Planck intermediate results. LIV. Polarized dust foregrounds

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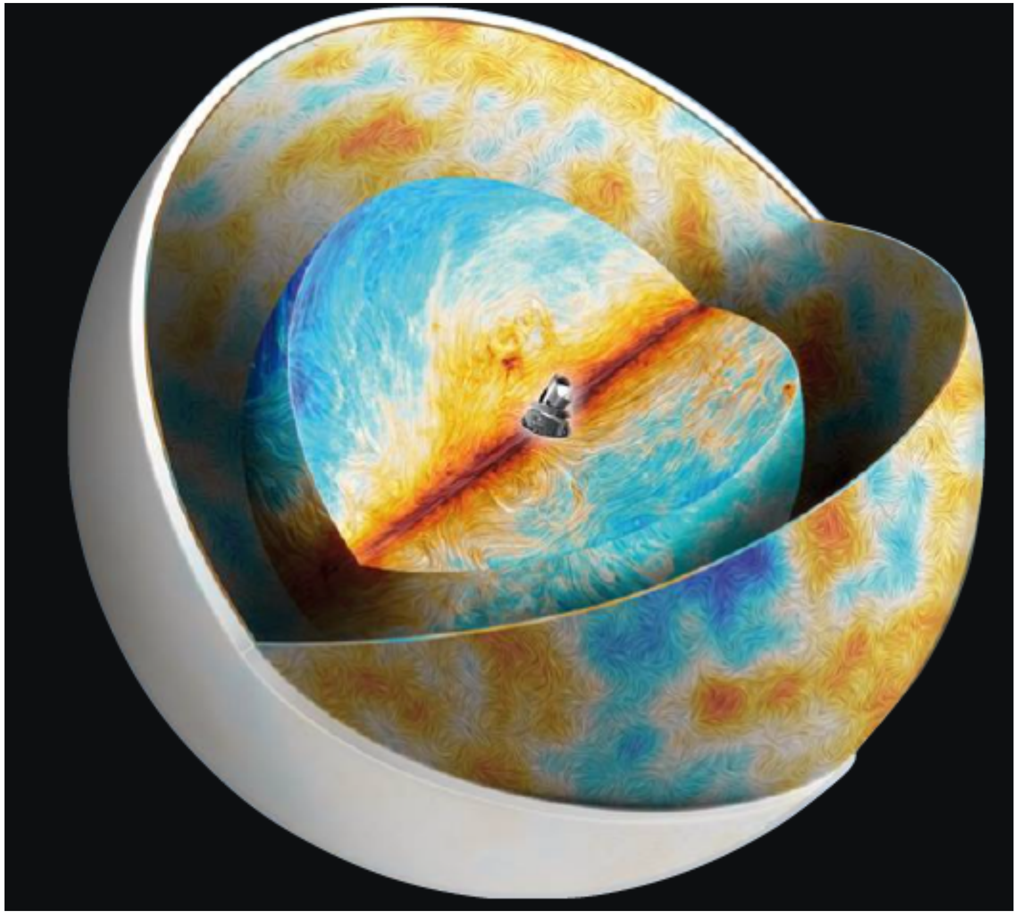
on behalf of the Planck Collaboration



Polarized Galactic and CMB skies

Motivation

Statistical and frequency characterization of polarized foregrounds using the latest Planck maps

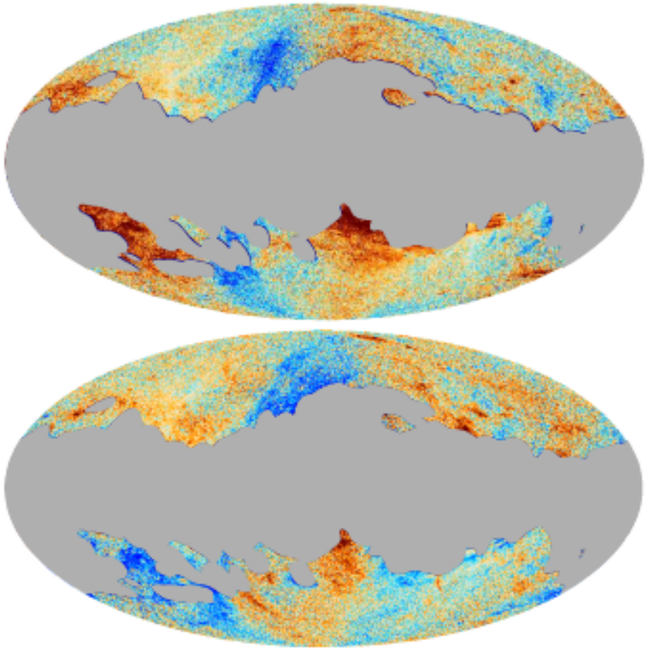
- Dust power spectra down to the lowest multipoles (follow-up of Planck Inter. XXX)

- Spectral energy distribution of Galactic polarized foregrounds (follow-up of Planck Inter. XXII)

- Frequency correlation of dust polarization maps (follow-up of Planck Inter. L)

➡ Data inputs for astrophysical and statistical modelling of polarized foregrounds to optimize component separation and assess uncertainties

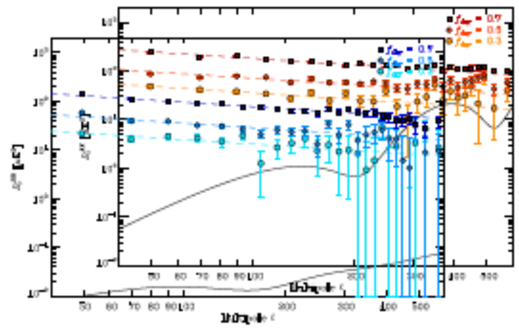
Methodology



Q and U maps at 353 GHz

XPOL
pseudo-C_ℓ estimator
based on **XSPECT**
[Tristram et al. 2005]

Corrects for incomplete sky coverage, pixel and beam window functions



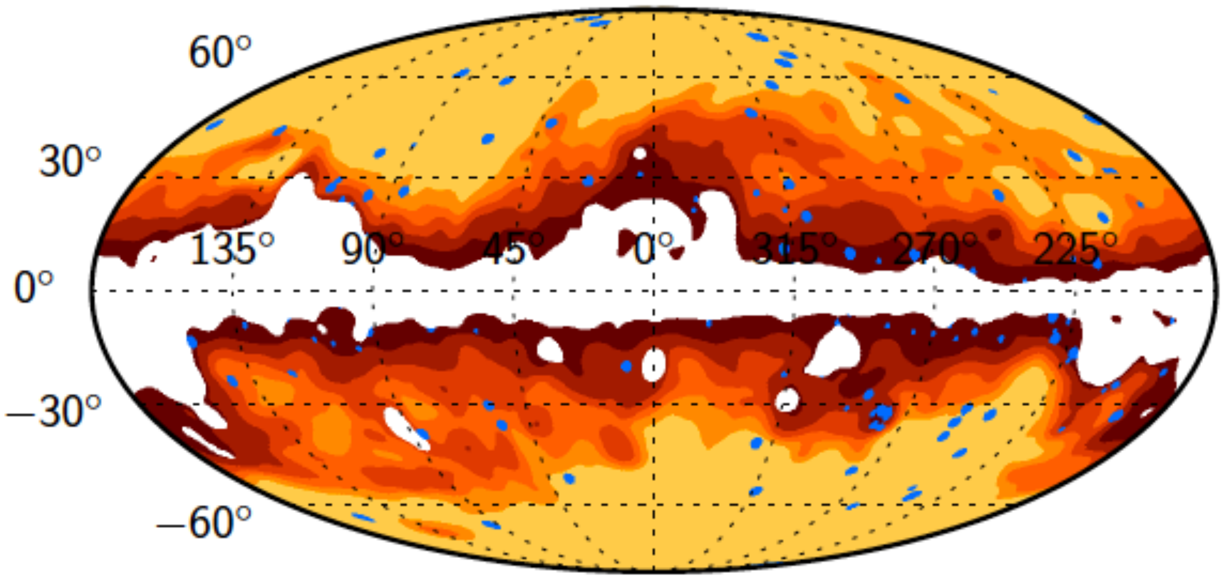
Angular power spectra

- Data analysis performed in harmonics space, within multipole bins, using cross spectra of polarization Planck (HFI & 30 GHz LFI) and WMAP (23 & 33 GHz) data. Spectra at a given frequency are computed from *independent* data subsets.
- CMB subtracted in power spectra using the Planck-2015 ΛCDM model
- Uncertainties from end-to-end (E2E) simulations include data noise and residual systematics

Sky regions

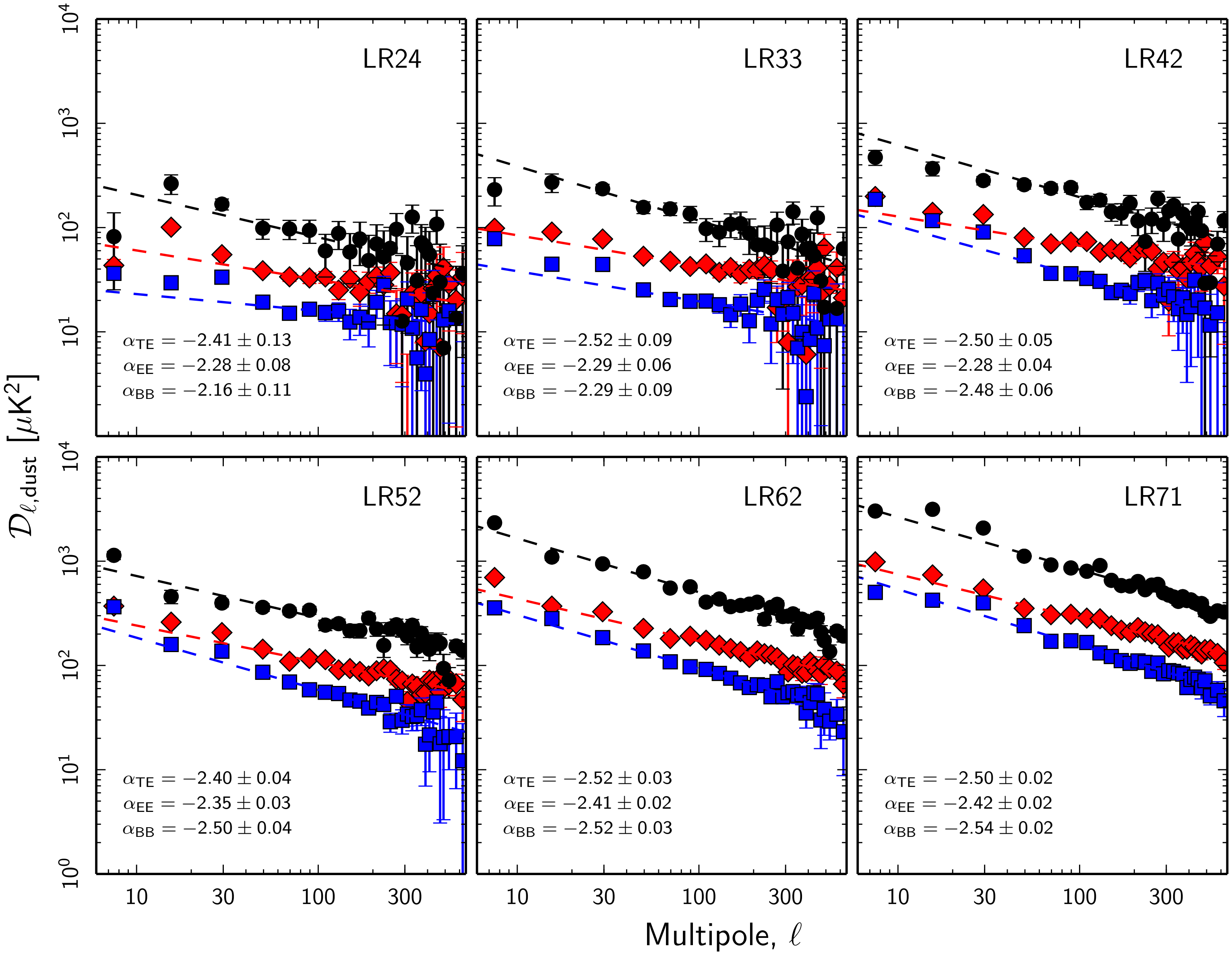
- Maks built from the smoothed (10°) dust intensity map at 857 GHz
- CO emitting regions and polarized point sources are masked
- Apodization (5°)

➡ Six nested sky regions with sky from 24 to 72% (LR24 to LR72) as in PXXX



Dust TE, EE and BB power spectra

TE, EE, BB spectra



Power-law fits

$$D_\ell^{XY} \equiv A^{XY} (\ell/80)^{\alpha_{XY}+2} \text{ for } 40 < \ell < 600$$

$$< A^{BB}/A^{EE} >= 0.52 \pm 0.01$$

$$< \alpha_{EE} >= -2.38 \pm 0.02$$

$$< \alpha_{BB} >= -2.51 \pm 0.02$$

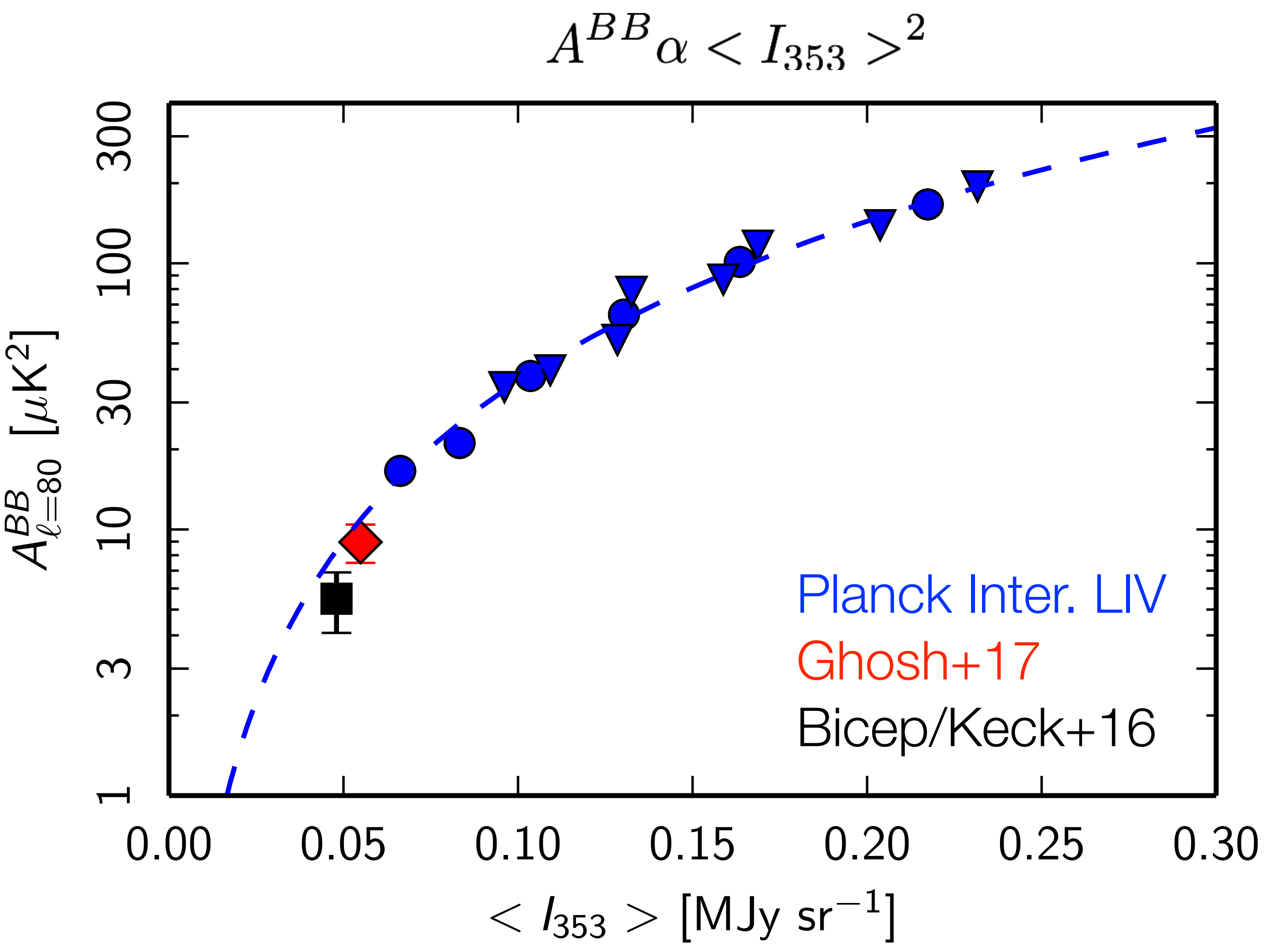
$$< \alpha_{TE} >= -2.49 \pm 0.02$$

- We find slightly different exponents for EE and BB
- No systematic reduction of the EE/BB power asymmetry at very low multipoles
- Large variations in the EE/BB ratio on the lowest ell-bin
- Spectra are not well fitted by a single power-law over the full multipole-range

➡ A model is required to interpret these results, in particular to model spectra and cosmic variance of dust polarization down to low multipoles.

➡ Update of the Vansyngel+2017 simulations of dust polarization, including a model of the ordered magnetic field

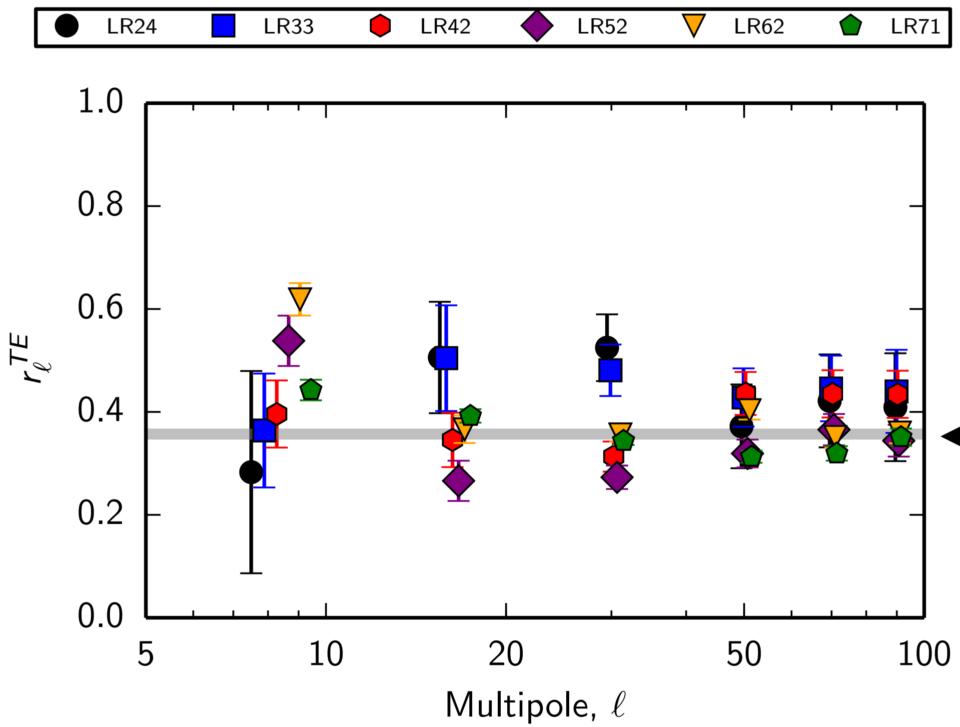
Scaling of BB power with dust total intensity



- B-mode dust power scales as the total dust intensity square
- Fit consistent with measurement for clean sky in the southern Galactic cap (fsky = 8.5%) in Ghosh+17
- Slightly above B-mode dust power derived from the cross-correlation with Planck for the Bicep/Keck field (fsky = 1%)

Dust TE correlation

$$r_\ell^{TE} = \mathcal{D}_\ell^{TE}/(\mathcal{D}_\ell^{TT} \times \mathcal{D}_\ell^{EE})^{0.5}$$



Mean ratio: 0.36

- The TE correlation extends to the lowest multipoles

➡ There is more to it than the alignment observed locally between the magnetic field and the filamentary structure of the ISM

➡ Symmetric variations of the mean orientation of the local magnetic field from the Galactic plane to the poles (follow-up model paper)

Frequency analysis of polarized foregrounds

Amplitude of EE/BB cross-spectra between frequencies $\boldsymbol{\nu}_1$ and $\boldsymbol{\nu}_2$:

Synchrotron

Dust

$$\mathcal{D}_\ell^{XX}(\nu_1 \times \nu_2) = A_\mathrm{s}^{XX}\left(\frac{\nu_1\nu_2}{30^2}\right)^{\beta_\mathrm{s}} + A_\mathrm{d}^{XX}\left(\frac{\nu_1\nu_2}{353^2}\right)^{\beta_\mathrm{d}-2}\frac{B_{\nu_1}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})}\frac{B_{\nu_2}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})}$$
$$+\rho^{XX}(A_\mathrm{s}^{XX}A_\mathrm{d}^{XX})^{0.5}\left[\left(\frac{\nu_1}{30}\right)^{\beta_\mathrm{s}}\left(\frac{\nu_2}{353}\right)^{\beta_\mathrm{d}-2}\frac{B_{\nu_2}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})} + \left(\frac{\nu_2}{30}\right)^{\beta_\mathrm{s}}\left(\frac{\nu_1}{353}\right)^{\beta_\mathrm{d}-2}\frac{B_{\nu_1}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})}\right],$$

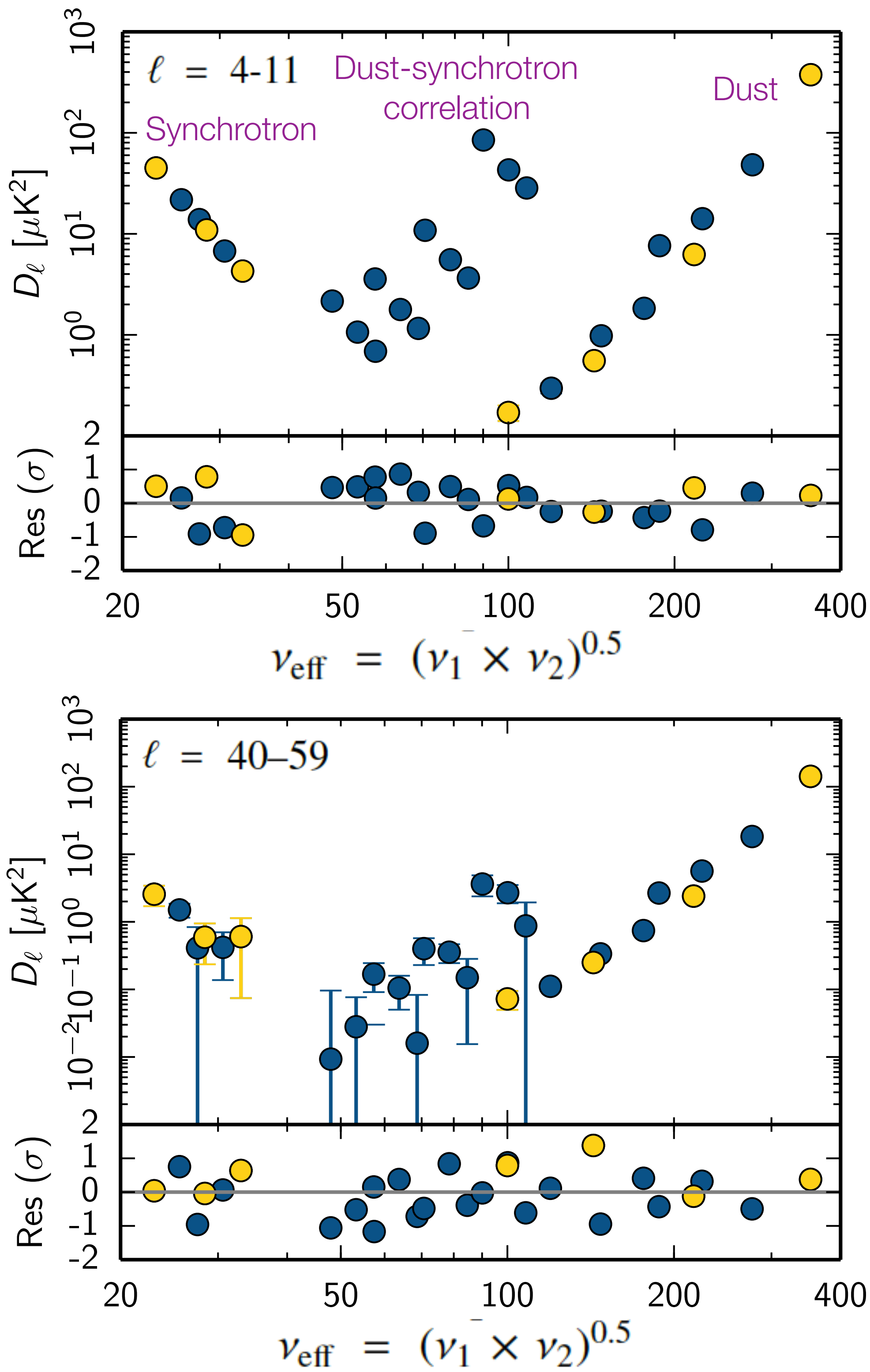
Synchrotron x Dust

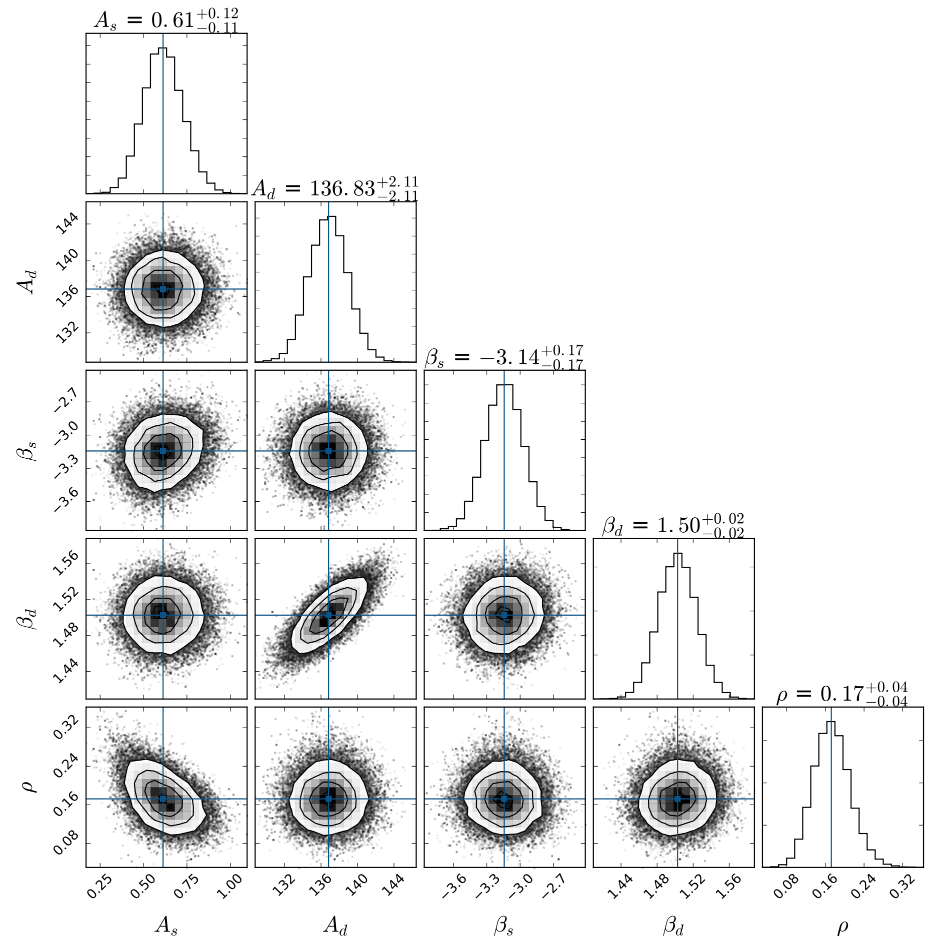
Same model as in Choi & Page (2015)

Five model parameters:

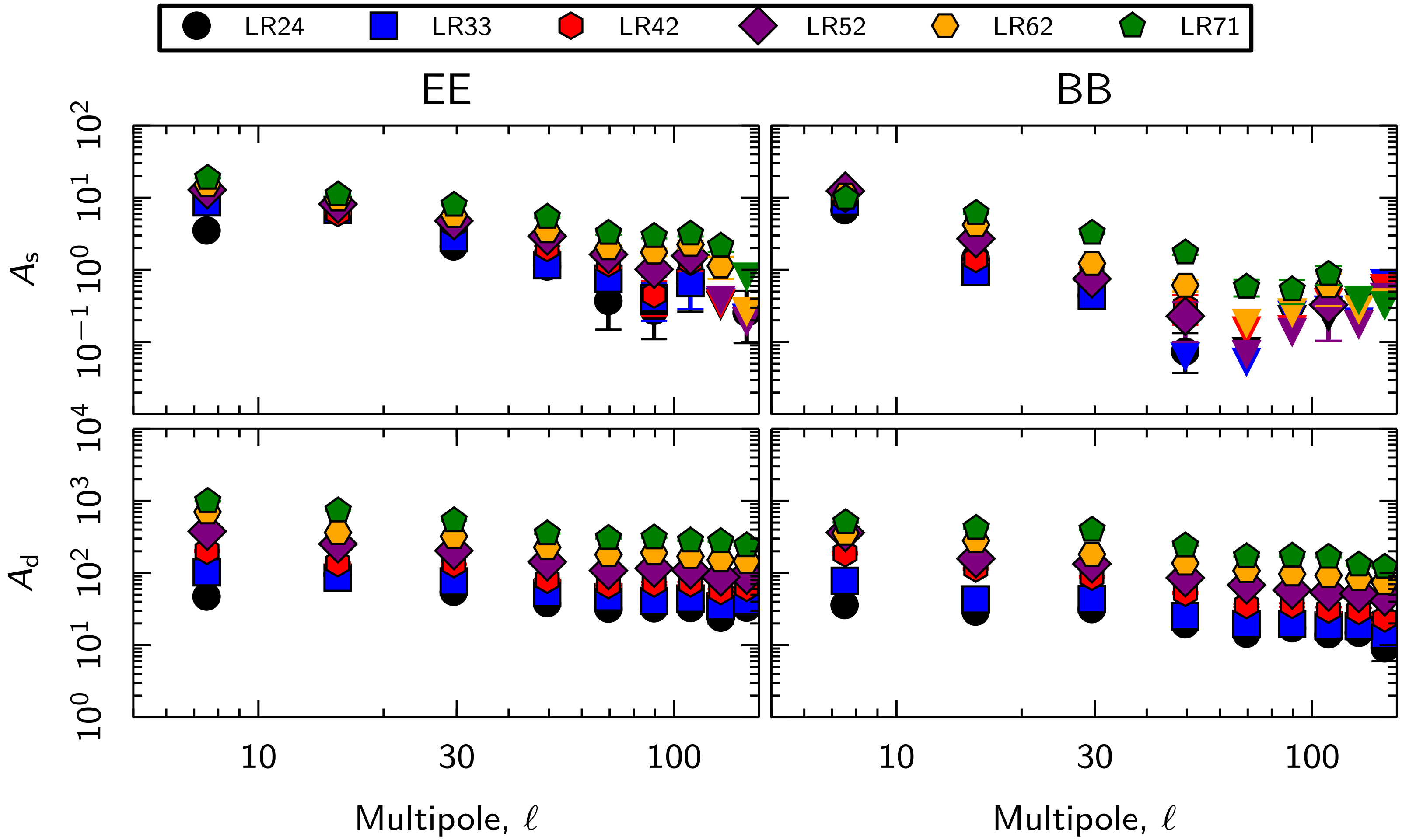
- The synchrotron and dust amplitudes A_s and A_d
- The two spectral indices β_s and β_d
- The dust/synchrotron polarization correlation parameter $\boldsymbol{\rho}$

Spectral fit of cross-spectra



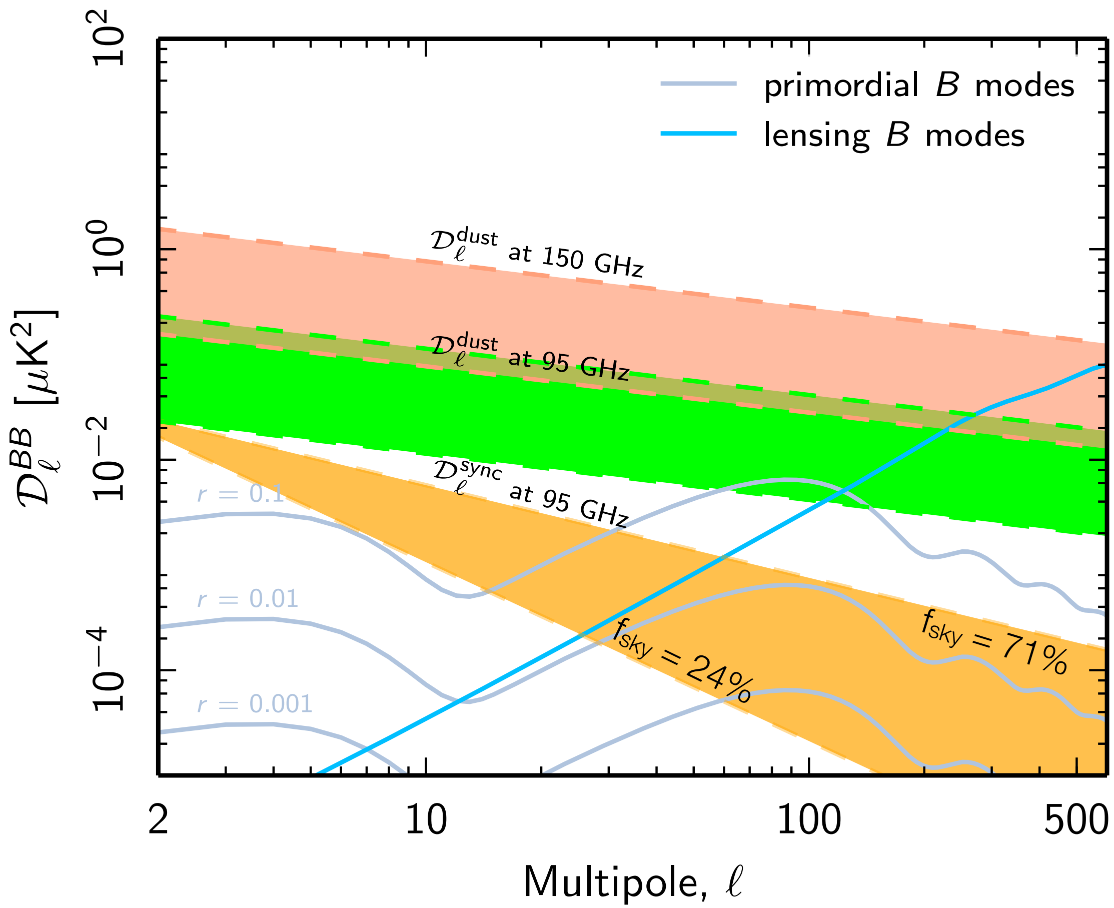


Dust and synchrotron power vs multipole

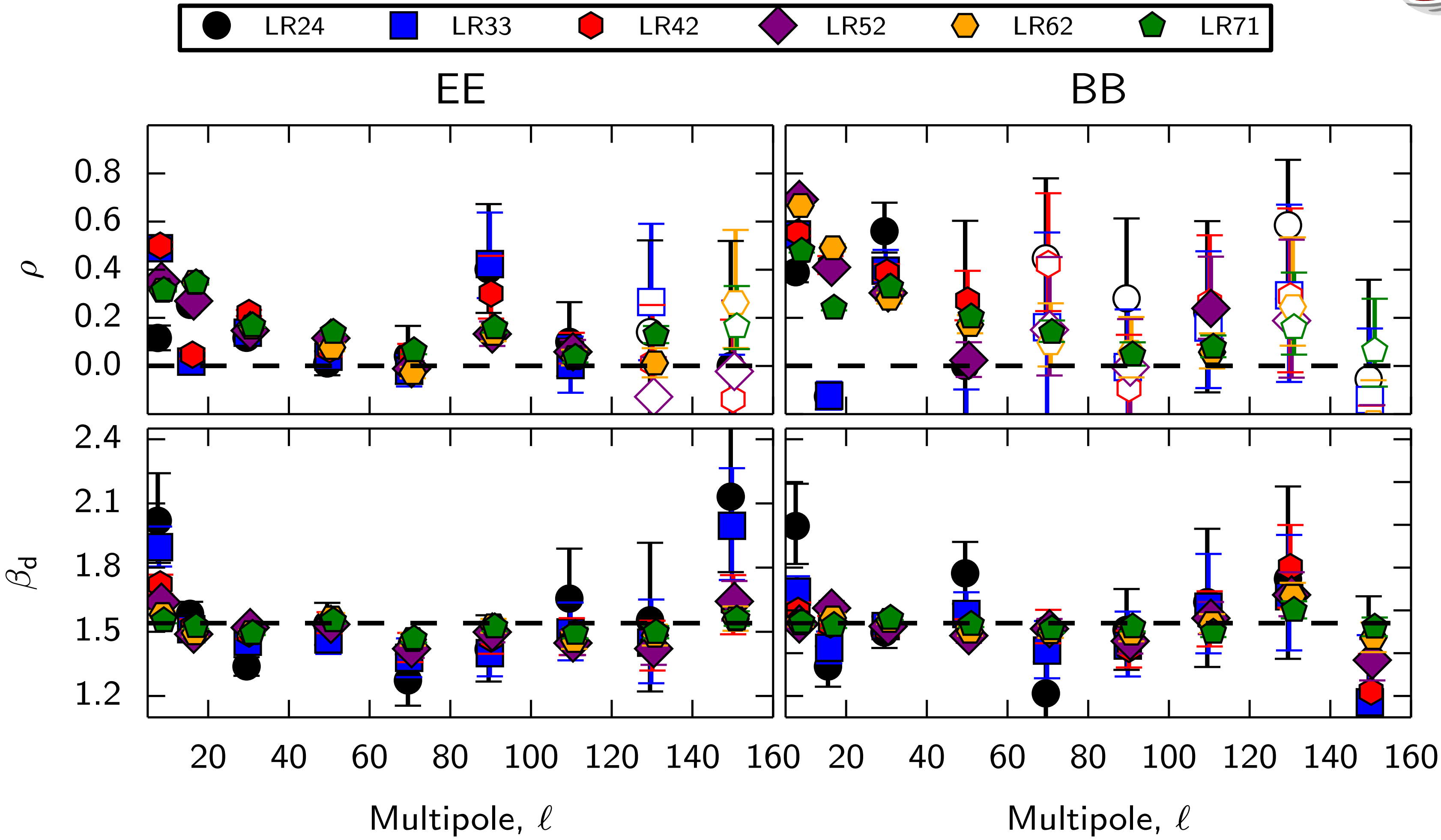


For B-modes, the synchrotron-to-dust ratio (A_s/A_d) is maximum at low multipoles and for the smallest sky region (LR24)

Comparison with CMB B-modes

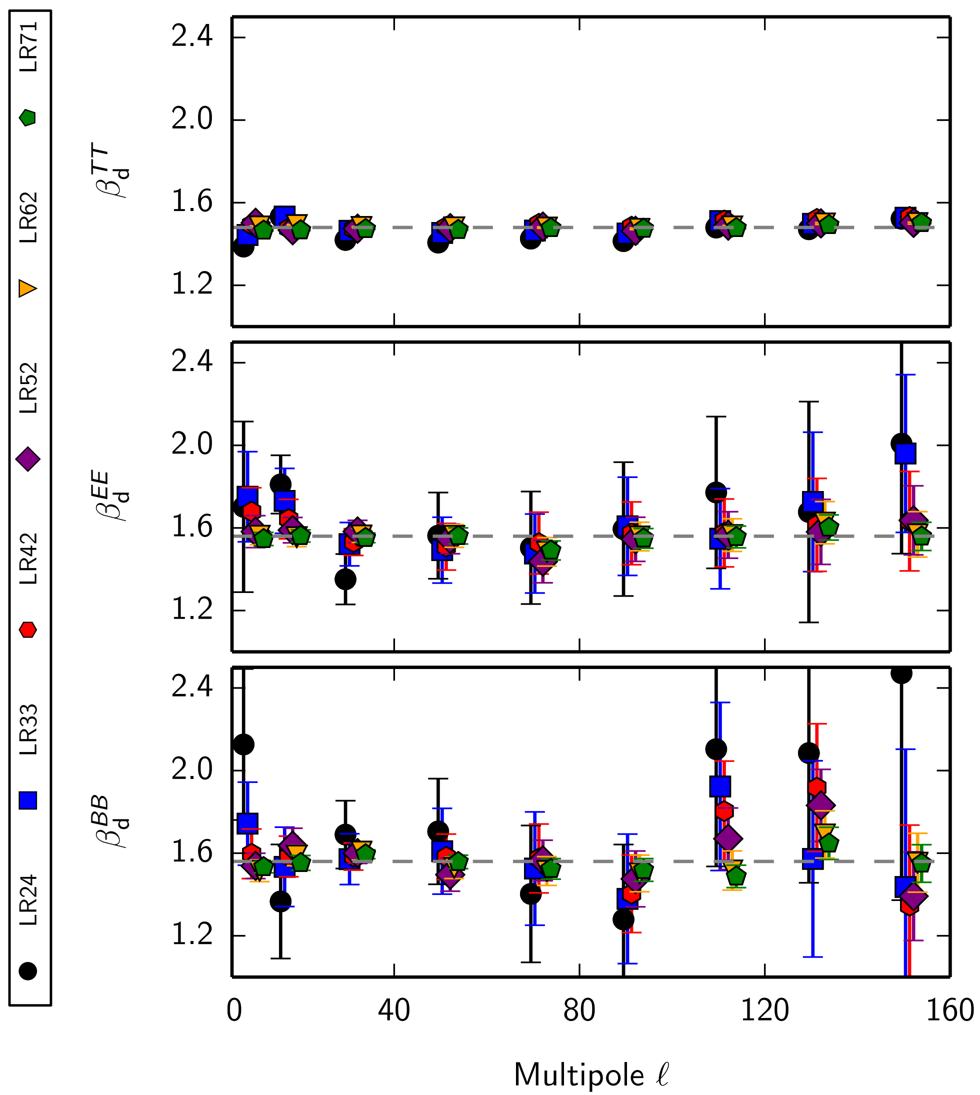


- *B*-modes dust and synchrotron power measured consistently for sky regions minimizing the dust foreground power for a given $f_{\rm sky}$
- Synchrotron B-modes power decreases with ℓ more steeply than dust. The difference is the strongest for the cleanest sky region (LR24)
- In the cleanest sky regions, synchrotron is not a significant problem to reach a sensitivity limit on *r* of 10^{-2} at 95 GHz.



- Only $\boldsymbol{\rho}$ depends systematically on ℓ
- No systematic variations with sky regions but for β_d in the lowest ℓ bin
- Spectral model fits well the data but for a few cases

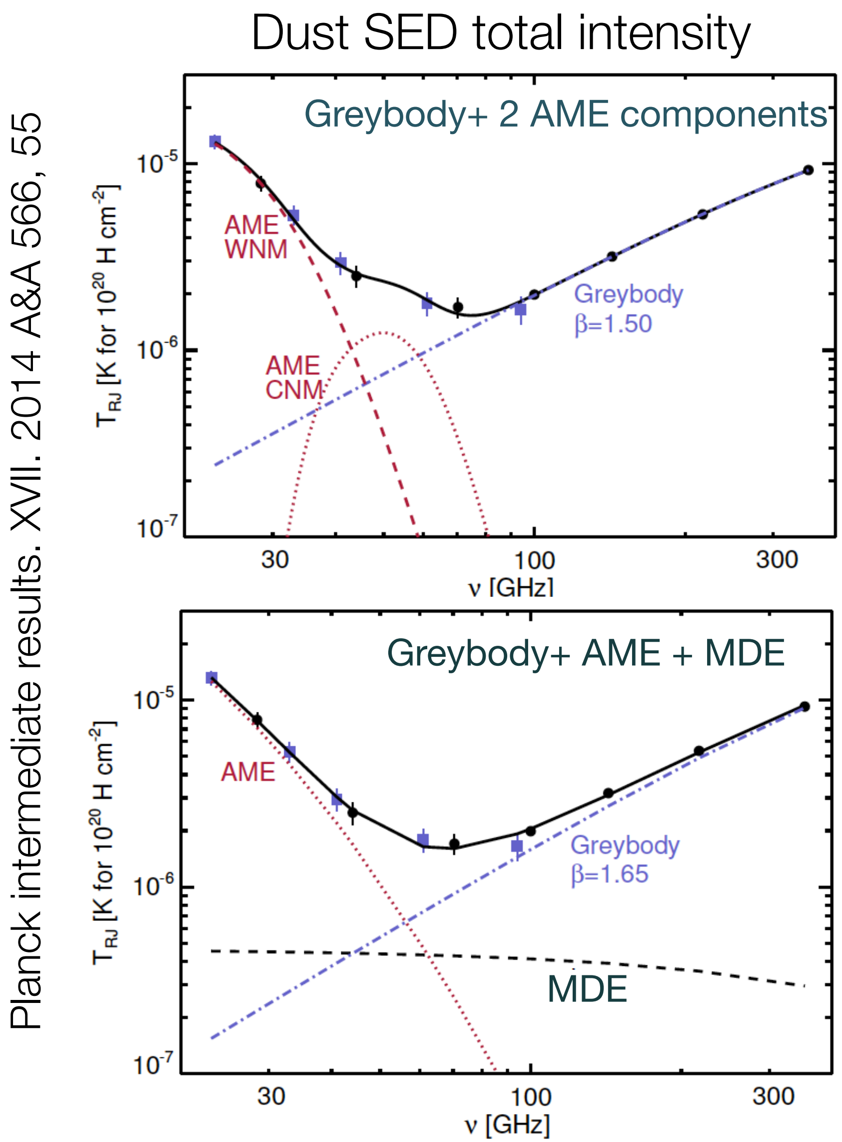
Dust SED for polarization and total intensity



- The mean spectral index for dust polarization is β(P) = 1.54±0.01 (for T_d=19.6K), a value slightly smaller than that (1.59) reported in PIP XXII
- We confirm the small difference between spectra indices for polarization and total intensity: β(P)-β(I) = 0.09±0.02 as in PIP XXII

➡ Dust emission includes at least two components with distinct polarization properties (Guillet+17, Hensley+17)

Degeneracy of spectral modelling



- Spectral model of dust emission is not unique
- Modelling of the dust-synchrotron correlation is an open issue
- For component separation, the correlation mimics anomalous microwave emission (AME) in total intensity. It may hide a contribution from an additional emission component, e.g. magnetic dipole emission (MDE).
- This degeneracy in the frequency modeling of dust polarization is analogous to that for total intensity.

Frequency decorrelation

The **interplay between interstellar magnetic fields with density structure and dust polarization properties** break the simplest assumption for component separation by which the spectral frequency dependence of the Galactic polarization and its angular structure on the sky are separable => ***frequency decorrelation***

✴Structure of the magnetized interstellar medium

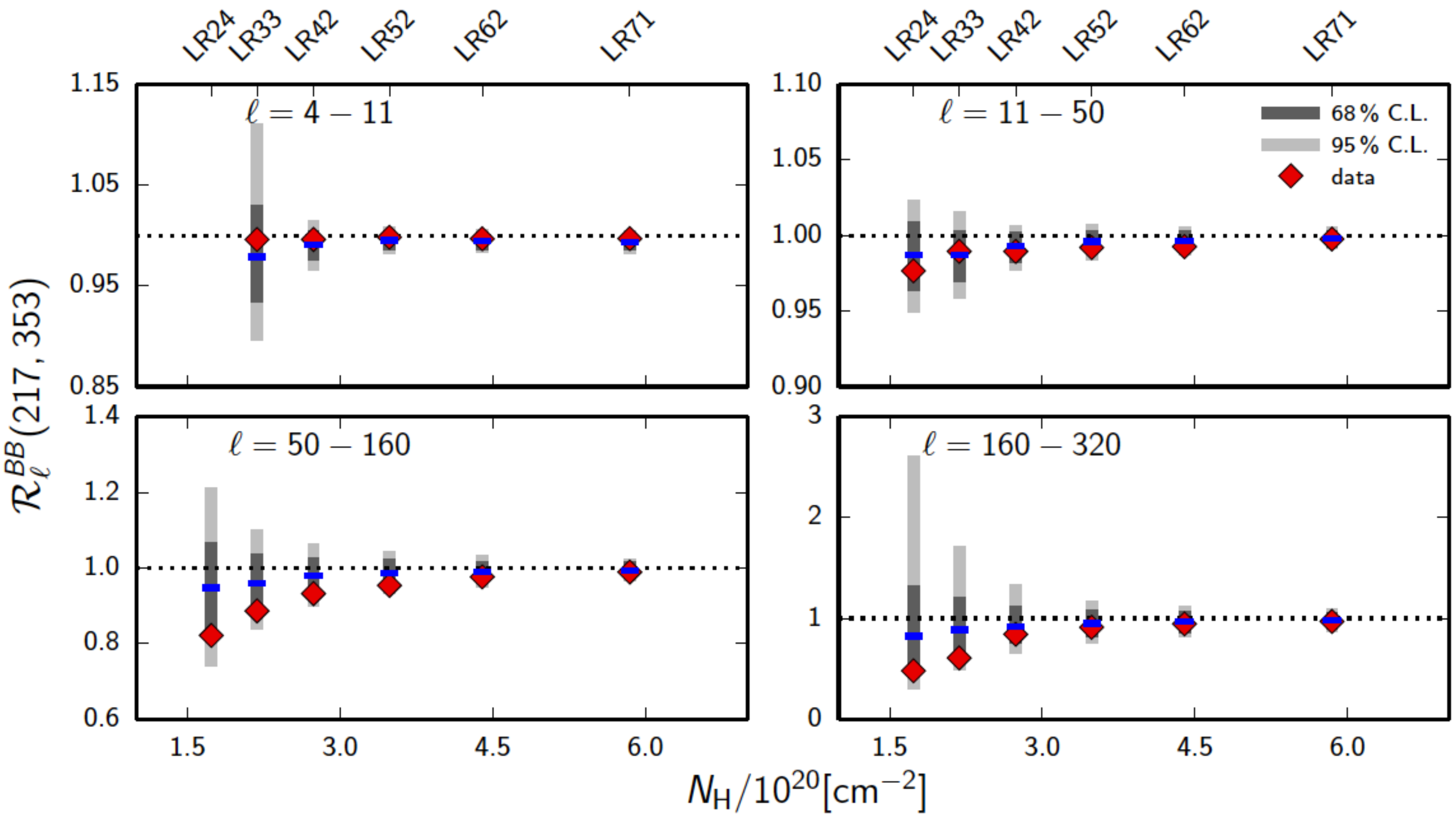
- Anisotropic random walk (Vansyngel+17)
- HI data (Clark+15, Ghosh+17)
- MHD waves (Caldwell+17, Kandel+17)
- MHD simulations (Planck Inter. XX, 2016, Kritsuk+17)

✴Dust polarization properties

- The spectral energy distribution of dust polarization (Guillet+17, Hensley+17)
- Its variations along the line of sight: dust heating, dust evolution and grain alignment (Fanciullo+17, Hoang+17)

Spectral correlation ratio

$$\mathcal{R}_\ell^{BB}(217,353) \equiv \frac{\mathcal{C}_\ell^{BB}(217\,\mathrm{x}\,353)}{(\mathcal{C}_\ell^{BB}(353\,\mathrm{x}\,353)\,\mathcal{C}_\ell^{BB}(217\,\mathrm{x}\,217))^{0.5}}$$



Confidence limits (68 and 95%) derived from E2E simulations

Planck Inter. LIV

2017 data

Results comparable to our earlier analysis on 2015 data (Planck Inter. L) but the **statistical significance** of this result **was overstated,** as also found by **Sheehy & Slosar (2017)**

To characterize the frequency decorrelation of dust B-modes over the multipole bin 50-160, we consider the four lowest *Planck* HFI frequency channels (100 – 353 GHz)

Amplitude of cross-spectra between HFI frequencies $\boldsymbol{\nu}_1$ and $\boldsymbol{\nu}_2$:

$$\mathcal{D}_\ell(\nu_1 \times \nu_2) = A_\mathrm{d} \left(\frac{\nu_1 \nu_2}{353^2}\right)^{\beta_\mathrm{d}-2} \frac{B_{\nu_1}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})} \frac{B_{\nu_2}(T_\mathrm{d})}{B_{353}(T_\mathrm{d})} R_\ell(\delta_\mathrm{d}, \nu_1, \nu_2)$$

where

$$T_\mathrm{d} = 19.6\,\mathrm{K}$$

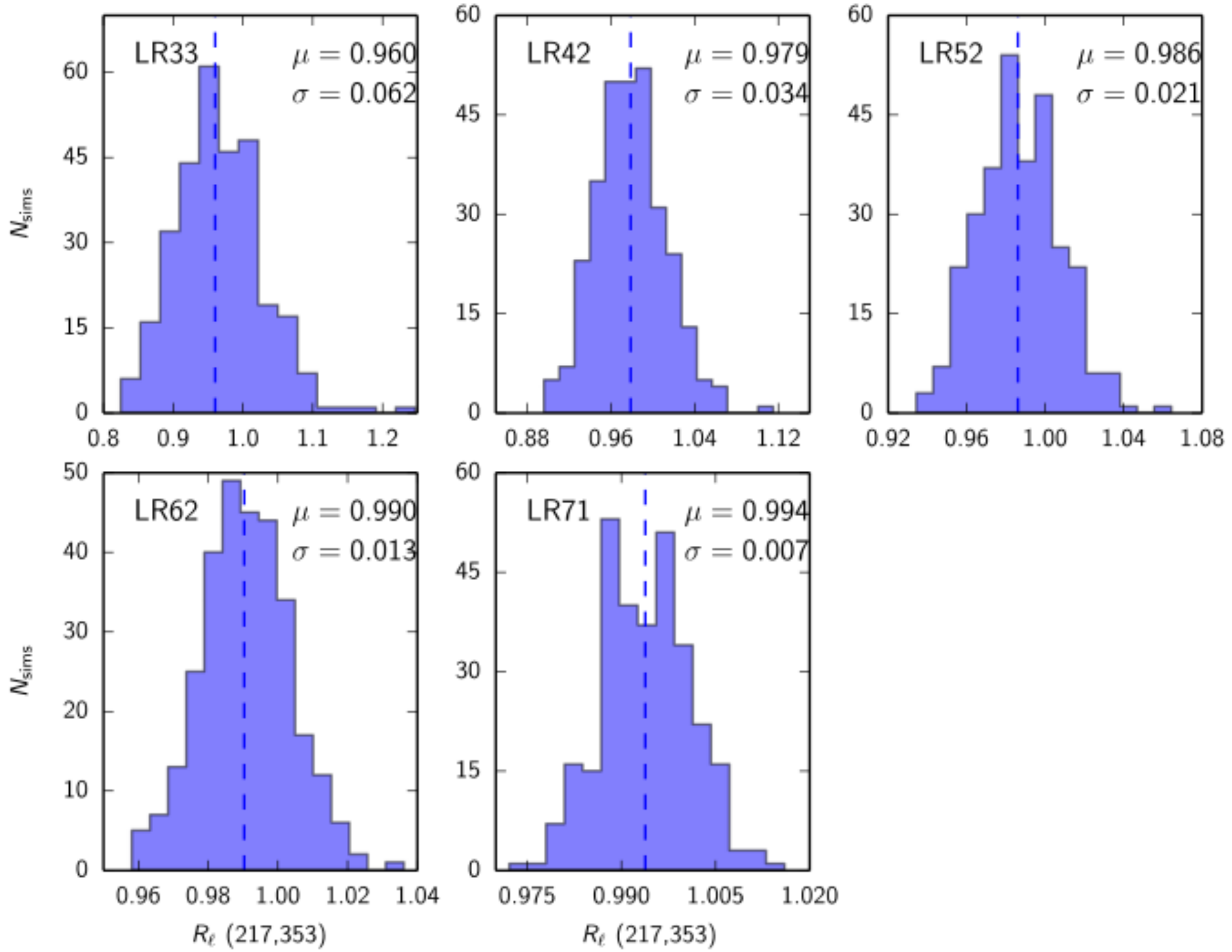
$$R_\ell(\delta_\mathrm{d}, \nu_1, \nu_2) = \exp\left[-\delta_\mathrm{d}\,\ln\left(\frac{\nu_1}{\nu_2}\right)^2\right]$$

Assumes a frequency dependence model of spectral decorrelation based on ***Vansyngel et al. 2017***.

Three model parameters:

- ➢ The dust amplitude A_d .
- ➢ The dust spectral index β_d .
- ➢ The dust decorrelation parameter δ_d .

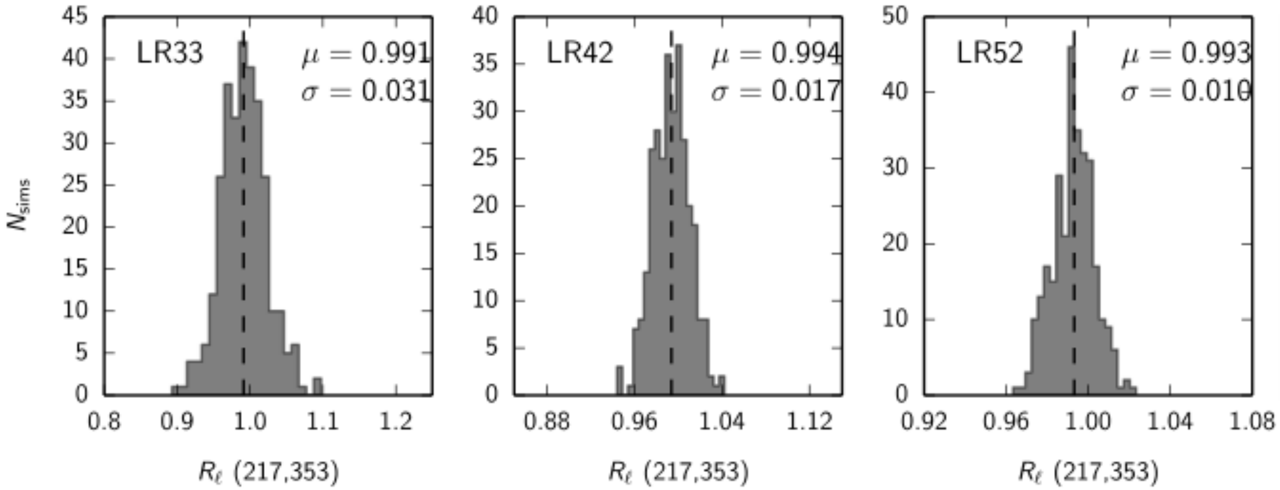
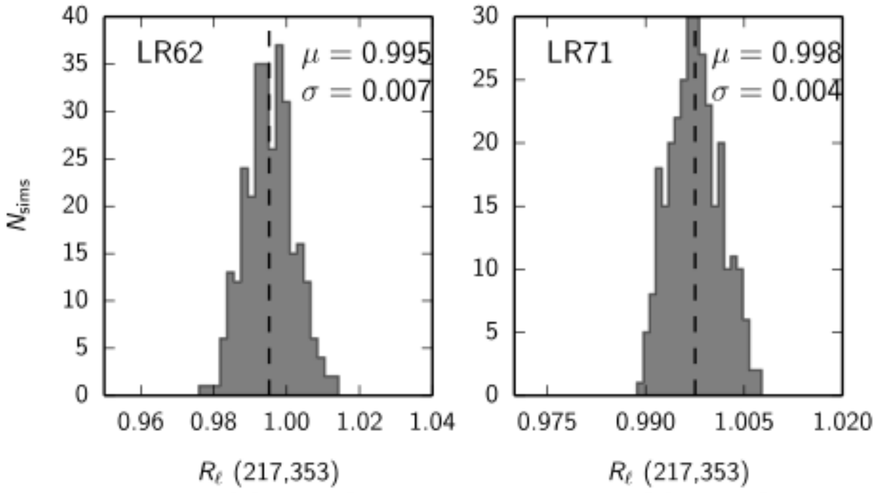
Frequency decorrelation



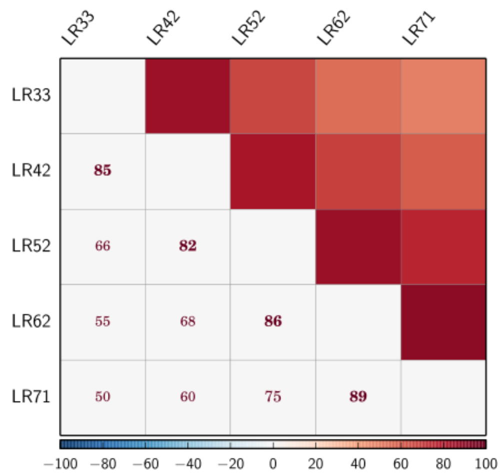
Correlation between 217 and 353 GHz.

<u>300 E2E simulations</u> :

- ➢ results of dust correlation ratio derived from 217 and 353 GHz bands over the multipole range 50 - 160.
- ➢ The mean of dust spectral correlation ratio is less than one (instrumental systematics, CMB lensing B-mode signal).

SED fit to HFI-only auto- and cross-spectra.



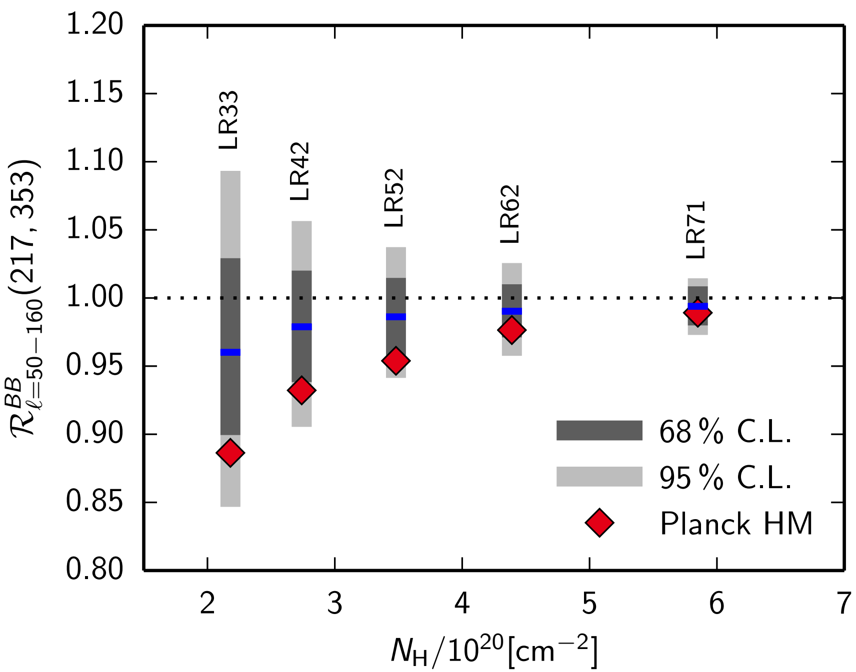
Correlation matrix (%)

<u>300 E2E simulations</u> :

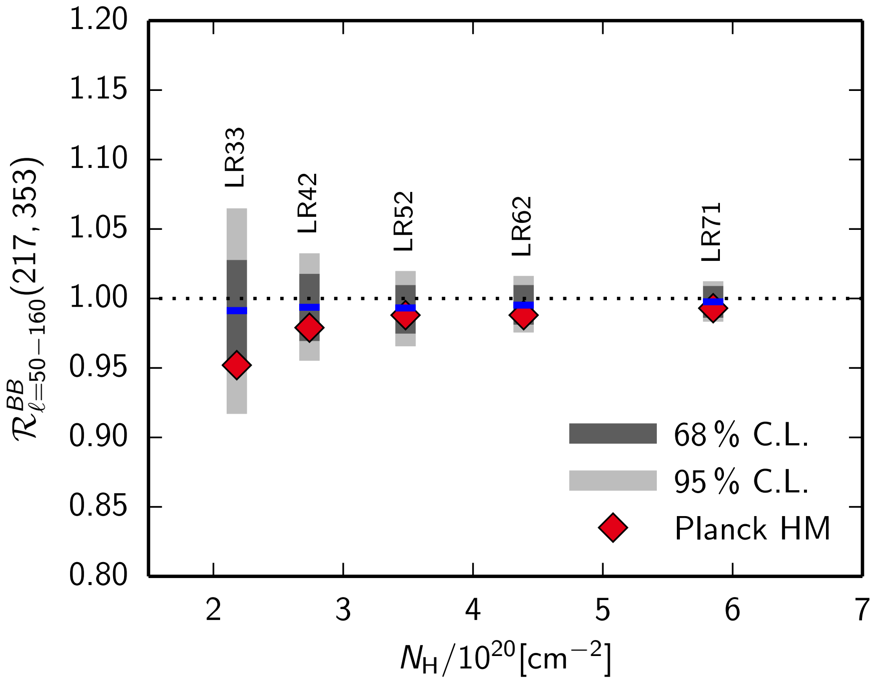
- ➢ Results of HFI-only (100 – 353 GHz) multi-frequency fit over the multipole range 50 – 160.
- ➢ The mean of spectral correlation ratio is consistent with 1, within 1 sigma error-bars.

Frequency decorrelation

Using 217/353 correlation ratio



Multi-frequency fit to all HFI spectra



➢ Multifrequency approach provides a tighter constraint on frequency decorrelation of dust B-modes.

Summary

- ✳ Planck is providing the observational inputs needed to statistically model Galactic polarized foregrounds for preparing future space missions, and optimizing and assessing component separations.
  - Dust polarization power spectra measured down to the lowest multipoles
  - Spectral model of the polarized foregrounds including dust-synchrotron correlation
  - Upper limits on frequency decorrelation of dust polarization
- ✳ The 353 GHz dust polarization map will remain a unique all-sky template of dust polarization until the next CMB space mission. Continuing efforts, beyond the next data release, are aiming at correcting residual systematics.
- ✳ The foregrounds challenge is calling for breakthroughs in our ability to characterize statistically polarized foregrounds: their structure on the sky, the SEDs and their correlations.
  - Additional data, e.g. sub-orbital experiments will provide further insight, in particular on the frequency decorrelation.
  - Astrophysics of the magnetized interstellar medium
  - Statistical modelling of non-Gaussian processes