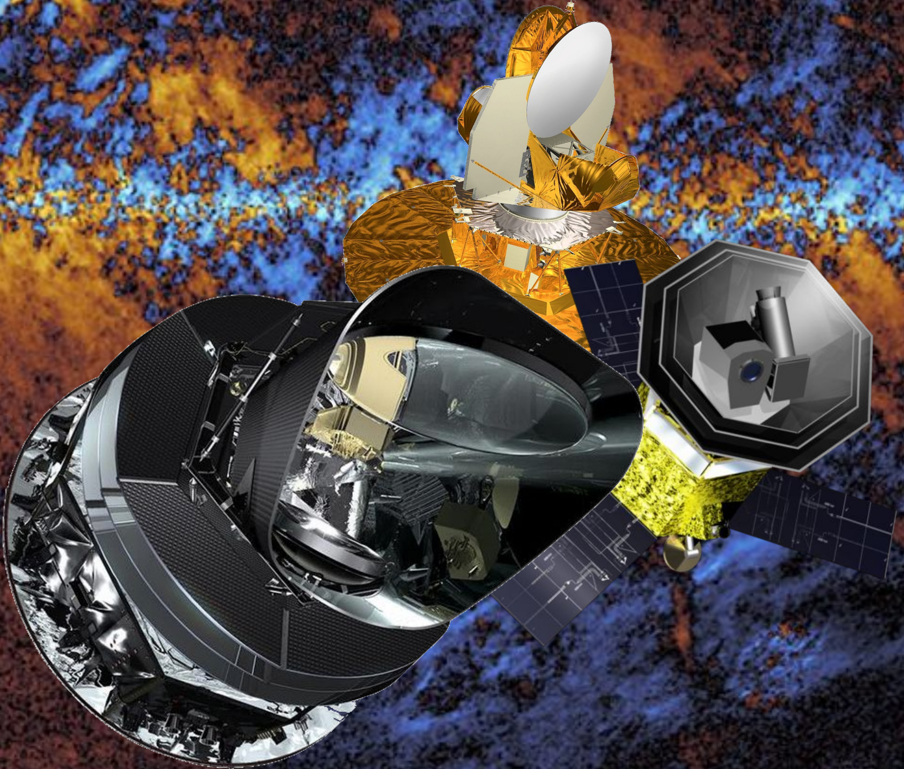
Polarized foregrounds

Trygve Leithe Svalheim



BeyondPlanck online release conference, November 18-20, 2020

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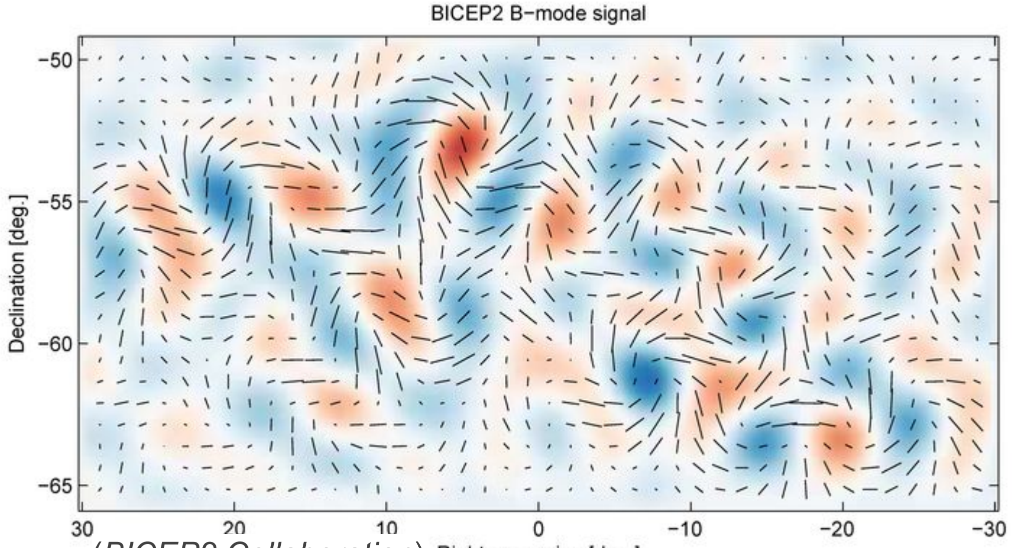
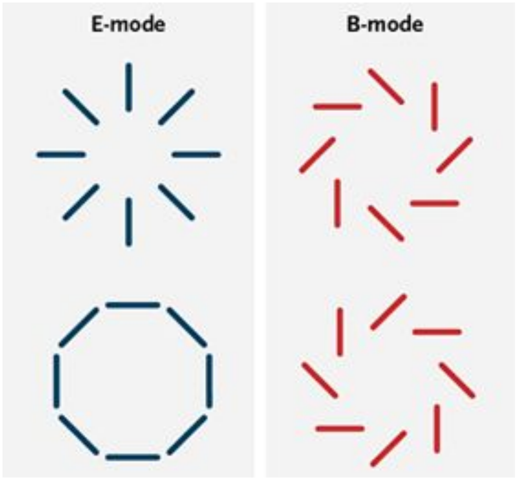
The hunt for B-modes

- The goal: Primordial gravitational waves

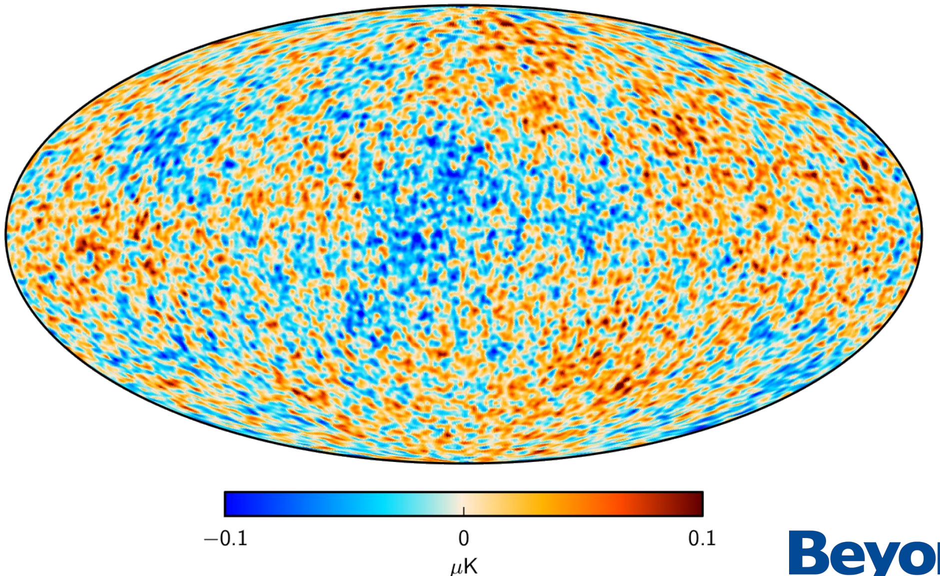


(BICEP2 Collaboration)

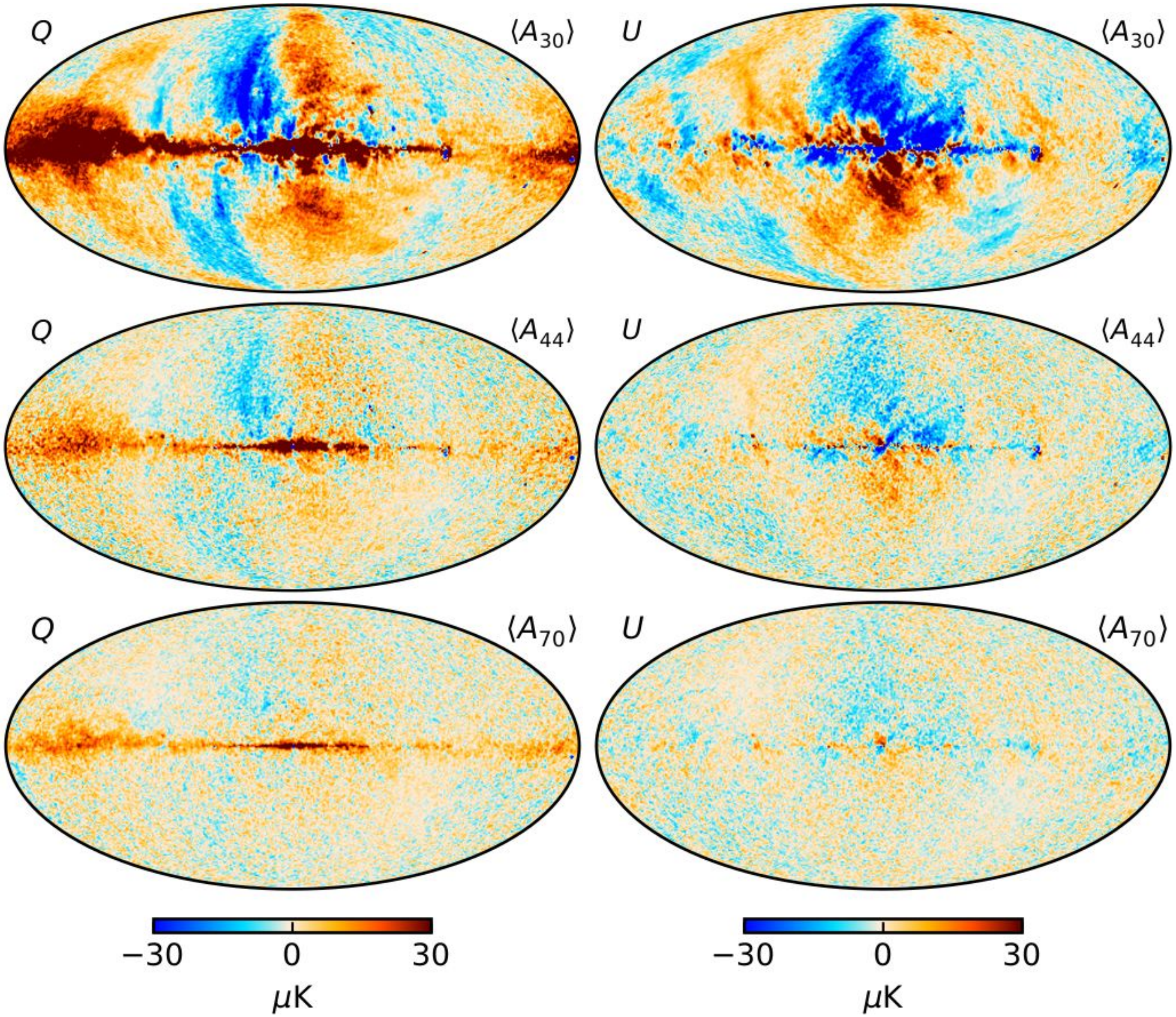


- Simulated stokes Q map for r = 0.01

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



Actual polarized sky



Suur-Uski et al. (2020)

Parameterizing the sky

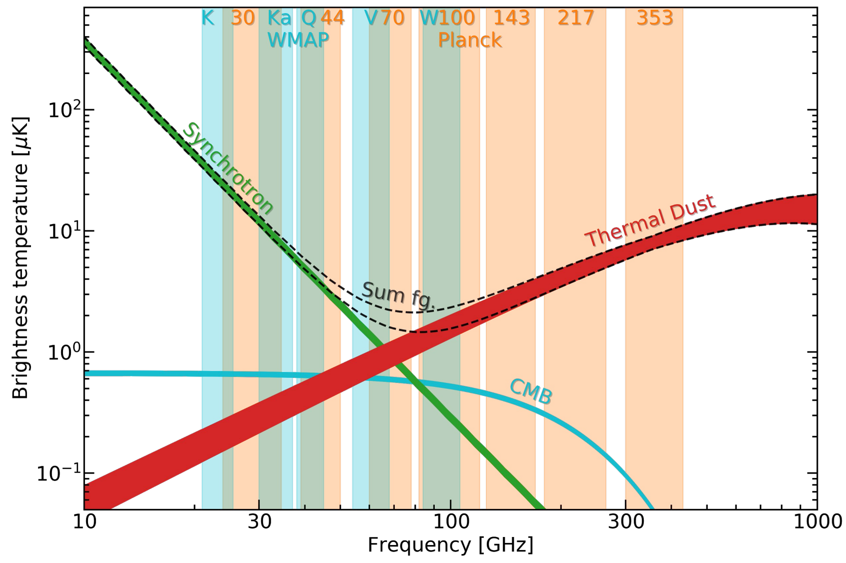
First step is creating the signal model

$$d_{j,t} = g_{j,t} \mathsf{P}_{tp,j} \left[\mathsf{B}^{\text{symm}}_{pp',j} \sum_c \mathsf{M}_{cj}(\beta_{p'}, \Delta^j_{\text{bp}}) a^c_{p'} + \mathsf{B}^{\text{asymm}}_j \left(s^{\text{orb}}_j + s^{\text{fsl}}_j \right) \right]$$

$$s_{\text{RJ}} = a_{\text{CMB}} \frac{x^2 e^x}{(e^x - 1)^2} \frac{(e^{x_0} - 1)^2}{x_0^2 e^{x_0}}$$

Power-law $$+ a_s \left(\frac{\nu}{\nu_{0,s}} \right)^{\beta_s}$$

Modified Blackbody $$+ a_d \left(\frac{\nu}{\nu_{0,d}} \right)^{\beta_d + 1} \frac{e^{h\nu_{0,d}/kT_d} - 1}{e^{h\nu/kT_d} - 1}$$



Bayesian component separation

Unfeasible to sample jointly with this number of parameters
We employ

Commander

New with BeyondPlanck

- Accounting for the interplay between foregrounds and systematics by sampling jointly

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

This work { (the $\boldsymbol{a}$ and β steps)

Amplitude sampling

- We want to sample the conditional distribution $P(\boldsymbol{a} \mid \boldsymbol{d}, \omega \setminus \boldsymbol{a})$

  We define $\boldsymbol{m}_\nu = \mathsf{A}_\nu \boldsymbol{a} + \boldsymbol{n}_\nu$. where $\mathsf{A}_\nu \equiv \mathsf{B}_\nu \mathsf{M}_\nu$

  And find that under the assumption of gaussian noise

$$
\begin{aligned}
P(\boldsymbol{a} \mid \boldsymbol{d}, \omega \setminus \boldsymbol{a}) &\propto P(\boldsymbol{d} \mid \omega) P(\boldsymbol{a}) \\
&\propto P(\boldsymbol{m} \mid \boldsymbol{a}) P(\boldsymbol{a}) \\
&\propto \left(\prod_\nu e^{-\frac{1}{2}(\boldsymbol{m}_\nu - \mathsf{A}_\nu \boldsymbol{a})^t \mathsf{N}_\nu^{-1} (\boldsymbol{m}_\nu - \mathsf{A}_\nu \boldsymbol{a})} \right) \overbrace{e^{-\frac{1}{2}(\boldsymbol{a} - \bar{\boldsymbol{a}})^t \mathsf{S}_\nu^{-1} (\boldsymbol{a} - \bar{\boldsymbol{a}})}}^{\text{Prior}}
\end{aligned}
$$

  using Bayes' theorem, which results in multivariate gaussian.

  One can show that we can draw a sample from this by solving
$$\left(\mathsf{S}^{-1} + \sum_\nu \mathsf{A}_\nu^t \mathsf{N}_\nu^{-1} \mathsf{A}_\nu\right) \boldsymbol{a} = \sum_\nu \mathsf{A}_\nu^t \mathsf{N}_\nu^{-1} \boldsymbol{m}_\nu + \sum_\nu \mathsf{A}_\nu^t \mathsf{N}_\nu^{-1/2} \eta_\nu + \mathsf{S}^{-1/2} \eta_0,$$

  for **a**, which we do using a conjugate gradient solver.

Spectral index sampling

- Standard Gibbs sampling step as before

$$P(\beta \mid \boldsymbol{d}, \boldsymbol{a}) \propto P(\boldsymbol{d} \mid \boldsymbol{a}, \beta) P(\beta)$$

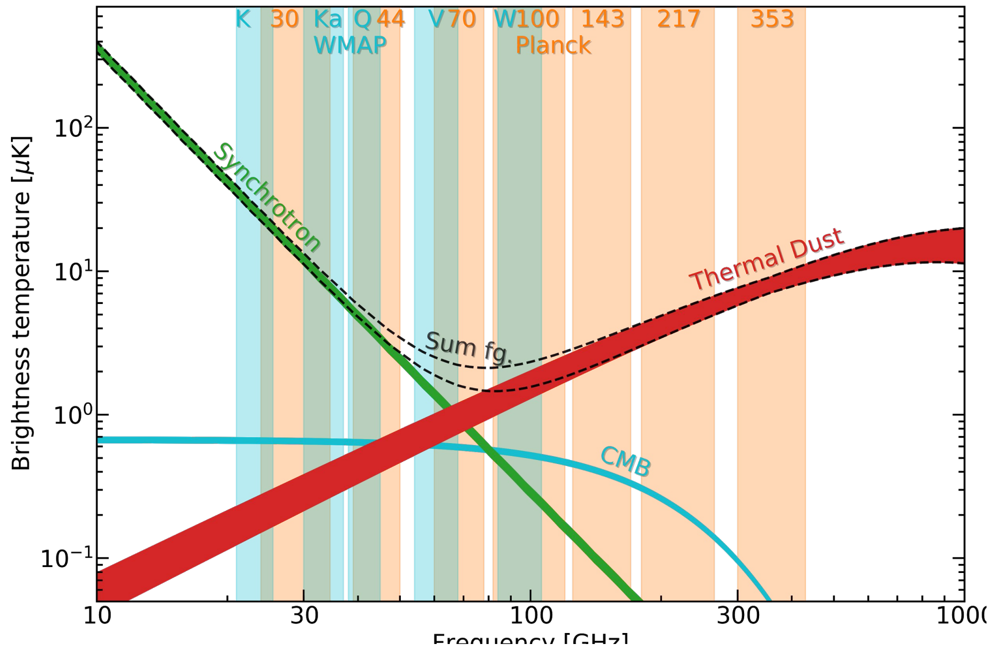
$$\propto \left[\prod_{\nu} \mathrm{e}^{-\frac{1}{2}(\boldsymbol{d}_\nu - \mathrm{A}(\beta)\boldsymbol{a})^t \mathrm{N}_\nu^{-1} (\boldsymbol{d}_\nu - \mathrm{A}(\beta)\boldsymbol{a})} \right] P(\beta),$$

- The nonlinear relationship between beta and d
  - Cannot use CG
- Use a Metropolis sampler
  - Draw a proposal for beta
  - Project to mapspace
  - Assess goodness-of-fit
  - accept or reject

Data selection

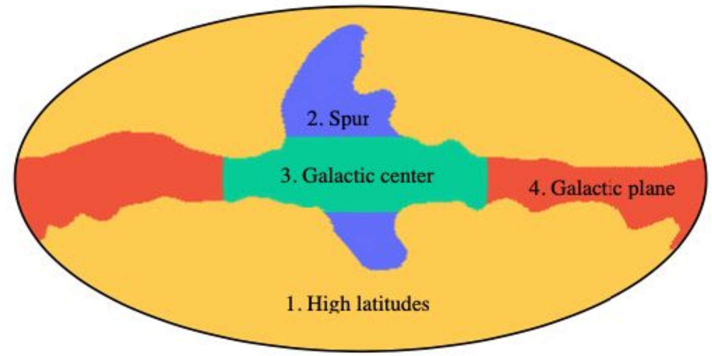
- ❑ **Planck LFI (30, 44, 70 Ghz) time ordered data**
- ❑ **Planck HFI 353 GHz**
- ❑ **WMAP Ka, Q and V**

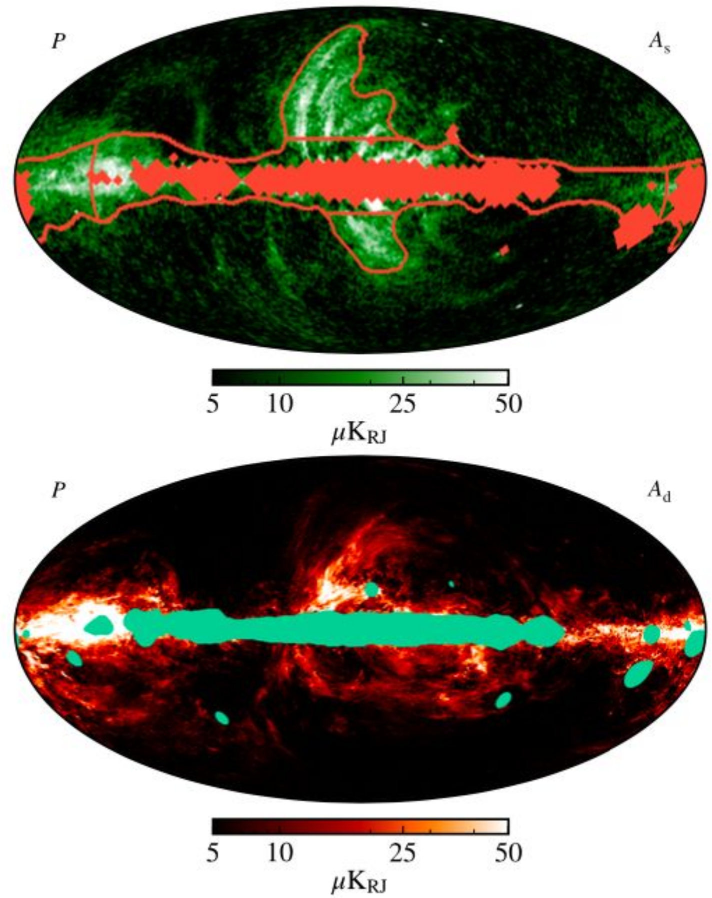
- ❑ Full covariance matrices for WMAP
  - ❑ Improves ability to identify noise on a band-to-band basis.
  - ❑ WMAP systematics contained to WMAP data.
- ❑ WMAP K band omitted
  - ❑ Too "good"
- ❑ WMAP W band omitted
  - ❑ Too "bad"
- ❑ Sparse dataset
  - ❑ Showcase of algorithm



Spectral index spatial variations

- Spatial variations in spectral indices
  - Sparse dataset
- Synchrotron Beta
  - Divide sky into disjoint regions sampled independently
- Thermal dust beta
  - Fullsky





$$s_{RJ} = a_{CMB}\frac{x^2 e^x}{(e^x - 1)^2}\frac{(e^{x_0} - 1)^2}{x_0^2 e^{x_0}}$$

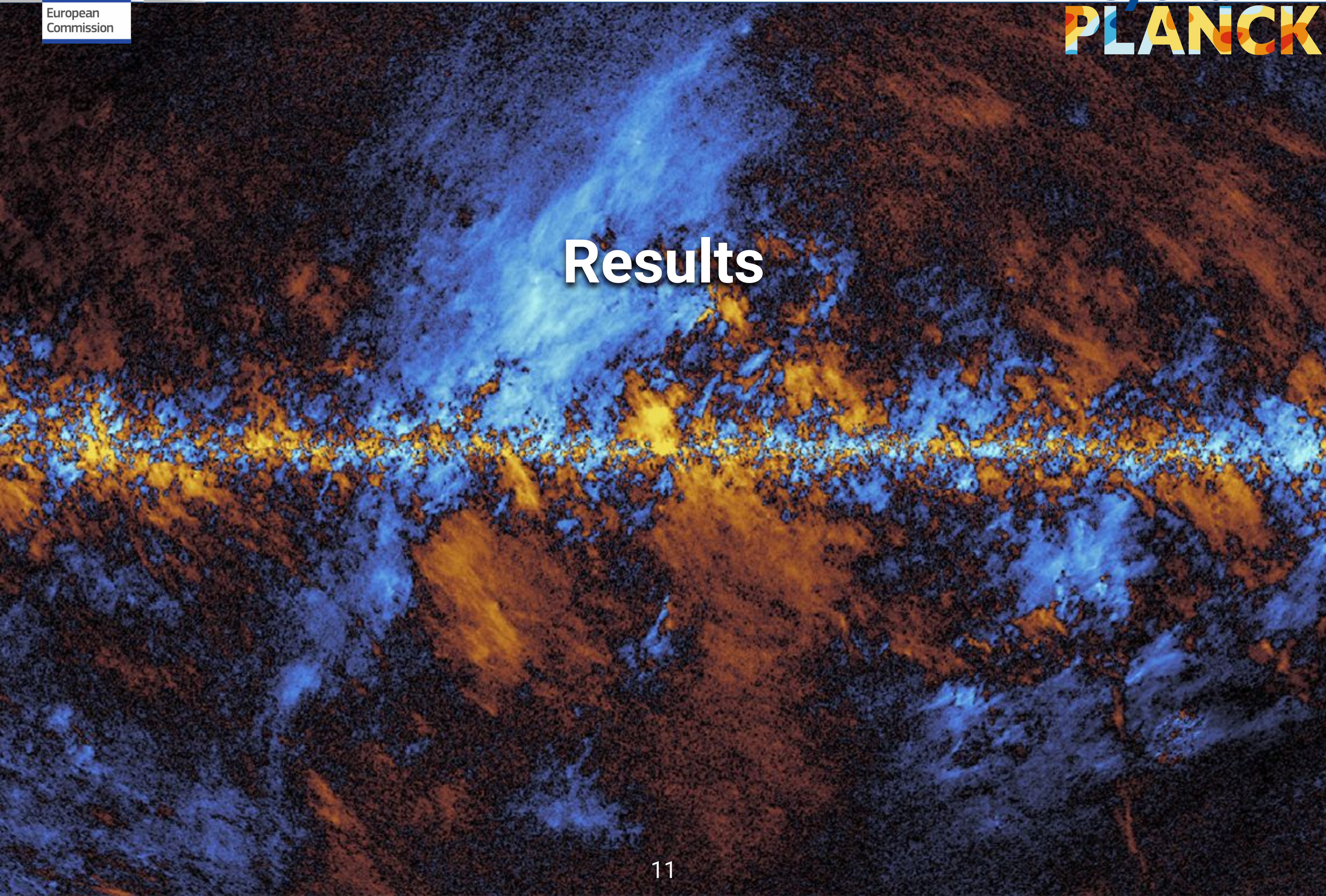
Power-law

$$+ a_s\left(\frac{\nu}{\nu_{0,s}}\right)^{\beta_s}$$

Modified Blackbody

$$+ a_d\left(\frac{\nu}{\nu_{0,d}}\right)^{\beta_d+1}\frac{e^{h\nu_{0,d}/kT_d} - 1}{e^{h\nu/kT_d} - 1}$$

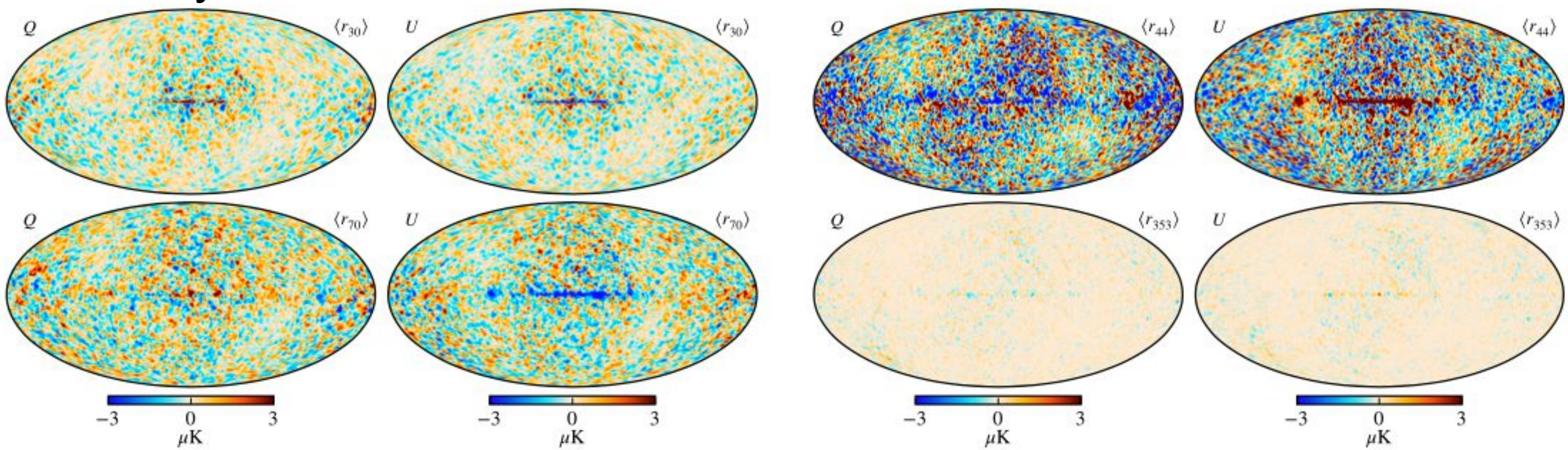
Results



Planck residual maps

$$(r_\nu = d_\nu - s_\nu)$$

Synchrotron reference



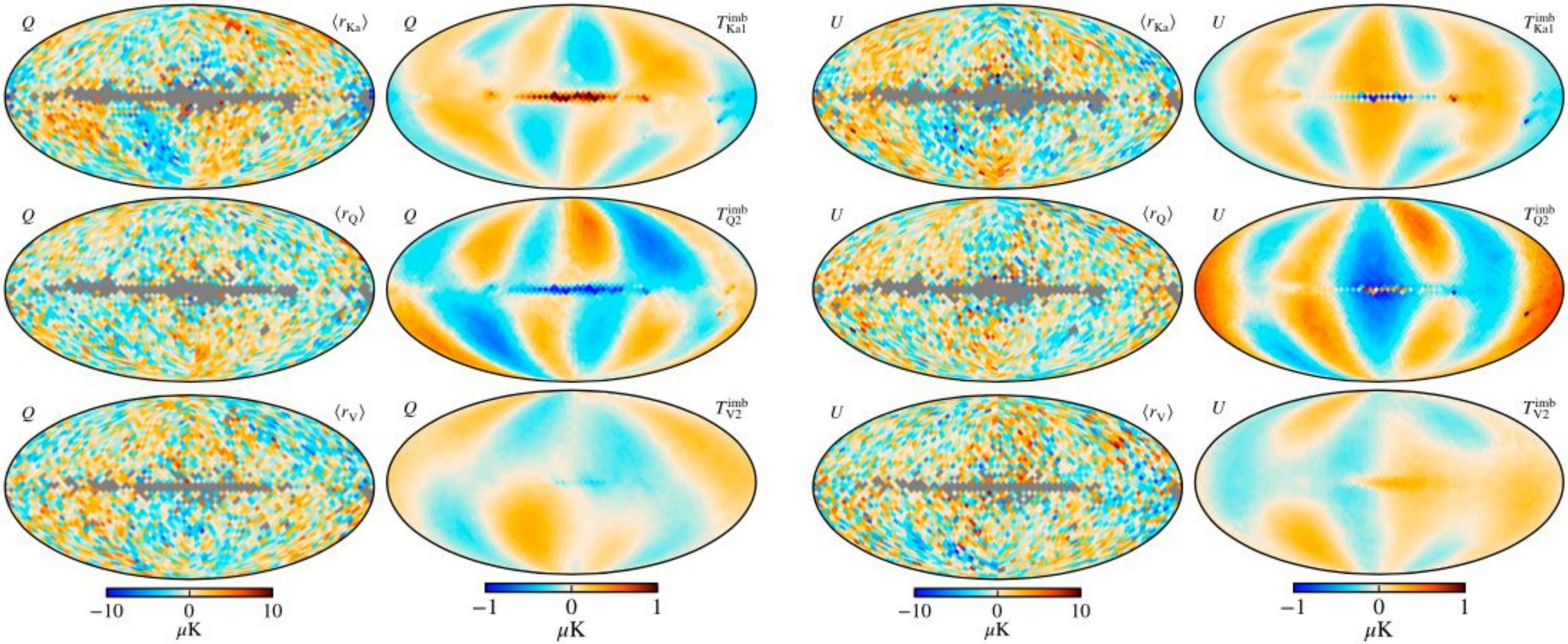
CMB reference

Thermal dust reference

How well do we fit our data as a function of frequency?
Some residual signal is a good sign!

WMAP Residuals and imbalance templates

European Commission



- Residual maps show clear correlation with imbalance templates.
- Due to uncertainties, not all modes were properly weighted
- Not an issue for this analysis (Covariance matrices)

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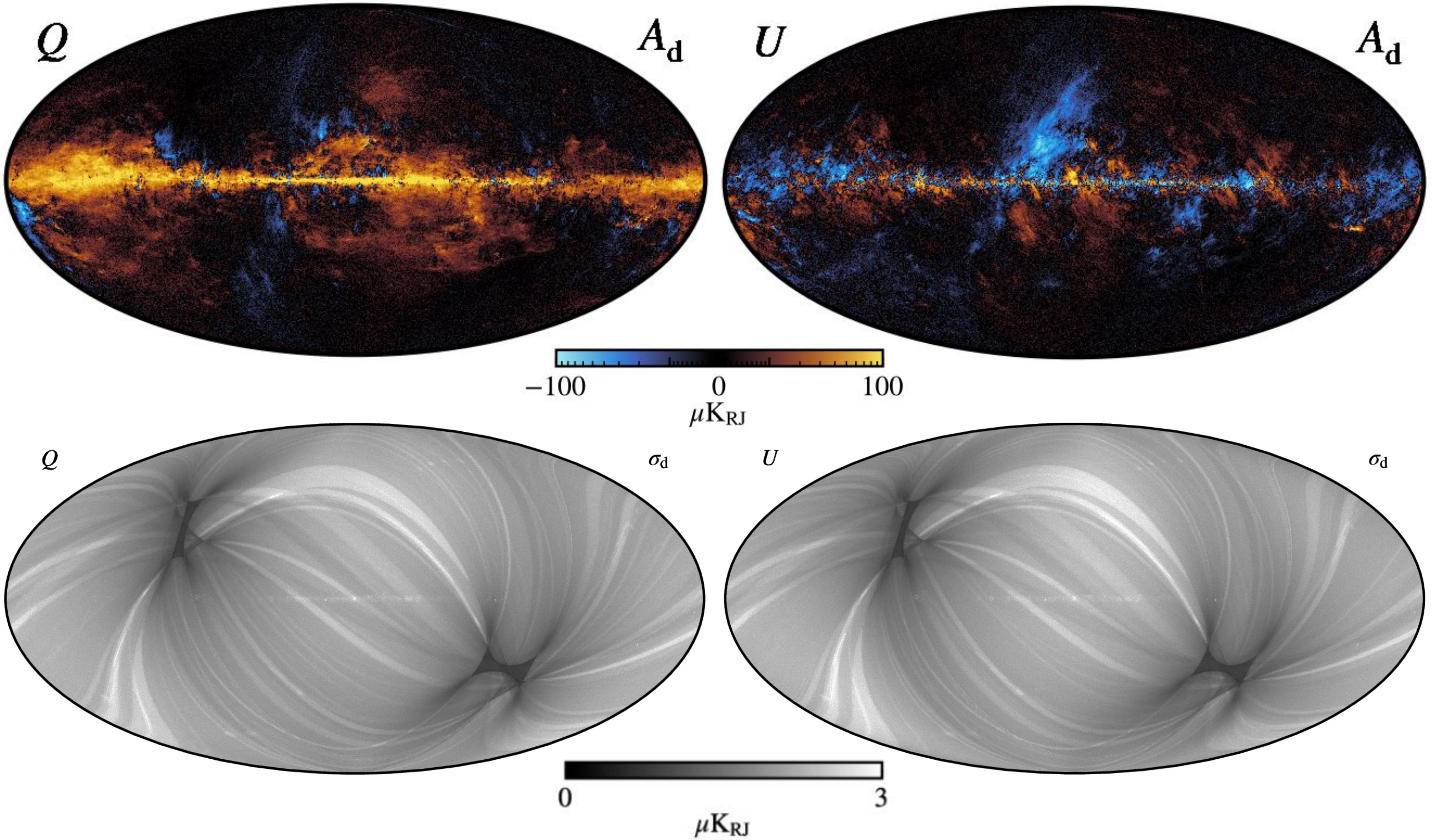
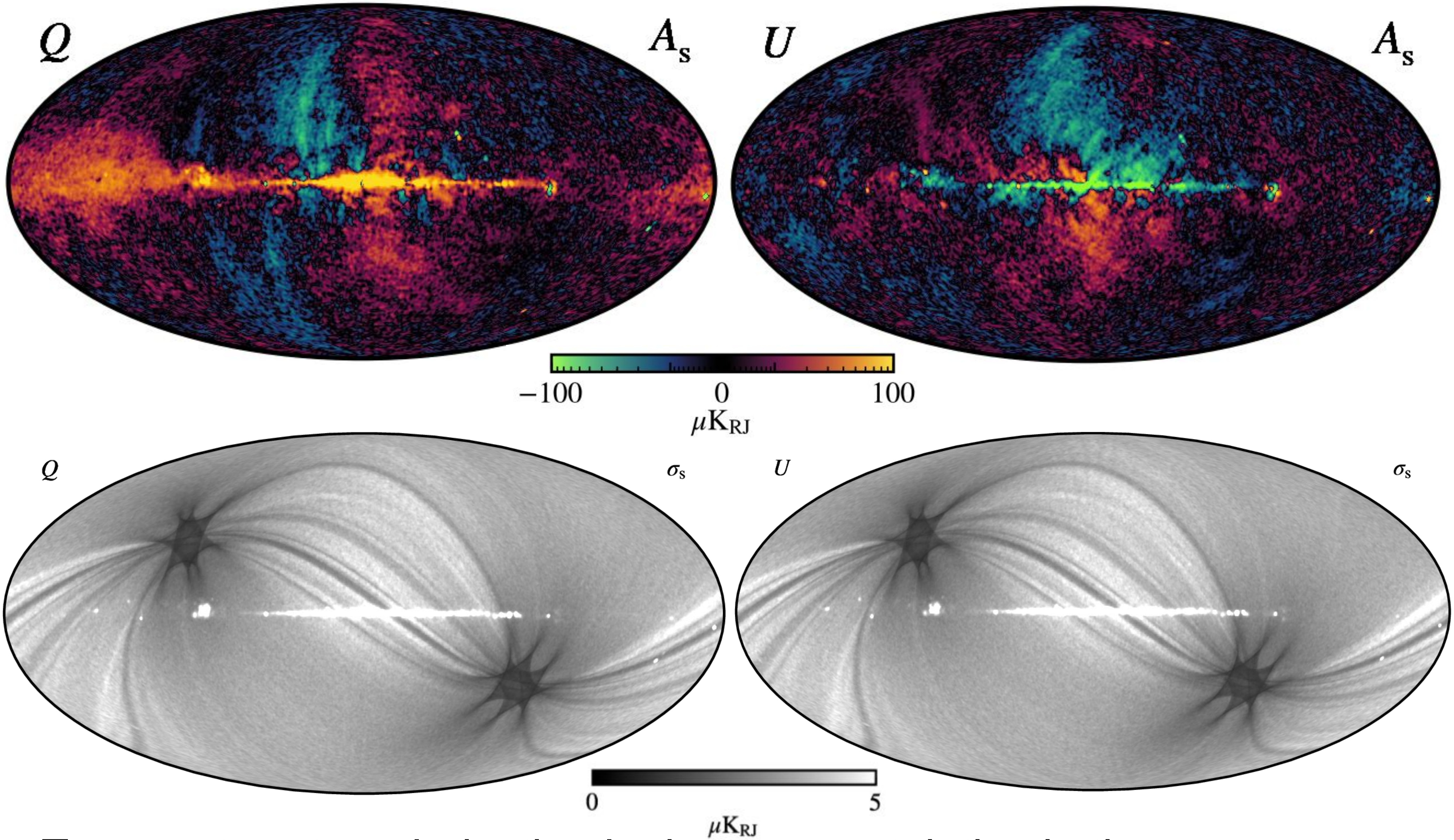
Dust amplitude

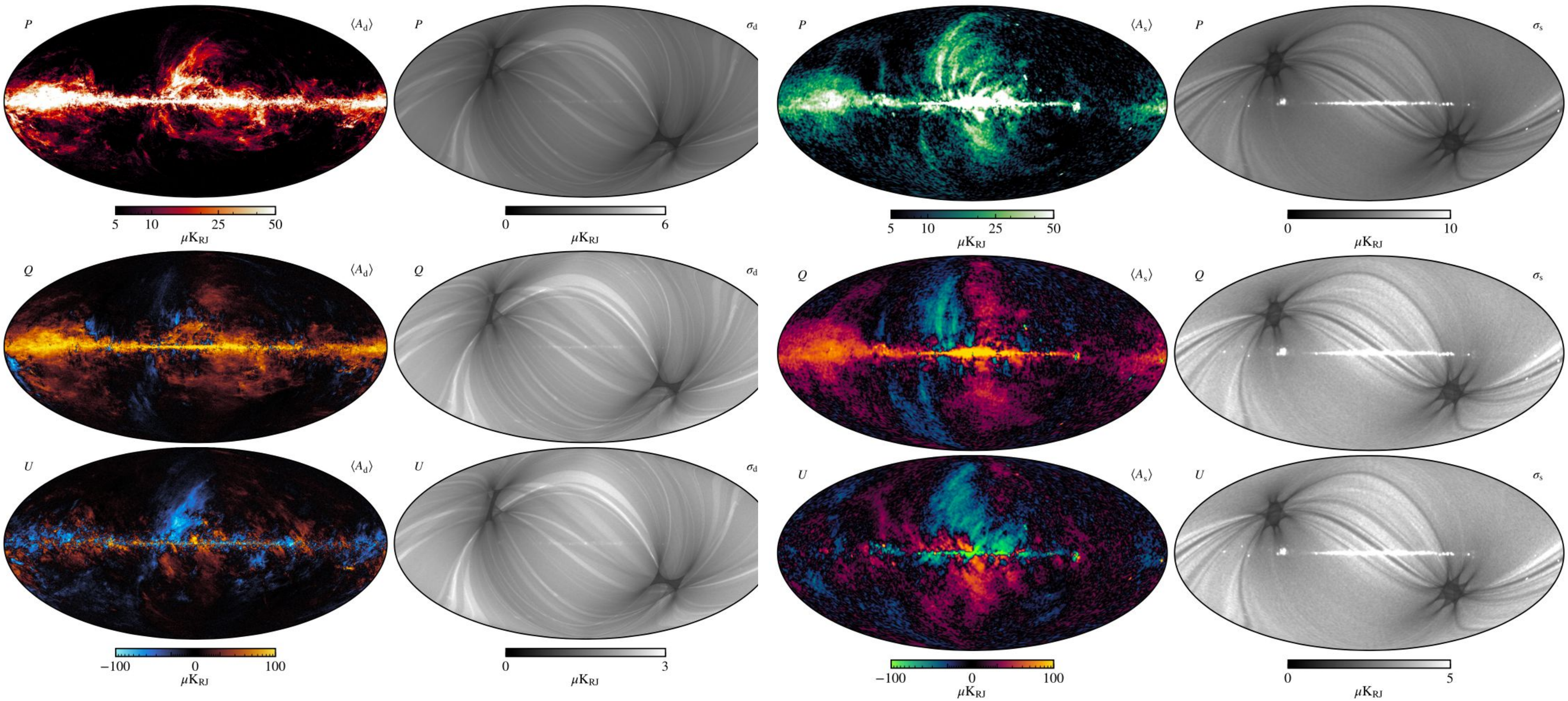


Little variation, determined by the HFI 353 GHz band.

Synchrotron amplitude

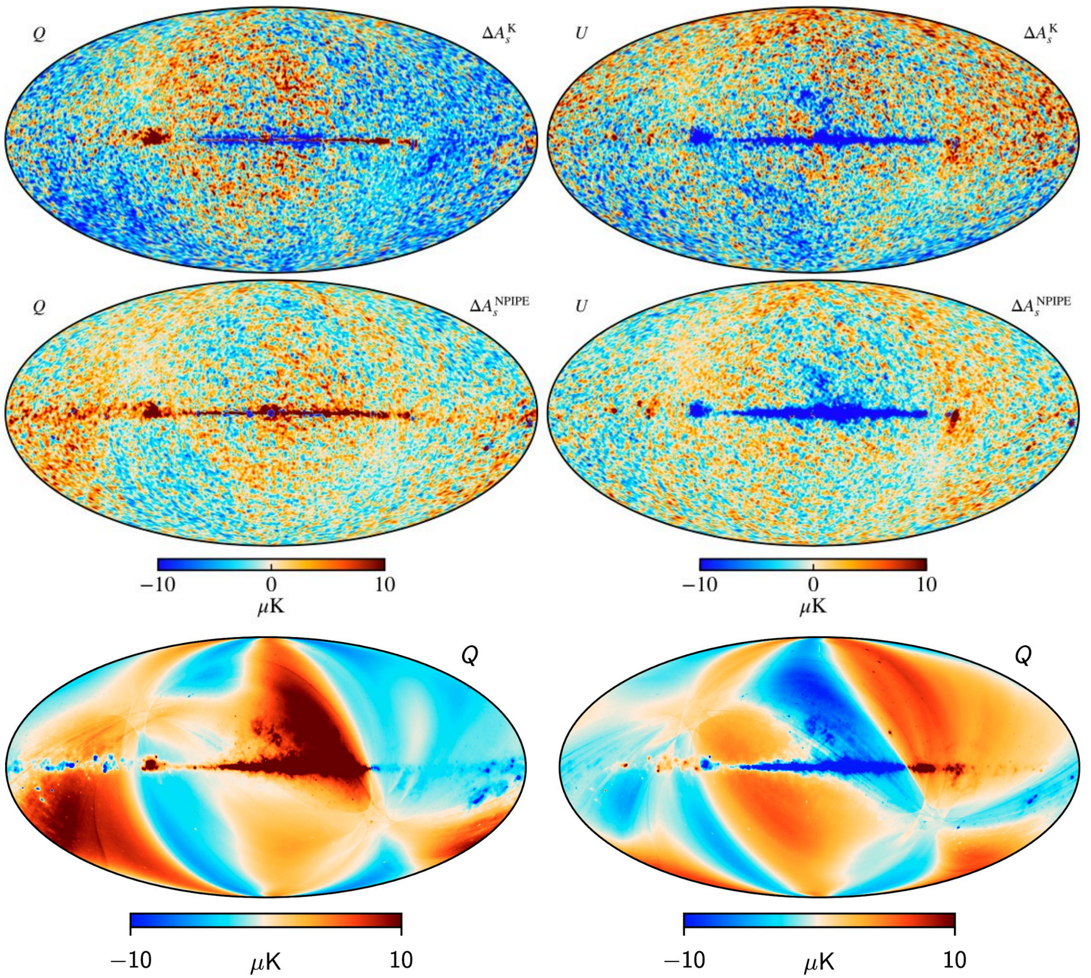


Temperature-to-polarization leakage uncertainties in the galactic plane


P
⟨A_d⟩
σ_d
⟨A_s⟩
σ_s
5 10 25 50
μK_RJ
0 6
0 10
Q
U
−100 0 100
0 3
0 5

Difference with K-BAND and NPIPE

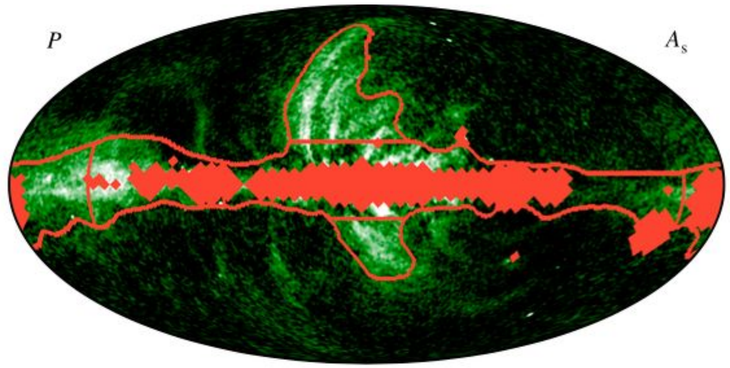
- Difference to WMAP K-band
  - Dipolar structure
  - Differences too big to be fully explained by spectral index
- Difference to NPIPE
  - Uncertainties in the time-dependent gain models adopted by NPIPE and BP
  - Well understood

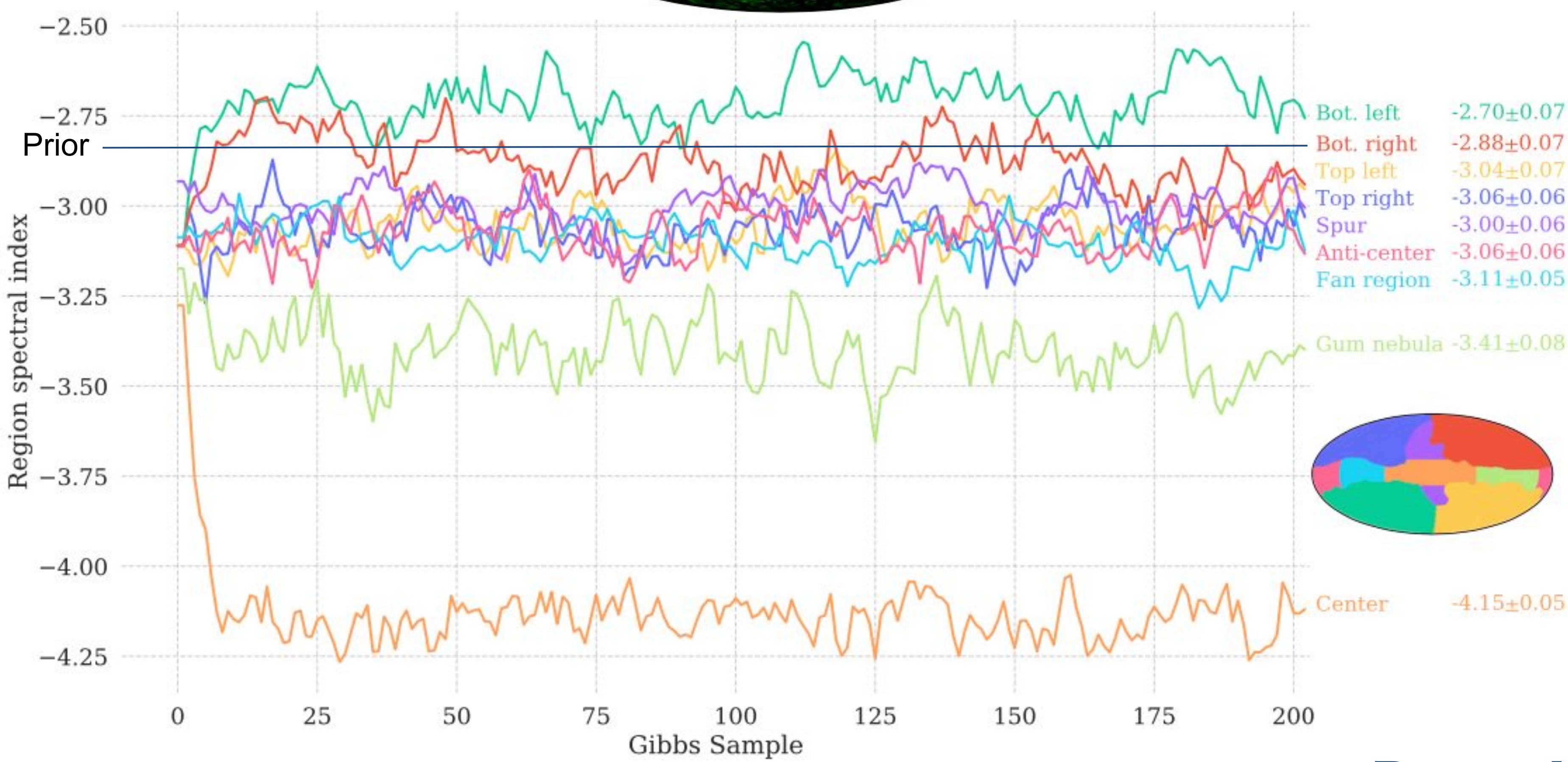


Gain residual template
from Gjerløw et al. (2020)

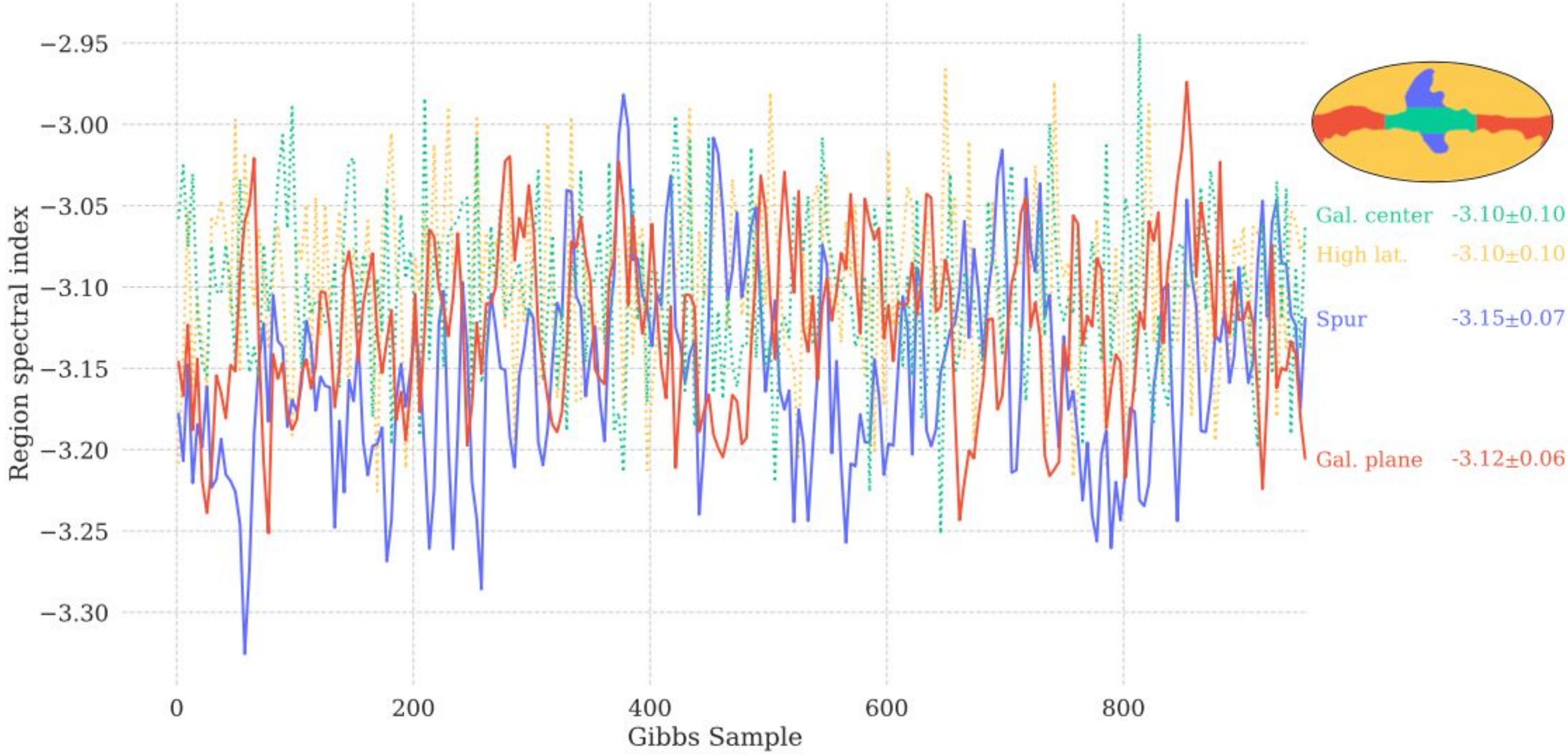
Spectral indices and its variations

Test case:
9 regions
Prior of -2.8+-0.1



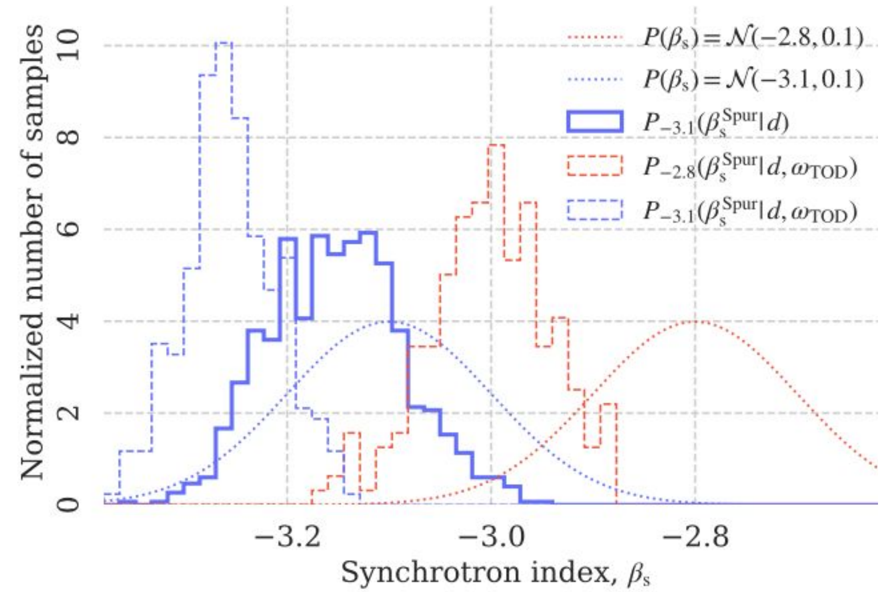


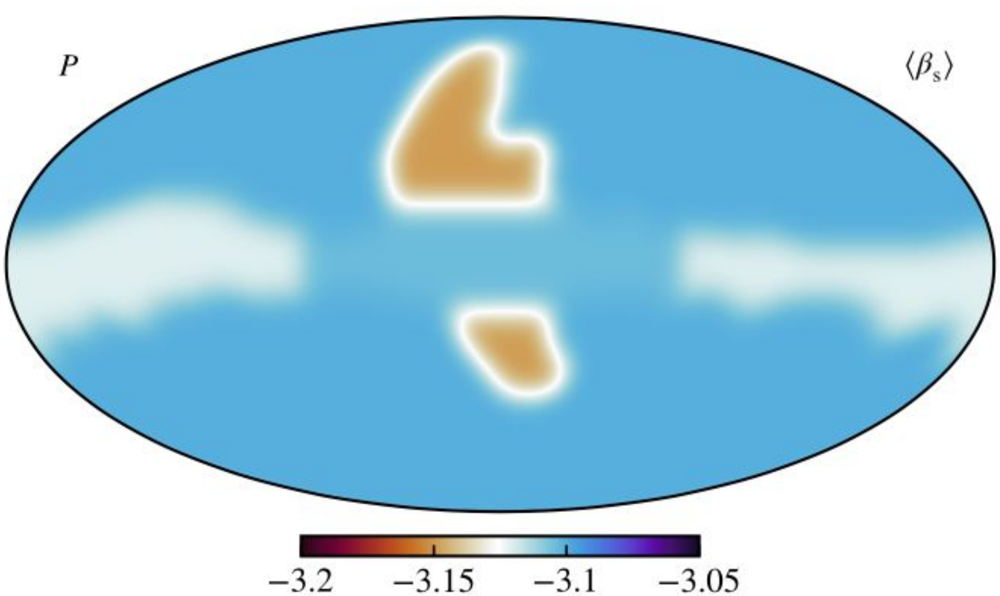
Sampling regions

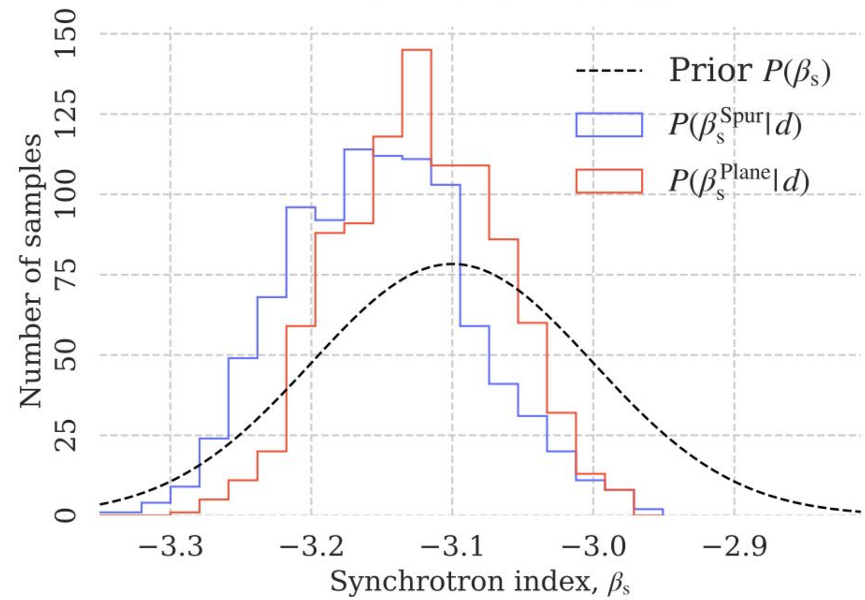


Synchrotron beta

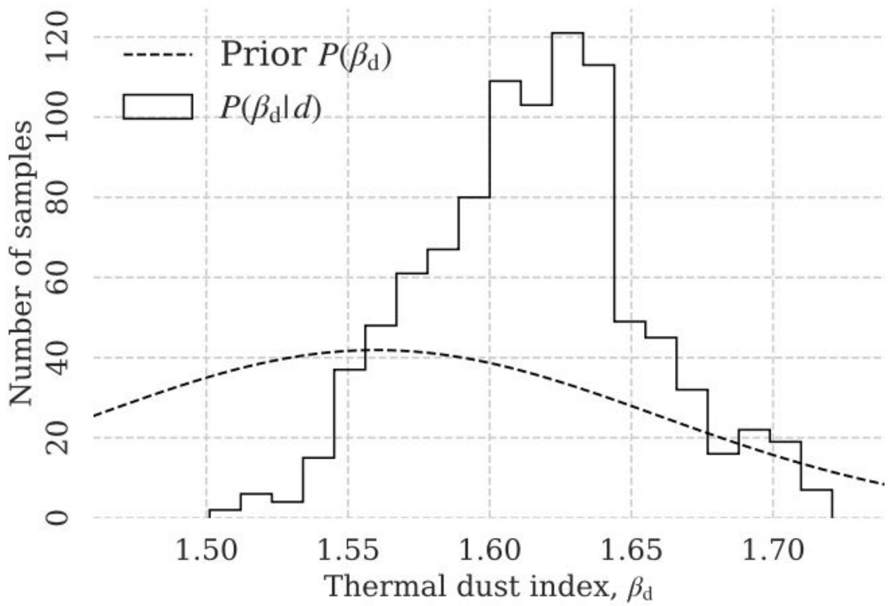
- ❑ Sampled regions data driven
- ❑ Beta_spur = -3.15 +- 0.07
- ❑ Beta_plane = -3.12 +- 0.06
- ❑ No significant spatial variation
- ❑ Validation: Advantage of full marginalization over TOD parameters.
  - ❑ Uncertainty from TOD







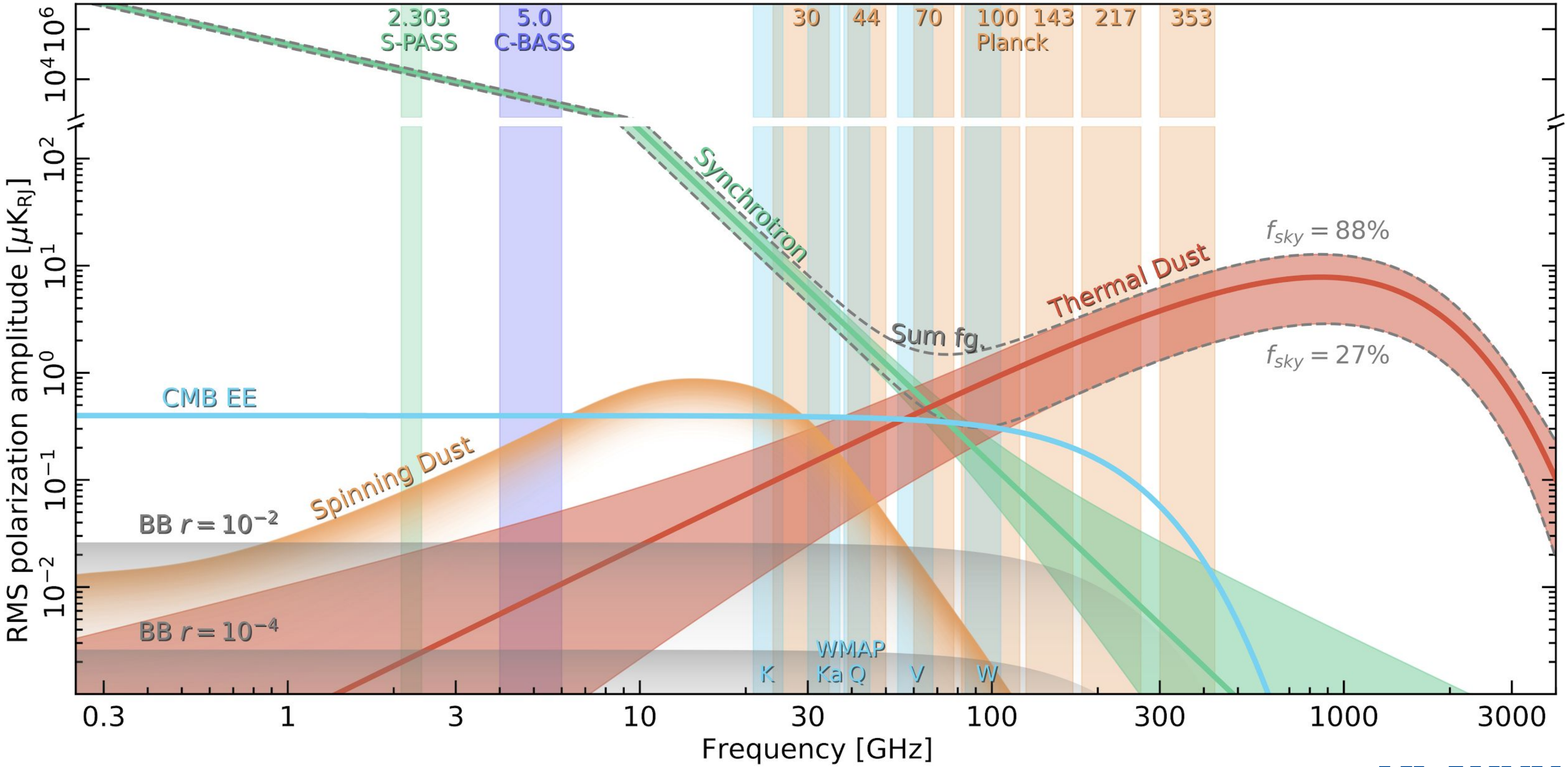
Dust spectral index



- Within the range of “healthy” values
- Slightly steep
  - Possibly steepening of dust-beta?
    - Similar effect has been seen in temperature analysis before
  - Warrants further investigation
    - Perhaps too simple bandpass correction?

Summary

- Constraints on synchrotron and dust polarized spectral indices
  - No evidence towards spatial variations in the sampled regions
- First joint sampling of amplitudes and spectral indices to combine LFI in time domain with low resolution WMAP data.



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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?

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