BeyondPlanck: a Bayesian Framework for end-to-end Cosmic Microwave Background Analysis

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on behalf of BeyondPlanck team

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The Cosmic Microwave Background

- Since its discovery in 1964, the **Cosmic Microwave Background** (CMB) has been our best source of information on the Universe and played a fundamental role in shaping modern cosmology
- From its existence and properties we have “learned” that:
  - in the far past, the Universe was very hot and dense ➡ there is no credible alternative to the **Big Bang**;
  - the Universe is very uniform on large scales ➡ it went through a short phase of very rapid expansion (**Inflation**);
  - most of the matter has no electromagnetic interaction ➡ **Dark Matter**;
  - and much more.
- It's still one of the most powerful cosmological probes.

The Origin of the CMB

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- It's a thermal radiation emitted **380,000** years after the Big Bang.
- At that time the Universe was:
  - simple: photons, baryons (73% H^+, 27% $^4He^{++}$, traces of D^+, T^+, $^3He^{++}$, Li^{+++}, n), electrons, plus Dark Matter (and neutrinos);
  - "empty" (2.4 10^6 nuclei/m^3);
  - in thermal equilibrium
    - ☆ opaque
    - ☆ blackbody spectrum (T ~ 3000K)
  - very small inhomogeneities (1 part in 10^5 in T, 1 part in 10^6-10^7 in P) that propagate as sound waves in the baryon-photon plasma.
- We understand this conditions very well (linear regime)!
- We can compute the properties of the very early Universe to high accuracy, as a function of **a small set of free parameters.**

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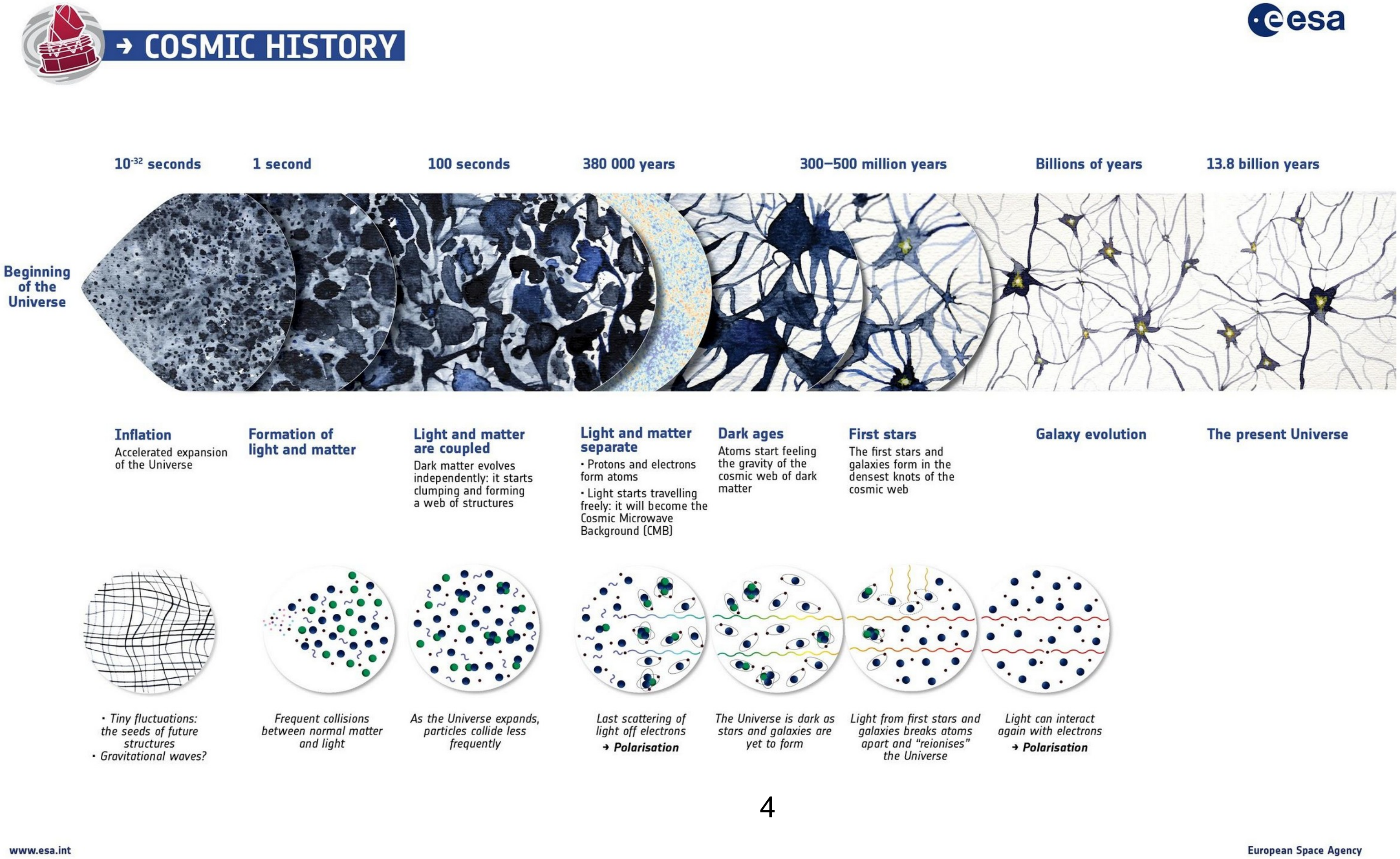
Cosmic timeline

- The Universe is expanding and cooling: after 380,000 years photons no longer have enough energy to keep electrons and protons separated, stable atoms form, and the universe become **transparent** to e.m. radiation (the CMB!).
- CMB photons travel for **13.8 By** until they are observed by our instruments. During their travel, the photons:
  - get redshifted to an effective temperature of **2.7K**.
  - learn about the intervening Universe.



The Standard Cosmological Model

- Our best model of the Universe (**ΛCDM** model) maintains that the Universe is:
  - spatially flat ($\Omega = 1$);
  - made up by 5 main components: Dark Energy, Cold Dark Matter, baryons (including electrons), photons, neutrinos;
  - underwent an early exponential expansion phase (inflation).
- In order to fully characterize the model, we need data to fix 6 numbers:
  - cold dark matter density $\mathbf{\Omega_c}$;
  - baryon density $\mathbf{\Omega_b}$;

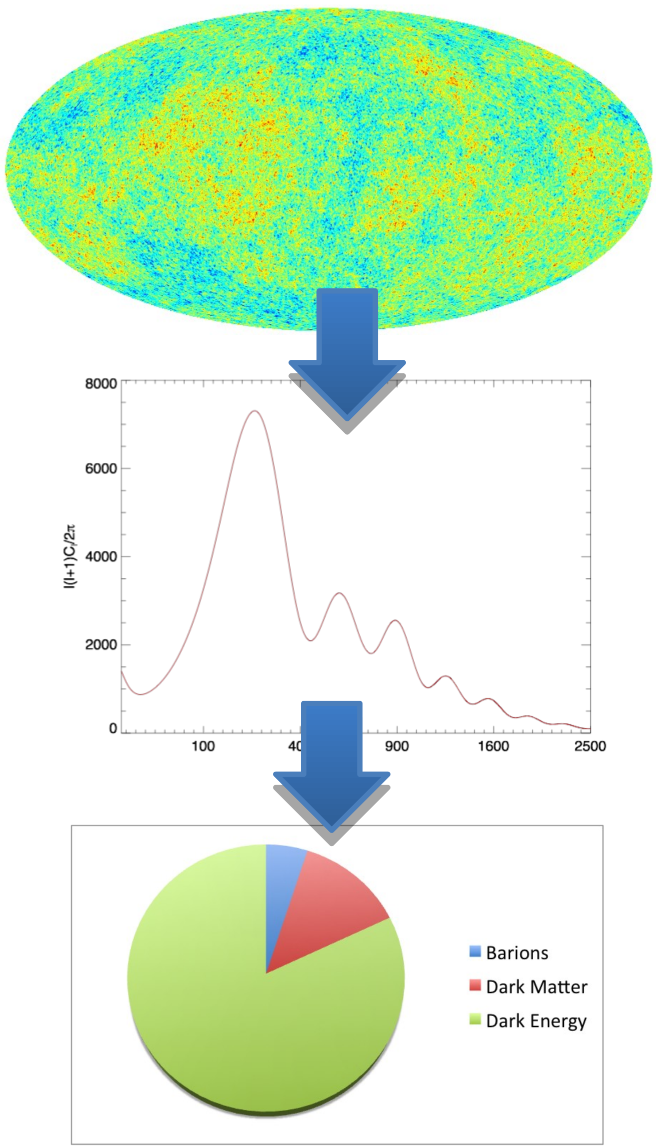
  } What the Universe is made of

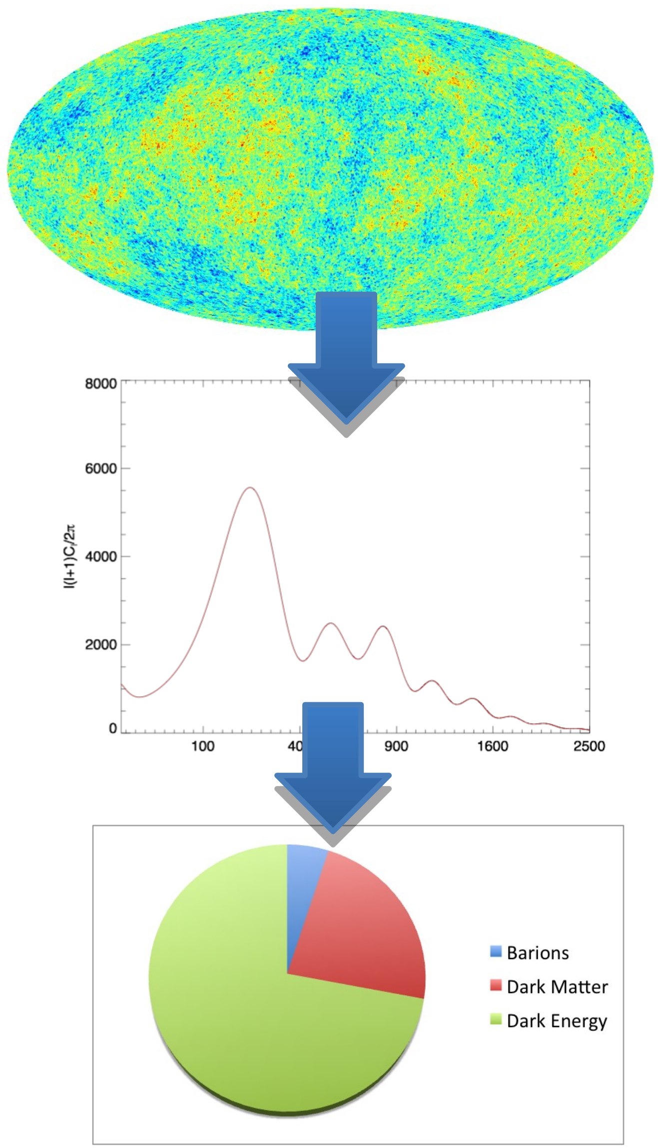
  - spectral index of primordial density fluctuations $\mathbf{n_s}$;
  - amplitude of primordial density fluctuations $\mathbf{A_s}$;

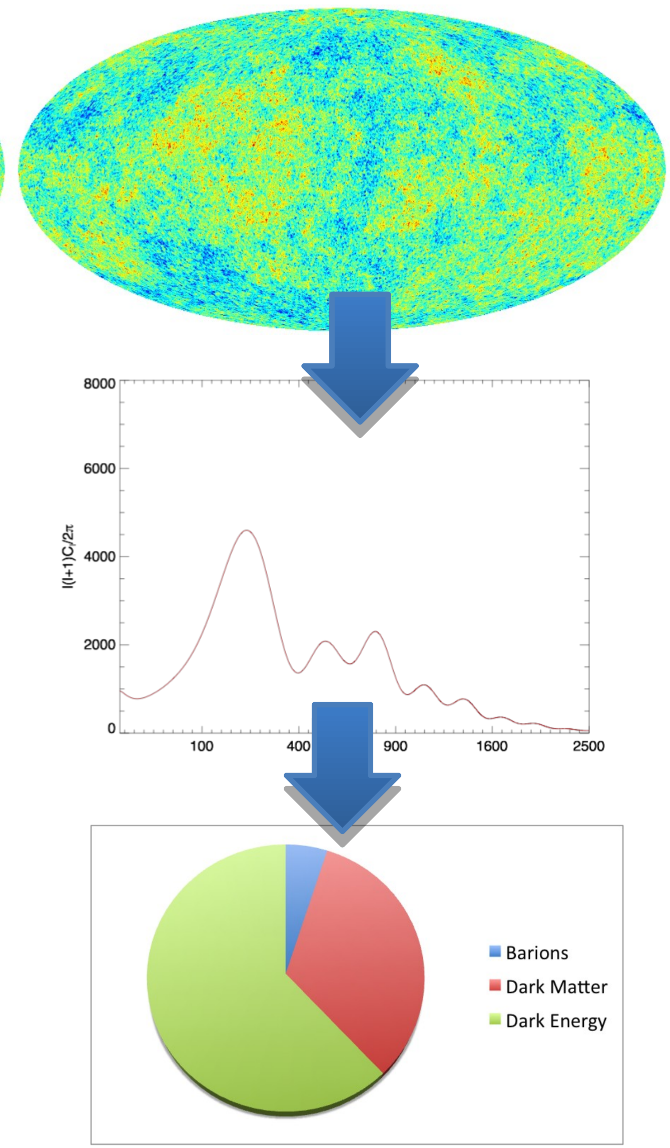
  } Initial Conditions

  - Hubble parameter $\mathbf{H_0}$; How fast is expanding
  - optical depth to reionization τ; How the first sources of light formed
- We are also looking for a 7th parameter: the tensor-to-scalar ratio **r**, which measures the amount of **primordial gravitational waves** and probes inflation.

From Maps to Cosmology

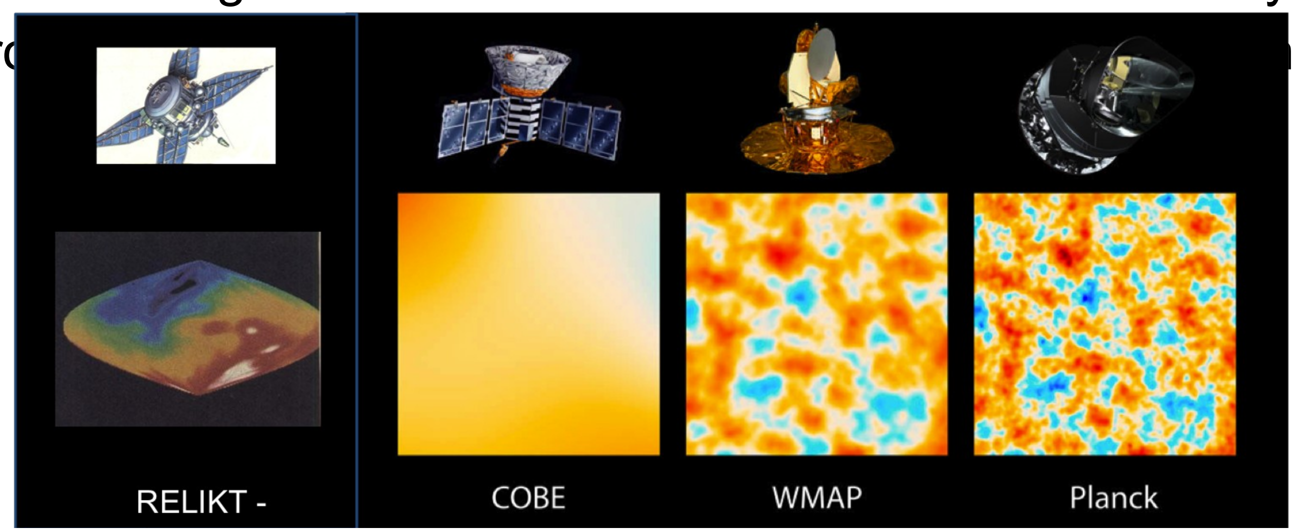






Planck

- Is the fourth generation CMB space mission (after RELIKT-1, COBE and WMAP)
  - European Space Agency (NASA contribution) satellite carrying 2 instruments:
    - ☆ **Low Frequency Instrument** (LFI), Radiometers
    - ☆ **High Frequency Instrument** (HFI), Bolometers
  - 9 frequencies: **30**, **44**, **70** (LFI), **100**, **143**, **217**, **353**, 545, 857 (HFI) GHz for systematic and foregrounds control
  - Planck leading channel has ~ 25x instantaneous sensitivity and ~3x impr el



1983 1989 2001 2009

Planck Data

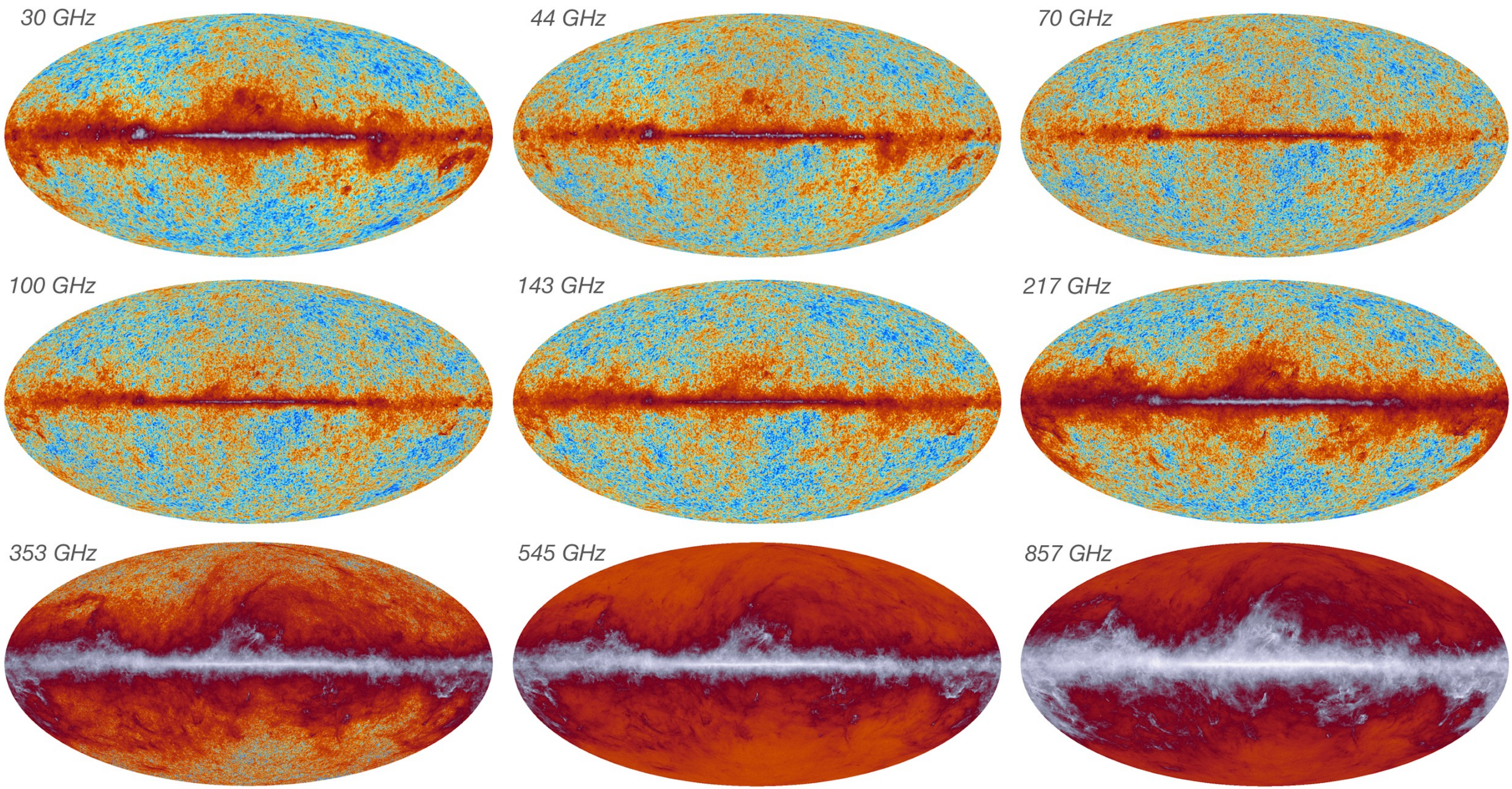
- Three (plus one upcoming) public data releases, covering 49 months of LFI data, 29 months of HFI data, including:

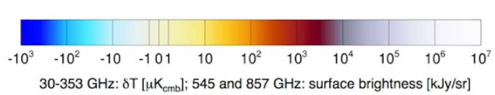
  - Timelines
  - Frequency maps (T+P)
  - CMB and astrophysical components maps (T+P)
  - Source and galaxy clusters catalogs
  - Cosmological parameters
  - Ancillary and instrumental data
  - …

- All data publicly available at:

https://pla.esac.esa.int

Planck 2018 temperature frequency maps





Cosmological dipole not included

Planck (2018), A&A, 641, A1

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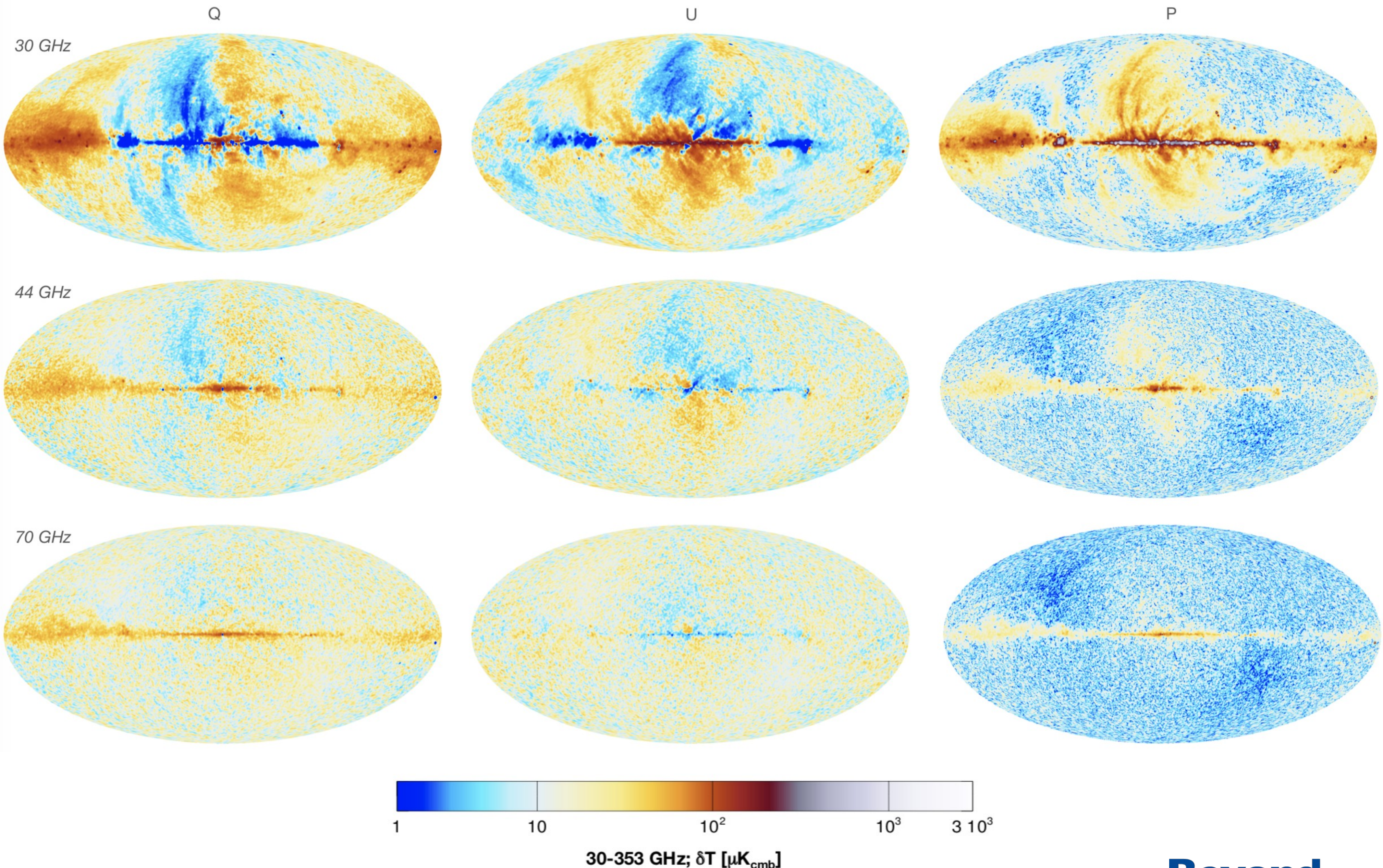
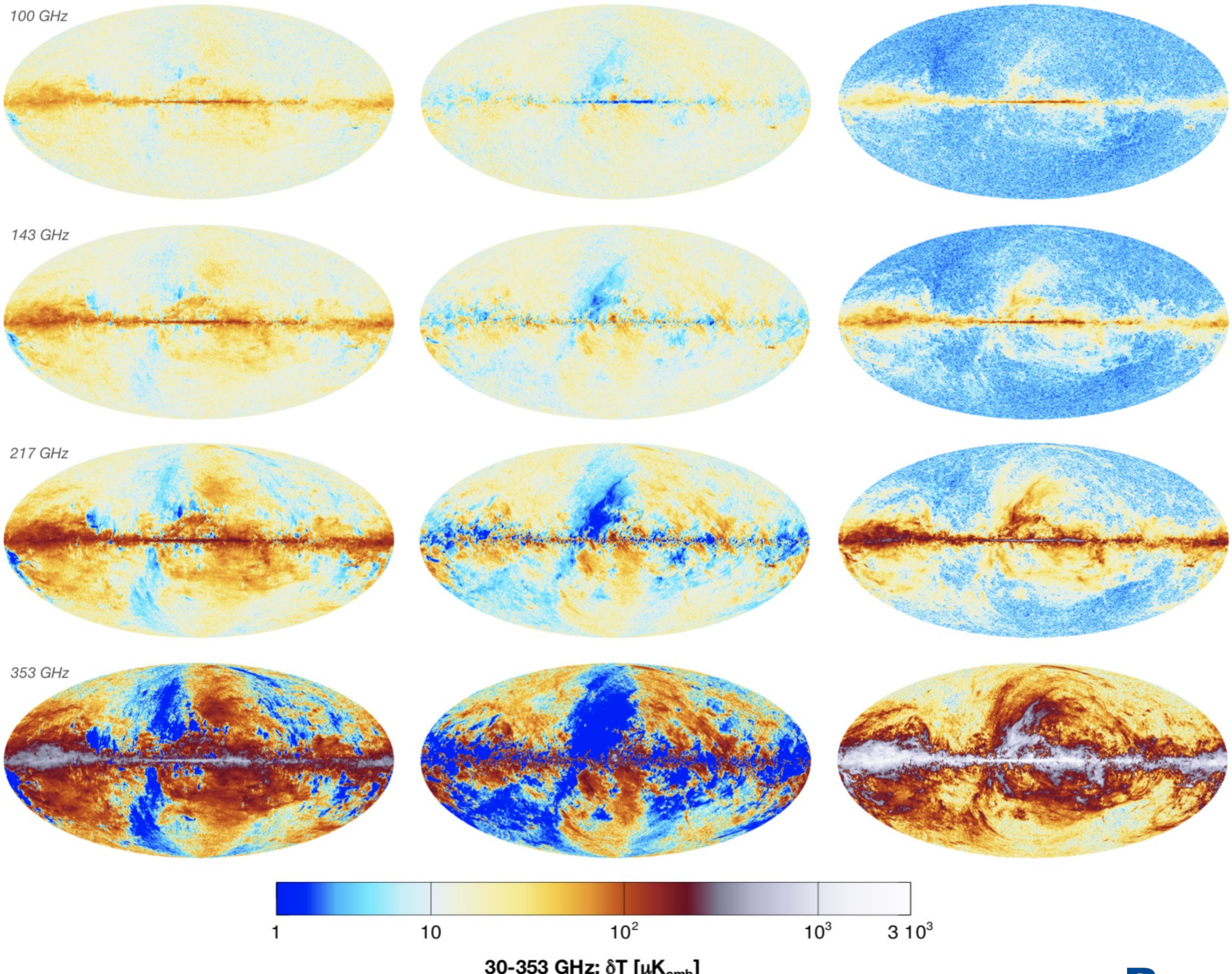
Planck-LFI 2018 polarization frequency maps



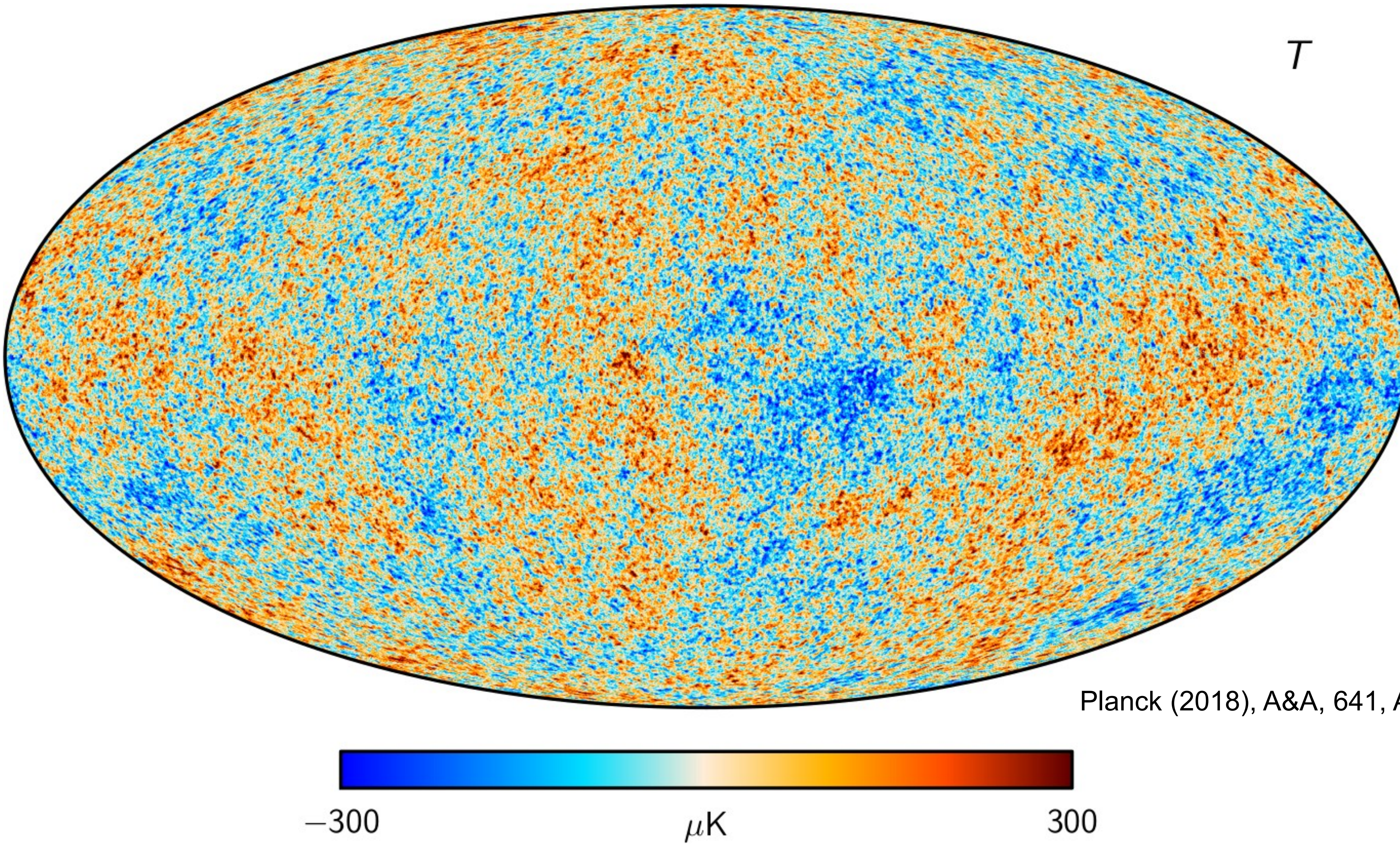
Planck (2018), A&A, 641, A1

Planck-HFI 2018 polarization frequency maps



Planck (2018), A&A, 641, A1

Planck 2018 CMB temperature map



Planck (2018), A&A, 641, A4

CMB power spectra and cosmological parameters

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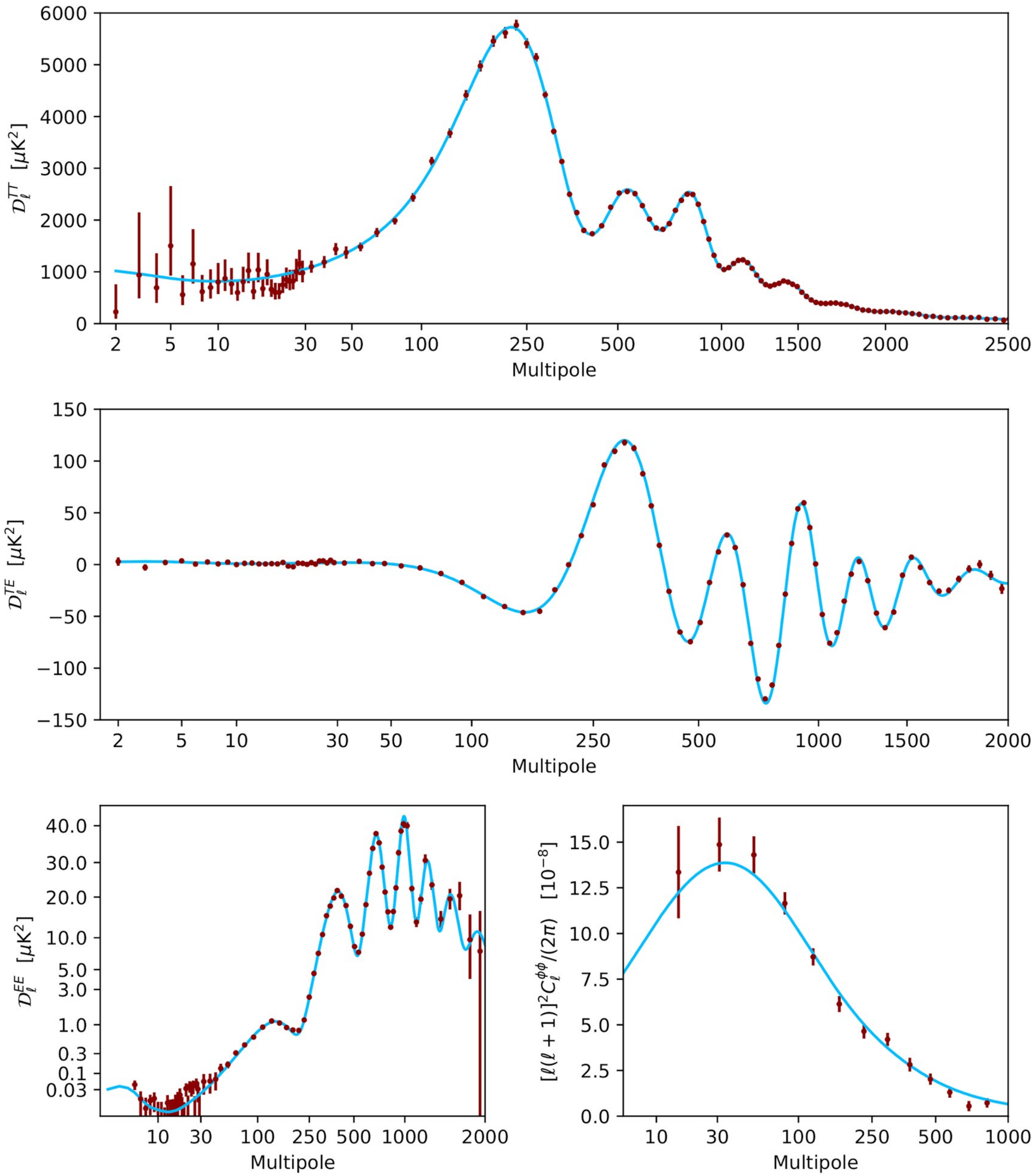

Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10} A_s)$	3.0448
n_s	0.96605
$\Omega_m h^2$	0.14314
H_0 [$\mathrm{km\,s^{-1} Mpc^{-1}}$] . . .	67.32
Ω_m	0.3158
Age [Gyr]	13.7971
σ_8	0.8120
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331
z_{re}	7.68
$100\theta_*$	1.041085
r_{drag} [Mpc]	147.049

Planck (2018), A&A, 641, A5

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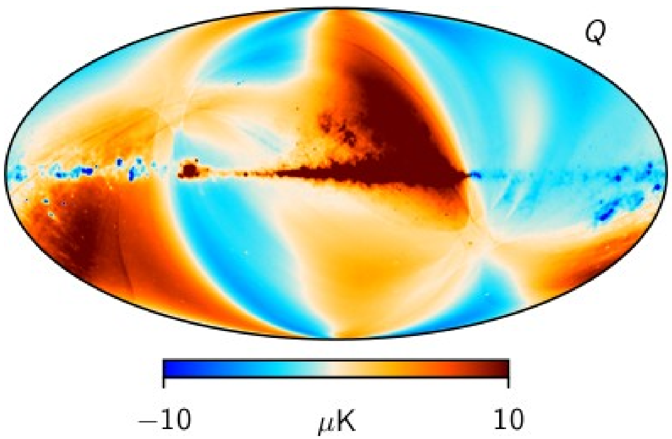
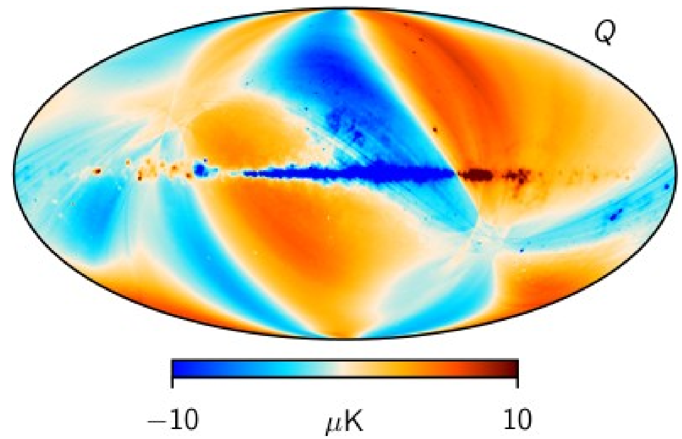
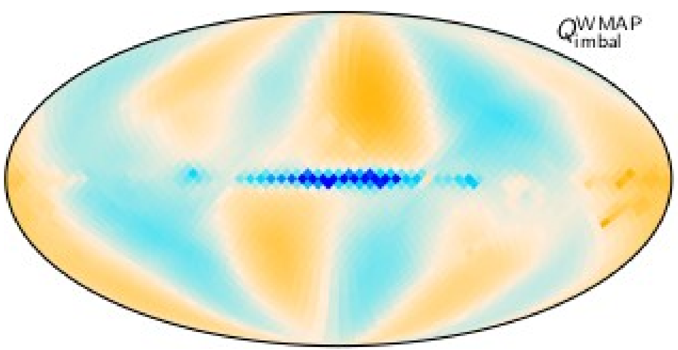
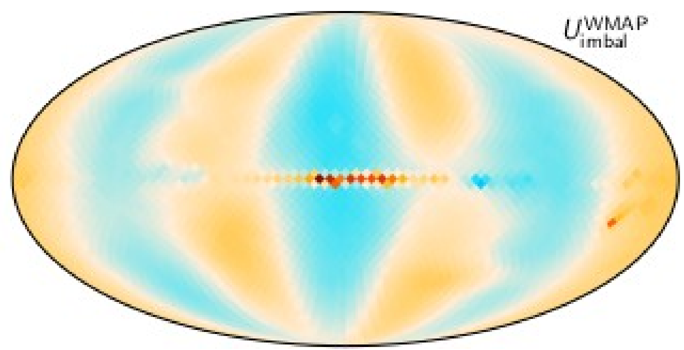
Are we done with Planck data?



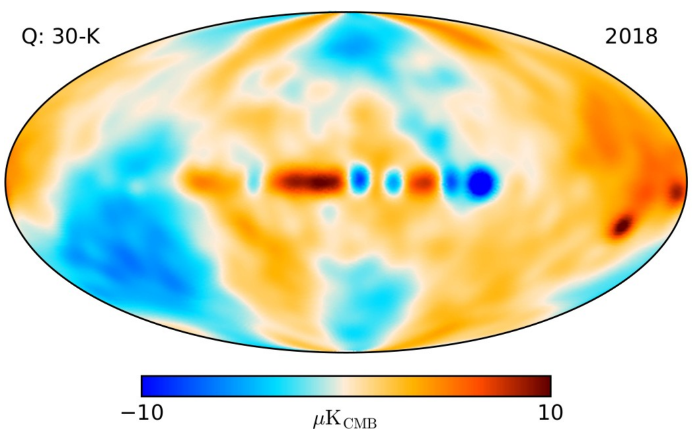


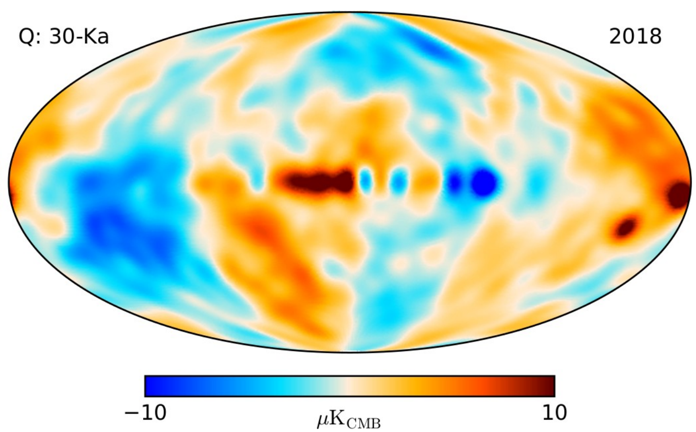
Planck 2018 30 GHz gain residual template





WMAP K-band transmission imbalance template





30 - K difference map

Beyond PLANCK

Residual Systematics

- Planck detectors measure voltage fluctuations produced by the incoming sky radiation, which need to be converted back into temperature values, by calibrating against a know signal.

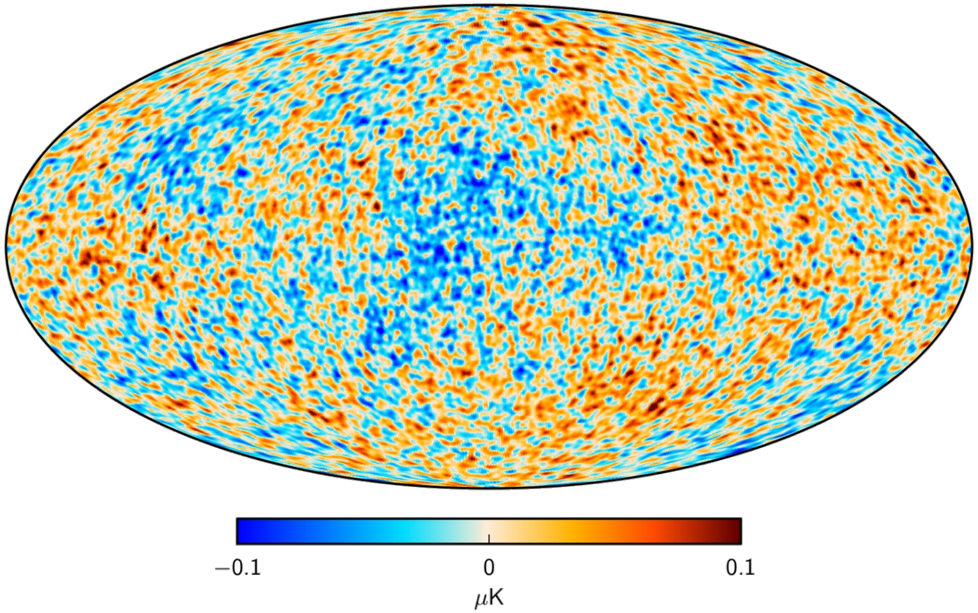
- Planck calibrates on the unpolarized orbital dipole, i.e. the doppler shift of the CMB temperature due to the spacecraft motion around the sun.

- When observing at 90º from the orbital motion, the dipole vanishes, and calibration becomes much more sensitive to the polarized emission from the Galaxy.

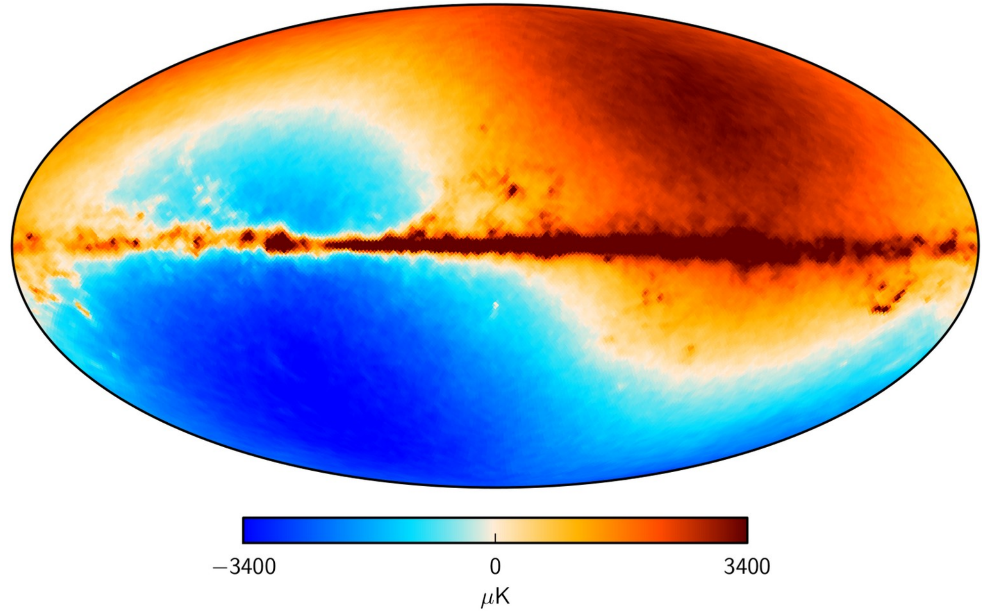
- There is a “Chicken and egg” problem: to measure the sky we need to calibrate the data, but to calibrate the data we need to know the sky.

What sort of precision is required for gravitational wav

Q expected signal r = 0.01



Actual sky

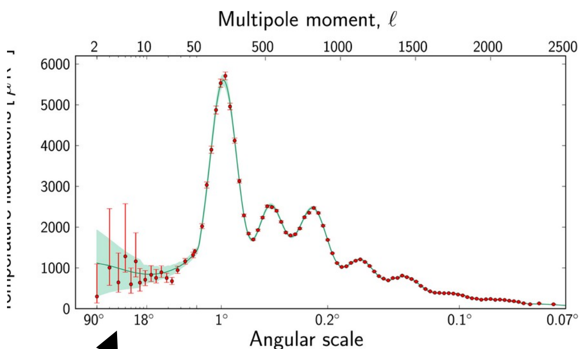


The sky is more than four orders of magnitude brighter than the signal!

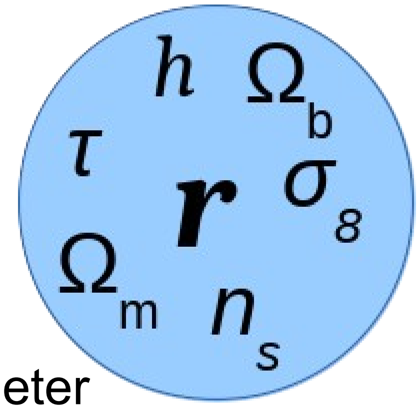
$\Downarrow$

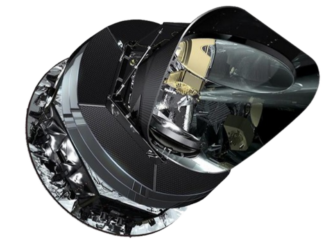
Need extremely accurate component separation
and control of instrumental systematic effects!

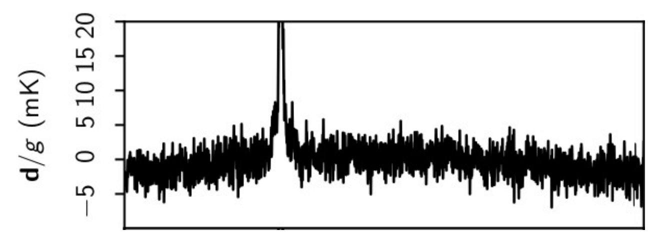
Classic CMB analysis



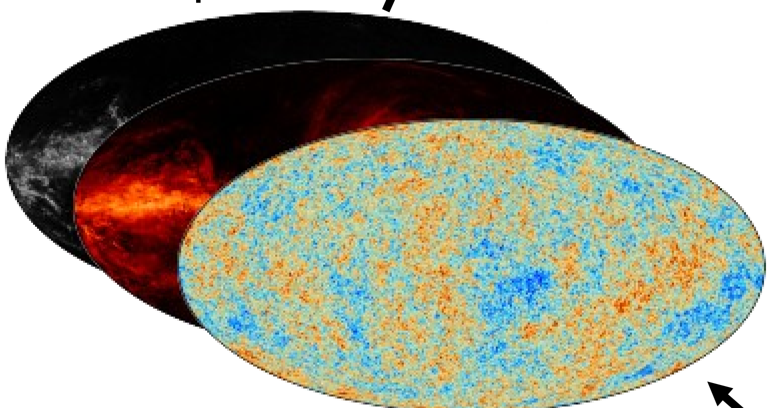
Parameter estimation





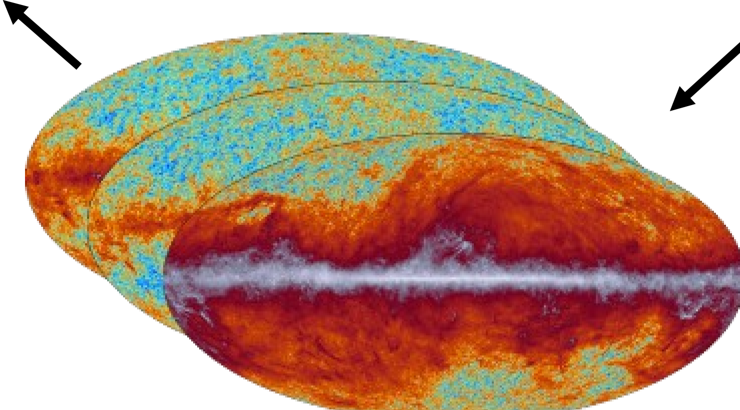


Power spectrum estimation

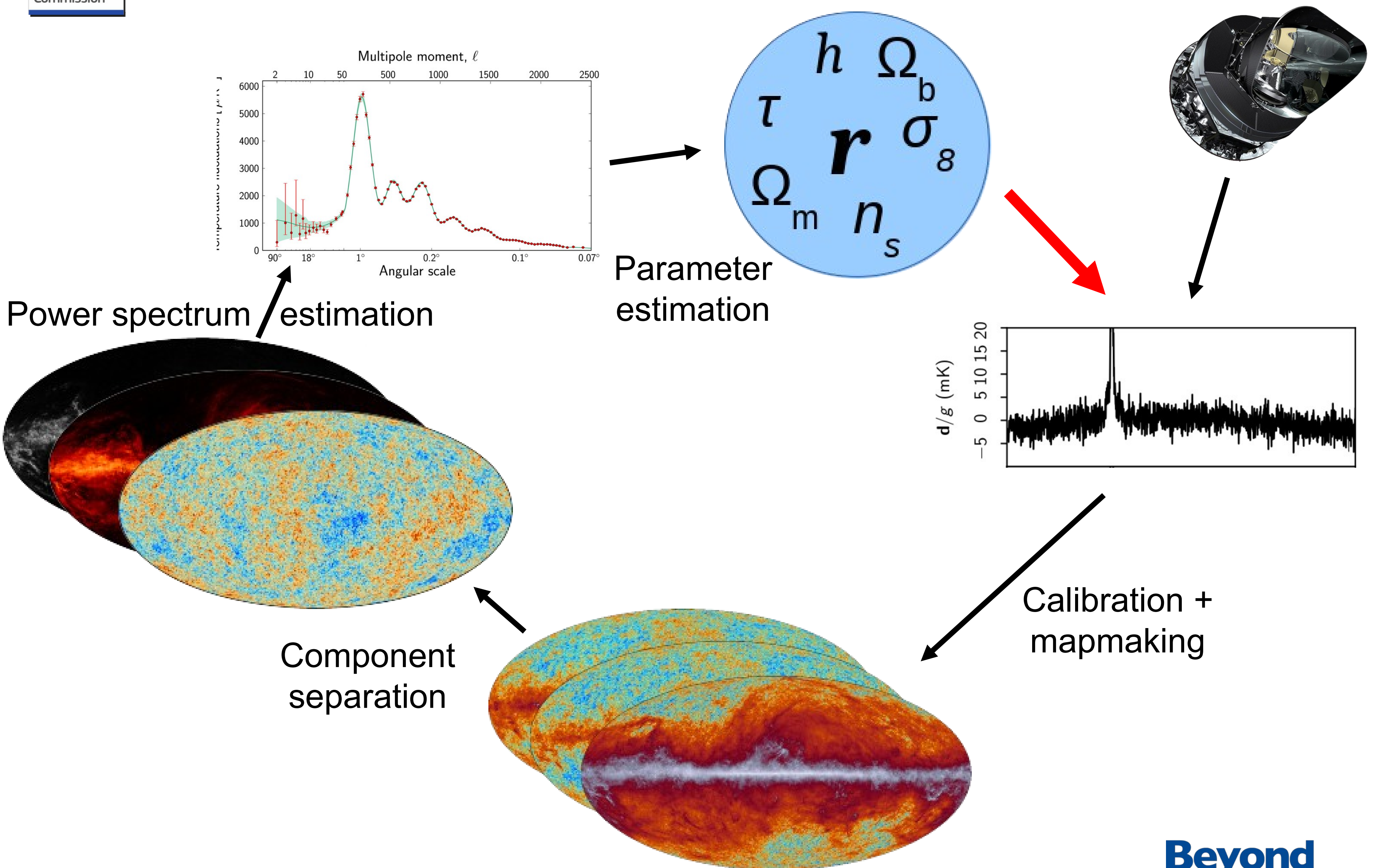


Calibration + mapmaking

Component separation



End-to-end iterative analysis



Starting point for BeyondPlanck

- For the 2018 data release, LFI implemented a “by hand” iterative approach. Different parts of the pipeline ran in different processing centers, by different people, leading to significant overheads.

- Each iteration took 2-3 weeks, limiting the number of cycles to 4. We stopped because we ran out of time.

- BeyondPlanck plans to overcome the above limitations by:

  1. speeding up the iteration process, and perform hundreds of component separation + calibration iterations, not just four?
  2. break internal Planck-specific degeneracies using external data, in particular WMAP?

- BeyondPlanck is the natural continuation of LFI activities, but also a starting point for the analysis of future experiments.

The BeyondPlanck project

Main goals of the BeyondPlanck project:

- Implement an end-to-end analysis framework for current and future CMB experiments using Planck experience
- Demonstrate this framework with Planck LFI data (with minor contribution from non-LFI datasets to break degeneracies and constrain Galactic foreground emission.)
- Make software and results publicly available under an OpenSource license

The BeyondPlanck pipeline in one slide

European Commission

1. Write down an explicit parametric model for the observed data:

$$d_{j,t} = g_{j,t}\mathsf{P}_{tp,j}\left[\mathsf{B}^{\mathrm{symm}}_{pp',j}\sum_{c}\mathsf{M}_{cj}(\beta_{p'},\Delta^{j}_{\mathrm{bp}})a^{c}_{p'} + \mathsf{B}^{\mathrm{asymm}}_{j,t}\left(\boldsymbol{s}^{\mathrm{orb}}_{j} + \boldsymbol{s}^{\mathrm{fsl}}_{t}\right)\right] + n^{\mathrm{corr}}_{j,t} + n^{\mathrm{w}}_{j,t}.$$

Let ω = {all free parameters}

2. Derive the joint posterior distribution with Bayes' theorem:

$$P(\omega \mid \boldsymbol{d}) = \frac{P(\boldsymbol{d} \mid \omega)P(\omega)}{P(\boldsymbol{d})} \propto \mathcal{L}(\omega)P(\omega),$$

3. Map out $P(\omega \mid \boldsymbol{d})$ with standard Markov Chain Monte Carlo (MCMC) methods

Beyond PLANCK

The BeyondPlanck data model

Data — Pointing — Bandpass — Sidelobe pickup — White noise

$$d_{j,t} = g_{j,t}\mathsf{P}_{tp,j}\left[\mathsf{B}^{\mathrm{symm}}_{pp',j}\sum_{c}\mathsf{M}_{cj}(\beta_{p'},\Delta^{j}_{\mathrm{bp}})a^{c}_{p'} + \mathsf{B}^{\mathrm{asymm}}_{j,t}\left(\boldsymbol{s}^{\mathrm{orb}}_{j} + \boldsymbol{s}^{\mathrm{fsl}}_{t}\right)\right] + n^{\mathrm{corr}}_{j,t} + n^{\mathrm{w}}_{j,t}.$$

Gain — Main beam — Sky model — Orbital CMB dipole — Correlated noise

Sky model:

$$s_{\mathrm{RJ}} = \boldsymbol{a}_{\mathrm{CMB}}\frac{x^2e^x}{(e^x-1)^2}\frac{(e^{x_0}-1)^2}{x_0^2e^{x_0}} +$$

CMB

$$+\,\boldsymbol{a}_{\mathrm{s}}\left(\frac{\nu}{\nu_{0,\mathrm{s}}}\right)^{\beta_{\mathrm{s}}} +$$

Synchrotron

$$+\,\boldsymbol{a}_{\mathrm{ff}}\frac{g_{\mathrm{ff}}(\nu;T_e)}{g_{\mathrm{ff}}(\nu_{0,\mathrm{ff}};T_e)}\left(\frac{\nu_{0,\mathrm{ff}}}{\nu}\right)^2 +$$

Free-free

$$+\,\boldsymbol{a}_{\mathrm{AME}}\left(\frac{\nu_{0,\mathrm{sd}}}{\nu}\right)^2\frac{s_0^{\mathrm{sd}}\left(\nu\cdot\frac{\nu_p}{30.0\,\mathrm{GHz}}\right)}{s_0^{\mathrm{sd}}\left(\nu_{0,\mathrm{sd}}\cdot\frac{\nu_p}{30.0\,\mathrm{GHz}}\right)} +$$

AME/spinning dust

$$+\,\boldsymbol{a}_{\mathrm{d}}\left(\frac{\nu}{\nu_{0,\mathrm{d}}}\right)^{\beta_{\mathrm{d}}+1}\frac{e^{h\nu_{0,\mathrm{d}}/kT_{\mathrm{d}}}-1}{e^{h\nu/kT_{\mathrm{d}}}-1} +$$

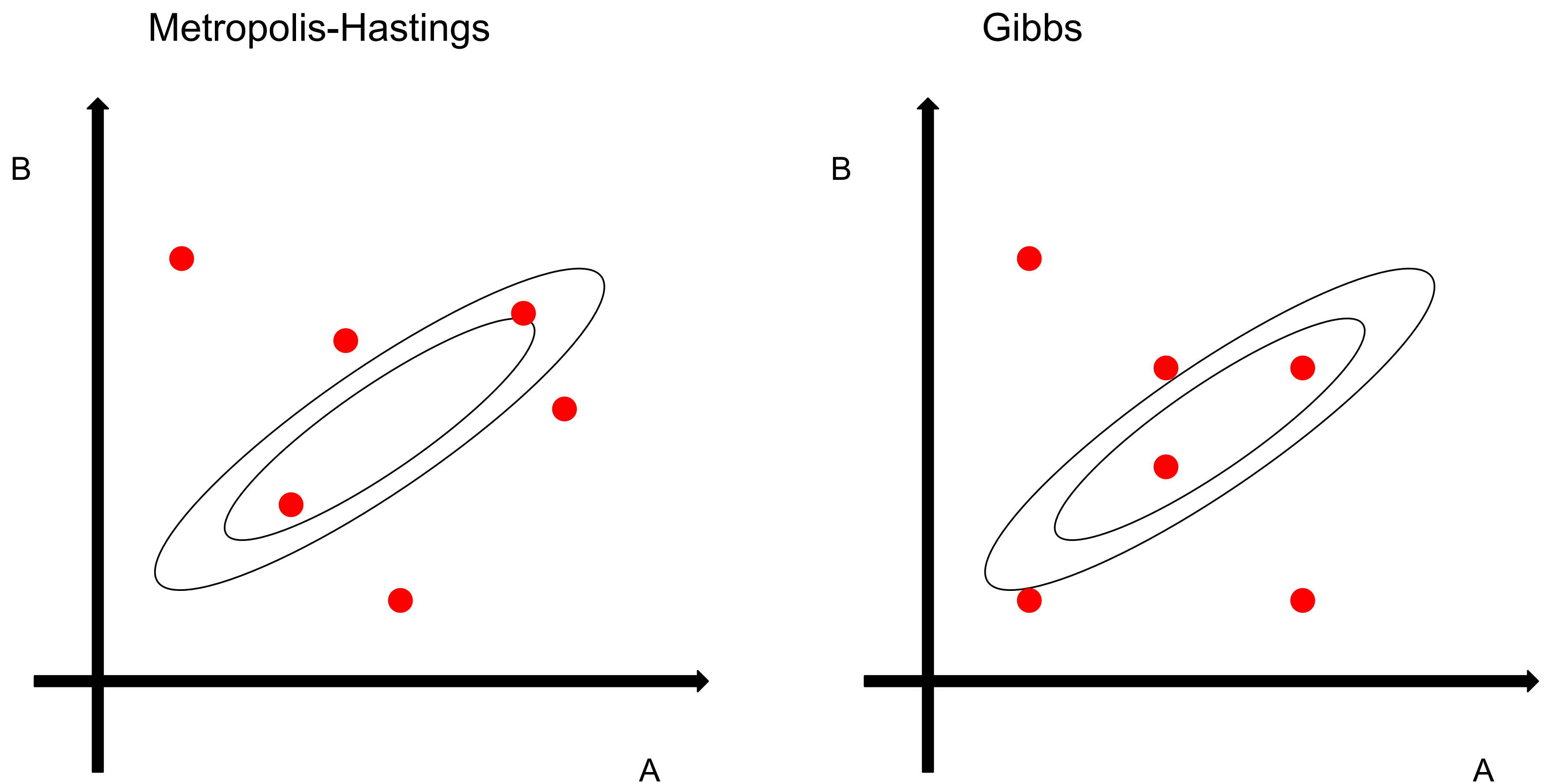
Thermal dust

$$+\sum_{j=1}^{N_{\mathrm{src}}}\boldsymbol{a}^{j}_{\mathrm{src}}\left(\frac{\nu}{\nu_{0,\mathrm{src}}}\right)^{\alpha_{j,\mathrm{src}}-2}$$

Point sources

Gibbs Sampling

Gibbs Sampling explores a multidimensional distribution P(A,B|d), by iteratively drawing samples from the conditional distributions P(A|B,d), P(B|A,d).



The BeyondPlanck Gibbs Sampler

- A full iteration of BeyondPlanck pipelines involves:

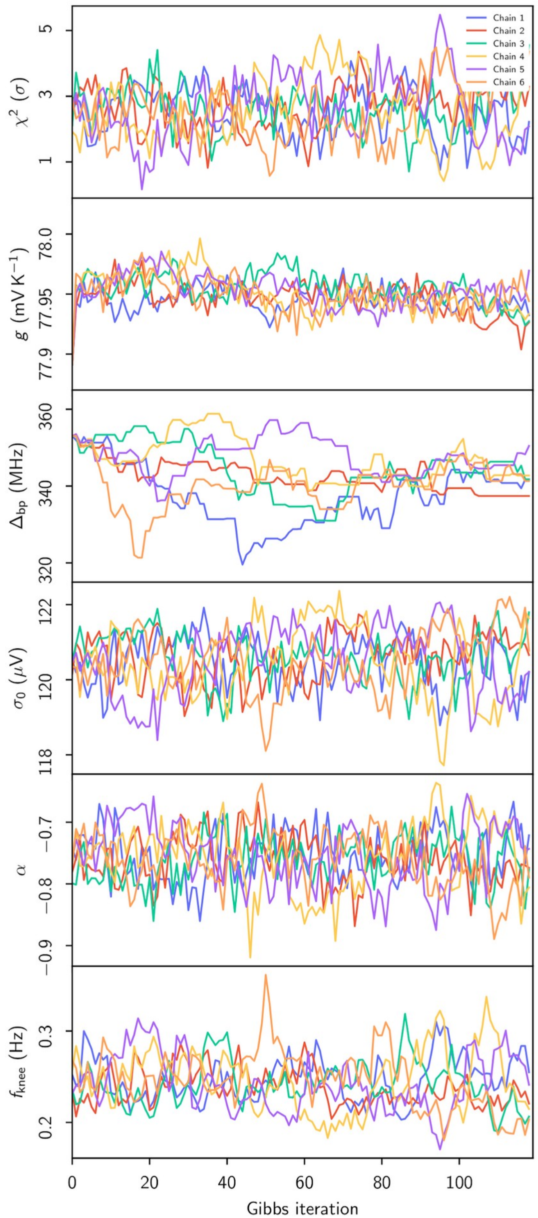
$$
\begin{aligned}
\boldsymbol{g} &\leftarrow P(\boldsymbol{g} \mid \boldsymbol{d}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) && \textbf{Gain}\\
\boldsymbol{n}_{\mathrm{corr}} &\leftarrow P(\boldsymbol{n}_{\mathrm{corr}} \mid \boldsymbol{d}, \boldsymbol{g}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) && \textbf{Correlated Noise}\\
\xi_n &\leftarrow P(\xi_n \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) && \textbf{White Noise PSD}\\
\Delta_{\mathrm{bp}} &\leftarrow P(\Delta_{\mathrm{bp}} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \boldsymbol{a}, \beta, C_\ell) && \textbf{Bandpass}\\
\beta &\leftarrow P(\beta \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, C_\ell) && \textbf{Foreground spectral indexes}\\
\boldsymbol{a} &\leftarrow P(\boldsymbol{a} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \beta, C_\ell) && \textbf{CMB and foregrounds amplitudes}\\
C_\ell &\leftarrow P(C_\ell \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta) && \textbf{CMB power spectrum}
\end{aligned}
$$

- BP products include the full set of samples for all parameters, not just the bestfit value.

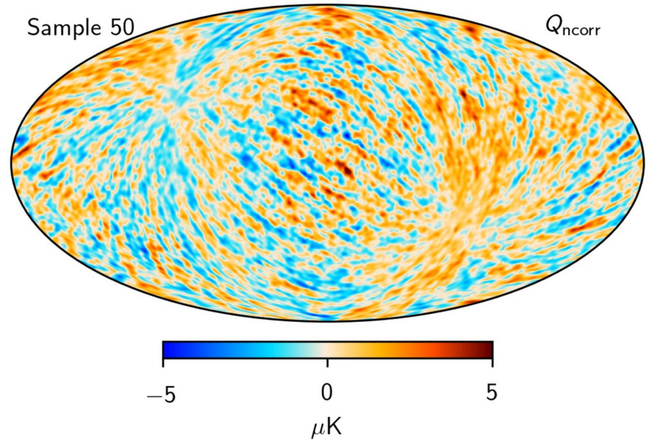
- 1 full iteration: 2.3h on 72-core 1.5TB node. Total runtime 3 weeks.

Main product: Ensemble of full sample sets

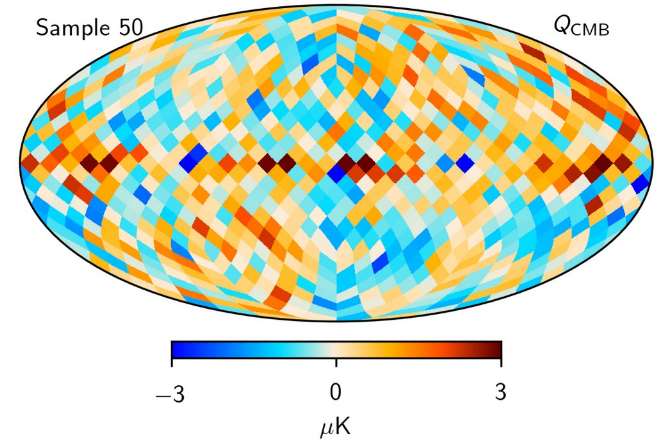
Instrument



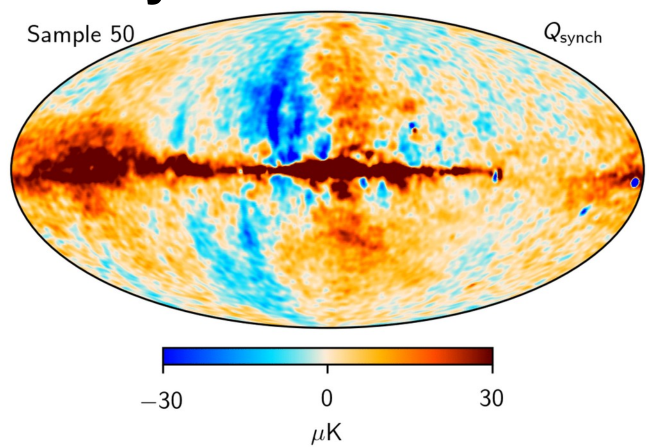
Correlated noise



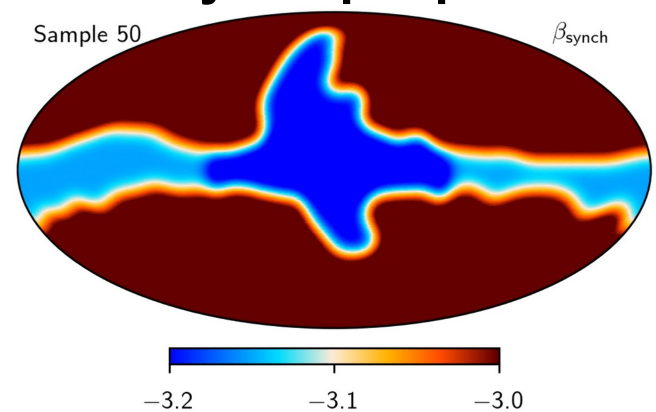
CMB Stokes Q



Synch Stokes Q



Synch pol β



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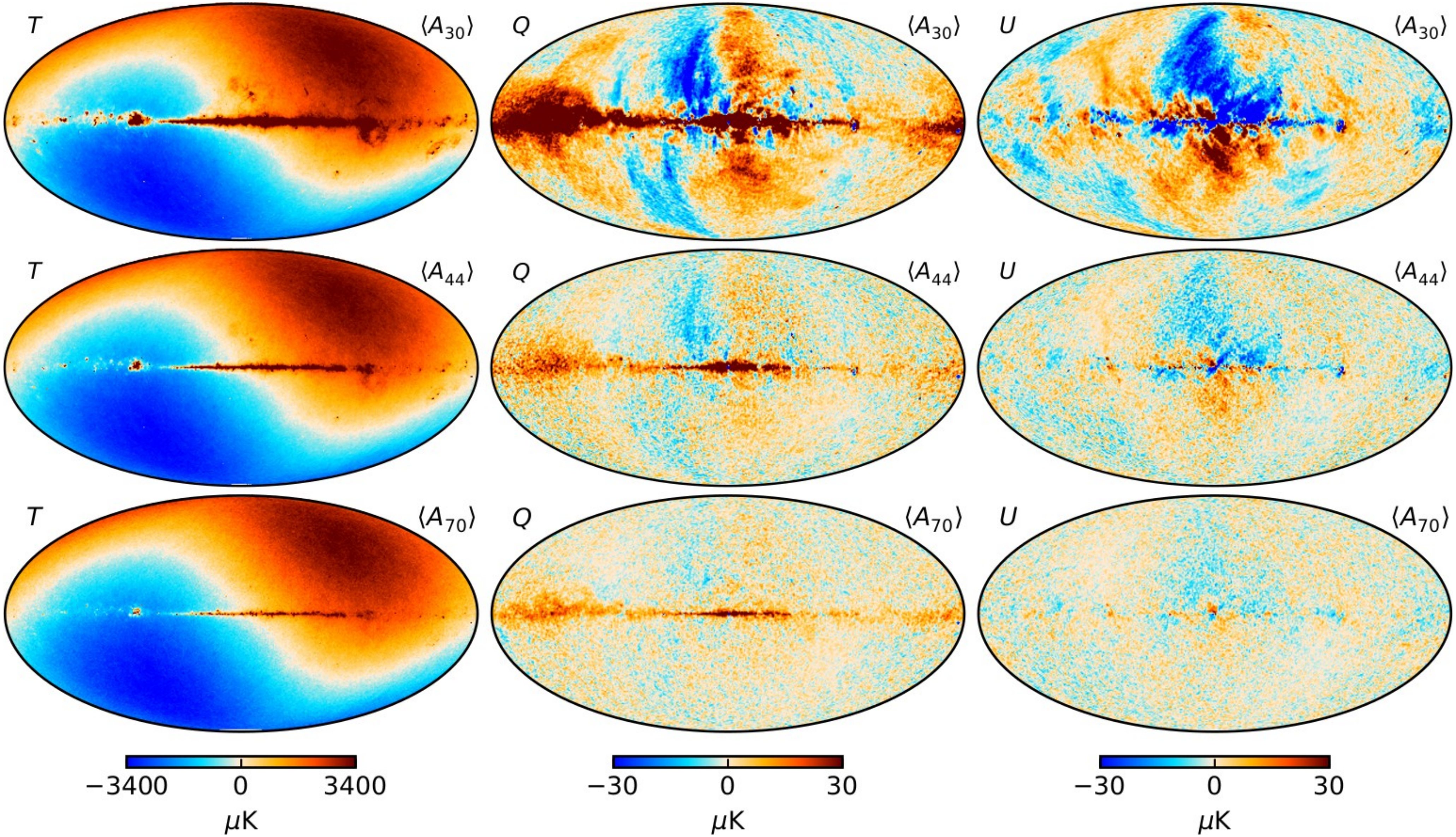
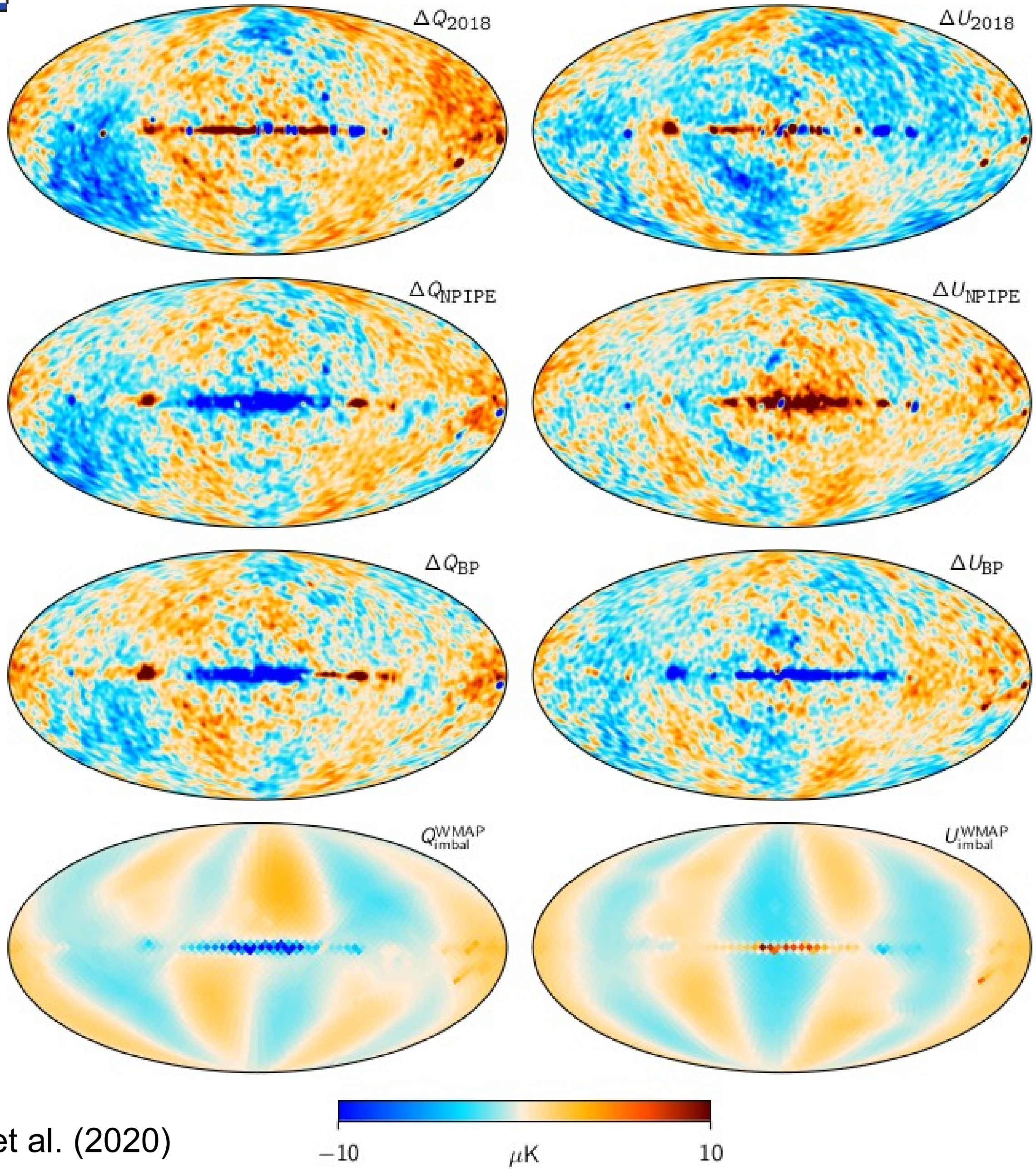
Frequency maps: Posterior mean



Suur-Uski et al. (2020)

Frequency maps: 30 GHz minus WMAP K-band



Planck 2018

NPIPE

BeyondPlanck

WMAP transmission imbalance template (Jarosik et al. 2007)

Gjerløw et al. (2020)

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 $\mathbf{S} = \mathbf{S}(C_l)$. 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:

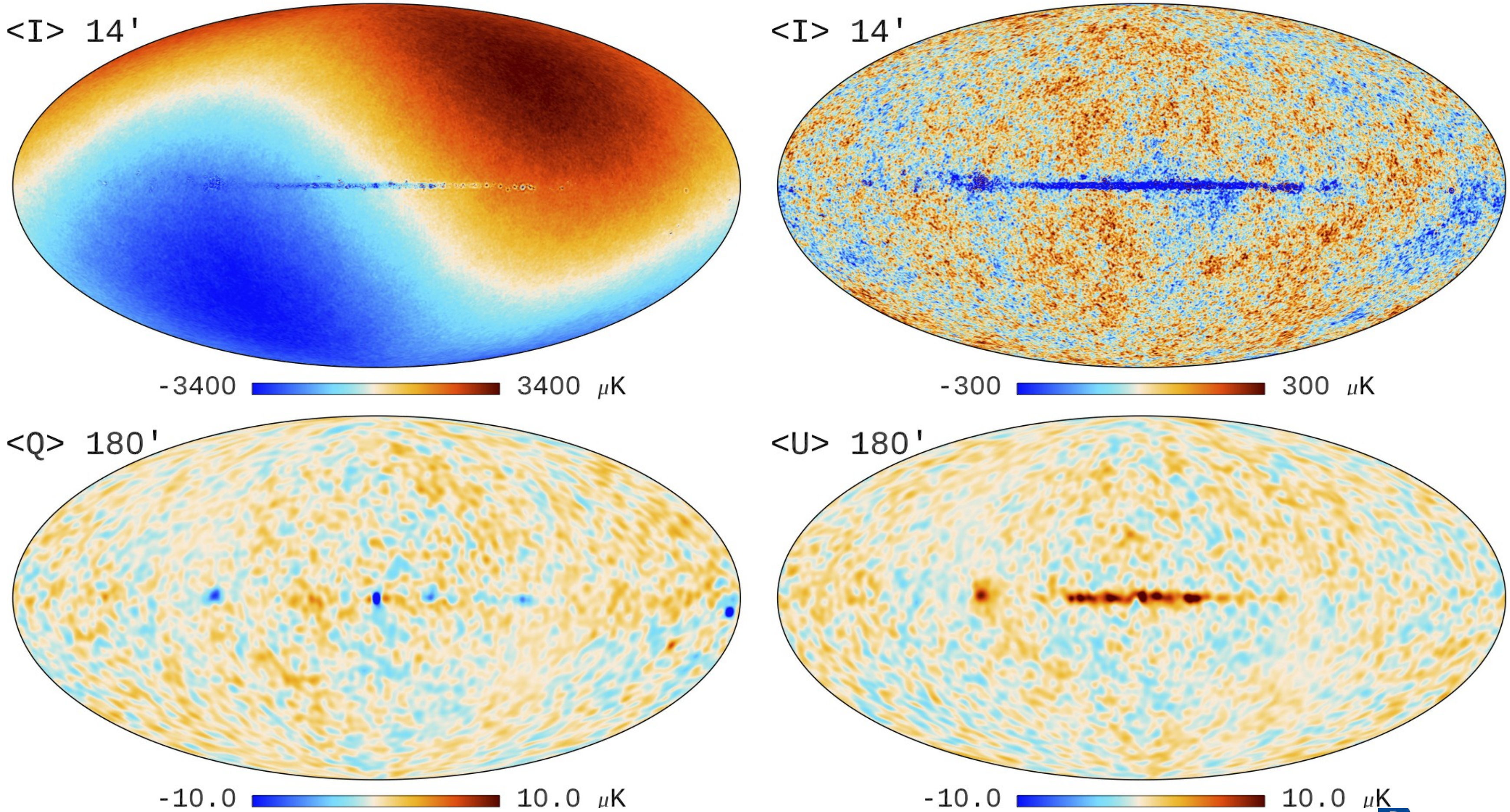
- In the main chain, we solve for CMB and astrophysical components fixing $\mathbf{S}^{-1}=0$, and without Galactic mask. This is the fastest approach, but the resulting CMB maps are suboptimal (no isotropy priors, Galactic plane residuals). These maps are only used internally to improve component separation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

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

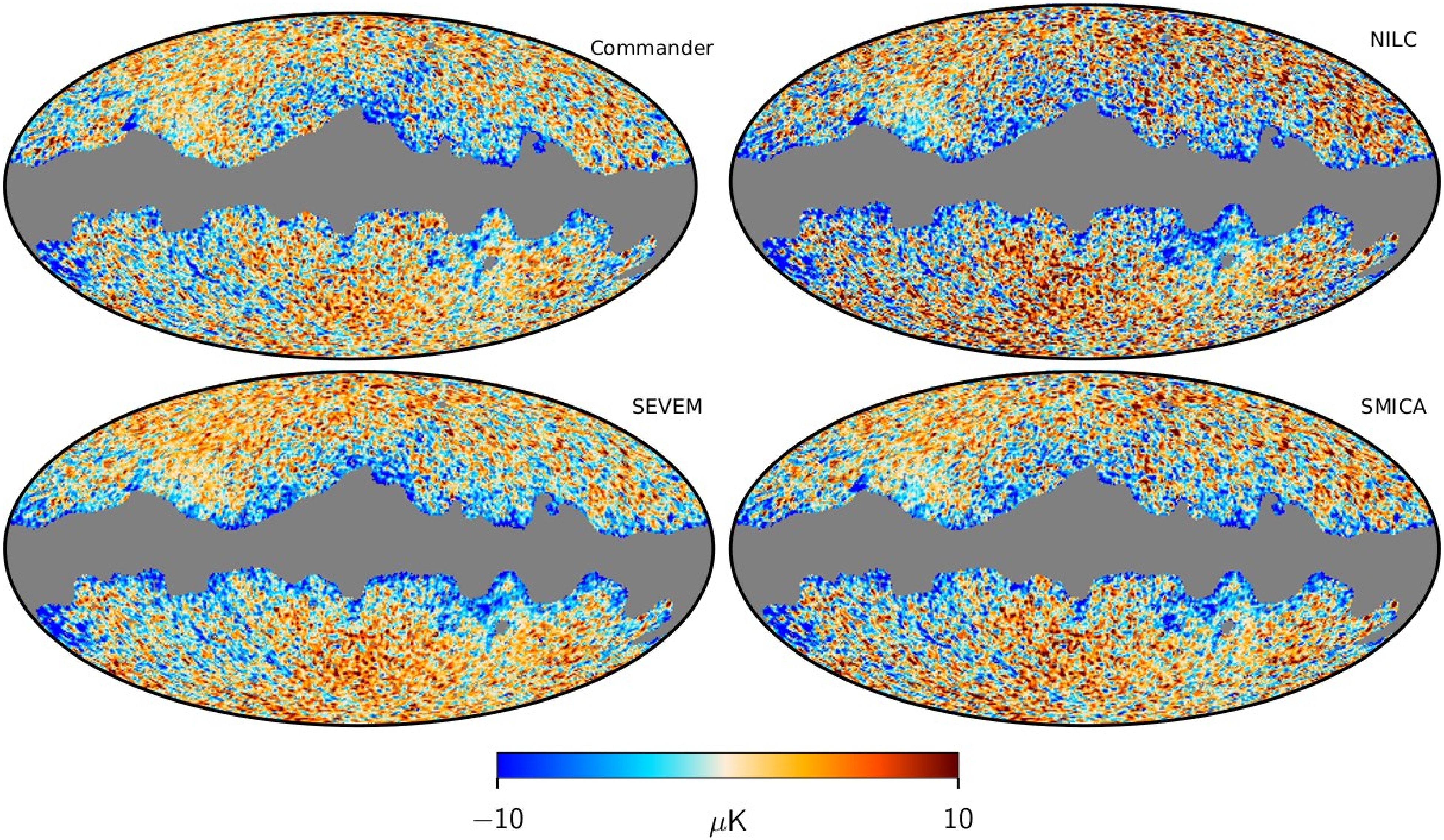
- For low-l polarization cosmological analysis, we resample $\mathbf{a}^{CMB}$ at multipoles $l \leq 64$, fixing higher multipoles and all instrumental and foreground parameters, assuming $\mathbf{S}^{-1}=0$ and no Galactic mask.

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

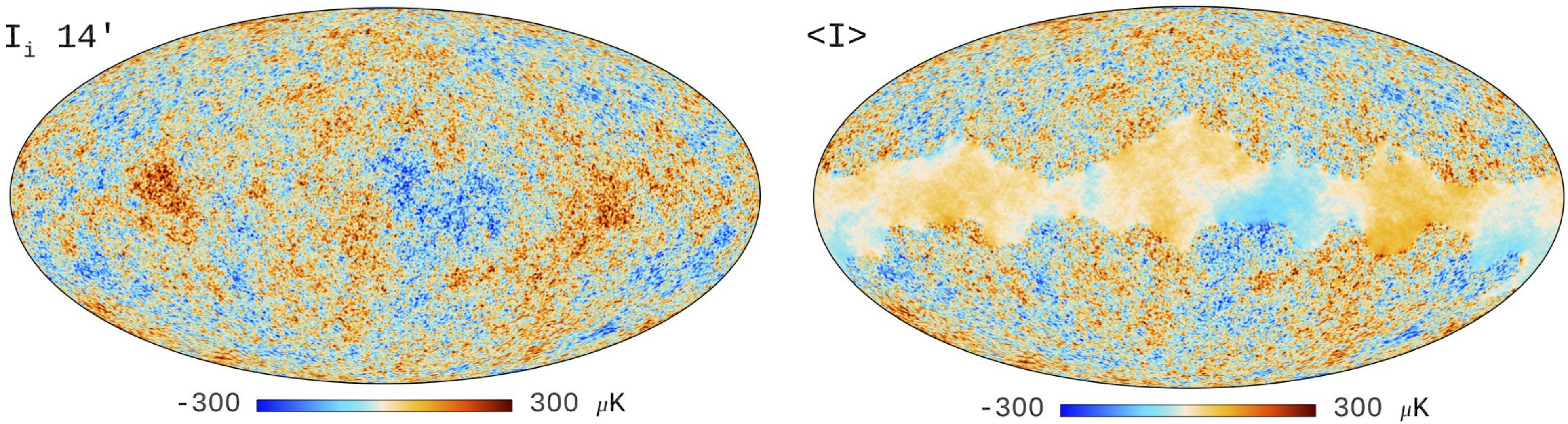


Struggle with thermal dust in the Galactic plane, because we do not use HFI. Relatively clean at high latitudes

Cosmology Temperature Maps

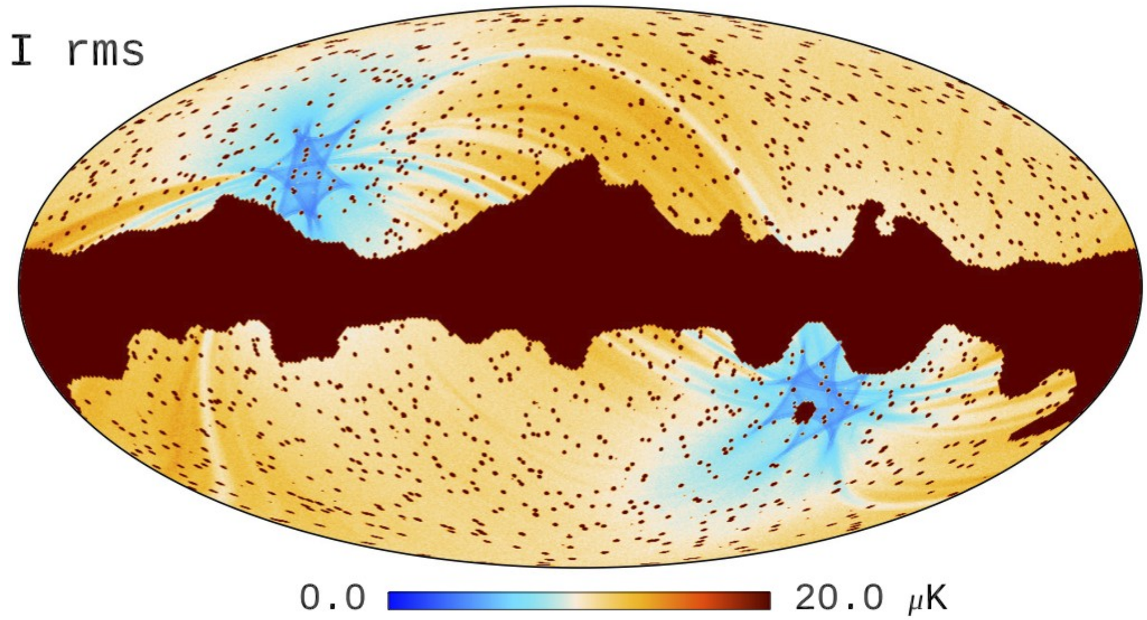
- When **s** = **s**(C_l), the posterior mean map corresponds to a Wiener-filtered map. Additionally, the region within the Galactic mask is filled with a constrained realization.

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



Map Variance

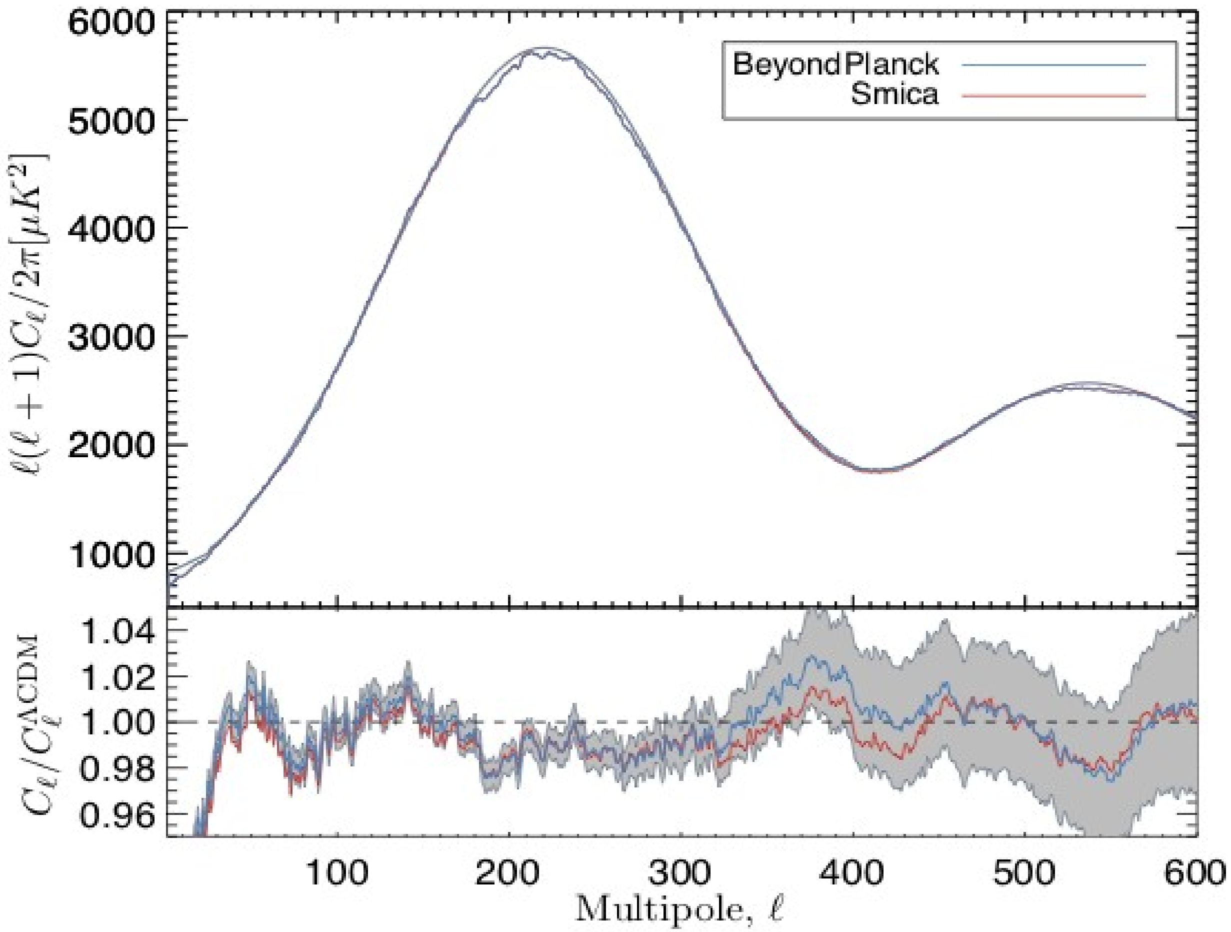
- Map variance shows the imprint of instrumental noise at high Galactic latitude, while inside the reprocessing mask is dominated by the random phases of the constrained CMB realizations.



- 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.
- Nonetheless, cut sky power spectra allows for a more direct comparison with other methods.



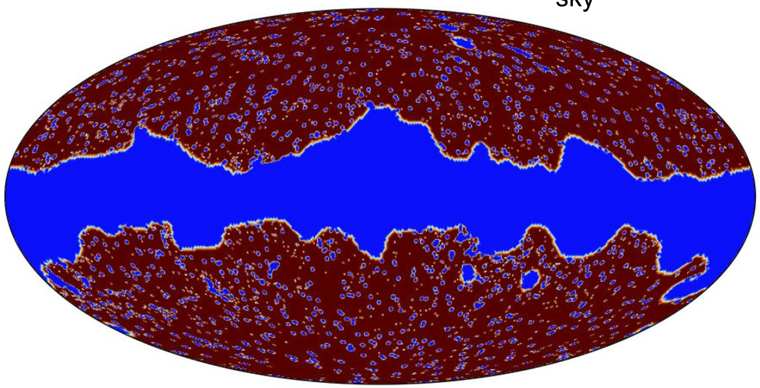
Bin Δl = 50

BP: mean power spectrum
$<C_l>$

Smica: HM1xHM2 cross-spectrum

68% chain scatter

$f_{sky} = 0.618$



Cosmological parameters

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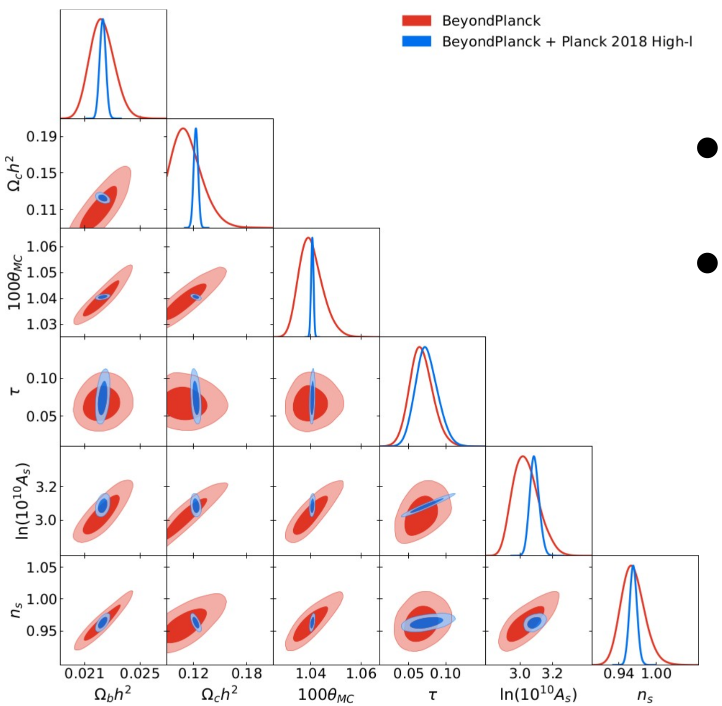
Paradiso et al. (2020)

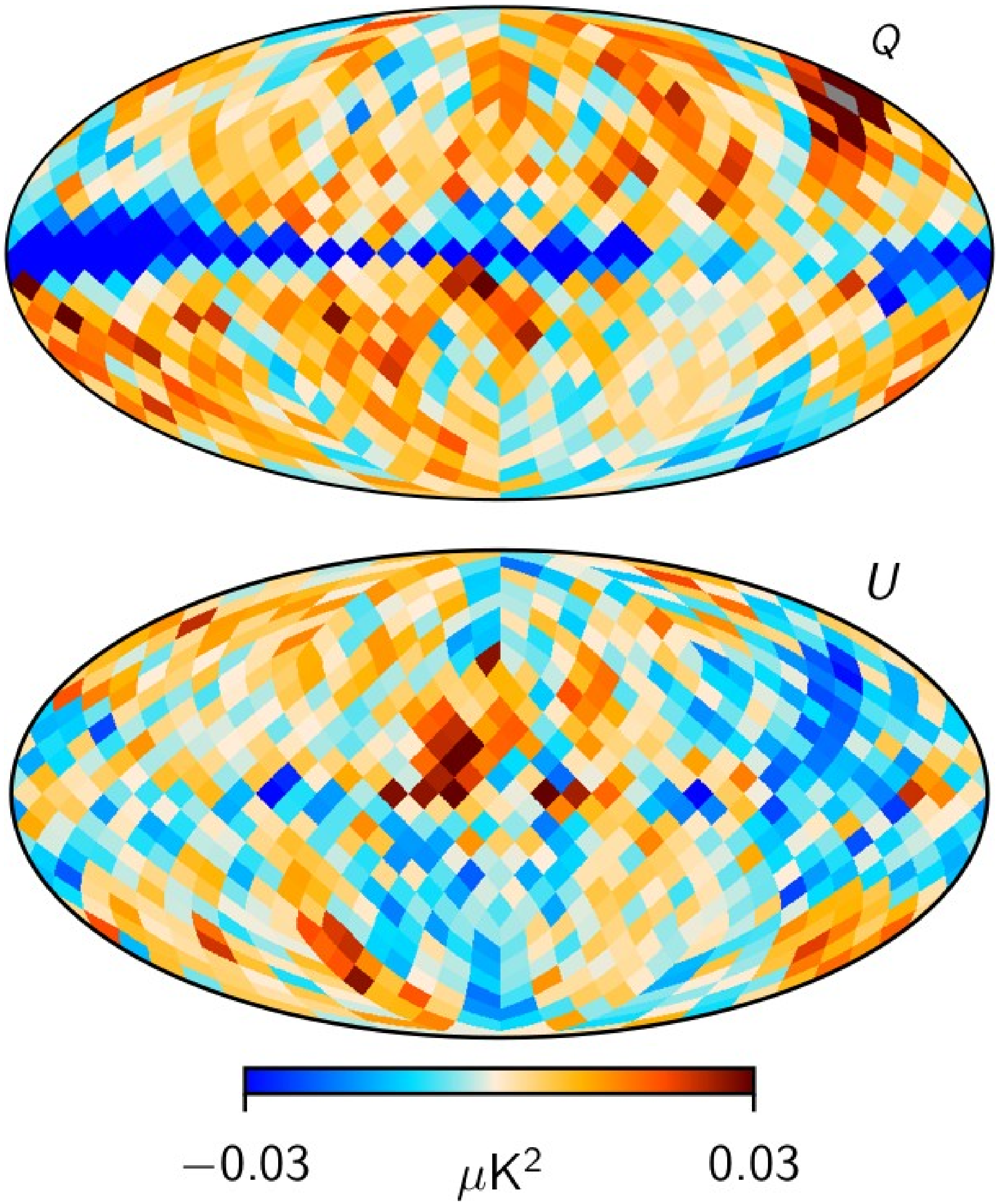
	BeyondPlanck		*Planck* 2018		*WMAP*	
Parameter	$\ell \leq 600$	$+Planck\ \ell > 600$	Estimate	$\Delta(\sigma)$	Estimate	$\Delta(\sigma)$
$\Omega_b h^2$	0.02226 ± 0.00088	0.02230 ± 0.00022	0.02237 ± 0.00015	-0.1	0.02243 ± 0.00050	-0.2
$\Omega_c h^2$	0.115 ± 0.016	0.1227 ± 0.0025	0.1200 ± 0.0012	-0.3	0.1147 ± 0.0051	0
Ω_Λ	. . .	. . .	. . .	. . .	0.721 ± 0.025	. . .
$100\theta_{MC}$	1.0402 ± 0.0048	1.04064 ± 0.00048	1.04092 ± 0.00031	-0.2	. . .	. . .
τ	0.067 ± 0.016	0.074 ± 0.015	0.054 ± 0.007	0.8	0.089 ± 0.0014	-1.4
$10^9 \Delta^2_{\mathcal{R}}$	. . .	. . .	. . .	. . .	2.41 ± 0.10	. . .
$\ln(10^{10} A_s)$	3.035 ± 0.079	3.087 ± 0.029	3.044 ± 0.014	-0.1	. . .	. . .
n_s	0.962 ± 0.019	0.9632 ± 0.0060	0.9649 ± 0.0042	-0.1	0.972 ± 0.013	-0.5



- Statistically consistent with previous estimates
- Larger error bars since we only use LFI and WMAP data
  - Formally speaking, we also marginalize over a much richer instrument and foreground model, but this is negligible in temperature compared to cosmic variance

Beyond PLANCK

Low-resolution CMB map and covariance matrix



Colombo et al. (2020)

Compute low-resolution CMB map and covariance matrix directly from samples:

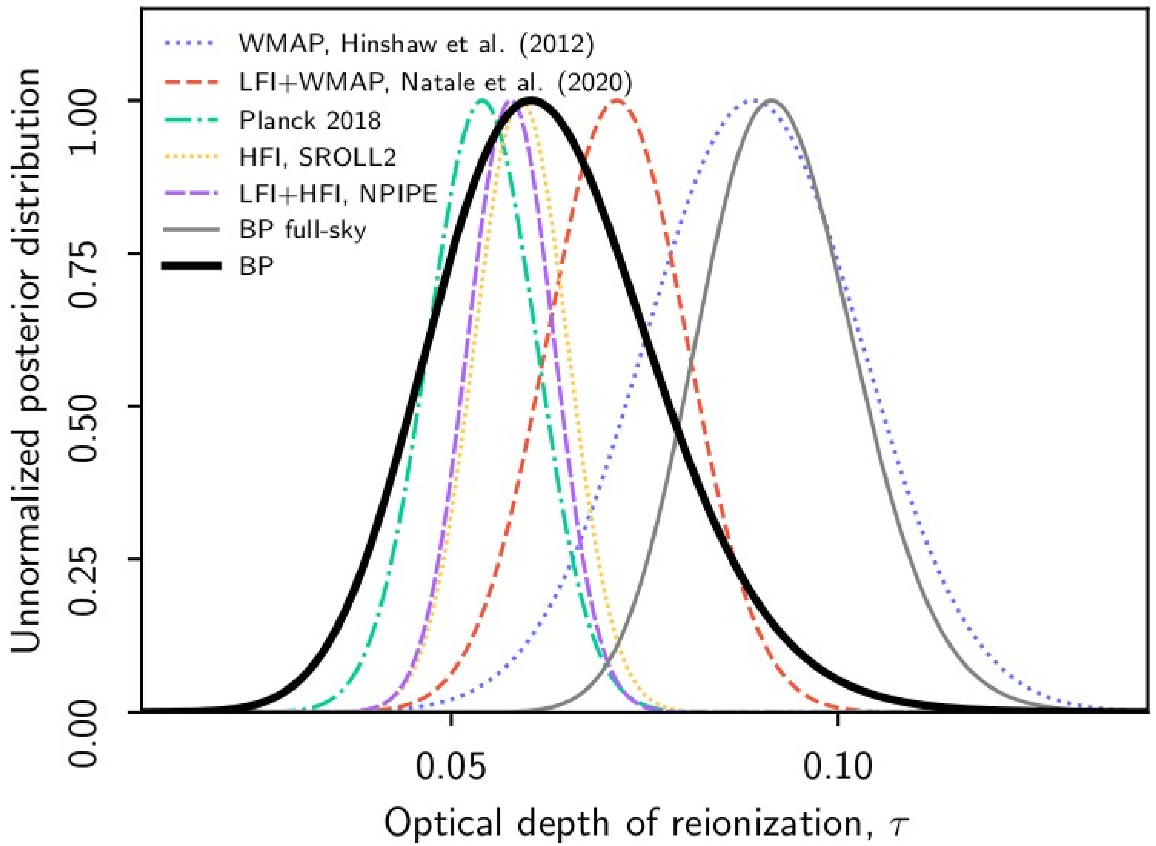
$$\hat{\boldsymbol{s}}_{\mathrm{CMB}} = \left\langle \boldsymbol{s}^{i}_{\mathrm{CMB}} \right\rangle$$

$$\mathrm{N} = \left\langle (\boldsymbol{s}^{i}_{\mathrm{CMB}} - \hat{\boldsymbol{s}}_{\mathrm{CMB}})(\boldsymbol{s}^{i}_{\mathrm{CMB}} - \hat{\boldsymbol{s}}_{\mathrm{CMB}})^{t} \right\rangle$$

*This is the first time uncertainties from **gain, bandpass and a fine-grained foreground model** have been consistently propagated into **CMB low-l likelihood** inputs!*

CMB: Low-ℓ polarization likelihood, τ

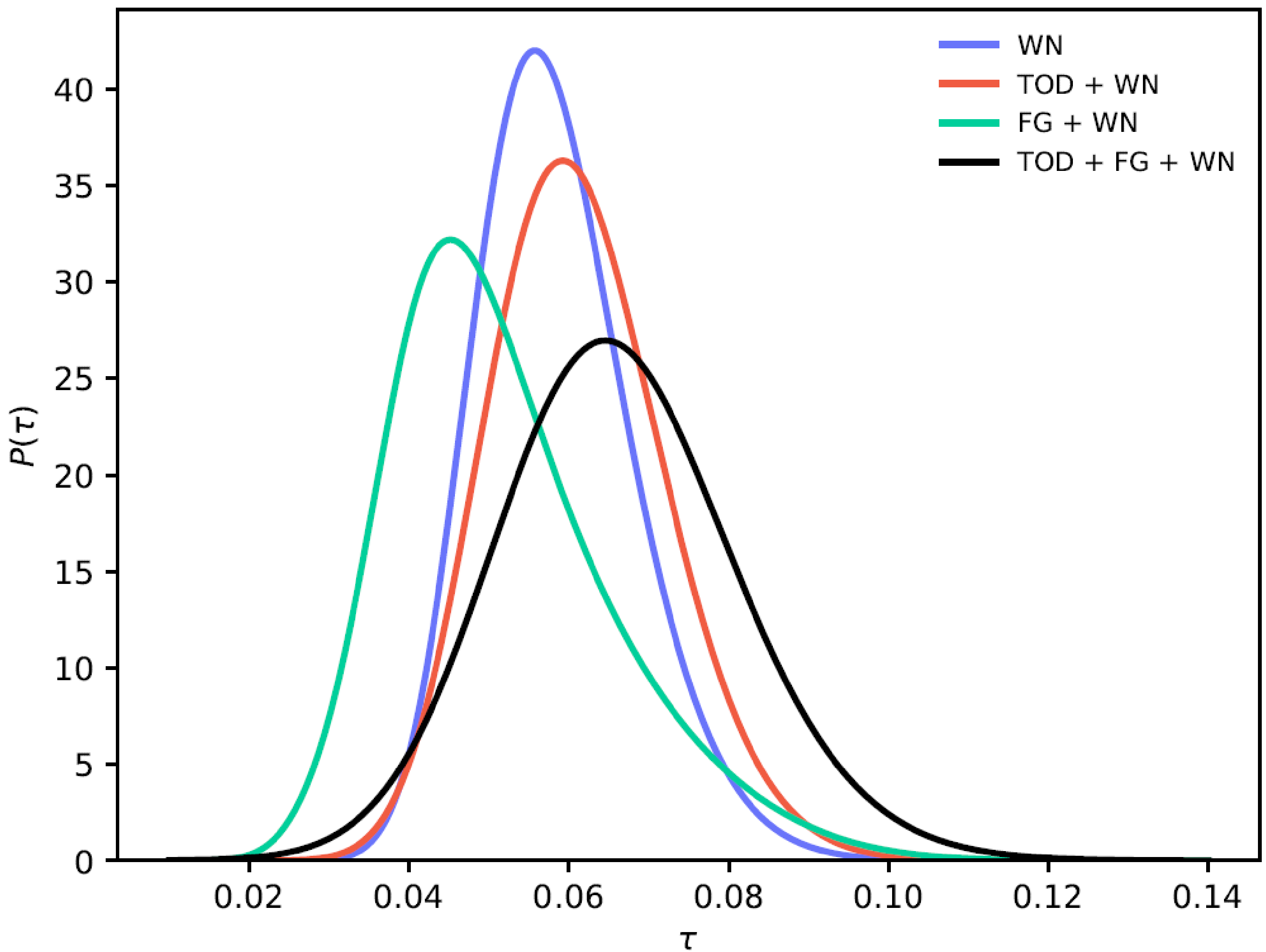
$$P(C_\ell \mid \hat{\mathbf{s}}_{\mathrm{CMB}}) \propto \frac{e^{-\frac{1}{2}\hat{\mathbf{s}}^t_{\mathrm{CMB}}(\mathsf{S}(C_\ell)+\mathsf{N})^{-1}\hat{\mathbf{s}}_{\mathrm{CMB}}}}{\sqrt{|\mathsf{S}(C_\ell)+\mathsf{N}|}}$$



Paradiso et al. (2020)

Uncertainties on the optical depth of reionization

European Commission



Paradiso et al. (2020)

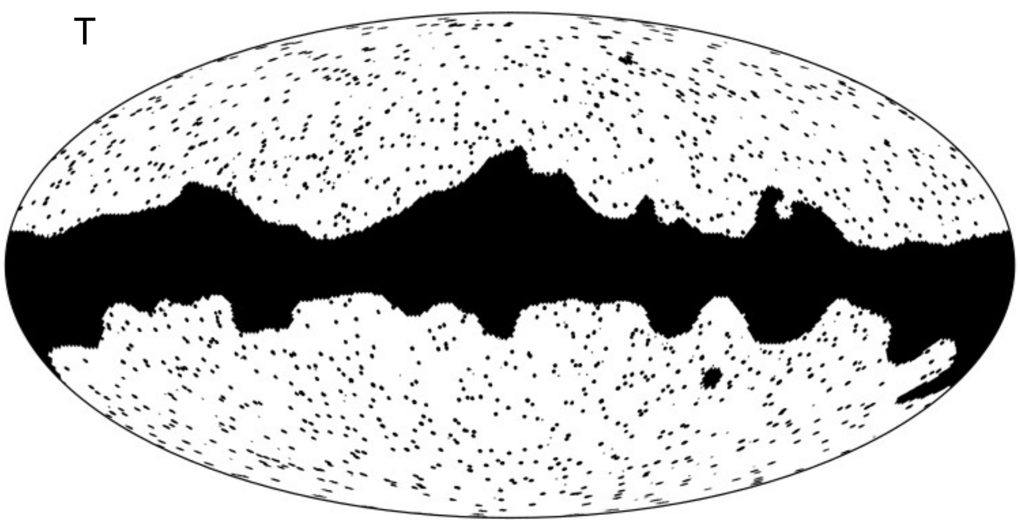
Beyond PLANCK

CMB: Goodness-of-fit and masking

Analysis Name	Data Sets	$f_{\rm sky}^{\rm pol}$	τ	$r^{BB}_{95\,\%}$	χ^2 PTE	Reference
BeyondPlanck, $\ell = 2$–8	LFI, *WMAP Ka–V*	0.36	$0.060^{+0.015}_{-0.013}$	< 4.3	0.16	Paradiso et al. (2020)
BeyondPlanck, $\ell = 3$–8	LFI, *WMAP Ka–V*	0.36	$0.061^{+0.015}_{-0.014}$	< 5.4	0.16	Paradiso et al. (2020)
BeyondPlanck, $\ell = 2$–8, full-sky . .	LFI, *WMAP Ka–V*	0.74	$0.091^{+0.010}_{-0.098}$	$2.9^{+1.3}_{-1.0}$	$5 \cdot 10^{-4}$	Paradiso et al. (2020)
WMAP 9-yr	*WMAP Ka–V*	0.76	0.089 ± 0.014			Hinshaw et al. (2013)
Natale et al.	LFI 70, *WMAP Ka–V*	0.54	0.071 ± 0.009			Natale et al. (2020)
Planck 2018	HFI 100×143	0.50	0.051 ± 0.009	< 0.41		Planck Collaboration V (2020)
SROLL2	HFI 100×143	0.50	0.059 ± 0.006			Pagano et al. (2020)
NPIPE (Commander CMB)	LFI+HFI	0.50	0.058 ± 0.006	< 0.16		Tristram et al. (2020)

Paradiso et al. (2020)

T



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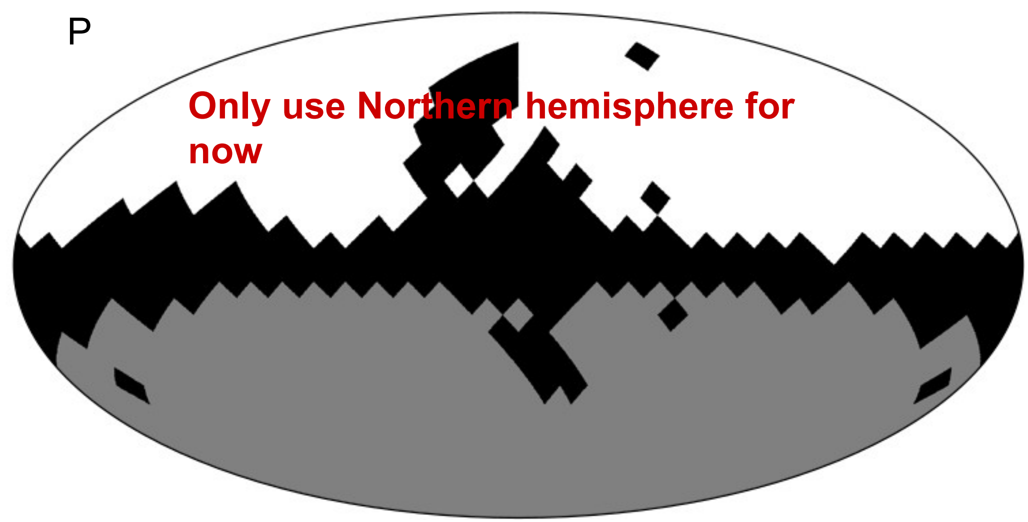
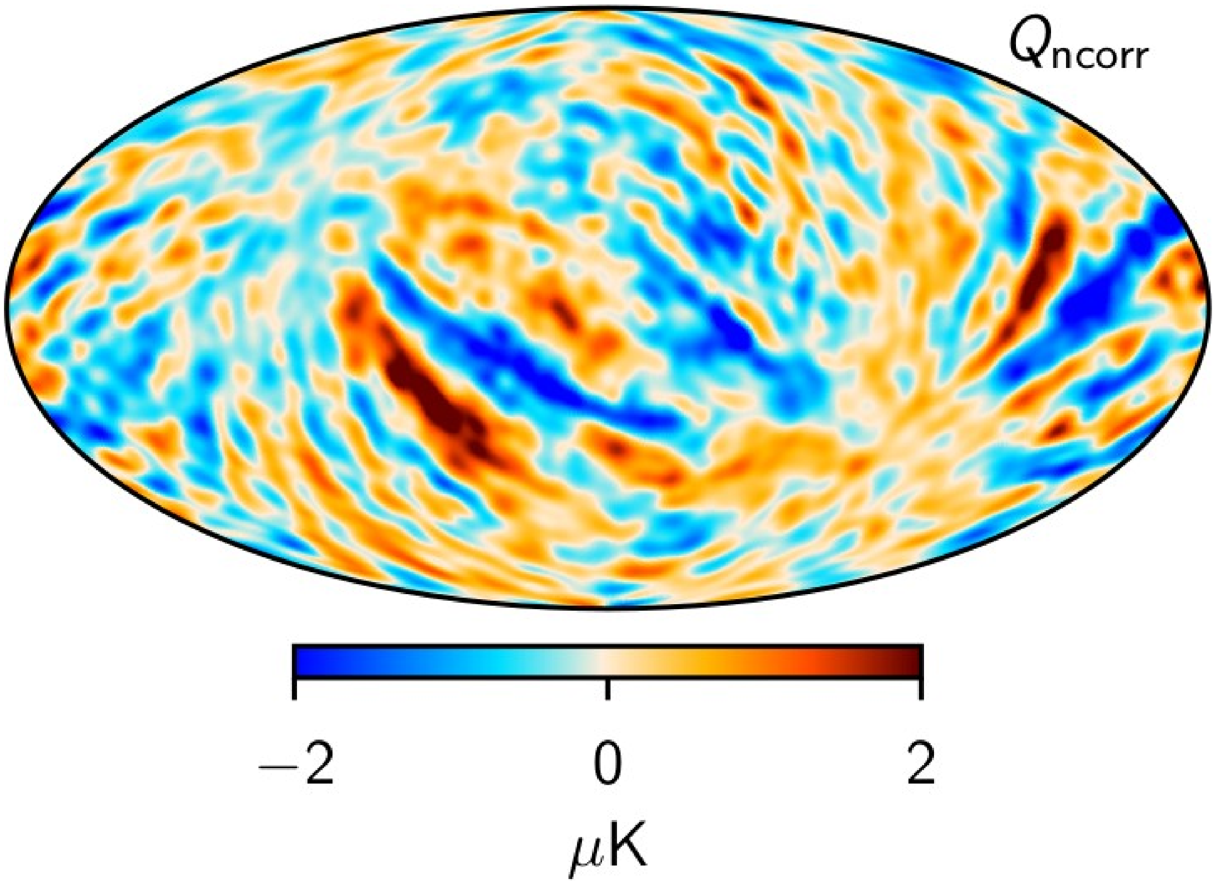


Full-sky polarization mask has unacceptable χ^2!

Outstanding issues 1: Stripes in 44 GHz

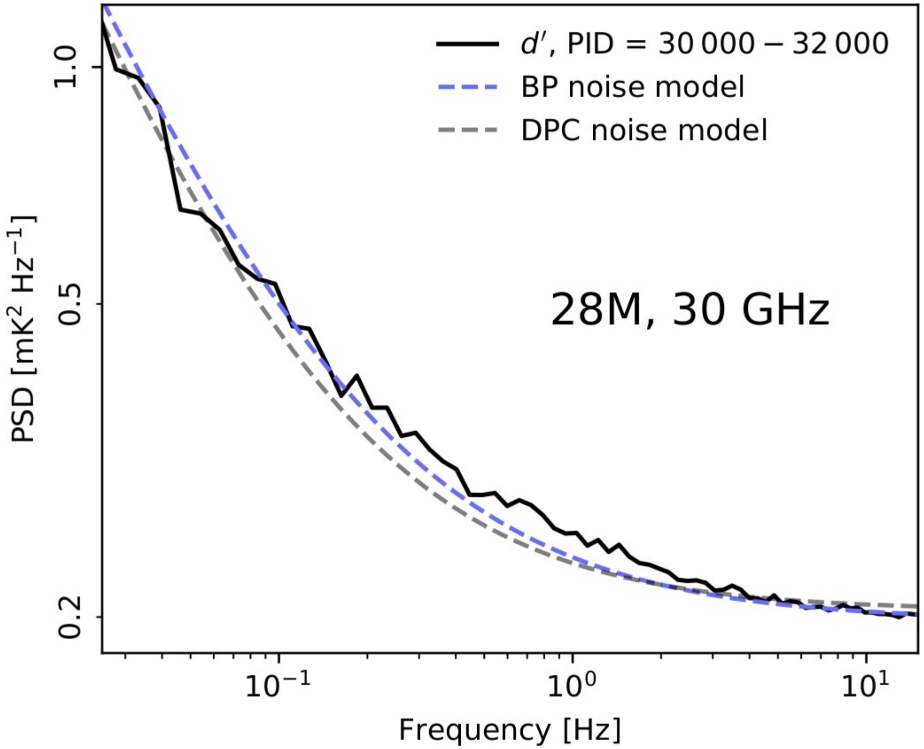


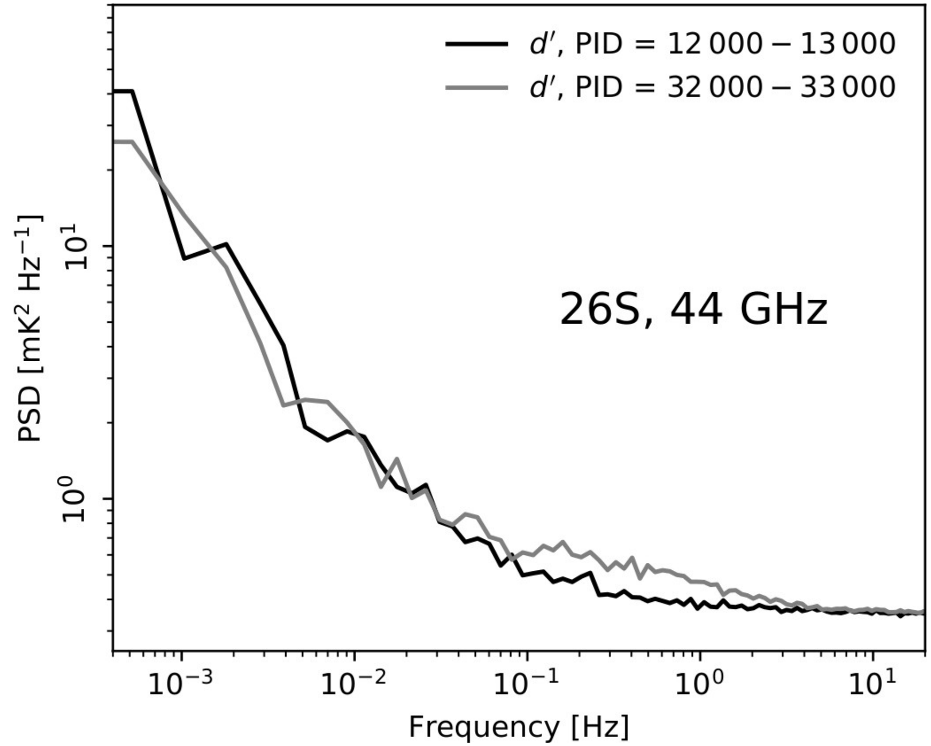
Ihle et al. (2020)

- Correlated noise map at 44 GHz shows strong stripes in Southern hemisphere
- Origin not yet understood, but being actively investigated
- Seems associated with poor gain model for some Planck scanning rings
  - Sub-optimal processing mask?
  - Undetected gain jumps?

Outstanding issues 2: 1/*f* model at 30 and 44 GHz

Ihle et al. (2020)





- Correlated noise is fitted using a standard 1/f model: $P(f) = \sigma_0^2 \left[1 + \left(\frac{f}{f_{\rm knee}}\right)^{\alpha}\right]$
- Not a statistically sufficient model for 30 and 44 GHz channels
- Significant and time-variable **excess between 0.1 and 5 Hz**, corresponding to angular scales beween **1 and 60 degrees on the sky**
  - Appears non-thermal in origin. Electrical issue? Investigation on-going

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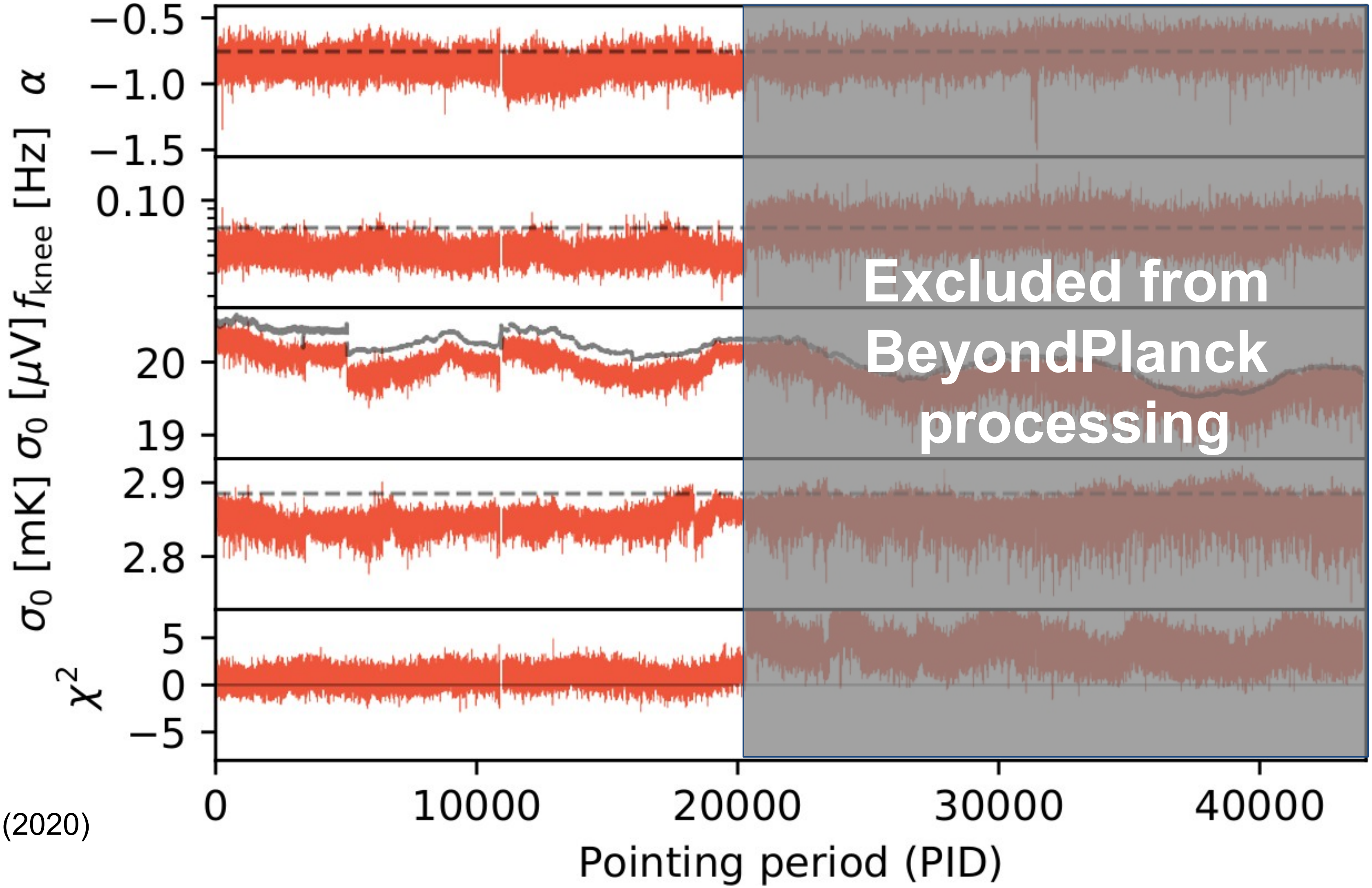
Outstanding issues 2: 1/*f* model at 30 and 44 GHz

Correlated noise parameters for 44GHz 26S radiometer



Ihle et al. (2020)

Summary

- We have implemented the first end-to-end CMB data analysis pipeline based on Gibbs sampling, eliminating previous bottlenecks and reducing iteration time by 2-3 orders of magnitude.
- Gibbs sampling allows to fully characterize the posterior of all instrumental, astrophysical and cosmological parameters, and self-consistently propagate all sources of uncertainty.
- BeyondPlanck pipeline was applied to Planck-LFI data, producing new estimates of frequency maps at 30,44 and 70GHz, low-frequency foregrounds, and CMB, and highlighting previously unknown systematics.
- Work is in progress to extend the pipeline to current and future CMB datasets.

BeyondPlanck papers

European Commission

Reference	Title
Pipeline	
BeyondPlanck Collaboration (2020) . . .	I. Global Bayesian analysis of the *Planck* Low Frequency Instrument data
Keihänen et al. (2020)	II. CMB mapmaking through Gibbs sampling
Galloway et al. (2020a)	III. Computational infrastructure and `Commander3`
Brilenkov et al. (2020)	IV. Time-ordered data simulations
Gerakakis et al. (2020)	V. Open Science and reproducibility
Instrument characterization	
Ihle et al. (2020)	VI. Noise characterization and modelling
Gjerløw et al. (2020)	VII. Calibration
Galloway et al. (2020b)	VIII. Sidelobe corrections
Svalheim et al. (2020a)	IX. Bandpass and beam leakage corrections
Cosmological and astrophysical results	
Suur-Uski et al. (2020)	X. LFI frequency map posteriors
Colombo et al. (2020)	XI. CMB constraints
Paradiso et al. (2020)	XII. Cosmological parameter estimation with end-to-end error propagation
Andersen et al. (2020)	XIII. Intensity foregrounds, degeneracies and priors
Svalheim et al. (2020b)	XIV. Polarized synchrotron emission
Herman et al. (2020)	XV. Limits on polarized anomalous microwave emission
External analysis	
Aurlien et al. (2020)	XVI. Application to simulated *LiteBIRD* observations
Watts et al. (2020)	XVII. Application to *WMAP*
Galeotta et al. (2020)	XVIII. End-to-end validation of BeyondPlanck

Papers, data, codes, etc. available through
https://beyondplanck.science

Beyond PLANCK

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European Commission

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Beyond PLANCK

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  - 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

European Commission

Questions?

Beyond PLANCK

Commander

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