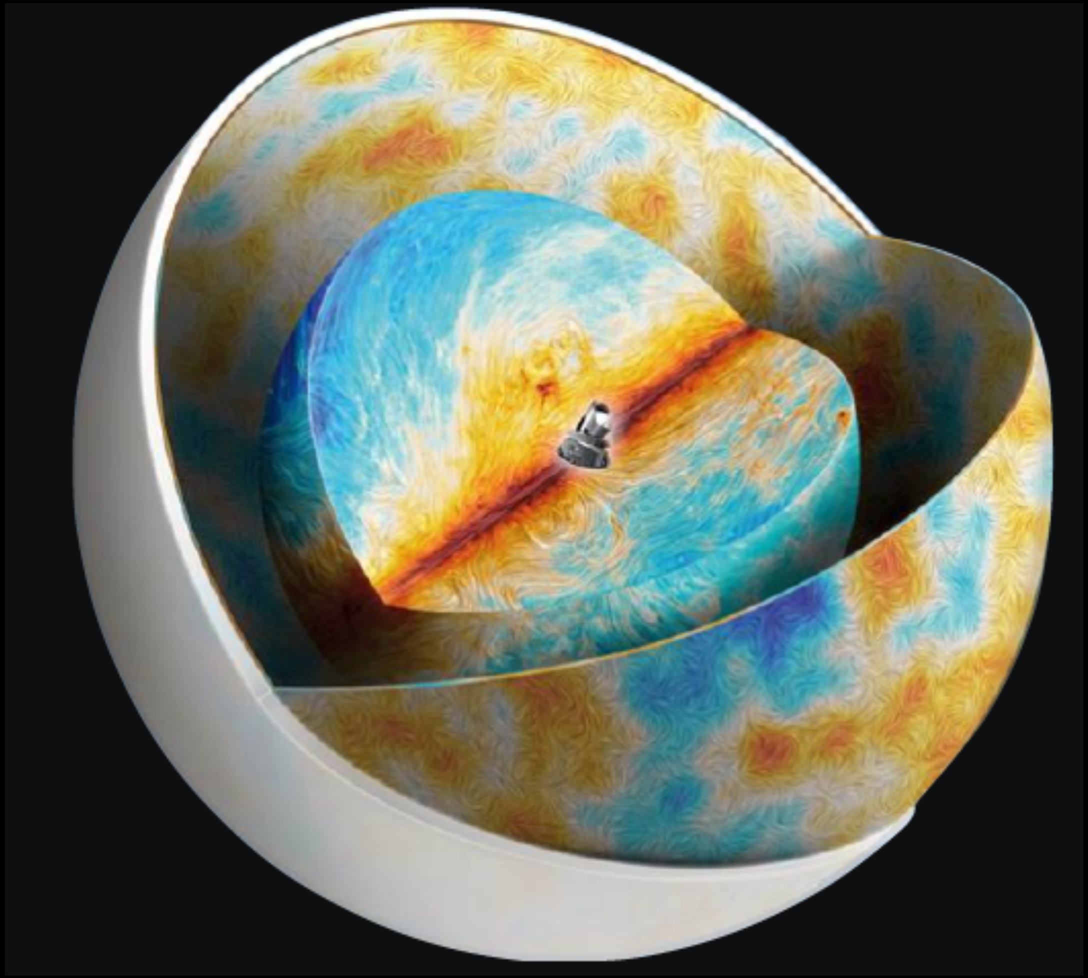
Polarized Foregrounds



François Boulanger

Ecole Normale Supérieure

Outline

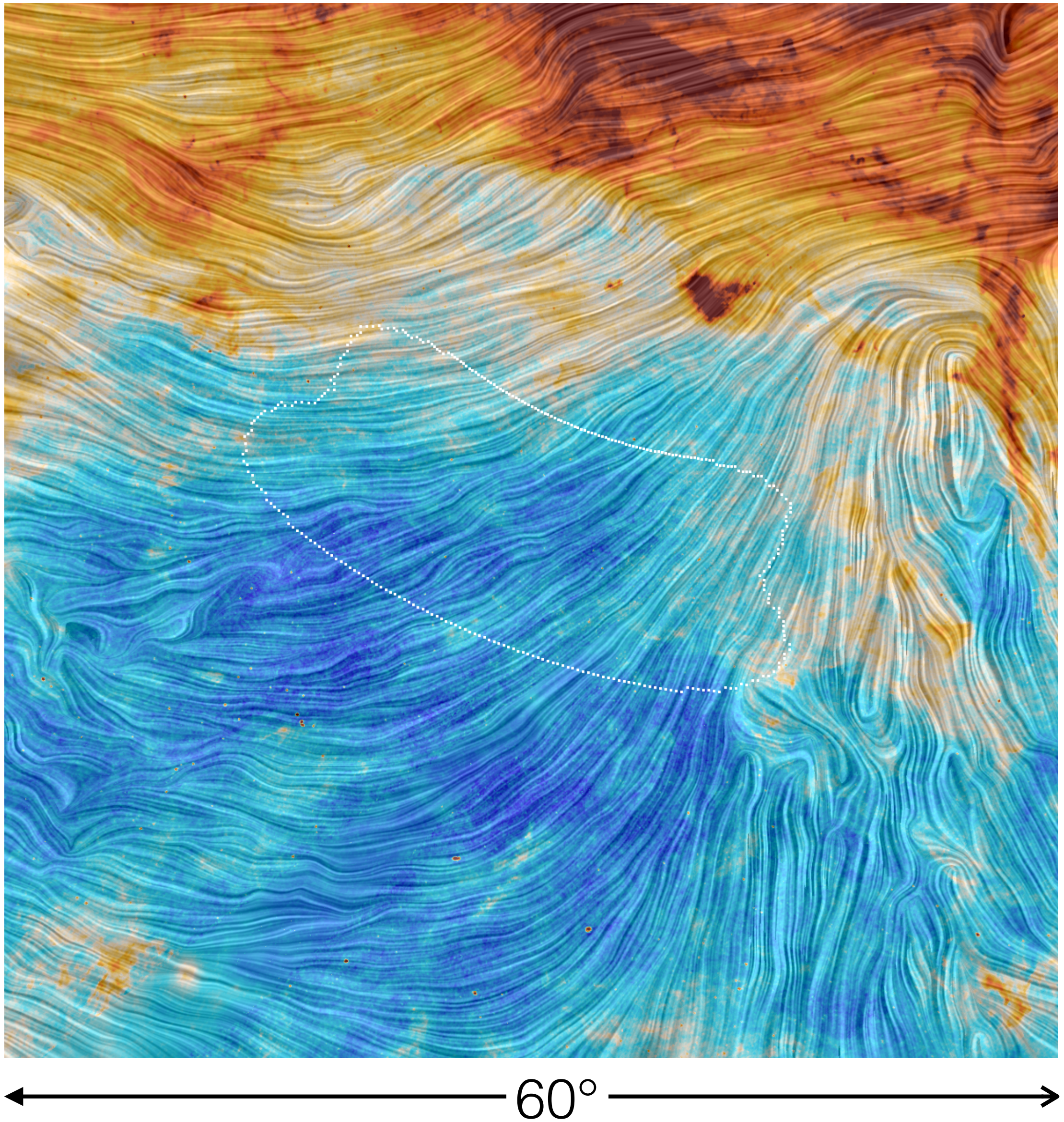
★Lecture III: Statistical description and modeling of polarized foregrounds

- Statistical description of dust polarization
- Statistical modelling

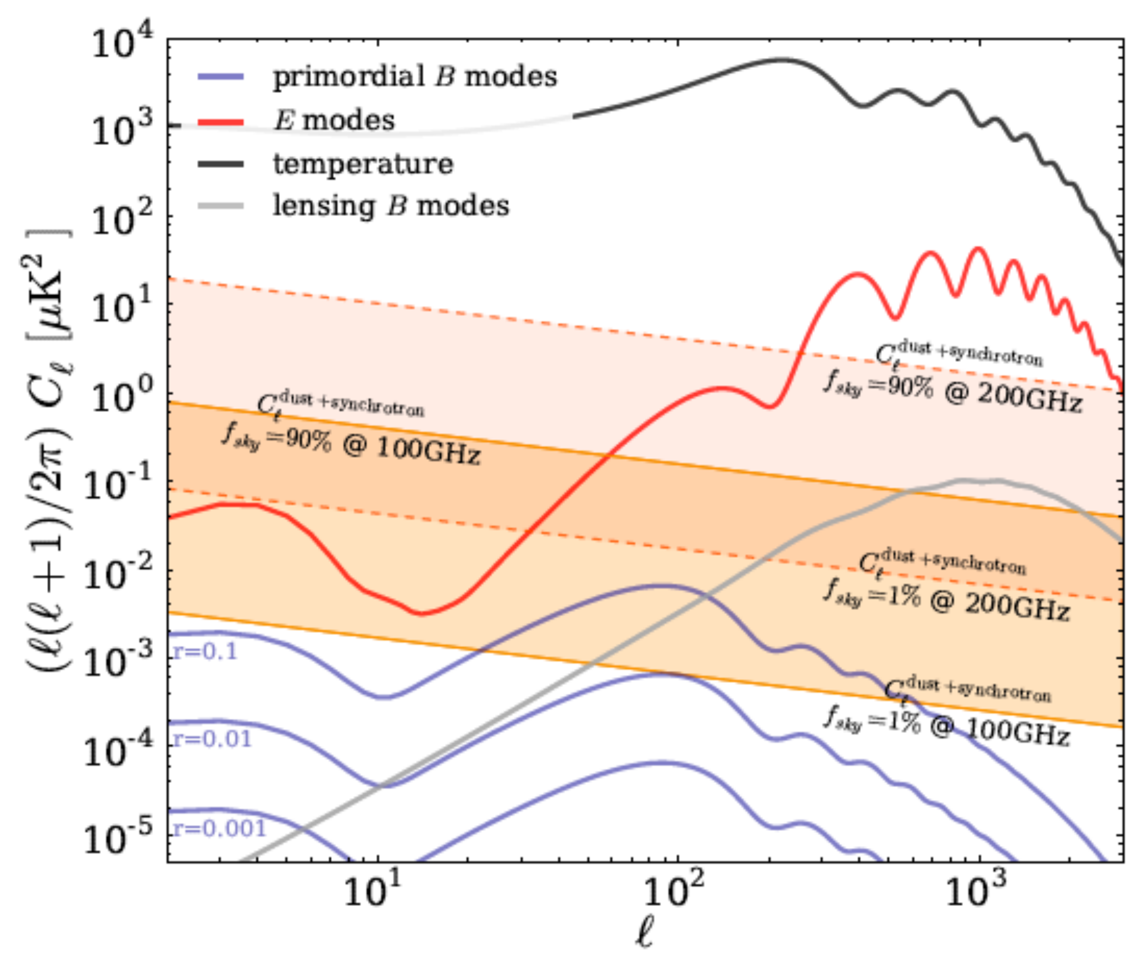
The foreground screen from the magnetized ISM

- The power spectra of dust polarization was characterized over the whole sky using Planck data
- There is no sky area where the Galactic signal may be neglected
- Any claim for a detection will face a critical assessment against alternative interpretations involving foregrounds

BICEP/Keck field on Planck image



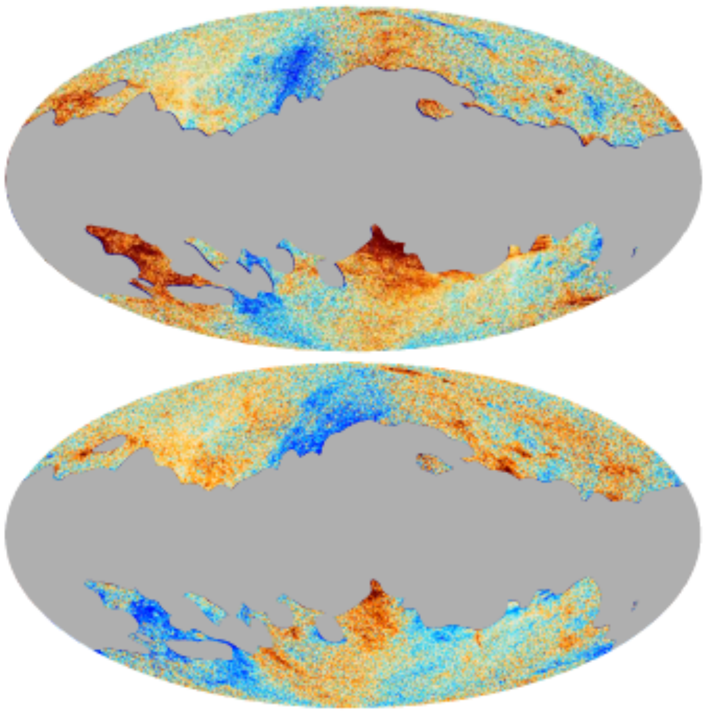
Primordial B-mode signal



Errard+ 2016

- Future experiments (CMB stage IV, LiteBIRD) will have the sensitivity to detect primordial B-modes down to r=0.001
- Component separation is an outstanding challenge
- Statistical of foregrounds modelling required to assess and optimize the separation of Galactic and CMB polarization

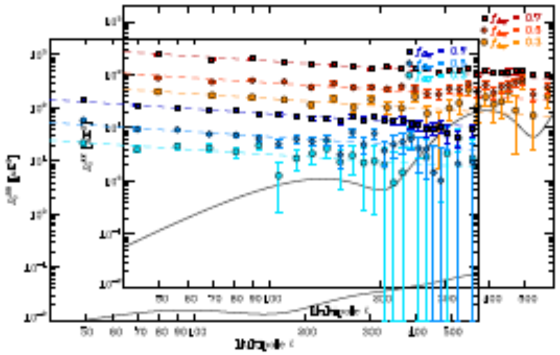
General methodology



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
C_ℓ^{EE} and C_ℓ^{BB}

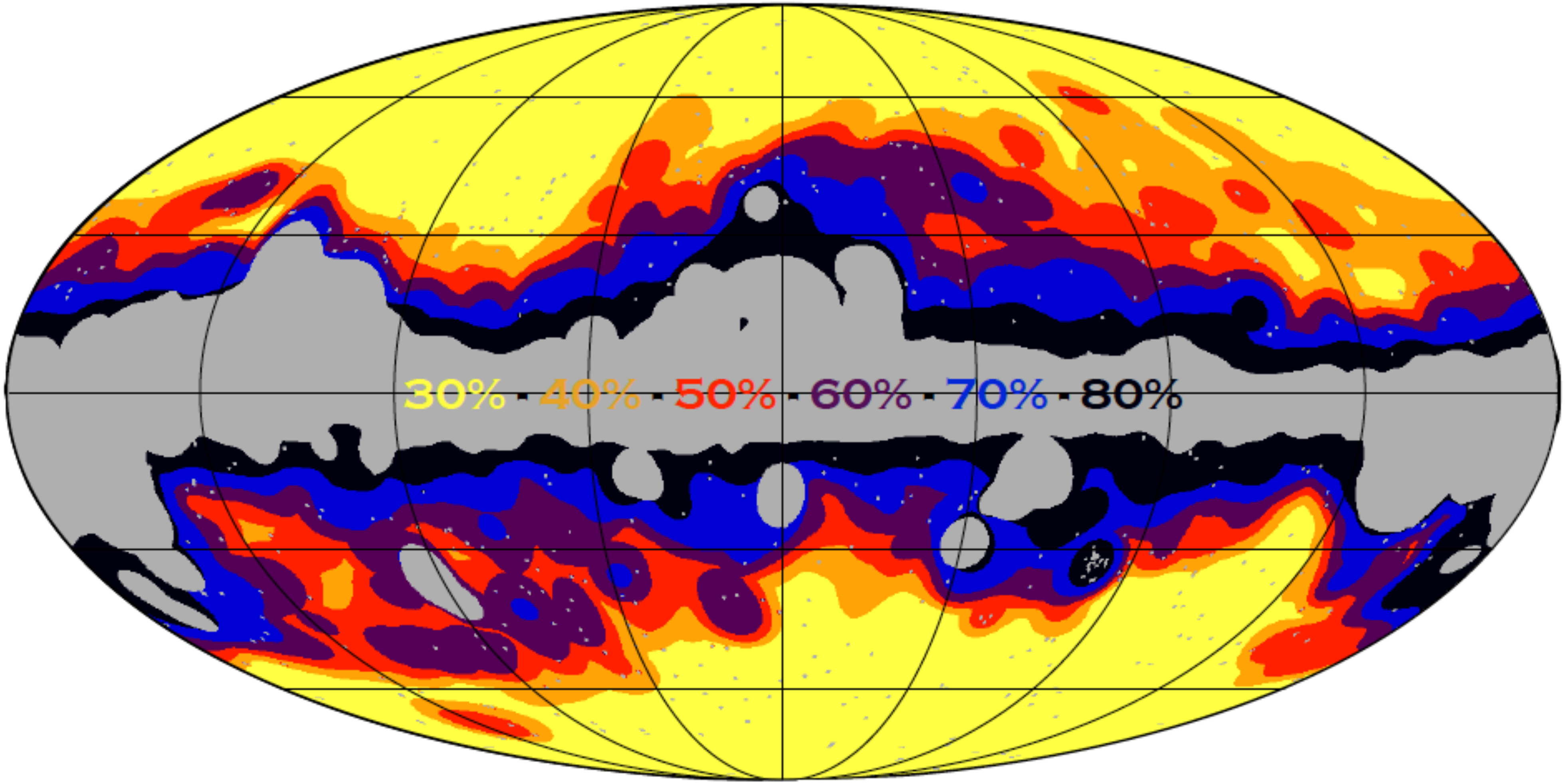
Spectra are computed from the two noise-independent Detector Set maps

$$C_\ell(\nu \times \nu) \equiv C_\ell(D^1_\nu \times D^2_\nu).$$

The CMB C_ℓ^{EE} best fit model is removed
[Planck Collaboration XIV 2014]

Large sky fraction regions

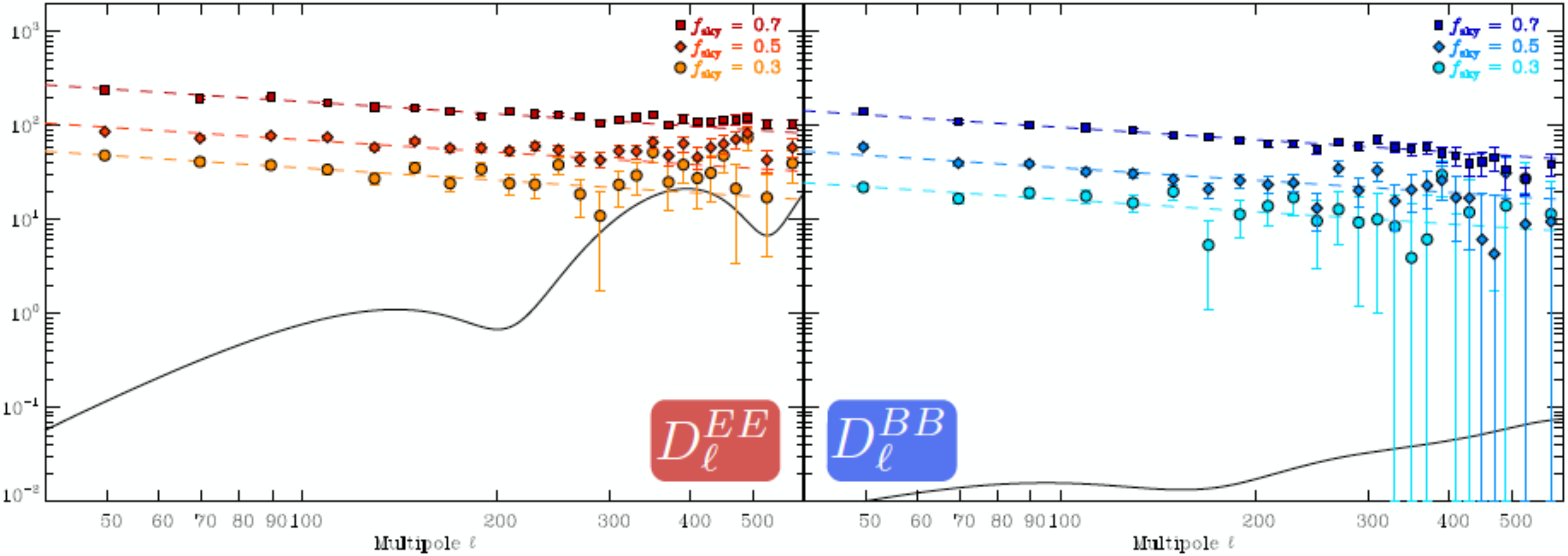
Masks: built from the smoothed (10 degrees) dust intensity map at 857 GHz



+ CO + radio point sources mask + apodization (5 degrees)

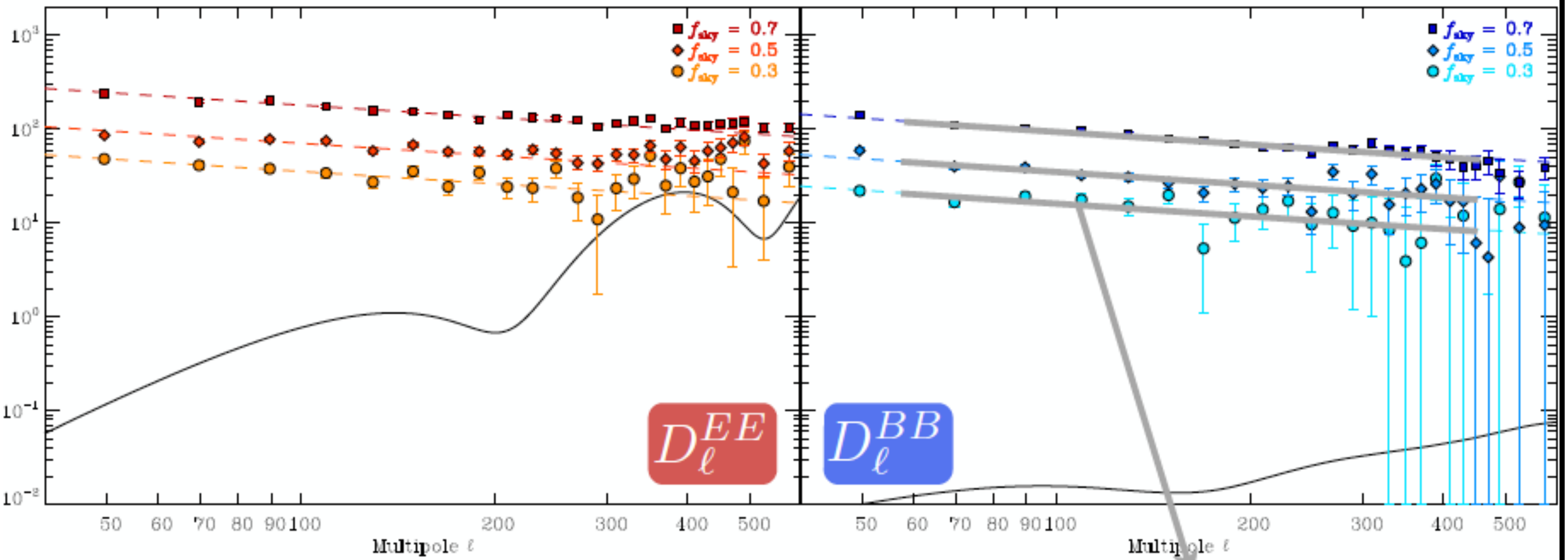
[Planck Intermediate XXX 2014, arXiv 1409.5738]

Dust polarization angular power spectra features at 353 GHz



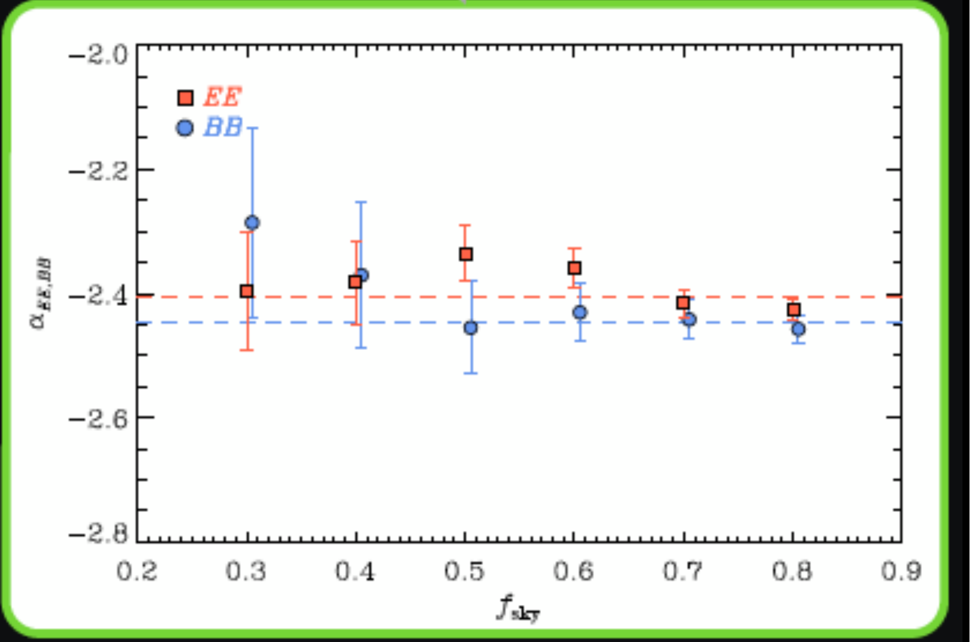
[Planck Intermediate 2014 XXX]

Dust polarization angular power spectra features at 353 GHz

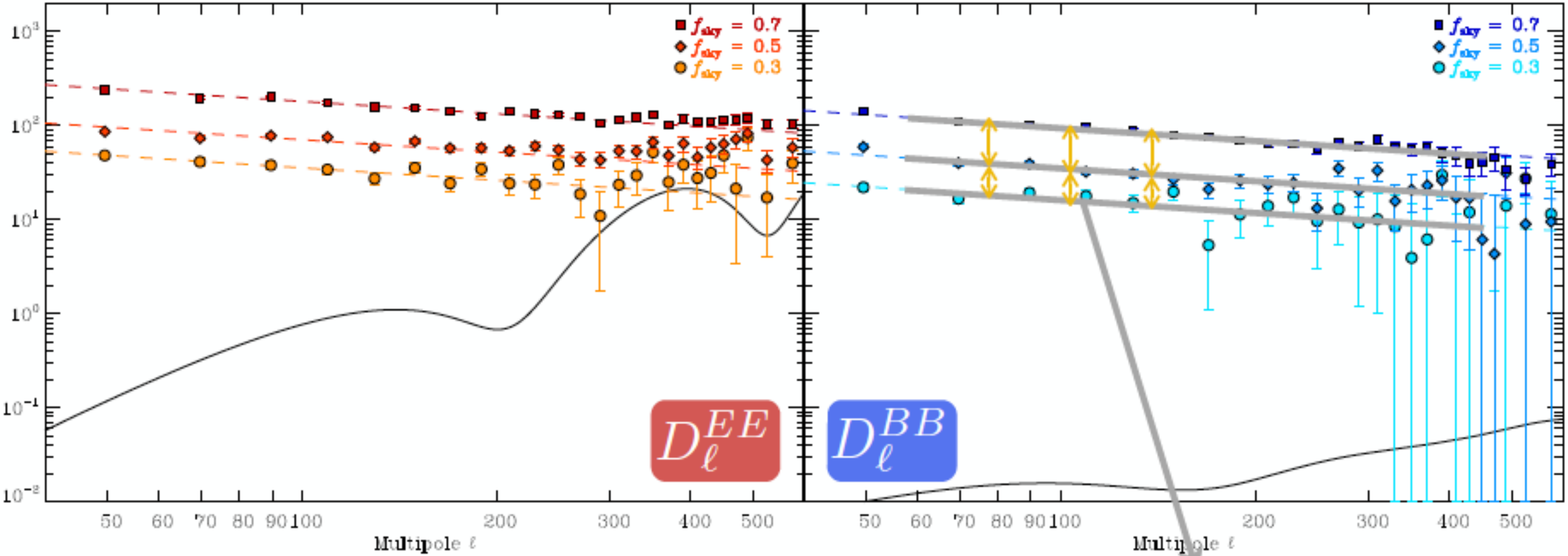


[Planck Intermediate 2014 XXX]

★ Dust polarization spectra follow power-laws of ℓ with a -2.42 slope

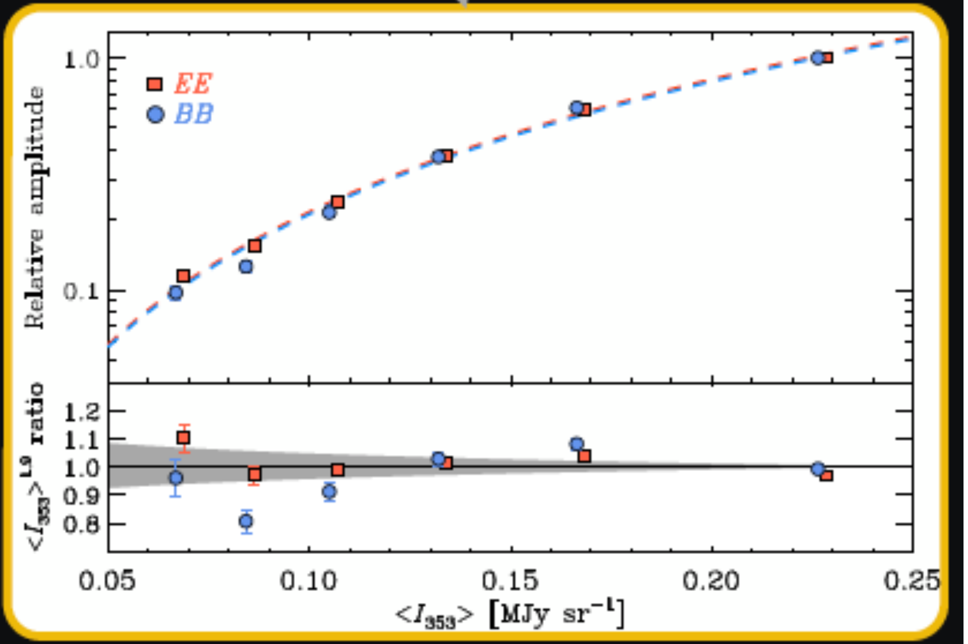


Dust polarization angular power spectra features at 353 GHz

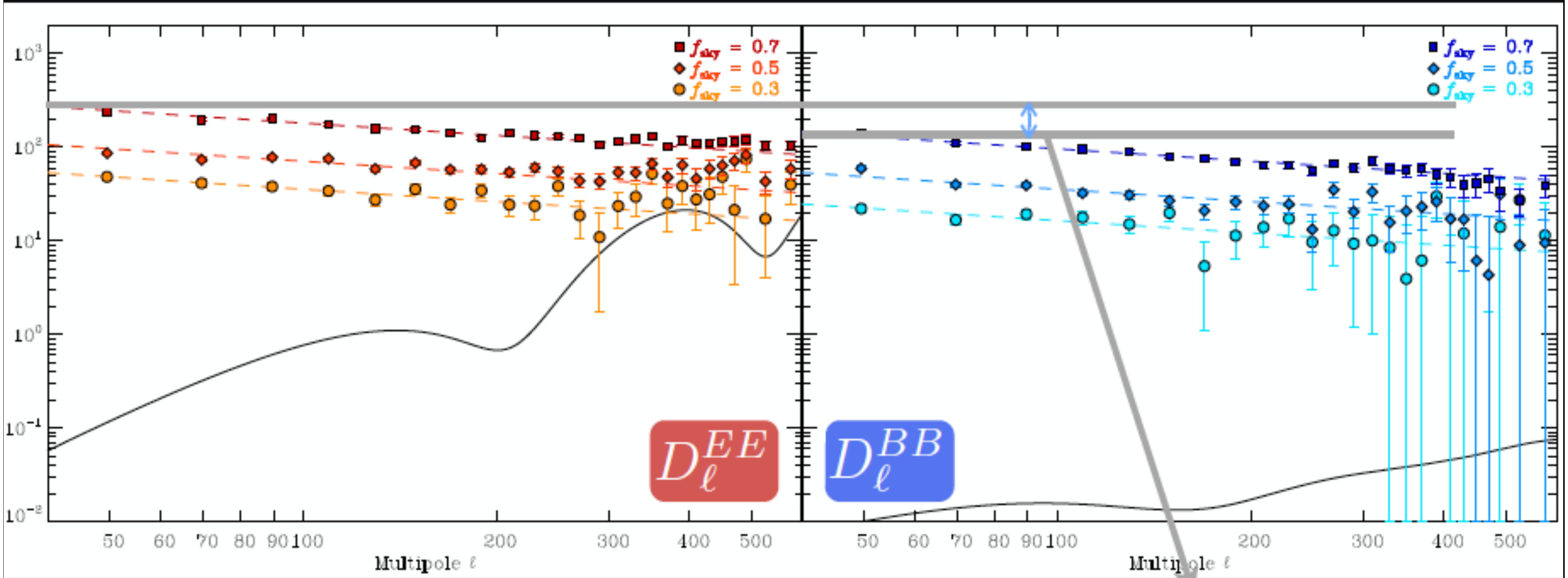


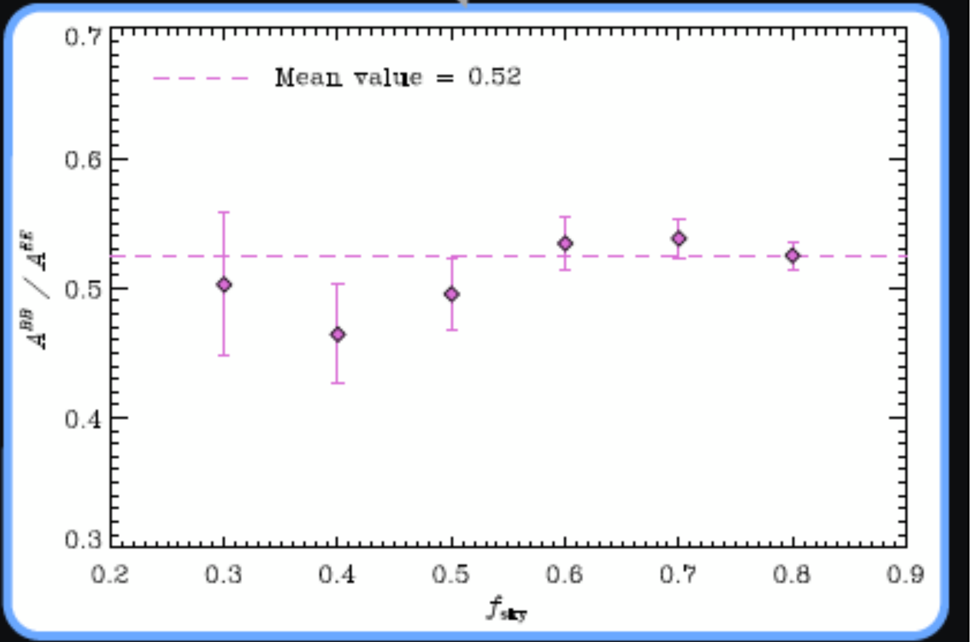
[Planck Intermediate 2014 XXX]

- ★ Dust polarization spectra follow power-laws of ℓ with a -2.42 slope
- ★ Spectra scale as a function of the mean intensity of the mask ($\langle I_{dust}\rangle^{1.9}$)



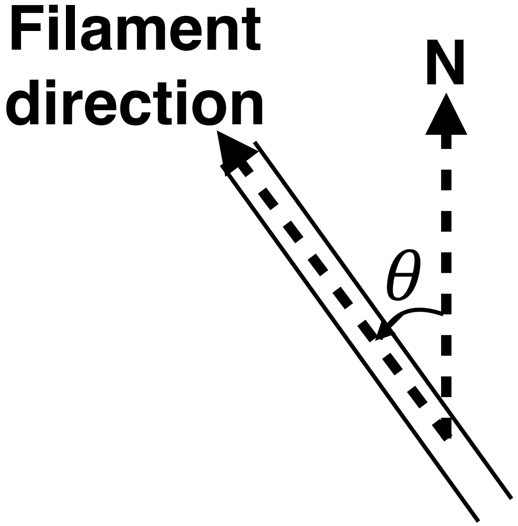
Dust polarization angular power spectra features at 353 GHz





[Planck Intermediate 2014 XXX]
[Planck Intermediate 2014 XXXVIII]

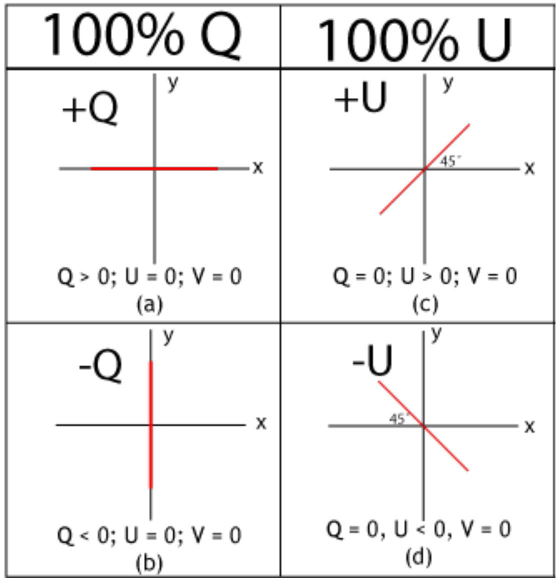
- ★ Dust polarization spectra follow power-laws of ℓ with a -2.42 slope
- ★ Spectra scale as a function of the mean intensity of the mask ($<I_{dust}>^{1.9}$)
- ★ $BB/EE \sim 0.5$

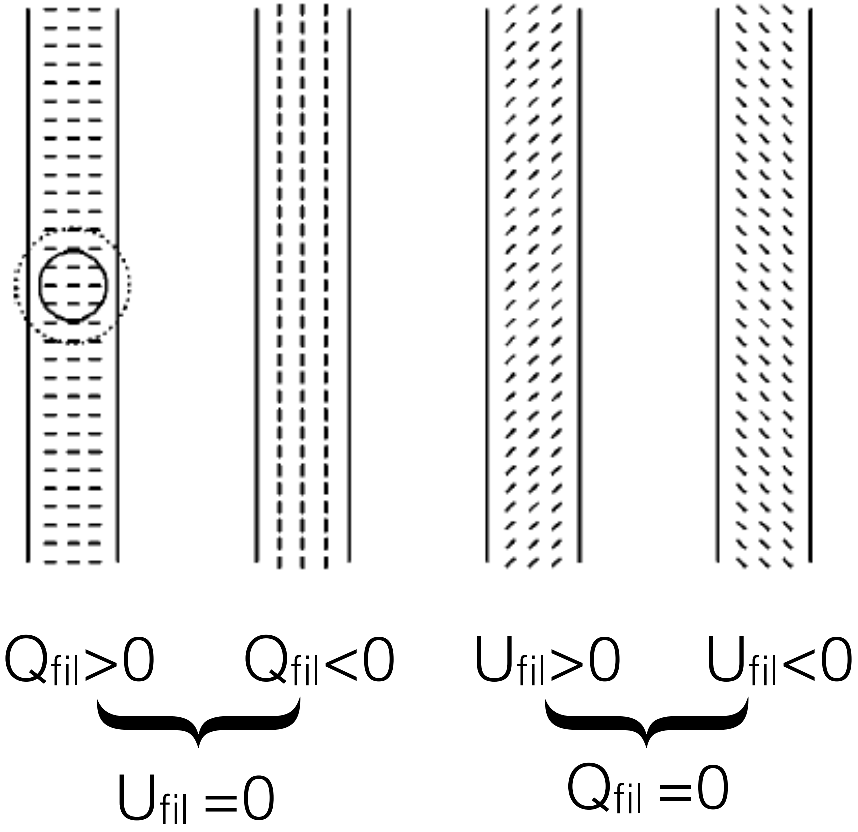


Stokes parameters computed with respect to the filament direction

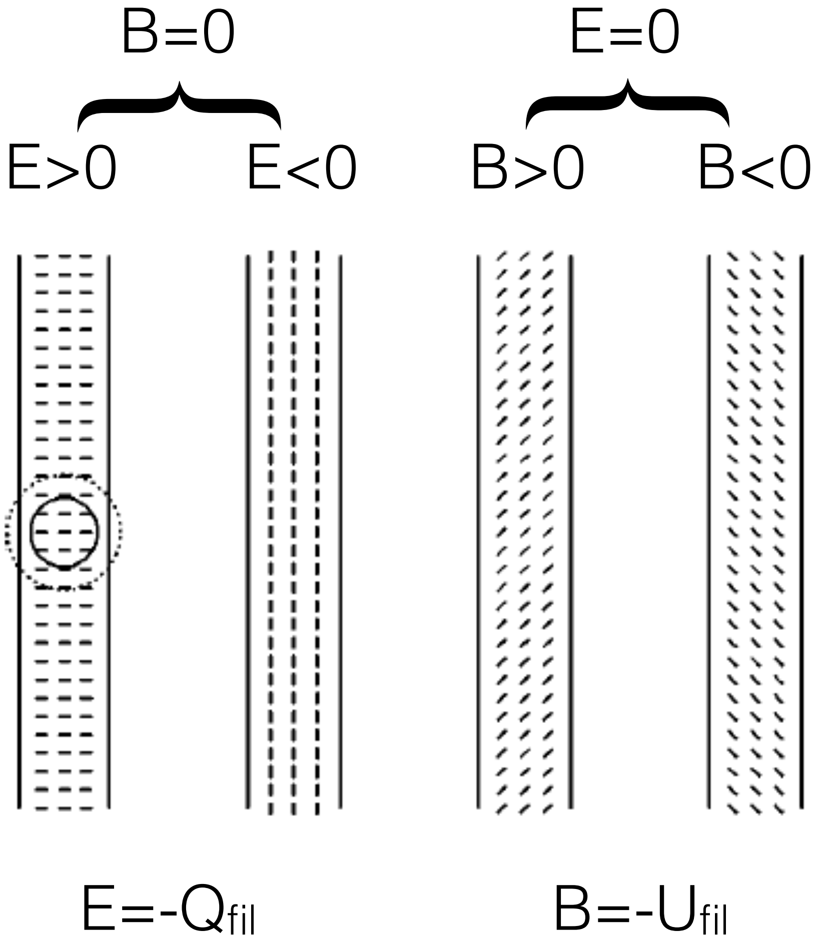
$$Q_{fil} = \ Q\,cos2\theta + U\,sin2\theta$$

$$U_{fil} = -Q\,sin2\theta + U\,cos2\theta$$





Polarization patterns

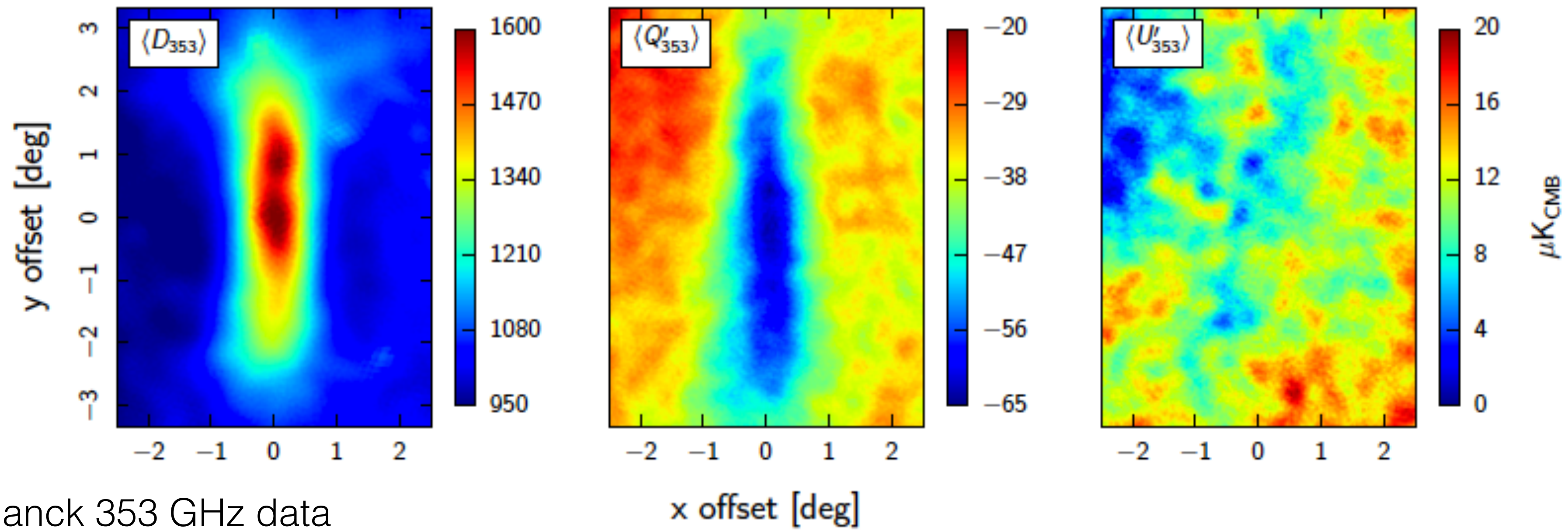


Zaldarriaga 2001

- E et B are scalars rotation invariant (they do not depend on θ)
- E is parity invariant (conserved after reflexion of the polarization pattern)
- B has an odd parity (changes sign by reflexion)

Stacking of filaments at high Galactic latitudes

I $\qquad$ Q_{fil} = -E $\qquad$ U_{fil} = -B



Planck 353 GHz data

Alignment of magnetic field and filamentary structures accounts for both the TE correlation and E/B asymmetry

[Planck int. res. XXXVIII, A&A 2016 586, 141]

Modelling approach

- Stokes I from 353 GHz dust-only sky map (CMB and cosmic infrared background subtracted)
- Magnetic field model required to compute noise-free Stokes Q and U maps
- Ordered magnetic field + statistical model of turbulent component
- Model parameters fitted on Planck dust power spectra EE, BB and TE and one-point statistics of polarization fraction and angle

Modelling motivations

- Statistical modeling of foregrounds is required to confidently identify primordial CMB B-modes (or set upper limits)
- Propagate instrumental effects in end-to-end simulations of data pipeline
- Optimize component separation for CMB polarization and assess statistically uncertainties
- Astrophysical interpretation of data

Parametric model

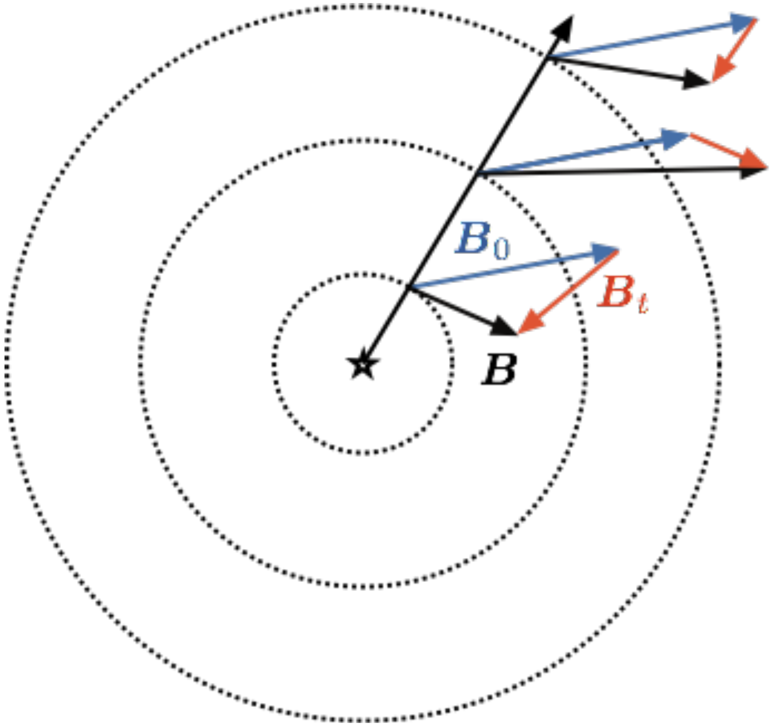
- Magnetic field
  - Uniform + random

$$\boldsymbol{B} = |\boldsymbol{B}_0|\,(\hat{\boldsymbol{B}}_0 + f_\mathrm{M}\,\hat{\boldsymbol{B}}_\mathrm{t})$$

  - Power-law spectrum

$$C_\ell \propto \ell^{\alpha_\mathrm{M}} \text{ for } \ell \geq 2$$

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



Turbulent field

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

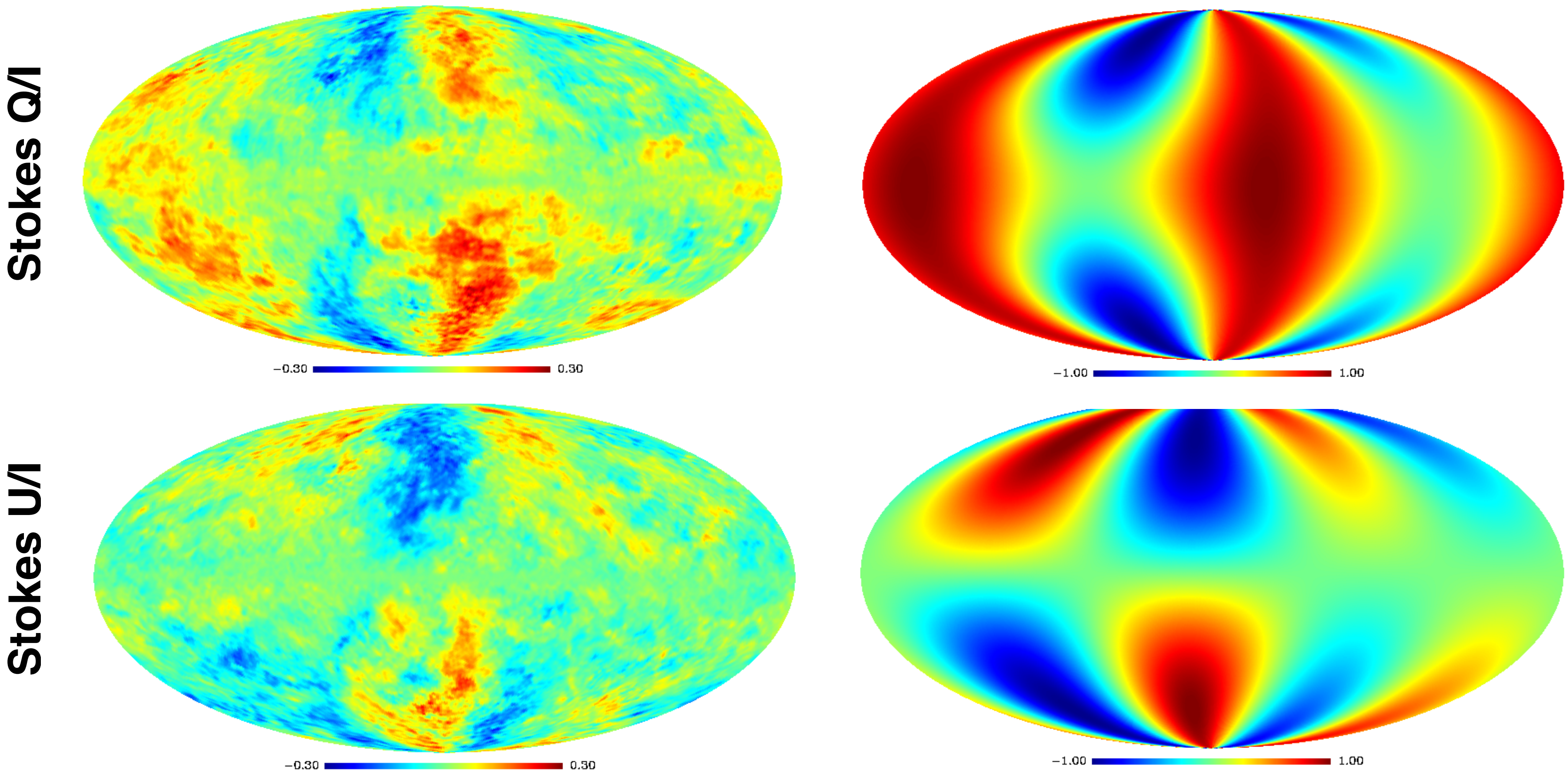
Ordered field

Planck collaboration XLIV (2016), Ghosh+ 2017, Vansyngel+ 2017

Ordered magnetic field

Planck maps smoothed (80’ beam)

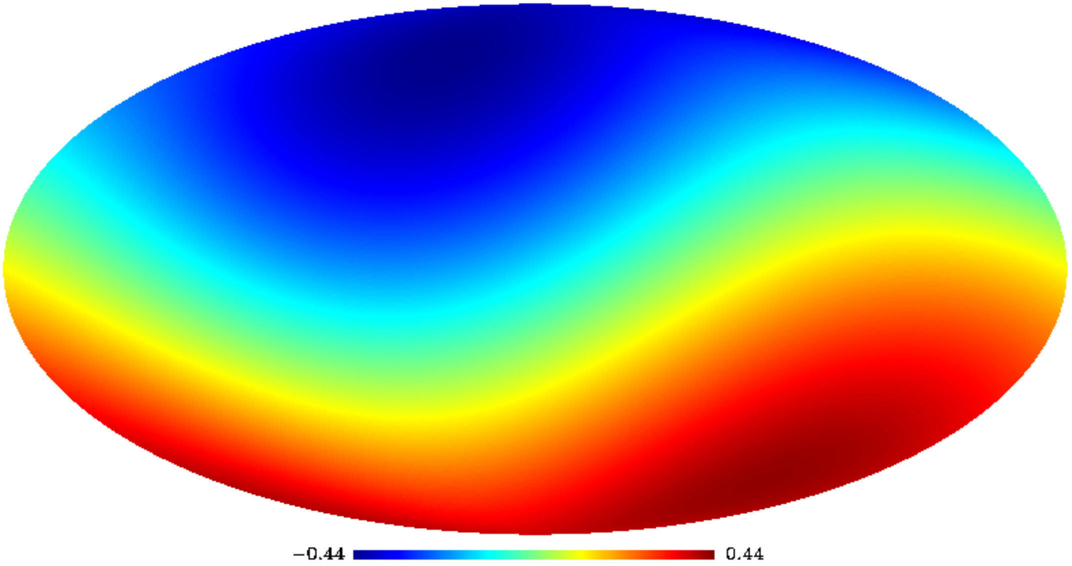
Model with no turbulence



Ordered magnetic field

- Ordered magnetic field inferred from data fitting includes a significant component pointing towards the Galactic disk at both poles
- We may be seeing a local deformation of the Galactic magnetic field associated with the Local Bubble

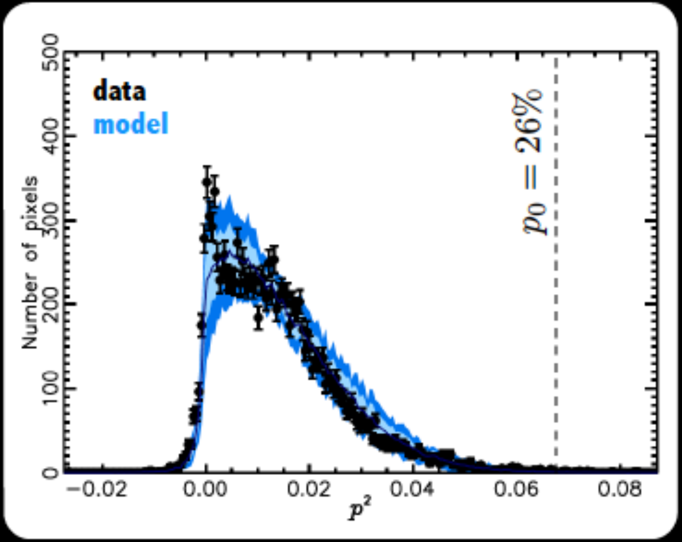
Component of B_0 perpendicular to Galactic disk



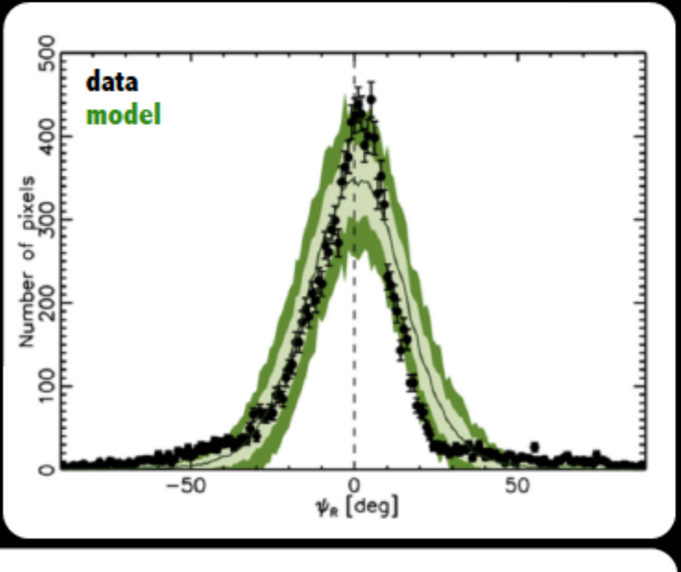
Dust polarization statistics

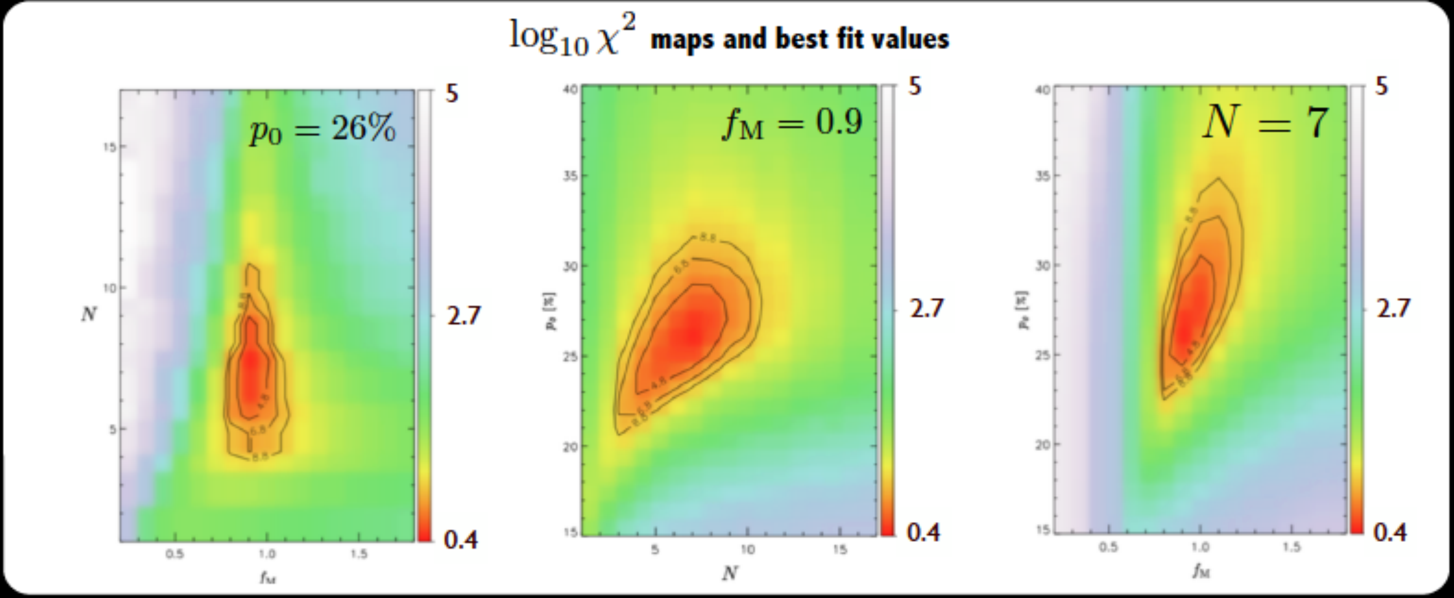
[Planck int. res. XLIV. arXiv:1604.01029]

Polarization fraction



Polarization angle

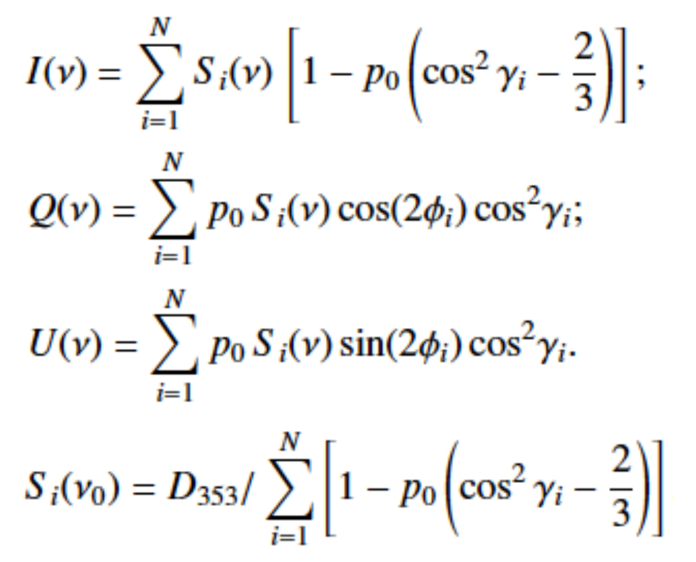




- High dust polarization fraction (p_0=0.26)
- Turbulence is sub/trans-Alvenic (f_M ~0.9)
- Small number of structures/turbulent cells along the line of sight

PhD Andrea Bracco

Model (a)



$$I(\nu) = \sum_{i=1}^{N} S_i(\nu)\left[1 - p_0\left(\cos^2\gamma_i - \frac{2}{3}\right)\right];$$

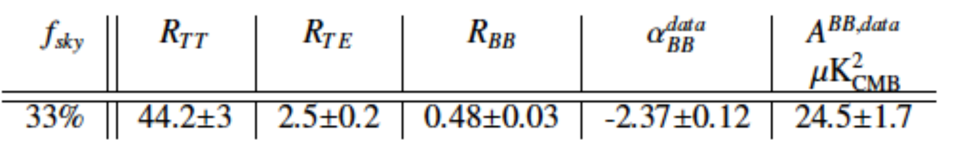
$$Q(\nu) = \sum_{i=1}^{N} p_0\, S_i(\nu)\cos(2\phi_i)\cos^2\gamma_i;$$

$$U(\nu) = \sum_{i=1}^{N} p_0\, S_i(\nu)\sin(2\phi_i)\cos^2\gamma_i.$$

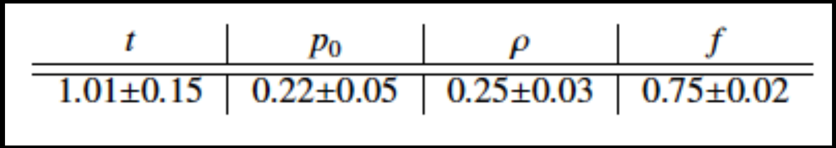
$$S_i(\nu_0) = D_{353} / \sum_{i=1}^{N}\left[1 - p_0\left(\cos^2\gamma_i - \frac{2}{3}\right)\right]$$

Angles computed from
Gaussian realizations

$N=4 \quad f_M = 0.9$

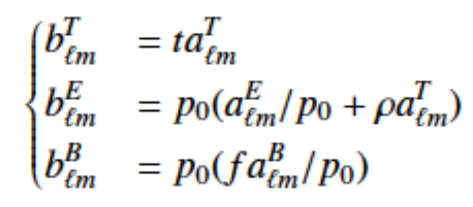


f_{sky}	R_{TT}	R_{TE}	R_{BB}	α_{BB}^{data}	$A^{BB,data}$ μK^2_{CMB}
33%	44.2±3	2.5±0.2	0.48±0.03	-2.37±0.12	24.5±1.7



t	p_0	ρ	f
1.01±0.15	0.22±0.05	0.25±0.03	0.75±0.02

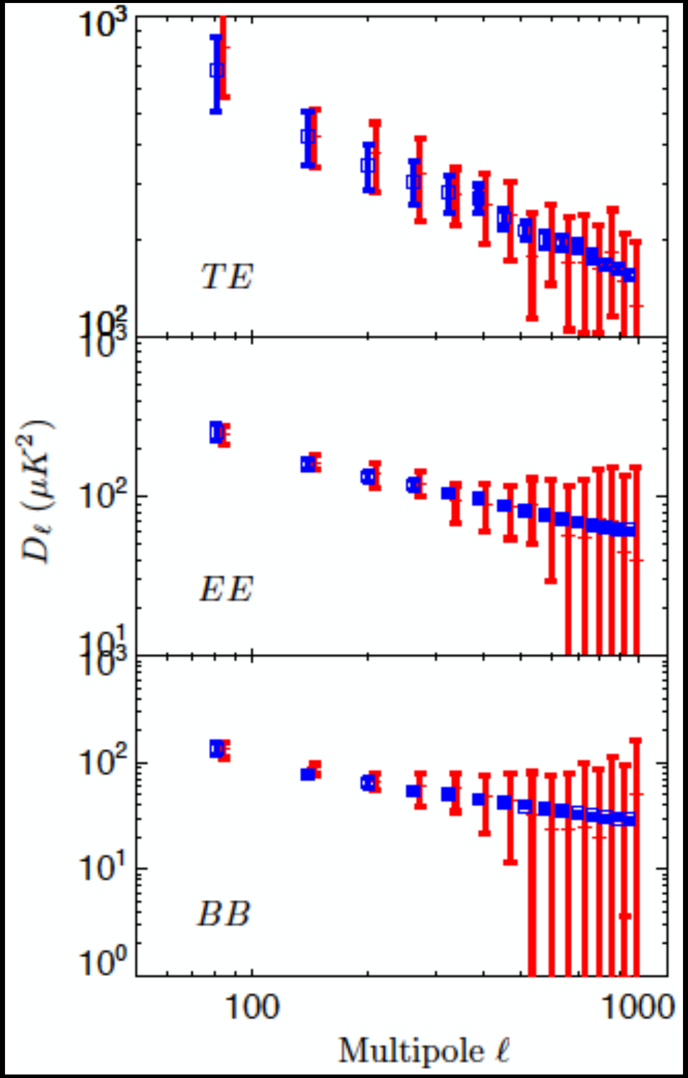
Model (b)

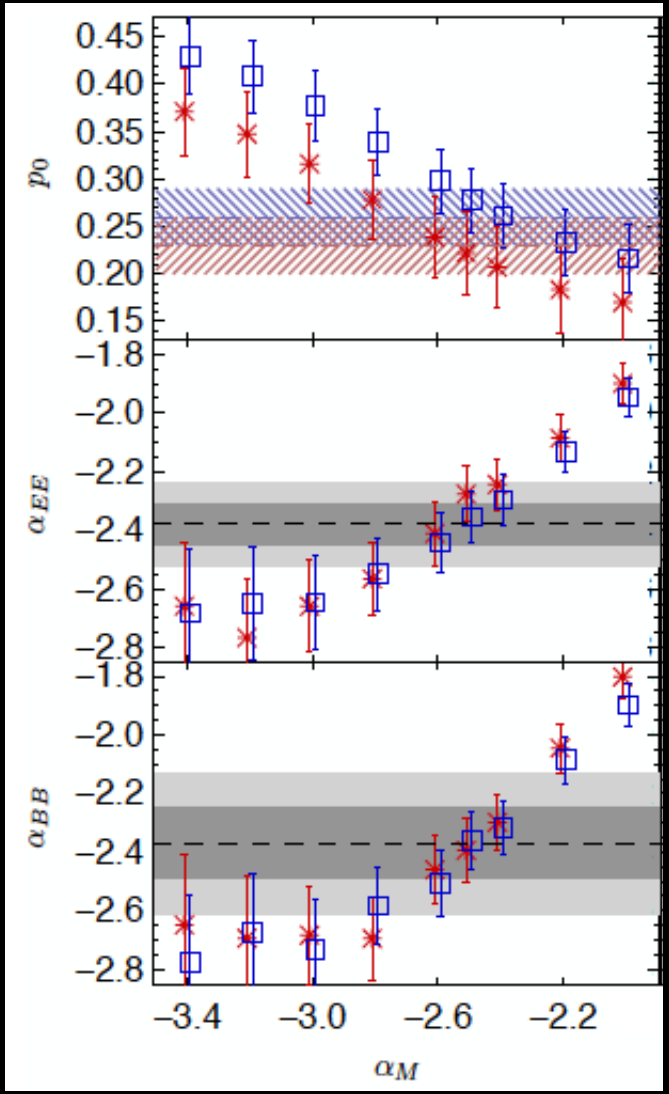


$$\begin{cases} b^T_{\ell m} & = t a^T_{\ell m} \\ b^E_{\ell m} & = p_0 (a^E_{\ell m}/p_0 + \rho a^T_{\ell m}) \\ b^B_{\ell m} & = p_0 (f a^B_{\ell m}/p_0) \end{cases}$$

Vansyngel+ 2016, arXiv: 1611.02577

Magnetic Field power spectrum



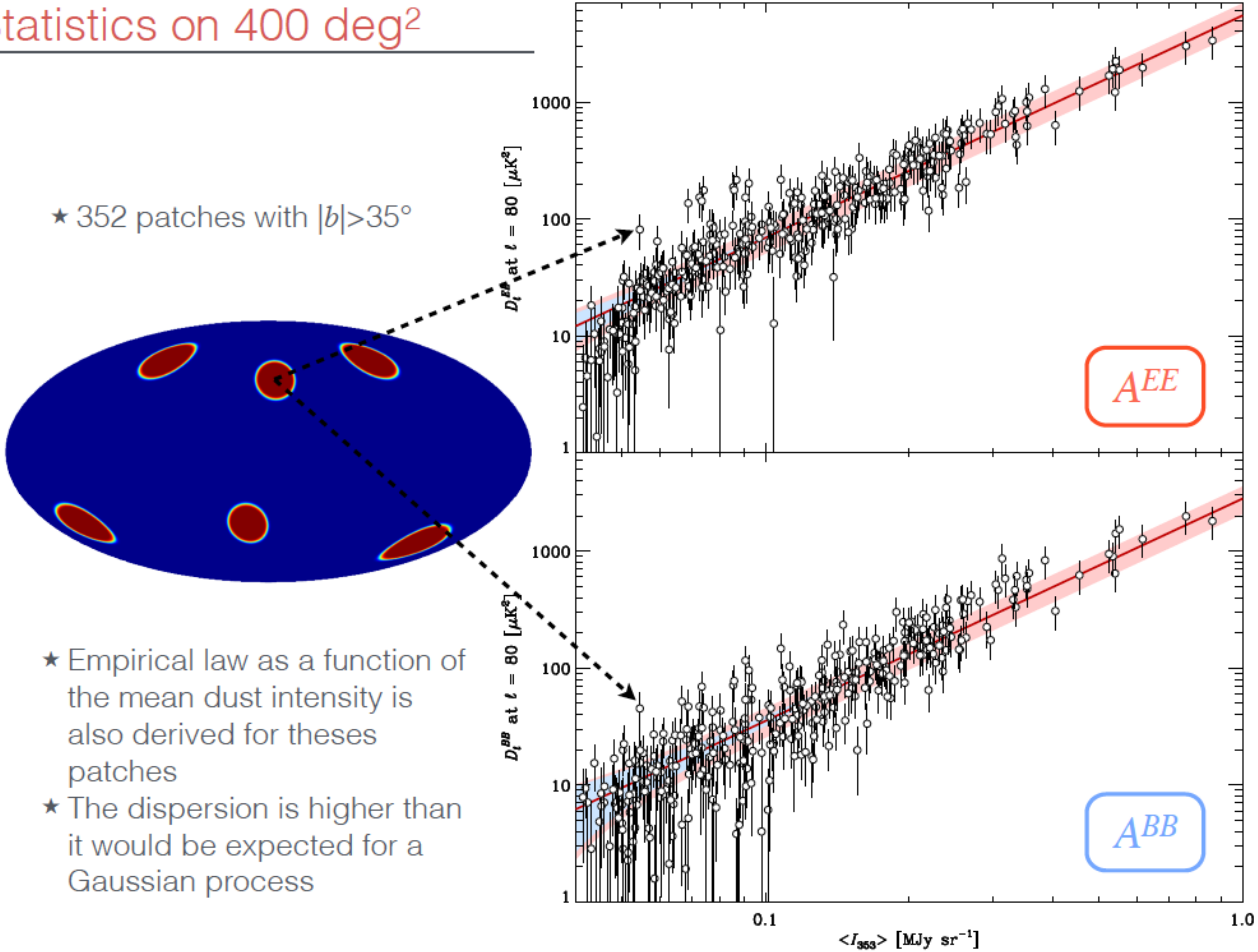


Vansyngel+ 2017

The slopes of power-spectra are matched for a magnetic field power spectrum index α_M = -2.5

Statistics on 400 deg^2

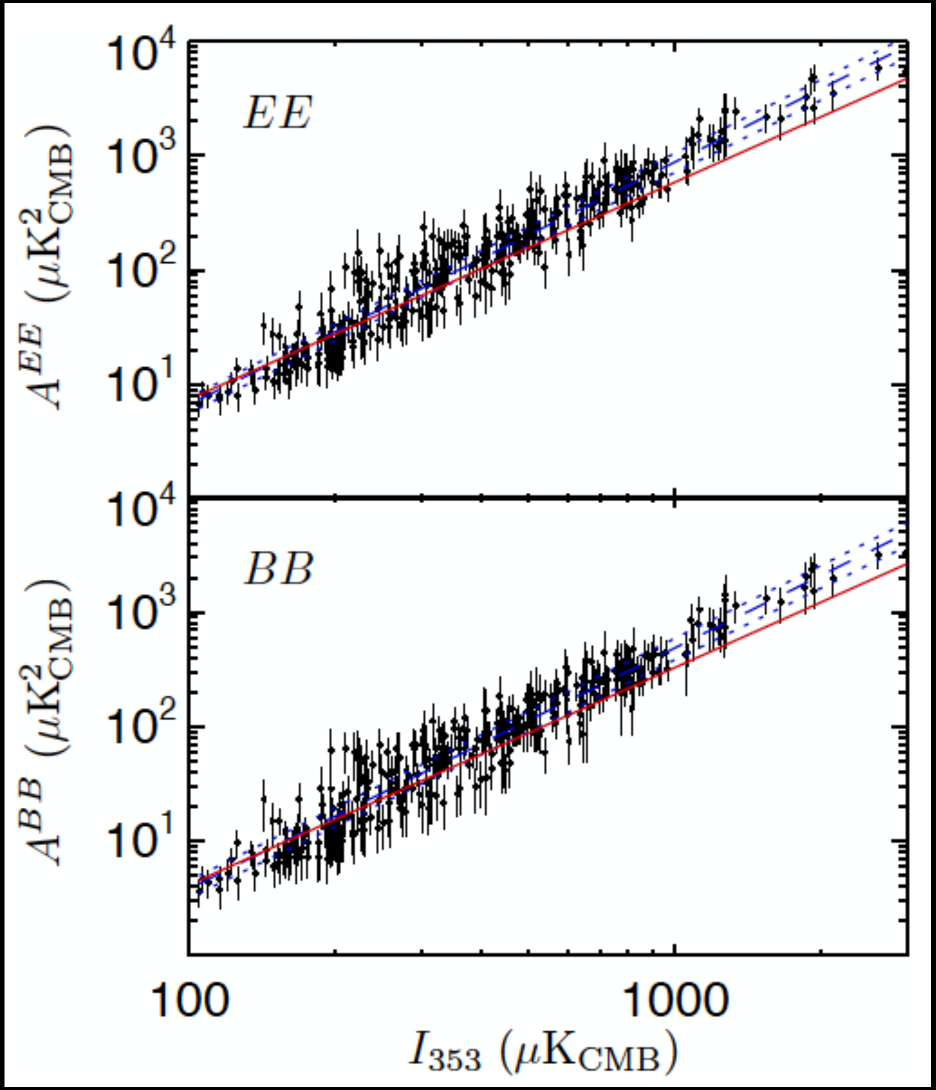
[Planck Intermediate XXX 2014, arXiv 1409.5738]



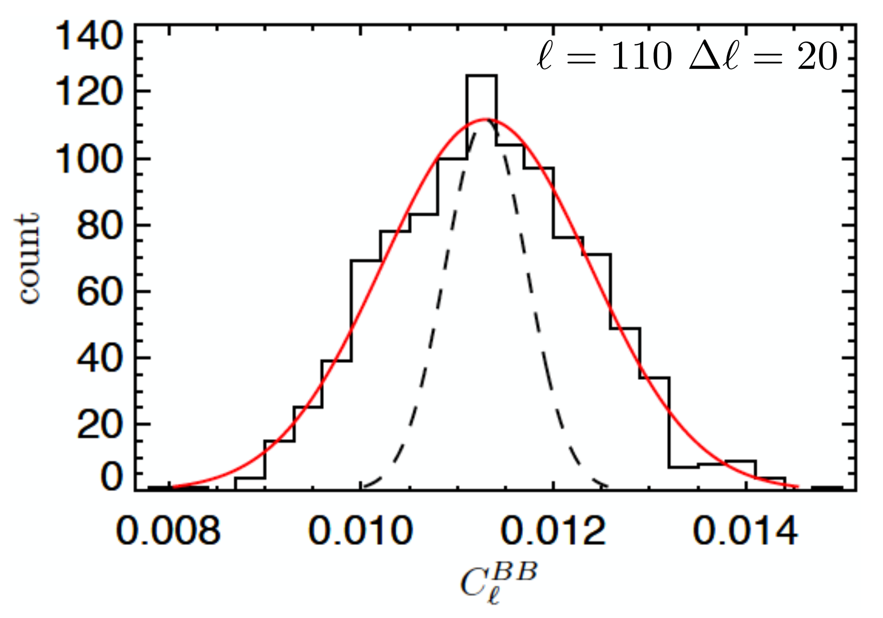
- ★ 352 patches with $|b|>35°$

- ★ Empirical law as a function of the mean dust intensity is also derived for theses patches
- ★ The dispersion is higher than it would be expected for a Gaussian process

Simulated dust polarization maps



Dispersion computed from 1000 realizations

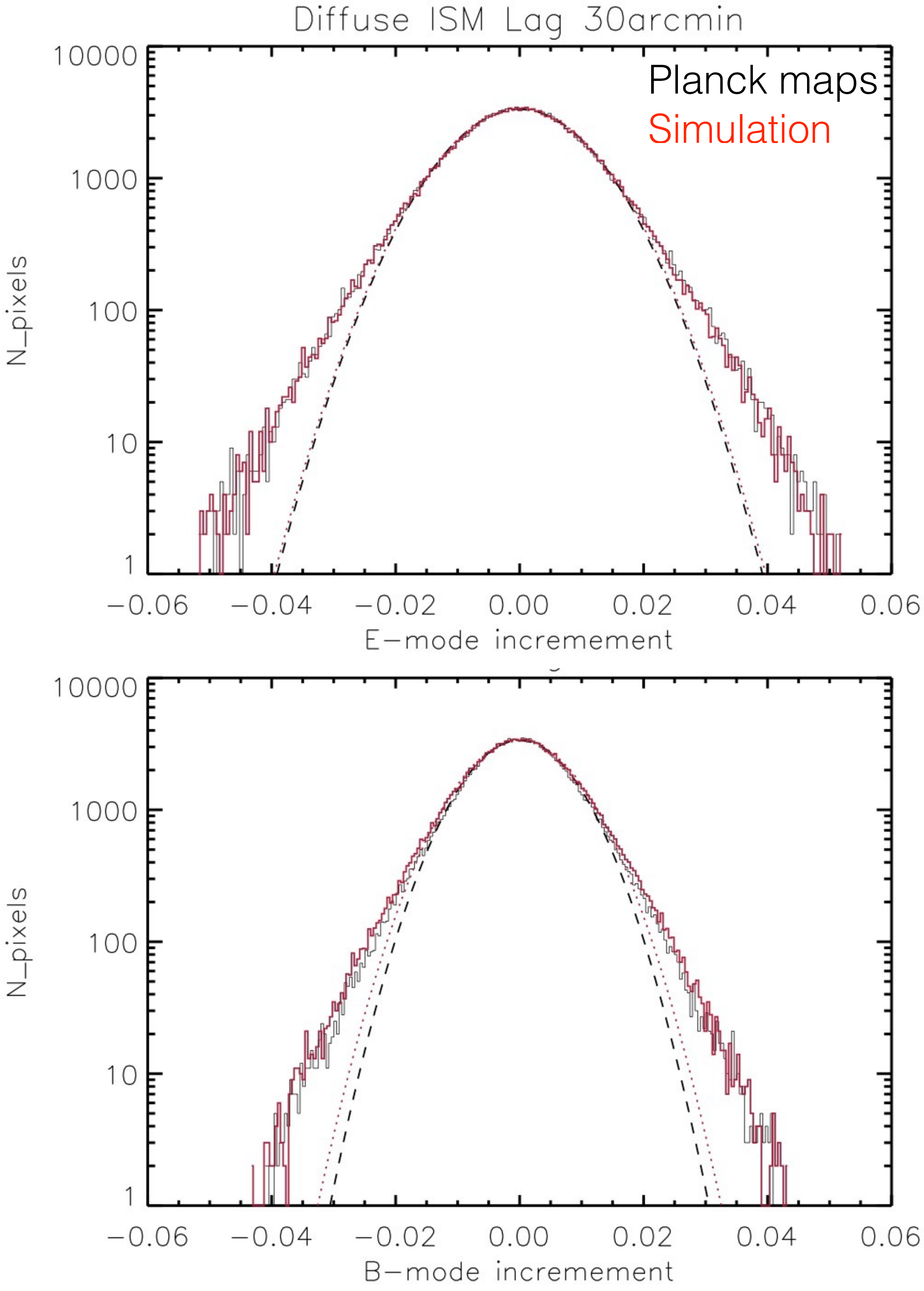


The distribution of power per bin is broader than the cosmic variance of a Gaussian random field

=> The simulations reproduce the observed scaling law with I_{353} and the variance at a given I_{353}

E and B decomposition of Q/I and U/I maps

Non-Gaussian wings of increments reproduced by the simulated map



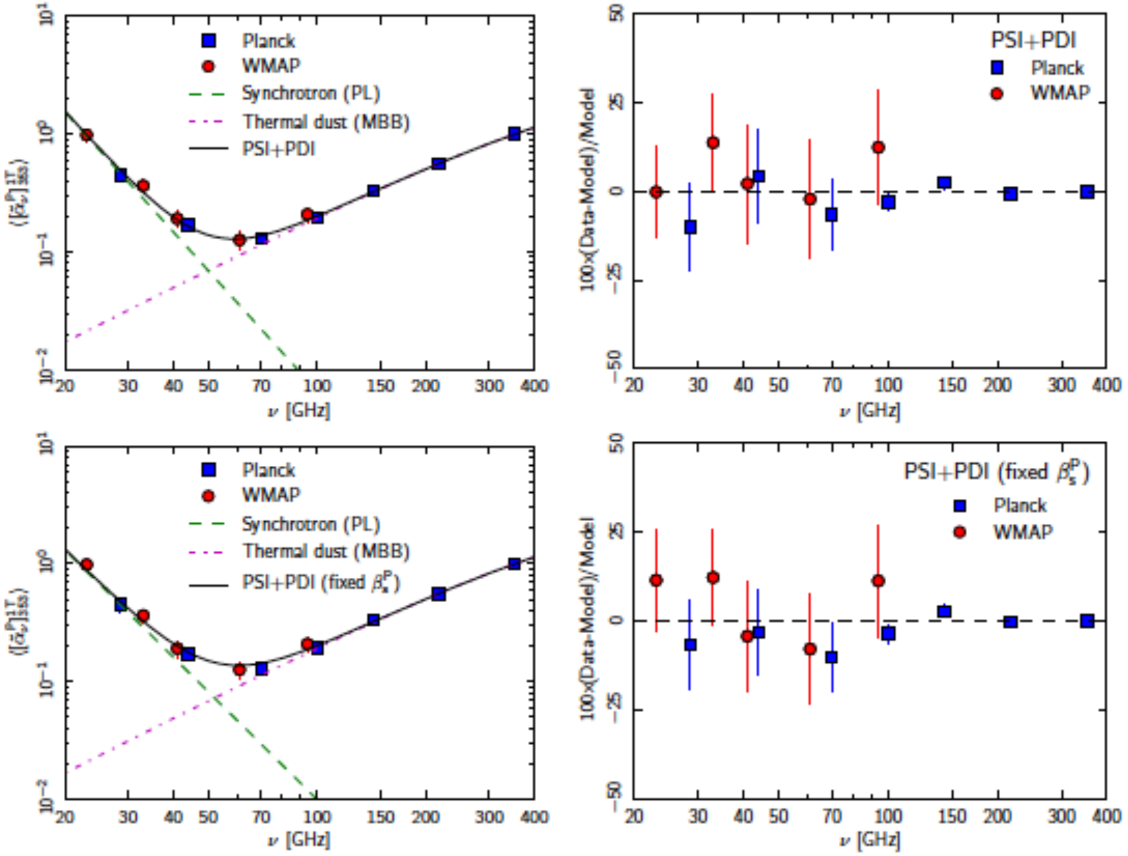
Polarization dust SED

Spectral modeling

Residuals

Free synchrotron spectral index

Fixed synchrotron spectral index ($\beta_s = -3.04$)



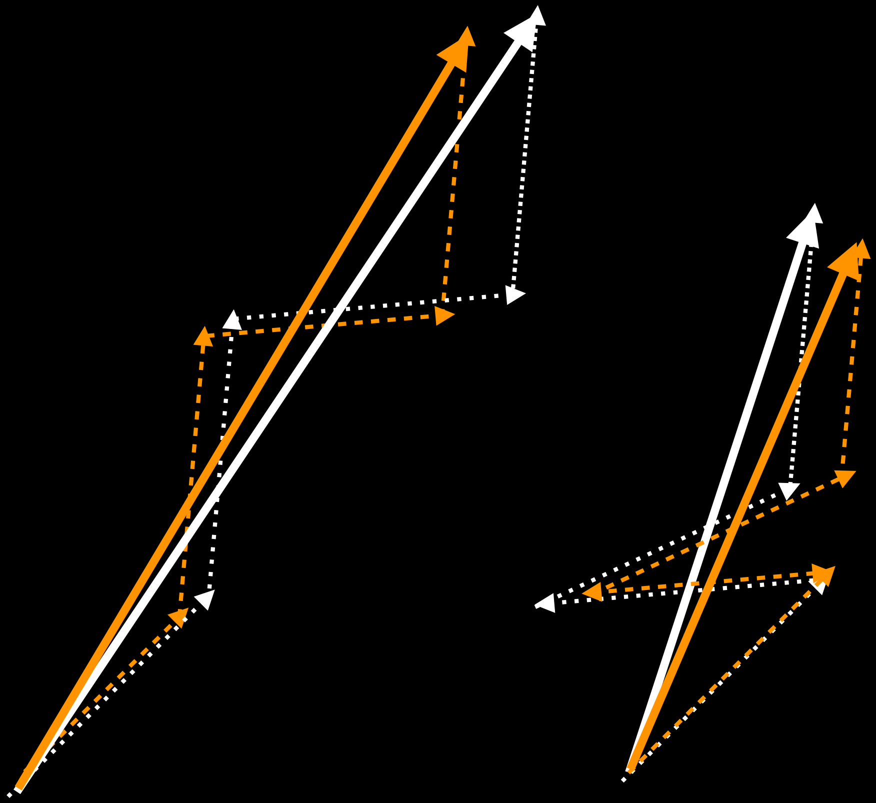
Power-law model of 353 GHz correlated synchrotron emission
+
MBB spectrum of polarized thermal dust emission

Parameters [a]	Unconstrained β_s^P	Fixed β_s^P
A_s^P	0.97 ± 0.10	0.86 ± 0.06
β_s^P	-3.40 ± 0.28	-3.04
$\beta_{d,mm}^P$	1.57 ± 0.01	1.58 ± 0.01
χ^2/N_{dof} . . .	6.6/9	8.6/10

[Planck Intermediate XXII 2014, arXiv:1406.0874]

Modelling spectral decorrelation

Polarization *random walks* at two frequencies



Sky pixel 1

Sky pixel 2

Frequencies ν_1 and ν_2

- Decorrelation of the dust polarization signal between frequencies is expected from the correlation between the magnetic field, ISM structure and dust polarization properties.
- Both the polarized intensity and polarization angle change with frequency.
- Decorrelation is a non-linear effect that modifies the frequency dependence of dust polarization.

➡We still do not know how to model this in a way that is realistic

Future steps

Learning from data. Statistical analysis of polarization foregrounds is on-going with Planck data and will continue to advance with additional data sub-orbital experiments

Bottom up approach. Infer a statistical description of polarized foregrounds from the data rather than from a parametrized model with a priori simplifying assumptions (presentation by Erwan Allys)

Interface with component separation. Use simulated foreground maps to the analysis of CMB polarization data and forecast for future experiments.

Synchrotron polarization. Current work needs to be extended to synchrotron with a consistent modeling of the magnetic field to account for the correlation with dust polarization.