Knot reconstruction of the scalar primordial power spectrum with Planck, ACT, and SPT CMB data

On arXiv:2503.10609 with Mario Ballardini

Antonio Raffaelli - Inflation 2025 - Paris, 01/12/2025

Università degli Studi di Ferrara

Agenzia Spaziale Italiana

INFN Istituto Nazionale di Fisica Nucleare

Primordial Power Spectrum

- The primordial curvature power spectrum (PPS) sets the initial conditions for cosmological fluctuations in our Universe.

$$P(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Primordial Power Spectrum

- The primordial curvature power spectrum (PPS) sets the initial conditions for cosmological fluctuations in our Universe.

$$P(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

- Being defined on all scales, it provides a tool to connect different cosmological observables from the early to the late Universe.

Primordial Power Spectrum

- The primordial curvature power spectrum (PPS) sets the initial conditions for cosmological fluctuations in our Universe.

$$P(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

- Being defined on all scales, it provides a tool to connect different cosmological observables from the early to the late Universe.
- It can be probed both with CMB and galaxy surveys.

Primordial Power Spectrum

- The primordial curvature power spectrum (PPS) sets the initial conditions for cosmological fluctuations in our Universe.

$$P(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

- Being defined on all scales, it provides a tool to connect different cosmological observables from the early to the late Universe.
- It can be probed both with CMB and galaxy surveys.
- Searching for features or departures from a power-law form in the PPS can shed light on the physics of inflation and other aspects of the early Universe.

Knot reconstruction

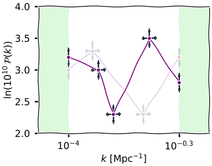


Figure: Visualization of knots reconstruction

- The aim of this research is to reconstruct the PPS in an model-independent way.
- This can be done through knots reconstruction (flexknot) [Millea and Bouchet 2018, Handley et al. 2019], sampling the amplitude and scale of the points of the PPS and then interpolate. This allows to probe the whole parameter space.

Knot reconstruction

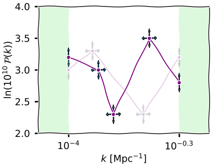


Figure: Visualization of knots reconstruction

- The aim of this research is to reconstruct the PPS in an model-independent way.
- This can be done through knots reconstruction (flexknot) [Millea and Bouchet 2018, Handley et al. 2019], sampling the amplitude and scale of the points of the PPS and then interpolate. This allows to probe the whole parameter space.

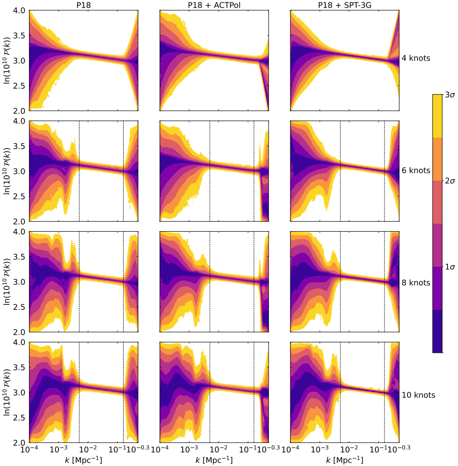
- As a Boltzmann-Einstein solver for computing spectra we use a modified version of CAMB that computes spectra starting from interpolated PPS.
- We use a modified version of Cobaya together with PolyChord for sampling parameters.

Parameter	Prior type	Prior range
$\Omega_b h^2$	Uniform	[0.019,0.025]
$\Omega_{cdm} h^2$	Uniform	[0.095,0.145]
τ_{reio}	Uniform	[0.01,0.4]
$100\theta_{MC}$	Uniform	[1.03,1.05]
$\ln\left(10^{10} A_s\right)$	Uniform	[1.61,3.91]
n_s	Uniform	[0.8,1.2]
$\log_{10}(k_i)$	Sorted Uniform	[-4,-0.3]
$\ln\left(10^{10}\mathcal{P}_{\mathcal{R}}\right)$	Uniform	[2,4]

Table: Priors on the cosmological parameters

PPS from CMB data

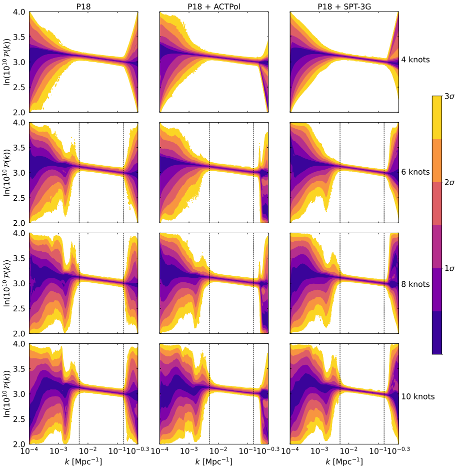
- The datasets used are from different CMB experiments: *Planck* [Planck 2018 results V. CMB Power spectra and likelihoods], Atacama Cosmology Telescope (ACTPol) DR4 [Choi et al. 2020], South Pole Telescope (SPT-3G) [Balkenhol et al. 2018].



PPS from CMB data

- The datasets used are from different CMB experiments: *Planck* [Planck 2018 results V. CMB Power spectra and likelihoods], Atacama Cosmology Telescope (ACTPol) DR4 [Choi et al. 2020], South Pole Telescope (SPT-3G) [Balkenhol et al. 2018].

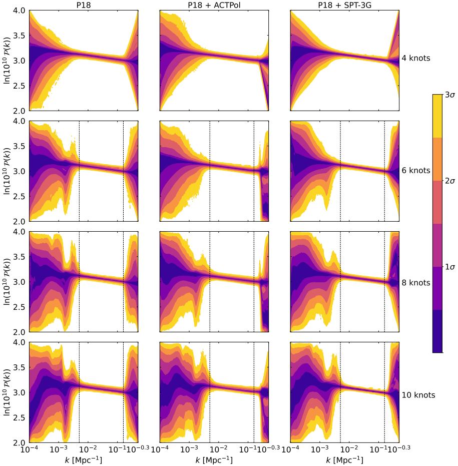
- With a growing number of knots, features in the PPS become more visible.
- Sampling logarithmically in scales focuses the search on large scales.



PPS from CMB data

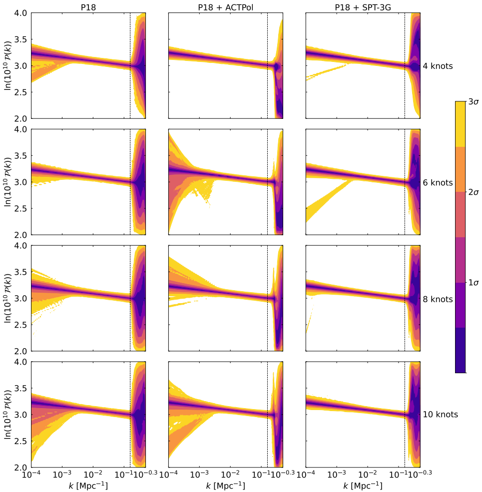
- The datasets used are from different CMB experiments: *Planck* [Planck 2018 results V. CMB Power spectra and likelihoods], Atacama Cosmology Telescope (ACTPol) DR4 [Choi et al. 2020], South Pole Telescope (SPT-3G) [Balkenhol et al. 2018].

- With a growing number of knots, features in the PPS become more visible.
- Sampling logarithmically in scales focuses the search on large scales.
- The power law holds up to $k = 0.16\,\mathrm{Mpc}^{-1}$ for Planck alone, and up to $k = 0.25\,\mathrm{Mpc}^{-1}$ and $k = 0.20\,\mathrm{Mpc}^{-1}$ when including ACTPol and SPT-3G, respectively.
- Deviations from a power-law PPS are constrained within a few percent in this range.



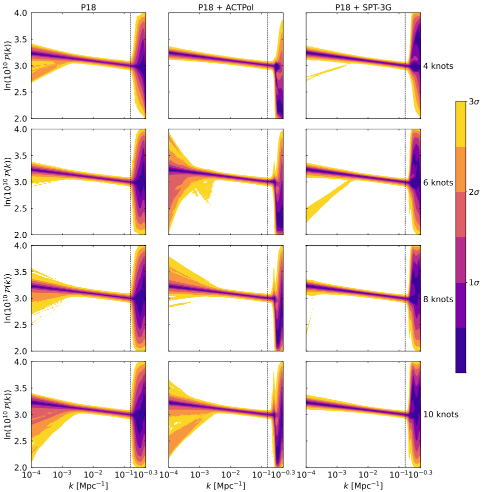
PPS from CMB data

- We also sampled linearly on the scales.
- This allows to look for features on small scales.



PPS from CMB data

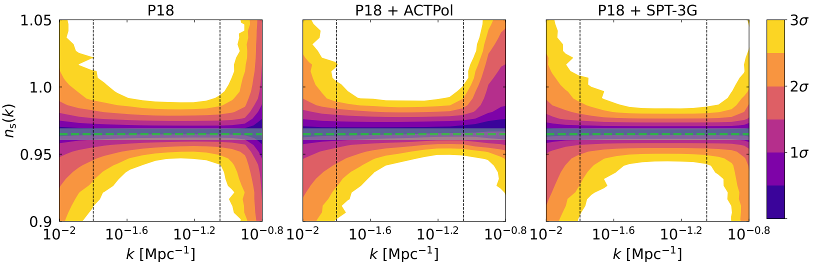
- We also sampled linearly on the scales.
- This allows to look for features on small scales.
- We do not see improvements in the scales up to which power law holds (same k_{max} as before).
- We do not observe features emerging at small scales.



Scalar spectral index

- The study of the scalar spectral index and its running can give important information on the underlying inflationary model

$$n_s - 1 = \frac{d \log P(k)}{d \log k}$$



- On the scales probed by Planck n_s is constant with negligible error compatible with 1σ constraints from ΛCDM. On small and large scales there is room for running of n_s.

Reconstruction results with A_{L}

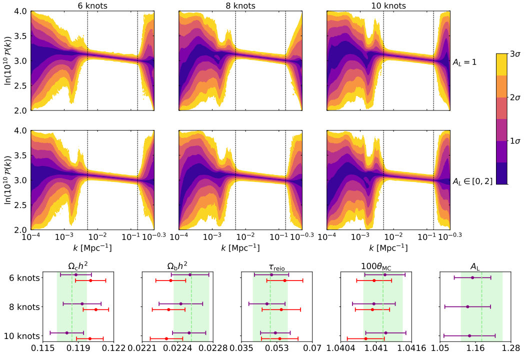


Figure: Red: reconstruction with $A_{\mathrm{L}} = 1$; purple: free A_{L}; green region: ΛCDM (power-law PPS).

- We also tested the reconstruction allowing A_{L} to vary. [Planck 2018 results X: Constraints on inflation. Domènech & Kamionkowski (2019); Ballardini & Finelli (2022)]
- In principle, features on small scales could absorb the effect of A_{L}.

Reconstruction results with A_{L}

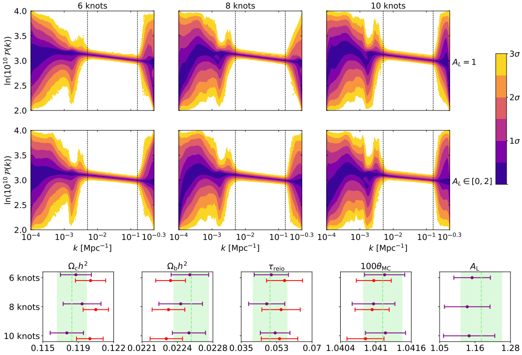


Figure: Red: reconstruction with $A_{\mathrm{L}} = 1$; purple: free A_{L}; green region: ΛCDM (power-law PPS).

- We also tested the reconstruction allowing A_{L} to vary. [Planck 2018 results X: Constraints on inflation. Domènech & Kamionkowski (2019); Ballardini & Finelli (2022)]
- In principle, features on small scales could absorb the effect of A_{L}.
- Running the free-A_{L} case against the fixed-$A_{\mathrm{L}} = 1$ case, we find that the reconstructed PPS remains unchanged between the two, and the recovered value of A_{L} is consistent as well.

PPS from inflation

- In inflationary models, curvature perturbations are generated from quantum fluctuations of the inflaton field.

$$\frac{\delta\phi}{\phi} \longrightarrow \frac{\delta\rho}{\rho} \longrightarrow \text{gauge-invariant curvature perturbations } \mathcal{R},\, \zeta$$

PPS from inflation

- In inflationary models, curvature perturbations are generated from quantum fluctuations of the inflaton field.

$$\frac{\delta\phi}{\phi} \longrightarrow \frac{\delta\rho}{\rho} \longrightarrow \text{gauge-invariant curvature perturbations } \mathcal{R},\ \zeta$$

- The background dynamics during inflation and the inflaton behavior can be parametrized through slow-roll parameters.

$$\epsilon_1 = -\frac{H'}{H^2},$$

$$\epsilon_2 \equiv \eta = \frac{d\log\epsilon_1}{dN}$$

- The slow-roll parameters and the sound speed c_s can be interpreted as generators of features in the PPS in the context of the EFT of inflation [Cheung et al. 2008]. Fourier inversion of the PPS [Palma 2014; Palma et al. 2016; Durakovic et al. 2019] relates these parameters to observable features.

$$k^3\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = -\frac{1}{4}\int_{-\infty}^{+\infty} d\tau \left[\frac{1}{8}\theta'''' + \frac{\delta_H''}{2\tau^2} - \frac{\delta_H}{\tau^4}\right]\sin(2k\tau)$$

$$\theta = 1 - c_s^2 \quad , \quad \delta_H = 3\epsilon + 3\eta/2 - \tau\eta'/2$$

PPS from inflation

- In inflationary models, curvature perturbations are generated from quantum fluctuations of the inflaton field.

$$\frac{\delta\phi}{\phi} \longrightarrow \frac{\delta\rho}{\rho} \longrightarrow \text{gauge-invariant curvature perturbations } \mathcal{R},\ \zeta$$

- The background dynamics during inflation and the inflaton behavior can be parametrized through slow-roll parameters.

$$\epsilon_1 = -\frac{H'}{H^2},$$

$$\epsilon_2 \equiv \eta = \frac{d\log\epsilon_1}{dN}$$

- The slow-roll parameters and the sound speed c_s can be interpreted as generators of features in the PPS in the context of the EFT of inflation [Cheung et al. 2008]. Fourier inversion of the PPS [Palma 2014; Palma et al. 2016; Durakovic et al. 2019] relates these parameters to observable features.

$$k^3\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = -\frac{1}{4}\int_{-\infty}^{+\infty} d\tau\ \left[\frac{1}{8}\theta'''' + \frac{\delta_H''}{2\tau^2} - \frac{\delta_H}{\tau^4}\right]\sin(2k\tau)$$

$$\theta = 1 - c_s^2 \quad , \quad \delta_H = 3\epsilon + 3\eta/2 - \tau\eta'/2$$

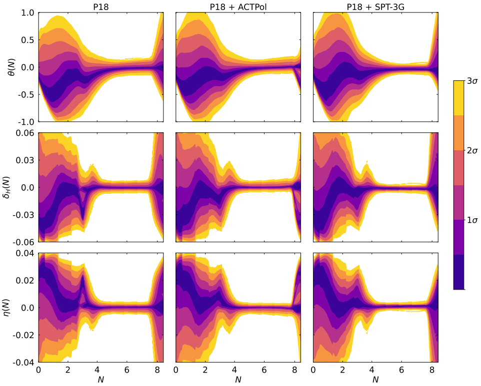
- We reconstructed the parameters emerging at first order in perturbation theory, namely ϵ, η, and c_s, the effective speed of sound of perturbations during inflation.

Reconstruction of inflationary parameters

$$k^3 \frac{\Delta \mathcal{P}}{\mathcal{P}_0}(k) = -\frac{1}{4}\int_{-\infty}^{+\infty} d\tau \left[\frac{1}{8}\theta'''' + \frac{\delta_H''}{2\tau^2} - \frac{\delta_H}{\tau^4}\right] \sin(2k\tau)$$

$$\theta = 1 - c_s^2 \quad , \quad \delta_H = 3\epsilon + 3\eta/2 - \tau\eta'/2$$

- We can separate the two components coming from variations of c_s (first row) and the slow roll parameters δ_H (second row).

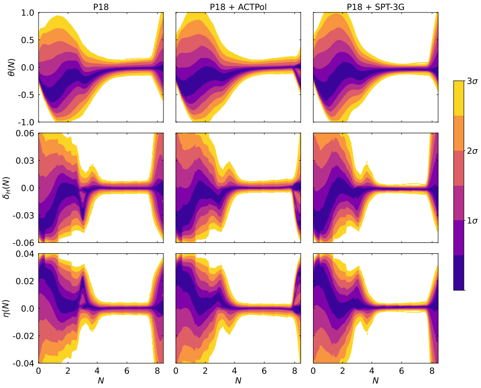


Reconstruction of inflationary parameters

$$k^3 \frac{\Delta \mathcal{P}}{\mathcal{P}_0}(k) = -\frac{1}{4}\int_{-\infty}^{+\infty} d\tau \left[\frac{1}{8}\theta'''' + \frac{\delta_H''}{2\tau^2} - \frac{\delta_H}{\tau^4}\right] \sin(2k\tau)$$

$$\theta = 1 - c_s^2 \quad , \quad \delta_H = 3\epsilon + 3\eta/2 - \tau\eta'/2$$

- We can separate the two components coming from variations of c_s (first row) and the slow roll parameters δ_H (second row).
- We then studied the case of sudden variations of the background during inflation $\theta = 0, \eta' \gg \eta, \epsilon$ and neglect subdominant terms (third row).



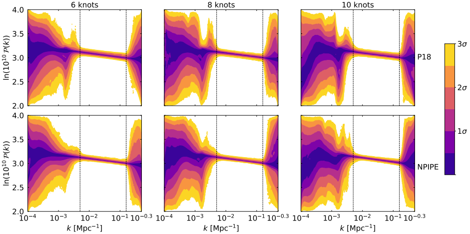
Conclusion

- We studied the reconstruction of the PPS and compared the reconstruction obtained with different datasets.
- We reconstructed parameters in the EFT of inflation: effective speed of sound and slow-roll parameters.
- We reconstructed the scalar spectral index. In principle it is possible to reconstruct the running of n_s, although one must be careful with the reconstruction method.

- AD Currently looking for a PostDoc!
- Main interests are initial conditions and extended cosmological models:
  - Features in primordial power spectrum from combined analysis of CMB and LSS
  - Running of the scalar spectral index from LSS
  - Cosmic Neutrino Background anisotropies

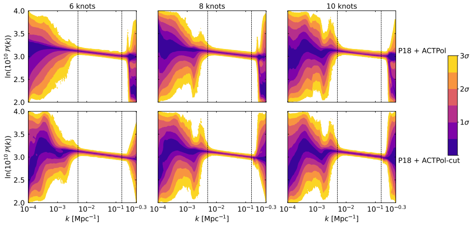
Thanks!

Comparison between *Planck* PR3 and *Planck* PR4



- We did a comparison between reconstruction with PR4 (indicated as NPIPE [Delouis et al 2019, Rosenberg et al 2022, Carron et al 2022]) and PR3 (indicated as P18) Planck data.
- We observe no significant difference between the two other than a little smoothing of the bump present at $k \sim 10^{-2.8}$ Mpc^{-1}.

ACT dataset cut



- Knot reconstruction is sensitive to features in datasets;
- We observed a weird behaviour at small scales when using ACTPol likelihood.
- We cut the last 4 datapoints and compared the reconstruction.
- We see how reconstruction changes when we do not include the last points even at large scales.

Cosmological parameters posteriors

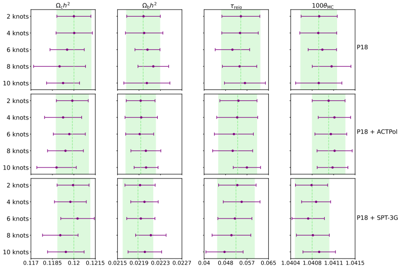


Figure: Posteriors on cosmological parameters for logarithmic sampling.

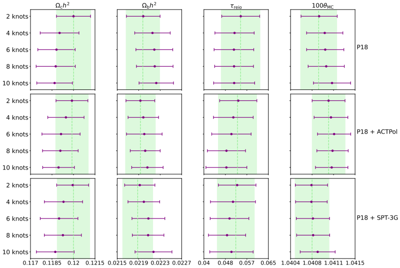


Figure: Posteriors on cosmological parameters for linear sampling.