



Inference from large-angular scale CMB data

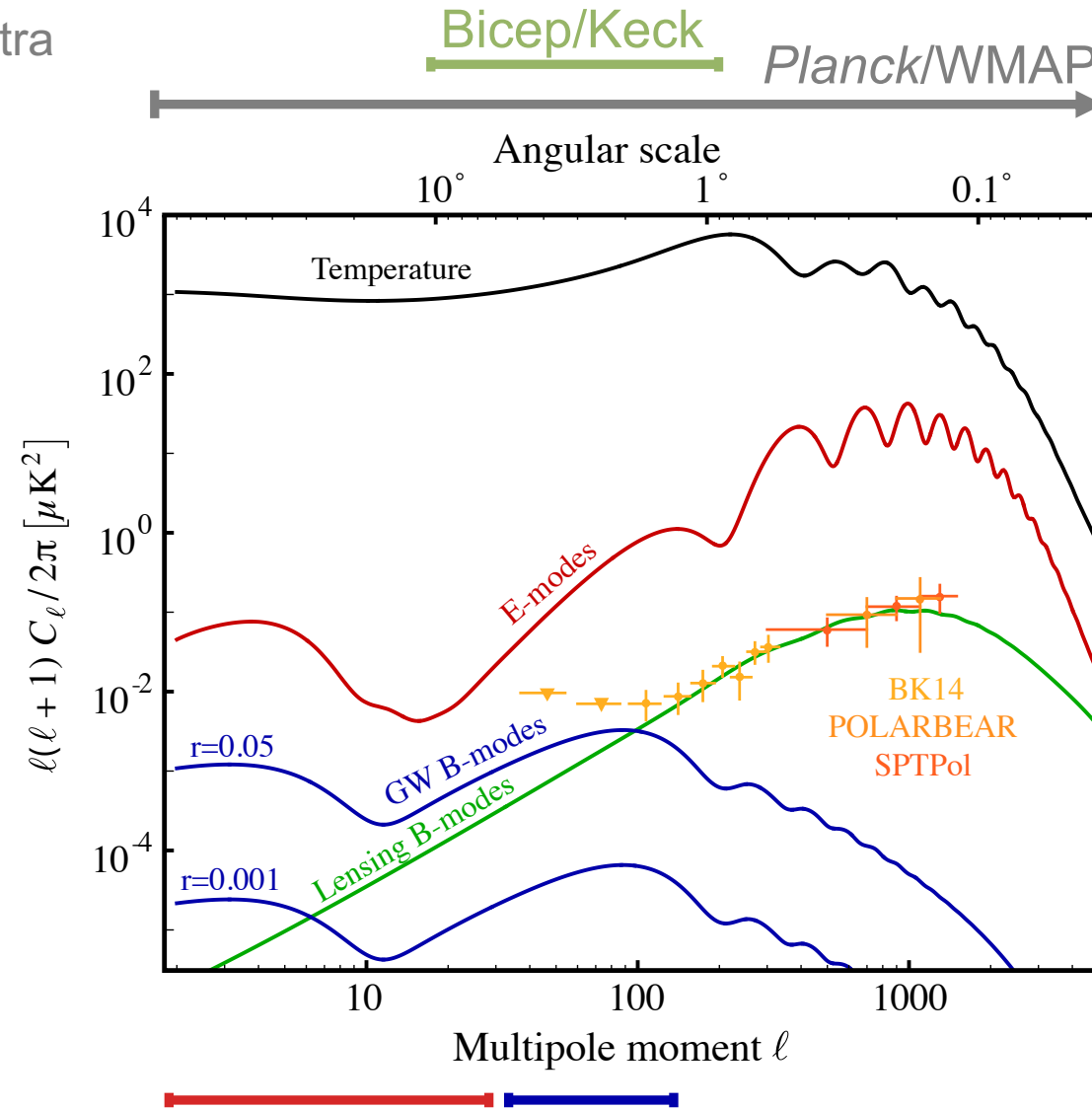
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+ **Steven Gratton, Will Coulton, George Efstathiou**

24.05.2022, *From Planck to the future of CMB* – Ferrara, Italy

E & B modes

Theory angular power spectra



reionization bump: $2 \leq \ell \lesssim 30$ recombination bump: $30 \lesssim \ell \lesssim 150$

Probe early Universe physics

Λ CDM 6-parameter model

¹ Lyth (1985)

1. Probe reionization

- Optical depth to reionization τ
- Sum of neutrino masses M_ν

2. Probe inflation

- Amplitude and spectral index of primordial power spectrum

$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_*} \right)^{n_s-1}, \quad \mathcal{P}_t(k) = A_t \left(\frac{k}{k_*} \right)^{n_t}$$

- Tensor-to-scalar ratio (single-field slow-roll inflation): $r = \frac{A_t}{A_s}$
- Energy scale of inflation¹

$$V^{1/4} \approx 1.04 \times 10^{16} \text{ GeV} \left(\frac{r}{0.01} \right)^{1/4}$$

Challenges for cosmological inference

Large angular scale CMB data

¹ *Planck* Collaboration XLVI (2016)

² *Planck* Collaboration VI (2020)

³ *Page et al.* (2007)

⁴ *Pagano et al.* (2020)

⁵ *BeyondPlanck XII.* (2022)

⁶ *Tristram et al.* (2020, 2021)

⁷ *Beck et al.* (2022)

⁸ *Campeti et al.* (2022)

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Optical depth to reionization¹⁻⁵

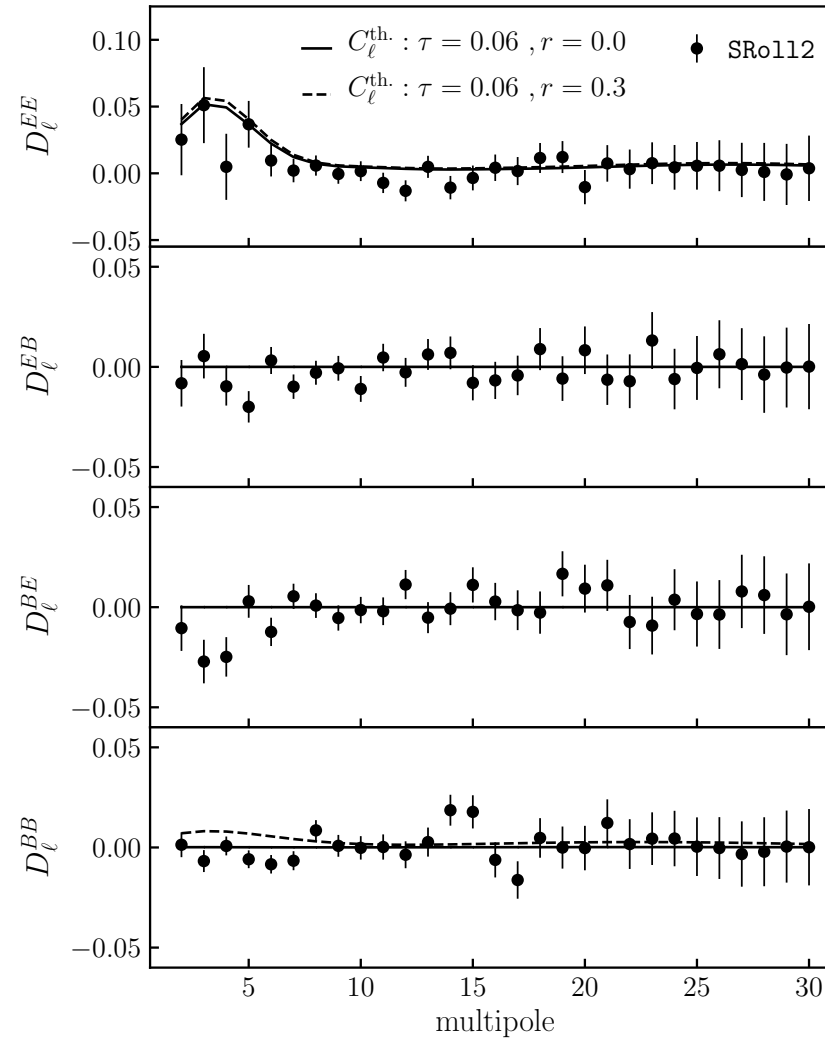
- ✓ signal-dominated at lowest multipoles
 - EE + TE + TT spectrum
- ✗ Systematics render signal non-Gaussian
 - Need robust likelihoods
- ✓ Galactic polarised foregrounds
 - Spatially uniform template cleaning sufficient

Primordial gravitational waves⁶⁻⁸

- ✗ Tiny signal amplitude compared to contaminants
 - EE + EB + BB spectrum
- ✗ Systematics render signal non-Gaussian
 - Need robust likelihoods
- ✗ Galactic polarised foregrounds
 - Sensitivity to spatially varying foregrounds

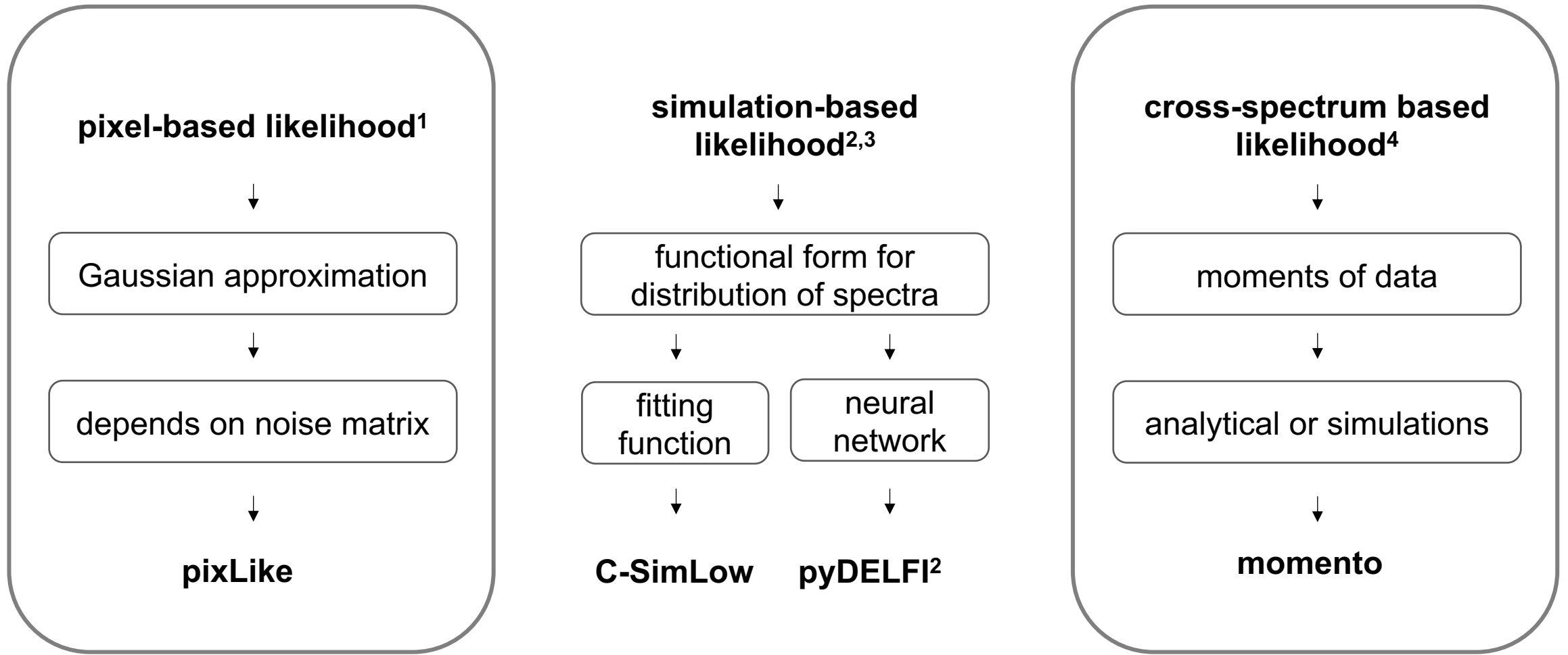
Large angular scale CMB data

Quadratic cross-spectrum estimate



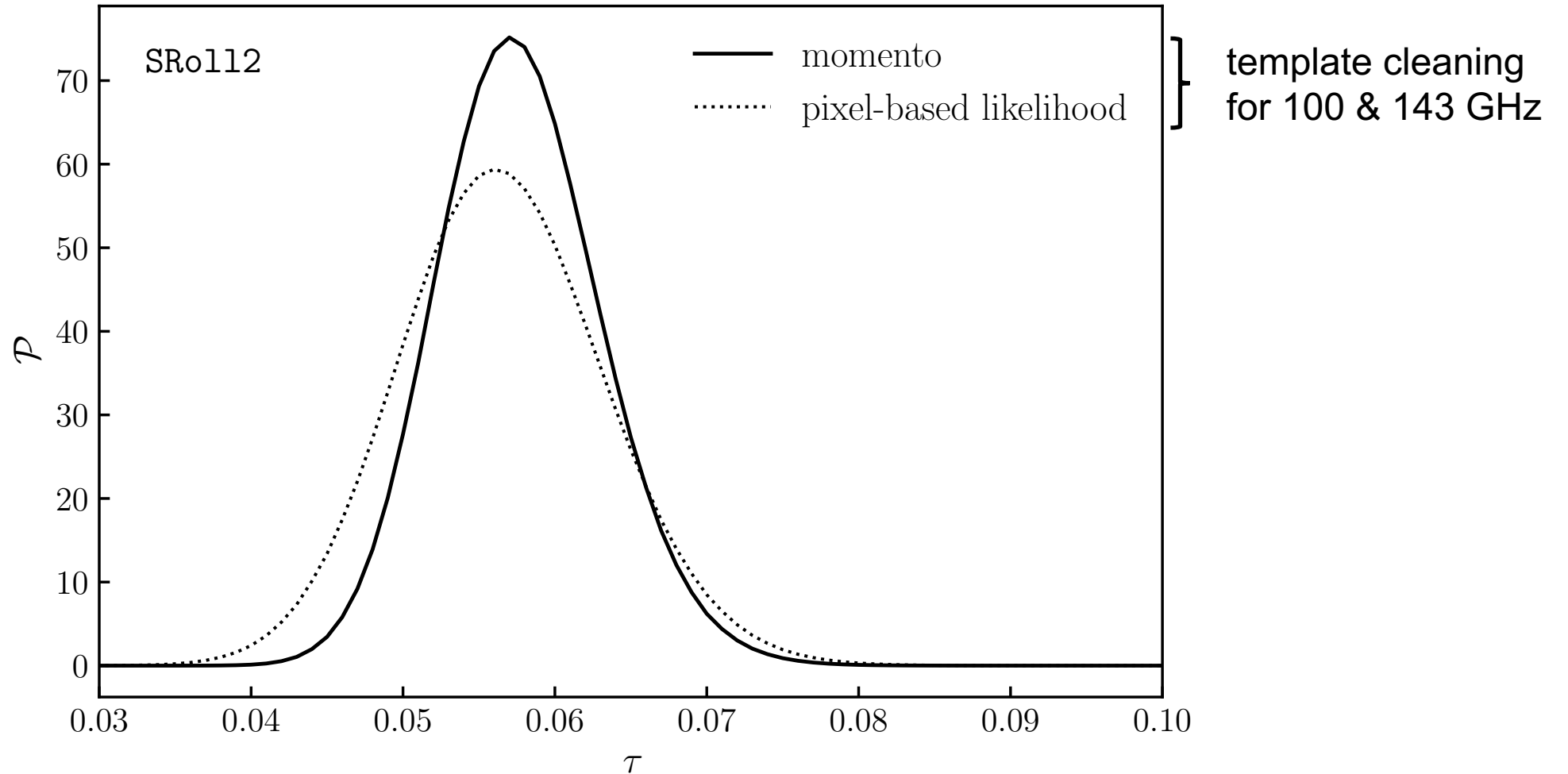
Comparison of likelihoods

- ¹ Page et al. (2007)
- ² *Planck* Collaboration XLVI (2016)
- ³ Alsing et al. (2018)
- ⁴ Gratton (2017)



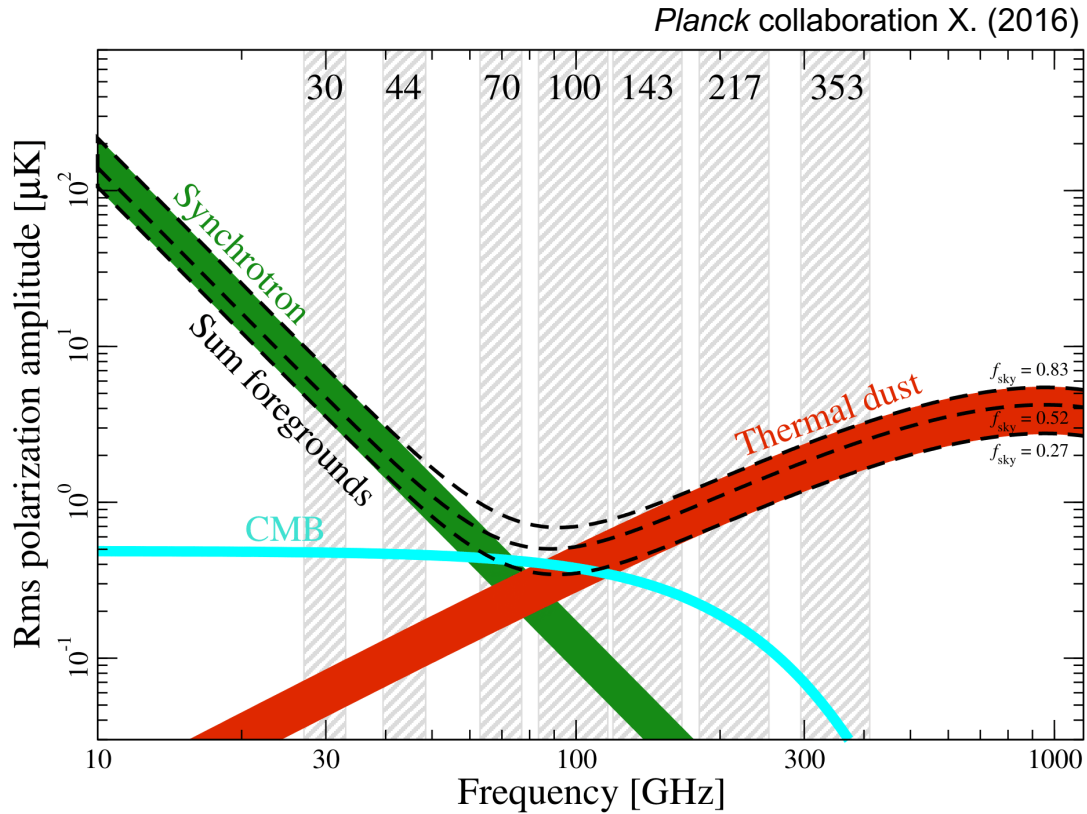
Robust inference of optical depth

Spatially-uniform foreground cleaning

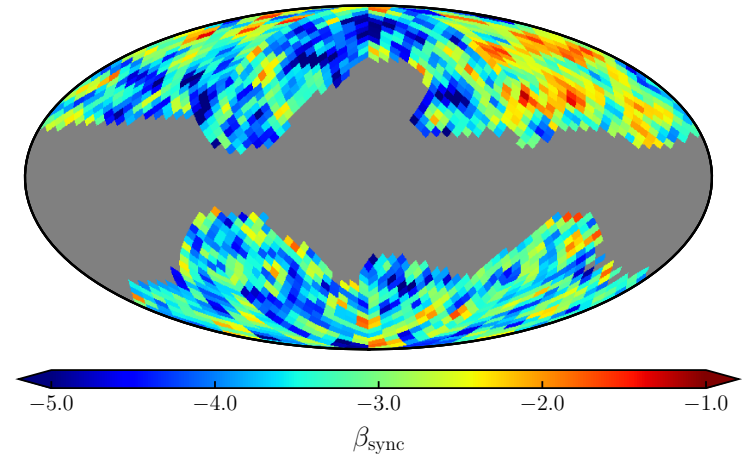


Galactic polarised foregrounds

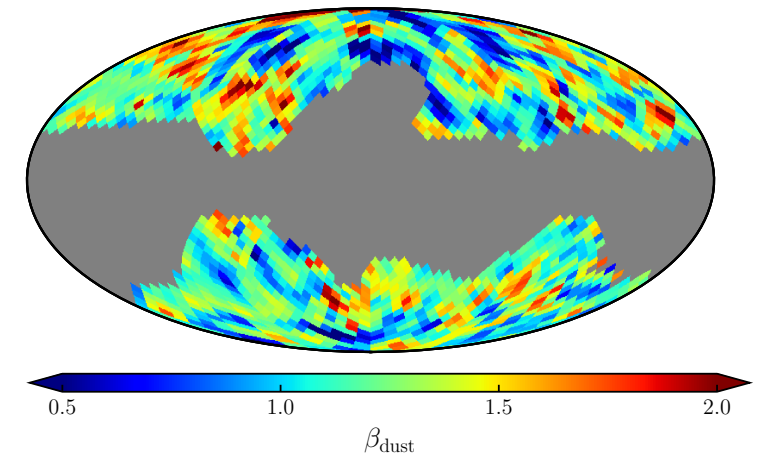
Evidence for spectral index variations in synchrotron



$$\beta_{\text{sync}} = -2.9 \pm 0.7$$

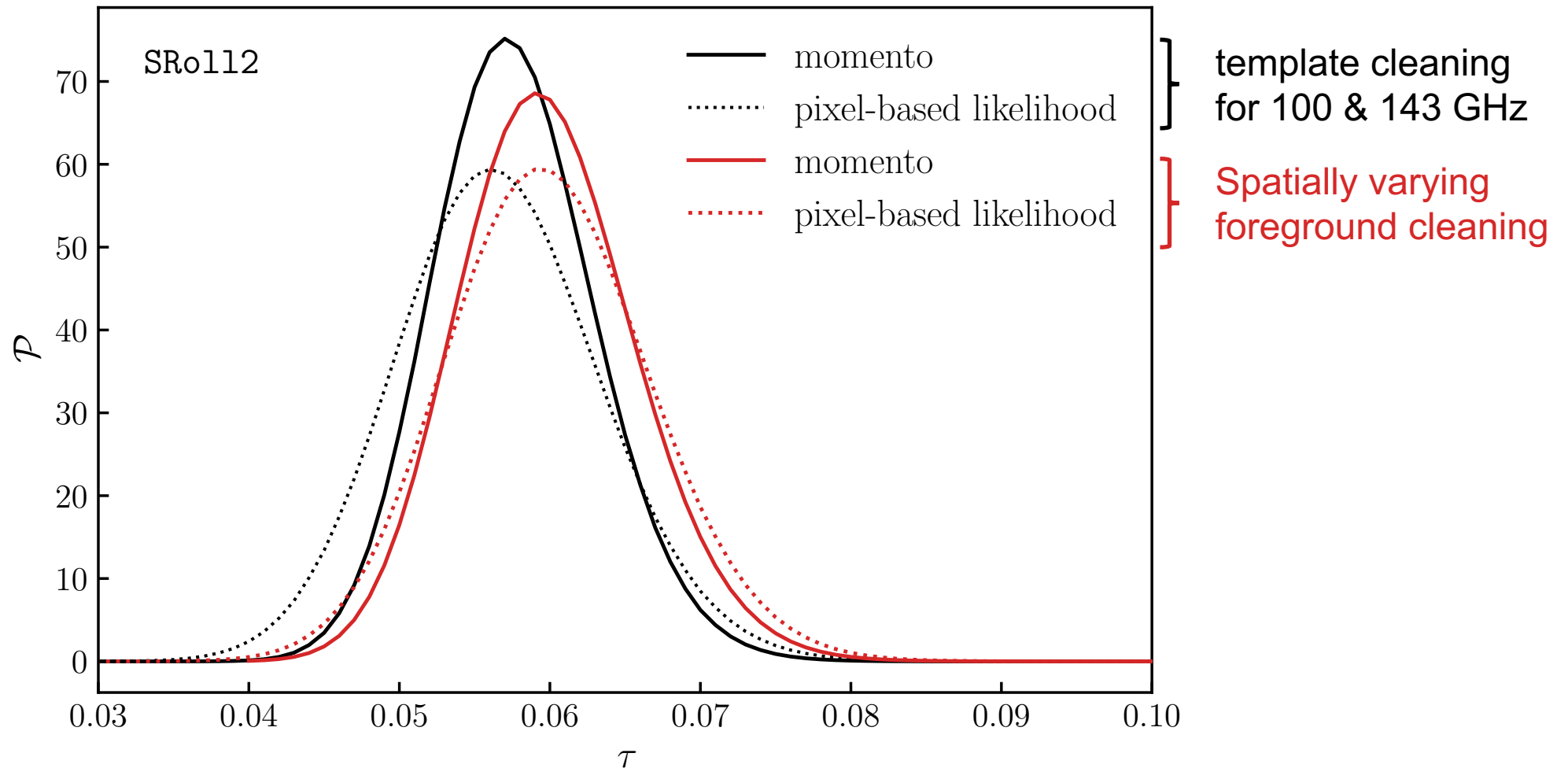


$$\beta_{\text{dust}} = 1.4 \pm 0.3$$



Robust inference of optical depth

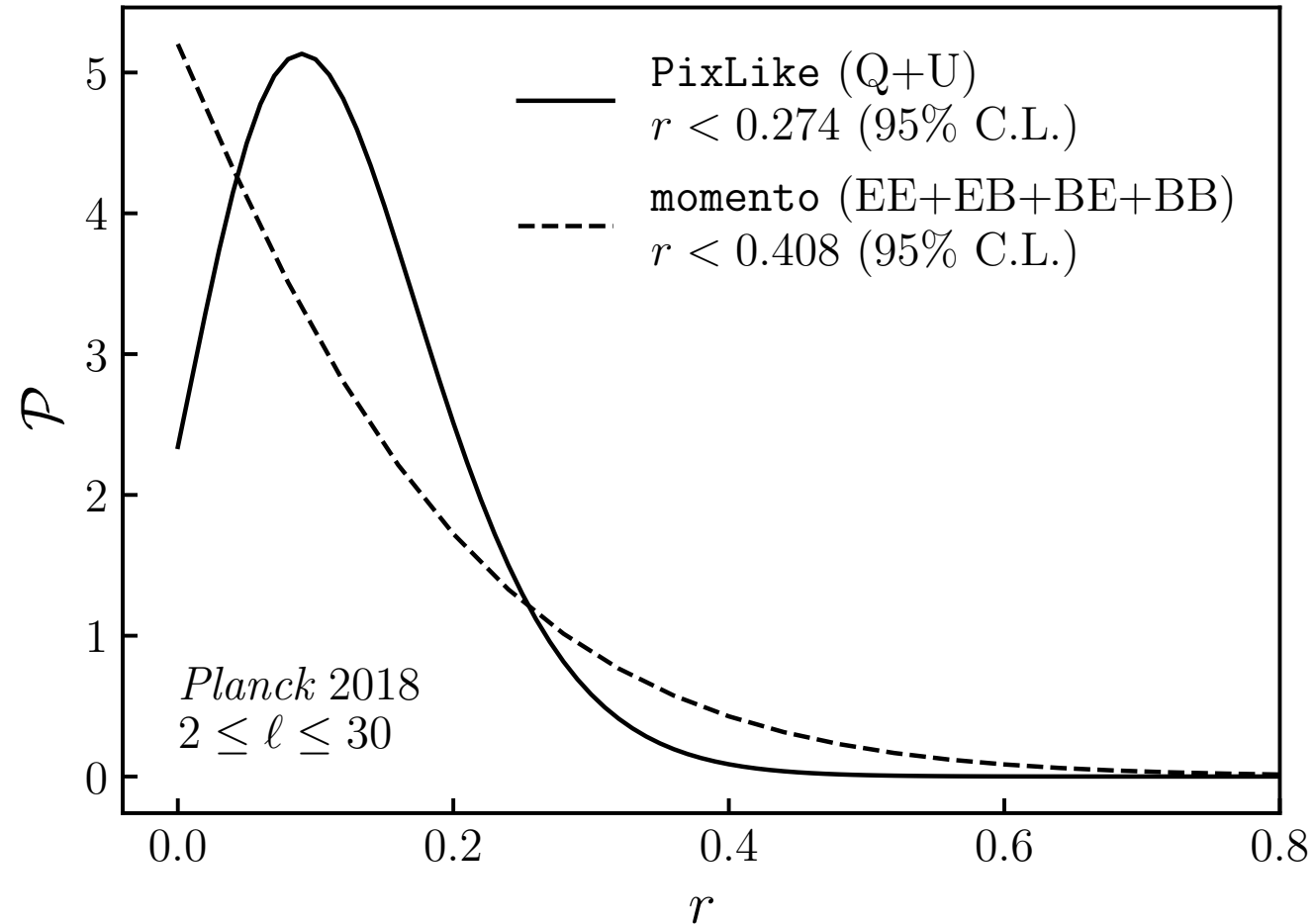
Evidence for spatially varying synchrotron spectral indices



τ constraints not sensitive to spatially varying polarized foregrounds ($<0.5\sigma$)

Tensor-to-scalar ratio r from reionization bump

Spatially varying foreground cleaning allows to measure signal



Planck low- ℓ polarization data loosely constrains the tensor-to-scalar ratio

Conclusion & next steps

Please get in touch if you want to chat more! (rmvd2@cam.ac.uk)

- Cosmological parameter estimation
 - Optical depth to reionization: τ
 - Primordial B -modes: r

	$2 \leq \ell \leq 30$	$2 \leq \ell$
τ	0.0581 ± 0.0055	$0.0627^{+0.0050}_{-0.0058}$
r	< 0.4 (95% C.L.)	?

- Low- ℓ inference pipeline for next-generation CMB satellites (LiteBIRD)
 - Galactic polarised foregrounds \rightarrow noise & systematics \rightarrow robust likelihoods
- Method applicable to cosmic birefringence
 - Accurate EB-BE cross-spectra required

Reached limit of low- ℓ *Planck* polarization data