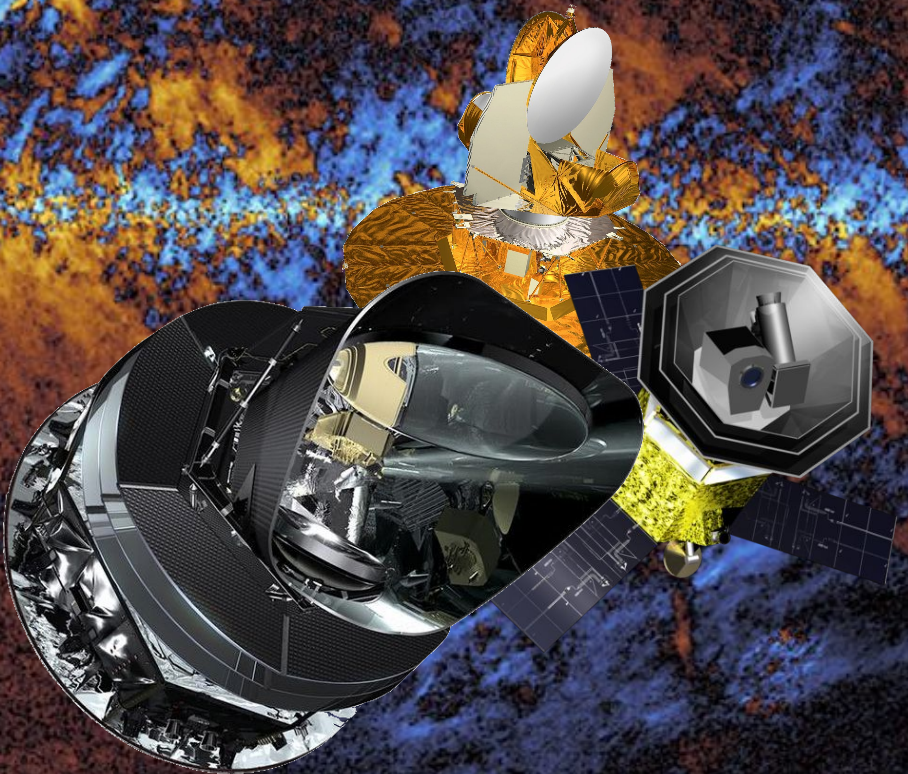
Overview and main results

Hans Kristian Eriksen



BeyondPlanck Final Review, December 10, 2020

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 776282

Primary BeyondPlanck goals (from proposal)

European Commission

1. Excellence

1.1 Objectives

(...)

Thus, building on this base of observations, we will:

1. deliver new legacy Planck LFI 30, 44 and 70 GHz frequency maps.

2. deliver the world's cleanest and most sensitive full-sky estimates of polarized synchrotron emission at CMB frequencies. This new model will form a bed-rock for future CMB B-mode experiments searching for inflationary gravitational waves in the coming decade, as well as for scientists studying the structure and dynamics of the Milky Way.

3. deliver a new likelihood code suitable for large-scale CMB polarization analysis, and use this to derive a new and robust estimate of the optical depth of reionization, one of the most critical parameters in contemporary cosmology.

4. make the software necessary for time-domain analysis available to the community under an Open Science license, allowing other projects and experiments to build on and extend our work.

Beyond PLANCK

Starting point for BeyondPlanck

Can we address the outstanding issues seen in Planck LFI by:

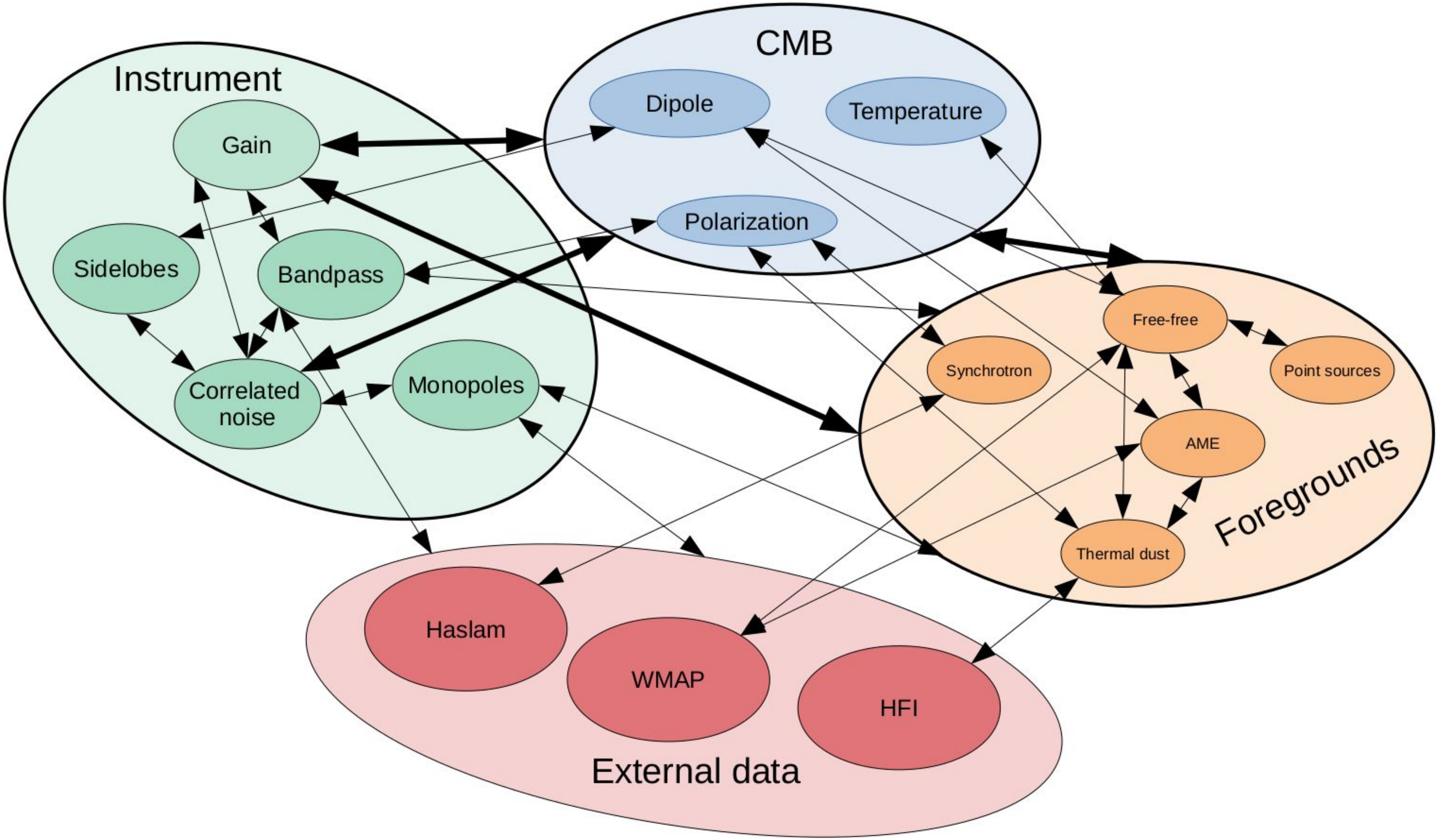
1. speeding up the iteration process, and perform hundreds of component separation + calibration iterations, not just four?

2. break internal Planck-specific degeneracies using external data, in particular WMAP?

The name BeyondPlanck was chosen to

- recognize that this work builds on, and is a natural continuation of, the official Planck analysis effort
- emphasize that this involves not only Planck, but also other data sets

“Planck LFI dependency map”



“The swamp”

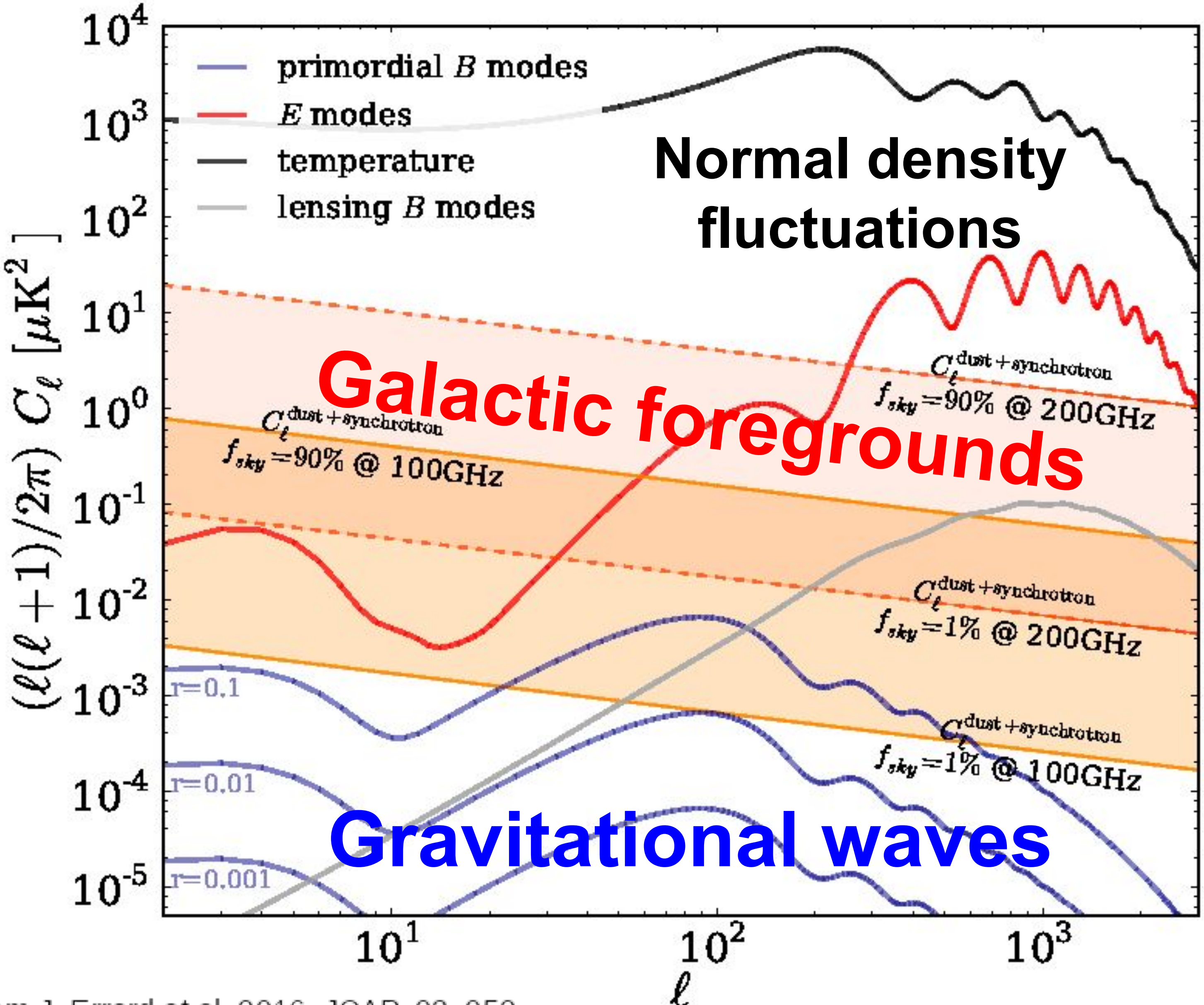


Figure from J. Errard et al. 2016, JCAP, 03, 052

"The swamp"

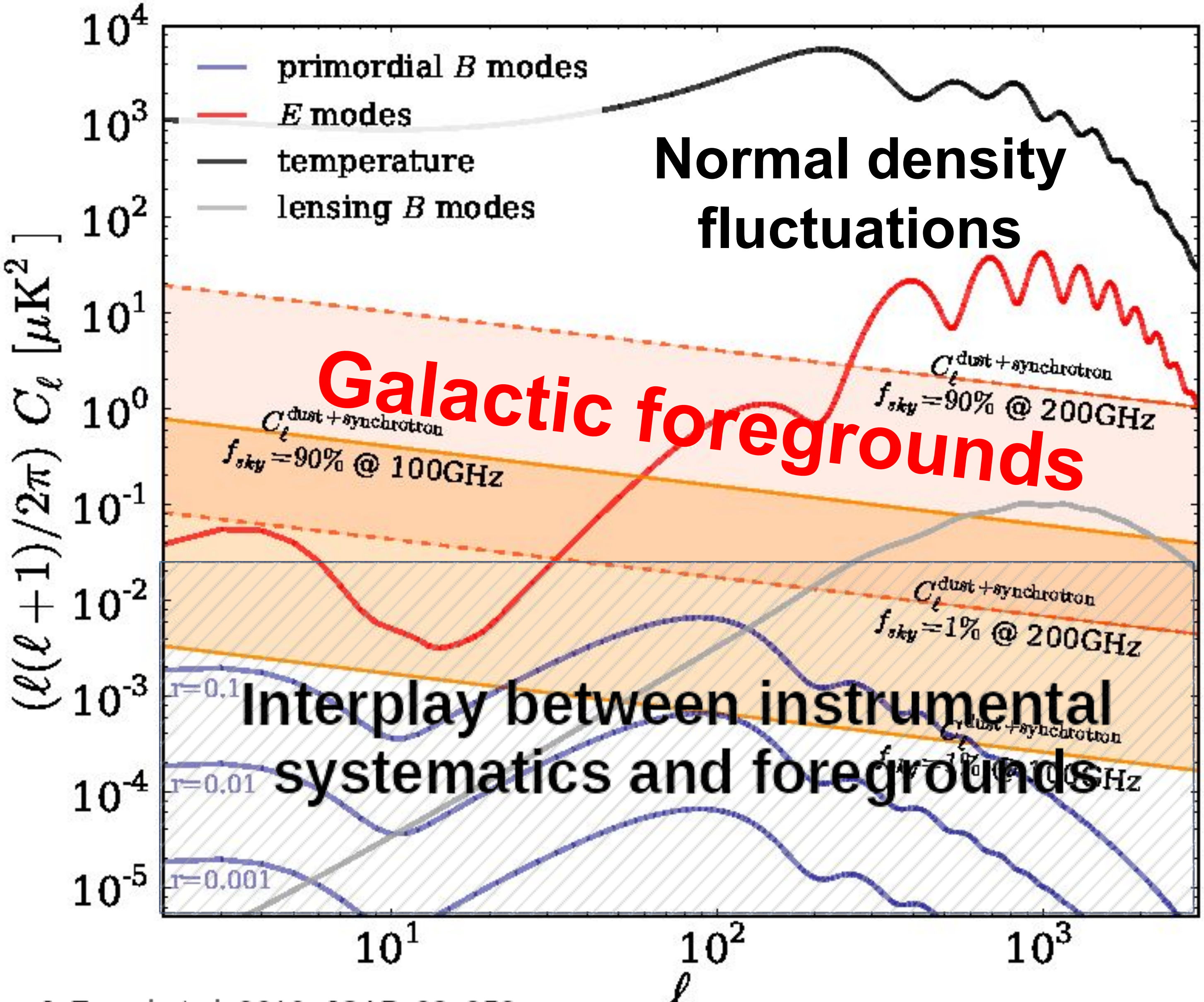
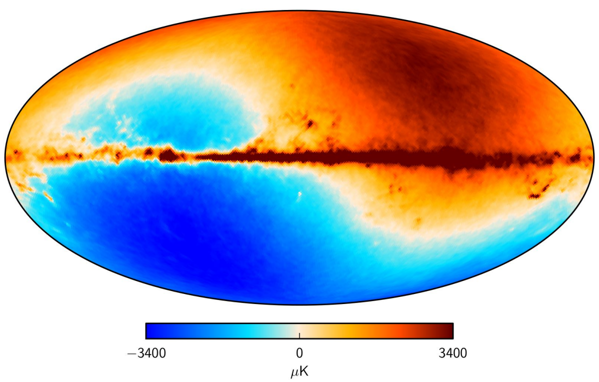


Figure from J. Errard et al. 2016, JCAP, 03, 052

CMB's "chicken and egg" problem

Need to know the instrument to measure the sky...

Data



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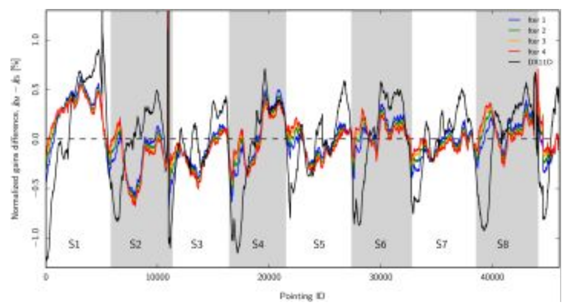
Instrument calibration



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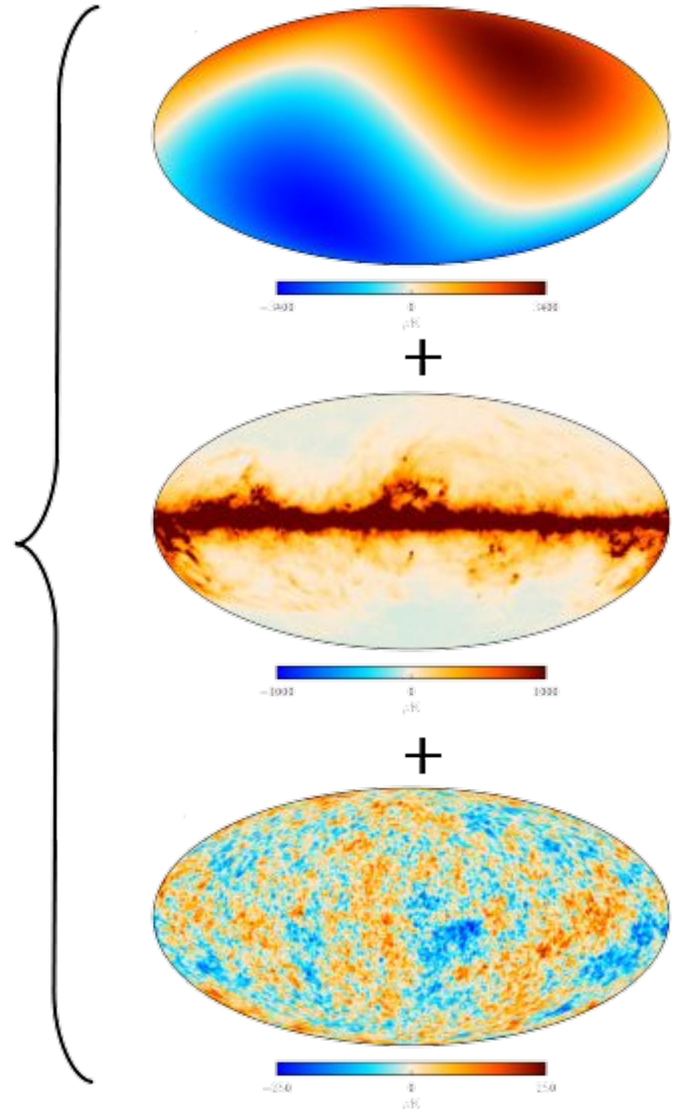
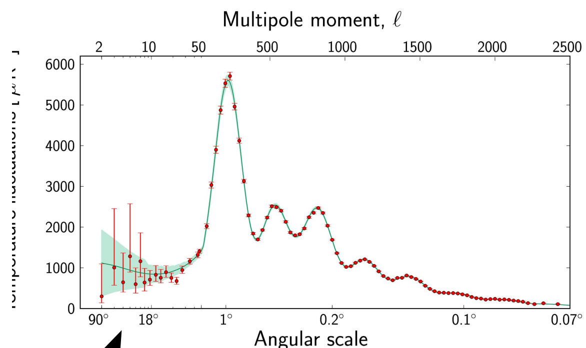
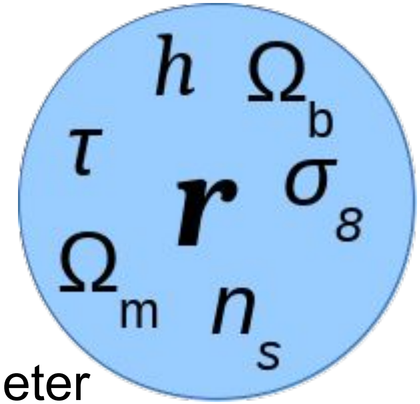
Sky



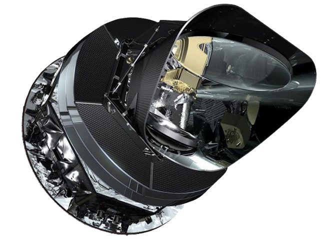
… but also need to know the sky in order to calibrate the instrument!

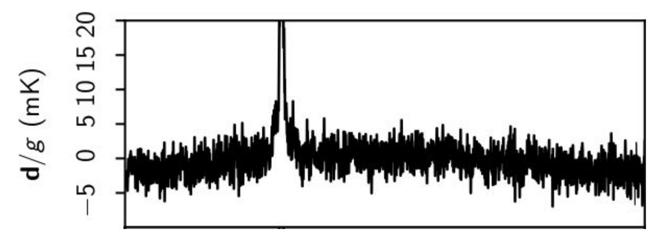
Classic CMB analysis



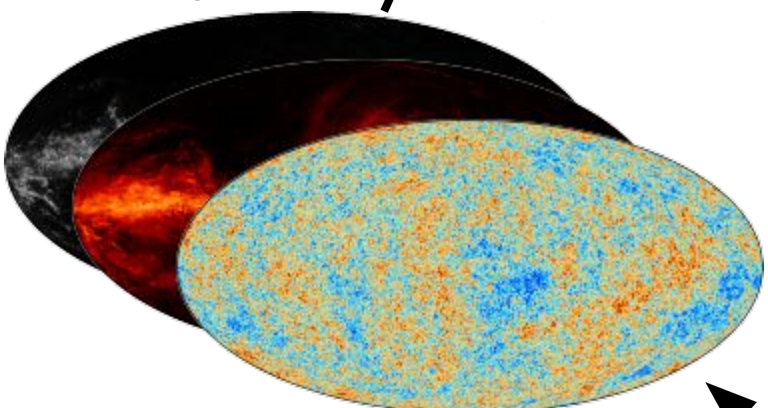


Parameter estimation

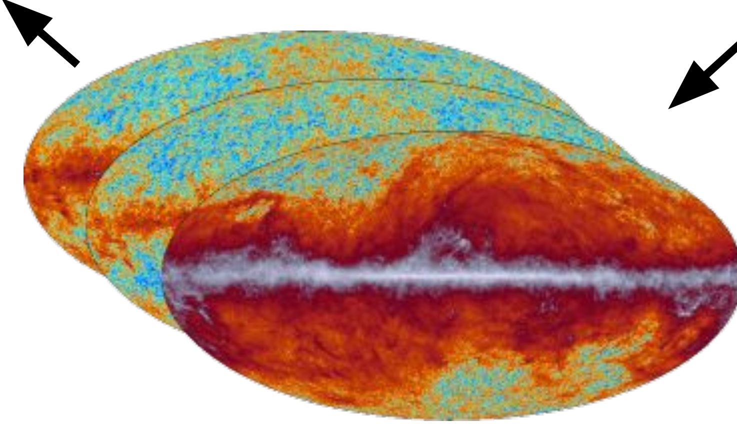




Power spectrum estimation

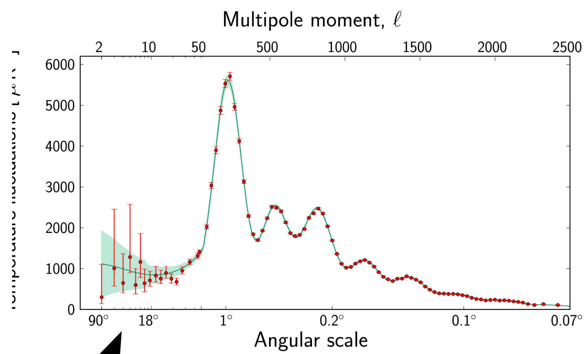


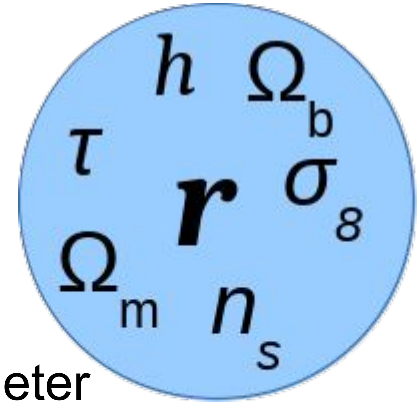
Component separation

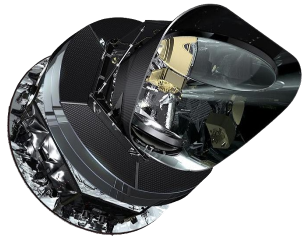


Calibration + mapmaking

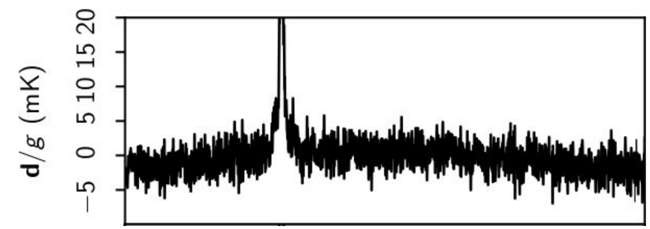
End-to-end iterative analysis



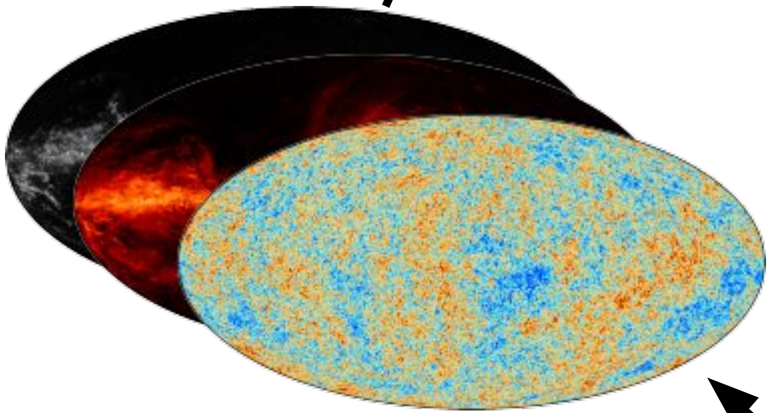




Parameter estimation

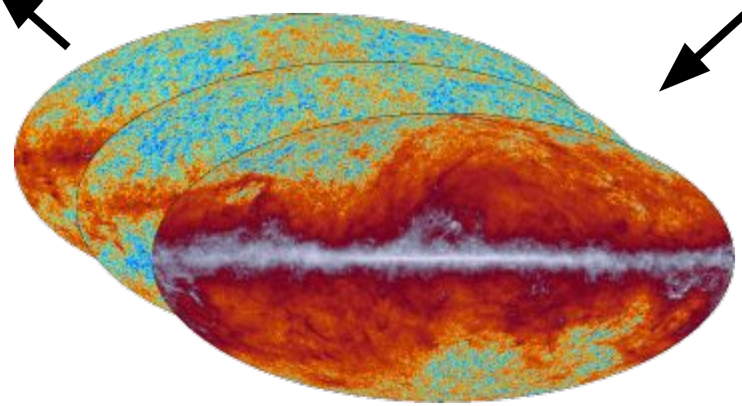


Power spectrum estimation



Calibration + mapmaking

Component separation



Beyond PLANCK

The BeyondPlanck pipeline in one slide

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

The BeyondPlanck data model

European Commission

Data

Pointing

Bandpass

Sidelobe pickup

White noise

$d_{j,t} =$ ... $n^{\mathrm{w}}_{j,t}.$

$$\omega \equiv \{g, \Delta_{\mathrm{bp}}, \boldsymbol{n}_{\mathrm{corr}}, \boldsymbol{a}_i, \beta_i, C_\ell, \ldots\}$$

$+ \sum_{j=1} \boldsymbol{a}^j_{\mathrm{src}} \left(\frac{\cdot}{\nu_{0,\mathrm{src}}} \right)$

Point sources

Beyond PLANCK

The posterior distribution

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

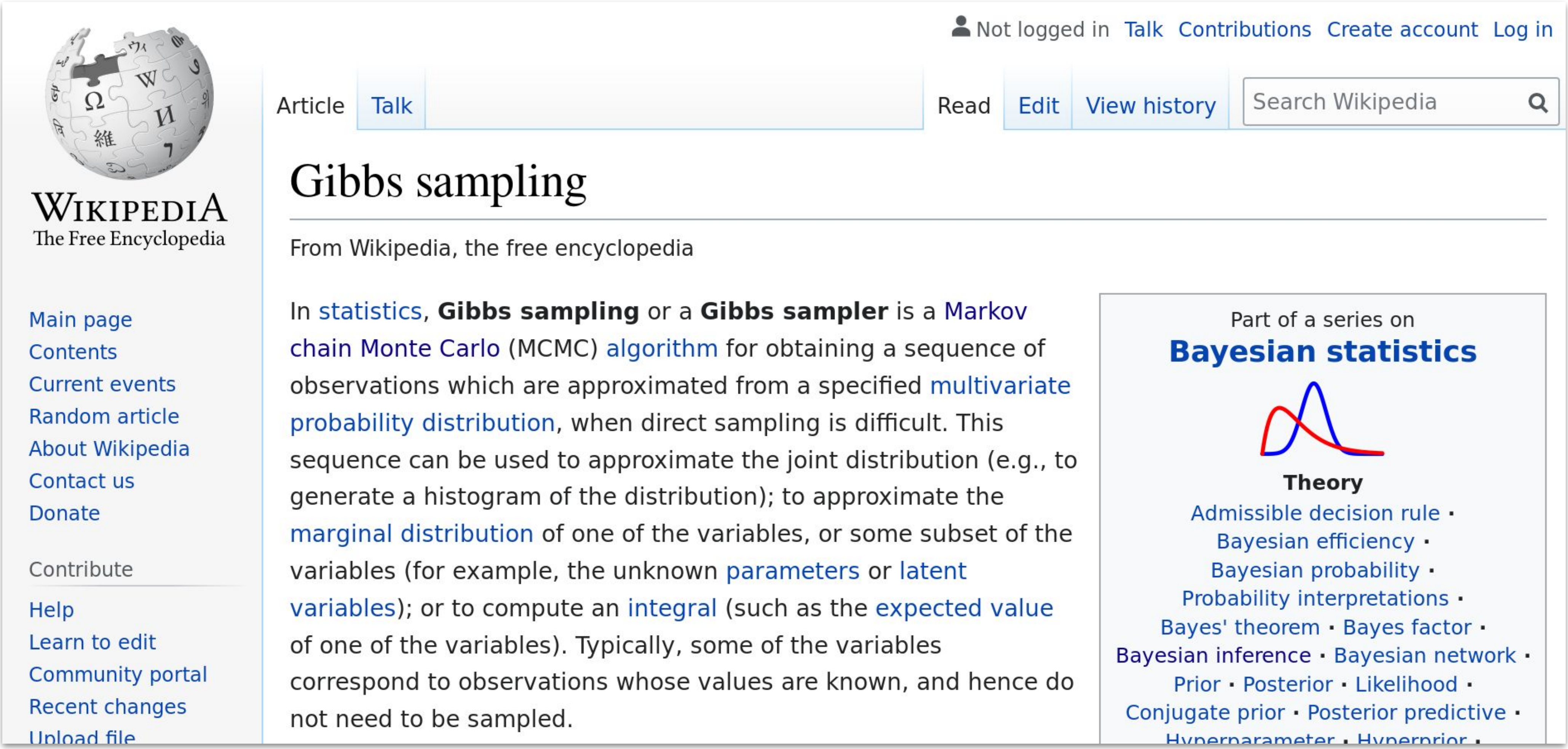
Gaussian noise

$$\mathcal{L}(\omega) = \frac{e^{-\frac{1}{2}(\boldsymbol{d}-\boldsymbol{s}(\omega))^t \mathrm{N}_{\mathrm{wn}}^{-1}(\boldsymbol{d}-\boldsymbol{s}(\omega))}}{\sqrt{|\mathrm{N}_{\mathrm{wn}}|}}$$

- $P(f_{knee})$ = lognorm(DPC, 0.1)
- $P(\beta_{synch})$ = -3.1 ± 0.1
- $P(T_{dust})$ = $\delta(T_{dust} - T_{dust,\,HFI})$
- $P(a_{ff})$ = $N(a_{ff,Planck}, \sigma^2_{l,ff})$
- $P(a_{ame})$ = $N(\alpha \cdot m_{857}, \sigma^2_{l,ame})$

⋮

How to sample from *big* distributions?



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Gibbs sampling

From Wikipedia, the free encyclopedia

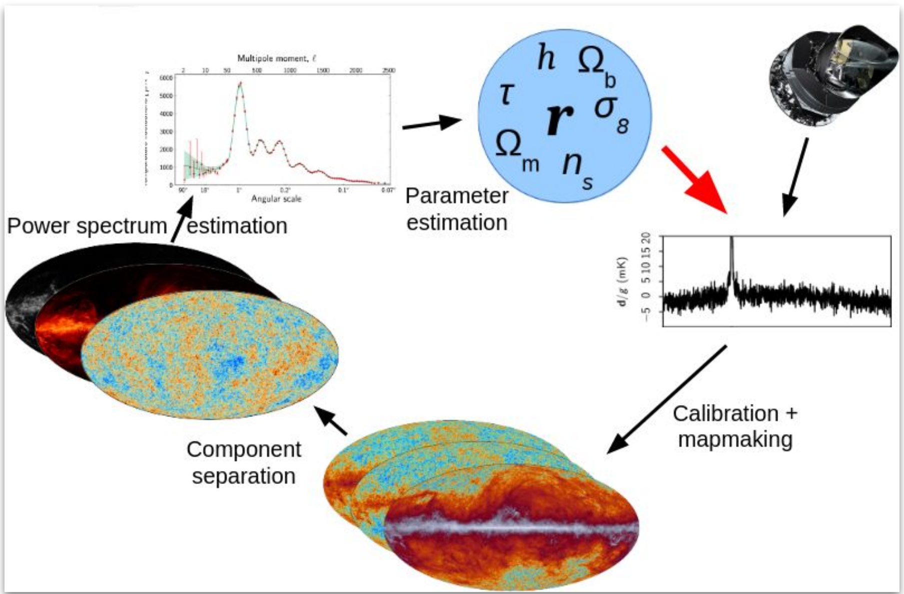
In statistics, **Gibbs sampling** or a **Gibbs sampler** is a Markov chain Monte Carlo (MCMC) algorithm for obtaining a sequence of observations which are approximated from a specified multivariate probability distribution, when direct sampling is difficult. This sequence can be used to approximate the joint distribution (e.g., to generate a histogram of the distribution); to approximate the marginal distribution of one of the variables, or some subset of the variables (for example, the unknown parameters or latent variables); or to compute an integral (such as the expected value of one of the variables). Typically, some of the variables correspond to observations whose values are known, and hence do not need to be sampled.

Part of a series on
Bayesian statistics

Theory
Admissible decision rule · Bayesian efficiency · Bayesian probability · Probability interpretations · Bayes' theorem · Bayes factor · Bayesian inference · Bayesian network · Prior · Posterior · Likelihood · Conjugate prior · Posterior predictive · Hyperparameter · Hyperprior ·

The BeyondPlanck Gibbs sampler

What we want to do:

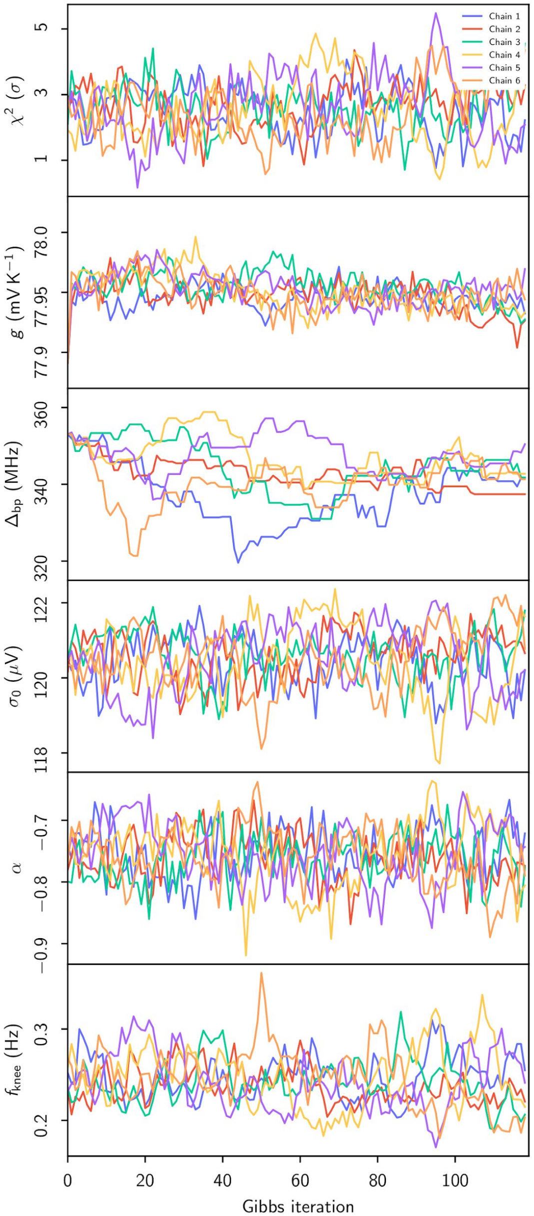


How we actually do it:

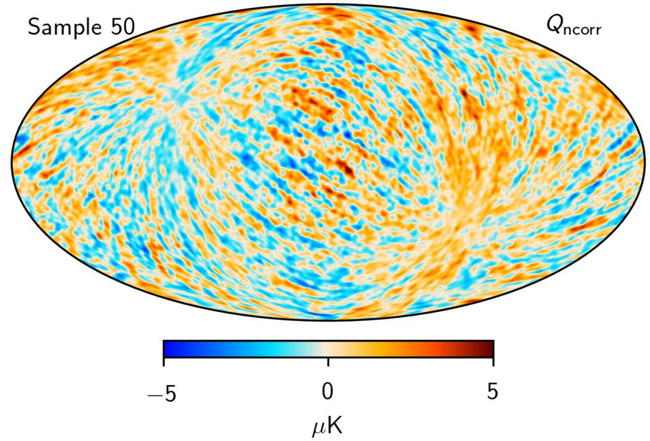
$$
\begin{aligned}
\boldsymbol{g} &\leftarrow P(\boldsymbol{g} \mid \boldsymbol{d}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\boldsymbol{n}_{\mathrm{corr}} &\leftarrow P(\boldsymbol{n}_{\mathrm{corr}} \mid \boldsymbol{d}, \boldsymbol{g}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\xi_n &\leftarrow P(\xi_n \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\Delta_{\mathrm{bp}} &\leftarrow P(\Delta_{\mathrm{bp}} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \boldsymbol{a}, \beta, C_\ell) \\
\beta &\leftarrow P(\beta \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, C_\ell) \\
\boldsymbol{a} &\leftarrow P(\boldsymbol{a} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \beta, C_\ell) \\
C_\ell &\leftarrow P(C_\ell \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta)
\end{aligned}
$$

Main product: Ensemble of full sample sets

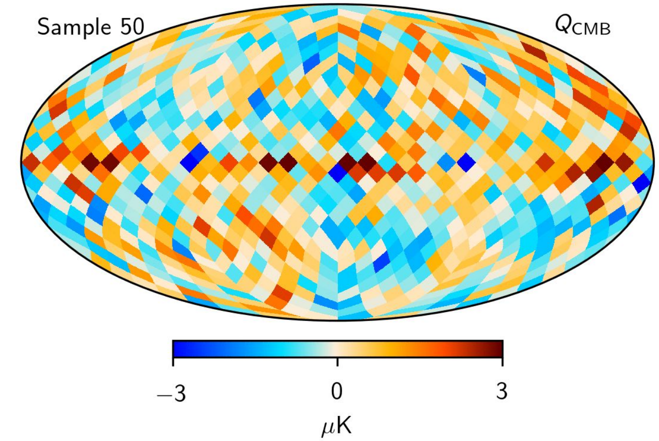
Instrument



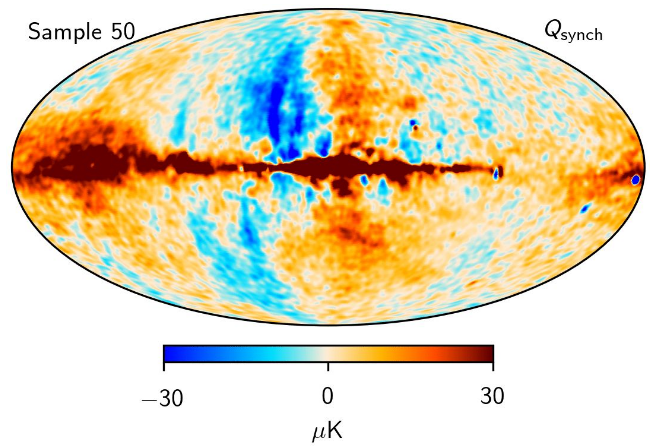
Correlated noise



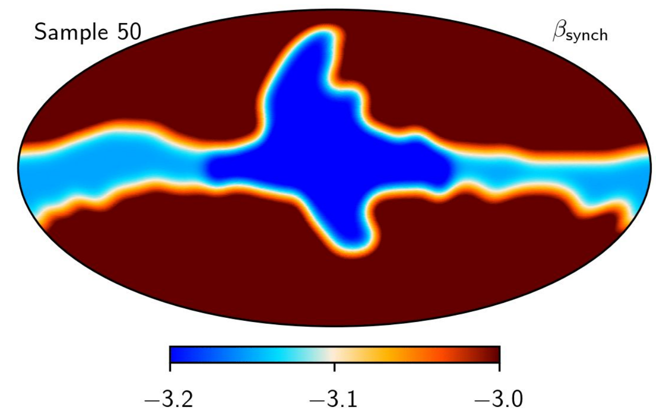
CMB Stokes Q



Synch Stokes Q



Synch pol β



...

BeyondPlanck data selection

European Commission

- To highlight the method itself, only the following data are included in the current analysis:

  - ***Planck LFI 30, 44 and 70 GHz*** ***time-ordered data***

  - ***Planck 857 GHz*** to constrain thermal dust intensity
  - ***Planck 353 GHz*** polarization-only to constrain thermal dust polarization
  - ***WMAP 33-61 GHz*** in T+P to constrain low-frequency foregrounds
  - ***Haslam 408 MHz*** to constrain synchrotron intensity

- Intermediate *Planck HFI* and *WMAP 23 GHz* data are ***not*** included, because they have higher signal-to-noise ratios than Planck LFI

Beyond PLANCK

European Commission

Computational resource requirements

Item	30 GHz	44 GHz	70 GHz	Sum
Data volume				
Uncompressed data volume	761 GB	1 633 GB	5 522 GB	7 915 GB
Compressed data volume/RAM requirements	86 GB	178 GB	597 GB	**861 GB**
Processing time (cost per run)				
TOD initialization/IO time	176 sec	288 sec	753 sec	1217 sec
Other initializati				663 sec
Total initializa				**1880 sec**
Gibbs sampling s				
Data decompre				393 sec
TOD projectio				330 sec
Sidelobe evalu				480 sec
Orbital dipole (				449 sec
Gain sampling				94 sec
Correlated nois				3138 sec
TOD binning (				498 sec
Loss due to po				502 sec
Sum of other T				306 sec
TOD processing				**6396 sec**
Amplitude sampling, $P(\boldsymbol{a} \mid \boldsymbol{d}, \omega \setminus \boldsymbol{a})$				527 sec
Spectral index sampling, $P(\beta \mid \boldsymbol{d}, \omega \setminus \beta)$				1080 sec
Other steps				149 sec
Total cost per sample				**8168 sec**

2.3 hours/sample

on

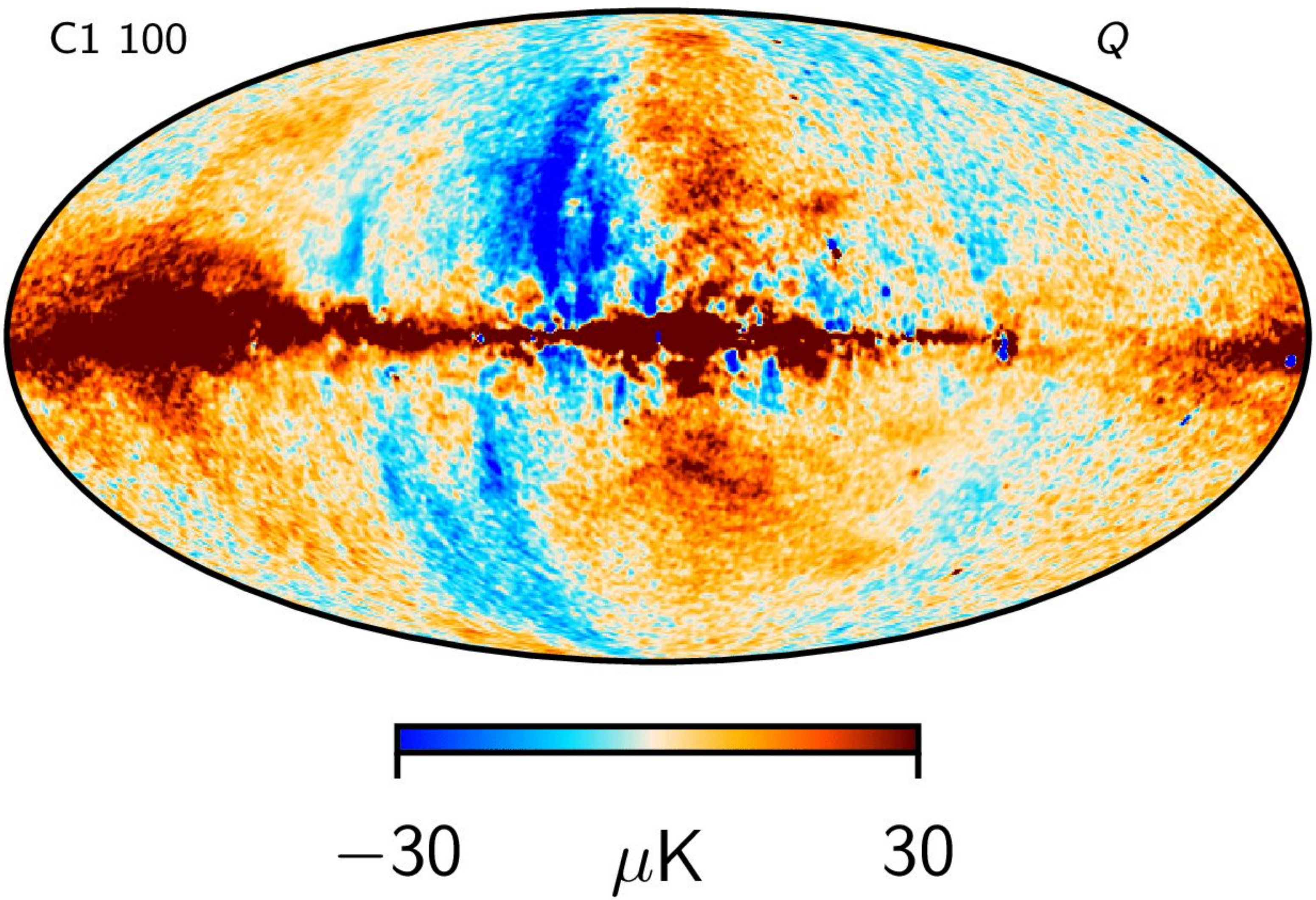
72-core node with 1.5 TB RAM

Galloway et al. (2020)

- **Six independent Gibbs chains of each 200 samples** were generated on 6 compute nodes
- Total wall production time for main run was **3 weeks**
- Total CPU cost for main run was **220,000 CPU hours**
  - For comparison, simulating one single traditional Planck Full Focal Plane 70 GHz realization costs $O(10^4)$ CPU hours (Planck Collaboration 2016, A&A, 596, A12)

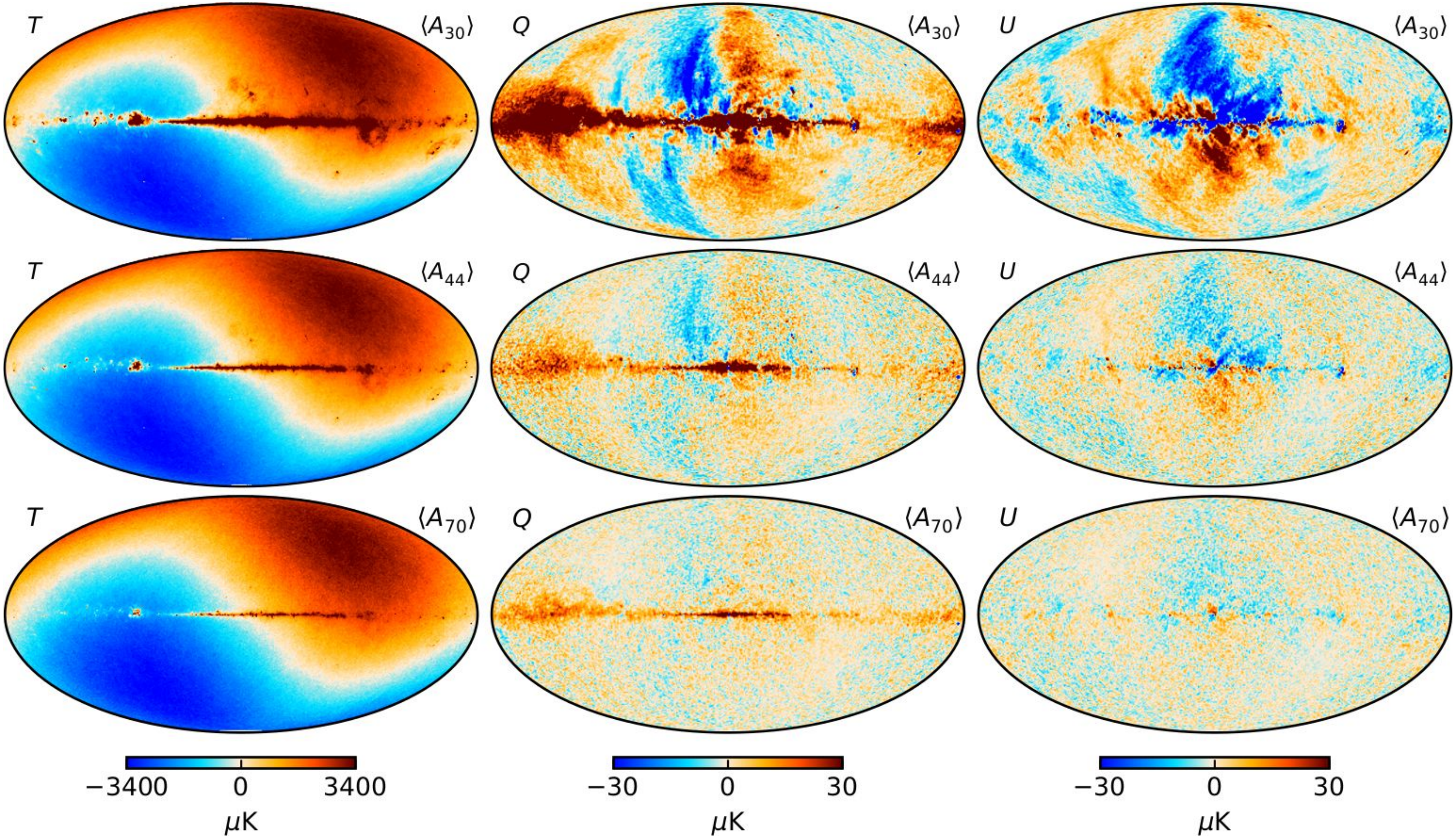
Beyond PLANCK

Frequency maps: 30 GHz Stokes Q



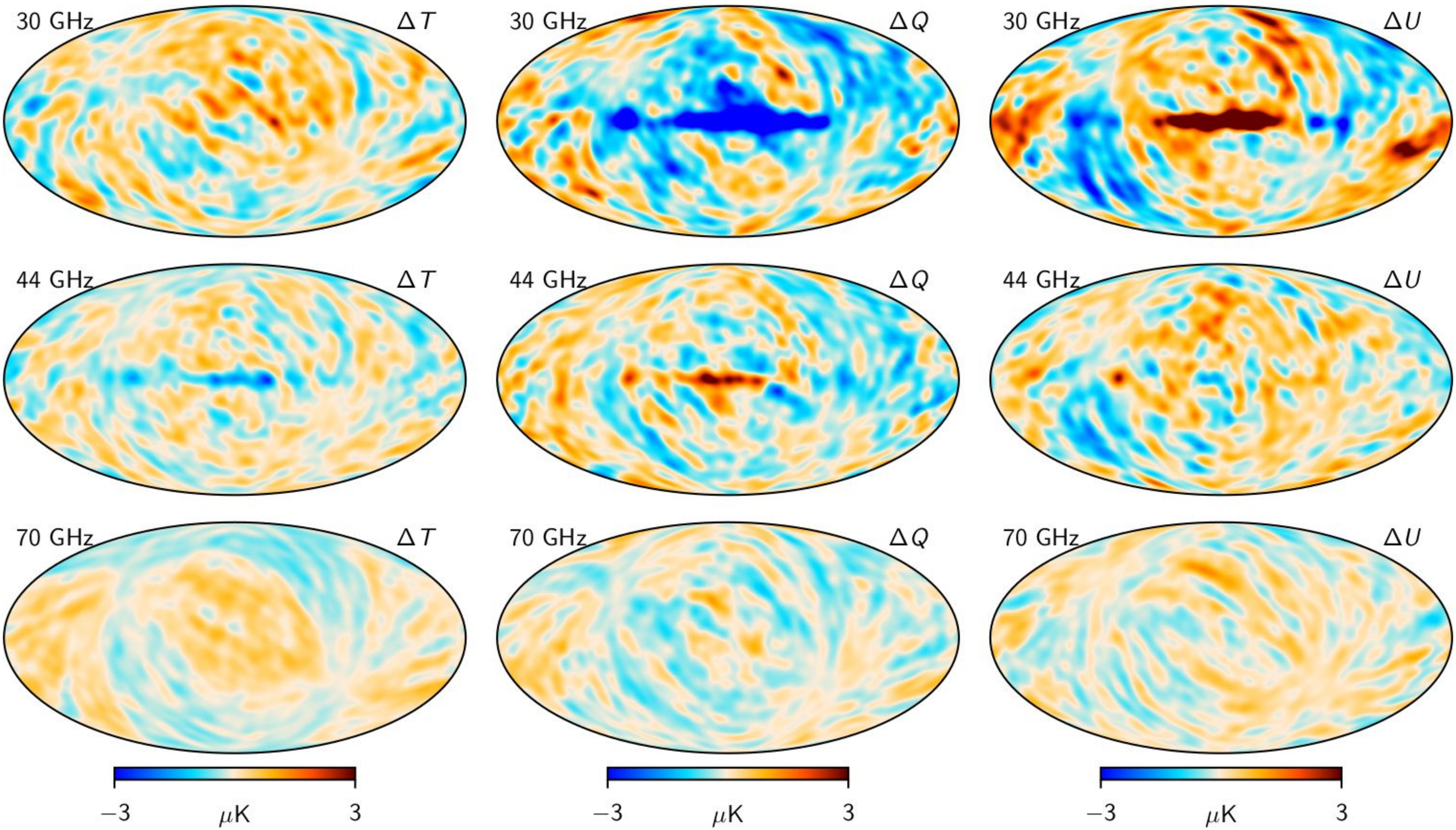
Suur-Uski et al. (2020)

Frequency maps: Posterior mean



Suur-Uski et al. (2020)

Frequency maps: Difference between two samples

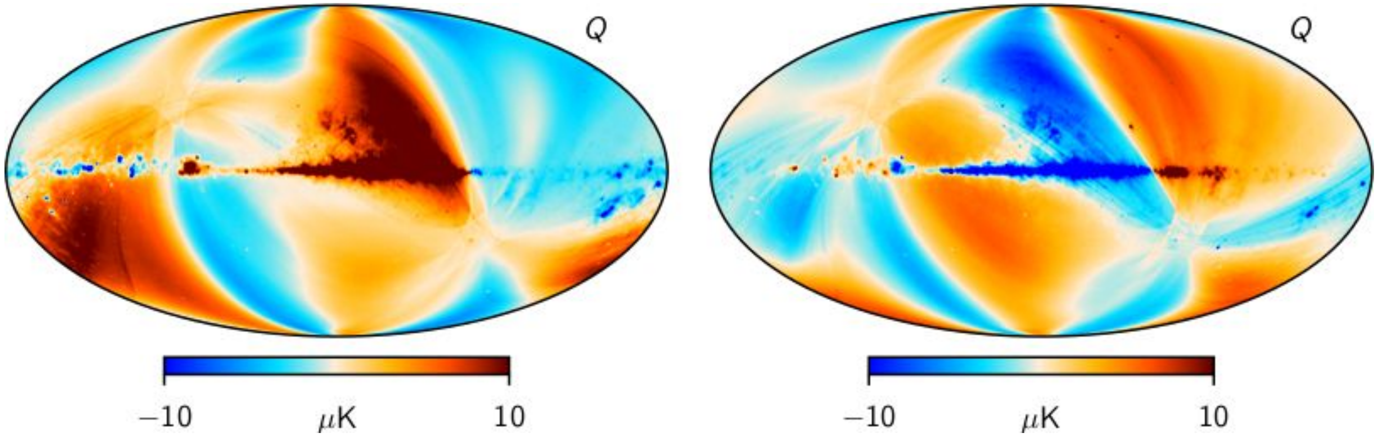


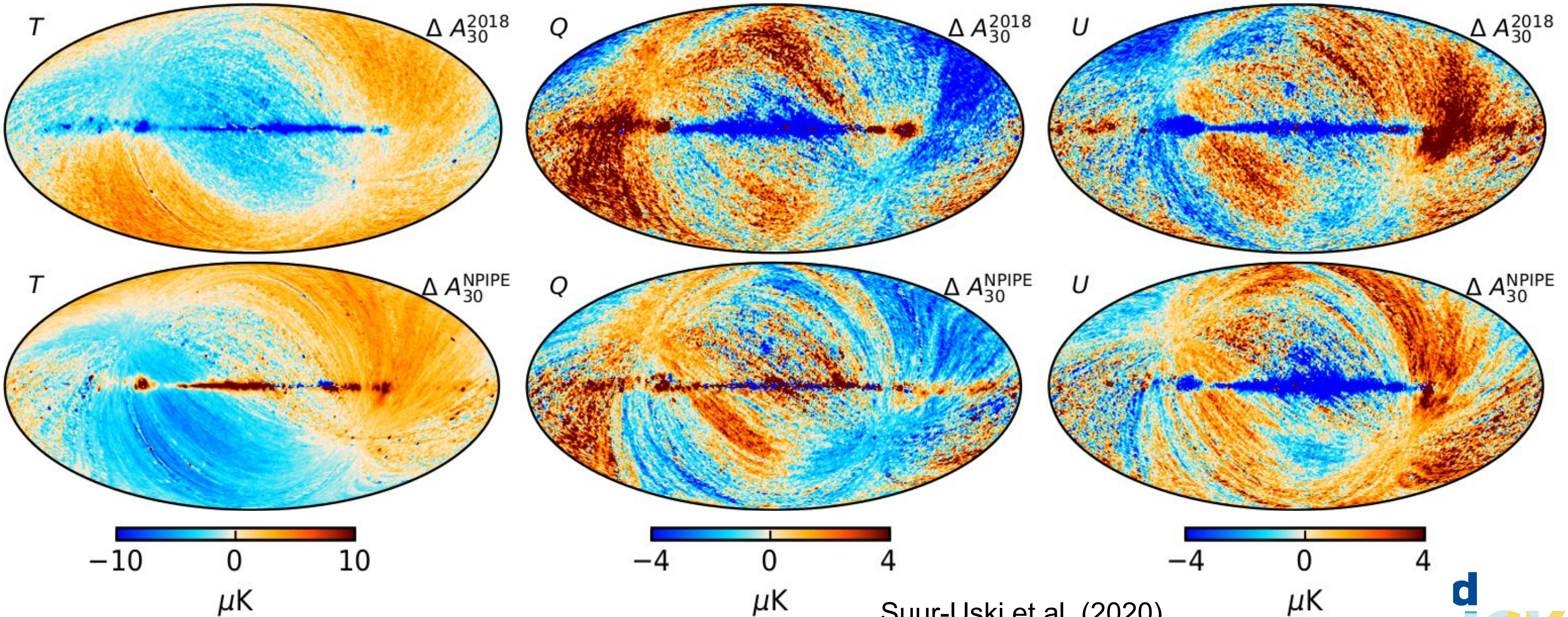
Suur-Uski et al. (2020)

Frequency maps: 30 GHz minus NPIPE/Planck 2018

European Commission

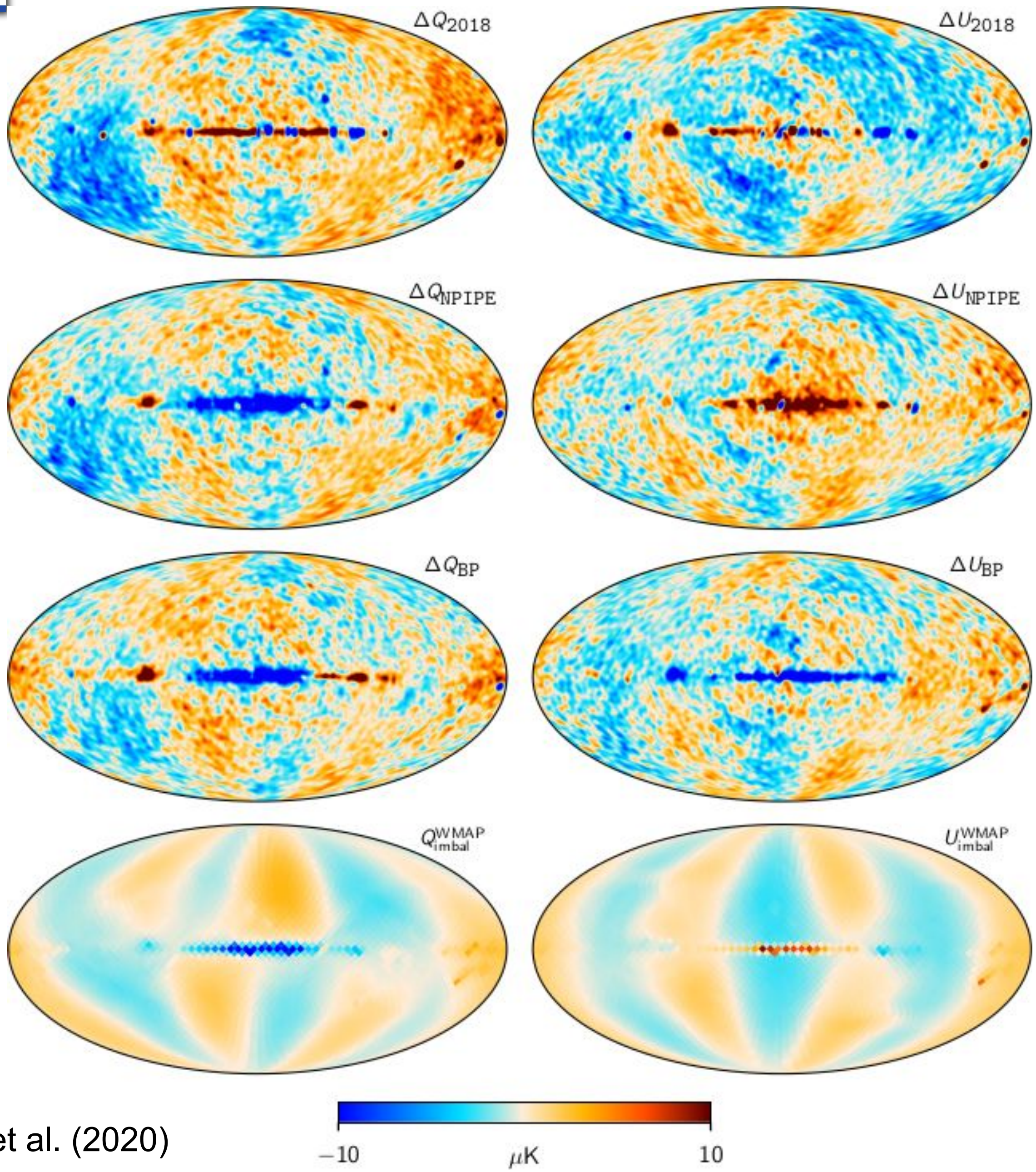
LFI DPC gain template (Planck Collaboration 2020, A&A, 641, A2





Suur-Uski et al. (2020)

Frequency maps: 30 GHz minus WMAP K-band



Planck 2018

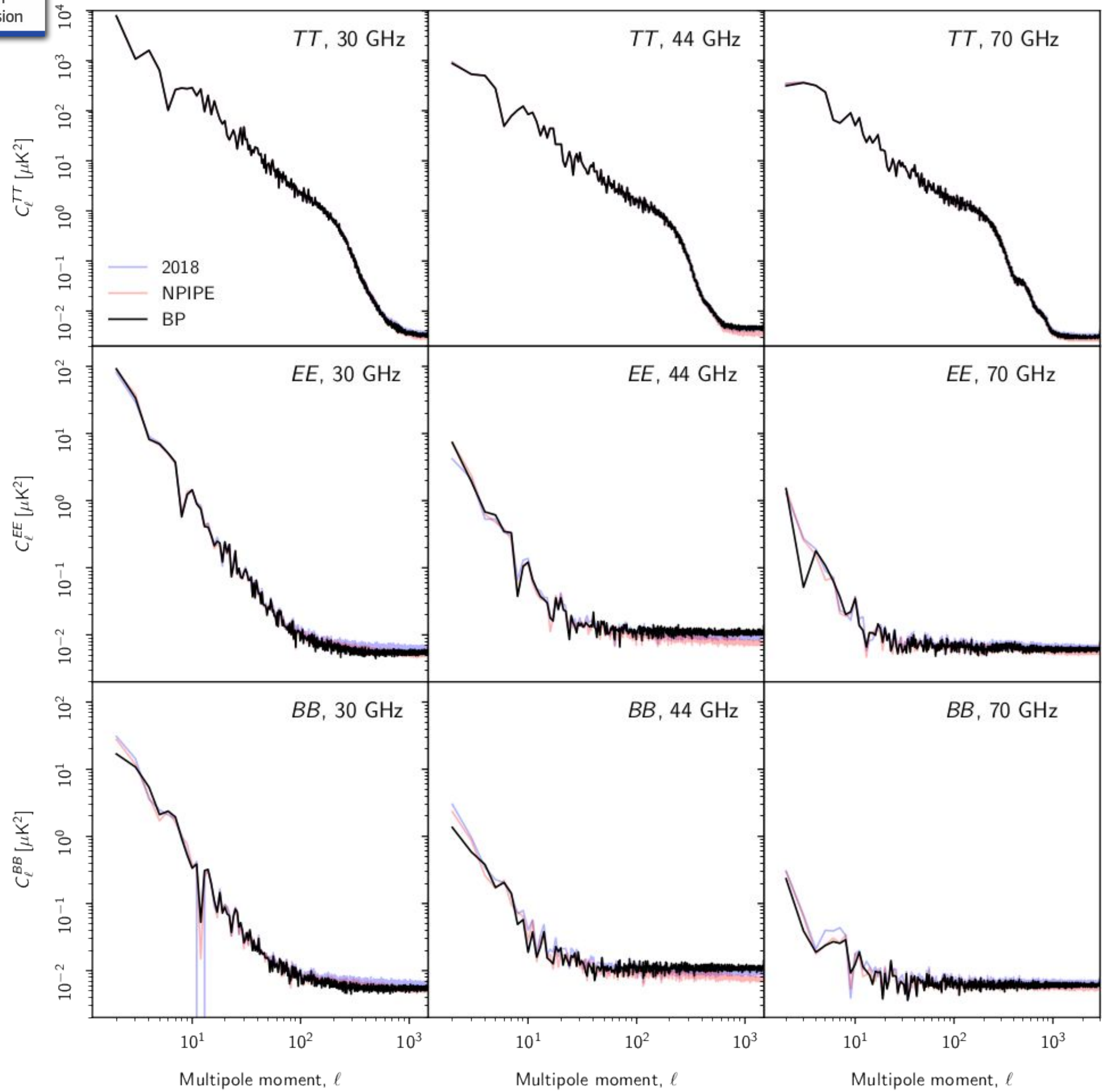
NPIPE

BeyondPlanck

WMAP transmission imbalance template (Jarosik et al. 2007)

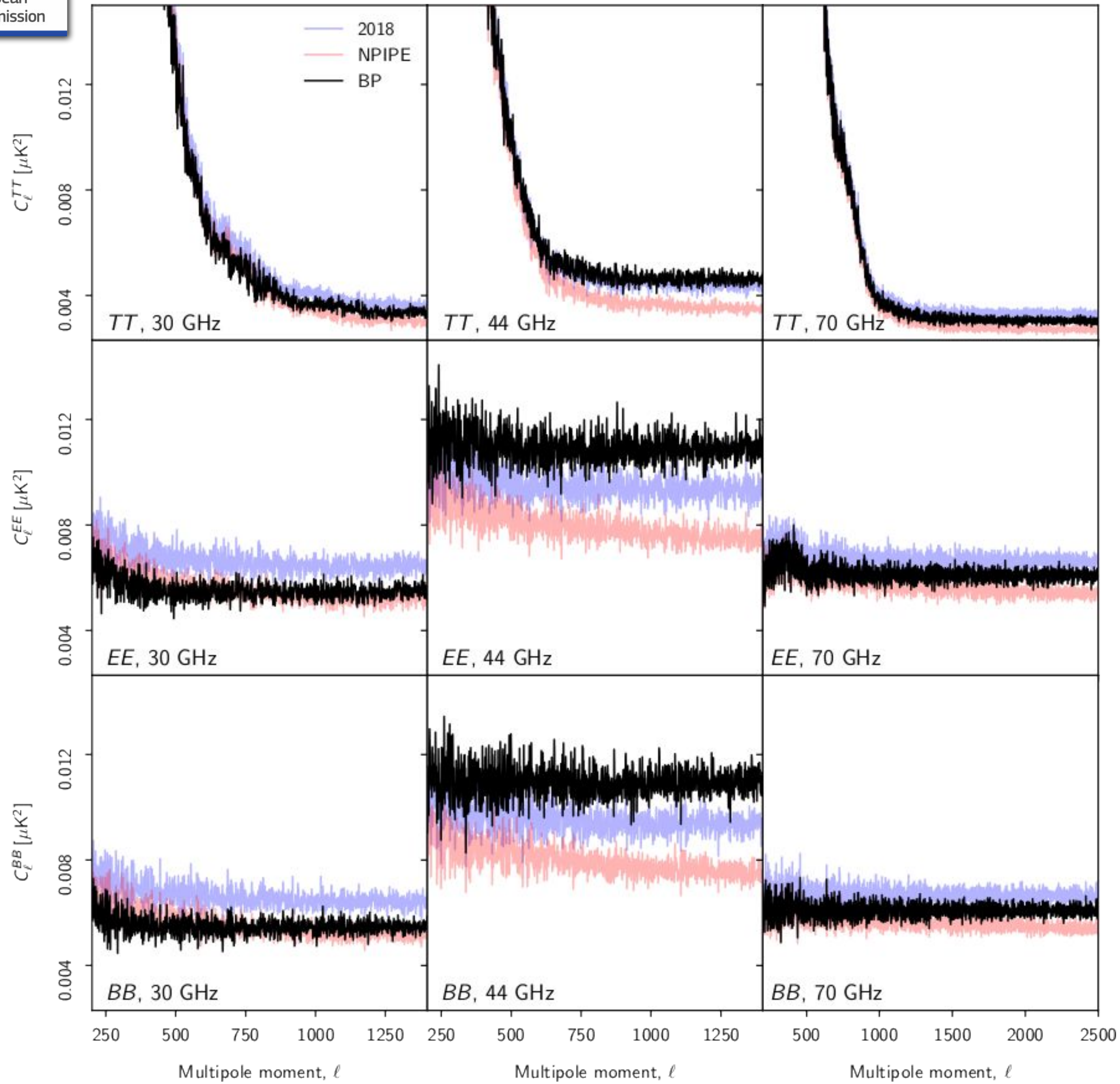
Gjerløw et al. (2020)

Frequency maps: Power spectrum



Suur-Uski et al. (2020)

Frequency maps: Power spectrum

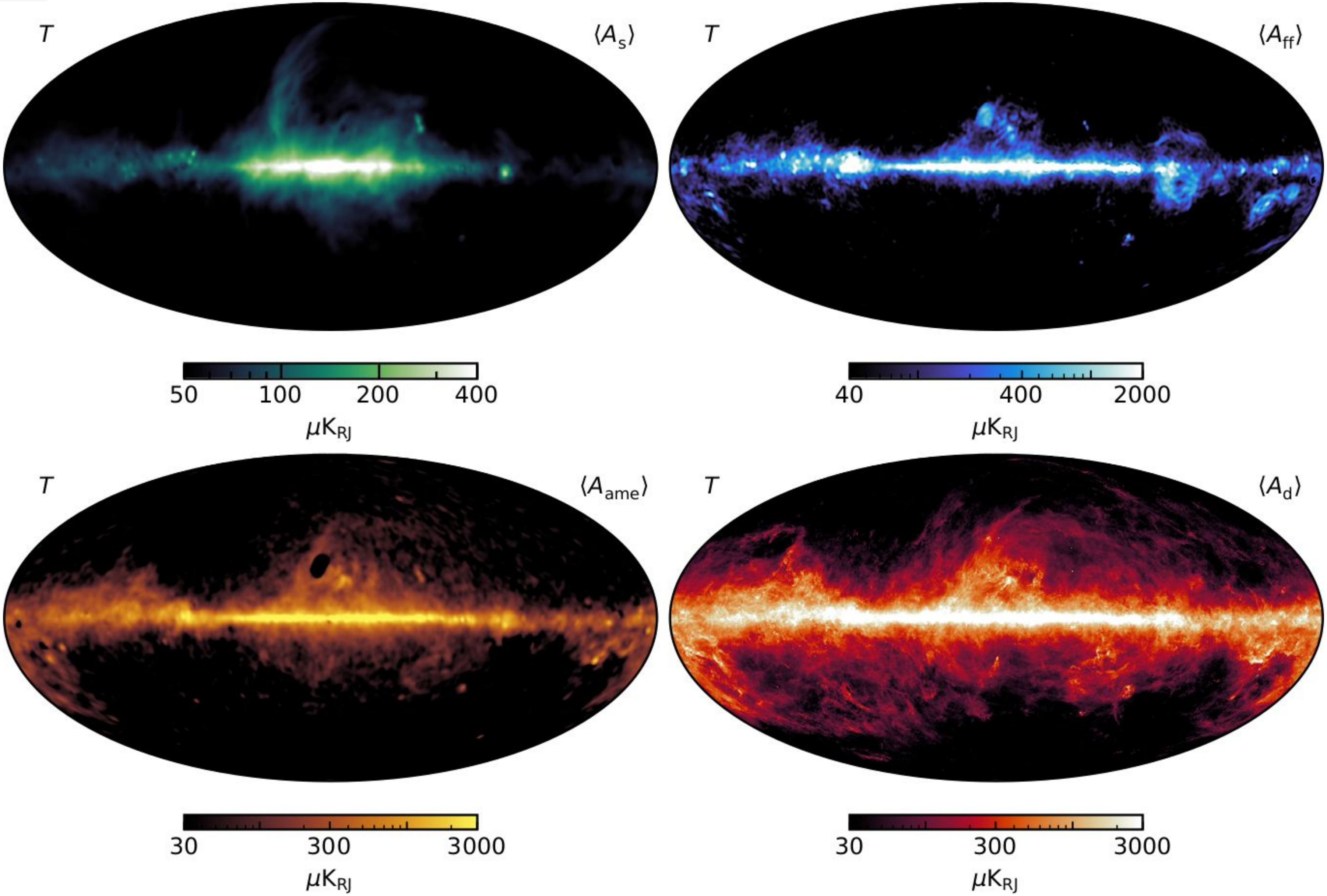


Flatter spectrum
=
Less correlated noise due to joint multi-frequency signal estimation

Higher white noise at 44 GHz because we discard more data

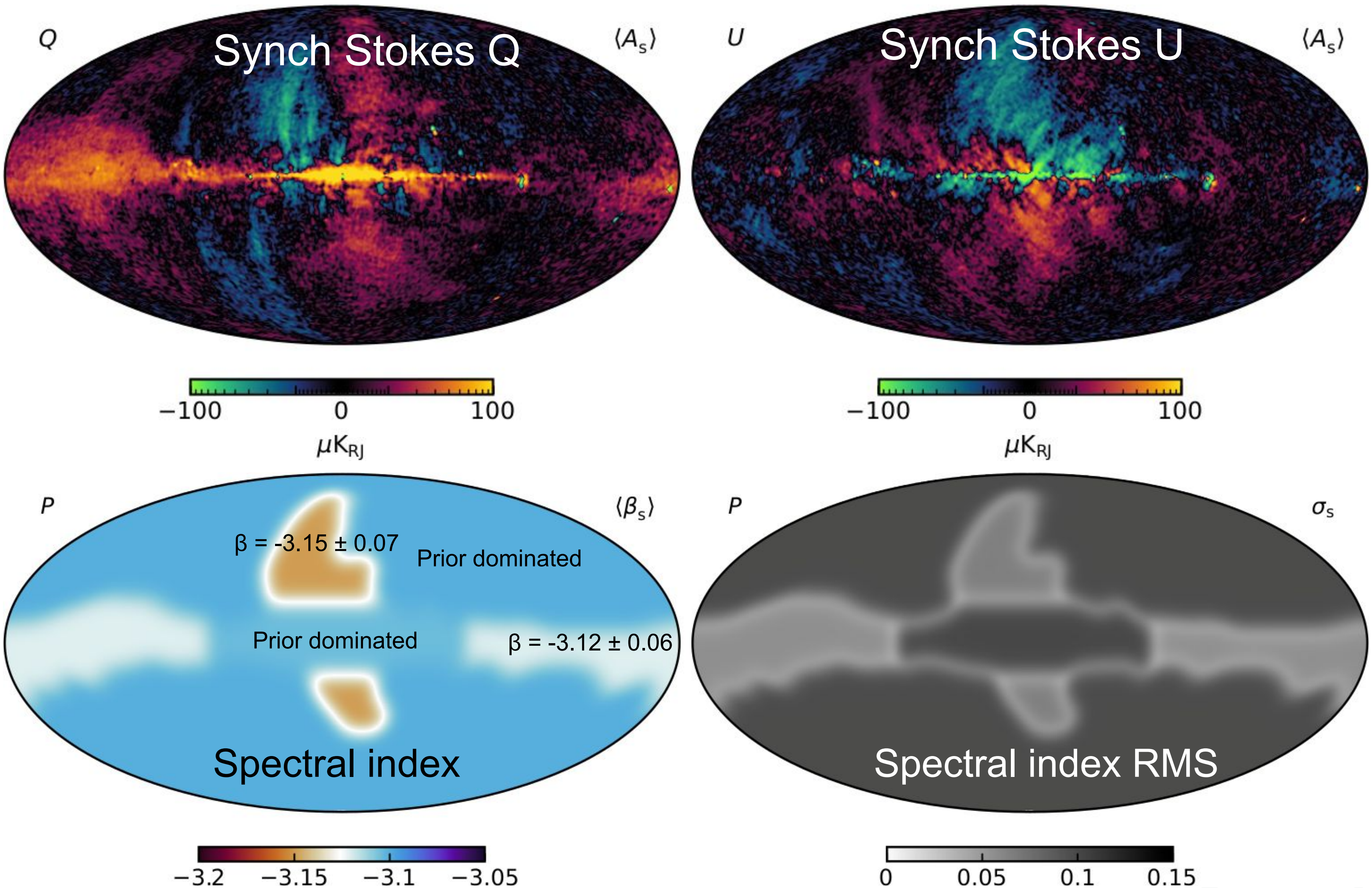
Suur-Uski et al. (2020)

Astrophysical foregrounds: Temperature sky



Andersen et al. (2020)

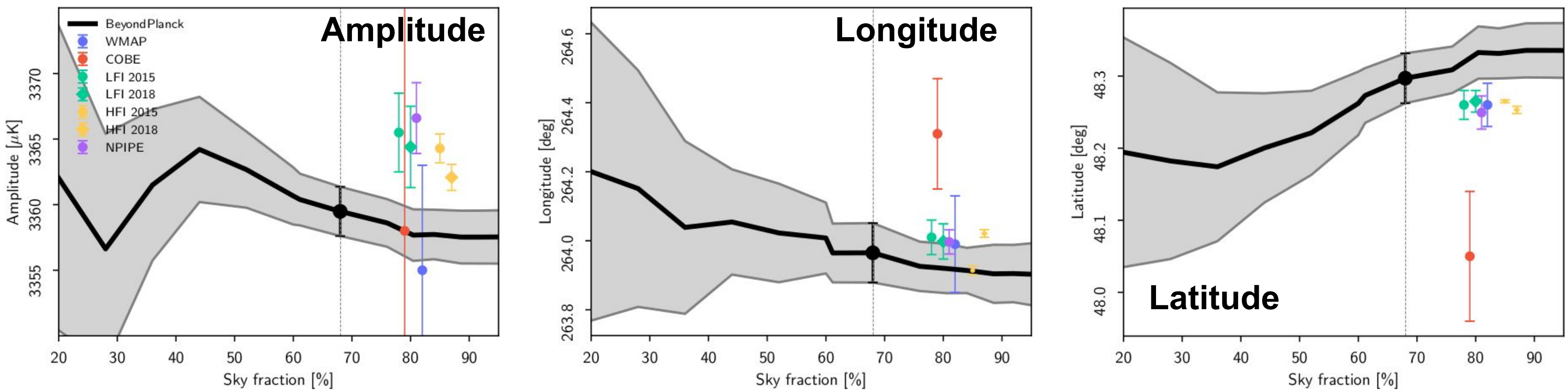
Astrophysical foregrounds: Polarized synchrotron emission



Svalheim et al. (2020)

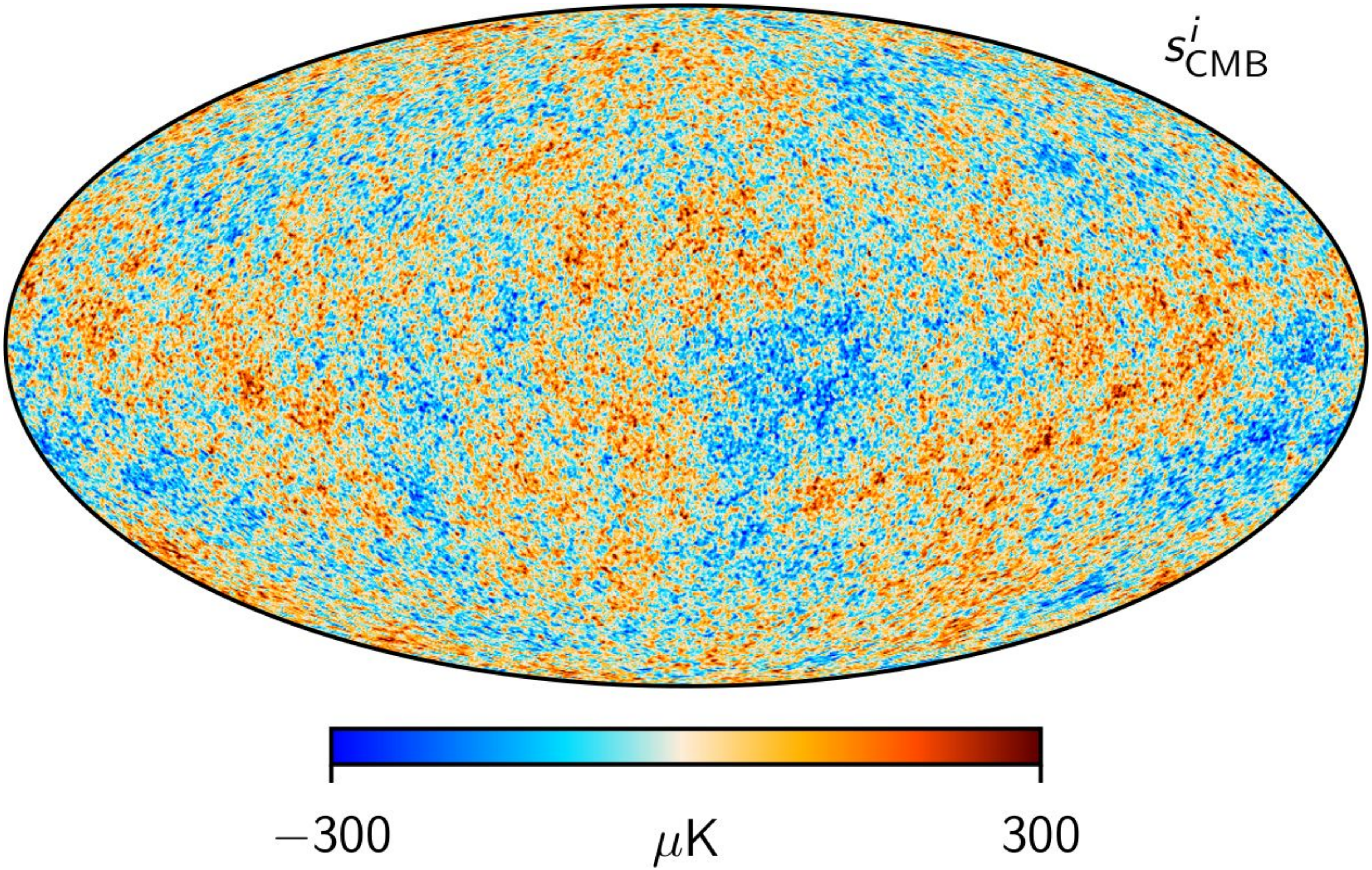
CMB: Solar dipole

Experiment	Amplitude [μK_{CMB}]	Galactic coordinates: l [deg]	Galactic coordinates: 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

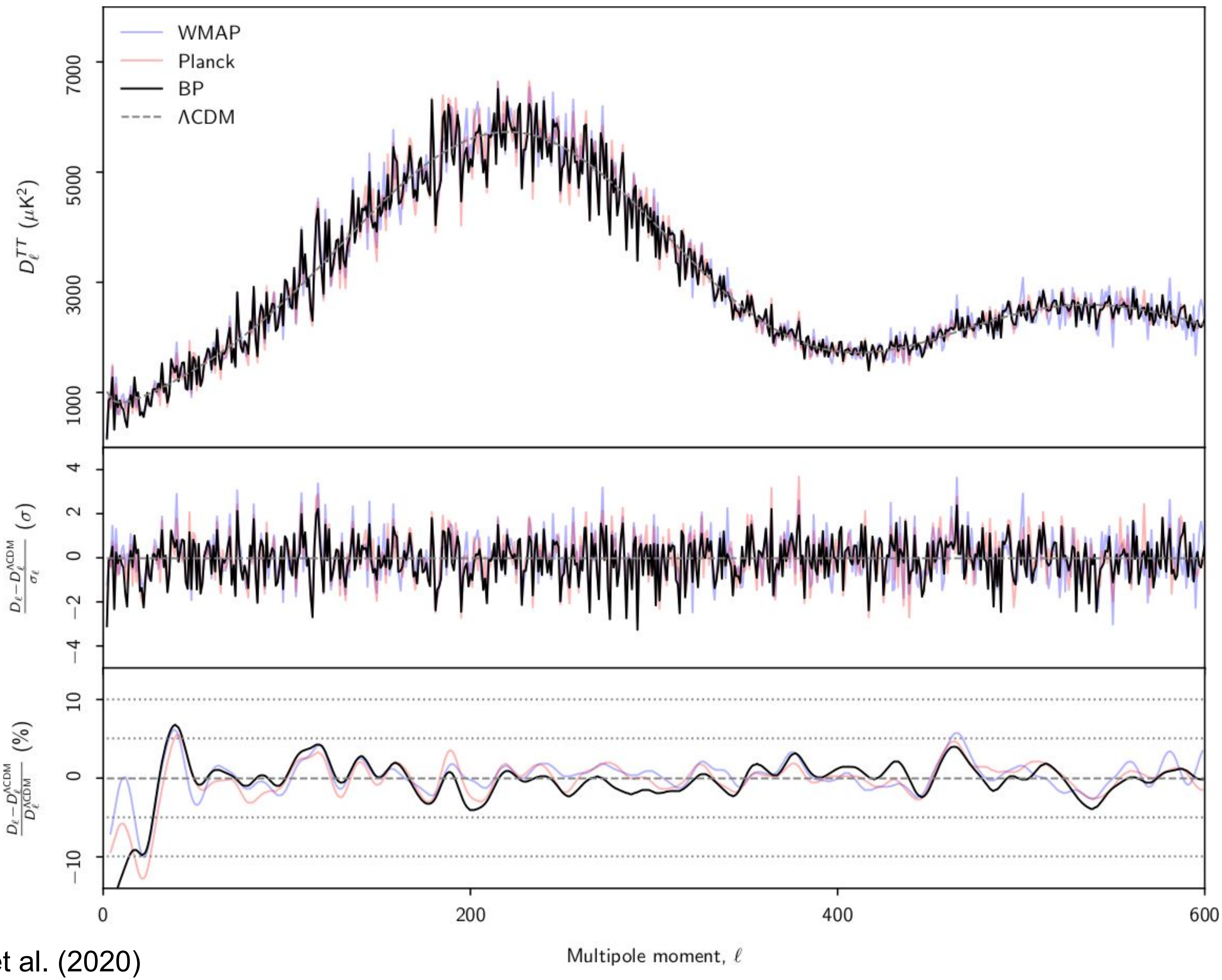


Colombo et al. (2020)

CMB temperature sample



CMB: High-l *TT* spectrum

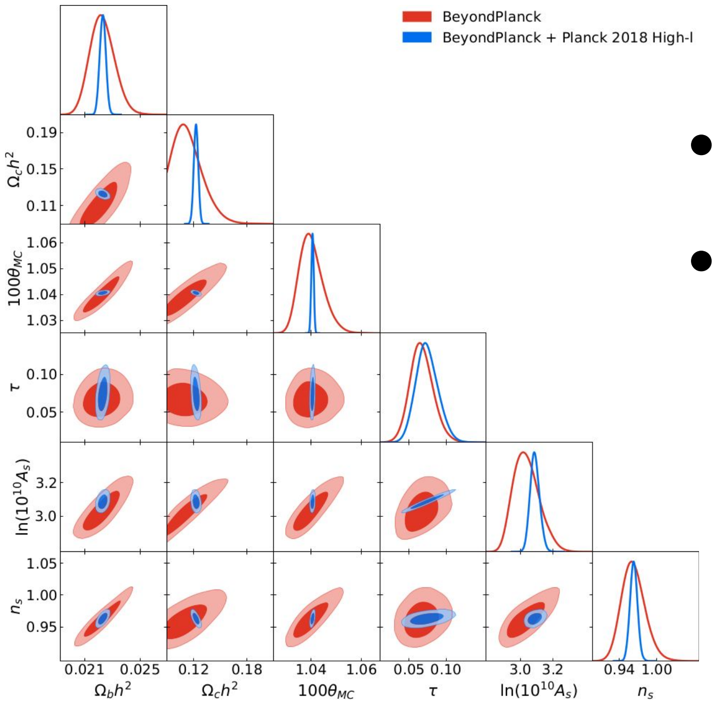


Colombo et al. (2020)

Cosmological parameters

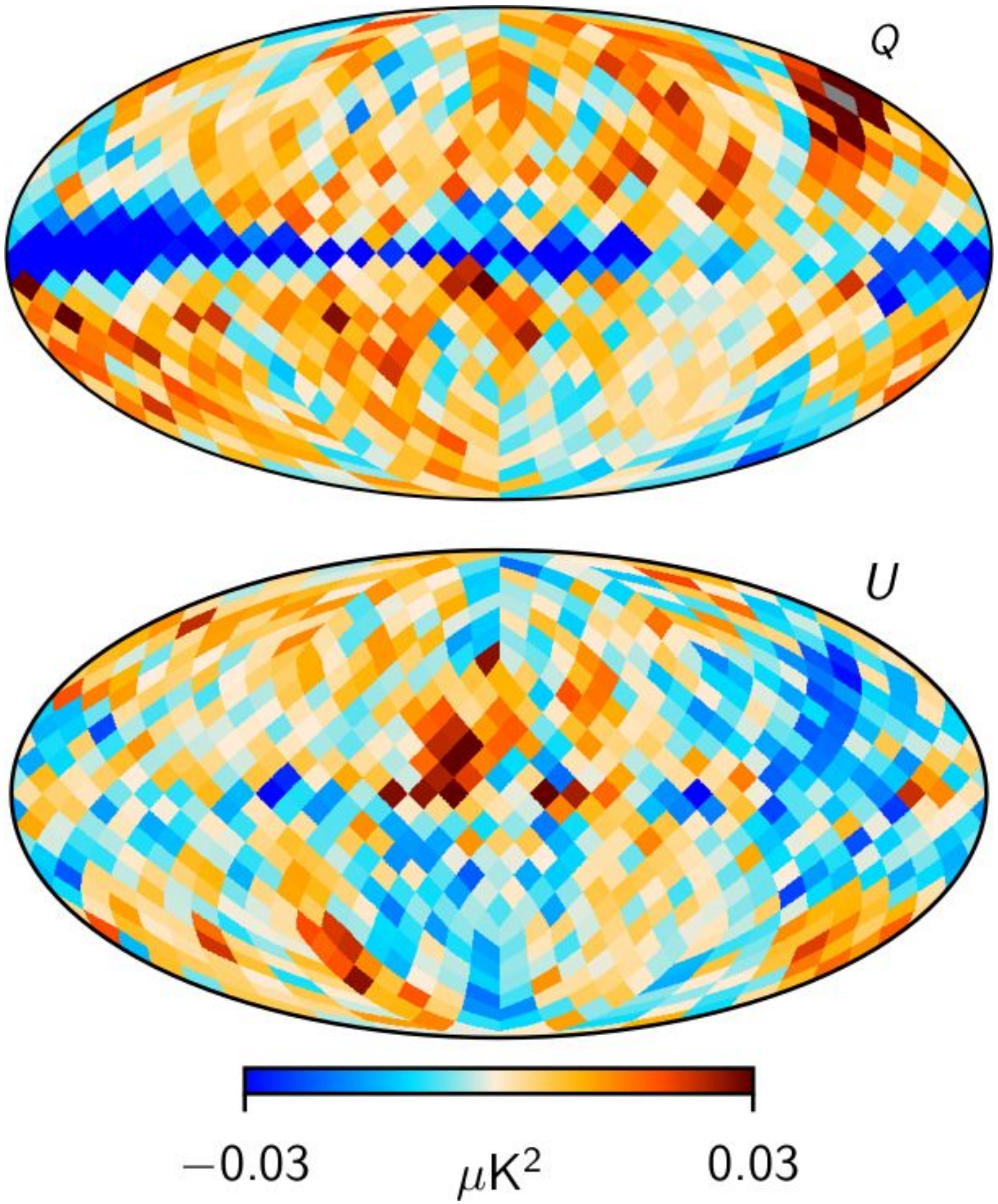
Paradiso et al. (2020)

Parameter	BeyondPlanck $\ell \leq 600$	BeyondPlanck $+Planck\ \ell > 600$	*Planck* 2018 Estimate	*Planck* 2018 $\Delta(\sigma)$	*WMAP* Estimate	*WMAP* $\Delta(\sigma)$
$\Omega_b h^2$	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

Low-resolution CMB map and covariance matrix



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

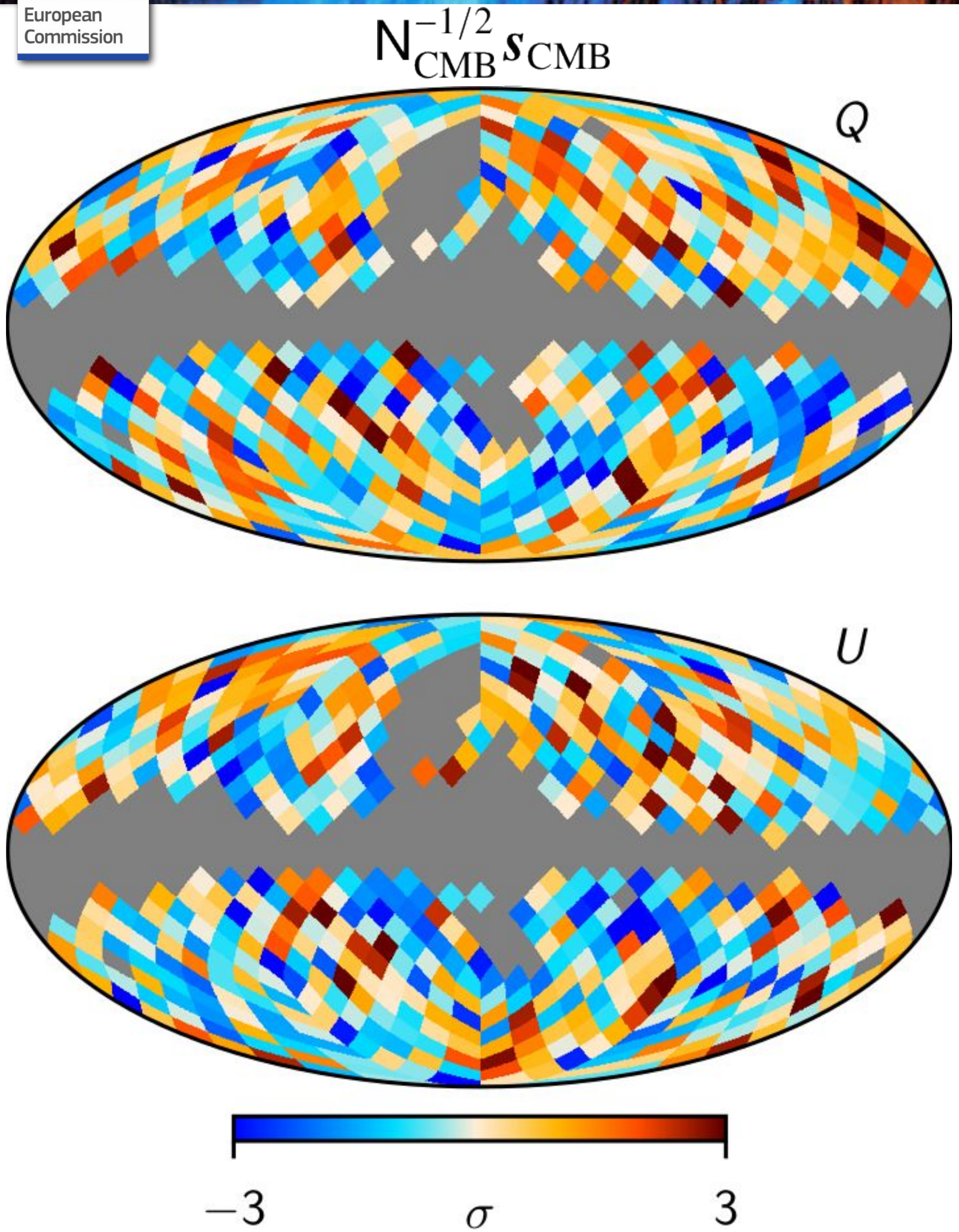
$$\hat{\boldsymbol{s}}_{\mathrm{CMB}} = \left\langle \boldsymbol{s}^{i}_{\mathrm{CMB}} \right\rangle$$

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

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!*

Colombo et al. (2020)

Low-resolution CMB map and covariance matrix



Colombo et al. (2020)

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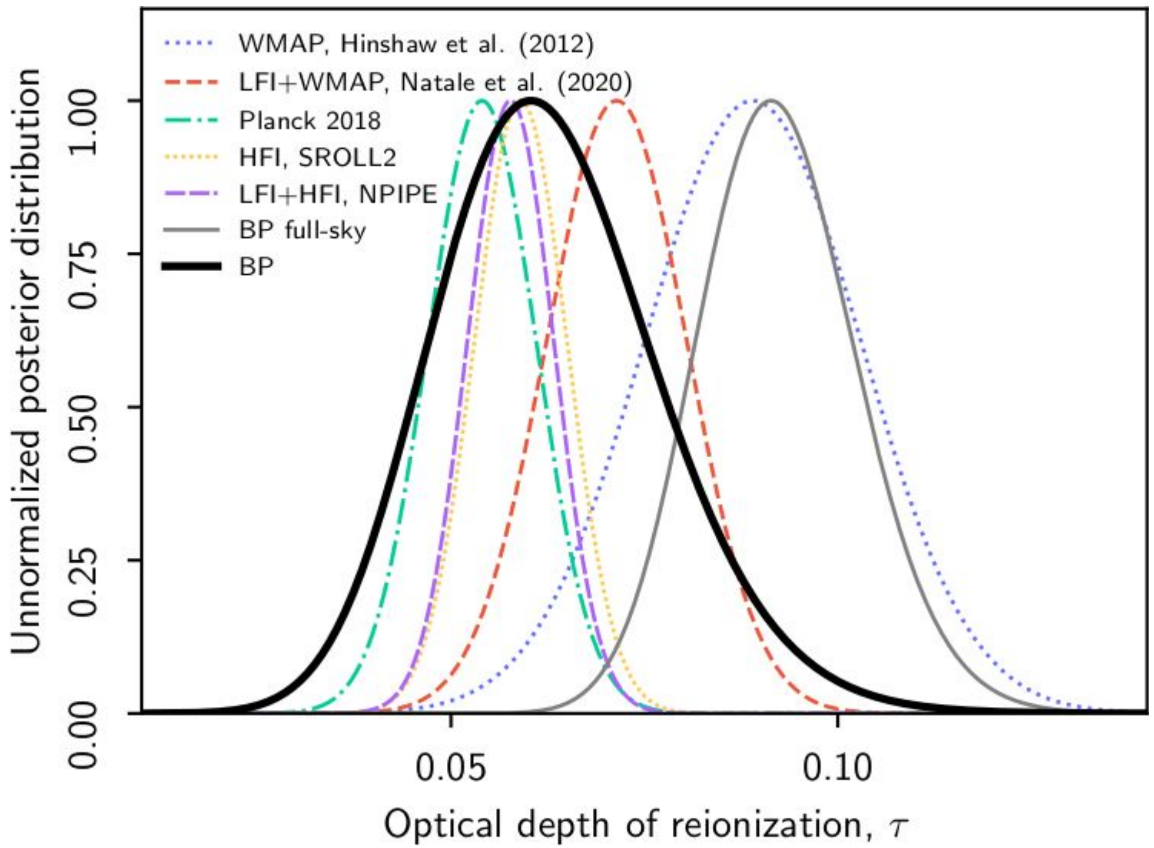
This is the first time uncertainties from ***gain, bandpass and a fine-grained foreground model*** *have been consistently propagated into* ***CMB low-l likelihood*** *inputs!*

CMB: Low-l polarization likelihood, τ and r

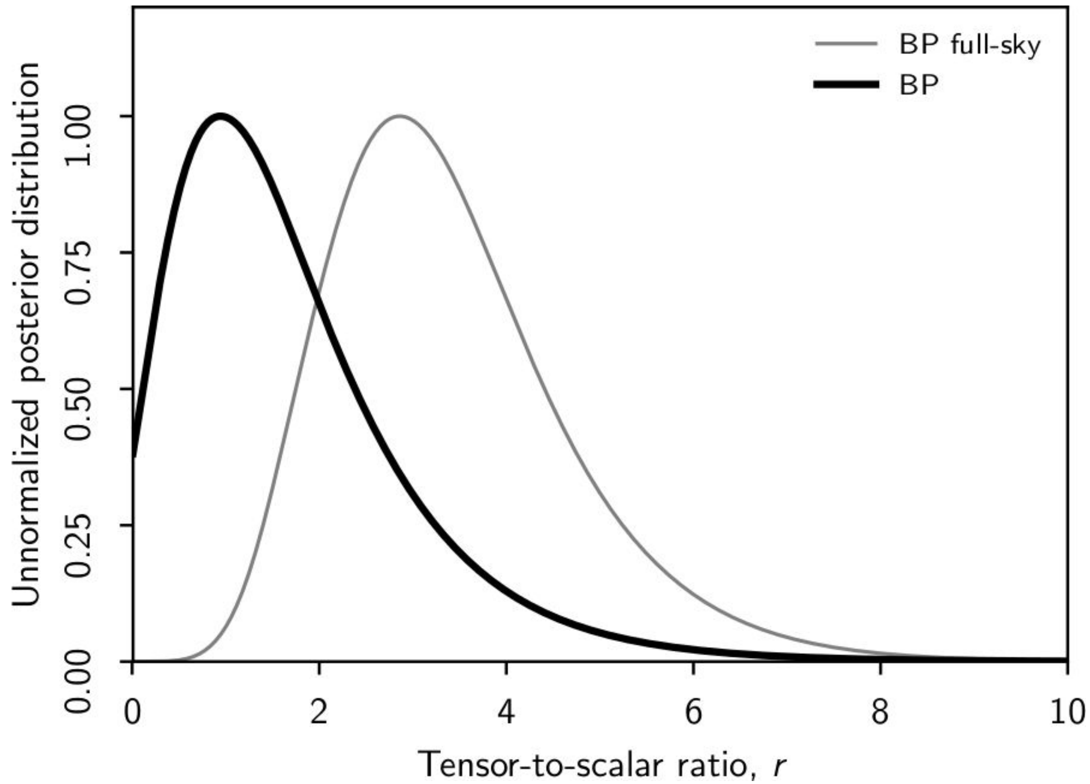
$$P(C_\ell \mid \hat{s}_{\mathrm{CMB}}) \propto \frac{e^{-\frac{1}{2}\hat{s}^t_{\mathrm{CMB}}(\mathrm{S}(C_\ell)+\mathrm{N})^{-1}\hat{s}_{\mathrm{CMB}}}}{\sqrt{|\mathrm{S}(C_\ell)+\mathrm{N}|}}$$



Paradiso et al. (2020)

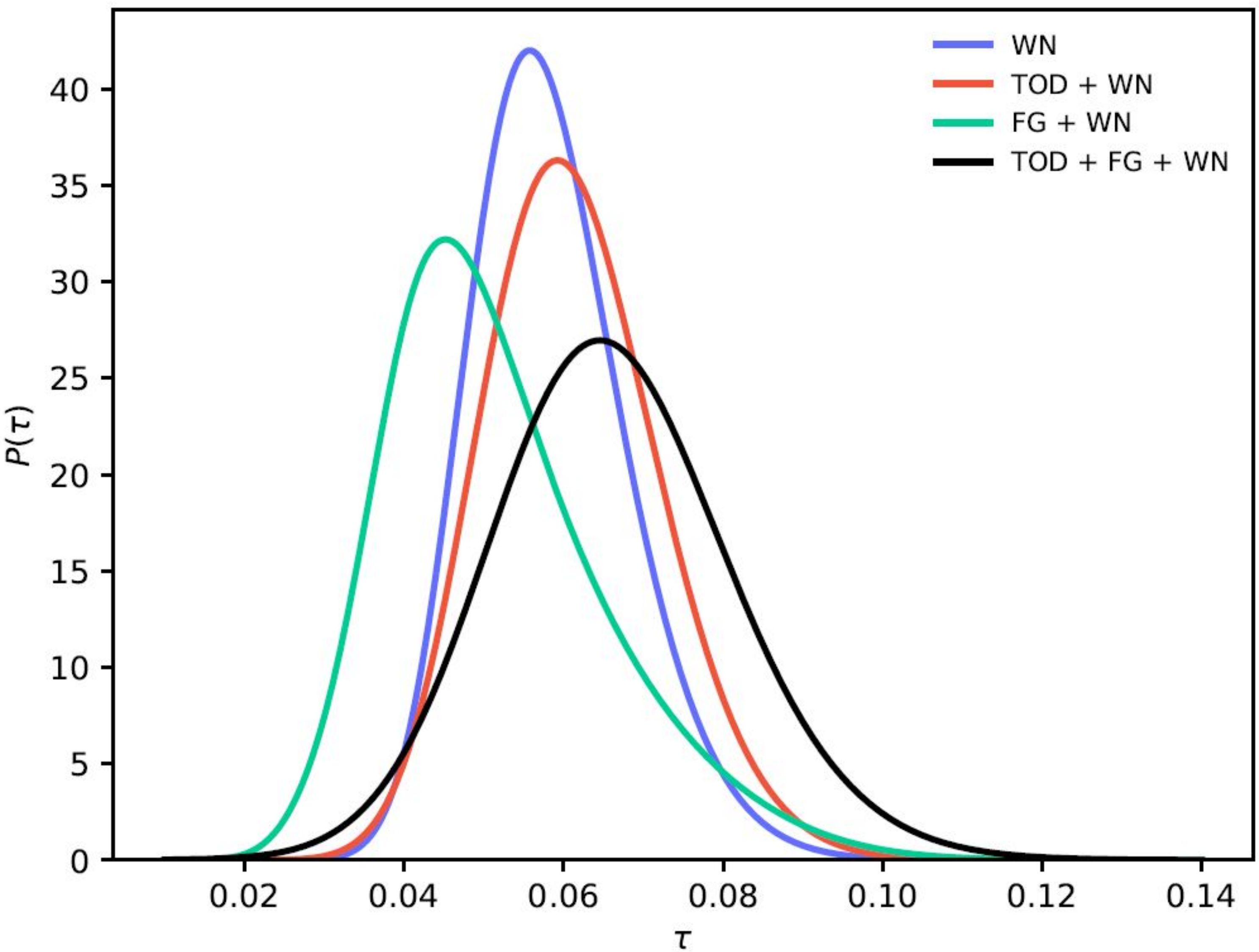
CMB: Low-l polarization likelihood, τ and r

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



Paradiso et al. (2020)

Uncertainties on the optical depth of reionization



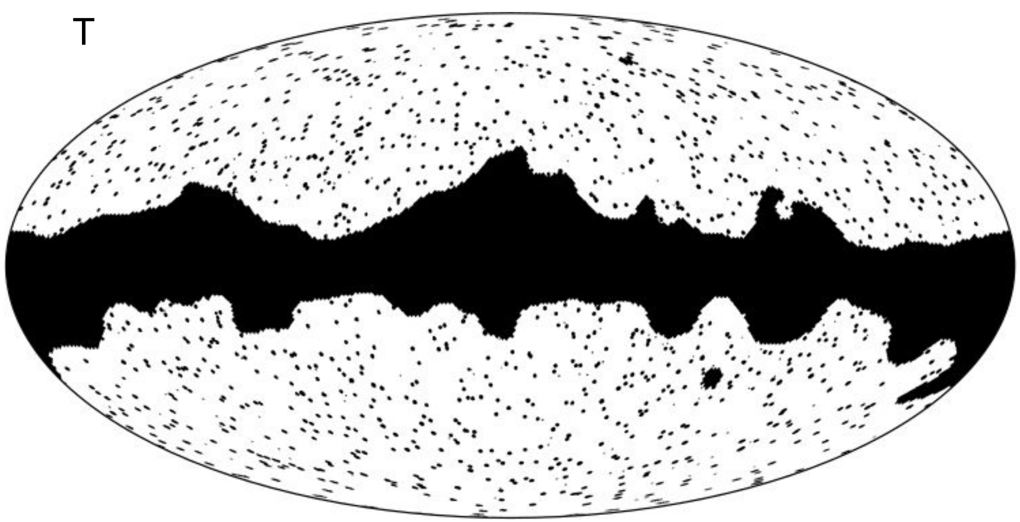
Paradiso et al. (2020)

CMB: Goodness-of-fit and masking

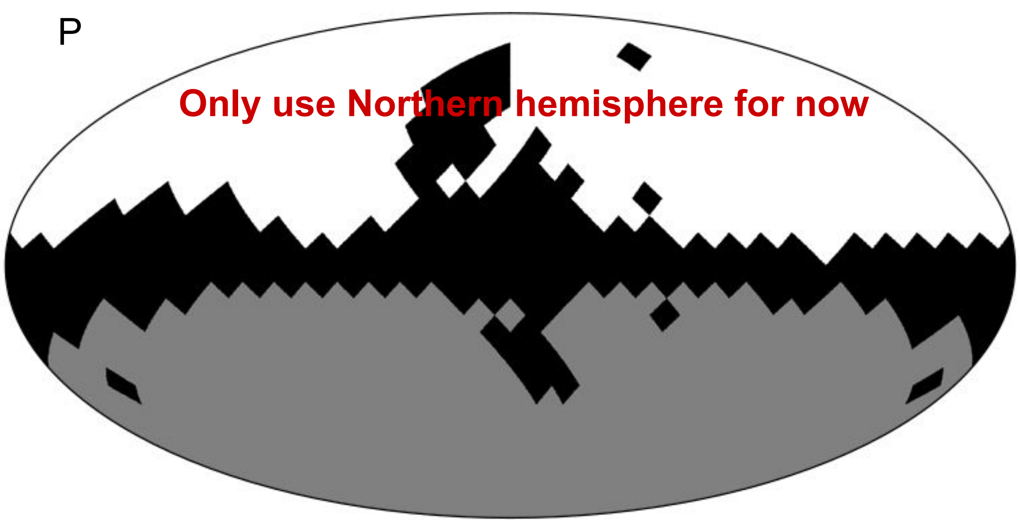
ANALYSIS NAME	DATA SETS	$f_{\rm sky}^{\rm pol}$	τ	$r_{95\,\%}^{BB}$	χ^2 PTE	REFERENCE
BEYONDPLANCK, $\ell = 2$–8	LFI, *WMAP Ka–V*	0.36	$0.060^{+0.015}_{-0.013}$	< 4.3	0.16	Paradiso et al. (2020)
BEYONDPLANCK, $\ell = 3$–8	LFI, *WMAP Ka–V*	0.36	$0.061^{+0.015}_{-0.014}$	< 5.4	0.16	Paradiso et al. (2020)
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

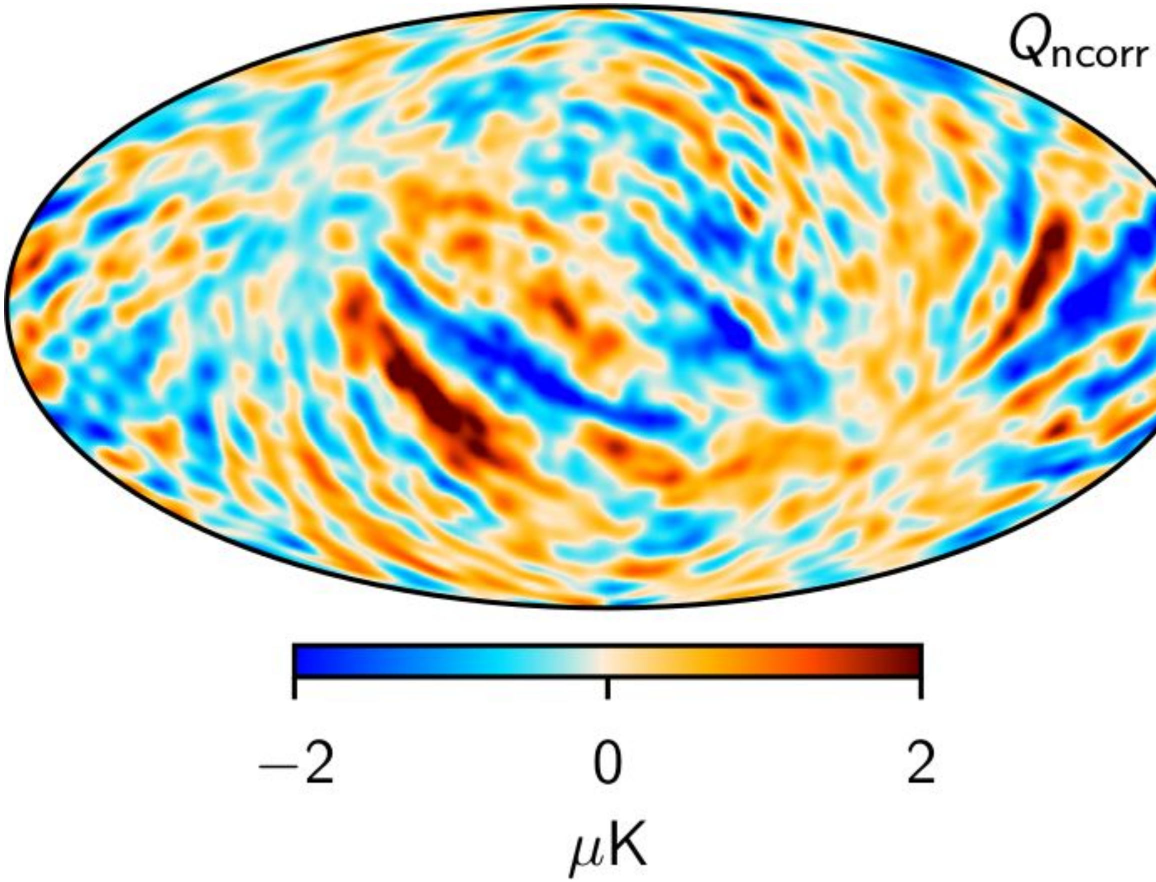


P



Full-sky polarization mask has unacceptable χ^2!

Outstanding issues 1: Stripes in 44 GHz

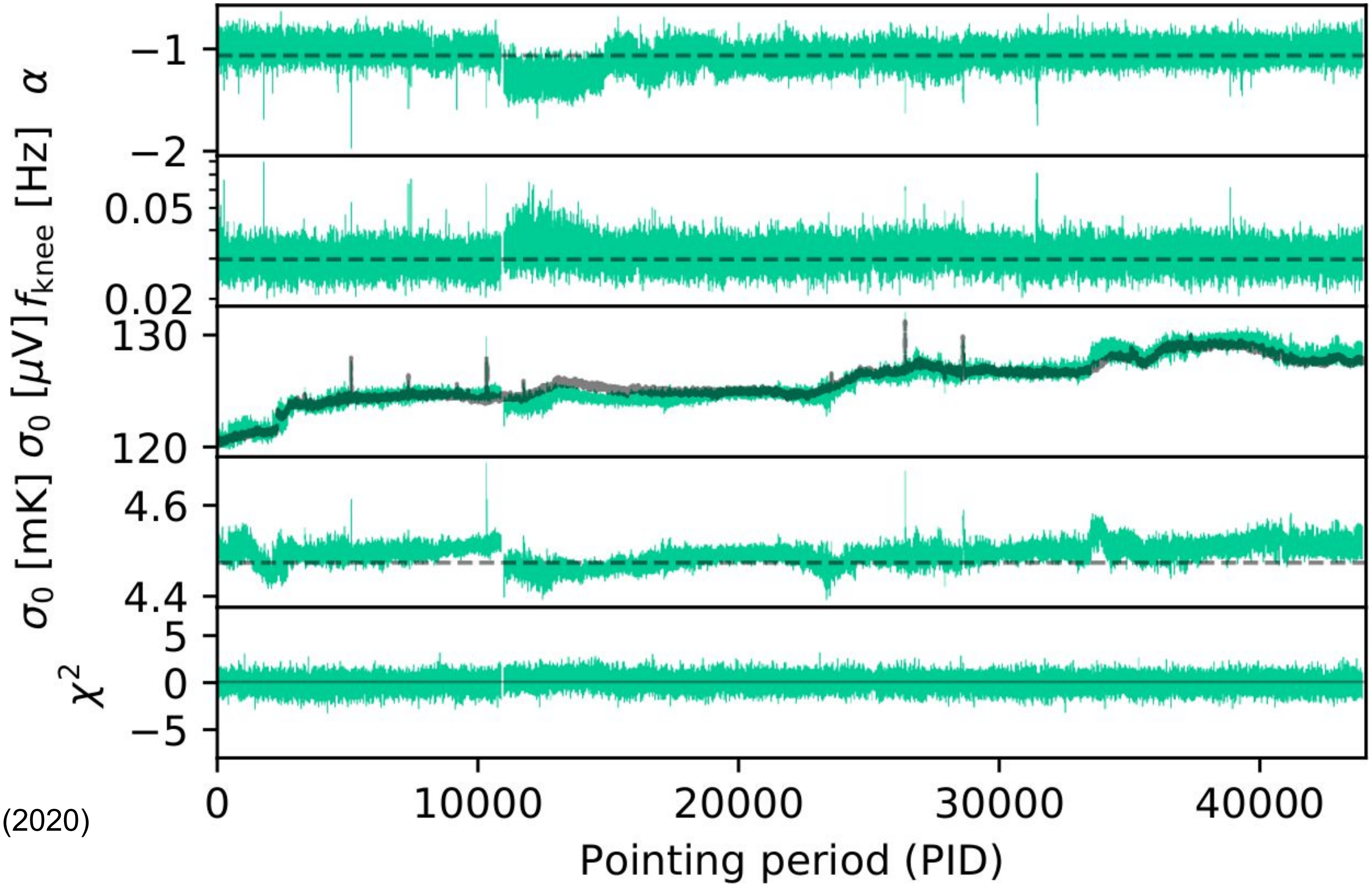


Ihle et al. (2020)

- 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?

1/*f* model at 70 GHz fits well

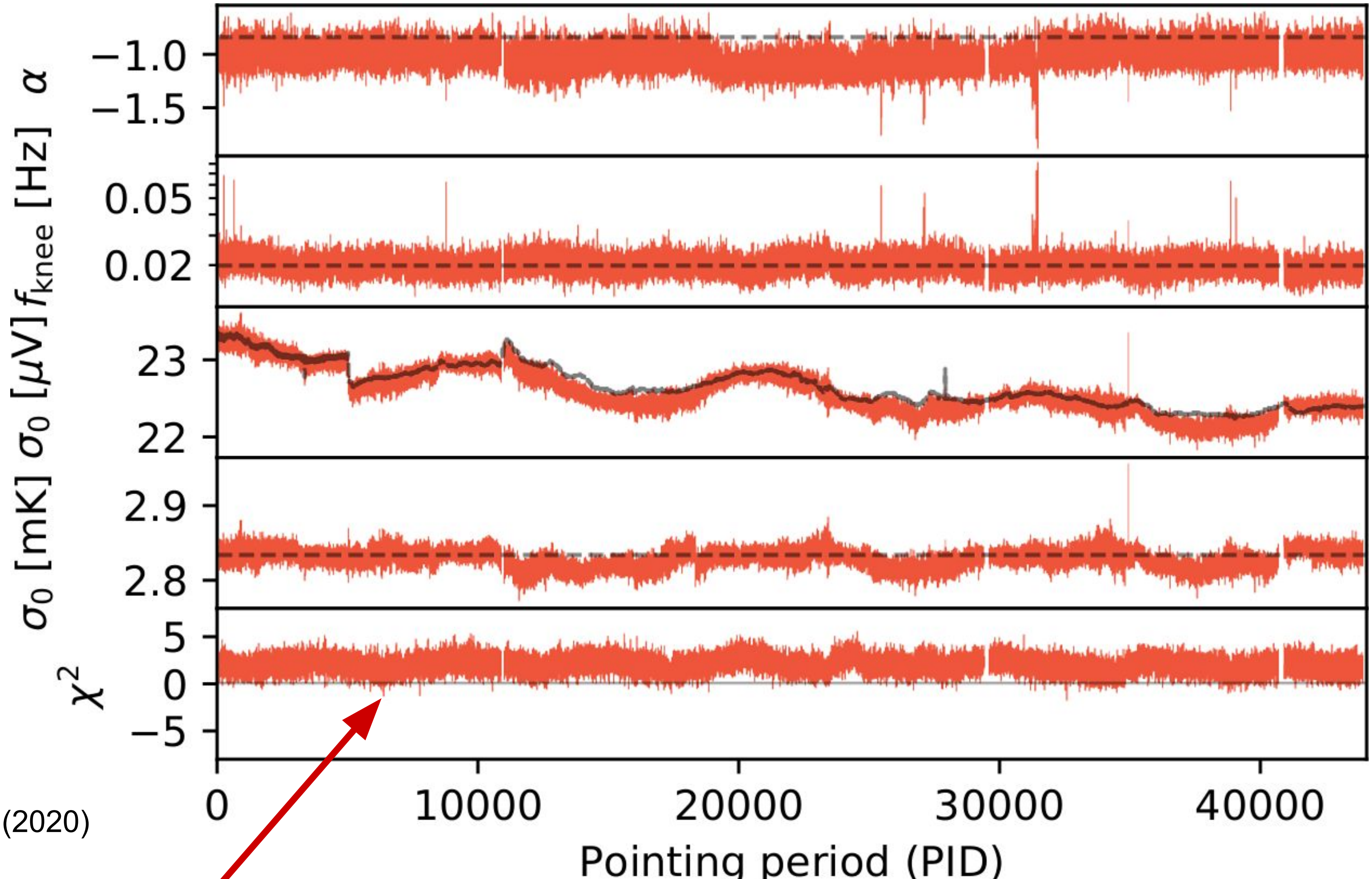
Correlated noise parameters for 70GHz 23M radiometer



Ihle et al. (2020)

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

Correlated noise parameters for 44GHz 25M radiometer

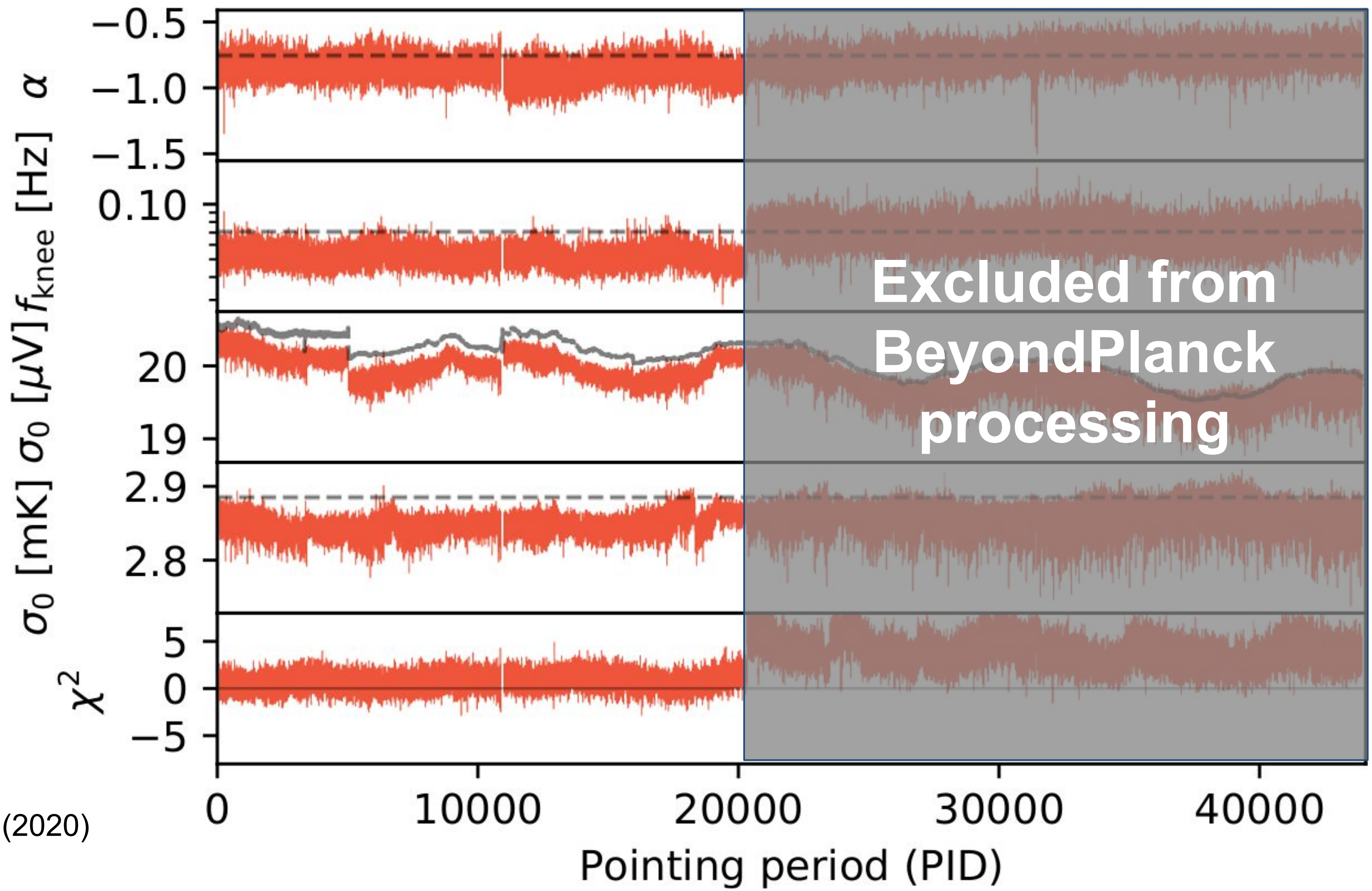


Ihle et al. (2020)

χ^2 excess of 2-3 sigma per PID!

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

Correlated noise parameters for 44GHz 26S radiometer



Ihle et al. (2020)

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

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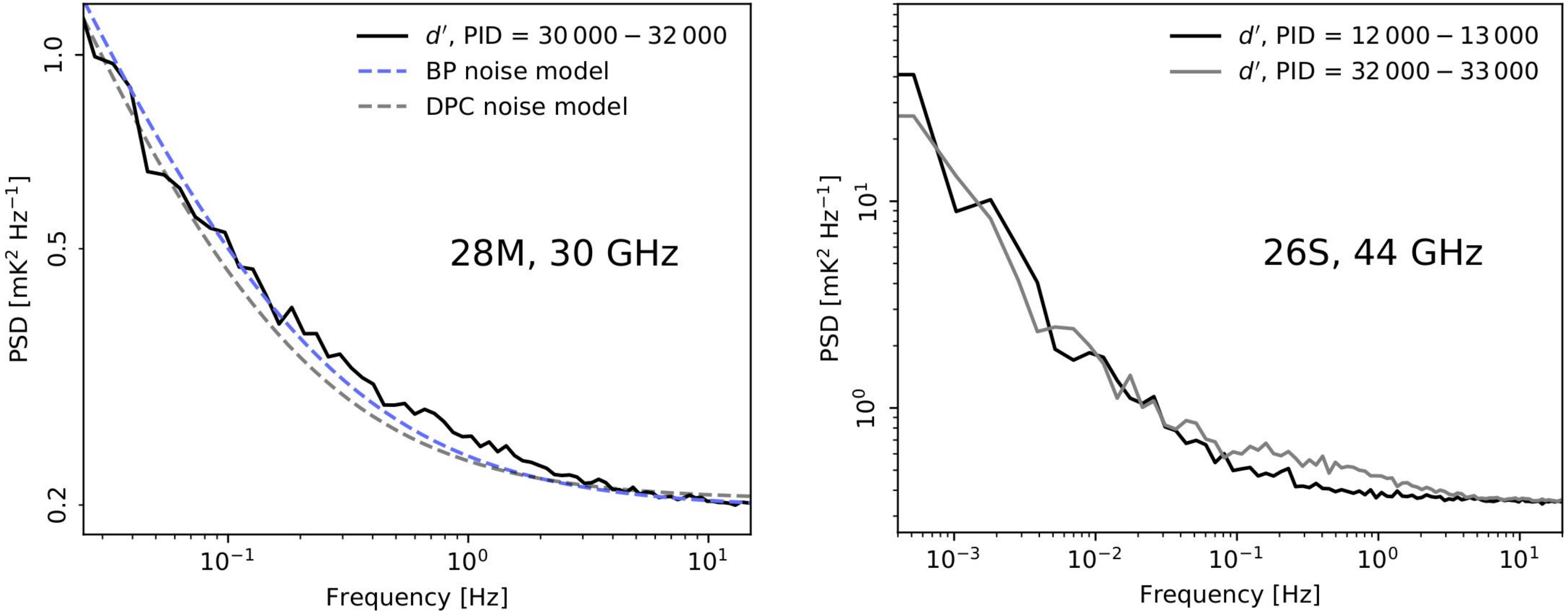
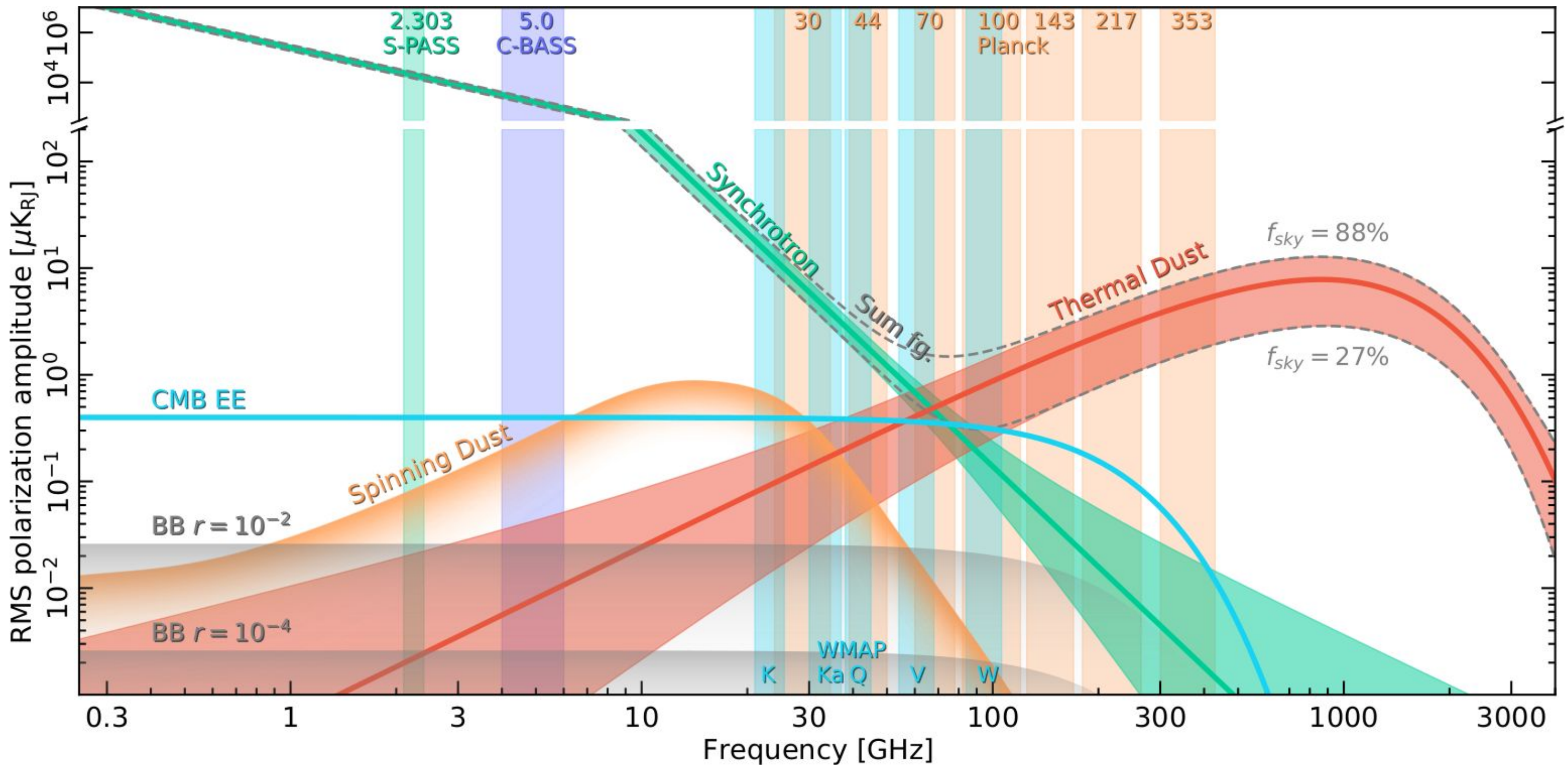
Ihle et al. (2020)



- 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

Beyond PLANCK

The future: Cosmoglobe



BeyondPlanck (2020)

- BeyondPlanck has successfully implemented an efficient end-to-end analysis framework for global CMB analysis
  - So far, only LFI has been fully integrated
- Now it needs to be populated with complementary datasets:
  - Public: Planck HFI, WMAP, FIRAS, DIRBE...
  - Proprietary: BICEPx, C-BASS, CLASS, COMAP, PASIPHAE, QUIJOTE, QUIET, S-PASS, SPIDER...?
- Obviously a community effort, and will rely on active participation from interested experiments
- This effort will be organized by the ***Cosmoglobe*** project; see talk by Ingunn Wehus on Friday

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

Paper finalization

- Already arranged for an Astronomy and Astrophysics Special Issue named *"BeyondPlanck -- end-to-end Bayesian analysis of Planck LFI"*

- Tentative submission deadline is January 31st, 2021
  - May be delayed if we manage to solve the 1/f and 44 GHz stripe problems before mid-January, and want to make one more final run

- Will include at least 13 papers
  - Papers IV, XV, XVI, XVII and XVIII may be submitted later as regular A&A papers

Data products

Home Project Products Publications Documentation Dissemination Cosmoglobe Contact

BEYONDPLANCK PRODUCTS

Parameter Files

Filename	Content	Filesize	Format specification
BP_param_c0001.txt	Main Commander parameter file	69 kB	Commander parameter file documentation
BP_param_Tresamp_v1.txt	Commander parameter file for high-resolution CMB TT resampling	69 kB	Commander parameter file documentation
BP_param_resamp_c0001.txt	Commander parameter file for low-resolution CMB polarization resampling	x kB	Commander parameter file documentation

Chain Files

Filename	Content	Filesize	Format specification
BP_c000x_v1.h5 (1, 2, 3, 4, 5, 6)	Main chain files	329 GB each	File Formats
BP_c000x_Tresamp_v1.h5 (1, 2, 3, 4, 5, 6)	High-res CMB T resamp chain files	(2.3, 1.5, 1.7, 1.6, 1.5, 1.7) GB	File Formats
BP_c000x_Presamp_v1.h5 (1, 2, 3, 4, 5, 6)	Low-res CMB P resamp chain files	(437, 437, 437, 376, 397, 392) MB	File Formats

Frequency Maps

Filename	Content	Filesize	Format specification
BP_030_IQU_n0512_v1.fits	LFI 30 GHz frequency map	108 MB	
BP_044_IQU_n0512_v1.fits	LFI 44 GHz frequency map	108 MB	

Source code and OpenSource

European Commission

Gerakakis et al. (2020)
Galloway et al. (2020)

- The main BeyondPlanck computer code is called `Commander3`
  - Direct generalization of `Commander2`, as used in the Planck 2018 analysis
- Commander3 is publicly released under a GPL3 license:

  https://github.com/Cosmoglobe/Commander

- BeyondPlanck products, software and documentation are available through the project home page:

  https://beyondplanck.science

- Caveats:
  - All software is provided as is, with no guarantees of any kind
  - This is a software platform for cutting-edge research, and therefore by nature a continuous work-in-progress
  - Support is provided on a strictly voluntary basis; there is no "help desk"
    - If you want hands-on assistance, proposing a joint research project with one or more experienced BeyondPlanck/Cosmoglobe team members is a good idea

Beyond PLANCK

Reproducibility

Three main components:

1. Downloader
    - Simple one-command line download of all required data
2. CMake automated compilation system
    - Very simple compilation of all required libraries (Healpix, CFITSIO, HDF, FFTW etc.) and Commander
    - Main solution for development and production systems
3. Docker environment
    - No-hazzle pre-compiled (but also non-optimized) environment

Online resources

BeyondPlanck project

Main webpage:	https://beyondplanck.science
Products:	https://products.beyondplanck.science
	https://pla.esac.esa.int (subset; when papers are accepted)
Papers:	https://beyondplanck.science/products/publications
Discussion forum:	https://forums.beyondplanck.science

Commander

Source code :	https://github.com/cosmoglobe/Commander
Documentation:	https://docs.beyondplanck.science

Cosmoglobe

Main webpage:	http://cosmoglobe.uio.no

Planck Legacy Archive (selected BeyondPlanck products coming soon)

Link:	https://pla.esac.esa.int

Summary

- **BeyondPlanck has successfully implemented a framework for global end-to-end Bayesian CMB analysis, and demonstrated this using Planck LFI**

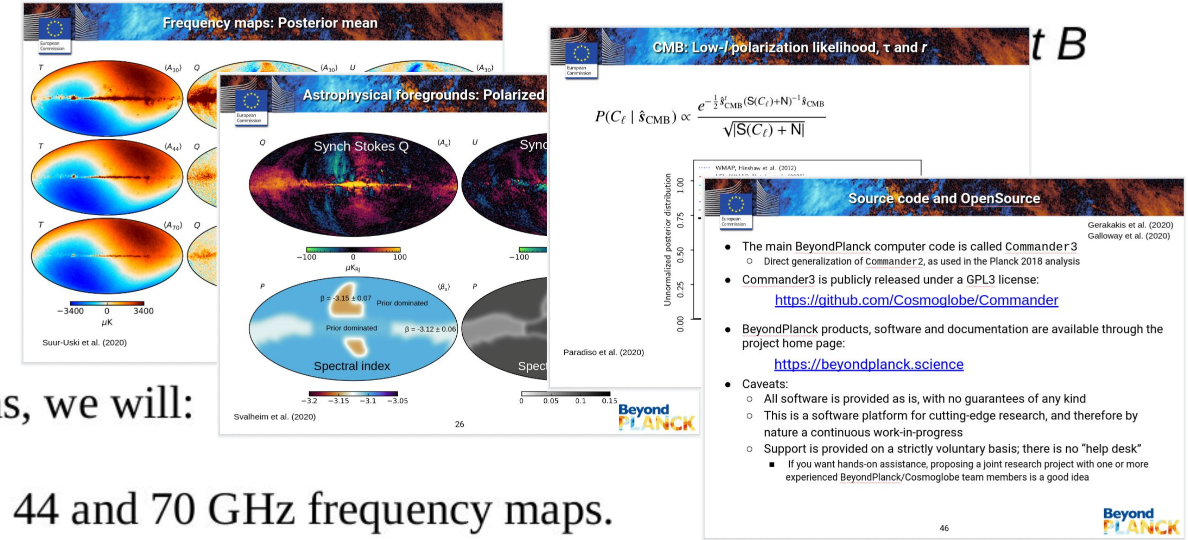
- Important advantages of this framework include:
    - Joint instrument and foreground modelling ⇒ more robust results
    - End-to-end error propagation ⇒ reliable uncertainties
    - Physically motivated models ⇒ intuitive interpretation
    - Multi-experiment analysis ⇒ naturally breaking degeneracies
    - Multi-level goodness-of-fit tests ⇒ detailed systematics monitoring
    - No intermediate human interaction ⇒ less room for mistakes
    - High computational efficiency ⇒ can run on inexpensive computers

- Next steps are to generalize and populate this framework with many more datasets, both public and proprietary, into Cosmoglobe

Primary BeyondPlanck goals (from proposal)

European Commission

H2020-COMPET-4-2017 ... *t B*



1. Excellence

1.1 Objectives

(...)

Thus, building on this base of observations, we will:

✓ 1. deliver new legacy Planck LFI 30, 44 and 70 GHz frequency maps.

✓ 2. deliver the world's cleanest and most sensitive full-sky estimates of polarized synchrotron emission at CMB frequencies. This new model will form a bed-rock for future CMB B-mode experiments searching for inflationary gravitational waves in the coming decade, as well as for scientists studying the structure and dynamics of the Milky Way.

✓ 3. deliver a new likelihood code suitable for large-scale CMB polarization analysis, and use this to derive a new and robust estimate of the optical depth of reionization, one of the most critical parameters in contemporary cosmology.

✓ 4. make the software necessary for time-domain analysis available to the community under an Open Science license, allowing other projects and experiments to build on and extend our work.

Beyond PLANCK

The BeyondPlanck collaboration

European Commission

EU-funded institutions

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Mathew Galloway
Daniel Herman
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Jeff Jewell

Reijo Keskitalo

Bruce Partridge

Martin Reinecke

Beyond PLANCK

The BeyondPlanck collaboration

European Commission

10 postdocs
10 PhD students

EU-funded institutions

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European Commission

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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

Beyond PLANCK