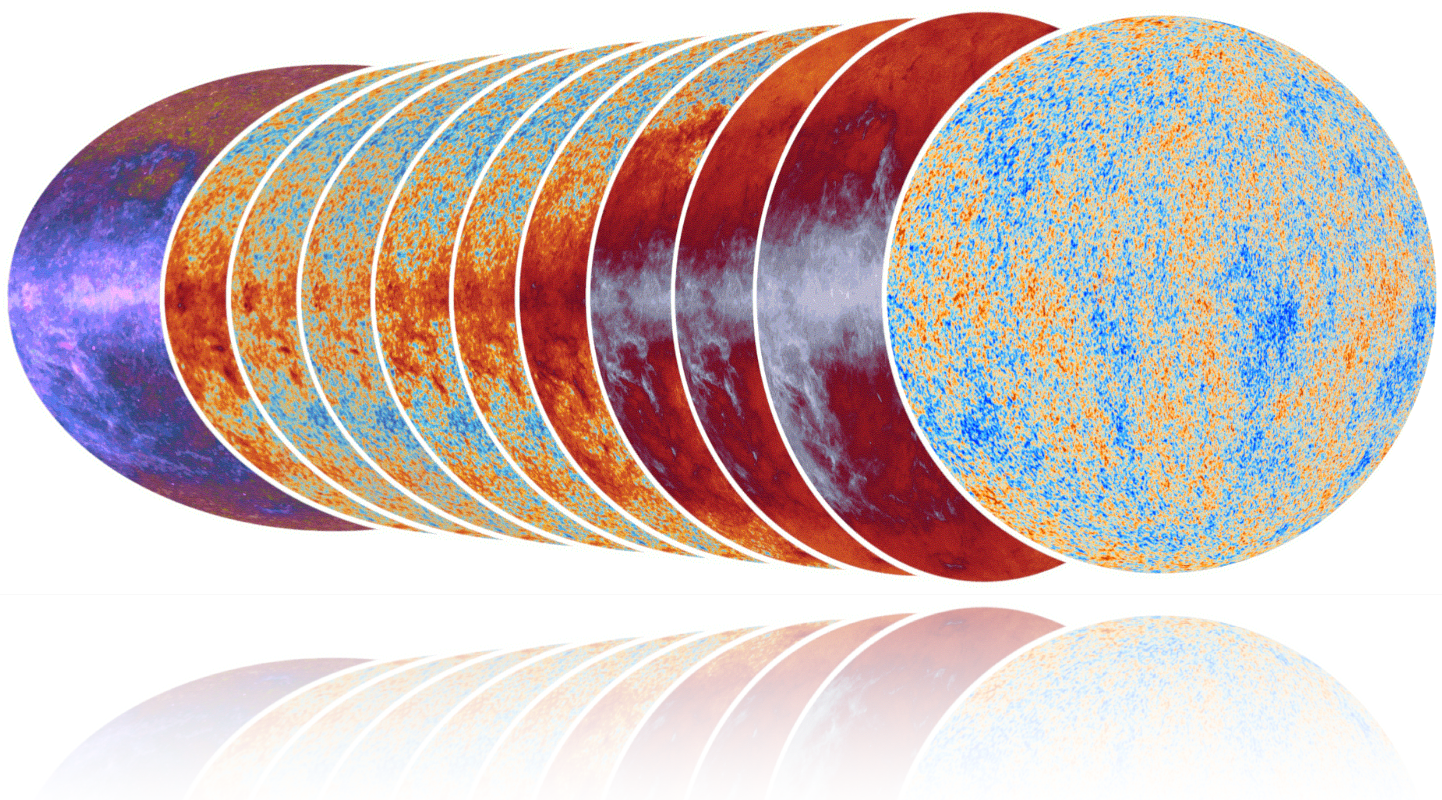

Planck constraints on the tensor-to-scalar ratio

Matthieu TRISTRAM
CNRS

team work

Planck constraints on the tensor-to-scalar ratio

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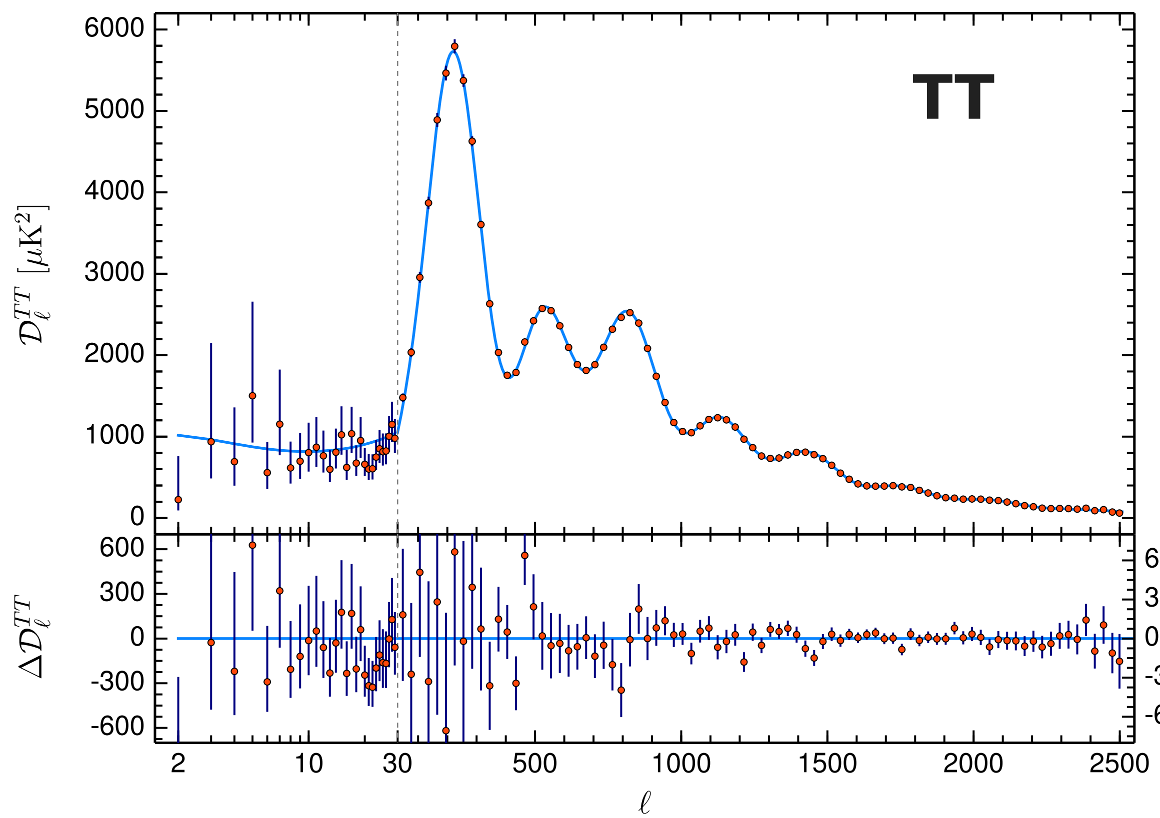
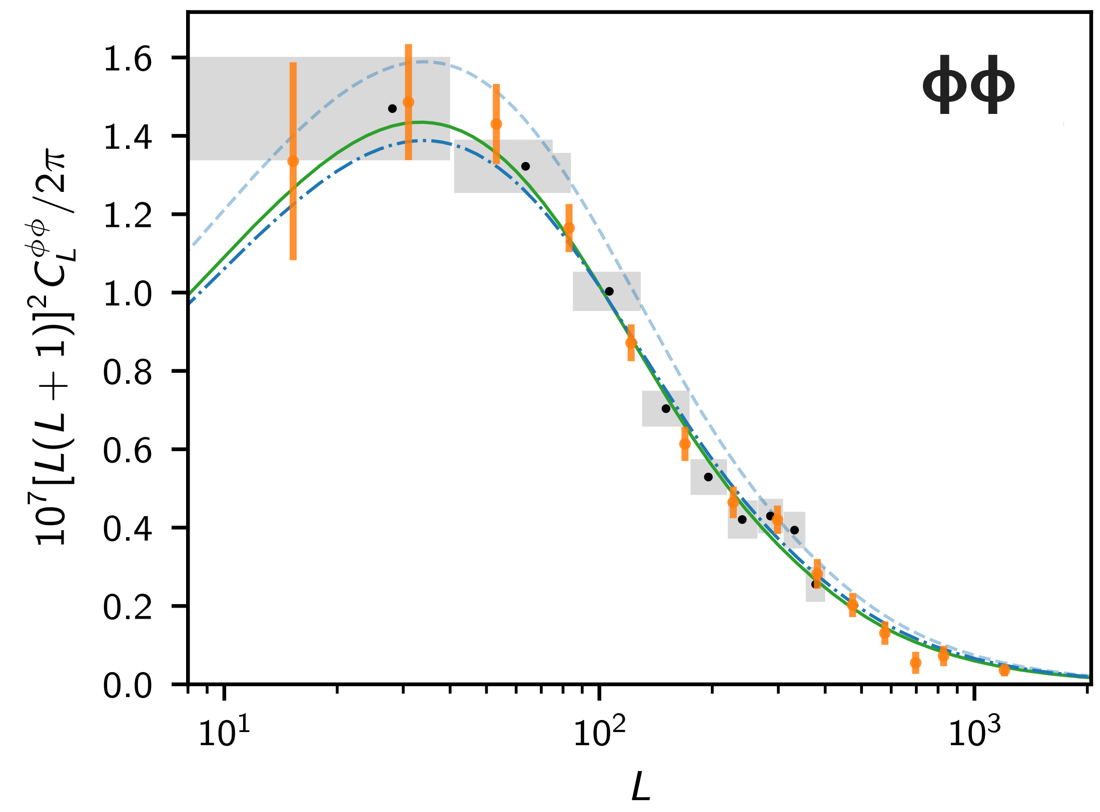
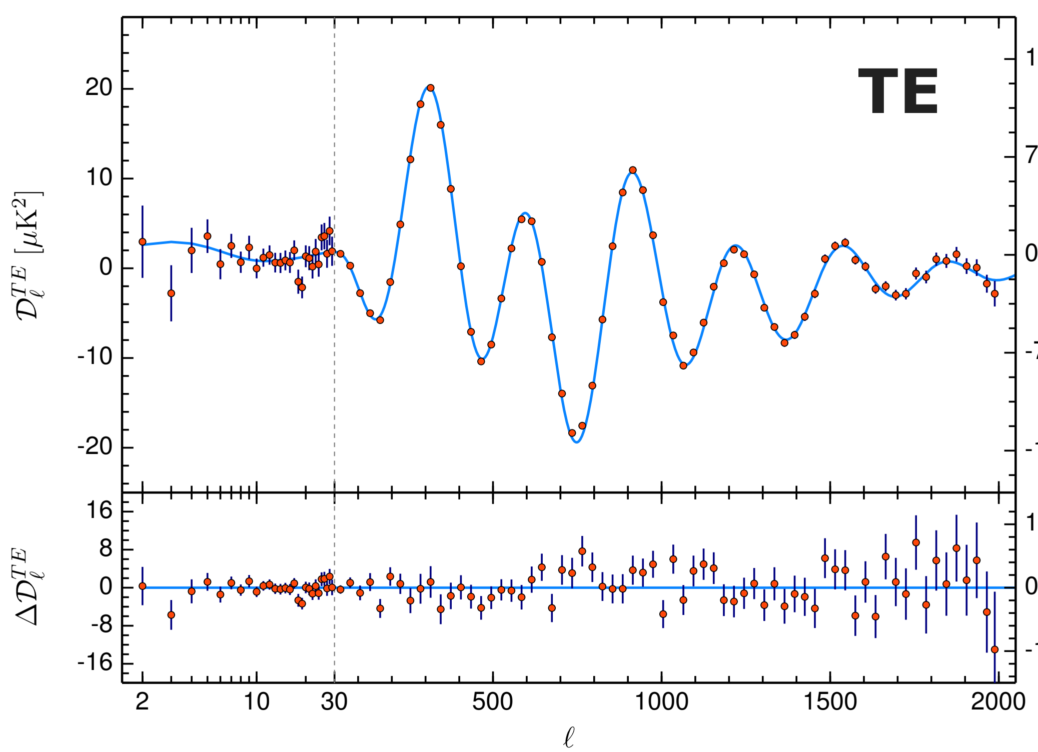
astro-ph/2010.01139

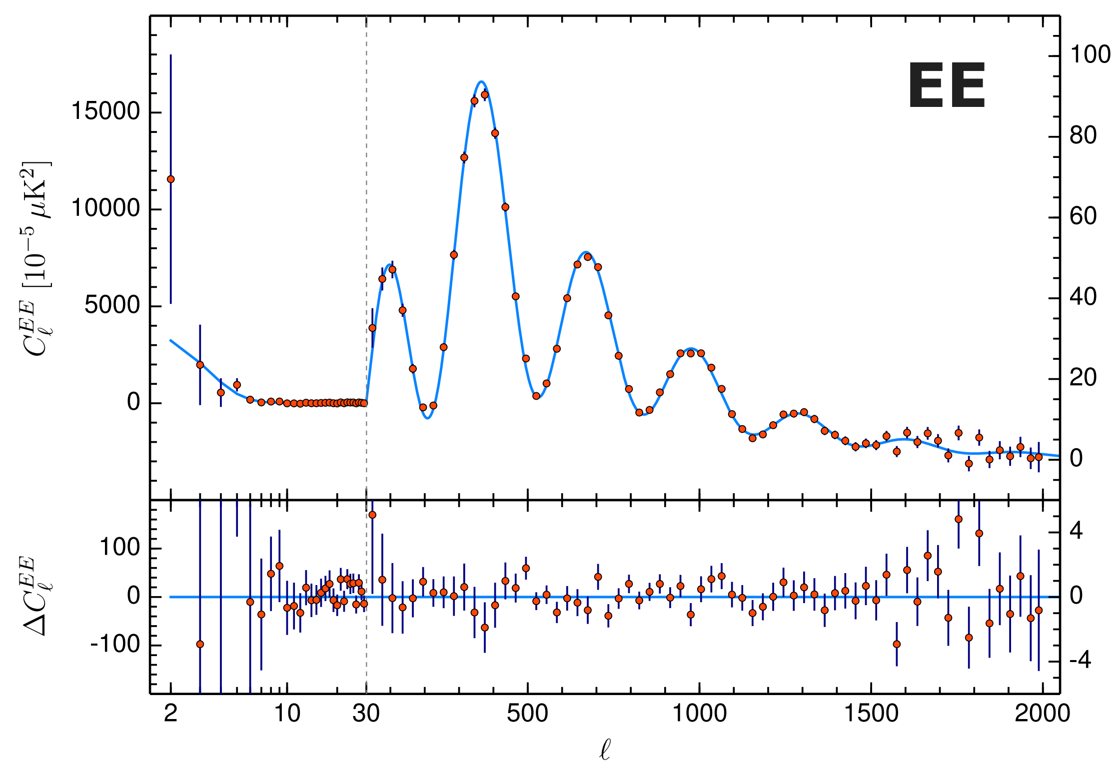
CMB power spectra

[Planck 2018 results. VI]
[Planck 2018 results. VIII]









ΛCDM

- **6 parameters**
  - 2 for the primordial matter spectrum

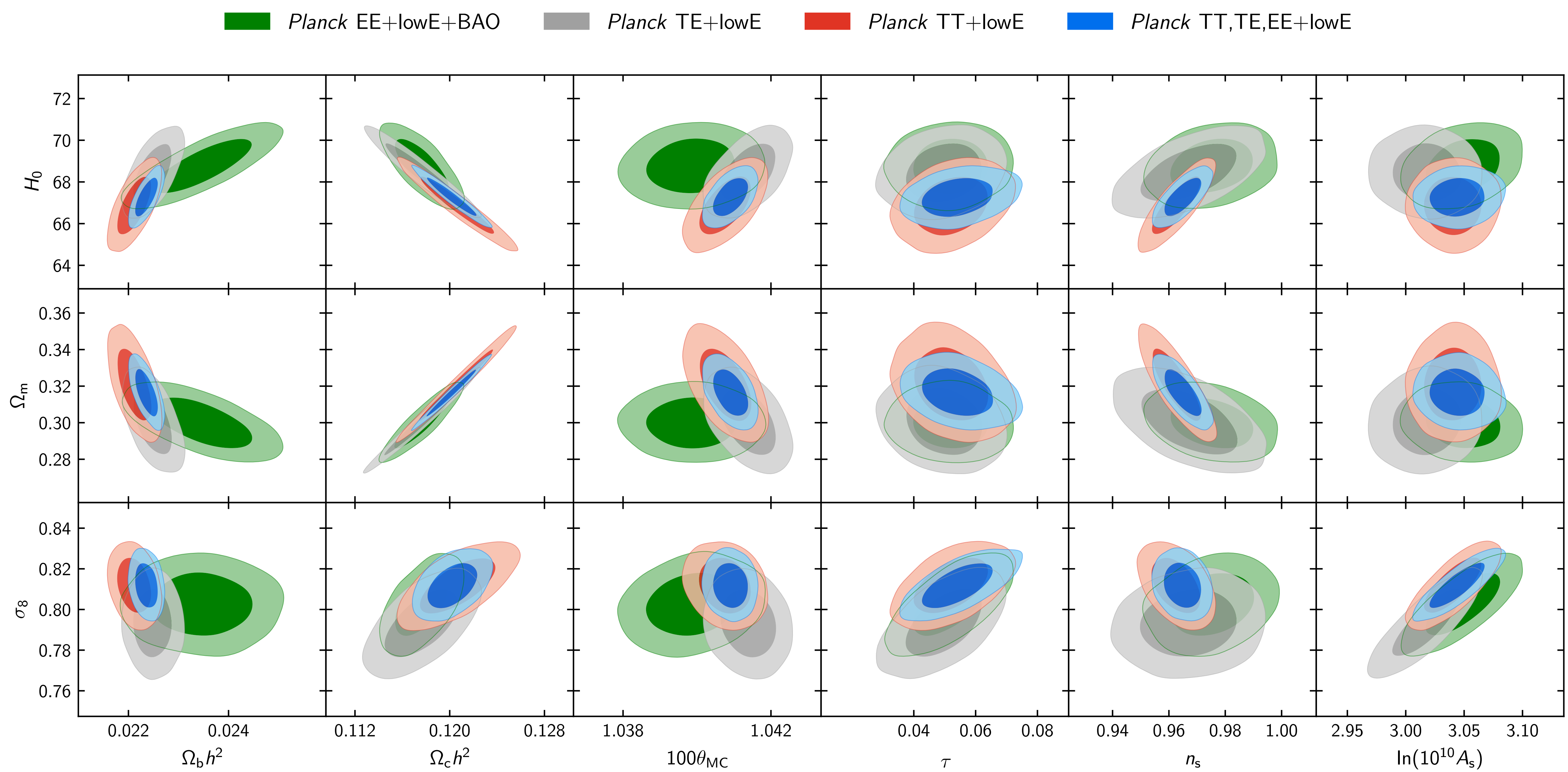
$$\mathcal{P}_{\mathcal{R}}(k) = \boxed{A_s} \left(\frac{k}{k_0}\right)^{\boxed{n_s}-1}$$

  - 1 expansion rate $\boxed{H_0}$ (in practice sound horizon $\boxed{\theta_s}$)
  - 2 parameters for densities $\boxed{\Omega_b h^2}$ $\boxed{\Omega_c h^2}$
  - reionization $\boxed{\tau}$

- **hypothesis (released in the extensions to ΛCDM)**
  - flat Universe $\Omega_k = 0$
  - No running $dn_s/d\ln k = 0$
  - No tensor $\mathcal{P}_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} = 0$
  - 3 neutrinos $N_{\mathrm{eff}} = 3.046$
  - standard neutrinos with low mass $\sum m_\nu = 0.06\ eV$

ΛCDM results
with spectra

[Planck 2018 results. VI]



polarization spectra TE and EE are generally highly consistent with TT spectrum

ΛCDM results
with time

	WMAP	Planck 2013	Planck 2015	Planck 2018
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205 ± 0.00028	0.02225 ± 0.00016	0.02236 ± 0.00015
$\Omega_c h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1198 ± 0.0015	0.1202 ± 0.0014
H_0	70.0 ± 2.2	67.3 ± 1.2	67.27 ± 0.66	67.27 ± 0.60
n_s	0.972 ± 0.013	0.960 ± 0.007	0.964 ± 0.005	0.965 ± 0.004
$10^9 A_s$	2.189 ± 0.090	2.196 ± 0.060	2.207 ± 0.074	2.101 ± 0.033
τ	0.089 ± 0.014	0.089 ± 0.014	0.079 ± 0.017	0.054 ± 0.007
Ω_Λ	0.721 ± 0.025	0.685 ± 0.018	0.684 ± 0.009	0.685 ± 0.007
Ω_m	0.279 ± 0.023	0.315 ± 0.018	0.316 ± 0.009	0.315 ± 0.007

- **Very stable with time**
- **Precision cosmology (below 1% error bar for most of them)**

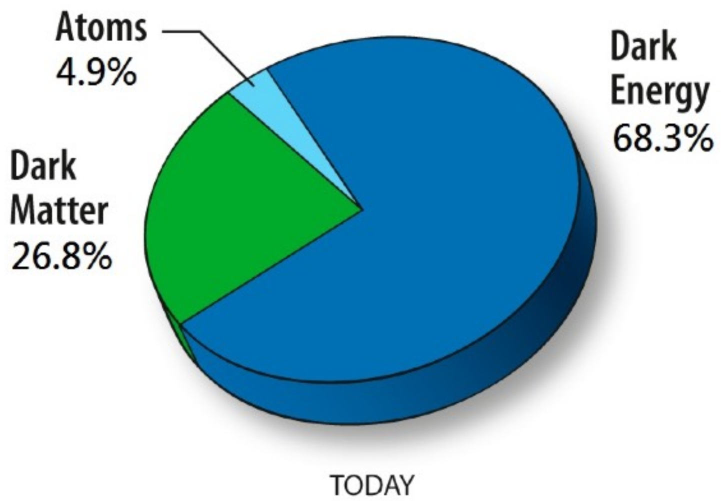
ΛCDM

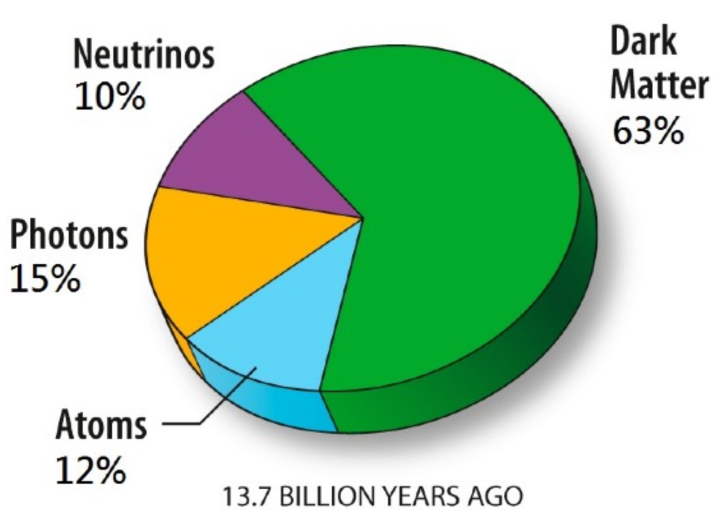
- **Consistency**
  The **CMB anisotropies** in temperature and polarisation (TT, TE, EE), **CMB lensing** ΦΦ, as well as **BAO**, **BBN**, and **SNIa** measurements are all consistent, among themselves and across experiments, within ΛCDM

- **Robustness**
  These probes allow many different checks of the robustness for the ΛCDM model and some of its extensions, including **flatness**, sum of **neutrinos masses** and **effective number**, **DM annihilation** limits, **dark energy** equation of state w(z), details of the **recombination** history ($A_{2s\to1}$, T_0, and also fundamental constants variation, or any energy input...)

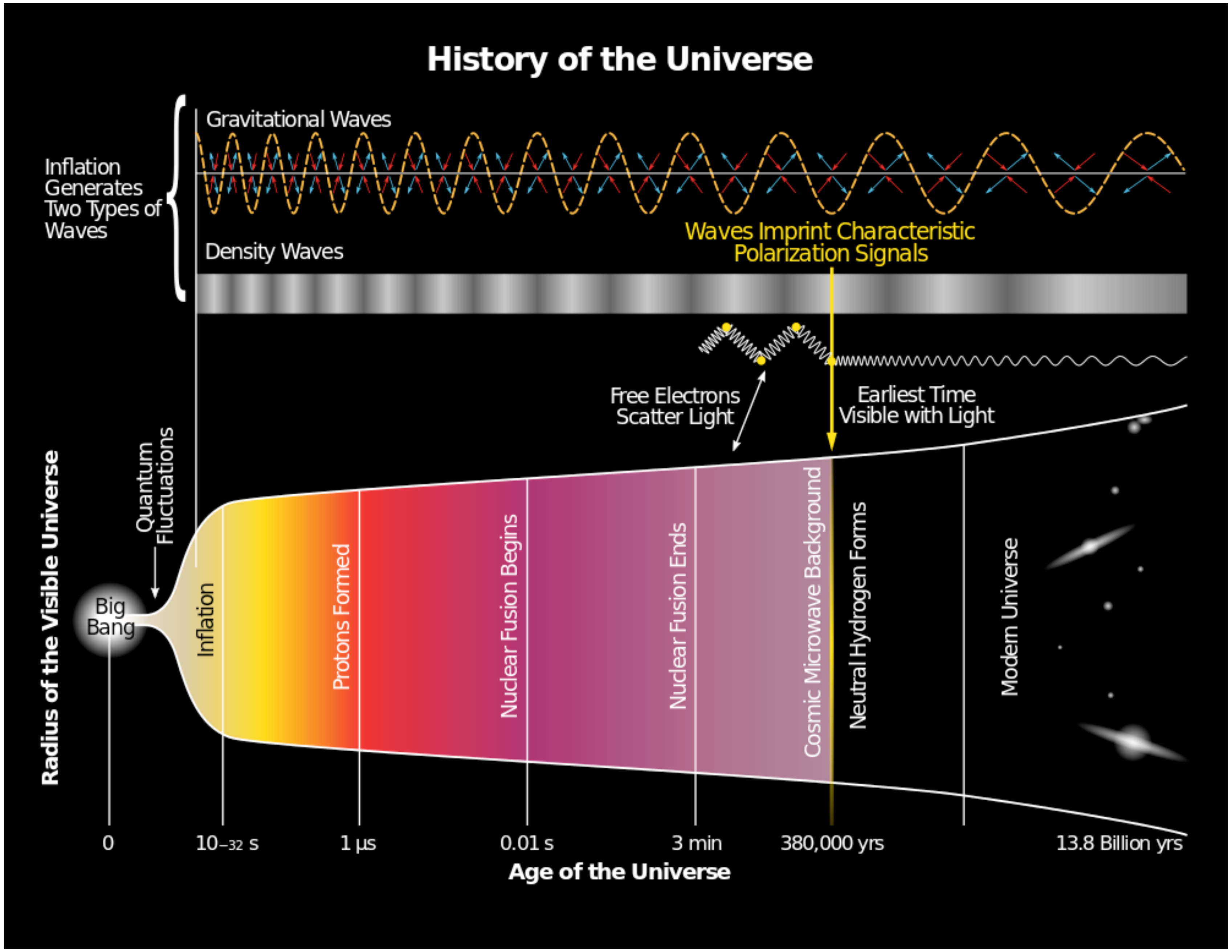
- **Precision**
  This network of consistency tests is passed with **per cent** level precision but for relative **tensions** (including A_L, H_0, S_8)

Parameter	TT,TE,EE+lowE+lensing 68% limits	
$\Omega_b h^2$	0.02237 ± 0.00015	**0.7%**
$\Omega_c h^2$	0.1200 ± 0.0012	**1.0%**
$100\theta_{MC}$	1.04092 ± 0.00031	**0.03%**
τ	0.0544 ± 0.0073	**13%**
$\ln(10^{10} A_s)$	3.044 ± 0.014	**0.5%**
n_s	0.9649 ± 0.0042	**0.4%**





Inflation



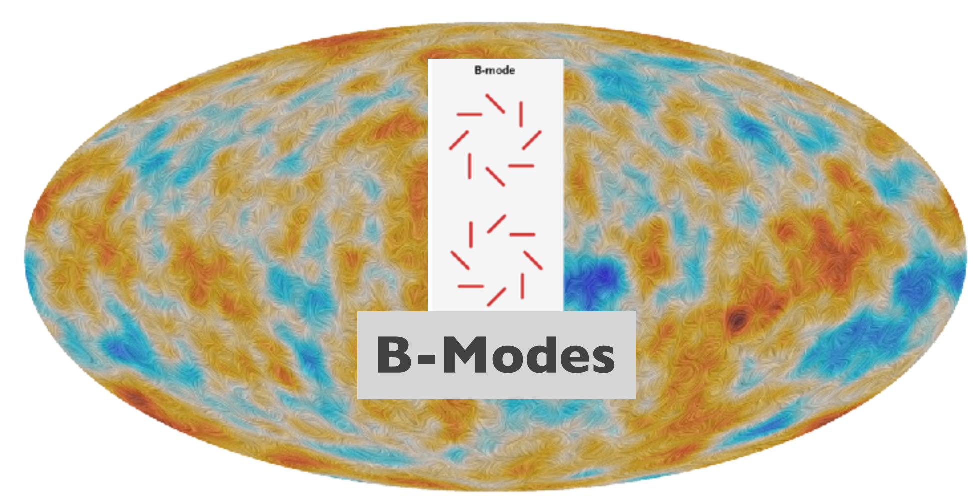
quantum fluctuations of spacetime

⇩ **Inflation**

primordial gravitational waves

⇩

imprints on the CMB
(B-modes: "vortex" in polarization)



Opportunity to probe the Cosmic Inflation but also to shed light on GUT-scale physics

Observational test of quantum gravity

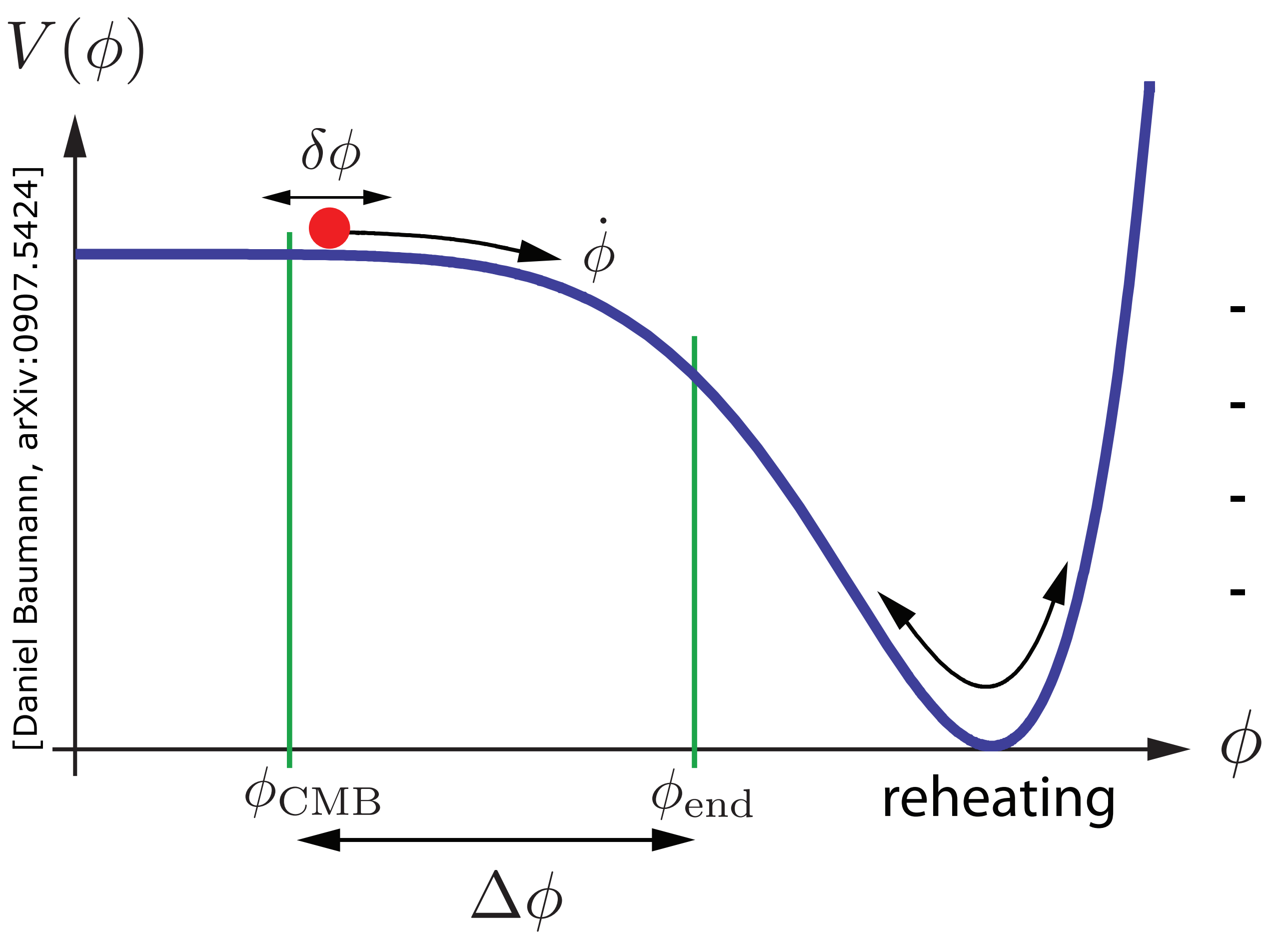
Inflation

inflation ϕ

- **dynamics of an homogeneous scalar field in a FRW geometry is given by**

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0 \qquad \text{and} \qquad H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

- **inflation happen when potential dominates over kinetic energy (slow-roll)**



- where did **V(Φ) comes from** ?
- why did the field start in **slow-roll** ?
- why is the potential so **flat** ?
- how do we convert the field energy into **particules** ?

Inflation

- **According to single field, slow-roll inflationary scenario, quantum vacuum fluctuations excite cosmological scalar and tensor perturbations**

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{\boxed{n_s}-1} \quad \text{scalar}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} \quad \text{tensor}$$

- **with the definition of the tensor-to-scalar ratio "r"** $\boxed{r} = A_t/A_s$

Inflation

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- **with the definition of the tensor-to-scalar ratio "r"** $\boxed{r} = A_t/A_s$

which characterises the amplitude of GW and gives direct constraints on the shape of the potential

- **energy scale of inflation**

$$V^{1/4}(\phi) \simeq 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

- **inflaton field excursion**

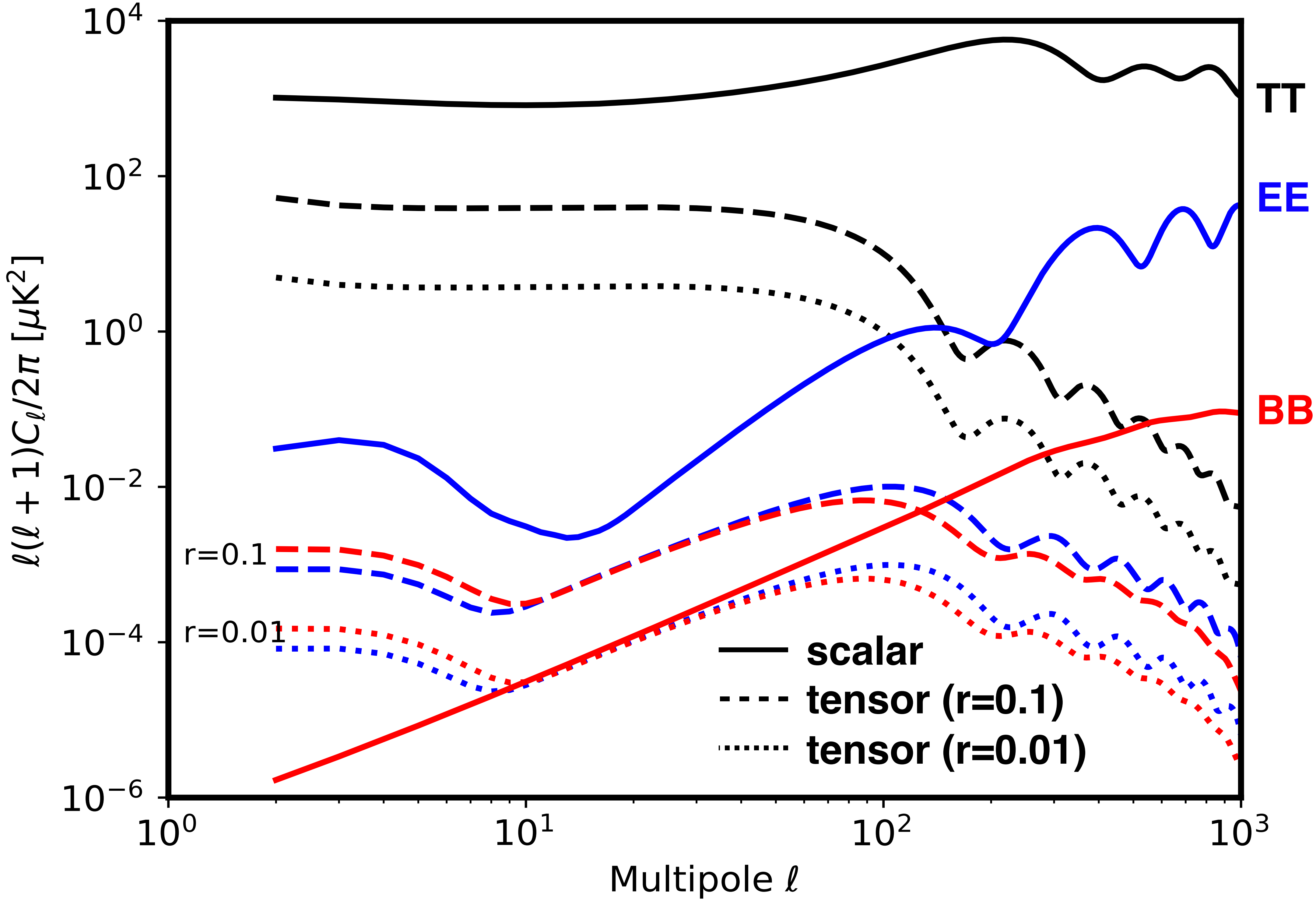
$$\frac{\Delta\phi}{M_P} \simeq \mathcal{N}_* \left(\frac{r_*}{8}\right)^{1/2} \simeq \left(\frac{r}{0.001}\right)^{1/2}$$

- **derivative of the potential**

$$r = 8M_{\mathrm{Pl}}^2\left(\frac{V_\phi}{V}\right)^2$$

$$n_{\mathrm{s}} - 1 \equiv \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k} \simeq -3M_{\mathrm{Pl}}^2\left(\frac{V_\phi}{V}\right)^2 + 2M_{\mathrm{Pl}}^2\frac{V_{\phi\phi}}{V}$$

Scalar v.s. Tensor fluctuations



Planck polarization

Planck provides full sky measurements of the polarized sky in 7 bands from 30 to 353GHz

- **Cosmological Parameters** [Planck 2018 results. V. (2020)]
  - consistency with LCDM model fitted on TT
  - break degenereacies with EE spectrum
  - add sensitivity with TE spectrum

- **Reionization history** [Planck intermediate results. XLVII (2016)]
  - Planck measured reionization optical depth accurately (or zre given a simple model)
  - but also go beyond and give constraints on ionization fraction evolution models

- **Foregrounds**
  - essential for large scale measurements
    - at low frequency : Synchrotron
    - at high frequency : Dust

[Planck 2015 results. X. (2016)]
[Planck 2015 results. XXV. (2016)]
[Planck Intermediate results. XXX (2016)]
...

Planck polarization

Planck provides full sky measurements of the polarized sky in 7 bands from 30 to 353GHz

this work

[Tristram et al. (2020), astro-ph/2010.01139]

- **Tensor modes**
  - Constraints from TT power spectrum **[Planck 2018 results. X. (2020)]**
  - Polarisation sensitivity is not at the level of ground-based measurements
  - But Planck is able to give constraints on tensor modes in **BB spectrum** both
    - at the reionization bump (ℓ =2-30)
    - at the recombination bump (ℓ =50-150)
  - reduce the upper limit on **tensor-to-scalar ratio** using EE-BB-EB spectra

Status of PLANCK polarization data

- Planck detectors are sensitive to **one polarization direction**

- Planck scanning strategy do not allow for polarization reconstruction for each detector independently

  ➡ need to **combine detectors** with different polarization orientation

- Any flux **mismatch** between detectors will create spurious polarization signal through well known **I-to-P leakage**.
  In particular : ADC non-linearity, bandpass mismatch, calibration mismatch, …

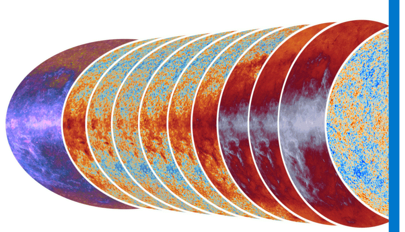
this is the major systematic in polarization at large scales

- We performed a lot of **consistency checks** in order to assess the impact on cosmological parameters
  - the radiometer from LFI have shown negligible residuals with respect to noise
  - the bolometer from HFI are more sensitive but show some residuals at the level of the noise

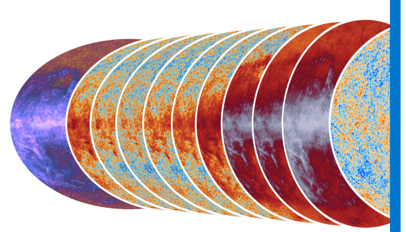
Planck Releases

[Planck Collaboration Int. LVII (2020)]

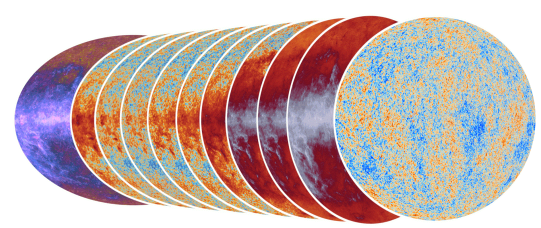
PR1
2013



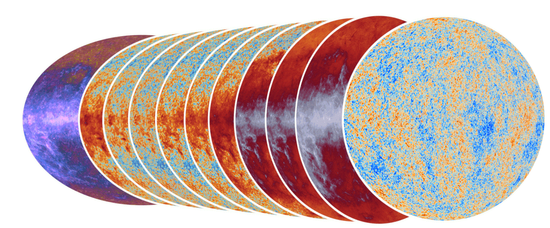
PR2
2015



PR3
2018



PR4
2020
"NPIPE"



Planck Release 4

NPIPE processing

NEW

- **Processing applied consistently over the whole 9 Planck frequencies (from 30 GHz to 857 GHz)**
- **NPIPE map-making includes templates for**
  - systematic effects
    (time transfer-function, ADC non-linearities, Far Side Lobes, bandpass-mismatch)
  - sky-asynchronous signals (orbital dipole, zodiacal light)
- **Provide frequency maps**
  - **cleaner**: less residuals (compared to PR3)
  - more accurate: **less noise** (compared to PR3)
  - no residuals from template resolution mismatch (as visible in PR3)

NEW

- **Provide independent split-maps**
  - PR3: time-split (half-mission or half-ring) ➡ correlated
  - PR4: detector-split (detset) ➡ independent

NEW

- **Provide low-resolution maps with pixel-pixel noise covariance estimates across all Planck frequencies**

Planck Release 4

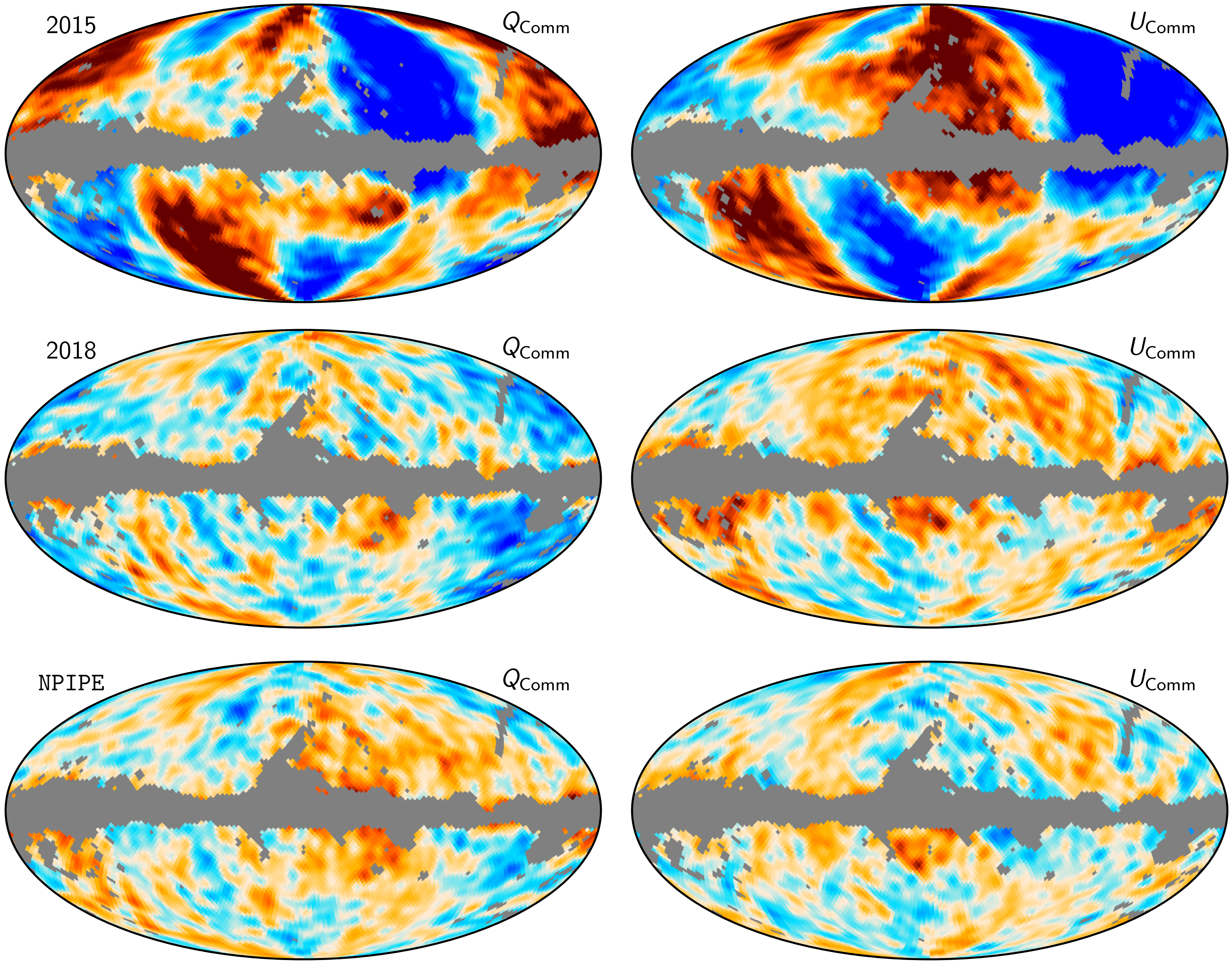
difference wrt PR3

NEW

- **hybrid calibration scheme for the CMB frequencies (44-217 GHz) to subtract an approximation of the polarized sky**
  - ➡ breaks degeneracies with systematic templates
  - ➡ **non-zero transfer function** at large scale
- **8% more data (repointing manoeuvre)**
  - ➡ **less noise**
- **new algorithm for pointing reconstruction (better accuracy)**
  - ➡ reduce pointing mismatch
- **update algorithm for glitch detection, removal, and flag**
  - ➡ **less small-scale noise** and lower noise correlations between half-rings

Planck Release 4

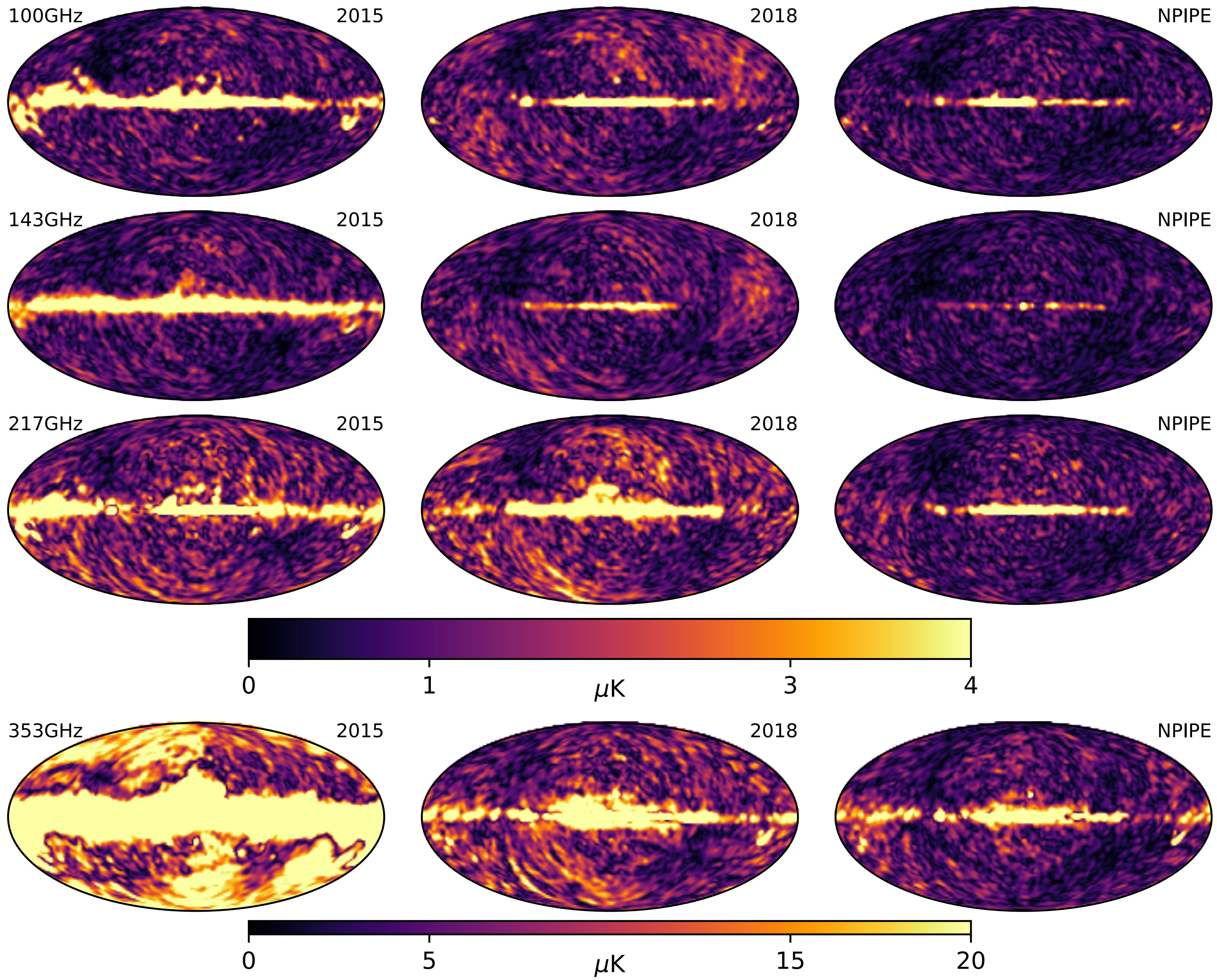
CMB polarized maps



Commander CMB Q and U maps
(large scale, 5° smoothing)

Planck Release 4

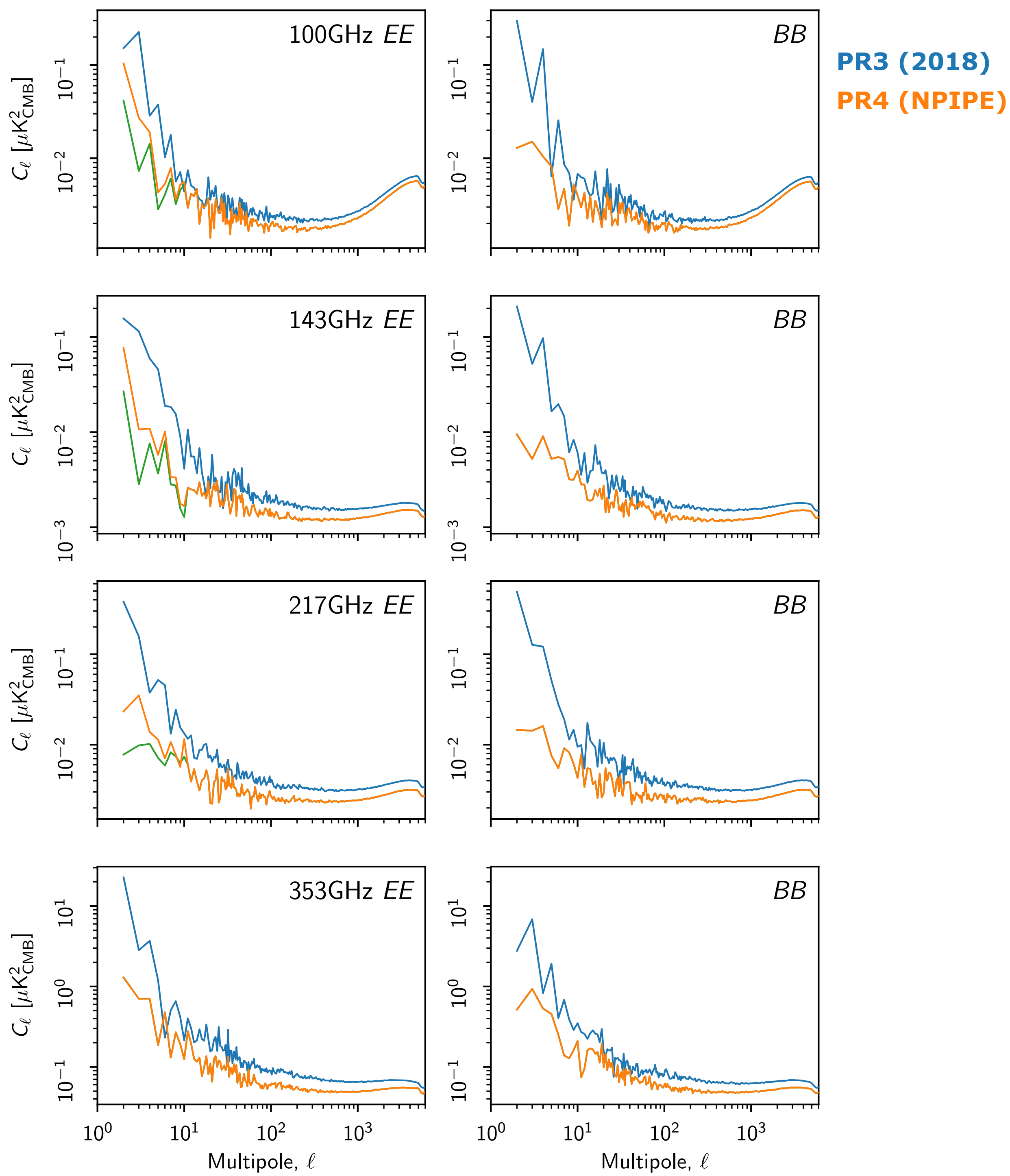
NPIPE null maps



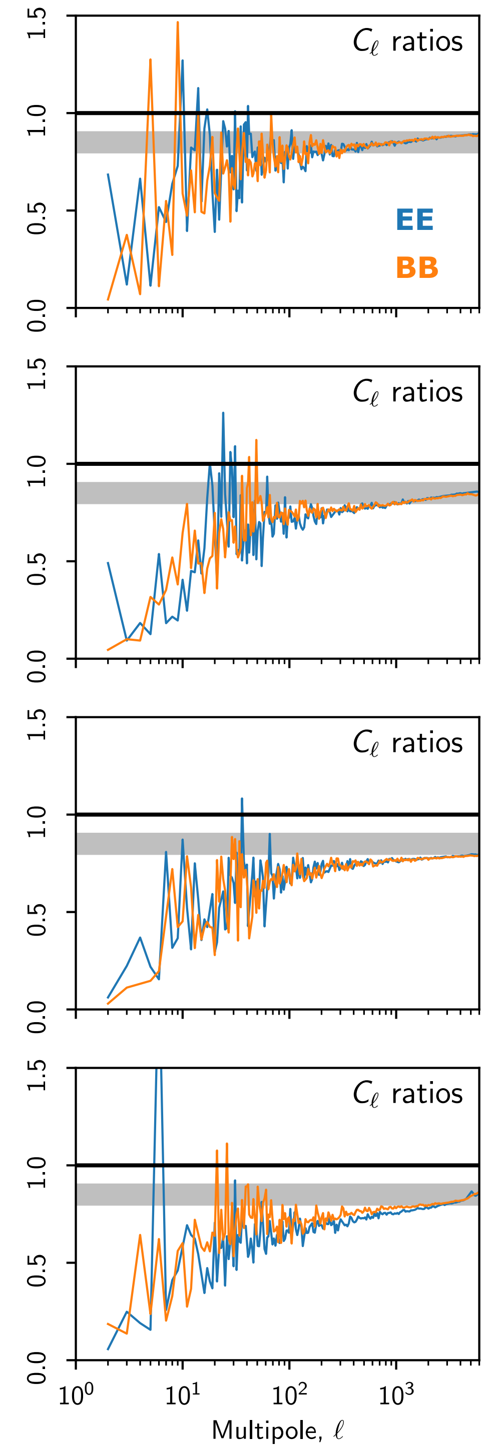
Polarization amplitudes of the detector-set difference null maps

Planck Release 4

NPIPE noise spectra



EE and *BB* detector-set difference power spectra



NPIPE/2018 *EE* and *BB* ratios

Planck Release 4

NPIPE simulations

NEW

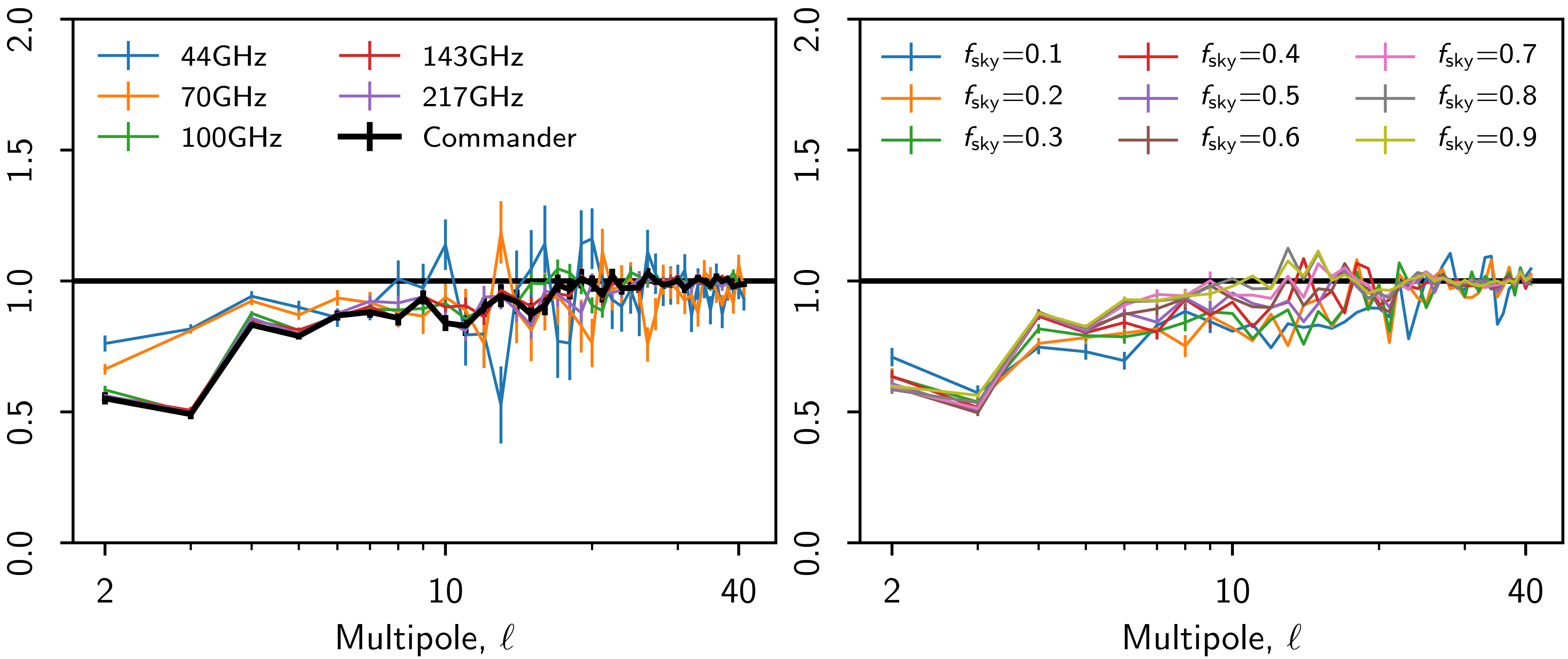
- **600 consistent simulations (frequency and split maps)**
- **Inputs**
  - including instrumental noise (consistent with data-split differences)
  - including models for systematics (ADC non-linearity)
  - random CMB with 4pi beam convolution
  - foreground sky model based on Commander Planck solution
- **Allow for**
  1. accurate effective description of the noise and covariance of the maps (including noise, instrumental systematics, foreground residuals)
  2. estimation of the **transfer function** from NPIPE processing

a realistic simulation set is essential to properly assess polarization uncertainties especially at large angular scales

NPIPE simulations
processing transfer function

Simulations allow to characterize accurately the processing transfer-function for each frequency

- stable with frequency (less for LFI with fewer systematic templates)
- stable with sky-fraction



NPIPE simulations

error budget

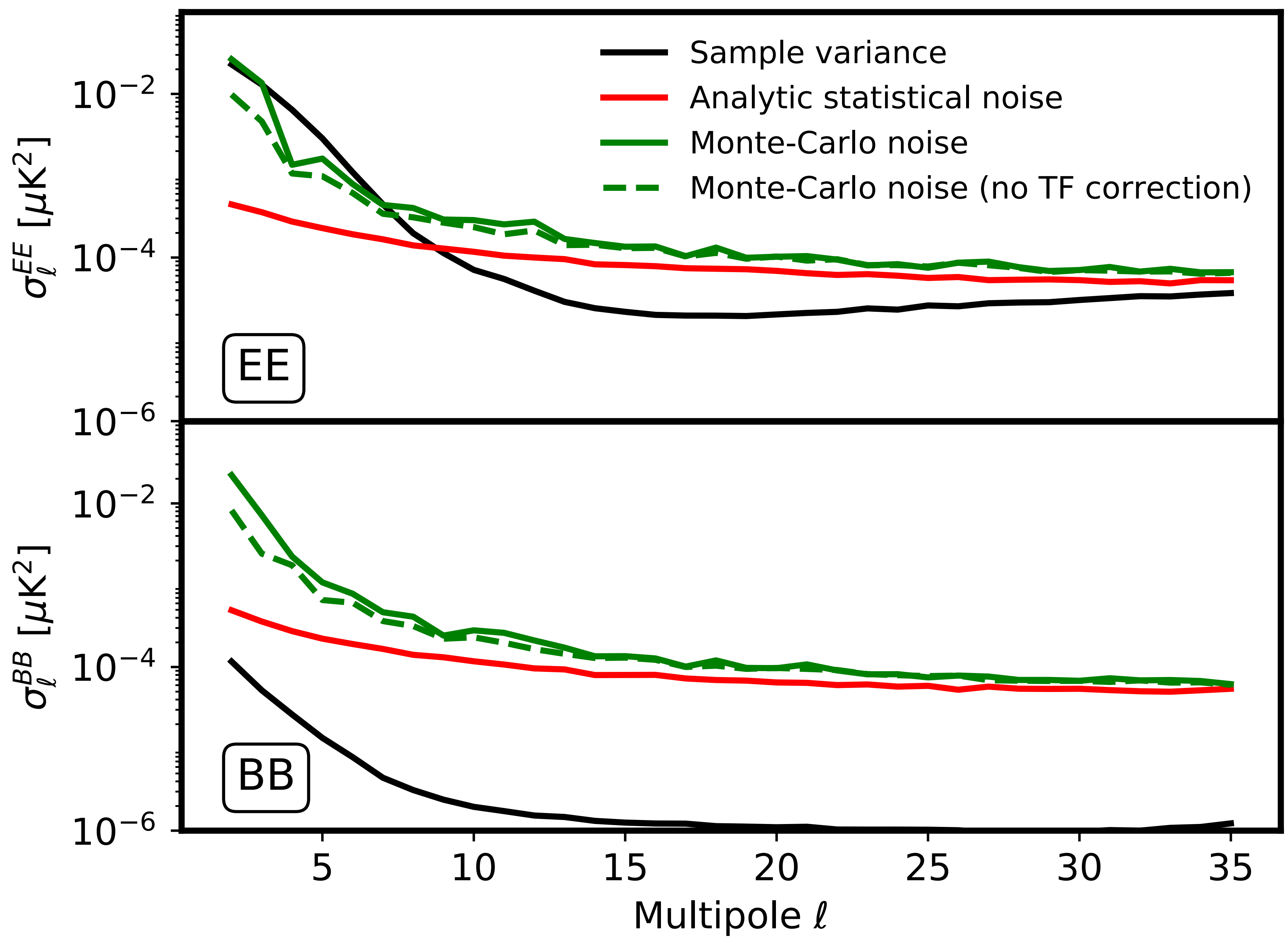
cosmic variance | statistical noise | systematic effects

- **Cosmic Variance**
  driven by the cosmology. Easy to simulate and propagate using a fiducial model (valid given our current level of sensitivity on power spectra and the range allowed for parameters)

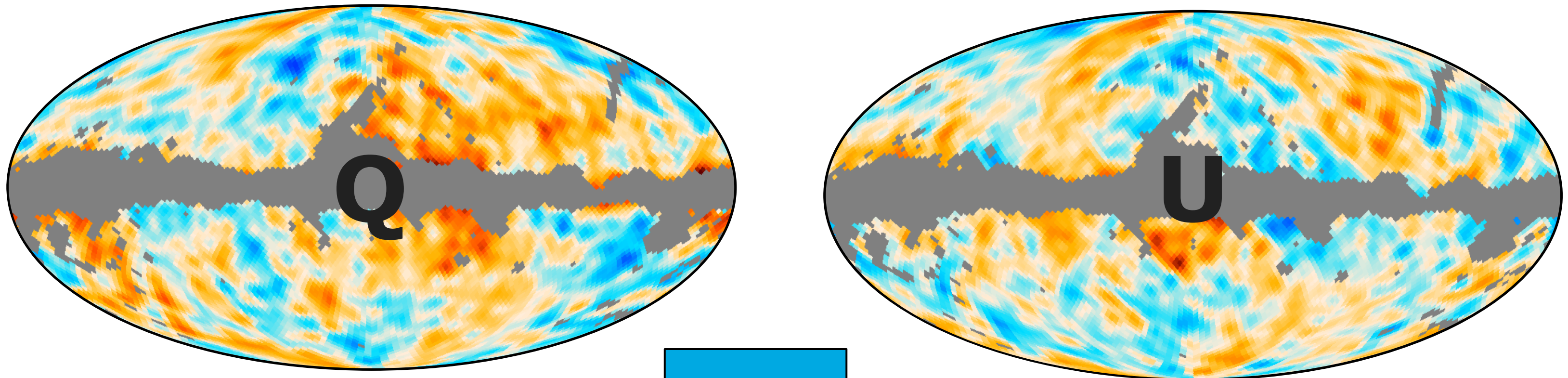
- **Statistical Noise**
  more complicated to estimate from the data. Current **Planck PR4 noise simulations match** the data jack-knives (no a-priori rescaling as in PR3).

- **Systematic effects**
  should include foreground models uncertainty + instrumental parameter uncertainties. not only important for potential bias but also for their effect on **increasing the variance**. Very hard but no other way than **realistic Monte Carlo**.

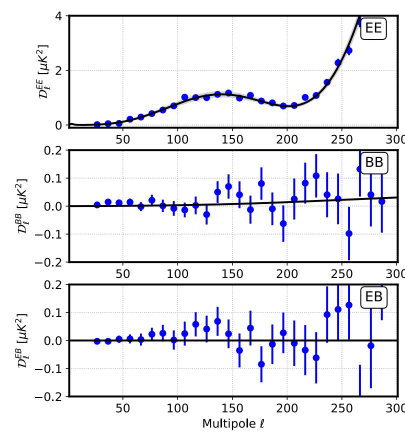
NPIPE simulations
noise estimation



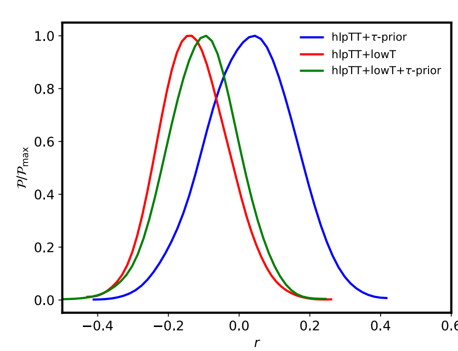
Data analysis



maps



power spectra



likelihood posterior

power spectra estimators

maximum likelihood

- from the pixel-pixel correlation matrix M

$$\mathcal{P}(C_\ell|T) \propto exp\left[-\frac{1}{2}\left(T^T M^{-1} T + Tr(lnM)\right)\right]$$

- can be sampled directly or approximated (QML)

- near optimal variance i.e. E/B mixing minimal

⇨ variance leakage minimal

- computationally expensive requiring

$\mathcal{O}(N_{\rm pix}^3)$ time

$\mathcal{O}(N_{\rm pix}^2)$ memory

xQML (https://gitlab.in2p3.fr/xQML)

[Bond et al. 1998, Tegmark 1997, Borrill 1999, Vanneste et al. 2018]

low ℓ

quadratic estimator or pseudo-Cℓ

- direct estimation of pseudo-spectra from data

$$\tilde{C}_\ell = \sum_{\ell'} M_{\ell\ell'} B_{\ell'}^2 C_{\ell'} + N_\ell$$

- debiasing from beam effect B_ℓ and cut-sky $M_{\ell\ell'}$

- E/B mixing can be important

⇨ use pure algorithm & appropriate apodization (but for noise-dominated maps, pCl are enough)

- very fast, requiring

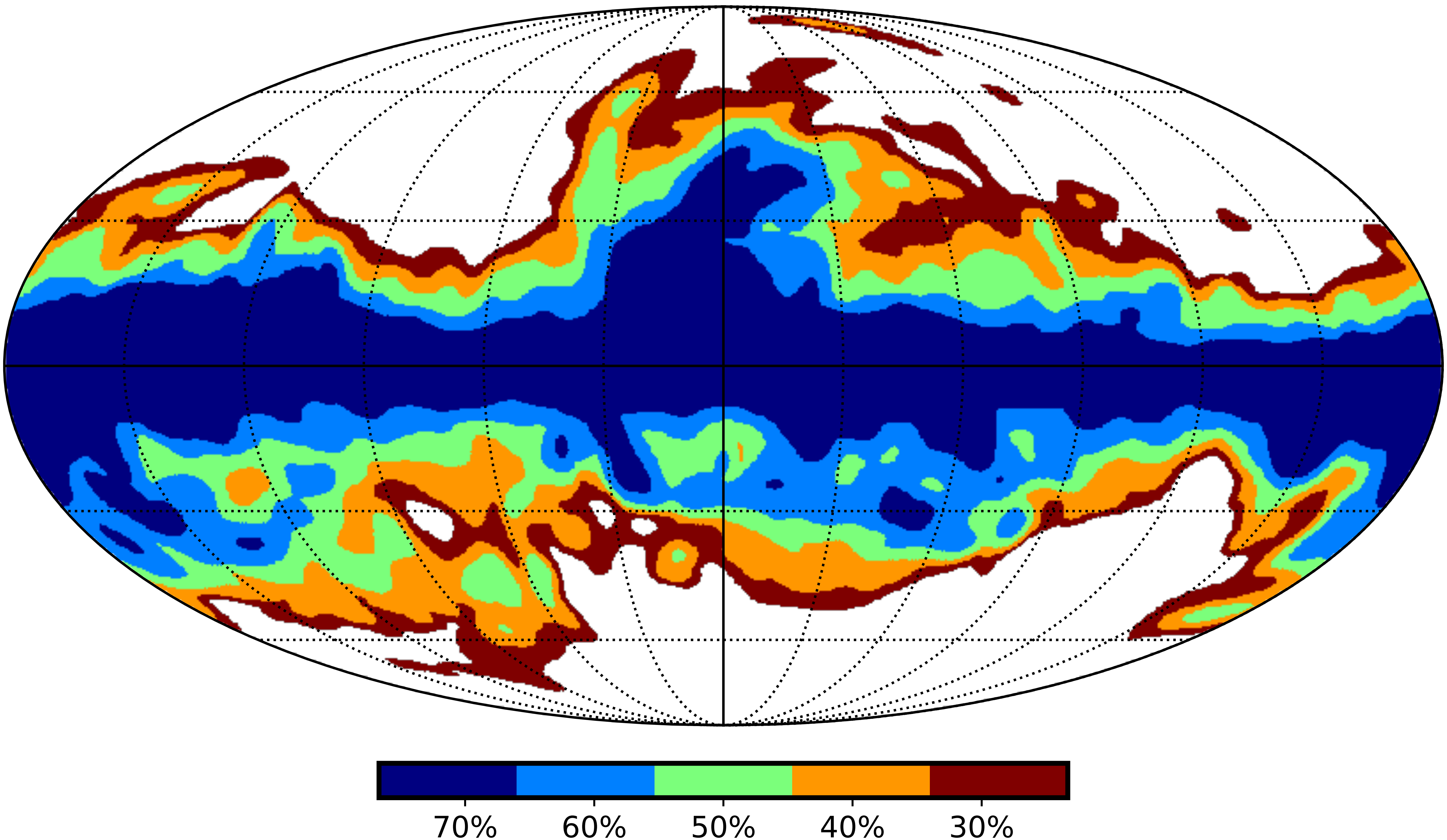
$\mathcal{O}(N_{\rm pix}^{3/2})$ time

Xpol (https://gitlab.in2p3.fr/tristram/Xpol)

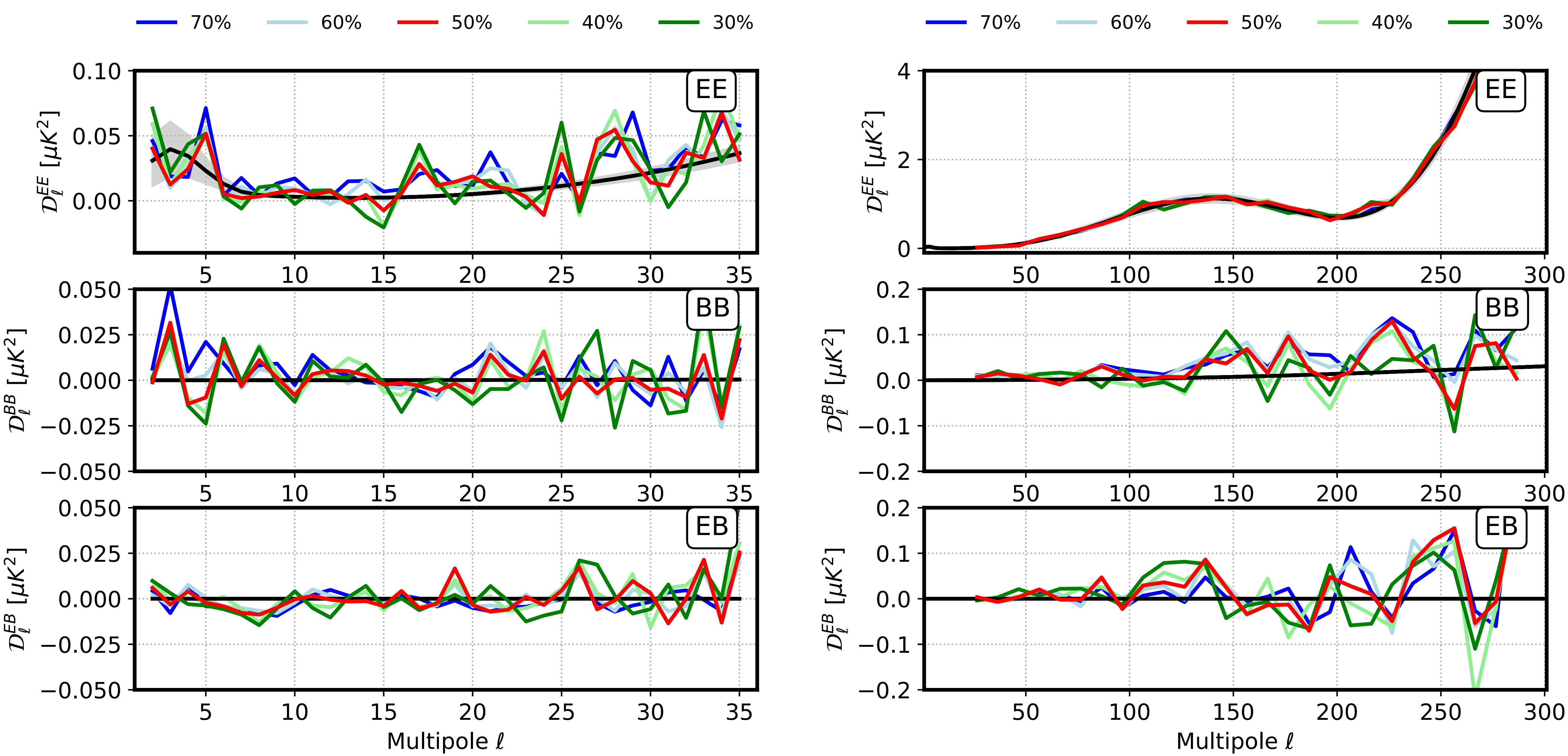
[Peebles & Hauser 1974, Wandelt et al. 2001, Hivon et al. 2002, Tristram et al. 2005, Grain et al. 2009]

high ℓ

Sky fractions

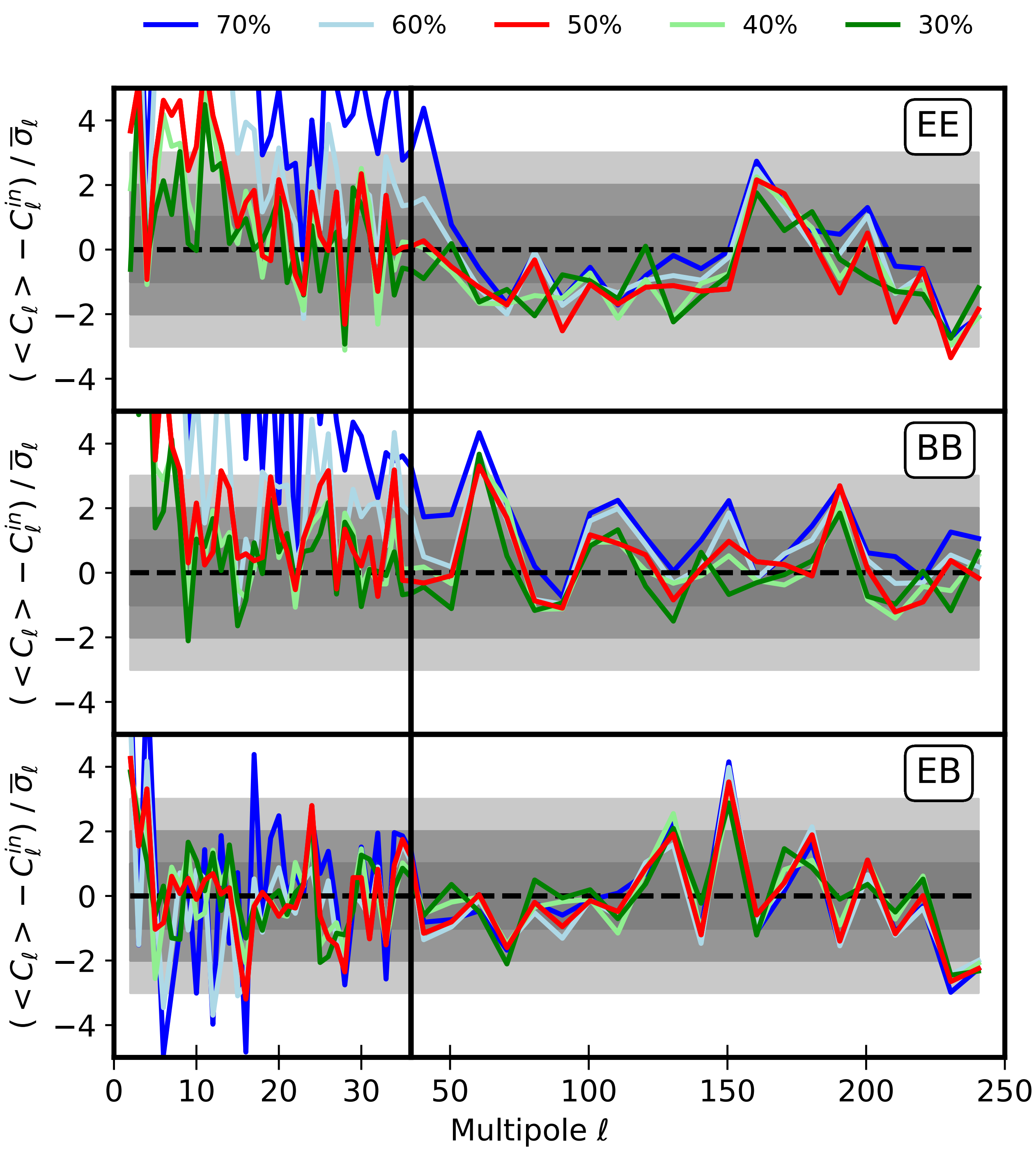


Planck Polarized Power Spectra



Simulations power spectra

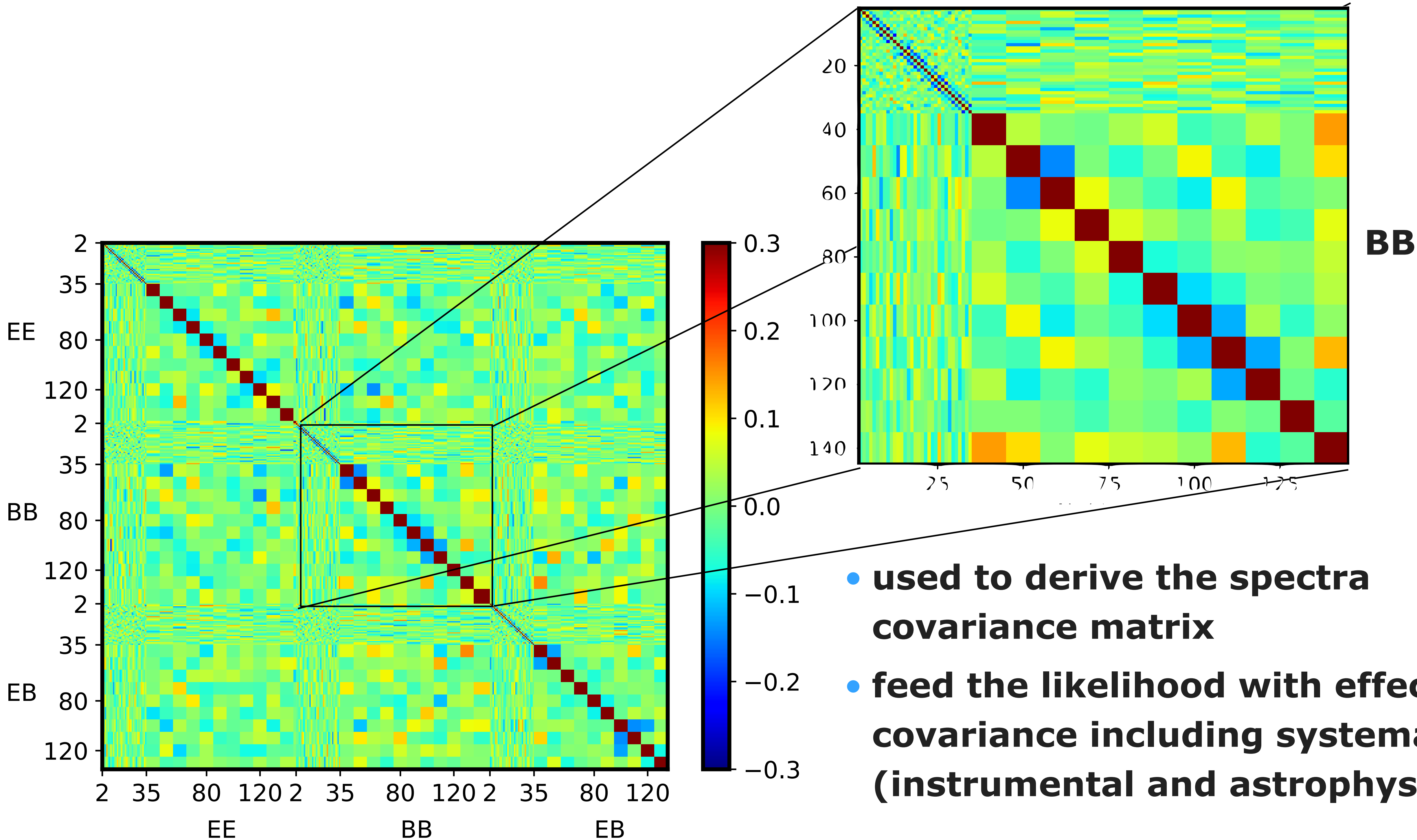
400 simulations of CMB reconstructed independently by Commander on each set of simulated frequency maps



- **Test the bias due to foreground residuals**
- **sky fractions ranging from 30% to 70%**
  ➥ **no bias for less than 50% sky fraction**

Simulations power spectra

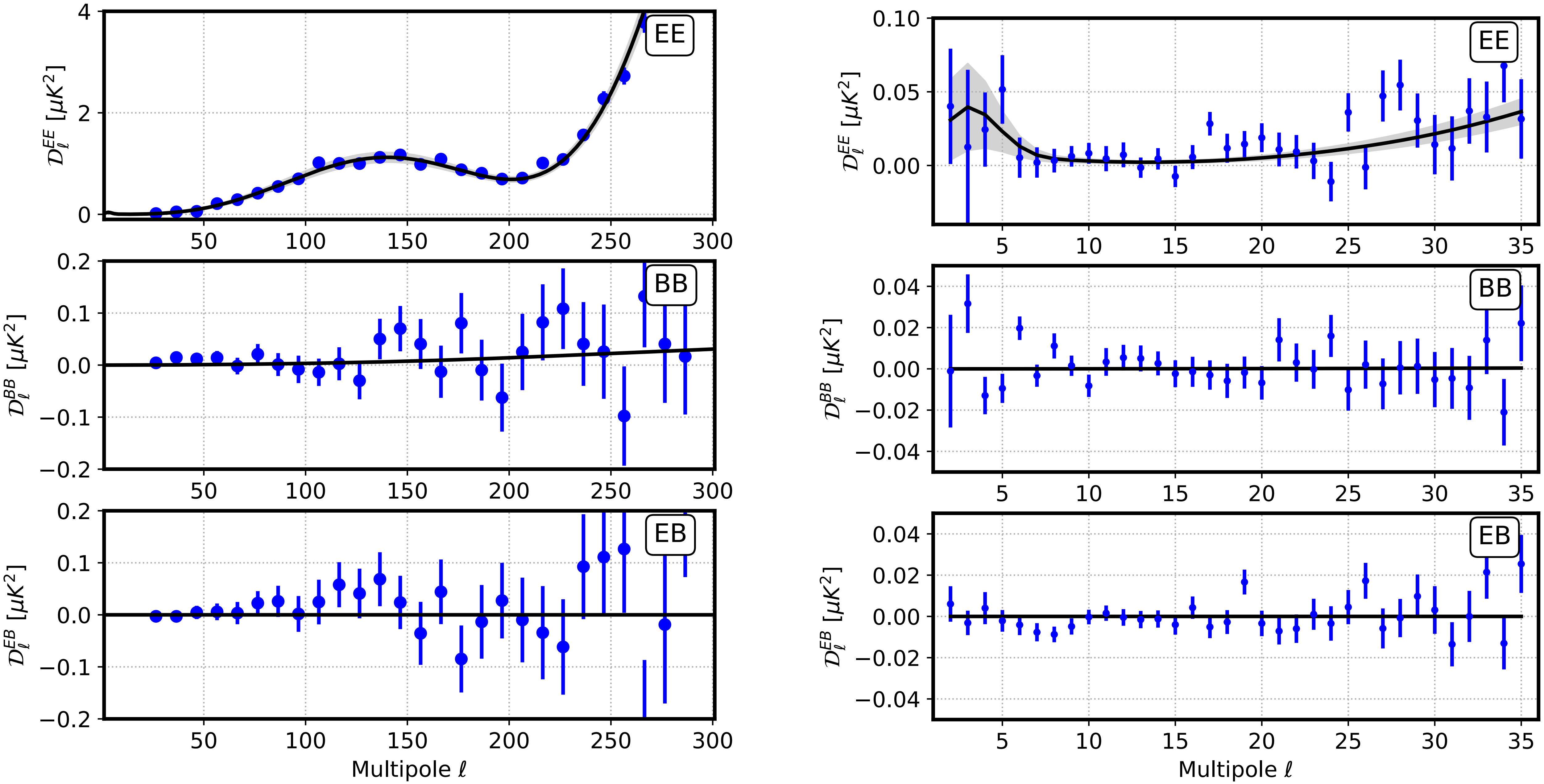
400 simulations of CMB reconstructed independently by Commander on each set of simulated frequency maps



- **used to derive the spectra covariance matrix**
- **feed the likelihood with effective covariance including systematics (instrumental and astrophysical)**

Planck Polarized Power Spectra

sky fraction 50%



Likelihoods

- **LowT**
  Commander likelihood from Planck 2018 (PR3)

- **Hillipop TT**
  high-l Gaussian likelihood for cross-spectra Planck 2020 (PR4)

- **Lollipop E-B**
  low-l polarized approximated likelihood Planck 2020 (PR4)

- **BK15**
  Bicep2/Keck likelihood from 2015 data *[BICEP2 Collaboration (2018)]*

lollipop

[Hamimeche & Lewis (2008)]
[Mangilli et al. (2015)]

- **Hamimeche&Lewis approximation modified for cross-spectra**
- **change of variable $C_\ell \rightarrow X_\ell$ so that statistics is Gaussian in X_ℓ**

$$X_\ell = \sqrt{C_\ell^{\mathrm{f}} + O_\ell}\; g\left(\frac{\widetilde{C}_\ell + O_\ell}{C_\ell + O_\ell}\right) \sqrt{C_\ell^{\mathrm{f}} + O_\ell}$$

$$g(x) = \sqrt{2(x - \ln(x) - 1)}$$

$\tilde{C}_\ell$ **is the measured spectrum**

C_ℓ **is the model to test**

O_ℓ **is the offset given by the level of noise** $\Delta C_\ell \equiv \sqrt{\frac{2}{2\ell + 1}} O_\ell$

- **then the likelihood approximation simply reads**

$$-2 \ln P(C_\ell | \widetilde{C}_\ell) = \sum_{\ell \ell'} X_\ell^{\mathsf{T}} M_{\ell \ell'}^{-1} X_{\ell'}$$

with the matrix $M_{\ell\ell'}$ being the covariance from the C_ℓ

Cosmological model: ΛCDMr

- **7 parameters**
  - 3 for the primordial matter spectra

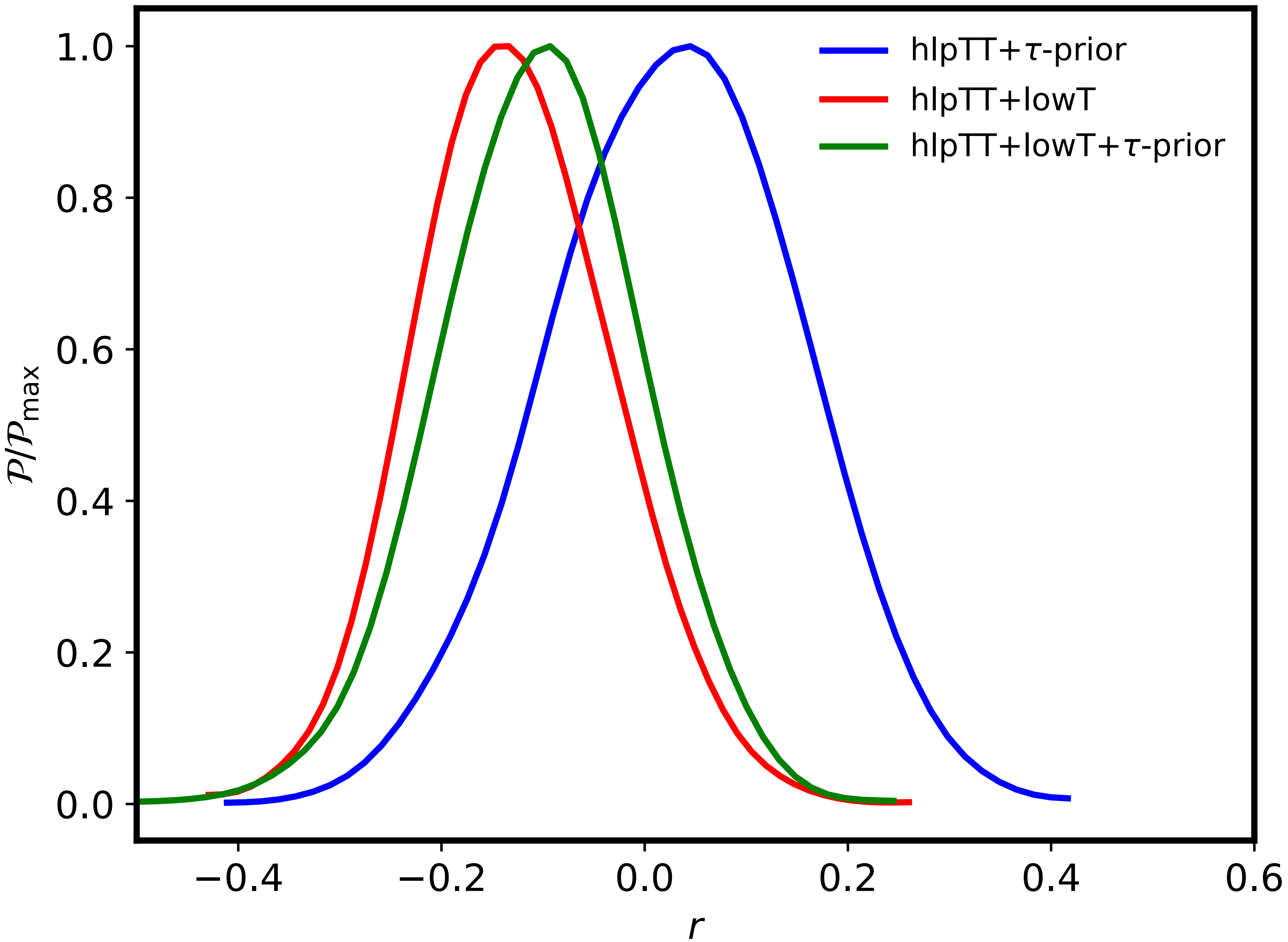
$$\mathscr{P}_s(k) = \boxed{A_s}\left(\frac{k}{k_0}\right)^{\boxed{n_s}-1}$$

$$\mathscr{P}_t(k) = A_t\left(\frac{k}{k_0}\right)^{n_t} \qquad \boxed{r} = A_t/A_s$$

  - 1 expansion rate $\boxed{H_0}$ (in practice sound horizon $\boxed{\theta_s}$)
  - 2 parameters for densities $\boxed{\Omega_b h^2}$ $\boxed{\Omega_c h^2}$
  - reionization $\boxed{\tau}$

- **hypothesis**
  - flat Universe $\Omega_k = 0$
  - No running $dn_s/d\ln k = 0$
  - Inflation $n_t = -r/8$
  - 3 neutrinos $N_{\text{eff}} = 3.046$
  - standard neutrinos with low mass $\sum m_\nu = 0.06$ eV

Constraints from Planck TT

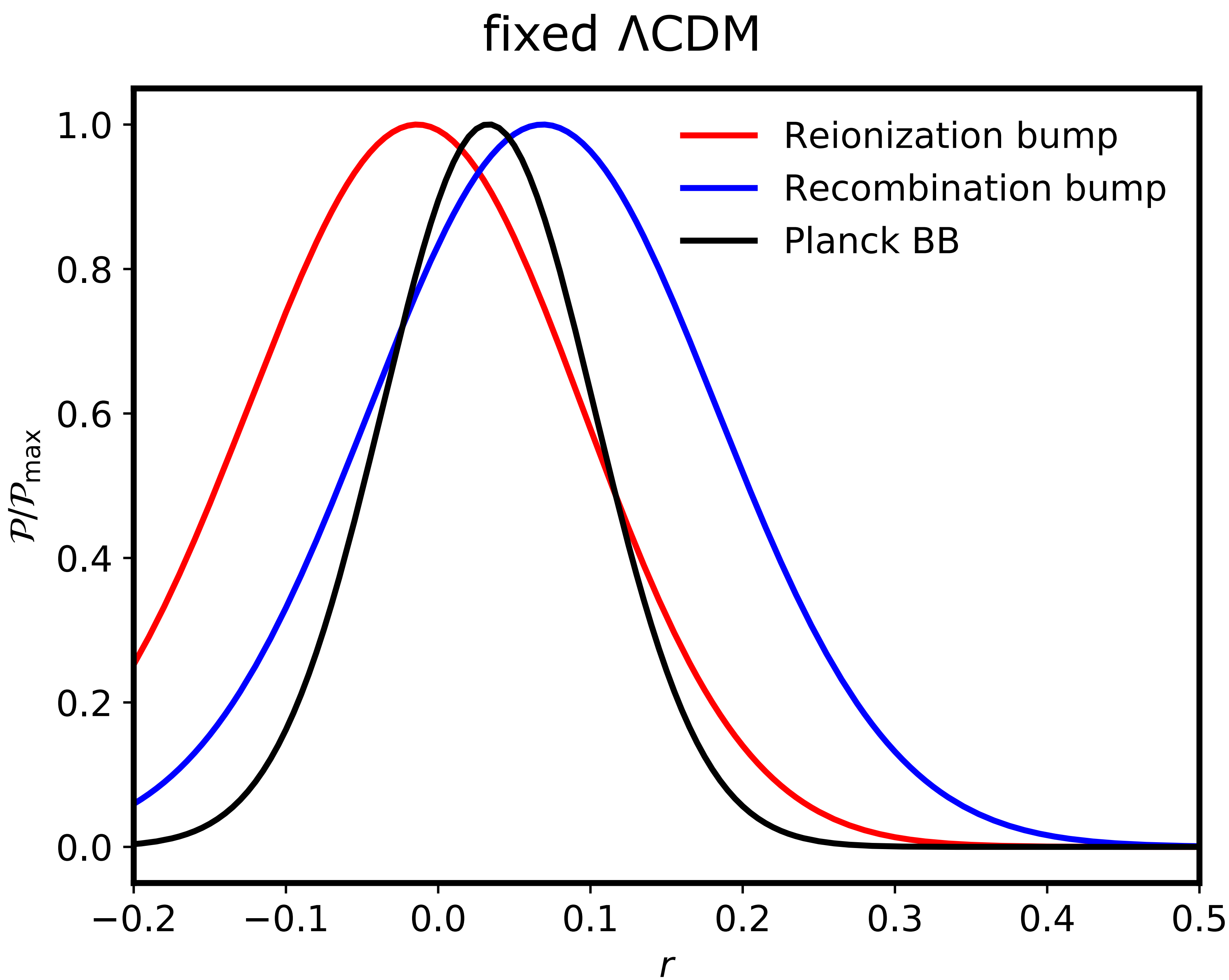


$r_{0.05} < 0.25$ (95%CL, hlpTT+τ-prior)

$r_{0.05} < 0.13$ (95%CL, hlpTT+lowT)

$r_{0.05} < 0.12$ (95%CL, hlpTT+lowT+τ-prior)

Constraints from Planck BB

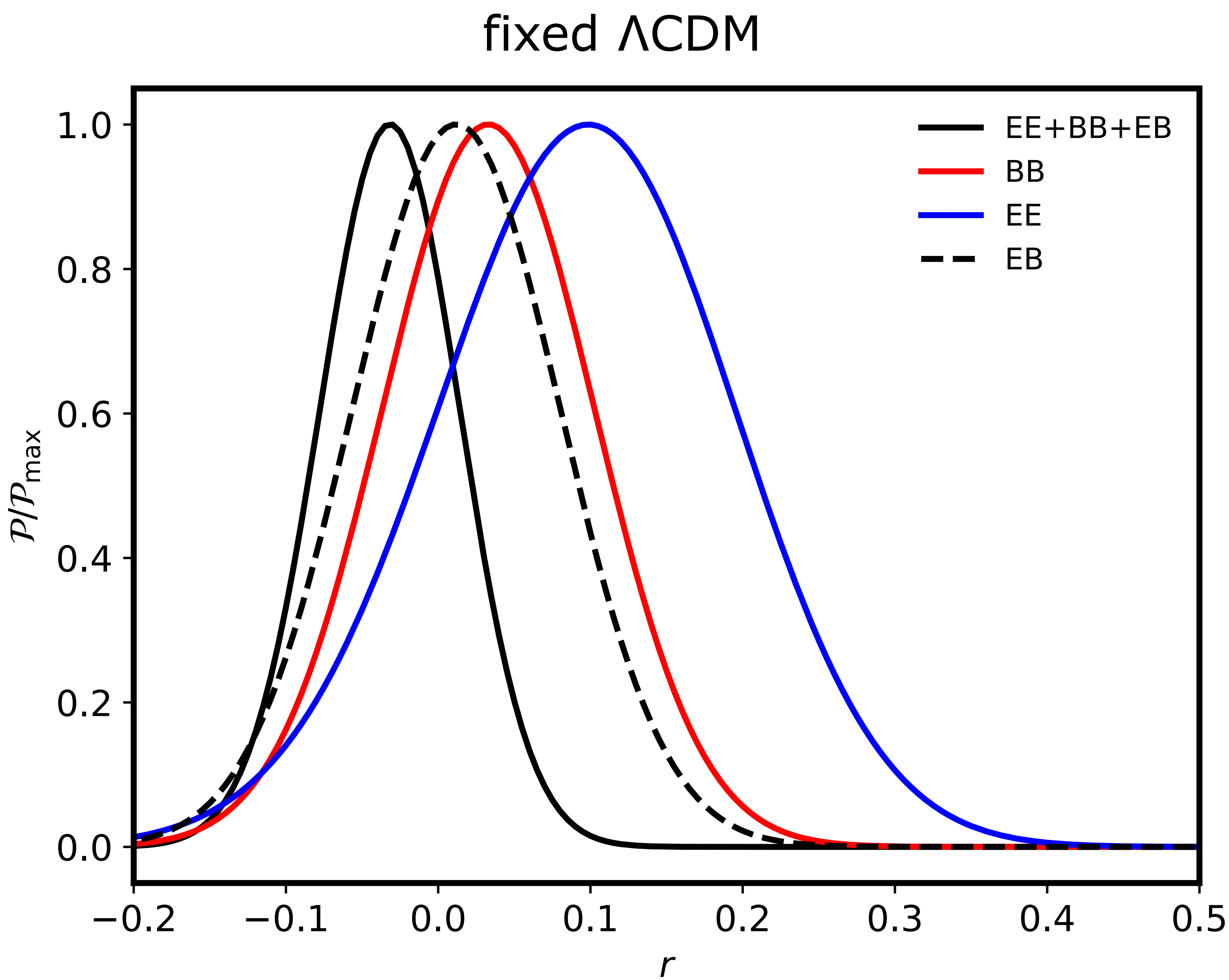


reionization bump $\ell = [2 - 35]$

recombination bump $\ell = [50 - 150]$

arbitrarily

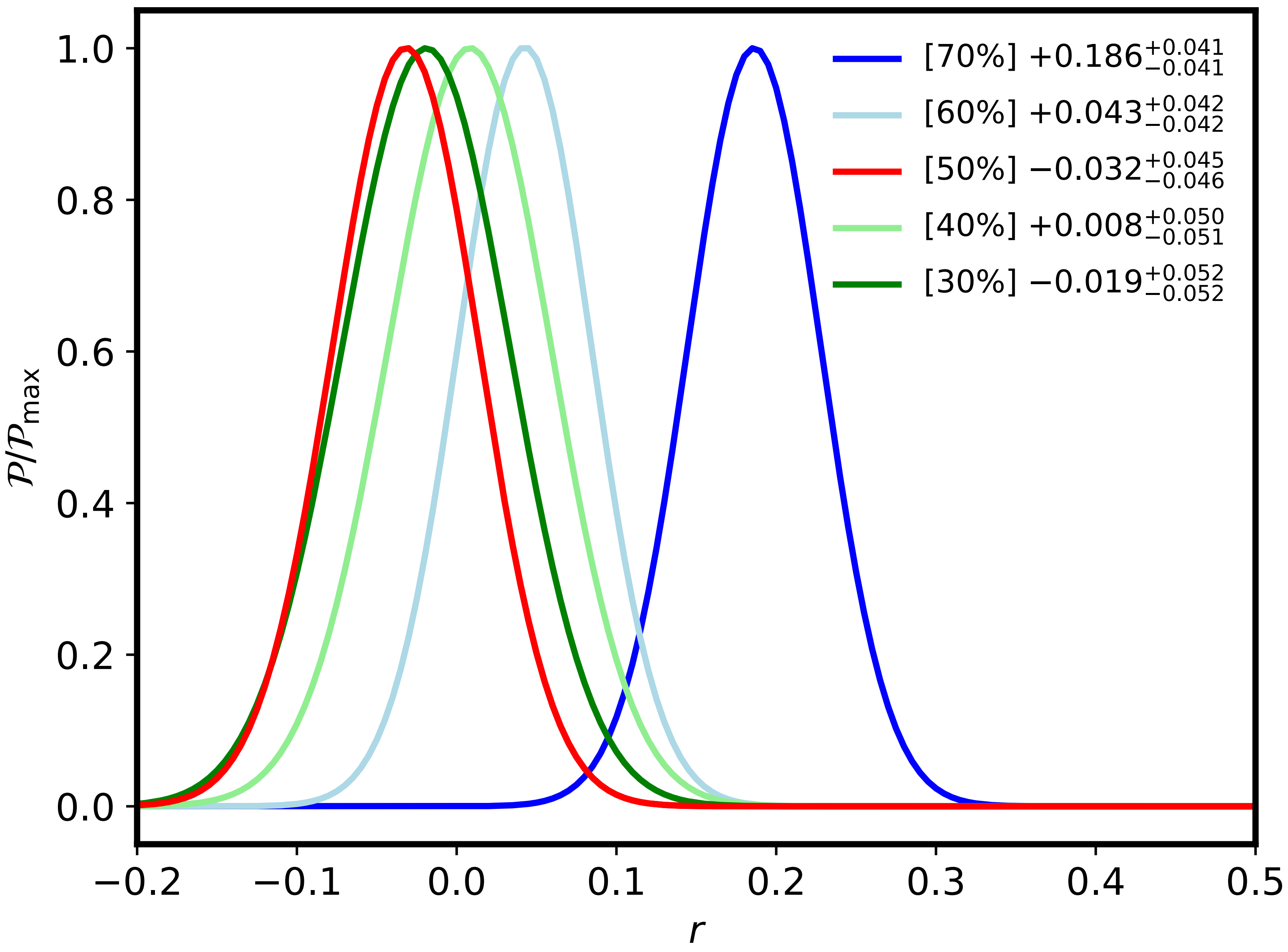
Constraints from Planck polarised spectra



$$r_{0.05} = \quad 0.033 \pm 0.069 \quad \text{(lowlB)},$$
$$r_{0.05} = -0.031 \pm 0.046 \quad \text{(lowlEB)}.$$

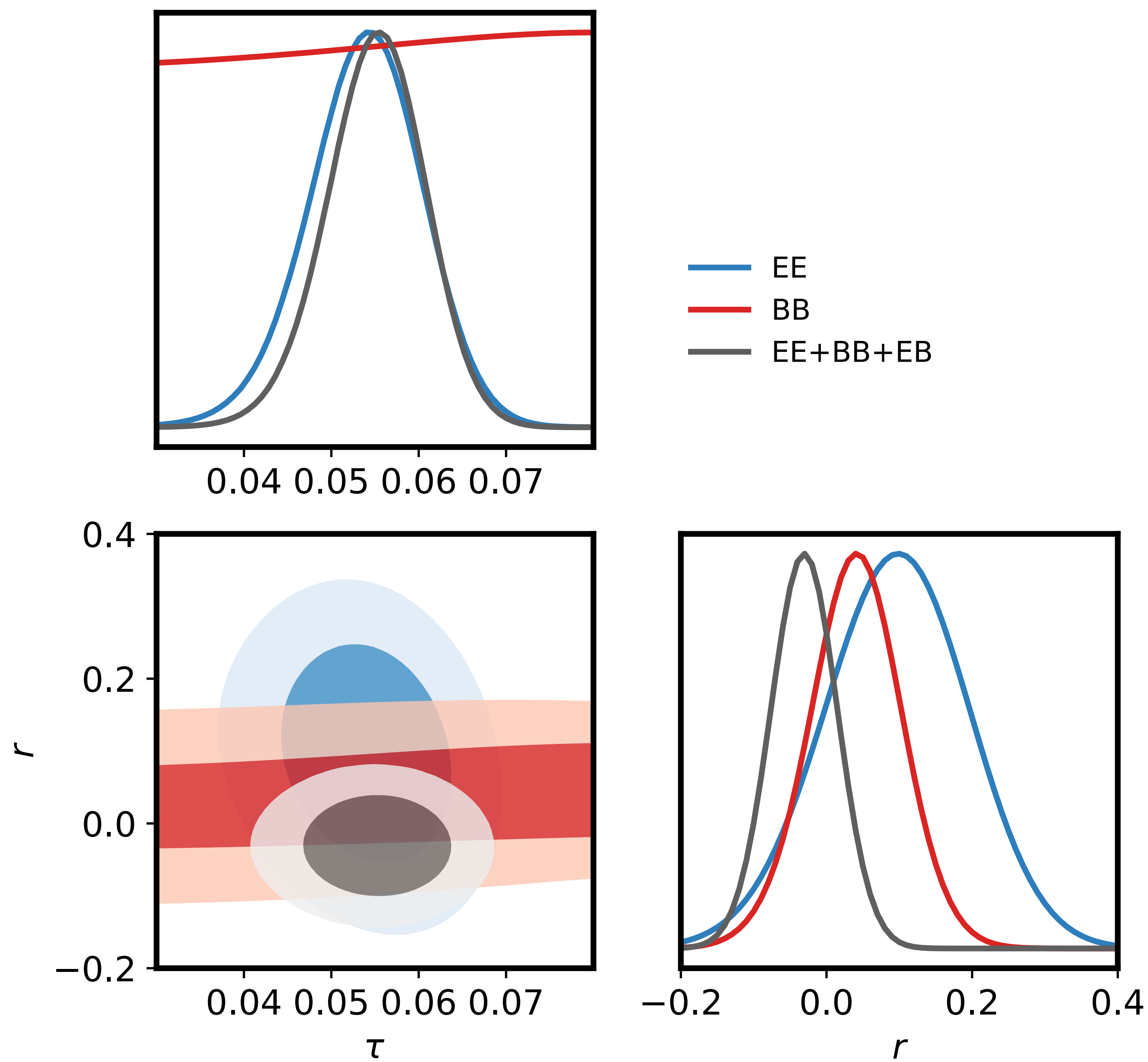
$$r_{0.05} < 0.158 \quad (95\,\%\ \text{CL, lowlB})$$
$$r_{0.05} < 0.069 \quad (95\,\%\ \text{CL, lowlEB}).$$

Constraints from Planck polarised spectra



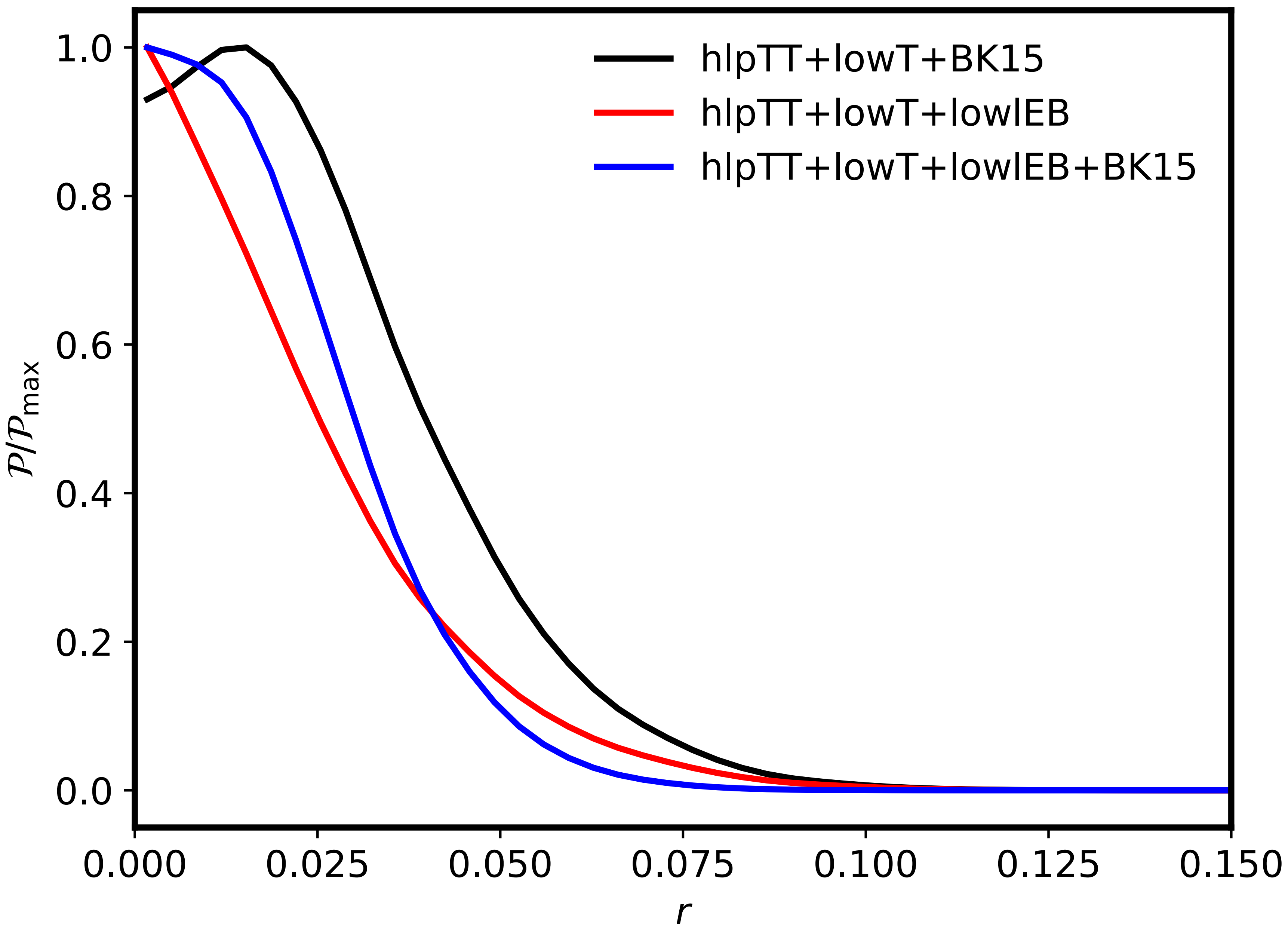
Constraints from Planck polarised spectra

fixed ΛCDM



$$\tau = 0.0577 \pm 0.0056$$

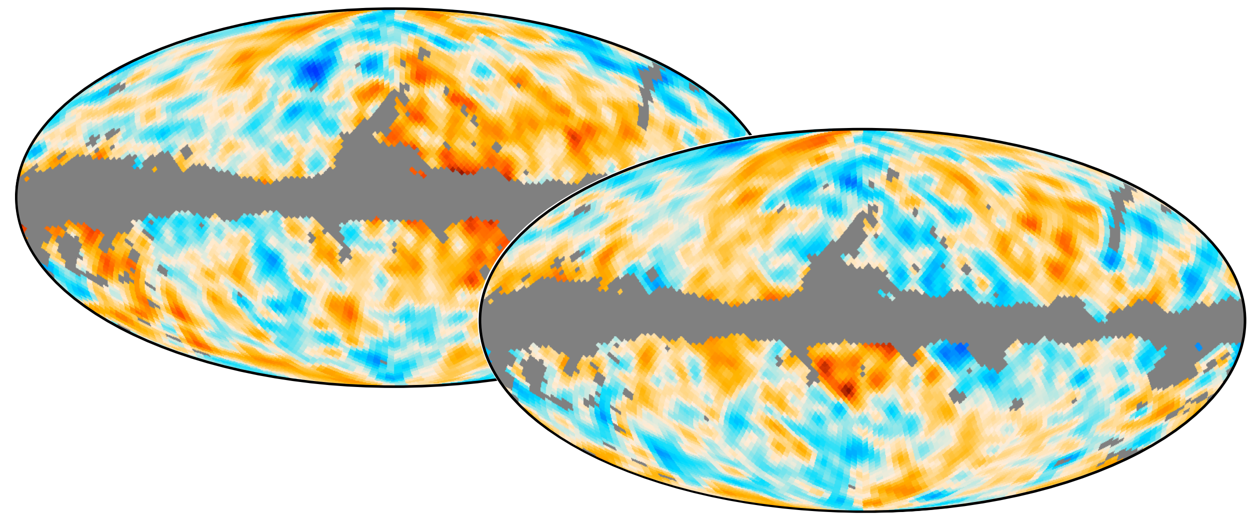
Combined results



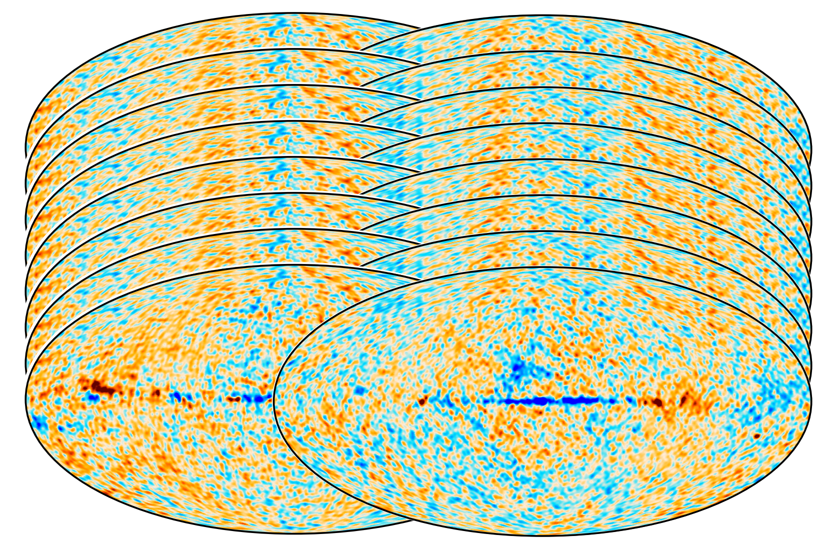
$$
\begin{aligned}
r_{0.05} &< 0.060 \quad (95\,\%\text{ CL, hlpTT+lowT+BK15});\\
r_{0.05} &< 0.056 \quad (95\,\%\text{ CL, hlpTT+lowT+lowlEB});\\
r_{0.05} &< 0.044 \quad (95\,\%\text{ CL, hlpTT+lowT+lowlEB+BK15})
\end{aligned}
$$

Conclusions

- **NPIPE maps**
  - cleaner
  - less noisy
  - split-maps less correlated



- **NPIPE sims**
  - consistent with the data
  - allow for TF and variance estimation
  - include uncertainties from systematics (both instrumental and astrophysical)



- **Results**

$r_{0.05} < 0.072$ (BICEP2/Keck) 1% of the sky

$r_{0.05} < 0.069$ (Planck EB) 50% of the sky

$$\boxed{r_{0.05} < 0.044 \quad \text{(Planck + BK15)}}$$