Power spectrum analysis of QUIJOTE with Planck and WMAP

Main goal: characterisation of the diffuse emissions as polarised CMB foregrounds

Horizon 2020
European Union Funding
for Research & Innovation

Flavien Vansyngel, Instituto de Astrofísica de Canarias

@ CMB foregrounds for B-mode studies, oct. 2018, Tenerife

QUIJOTE data used and region of analysis

QUIJOTE polarised data set:

11, 13 GHz from Horn 3
17, 19 GHz

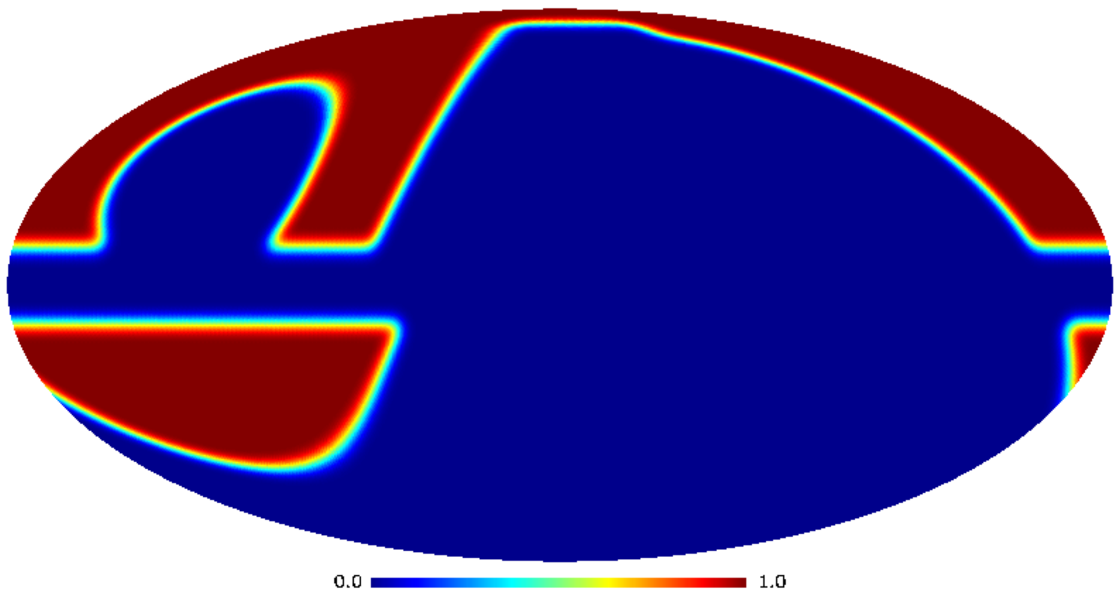
full mission (final results)
half mission —> half difference (noise, null test)

Resolution:
11, 13 GHz —> 50 arcm.
17, 19 GHz —> 39 arcm.

Noise level:
11, 13 GHz —> 54, 48 μK/deg
17, 19 GHz —> 41, 42 μK/deg

Region of analysis (galactic coord.):

$f_{sky} = 0.22$



- 12° < declination < 60°
- galactic cut: ±10°
- patch to mask the spur

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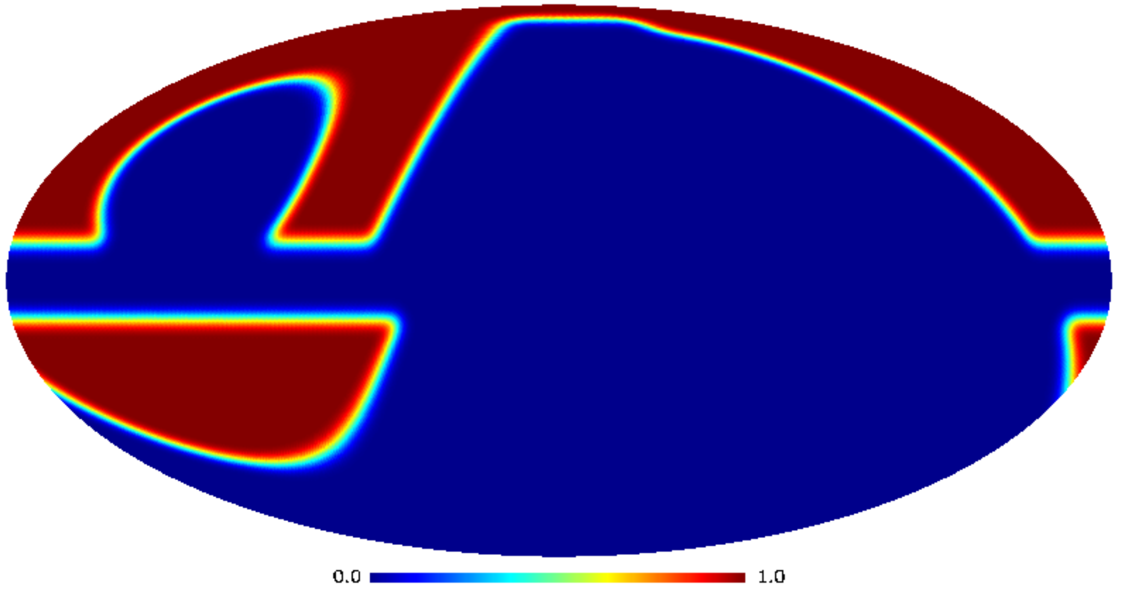

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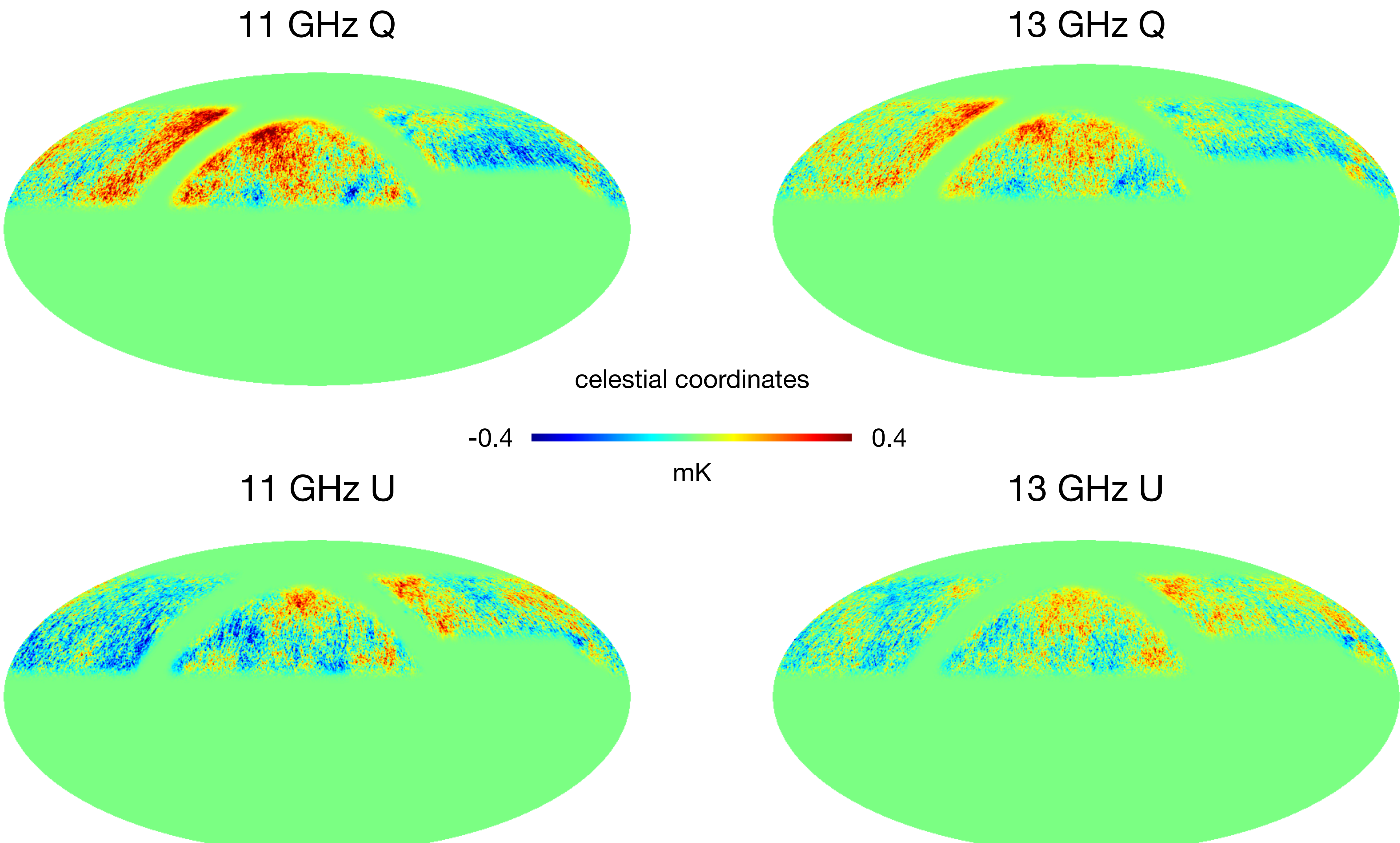


Data set

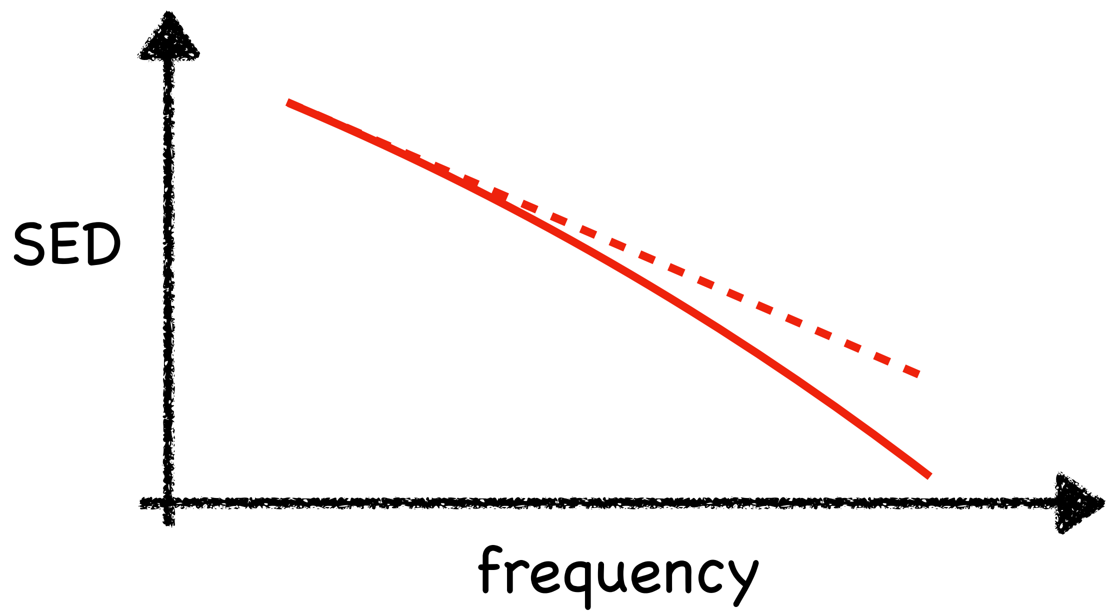
QUIJOTE:
- Horn 3, 11 GHz
- Horn 3, 13 GHz

Planck PR3:
- all polarised channels of HFI
- LFI 30 GHz

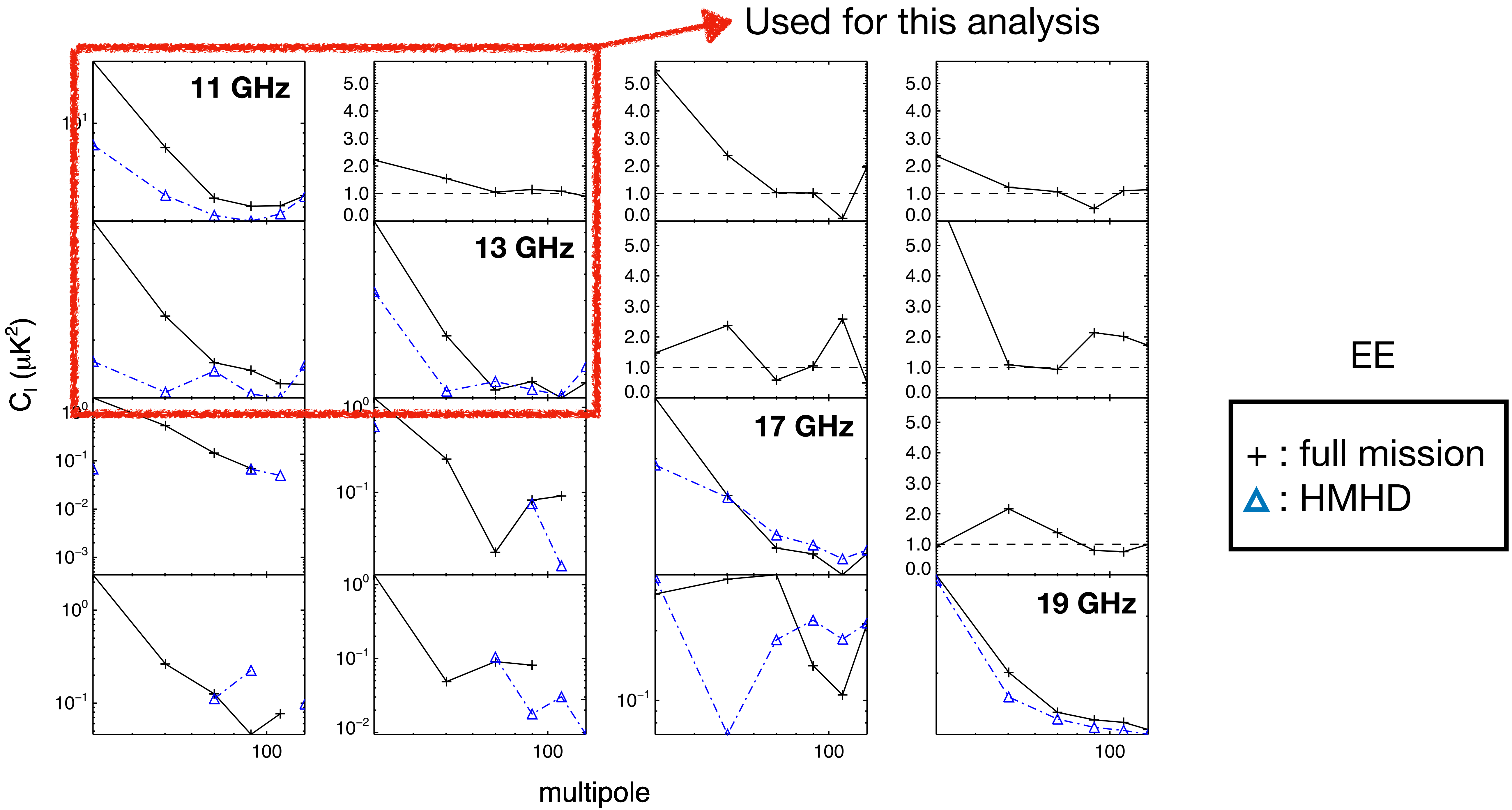
WMAP 9yr:
- K band
- Ka band

→ 9 auto-spectra and 36 cross-spectra

To characterise the synchrotron, we need to go up to high frequencies in order to catch any hints of a deviation from a power law SED



Data power spectra

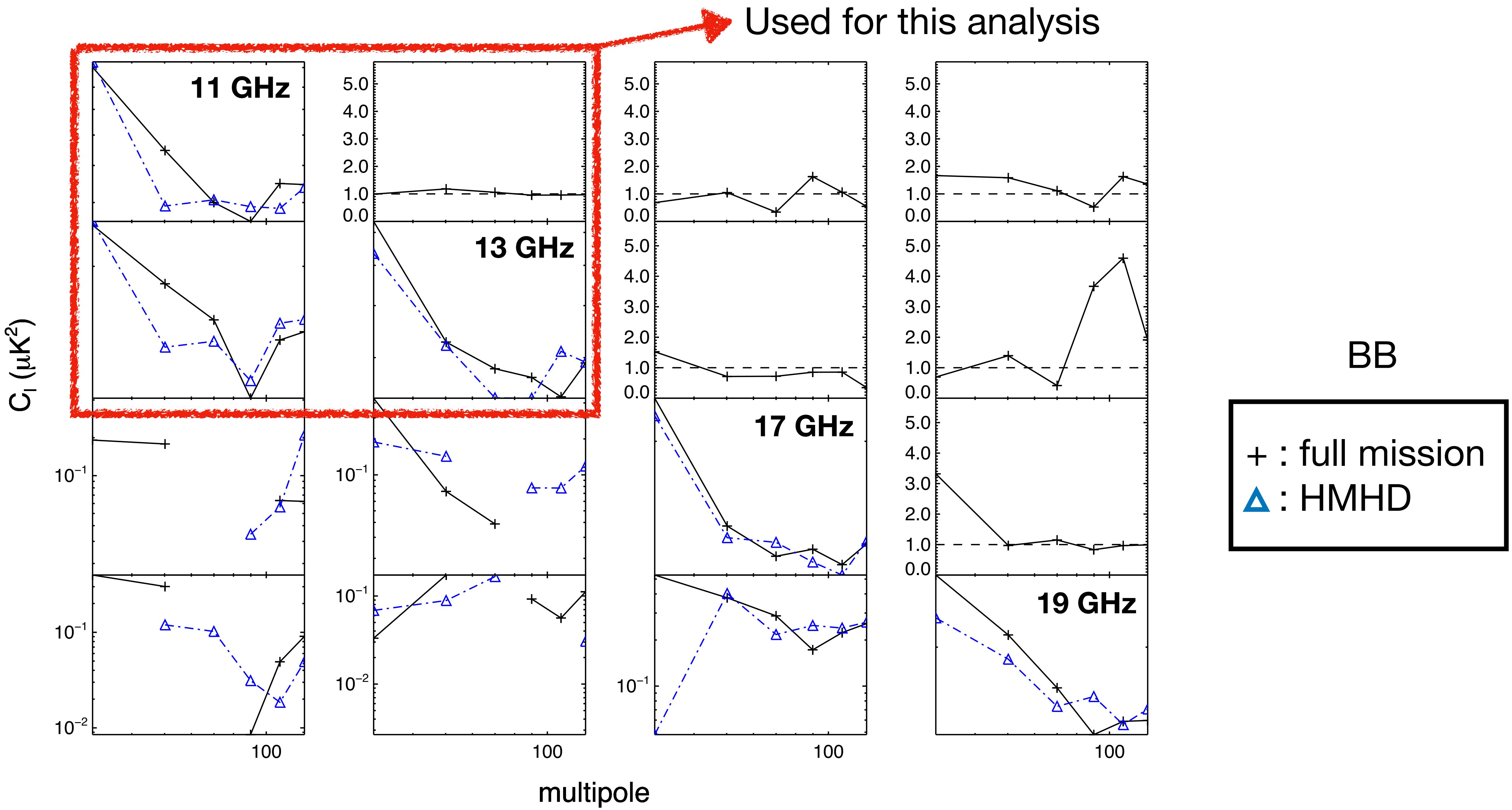


Diagonal: auto-spectra (11, 13, 17, 19 GHz, Horn 3/4)

Lower triangle: Cross-spectra

Upper triangle: estimate of the SNR in the cross spectra $\sqrt{|X_\ell^{\mathrm{full}}/X_\ell^{\mathrm{HMHD}}|}$

Data power spectra



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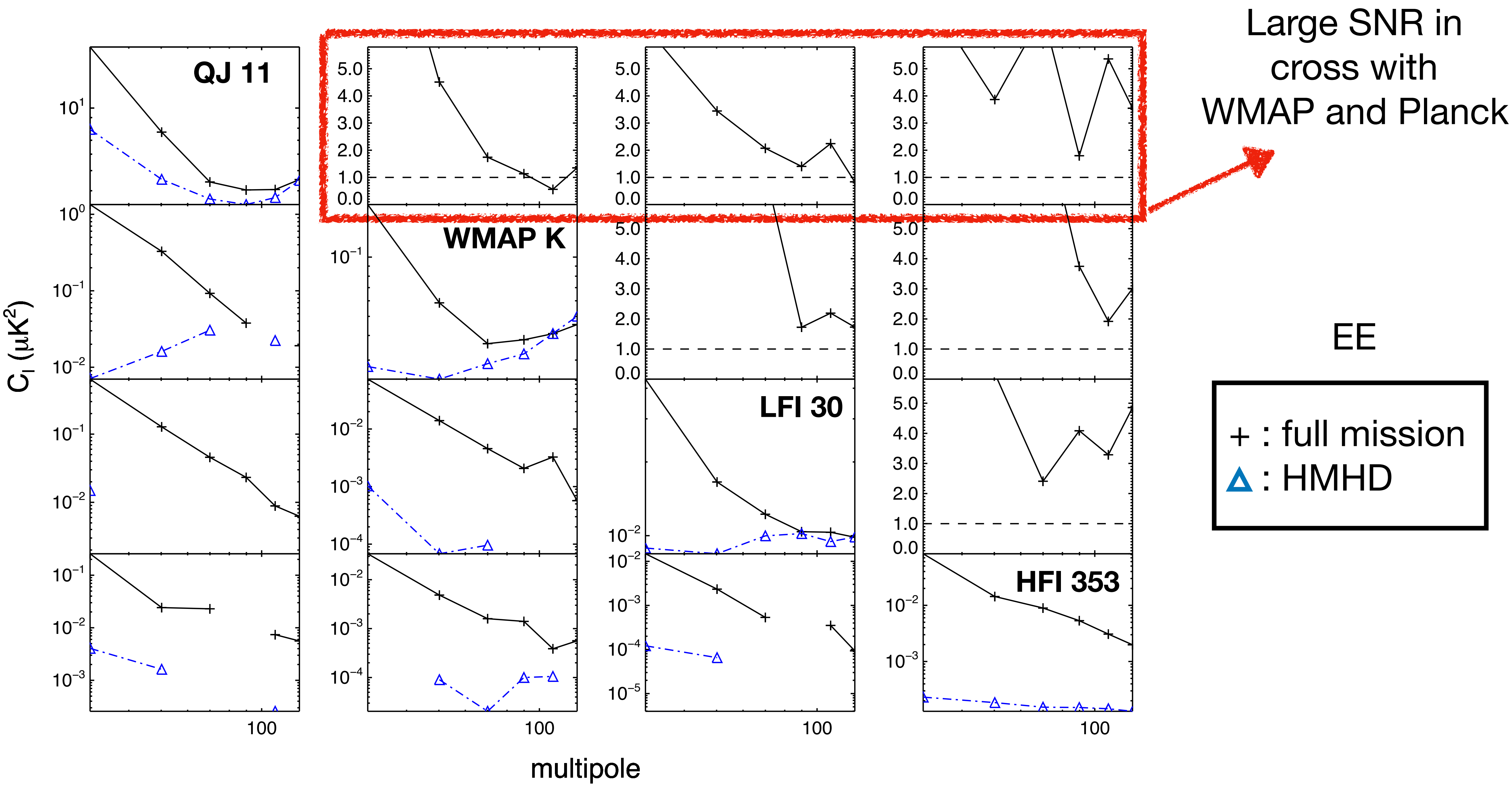

Diagonal: auto-spectra (QJ 11 GHz Horn 3, WMAP K, LFI 30GHz, HFI 353 GHz)

Lower triangle: Cross-spectra

Upper triangle: estimate of the SNR in the cross spectra $\sqrt{|X_\ell^{\rm full}/X_\ell^{\rm HMHD}|}$

Method: data model

$$d_{\ell m} = \underline{A\, s_{\ell m}} + n_{\ell m}$$

data

synchrotron
dust
CMB (EE)

noise

Supposing **small variation of SED** across the sky
and
using **first order expansion** of the SED
following
Chluba, Hill, Abitbol, 2017

Mixing matrix $A(\theta)$ contains the SEDs in K_{RJ}, it is **fixed across multipoles**

Synchrotron (2 compo.):

$$A(\theta)_{\nu\,1} = \left(\frac{\nu}{30}\right)^{\beta_s}$$

$$A(\theta)_{\nu\,2} = \left(\frac{\nu}{23}\right)^{\beta_s} \log\left(\frac{\nu}{23}\right)$$

Dust (2 compo., fixed temp.):

$$A(\theta)_{\nu\,3} = \left(\frac{\nu}{353}\right)^{\beta_d - 2} \frac{B_\nu(T_d)}{B_{353}(T_d)}$$

$$A(\theta)_{\nu\,4} = \left(\frac{\nu}{353}\right)^{\beta_d - 2} \frac{B_\nu(T_d)}{B_{353}(T_d)} \log\left(\frac{\nu}{353}\right)$$

CMB (fixed): $A(\not\theta)_{\nu\,5} = \mathrm{SED}_{\mathrm{CMB}}(\nu)$

Method: data model

Power spectrum analysis

$$A\, s_{\ell m} + n_{\ell m}$$

(map level)

→

$$A(\theta) S_\ell(\theta) A(\theta)^T + N_\ell$$

(power spectrum level)

$$S_\ell(\theta) = \begin{pmatrix} F_\ell & 0 \\ 0 & C_\ell \end{pmatrix}$$

Foregrounds: cov. matrix with all **auto- and cross-spectra free**

CMB (EE): strongly constrained

Second component for synchrotron or dust is **proportional to the *δβ* map** (in the first order approx.)

Method: fitting procedure

$$A\, s_{\ell m} + n_{\ell m} \quad \longrightarrow \quad A(\theta) S_\ell(\theta) A(\theta)^T + N_\ell \hat{=} R_\ell(\theta)$$

Explore with MCMC the following posterior PDF:

$$P(\theta\,|\,d) \propto \prod_{bin} |R(\theta)|^{-\frac{\gamma}{2}} \exp\left[-\frac{\gamma}{2}\mathrm{Tr}\left\{R(\theta)^{-1}\hat{R}(d)\right\}\right] \times \mathrm{Prior}(\theta)$$

(Parametrised SMICA likelihood x priors)

data spectra ($\hat{R}(d)$):

(1) computed using PolSpice
(2) binned with a 2ell+1 weighting scheme and with Δell = 20

Prior(θ):

$\beta_d \sim \mathcal{N}(1.53, 1)$ $\quad F_\ell \sim \mathrm{flat}$

$\beta_s \sim \mathcal{N}(-3, 1)$ $\quad C_\ell^{\mathrm{CMB}} \sim \mathrm{InvGamma}$

strongly constrains the CMB:
peaks at Planck best fit EE spectrum
and
variance is 2x the cosmic variance

Model selection

Synchrotron (2 compo.):

$$A(\theta)_{\nu\,1} = \left(\frac{\nu}{30}\right)^{\beta_s}$$

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4 models:

s1d1 → 1-component Synchrotron + 1-component Dust

s1d2 → 1-component Synchrotron + 2-component Dust

s2d1 → 2-component Synchrotron + 1-component Dust

s2d2 → 2-component Synchrotron + 2-component Dust

PRELIMINARY

Model selection

Relative likelihood using rough estimate of Akaike Information Criterion (AIC)
(~ probability to be the best model among the proposed models)

QJ + WMAP + Planck

	s1d1	s1d2	s2d1	s2d2
EE	8×10^{-27}	1	2×10^{-36}	7×10^{-16}
BB	5×10^{-30}	1	1×10^{-21}	4×10^{-5}
EE+BB	1×10^{-62}	1	3×10^{-57}	1×10^{-11}

WMAP + Planck

	s1d1	s1d2	s2d1	s2d2
EE	4×10^{-26}	1	7×10^{-28}	8×10^{-13}
BB	2×10^{-30}	1	3×10^{-17}	2×10^{-11}
EE+BB	2×10^{-62}	1	2×10^{-44}	6×10^{-15}

Favored model: 1-compo synchrotron and 2-compo dust with constant β

PRELIMINARY

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Sensitivity to a **variation of beta** synchrotron increases after adding QUIJOTE

Favored model: 1-compo synchrotron and 2-compo dust with constant β

Model selection

Synchrotron (1 compo.):

$$A(\theta)_{\nu\,1} = \left(\frac{\nu}{30}\right)^{\beta_s}$$

β_s different for each multipole

Dust (1 compo., fixed temp.):

$$A(\theta)_{\nu\,3} = \left(\frac{\nu}{353}\right)^{\beta_d - 2} \frac{B_\nu(T_d)}{B_{353}(T_d)}$$

β_d different for each multipole

4 models:

s1d1	→	β_s fixed	+	β_d fixed
s1dm	→	β_s fixed	+	β_d not fixed
smd1	→	β_s not fixed	+	β_d fixed
smdm	→	β_s not fixed	+	β_d not fixed

Model selection

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$$A(\theta)_{\nu\,1} = \left(\frac{\nu}{30}\right)^{\beta_s}$$

β_s different for each multipole

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β_d different for each multipole

4 models:

s1d1	→	β_s fixed	+	β_d fixed
s1dm	→	β_s fixed	+	β_d not fixed
smd1	→	β_s not fixed	+	β_d fixed
smdm	→	β_s not fixed	+	β_d not fixed

Will be used to compare with the results from S-PASS and Planck

Krachmalnicoff et al. (2018)

Planck collab. XI (2018)

PRELIMINARY

Model selection

Relative likelihood using rough estimate of Akaike Information Criterion (AIC)
(~ probability to be the best model among the proposed models)

Multiple compo. →

QJ + WMAP + Planck	s1d1	s1d2	s2d1	s2d2
EE	8×10^{-27}	1	2×10^{-36}	7×10^{-16}
BB	5×10^{-30}	1	1×10^{-21}	4×10^{-5}
EE+BB	1×10^{-62}	1	3×10^{-57}	1×10^{-11}

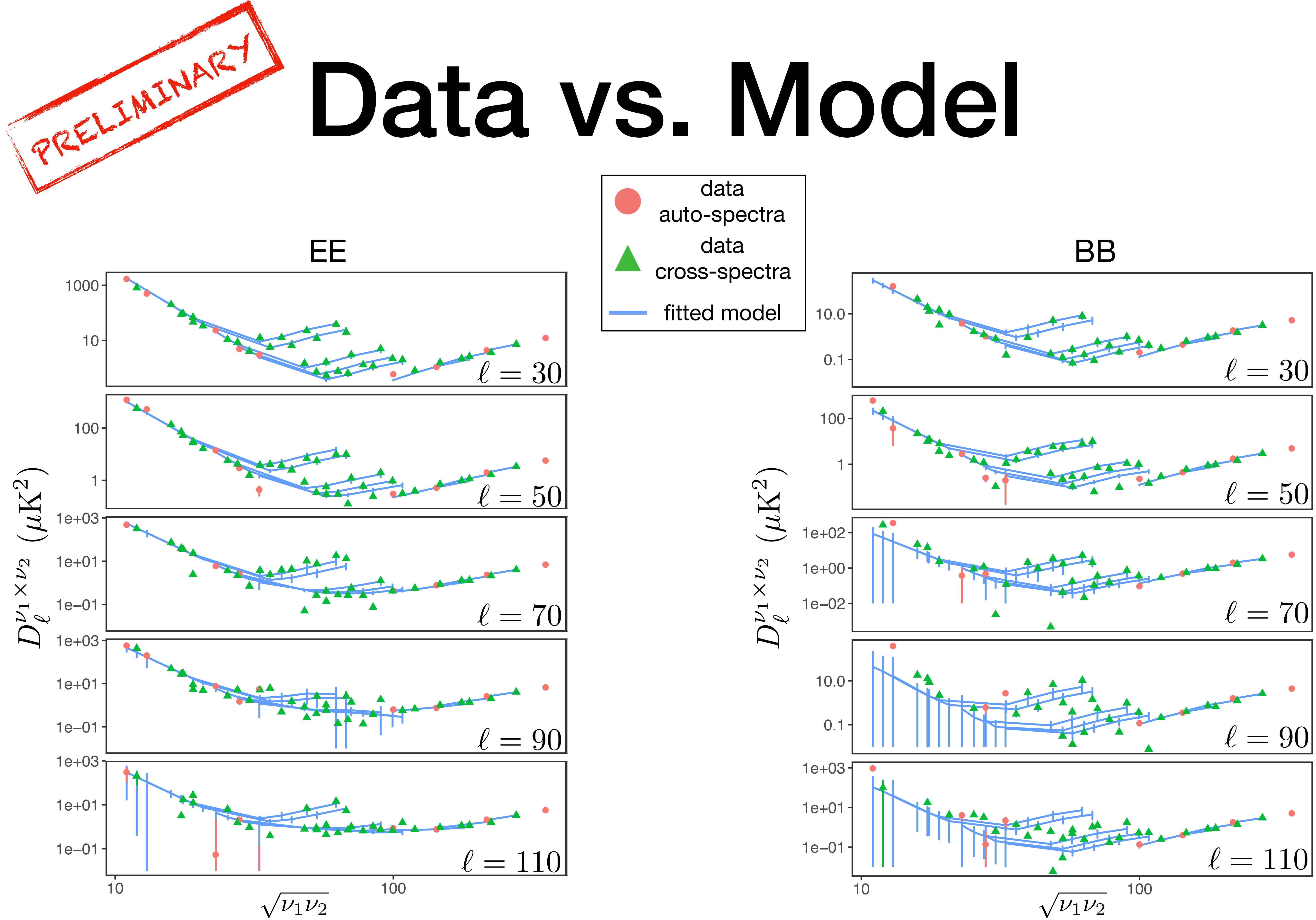
Varying betas →

QJ + WMAP + Planck	s1d1	s1dm	smd1	smdm
EE	1	0.005	0.003	3×10^{-6}
BB	1	0.001	0.0003	0.006
EE+BB	1	0.0003	4×10^{-5}	6×10^{-5}

Favored model: 1-compo synchrotron and 2-compo dust with constant β

This talk presents results from **s1d2**, except when comparing with previous results

Data vs. Model



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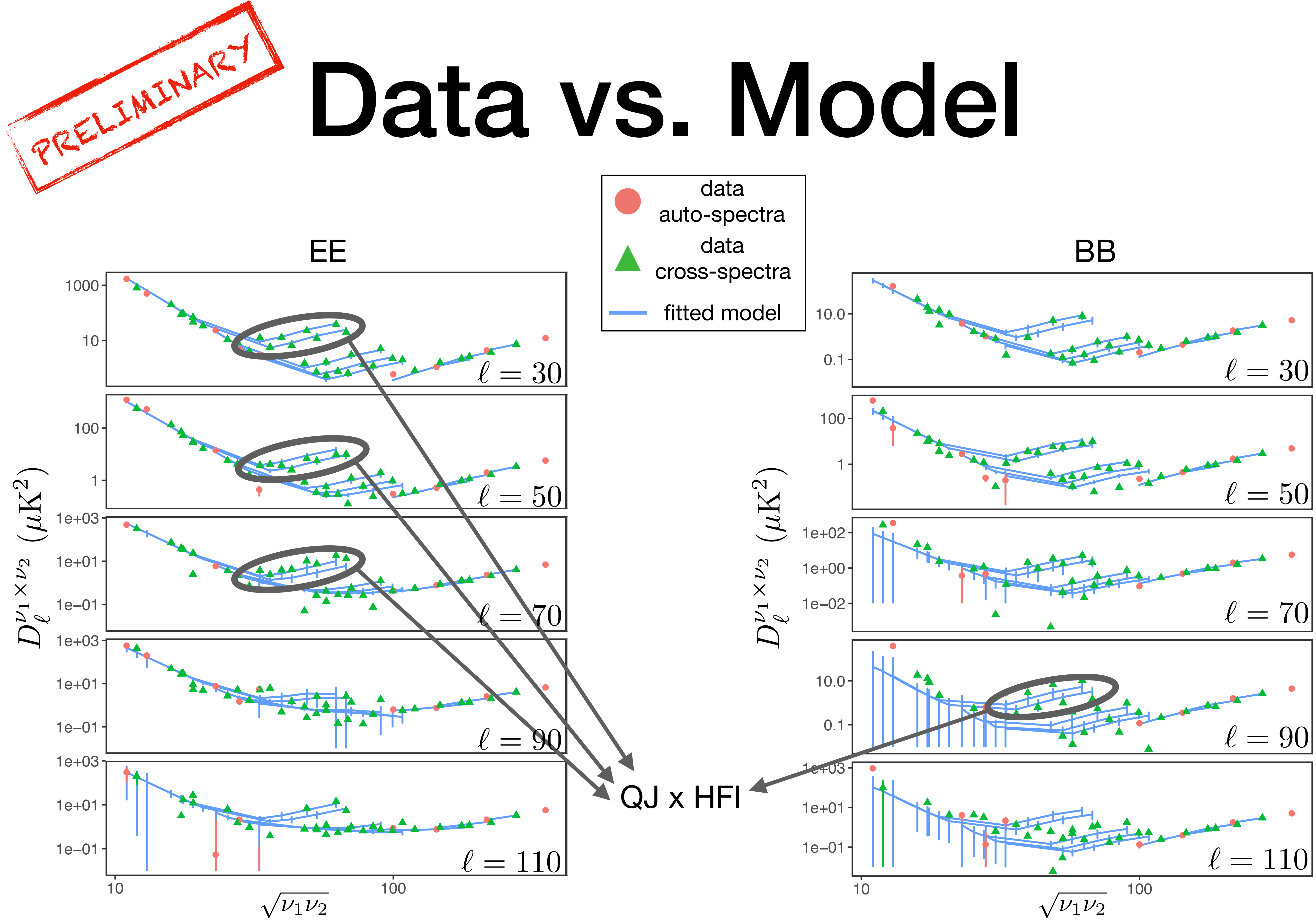
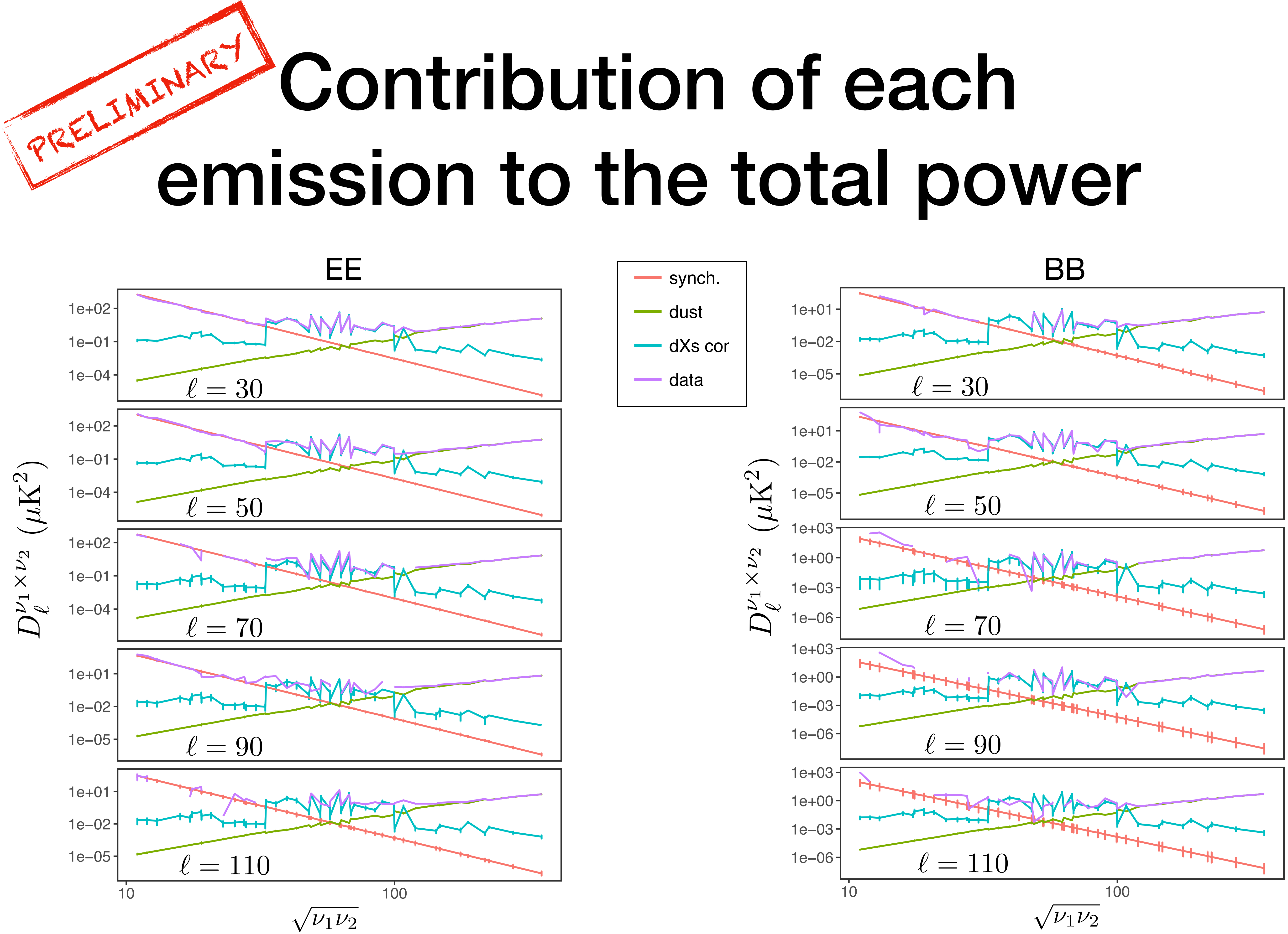


Contribution of each emission to the total power

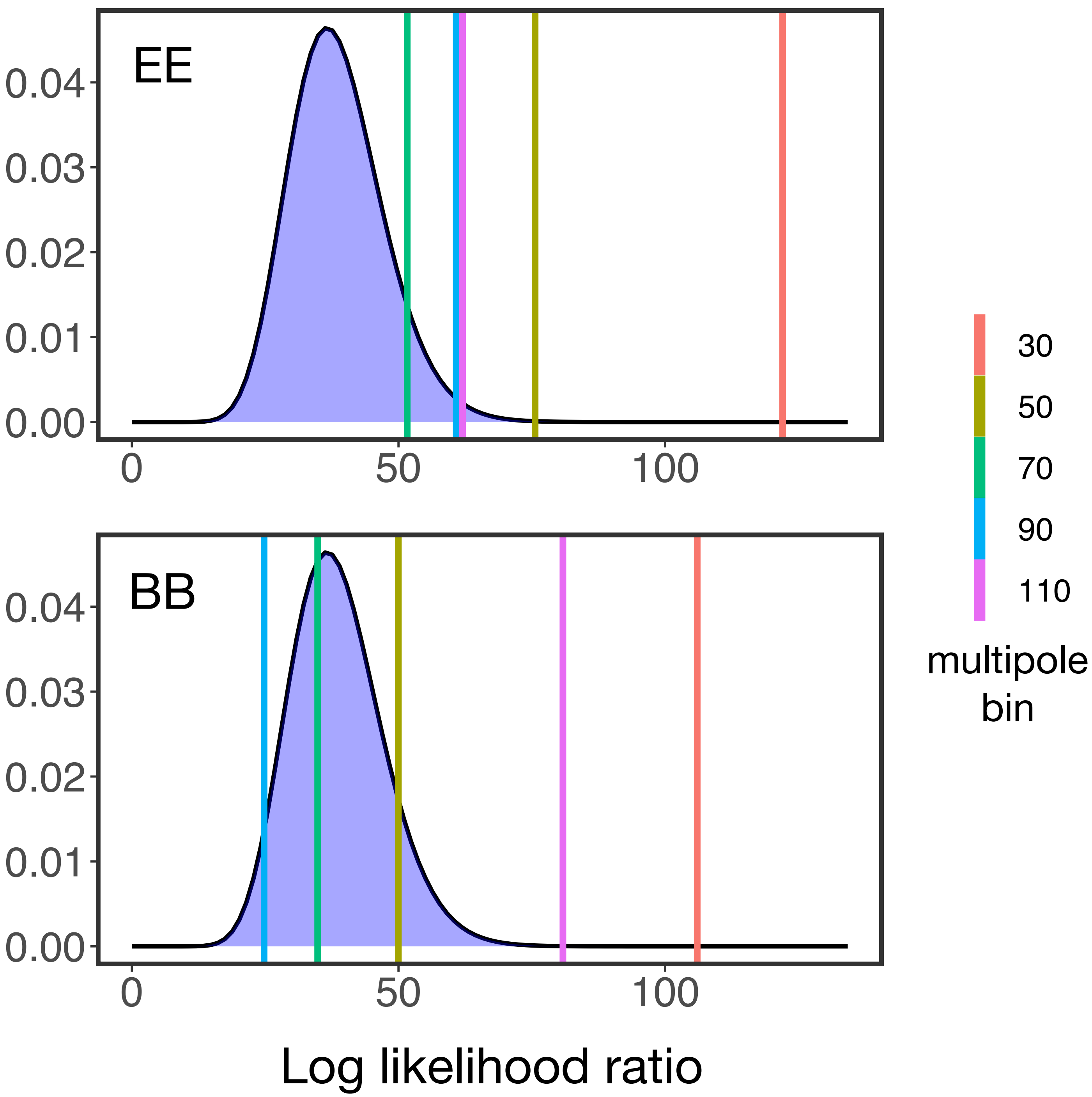


(CMB not plotted)

PRELIMINARY

Goodness of fit

Log likelihood ratio test, per bin



Using the fitted parameters and the data we can define a quantity that tends to be distributed as a **chi-squared** if the model is good enough.

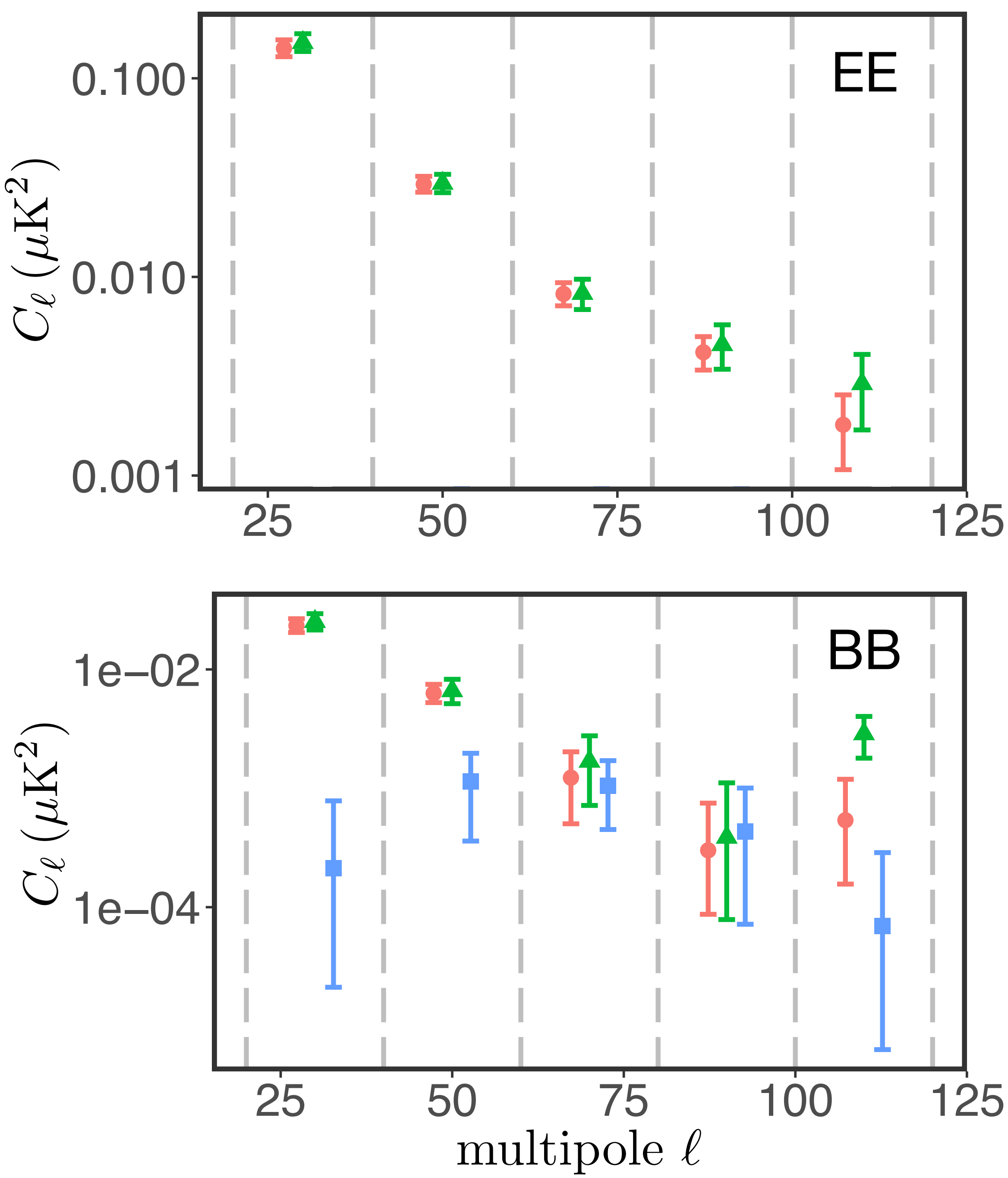
Similar to the KL divergence test used in SMICA

The model needs more complexity to explain the first bin (**red**).

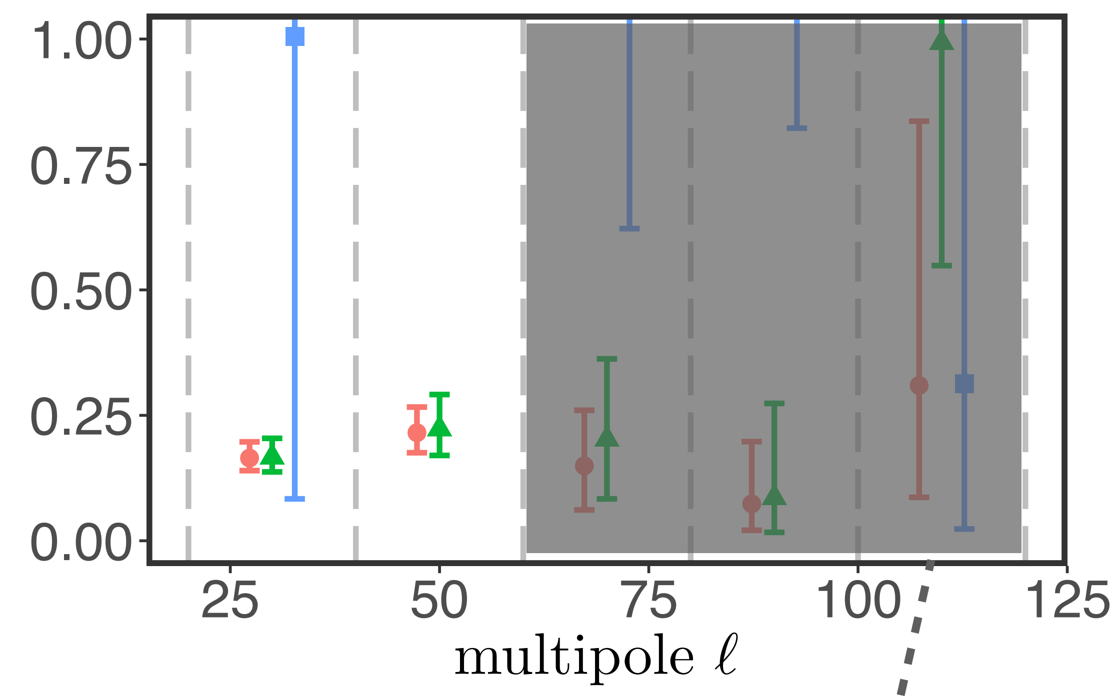
PRELIMINARY

Synchrotron polarisation power spectrum

Power spectra at 23 GHz



BB / EE ratio at 23 GHz



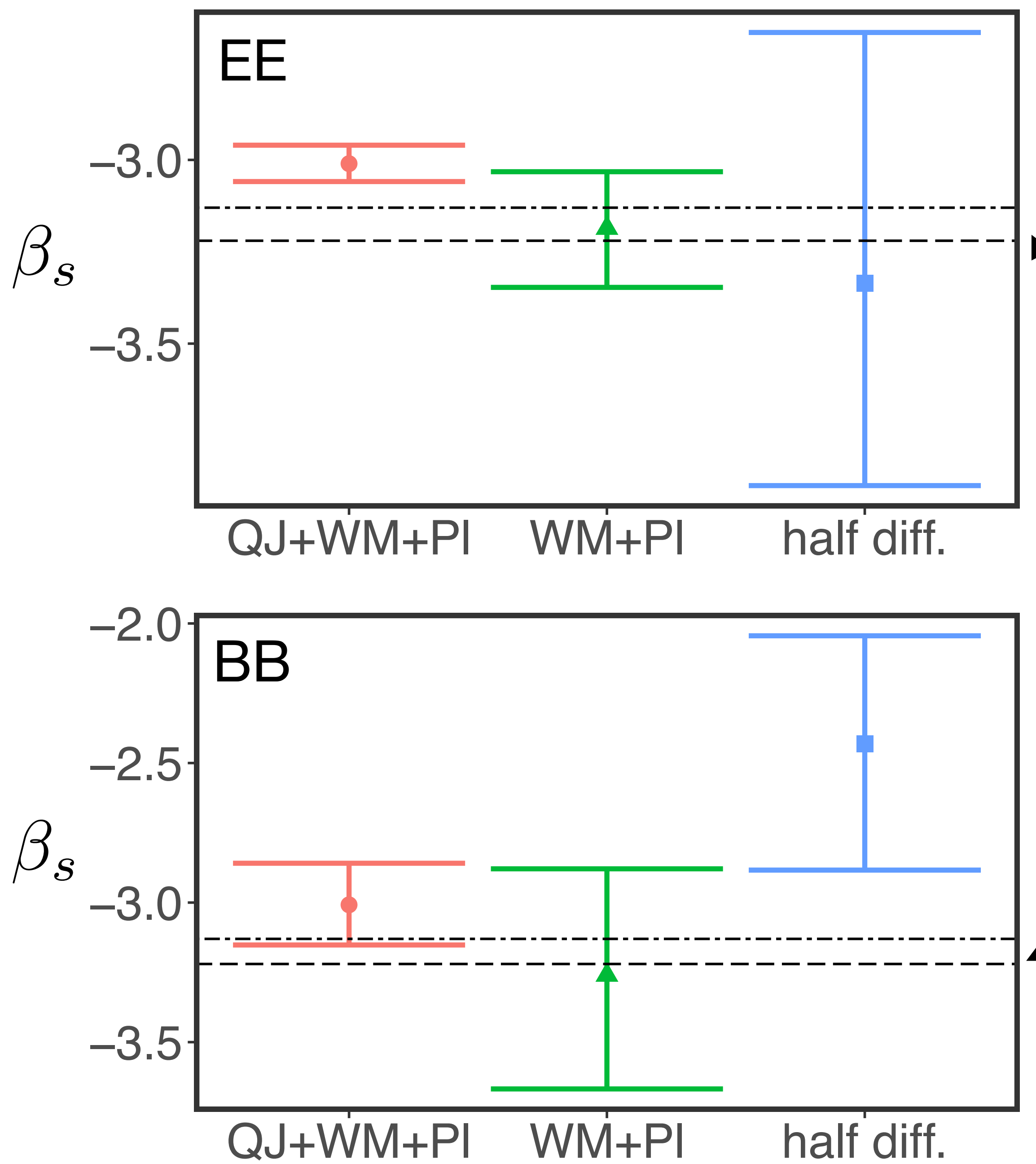
QJ+WM+PI

WM+PI

half diff.

BB spectrum not well enough detected in this multipole range

Synchrotron polarisation SED spectral index



Adding QUIJOTE frequencies leads to **error bars more than twice smaller**

β_s = -3.00 ± 0.05 (EE)

β_s = -3.01 ± 0.15 (BB)

(s1d2 model)

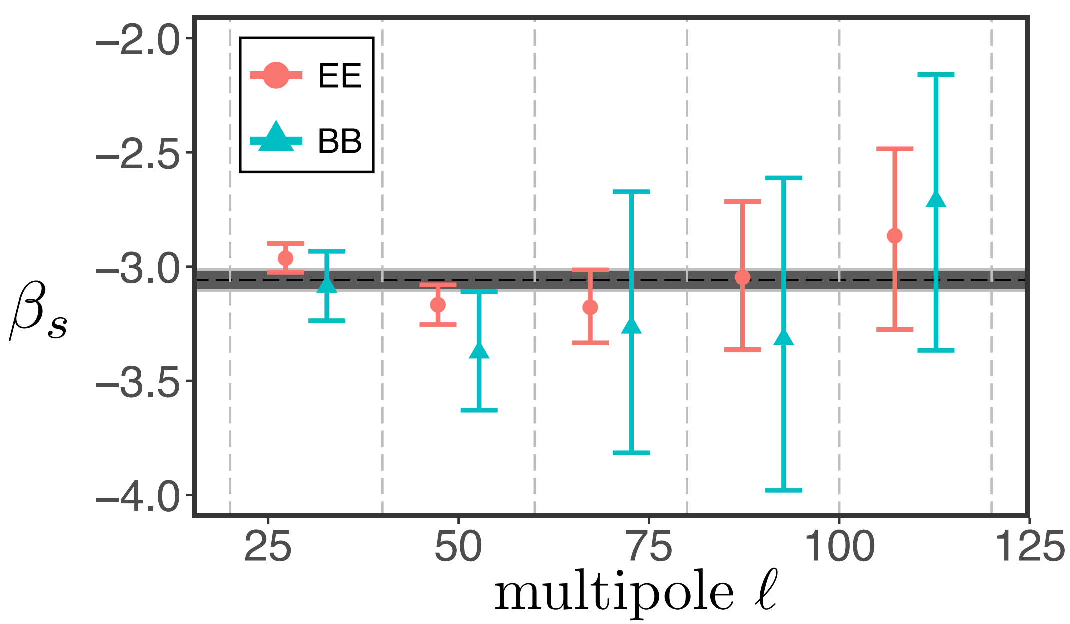
Planck: -3.13 ± 0.13

S-PASS: -3.22 ± 0.08

PRELIMINARY

Synchrotron polarisation SED spectral index

this work (smdm model), **NORTH**



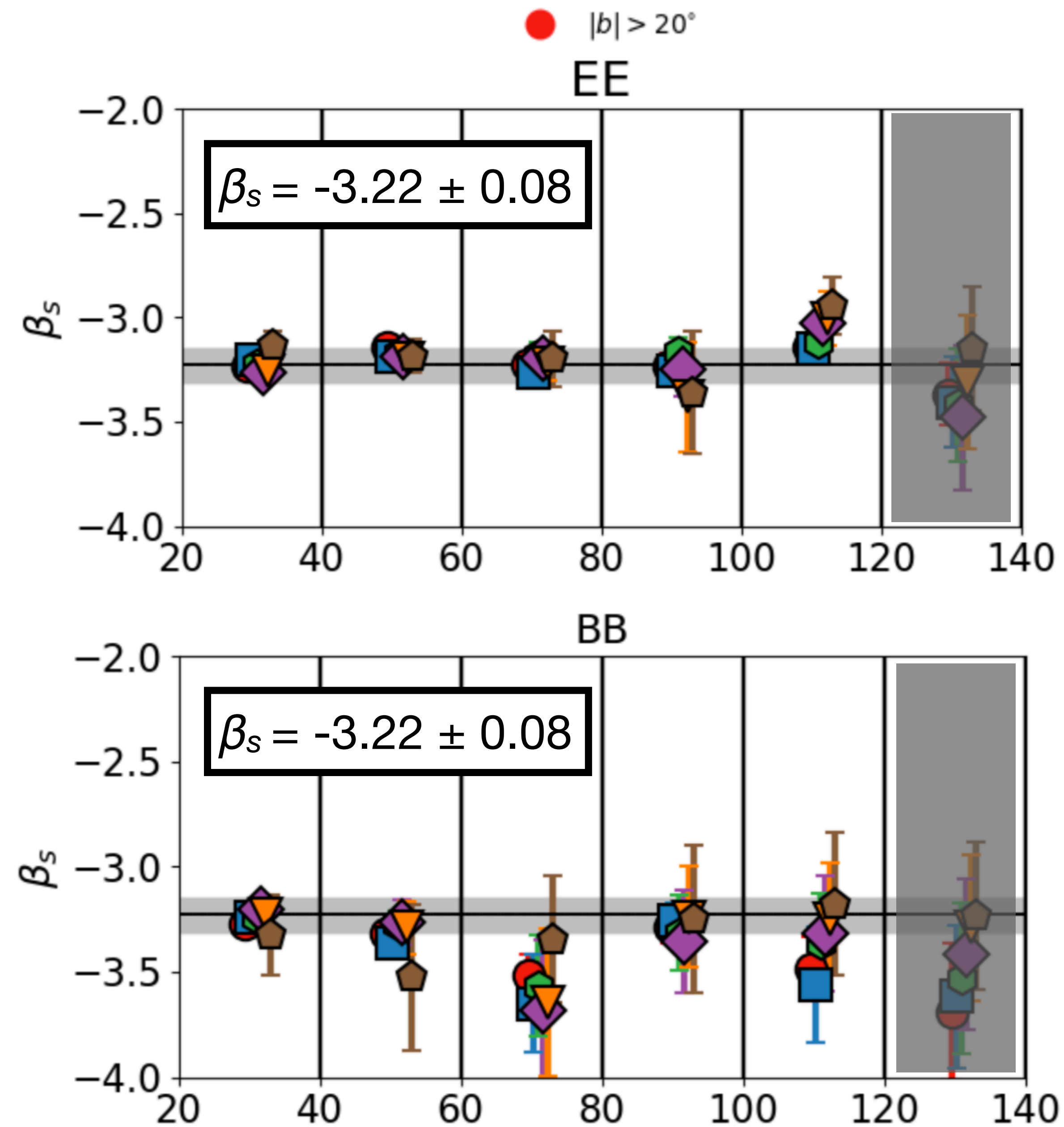
Combined values:

β_s = -3.04 ± 0.05 (EE)

β_s = -3.15 ± 0.13 (BB)

β_s = -3.06 ± 0.04 (EE+BB)

S-PASS results, **SOUTH**



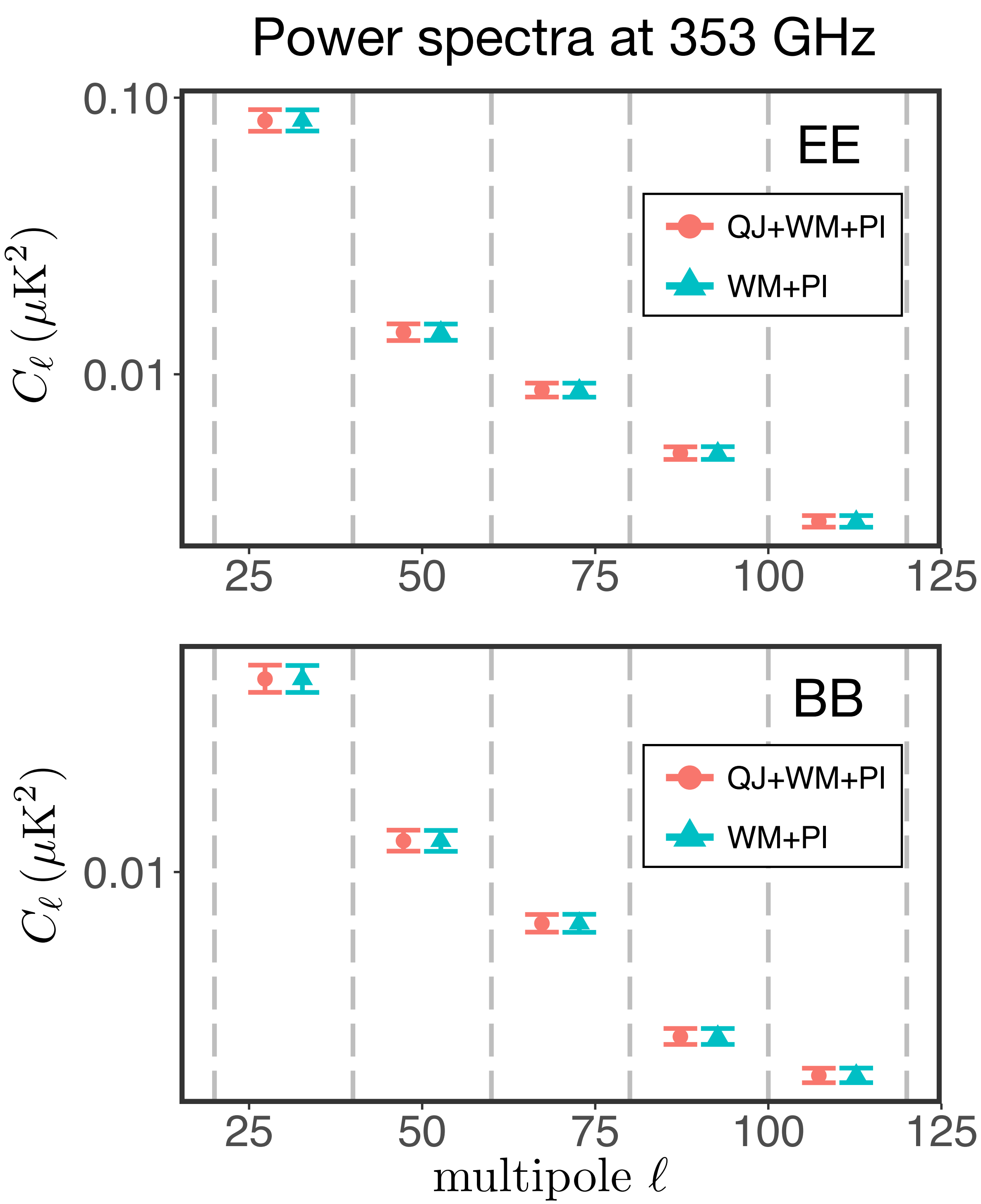
Each analysis done on a different sky region

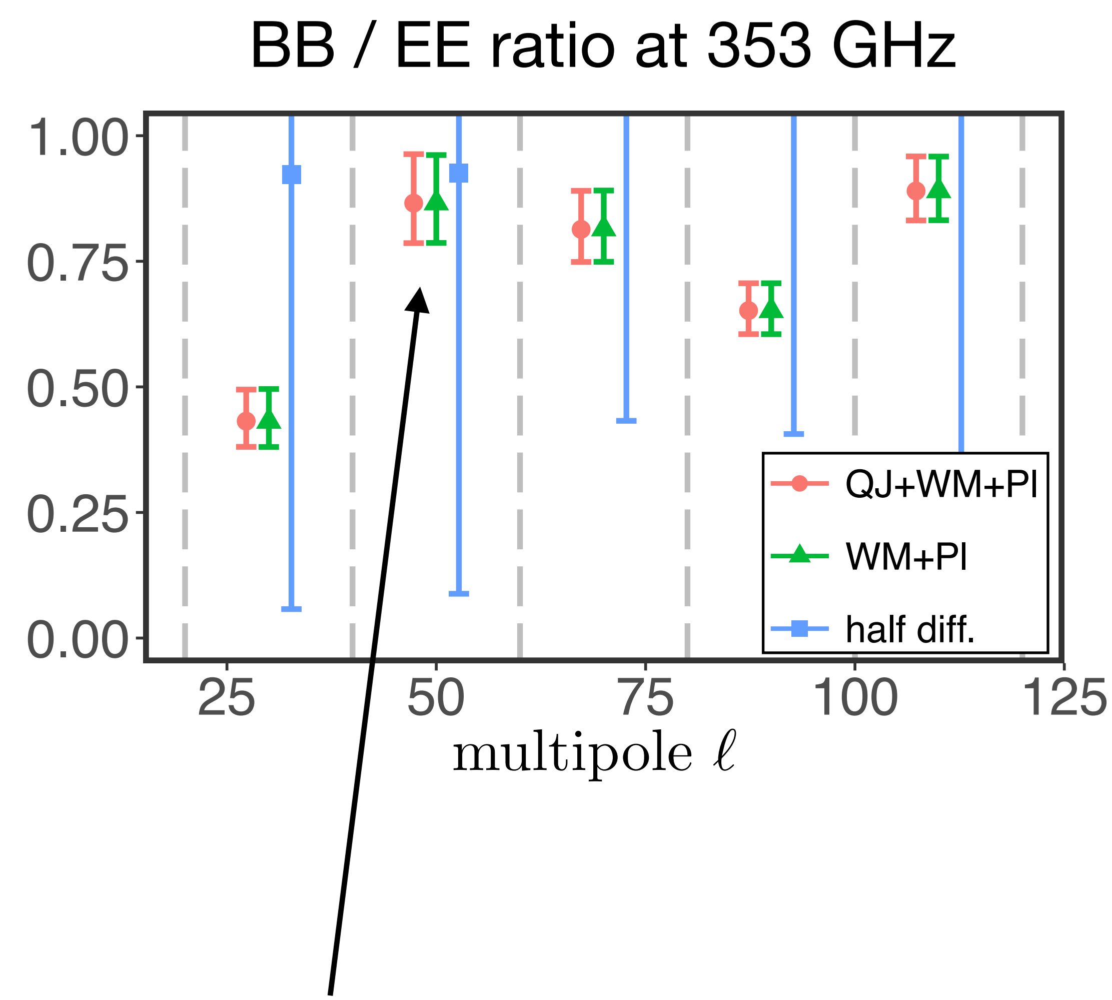
—> Variability of β_s over the sky

Planck results, **NORTH and SOUTH**

β_s = -3.13 ± 0.13

Dust polarisation power spectrum





Not around .5 but we checked by directly computing the ratio of raw Planck 353 GHz spectra on the region of analysis, and got the same values

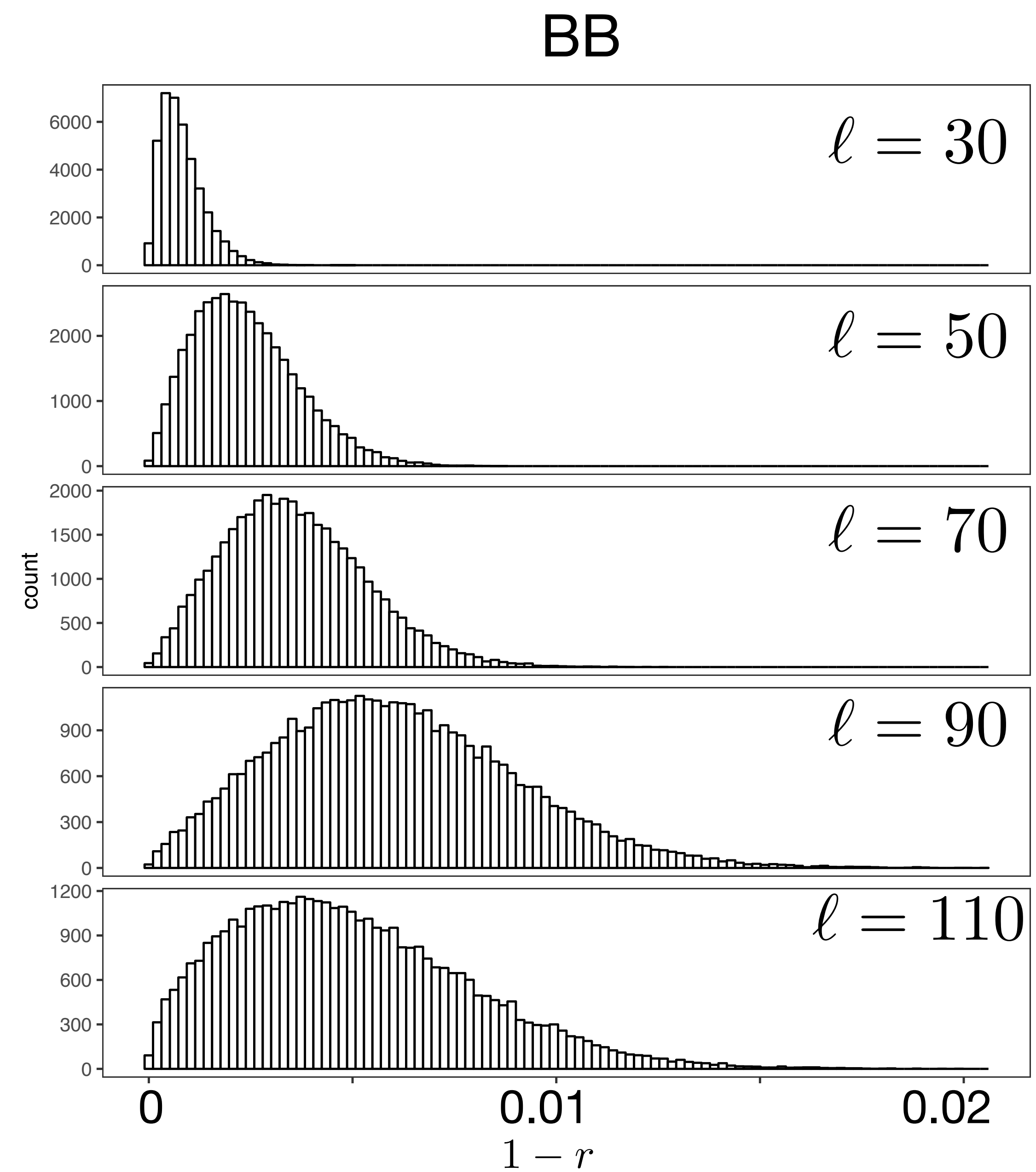
PRELIMINARY

Dust decorrelation distribution

Since the dust has 2 components, it has not exactly the same spatial distribution from one frequency to another

$$r = \frac{C_\ell^{217\times353}}{\sqrt{C_\ell^{217\times217}C_\ell^{353\times353}}}$$

Less than 1 % decorrelation of dust B-modes between Planck 217 and 353 GHz

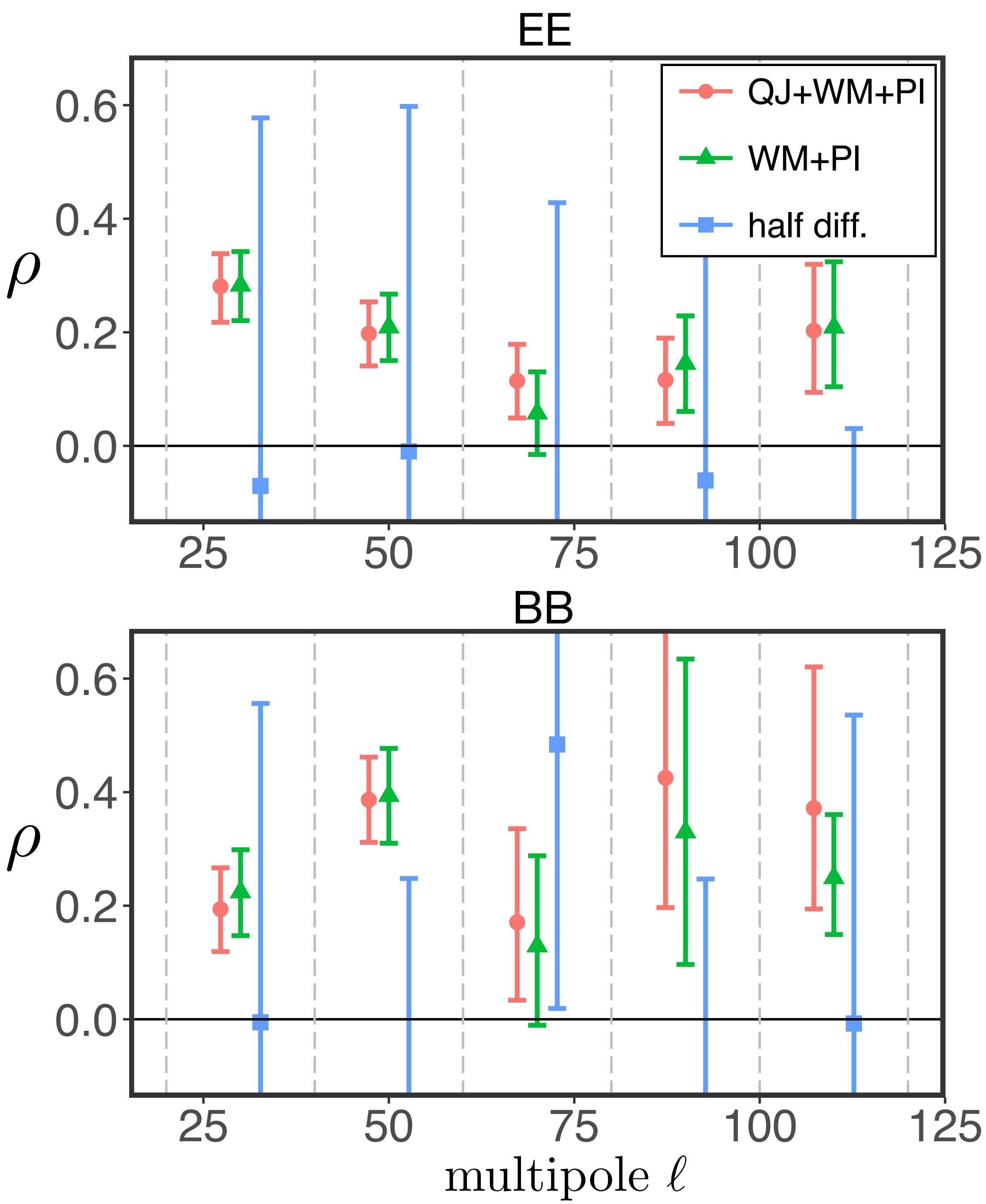


again: **may not be valid in the general case**

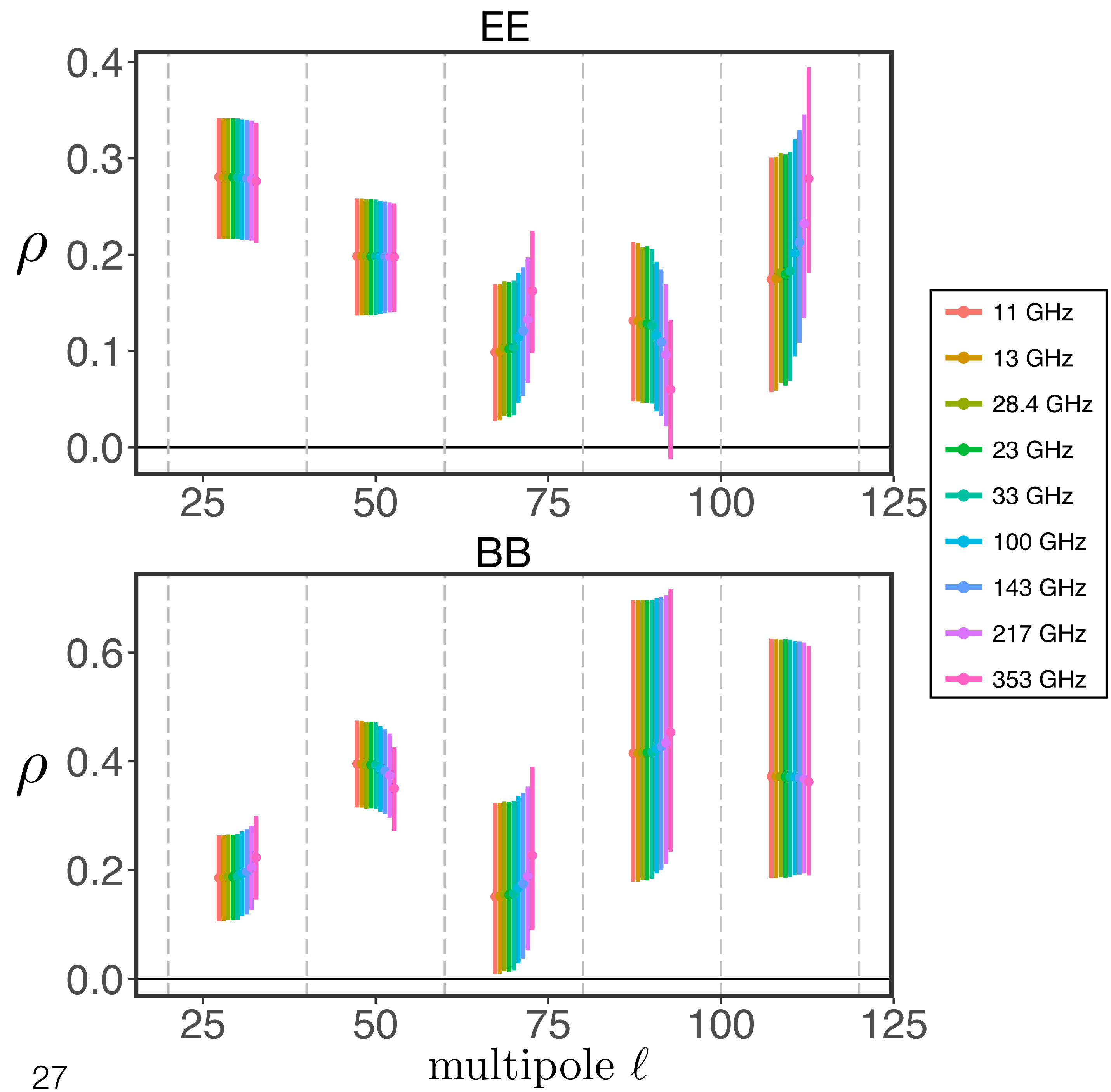
PRELIMINARY

Dust-Synchrotron correlation

Correlation at 100 GHz



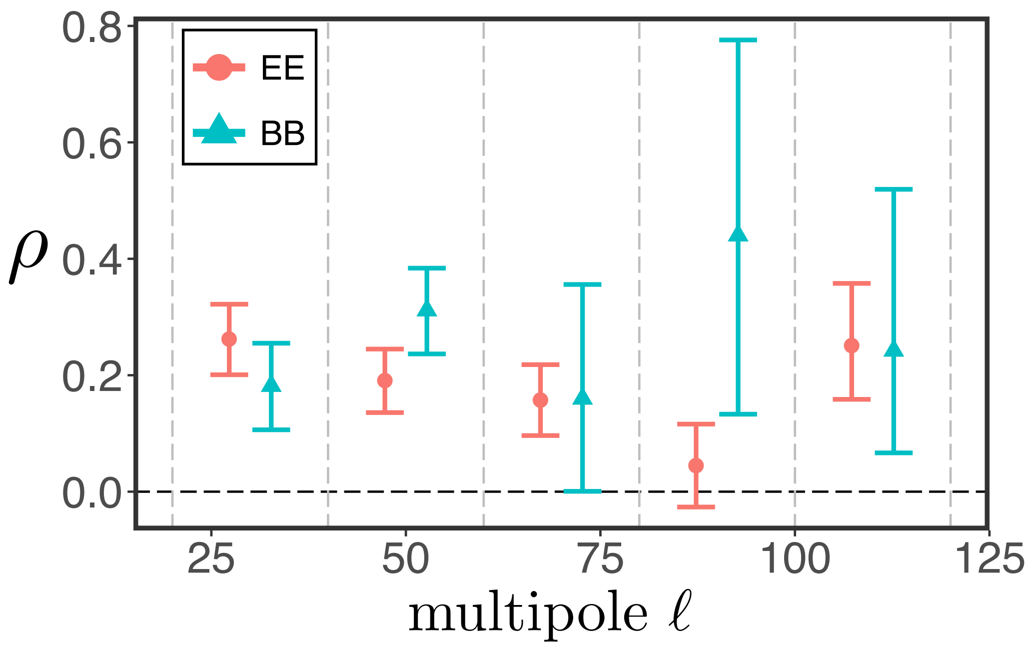
The correlation varies across frequencies



PRELIMINARY

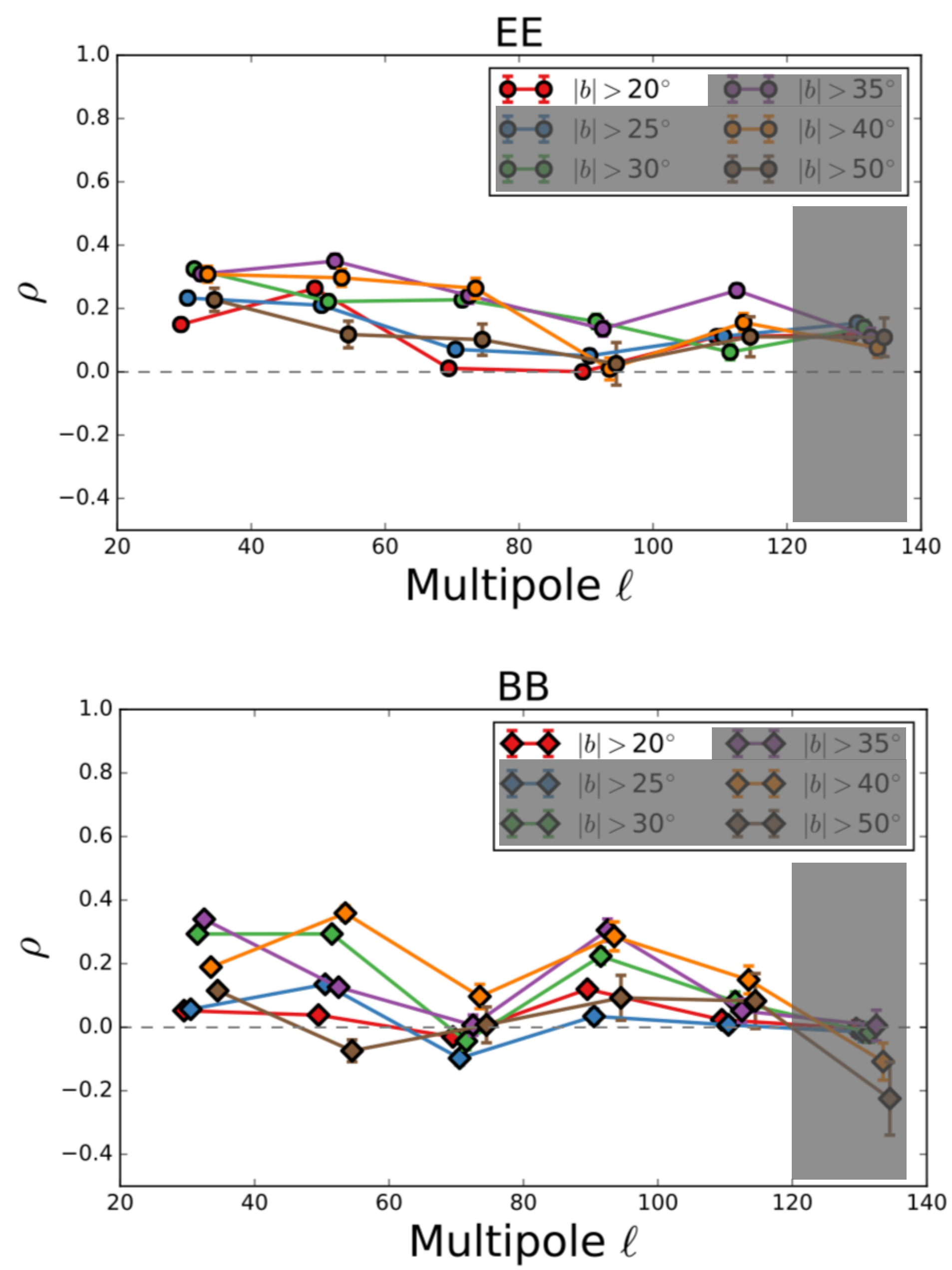
Dust-Synchrotron correlation

<u>this work (smdm model)</u>

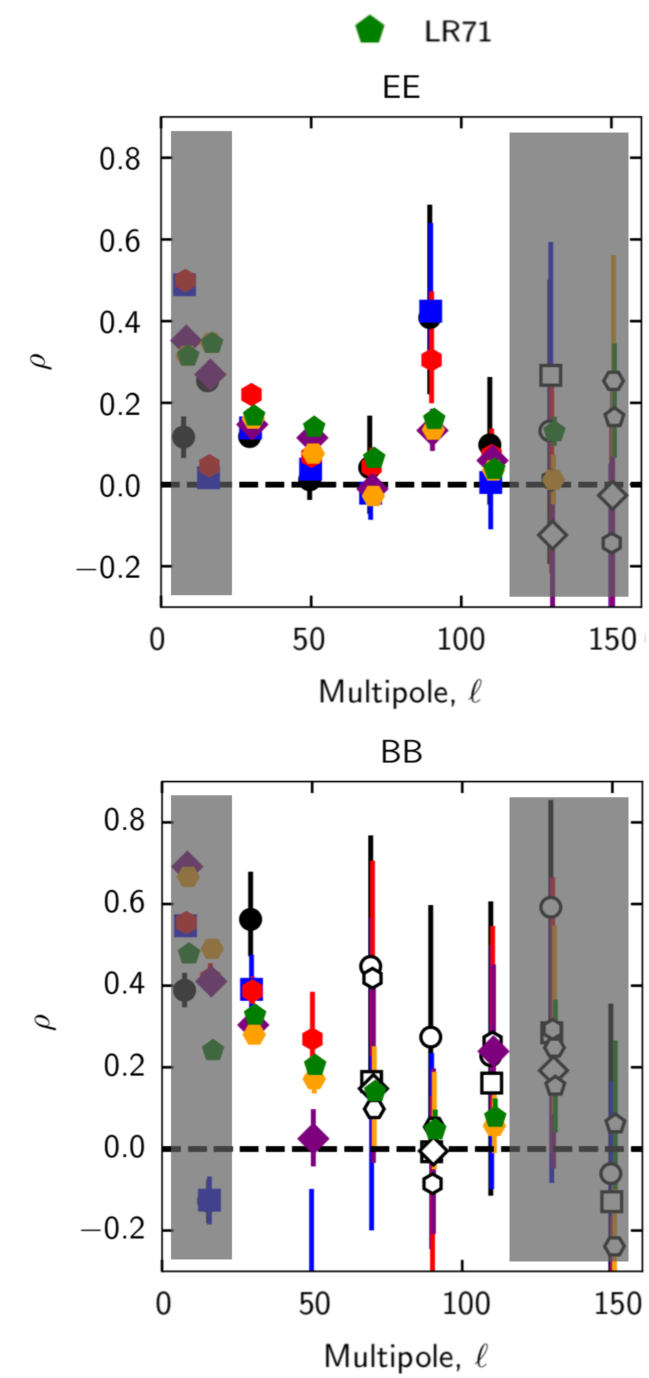


Each analysis done on a different sky region
—> Variability of ρ over the sky

<u>S-PASS results</u>



<u>Planck results</u>

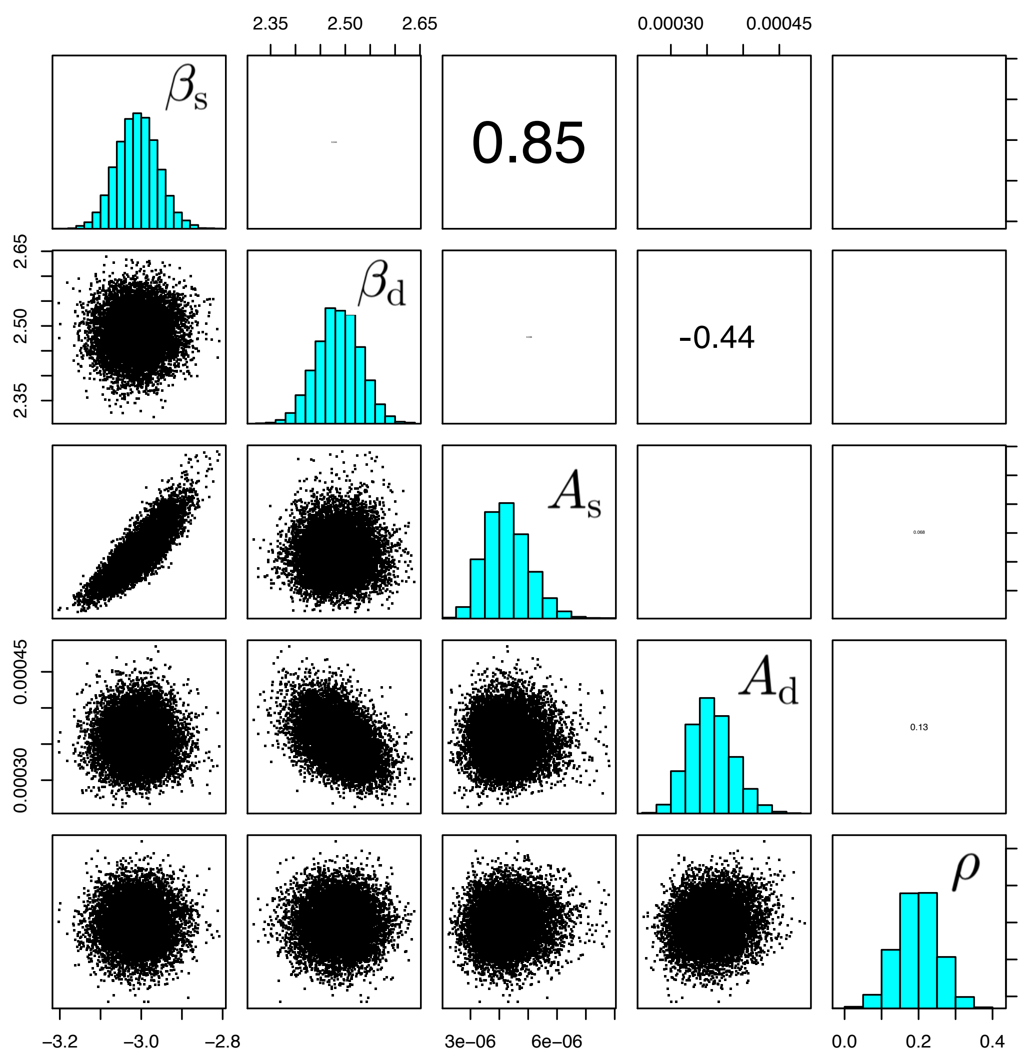


PRELIMINARY

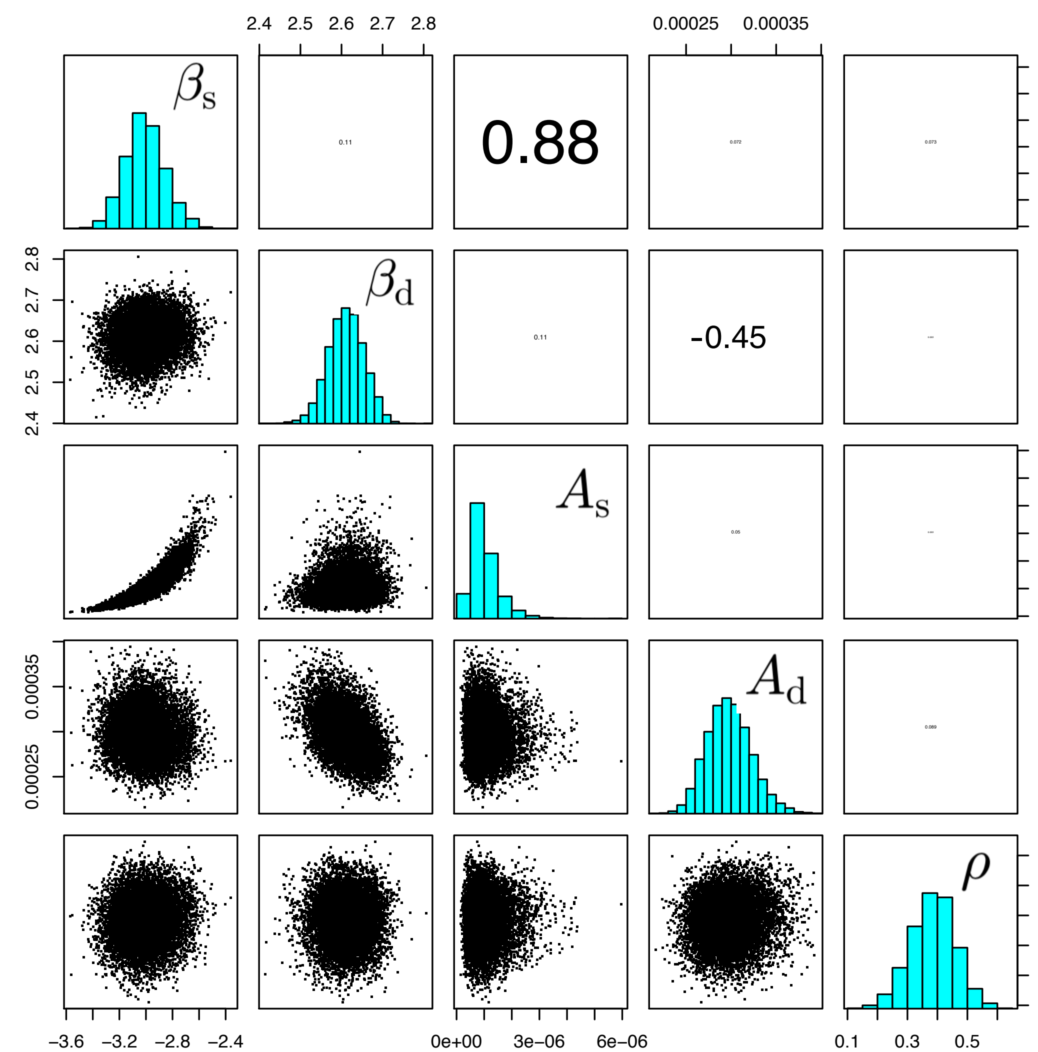
Parameter space

2nd bin (ell=50), 100 GHz

EE



BB



β_s = -3.00 ± 0.05

β_d = 2.48 ± 0.04

ρ = 0.20 ± 0.06

unusual value of β_d because of the unusual 2-compo model. In the end what's important is the resulting dust at each frequency.

β_s = -3.01 ± 0.15

β_d = 2.61 ± 0.04

ρ = 0.39 ± 0.07

Conclusion

- Synchrotron index well constrained using QUIJOTE frequencies

β_s = -3.00 ± 0.05

- Significant variation of synchrotron index not detected at the power spectrum level in this analysis alone

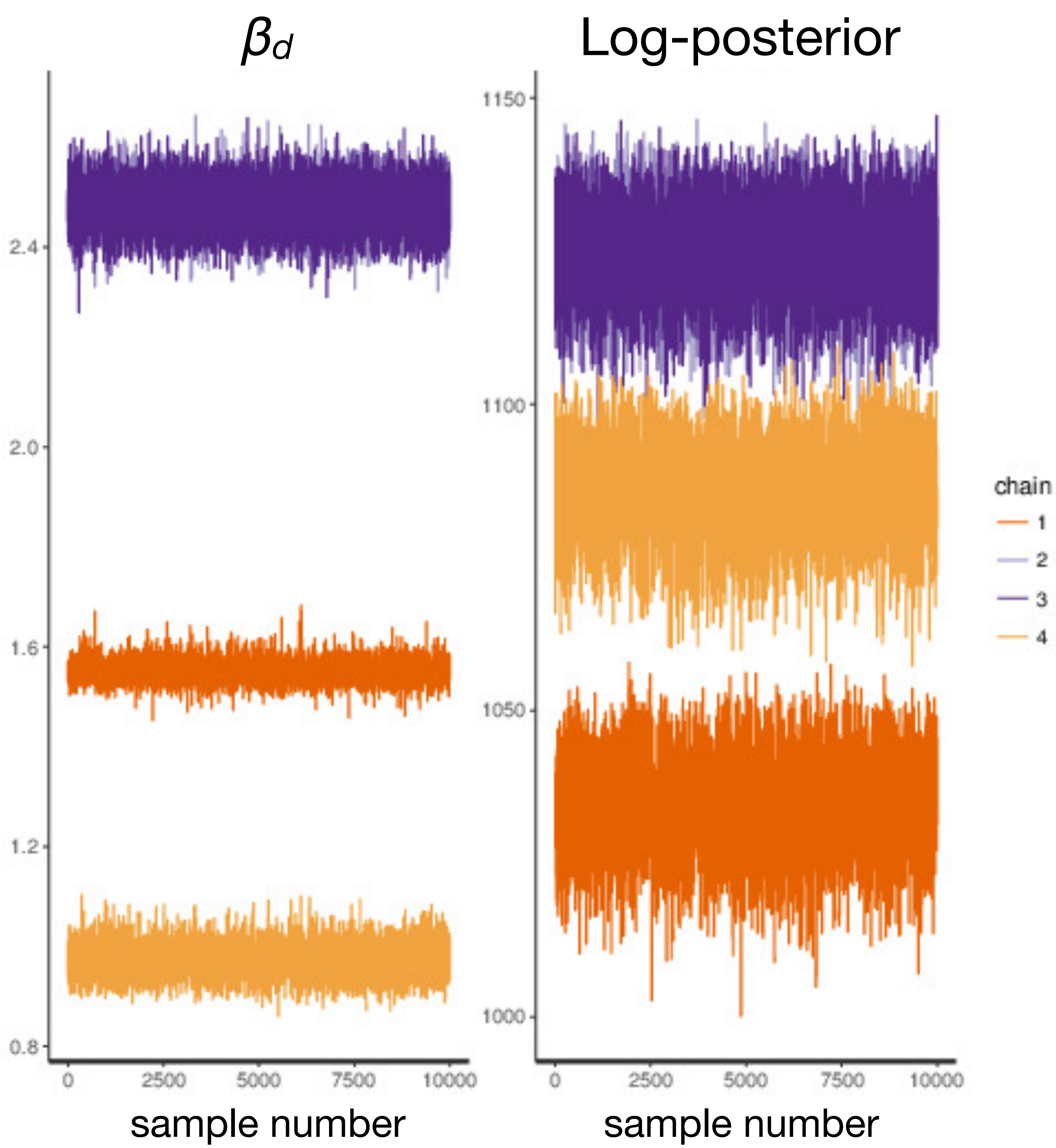
but

- Large scale variability of synchrotron index and dust-synchrotron correlation confirmed when comparing with previous results

Thank you for your attention

Back up

Multimodal posterior

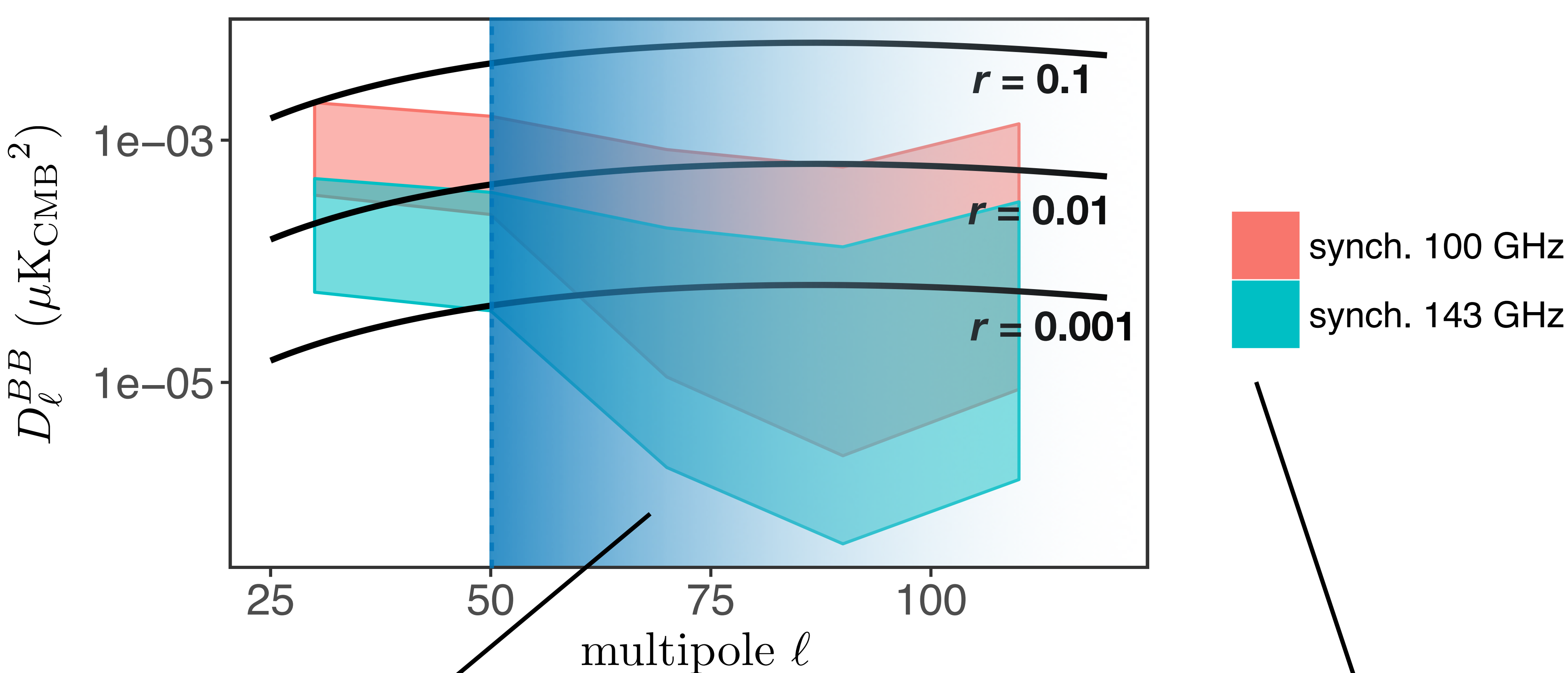


For models with **2-compo dust**, usual β_d of **1.55 does not lead to maximum posterior**, even with a prior centred around that value.

PRELIMINARY

Application to CMB B-modes study: Synchrotron vs. CMB B-modes power

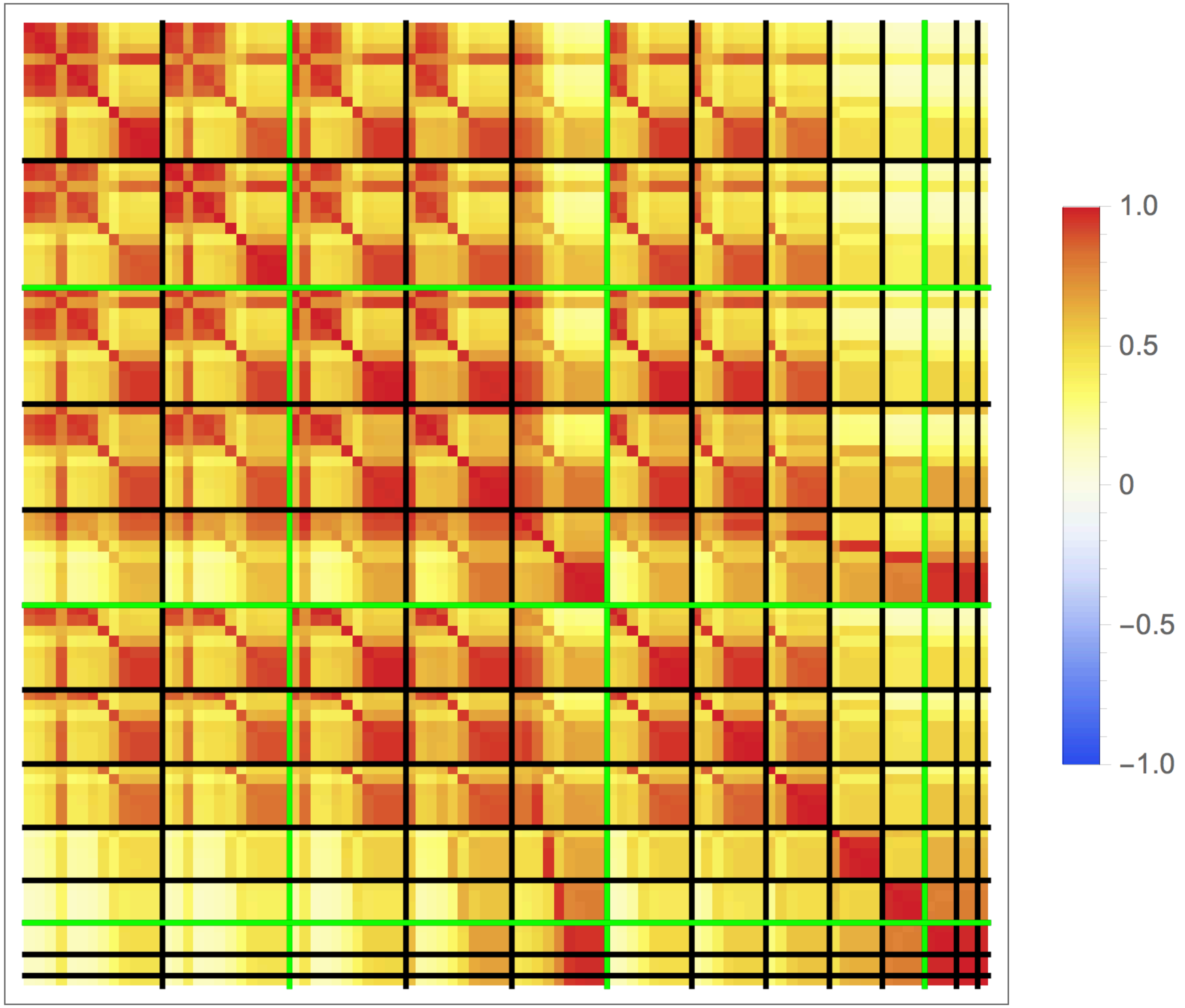
B-modes power at 100 and 143 GHz



range where synchrotron BB spectrum is poorly estimated
—> Do not trust

95 % confidence region from the analysis

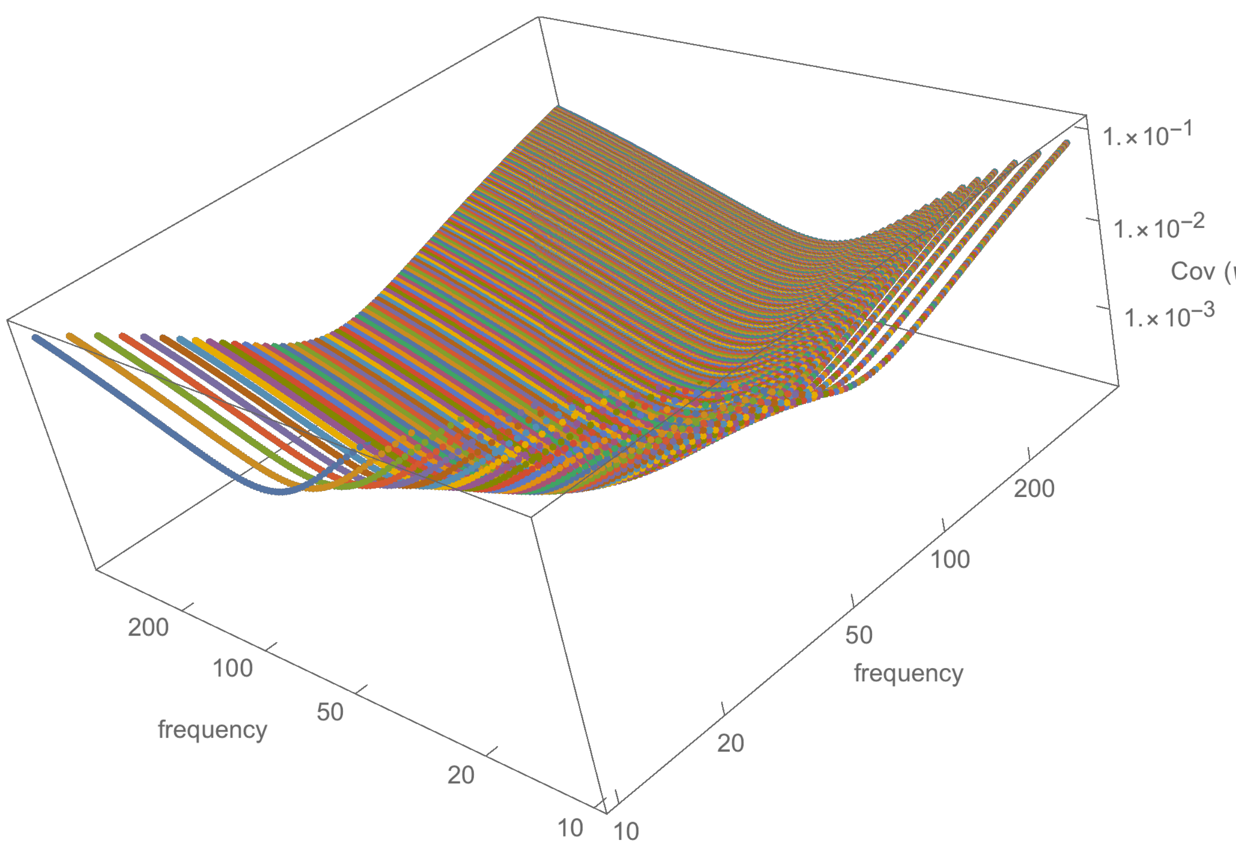
Exemple of correlation structure between the cross spectra

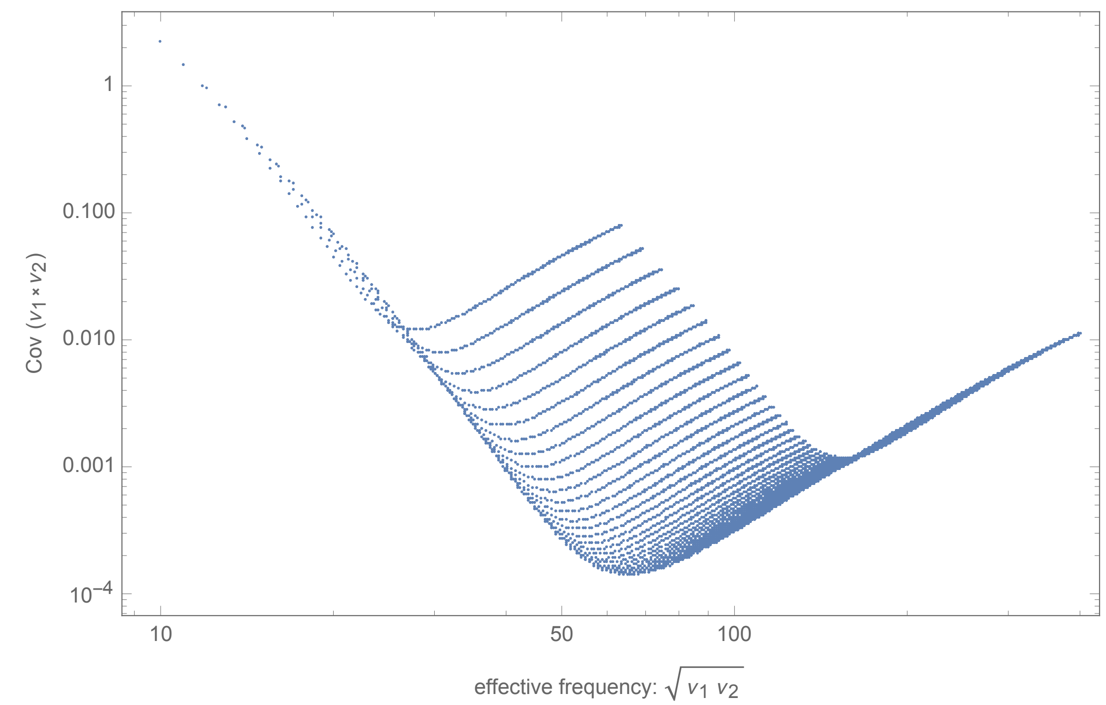


Cross-spectra on a 2D plot

$$S_\ell^{i\times j} = A_s \mathrm{SED}_s(\nu_i)\mathrm{SED}_s(\nu_j) + A_d \mathrm{SED}_d(\nu_i)\mathrm{SED}_d(\nu_j) + r\sqrt{A_s A_d}\left(\mathrm{SED}_s(\nu_j)\mathrm{SED}_d(\nu_i) + \mathrm{SED}_s(\nu_i)\mathrm{SED}_d(\nu_j)\right)$$

r = 0.5, β_s = -3, β_c = -1, β_d = 1.6

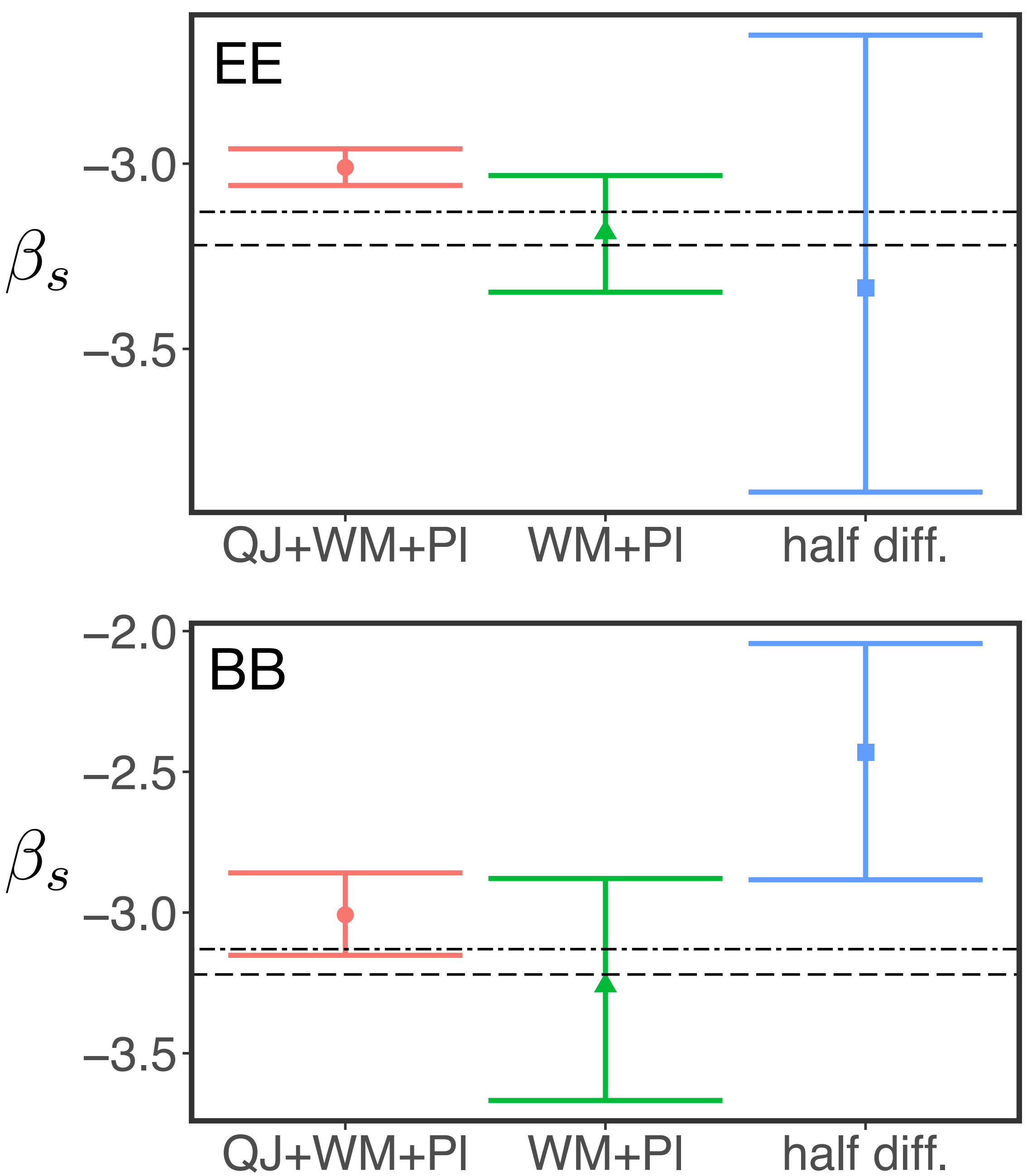




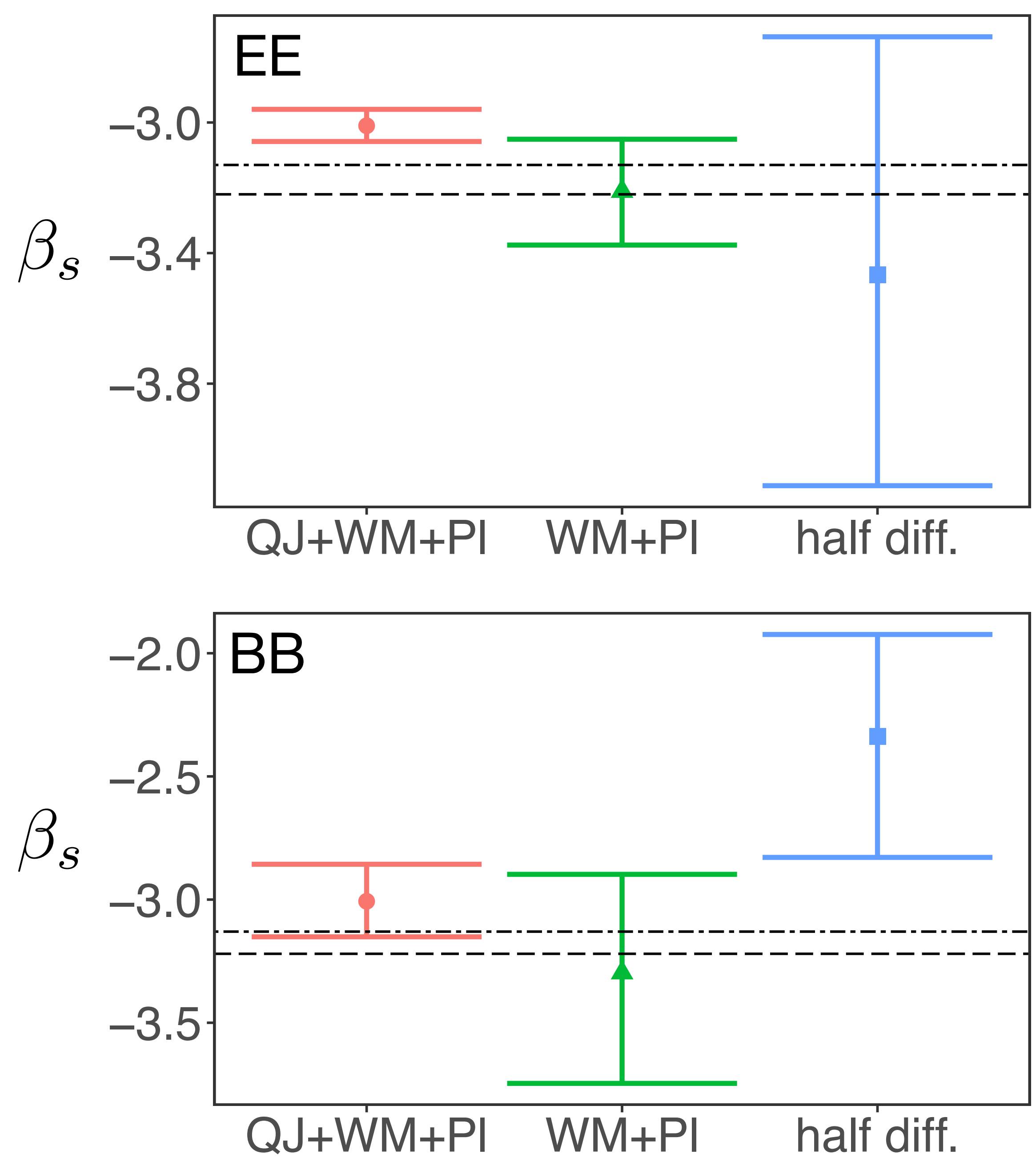
PRELIMINARY

Relaxing the prior on beta synchrotron

β_s ~ N(μ=-3, **σ=1**)



β_s ~ N(μ=-3, **σ=5**)

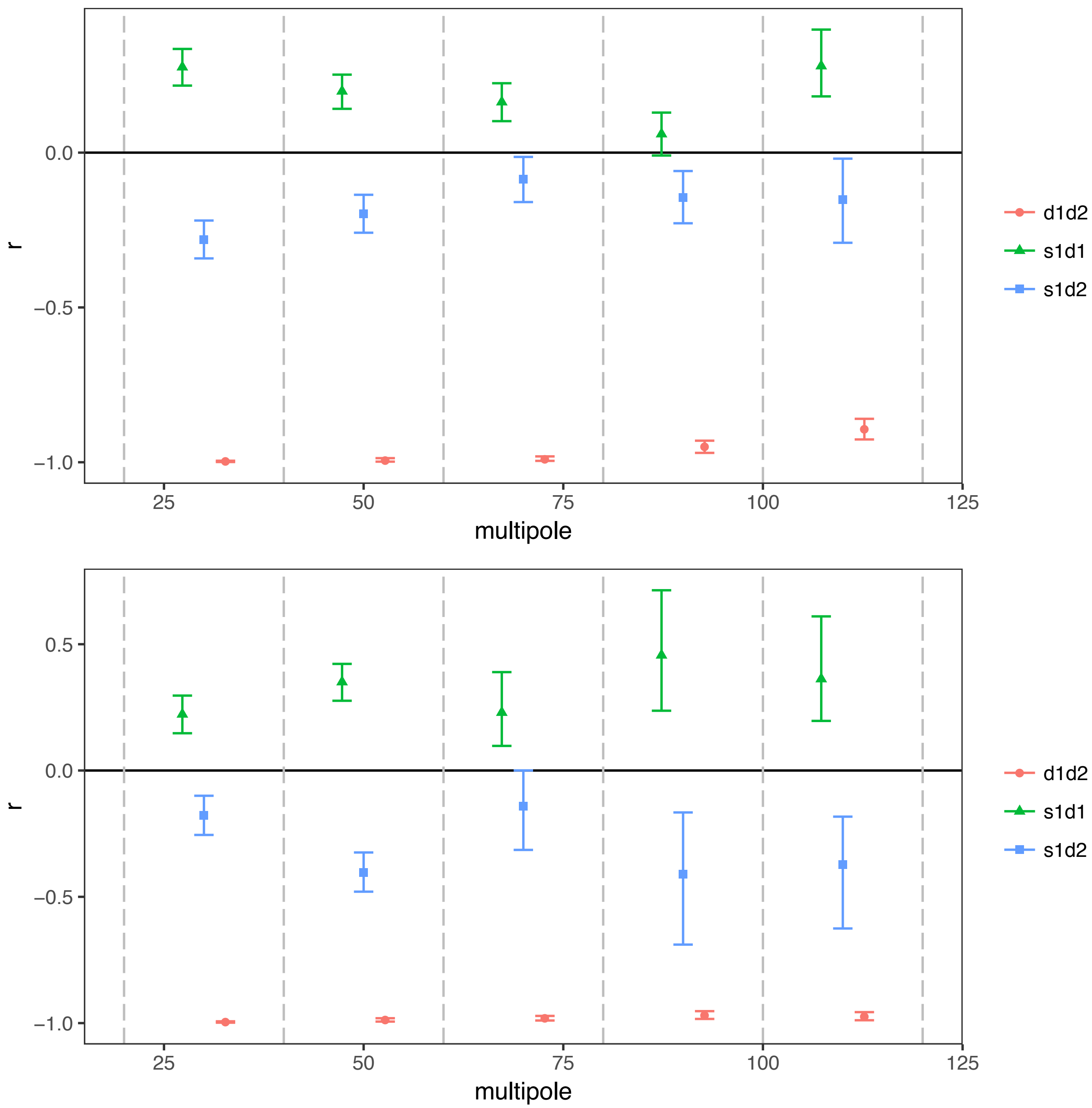


Number of parameters of the different models

Model	description	Number of parameters for 5 bins
s1d1	1-component Synchrotron + 1-component Dust	17
s1d2	1-component Synchrotron + 2-component Dust	32
s2d1	2-component Synchrotron + 1-component Dust	32
s2d2	2-component Synchrotron + 2-component Dust	52
smd1	β_s not fixed + β_d fixed	21
s1dm	β_s fixed + β_d not fixed	21
smdm	β_s not fixed + β_d not fixed	25

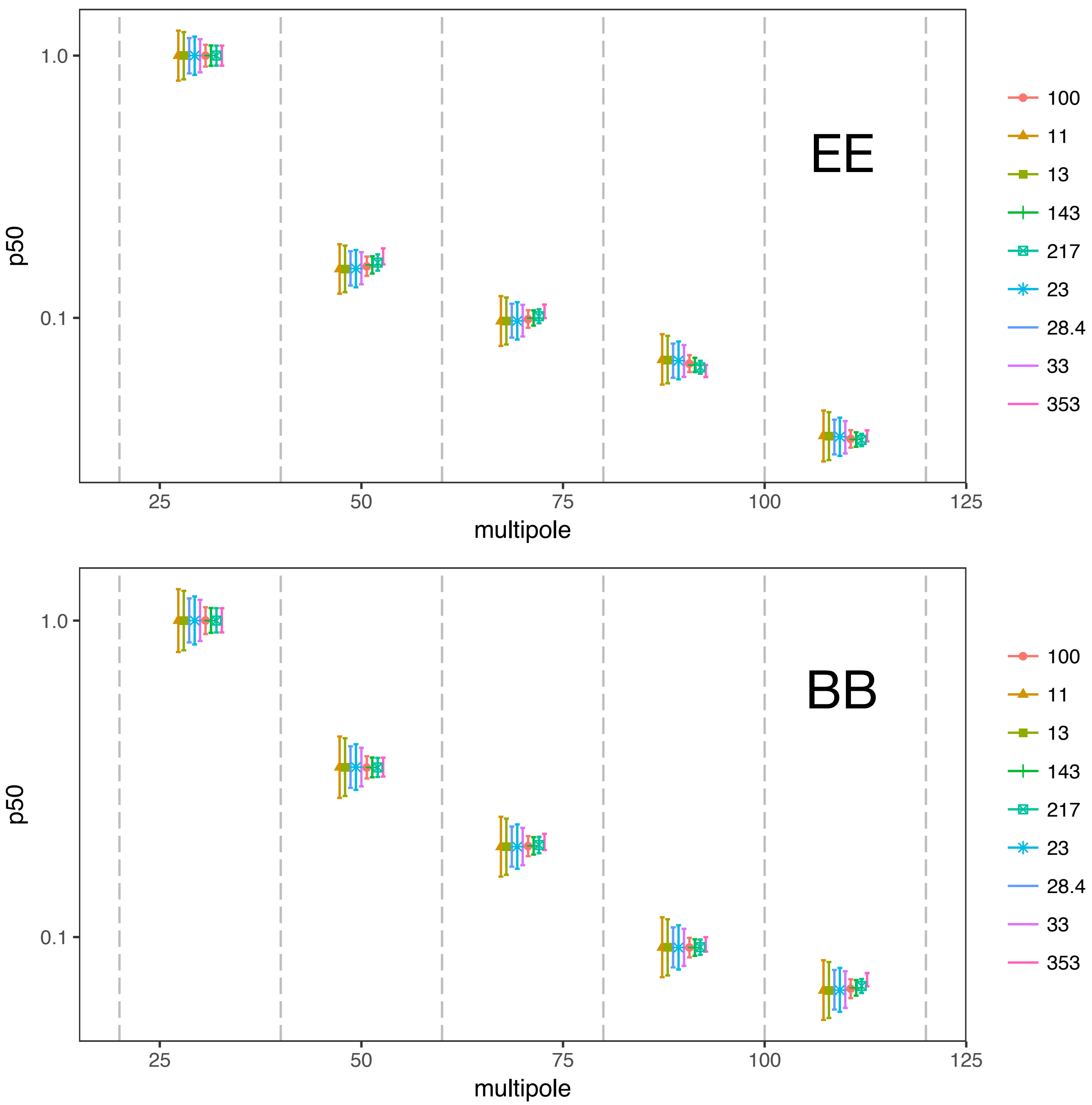
PRELIMINARY

correlations between synchrotron and sub-components of dust



The 2 dust components (red) are strongly correlated because the total dust is rather coherent through frequencies

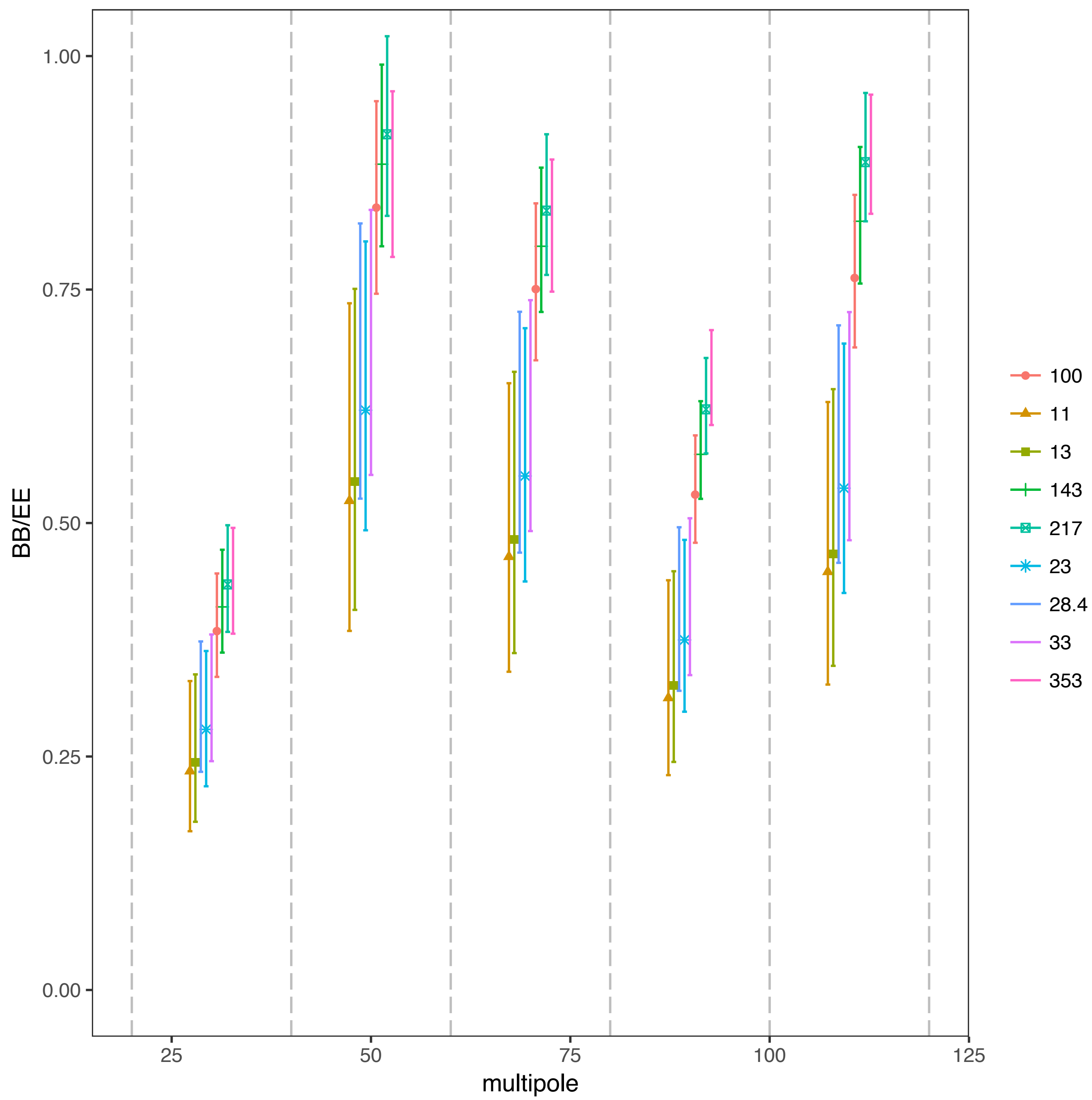
relative dust spectra over frequency range



Shape of the dust polarisation spectra at each frequency.

Almost the same shape at all frequencies

dust BB/EE ratio over frequency range



Ratio changes because sed is note the same for EE and BB

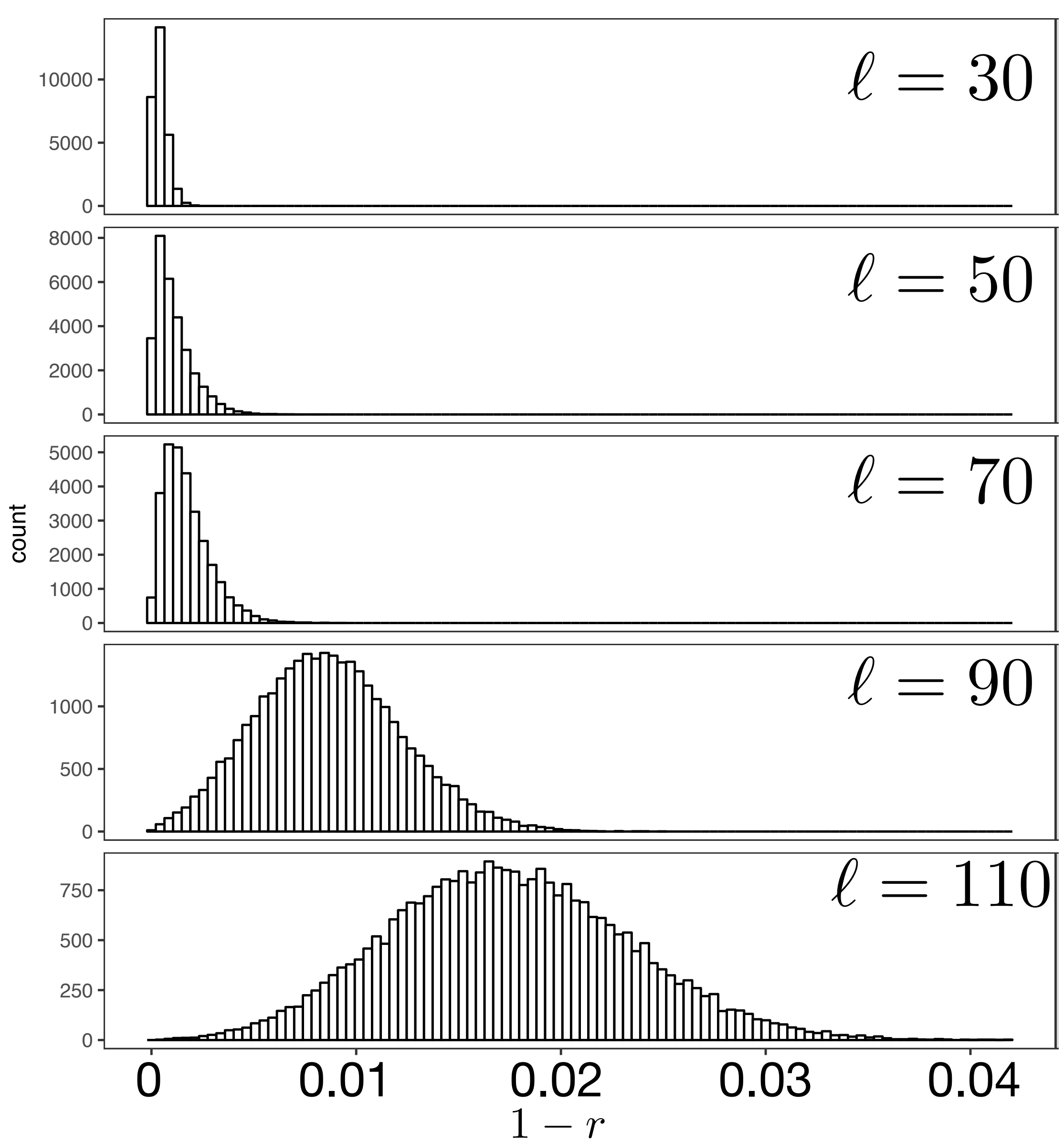
PRELIMINARY

Dust decorrelation distribution

Since the dust has 2 components, it has not exactly the same spatial distribution from one frequency to another

$$r = \frac{C_\ell^{217\times353}}{\sqrt{C_\ell^{217\times217} C_\ell^{353\times353}}}$$

EE



BB