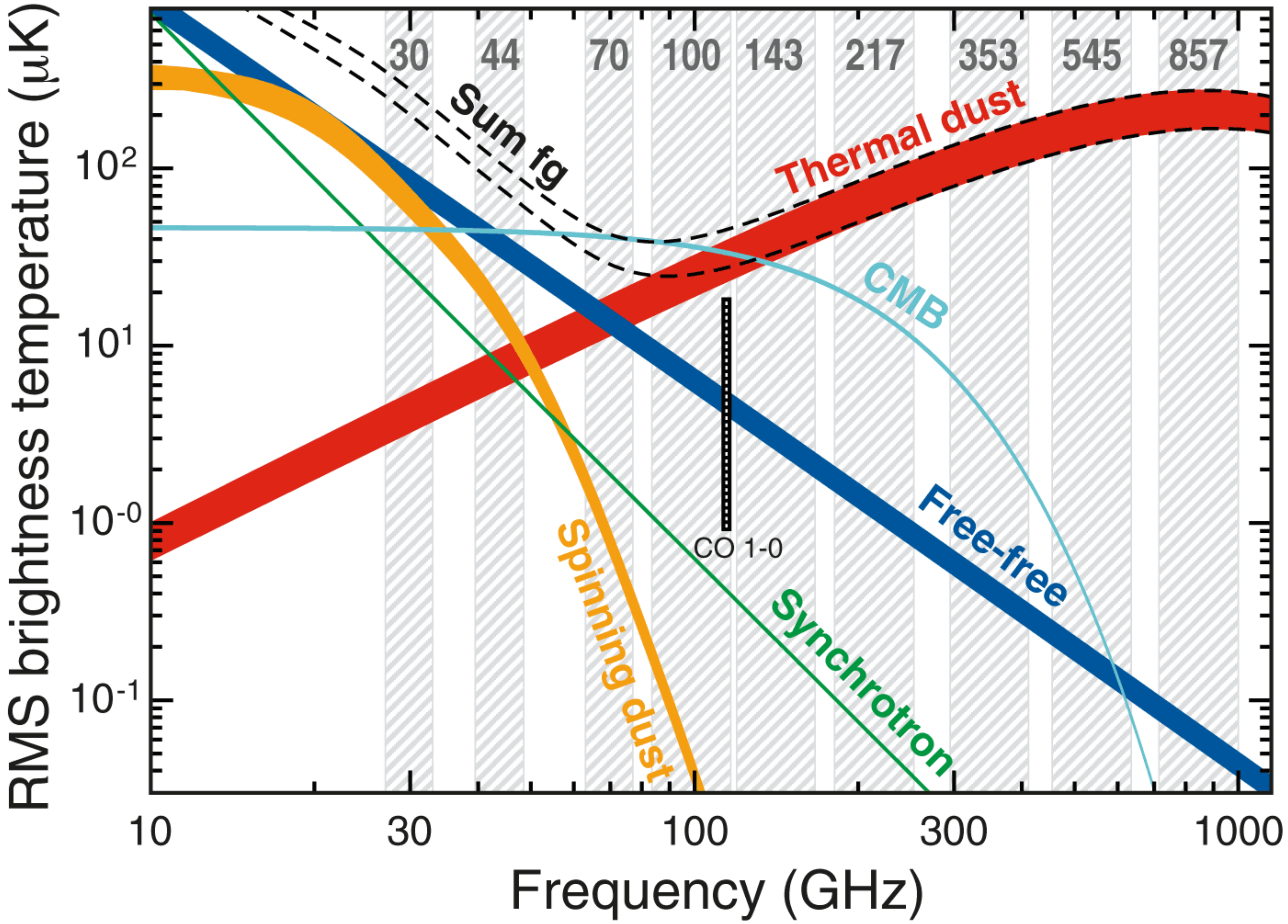
SISSA
Nicoletta
Krachmalnicoff

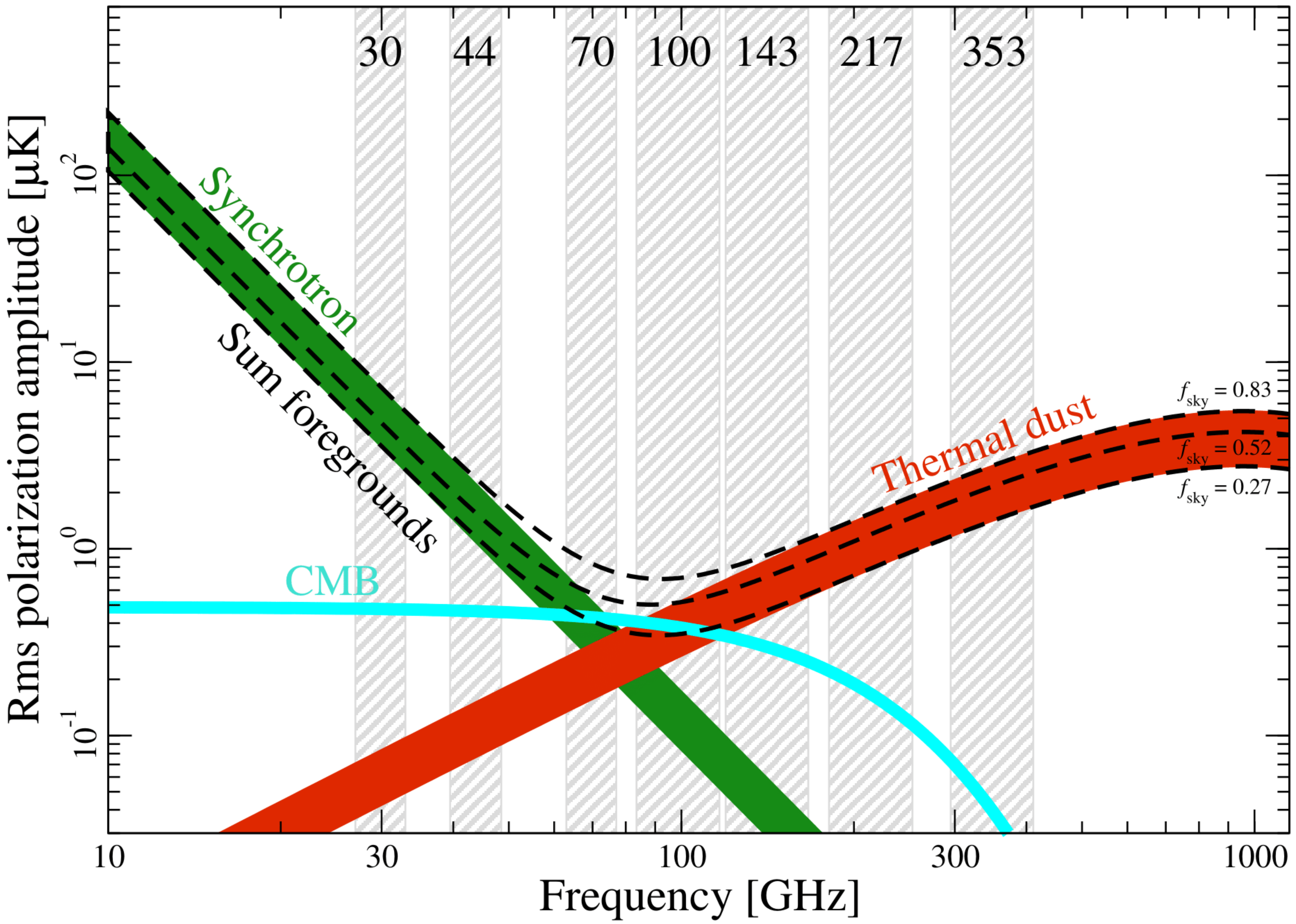
From Planck to the future of CMB
May 2022

Characterization of foreground emission for CMB experiments:

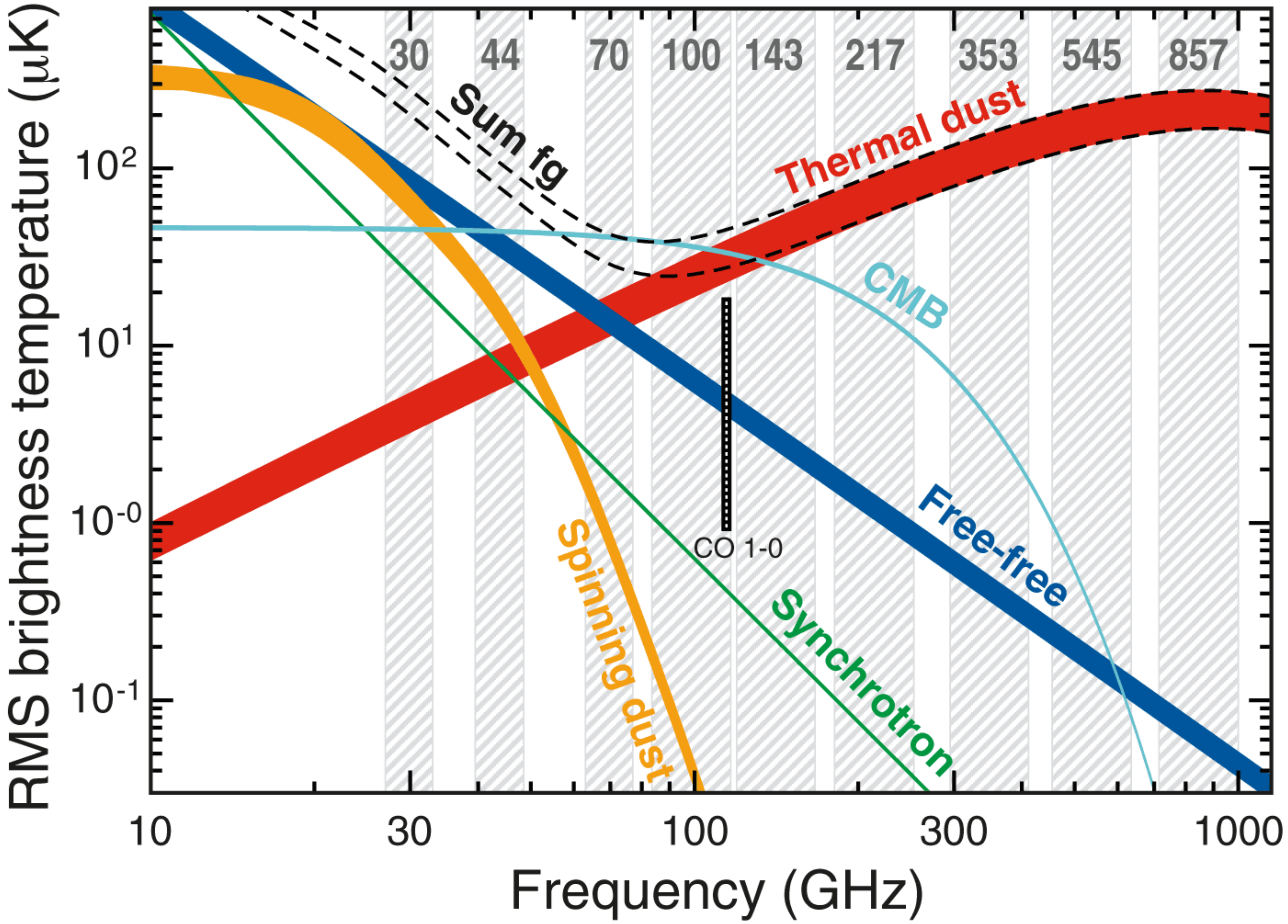
current status and future prospective

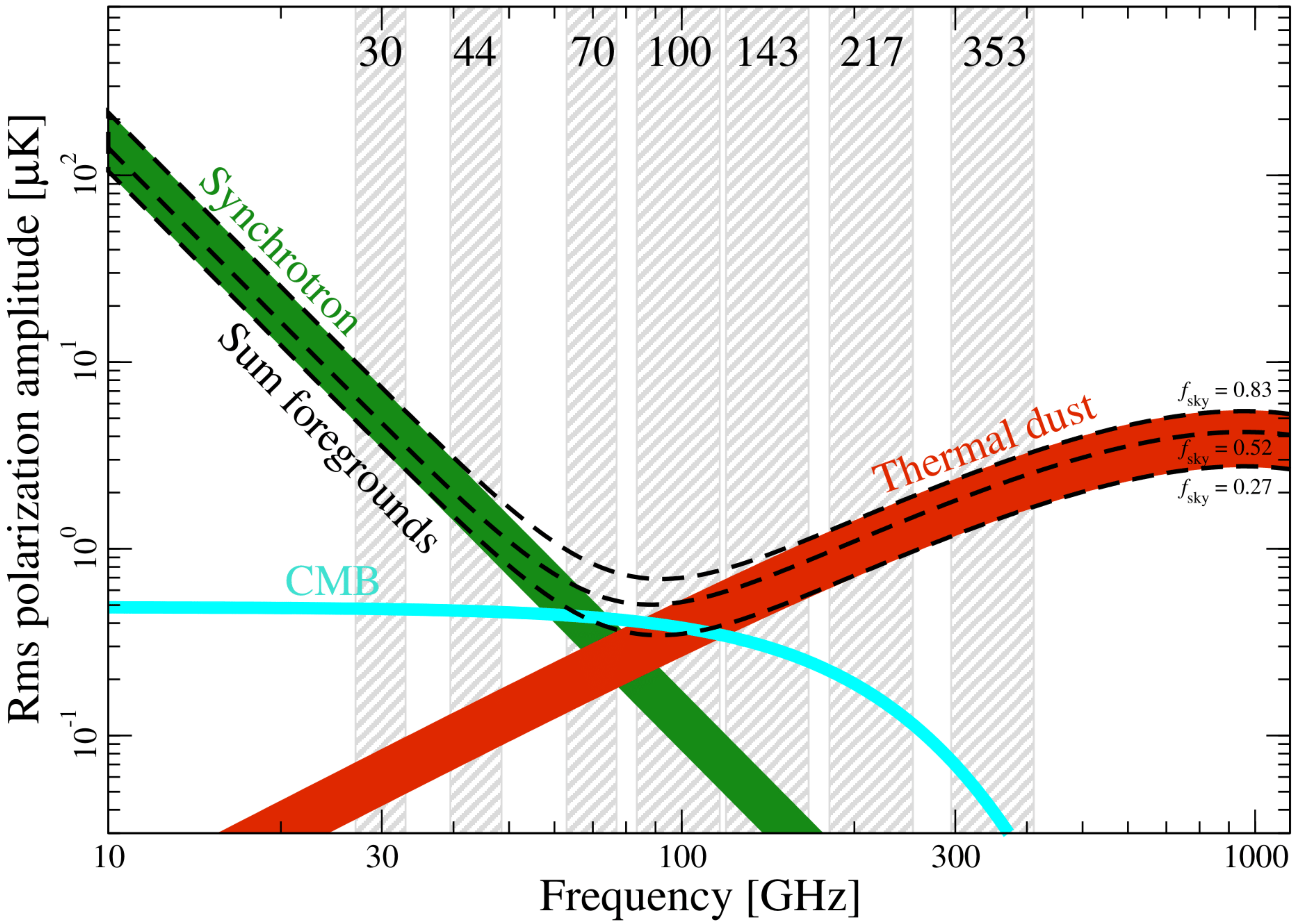
Foreground overview



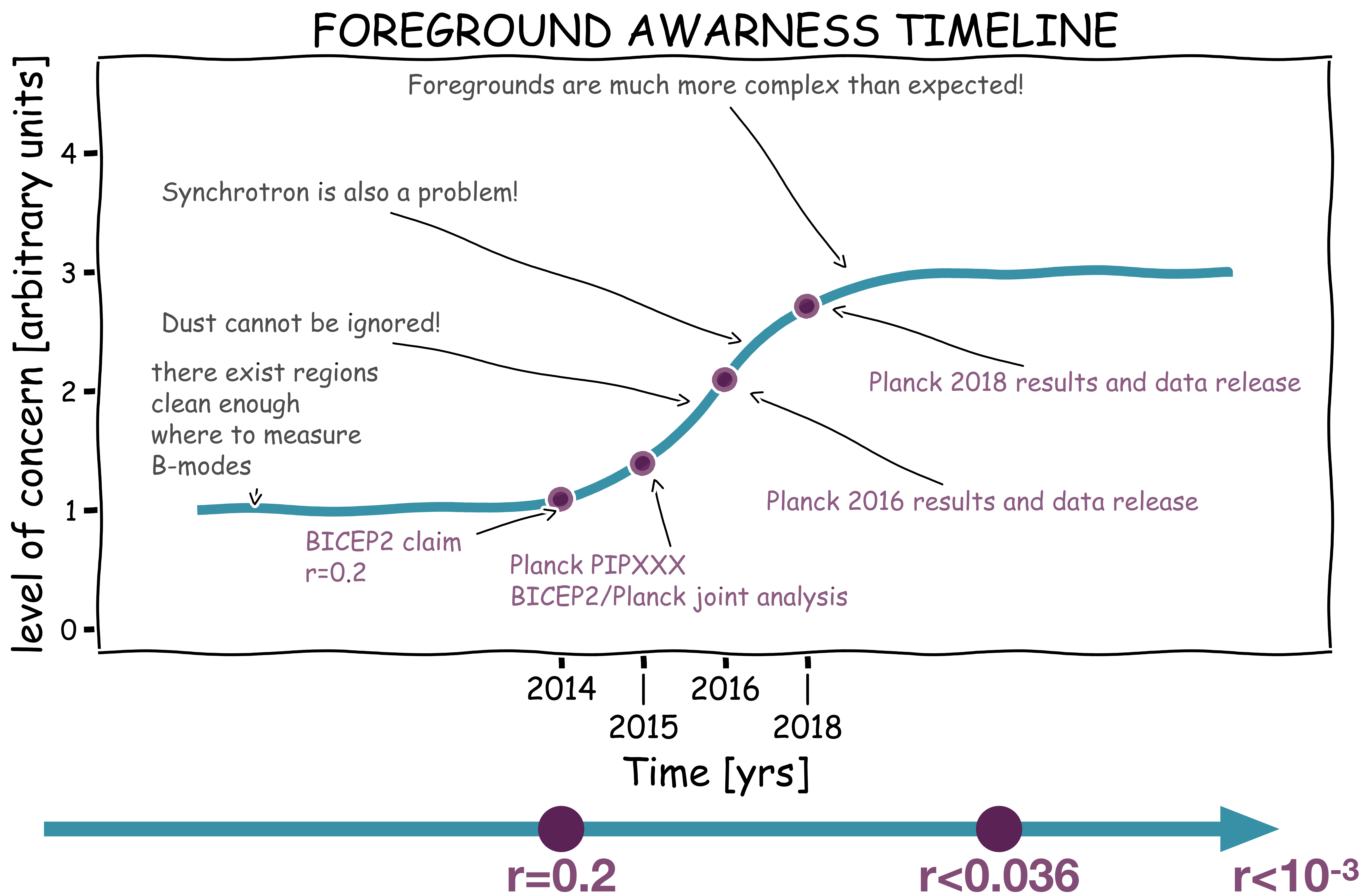


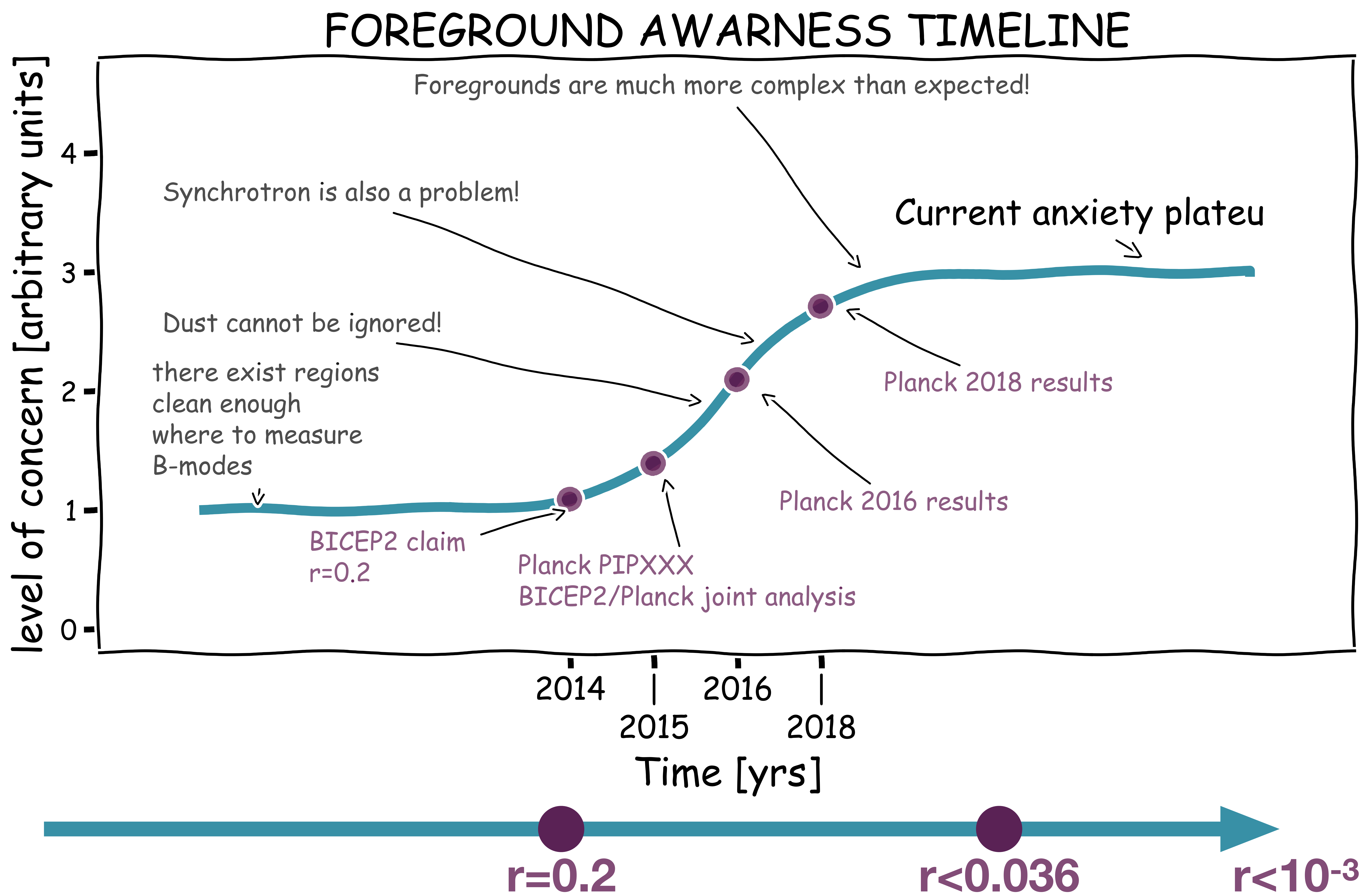
Foreground overview





Disclaimer: Foregrounds are not only Galactic
CMB science is not only r


FOREGROUND AWARNESS TIMELINE
Foregrounds are much more complex than expected!
Synchrotron is also a problem!
Dust cannot be ignored!
there exist regions
clean enough
where to measure
B-modes
Planck 2018 results and data release
Planck 2016 results and data release
BICEP2 claim
r=0.2
Planck PIPXXX
BICEP2/Planck joint analysis
level of concern [arbitrary units]
0
1
2
3
4
2014
2015
2016
2018
Time [yrs]
r=0.2
r<0.036
r<10-3



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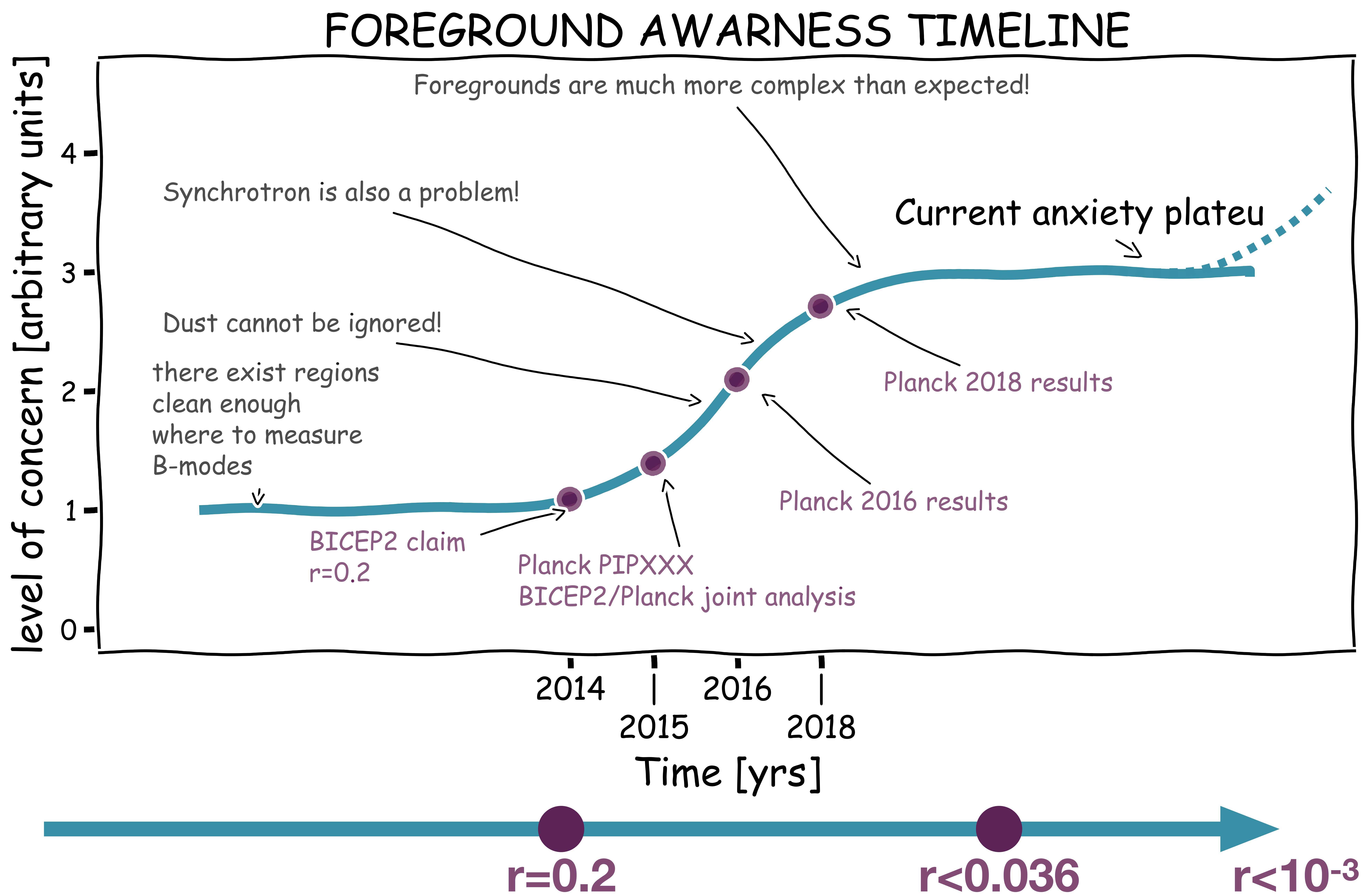
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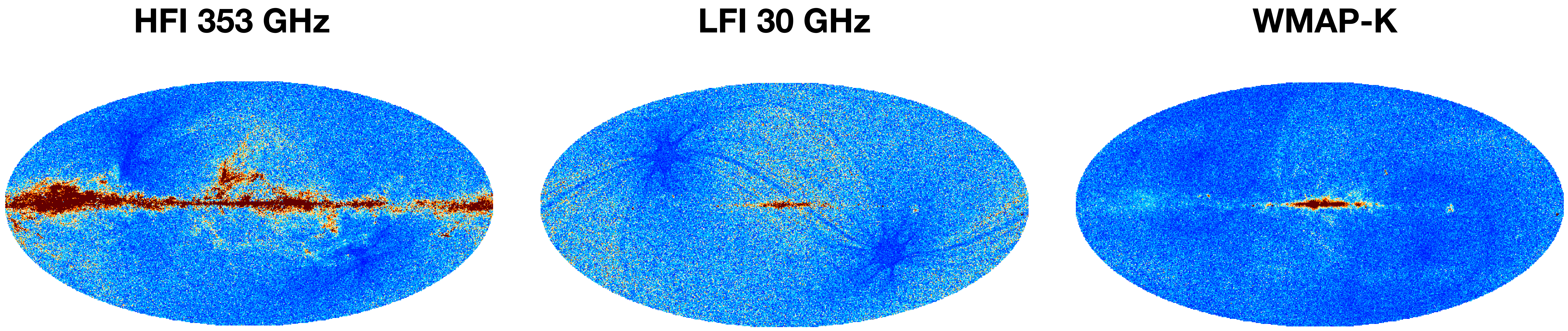
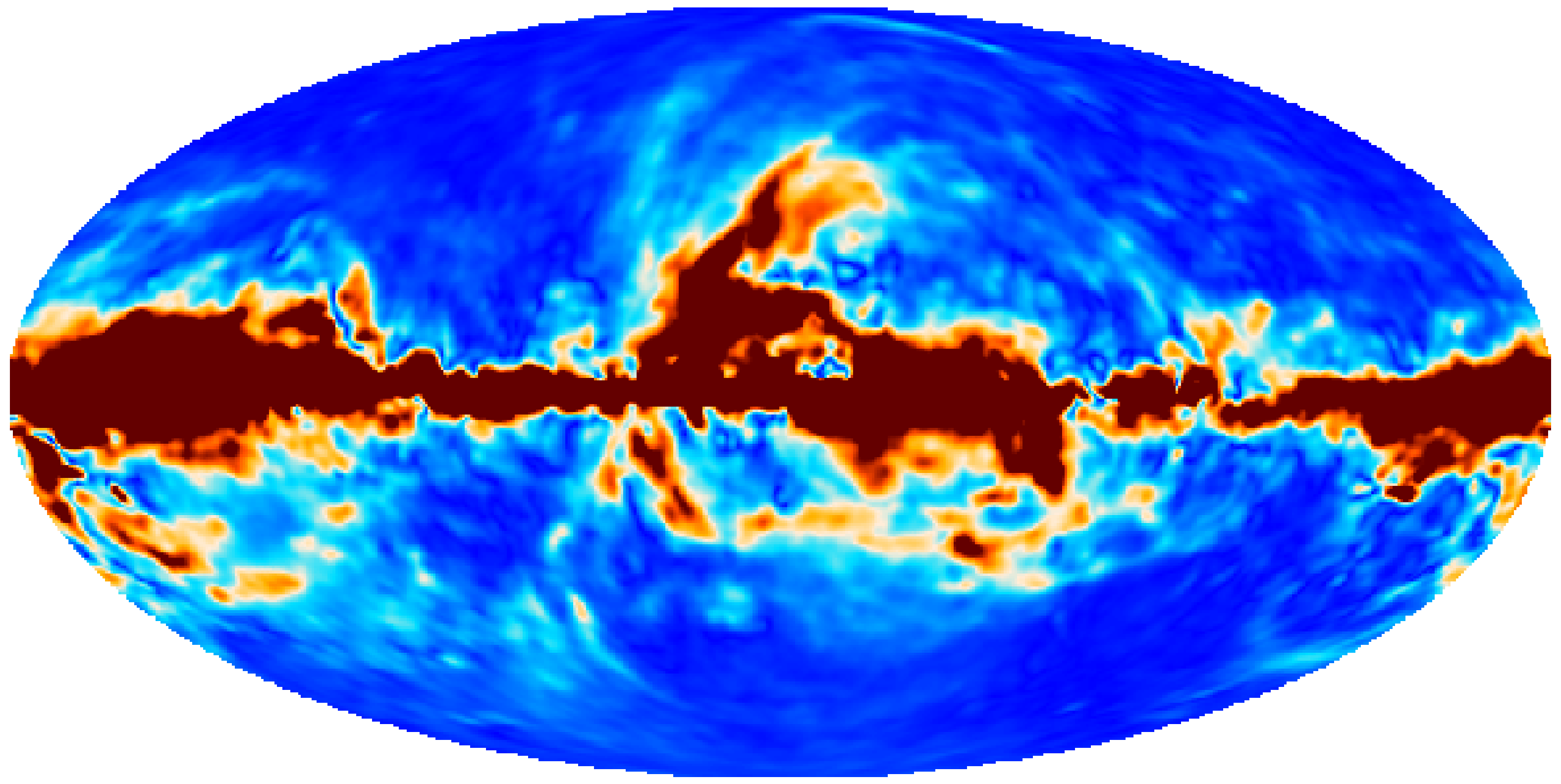
Available data



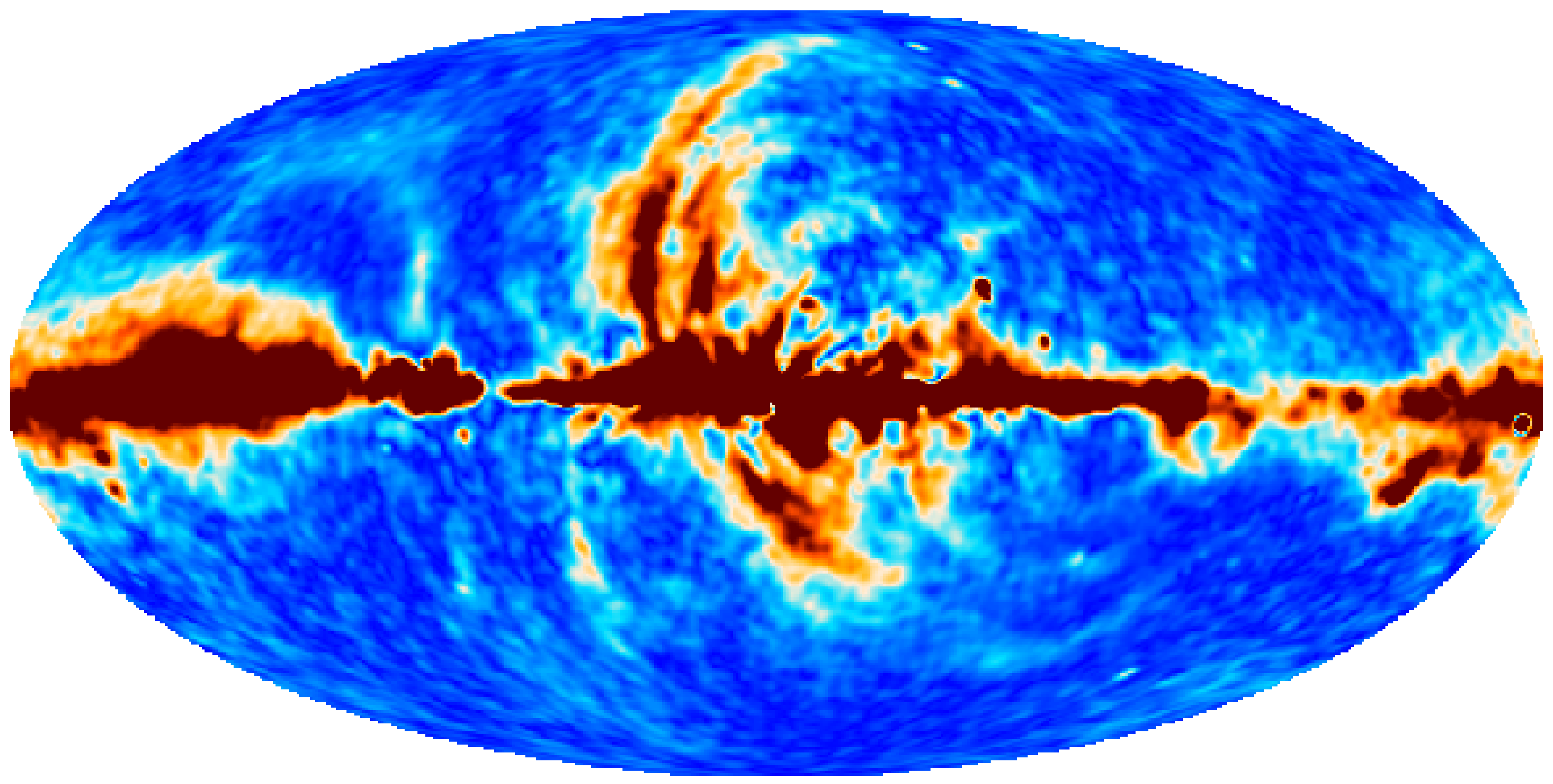
- Characterization of foreground emission relies mostly on **Planck and WMAP full sky maps** + **ancillary data** (HI, low frequency observations, …)
- Great datasets, but not enough to characterize FGs at the level needed to avoid surprises in the analysis of the next generation of CMB experiments

Available data

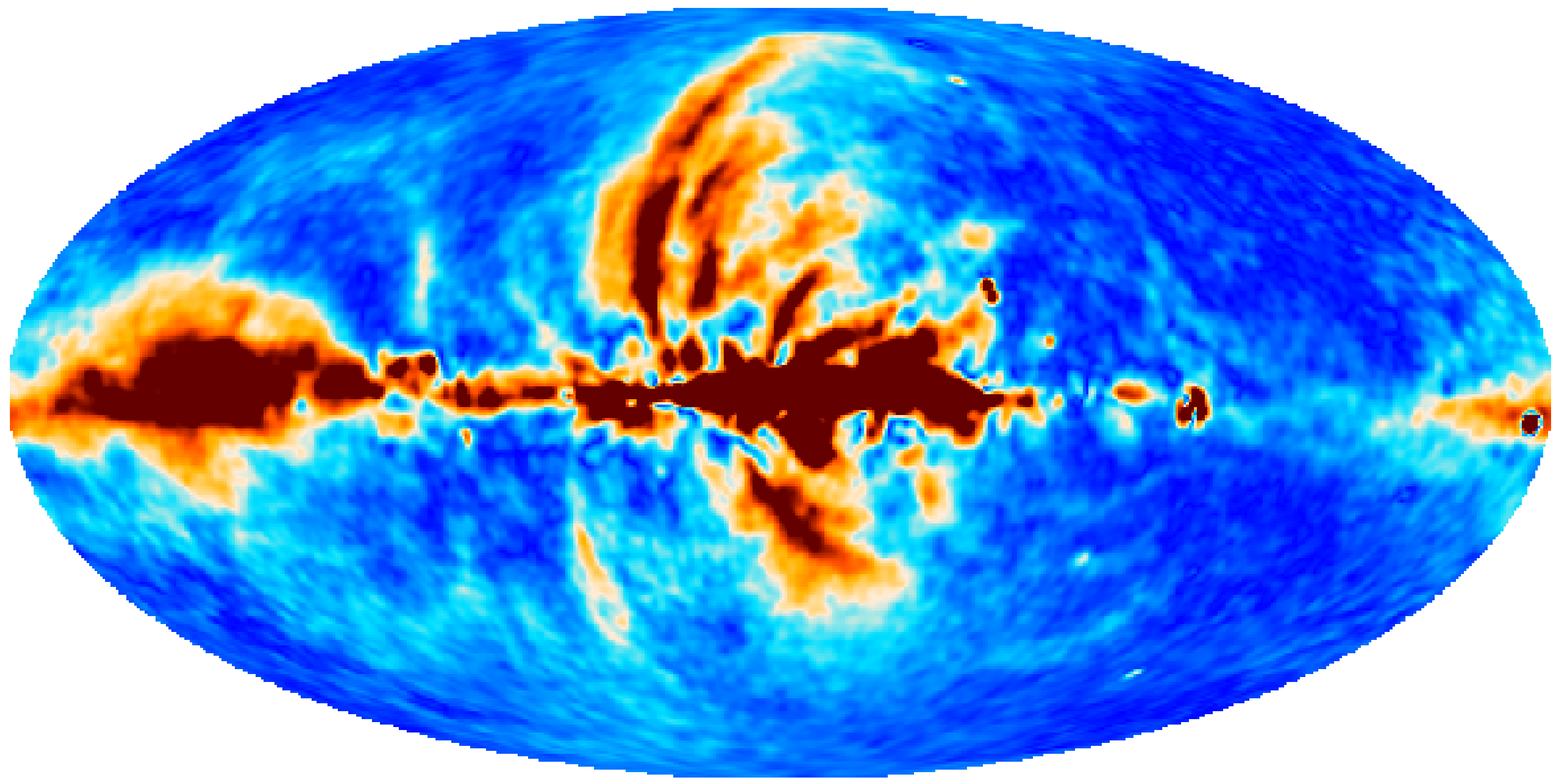
HFI 353 GHz
2deg



LFI 30 GHz
2deg



WMAP-K
2deg



- Characterization of foreground emission relies mostly on **Planck and WMAP full sky maps** + **ancillary data** (HI, low frequency observations, …)

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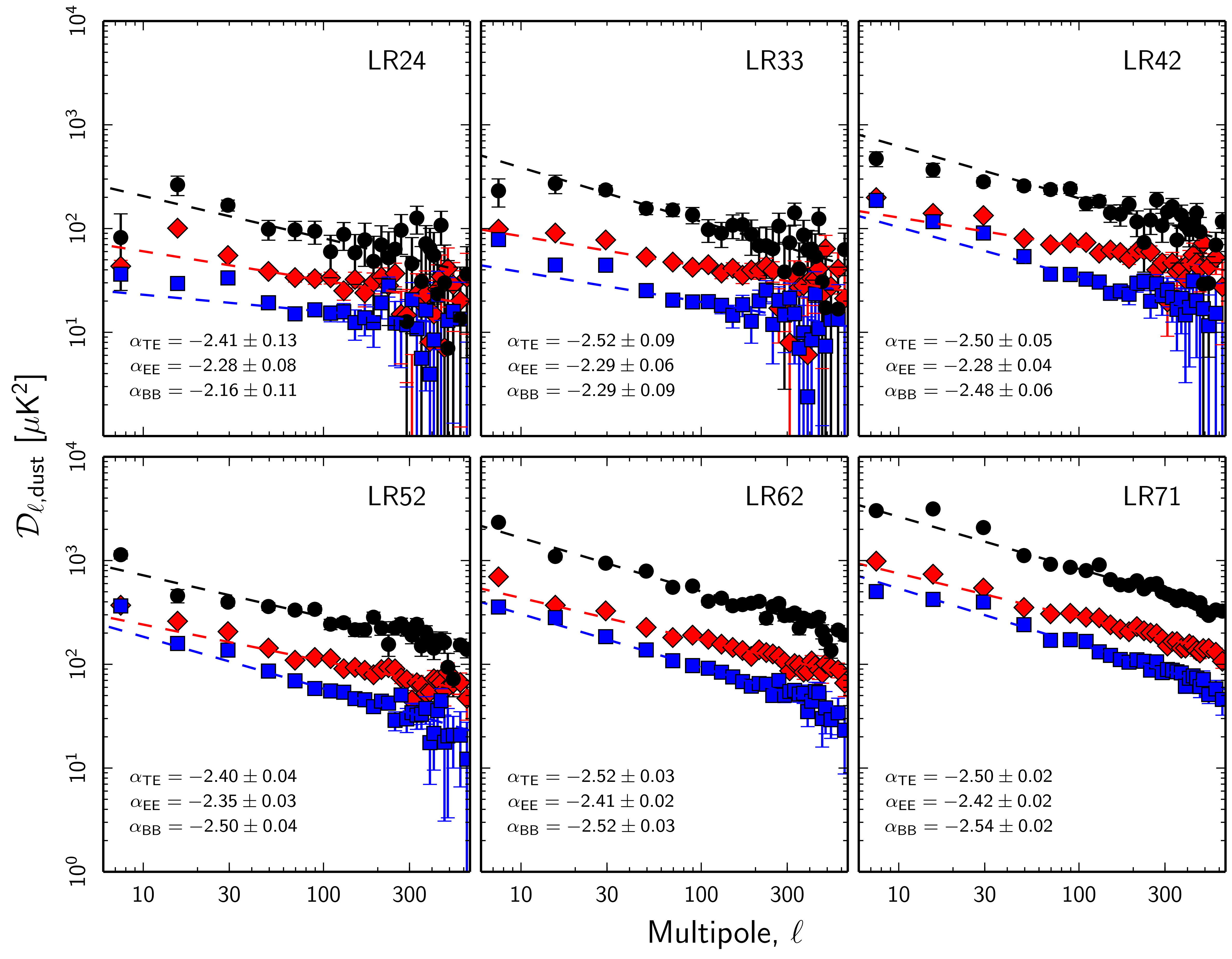
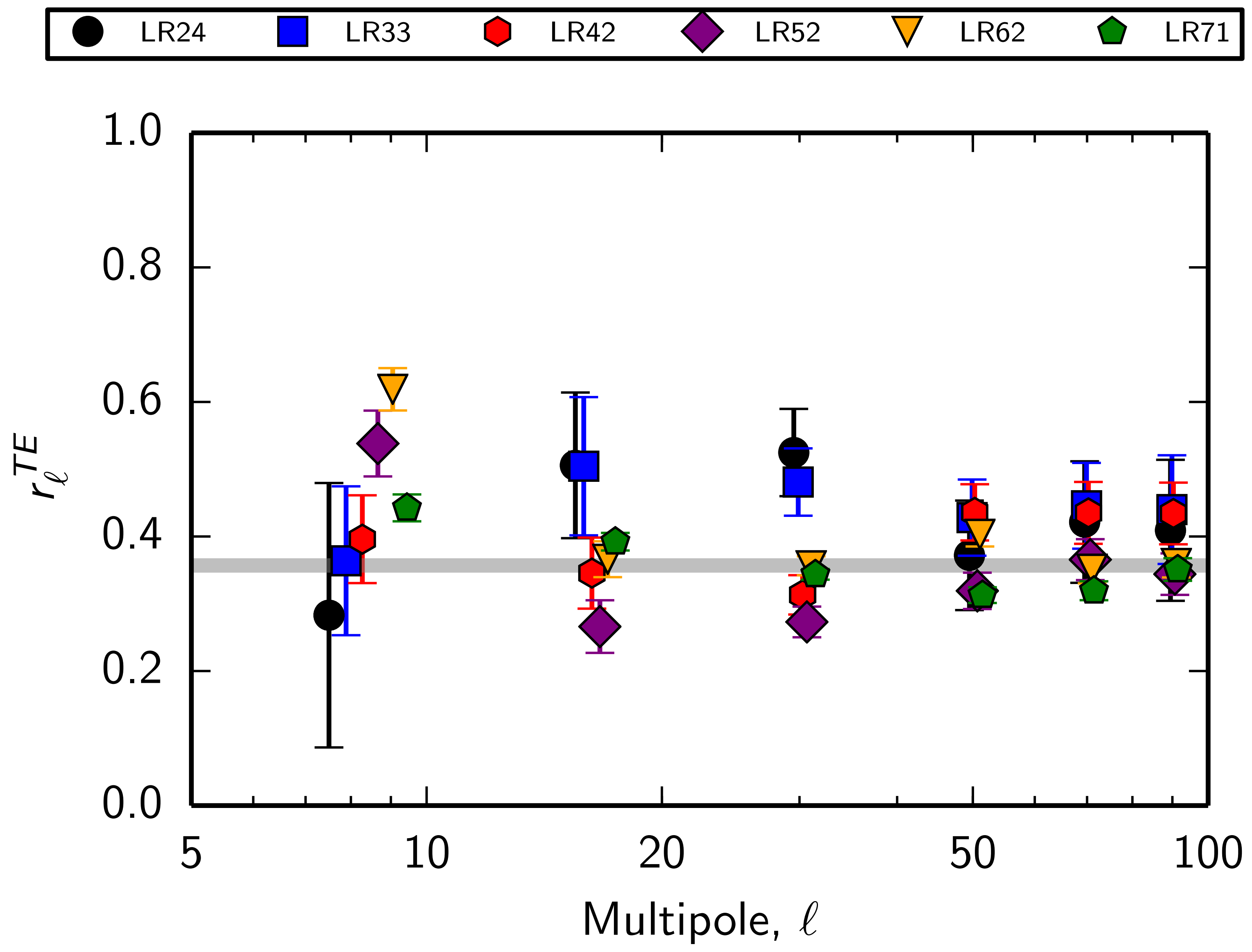
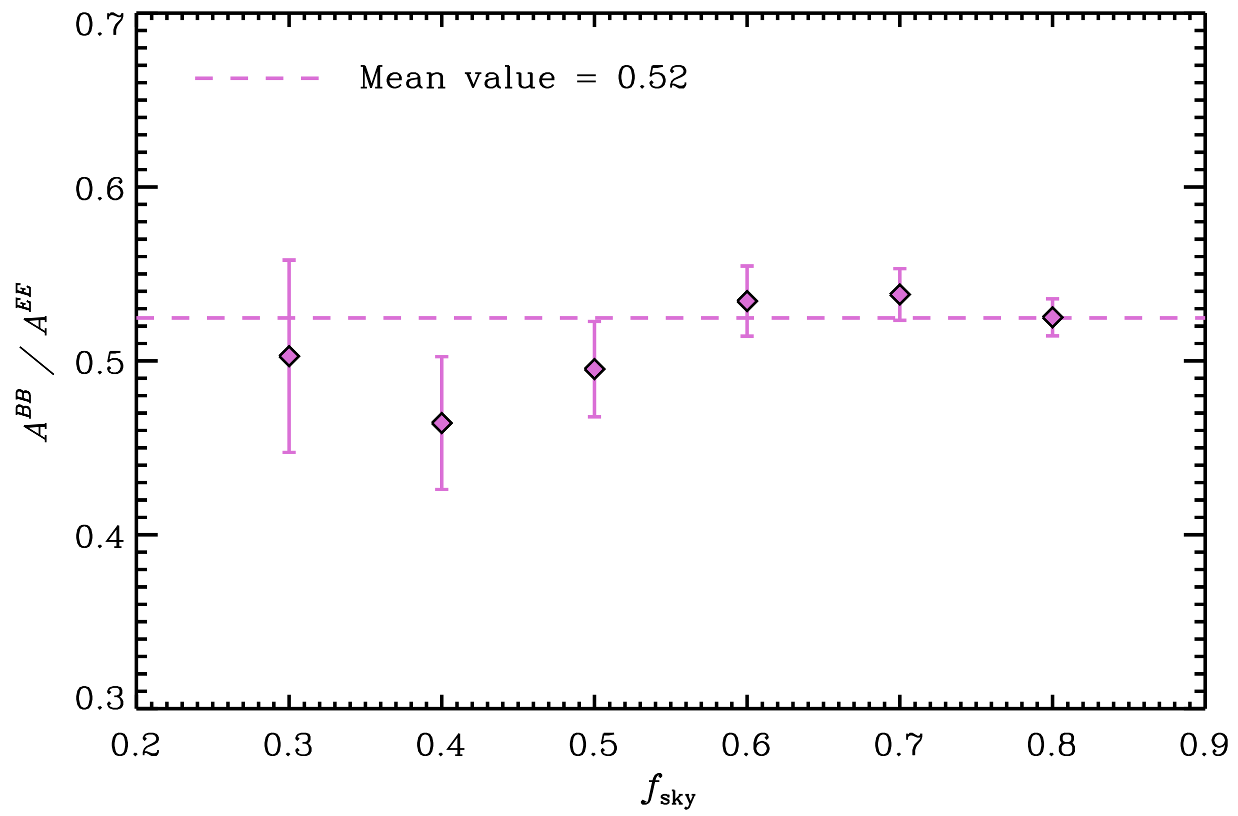
Power spectra of thermal dust emission

- Planck HFI 353GHz data allows to measure power spectra on large portions of the sky, up to sub-degree scales
- Positive TE correlation + E/B asymmetry: possibly due to alignment of dust filaments with Galactic magnetic field

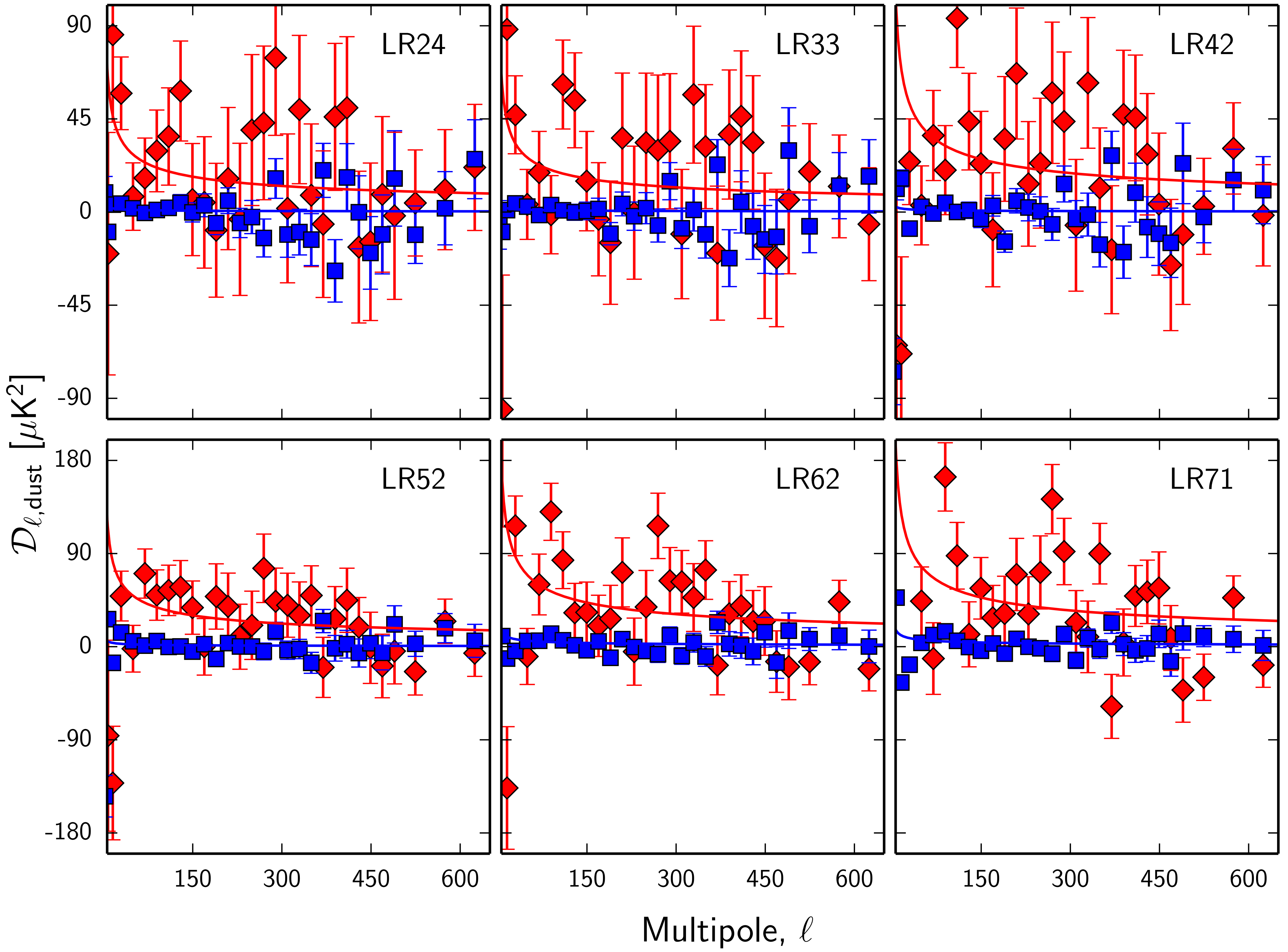






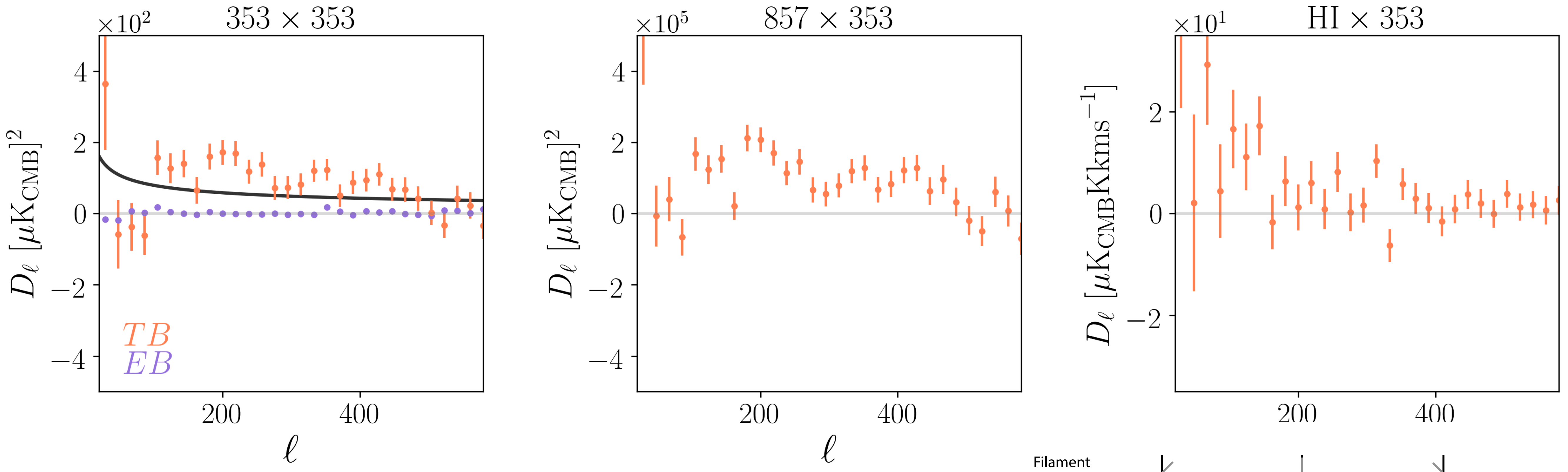
Planck 2018 results XI, Planck Intermediate results XXX 2015

Power spectra of thermal dust emission

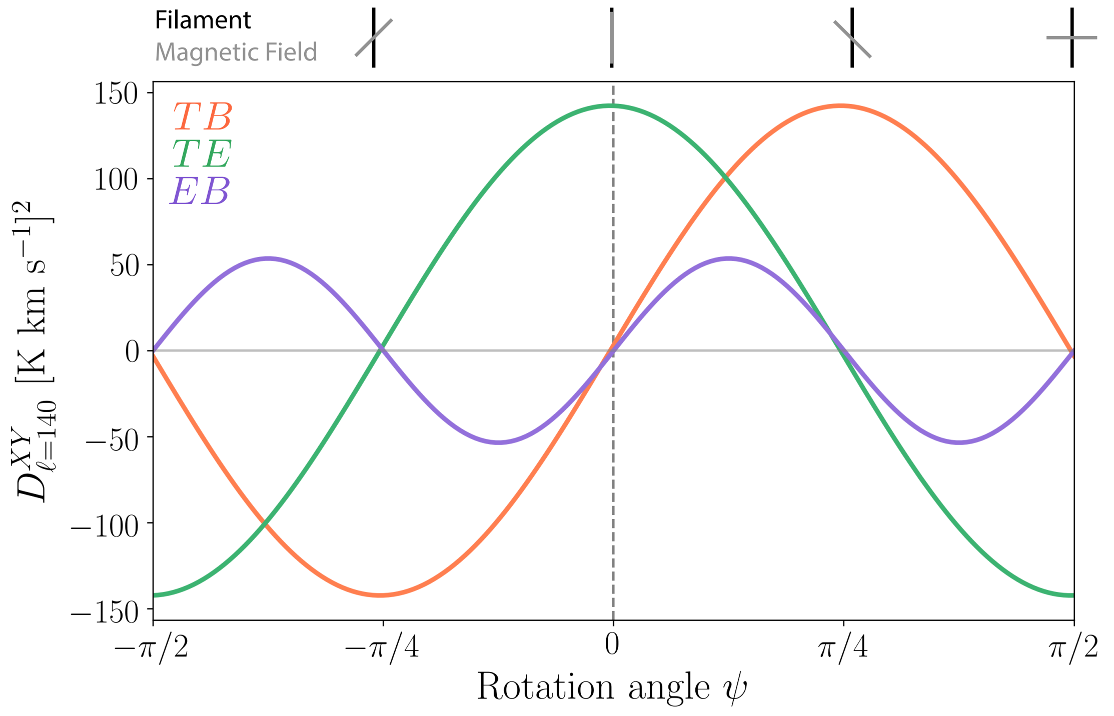


Planck 2018 results XI

- Robust detection of **positive TB correlation** with $r^{TB} = \frac{C_\ell^{TB}}{\sqrt{C_\ell^{TT} \times C_\ell^{BB}}} \sim 0.05$
- C_ℓ^{EB} **consistent with zero**



- Possible physical explanation related to filament-magnetic field (mis-)alignment



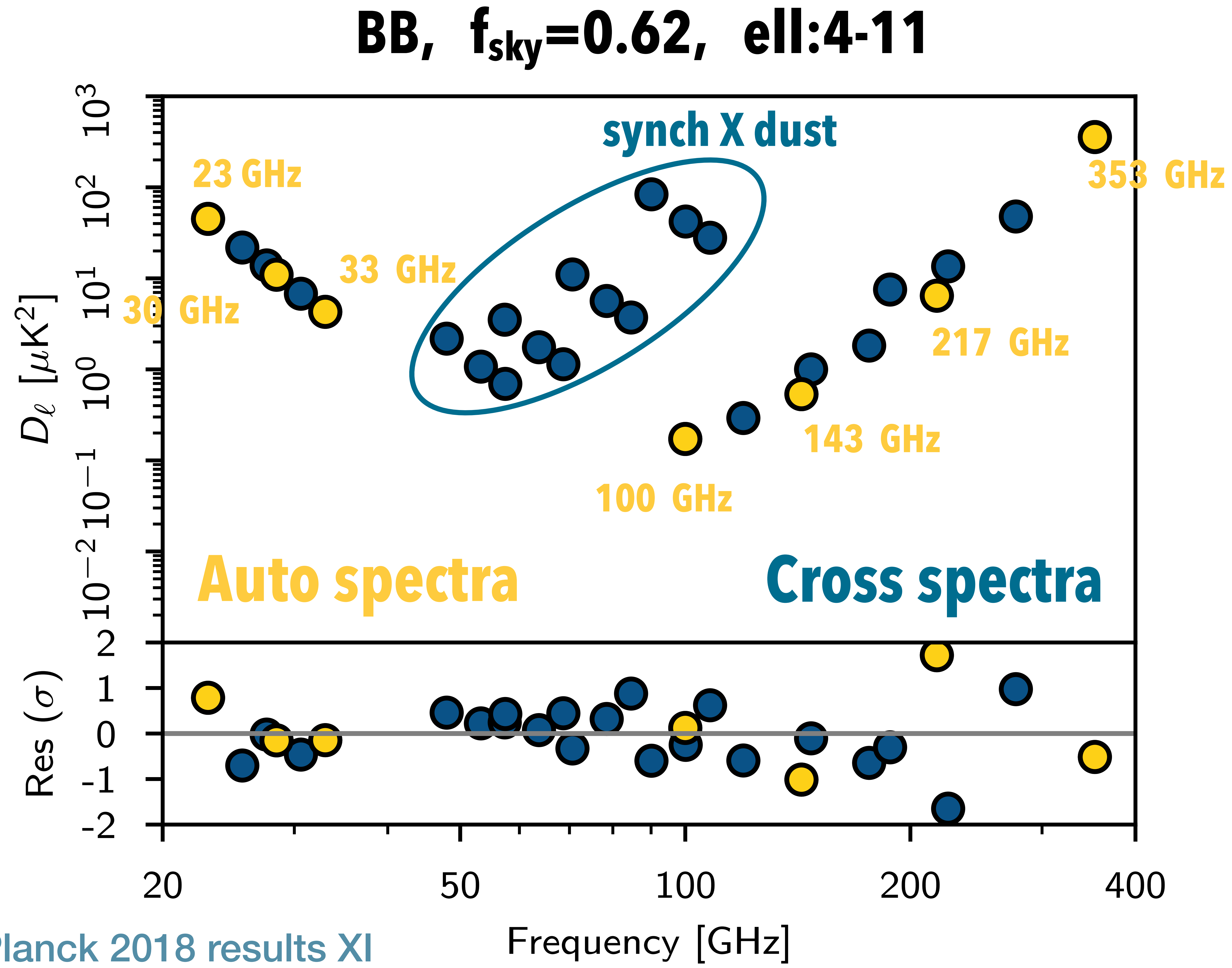
Clark et al. 2021

- Under this hypothesis it is possible to predict the amplitude of EB correlation:

$$< D_\ell^{EB} > \lesssim 2.5\, \mu K^2_{CMB}$$

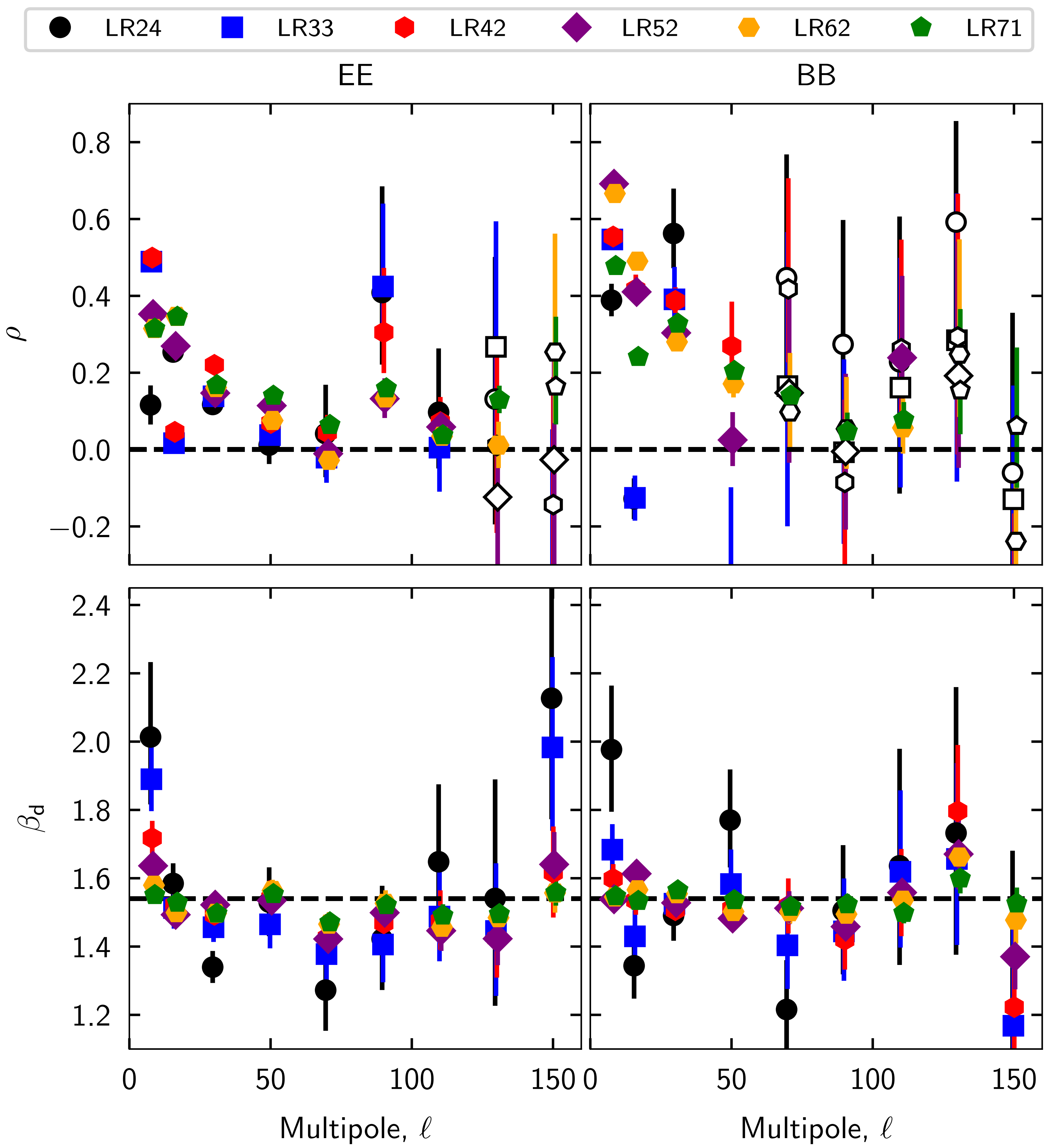
- **Implications for Cosmic birefringence?**

Thermal dust SED



Planck 2018 results XI

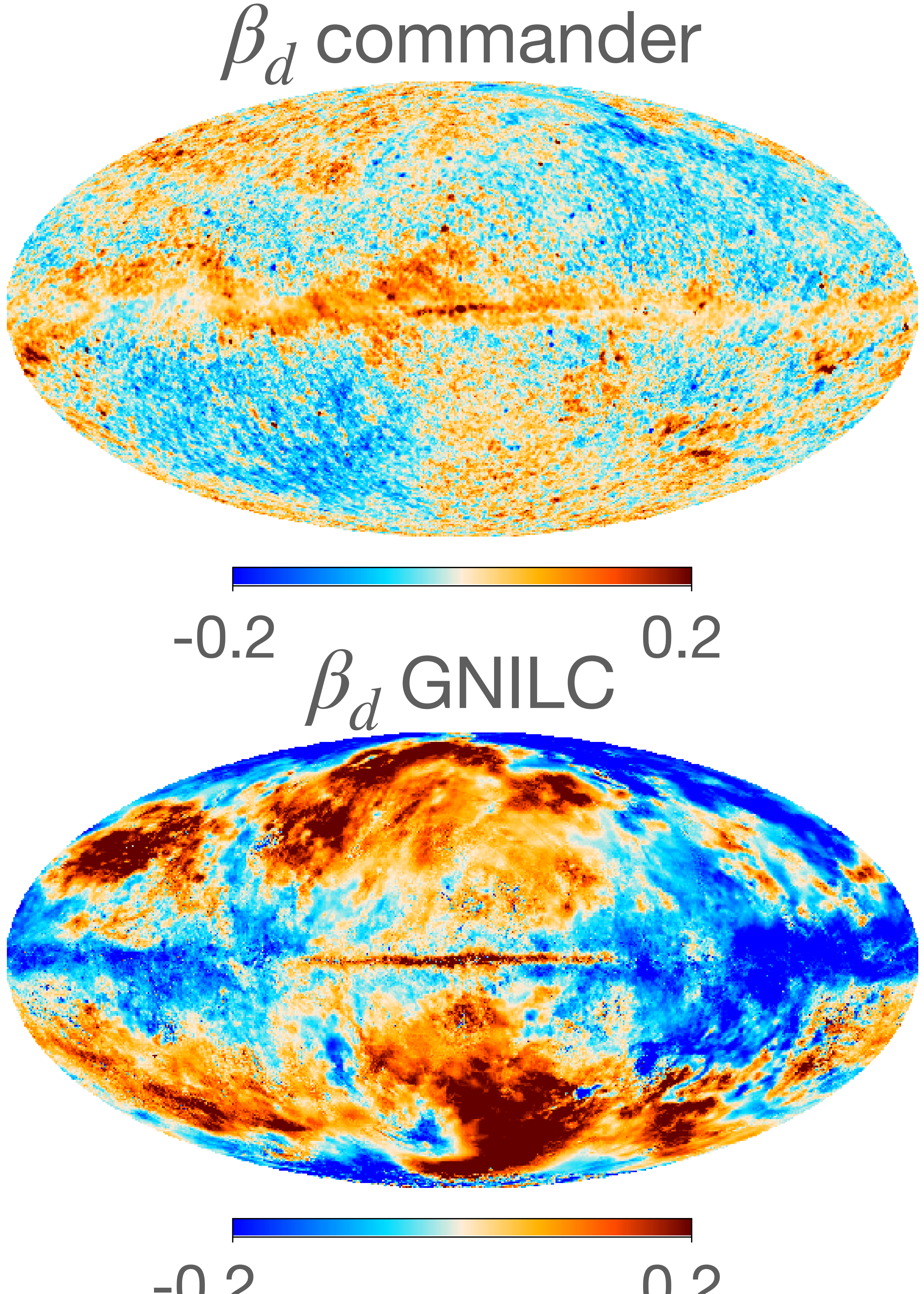
Effective frequency: $\nu_{eff} = \sqrt{\nu_1 \nu_2}$

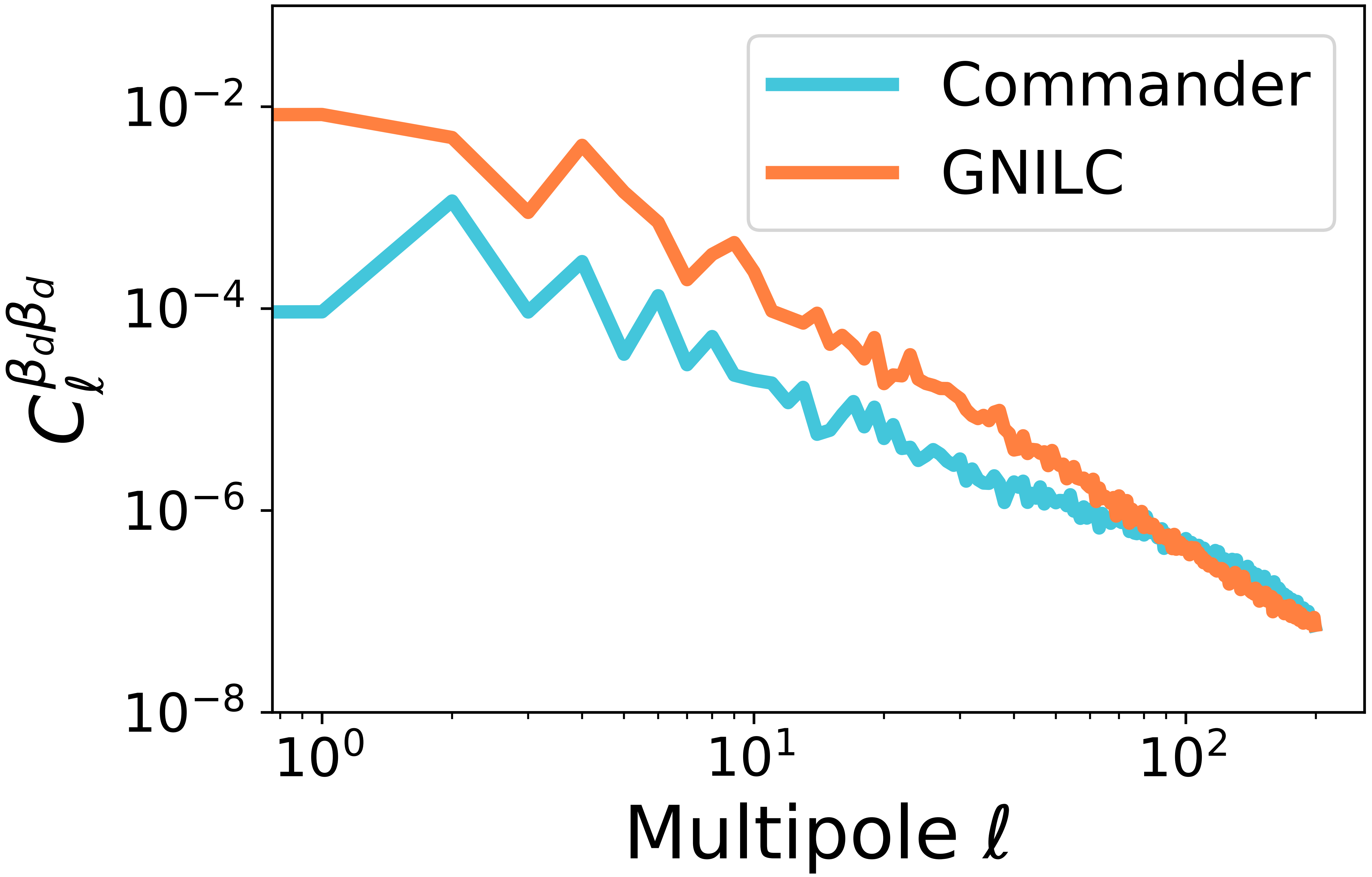


$$\beta_d = 1.53 \pm 0.02$$

Thermal dust SED: spatial variation

- Spatial variation of dust spectral parameters still uncertain



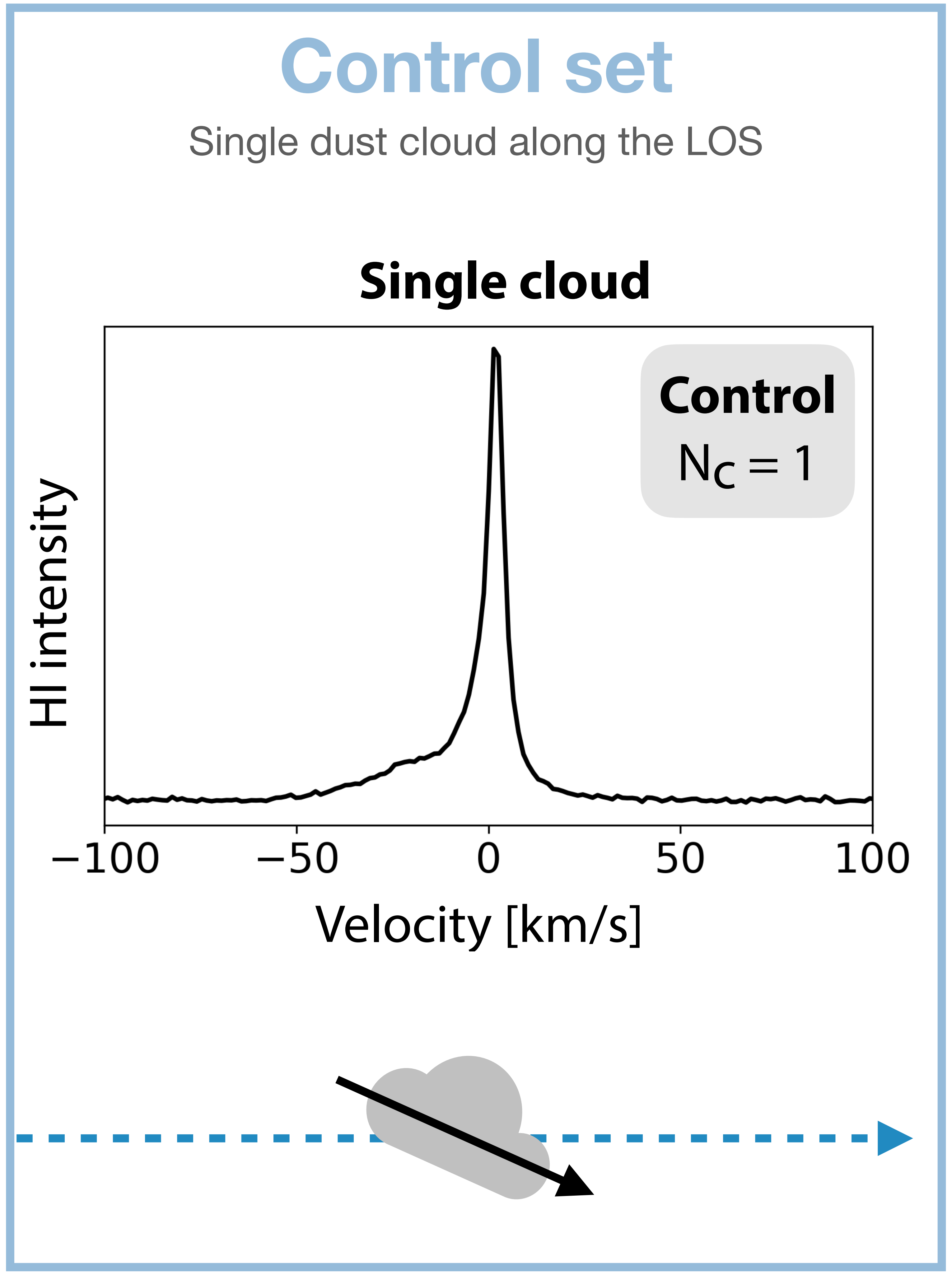


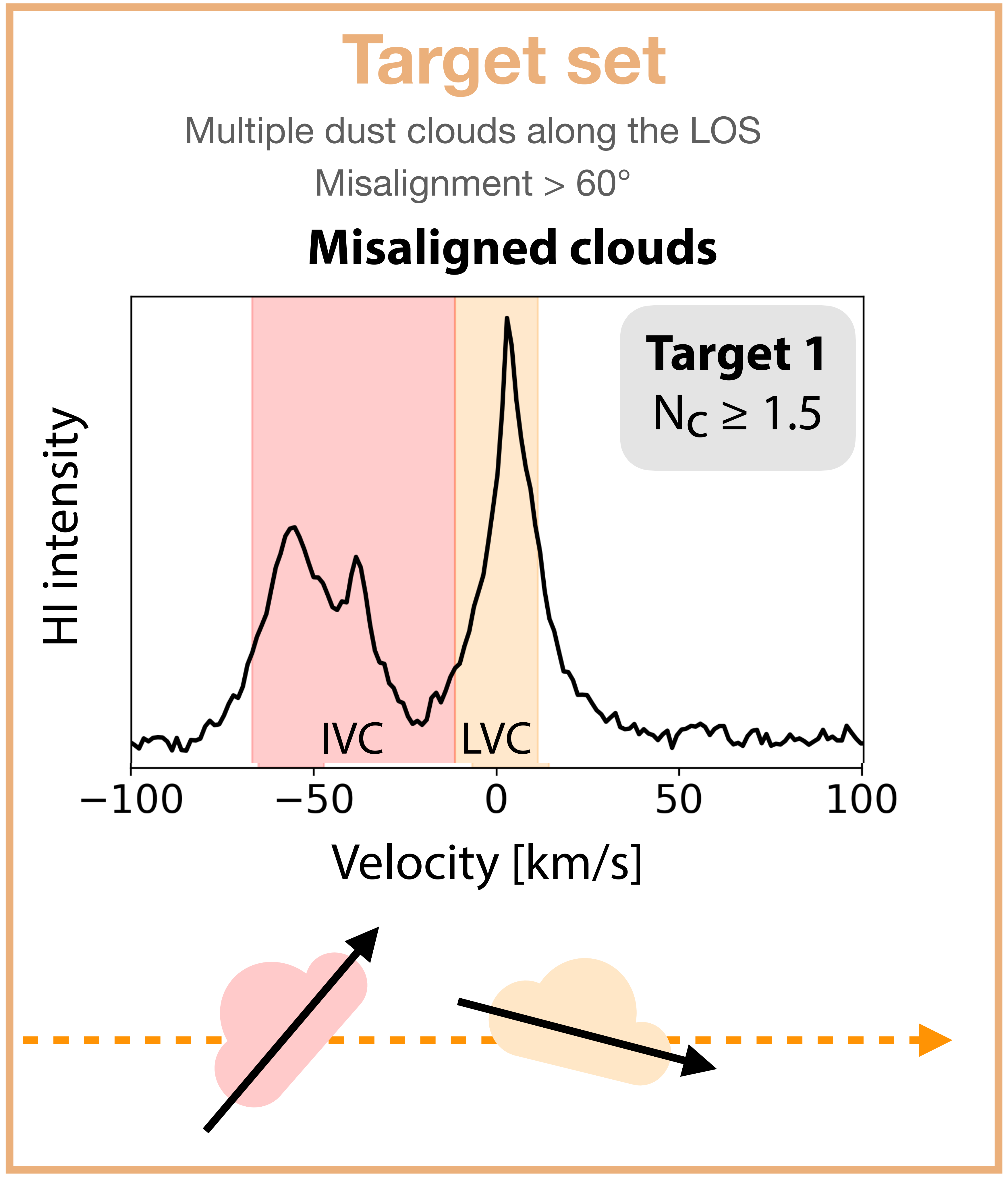
Planck intermediate results XLVIII, 2016

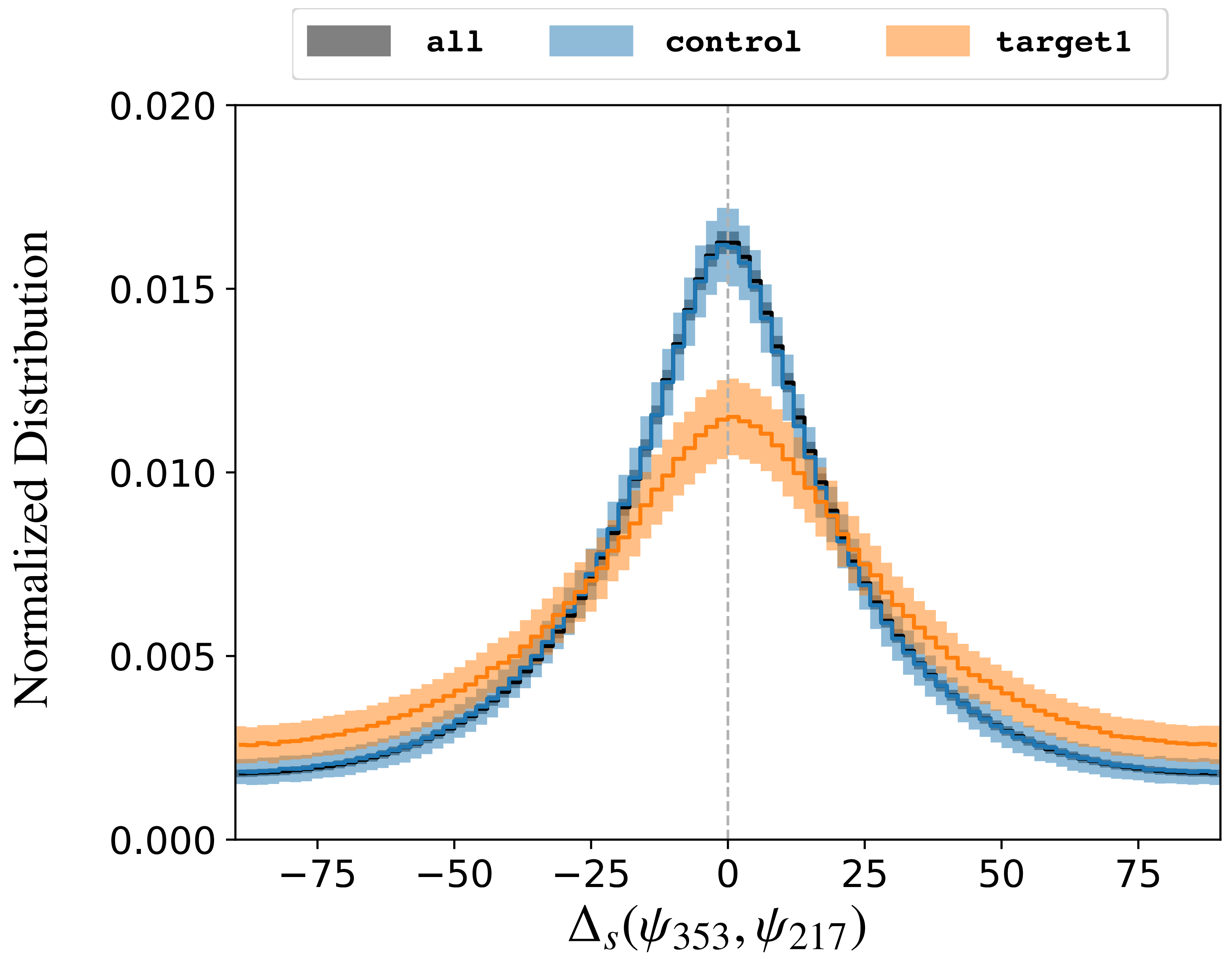
Thermal dust SED: frequency de-correlation

- If multiple dust clouds are present along the line-of-sight with different SED and orientation de-correlation is expected, as Q and U have different frequency scaling
- Evidence of detection in Planck 353 GHz map

Pelgrims et al. 2021





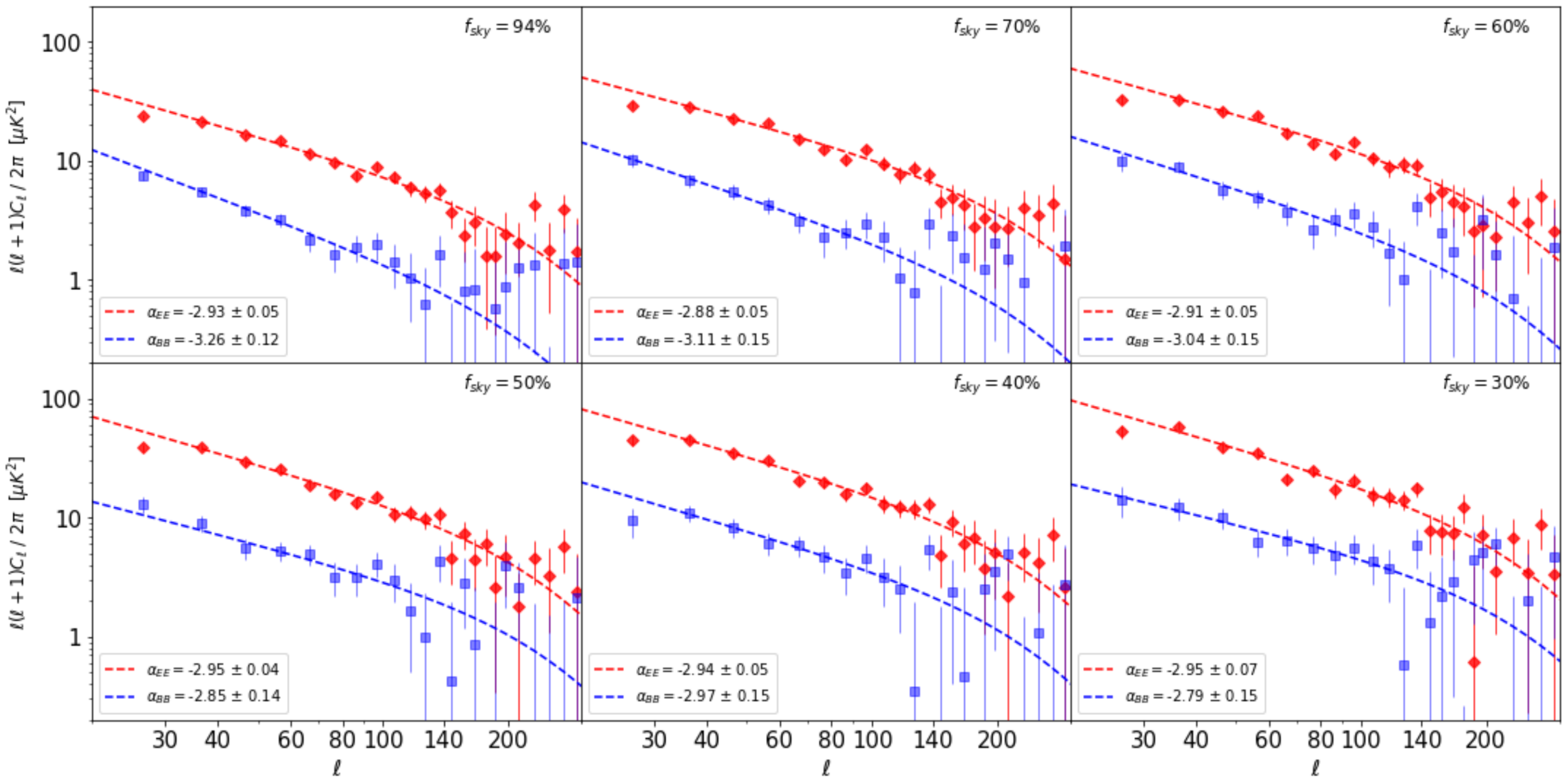


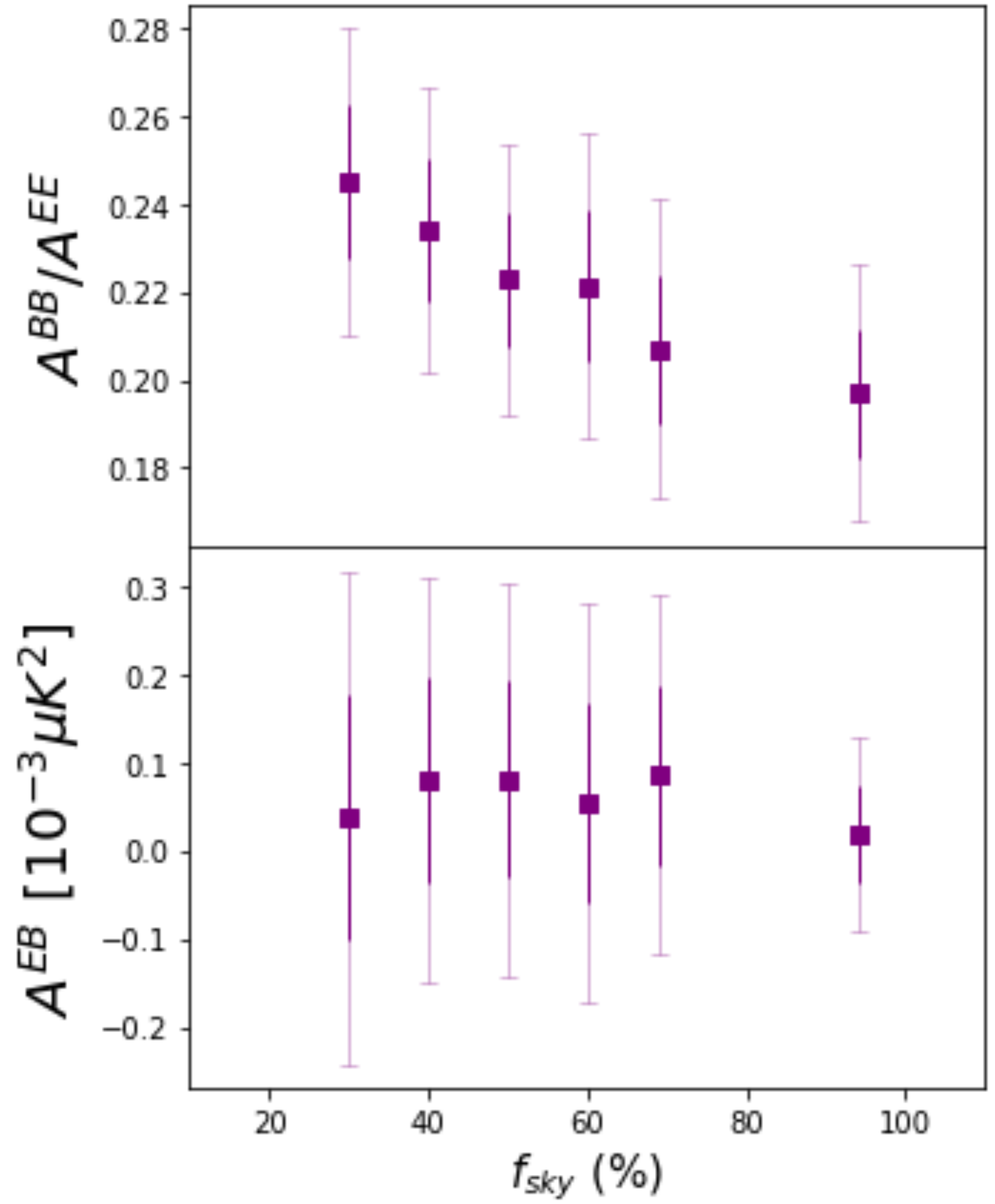
signed difference in the polarization direction between 353 and 217 GHz

Synchrotron from WMAP and Planck

WMAP 23GHz x Planck 30GHz

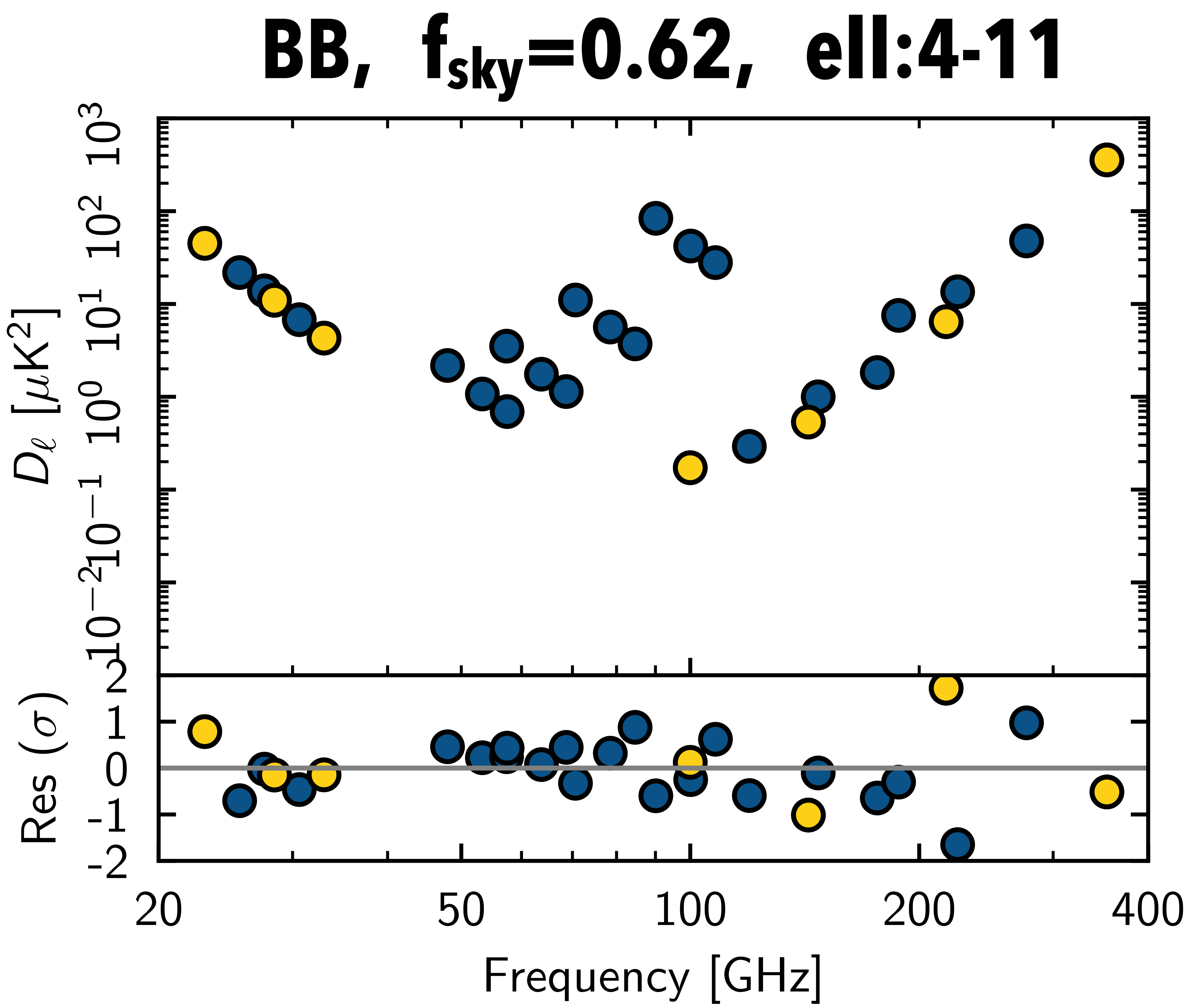
Martire et al. 2022



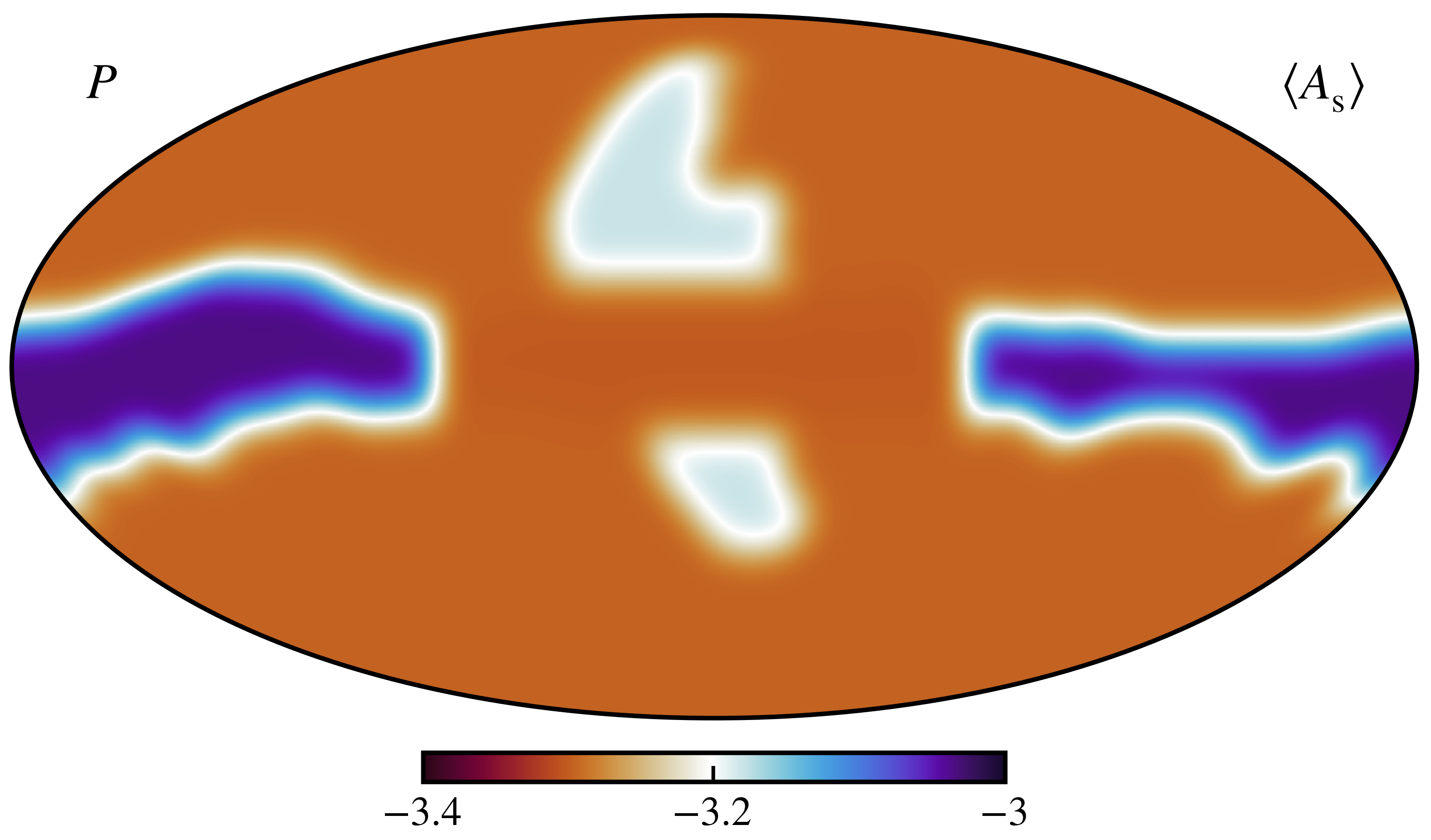


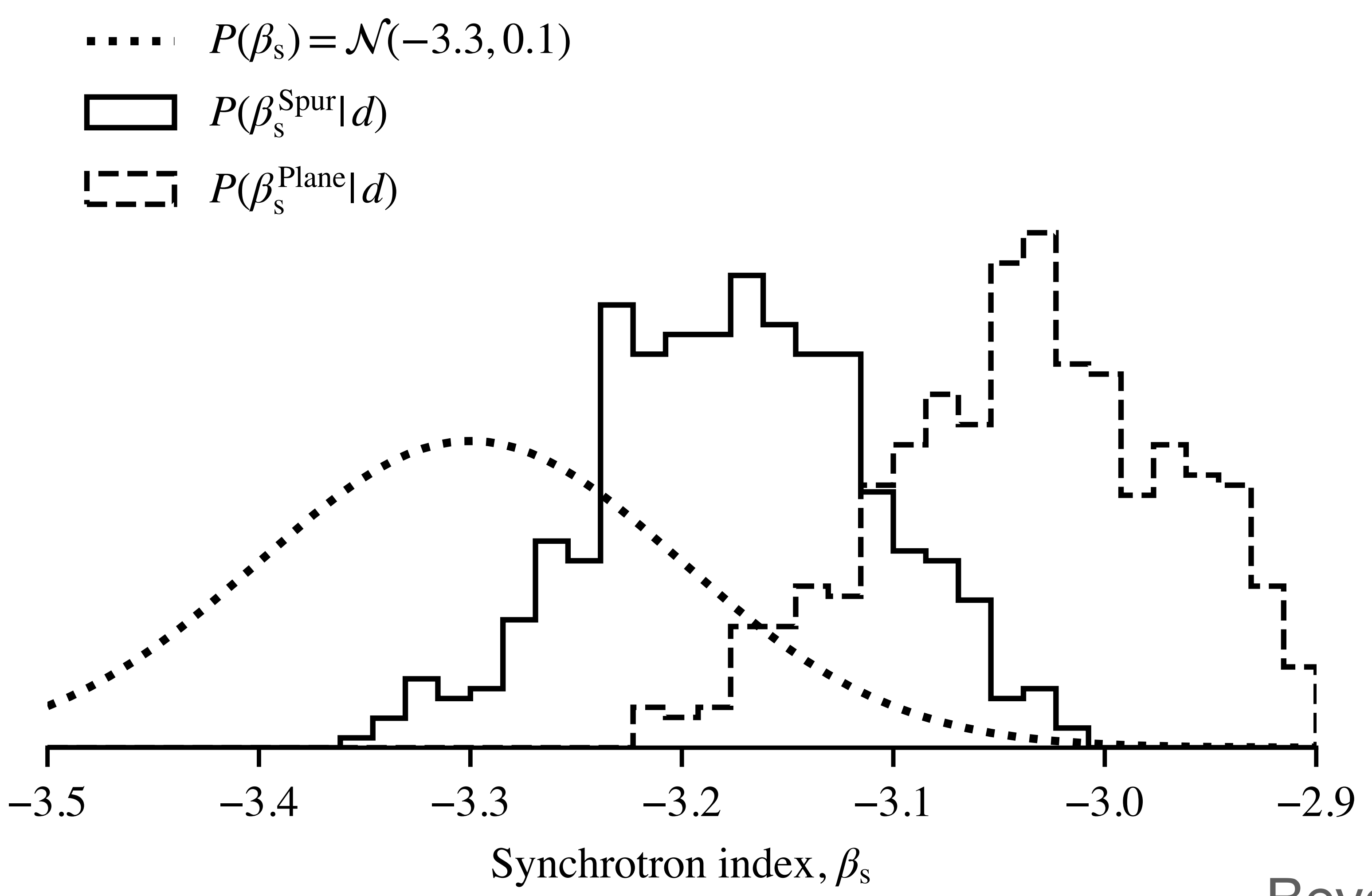
- Synchrotron power spectra show steeper decay in ℓ wrt thermal dust (constraints up to $\ell \sim 200$ on large portions of the sky)
- Large E-to-B asymmetry with $A^{BB}/A^{EE} \lesssim 0.25$
- No detection of EB correlation

Synchrotron SED



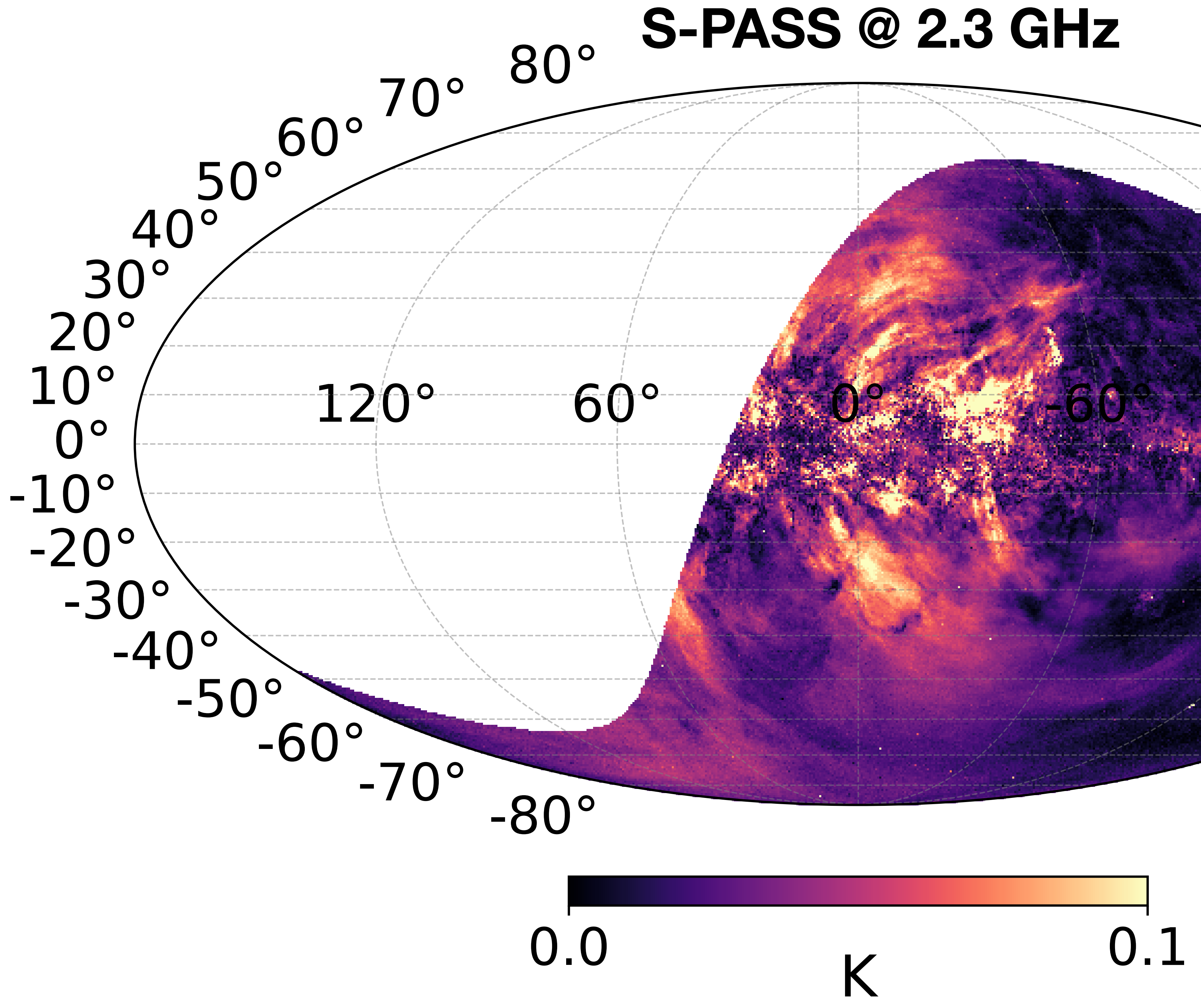
- Planck x WMAP data allow to constrain synchrotron spectral index from power spectra, resulting in $\beta_s = -3.13 \pm 0.13$ at intermediate and high Galactic latitudes
- Signal-to-noise level too low to properly measure spatial variation

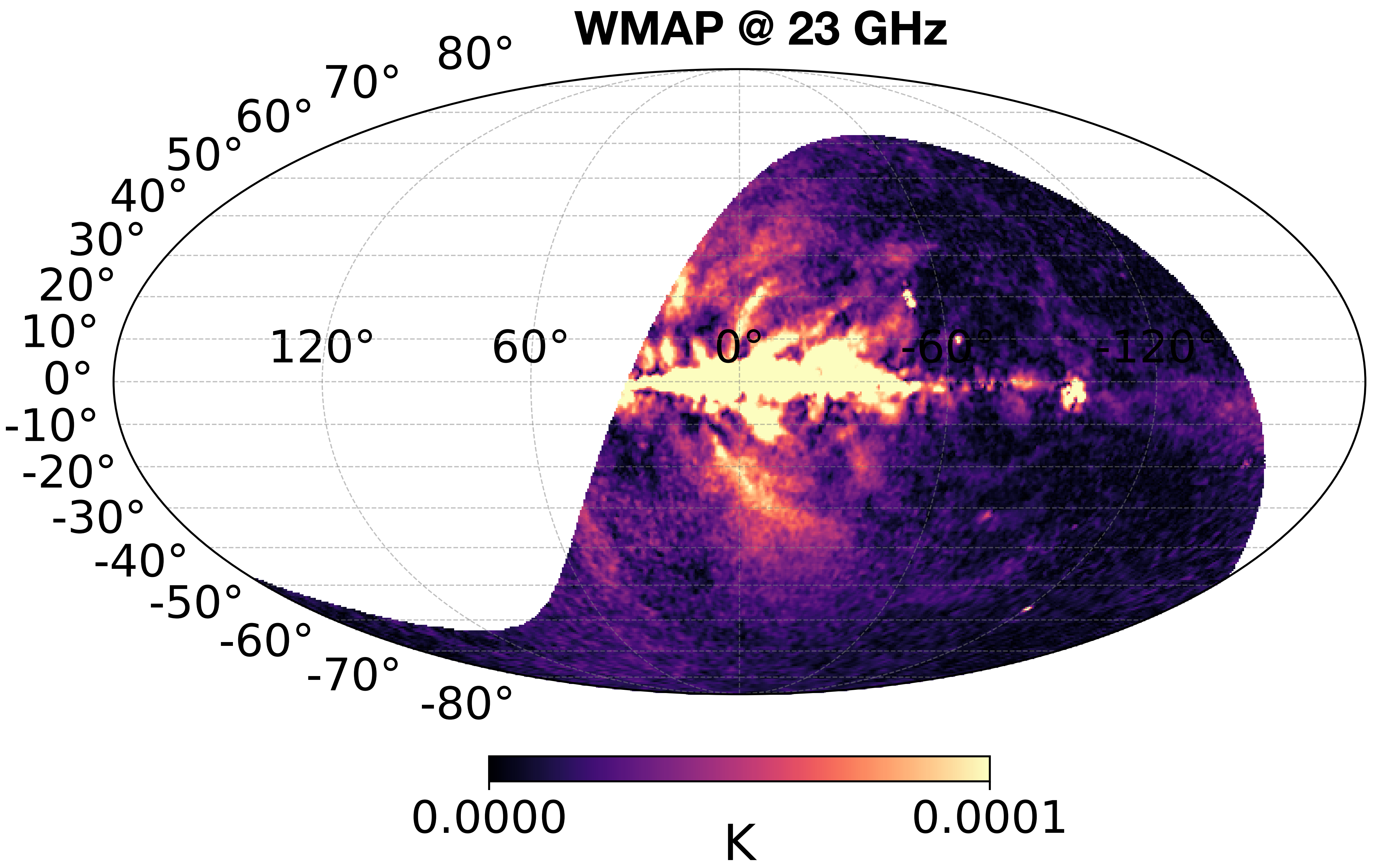




BeyondPlanck XV, 2022

Synchrotron with low frequency data

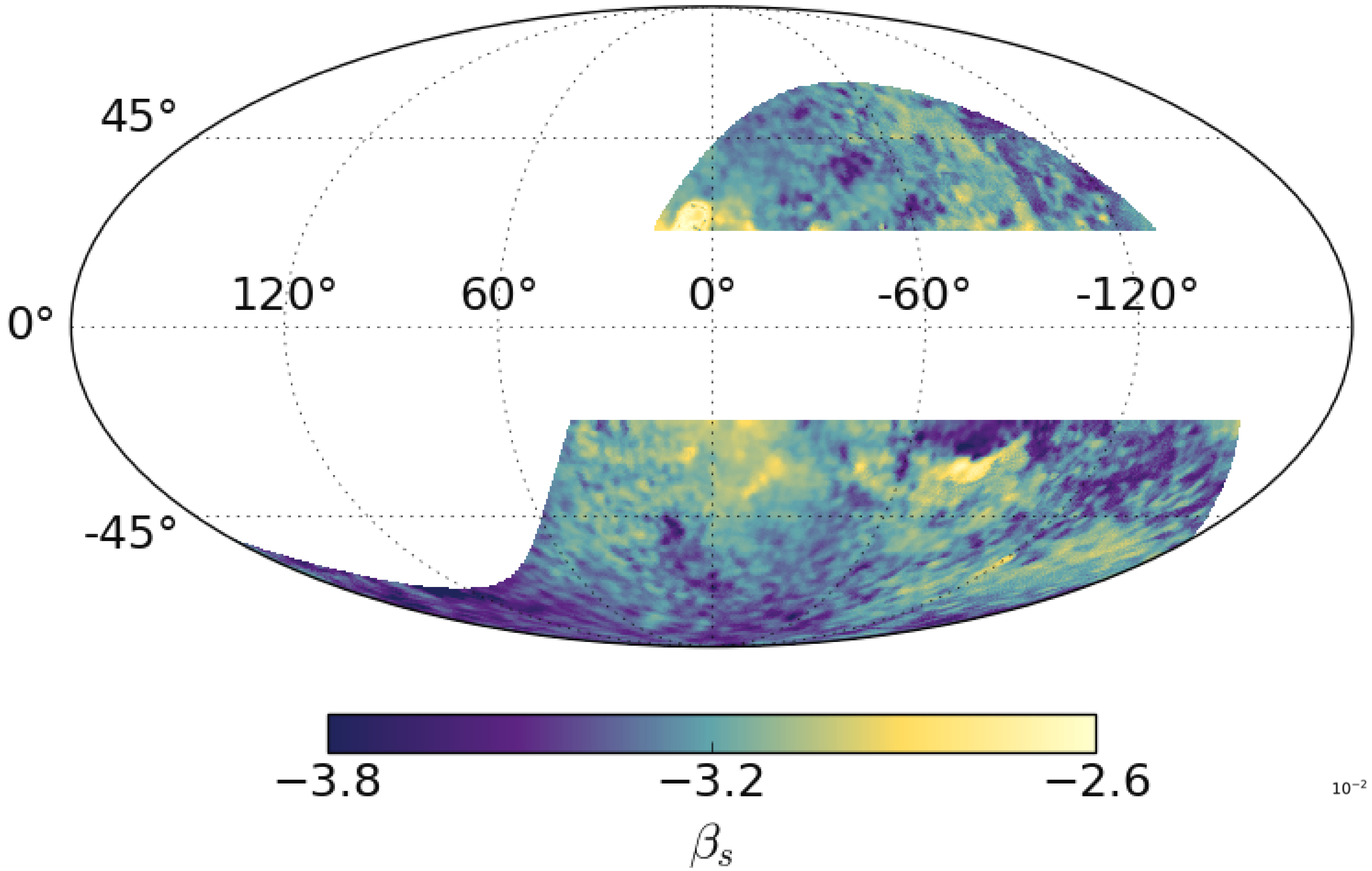


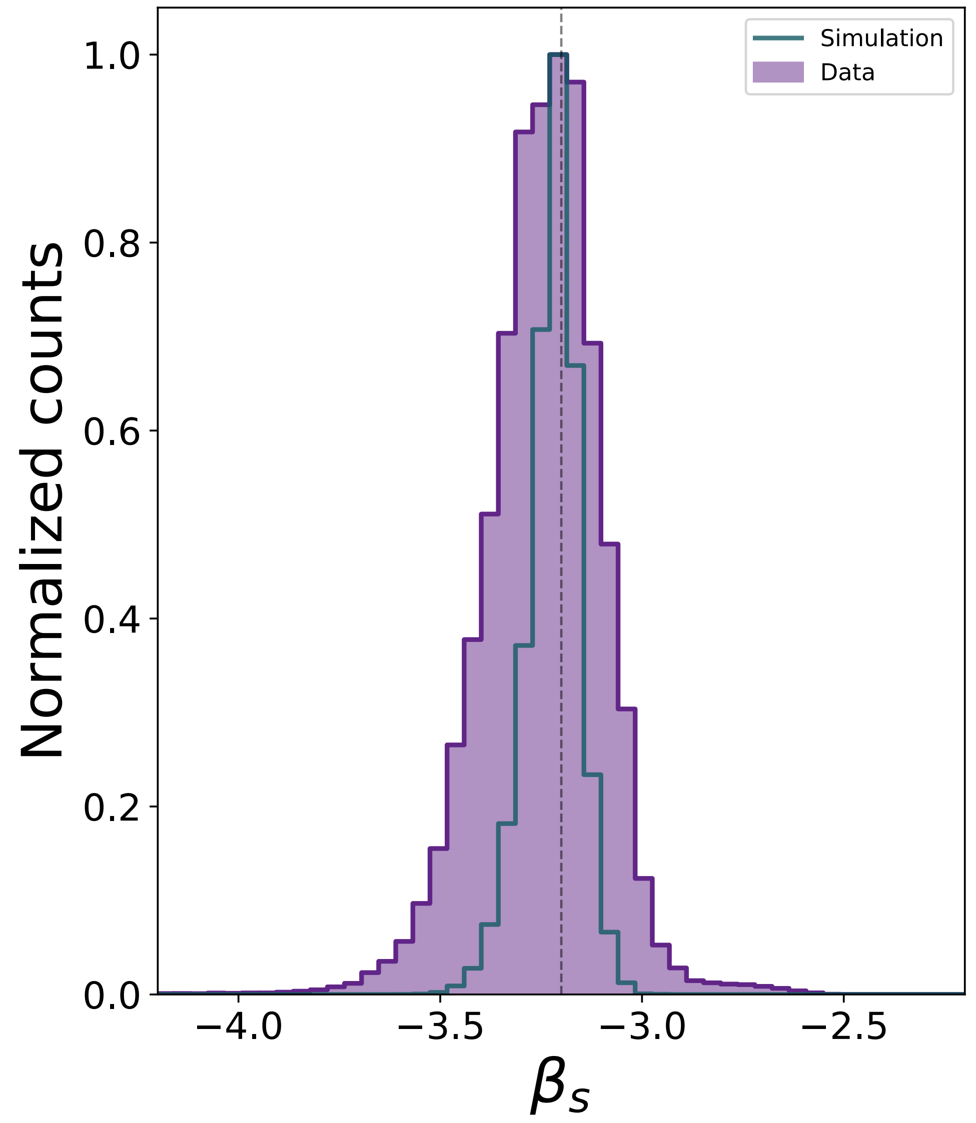


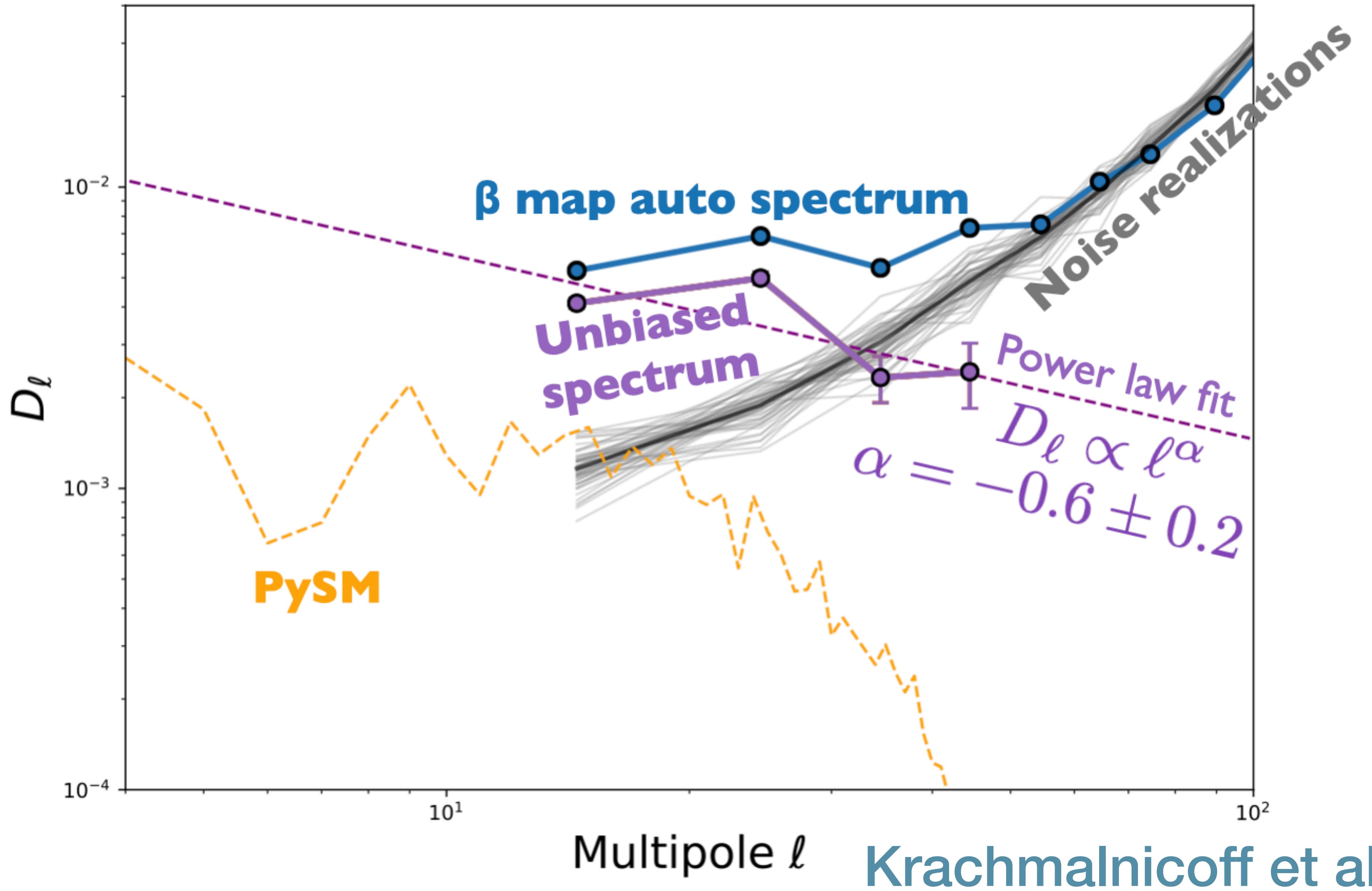
- S-PASS survey @ 2.3GHz, 9 arcmin angular resolution, 50% sky coverage (Carretti et al. 2019)
- Analysis in harmonic space with WMAP+Planck-LFI: $\beta_s = -3.22 \pm 0.08$

Krachmalnicoff et al. 2018

Synchrotron with low frequency data



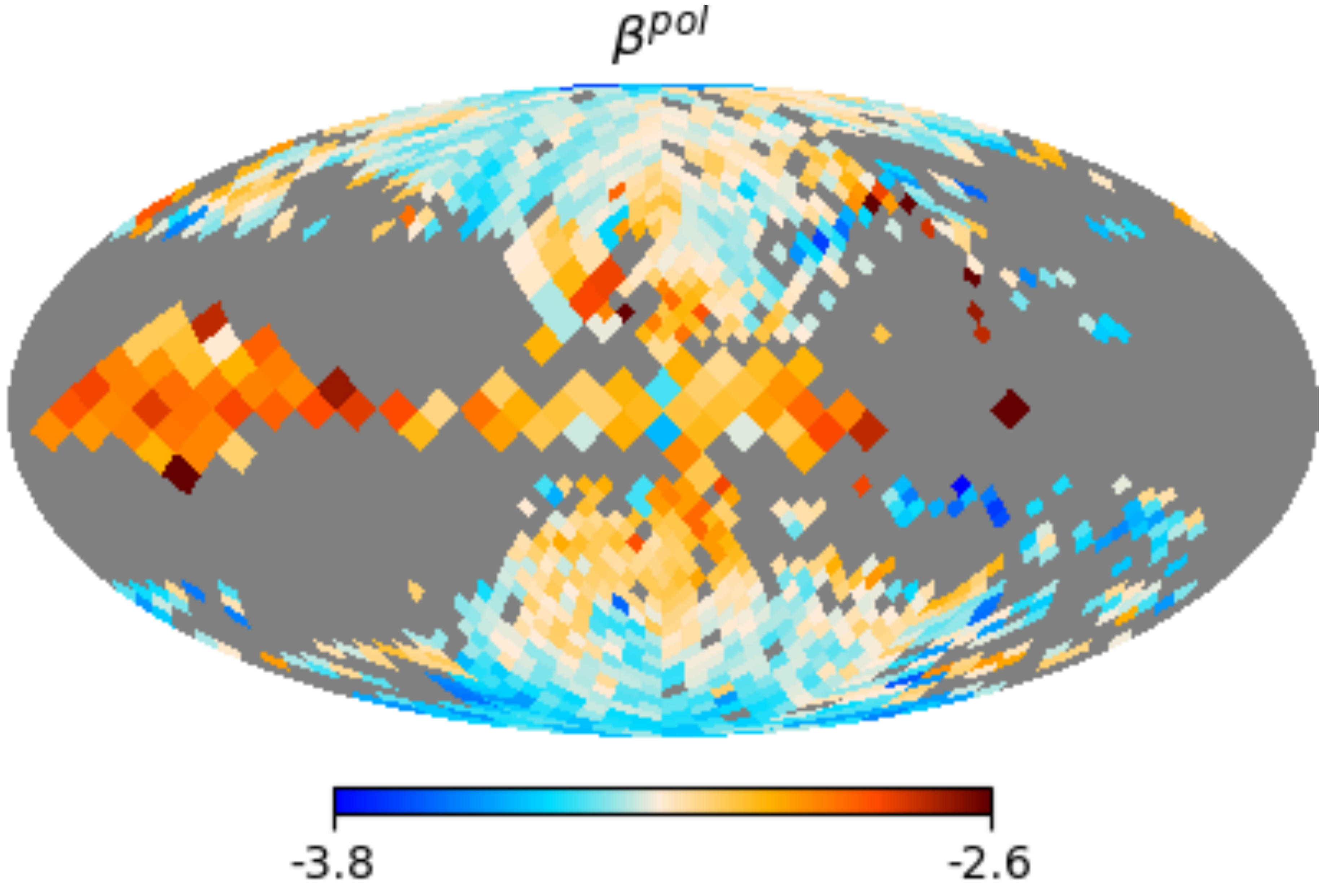


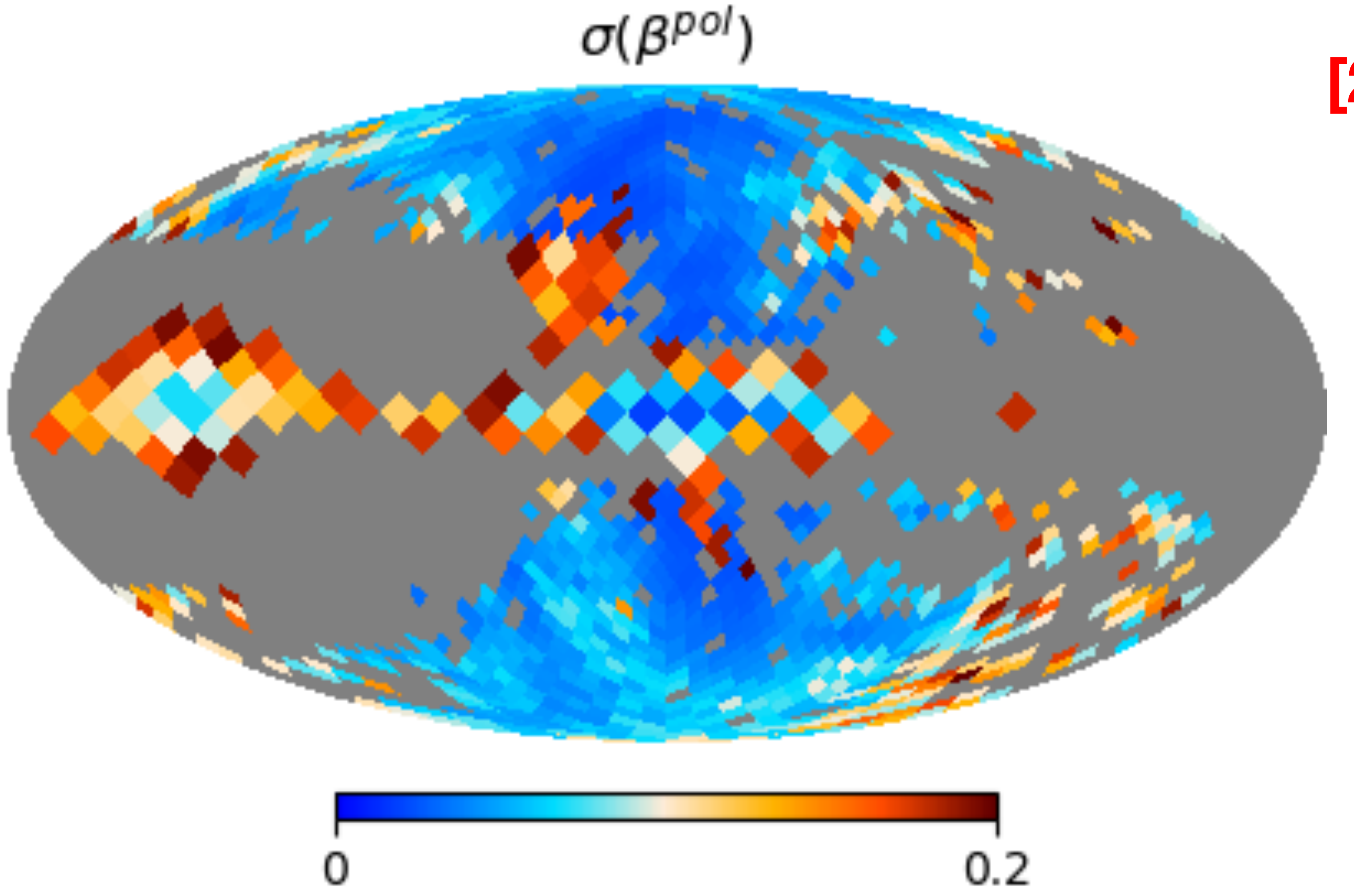


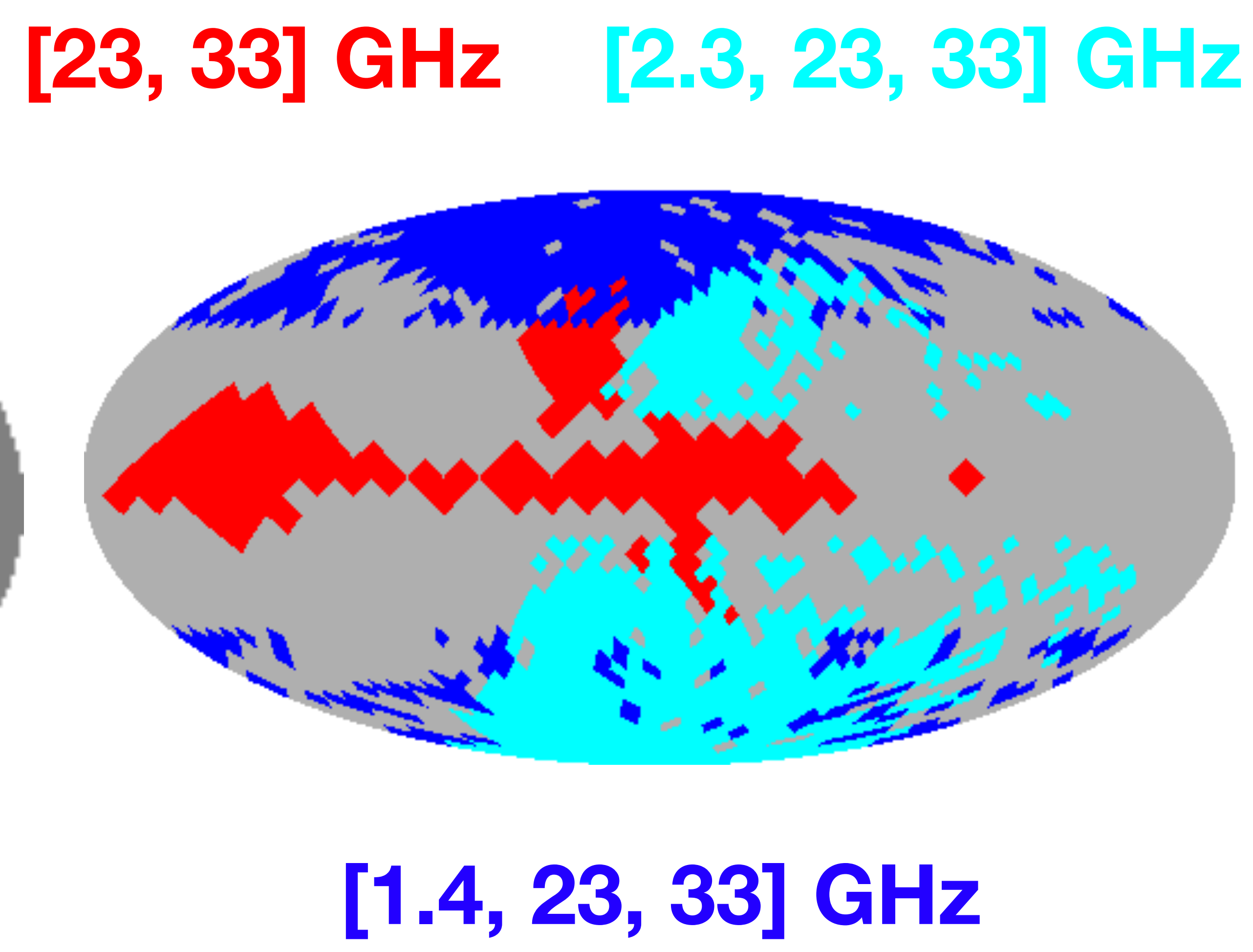
- Power law fit in range **2.3 - 33 GHz**
- Fit in each pixel in **total polarized intensity** taking into account the noise bias
- **Angular resolution of 2°**
- Sky coverage ~ 30%
- Flat prior

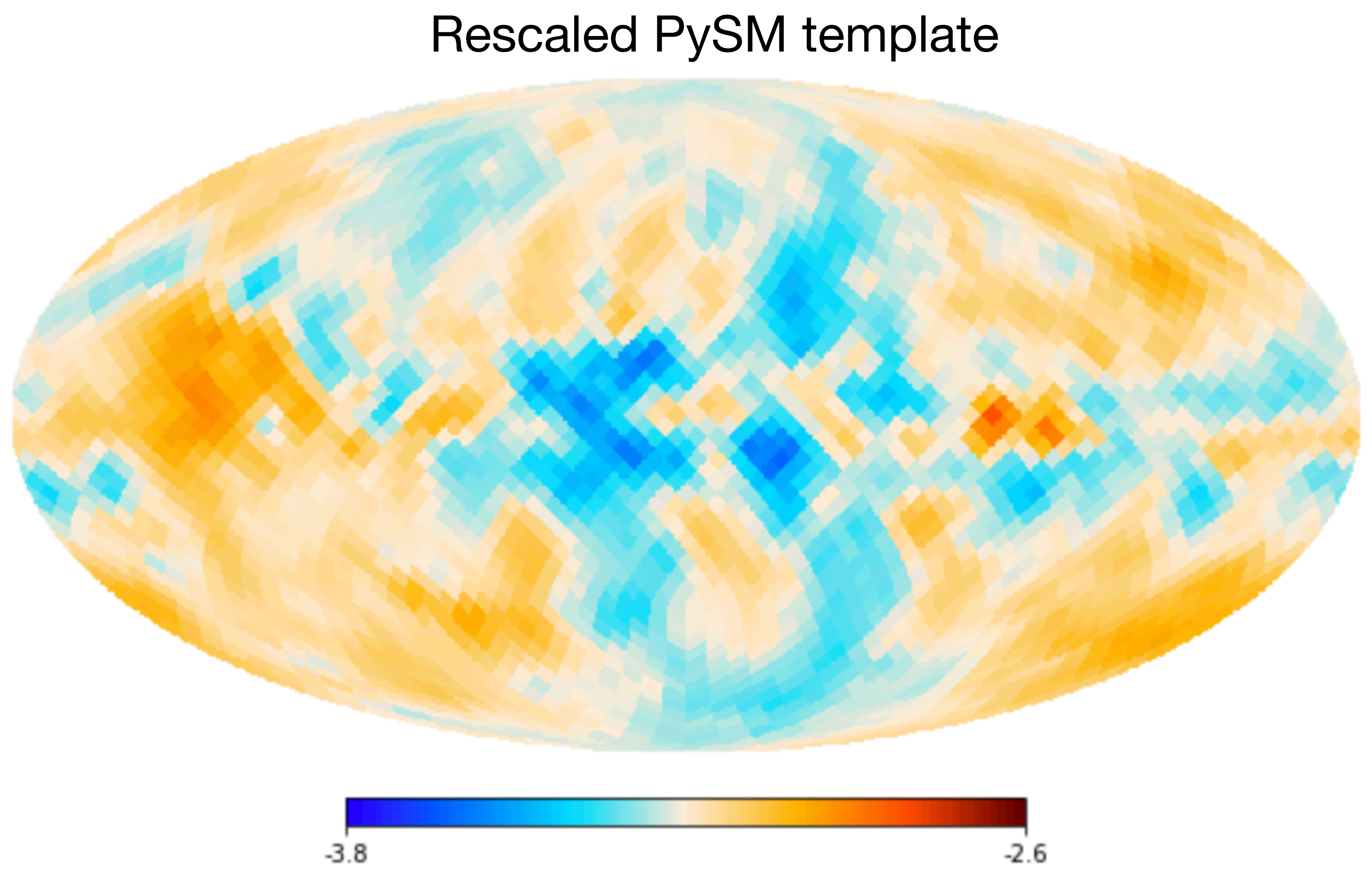
Krachmalnicoff et al. 2018

Synchrotron SED with low frequency data





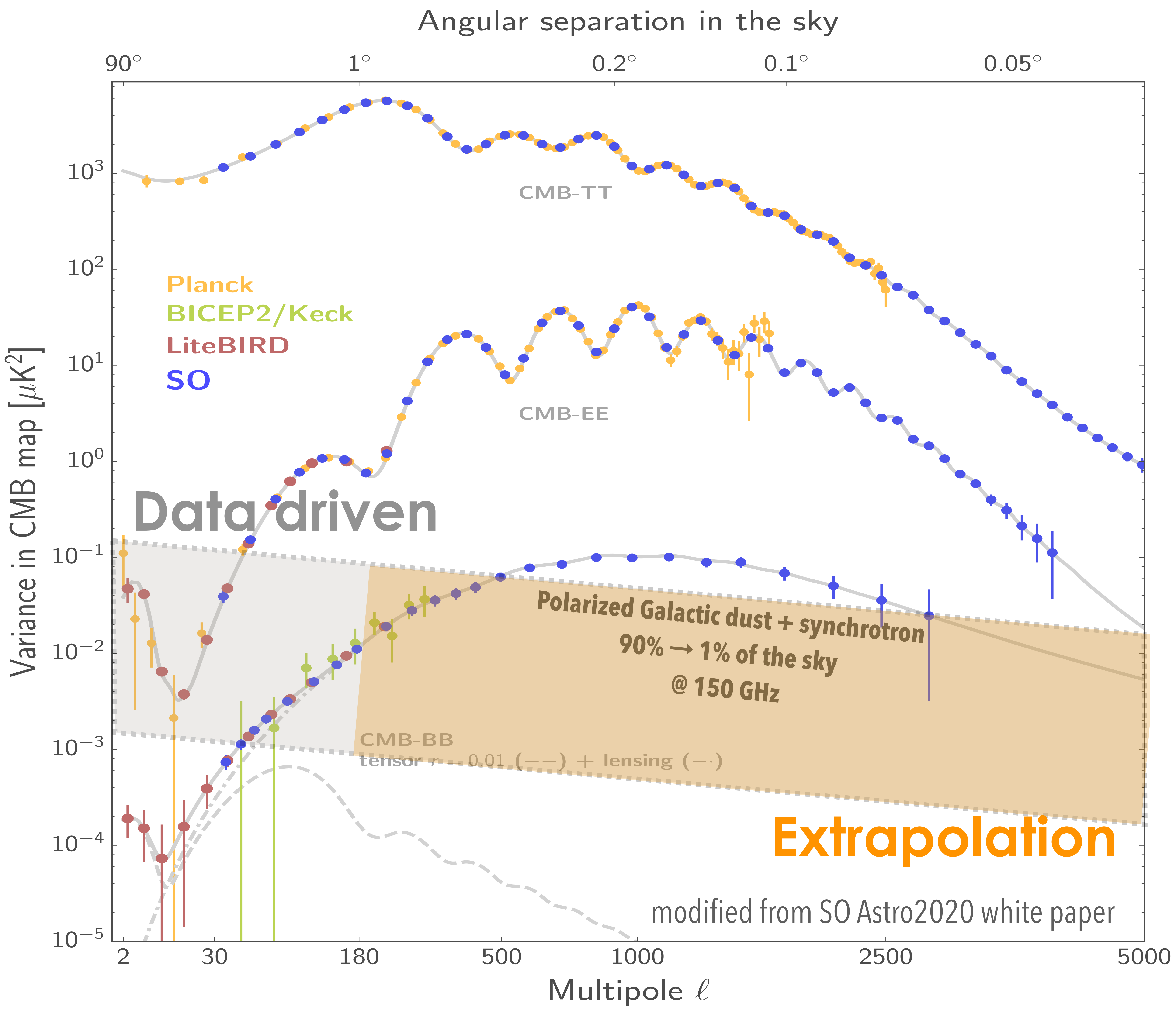


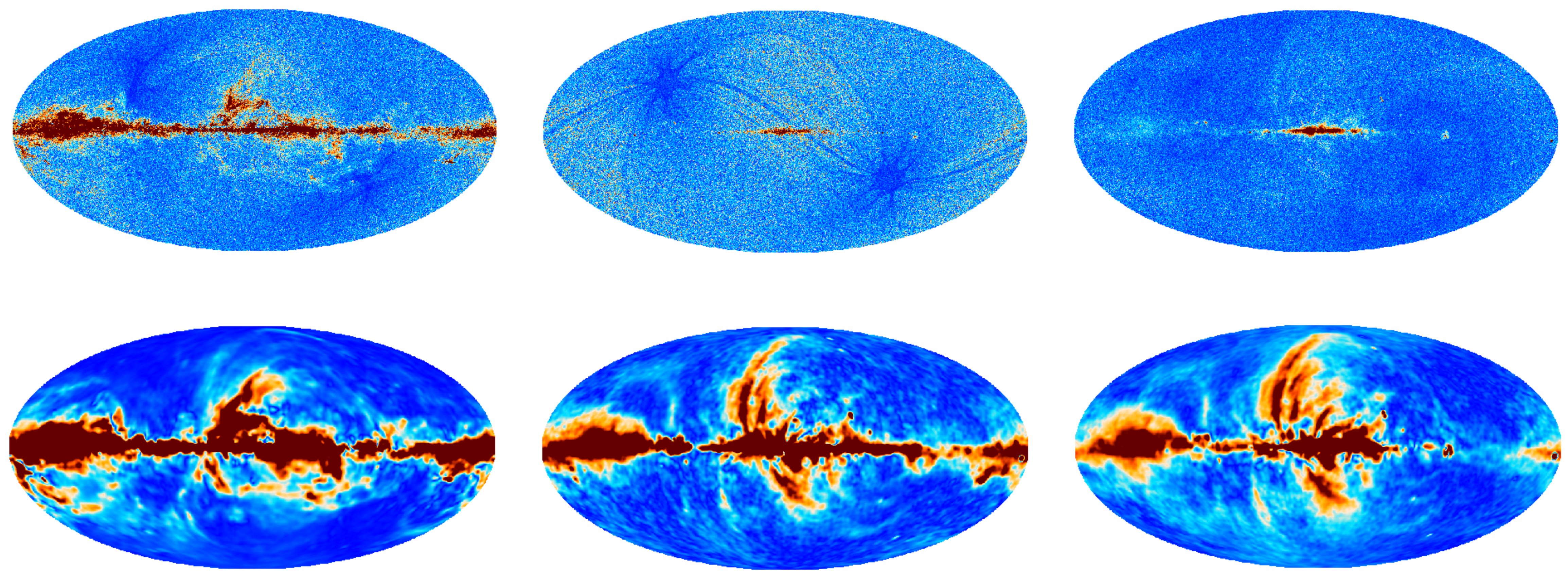


- Combination of available low frequency data allows to build a β_s map covering ~ 44% of the sky
- Filling gaps with total intensity data at lower frequency (i.e. 408 MHz) is tricky due to systematic differences between currently available observations
- Additional data in the [10 - 20] GHz window will be fundamental

Weiland et al. 2022

Foregrounds at small scales





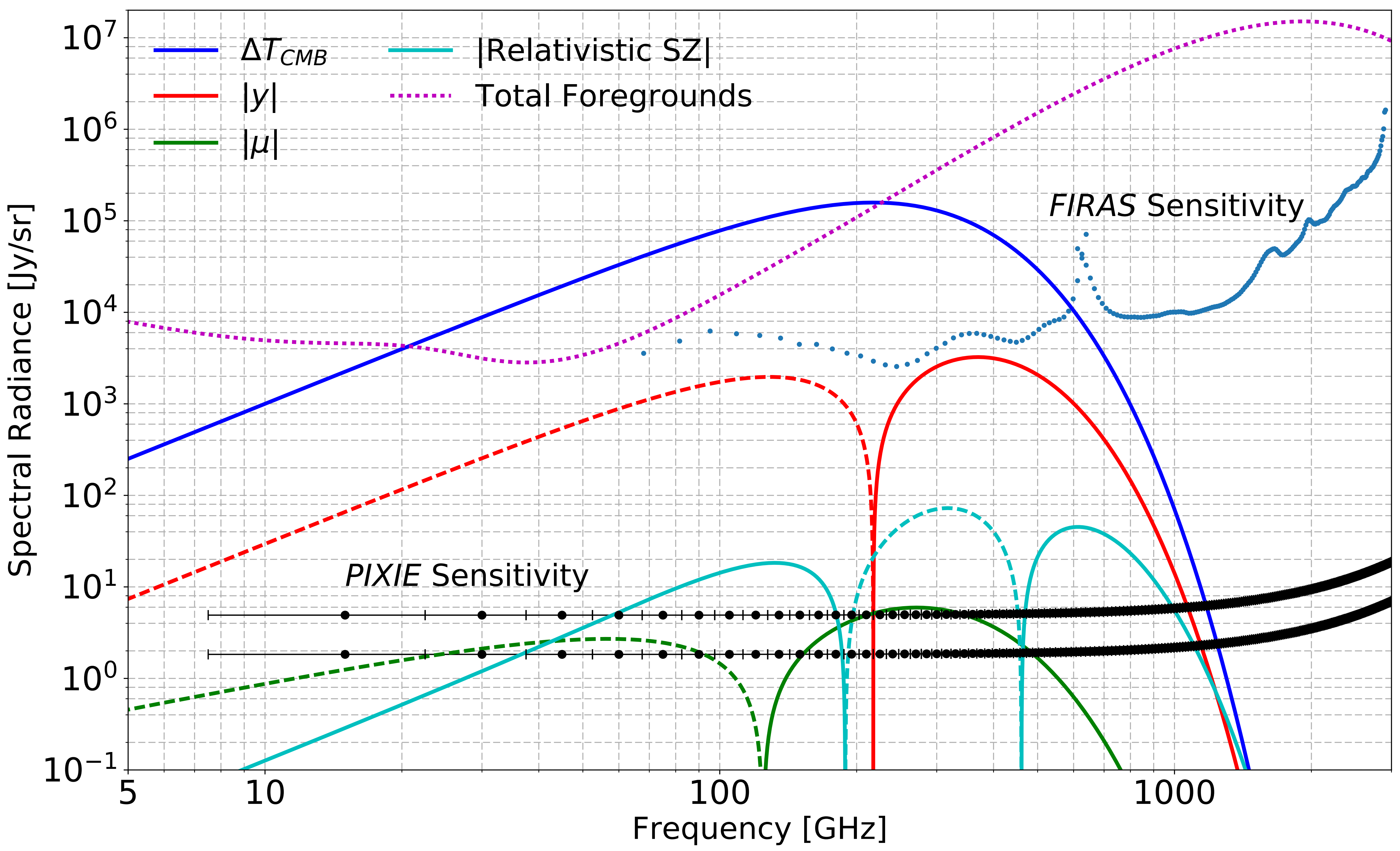
- From available data we only have information of large scale polarized foregrounds (> 1deg)
- What's the behavior at small scales? ($C_\ell^{\rm dust,TT} \propto \ell^{-2.6}$ vs $C_\ell^{\rm dust,P} \propto \ell^{-2.4}$)
- Statistical properties?
- Impact on lensing, de-lensing, component separation?

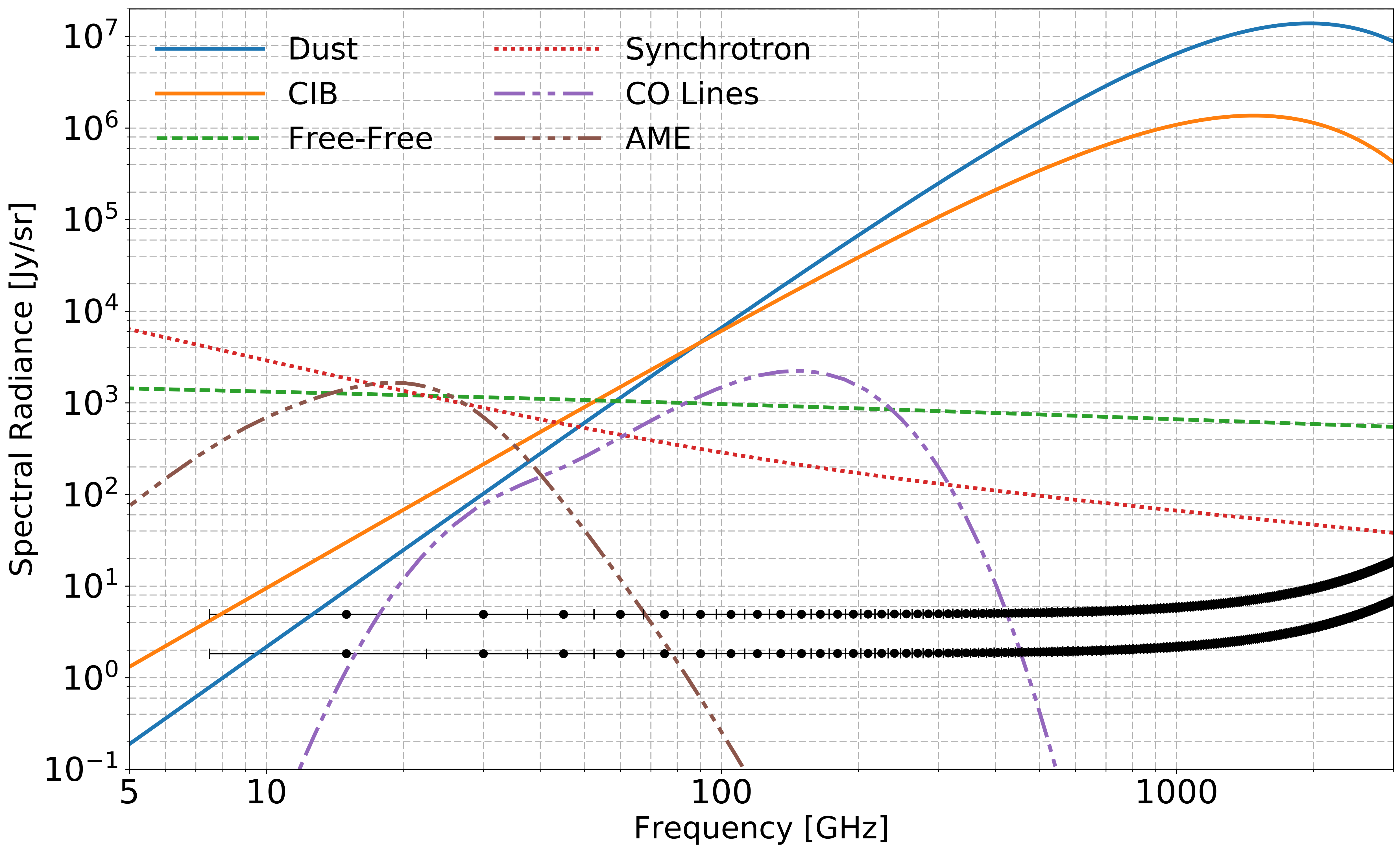
Conclusions

- Analysis of data over the past years has allowed a **deeper understanding** of foreground properties and their contamination to CMB
- This has triggered great development of component separation algorithms
- Are we safe? **Probably NO!** We need to keep working on our FG models and keep testing component separation!
- Many questions are still open: e.g. SED spatial variation? Frequency de-correlation? TB, EB? synchrotron curvature? small scales?
- New low frequency observations will be crucial (see talks/posters on C-BASS and Quijote)

FG contamination to CMB spectral distortions

Abitbol et al. 2017

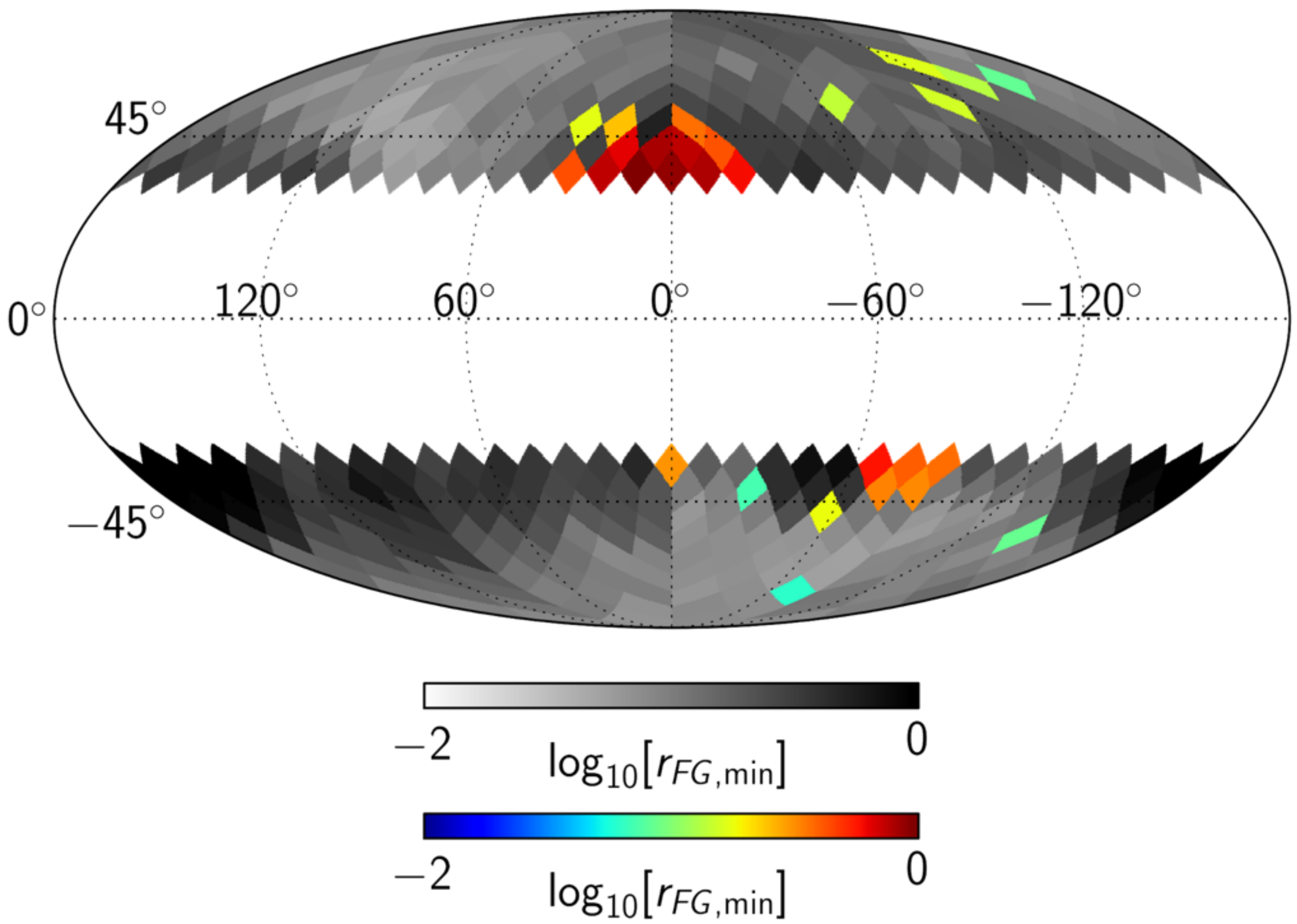


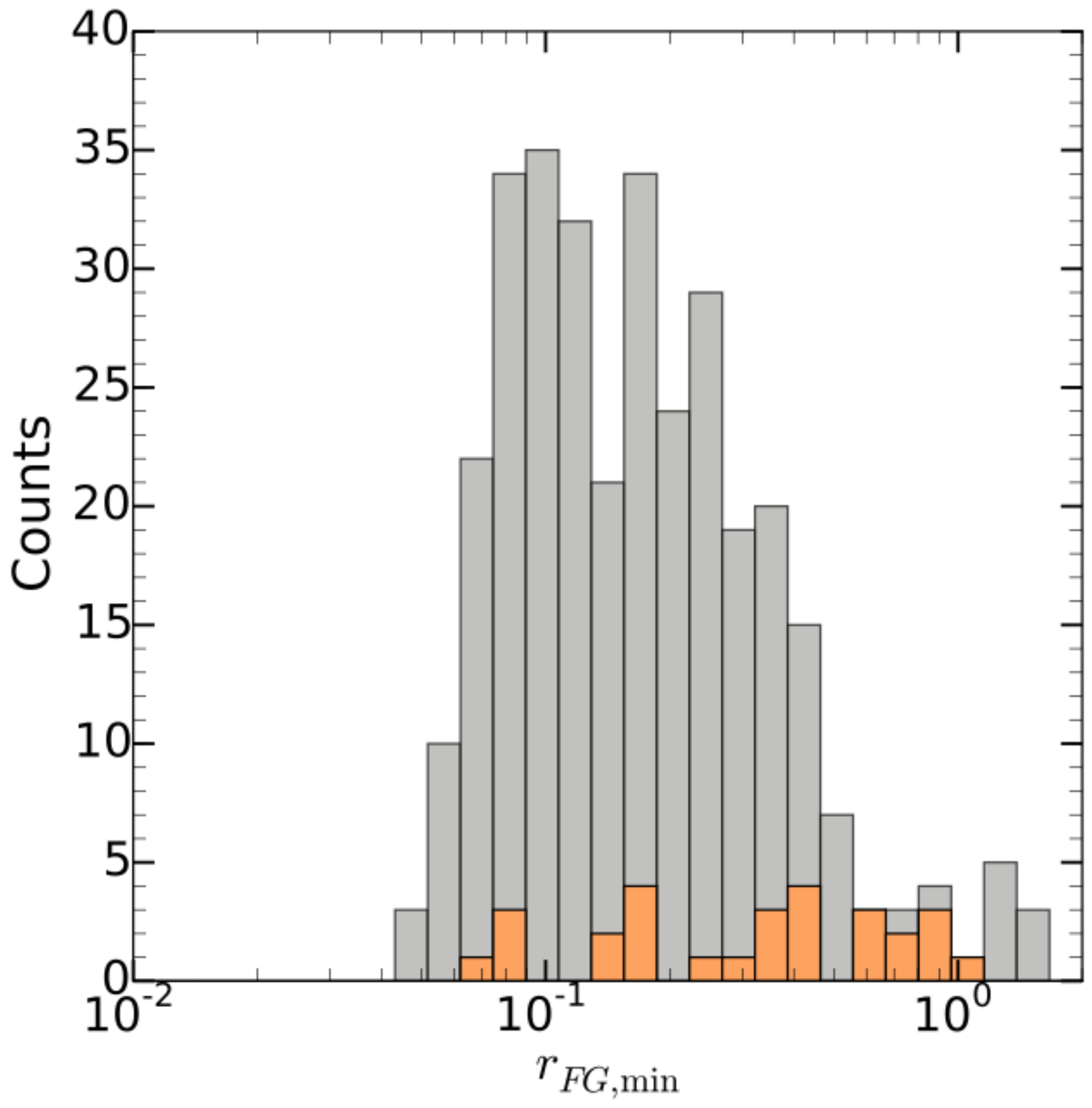


FG contamination to B-modes from Planck x WMAP

Krachmalnicoff et al. 2016

- Foreground contamination at $\ell = 80$ in 352 circular patches (fsky ~ 1%) at intermediate and high Galactic latitudes
- Dust from Planck-HFI 353 GHz
- Synchrotron from WMAP-K x Planck-LFI 30GHz



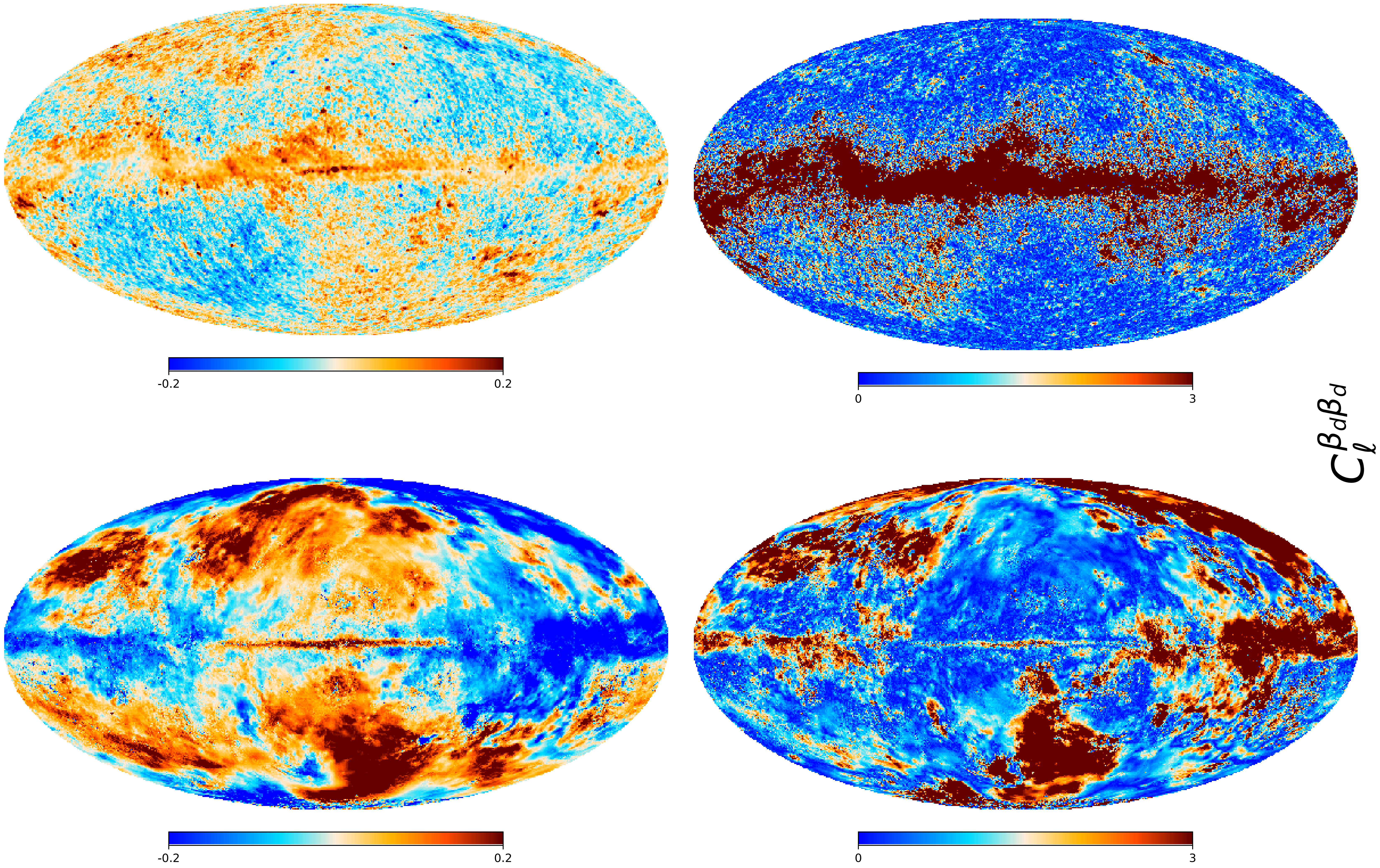


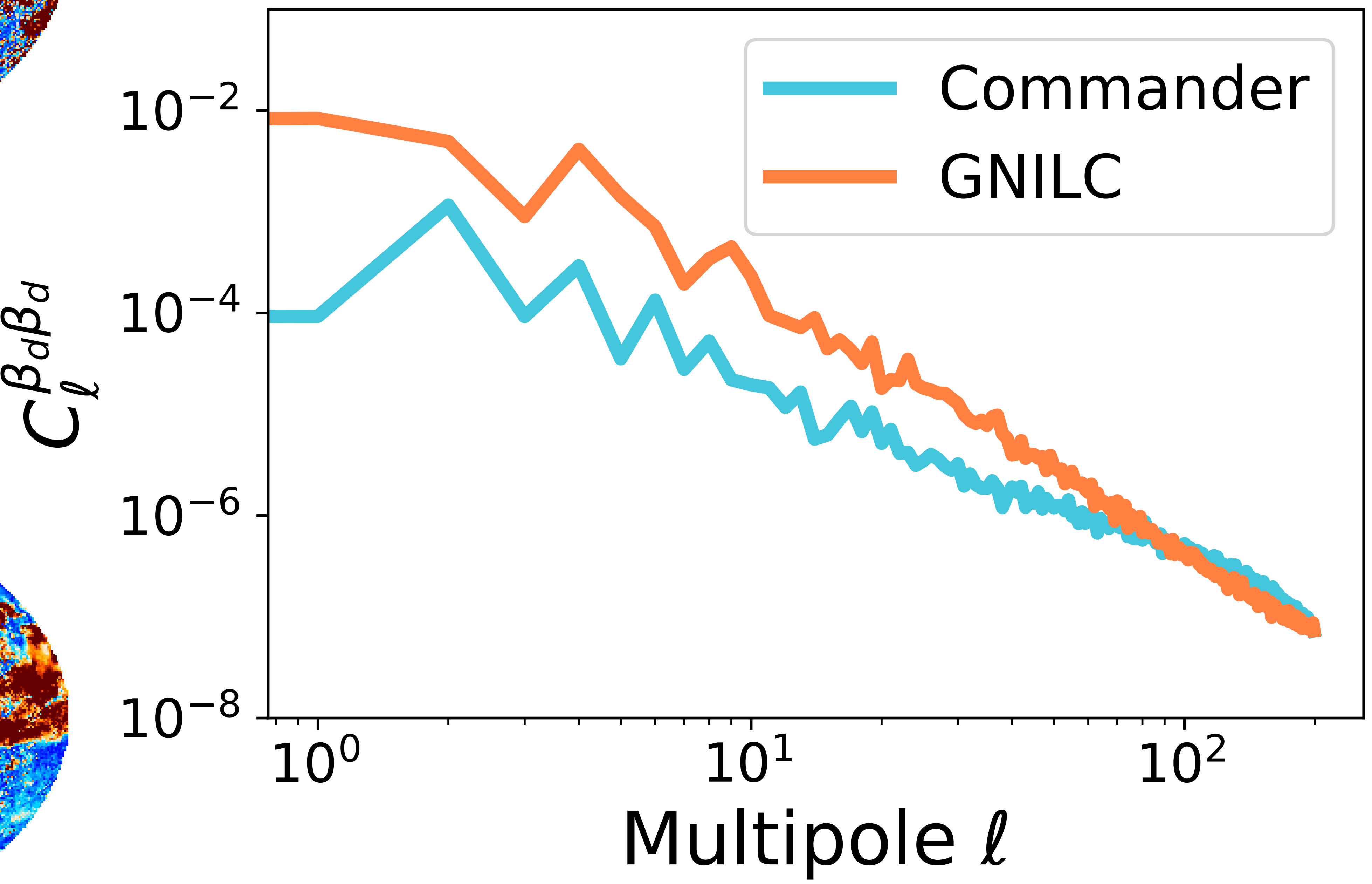
Detection of both dust and synchrotron

Upper limits

Thermal dust SED: spatial variation

- Spatial variation of dust spectral parameters still uncertain



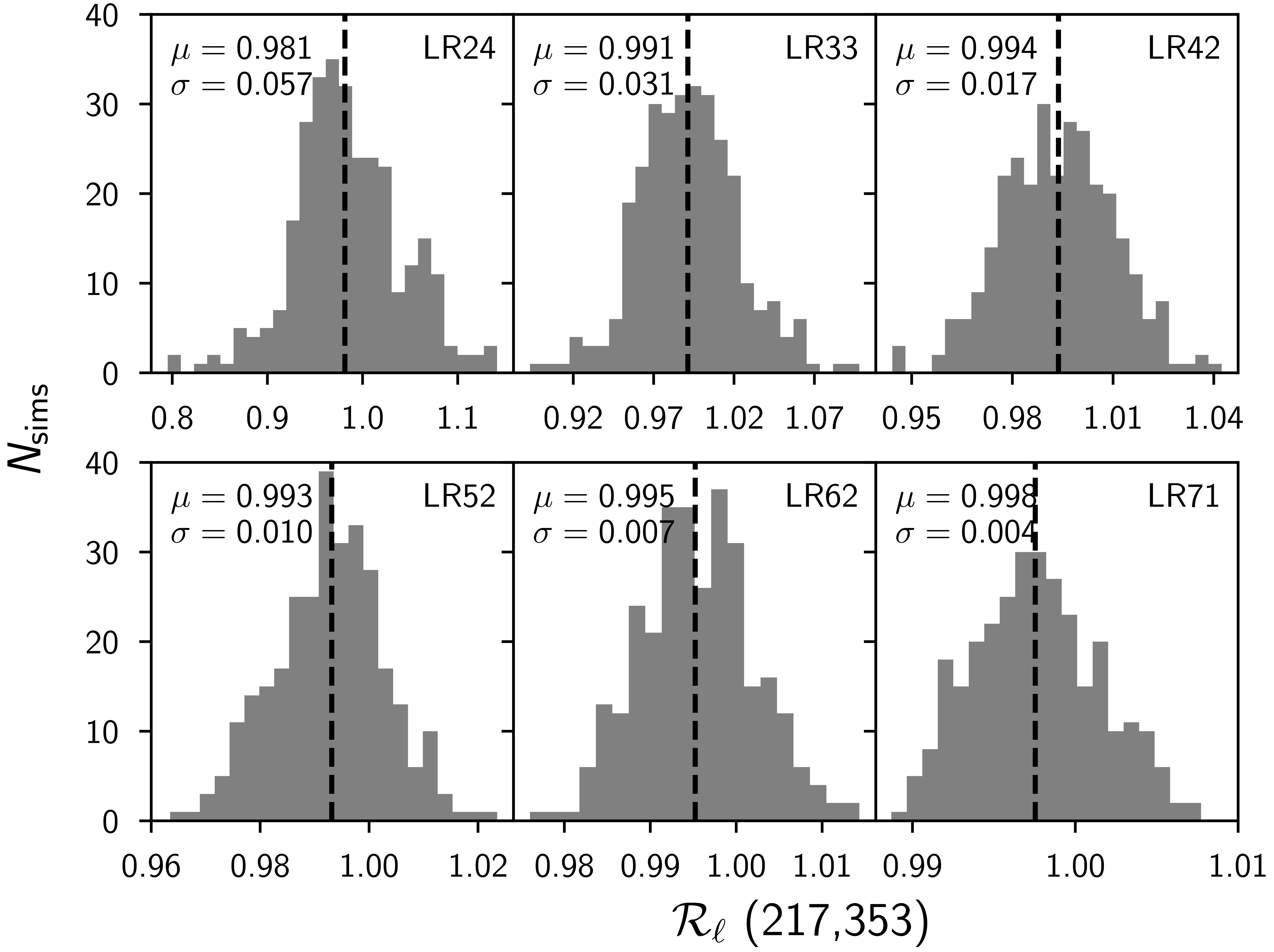


Planck intermediate results XLVIII, 2016

Thermal dust SED: frequency de-correlation

- Spatial variation of spectral parameter can lead to frequency de-correlation
- No detection so far, given the noise level on Planck maps

$$\mathcal{R}_\ell^{BB} \equiv \frac{C_\ell^{BB}(217\times353)}{\sqrt{C_\ell^{BB}(353\times353)\,C_\ell^{BB}(217\times217)}}\,.$$



Planck 2018 results XI

Synchrotron with low frequency data

Krachmalnicoff et al. 2018