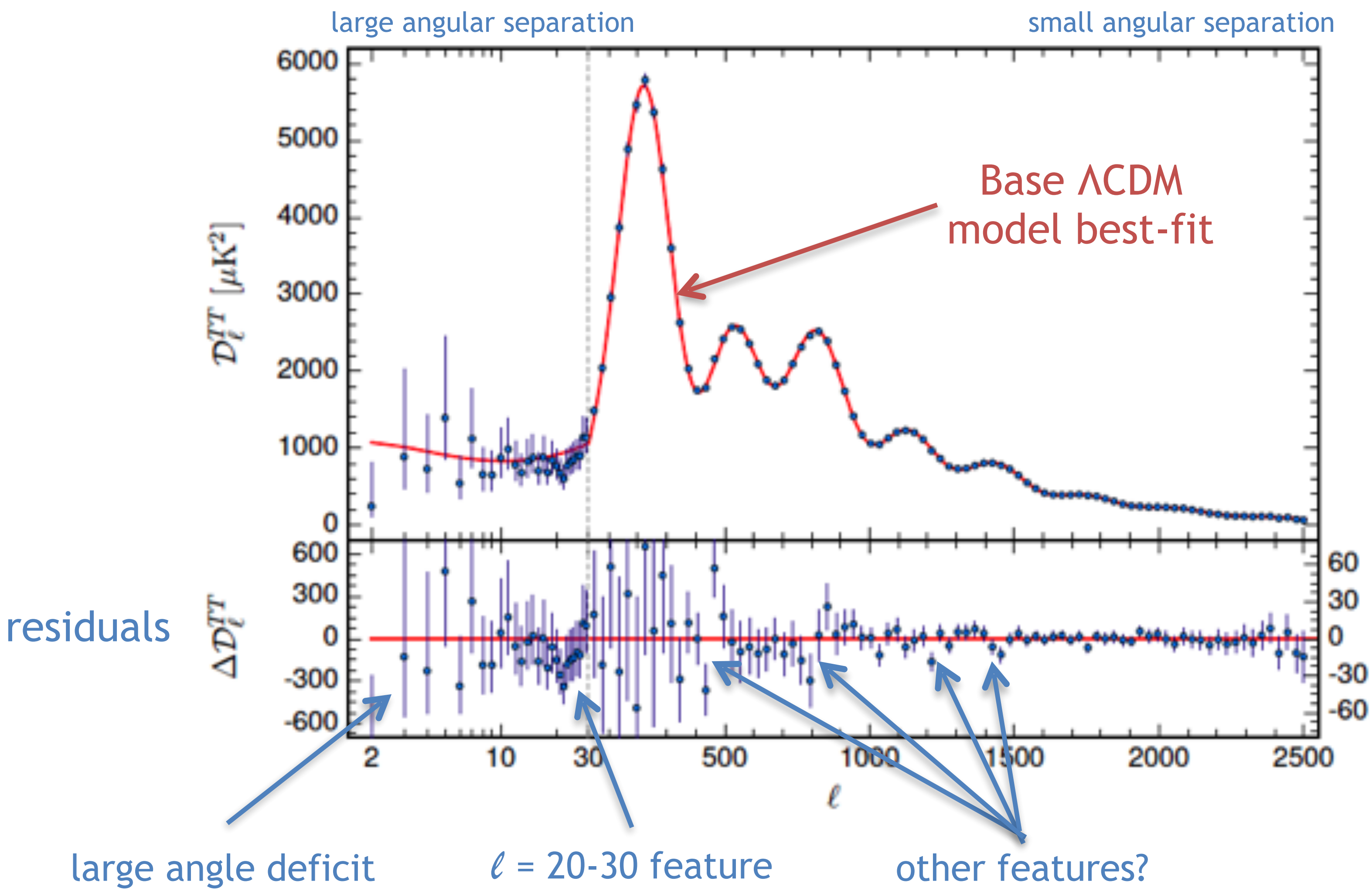
… and polarisation



Planck temperature angular power spectrum

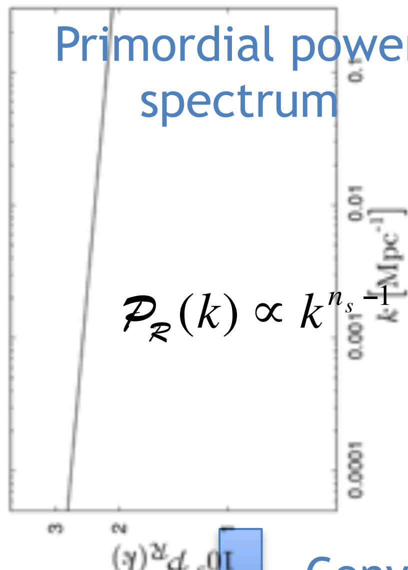


Planck temperature angular power spectrum



The primordial power spectrum

earlier
(z > 10^6)

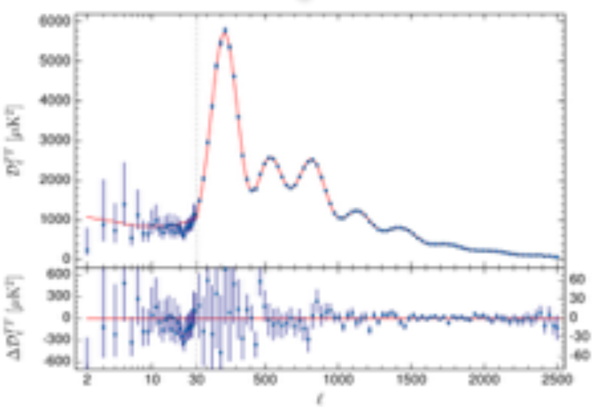


Primordial power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) \propto k^{n_s-1}$$

Convolution with transfer functions

today



The primordial power spectrum

earlier
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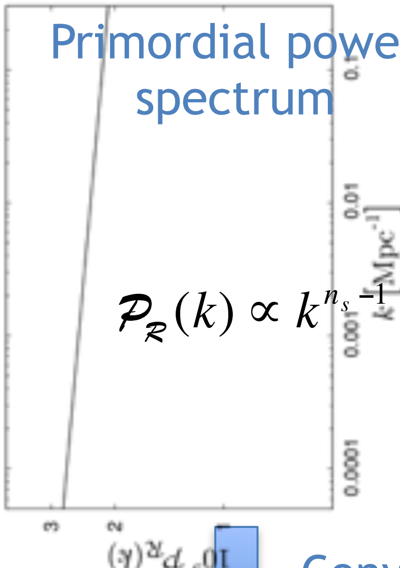
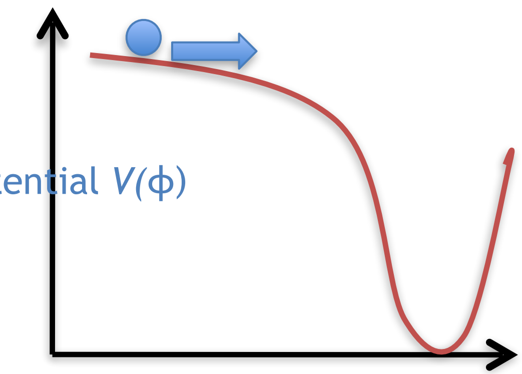


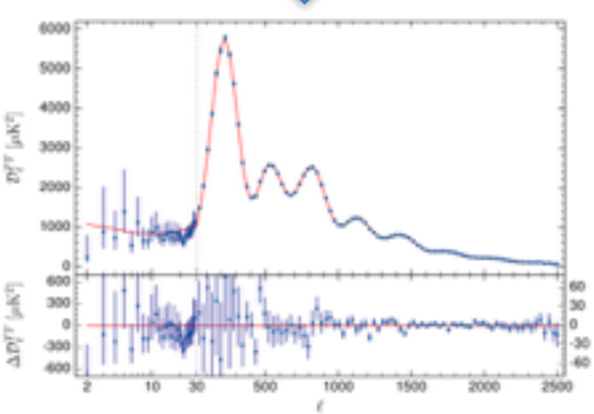
quantum fluctuations of ϕ



even earlier
($z \approx 10^{25\text{-ish}}$)

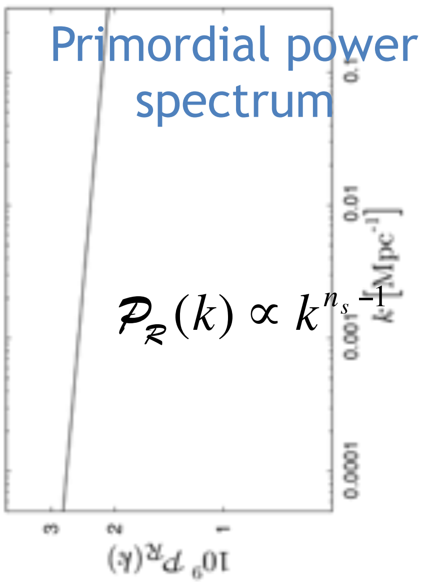
Convolution with transfer functions

today



A smooth primordial power spectrum?

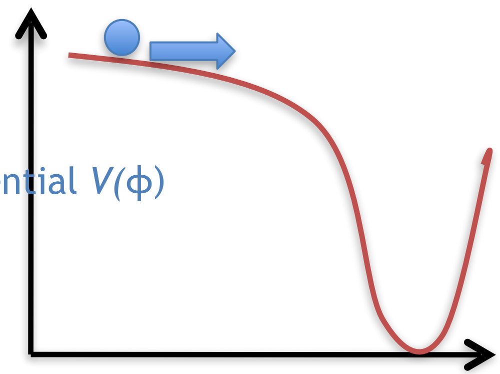
Primordial power spectrum



$$\mathcal{P}_\mathcal{R}(k) \propto k^{n_s-1}$$

quantum fluctuations of ϕ

Inflation



Assumptions

- Smooth inflaton potential
- Slow-roll attractor reached
- Bunch-Davies vacuum
- Other fields can be integrated out

Do the data support these assumptions?

Looking for features

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

"Bottom-up"

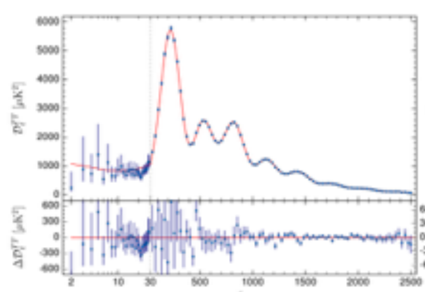
Reconstruct shape of primordial power spectrum from measurement of the CMB angular power spectrum

3 methods

"Top-down"

Fit a specific physical features model or parameterised features spectrum to the data

4 models



Reconstruction of the primordial power spectrum

Method 1:
Penalised likelihood reconstruction

- Consider deviations from power-law spectrum

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

- 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

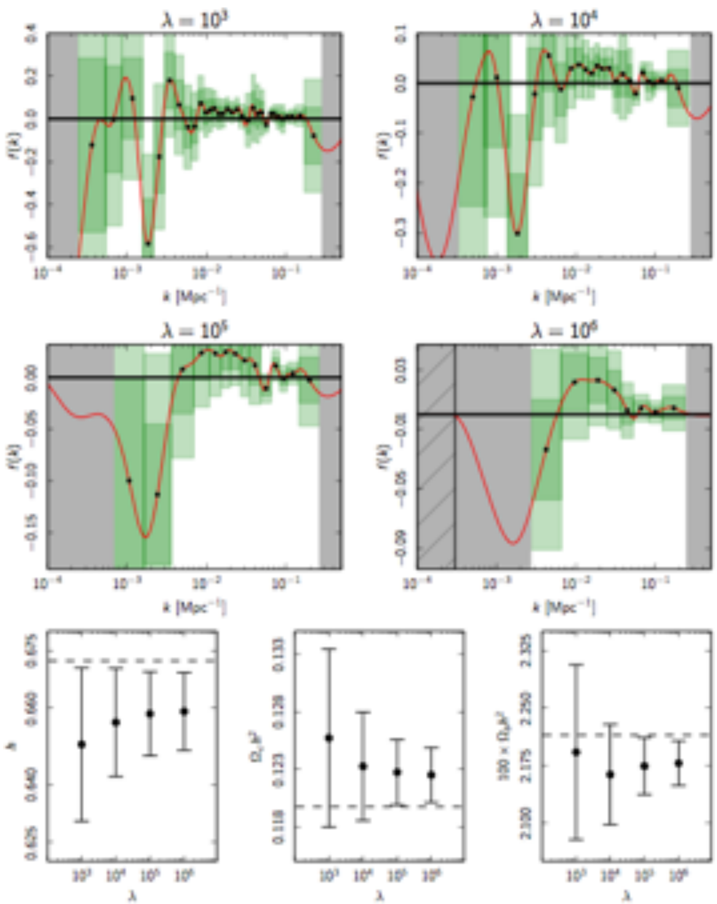
drive f(k) to zero at the largest and smallest scales

- Maximise penalised likelihood w.r.t. $f_i(k)$, 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

Temperature data



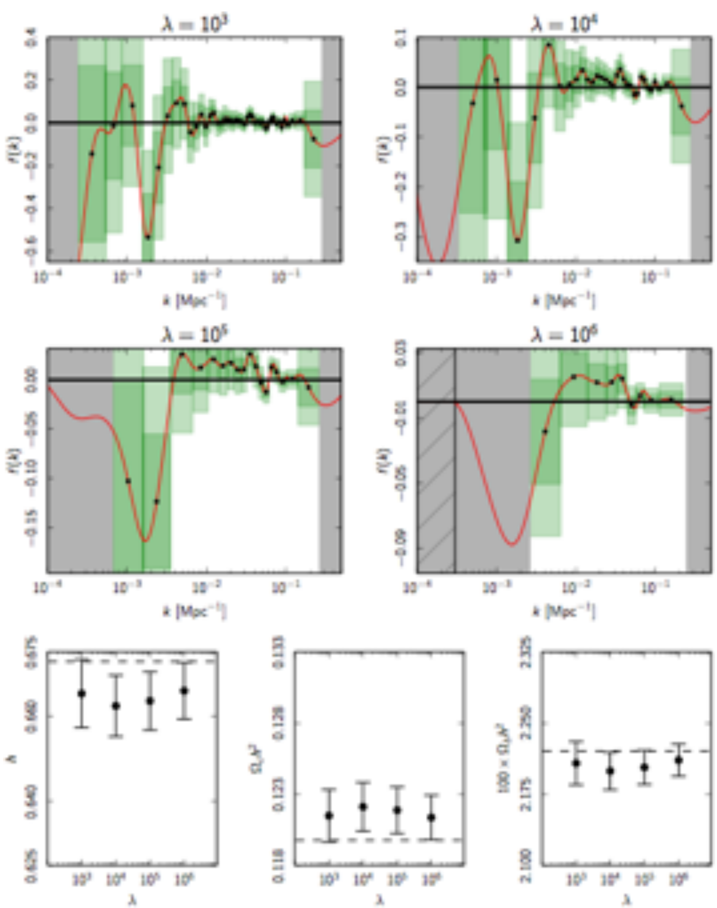
Deviation from power-law for different smoothness penalties

- Dip around $2{\times}10^{-3}$ Mpc^{-1}, corresponding to $\ell \approx 20$-30 feature
- Local significance >2σ, but not significant globally (look-elsewhere-effect)
- Outside the dip, deviation from power-law constrained to be within a few per cent
- Inclusion of polarisation data increases resolution and reduces scatter

Cosmological parameter values are remarkably stable under changes to primordial spectrum

Method 1:
Penalised likelihood reconstruction

Temperature + Polarisation data



Deviation from power-law for different smoothness penalties

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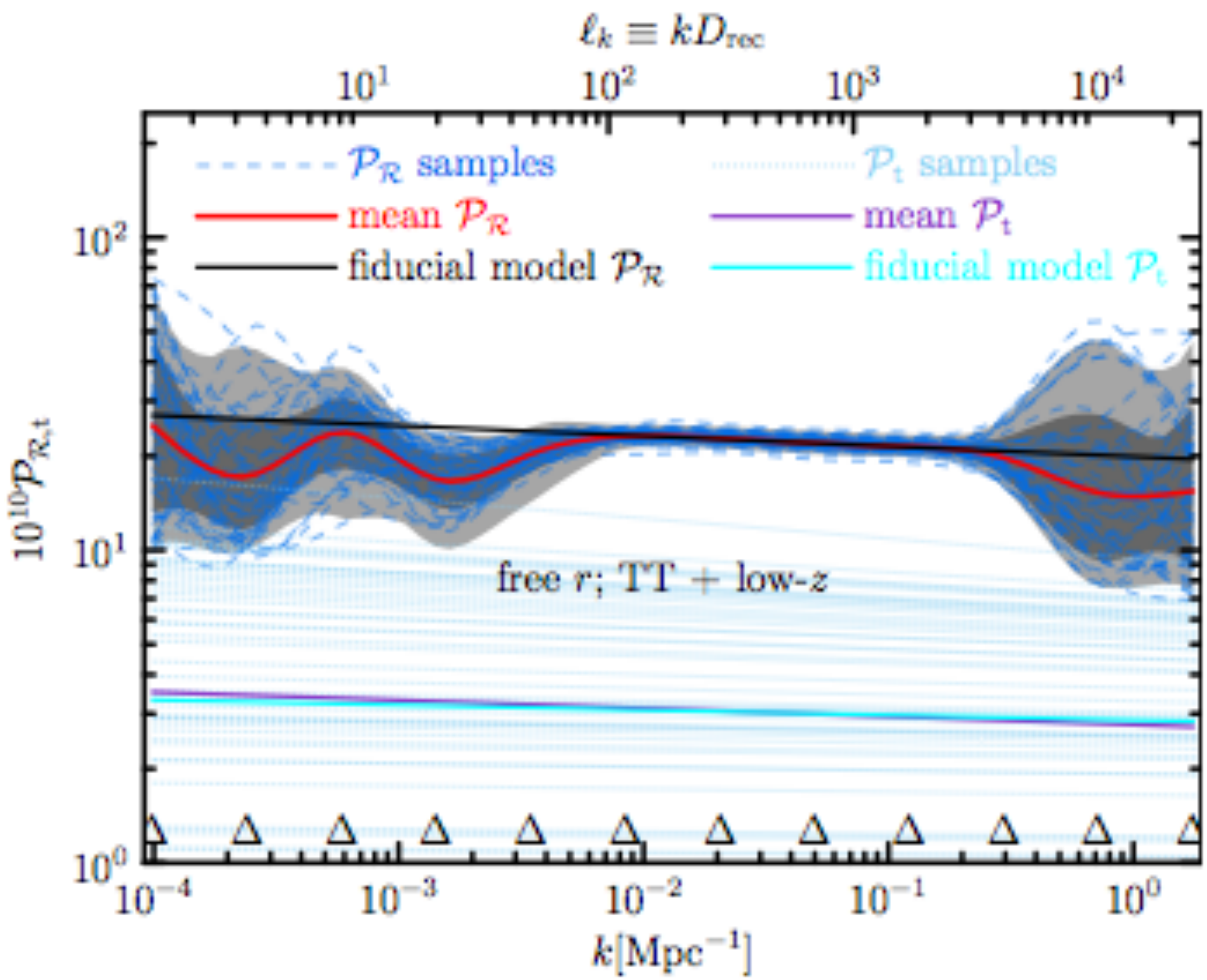
Cosmological parameter values are remarkably stable under changes to primordial spectrum

Method 2: Bayesian reconstruction with cubic splines and fixed knot positions

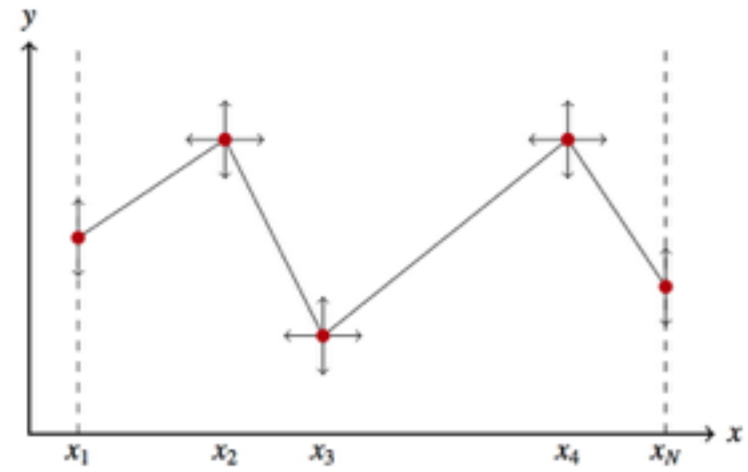
- Primordial power spectrum taken as cubic spline interpolation between fixed logarithmically spaced knots
- Extra degrees of freedom = N_{knots} - 2
- Bayesian method
- MCMC analysis, varying $P_i(k)$, tensor amplitude (assumed to be power-law), cosmological and foreground parameters

Method 2:
Bayesian reconstruction with cubic splines and fixed knot positions



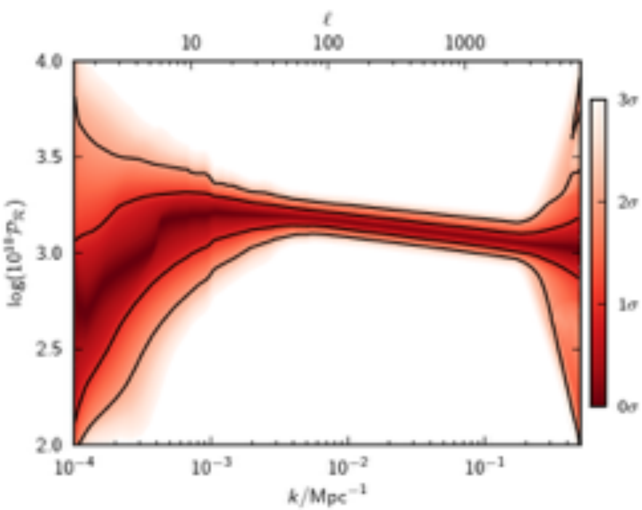
Method 3:
Bayesian reconstruction with linear splines and variable knot positions

- Primordial power spectrum taken as linear interpolation between knots with variable positions
- Bayesian method
- Varying all primordial, cosmologica 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}

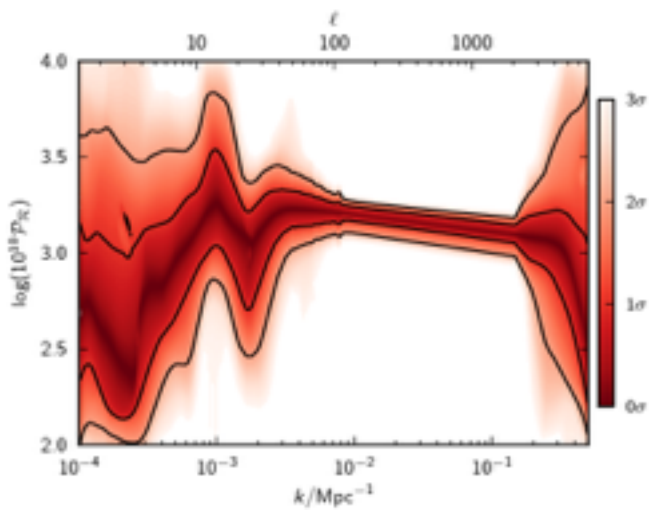


Method 3:
Bayesian reconstruction with linear splines and variable knot positions

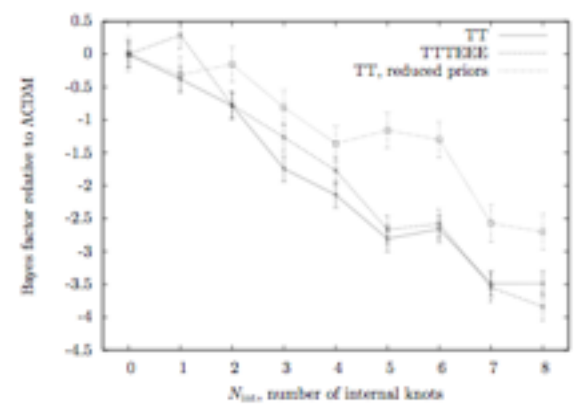
2 knots



8 knots



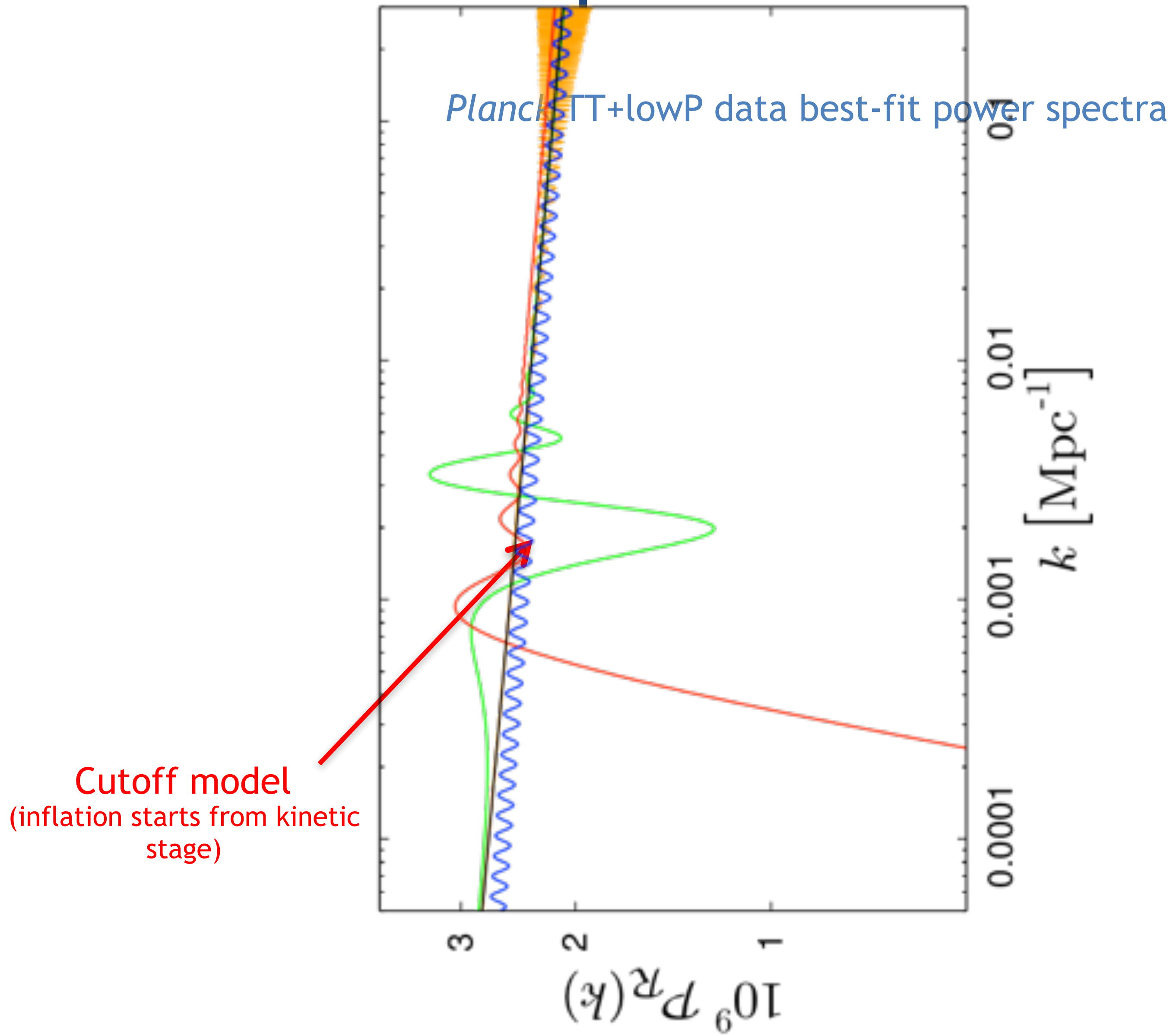
Bayesian evidence
vs. number of knots



Bayesian evidence does not favour
the introduction of extra knots

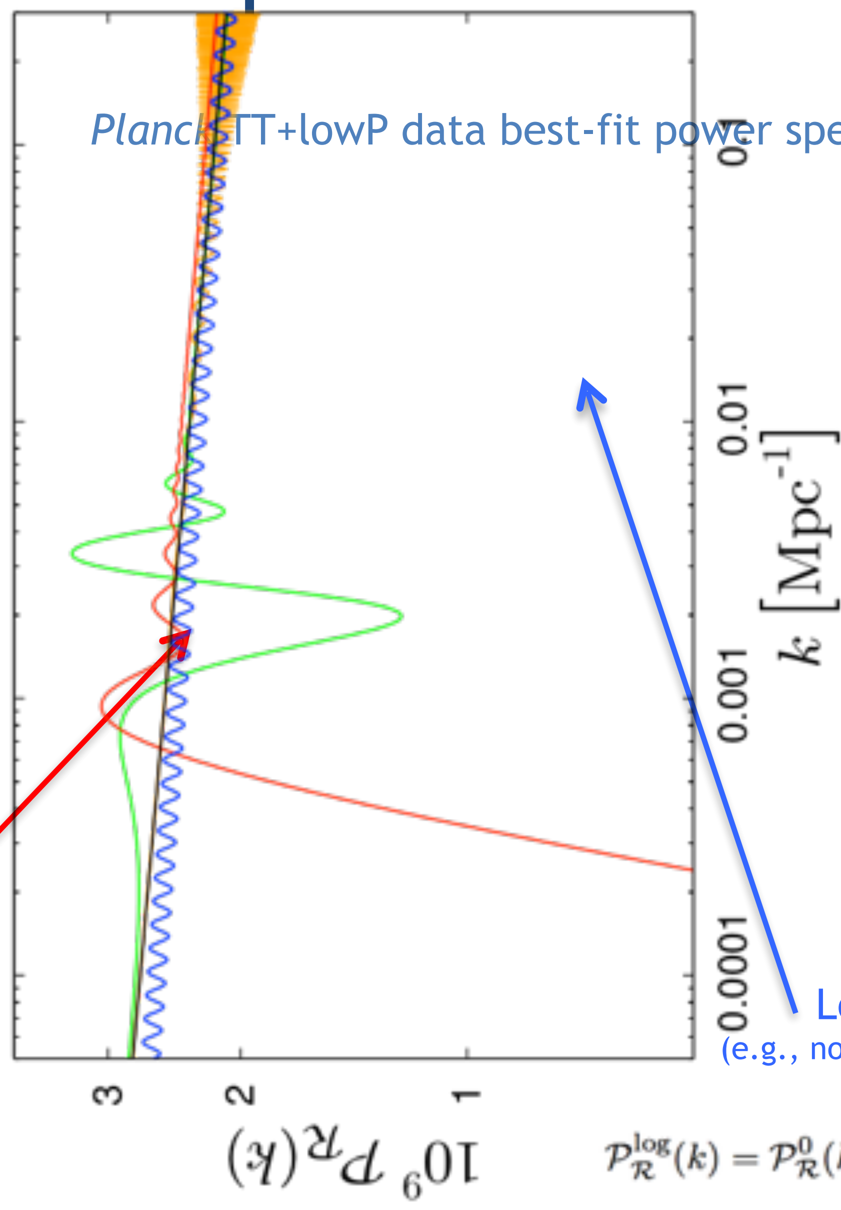
Testing physical models with features in the primordial power spectrum

Search for parameterised features



Search for parameterised features

Planck TT+lowP data best-fit power spectra



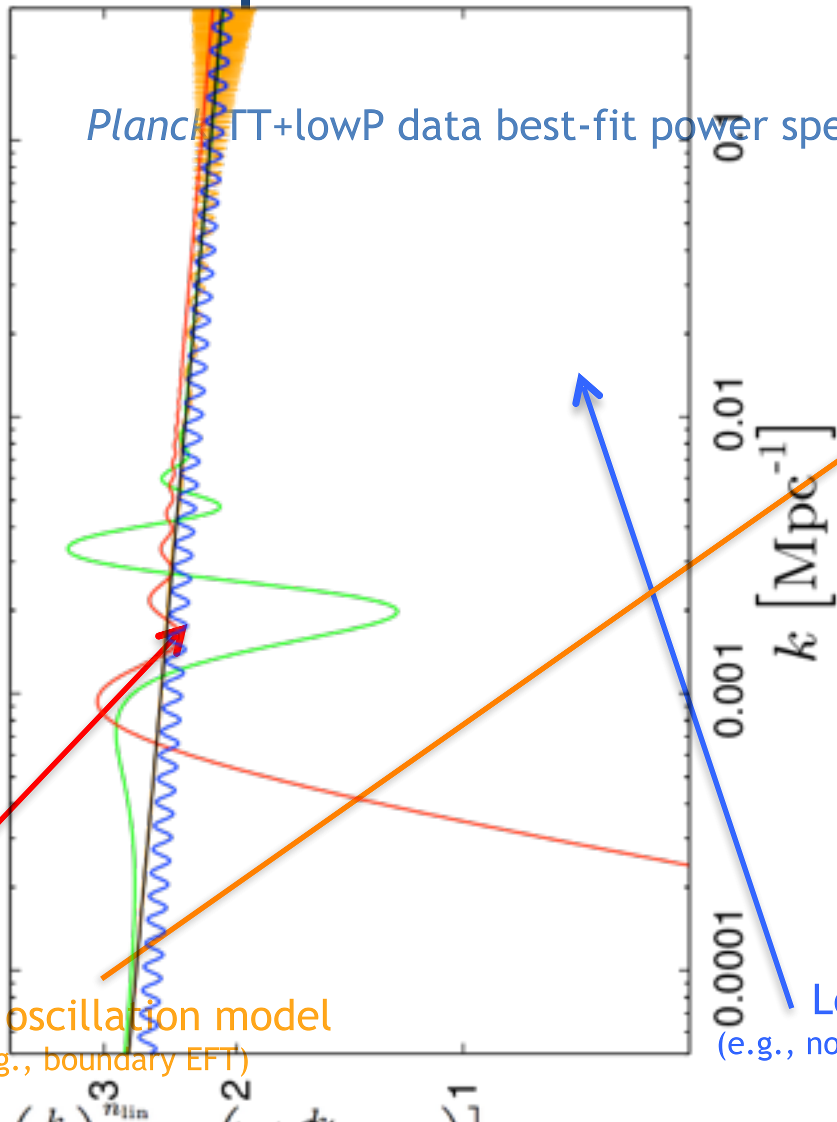
Cutoff model
(inflation starts from kinetic stage)

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

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

Search for parameterised features

Planck TT+lowP data best-fit power spectra



Cutoff model
(inflation starts from kinetic stage)

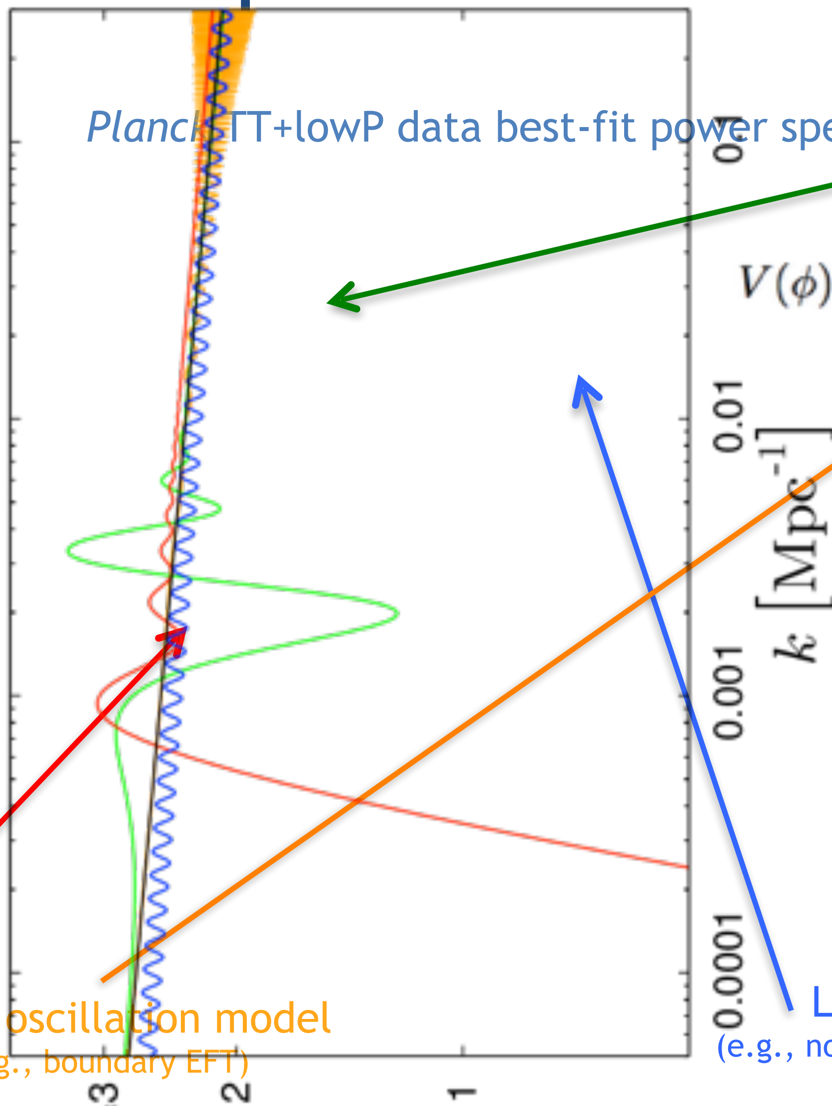
Linear oscillation model
(e.g., boundary EFT)

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

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

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

Search for parameterised features



Planck TT+lowP data best-fit power spectra

Step model
(step in inflaton potential)

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

Cutoff model
(inflation starts from kinetic stage)

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

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

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

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

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

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

cutoff
(1 extra parameter)

	T	T+P
$\Delta\chi^2$	-2.0	-2.2
ln B_{01}	-0.4	-0.6

step
(3 extra parameters)

	T	T+P
$\Delta\chi^2$	-8.6	-7.3
ln B_{01}	-0.3	-0.6

ln B_{01} < 0:
prefer power-law
ln B_{01} > 0:
prefer features

Caveat:
Bayes factors are prior dependent!

log oscillations
(3 extra parameters)

	T	T+P
$\Delta\chi^2$	-10.6	-10.1
ln B_{01}	-1.9	-1.5

linear oscillations
(4 extra parameters)

	T	T+P
$\Delta\chi^2$	-8.9	-10.9
ln B_{01}	-0.4	-0.6

T: Planck TT+lowP data
T+P: PlanckTTTEEE+lowP data

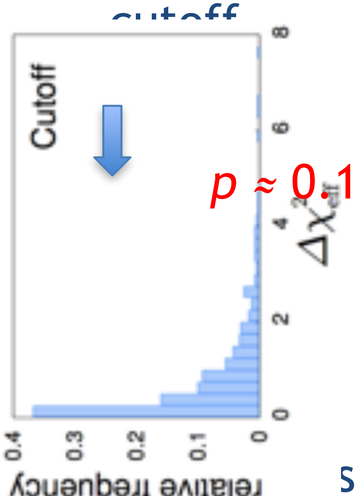
Search for parameterised features: Frequentist analysis

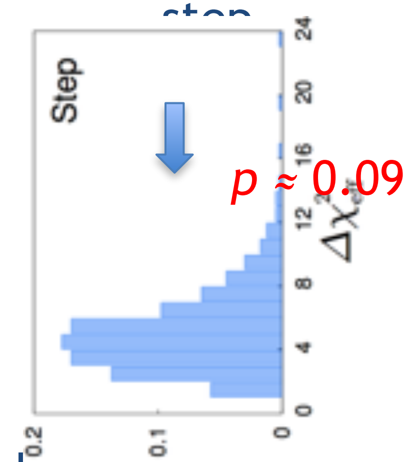
"What would be the typical improvement in the fit if the underlying model was power-law ΛCDM?"

- 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 x^2 and parameters
  - Find features models best-fit effective x^2 (varying only primordial parameters, other cosmological parameters fixed to their respective best-fit values)
  - Evaluate effective Δx^2 (conservative, i.e., underestimates the maximum obtainable value)
- Compare distribution of simulated effective Δx^2 with observed effective Δx^2

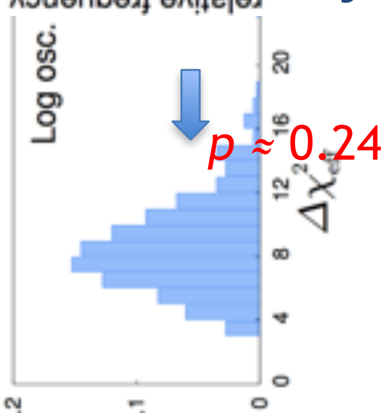
Search for parameterised features: Frequentist analysis

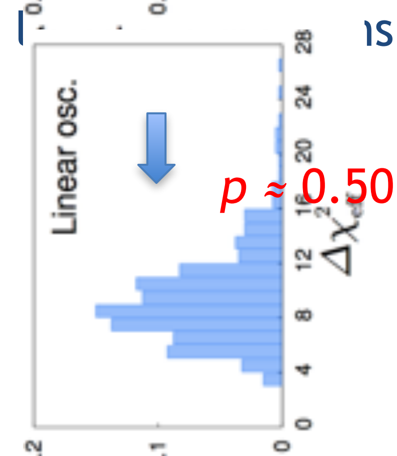
"What would be the typical improvement in the fit if the underlying model was power-law ΛCDM?"





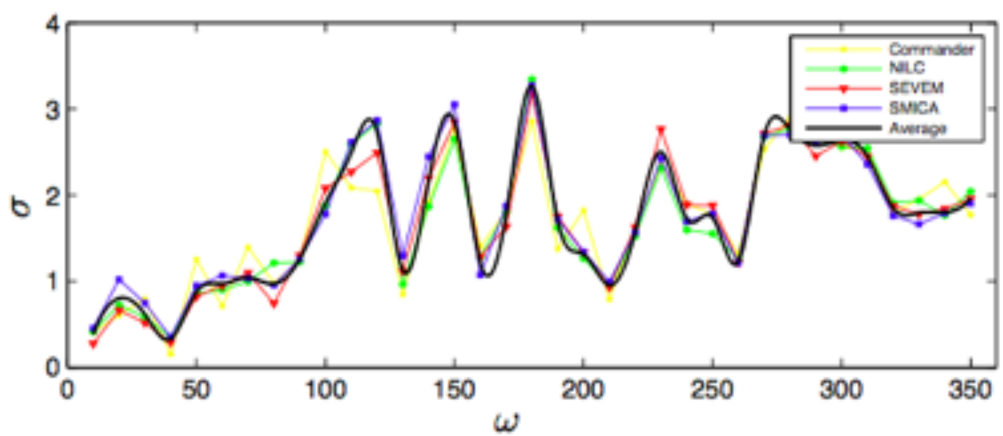
Probability to exceed observed Δx^2 (p-value)





Where else to look? Bispectrum

- Physical features models tend to also predict signatures in higher order correlations
- Some features templates tested with Planck bispectrum data, e.g., equilateral features model:

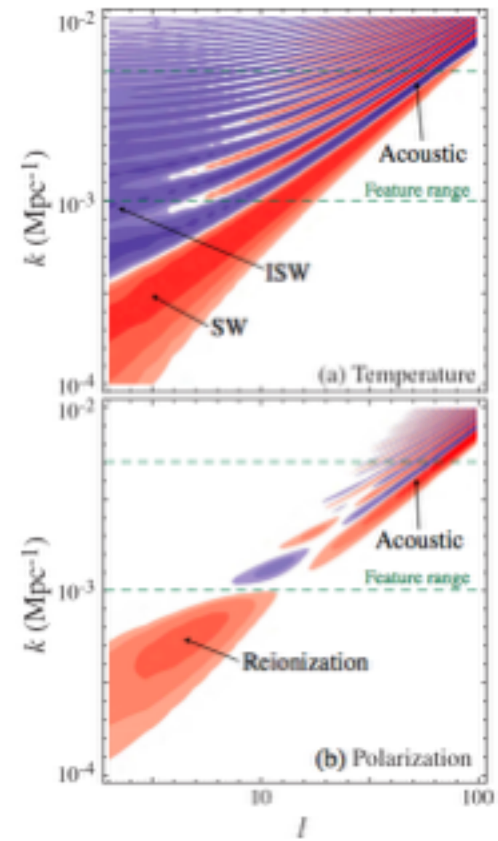


- Ideally, want to do joint power spectrum/bispectrum analysis

Where else to look? Polarisation

- Polarisation transfer functions are narrower than temperature ones, i.e., better resolution of features
- Expect improvements from upcoming ground-based CMB experiments (Advanced ACT, SPTPol, PolarBear, SPIDER, …, Stage-IV)

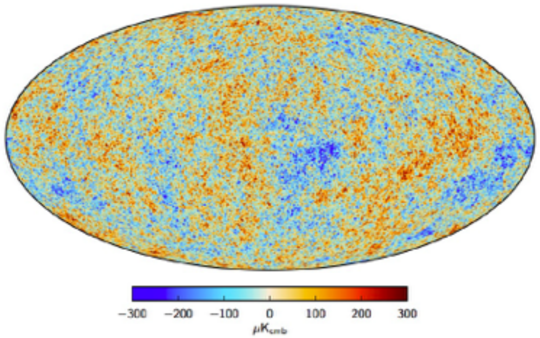
Transfer function



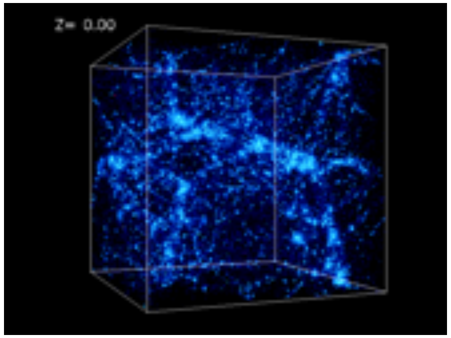
[Mortonson+ 2009]

Where else to look?
Large scale structure

CMB: 2d



LSS: 3d



- Can extract much more information from large scale structure
- With 21 cm, potentially improve sensitivity to features amplitude by one (*Tianlai*) to two (*SKA*) orders of magnitude compared to Planck

[Xu, Chen, JH, Shiu, Wang; in preparation]

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 $Mpc^{-1} < k < 0.2$ 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