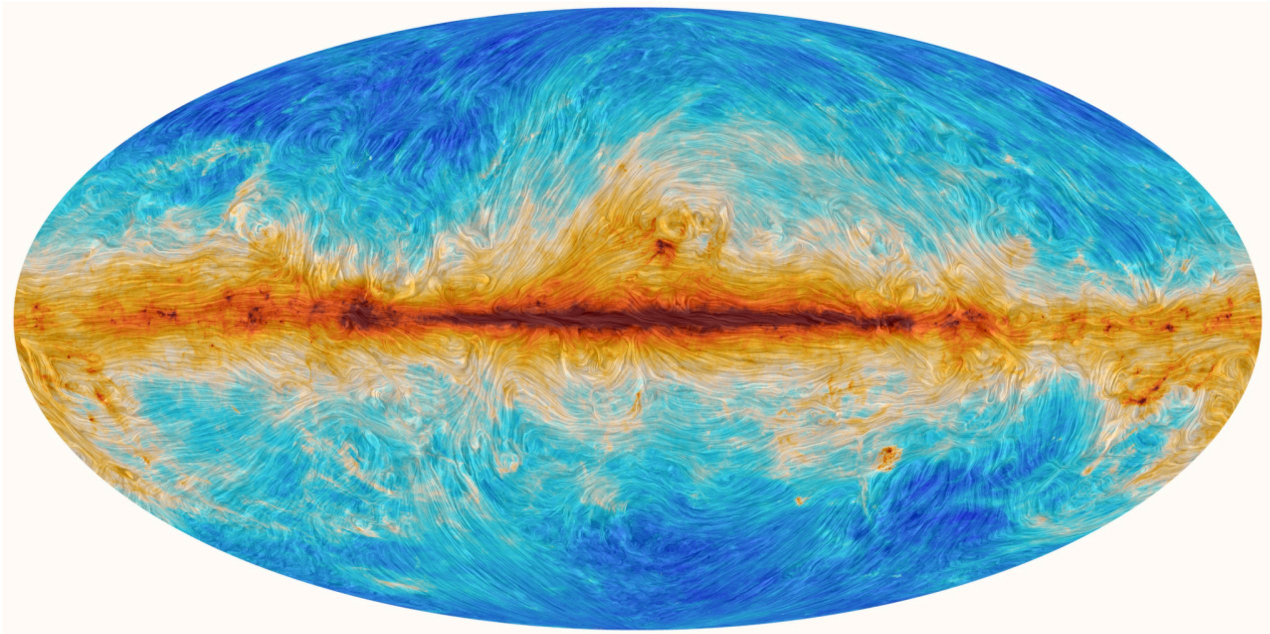
The astrophysics of the dusty magnetized ISM



F. Boulanger (Ecole Normale Supérieure)
on behalf of the Planck Collaboration

Input Planck legacy papers

- **Planck 2018 results. XI. Polarized dust foregrounds**
  - Power spectra analysis of dust polarization maps
  - Spectral energy distribution of dust polarized emission
  - Correlation of dust polarization over microwave frequencies
- **Planck 2018 results. XII. Galactic astrophysics using polarized dust emission**
  - Statistical analysis of polarization fraction and angle
  - Correlation of dust polarization in emission (sub-mm wavelengths from Planck) and extinction (stellar optical data)

This presentation is organized in three sections

I. Galactic Magnetic field in the Solar Neighbourhood

II. Statistical and spectral characterization of polarized foregrounds

III. The nature of interstellar dust: its polarization properties including grain alignment

I. **Galactic Magnetic field in the Solar Neighbourhood**

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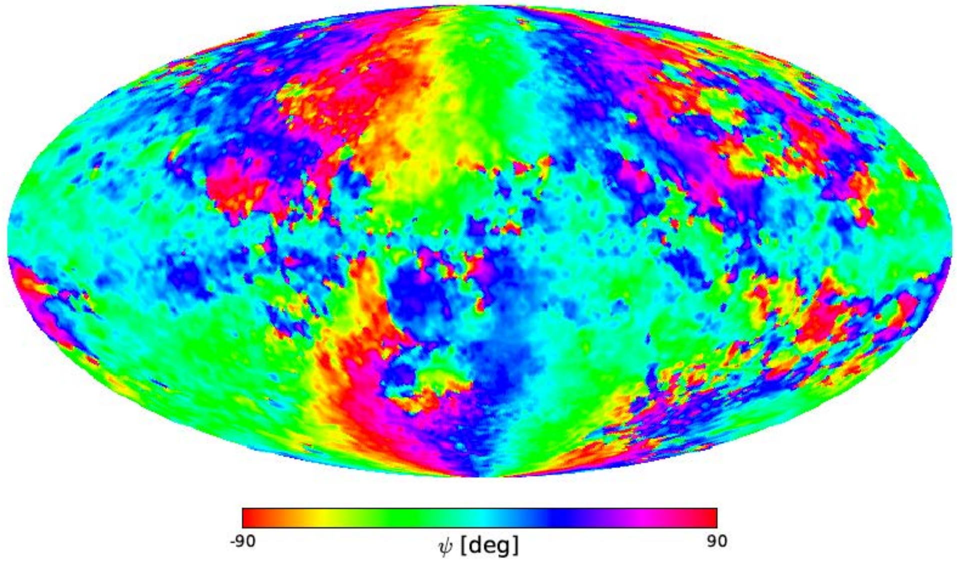
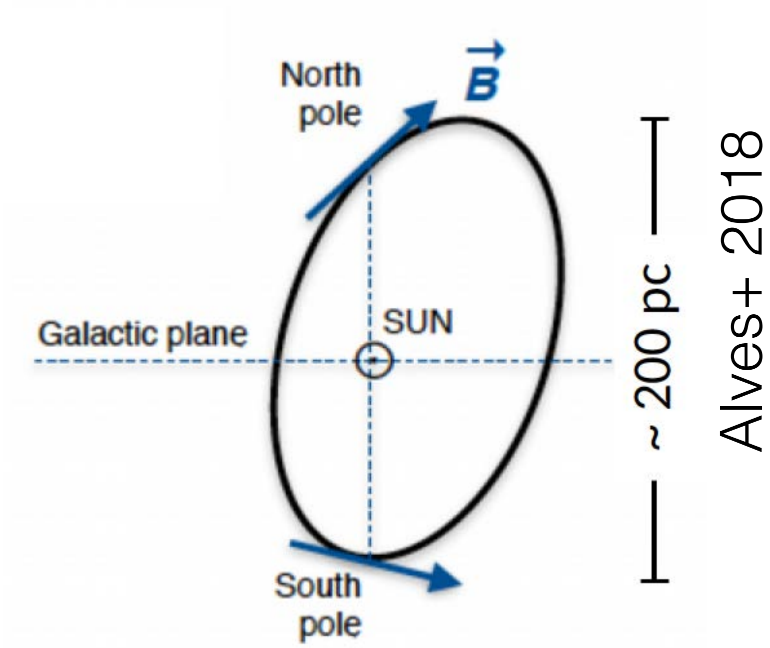
Solar Neighborhood magnetic field

Polarization angle ψ



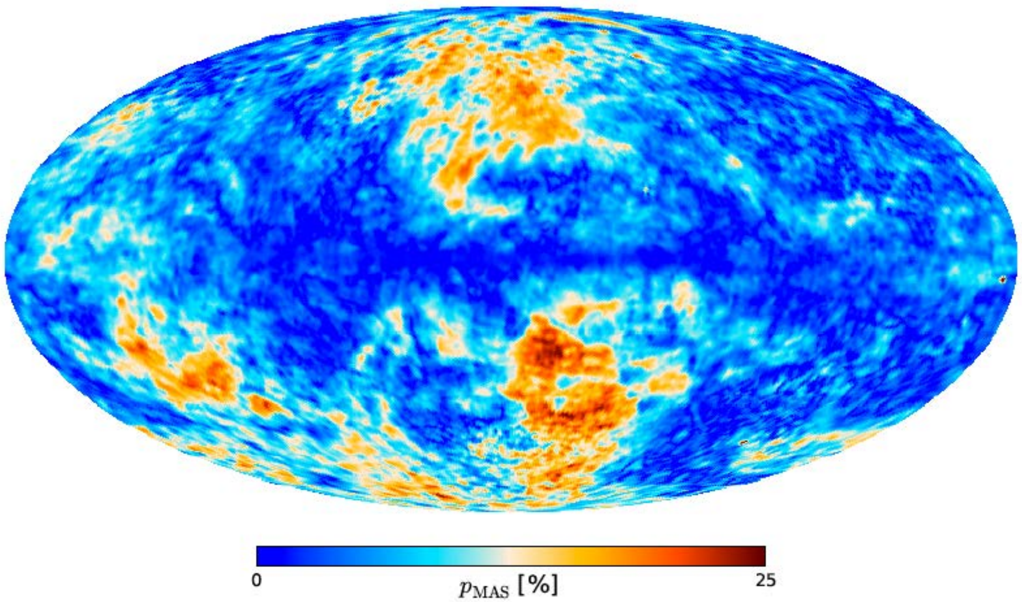
Local Bubble



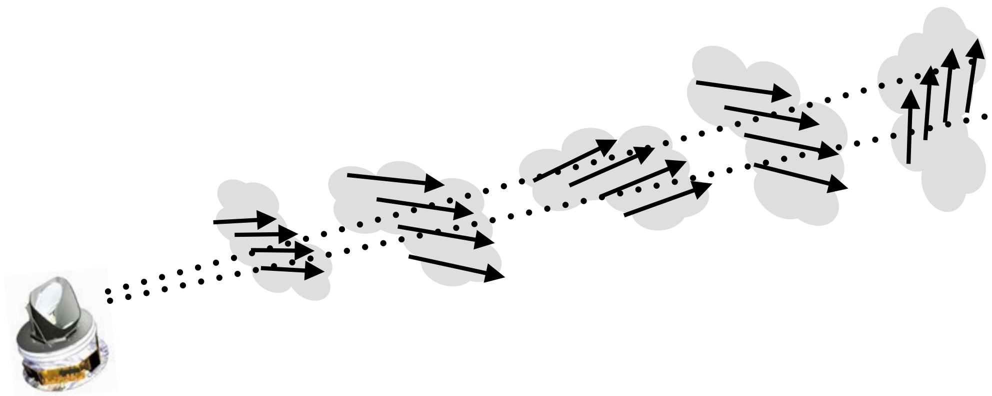
- Imprint from an ordered magnetic field is clearly apparent on the map of polarization angles
- We may be seeing a local deformation of the Galactic magnetic field associated with the Local Bubble (Alves et al. 2018)
- Dust, unlike synchrotron, polarization is sensitive to this because the extension of the Bubble towards the pole is comparable to the dust scale-height

Dust polarization fraction

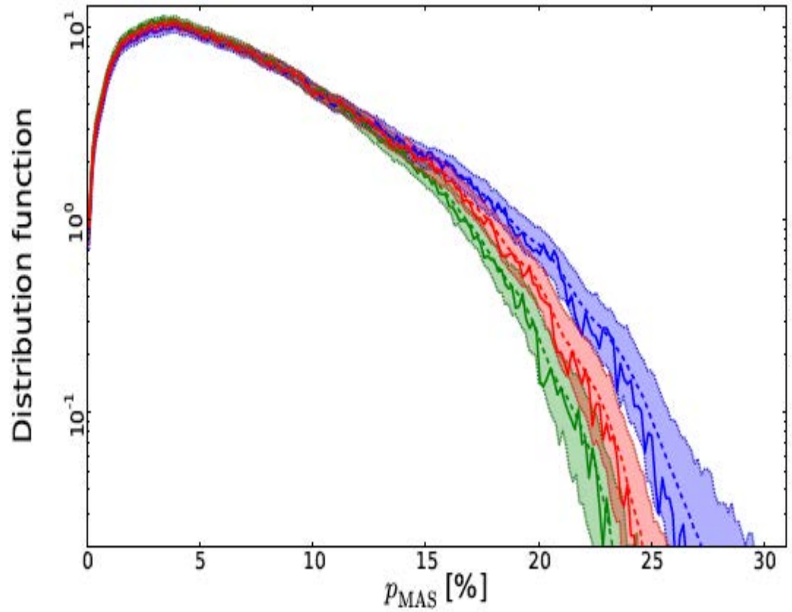
polarization fraction



- The maximal polarization fraction is large (>20%). It is a challenge for dust models to explain such high values (Guillet+ 2018)
- Variable degree of depolarization from the superposition of a small number of ISM *clouds* along the line of sight with distinct polarization

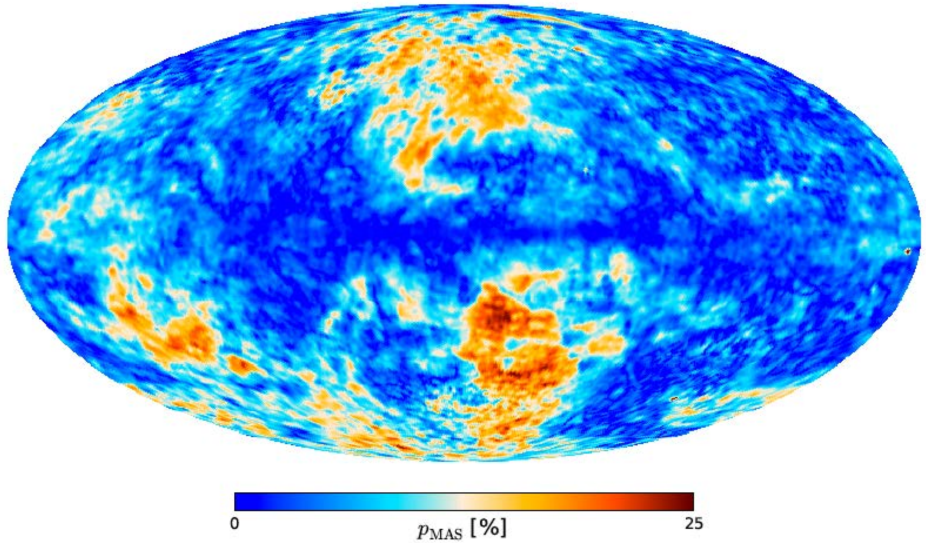


polarization fraction



Dust polarization fraction

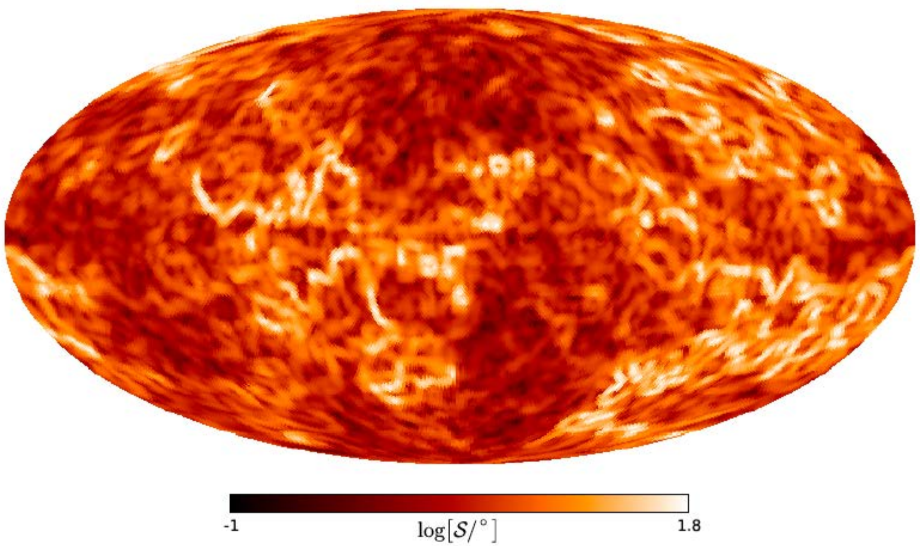
- The dust polarization maps trace magnetic field structure
- The data analysis shows no clear evidence for variations in the degree of grain alignment, nor in the intrinsic degree of dust polarization

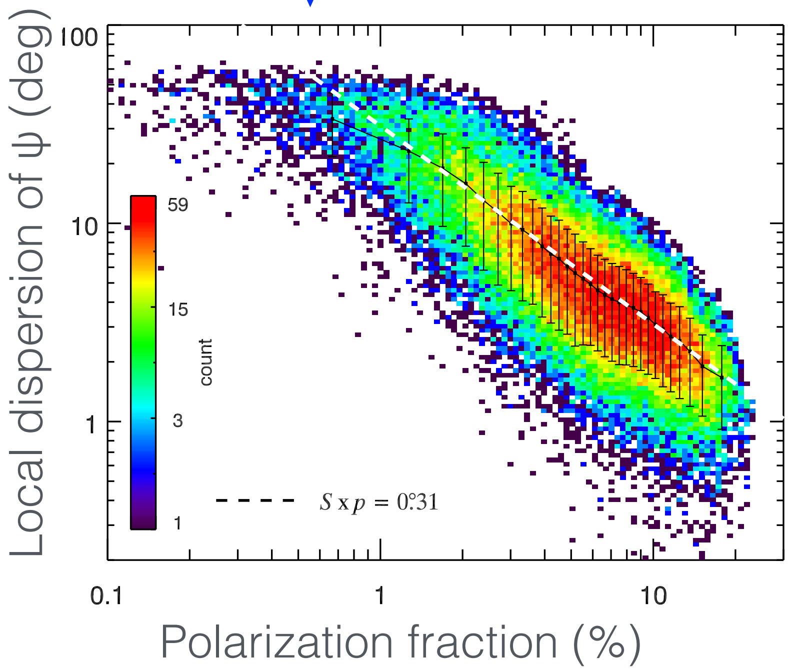


Polarization fraction

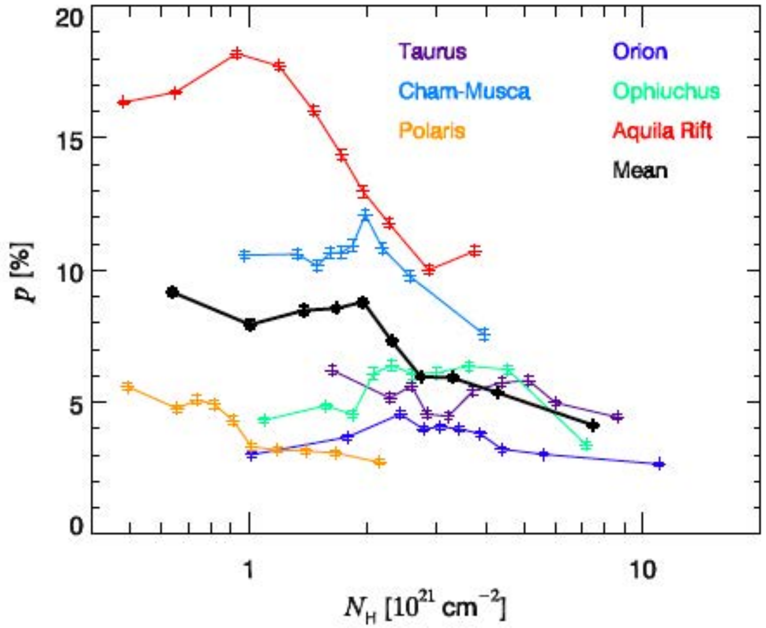
Local dispersion of ψ

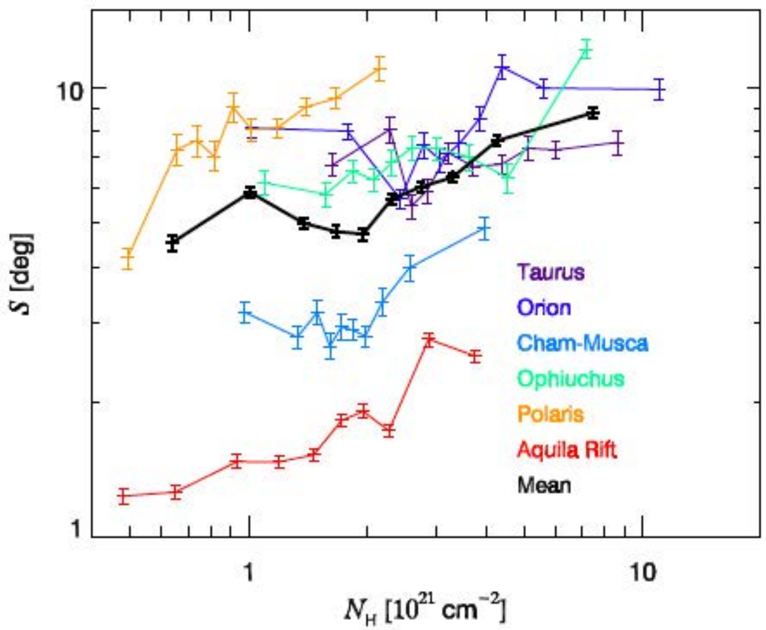
$$\mathcal{S}(\boldsymbol{r},\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\psi(\boldsymbol{r}+\boldsymbol{\delta}_i) - \psi(\boldsymbol{r})\right]^2}$$



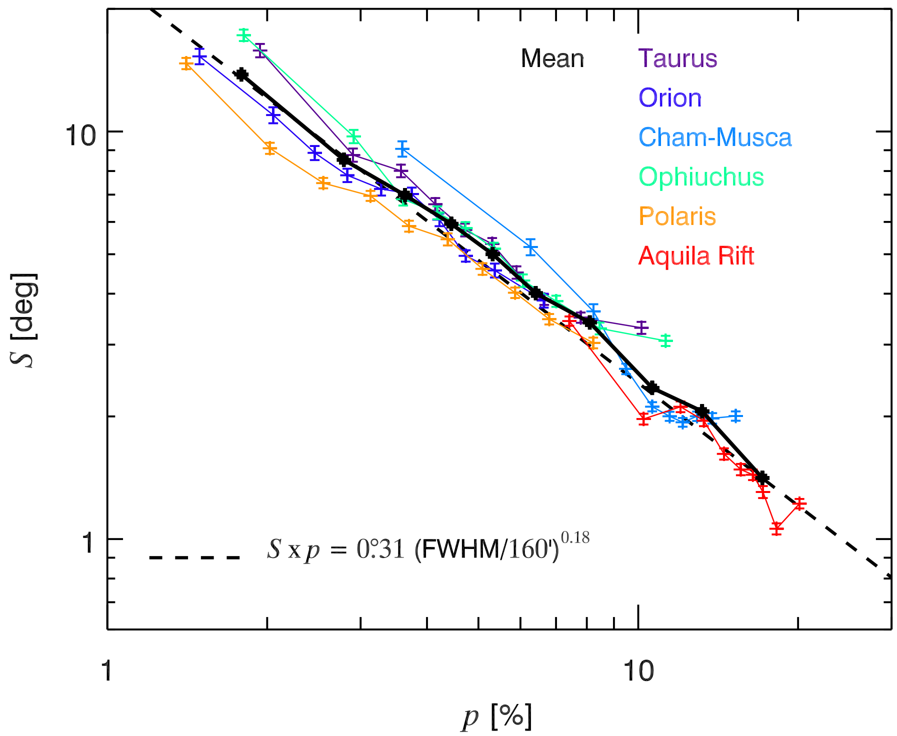


Molecular Clouds





- The decrease of p for increasing N_H is compensated by a comparable increase in S
- It is a signature of the magnetic field structure and not, as often assumed, of a decrease in the degree of grain alignment



Statistical model

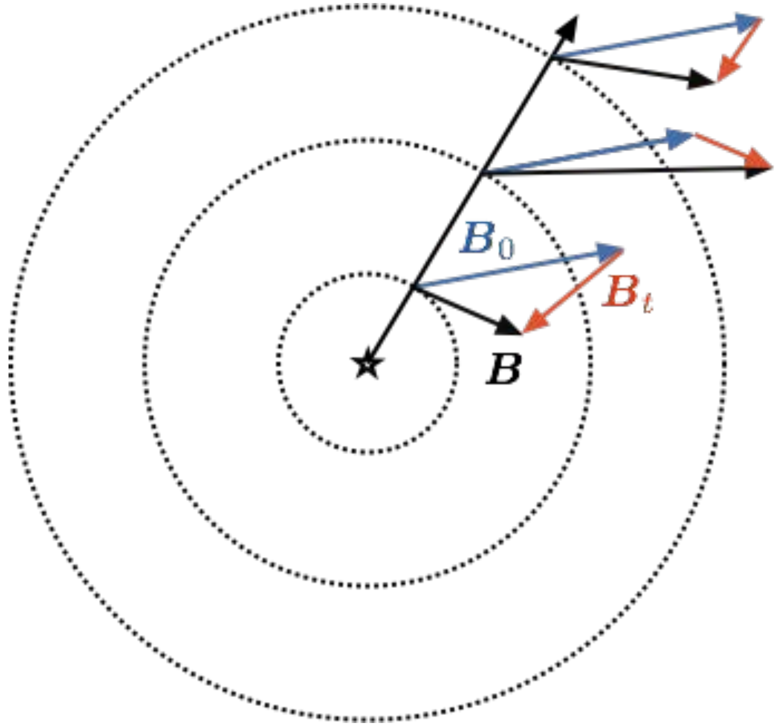
- Magnetic field
  - ordered + turbulent

$$\boldsymbol{B} = |\boldsymbol{B_0}|\,(\hat{\boldsymbol{B}}_{\mathbf{0}} + f_{\mathrm{M}}\,\hat{\boldsymbol{B}}_{\mathbf{t}}) \qquad f_M \simeq 0.9$$

  - Power-law spectrum

$$C_\ell \propto \ell^{\alpha_{\mathrm{M}}} \text{ for } \ell \geq 2 \qquad \alpha_M = -2.5$$

- Distribution of matter from total intensity Planck map
- Summing emission over N emitting layers (ISM structure along the line of sight)



Turbulent field

$$\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_t$$

Ordered field

➡This phenomenological model, introduced in Planck Intermediate XLIV, accounts for statistical results on p and ψ in Planck Legacy XII, and the dust polarization power spectra (Ghosh+ 2017, Vansyngel+ 2017)

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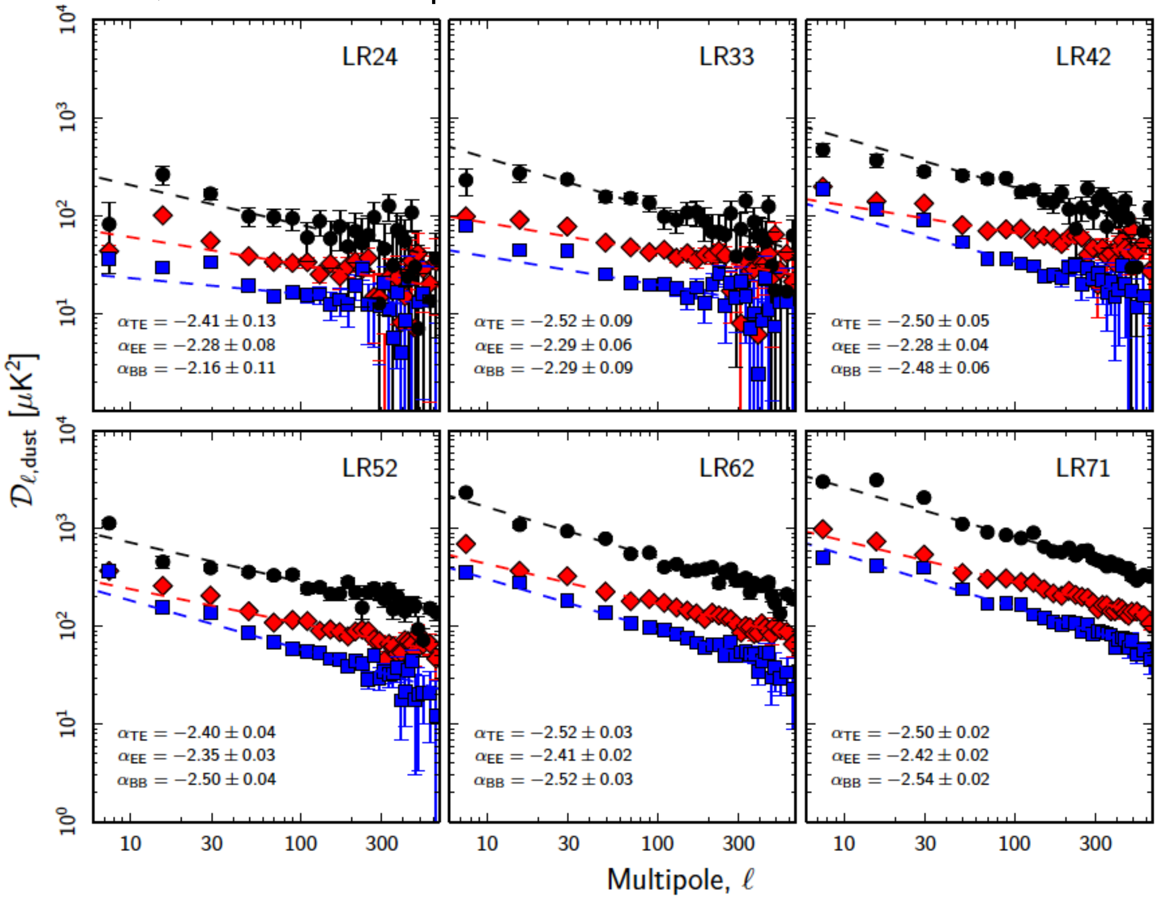
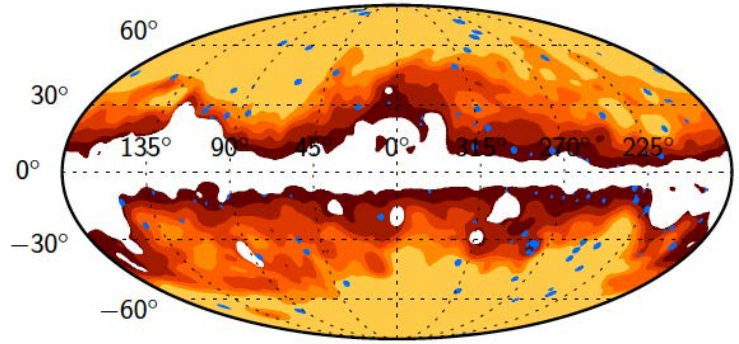
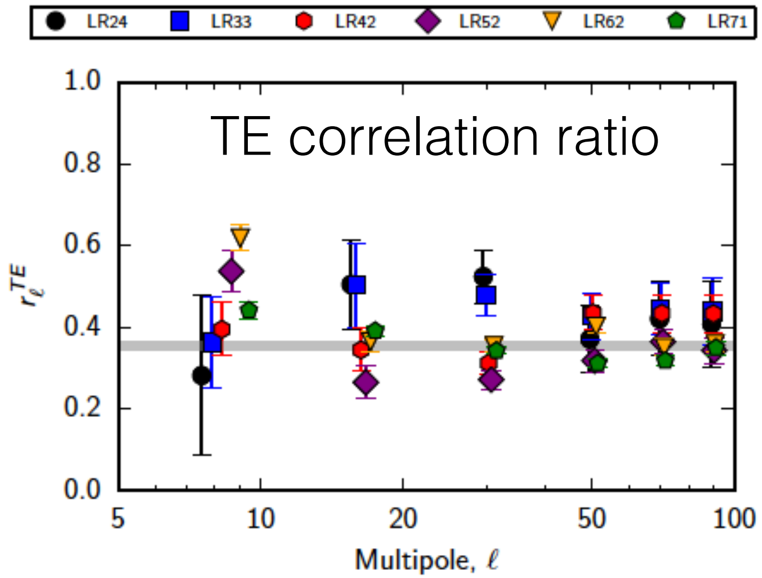
Dust power spectra

TE, EE & BB spectra



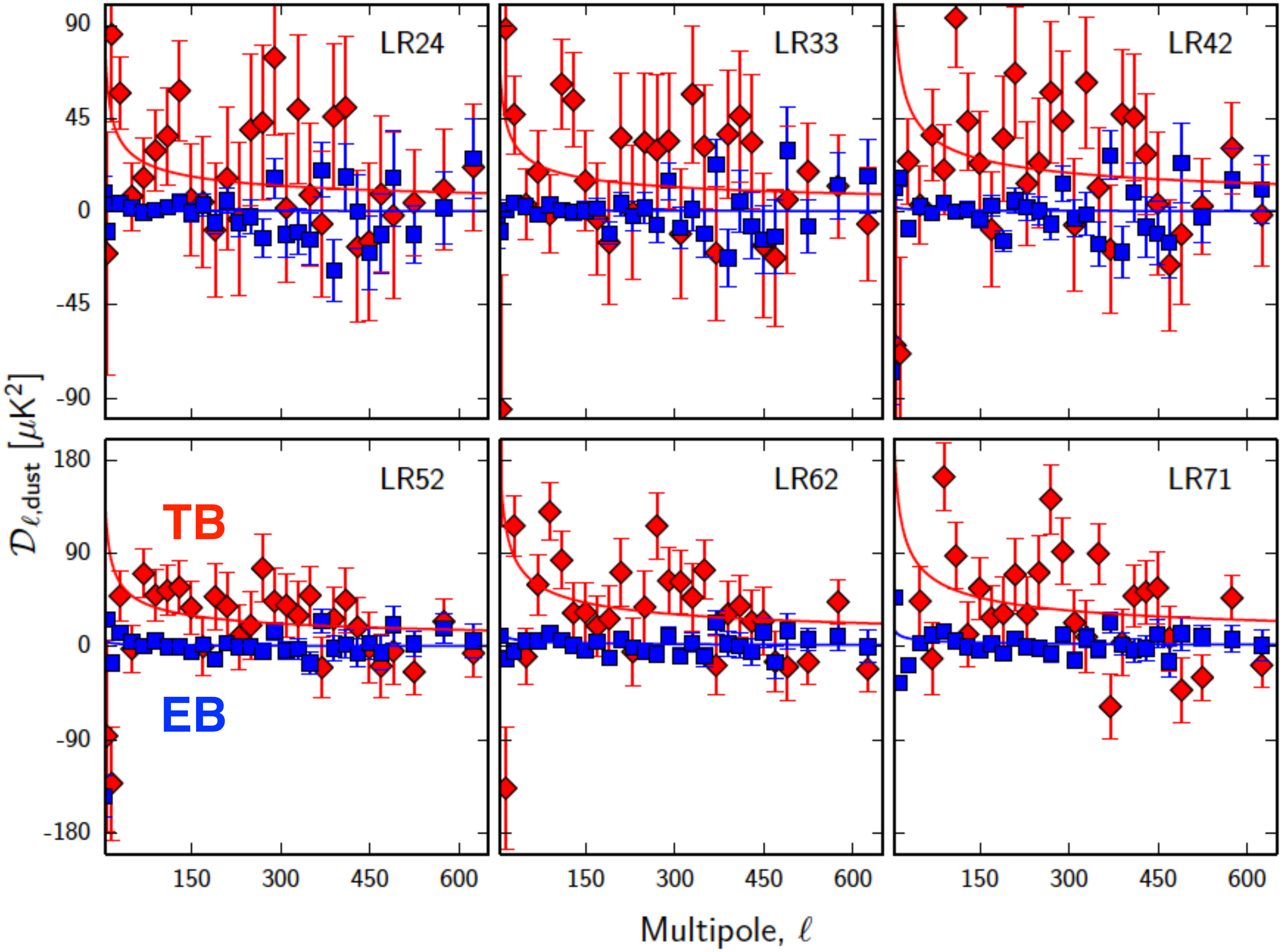
Sky regions





- The E/B asymmetry and TE correlation extend to low multipoles
- The power-law exponents for EE and BB are slightly different
- Spectra are not well fitted by a single power-law over the full multipole-range

Positive TB Correlation of dust polarization



➡ Dust polarization is not mirror symmetric. This result has not yet received an astrophysical interpretation

Frequency analysis

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

Synchrotron

Dust

$$\mathcal{D}_\ell^{XX}(\nu_1 \times \nu_2) = A_s^{XX}\left(\frac{\nu_1\nu_2}{30^2}\right)^{\beta_s} + A_d^{XX}\left(\frac{\nu_1\nu_2}{353^2}\right)^{\beta_d-2}\frac{B_{\nu_1}(T_d)}{B_{353}(T_d)}\frac{B_{\nu_2}(T_d)}{B_{353}(T_d)}$$
$$+\rho^{XX}(A_s^{XX}A_d^{XX})^{0.5}\left[\left(\frac{\nu_1}{30}\right)^{\beta_s}\left(\frac{\nu_2}{353}\right)^{\beta_d-2}\frac{B_{\nu_2}(T_d)}{B_{353}(T_d)} + \left(\frac{\nu_2}{30}\right)^{\beta_s}\left(\frac{\nu_1}{353}\right)^{\beta_d-2}\frac{B_{\nu_1}(T_d)}{B_{353}(T_d)}\right],$$

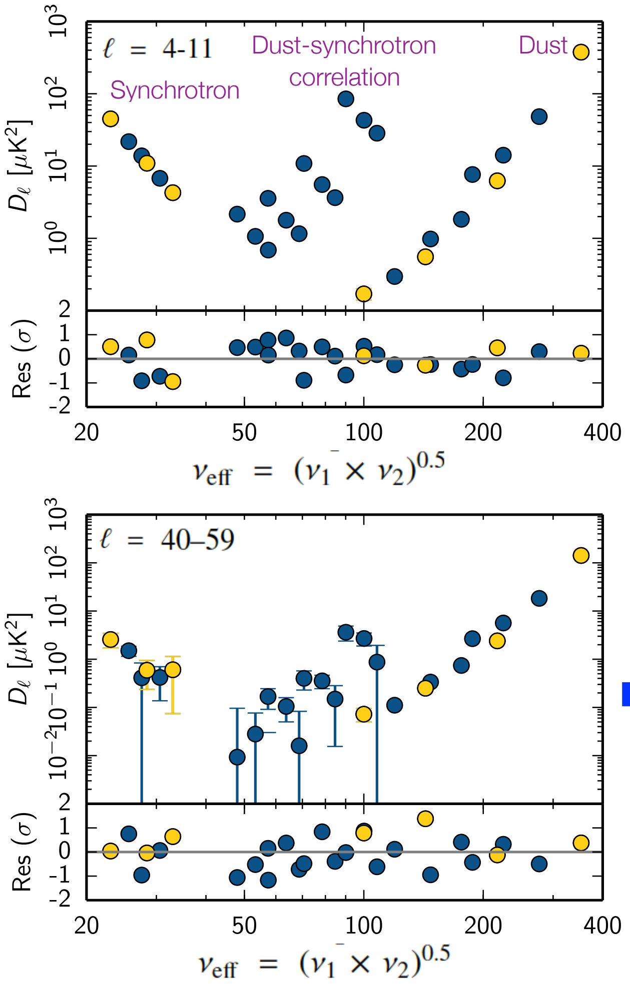
Synchrotron x Dust

Same model as in Choi & Page (2015)

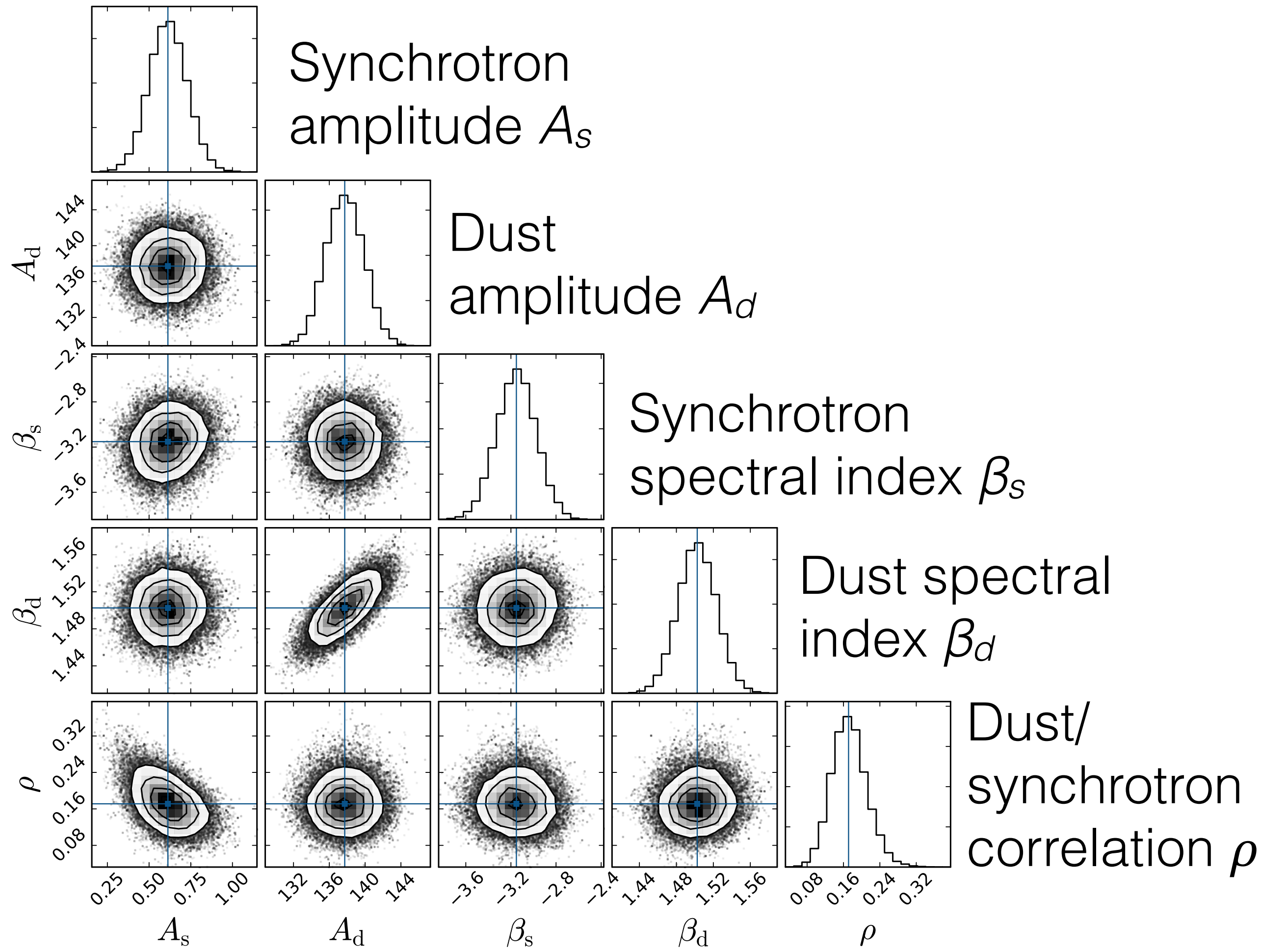
Five model parameters:

- 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 ρ

LR62 Sky region

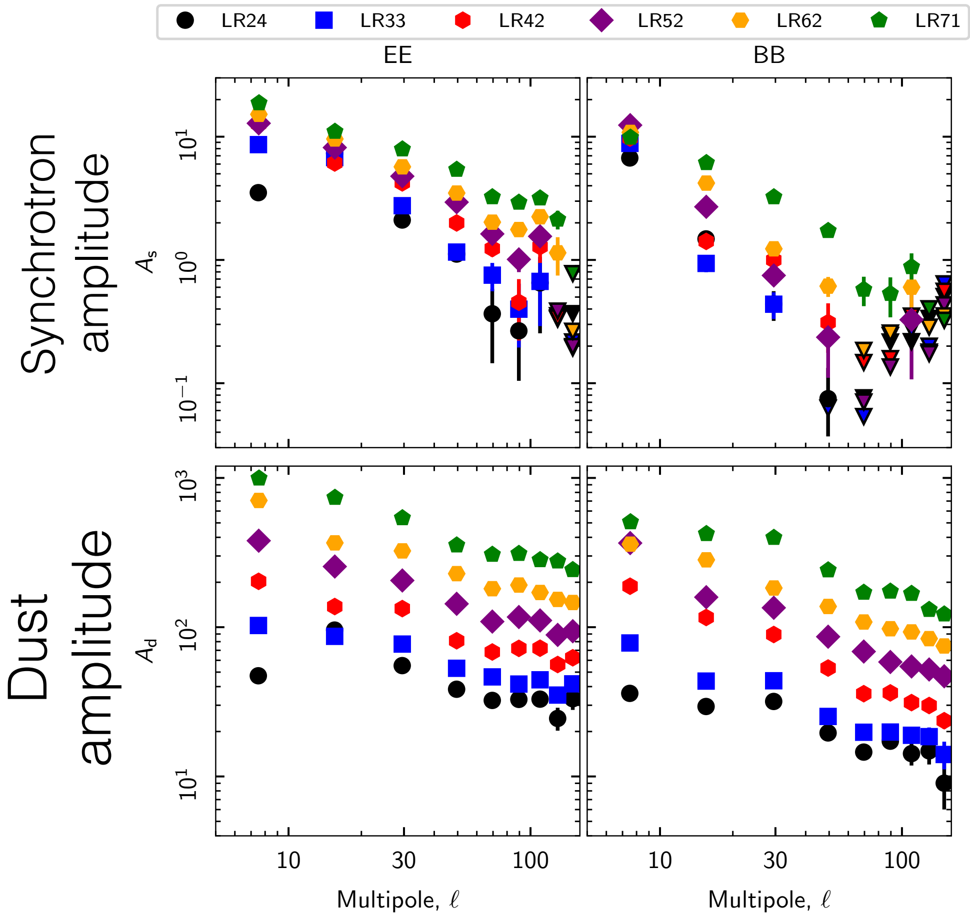


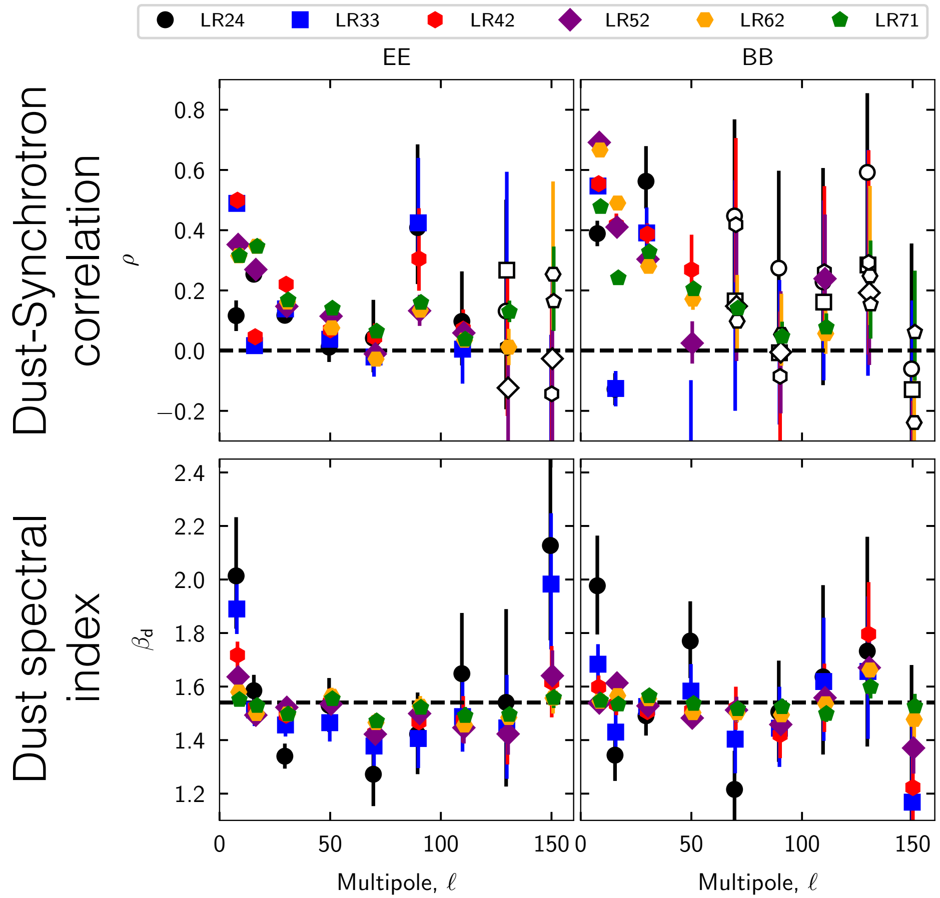
Model Parameters



➡ Spectral fits characterize polarized foregrounds vs ℓ and ν

Spectral fit parameters



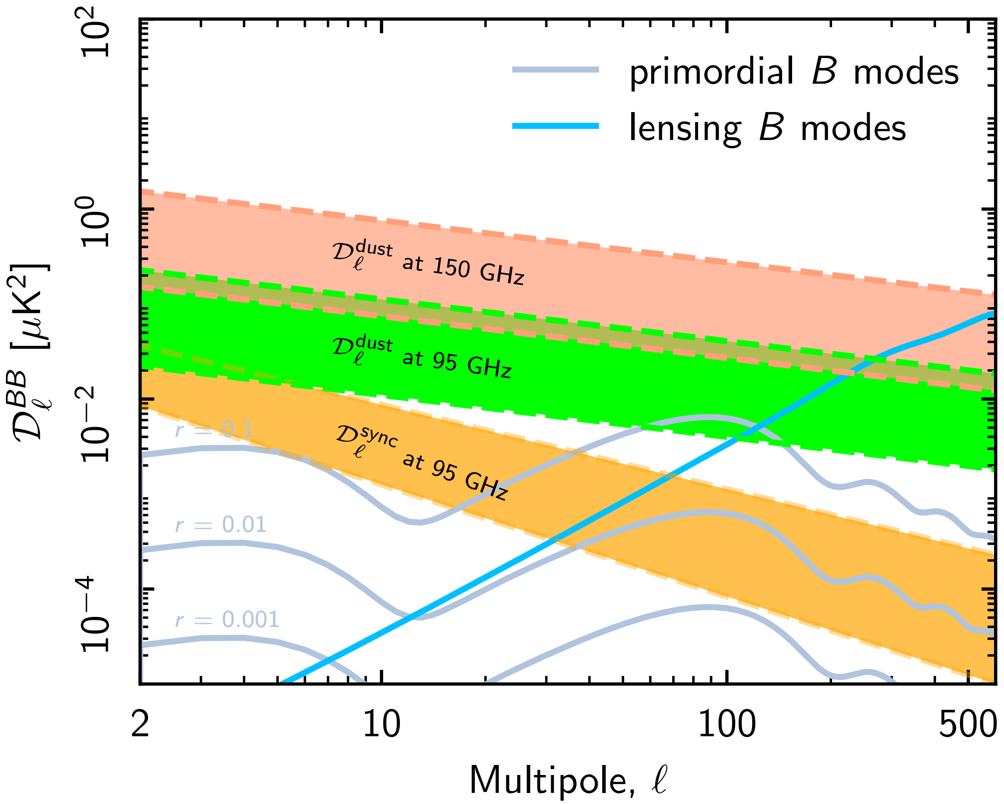


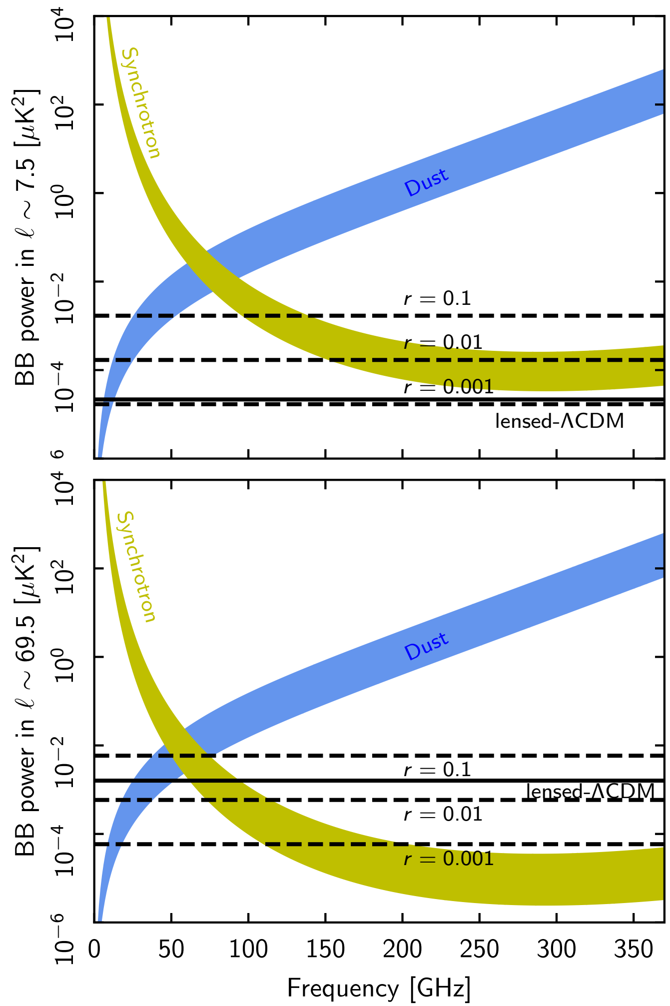
➡ Different scaling with respect to ℓ and sky regions for dust and synchrotron polarization

➡ Significant dust-synchrotron correlation at ℓ ≲ 50

➡ β_d does not depend on ℓ

Polarized foregrounds power





➡ Planck data quantify the challenge of the component-separation procedure required for measuring the low-ℓ CMB *E*-mode reionization signal, and detecting the reionization and recombination peaks of primordial CMB *B*-modes

Frequency correlation

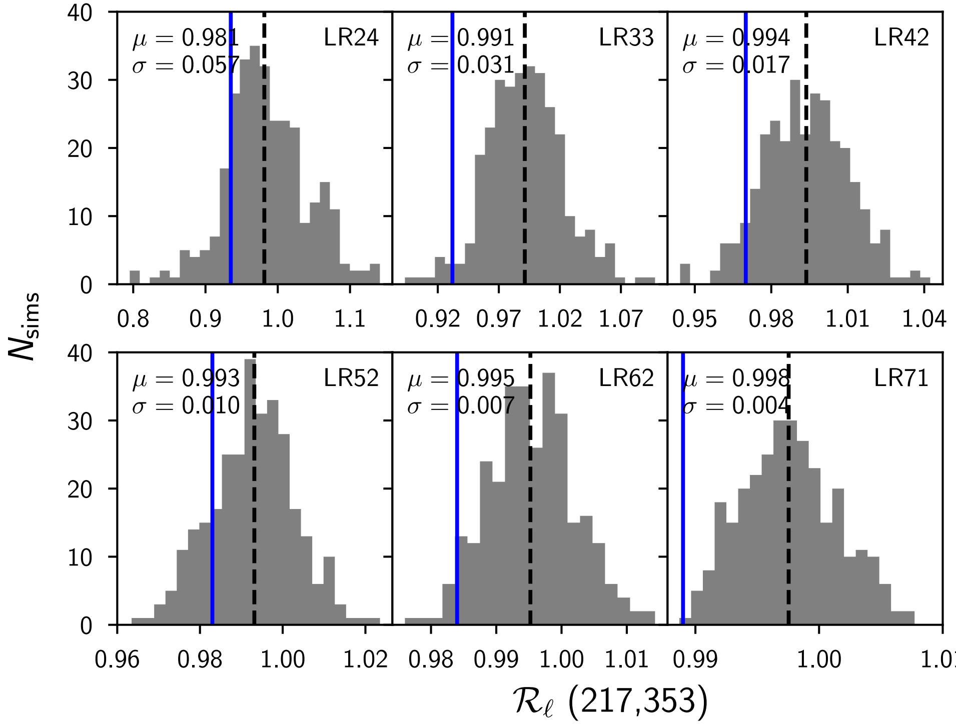
Dust spectral model with frequency decorrelation

$$\mathcal{D}_\ell^{BB_d}(\nu_1 \times \nu_2) = A_d \left(\frac{\nu_1 \nu_2}{353^2}\right)^{\beta_d - 2} \times \frac{B_{\nu_1}(T_d)}{B_{353}(T_d)} \frac{B_{\nu_2}(T_d)}{B_{353}(T_d)} f_d(\delta_d, \nu_1, \nu_2)\,,$$

$$f_d(\delta_d, \nu_1, \nu_2) = \exp\left\{ -\delta_d \left[\ln(\nu_1/\nu_2)\right]^2 \right\}$$

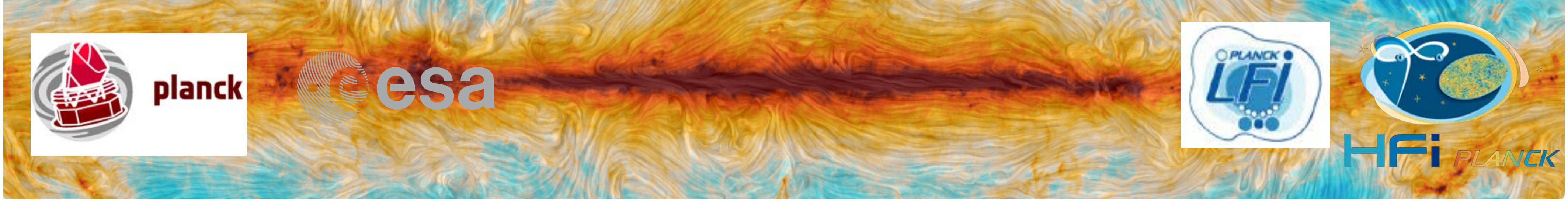
Model fitted on cross-spectra between 4 HFI polarized frequencies

End-to-end simulations
+ Planck value (blue line)



	LR24	LR33	LR42	LR52	LR62	LR71
HFI data	0.935 ± 0.054	0.932 ± 0.039	0.970 ± 0.021	0.983 ± 0.013	0.984 ± 0.008	0.989 ± 0.005
Mean E2E simulations[a]	0.976 ± 0.043	0.988 ± 0.026	0.993 ± 0.016	0.993 ± 0.011	0.995 ± 0.008	0.997 ± 0.005
E2E lower limits[b]	0.865	0.924	0.963	0.973	0.983	0.991

➡ No conclusive evidence of frequency decorrelation at the Planck sensitivity



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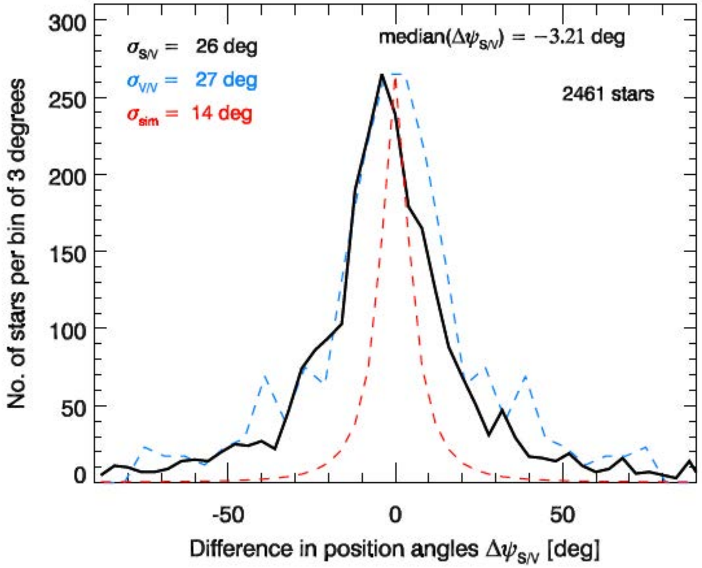
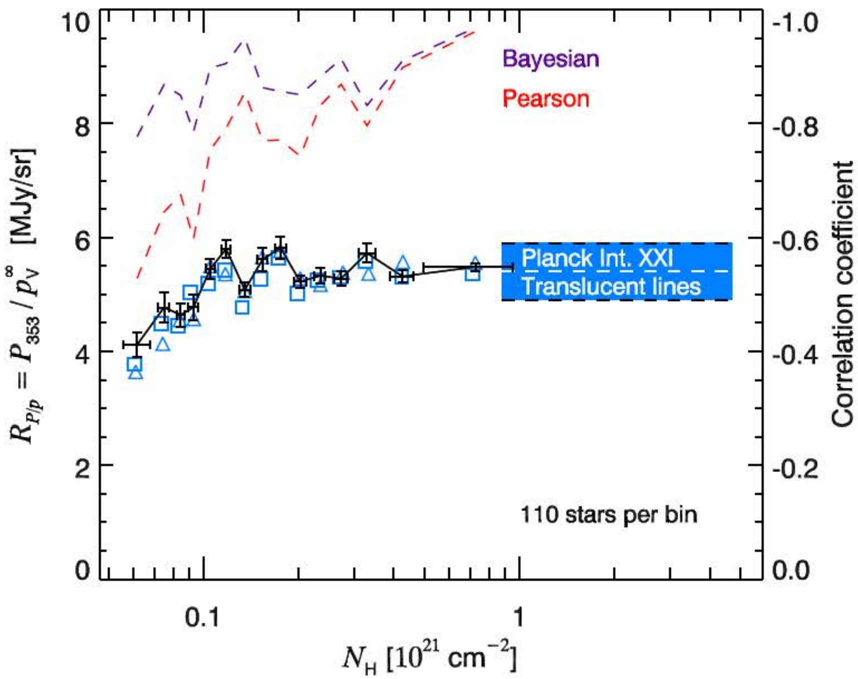
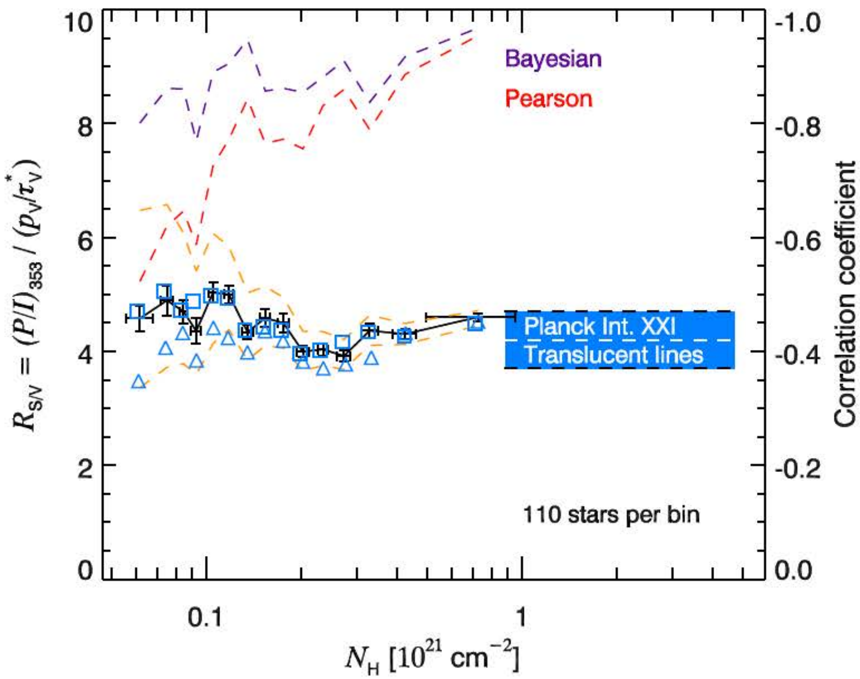
Dust extinction vs emission



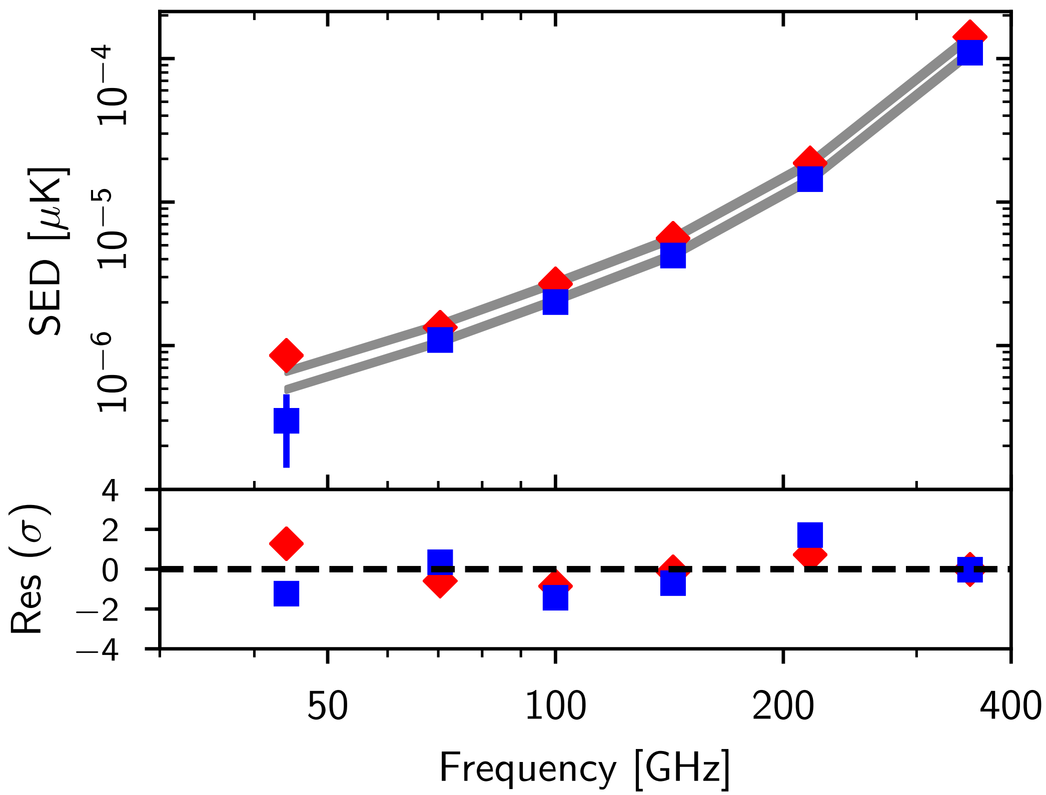
- Good correlation between Planck and stellar polarization
- The measured ratios between Stokes parameters and polarization fraction constrain dust models
- The values first determined in translucent lines of sight apply to lower column densities





Dust spectral energy distribution

Dust SED in polarization



- The dust SED in polarization from blind component separation is remarkably well fit by a single temperature modified black-body emission law from 353 to 44 GHz

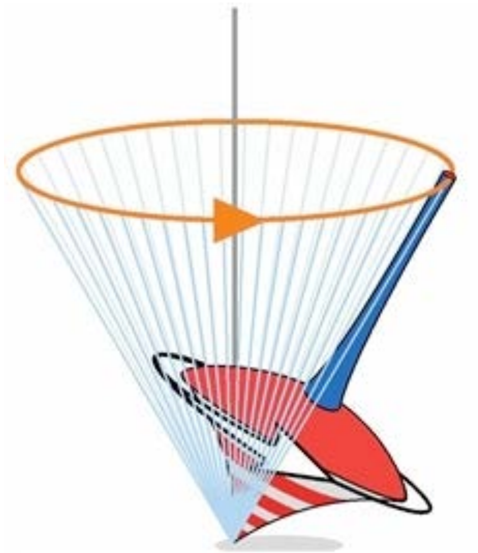
Polarization vs total intensity

- The difference between spectral indices for polarization and total intensity is small (0.05 ± 0.03) and not of high statistical significance
- This result suggests that the emission from a single grain type dominates the long-wavelength emission in both polarization and total intensity.
- It constrains dust models involving multiple dust components (e.g., separate carbon and silicate grains) and magnetic dipole emission

Grain Alignment

- Interstellar grains spin like tops around their axis of maximal inertia. Their rotation axis precesses around the magnetic field lines.

- Alignment of interstellar grains is thought to result from the combined action of radiative torques and paramagnetic relaxation (Hoang and Lazarian 2016). For this to be effective interstellar silicates must comprise magnetic inclusions.



➡ The Planck data fit with a degree of grain alignment that is homogeneous in the diffuse ISM and molecular cloud envelopes

➡ This result and the high polarization fraction indicate that grain alignment is an efficient interstellar process

Summary

★ Planck dust polarization maps reveal the imprint of interstellar magnetic fields on matter. The data probe the field structure in the diffuse ISM and in star-forming molecular clouds, on scales relevant to the formation of their filamentary structure.

★ 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

★ Polarization data set valuable constraints on dust composition, which call for new efforts in dust modeling