Cosmoglobe

Cosmoglobe Data Release 1:
Better *WMAP* data through joint processing

Duncan J. Watts

University of Oslo

Rencontres du Vietnam

Cosmoglobe

- Main idea: **To integrate the world's best data from radio to sub-mm wavelengths into a single model through global analysis**

- Use this to derive transformational science, from detecting primordial gravitational waves to mapping out cosmic structure formation

- Builds on well-established and flexible Bayesian parameter estimation techniques as developed by Planck and BeyondPlanck, and implemented in Commander

European Commission

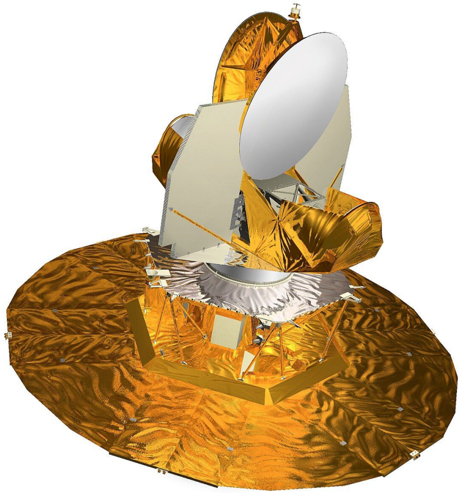
Main data sets: WMAP and Planck

WMAP

- *K*, *Ka*, *Q*, *V*, and *W*-bands (23, 33, 41, 61, 94 GHz)
- ~50 – 13 arcmin resolution

Planck

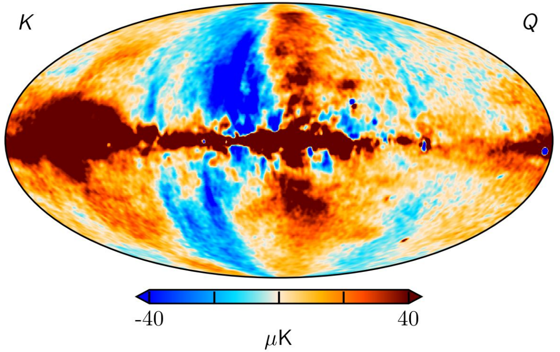
- LFI: 30, 44, 70 GHz
  HFI: 100, 143, 217, 353, 545, 857 GHz
- ~30 – 5 arcmin resolution



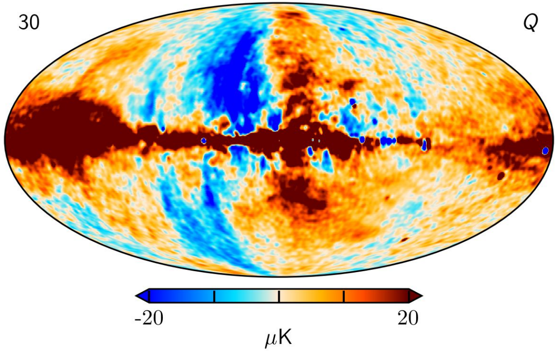
European Commission

Are WMAP and Planck actually consistent?

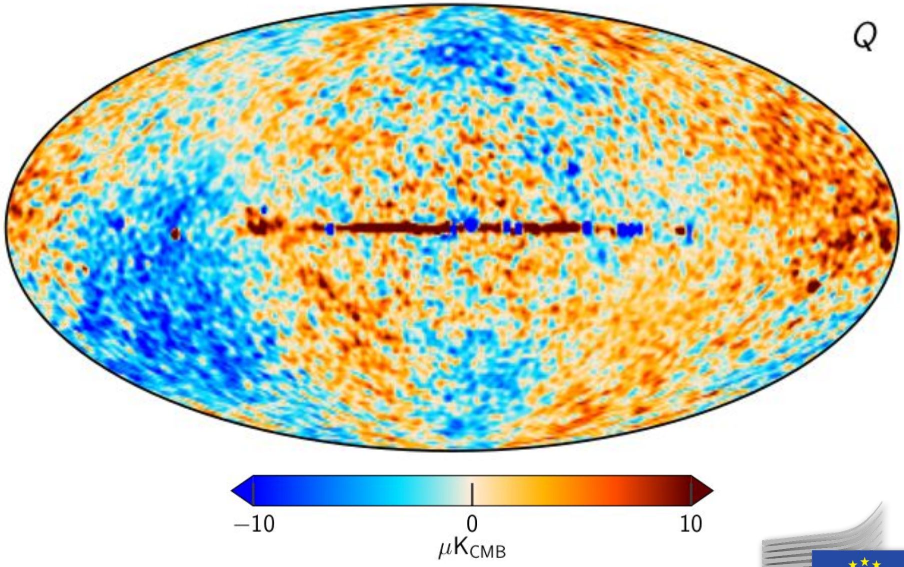
WMAP K-band



Planck 30 GHz



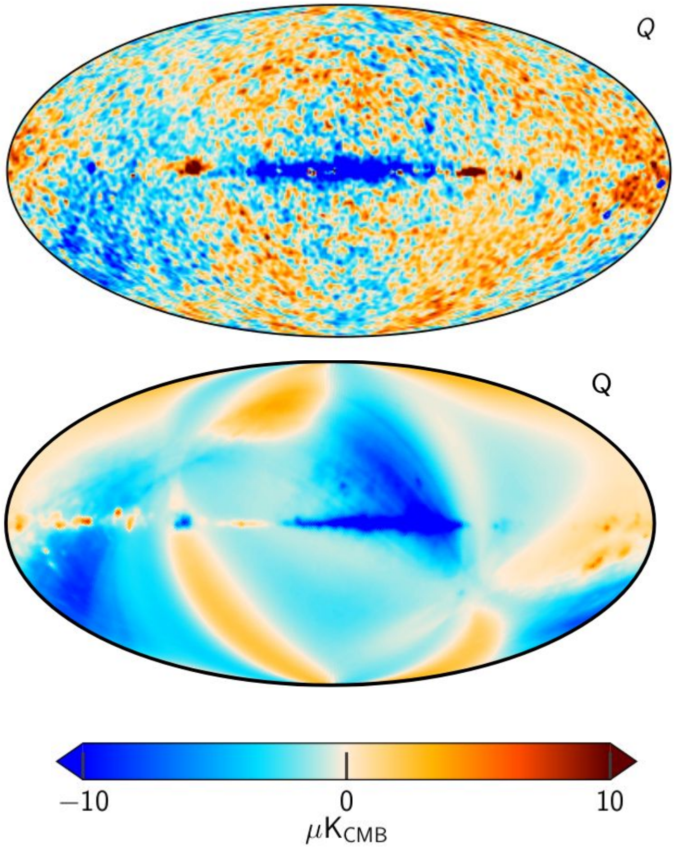
Planck 30 GHz - WMAP K-band



Reason 1: Planck LFI gain uncertainties

Planck 30 - WMAP K-band

Planck team's gain uncertainty template

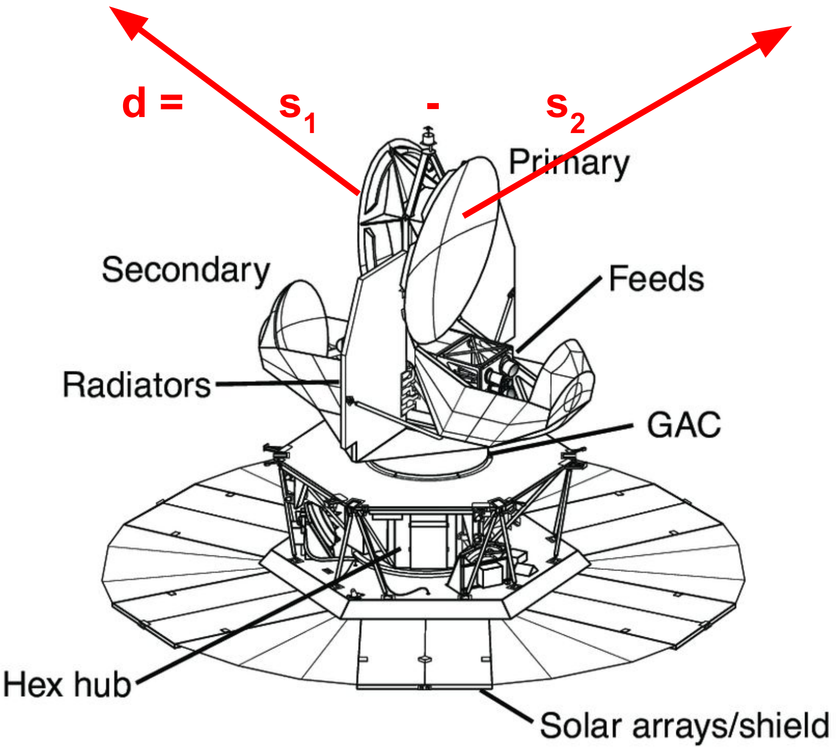


Planck (2018), A&A, 641, A2

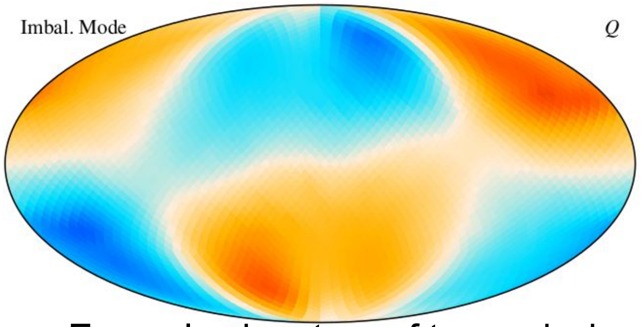
European Commission

Reason 2: WMAP transmission imbalance

$d = s_1 - s_2$

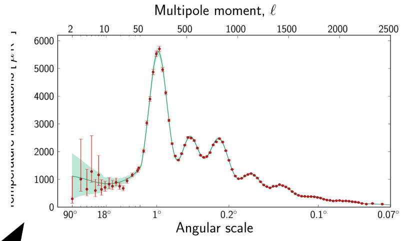


Transmission imbalance
=
Different gain in s_1 and s_2

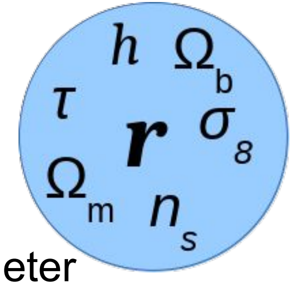


Example signature of transmission imbalance misestimation

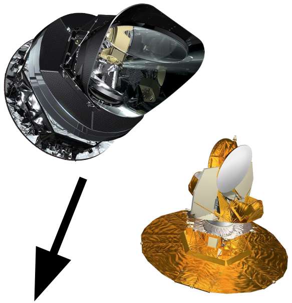
Solution: Joint end-to-end iterative analysis

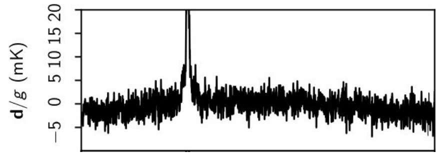


Power spectrum estimation

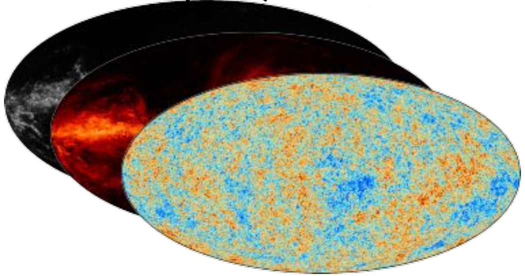


Parameter estimation

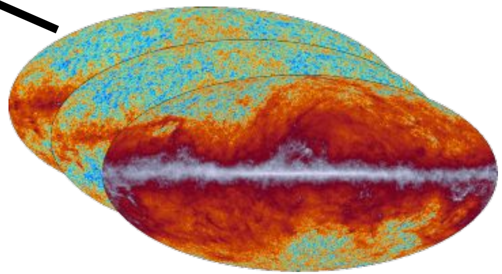




Calibration + mapmaking



Component separation



The Commander pipeline in one slide

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

$$d_{j,t} = g_{j,t} \mathsf{P}_{tp,j} \left[\mathsf{B}_j^{\mathrm{mb}} s_j^{\mathrm{sky}} + \mathsf{B}_j^{\mathrm{fsl}} s_j^{\mathrm{sky}} + \mathsf{B}_j^{4\pi} s_j^{\mathrm{orb}} \right] + n_{j,t}^{\mathrm{corr}} + n_{j,t}^{\mathrm{w}}$$

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

European Commission

March 14 2023: Cosmoglobe Data Release 1

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 14 Mar 2023]

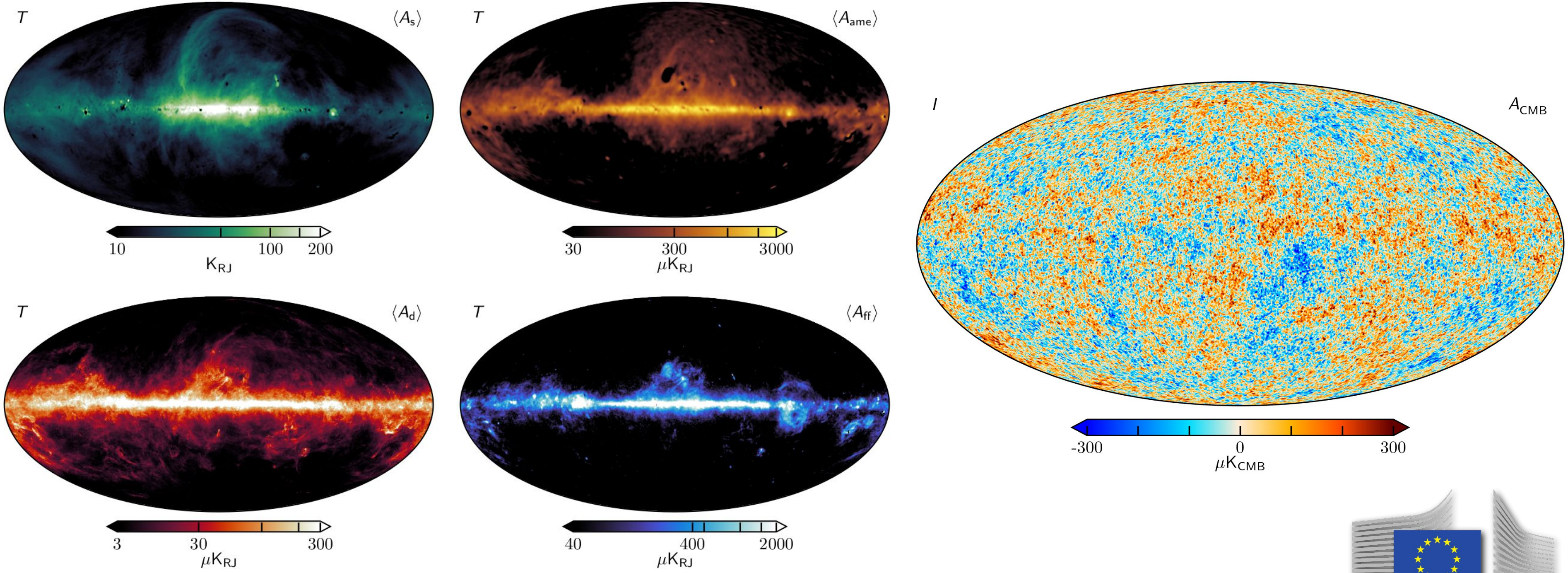
Cosmoglobe DR1 results. I. Improved Wilkinson Microwave Anisotropy Probe maps through Bayesian end-to-end analysis

D. J. Watts, A. Basyrov, J. R. Eskilt, M. Galloway, L. T. Hergt, D. Herman, H. T. Ihle, S. Paradiso, F. Rahman, H. Thommesen, R. Aurlien, M. Bersanelli, L. A. Bianchi, M. Brilenkov, L. P. L. Colombo, H. K. Eriksen, C. Franceschet, U. Fuskeland, E. Gjerløw, B. Hensley, G. A. Hoerning, K. Lee, J. G. S. Lunde, A. Marins, S. K. Nerval, S. K. Patel, M. Regnier, M. San, S. Sanyal, N.-O. Stutzer, A. Verma, I. K. Wehus, Y. Zhou

We present Cosmoglobe Data Release 1, which implements the first joint analysis of WMAP and Planck LFI time-ordered data, processed within a single Bayesian end-to-end framework. This framework builds directly on a similar analysis of the LFI measurements by the BeyondPlanck collaboration, and approaches the CMB analysis challenge through Gibbs sampling of a global posterior distribution, simultaneously accounting for calibration, mapmaking, and component separation. The computational cost of producing one complete WMAP+LFI Gibbs sample is 812 CPU-hr, of which 603 CPU-hrs are spent on WMAP low-level processing; this demonstrates that end-to-end Bayesian analysis of the WMAP data is computationally feasible. We find that our WMAP posterior mean temperature sky maps and CMB temperature power spectrum are largely consistent with the official WMAP9 results. Perhaps the most notable difference is that our CMB dipole amplitude is $3366.2 \pm 1.4\ \mu$K, which is $11\ \mu$K higher than the WMAP9 estimate and $2.5\ \sigma$ higher than BeyondPlanck; however, it is in perfect agreement with the HFI-dominated Planck PR4 result. In contrast, our WMAP polarization maps differ more notably from the WMAP9 results, and in general exhibit significantly lower large-scale residuals. We attribute this to a better constrained gain and transmission imbalance model. It is particularly noteworthy that the W-band polarization sky map, which was excluded from the official WMAP cosmological analysis, for the first time appears visually consistent with the V-band sky map. Similarly, the long standing discrepancy between the WMAP K-band and LFI 30 GHz maps is finally resolved, and the difference between the two maps appears consistent with instrumental noise at high Galactic latitudes. All maps and the associated code are made publicly available through the Cosmoglobe web page.

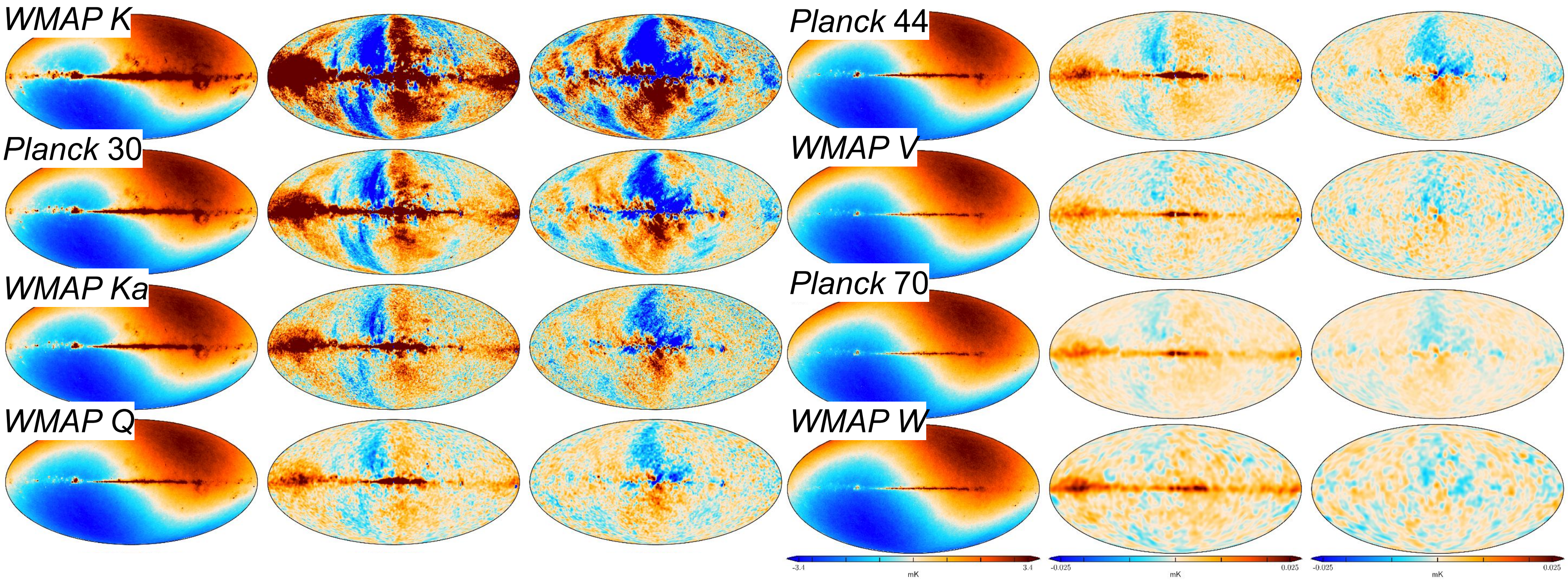
European Commission

First product: a model of the microwave sky



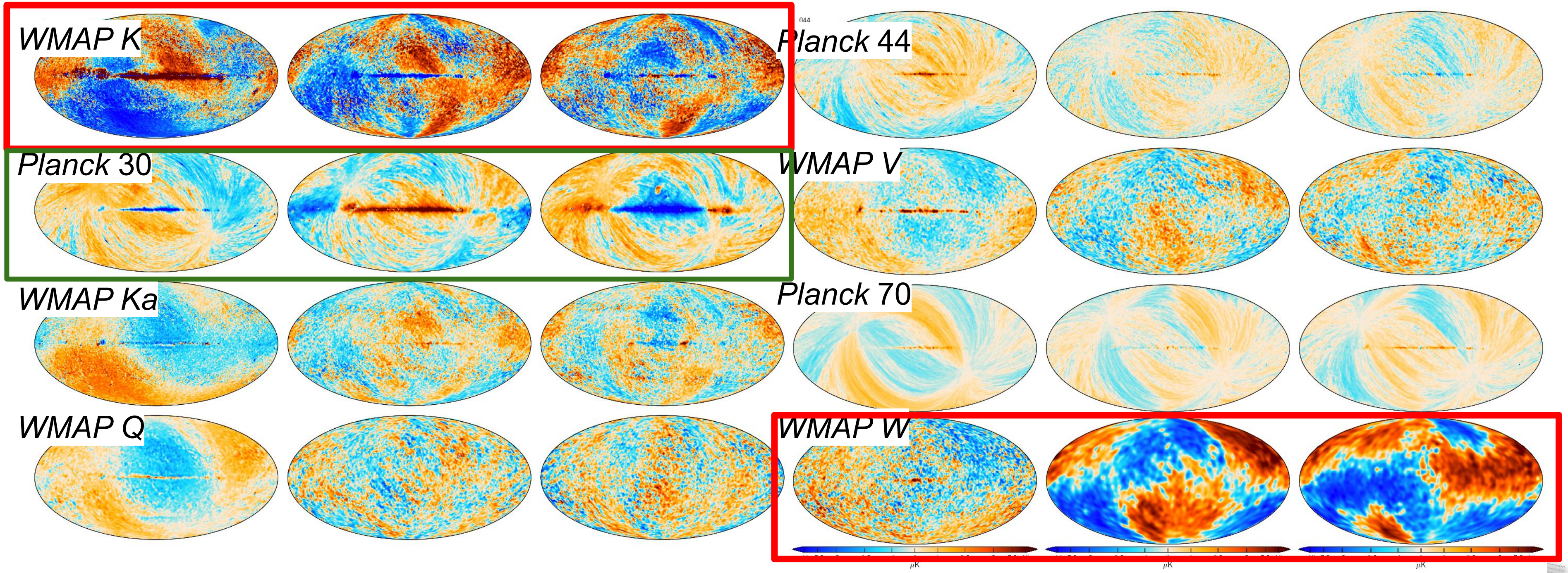
European Commission

Map product:
jointly analyzed WMAP/LFI from raw TODs



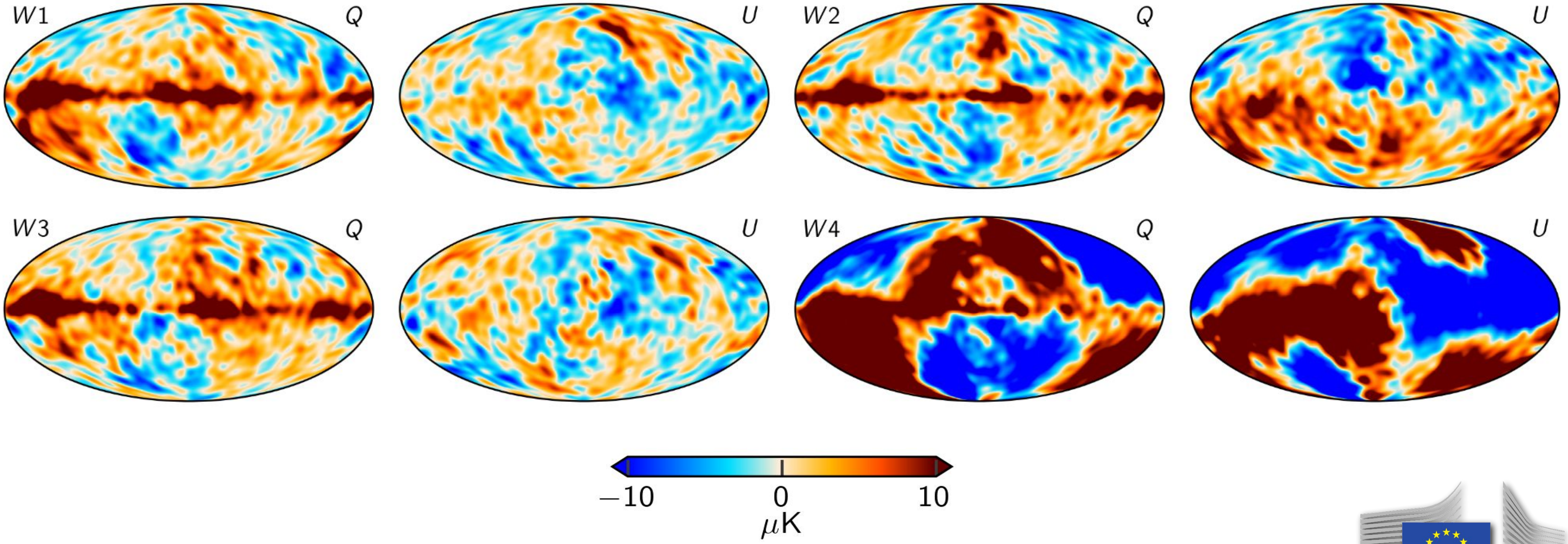
European Commission

Differences with previous state-of-the-art

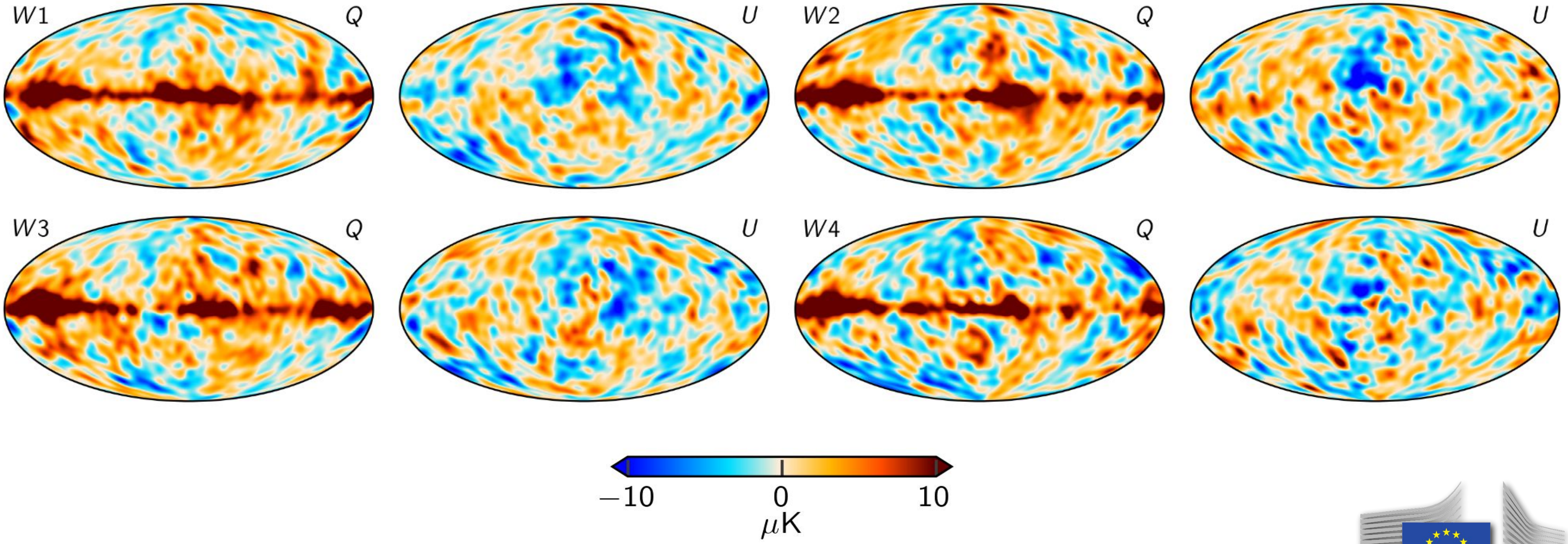


Obvious differences – but which is *better*?

9-year WMAP W-band maps

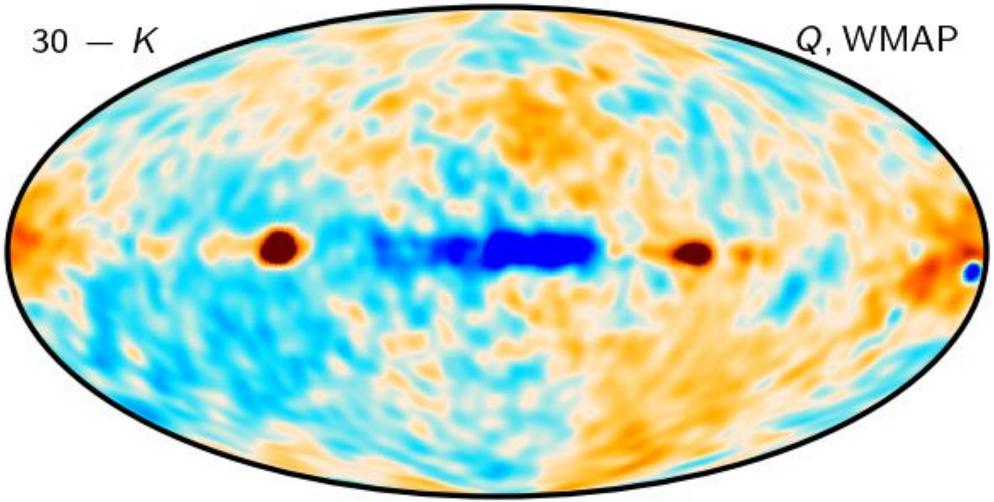


Cosmoglobe W-band sky maps



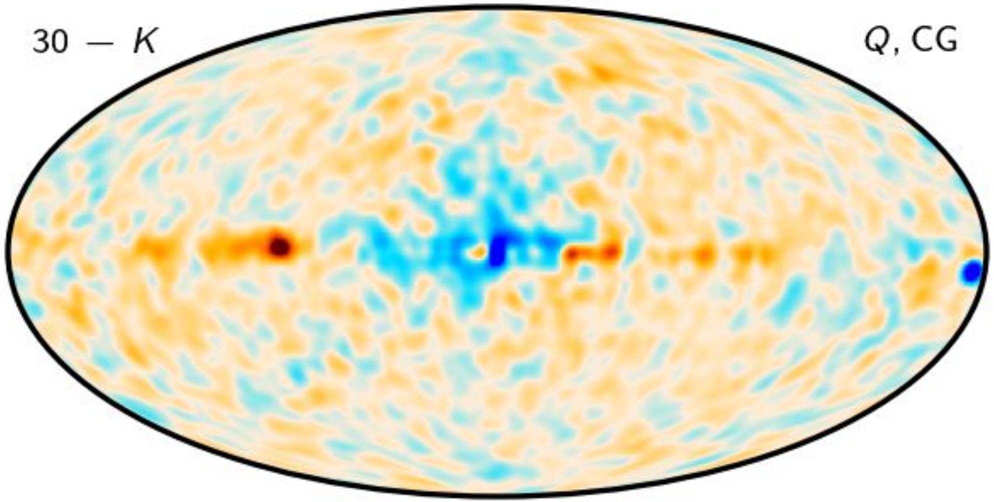
Planck 30 GHz - WMAP K revisited

Legacy maps

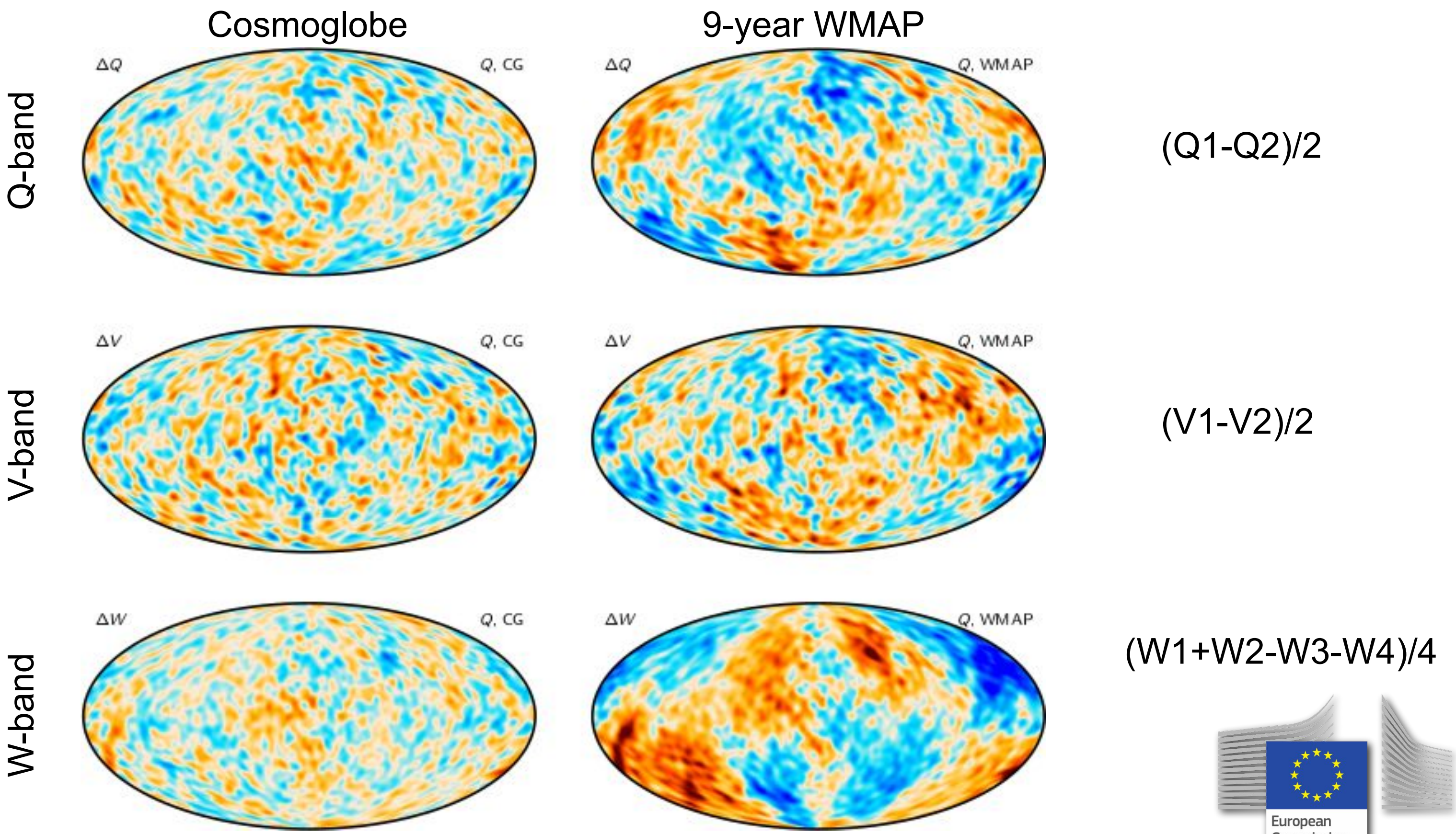


Planck 30 GHz - WMAP K revisited

Cosmoglobe

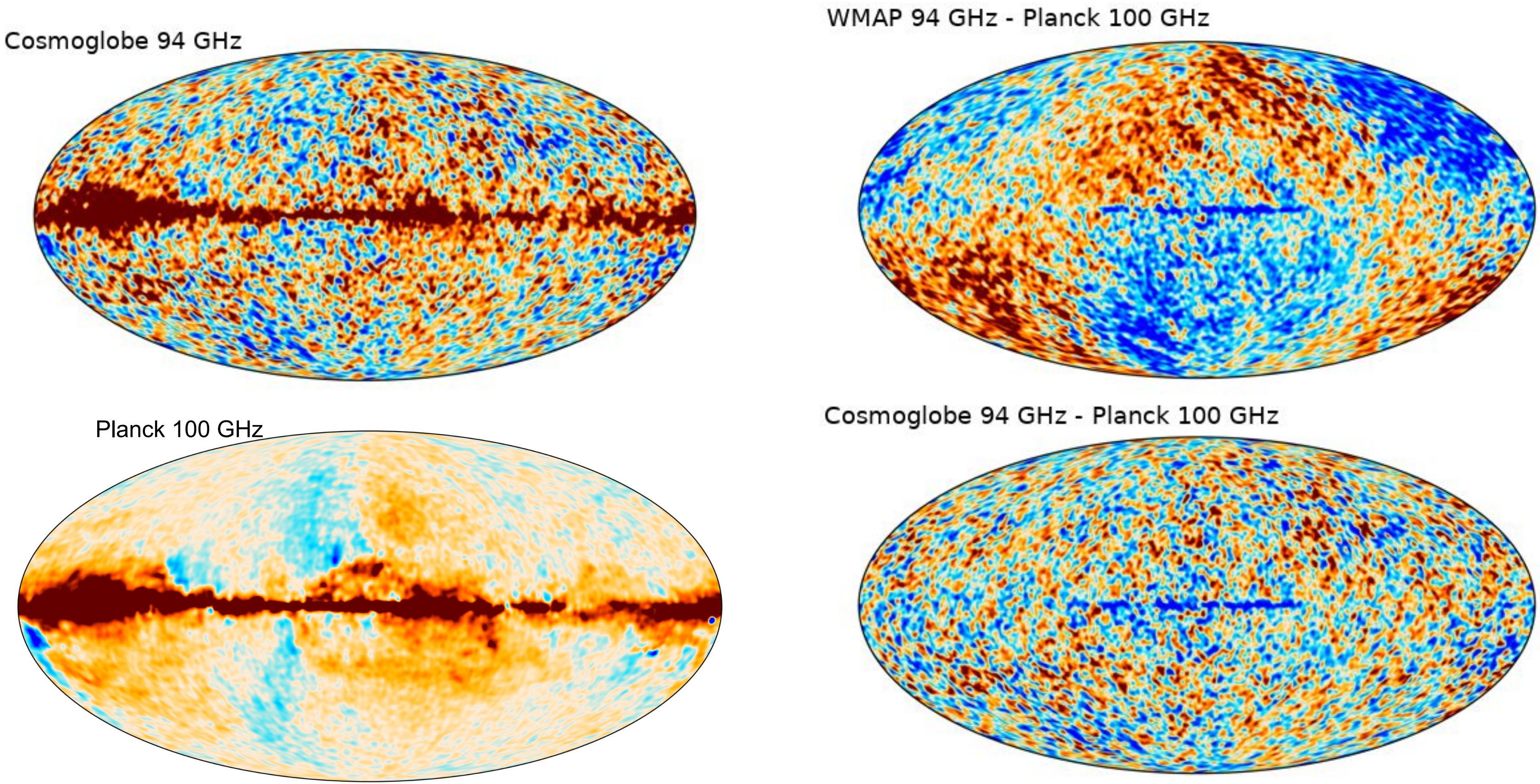


Detector half-difference maps

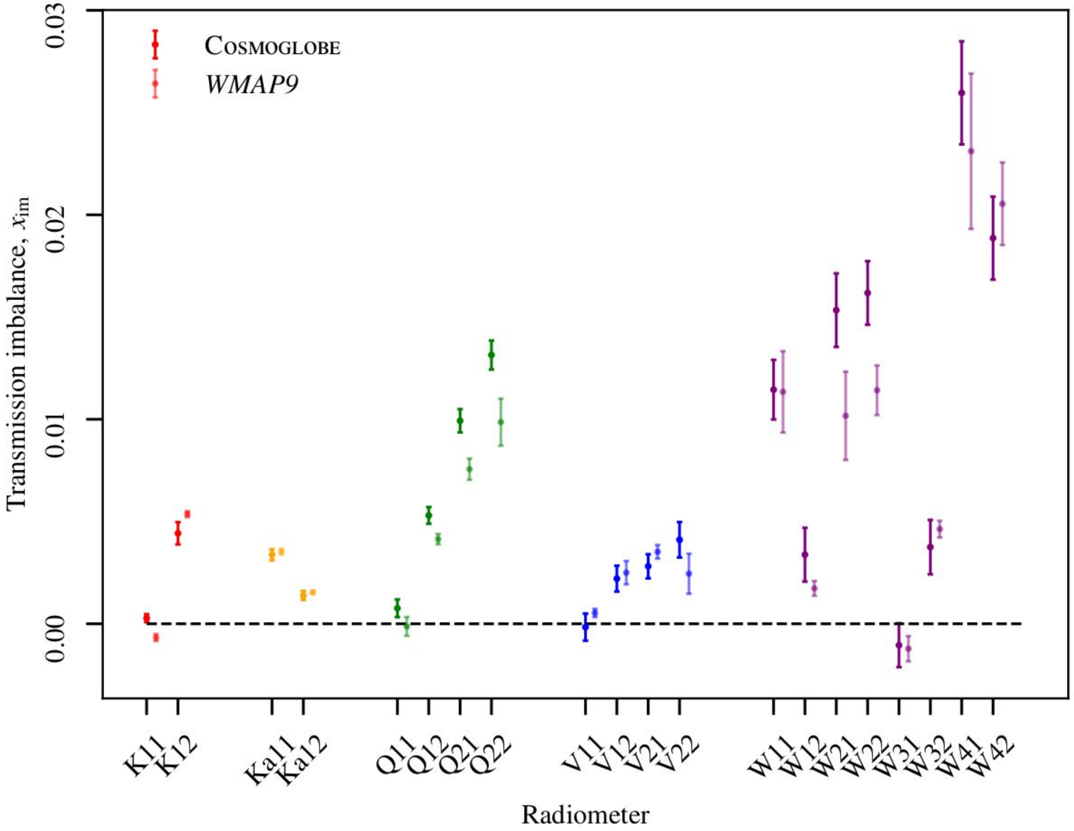


European Commission

Comparison with HFI 100 GHz



Why the improvement?



Transmission imbalance correction for each detector

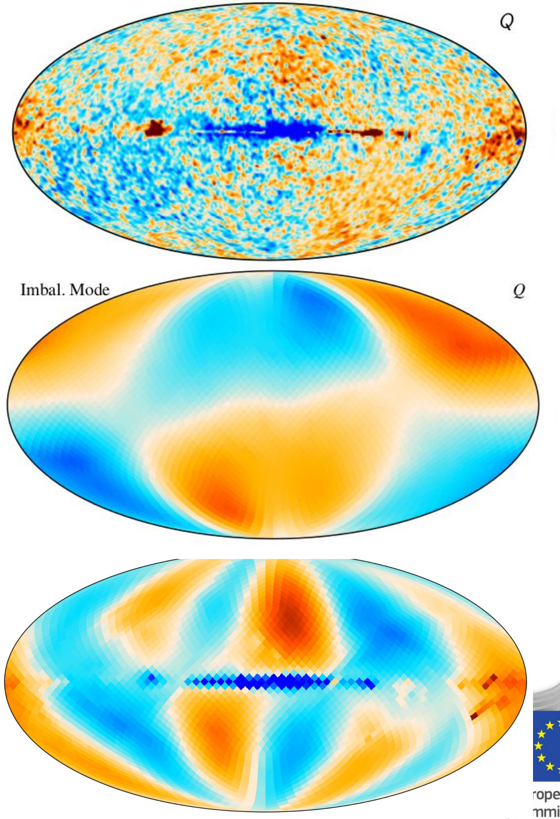
WMAP: "Transmission imbalance modes are understood and properly modelled"

E Astrophysical Journal, 863:161 (12pp), 2018 August 20 https://doi.org/10.3847/1538-4357/aad18b

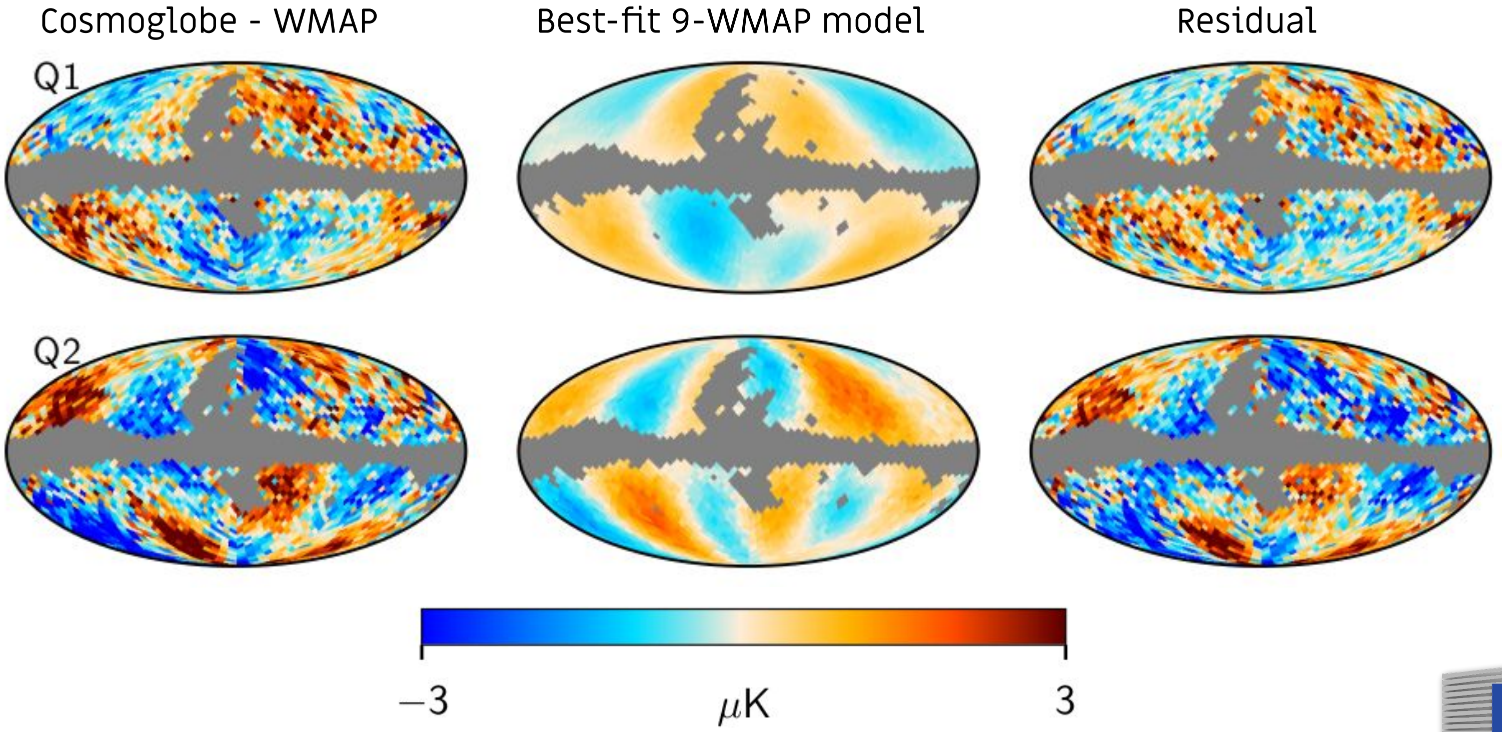
Effect of Template Uncertainties on the *WMAP* and *Planck* Measures of the Optical Depth Due to Reionization

J. L. Weiland[1], K. Osumi[1], G. E. Addison[1], C. L. Bennett[1], D. J. Watts[1], M. Halpern[2], and G. Hinshaw[2]
[1] Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD-21218, USA; jweilan2@jhu.edu
[2] Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
Received 2018 January 3; revised 2018 June 28; accepted 2018 July 3; published 2018 August 20

The attribution of the residual signature to *WMAP* poorly measured modes carries consequences only in terms of visual presentation, as it is not a true systematic residual. When constructing and viewing maps without accounting for variance, as we have in Figure 1, there can appear to be large angular scale structure because of the enhanced noise. However, within the context of a low multipole likelihood, where full covariance matrices are included, poorly measured modes are correctly weighted in the analysis (Page et al. 2007).



How much of the full effect did the WMAP transmission imbalance model capture?



How much of the full effect did the WMAP transmission imbalance model capture?

"How much of the Cosmoglobe - 9-year WMAP difference can be explained by WMAP model?"

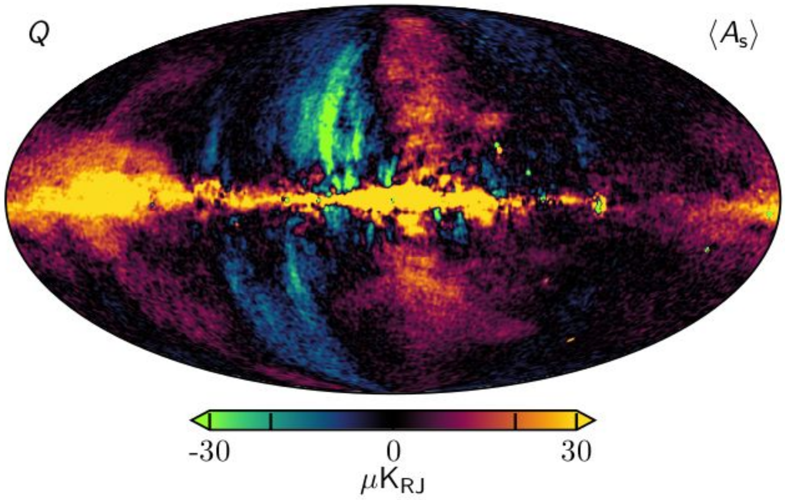
DA	a_1	a_2	$\Delta\sigma/\sigma$
$K1$	−27.5	−50.6	0.30
$Ka1$	−1.4	−1.9	0.25
$Q1$	−30.0	−71.6	0.11
$Q2$	−7.1	−1.5	0.20
$V1$	−32.8	−53.4	0.06
$V2$	8.8	−4.1	0.16
$W1$	−2.8	4.6	0.08
$W2$	−6.9	−3.5	0.11
$W3$	29.1	53.4	0.12
$W4$	15.5	−6.8	0.52

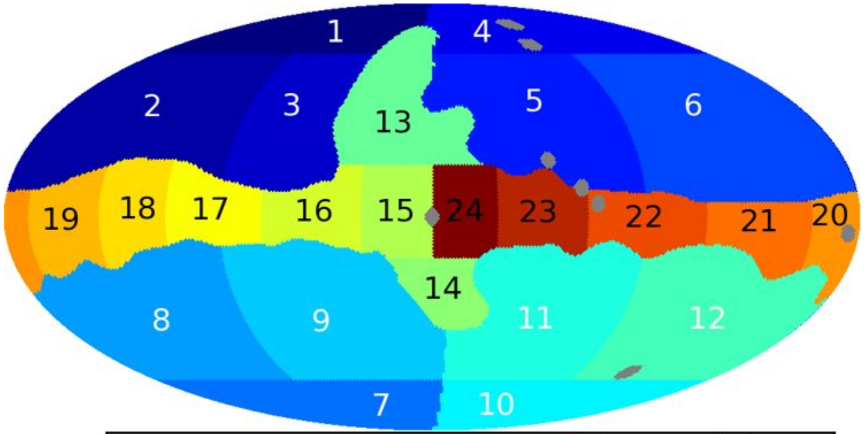
The WMAP model was only able to account for between 6 and 52% of the full effect.

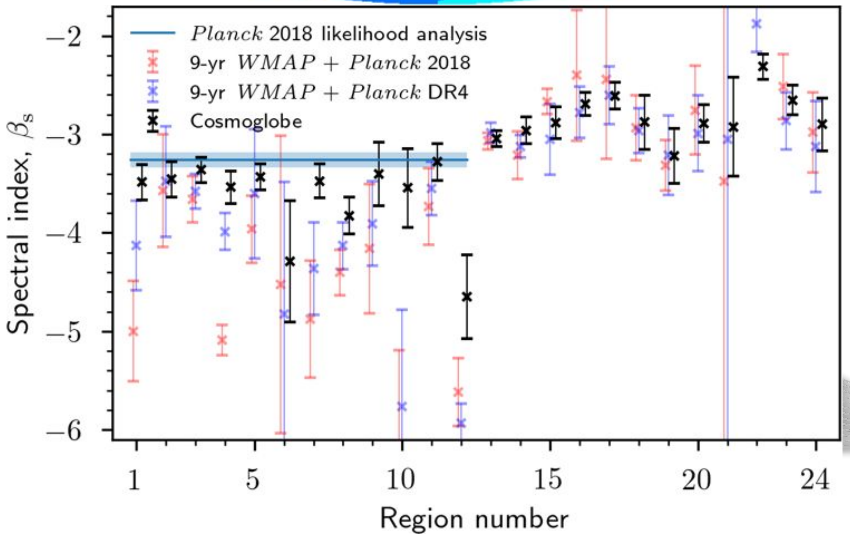
The rest leaked into astrophysical results

European Commission

Application 1: Polarized synchrotron emission from LFI+WMAP

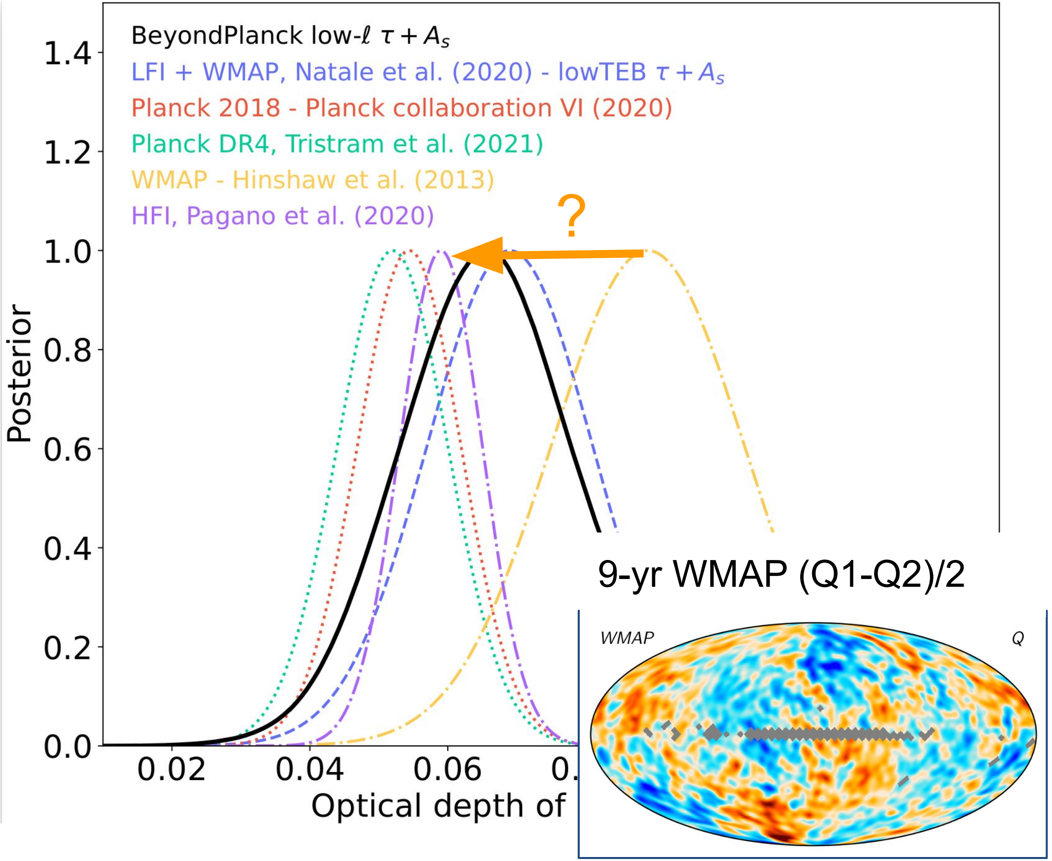






Synchrotron maps free of poorly measured modes

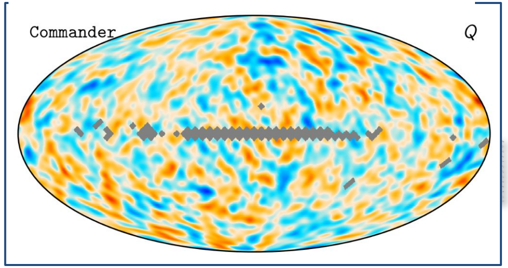
Application 2: Optical depth of reionization?



Rather than project modes out in the likelihood, we remove them in the joint low-level analysis.

Residuals at the ~3 uK level due to poorly measured modes could be enough to explain the WMAP/LFI discrepancy in tau.

Cosmoglobe (Q1-Q2)/2



Summary

- Cosmoglobe is an extremely ambitious project that aims to combine all large-scale state-of-the-art datasets from radio to sub-millimeter frequencies into one global model

- **With Cosmoglobe DR1, we have for the first time analyzed WMAP and Planck LFI together, resulting in better science from both**

- Strong emphasis on Open Science, and are always looking for new collaborators

European Commission

Funding

This project has received funding from the European Research Council (ERC) under the Horizon 2020 Research and Innovation Programme

- Cosmoglobe
  - EU ERC-CoG Grant agreement No. 819478 - PI I. K. Wehus - 2019-2024
- bits2cosmology
  - EU ERC-CoG Grant agreement No. 772253 - PI H. K. Eriksen - 2018-2023
- BeyondPlanck
  - EU COMPET-4 Grant agreement No. 776282 - PI H. K. Eriksen - 2018-2020
- Global Component Separation Network
  - Diku/RCN INTPART Grant agreement No. 274990 - PI I. K. Wehus - 2018-2023