CMB analysis with end-to-end error propagation: CMB anisotropies

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on behalf of BeyondPlanck team

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CMB sampling in BeyondPlanck

- A new CMB sample is characterized by an amplitude map $\mathbf{a}^{\mathrm{CMB}}$ and a power spectrum C_ℓ ,sampled in a two step procedure:

$$\mathbf{a}^{\mathrm{CMB}} \leftarrow P(\mathbf{a}^{\mathrm{CMB}} | \mathbf{d}, C_\ell, \omega)$$

$$C_\ell \leftarrow P(C_\ell | \mathbf{a}^{\mathrm{CMB}})$$

- The first step is a multivariate Gaussian distribution:

$$\left(\mathbf{S}^{-1} + \sum_\nu \mathbf{A}_\nu^t \mathbf{N}_\nu^{-1} \mathbf{A}_\nu\right) \mathbf{a}^{\mathrm{CMB}} = \sum_\nu \mathbf{A}_\nu^t \mathbf{N}_\nu{}^{-1} \mathbf{m}_\nu + \sum_\nu \mathbf{A}_\nu^t \mathbf{N}_\nu^{-1/2} \eta_\nu + \mathbf{S}^{-1/2} \eta_0$$

$$\mathbf{A}_\nu = \mathbf{B}_\nu \mathbf{M}_\nu$$

- $\mathbf{S}^{-1}$ acts as a prior on the spatial structure of the CMB map. For a Gaussian and isotropic field $\mathbf{S} = \mathbf{S}(C_\ell)$. Alternatively we can avoid a prior by fixing $\mathbf{S}^{-1}=0$.

BeyondPlanck CMB products

Solving for component amplitudes is a very time consuming step. To optimize runtime, BeyondPlanck generated 3 sets of CMB products, targeted to different goals:

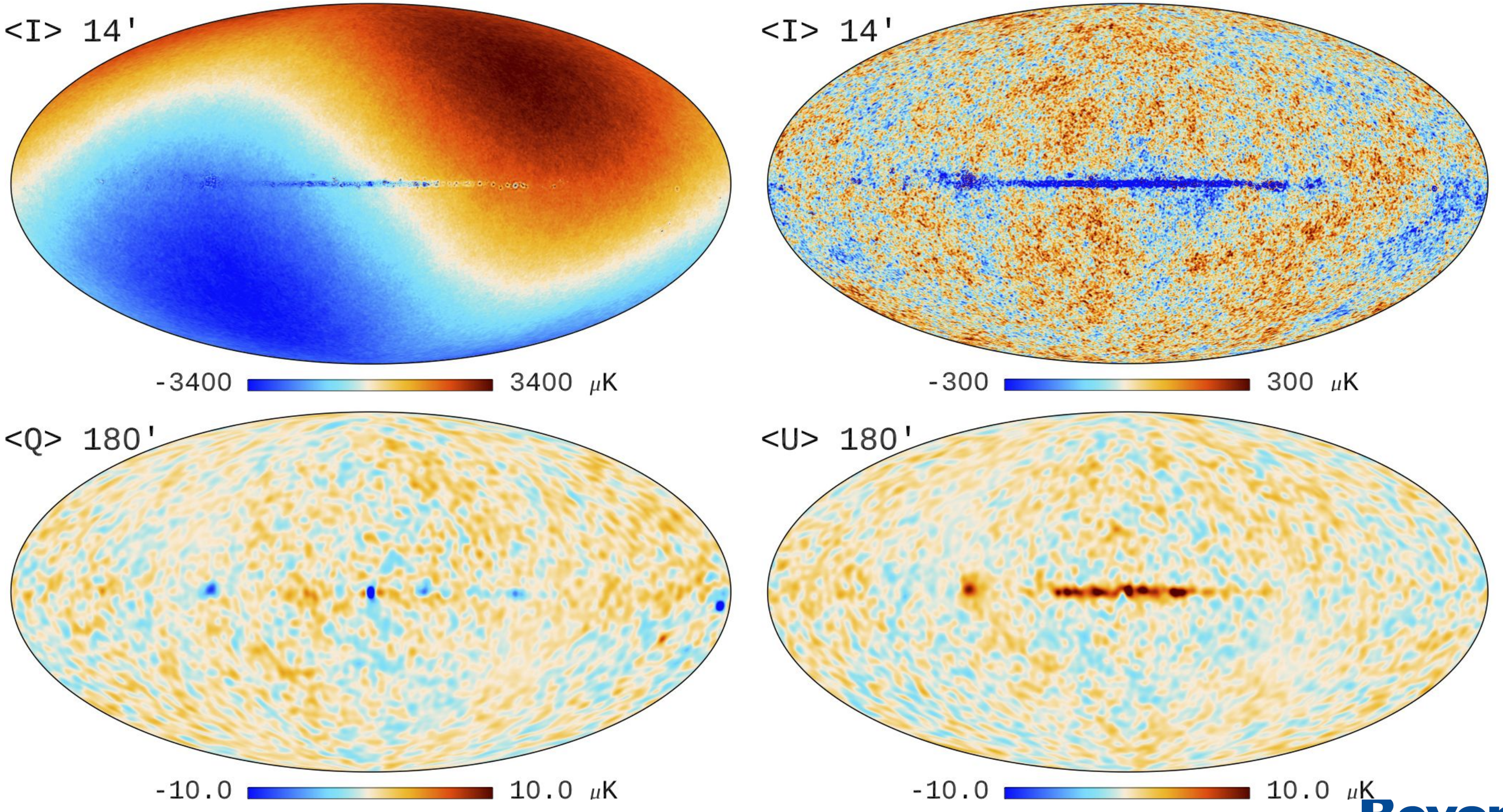
- In the main chain, we solve for CMB and astrophysical components fixing $\mathbf{S}^{-1}=0$, and without Galactic mask. This is the fastest approach, but the resulting CMB maps are suboptimal (no isotropy priors, Galactic plane residuals). These maps are only used internally to improve component separation and produce cleaner calibration and frequency maps, but not for cosmological analysis.

- For temperature cosmological analysis, we resample ($\mathbf{a}^{\mathrm{CMB}}, C_\ell$) fixing all instrumental and foreground parameters to the values sampled in the main chain. In this step we apply a Galactic mask, and $\mathbf{S} = \mathbf{S}(C_\ell)$.

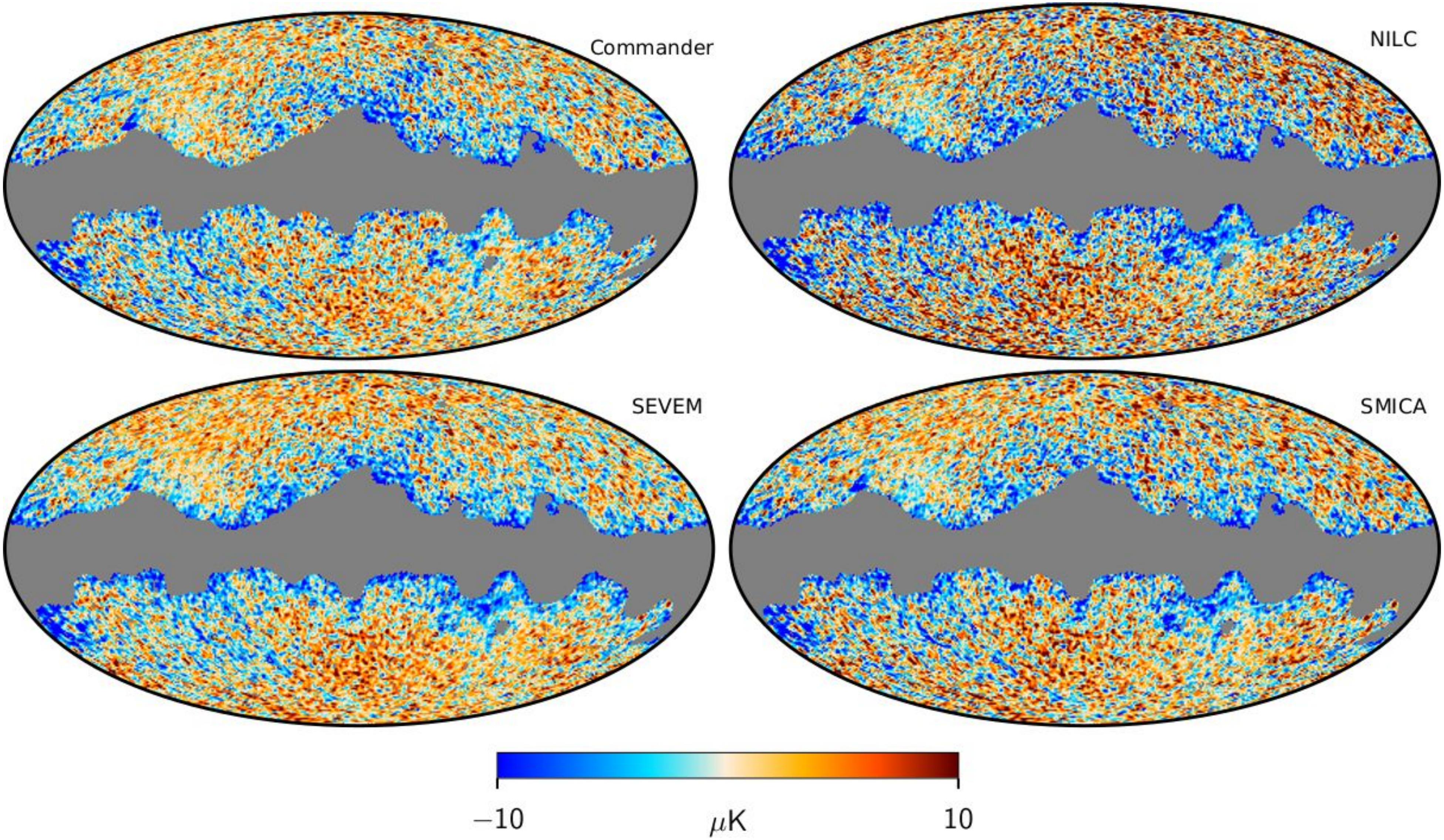
- For low-ℓ polarization cosmological analysis, we resample $\mathbf{a}^{\mathrm{CMB}}$ at multipoles $\ell \leq 64$, fixing higher multipoles and all instrumental and foreground parameters, assuming $\mathbf{S}^{-1}=0$ and no Galactic mask (see Simone's talk).

Prior Free CMB maps

- The main chain CMB posterior mean map is the direct equivalent to the Planck Collaboration Commander maps (except for the cosmological dipole).



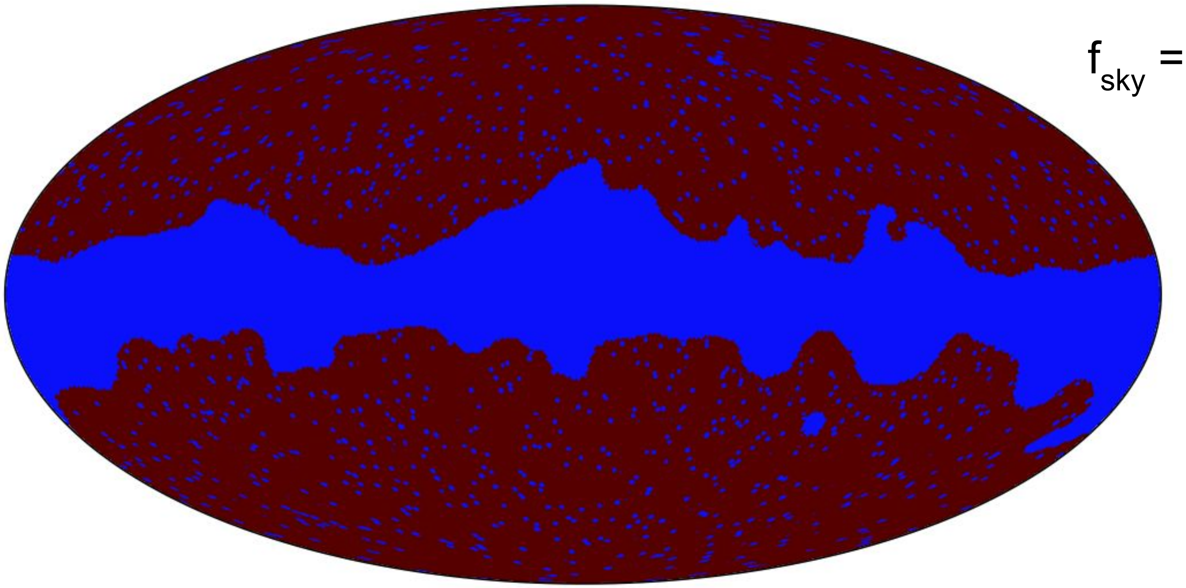
CMB: Difference with Planck 2018



Struggle with thermal dust in the Galactic plane, because we do not use HFI. Relatively clean at high latitudes

Resampling Mask

- For the high-ℓ temperature resampling we adopt a processing mask combining 3 main indicators:
  - 1 degree-smoothed χ^2 map;
  - 2 degree-smoothed absolute difference map w.r.t. Planck 2018 component separation codes;
  - Planck 2018 30, 44, and 70GHz point source mask.

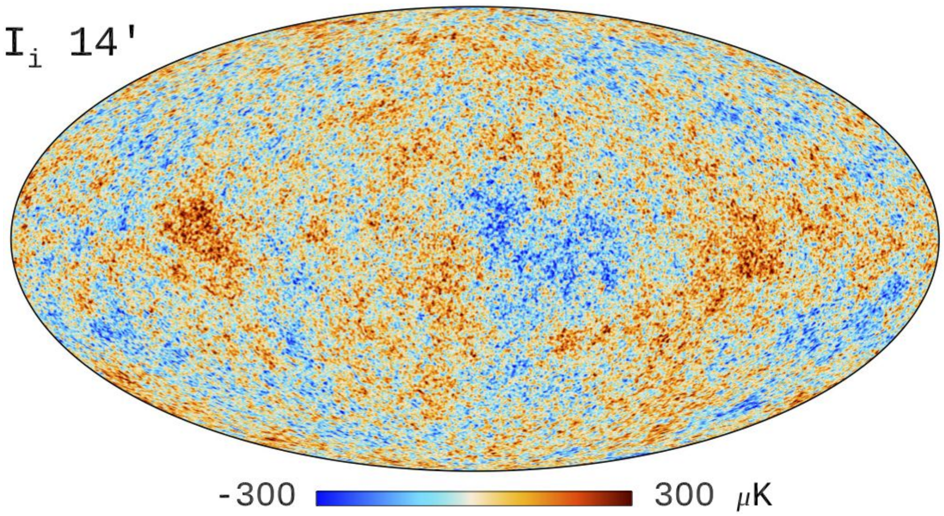


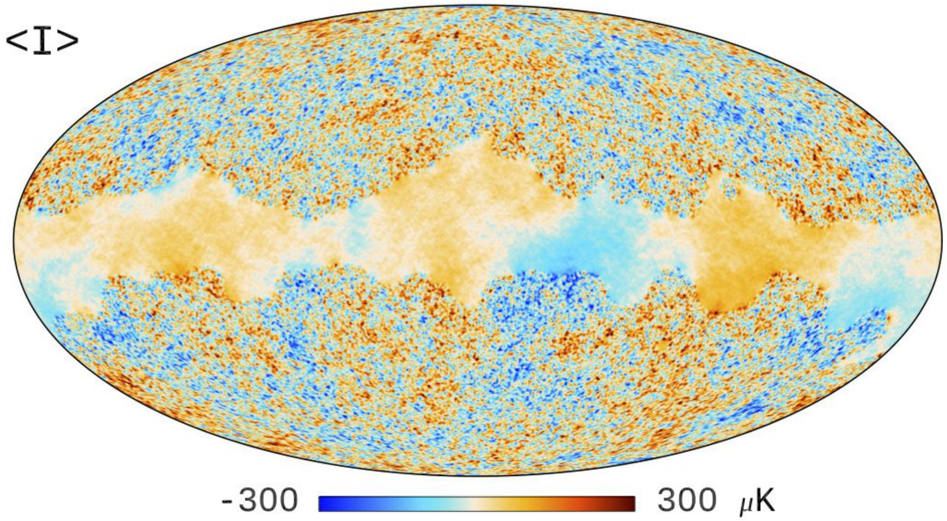
$f_{sky} = 0.691$

Cosmology Temperature Maps

- When $\mathbf{S} = \mathbf{S}(\mathcal{C}_\ell)$, the posterior mean map corresponds to a Wiener-filtered map. Additionally, the region within the Galactic mask is filled with a constrained realization.

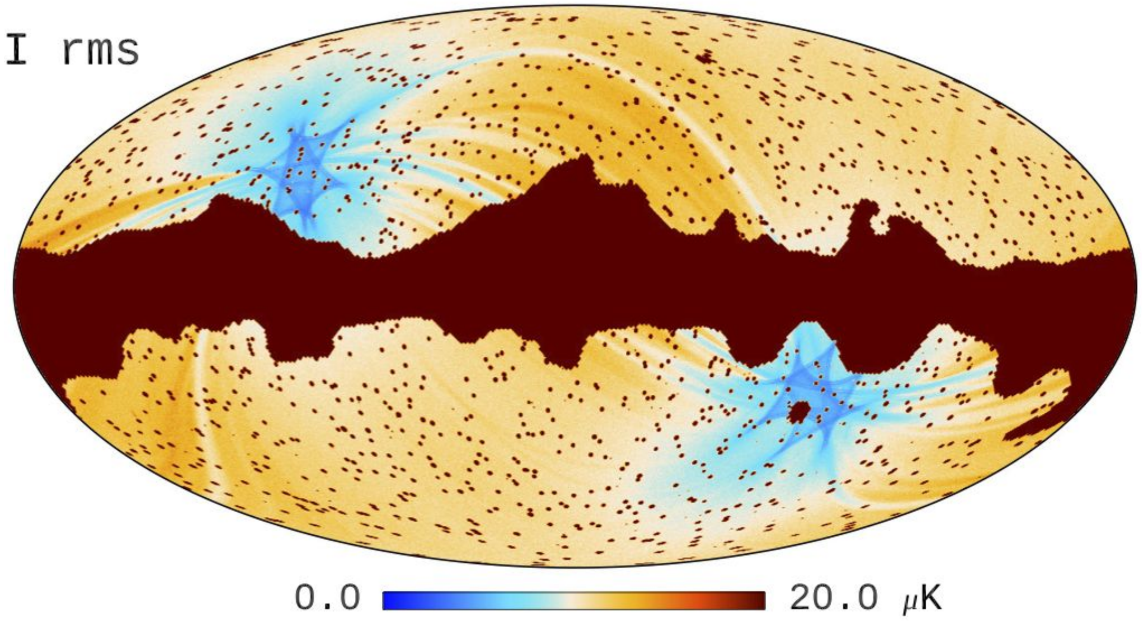
- On the other hand individual samples are realizations of a isotropic noiseless field, making the analysis of such maps straightforward.





Map Variance

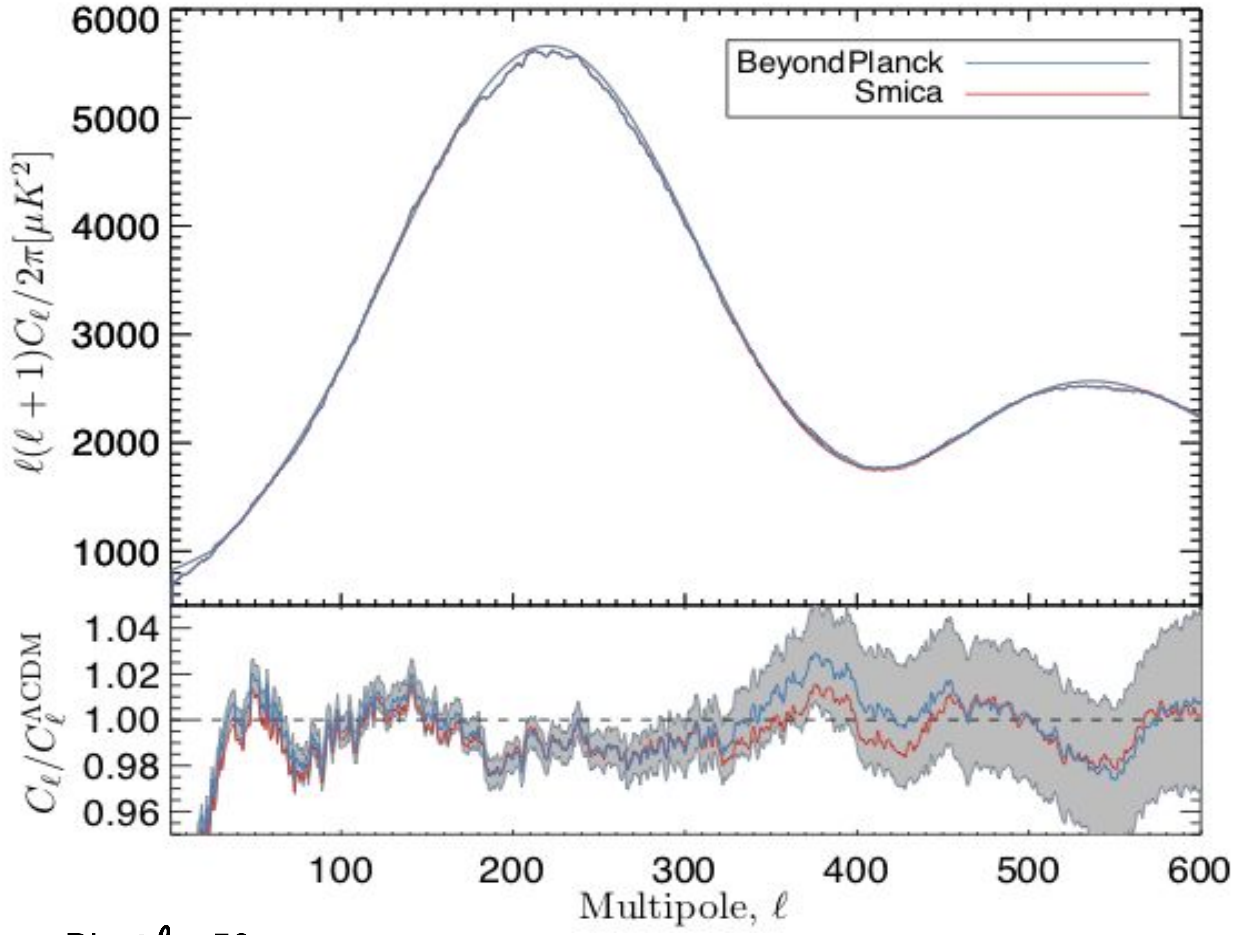
- Map variance shows the imprint of instrumental noise at high Galactic latitude, while inside the reprocessing mask is dominated by the random phases of the constrained CMB realizations.



- Propagating pipeline uncertainties to the final science involves simply applying the relevant estimator to each of the samples, and computing mean, standard deviation, etc. from the resulting distribution.

CMB Power spectra

- CMB resampled maps are formally noiseless and fullsky, and parameter estimation takes advantage of this property (see Simone’s talk).
- Nonetheless, cut sky power spectra allows for a more direct comparison with other methods.



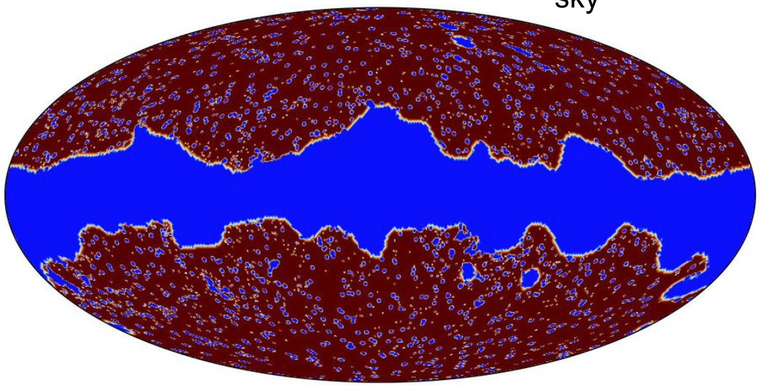
Bin $\Delta\ell$ = 50

BP: mean power spectrum $\langle C_\ell \rangle$

Smica: HM1xHM2 cross-spectrum

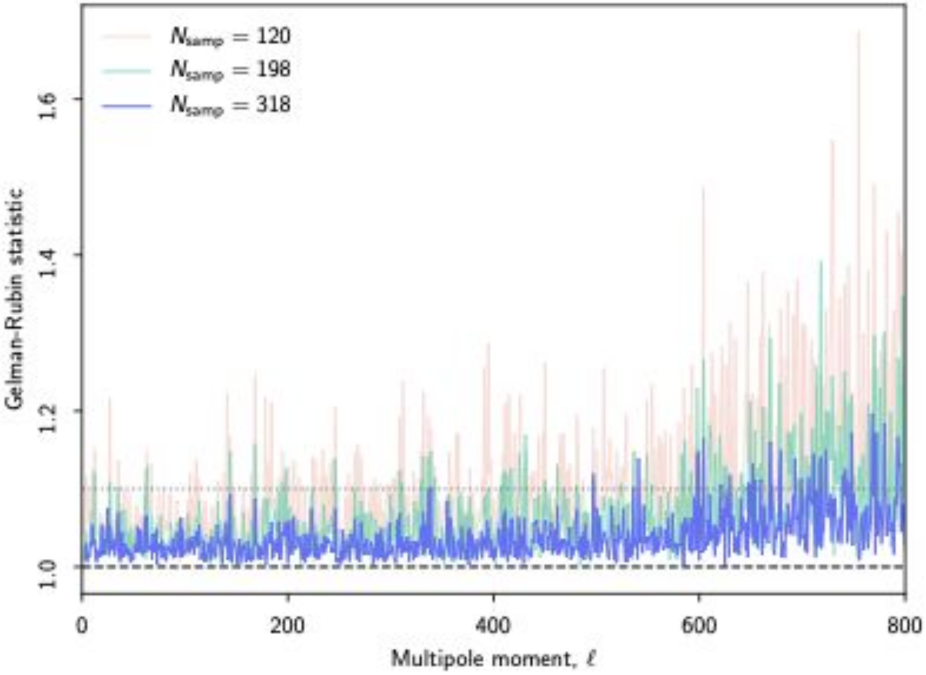
68% chain scatter

f_{sky} = 0.618



Chain Convergence

- For multiple-chain MCMC, the Gellman-Rubin statistics, compares the the parameter variance measured within the individual chain, to the variance measured between the chains. Large differences between these variance estimates indicate non-convergence.



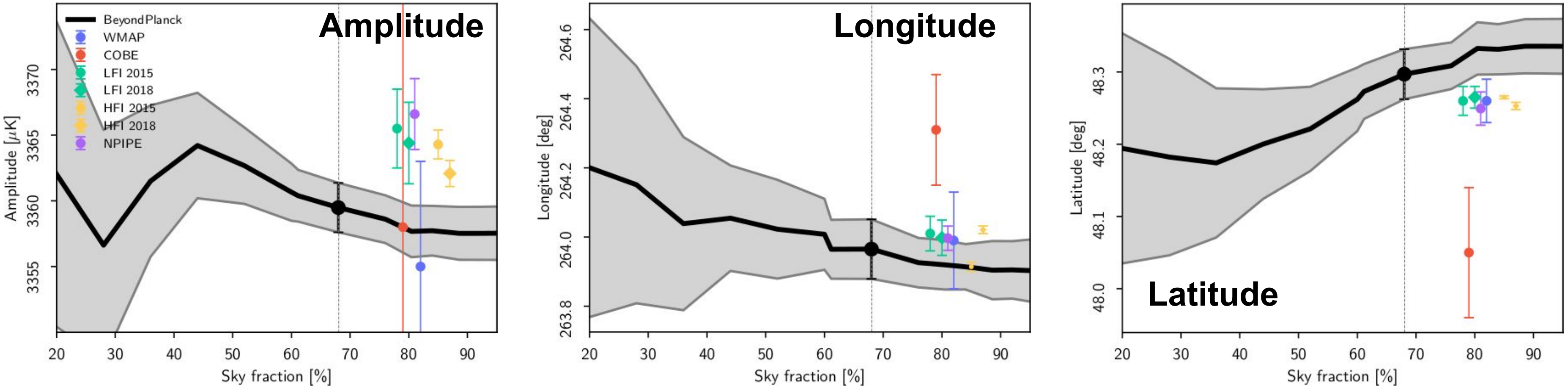
- For the map power spectrum, R shows stable convergence level up to $\ell \sim 600$.

CMB: Solar Dipole

- In BeyondPlanck the solar dipole is treated as part of the CMB component, without needing ad-hoc component separation, but we make use of effective priors to break degeneracies with absolute calibration, correlated noise, astrophysical foregrounds.
- Dipole amplitude and direction estimation is performed on the masked sky, and we account for the impact of higher multipoles on the uncertainty in individual sample estimates (Thommesen et al. 2020).
- By repeating the dipole estimation on the full chain we propagate the full instrumental and astrophysical uncertainties. An additional 0.7μK contribution accounts for the error on CMB monopole (Fixsen 2009).

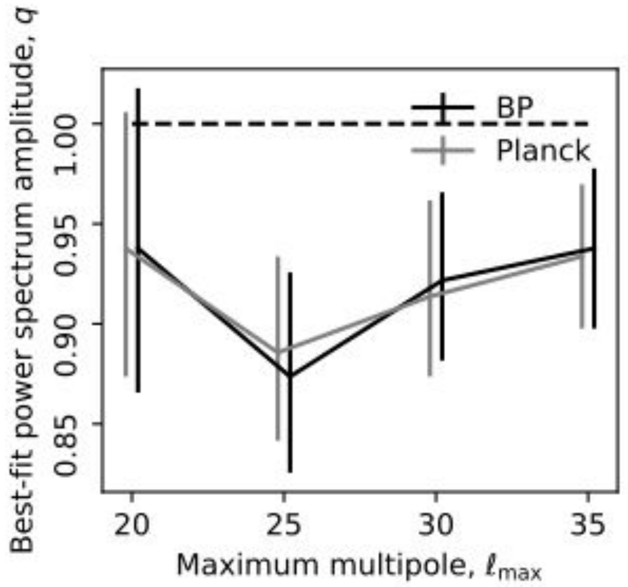
Solar dipole estimates

EXPERIMENT	AMPLITUDE [μK_{CMB}]	GALACTIC COORDINATES l [deg]	 b [deg]	REFERENCE
COBE[a,b]	3358 ± 23	264.31 ± 0.16	48.05 ± 0.09	Lineweaver et al. (1996)
WMAP[c]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03	Hinshaw et al. (2009)
LFI 2015[b]	3365.5 ± 3.0	264.01 ± 0.05	48.26 ± 0.02	Planck Collaboration II (2016)
HFI 2015[d]	3364.29 ± 1.1	263.914 ± 0.013	48.265 ± 0.002	Planck Collaboration VIII (2016)
LFI 2018[b]	3364.4 ± 3.1	263.998 ± 0.051	48.265 ± 0.015	Planck Collaboration II (2020)
HFI 2018[d]	3362.08 ± 0.99	264.021 ± 0.011	48.253 ± 0.005	Planck Collaboration III (2020)
NPIPE[a,c]	3366.6 ± 2.6	263.986 ± 0.035	48.247 ± 0.023	Planck Collaboration (2020)
BEYONDPLANCK[e]	**3359.5 ± 1.9**	**263.97 ± 0.09**	**48.30 ± 0.03**	Section 9.5

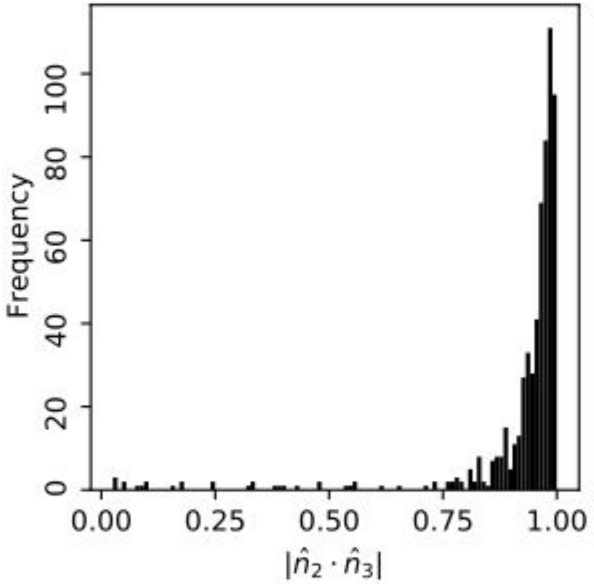


Temperature anomalies

- Primary CMB is Gaussian and isotropic to high accuracy, nonetheless several intriguing anomalies have been observed, including the low-quadrupole, quadrupole-octupole alignment, low-l anomaly, etc.



Low-ℓ anomaly



Quadrupole-octupole alignment

Summary

- BeyondPlanck produces 3 different sets of CMB maps, targeted to different goals:
  - Prior-free I,Q,U maps used internally to increase the robustness of the component separation model,
  - Resampled I full resolution maps for science analysis,
  - Resampled I,Q,U low resolution maps for science analysis.

- Each full resolution resampled map represent a realization of an isotropic, noiseless CMB field compatible with the observed data.

- The full posterior of the resampled maps includes uncertainty from noise, instrumental and astrophysical parameters, which can then be propagated to the final science results by analysing each of the samples and studying the resulting distribution for the quantities of interest (CMB dipole, anomalies, cosmological parameters,...)

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- “*BeyondPlanck*”
  - COMPET-4 program
  - PI: Hans Kristian Eriksen
  - Grant no.: 776282
  - Period: Mar 2018 to Nov 2020

Collaborating projects:

- “*bits2cosmology*”
  - ERC Consolidator Grant
  - PI: Hans Kristian Eriksen
  - Grant no: 772 253
  - Period: April 2018 to March 2023
- “*Cosmoglobe*”
  - ERC Consolidator Grant
  - PI: Ingunn Wehus
  - Grant no: 819 478
  - Period: June 2019 to May 2024

Questions?

Beyond PLANCK

Commander

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