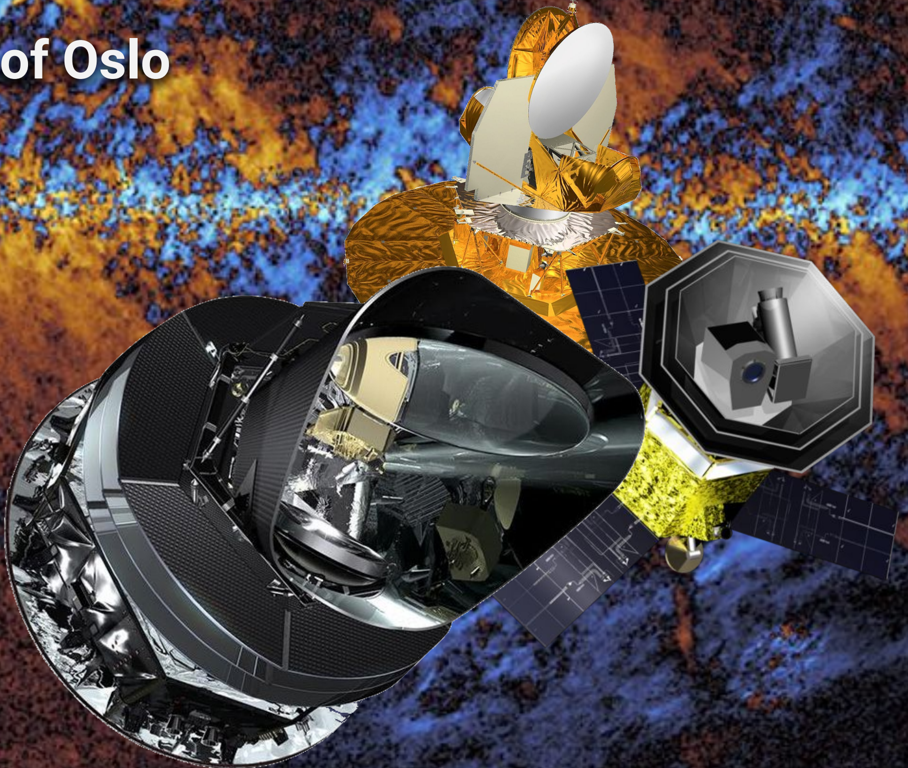
BeyondPlanck and Cosmoglobe

Mathew Galloway

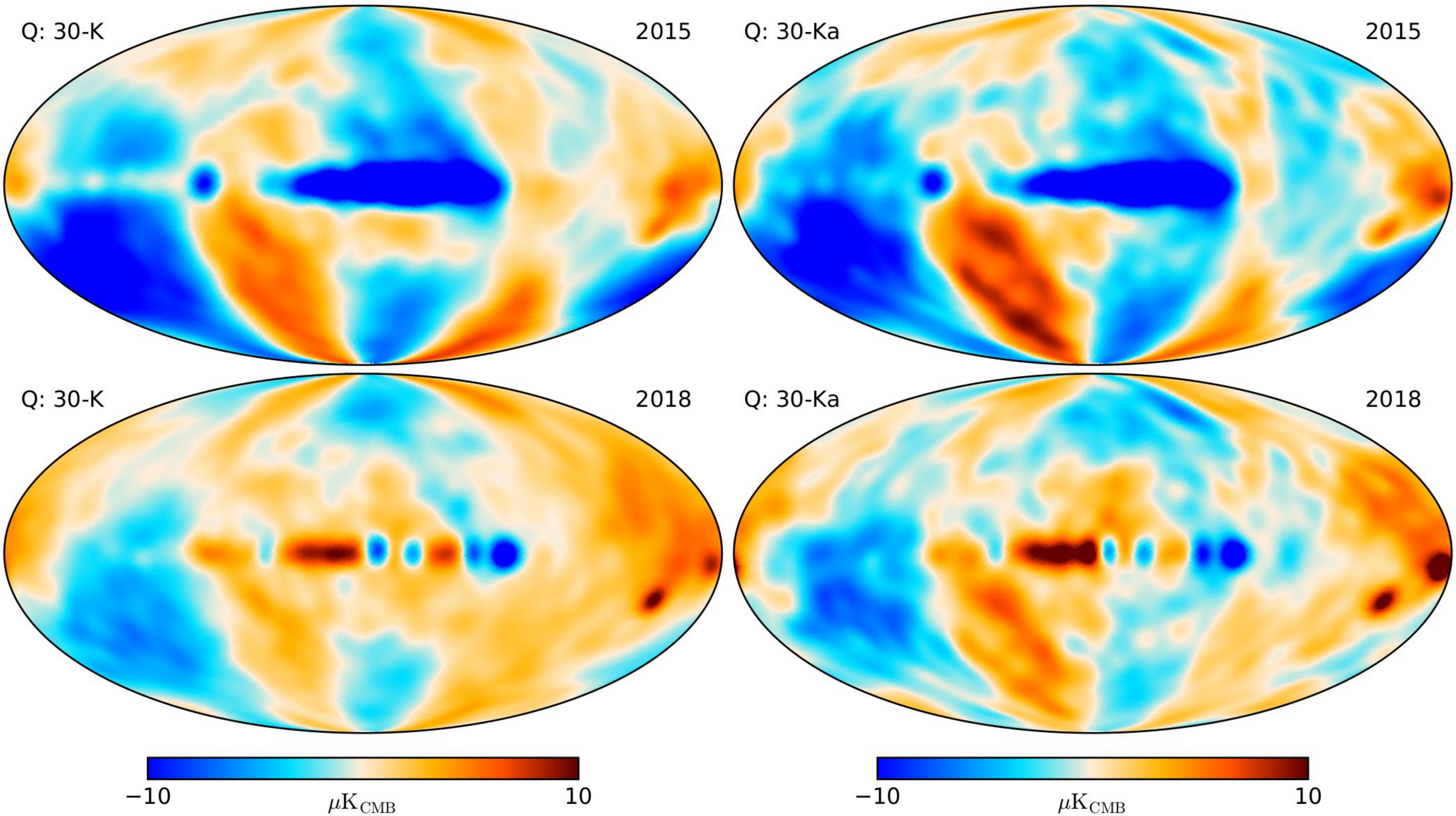
University of Oslo



From Planck to the Future of CMB, May 26, 2022

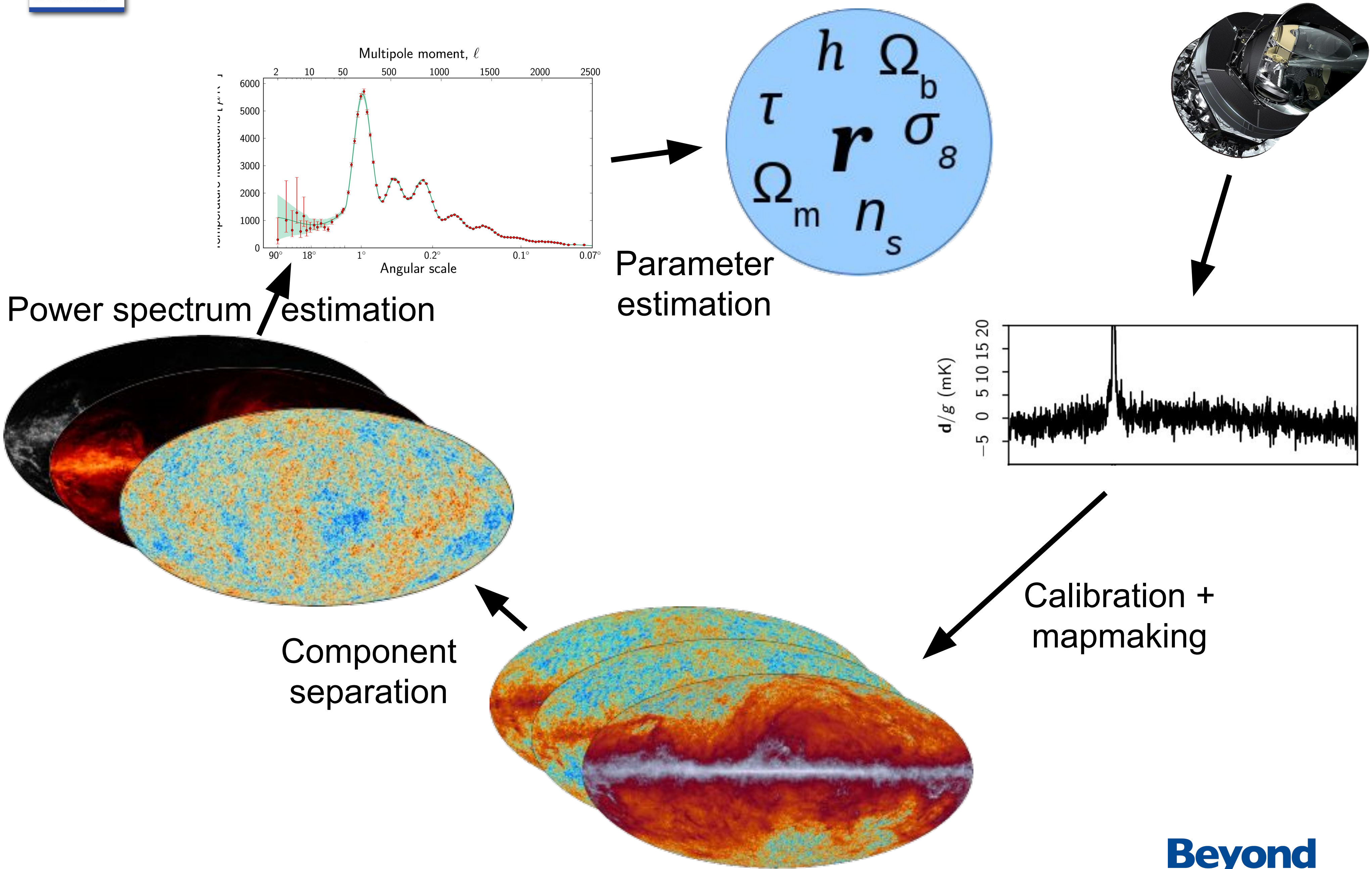
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 776282

Planck - WMAP after the Planck 2018 release

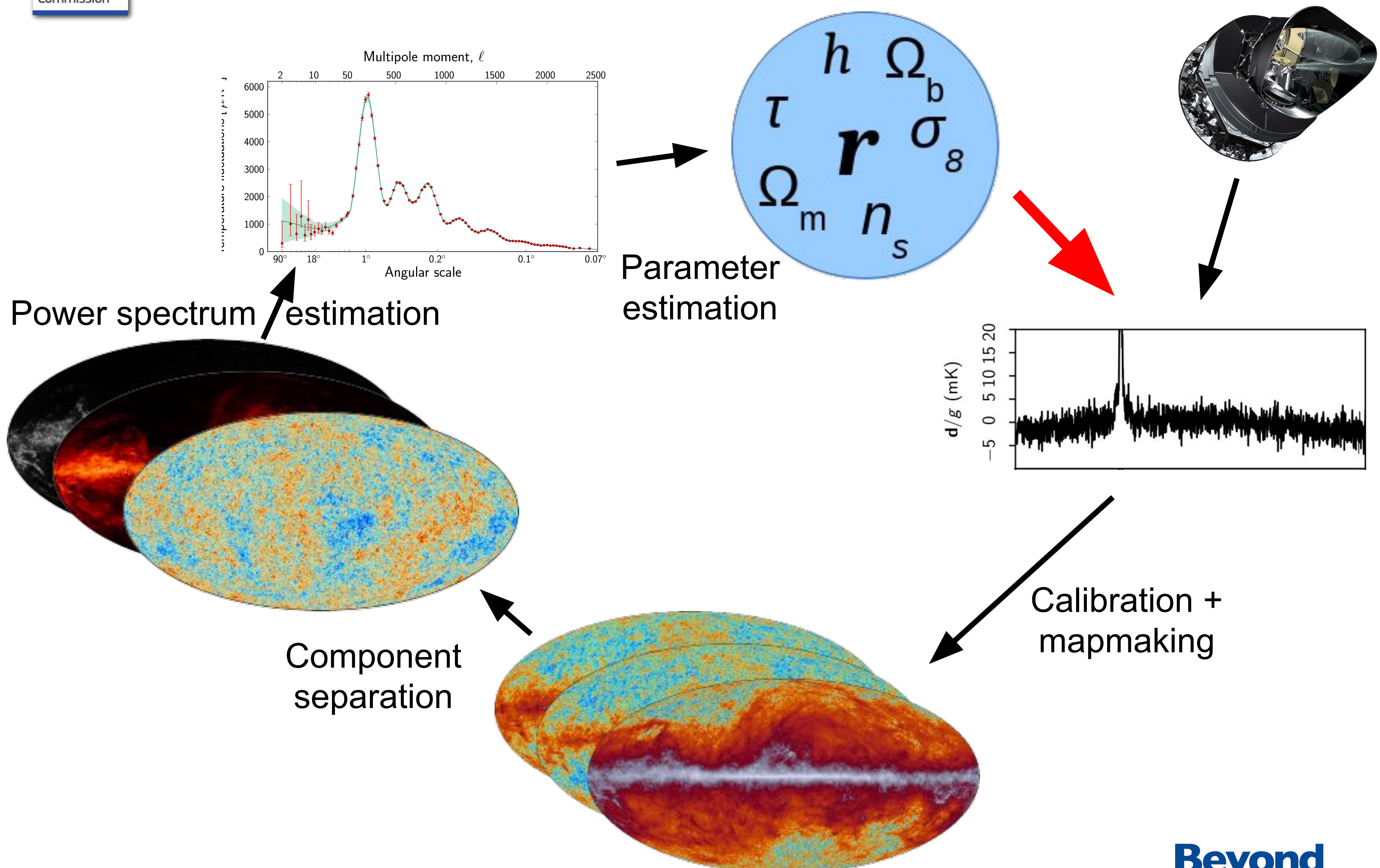


Planck (2018), A&A, 641, A2

End-to-end iterative analysis



End-to-end iterative analysis



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

- Make software and results publicly available under an OpenSource license

The BeyondPlanck collaboration

European Commission

EU-funded institutions

Kristian Joten Andersen
Ragnhild Aurlien
Ranajoy Banerji
Maksym Brilenkov
Hans Kristian Eriksen
Johannes Røsok Eskilt
Marie Kristine Foss
Unni Fuskeland
Eirik Gjerløw
Mathew Galloway
Daniel Herman
Ata Karakci
Håvard Tveit Ihle
Metin San
Trygve Leithe Svalheim
Harald Thommesen
Duncan Watts
Ingunn Kathrine Wehus

Marco Bersanelli
Loris Colombo
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Sara Bertocco
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External collaborators

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Jeff Jewell
Reijo Keskitalo
Bruce Partridge
Martin Reinecke

Beyond PLANCK

The BeyondPlanck collaboration

European Commission

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Aniello Mennella
Simone Paradiso

External collaborators

Hensley
l
kitalo
rtridge
inecke

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

BeyondPLANCK

The BeyondPlanck data model

European Commission

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

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

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

BeyondPLANCK

The BeyondPlanck data model

European Commission

Sidelobe pickup

Pointing

Bandpass

White noise

Data

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

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

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

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

Point sources

Beyond PLANCK

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

Key Differences between BeyondPlanck and DR3/DR4

European Commission

- BeyondPlanck **analyzes all frequencies simultaneously**, while Planck does it channel-by-channel; higher S/N and fewer degeneracies

- BeyondPlanck **fits all parameters jointly**, including the CMB dipole, gain and foregrounds etc.; Planck conditioned on many key parameters during low-level processing, including foreground model and CMB dipole

- BeyondPlanck **uses external data** from WMAP to constrain poorly measured CMB polarization modes; breaks key gain and foreground degeneracies

- BeyondPlanck **performs 4000 iterations** between instrument calibration and component separation, while Planck 2018 performed 4 iterations

- BeyondPlanck models **correlated noise as a free time-domain stochastic parameter**; allows for the first time correlated noise error propagation at all angular scales without the need of an expensive dense covariance matrix

Beyond PLANCK

Key Differences between BeyondPlanck and DR3/DR4

- BeyondPlanck **smooths the gain with an optimal Wiener filter**, while Planck LFI used a boxcar average; significantly reduces striping, in particular at 44 GHz
- BeyondPlanck **allows time-variable correlated noise parameters**, while Planck assumed constant parameters throughout the mission
- BeyondPlanck **uses a 1/f + log-normal correlated noise model at 30+44 GHz**, while Planck LFI used only a 1/f model; accounts for previously unknown noise excess around 0.1-1 Hz
- BeyondPlanck **corrects for several known bandpass issues**, including standing waves; better consistency between detector maps
- BeyondPlanck **accounts for bandpass leakage at the TOD level,** using a WMAP-style spurious map optimization algorithm
- BeyondPlanck **uses a minimal ADC correction** that only affects the critical bits; less chance of accidentally filtering out real sky signal
- …

Main product: Ensemble of full sample sets

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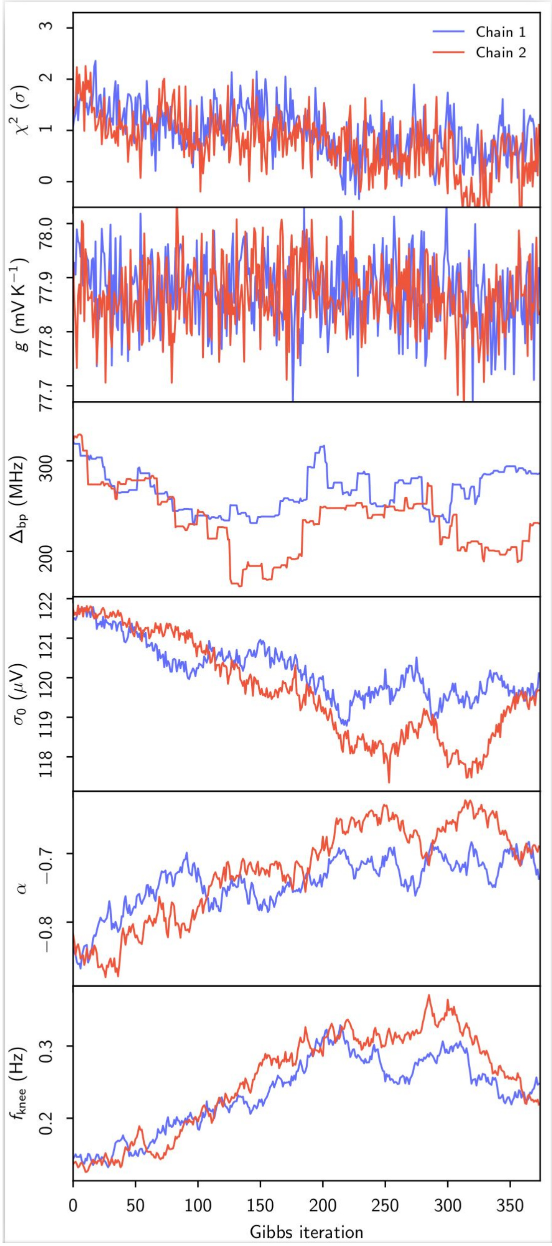
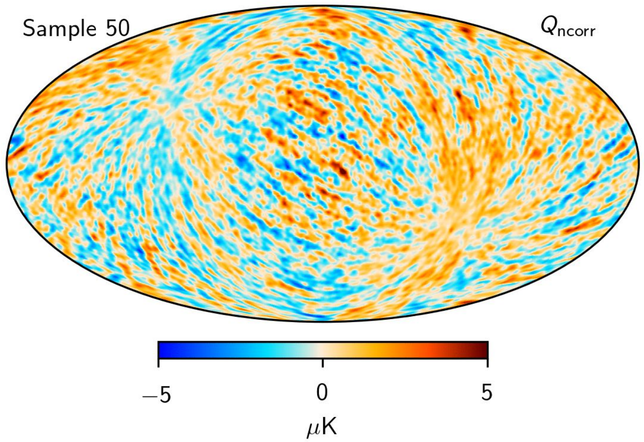
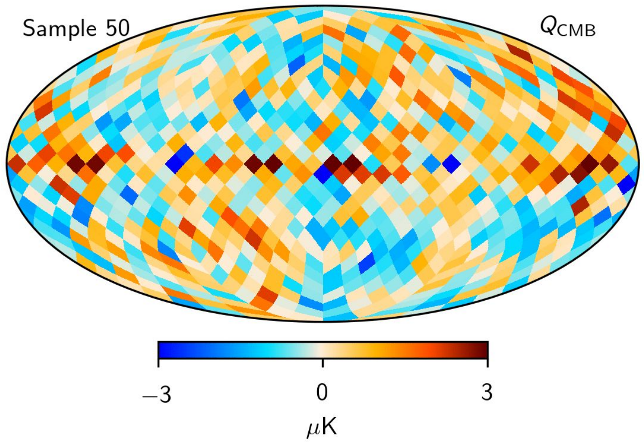
Instrument



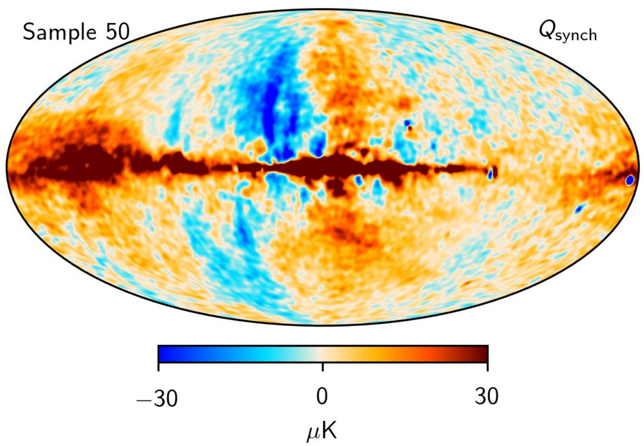
Correlated noise



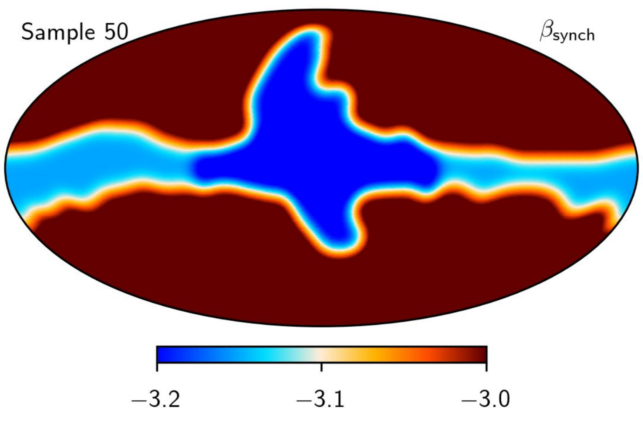
CMB Stokes Q



Synch Stokes Q



Synch pol β



...

Beyond PLANCK

Computational resource requirements

Item	30 GHz	44 GHz	70 GHz	Sum
Data volume				
Uncompressed TOD volume	761 GB	1 633 GB	5 522 GB	7 915 GB
Compressed TOD volume	86 GB	178 GB	597 GB	861 GB
Non-TOD-related RAM usage				659 GB
Total RAM requirements				**1 520 GB**
Processing time (cost per run)				
TOD initialization/IO time	3.8 h	4.3 h	12.5 h	20.6 h
Other initialization				43.4 h
Total initialization				**64.0 h**
Gibbs sampling steps (cost per sample)				
Huffman decompression	1.1 h	1.8 h	7.1 h	10.0 h
TOD projection (P operation)	0.3 h	0.7 h	3.1 h	4.1 h
Sidelobe evaluation (s_{sl})	1.1 h	2.1 h	6.5 h	9.7 h
Orbital dipole (s_{orb})	0.5 h	1.1 h	4.6 h	6.2 h
Gain sampling (g)	0.6 h	0.7 h	4.7 h	6.0 h
1 Hz spike sampling (s_{1hz})	0.2 h	0.3 h	1.9 h	2.4 h
Correlated noise sampling (n_{corr})	1.7 h	3.6 h	24.8 h	30.1 h
Correlated noise PSD sampling (ξ_n)	3.3 h	4.0 h	1.1 h	8.4 h
TOD binning (P^t operation)	0.2 h	0.5 h	4.1 h	4.8 h
Sum of other TOD processing	1.3 h	2.5 h	10.9 h	14.7 h
TOD processing cost per sample	**10.4 h**	**17.4 h**	**69.1 h**	**96.9 h**
Amplitude sampling, $P(a \mid d, \omega \setminus a)$				23.9 h
Spectral index sampling, $P(\beta \mid d, \omega \setminus \beta)$				40.3 h
Other steps				0.6 h
Total cost per sample				**163.9 h**

Galloway et al. (2021)

- **Four independent Gibbs chains of 1000 samples** were generated on 2 compute nodes
- Total wall production time for main run was **15 weeks**
- Total CPU cost for main run was **600 000 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)

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TOD project				
Sidelobe eva				
Orbital dipol				
Gain sampli				
1 Hz spike s				
Correlated n				
Correlated n				
TOD binnin				
Sum of othe				
TOD process				**h**
Amplitude sampling, $P(\boldsymbol{a} \mid \boldsymbol{d}, \omega \setminus \boldsymbol{a})$				23.9 h
Spectral index sampling, $P(\beta \mid \boldsymbol{d}, \omega \setminus \beta)$				40.3 h
Other steps				0.6 h
Total cost per sample				**163.9 h**

1.3 hours/sample

on

128-core node with 2 TB RAM

Galloway et al. (2021)

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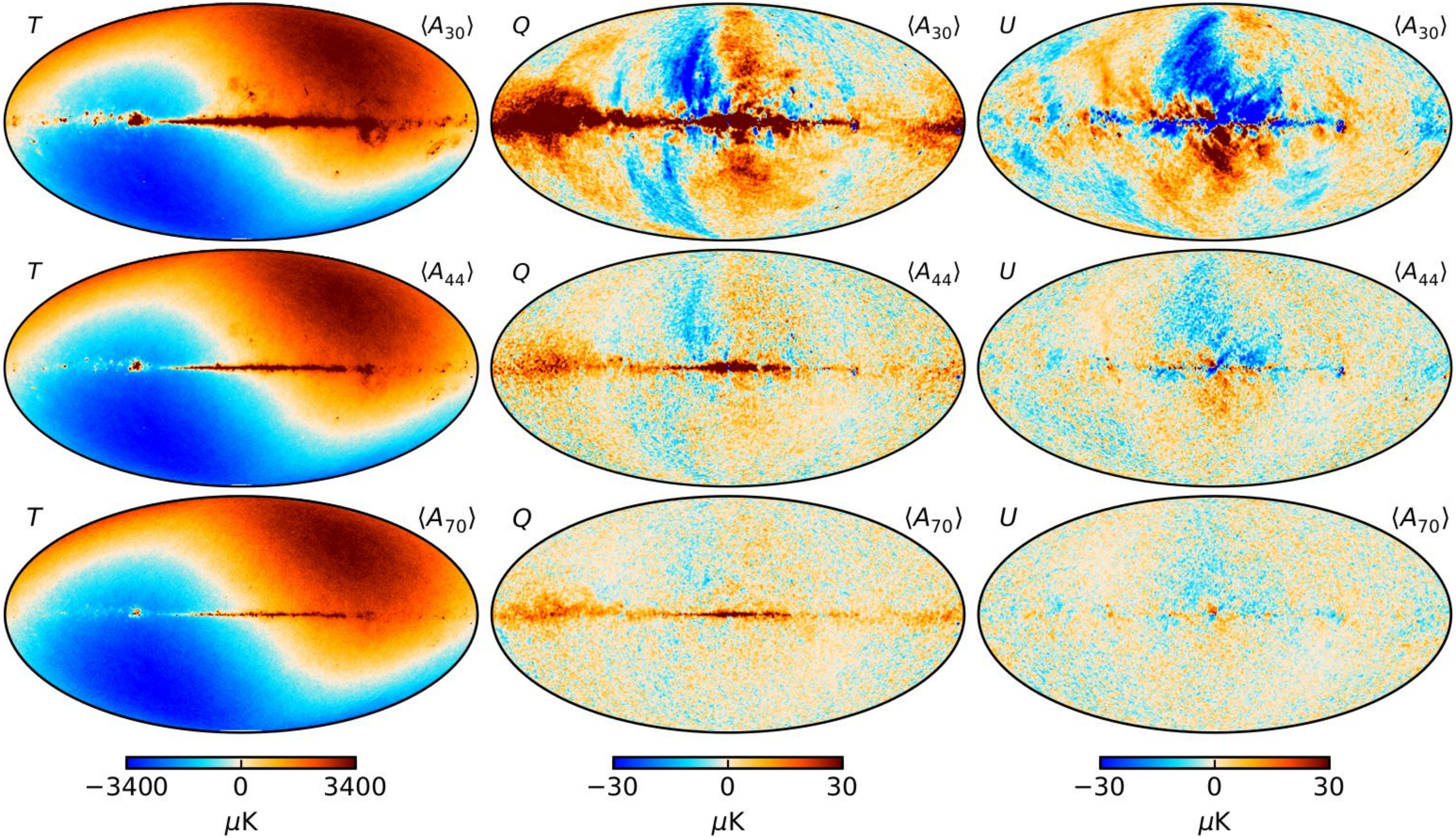
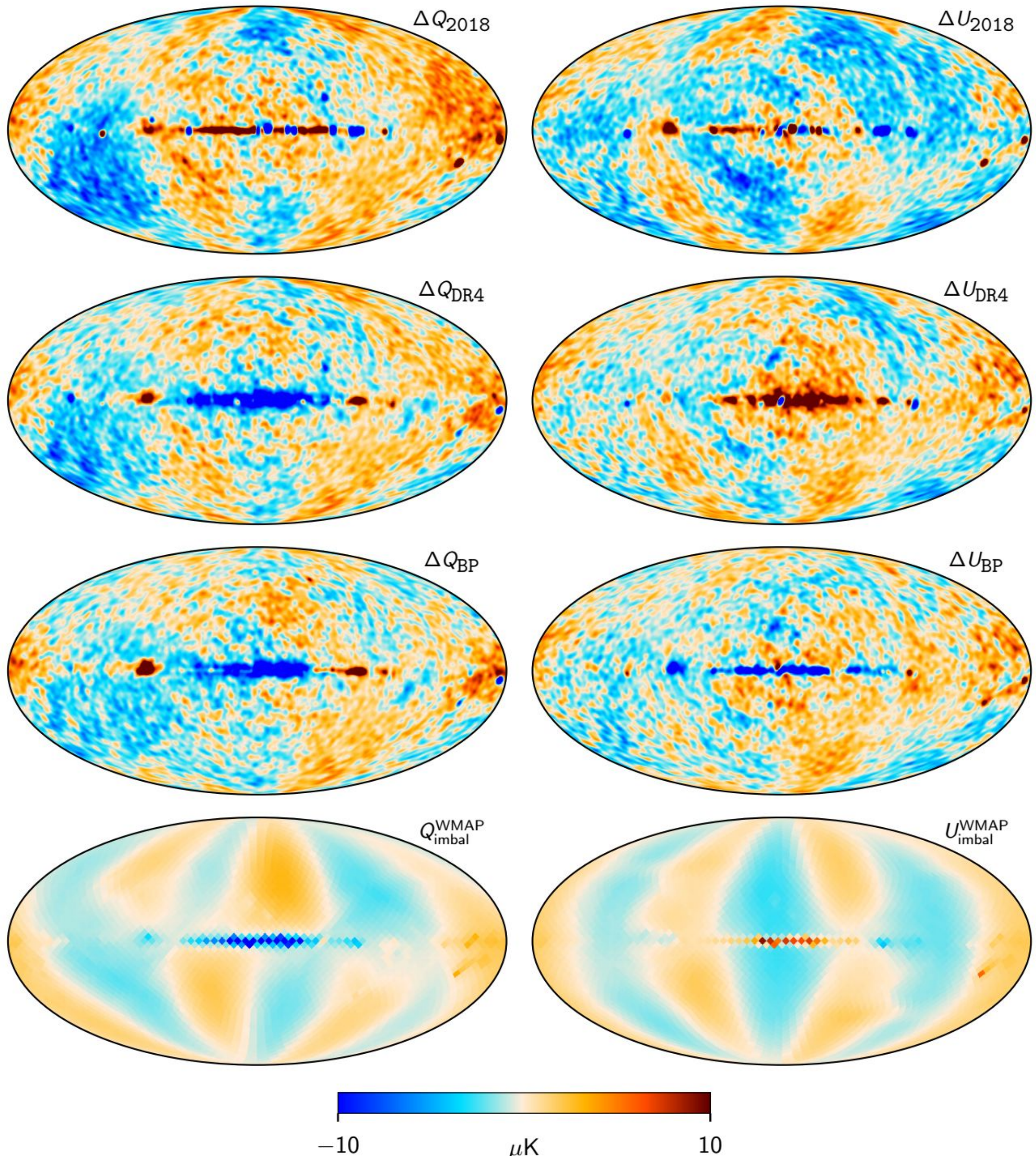
Frequency maps: Posterior mean



Suur-Uski et al. (2022)

Frequency maps: 30 GHz minus WMAP K-band



Planck 2018

NPIPE

BeyondPlanck

WMAP transmission imbalance template (Jarosik et al. 2007)

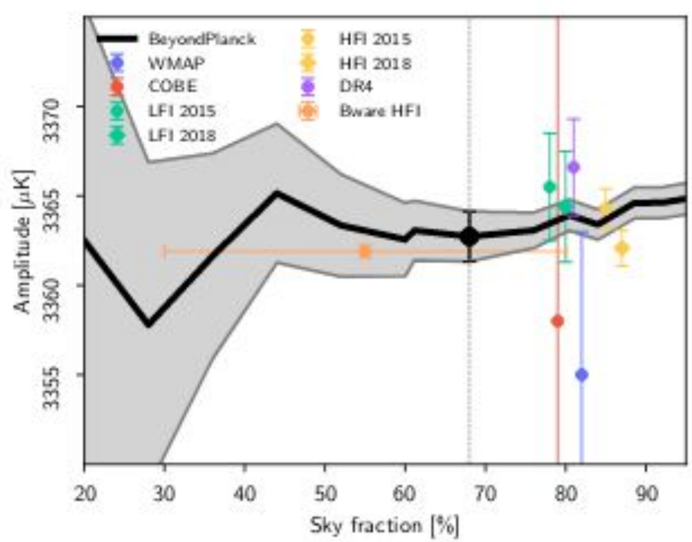
Gjerløw et al. (2022)

CMB Solar Dipole

Colombo et al. (in prep)

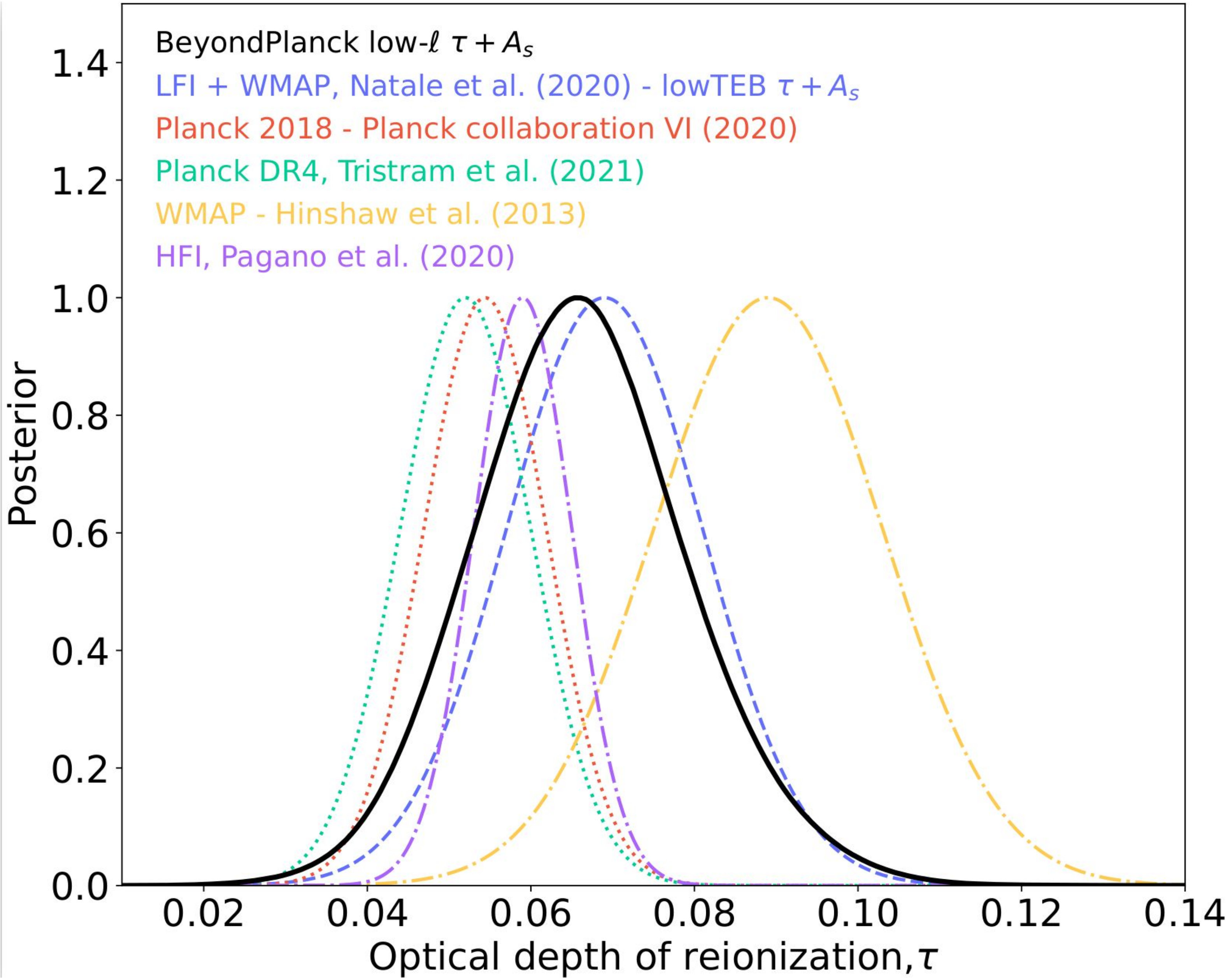
Experiment	Amplitude [μK_{CMB}]	Galactic coordinates: l [deg]	Galactic coordinates: b [deg]	Reference
COBE[a,b]	3358 ± 23	264.31 ± 0.16	48.05 ± 0.09	Lineweaver et al. (1996)
WMAP [c]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03	Hinshaw et al. (2009)
LFI 2015 [b]	3365.5 ± 3.0	264.01 ± 0.05	48.26 ± 0.02	Planck 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 Int. LVII (2020b)
BeyondPlanck [e] . .	**3362.7 ± 1.4**	**264.11 ± 0.07**	**48.279 ± 0.026**	This paper

Statistical and systematic uncertainty estimates are added in quadrature.
Computed with a naive dipole estimator that does not account for higher-order CMB fluctuations.
Computed with a Wiener-filter estimator that estimates, and marginalizes over, higher-order CMB fluctuations jointly with the dipole.
Higher-order fluctuations as estimated by subtracting a dipole-adjusted CMB-fluctuation map from frequency maps prior to dipole evaluation.
Estimated with a sky fraction of 68 %. Error bars include only statistical uncertainties, as defined by the global BeyondPlanck posterior framework, and they thus account for instrumental noise, gain fluctuations, parametric foreground variations etc.



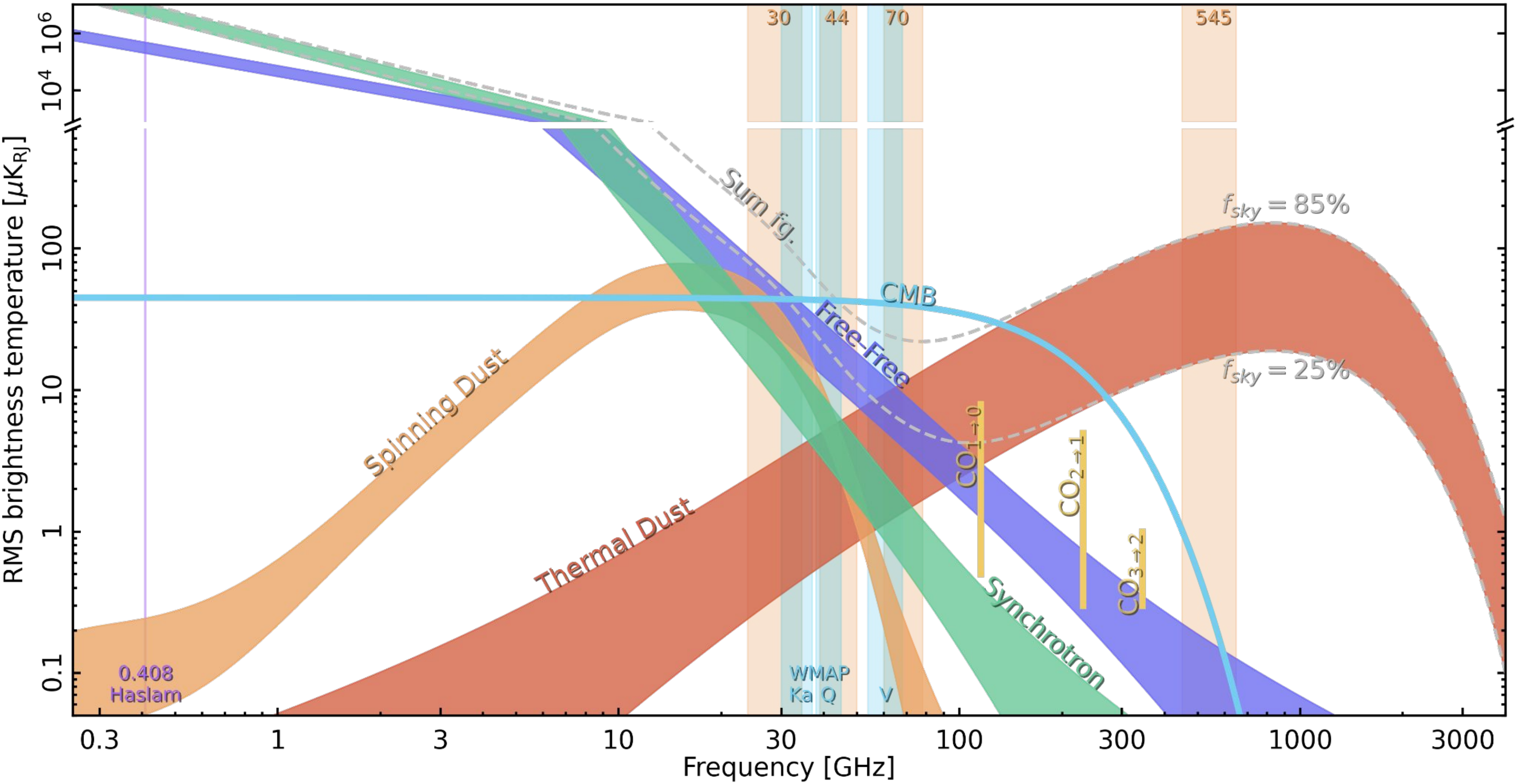
Excellent agreement between latest BeyondPlanck results and HFI 2018

Tau

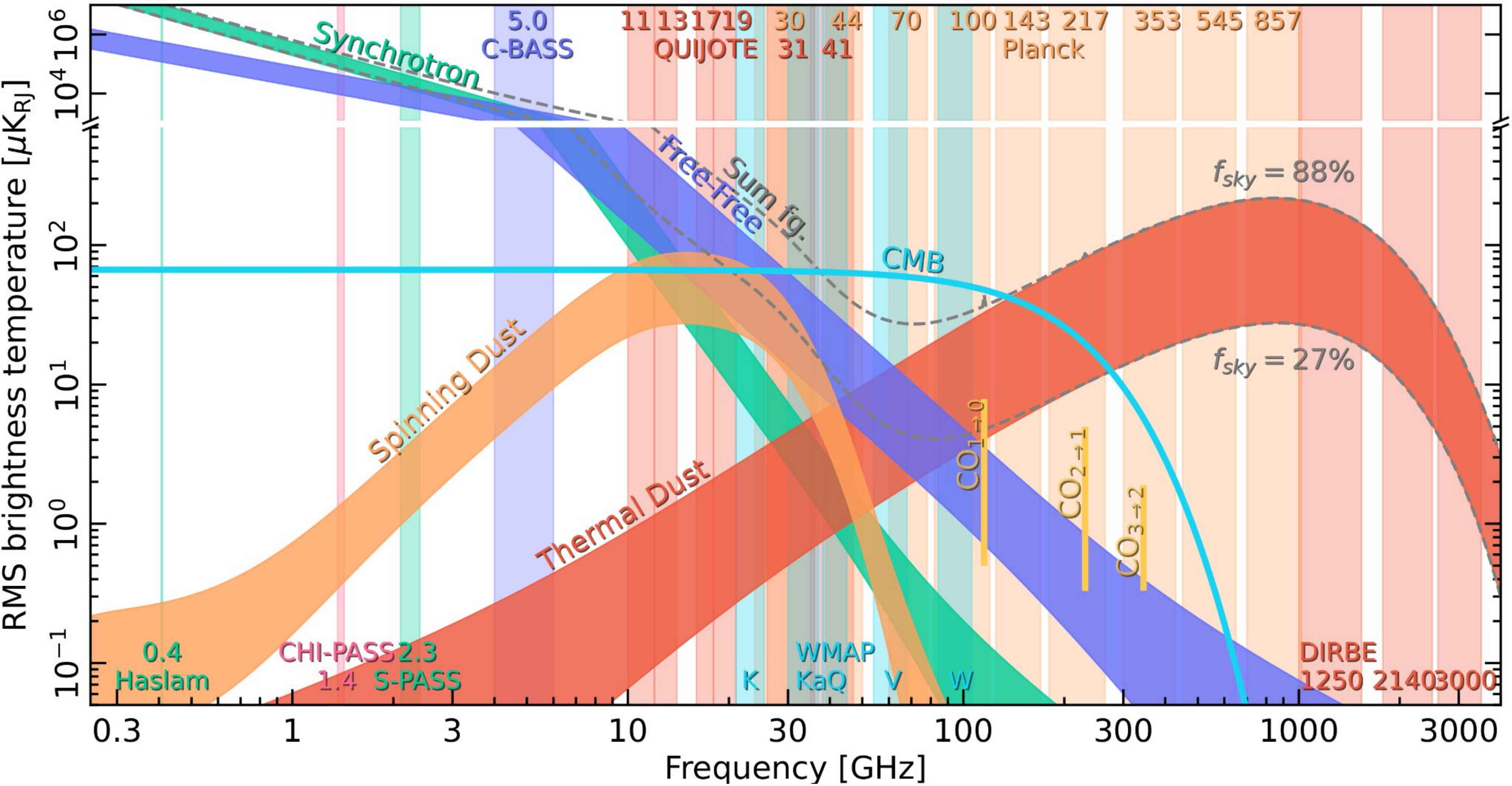


Paradiso et al. (2022)

The Present: BeyondPlanck

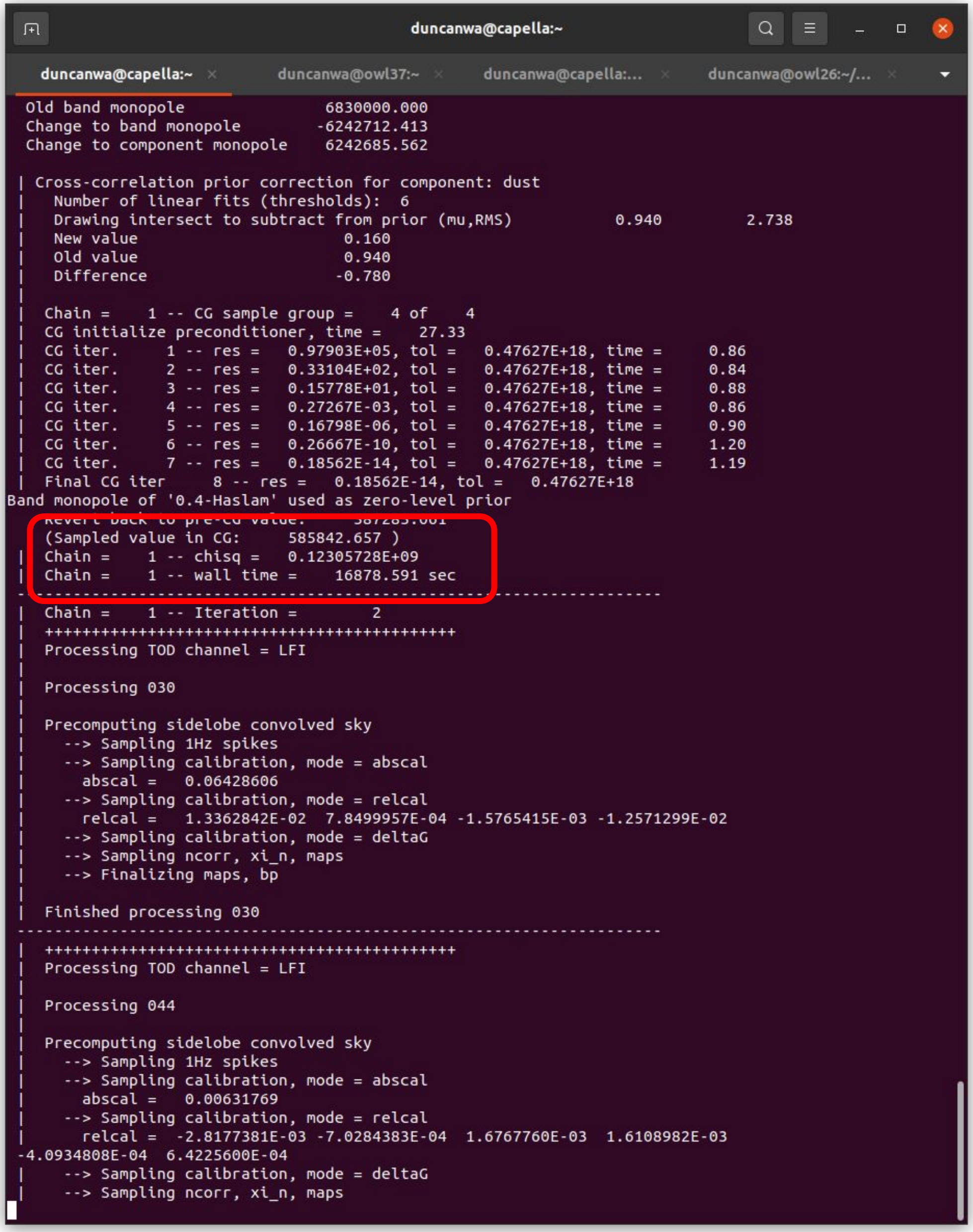


The Future: Cosmoglobe



Preliminary WMAP K+Ka+Q+V Cosmoglobe analysis

European Commission



Milestone reached on May 18th, 2022:

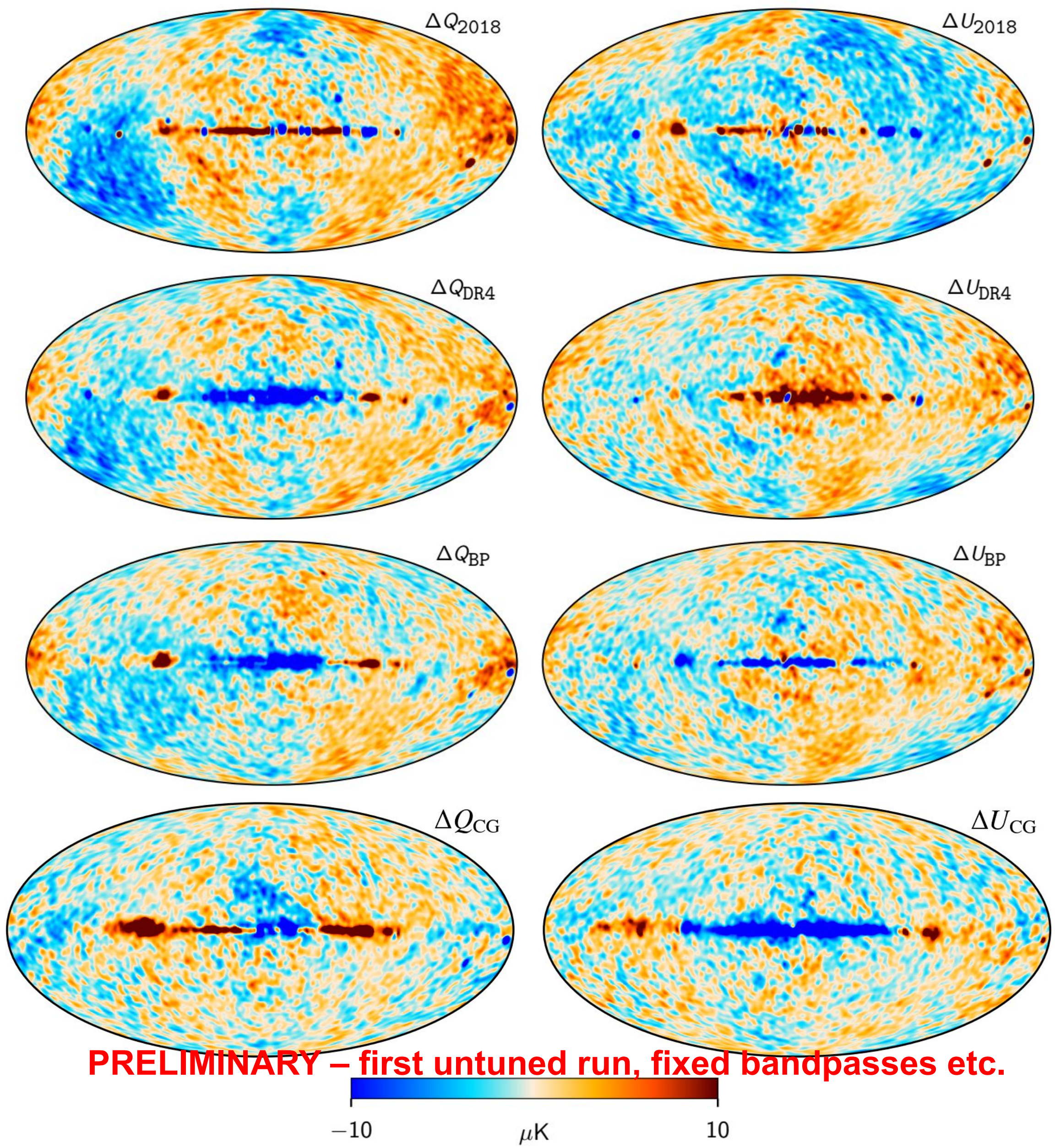
First end-to-end sample of Planck LFI and WMAP K-V successfully produced in about five hours runtime!

Beyond PLANCK

Preliminary WMAP K+Ka+Q+V Cosmoglobe analysis

LFI 30 - 0.495 x WMAP K

Lots of great stuff coming up soon. If you want to join, please contact Duncan Watts and the Cosmoglobe team :-)



Planck 2018

NPIPE

BeyondPlanck

Cosmoglobe

PRELIMINARY – first untuned run, fixed bandpasses etc.

Final BeyondPlanck Product Release available now

European Commission

https://www.cosmoglobe.uio.no/products/index.html

Products

BeyondPlanck release 2 (2022; final release)

- **Parameter files (documentation)**
  - Main Commander parameter file
  - Commander parameter file for high-resolution CMB TT resampling
  - Commander parameter file for low-resolution CMB polarization resamplin
- **Chain Files (documentation)**
  - Main chain files (1, 2, 3, 4; note: these are 1.6 TB each)
  - High-res CMB T resamp chain files (1, 2, 3, 4)
  - Low-res CMB P resamp chain files (1, 2, 3, 4)
- **Frequency Maps**
  - LFI 30 GHz frequency map
  - LFI 44 GHz frequency map
  - LFI 70 GHz frequency map
- **Astrophysical Component Maps**
  - AME (spinning dust) map
  - Thermal dust emission map
  - Free-free emission map
  - Synchrotron map
- **CMB maps**
  - CMB posterior mean temperature map
  - CMB posterior mean polarization map
  - Single constrained CMB realisation
- **Masks**
  - High-resolution CMB (T-only) analysis mask
  - Low-resolution CMB (T+P) analysis mask
- **Likelihood (coming soon)**
  - CMB likelihood (code and data)
  - CMB Temperature angular power spectrum
  - Best-fit CMB LCDM power spectrum

For the preliminary BeyondPlanck release 1 products (released in 2020), see the BeyondPlanck webpage

Astronomy & Astrophysics

Beyond*Planck*: end-to-end Bayesian analysis of *Planck* LFI

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BeyondPlanck. II. CMB map-making through Gibbs sampling

E. Keihänen, A.-S. Suur-Uski, et al. (BeyondPlanck collaboration)

Received: 01 December 2021 / Accepted: 19 March 2022

DOI: https://doi.org/10.1051/0004-6361/202142799

PDF (6.947 MB)

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BeyondPlanck X. Bandpass and beam leakage corrections

T. L. Svalheim, K. J. Andersen, R. Aurlien, R. Banerji, M. Bersanelli, S. Bertocco, M. Brilenkov, M. Carbone, L. P. L. Colombo, H. K. Eriksen, M. K. Foss, C. Franceschet, U. Fuskeland, S. Galeotta, M. Galloway, S. Gerakakis, E. Gjerlow, B. Hensley, et al.

Received: 10 January 2022 / Accepted: 25 February 2022

DOI: https://doi.org/10.1051/0004-6361/202243080

PDF (15.86 MB)

Free Access

BeyondPlanck. XVI. Limits on large-scale polarized anomalous mcrowave emission from Planck LFI and WMAP

D. Herman, B. Hensley, K. J. Andersen, R. Aurlien, R. Banerji, M. Bersanelli, S. Bertocco, M. Brilenkov, M. Carbone, L. P. L. Colombo, H. K. Eriksen, M. K. Foss, C. Franceschet, U. Fuskeland, S. Galeotta, M. Galloway, S. Gerakakis, et al.

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DOI: https://doi.org/10.1051/0004-6361/202243081

PDF (5.353 MB)

Free Access

BeyondPlanck. III. Commander3

M. Galloway, K. J. Andersen, R. Aurlien, R. Banerji, M. Bersanelli, S. Bertocco, M. Brilenkov, M. Carbone, L. P. L. Colombo, H. K. Eriksen, J. R. Eskilt, M. K. Foss, C. Franceschet, U. Fuskeland, S. Galeotta, S. Gerakakis, et al.

Received: 17 January 2022 / Accepted: 25 February 2022

DOI: https://doi.org/10.1051/0004-6361/202243137

PDF (1.582 MB)

Free Access

BeyondPlanck VIII. Efficient sidelobe convolution and corrections through spin harmonics

M. Galloway, M. Reinecke, K. J. Andersen, R. Aurlien, R. Banerji, M. Bersanelli, S. Bertocco, M. Brilenkov, M. Carbone, L. P. L. Colombo, H. K. Eriksen, J. R. Eskilt, M. K. Foss, C. Franceschet, U. Fuskeland, S. Galeotta, S. Gerakakis...

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DOI: https://doi.org/10.1051/0004-6361/202243138

PDF (6.029 MB)

Free Access

BeyondPlanck XV. Polarized foreground emission between 30 and 70 GHz

T. L. Svalheim, K. J. Andersen, R. Aurlien, R. Banerji, M. Bersanelli, S. Bertocco, M. Brilenkov, M. Carbone, L. P. L. Colombo, et al.

Received: 19 January 2022 / Accepted: 21 February 2022

DOI: https://doi.org/10.1051/0004-6361/202243160

PDF (24.05 MB)

… more coming soon!

Code: https://github.com/Cosmoglobe/Commander

Beyond PLANCK

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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

Thanks for Listening!

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