BeyondPlanck:

Optimal end-to-end Bayesian analysis of Planck LFI

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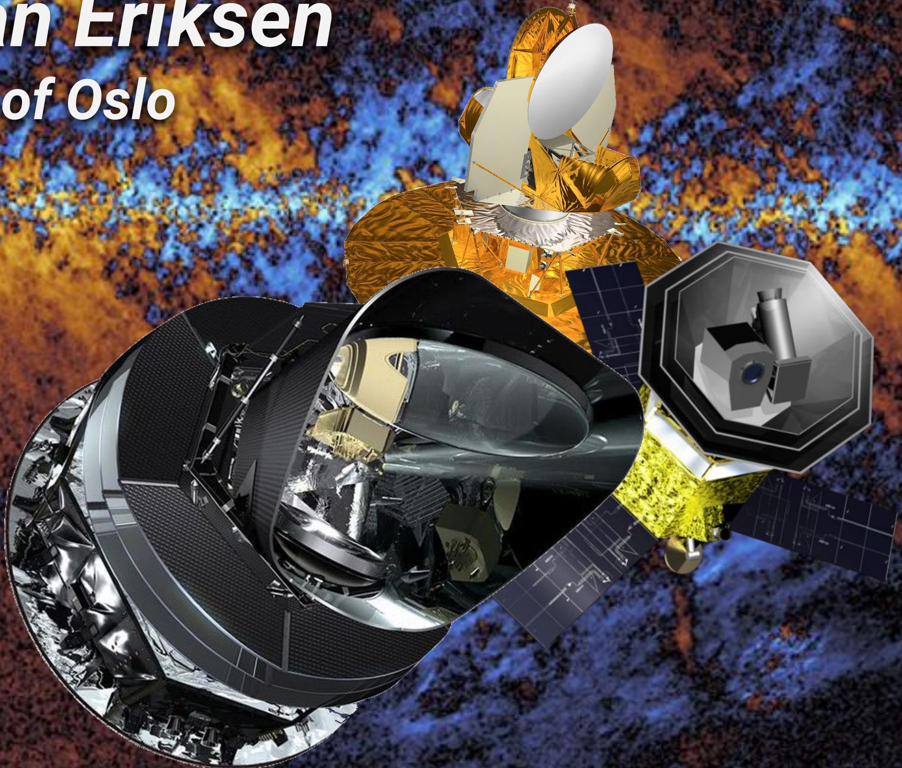

March 15th, 2021

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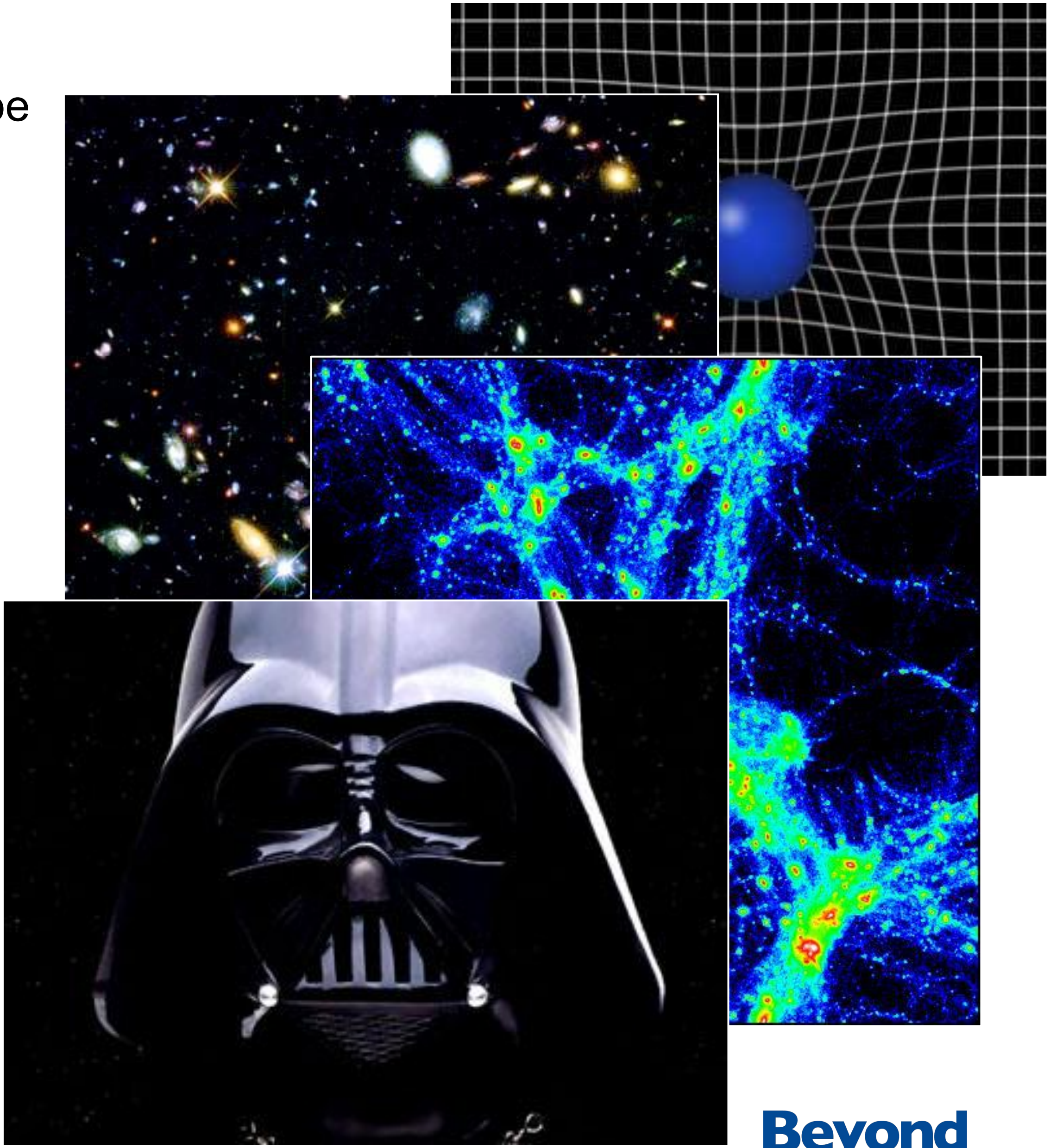
Cosmology at a glance

- How can we mathematically describe the properties of space?
- How many stars and galaxies are there?
- Is there matter we cannot see?
- Could the evolution of the universe be dominated by dark forces?



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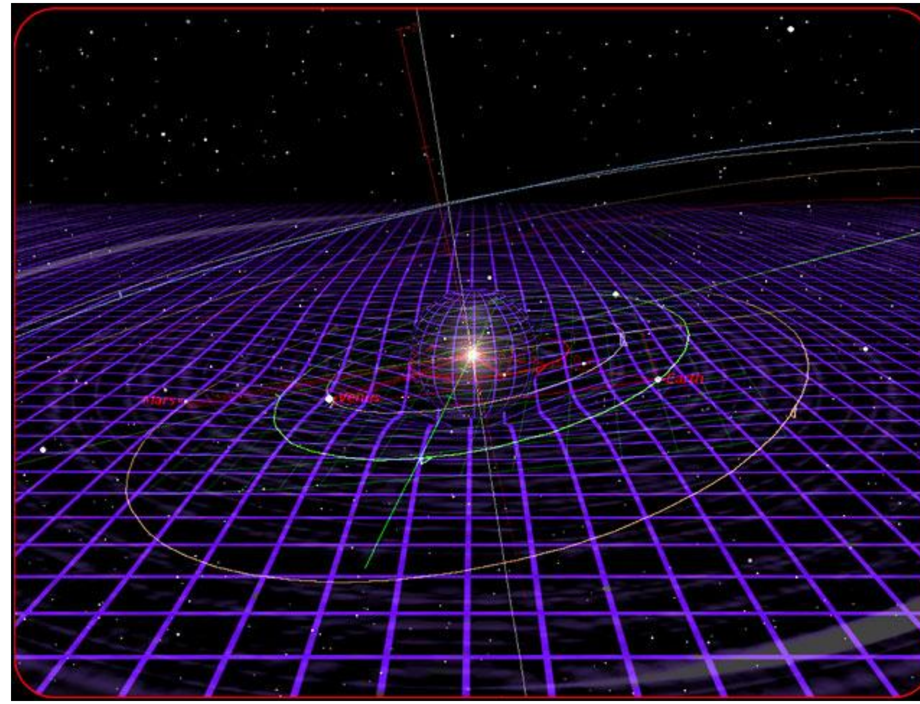
Einstein's theory of General Relativity



In 1916 Einstein published a new theory of gravity (GR), correcting Newton's theory from 1687

GR summarized in one equation:

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Geometry — Contents

GR summarized in one sentence:

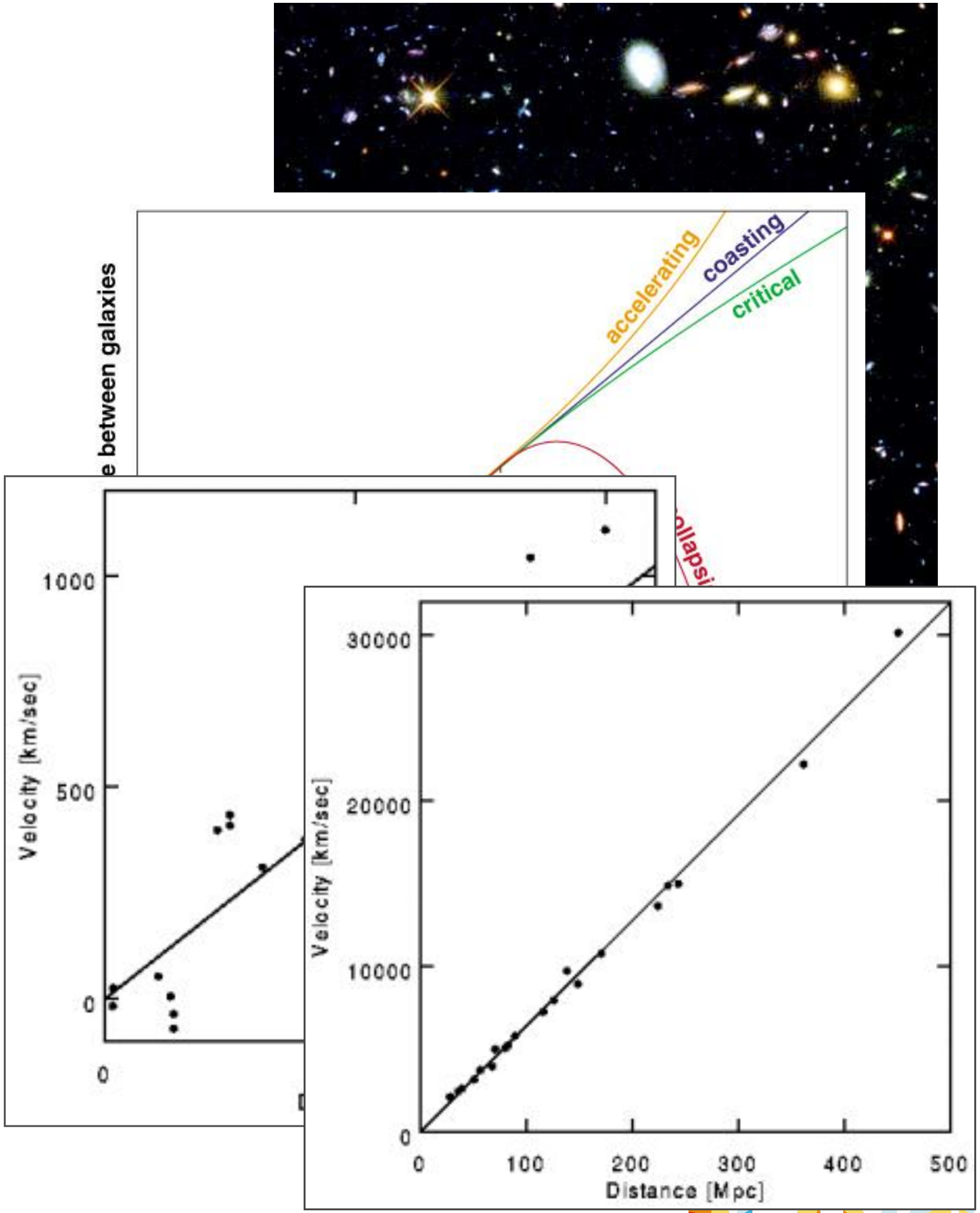
Matter tells space how to curve, and space tells matter how to move

"The greatest blunder of my life"

European Commission

- The dynamics of the universe is dominated by gravity
- GR is therefore our best theory to describe the universe
  - Published in 1916
- "Problem": GR does not allow static solutions!
  - The universe must either expand or contract
  - Einstein was convinced that the universe was unchanging, and «corrected» his theory by adding a term

1925: Edwin Hubble publishes measurements of galaxy velocities as a function of distance – and finds that the universe expands!!



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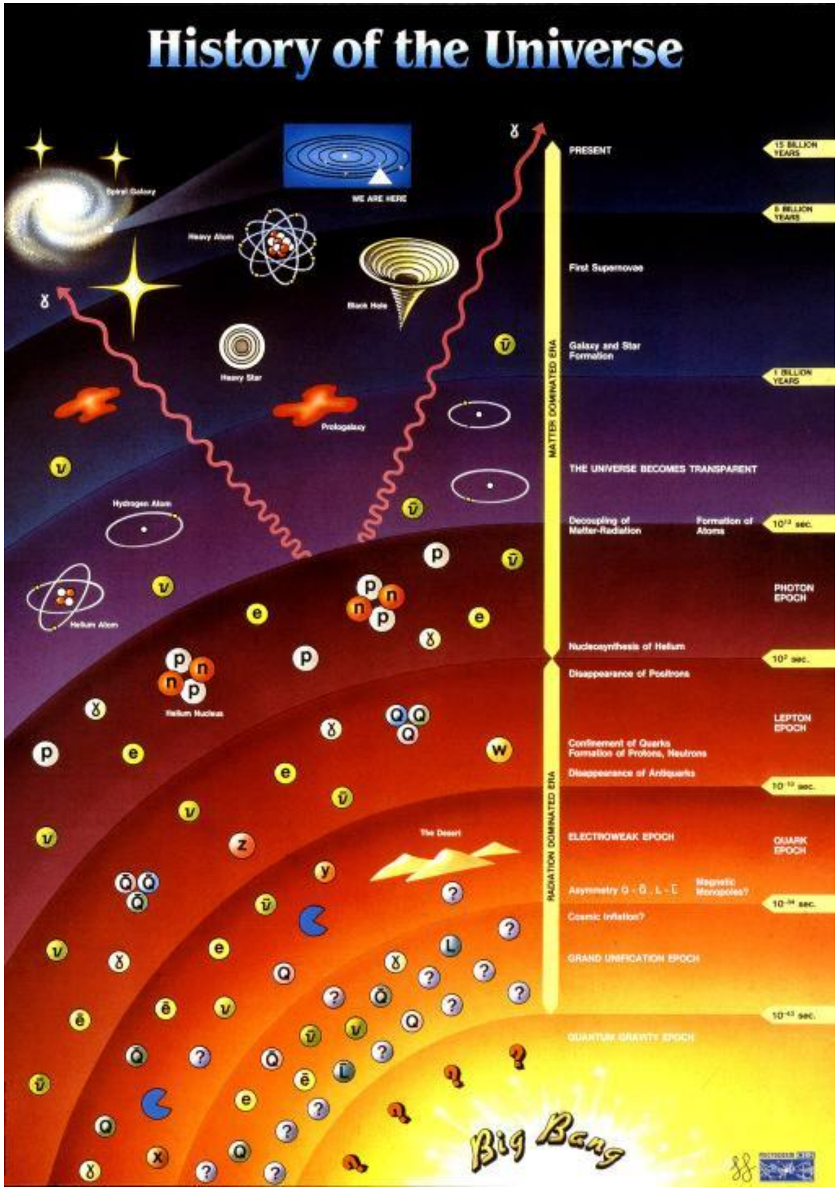
Creation in a hot Big Bang?

George Gamow (1948) –
"The origins of elements"

- If the universe expands today, it must have been smaller earlier
- When you compress a gas, the temperature increases
- Very early the temperature must have been very high; only photons and free elementary particles could exist

- Predictions from Gamow's theory:
  - There must be about 75% hydrogen and 25% helium in the universe
  - The universe should be filled by electromagnetic radiation with a temperature of ~5°K
  - This radiation should be isotropic, ie., equally intense in all directions
  - The intensity should follow a blackbody (Planck) spectrum



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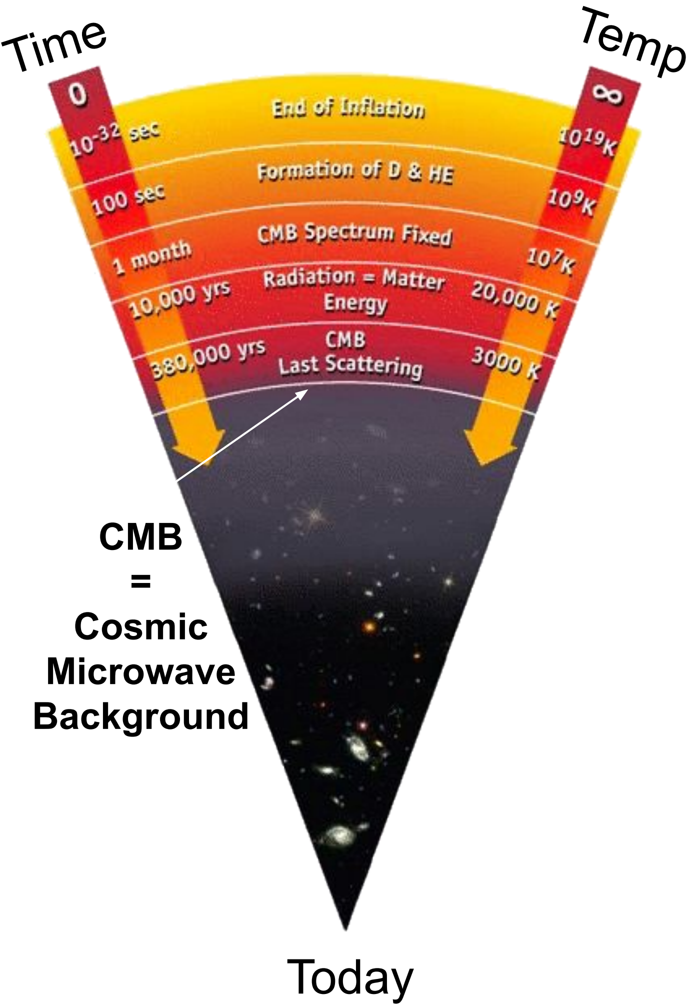
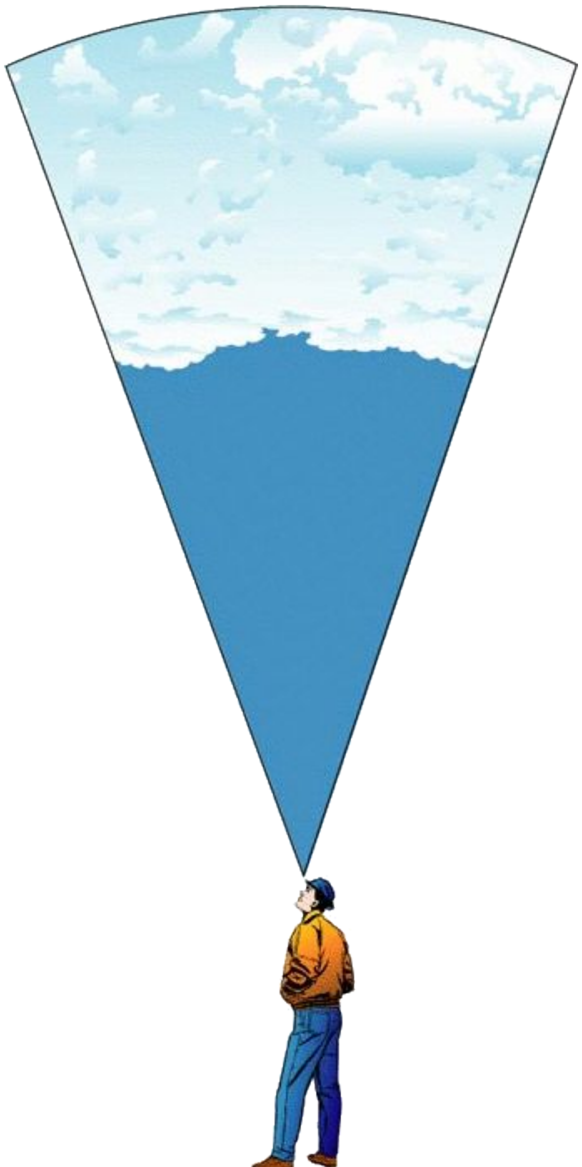
Radiation from the Big Bang



- The universe started as a hot gas of electrons, protons and photons
  - Frequency collisions led to thermodynamic equilibrium
  - Photons could only move a few meters before hitting an electron
- This gas expanded rapidly, and cooled
- When the temperature dropped below 3000°K, electrons and protons combined into neutral hydrogen
- Without free electrons, photons could move freely throughout the universe!



The significance of the CMB

Two important properties:

- Frequency dependency

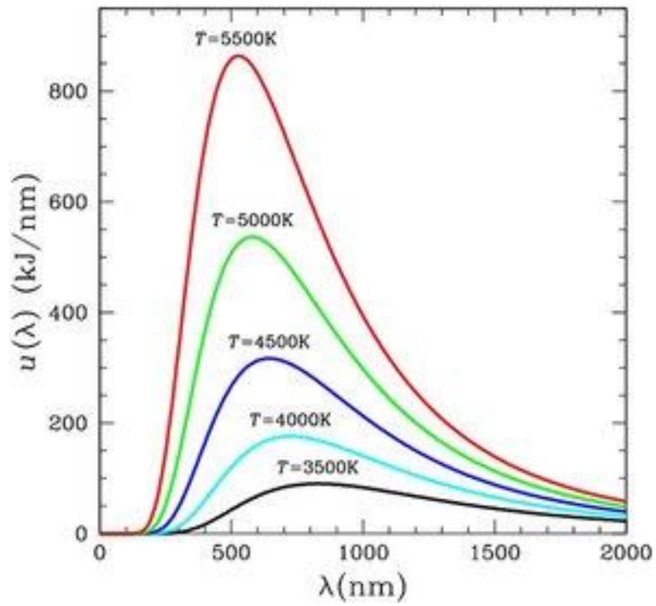
  Photons and electrons in thermodynamic equilibrium generates a Planck spectrum

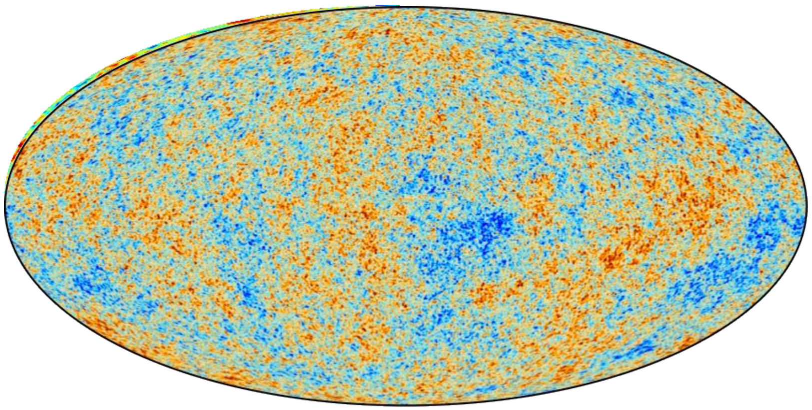
- Spatial temperature variations

  Small temperature variations corresponds to small density variations

  Regions with high density 380,000 years after the Big Bang were the seeds for later galaxy formation

  A CMB map represents a map of the matter in the universe shortly after the Big Bang!





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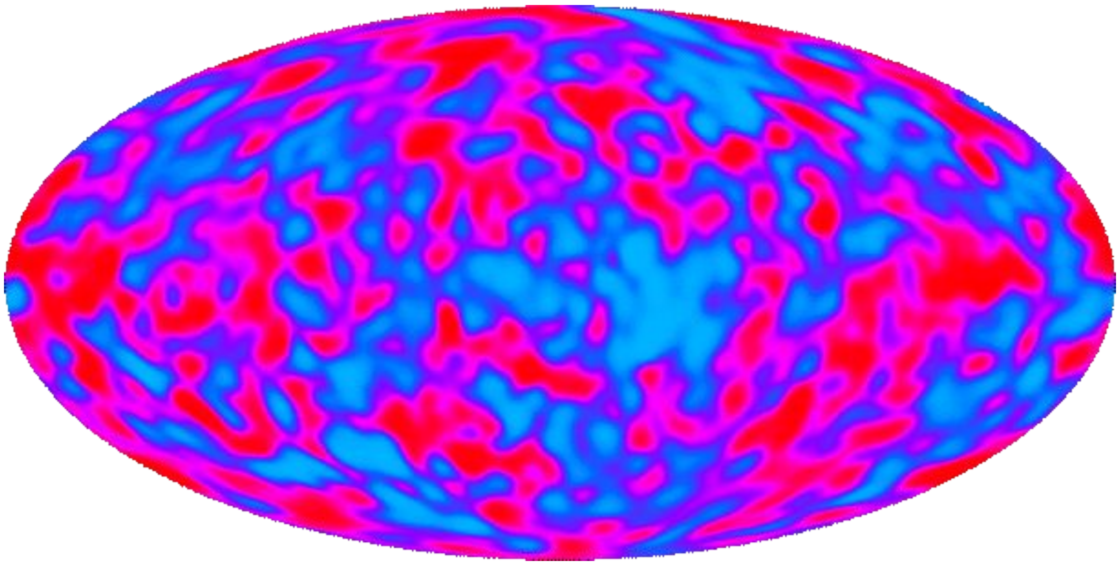
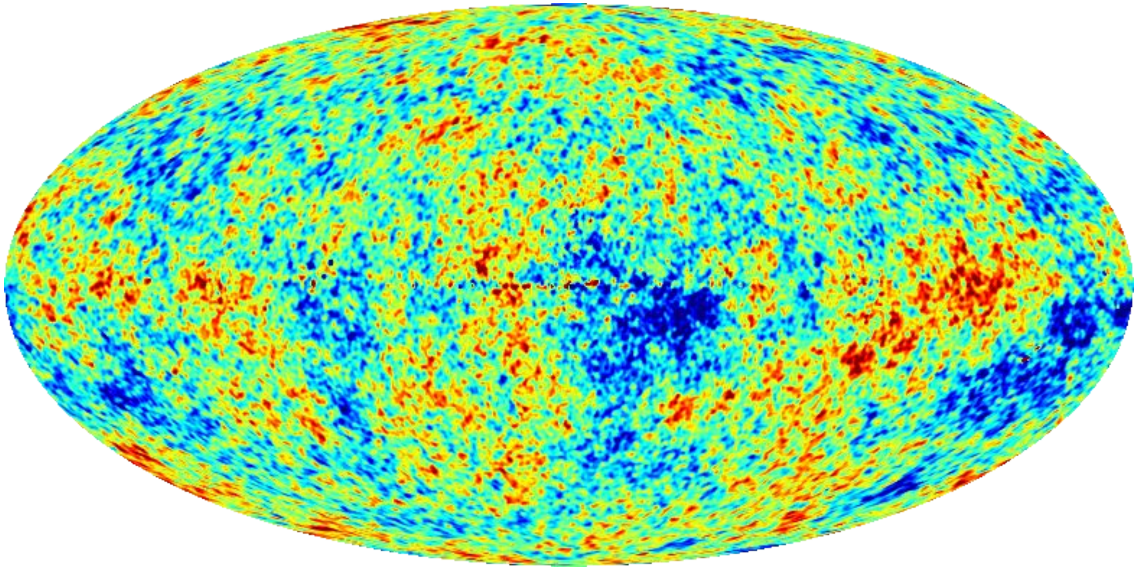
From COBE to Planck and beyond

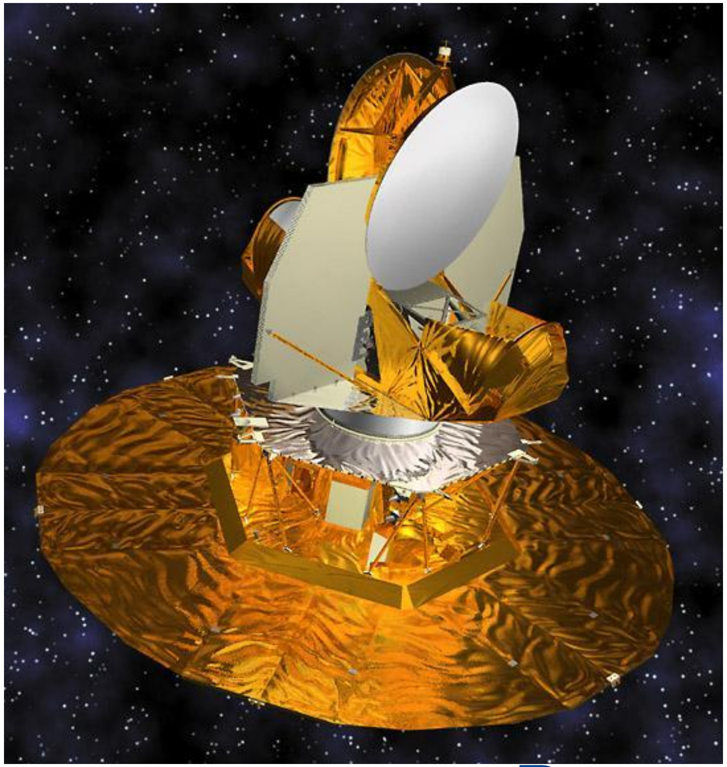


COBE-DMR
1989-1993
NASA funded

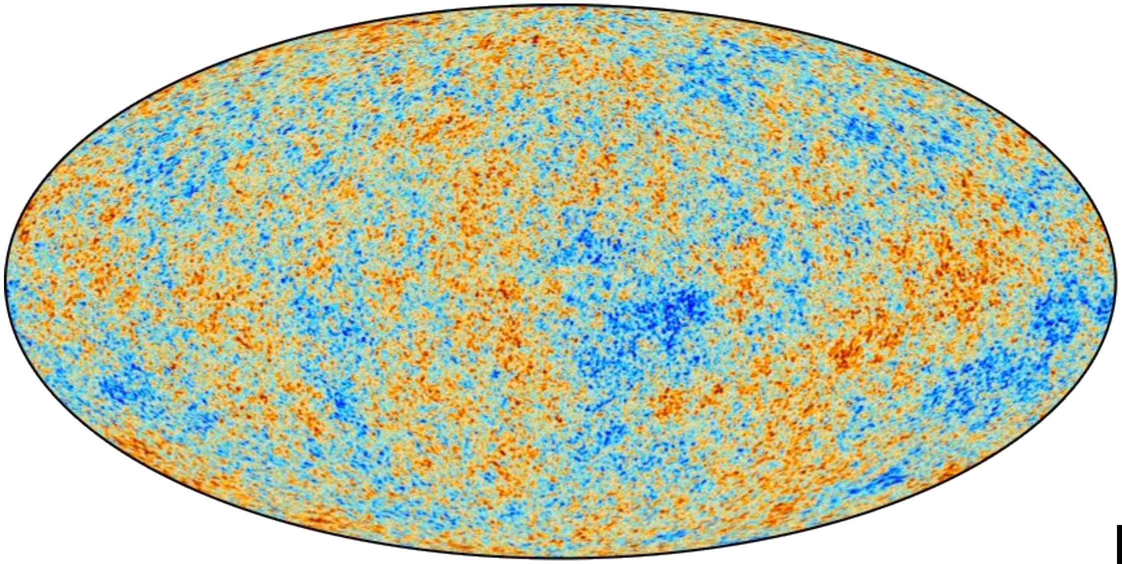
From COBE to Planck and beyond



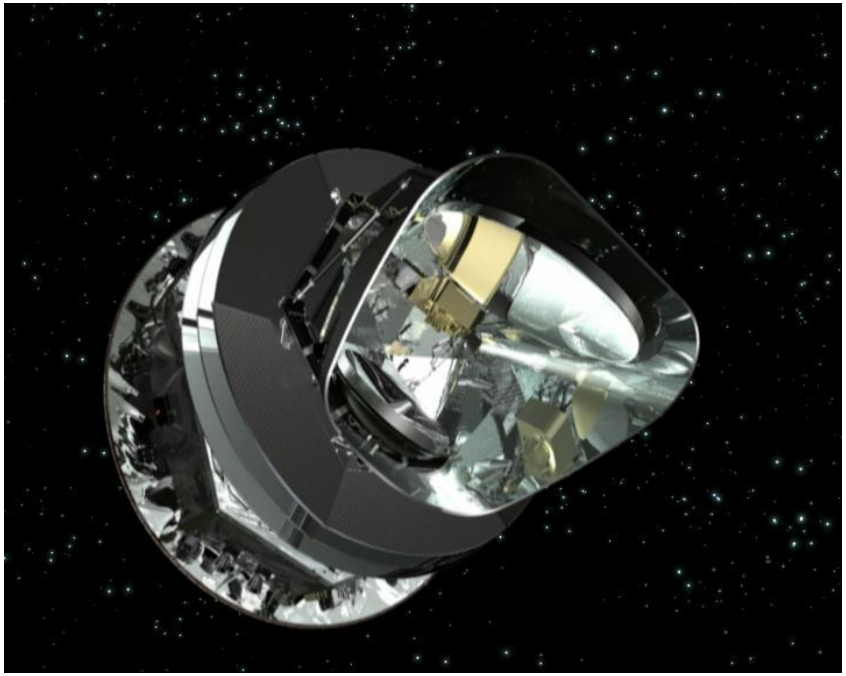
WMAP
2003-2010
NASA funded



From COBE to Planck and beyond

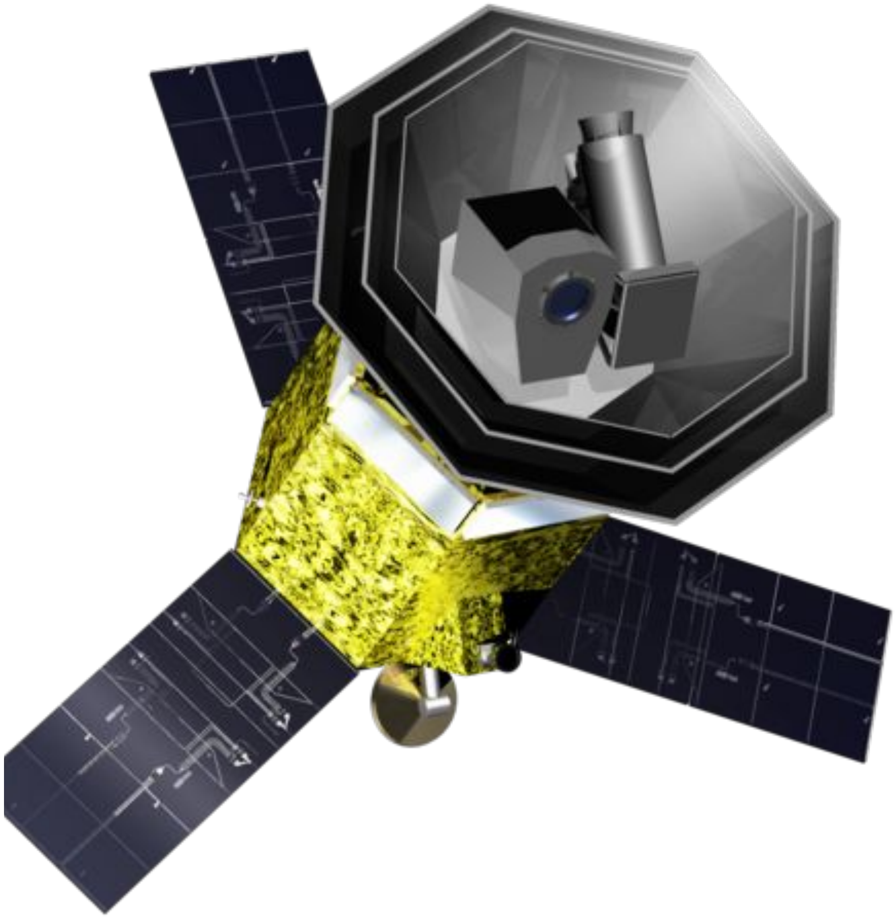


Planck
2009-2013
ESA funded



From COBE to Planck and beyond

LiteBIRD
2028-2032?
JAXA-led



COBE vs WMAP vs Planck

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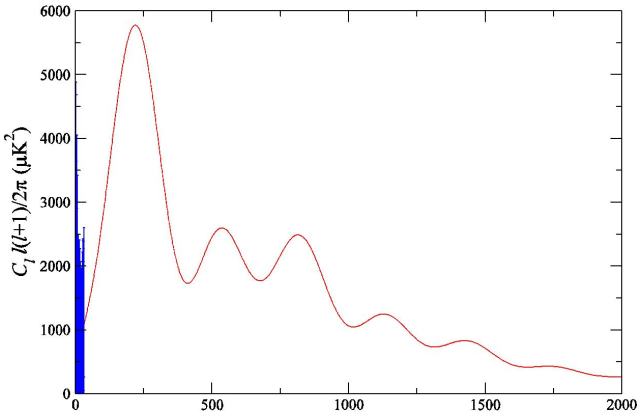
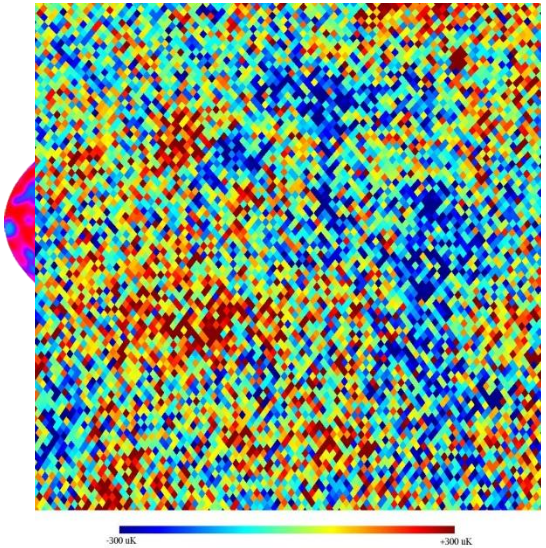
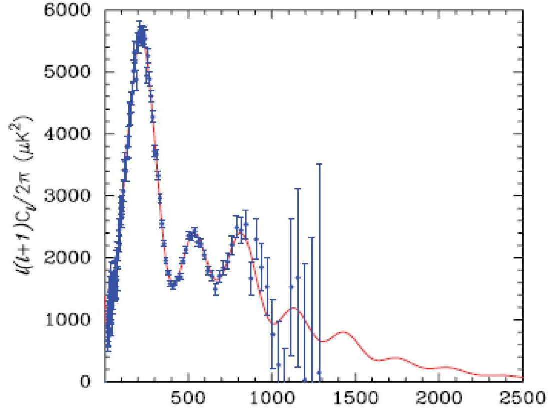
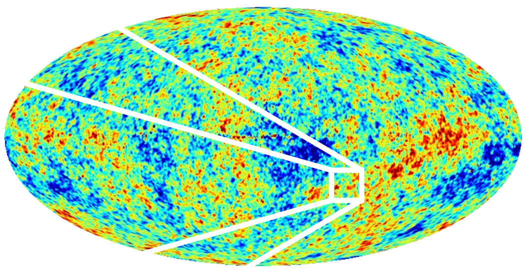
COBE



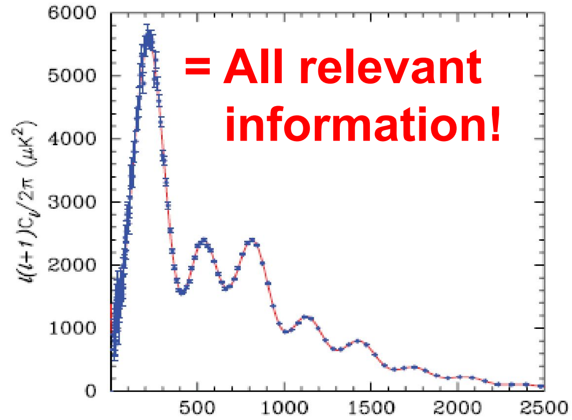


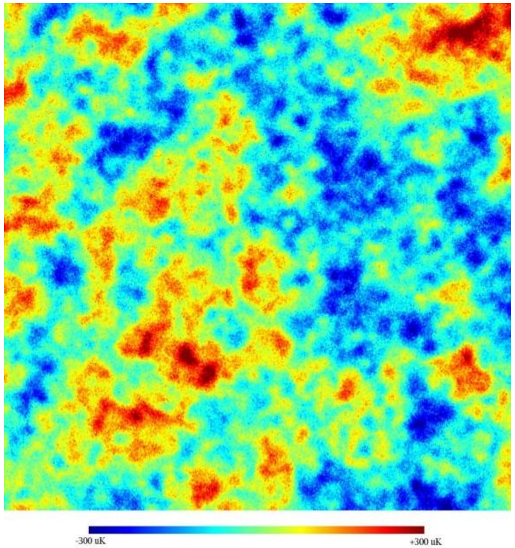
WMAP





Planck





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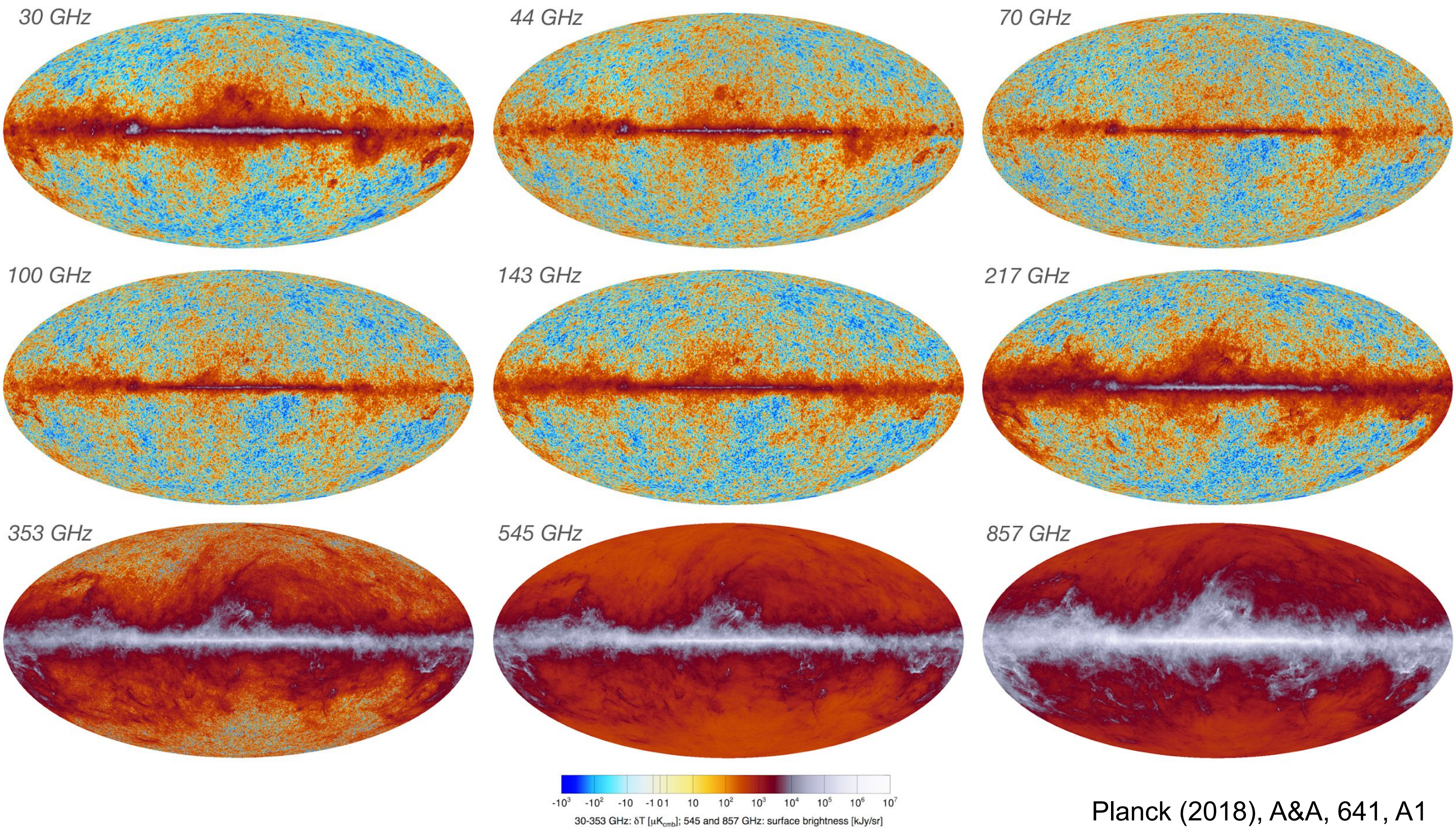
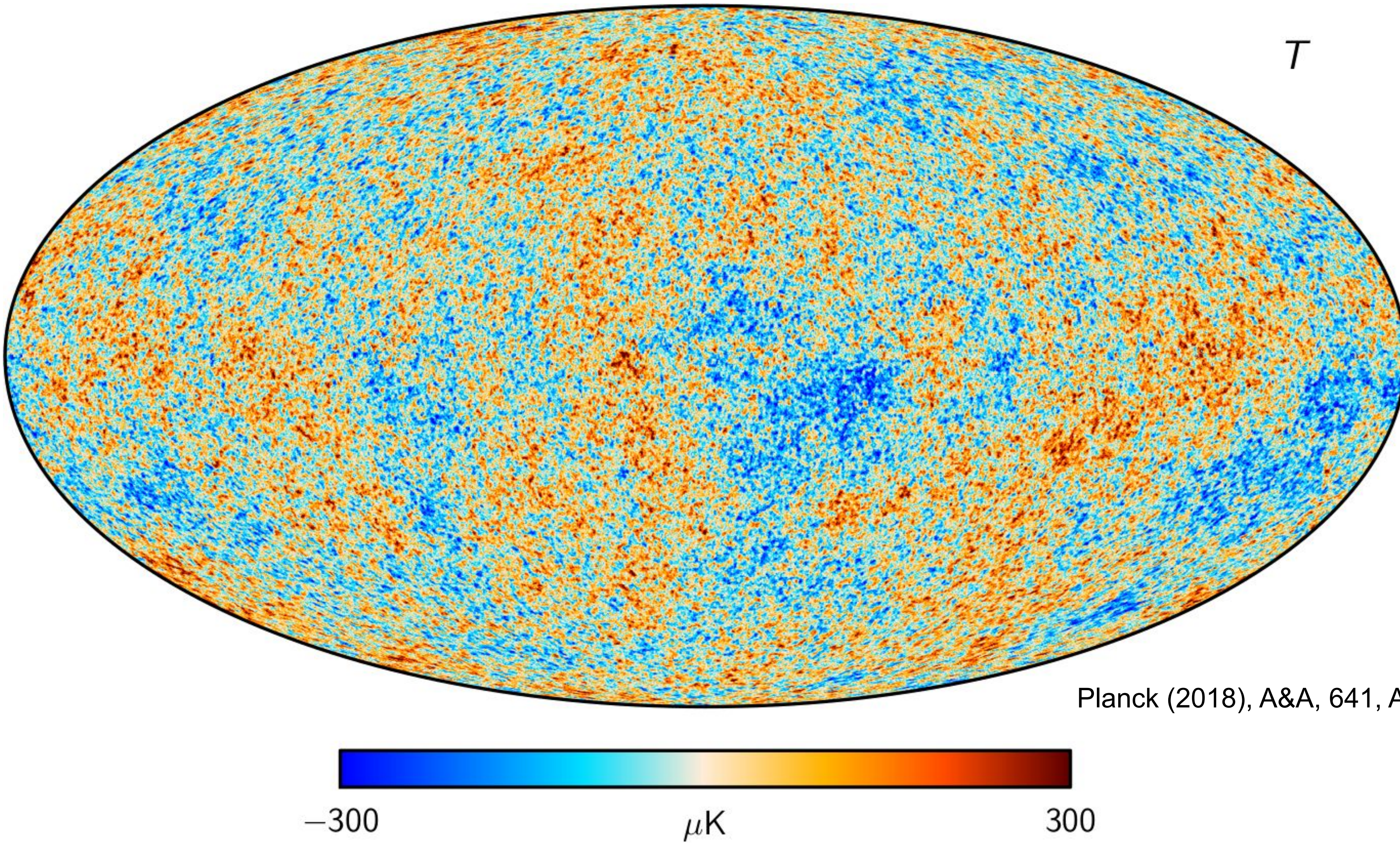
Planck 2018 frequency maps



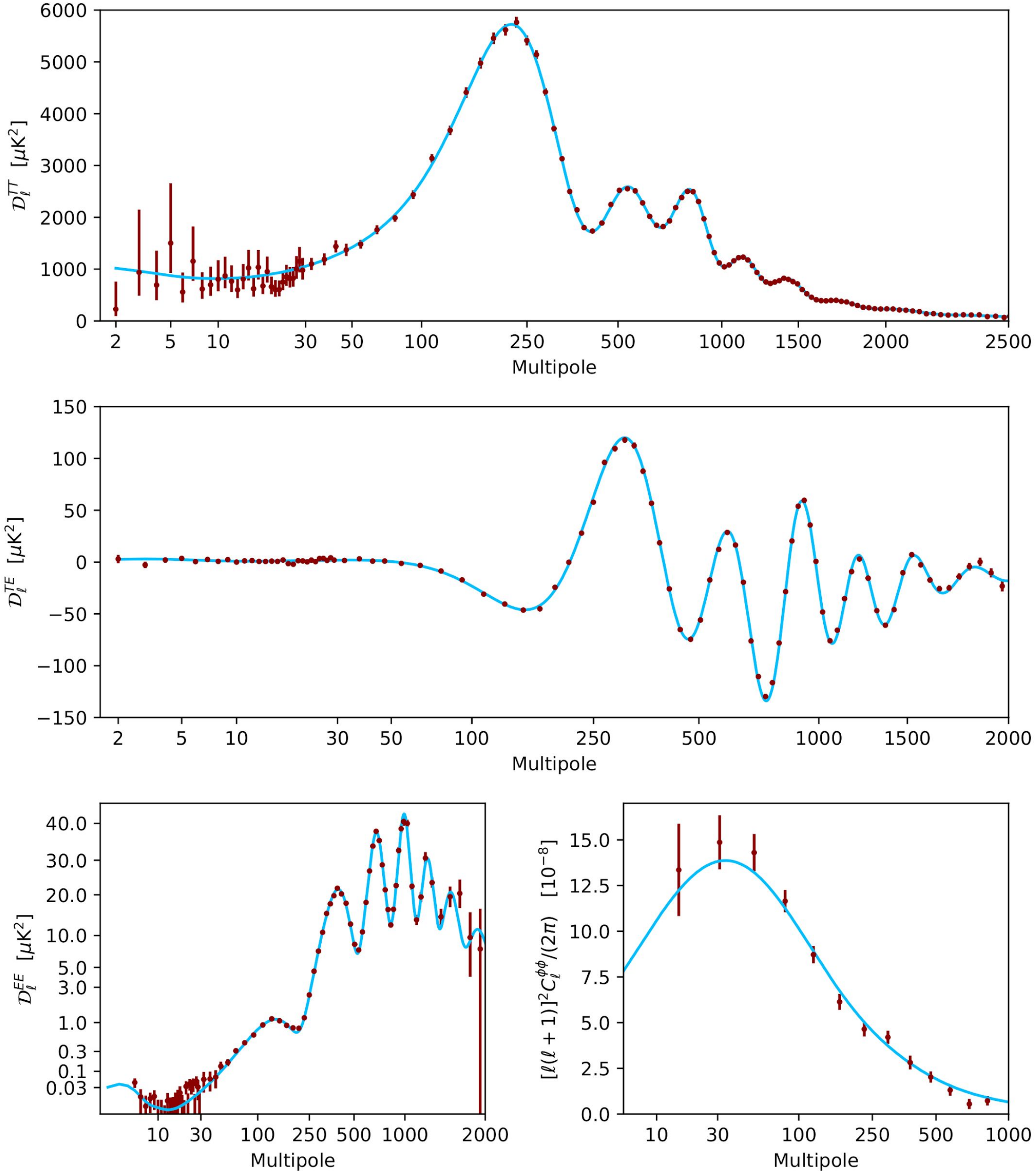
Planck (2018), A&A, 641, A1

Planck 2018 CMB temperature map



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

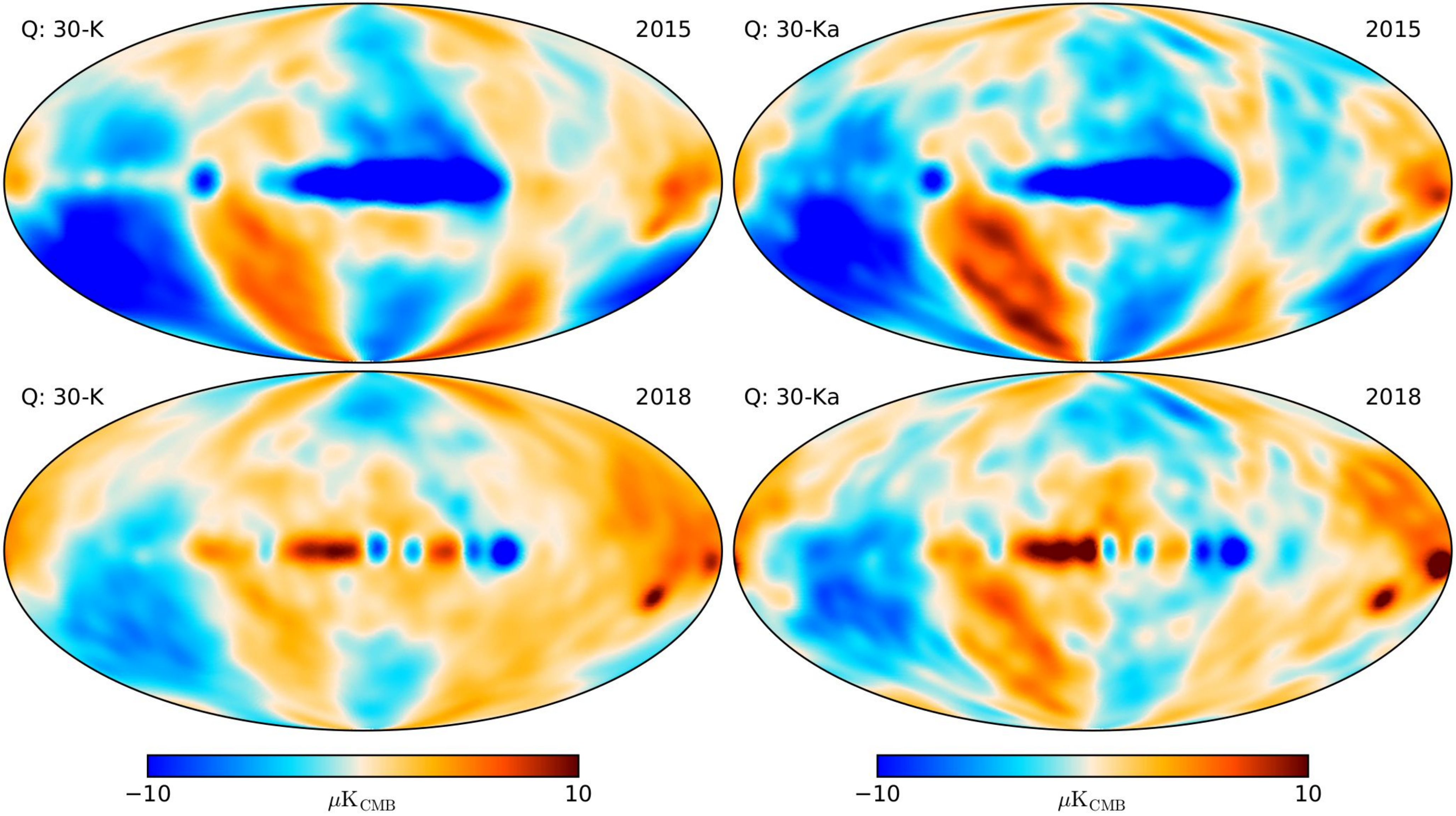
CMB power spectra and cosmological parameters



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

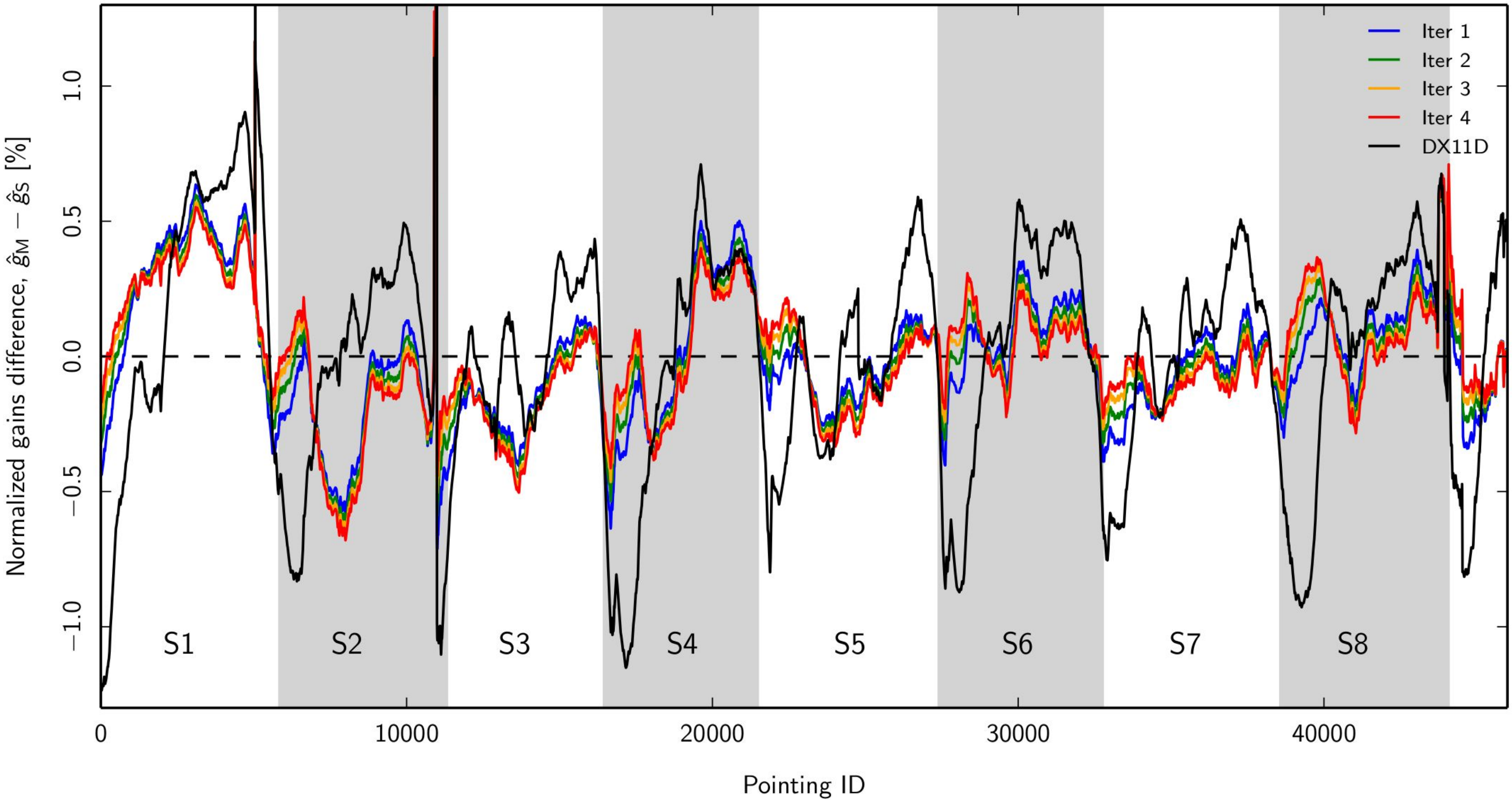
Planck (2018), A&A, 641, A5

What about Planck - WMAP?



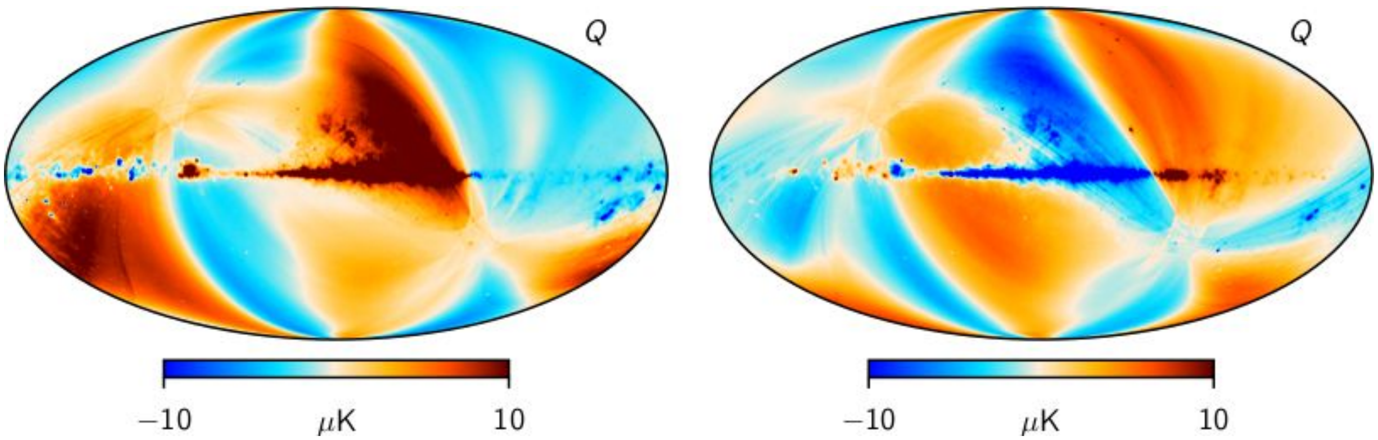
Planck (2018), A&A, 641, A2

Critical question: How well do we really know the gain?

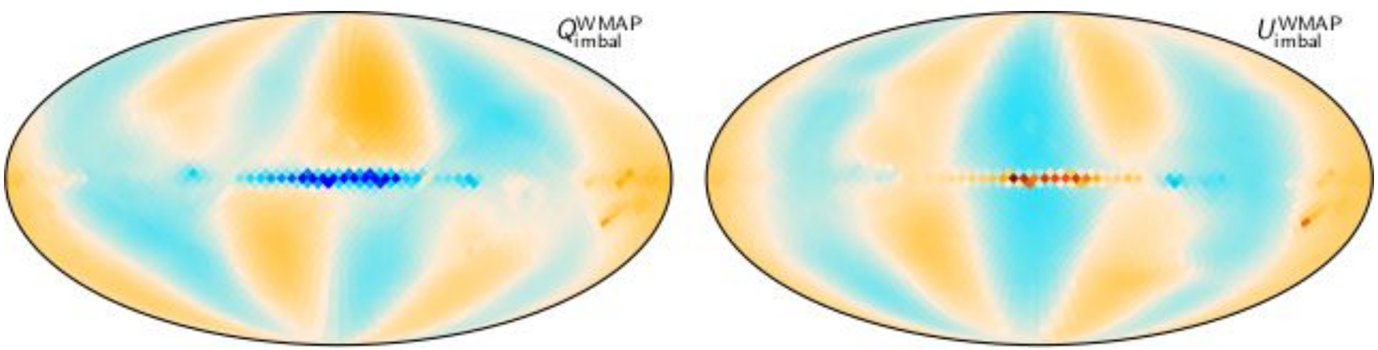


Planck (2018), A&A, 641, A2

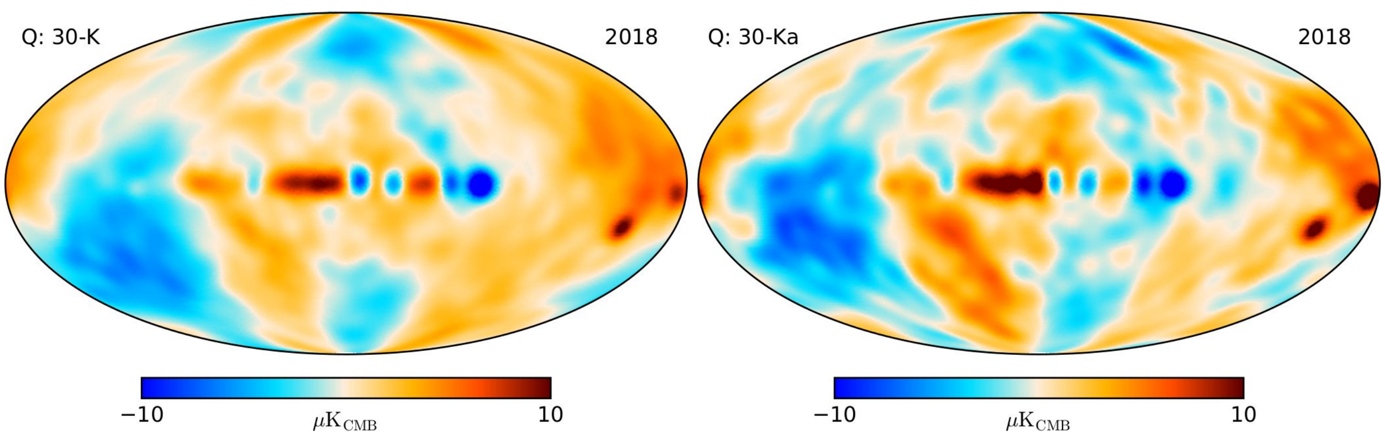
Known poorly measured modes in Planck and WMAP



Planck 2018 30 GHz gain residual template



WMAP K-band transmission imbalance template



30 - K difference map

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?

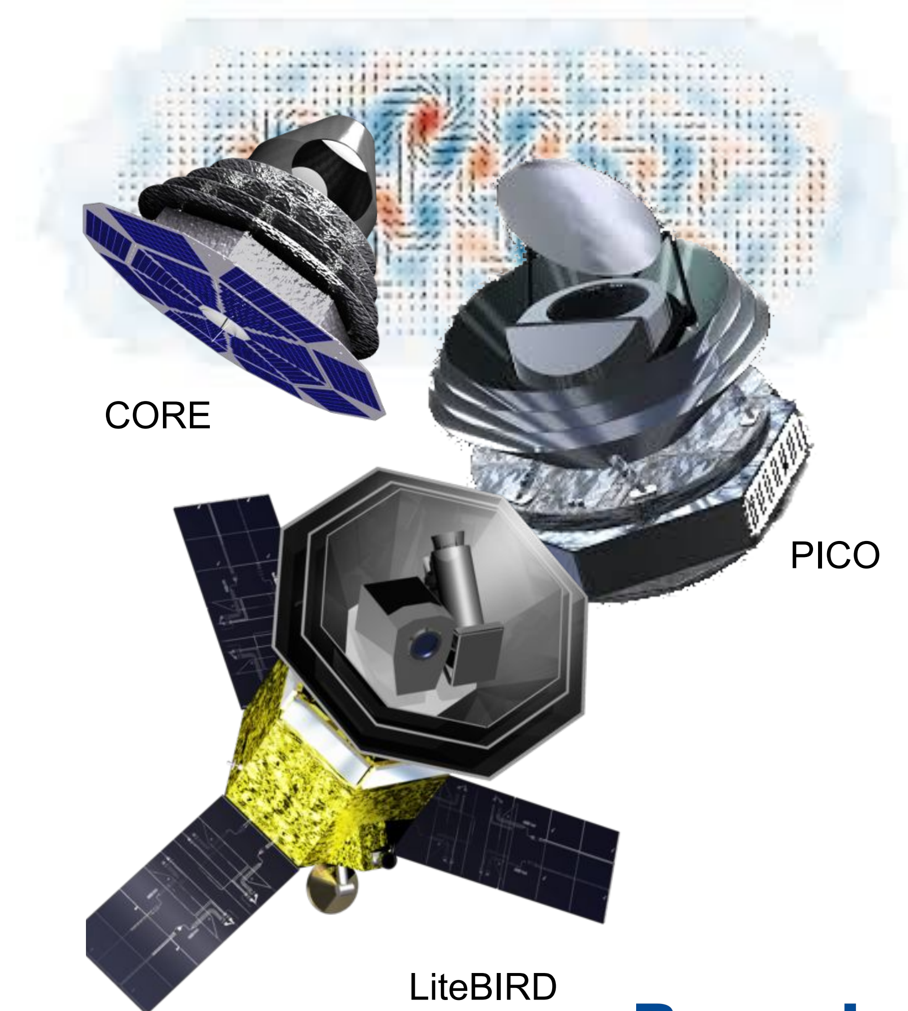
The name BeyondPlanck was chosen to

- 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

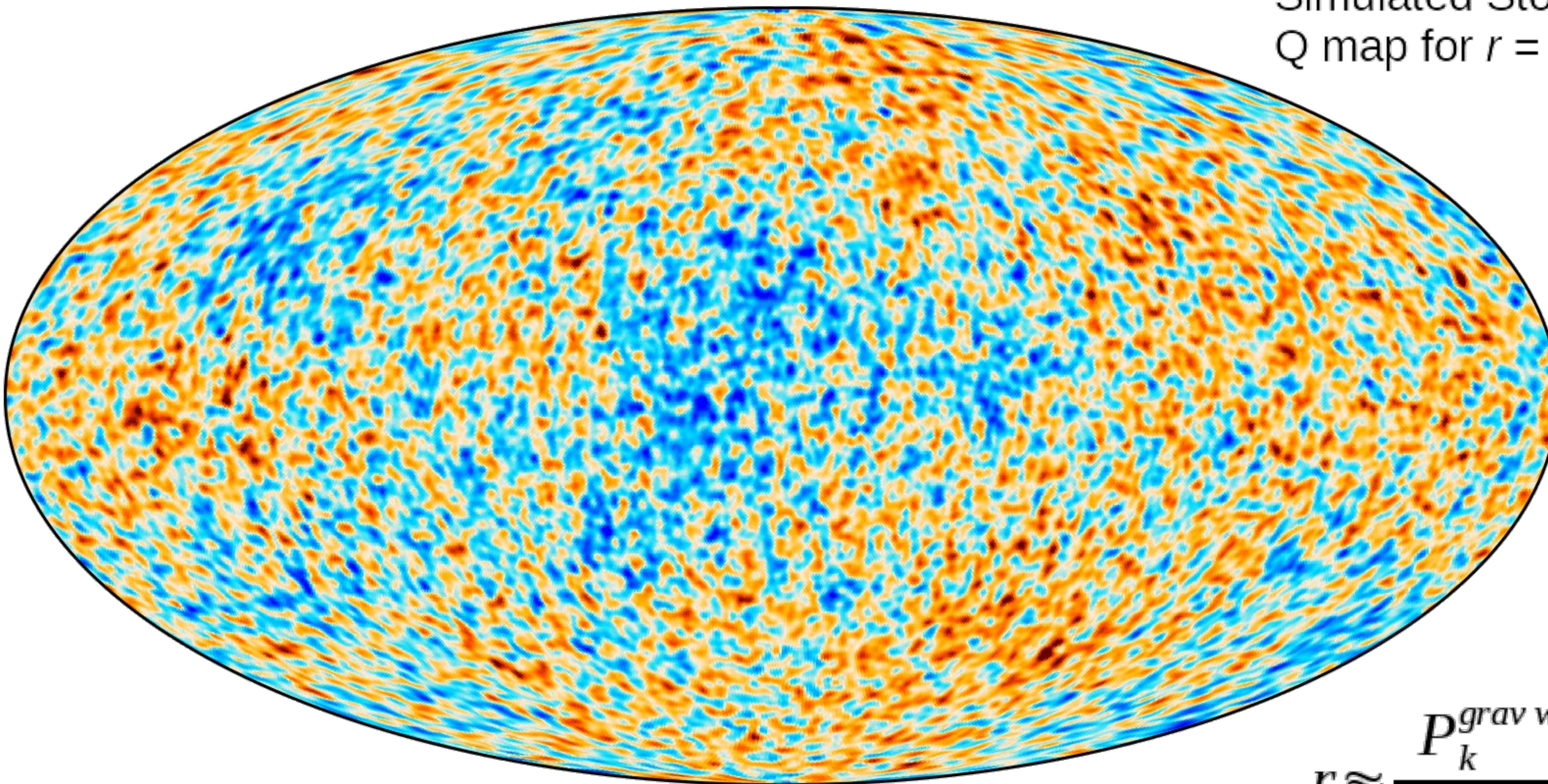
Why do we care?

Gravitational waves from black holes

Gravitational waves from the Big Bang



What sort of precision is required for gravitational waves?

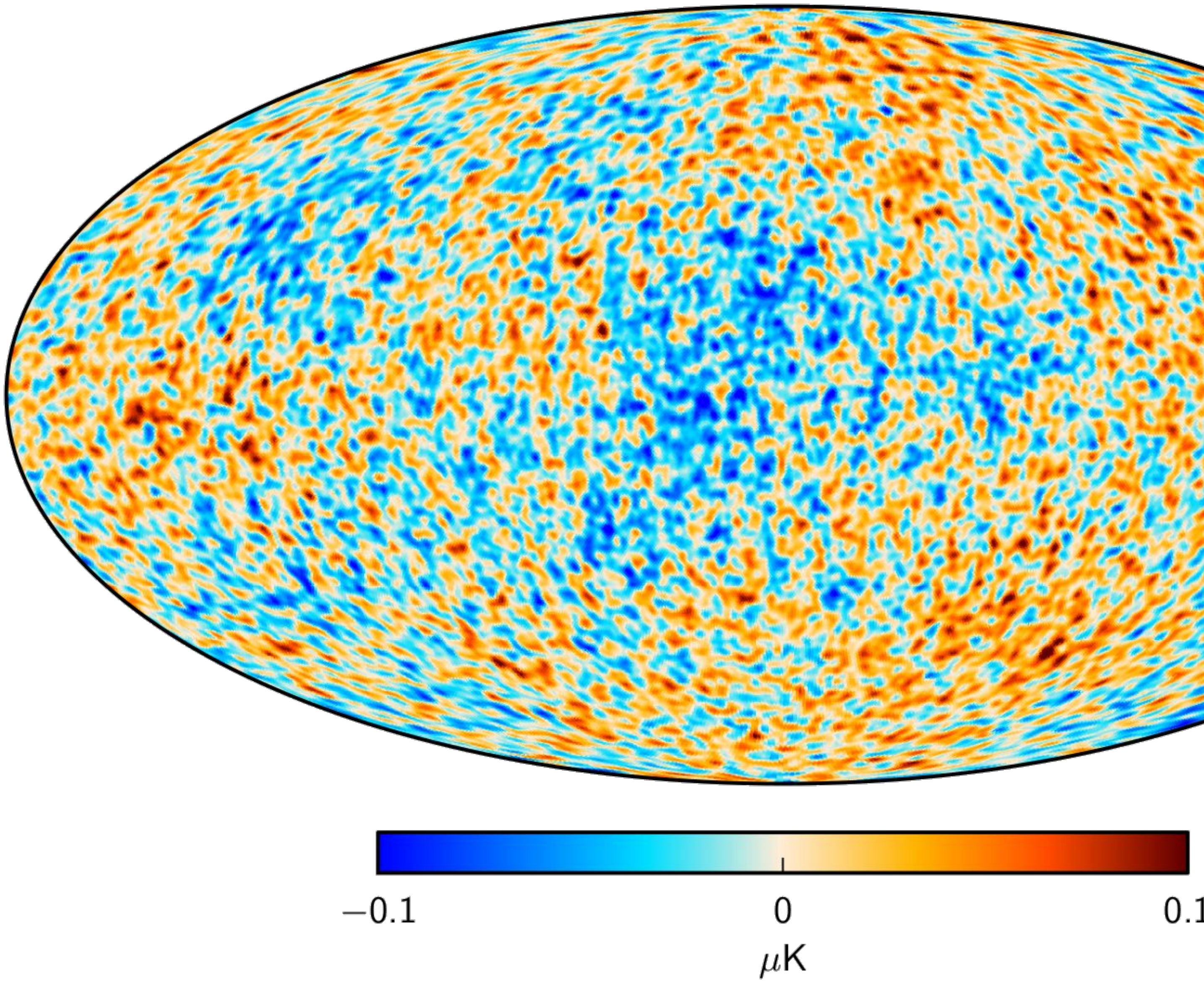


Simulated Stokes Q map for $r = 0.01$

$$r \approx \frac{P_k^{\text{grav waves}}}{P_k^{\text{density waves}}}$$

What sort of precision is required for gravitational waves?

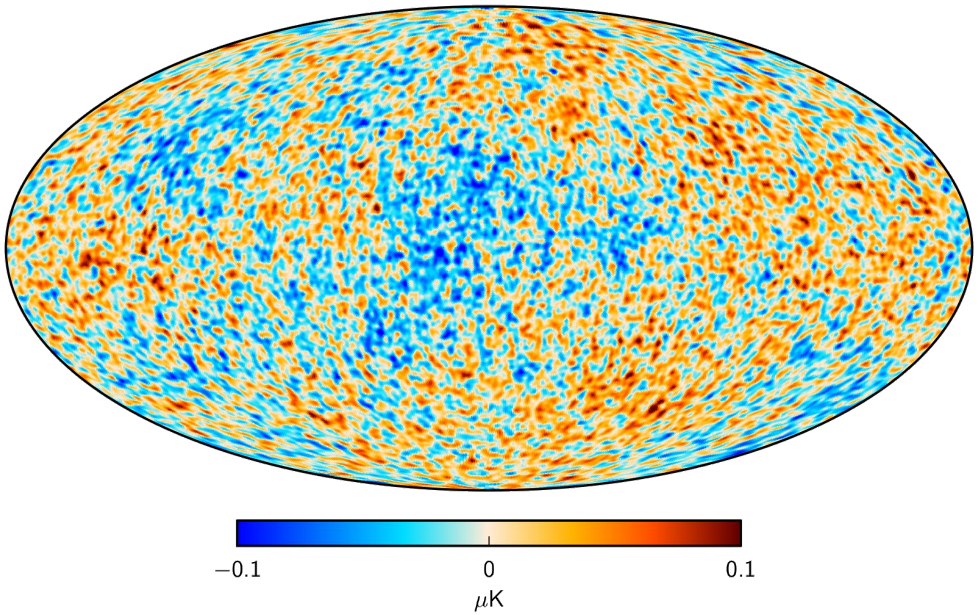
Simulated Stokes Q map for $r = 0.01$



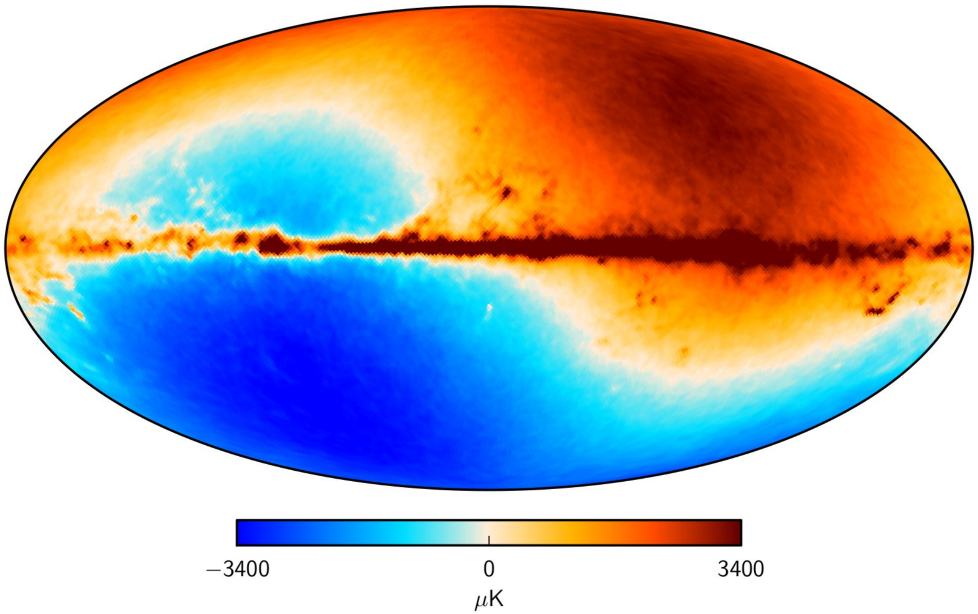
$$r \approx \frac{P_k^{grav\ waves}}{P_k^{density\ waves}}$$

What sort of precision is required for gravitational waves?

Expected signal



Actual sky

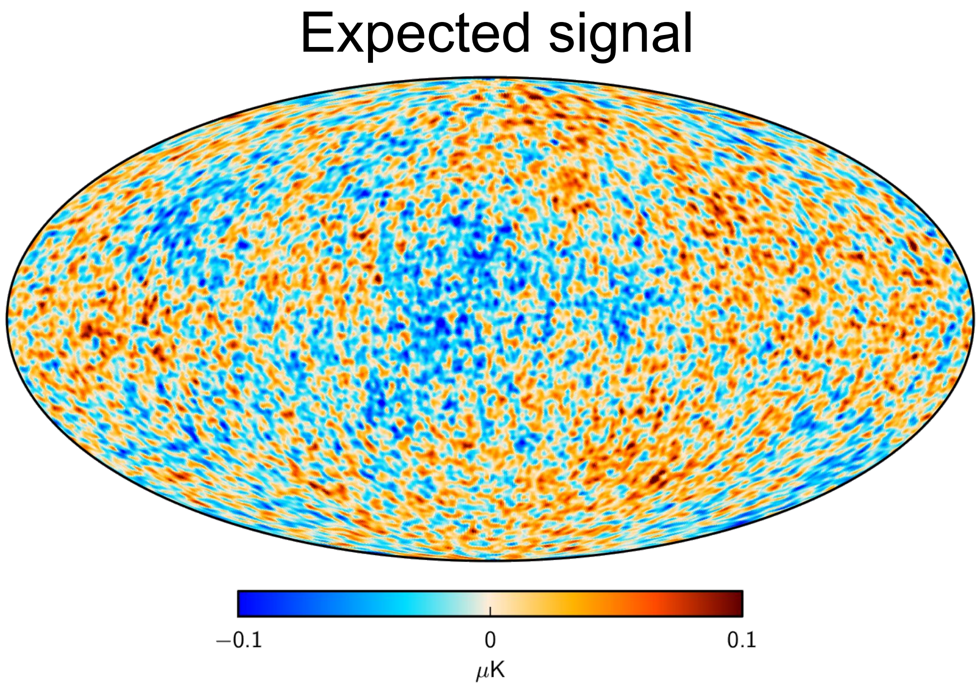


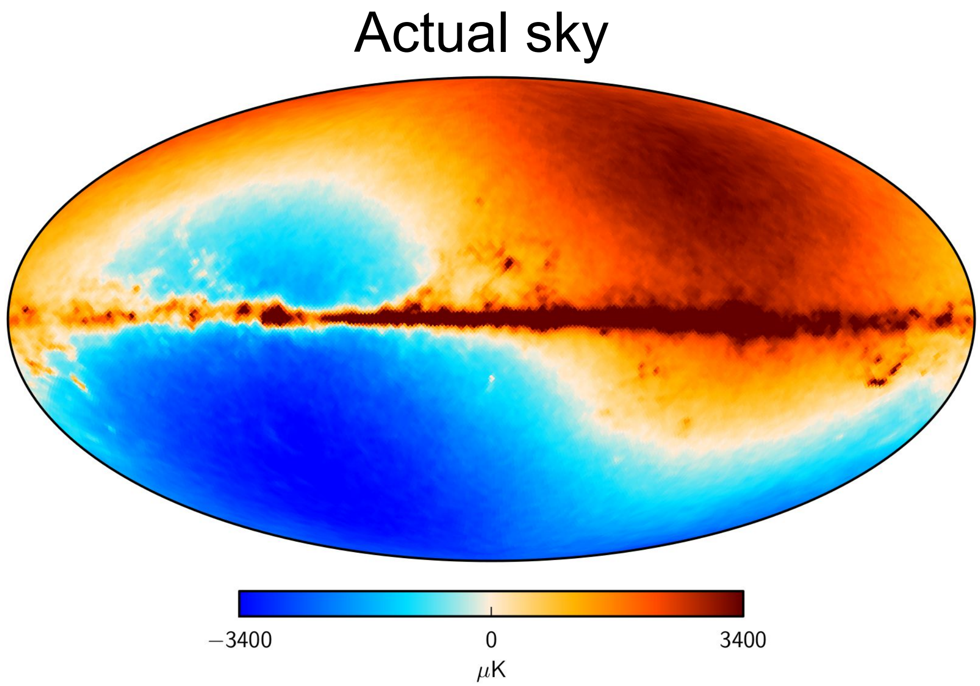
The sky is more than four orders of magnitude brighter than the signal!

⇓

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

What sort of precision is required for gravitational waves?





What sort of precision is required for gravitational waves?

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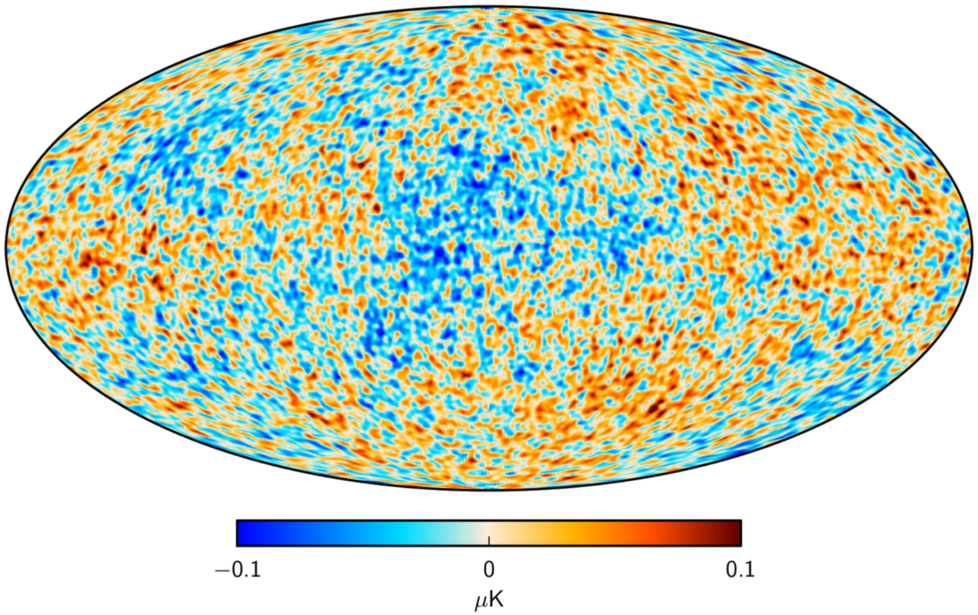
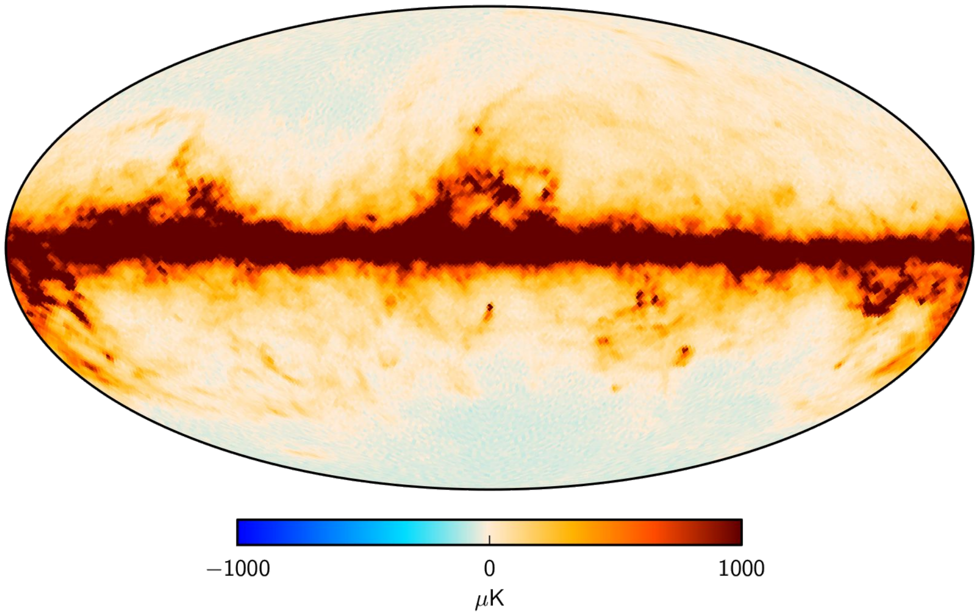
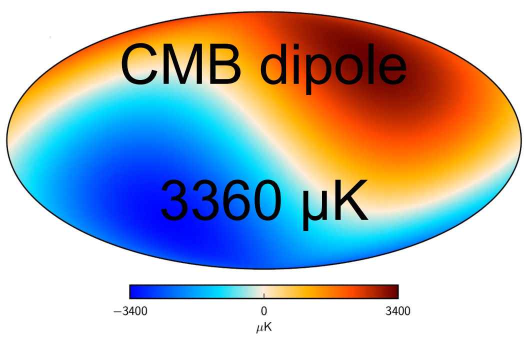
Expected signal



Actual sky - dipole





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What sort of precision is required for gravitational waves?

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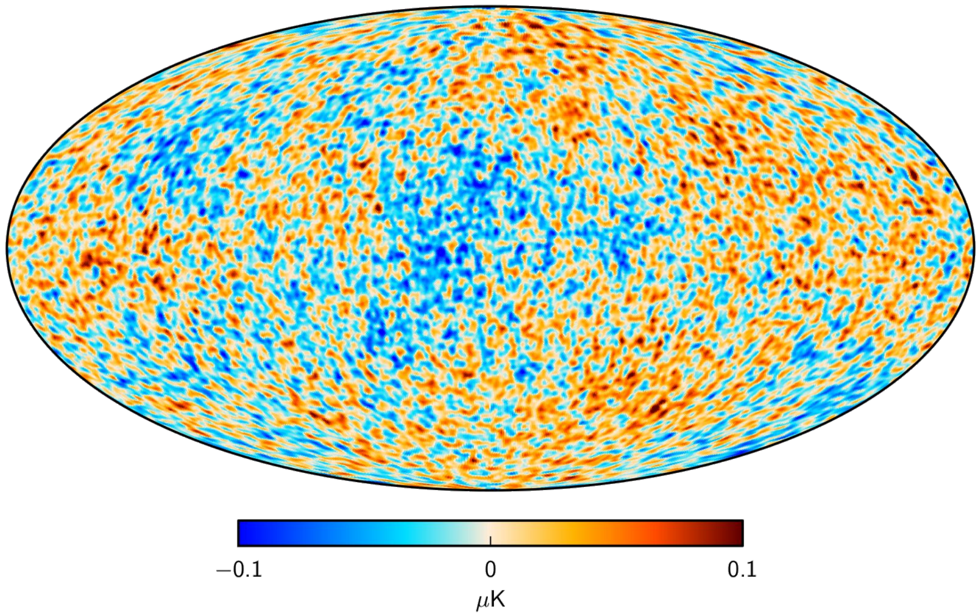
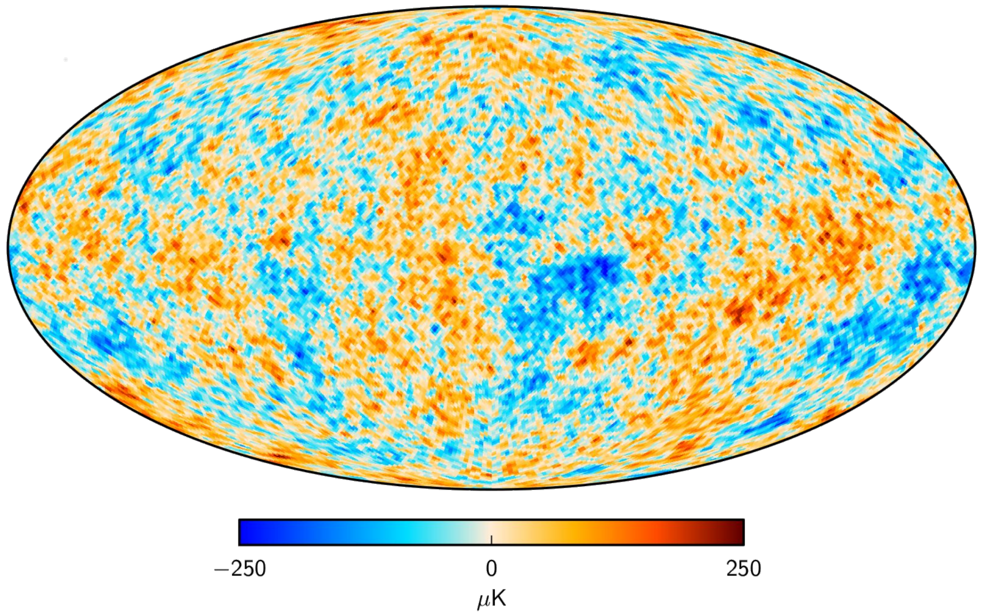
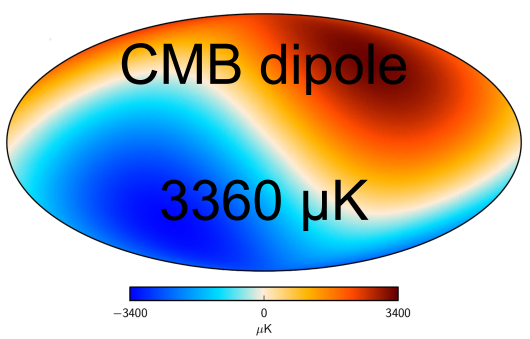
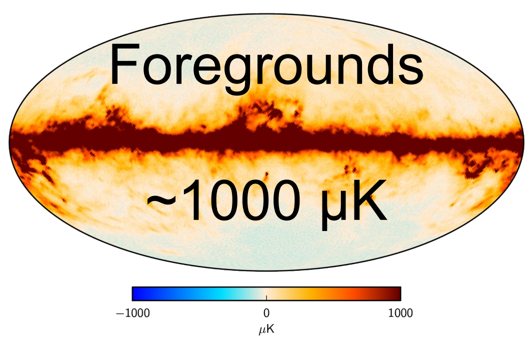
Expected signal



Actual sky - dipole - foregrounds







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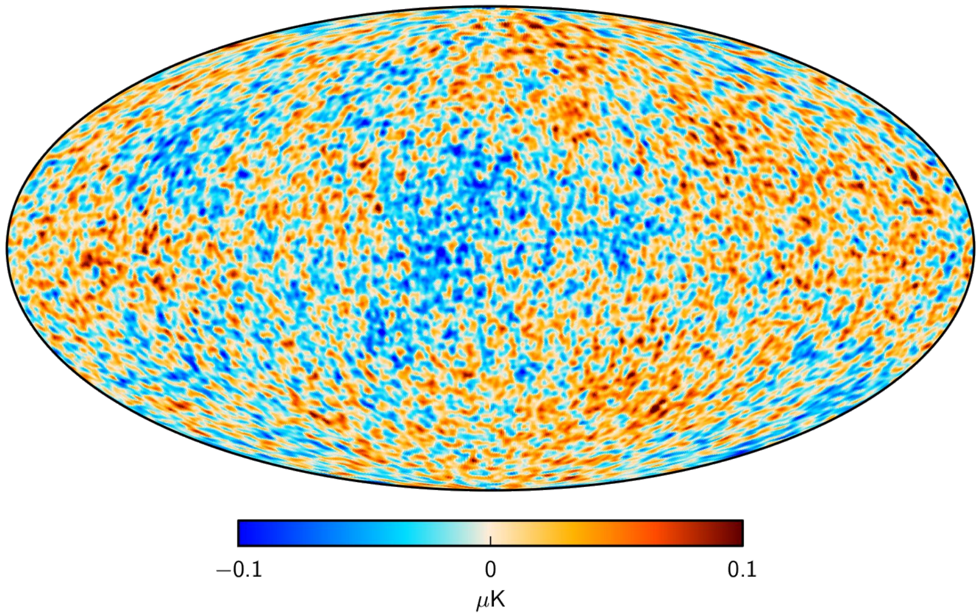
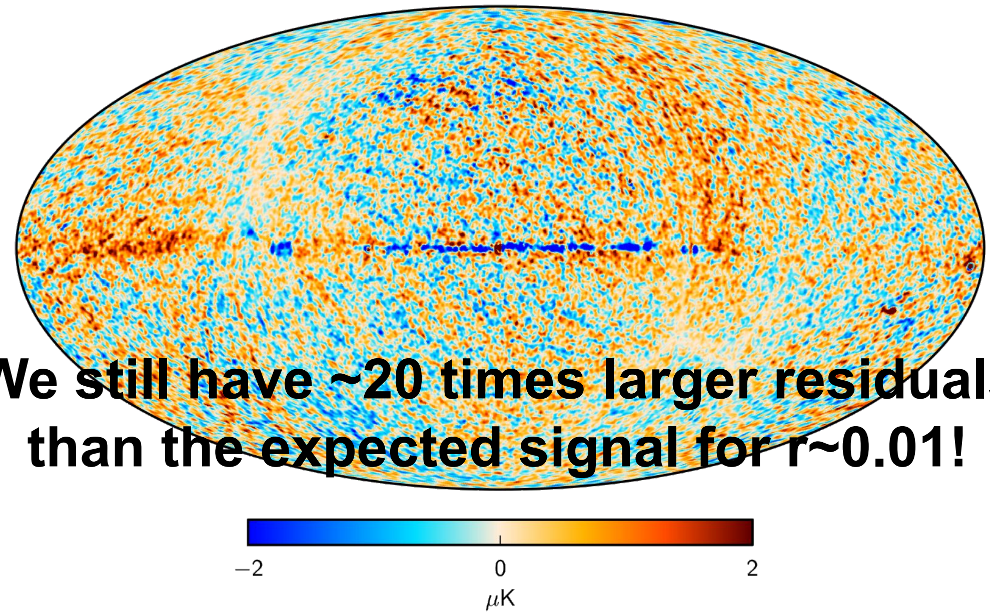
What sort of precision is required for gravitational waves?

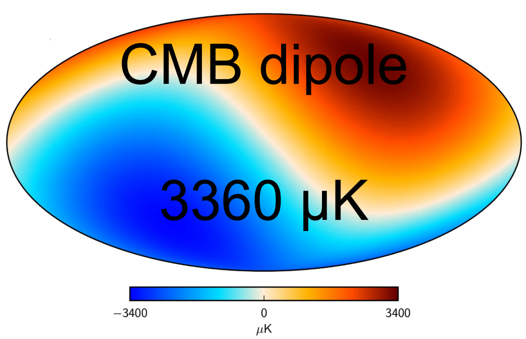
Expected signal

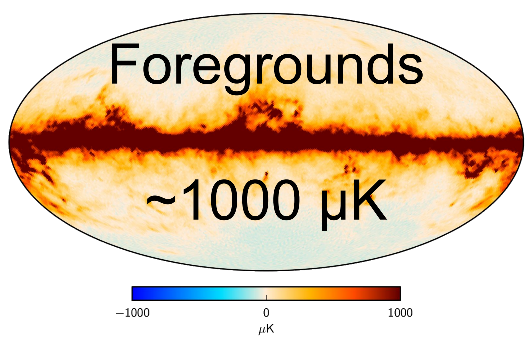


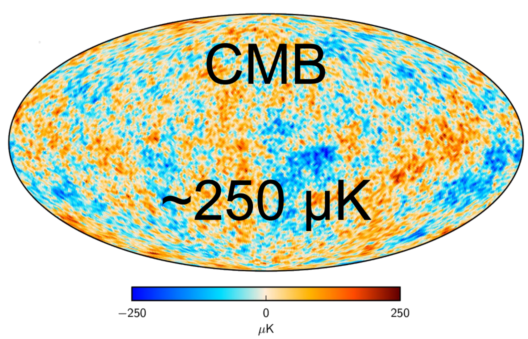
Actual sky - dipole - foregrounds



We still have ~20 times larger residuals than the expected signal for r~0.01!







What sort of precision is required for gravitational waves?

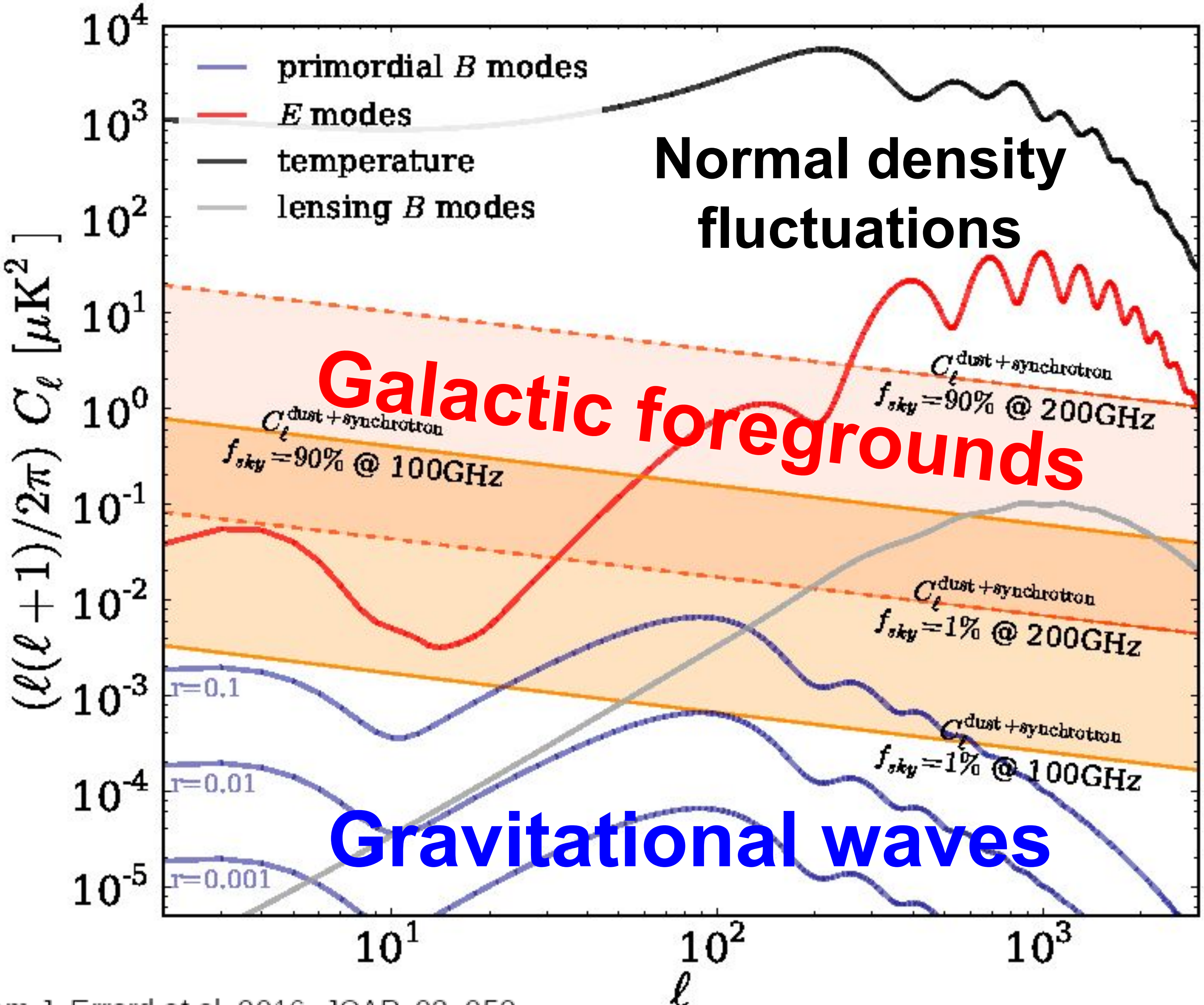


Figure from J. Errard et al. 2016, JCAP, 03, 052

What sort of precision is required for gravitational waves?

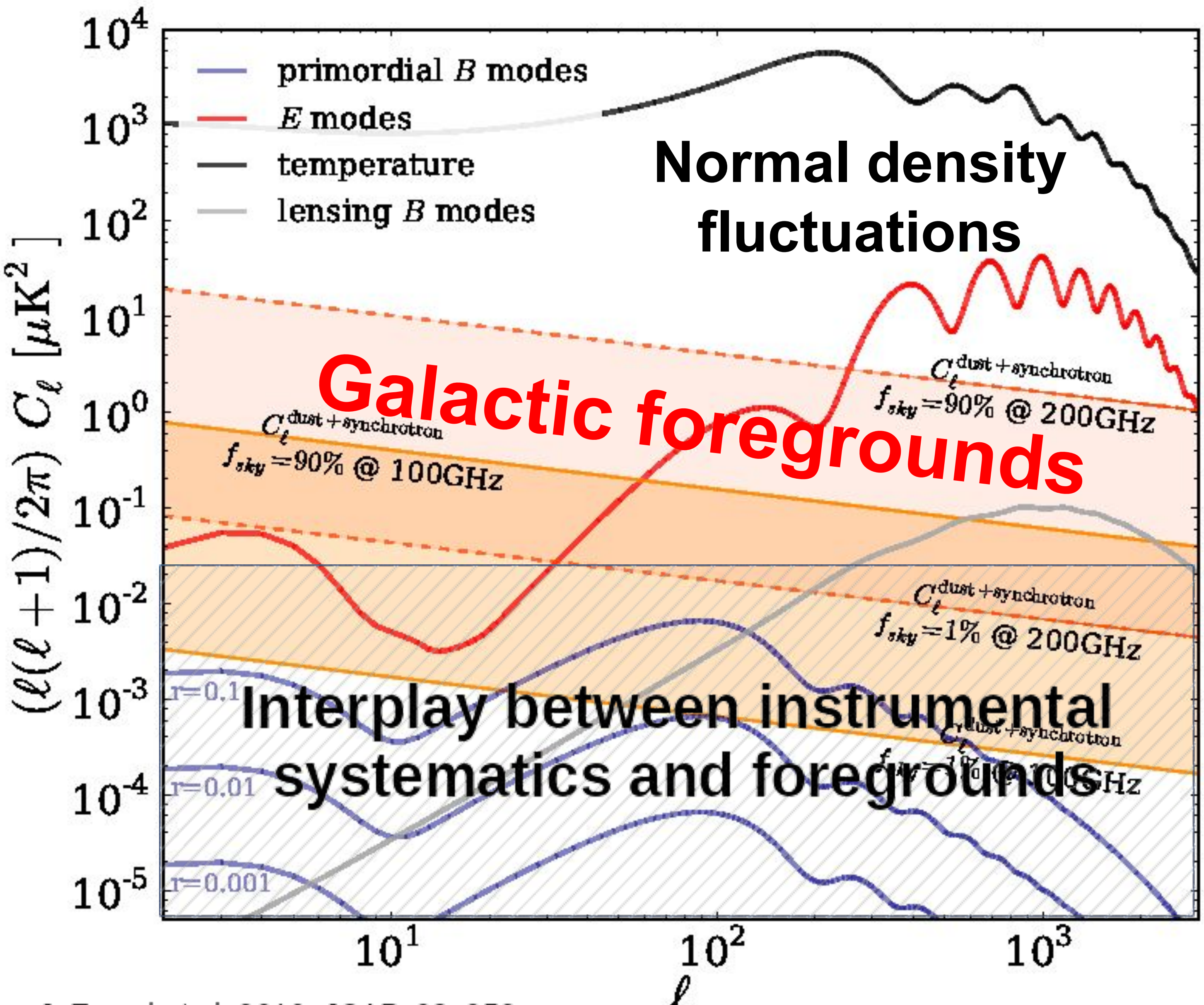
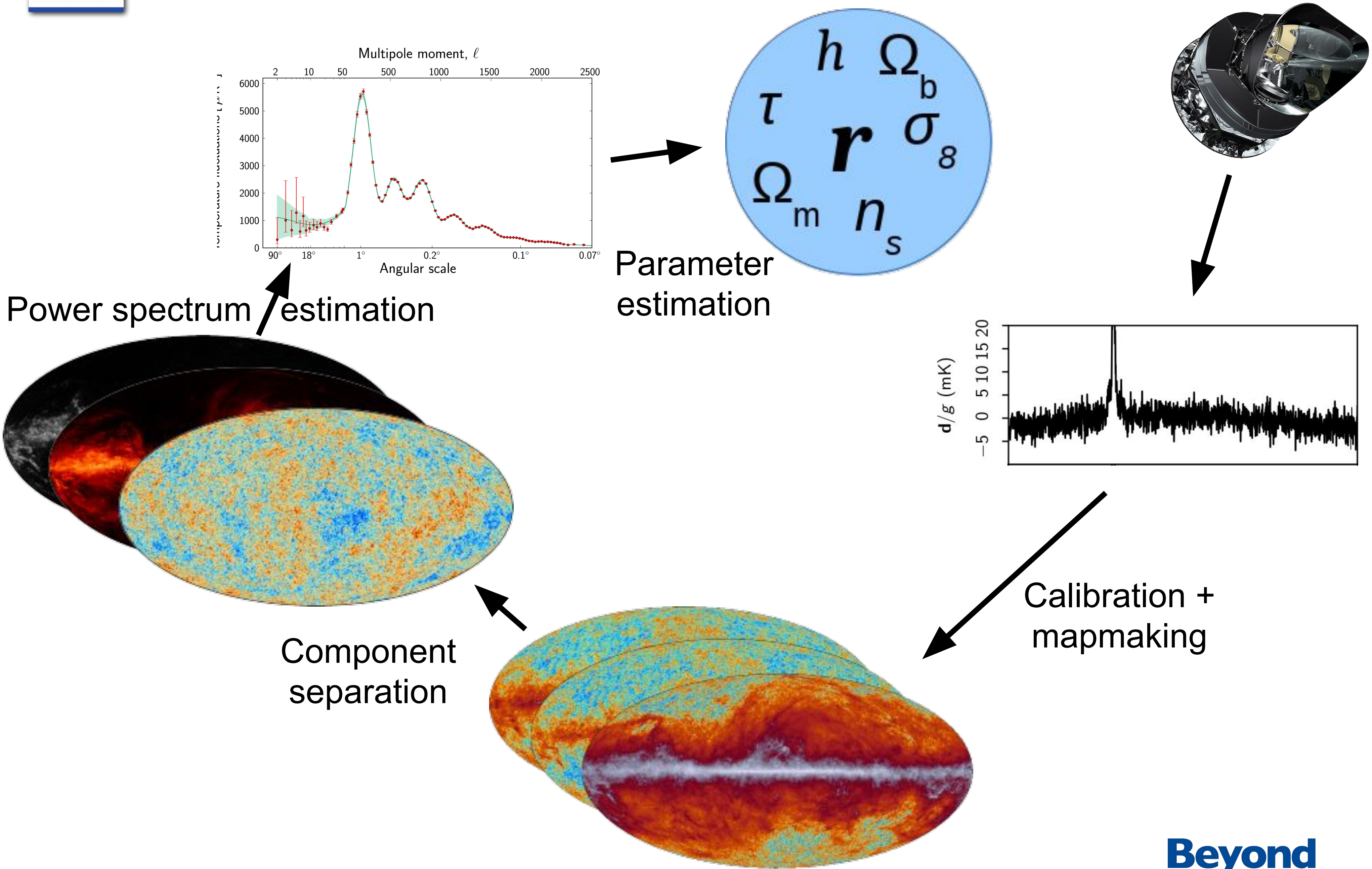


Figure from J. Errard et al. 2016, JCAP, 03, 052

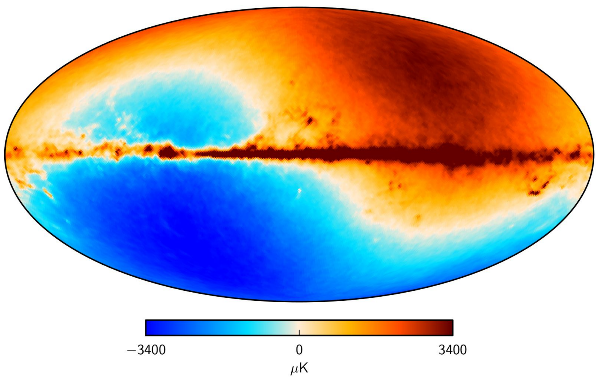
Classic CMB analysis



CMB's "chicken and egg" problem

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

Data



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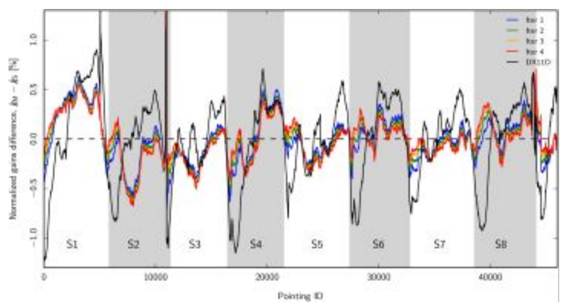
Instrument calibration



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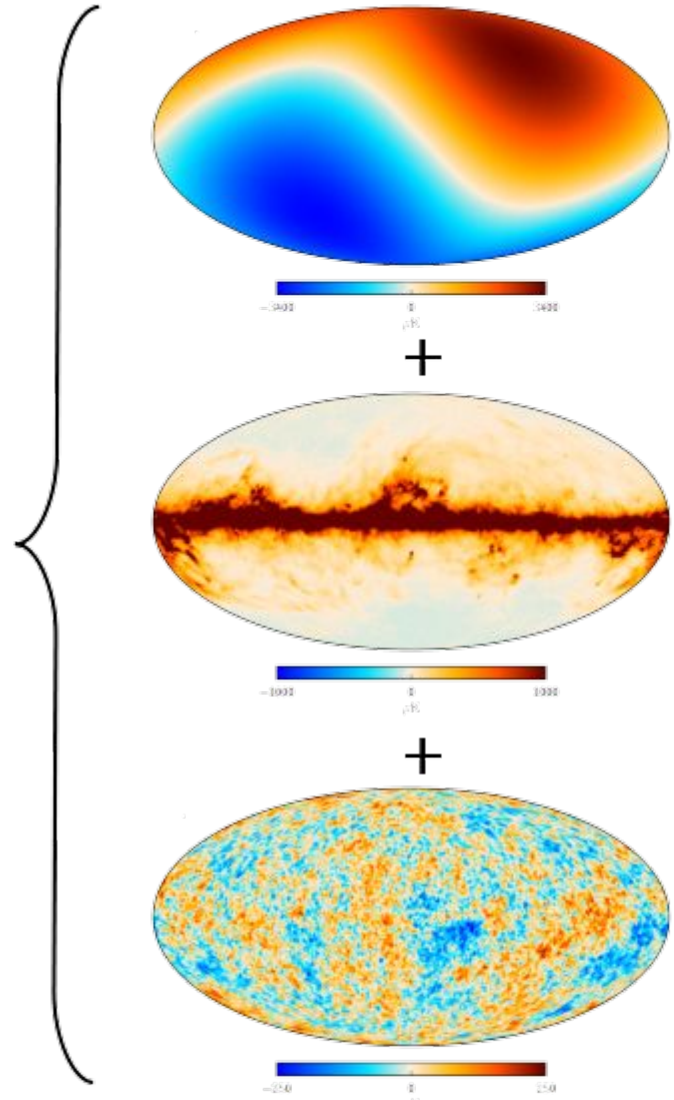
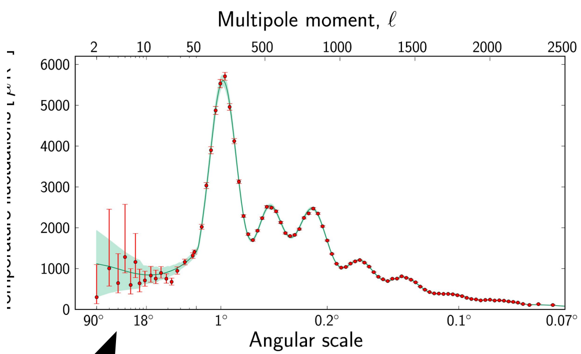
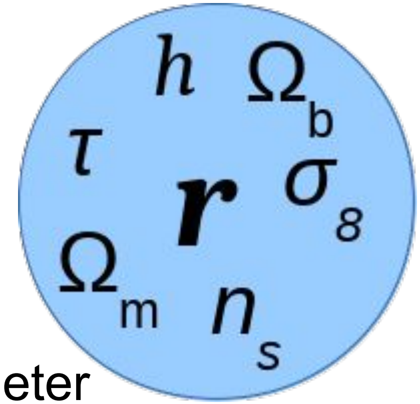
Sky

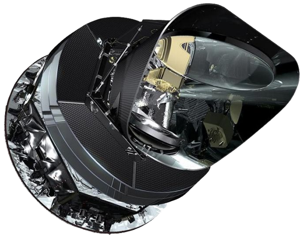


… but also need to know the sky in order to calibrate the instrument!

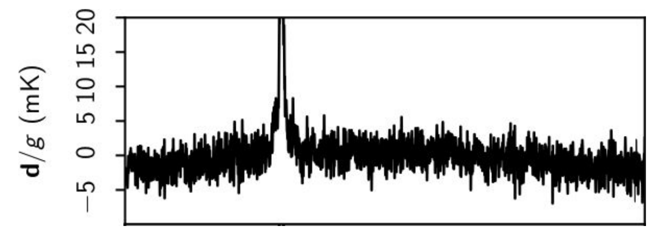
End-to-end iterative analysis



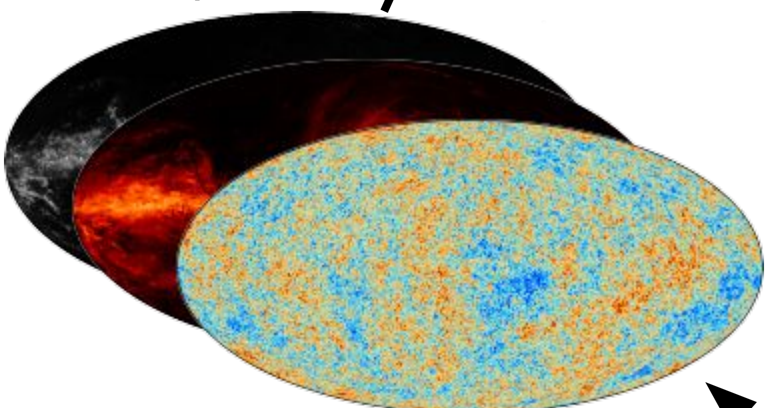




Parameter estimation

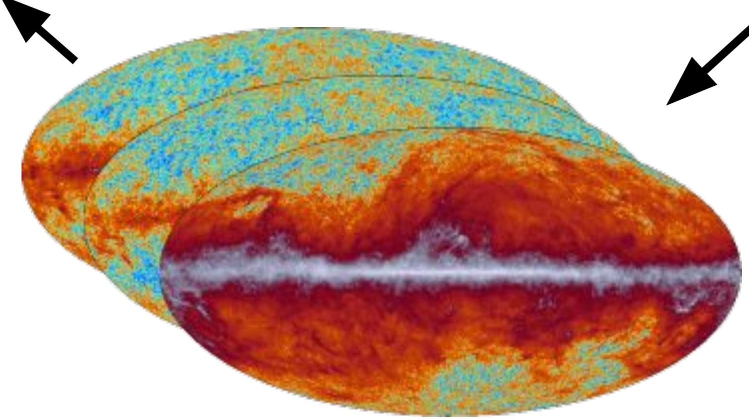


Power spectrum estimation



Calibration + mapmaking

Component separation



Beyond PLANCK

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 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

Sidelobe pickup

White noise

Pointing

Bandpass

Data

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

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

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

Point sources

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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

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

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

⋮

Beyond PLANCK

How to sample from *big* distributions?

European Commission

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Gibbs sampling

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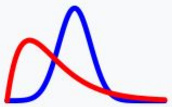
In statistics, **Gibbs sampling** or a **Gibbs sampler** is a Markov chain Monte Carlo (MCMC) algorithm for obtaining a sequence of observations which are approximated from a specified multivariate probability distribution, when direct sampling is difficult. This sequence can be used to approximate the 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 ·

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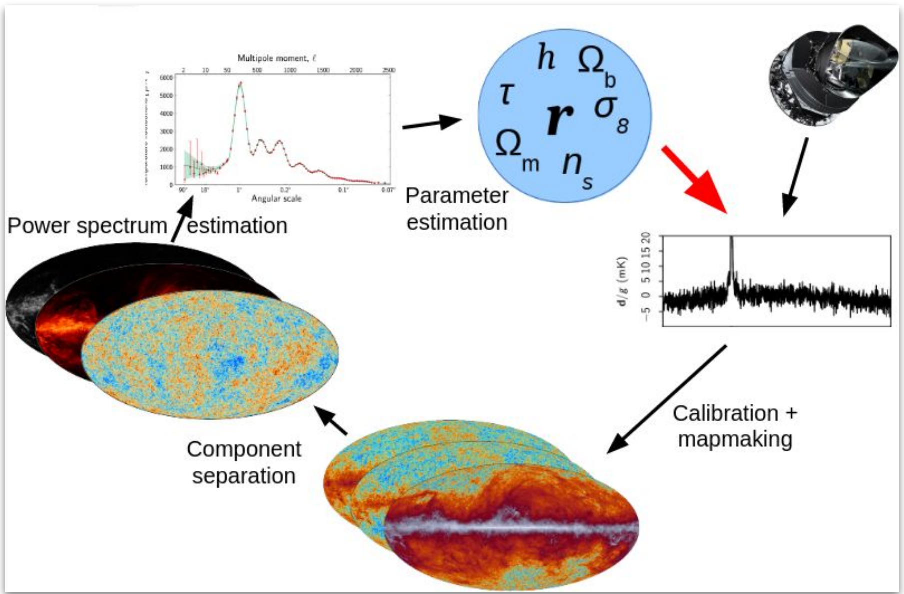
The BeyondPlanck Gibbs sampler

What we want to do:



How we actually do it:

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

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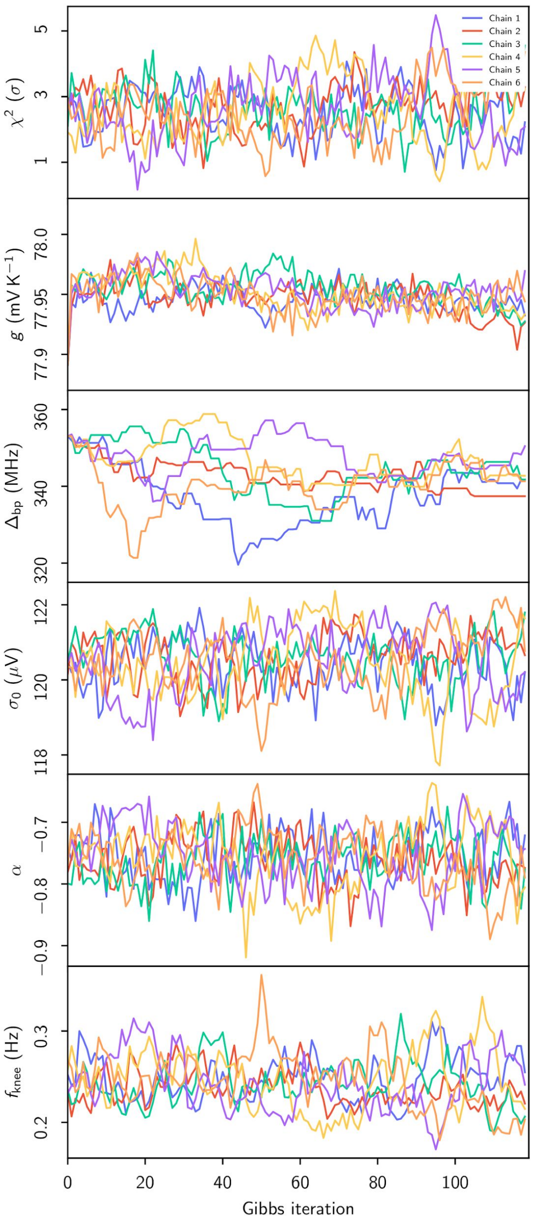
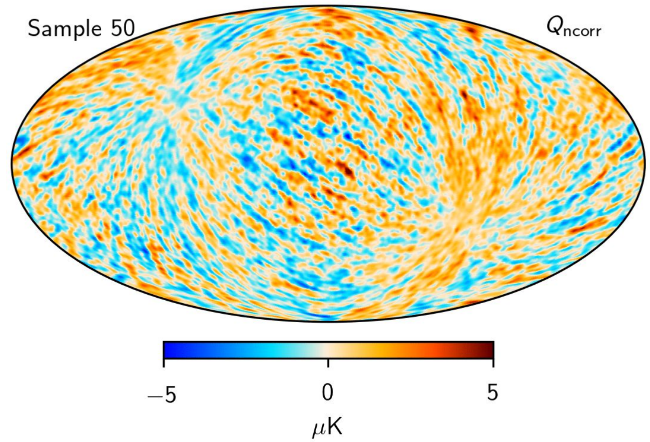
Main product: Ensemble of full sample sets

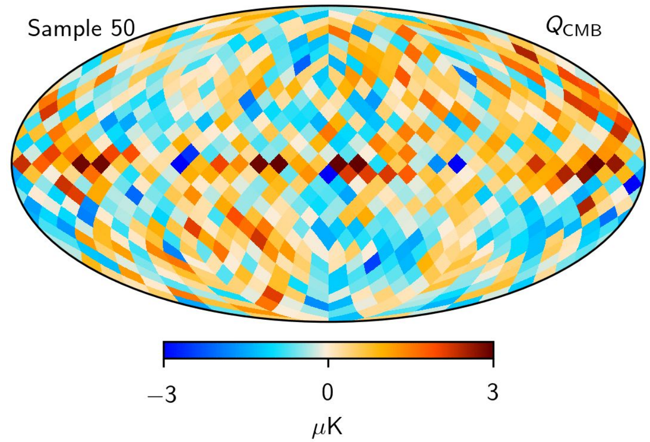
Instrument



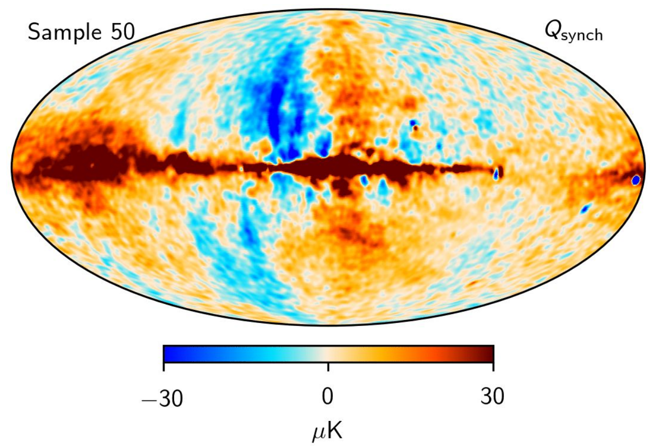
Correlated noise



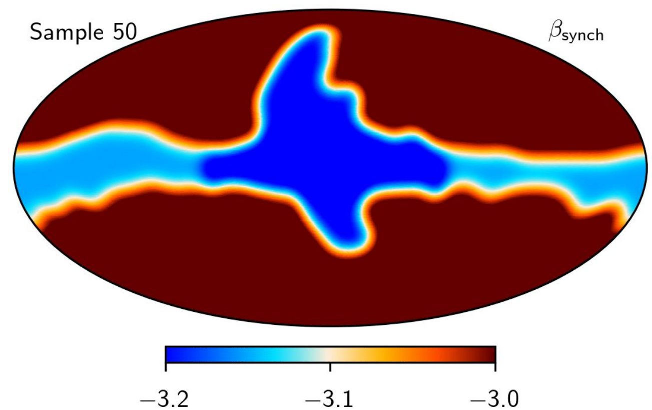
CMB Stokes Q



Synch Stokes Q



Synch pol β



...

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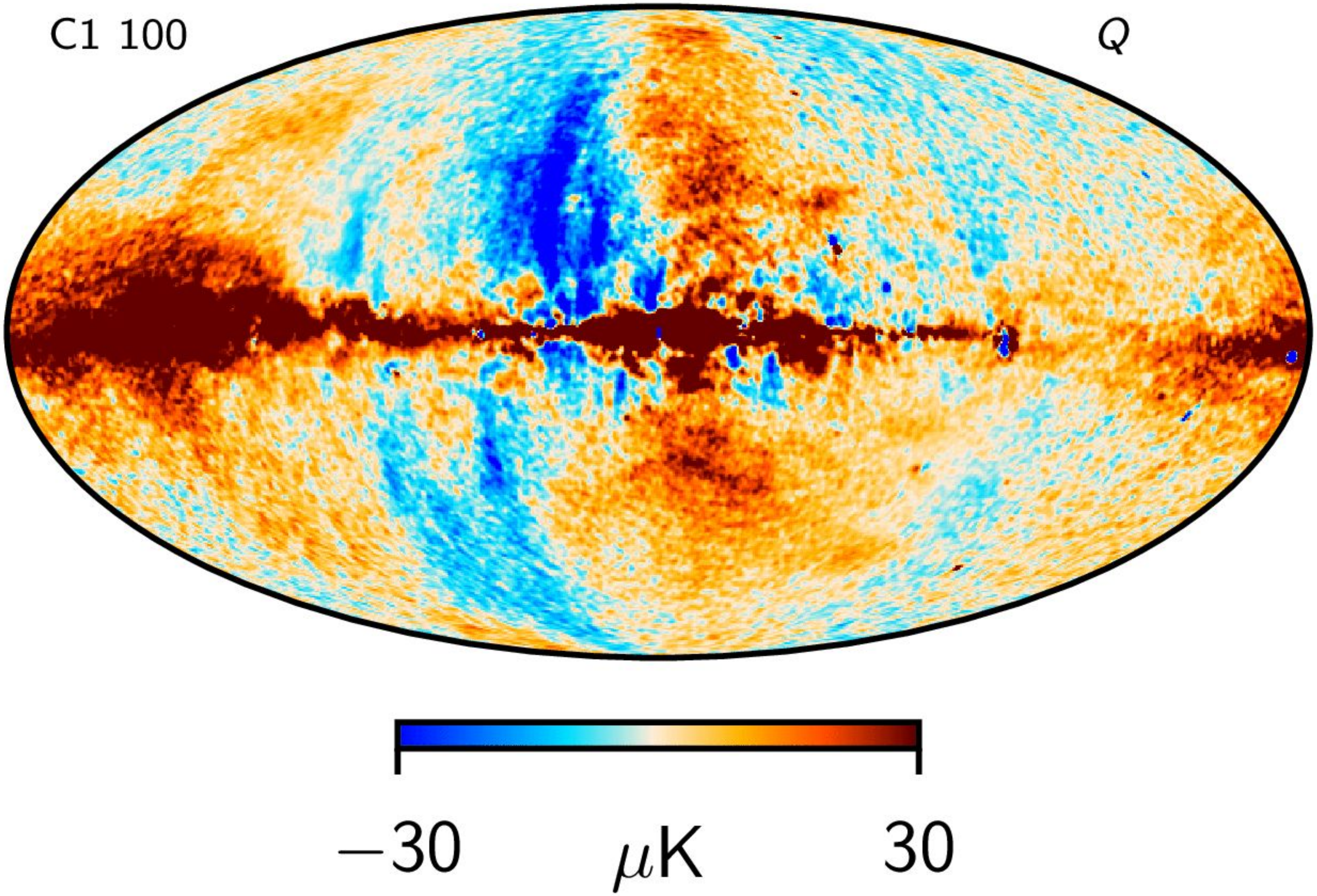
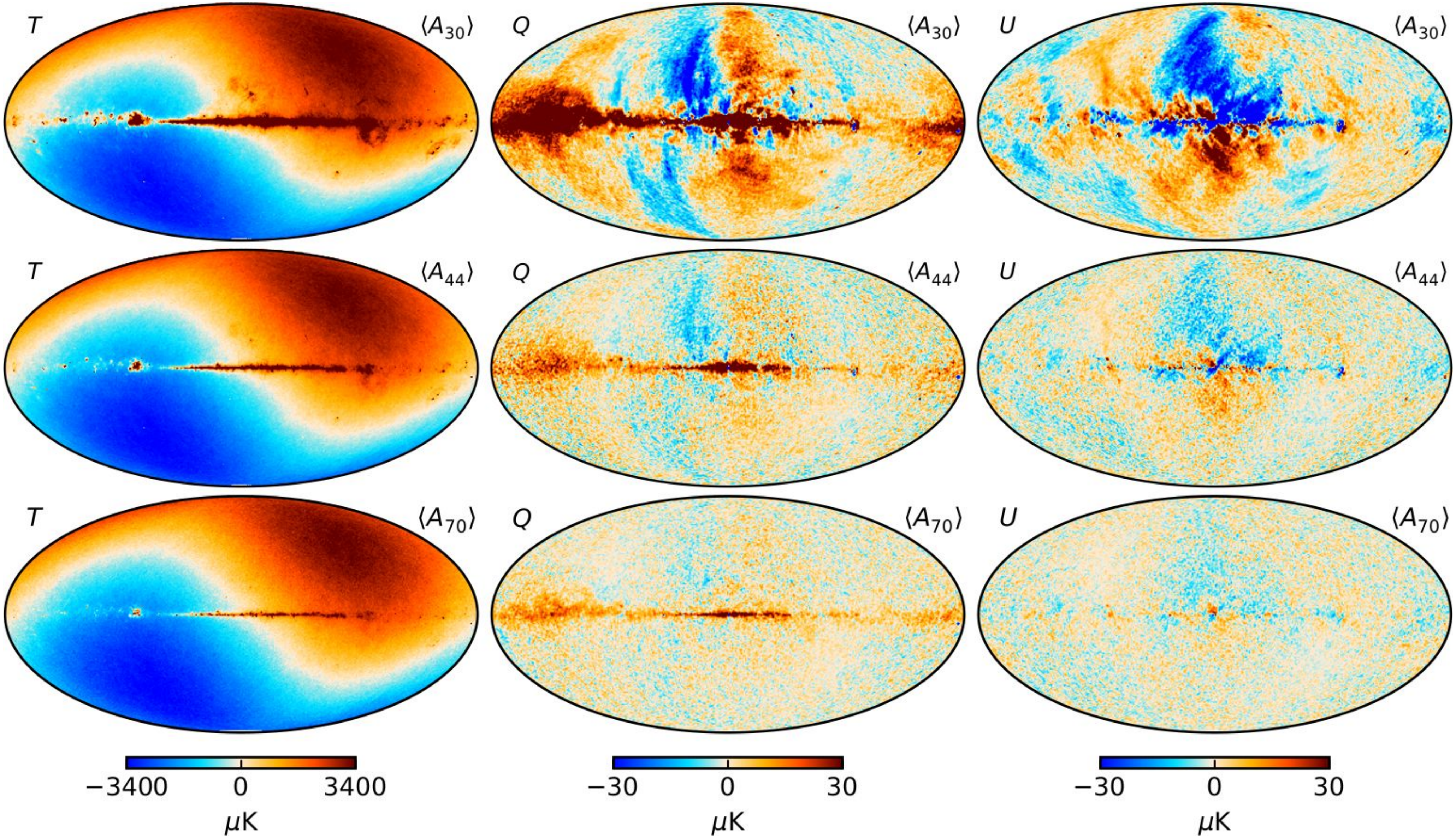
Frequency maps: 30 GHz Stokes Q



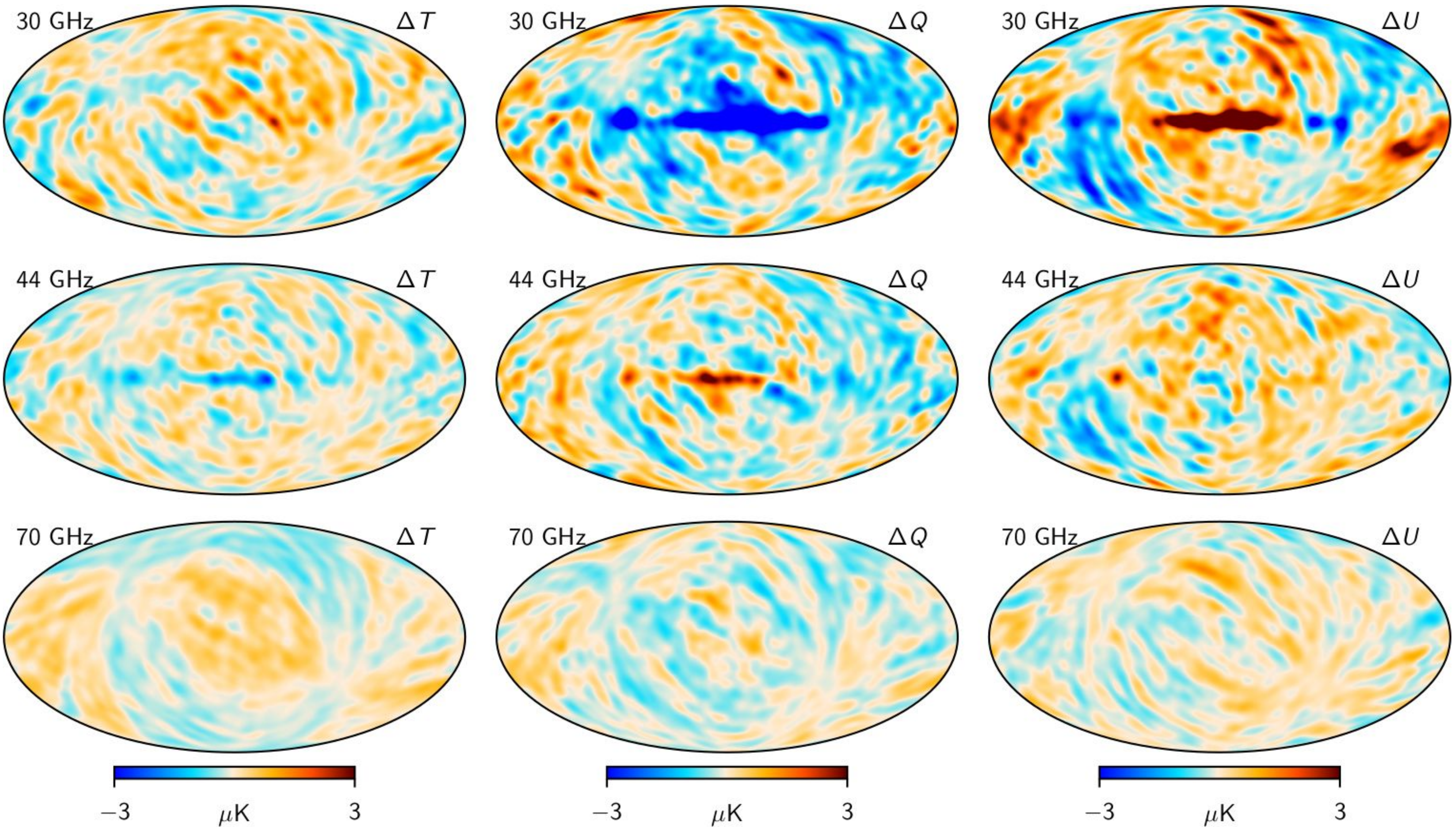
Suur-Uski et al. (2020)

Frequency maps: Posterior mean



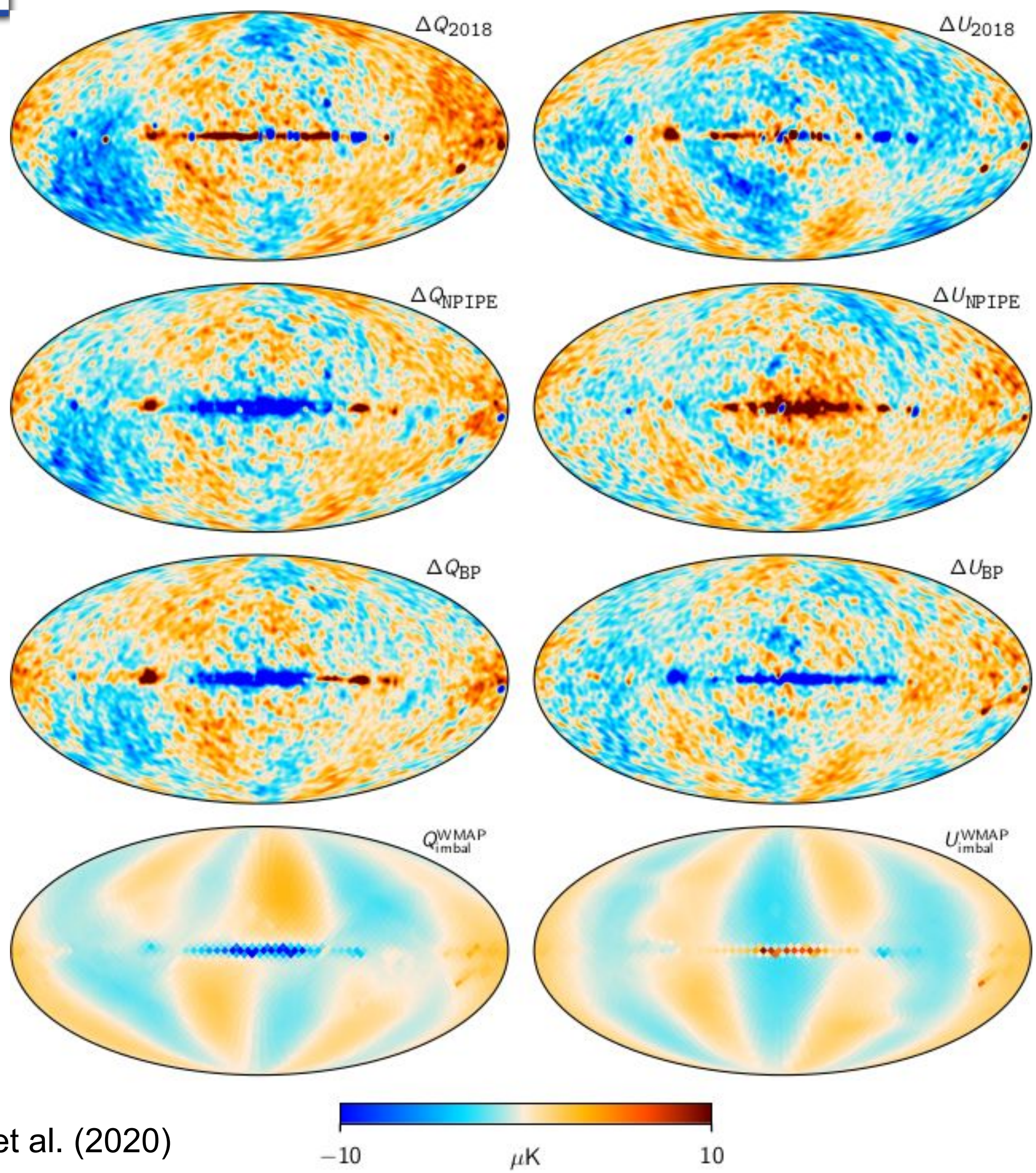
Suur-Uski et al. (2020)

Frequency maps: Difference between two samples



Suur-Uski et al. (2020)

Frequency maps: 30 GHz minus WMAP K-band



Planck 2018

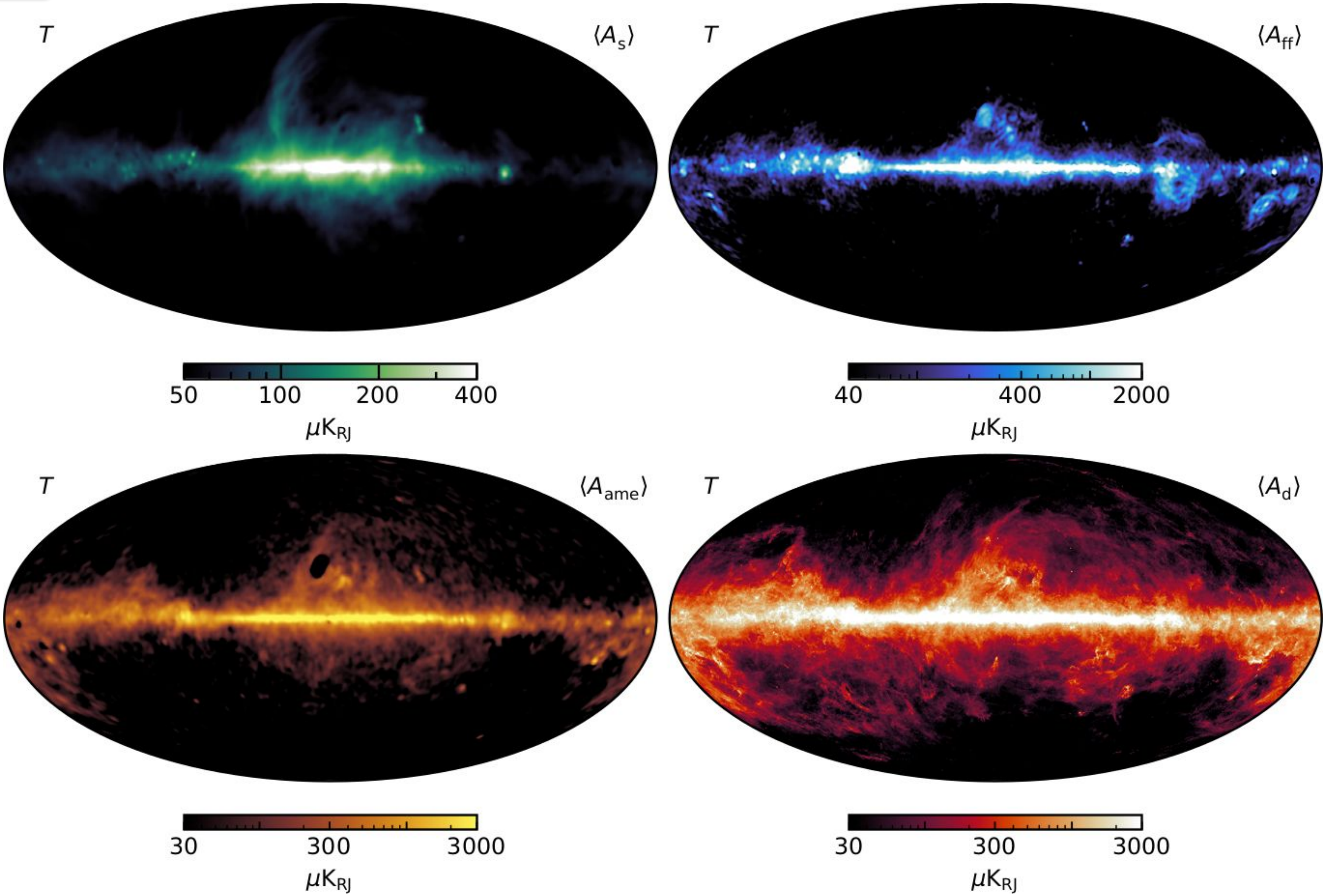
NPIPE

BeyondPlanck

WMAP transmission imbalance template (Jarosik et al. 2007)

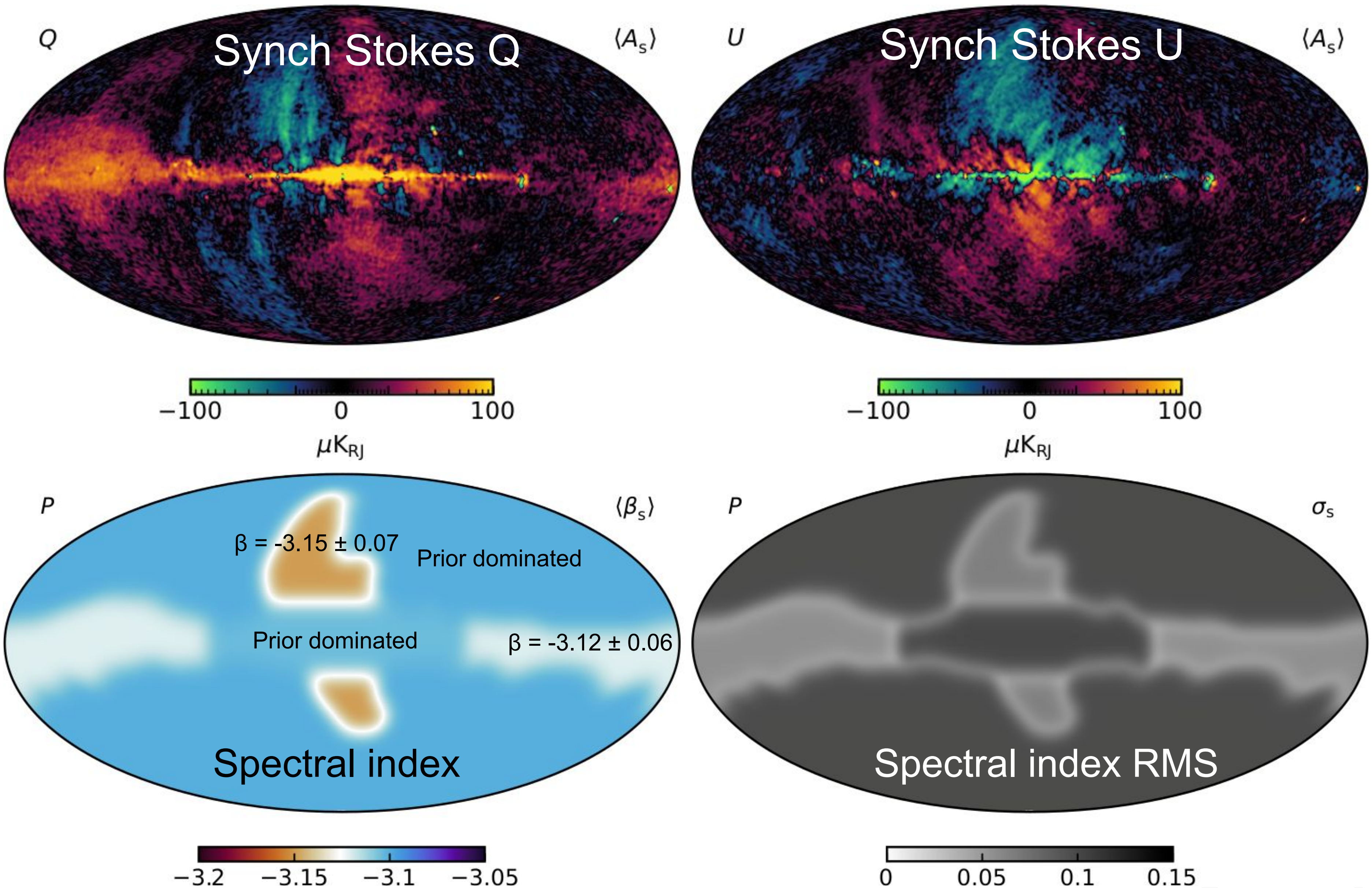
Gjerløw et al. (2020)

Astrophysical foregrounds: Temperature sky



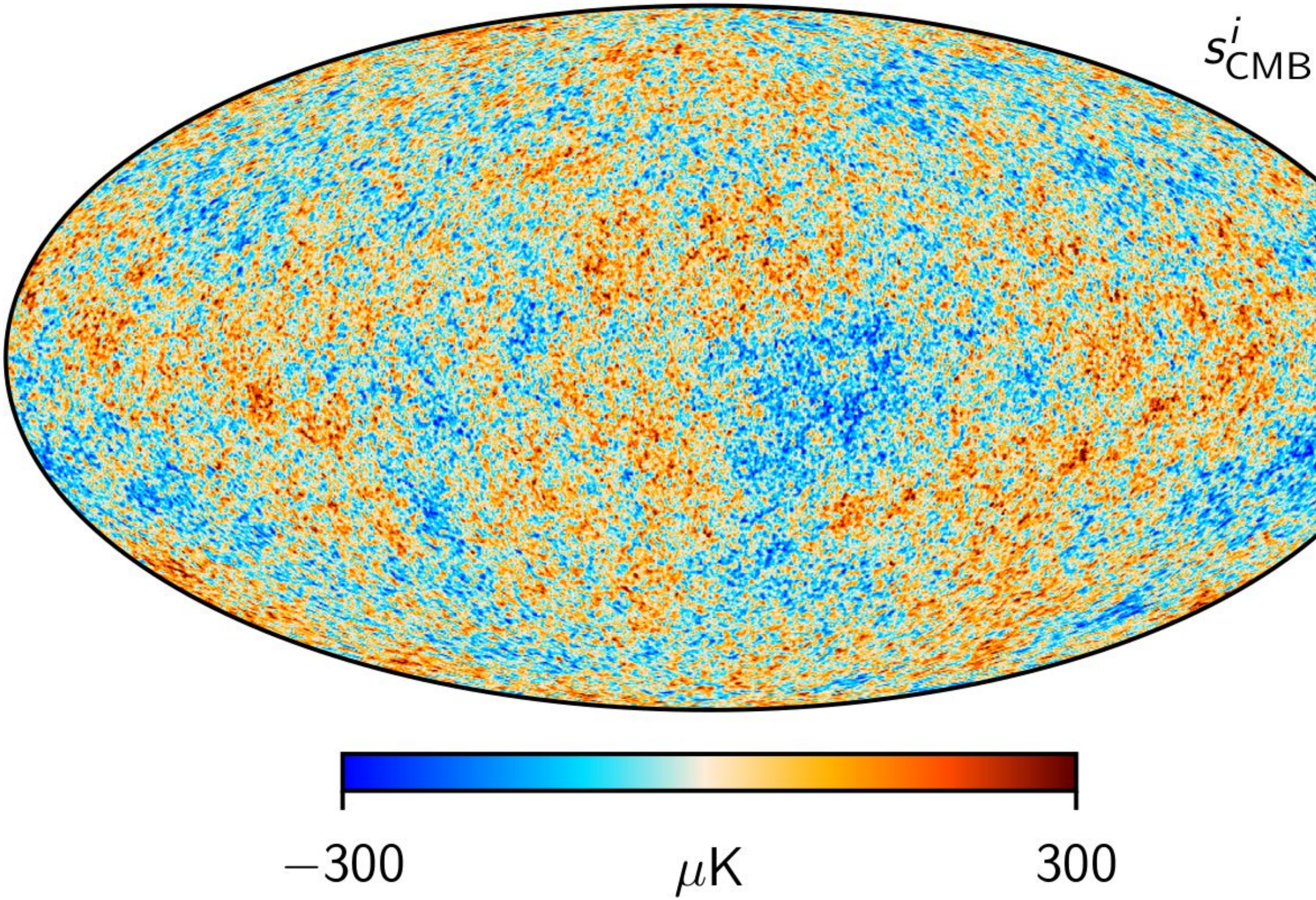
Andersen et al. (2020)

Astrophysical foregrounds: Polarized synchrotron emission

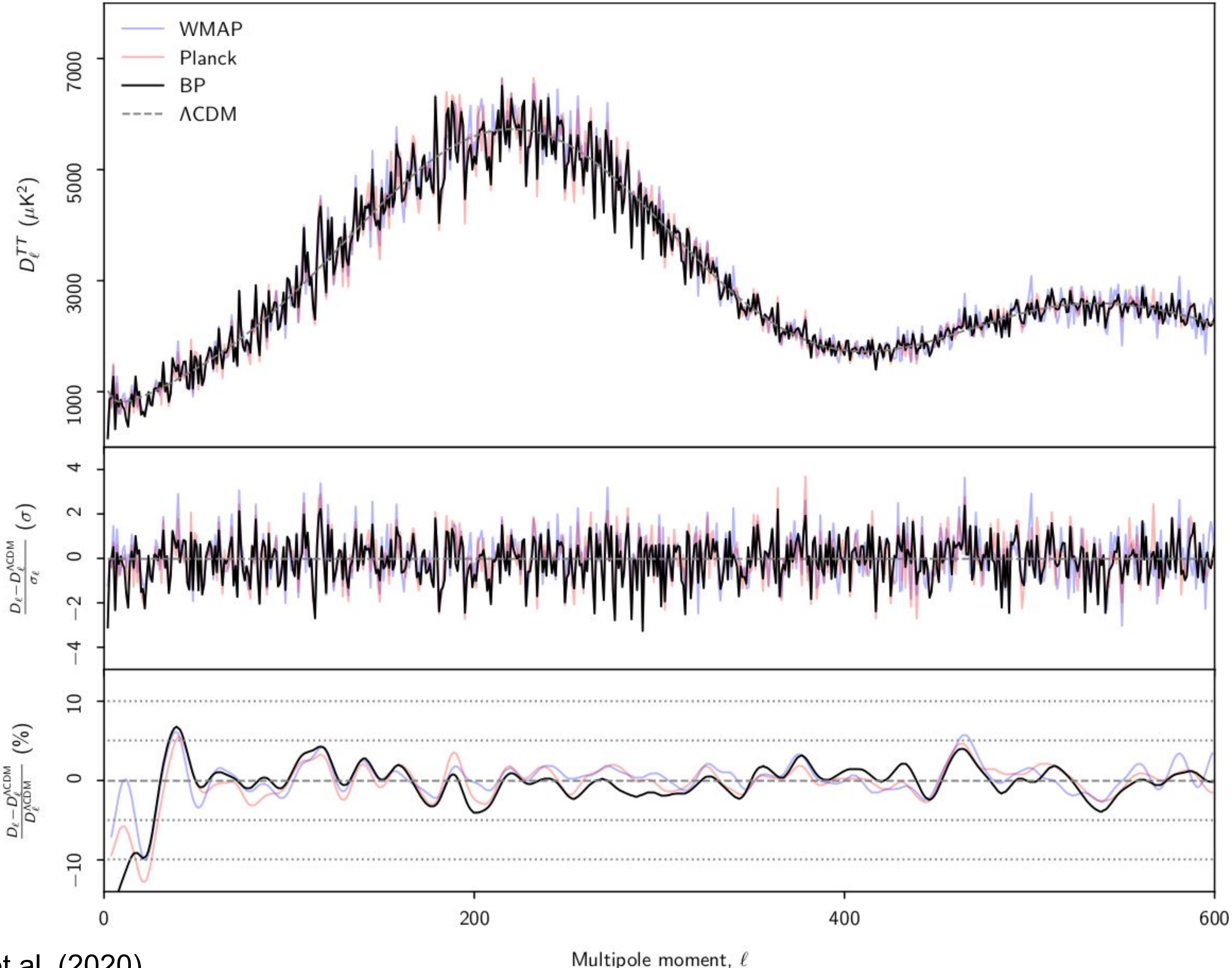


Svalheim et al. (2020)

CMB temperature sample

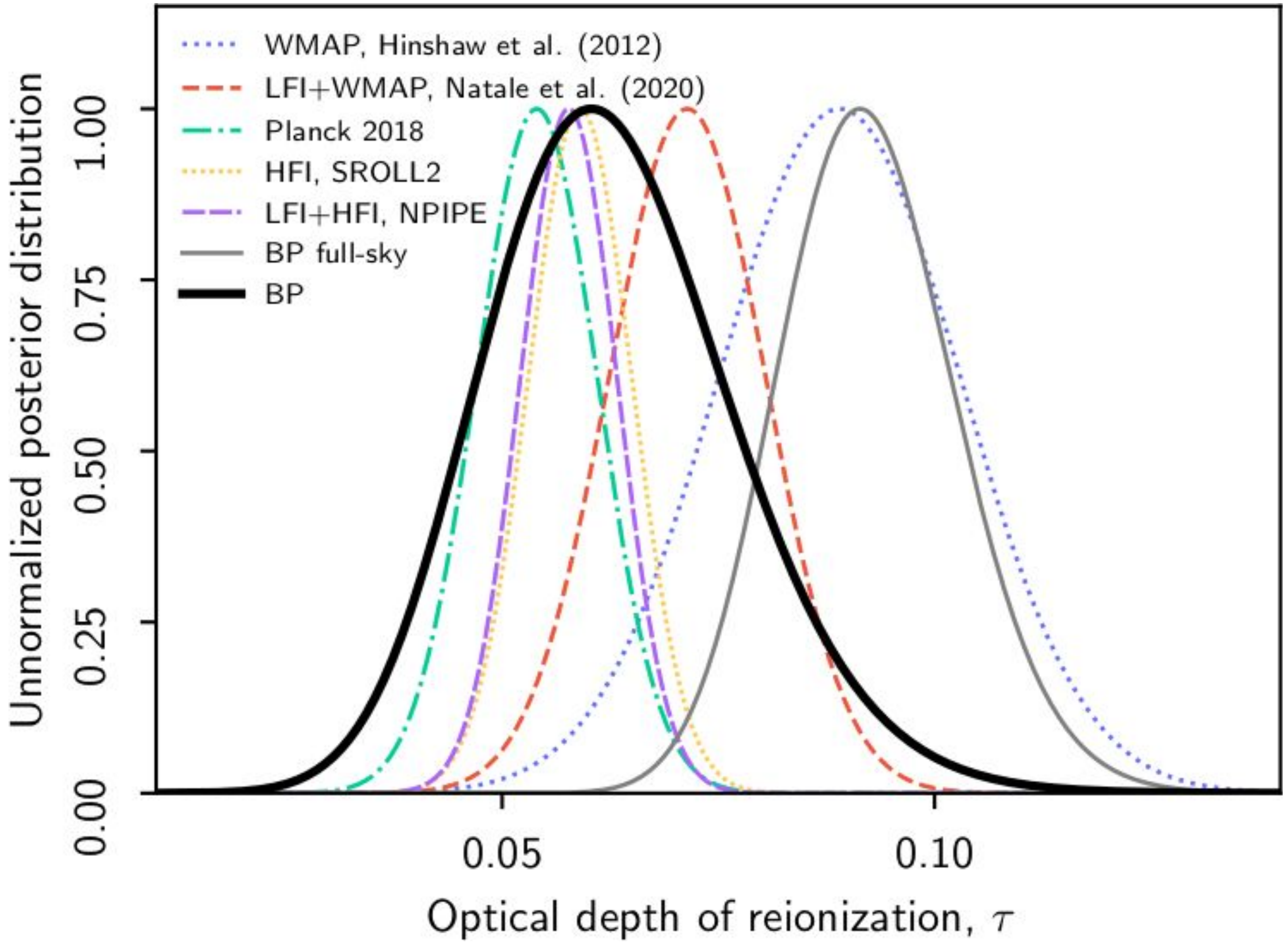


CMB: High-l *TT* spectrum



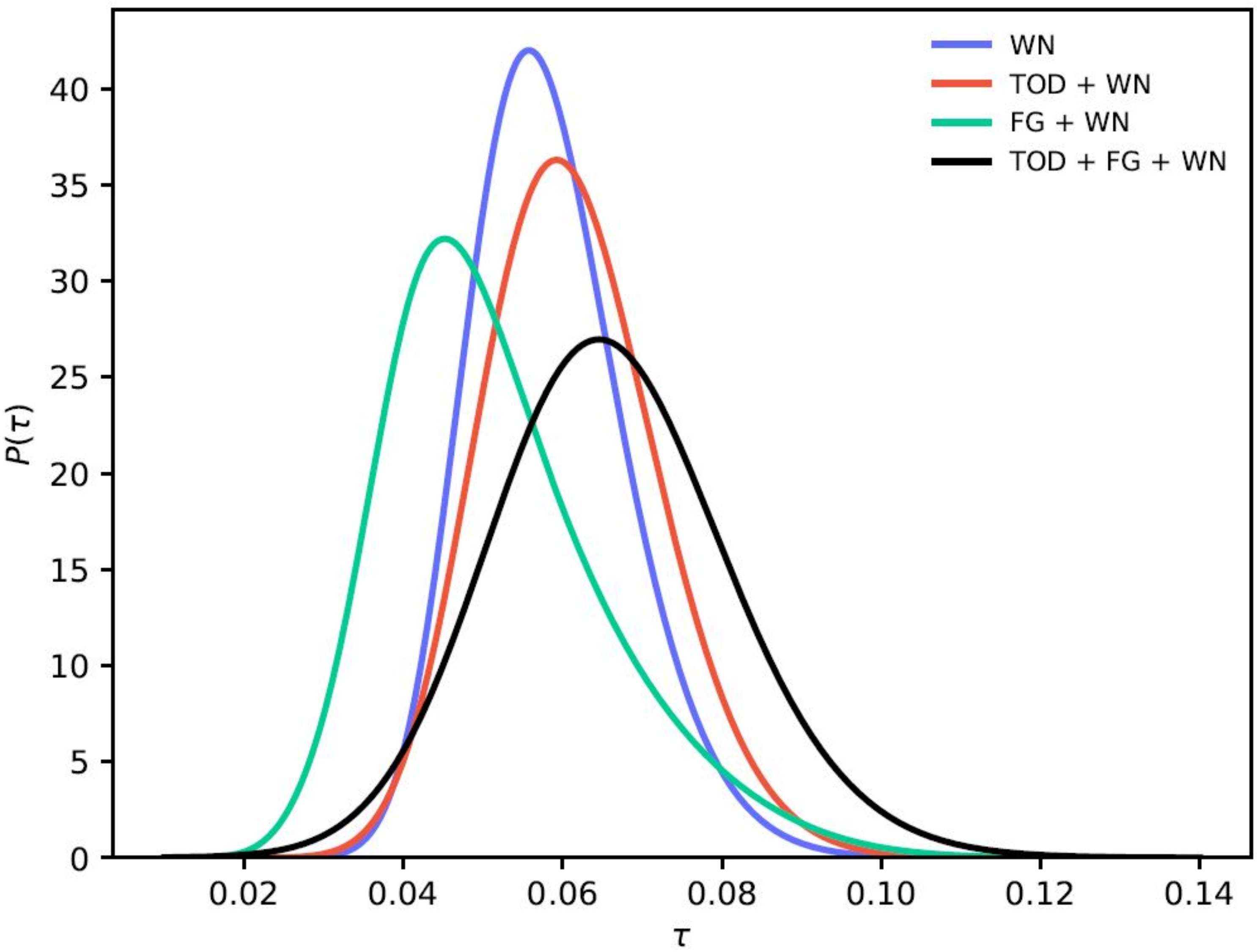
Colombo et al. (2020)

CMB: Low-*l* polarization likelihood, τ and *r*



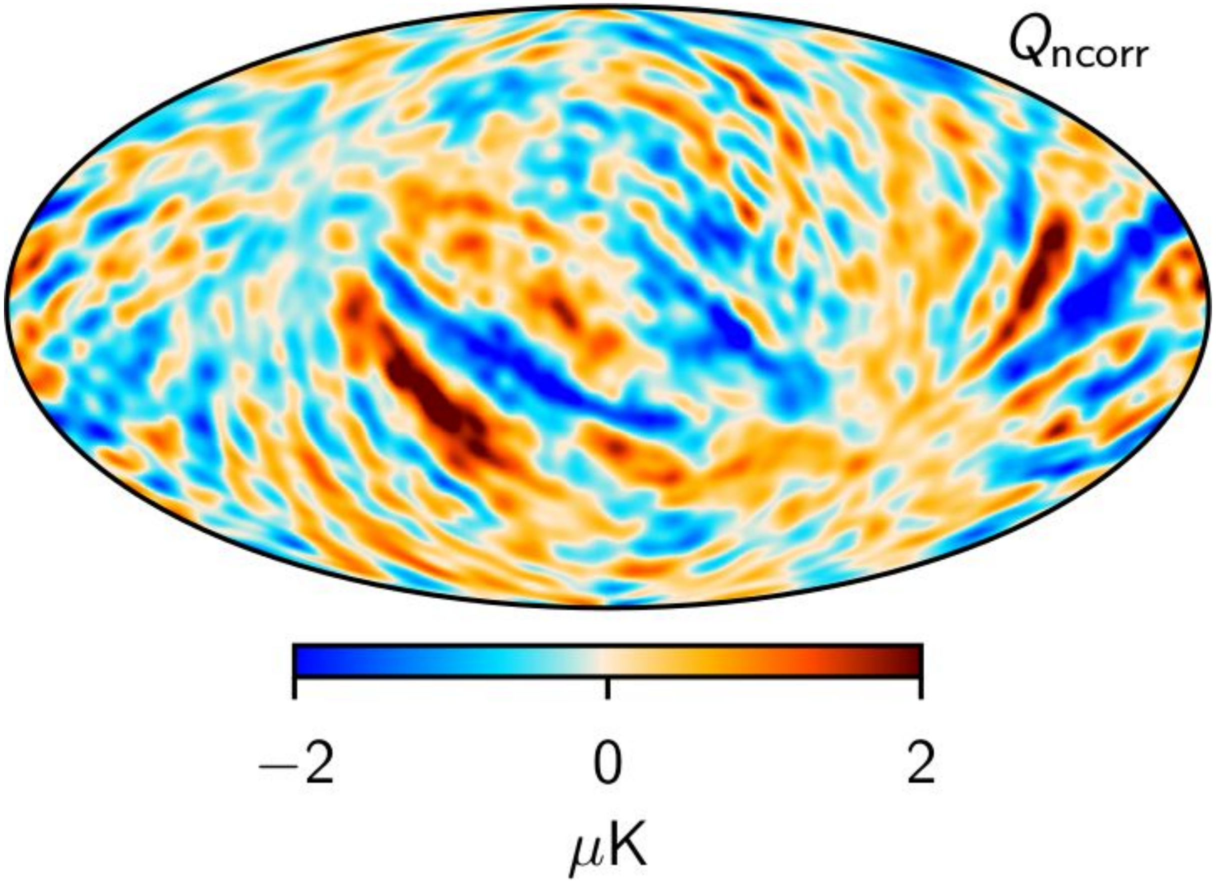
Paradiso et al. (2020)

Uncertainties on the optical depth of reionization



Paradiso et al. (2020)

Outstanding issues 1: Stripes in 44 GHz

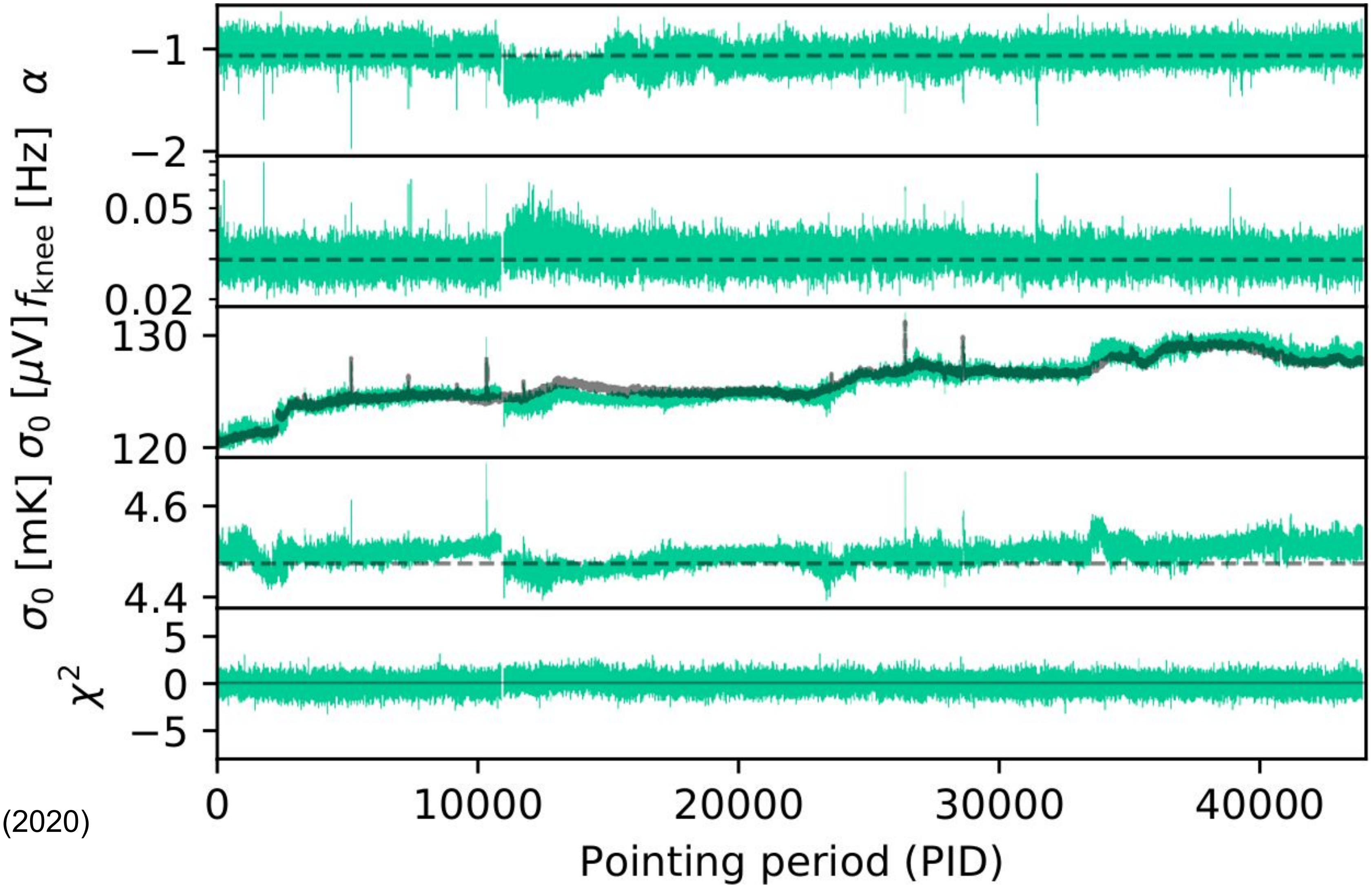


Ihle et al. (2020)

- 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

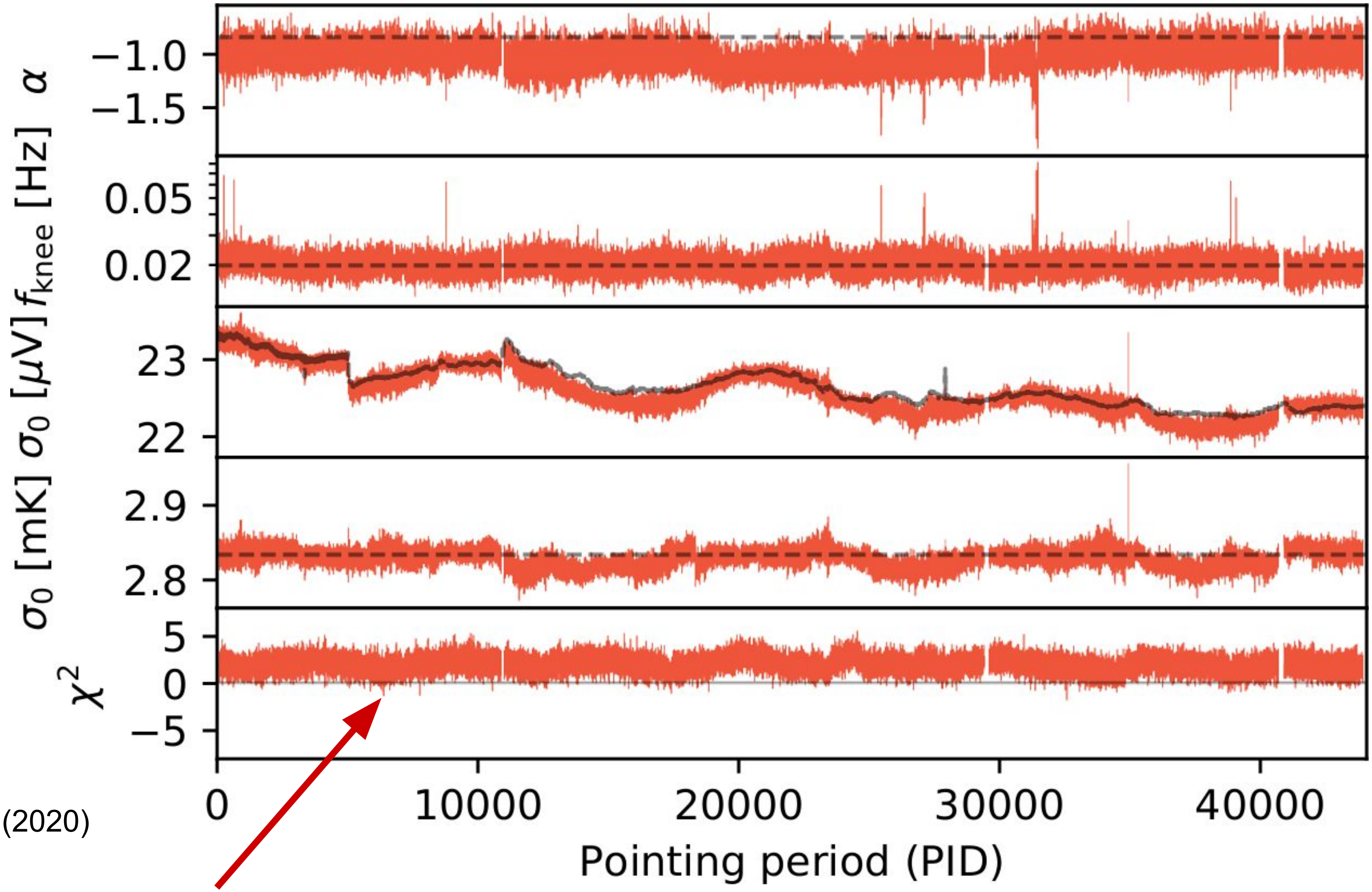
Correlated noise parameters for 70GHz 23M radiometer



Ihle et al. (2020)

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

Correlated noise parameters for 44GHz 25M radiometer

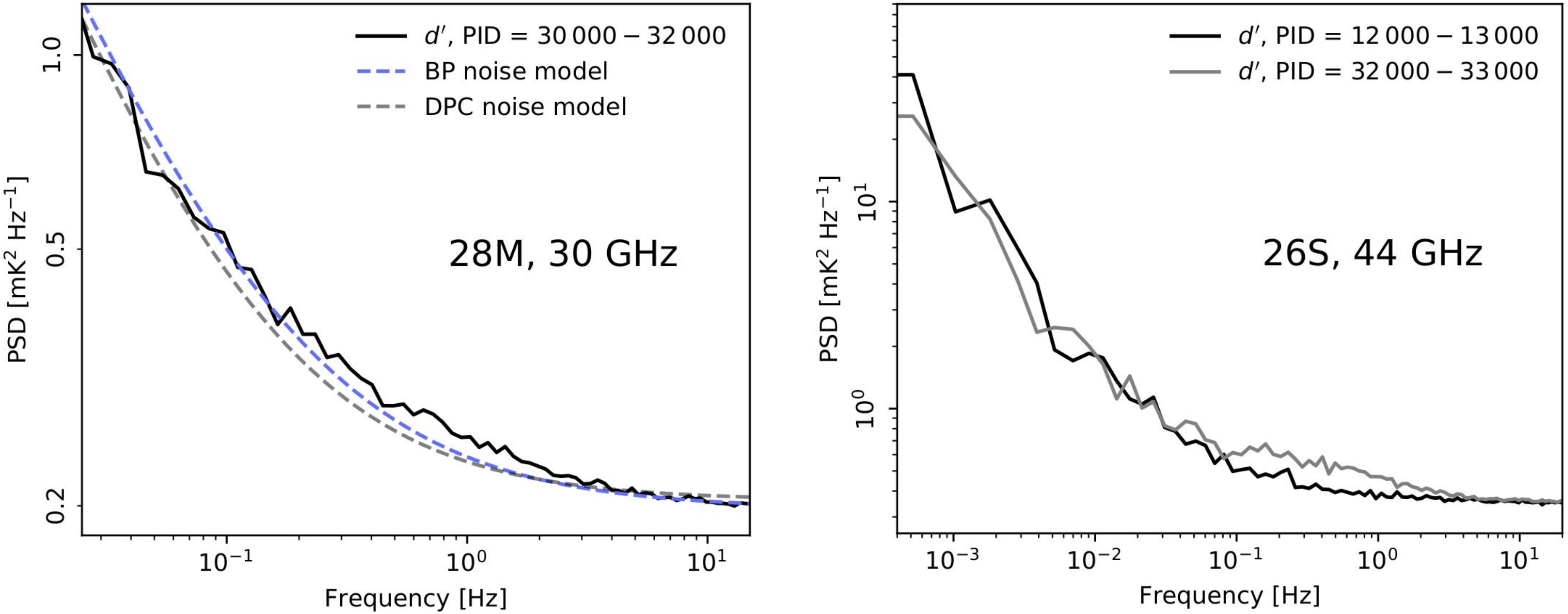


Ihle et al. (2020)

χ^2 excess of 2-3 sigma per PID!

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

Ihle et al. (2020)



- Correlated noise is fitted using a standard 1/f model: $P(f) = \sigma_0^2 \left[1 + \left(\frac{f}{f_{\mathrm{knee}}}\right)^{\alpha}\right]$
- 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

Computational resource requirements

European Commission

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 initializatio[illegible]	[illegible]	[illegible]	[illegible]	663 sec
Total initializa[illegible]	[illegible]	[illegible]	[illegible]	**1880 sec**
Gibbs sampling s[illegible]				
Data decompre[illegible]	[illegible]	[illegible]	[illegible]	393 sec
TOD projectio[illegible]	[illegible]	[illegible]	[illegible]	330 sec
Sidelobe evalu[illegible]	[illegible]	[illegible]	[illegible]	480 sec
Orbital dipole [illegible]	[illegible]	[illegible]	[illegible]	449 sec
Gain sampling [illegible]	[illegible]	[illegible]	[illegible]	94 sec
Correlated nois[illegible]	[illegible]	[illegible]	[illegible]	3138 sec
TOD binning [illegible]	[illegible]	[illegible]	[illegible]	498 sec
Loss due to po[illegible]	[illegible]	[illegible]	[illegible]	502 sec
Sum of other T[illegible]	[illegible]	[illegible]	[illegible]	306 sec
TOD processing [illegible]	[illegible]	[illegible]	[illegible]	**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

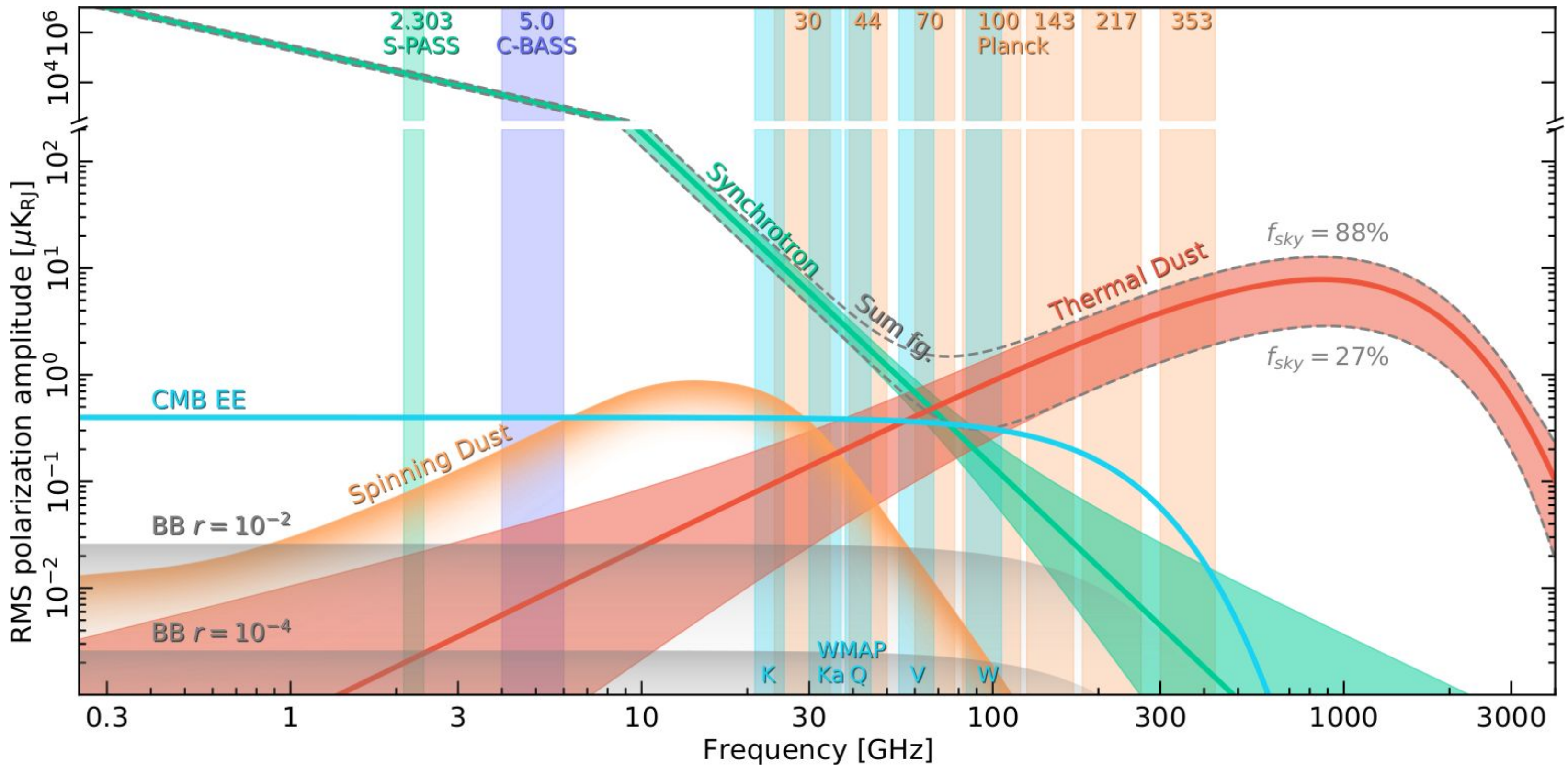
72-core node with 1.5 TB RAM

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

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, led by Prof. Ingunn Wehus; kick-off in May. More than 15 experiments signed up!

"BeyondPlanck for Experiment X"

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

$$d = d(\omega) = \text{signal} + \text{noise}$$

where 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

(It actually works, and it is probably both faster and less error-prone than distributed analysis!)

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
  - All interested parties are invited to join Cosmoglobe, working together toward a global model of the Universe in an Open Science-based community!
- **The basic philosophy is generally applicable to most experiments: Model both instrument and science jointly, and fit everything at once!**

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

The BeyondPlanck collaboration

EU-funded institutions

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Martin Reinecke

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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

European Commission

Questions?

Beyond PLANCK

Commander

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