Cosmoglobe

Cosmoglobe

– mapping the sky from the Milky Way to the Big Bang

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University of Oslo

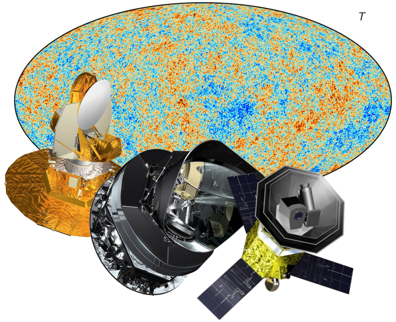
MPA Garching, 21 September 2023

European Commission

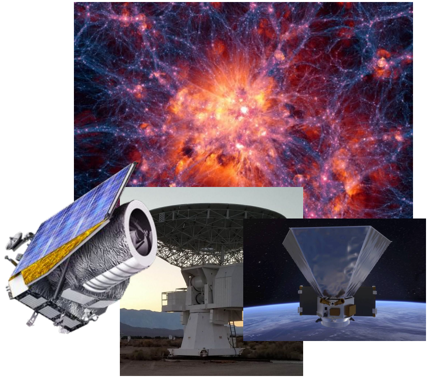
Cosmoglobe

-mapping the universe from the Solar system to the Big Bang

Early universe

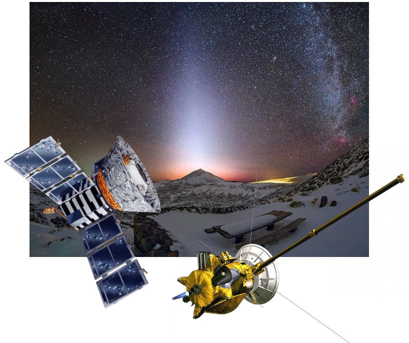


Large-scale structure

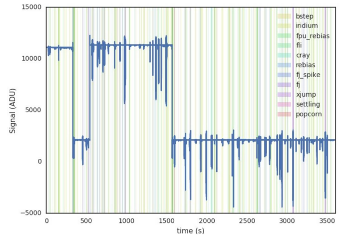


Milky Way

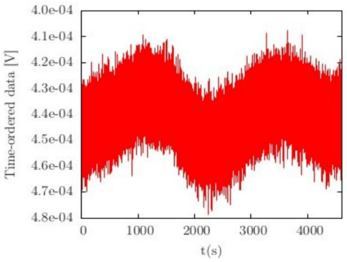
Solar system



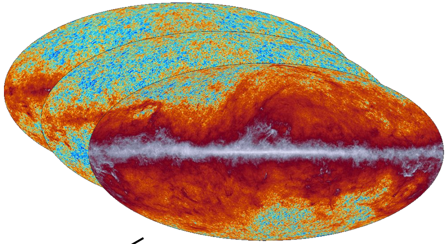
Classic linear CMB analysis pipeline



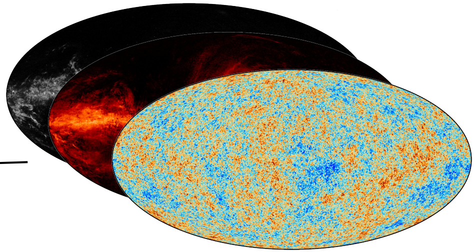
Data selection + calibration



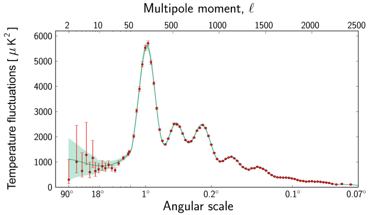
Map making



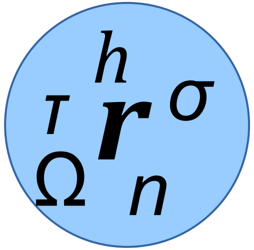
Component separation



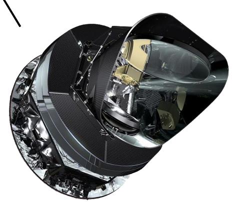
Power spectrum estimation



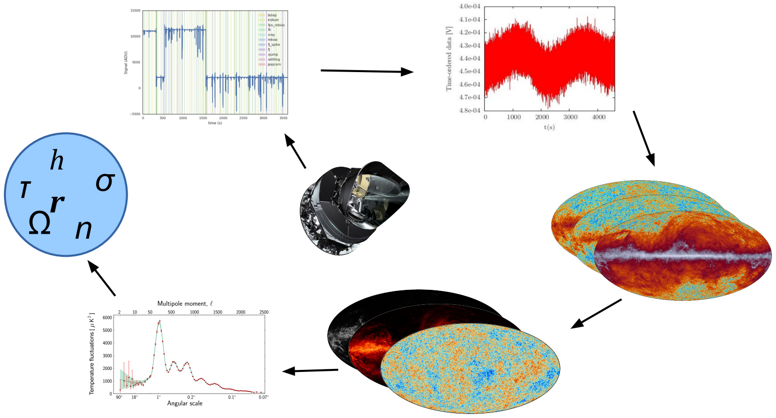
Parameter estimation

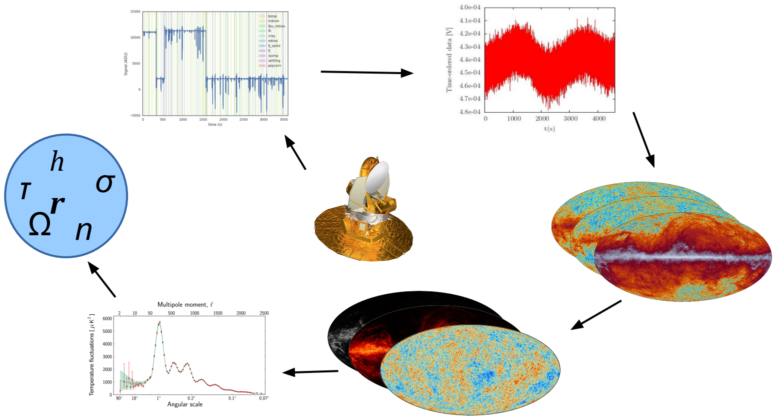


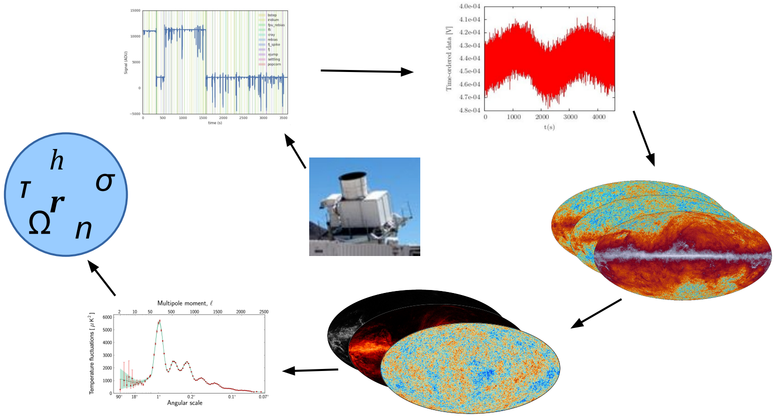
Observations



Classic linear CMB analysis pipelines



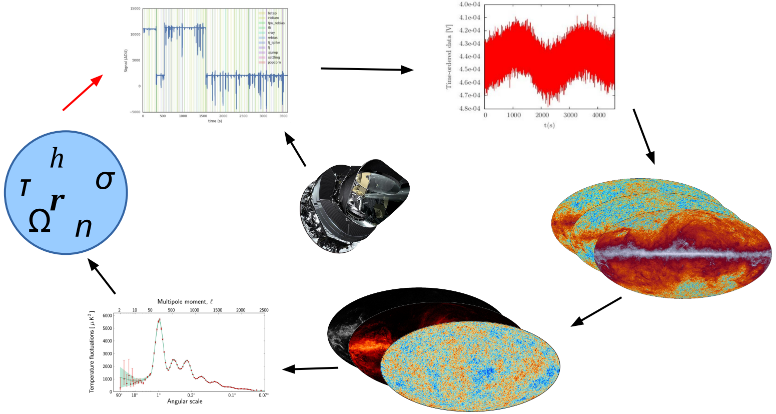


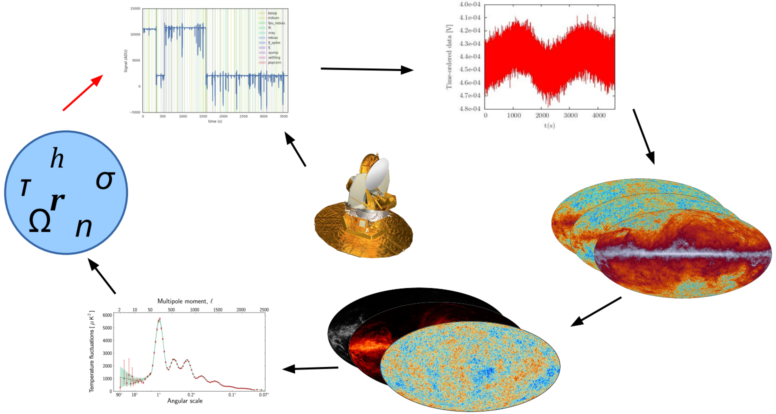


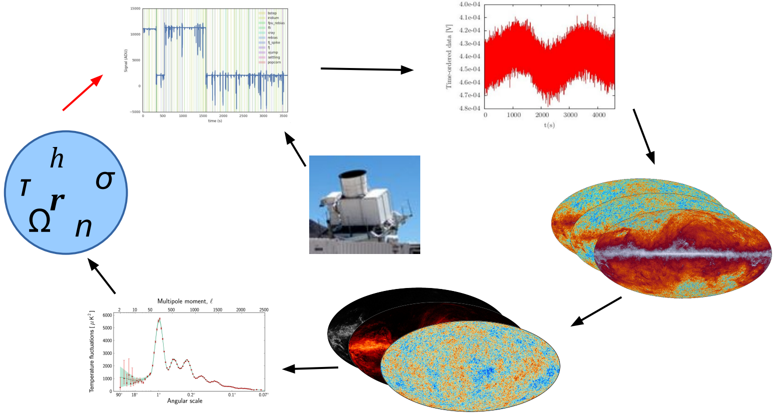
Challenges

- parameter degeneracies
- single-experiment blind spots
- information loss
- resource demanding

Classic linear CMB analysis pipelines







Challenges

- parameter degeneracies
- single-experiment blind spots
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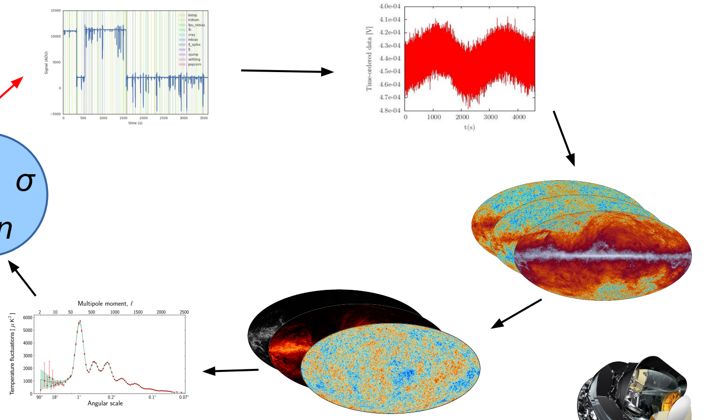
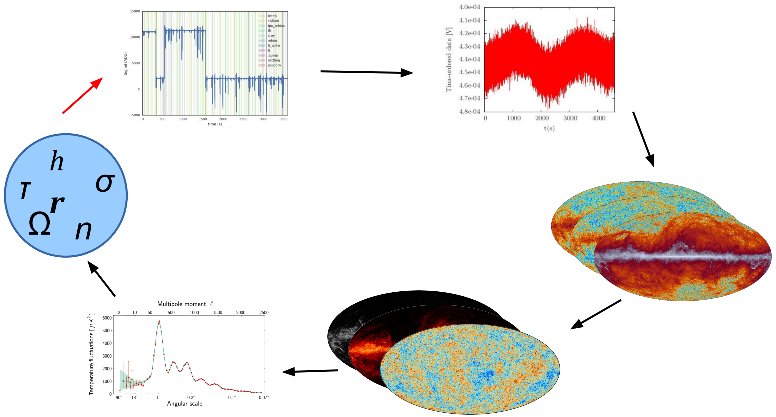
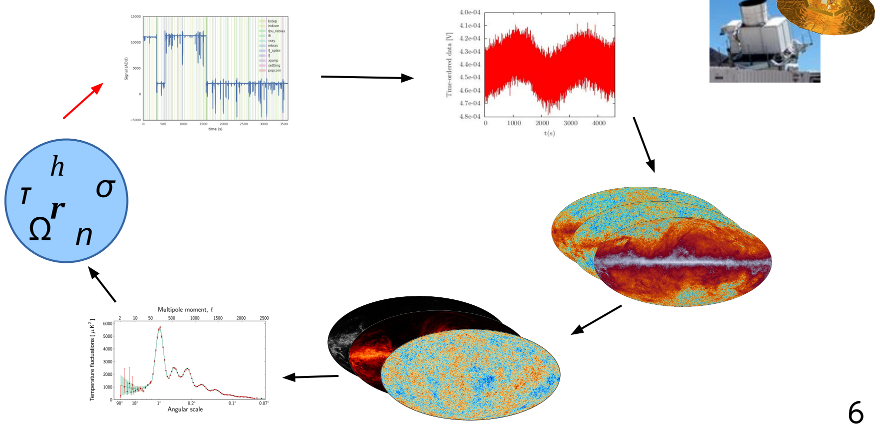
- resource demanding

Classic linear CMB analysis pipelines



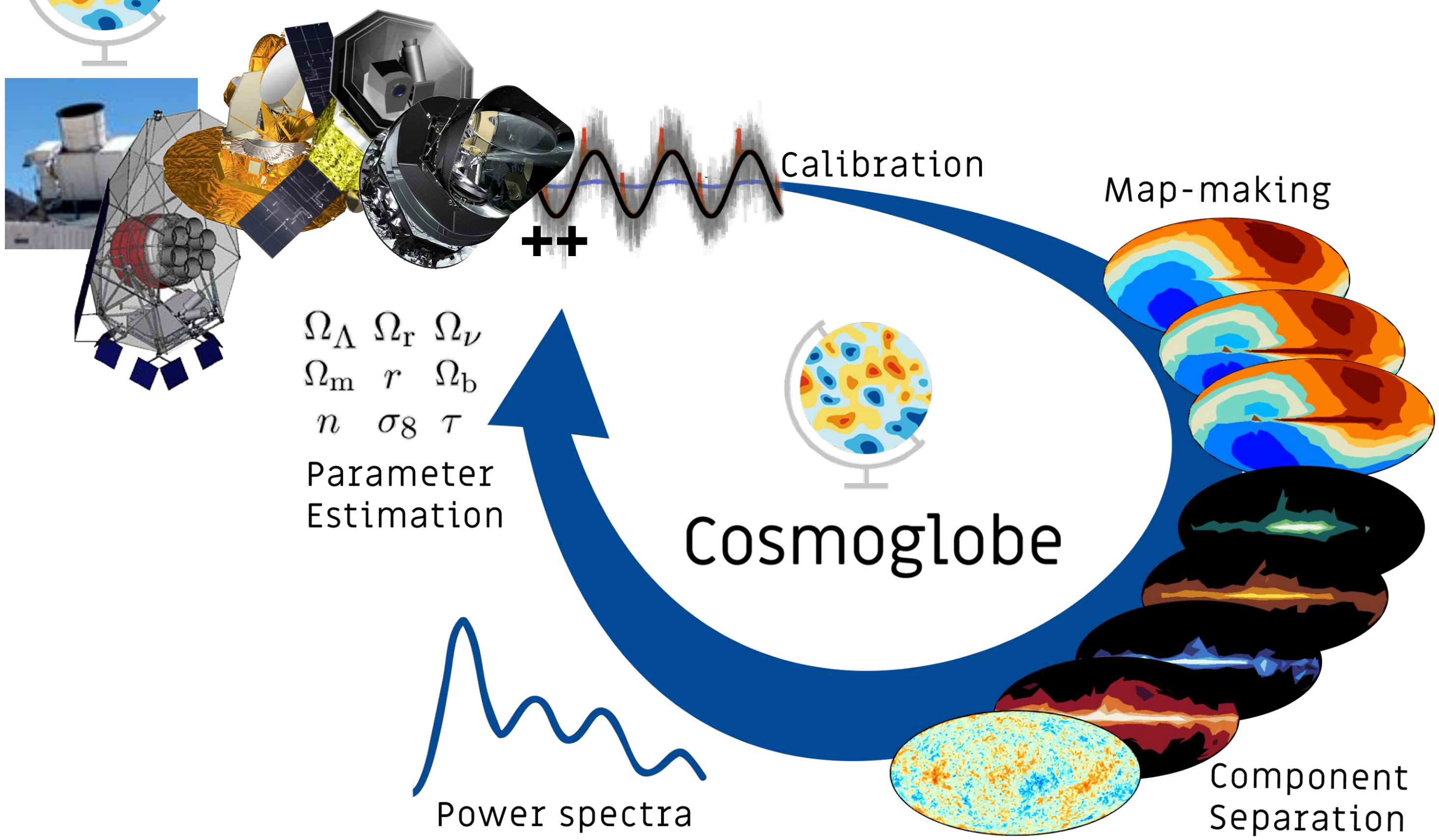




Challenges

- parameter degeneracies
- single-experiment blind spots
- information loss
- resource demanding

Global end-to-end analysis pipeline



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Cosmoglobe

-mapping the universe from the Solar system to the Big Bang

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

- Global analysis: Joint end-to-end pipeline
    - joint estimation of instrumental, astrophysical and cosmological parameters
    - implemented in the Commander code, developed by Planck and BeyondPlanck

- Global analysis: Joint multi-experiment analysis
    - complementary experiments break each other's degeneracies
    - data can be integrated both in the form of (preferably) time-ordered data and (secondarily) sky maps

- Global analysis: Joint effort from global community
    - open Science philosophy with strong focus on collaboration
    - the Cosmoglobe idea/project/community is input driven and evolving
    - driven by young scientists

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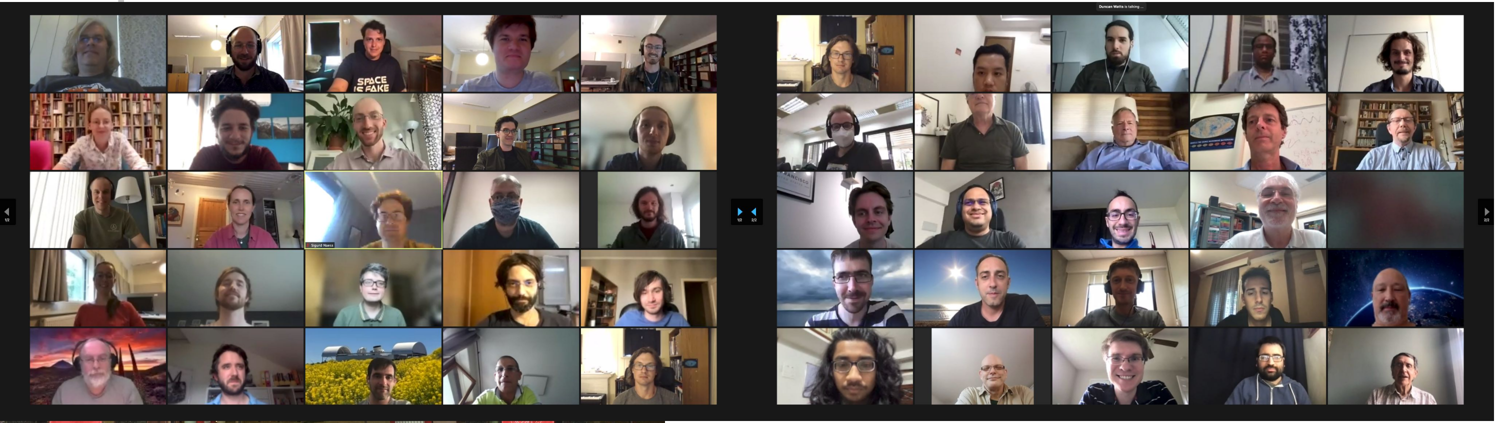
Cosmoglobe global community

cosmoglobe.uio.no



Yearly intensive course and workshops

Please join us :-)

Cosmoglobe algorithm 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:

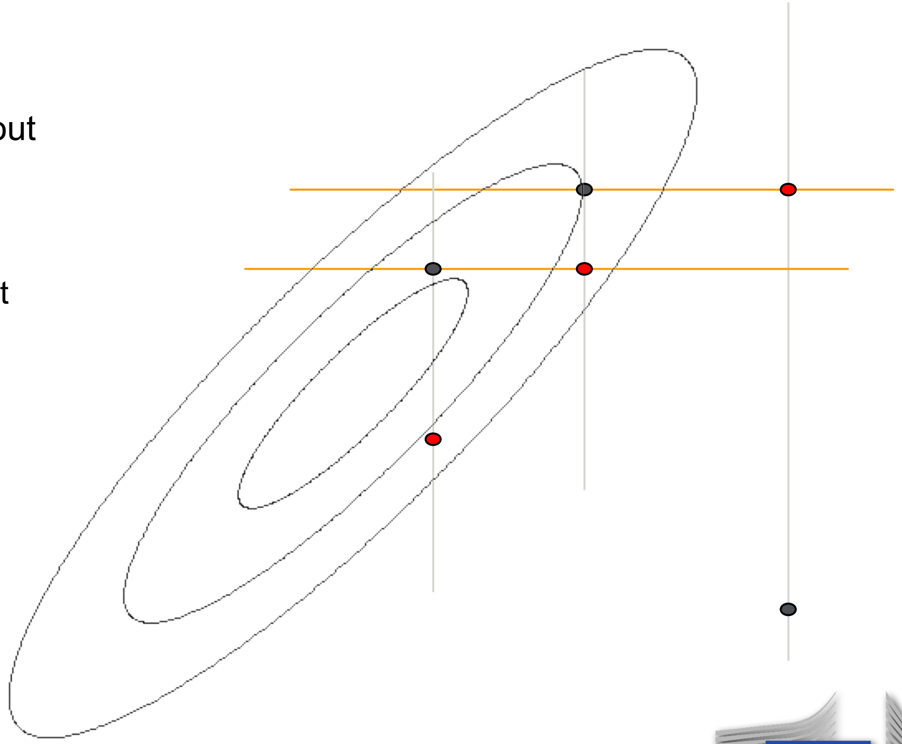
$$P(\omega \mid \boldsymbol{d}) = \frac{P(\boldsymbol{d} \mid \omega)P(\omega)}{P(\boldsymbol{d})} \propto \mathcal{L}(\omega)P(\omega),$$

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

Gibbs sampling

- The posterior contains millions of correlated and non-Gaussian parameters. How is it possible to map out this distribution?
- Answer: Gibbs sampling
  - Rather than sampling from or maximizing the full joint distribution, iterate over conditionals
- We apply this to our problem in terms of the following Gibbs chain:

$$
\begin{aligned}
\mathbf{a}_i &\leftarrow P(\mathbf{a}_i|\beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
\beta_i &\leftarrow P(\beta_i|\mathbf{a}_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
g_\nu &\leftarrow P(g\nu|\mathbf{a}_i, \beta_i, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
\mathbf{m}_\nu &\leftarrow P(m_\nu|\mathbf{a}_i, \beta_i, g_\nu, \Delta_\nu, C_\ell) \\
\Delta\nu &\leftarrow P(\Delta_\nu|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, C_\ell) \\
C_\ell &\leftarrow P(C_\ell|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu)
\end{aligned}
$$



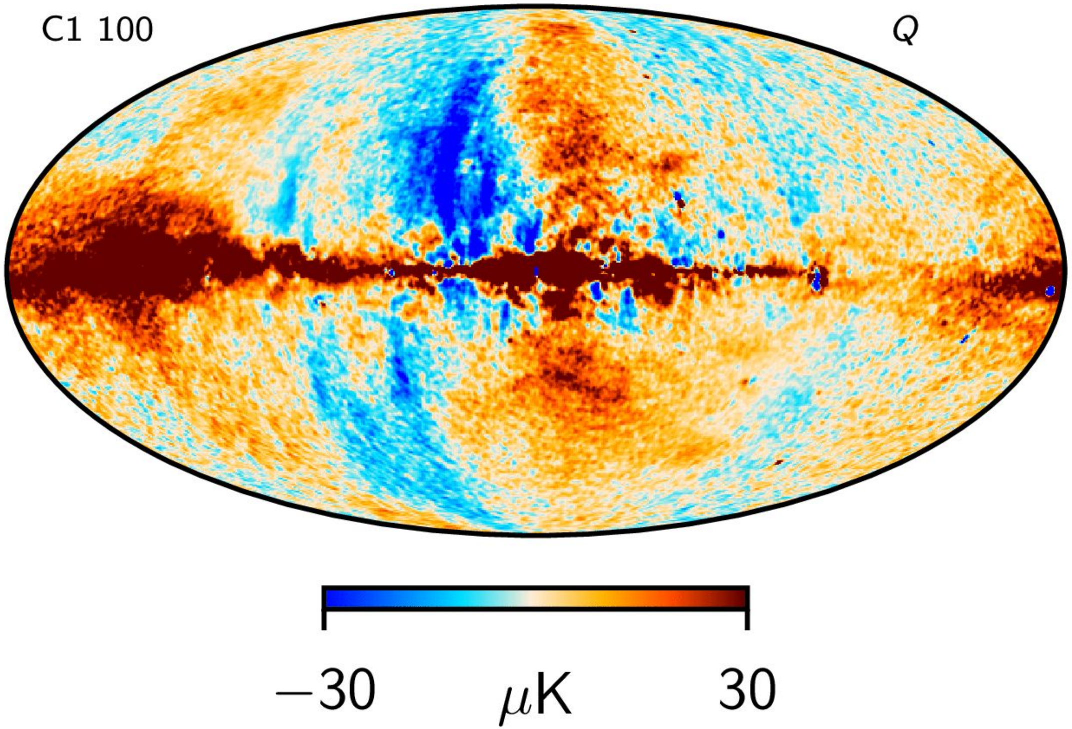
Global analysis proof of concept:
BeyondPlanck - reanalysis of Planck LFI data

- Included data
    - ***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 polarizatio
    - ***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 were ***not*** included, becau they have higher signal-to-noise ratios than Planck LFI

Global analysis proof of concept:

BeyondPlanck - reanalysis of Planck LFI data

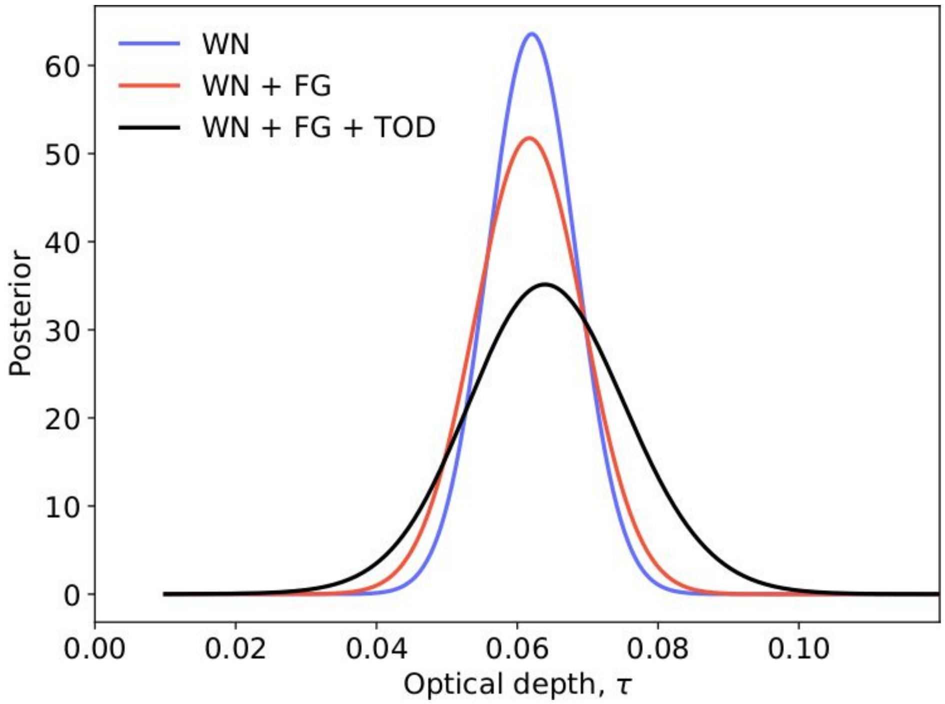
Joint analysis of Planck LFI (tod) + 353/857 + WMAP Ka-V + Haslam (maps)



BeyondPlanck (2023)

Global analysis impact on cosmological parameters

BeyondPlanck

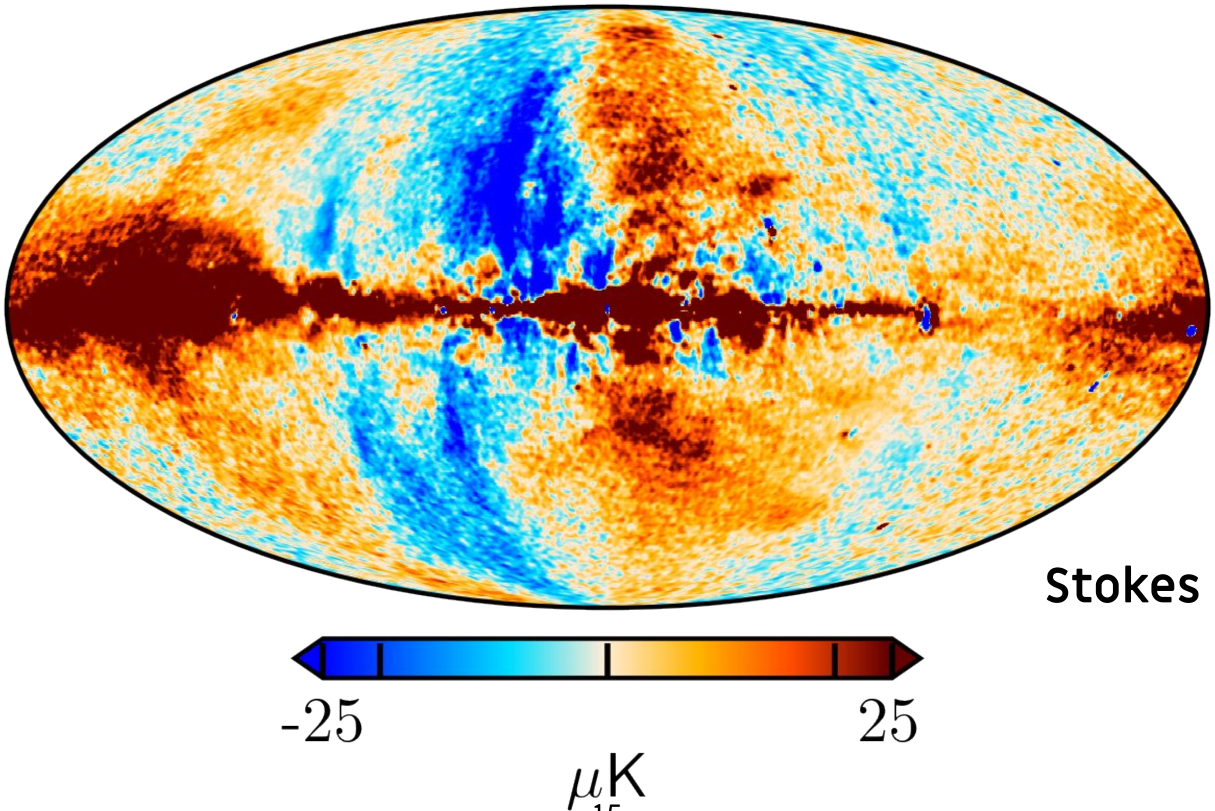


End-to-end global analysis generally yields:

- larger *and more accurate* uncertainties
- lower systematic uncertainties

BeyondPlanck - map results

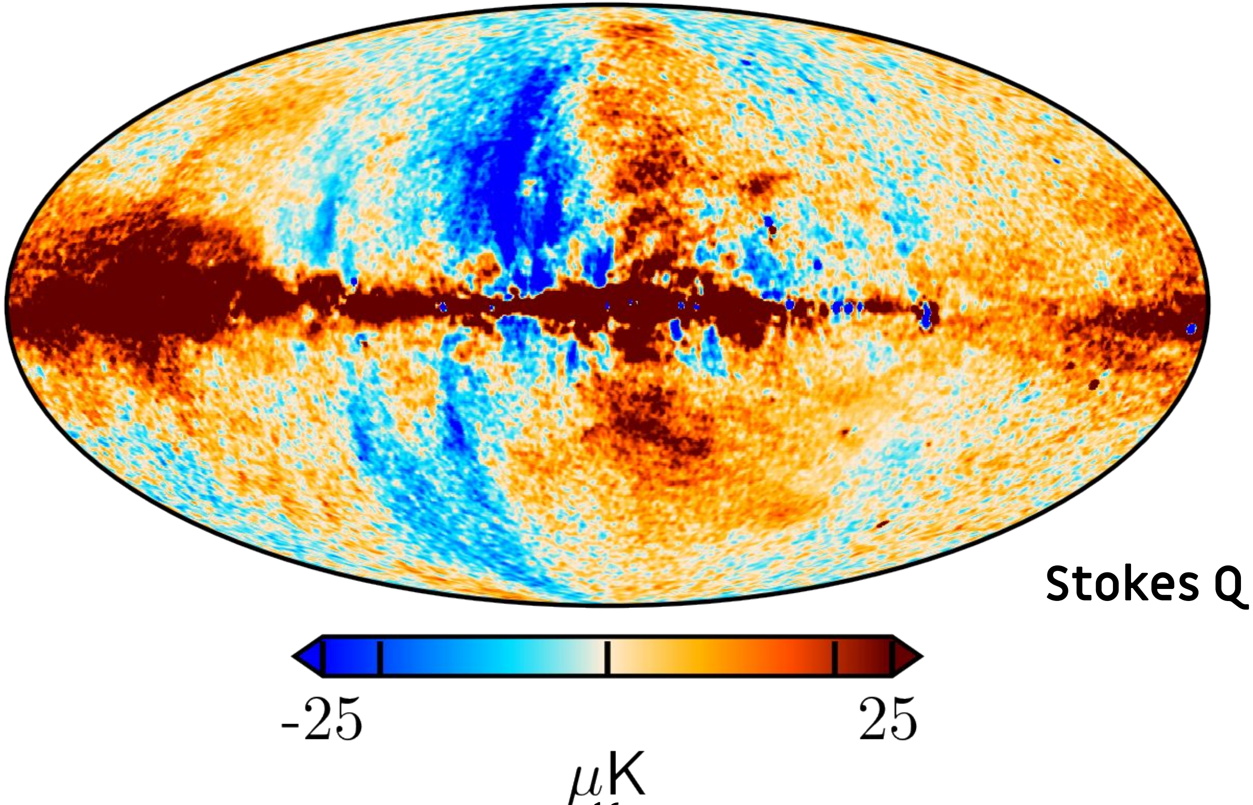
30 GHz BeyondPlanck map



Stokes Q

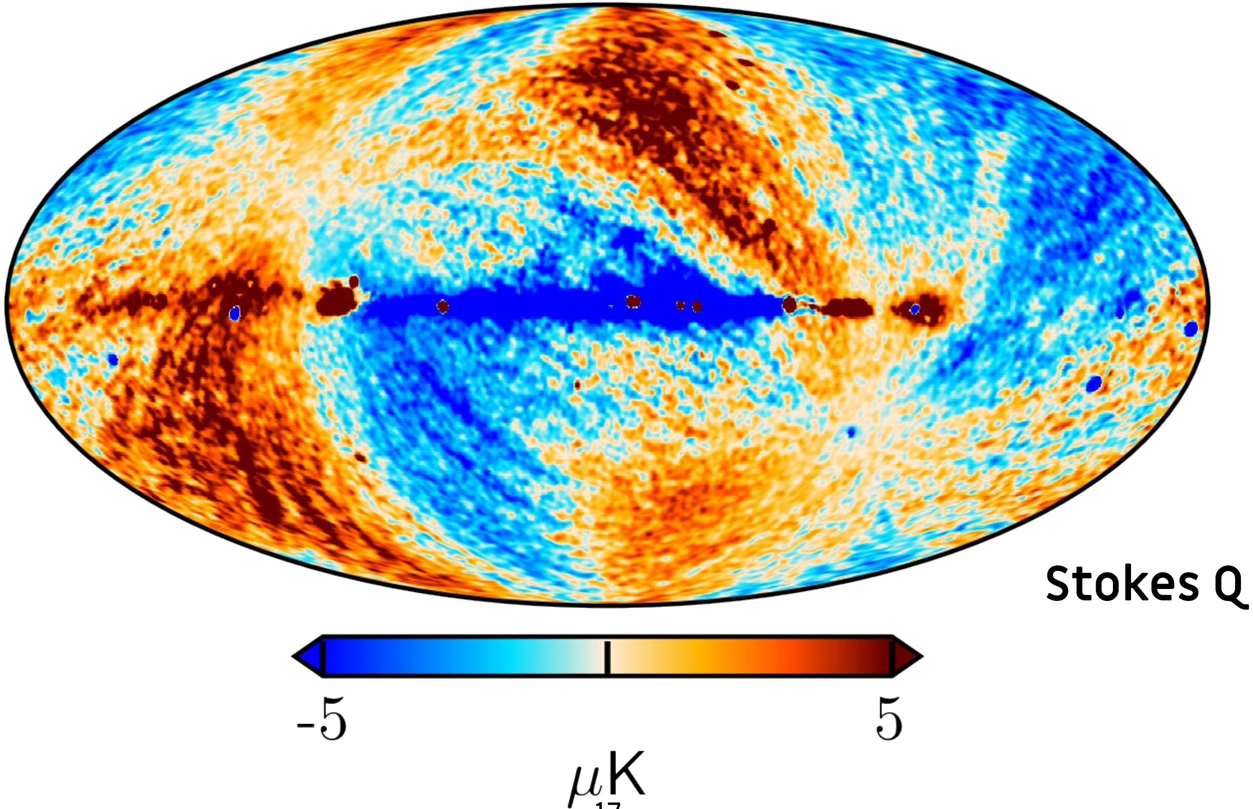
BeyondPlanck - map results

30 GHz Planck legacy map



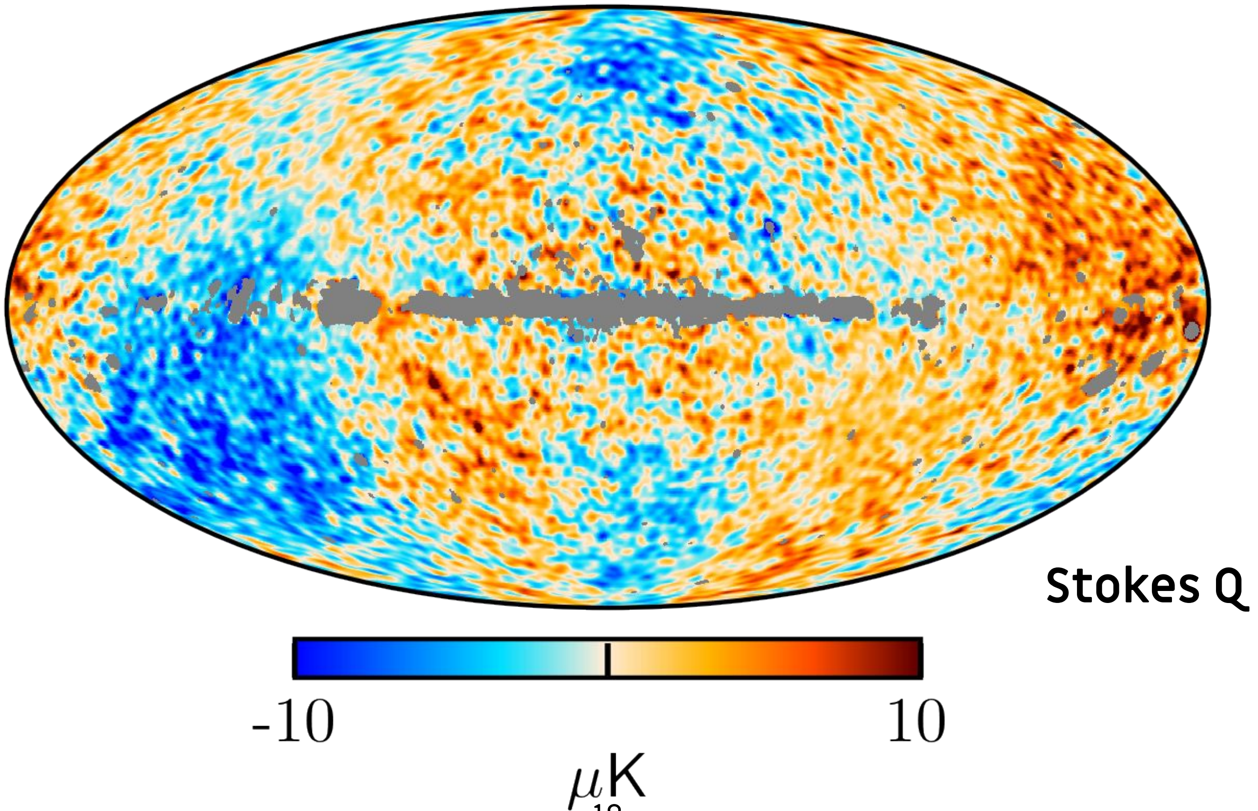
BeyondPlanck - map results

Planck 30 GHz difference map (BeyondPlanck - Planck legacy)



0.495 * WMAP 23 GHz - 30 GHz Planck consistency

WMAP 9-year - Planck legacy



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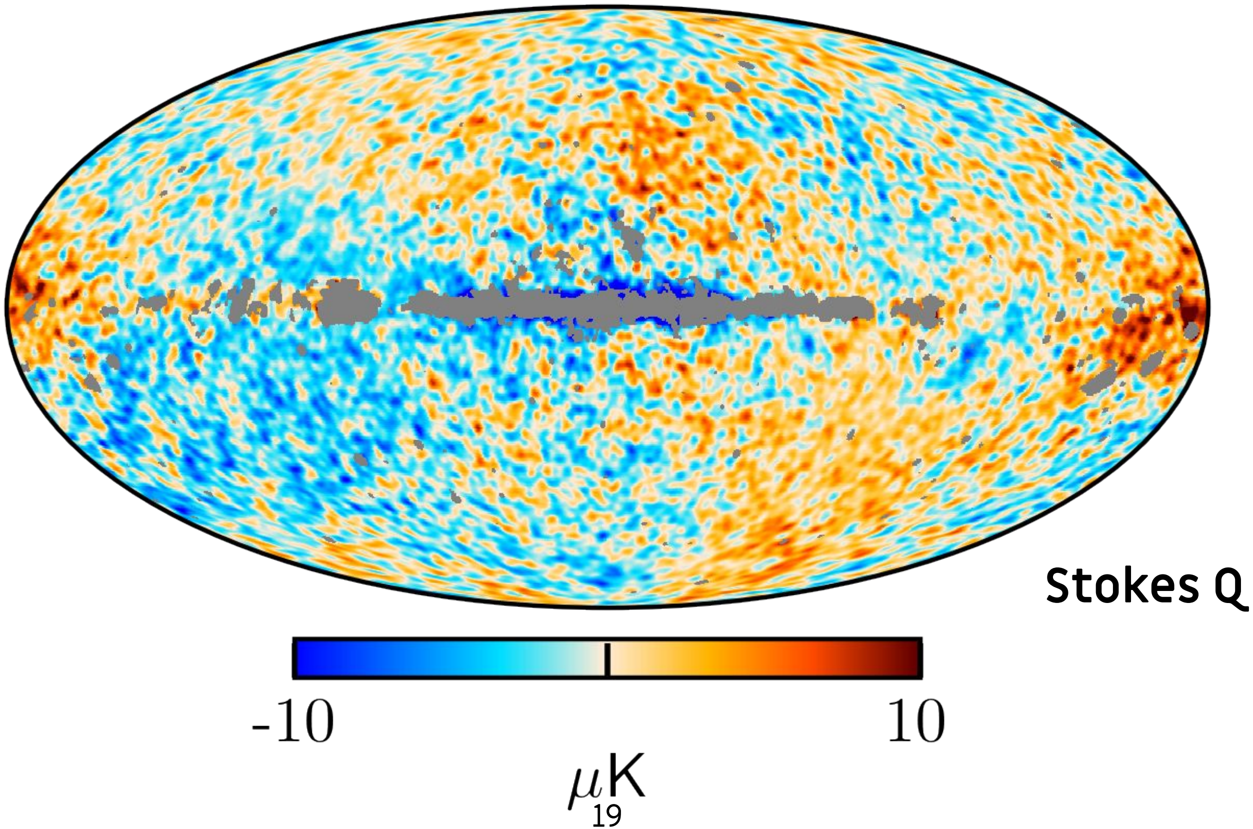
WMAP 9-year - BeyondPlanck



Cosmoglobe DR1: WMAP reanalysis

- Included data
  - ***WMAP 23-94 GHz* time-ordered data**
  - ***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 polarizatio
  - ***Haslam 408 MHz*** to constrain synchrotron intensity
- Intermediate *Planck HFI* still not included

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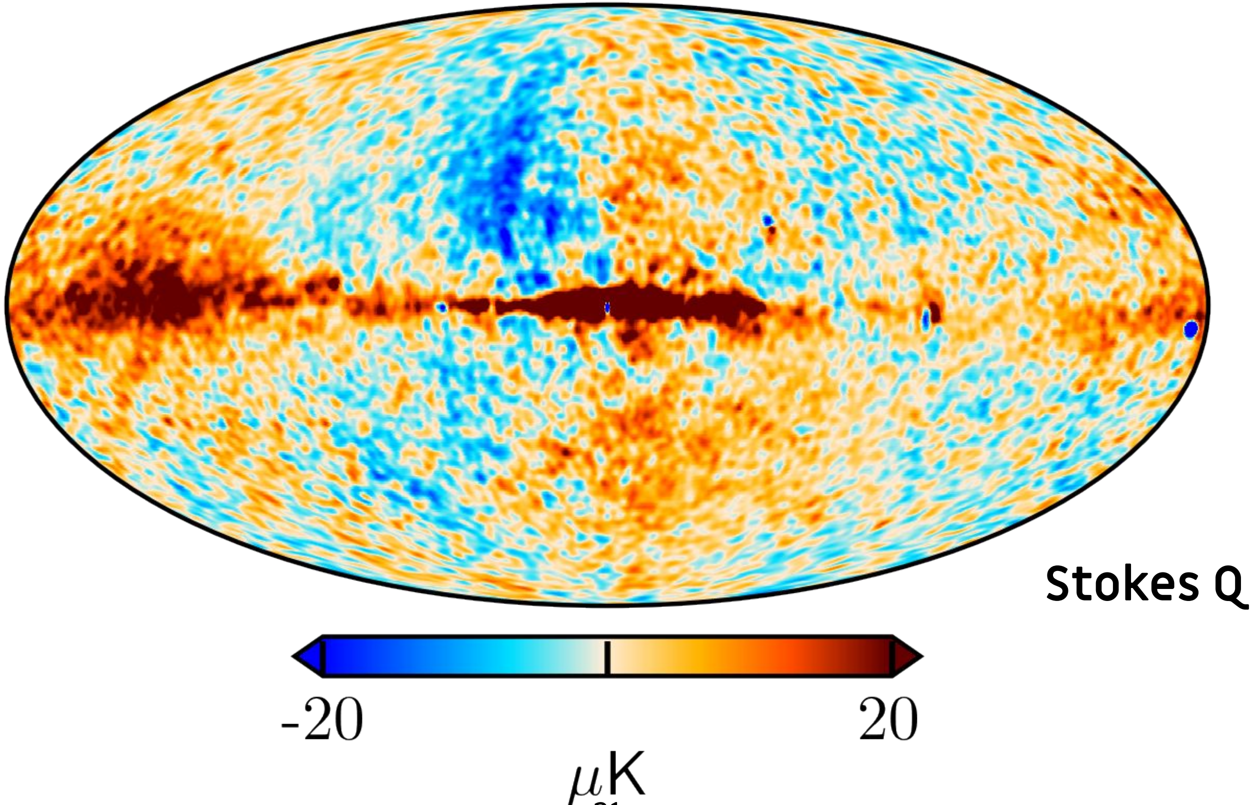
Cosmoglobe DR1: WMAP reanalysis

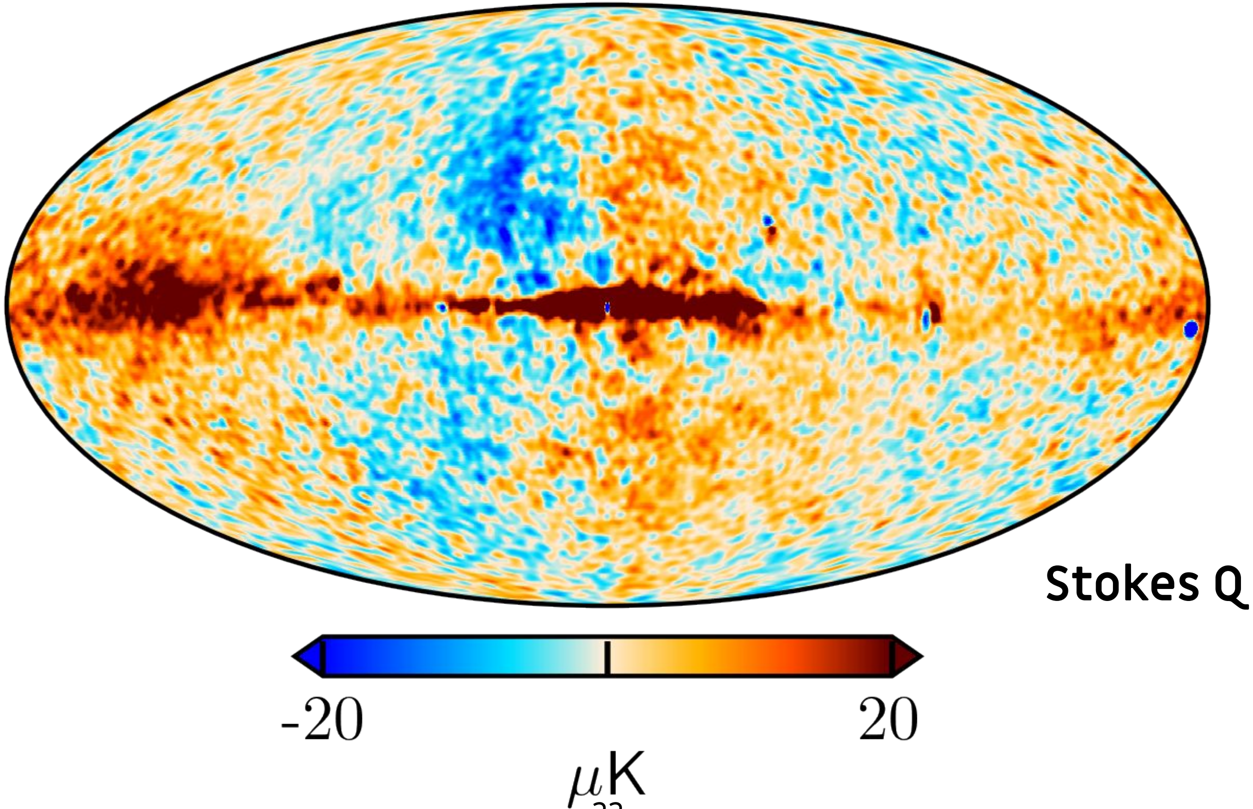
Q-band (41 GHz) 9-year WMAP



Watts et al. (2023)

Cosmoglobe DR1: WMAP reanalysis

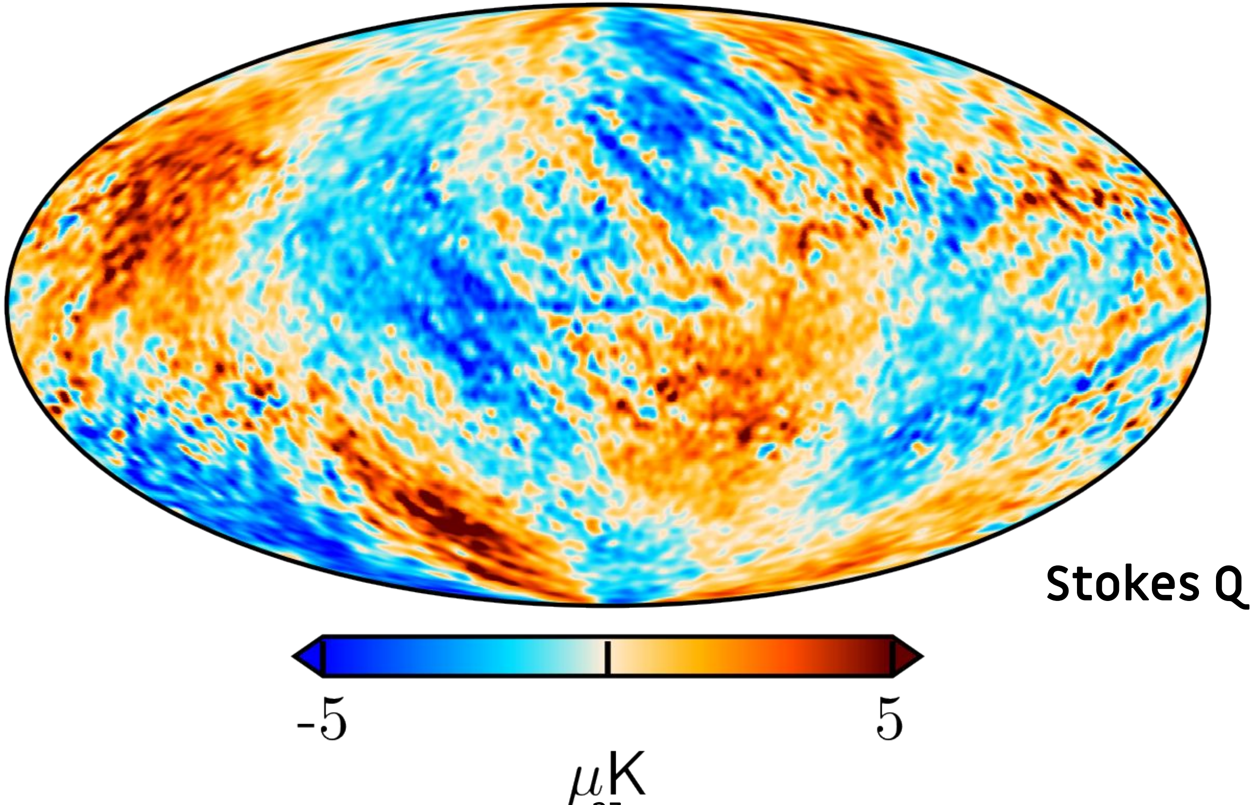
Q-band (41 GHz) Cosmoglobe WMAP



Watts et al. (2023)

Cosmoglobe DR1: WMAP reanalysis

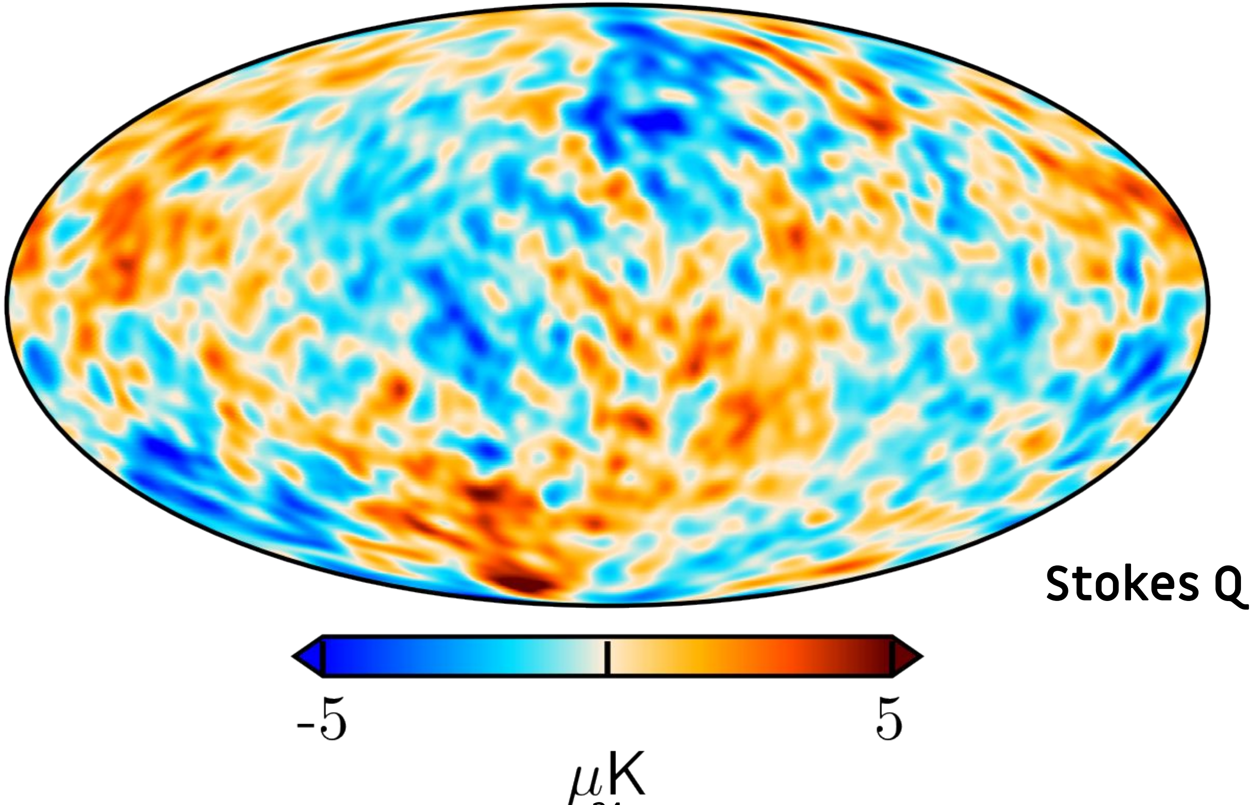
WMAP Q-band difference map (Cosmoglobe - 9-year)



Watts et al. (2023)

Cosmoglobe DR1: WMAP reanalysis

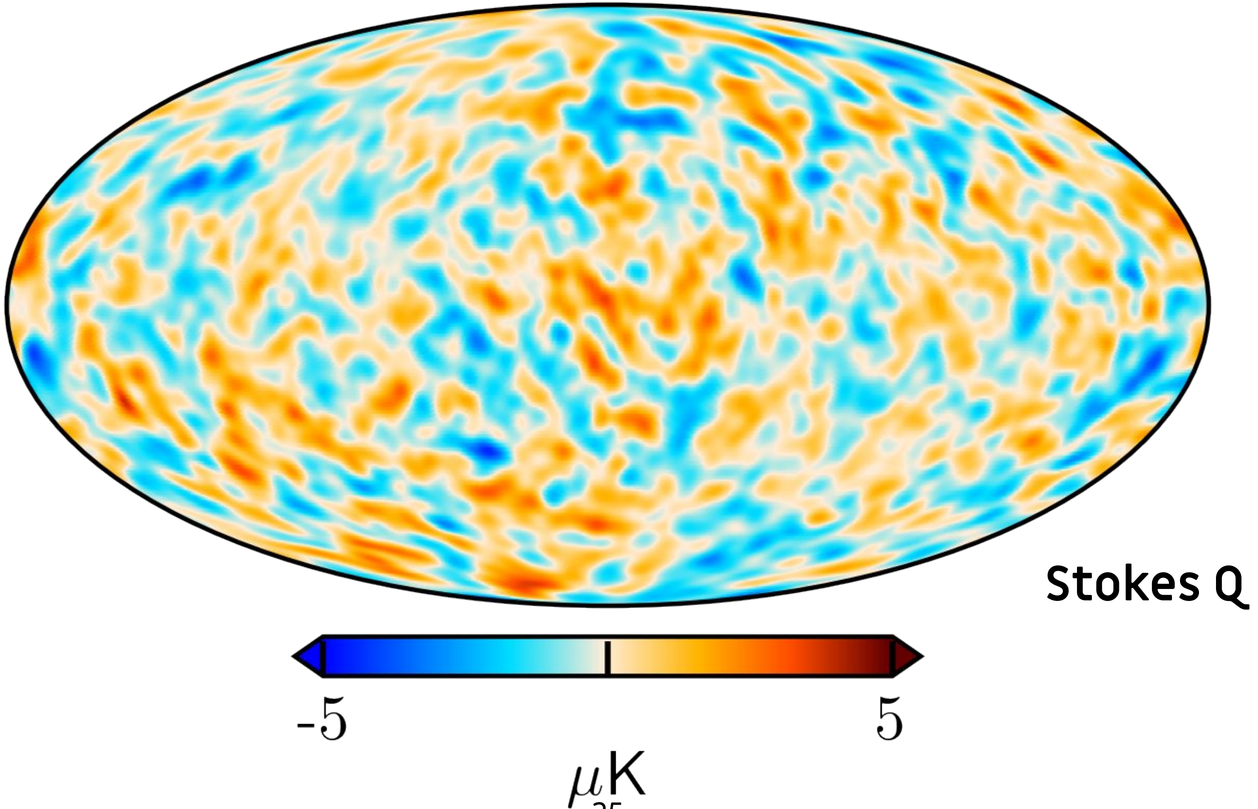
WMAP Q-band internal detector (Q1-Q2)/2 difference map: 9-year



Watts et al. (2023)

Cosmoglobe DR1: WMAP reanalysis

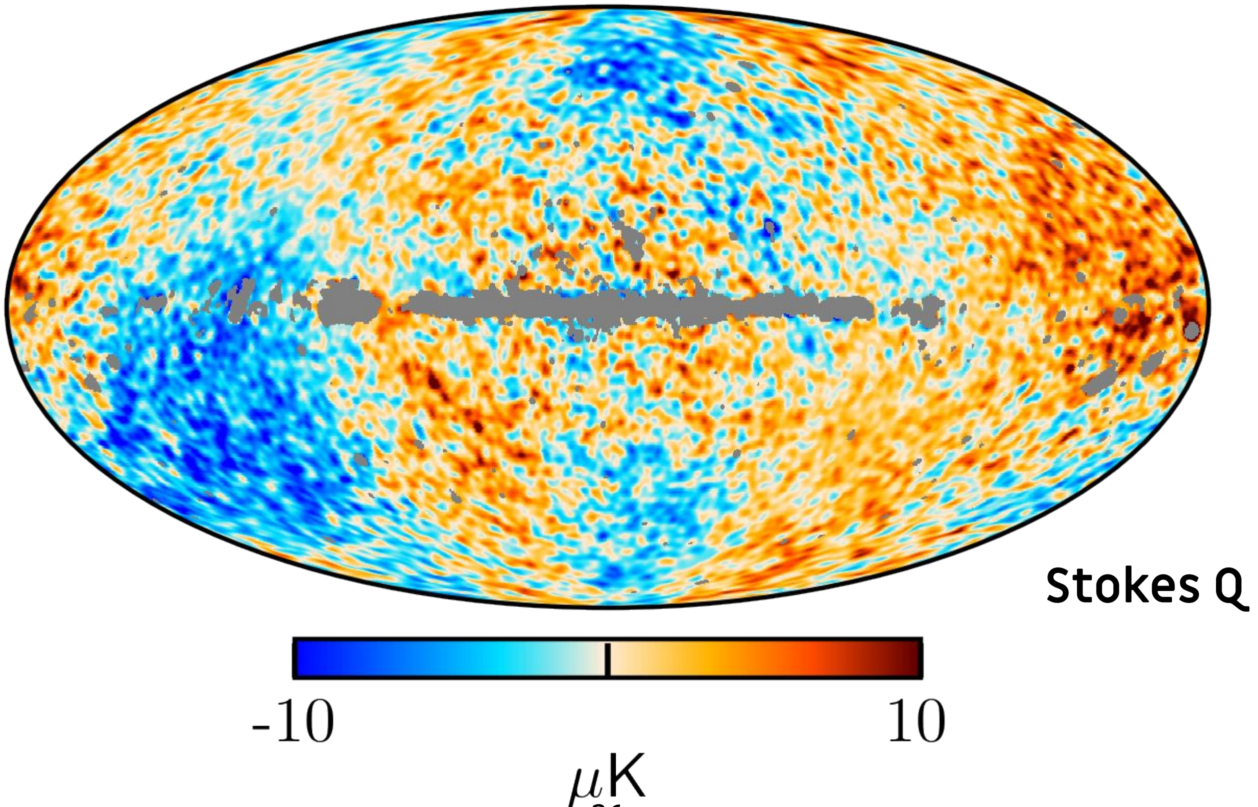
WMAP Q-band internal detector (Q1-Q2)/2 difference map: Cosmoglobe



Watts et al. (2023)

0.495 * WMAP 23 GHz - 30 GHz Planck consistency

WMAP 9-year - Planck legacy



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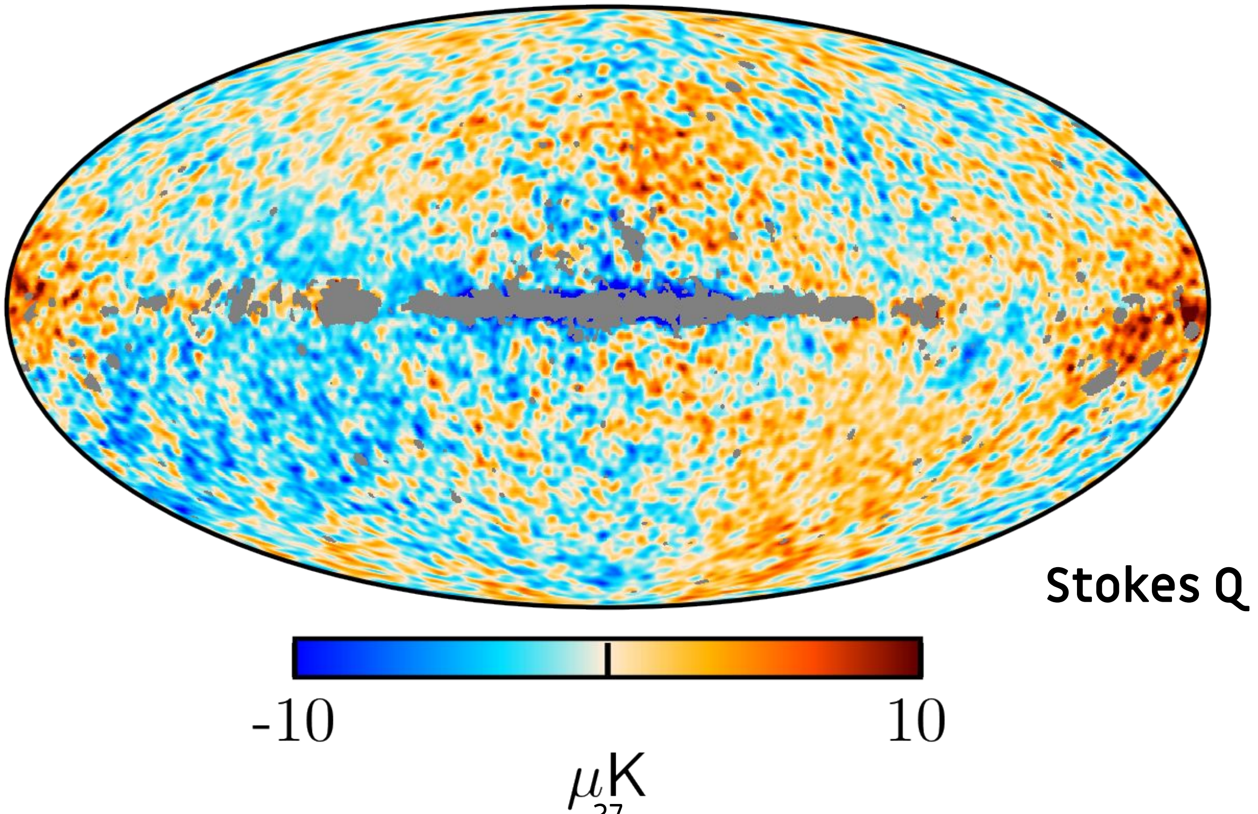
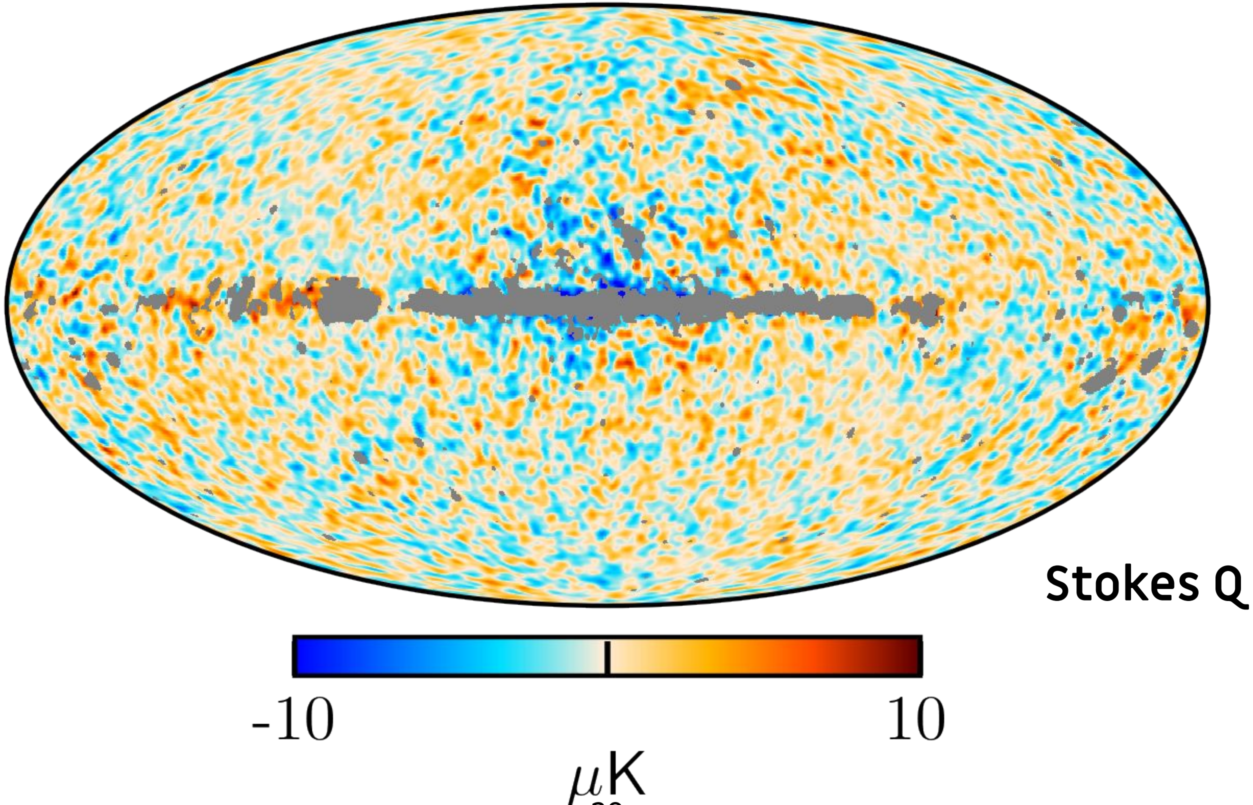
WMAP 9-year - BeyondPlanck

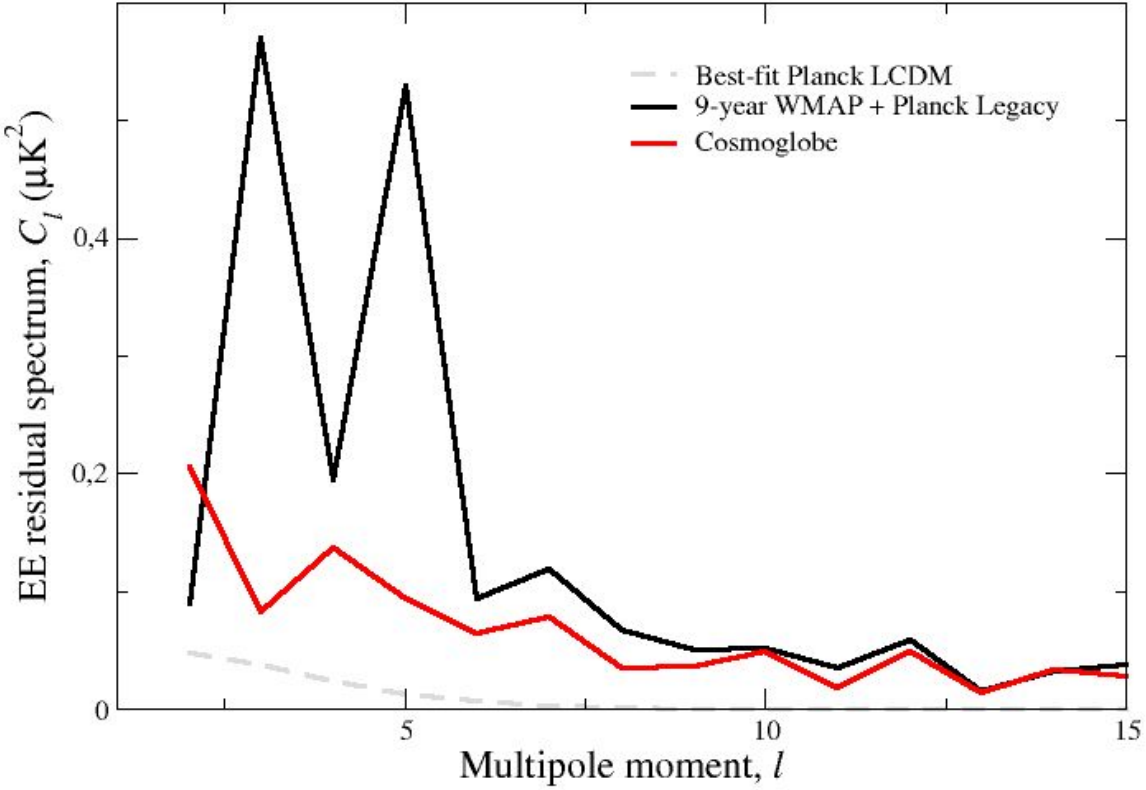


0.495 * WMAP 23 GHz - 30 GHz Planck consistency

Cosmoglobe WMAP - Cosmoglobe LFI



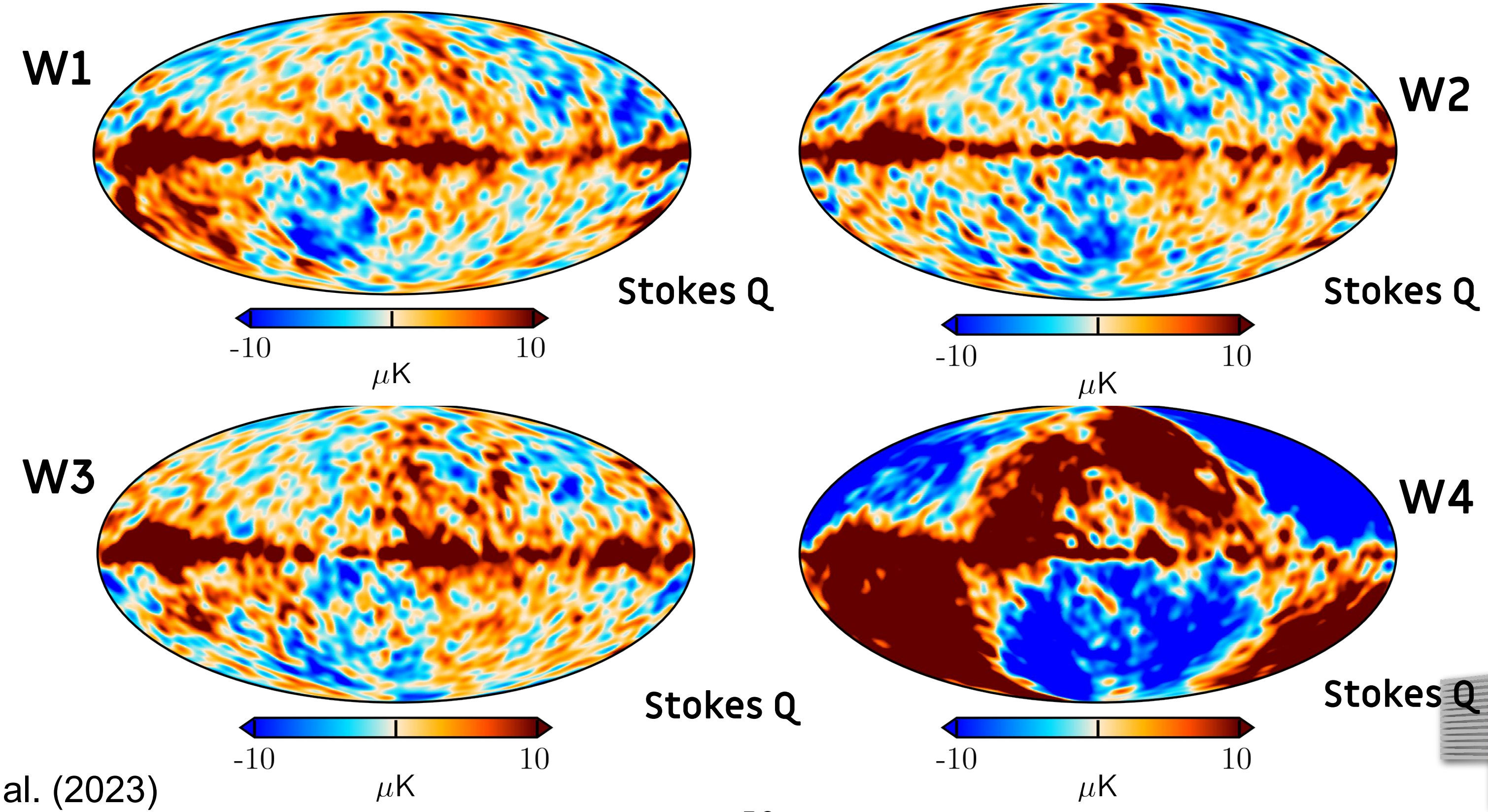
WMAP 23 GHz - Planck 30 GHz: Difference map spectra



Watts et al. (2023)

Cosmoglobe DR1: WMAP reanalysis

W-band (94 GHz) 9-year WMAP detector maps



Watts et al. (2023)

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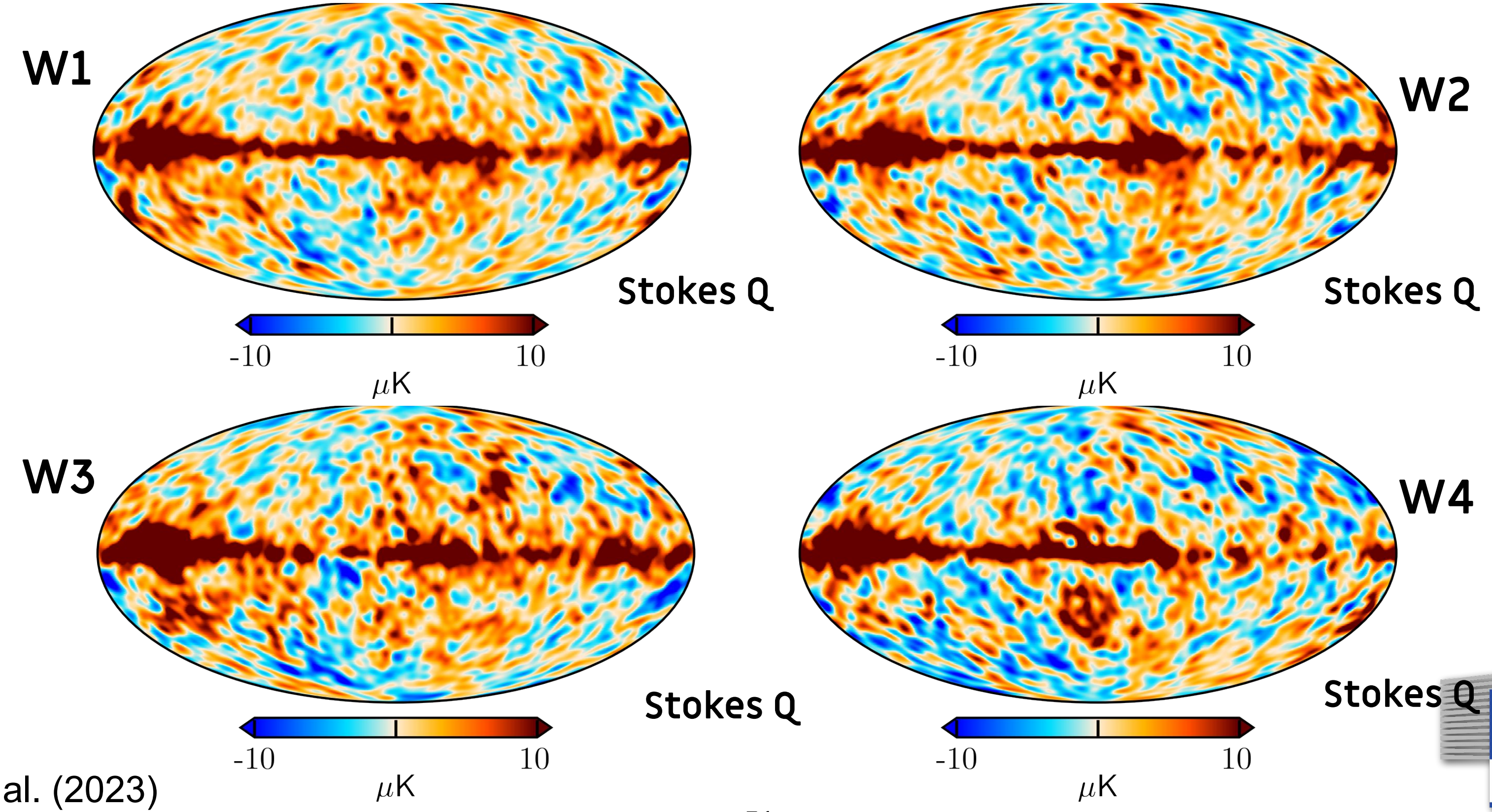
Cosmoglobe DR1: WMAP reanalysis

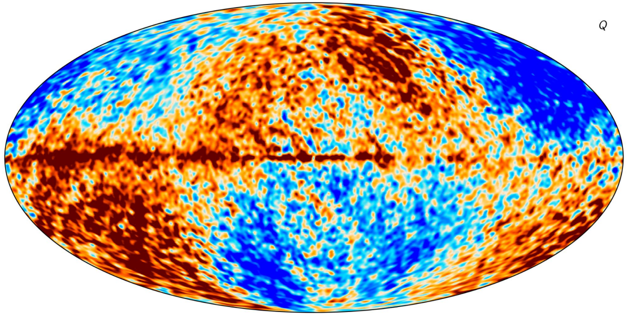
W-band (94 GHz) Cosmoglobe WMAP detector maps



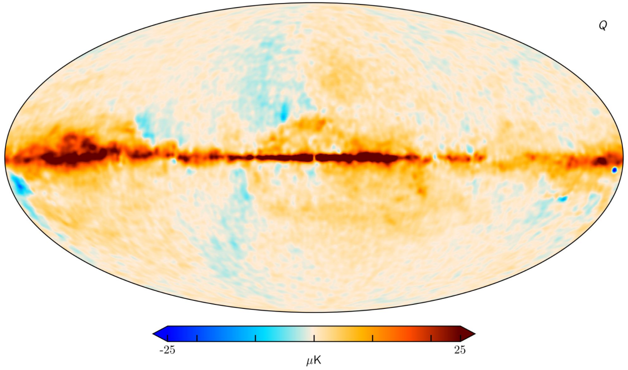
Watts et al. (2023)

WMAP W-band minus Planck PR4 100 GHz

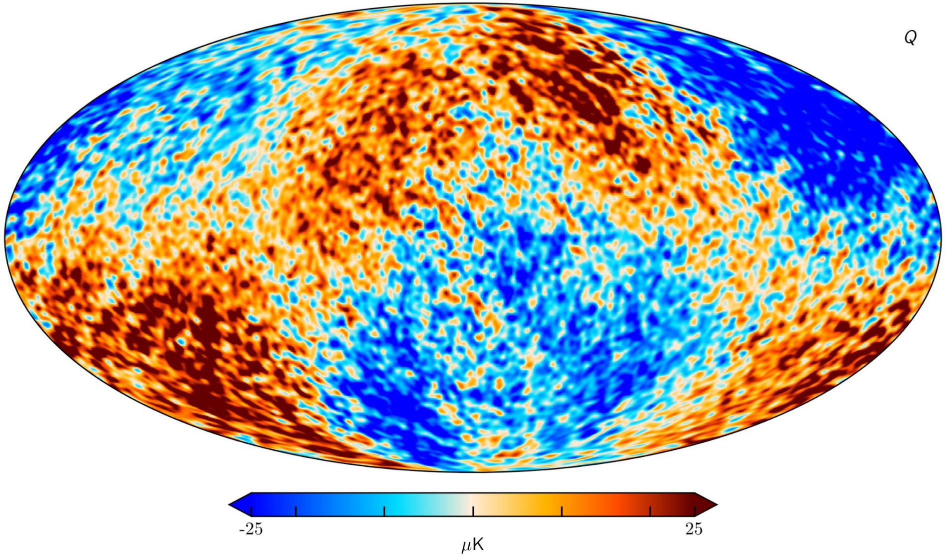
WMAP 9-year (90 GHz)



Planck PR4 (100 GHz)



Difference



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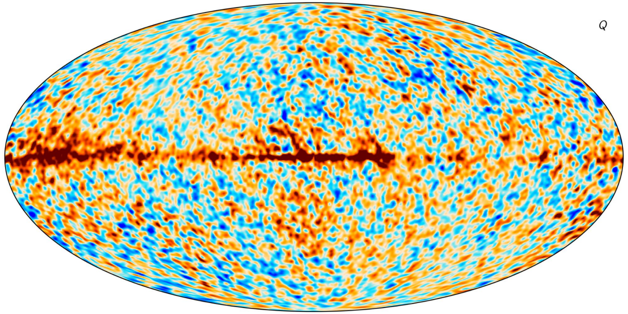
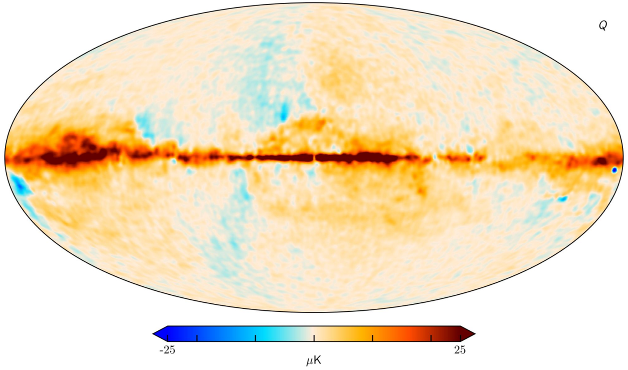
WMAP W-band minus Planck PR4 100 GHz

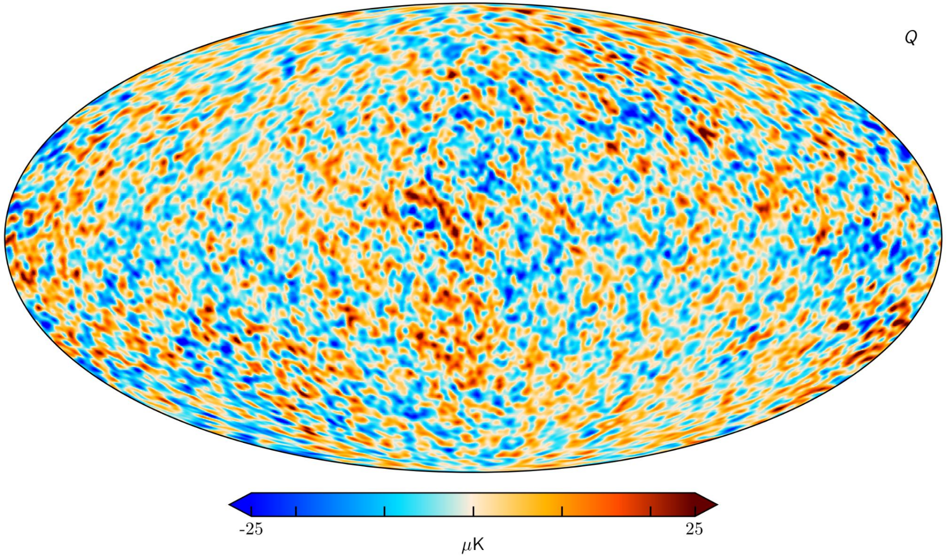
Cosmoglobe (90 GHz)



Planck PR4 (100 GHz)



Difference



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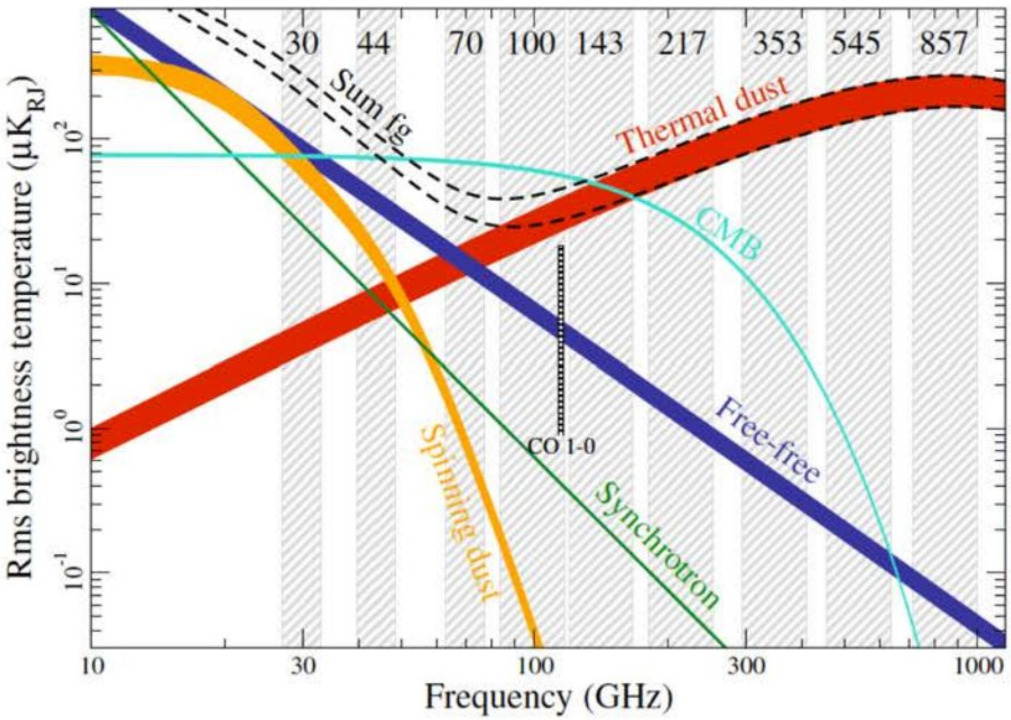
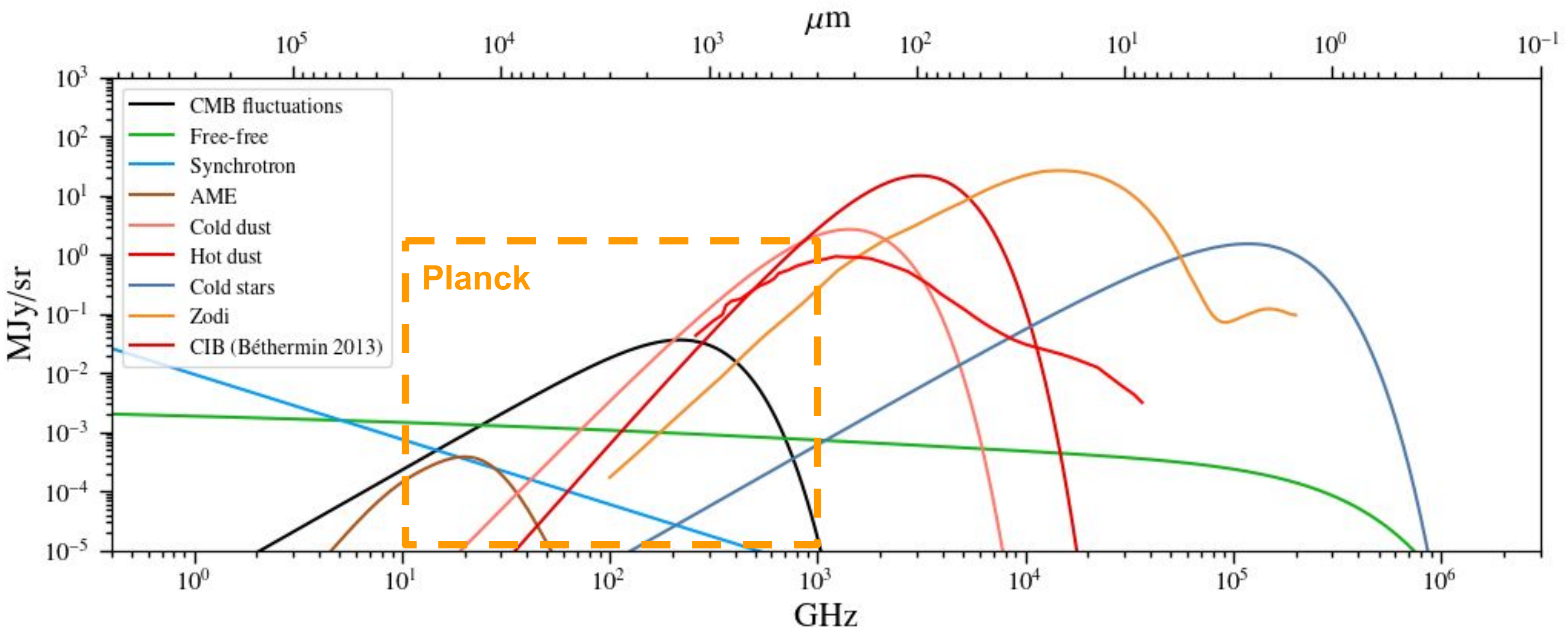
Cosmoglobe DR1: The CMB frequency range

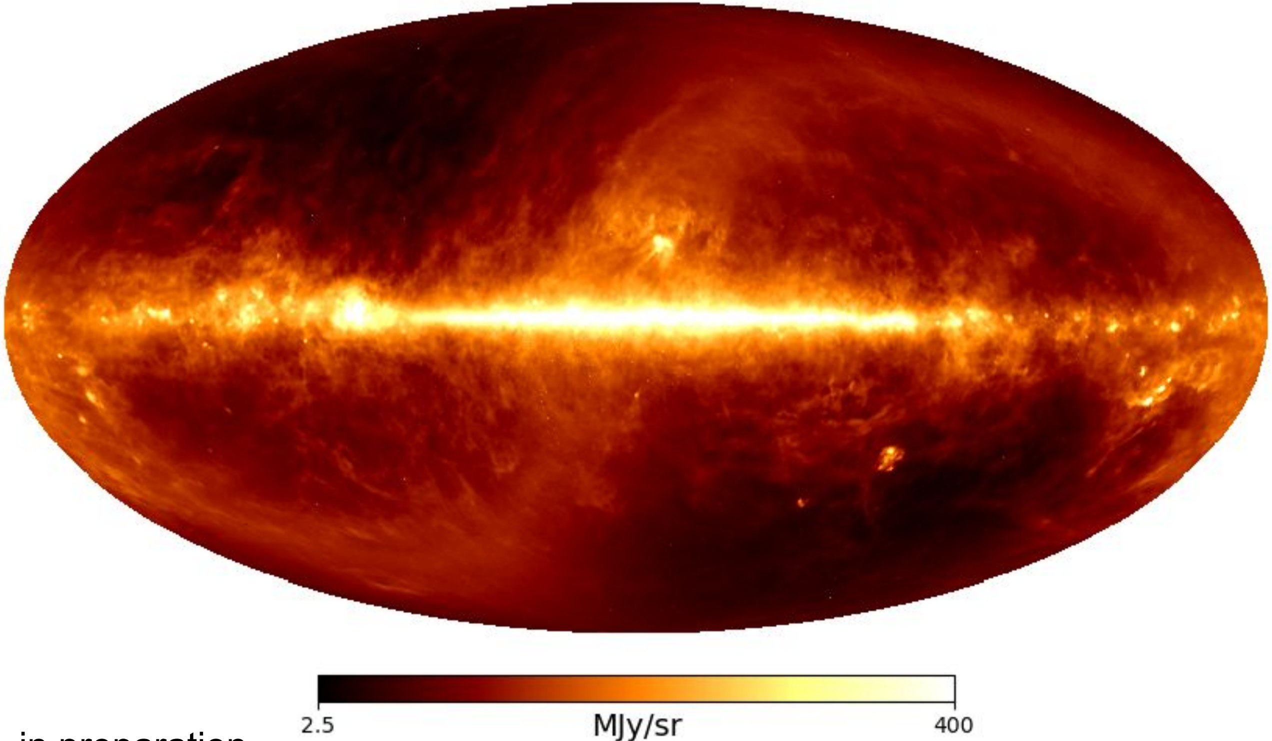


Cosmoglobe DR2: Sub-mm and infrared frequencies



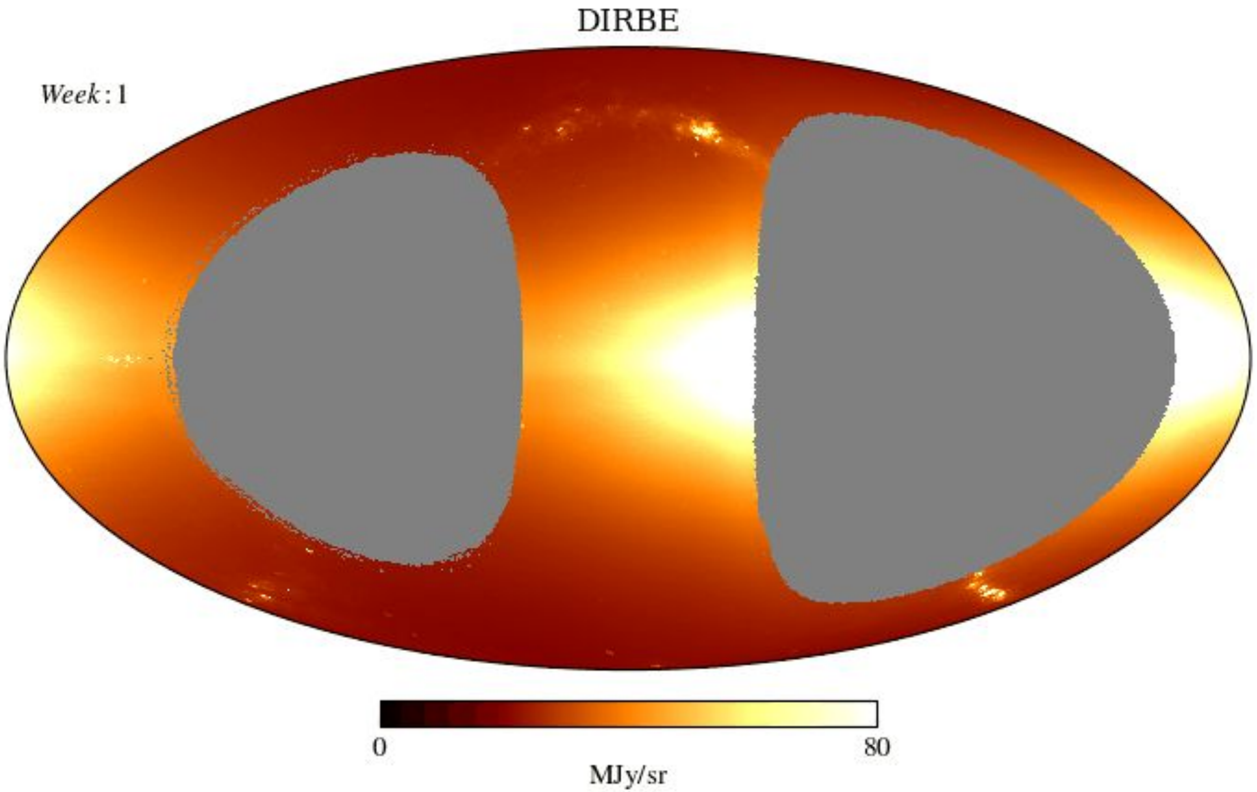
Cosmoglobe DR2 preview: DIRBE reanalysis

DIRBE 100μm map



San et al. (2023), in preparation

Major new feature: Time-domain Zodiacal light modeling



San et al. (2024), in preparation

Cosmoglobe DR2 data

- **DIRBE: TODs for 10 frequencies between 1.25 and 240 μm**
- Planck HFI DR4: Maps for 100 - 857 GHz
  - Pre-subtracted CMB and zodiacal light emission
- FIRAS: Low-resolution maps, included for cross-checking calibration
- (If necessary and given enough time, we have very recently secured IRAS Level 1 data from IPAC on disk in Oslo, which could help with improving angular resolution to ~1 arcmin between 12 and 100 μm)

Cosmoglobe DR2 model

Current data model includes:

- Six-component time-domain zodical light model (Kelsall et al. 1998):
  - Cloud
  - Three asteroid bands
  - Circumsolar ring + Earth-trailing feature
- Three thermal dust components with constant spectral indices:
  - Local dust traced by Edenhofer et al. 3D template
  - Distant HI correlated dust
  - Distant CII correlated dust
- WISE catalog of ~240k stars, fixed position, but free amplitude and spectral index per star
- Free-free emission given by Planck 2015 model

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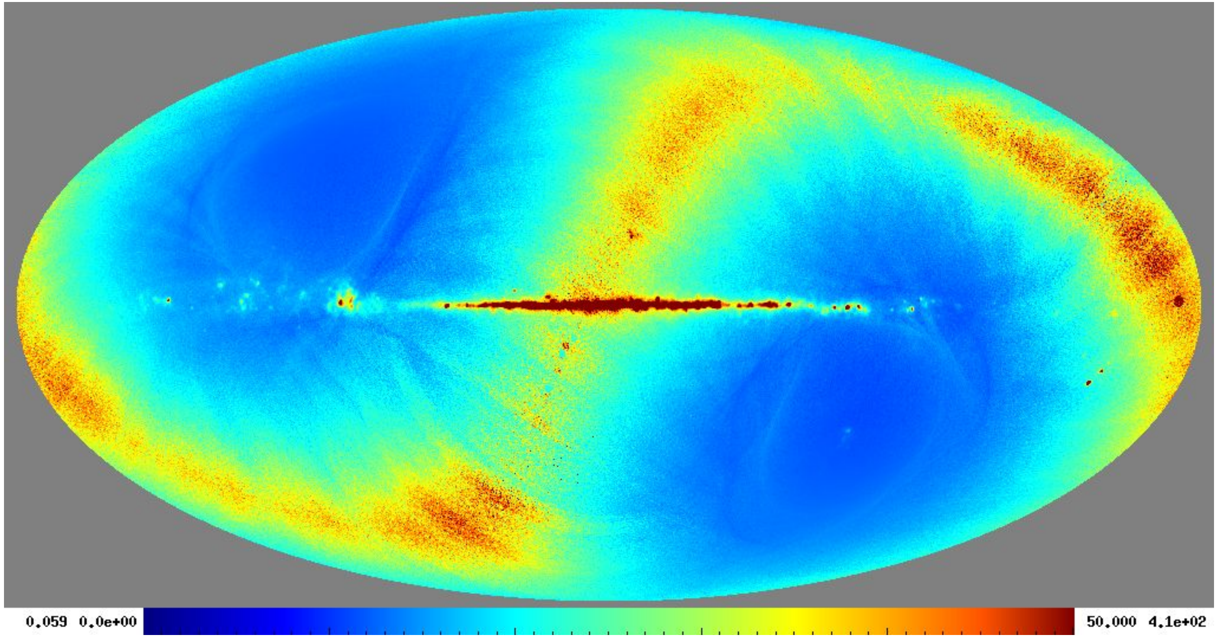
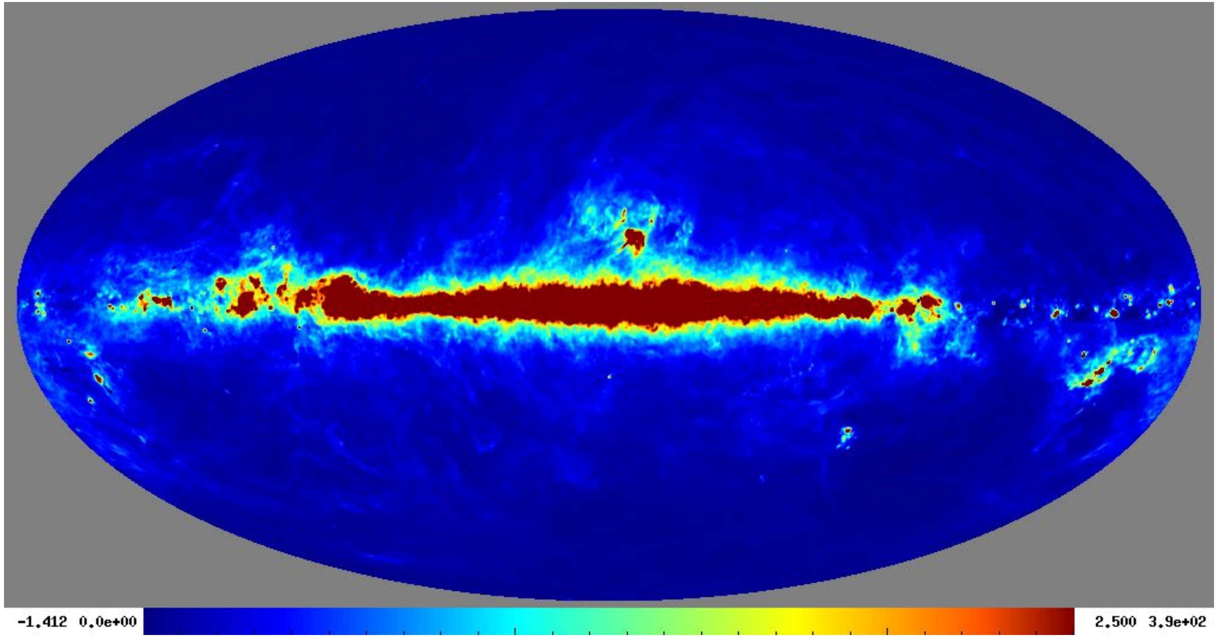
Example: Decomposing DIRBE 12 μm

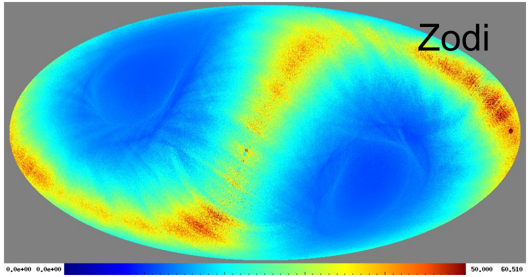


Color scale: +/- 50 MJy/sr

Example: Decomposing DIRBE 12 μm



Color scale: +/- 2.5 MJy/sr



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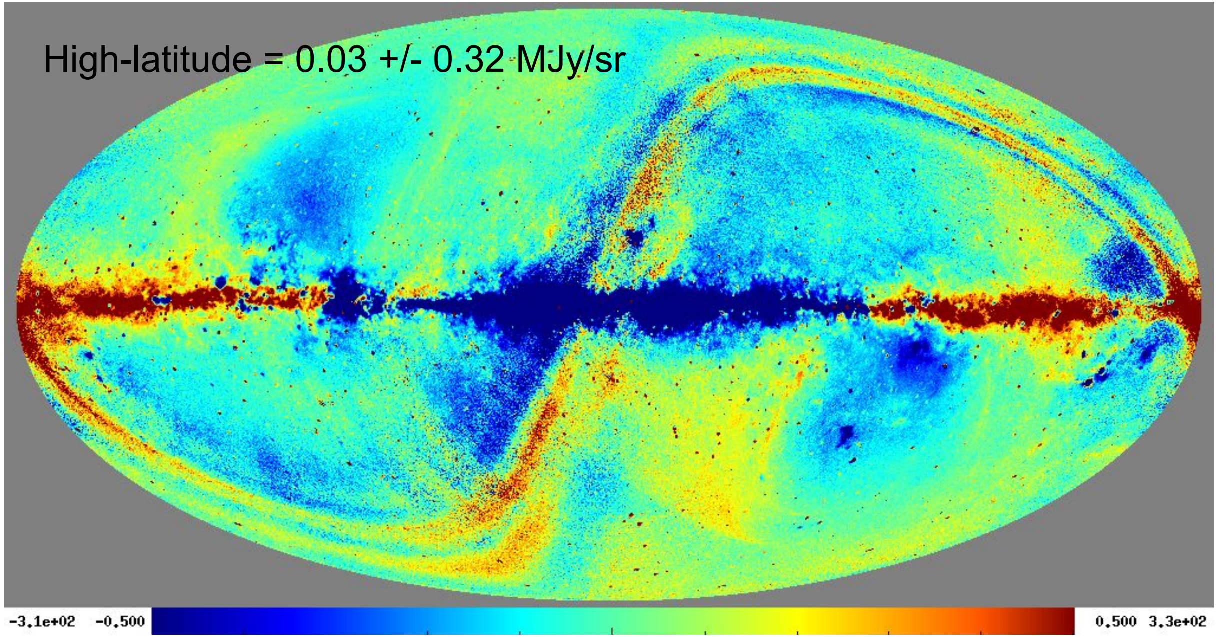
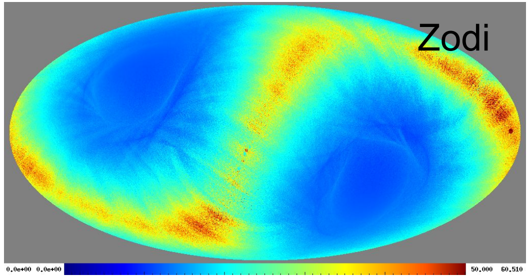
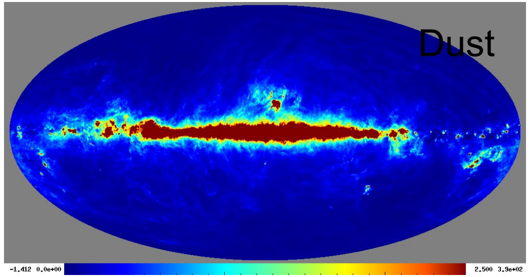
Example: Decomposing DIRBE 12 μm

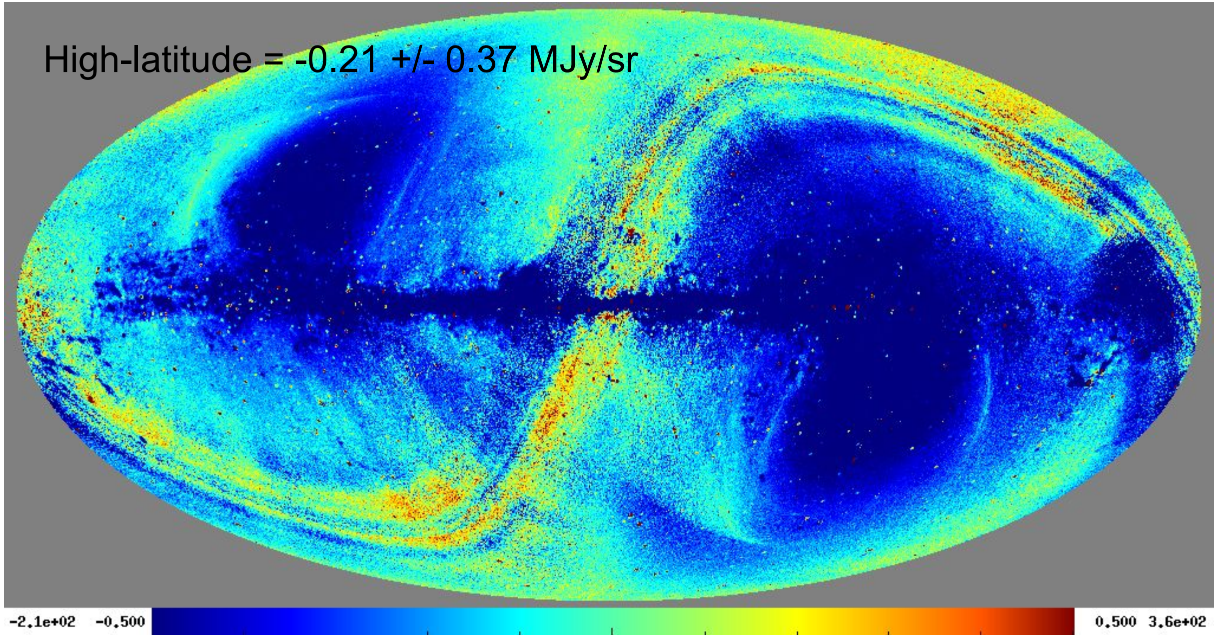


Color scale: +/- 0.5 MJy/sr



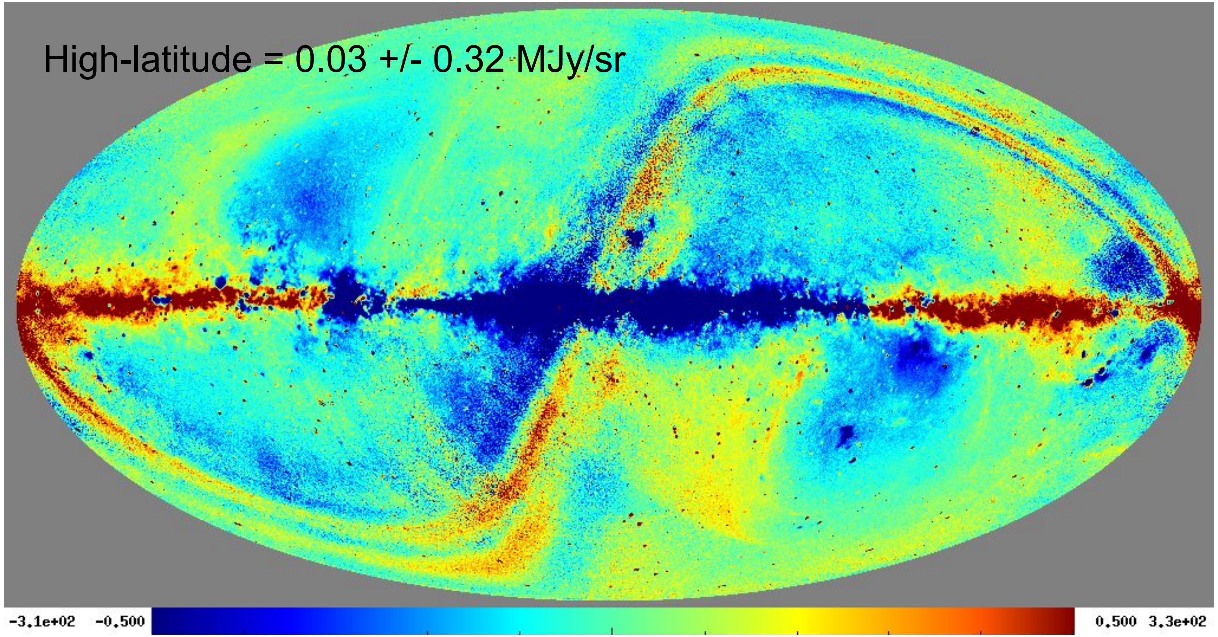


DIRBE 12 μm residual with Kelsall et al. (1998) model



Color scale: +/- 0.5 MJy/sr

Example: Decomposing DIRBE 12 μm

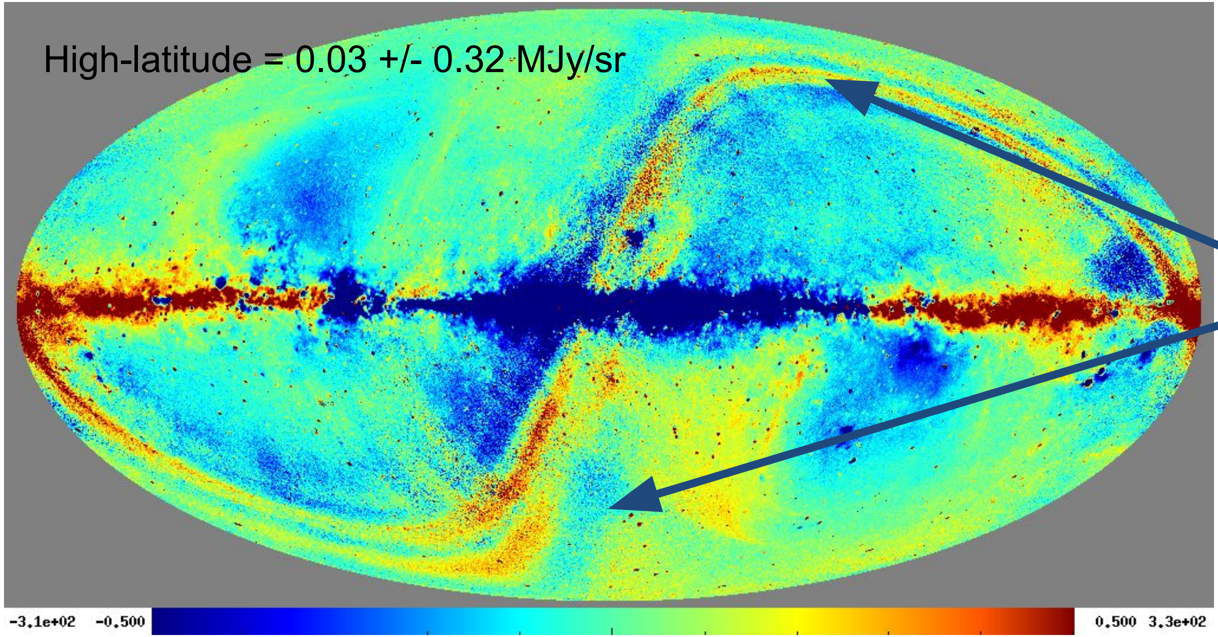


Color scale: +/- 0.5 MJy/sr

Same parametric model used in both cases

Commander improvements comes exclusively from better fitting algorithms (using TOD, all data, joint foregrounds etc.)

Example: Decomposing DIRBE 12 μm



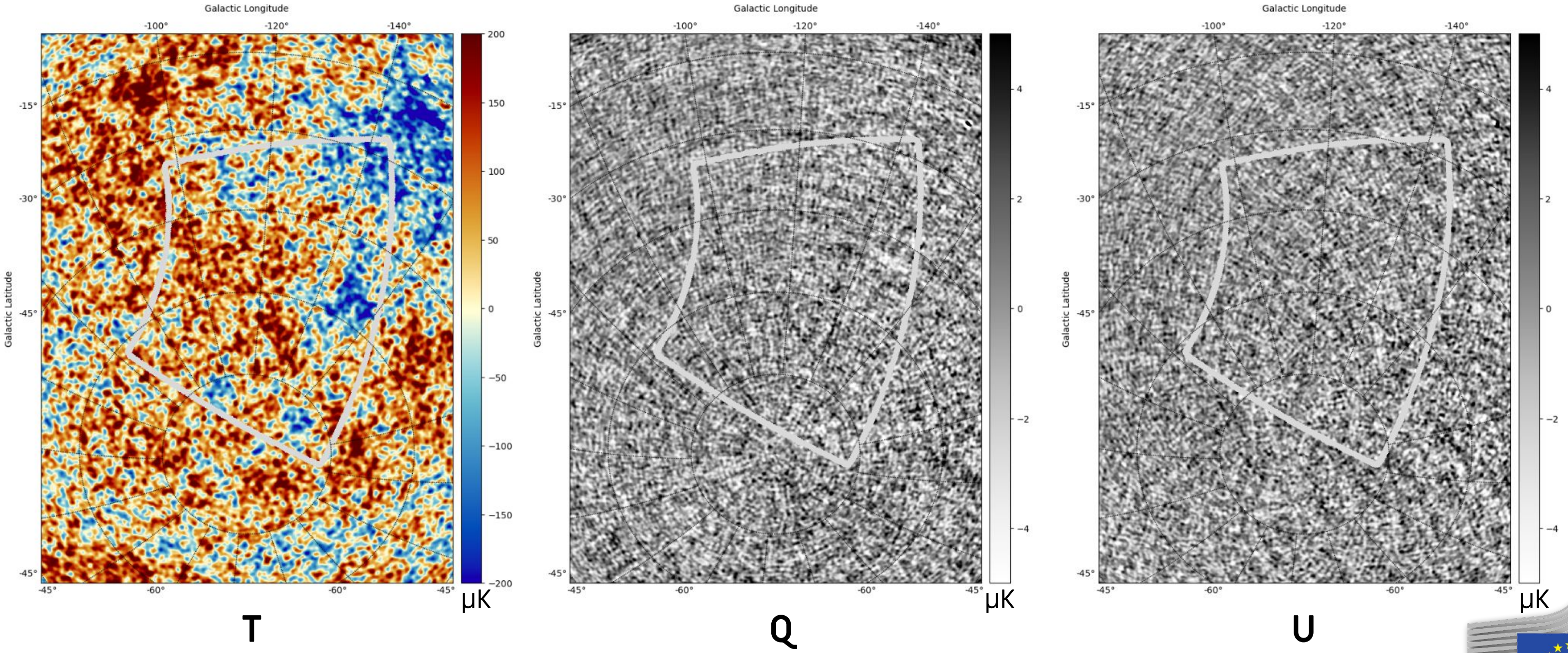
Color scale: +/- 0.5 MJy/sr

Cannot fit asteroid bands properly with K98 model

Need to add more components (bands, rings etc.) as seen by IRAS to the parametric model to dig much deeper

On-going: SPIDER – first demonstration of partial sky analysis

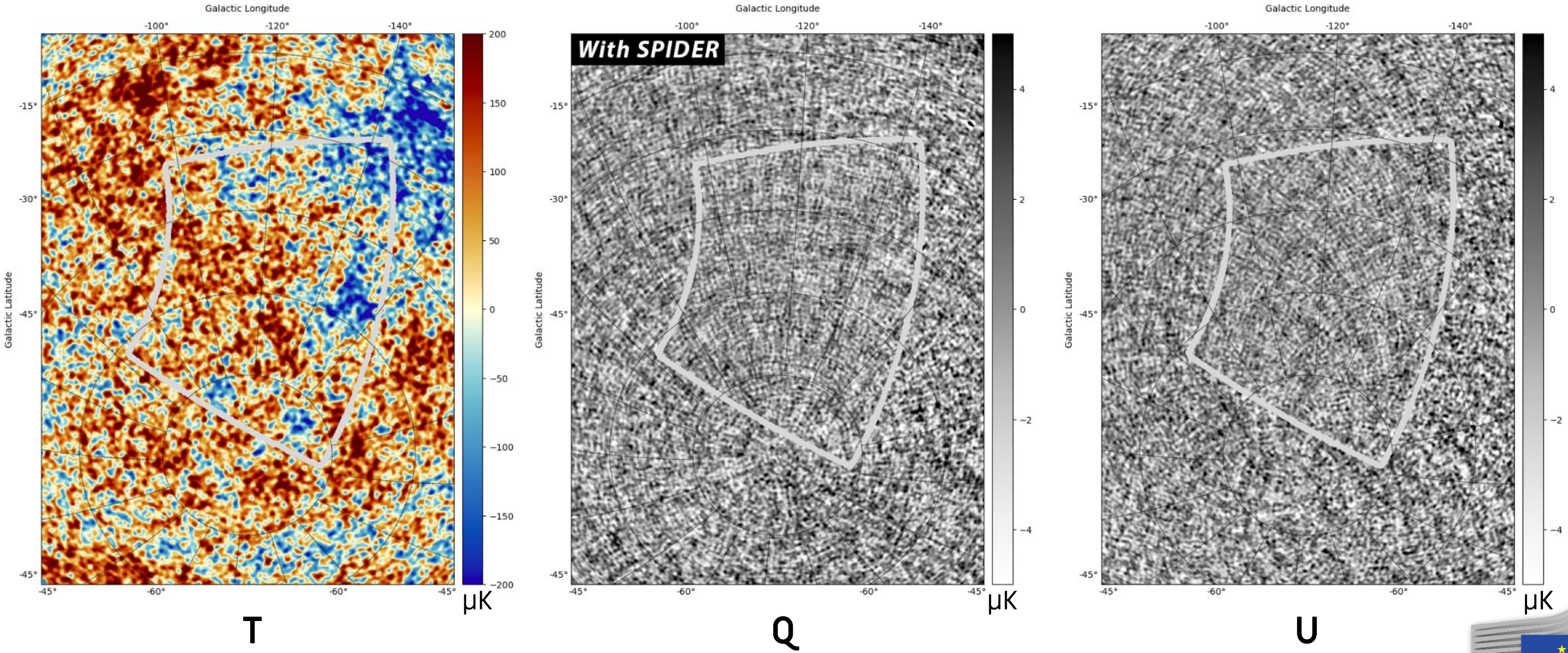
Joint Planck + WMAP + Haslam analysis (without SPIDER)



Thommesen et al. (2023), in preparation

On-going: SPIDER – first demonstration of partial sky analysis

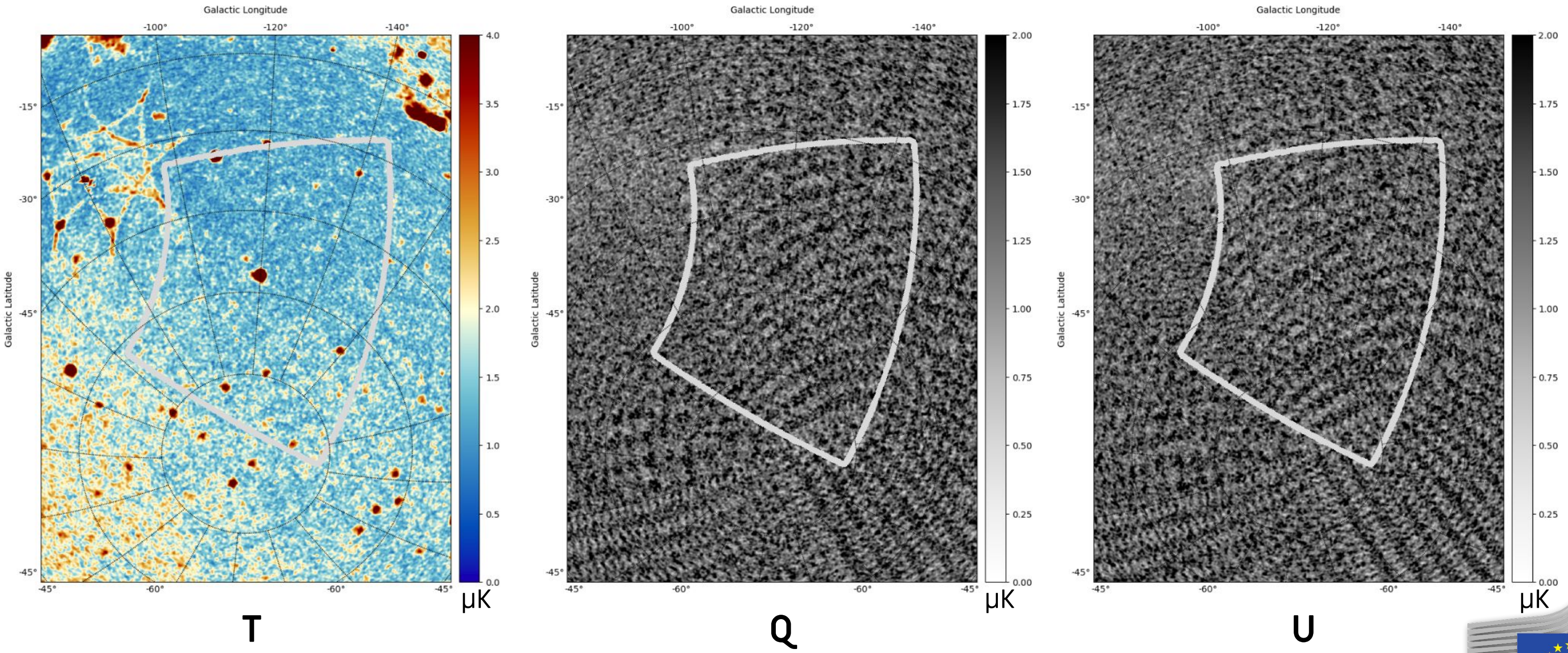
Joint Planck + WMAP + Haslam + SPIDER analysis



Thommesen et al. (2023), in preparation

SPIDER – noise uncertainty per pixel

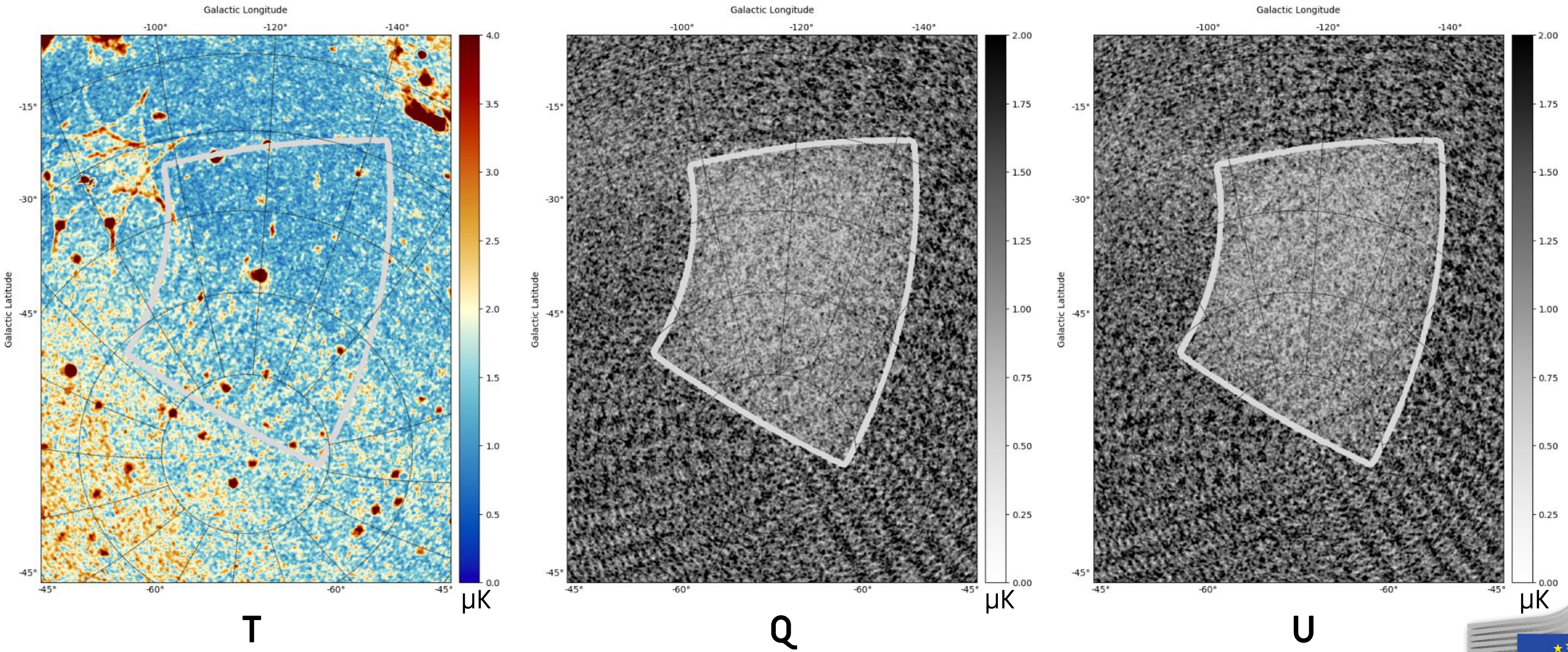
Joint Planck + WMAP + Haslam analysis (without SPIDER)



Thommesen et al. (2023), in preparation

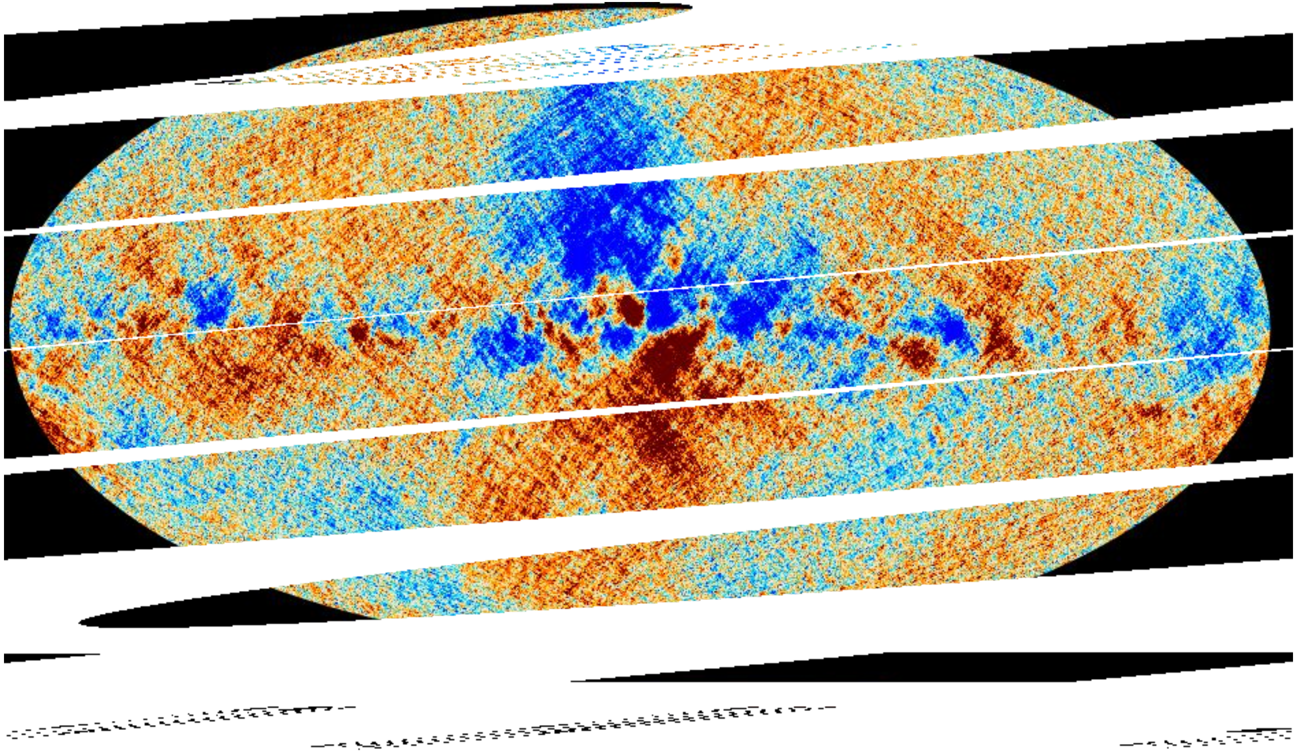
SPIDER – noise uncertainty per pixel

Joint Planck + WMAP + Haslam + SPIDER analysis



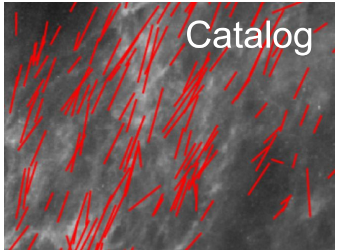
Thommesen et al. (2023), in preparation

The future: LiteBIRD simulated TOD analysis

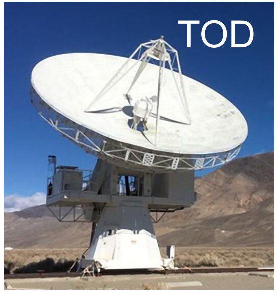


Aurlien et al. (2023), in preparation

Also on-going (but early days) efforts



PASIPHAE
Optical 3D starlight polarization



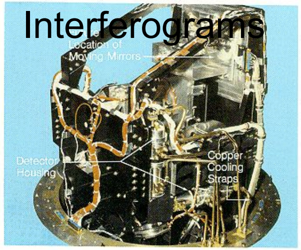
COMAP
High-res 26-34 GHz spectrometer

CHIPASS
1.4 GHz survey

QUIJOTE
11-19 GHz polarization

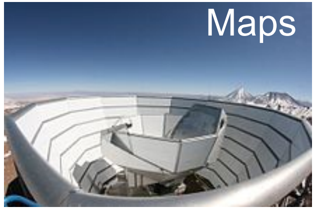
C-BASS
5 GHz all-sky T+P

Planck HFI
100 - 857 GHz



Test unit being prepared for vibration test. Horn, calibrator, and mirror mechanism are not shown.

COBE-FIRAS
Absolute calibration



ACT
High-res T+P

European Commission

Global analysis summary

- Joint end-to-end analysis needed to constrain correlated parameters
- Joint analysis of independent experiments break each other degeneracies
- Joint analysis give more complete noise characterization
- Single pipeline is fast and effective and require less human interaction

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- Global Component Separation Network
  - Diku/RCN INTPART Grant agreement No. 274990 - PI I. K. Wehus - 2018-2023

Useful papers for readers interested in general Bayesian CMB analysis

- First proposals of Bayesian CMB Gibbs sampling
  - Jewell et al. (2004; arxiv:0209560), Wandelt et al. (2004; 0310080)
- Commander1: First high-resolution CMB Gibbs sampling implementation
  - Eriksen et al. (2004; arxiv:0407028)
- First joint CMB and foreground sampler (pixel-by-pixel)
  - Eriksen et al. (2008; arxiv:0709.1058)
- Global sky model from Planck derived with Commander
  - Planck collaboration (2016; arxiv:1502.01588)
- Commander2: First multi-resolution CMB Gibbs sampler
  - Seljebotn et al. (2019; arxiv: 1710.00621)
- Commander3: First TOD-based CMB Gibbs sampler and application to LFI
  - BeyondPlanck collaboration (2020; arxiv:2011.05609)
- Cosmoglobe DR1: First CMB multi-experiment analysis (LFI+WMAP)
  - Watts et al. (2023; arxiv:2303.08095)

Technical papers for specially interested readers

- Bayesian TOD-level **noise estimation**
  - Wehus et al. (2012; arxiv:1110.1343)
  - Ihle et al. (2023; arxiv:2011.06650)
- Fast and optimal **CMB map-making** by Gibbs sampling
  - Keihänen et al. (2023; arxiv:2011.06024)
- Bayesian **gain estimation**
  - Gjerløw et al. (2023; arxiv:2011.08082)
- Bayesian **bandpass estimation** and correction
  - Svalheim et al. (2023; arxiv:2201.03417)
- Integrated **cosmological parameter estimation**
  - Jewell et al. (2008; arxiv:0807.0624) – first proposal
  - Racine et al. (2017; arxiv:1512.06619) – breaking the low S/N degeneracy
  - Eskilt et al. (2023; arxiv:2306.15511) – first integrated Commander implementation

For more information, see cosmoglobe.uio.no