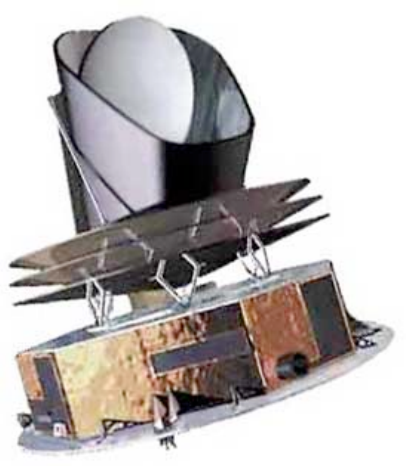
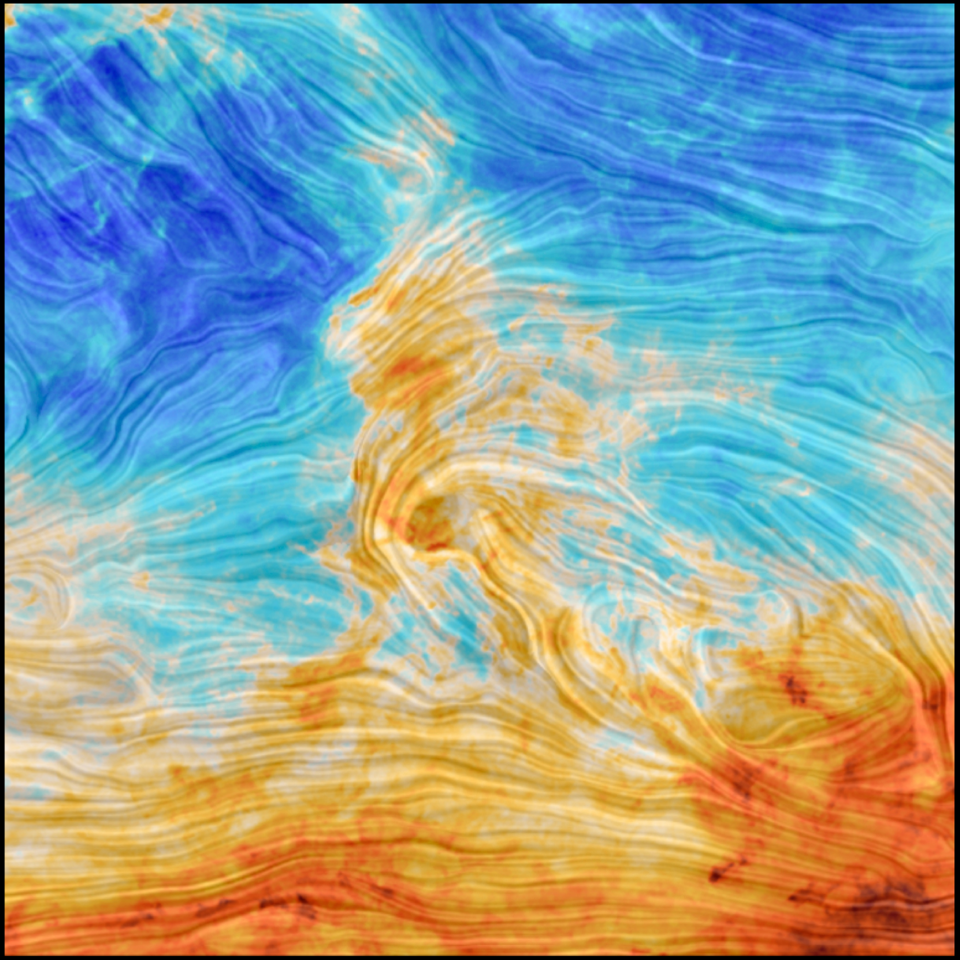


The Astrophysics of Dust Polarization



F. Boulanger (IAS, Orsay)
on behalf of the
Planck Collaboration

Overview

I. The astrophysics of dust polarization

- The magnetized interstellar medium
- Dust polarization properties

II. The Planck dust polarization sky

- Polarization maps
- Magnetic field structure

III. Dust foreground to CMB polarization

- Frequency dependence
- Power spectra analysis

Part I

The astrophysics of dust polarization

- The magnetized interstellar medium
- Dust polarization properties

The dynamics of the ISM

Gravity

Turbulence

Magnetic fields

In the diffuse ISM HI observations and Zeeman measurements show:

$$E_{grav} << E_{turb} \approx E_{mag}$$

(Heiles & Troland 2005)

The dynamics of the ISM

Gravity

Turbulence

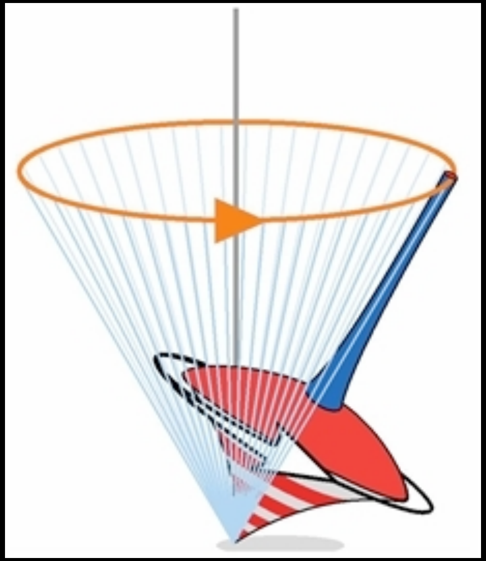
Magnetic fields

Open issue:

How does gravity become the local dominant force to allow for Star Formation ?

Grain Alignment

Why are grains aligned with the field?

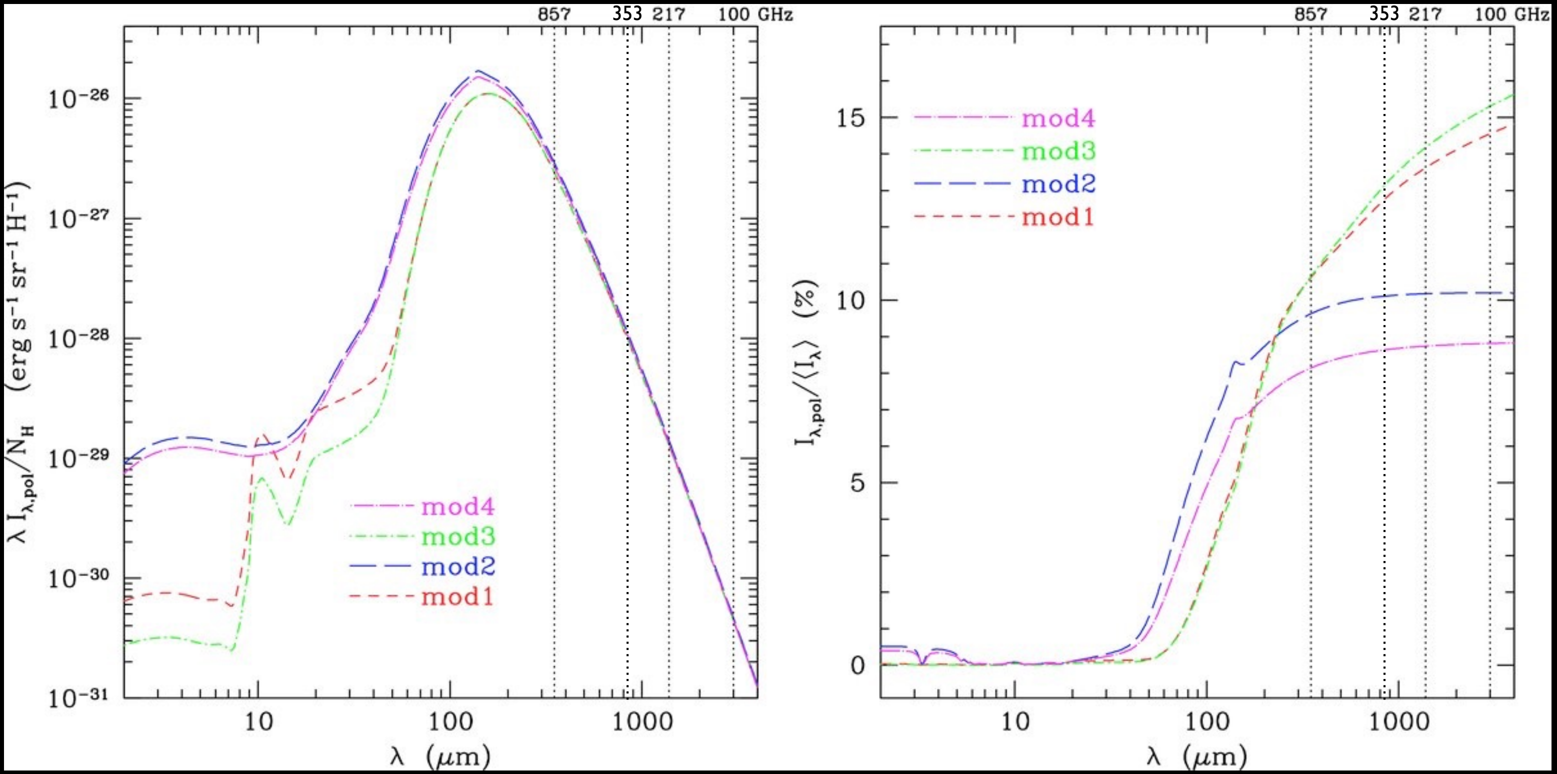


- Interstellar grains spin like tops around their axis of maximal inertia. Their rotation axis precesses around the magnetic field lines.
- Dissipation of precession energy leads to alignment with the field. Alignment may be associated with paramagnetic relaxation or radiative torques. H_2 formation can also locally contribute.

The degree of grain alignment may vary, but it is difficult to discriminate this possibility from magnetic field structure

Dust Polarization Properties

Dust includes grain with different sizes and composition that have different polarization properties



Only silicates are aligned

Carbon grains and silicates are aligned

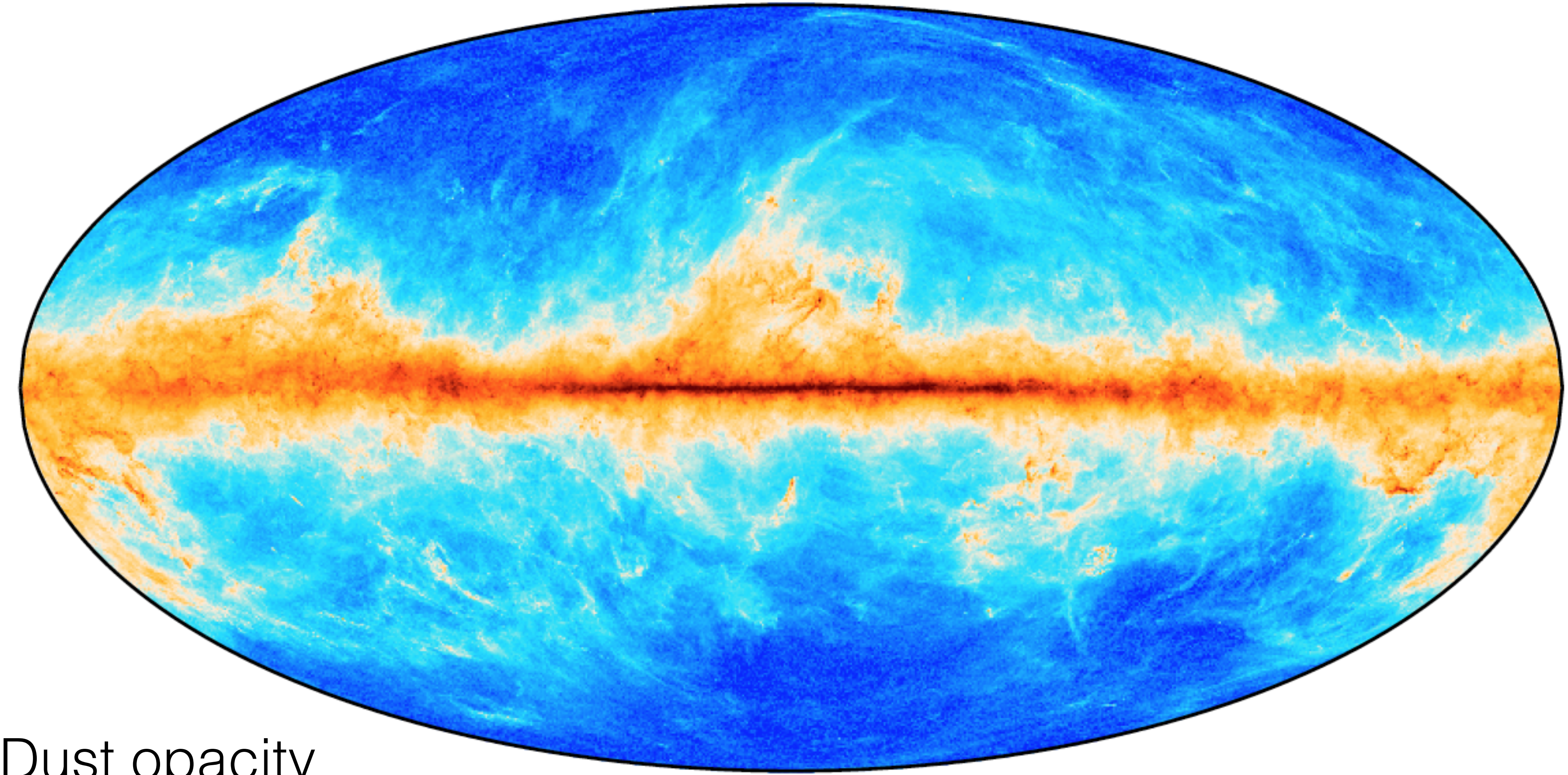
All models produce the same polarization opacity in the visible and near-IR but distinct values of P/I in the sub-millimeter (Draine and Fraisse 2009)

Part II

The Planck polarization sky

- Polarization maps
- Magnetic field structure

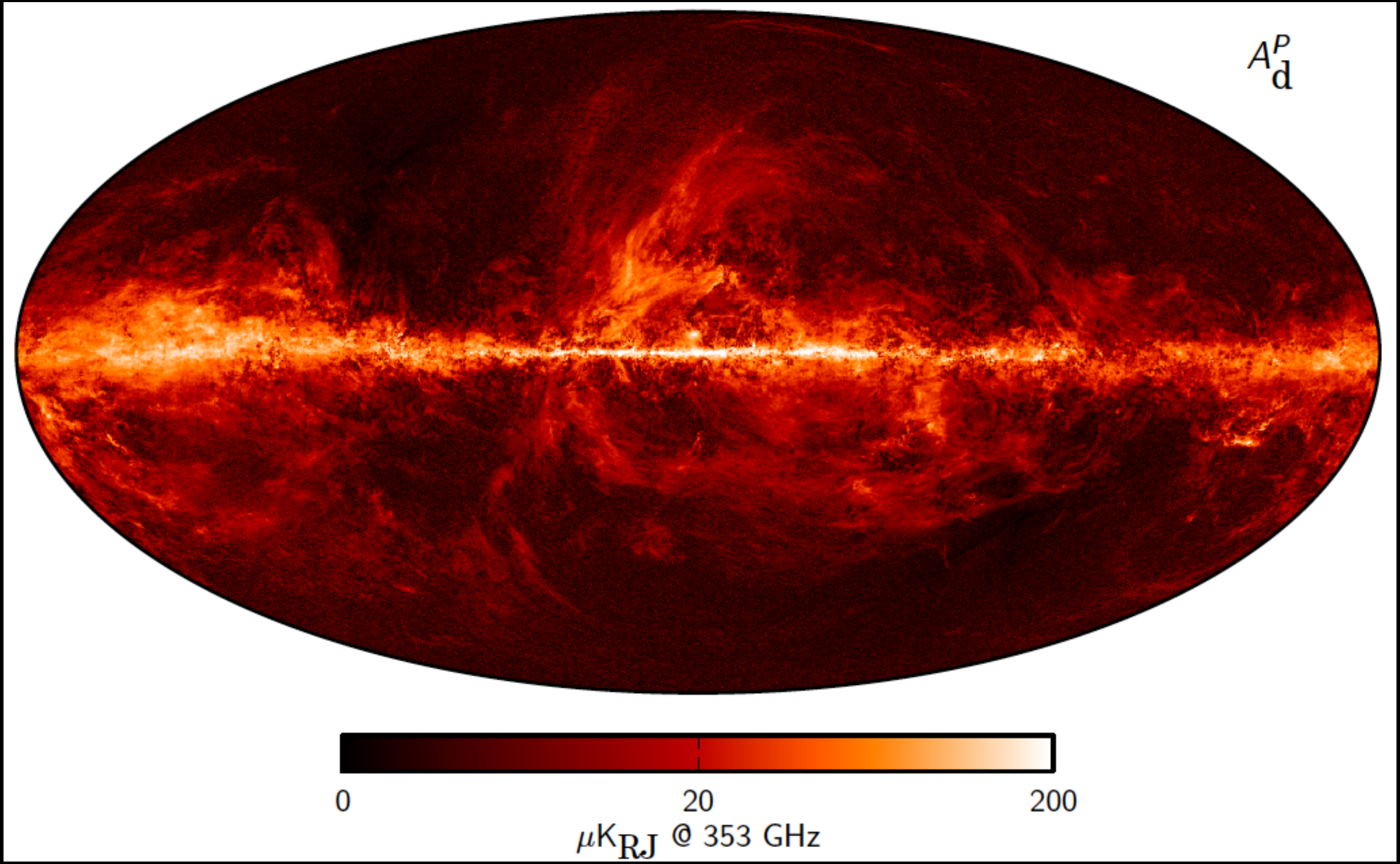
Dust emission



Dust opacity

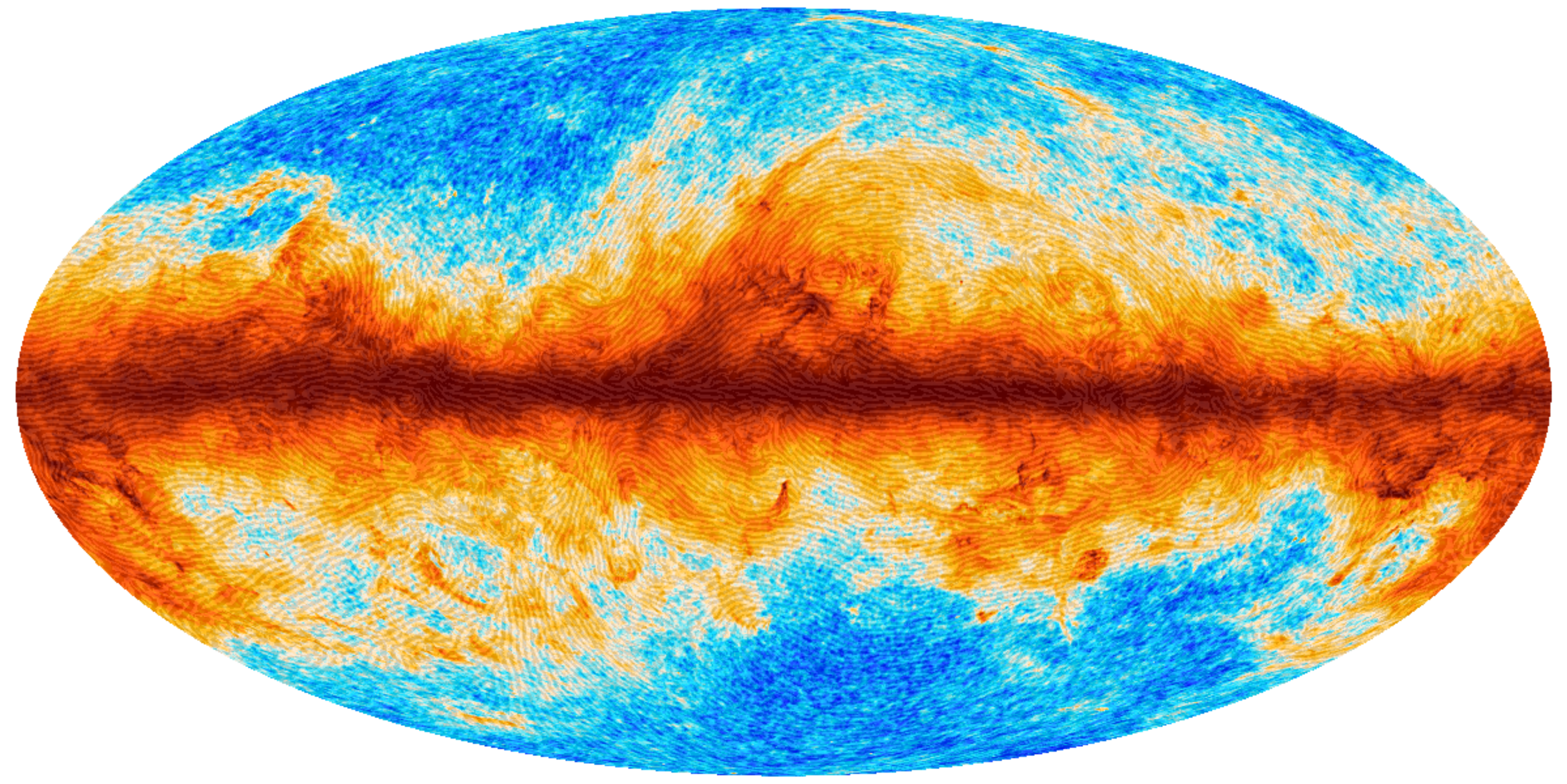
Planck collaboration (2014)

Polarized dust emission



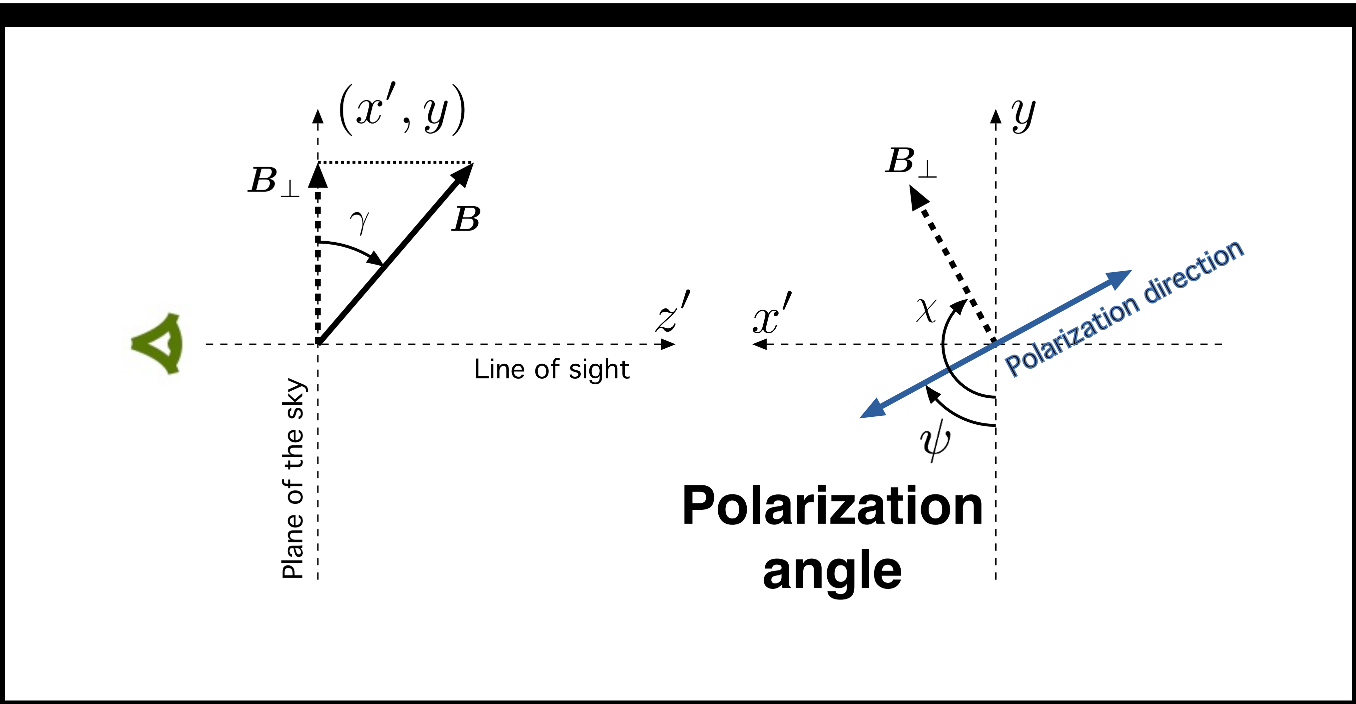
Planck collaboration (2015)

Magnetic Field Fingerprints



Planck collaboration (2014)

What are we measuring?



$$
\begin{aligned}
Q &= \int p_{\max} R \, cos(2\psi) \, cos^2\gamma \, dI \\
U &= -\int p_{\max} R \, sin(2\psi) \, cos^2\gamma \, dI
\end{aligned}
$$

Polarization fraction

$$
\begin{aligned}
p &= p_{\max} R \, F \, cos^2\gamma \\
R &\ \text{and} \ F \leq 1
\end{aligned}
$$

$$
\begin{aligned}
P &= (Q^2 + U^2)^{0.5} \\
p &= P/I \\
\psi &= 0.5 \arctan(-U, Q)
\end{aligned}
$$

R: Rayleigh reduction factor (efficiency of grain alignment)

F: Depolarization factor (change of B orientation within the beam)

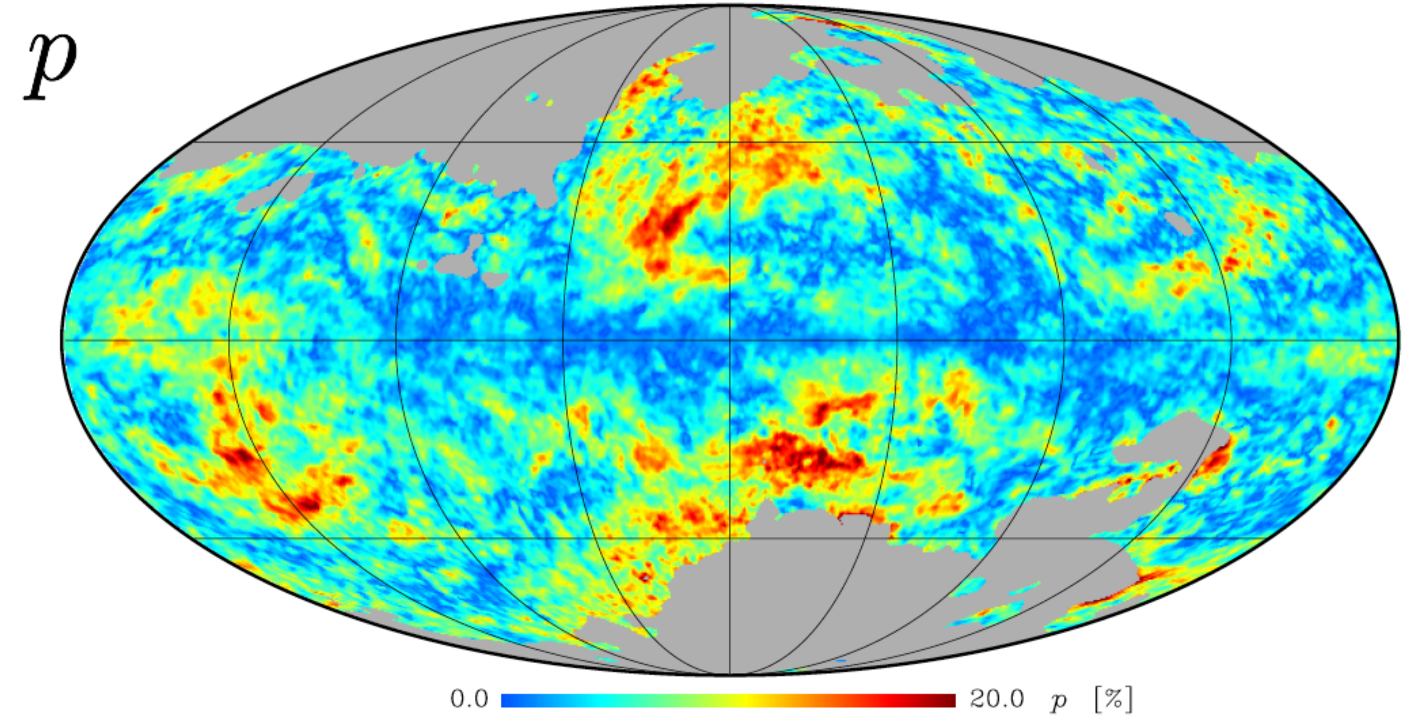
What are we learning from Planck?

Planck probes the field structure in the diffuse ISM and in star-forming molecular clouds, on scales relevant to the formation of their filamentary structure.

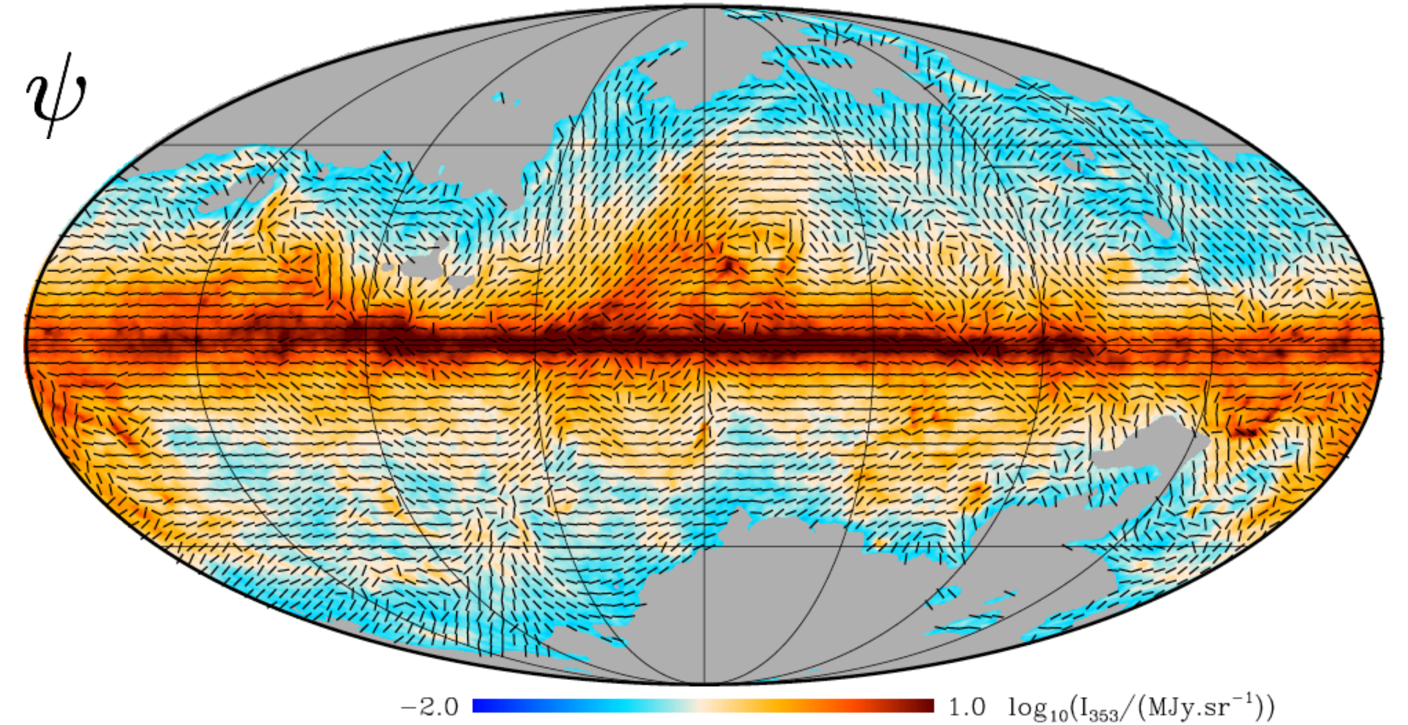
- The dust polarization fraction
- The structure of the magnetic field
- Correlation between the matter and the magnetic field.

More results on Planck intermediate papers available on Arxiv.

Polarization degree



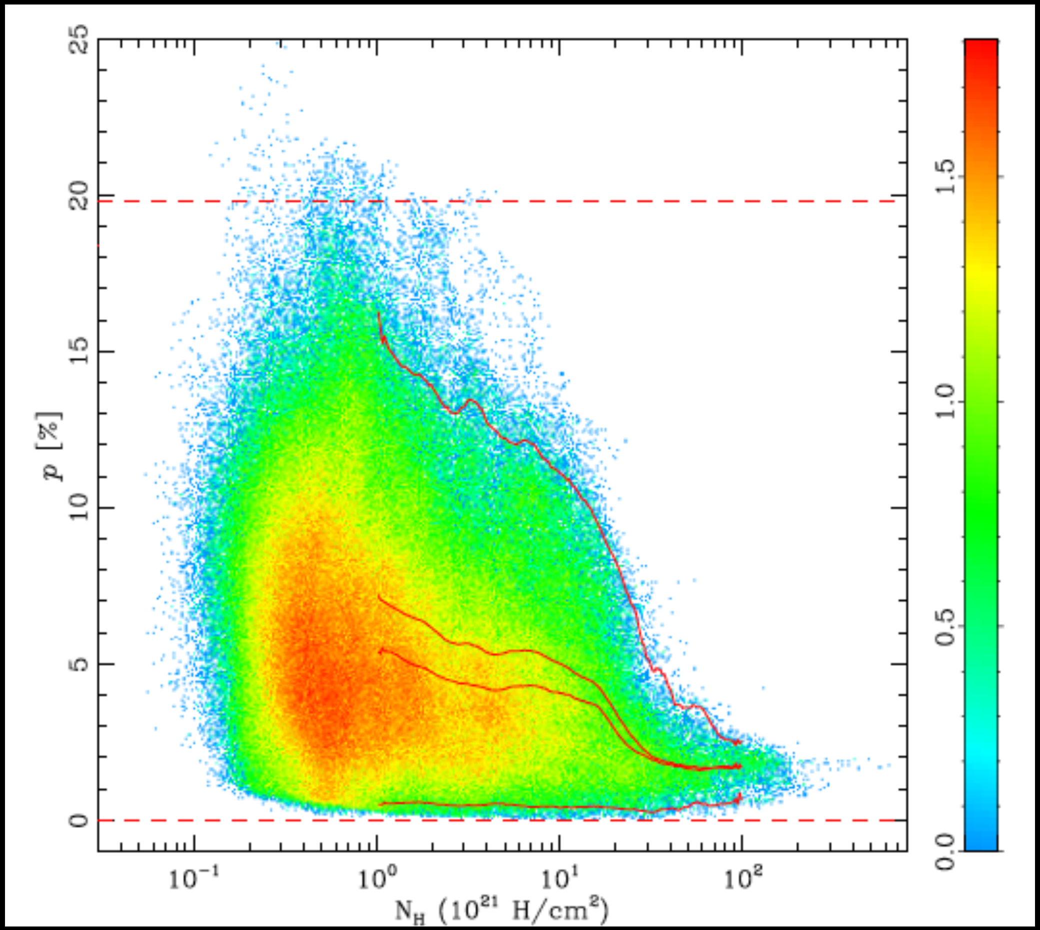
Polarization angle



[Planck Intermediate XIX 2014, arXiv:1405.0871]

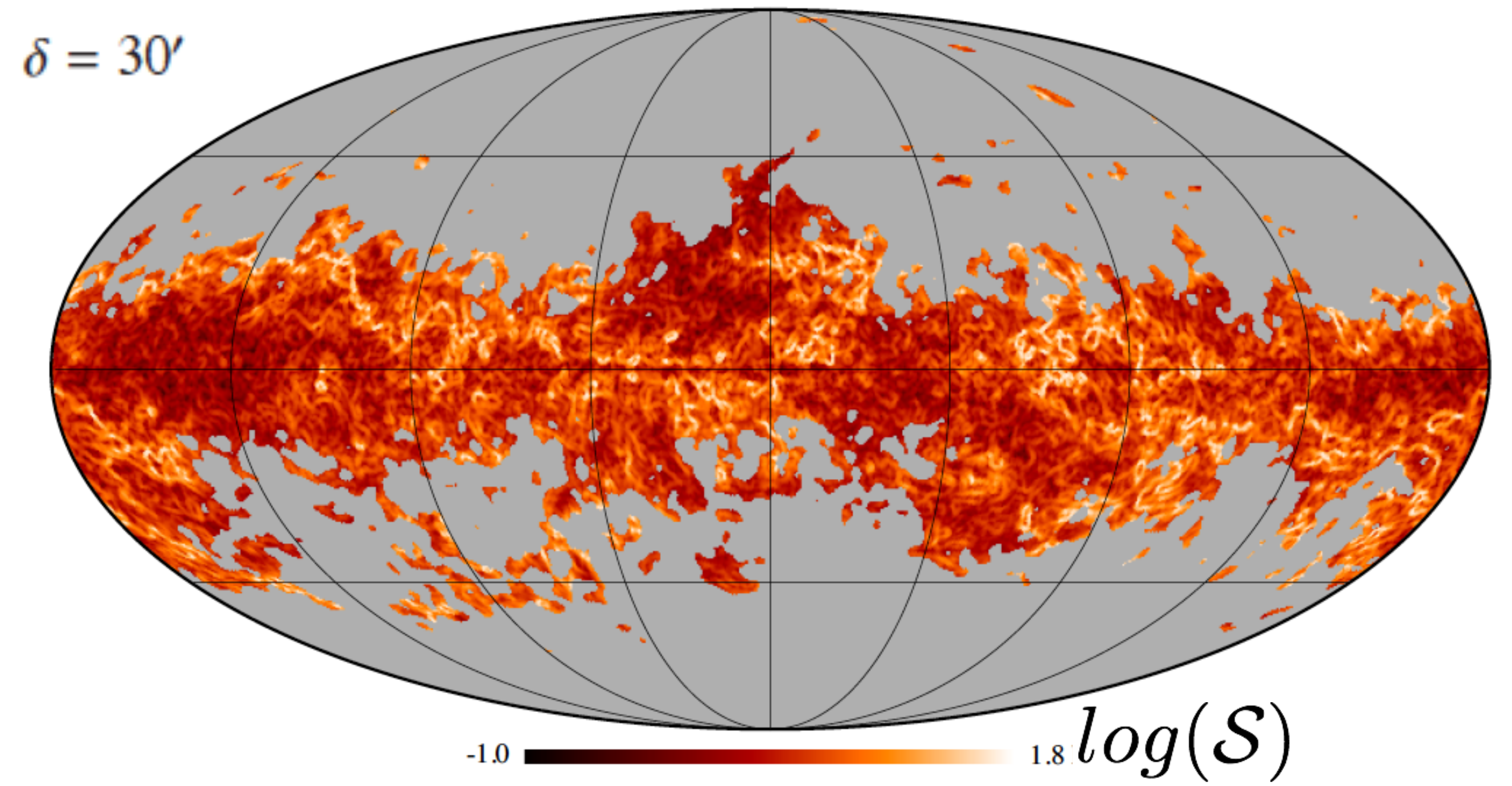
Polarization fraction *p* vs N_H

[Planck Intermediate XIX 2014, arXiv:1405.0871]



- Polarization fraction up to 20%.
- Large dispersion of *p* at all N_H, tracing changes in B-field orientation and depolarization within the beam.
- Sharp decrease of *p* for $N_H > 10^{22}$ cm^{-2}. Consistent with earlier results from ground-based observations, which has been interpreted by a loss of grain alignment in the shielded interiors of clouds.

Filamentary structure of the B-field

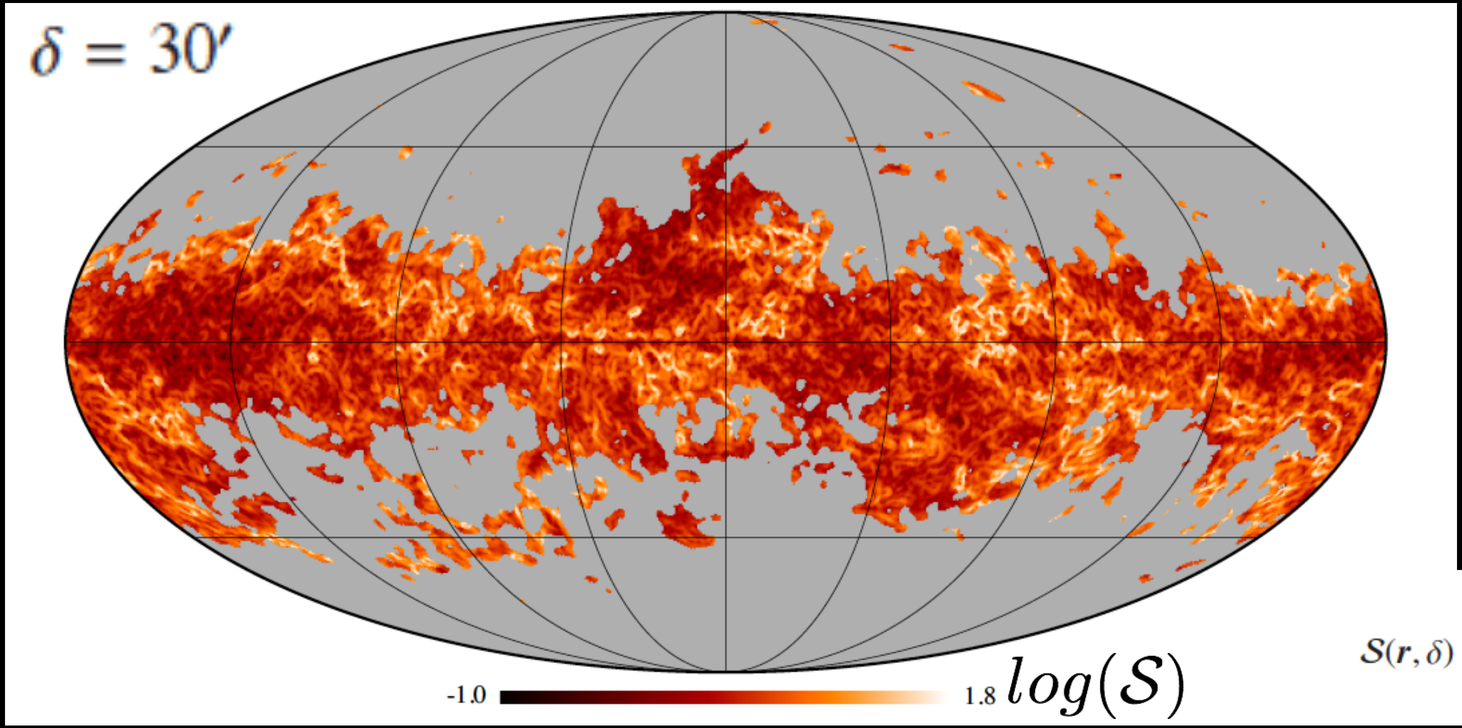


$$\mathcal{S}(\boldsymbol{r},\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\psi(\boldsymbol{r}) - \psi(\boldsymbol{r}+\boldsymbol{\delta}_i)\right]^2}$$

[Planck Intermediate XIX 2014, arXiv:1405.0871]

The polarization angle dispersion highlights filamentary structure of the magnetic field

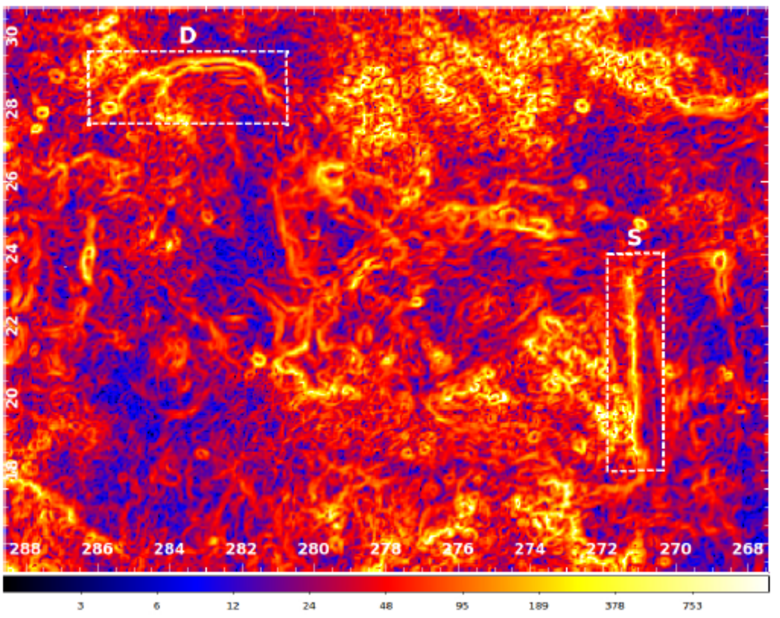
[Planck Intermediate XIX 2014, arXiv:1405.0871]



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

$|\nabla \mathbf{P}|/|\mathbf{P}|$ S-PASS 2.3 GHz

Iacobelli+14

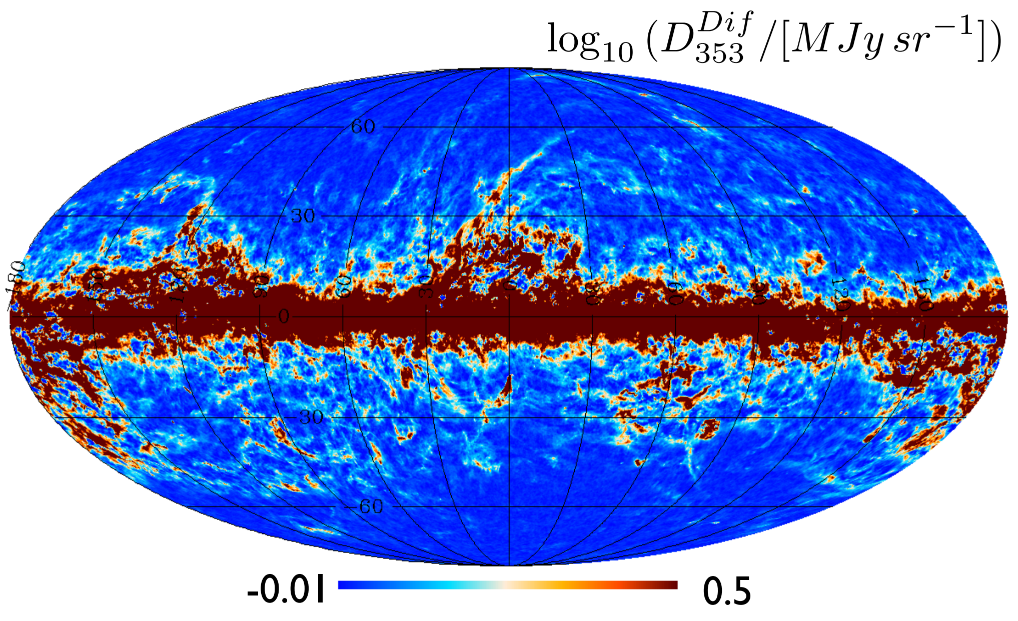


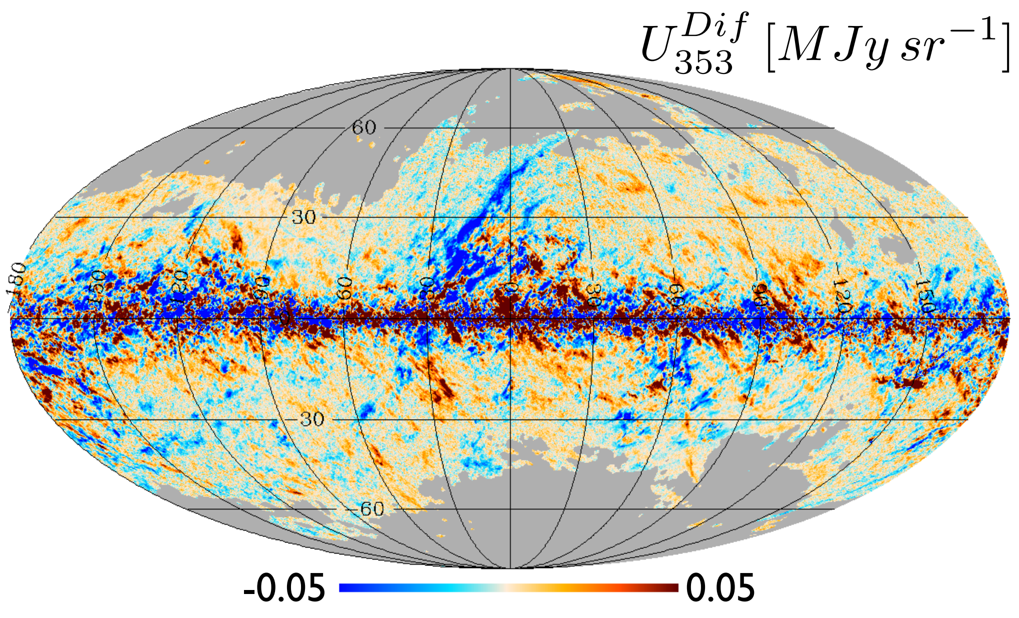
Filamentary structures are observed in dust polatization as in synchrotron polarization

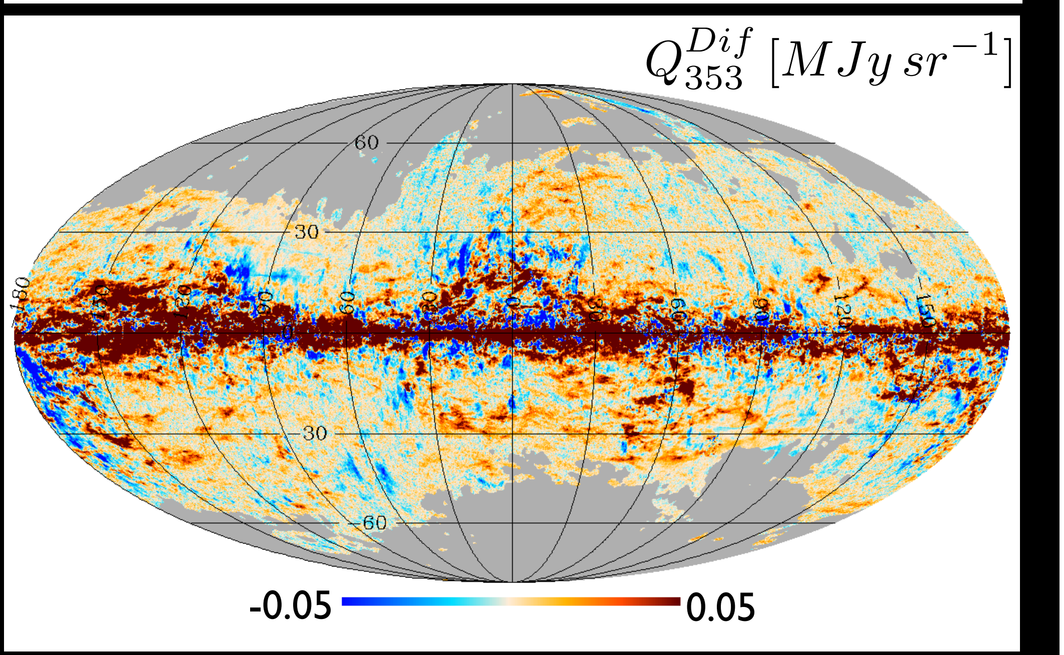
Matter/B-field Correlation

Stokes filtered maps (Dif) after subtraction of a local background

[Planck Intermediate XXXII 2014, arXiv:1409.6728]


$\log_{10}\left(D_{353}^{Dif}/[MJy\,sr^{-1}]\right)$

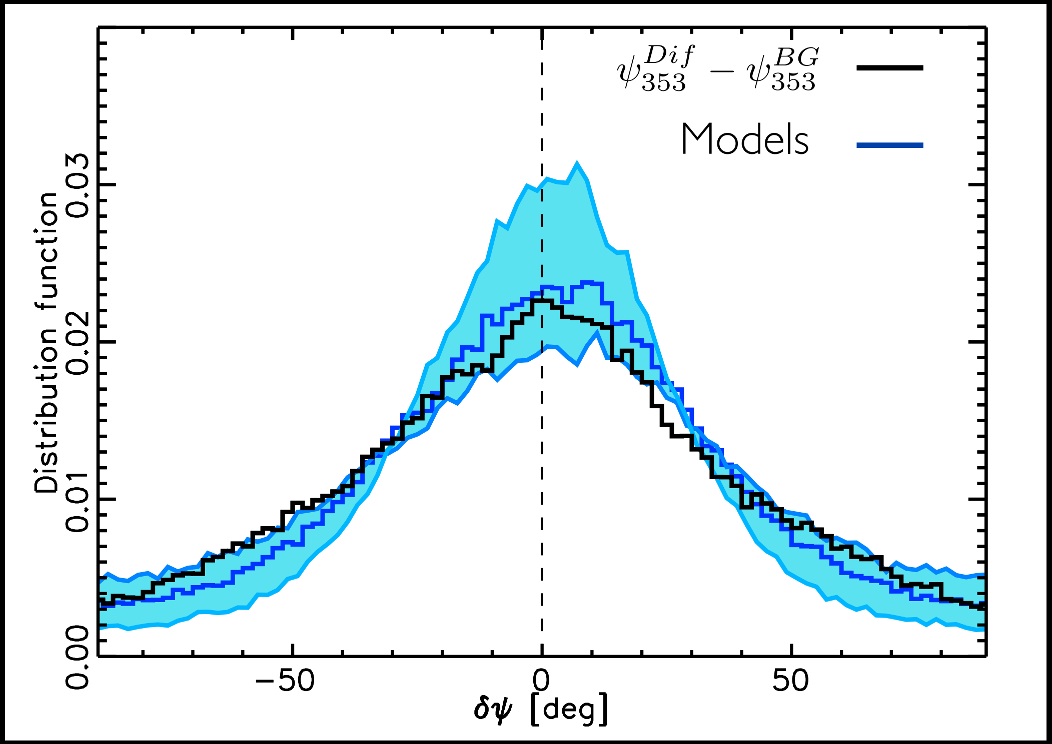

$U_{353}^{Dif}\ [MJy\,sr^{-1}]$

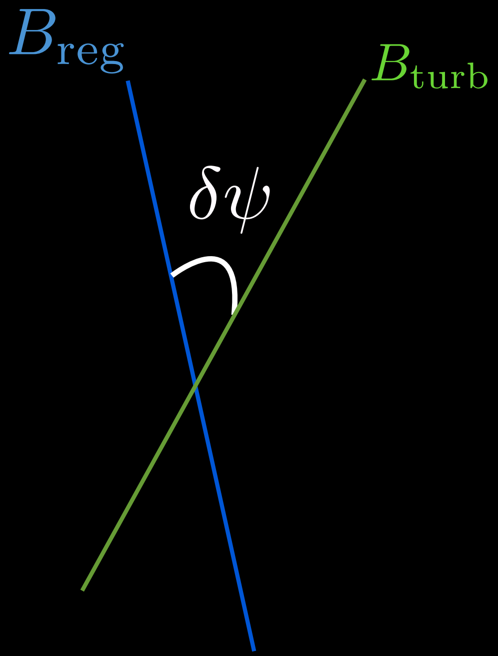

$Q_{353}^{Dif}\ [MJy\,sr^{-1}]$

Turbulent component of magnetic field

$$\vec{B} = \vec{B}_{\rm reg} + \vec{B}_{\rm turb} \quad (< \vec{B}_{\rm turb} >= 0)$$

[Planck Intermediate XXXII 2014, arXiv:1409.6728]



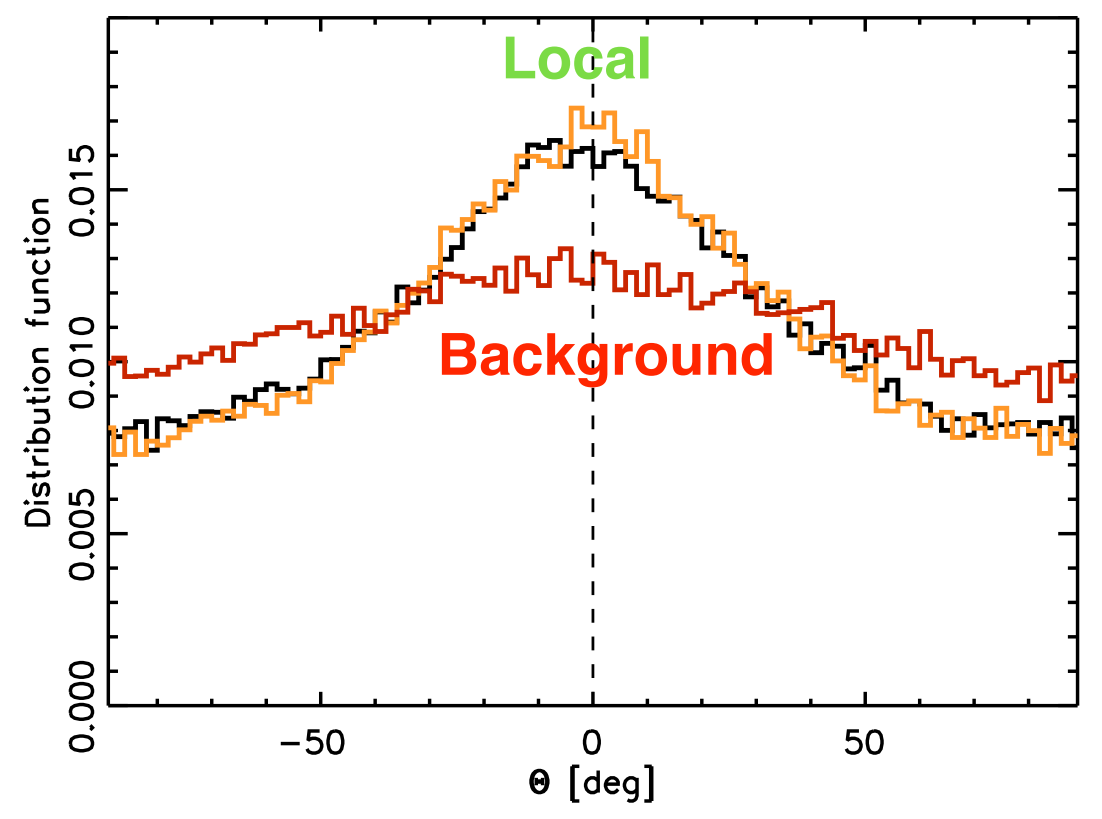


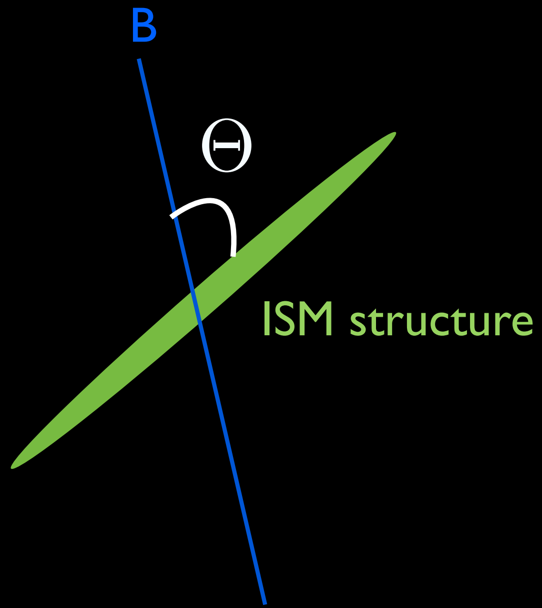
- Comparing the orientation of the field at two scales: *structures* (~2pc) and *background* (~40pc)

- Models quantifying the ratio between the strengths of the turbulent and mean components of the magnetic field. Best fit model for : $B_{\rm turb}/B_{\rm reg} = 0.8$ (trans-Alfvenic turbulence)

Matter vs Magnetic Field

[Planck Intermediate XXXII 2014, arXiv:1409.6728]





The structures tend to be aligned with the local magnetic field

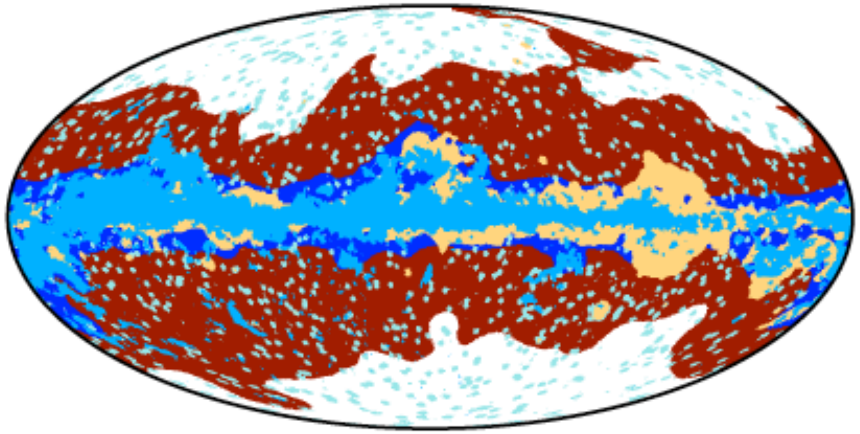
Projection effects (3D to 2D) are crucial for the interpretation of the shape of the distribution!

Part III

Dust foreground to CMB polarization

- Frequency dependence
- Power spectra analysis

Dust SED at intermediate latitude sky



Only red region is analysed in our study

Cross-correlation analysis with three templates

a. 408 MHz survey -> synchrotron emission
b. Halpha map -> free-free emission
c. 353 GHz map -> dust emission

$$I_\nu = \tau_{353}\ B_\nu(T_\mathrm{d})\ \left(\frac{\nu}{353}\right)^{\beta_\mathrm{d}}$$

$$\langle \beta^\mathrm{I}_\mathrm{d,mm} \rangle = 1.51 \pm 0.06,\ T_\mathrm{d} = 19.6\ \mathrm{K}$$

The cross-correlation coefficients at and above 100 GHz can be decomposed as

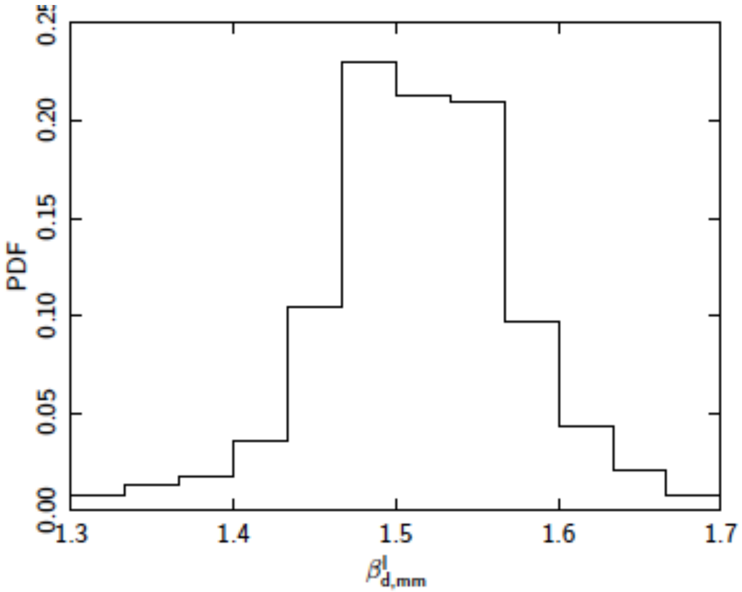
$$[\alpha^\mathrm{I}_\nu]^{3\mathrm{T}}_{353} = \alpha^\mathrm{I}(c^3_{353}) + \alpha^\mathrm{I}_\nu(d_{353})$$

We work with the colour ratio between two frequencies ν_1 and ν_2 (ν_0 is used as a reference to get rid of the CMB contribution)

$$R^\mathrm{I}_{\nu_0}(\nu_2,\nu_1) = \frac{[\alpha^\mathrm{I}_{\nu_2}]^{3\mathrm{T}}_{353} - [\alpha^\mathrm{I}_{\nu_0}]^{3\mathrm{T}}_{353}}{[\alpha^\mathrm{I}_{\nu_1}]^{3\mathrm{T}}_{353} - [\alpha^\mathrm{I}_{\nu_0}]^{3\mathrm{T}}_{353}}$$

$$= \frac{\alpha^\mathrm{I}_{\nu_2}(d_{353}) - \alpha^\mathrm{I}_{\nu_0}(d_{353})}{\alpha^\mathrm{I}_{\nu_1}(d_{353}) - \alpha^\mathrm{I}_{\nu_0}(d_{353})},$$

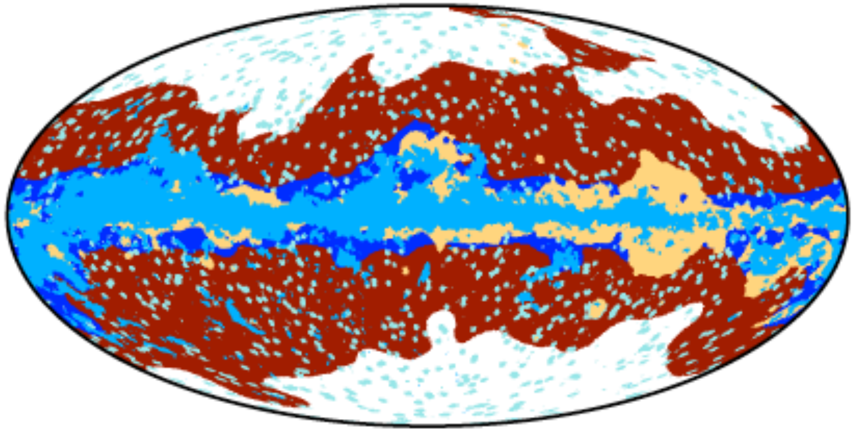
$$= g(\beta_\mathrm{d}, T_\mathrm{d})$$



Histogram of $\beta^\mathrm{I}_\mathrm{d,mm}$

[Planck Intermediate XXII 2014, arXiv:1406.0874]

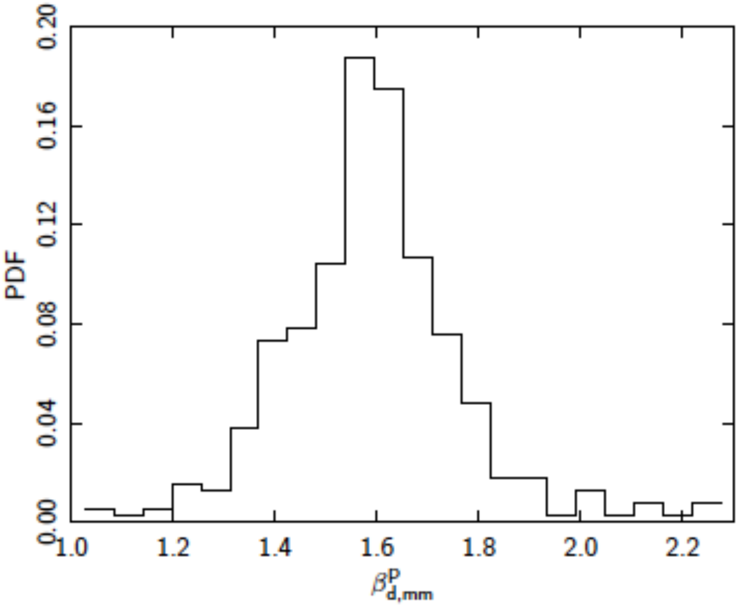
Polarized Dust SED at intermediate latitude sky



Only red region is analysed
in our study

Cross-correlation analysis with 353 GHz polarized dust template

$$\langle\beta^{\mathrm{P}}_{\mathrm{d,mm}}\rangle = 1.59 \pm 0.17,\ T_{\mathrm{d}} = 19.6\ \mathrm{K}$$



Histogram of $\beta^{\mathrm{P}}_{\mathrm{d,mm}}$

Polarized SED is slightly steeper than the intensity SED for a fixed T_{d}.

[Planck Intermediate XXII 2014, arXiv:1406.0874]

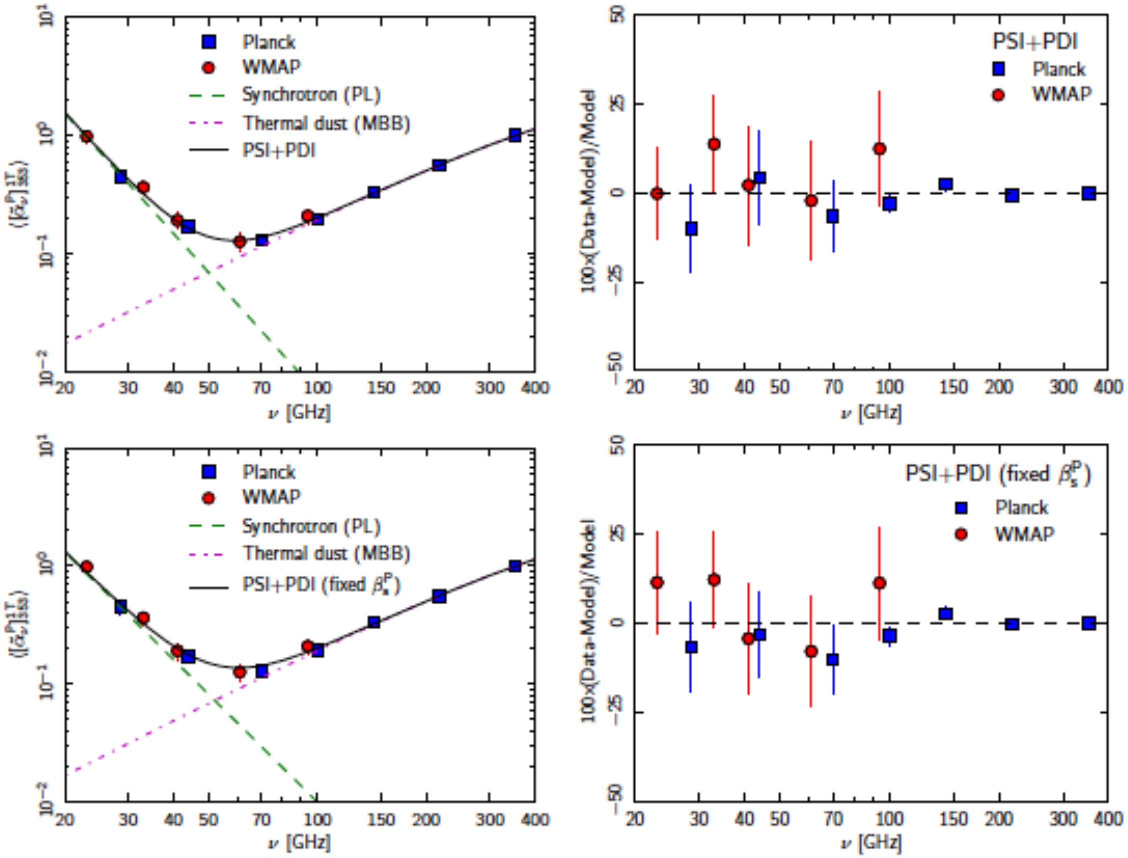
Polarization dust SED

Spectral modeling

Residuals

Free synchrotron spectral index

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



Power-law model of 353 GHz correlated synchrotron emission

+

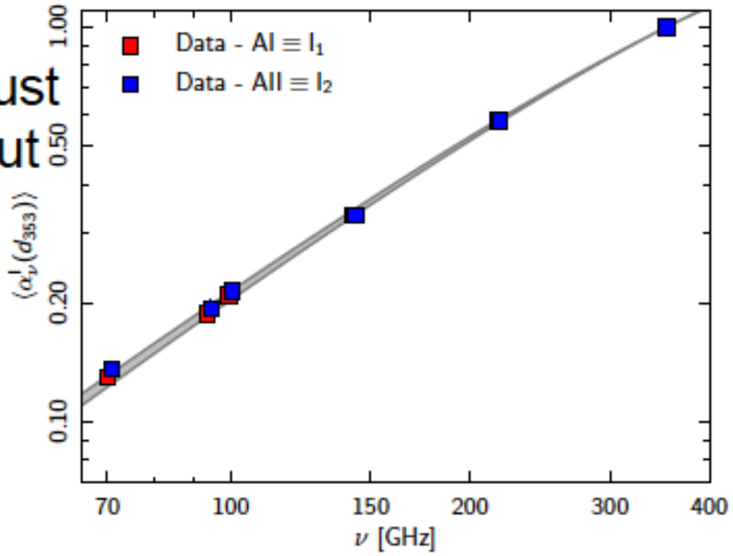
MBB spectrum of polarized thermal dust emission

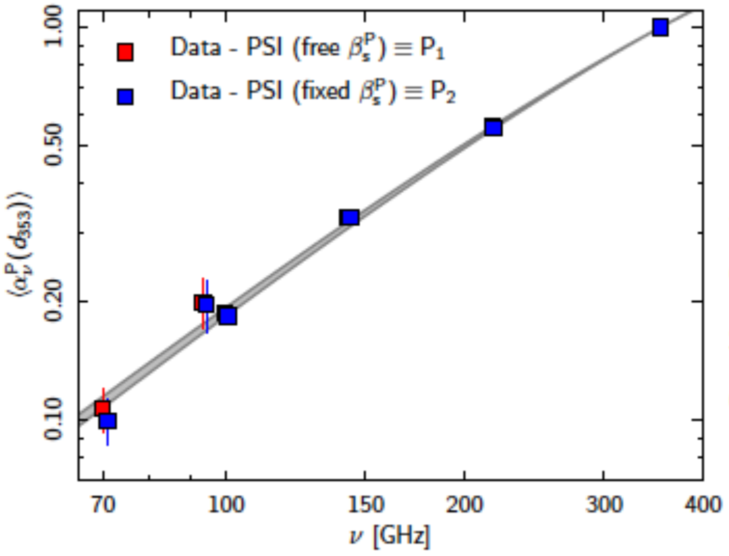
Parameters ^{a}	Unconstrained β_s^P	Fixed β_s^P
A_s^P	0.97 ± 0.10	0.86 ± 0.06
β_s^P	-3.40 ± 0.28	-3.04
$\beta_{d,mm}^P$	1.57 ± 0.01	1.58 ± 0.01
χ^2/N_{dof} ...	6.6/9	8.6/10

[Planck Intermediate XXII 2014, arXiv:1406.0874]

Variation of polarization fraction with frequency

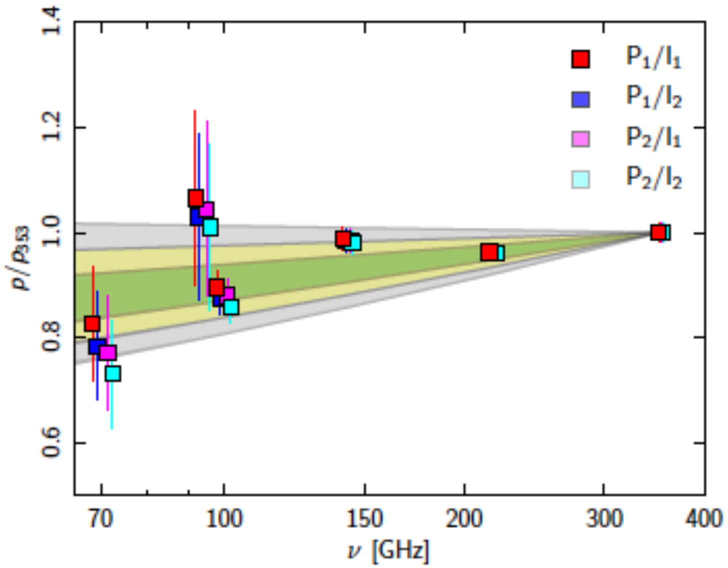
Intensity dust SED without AME





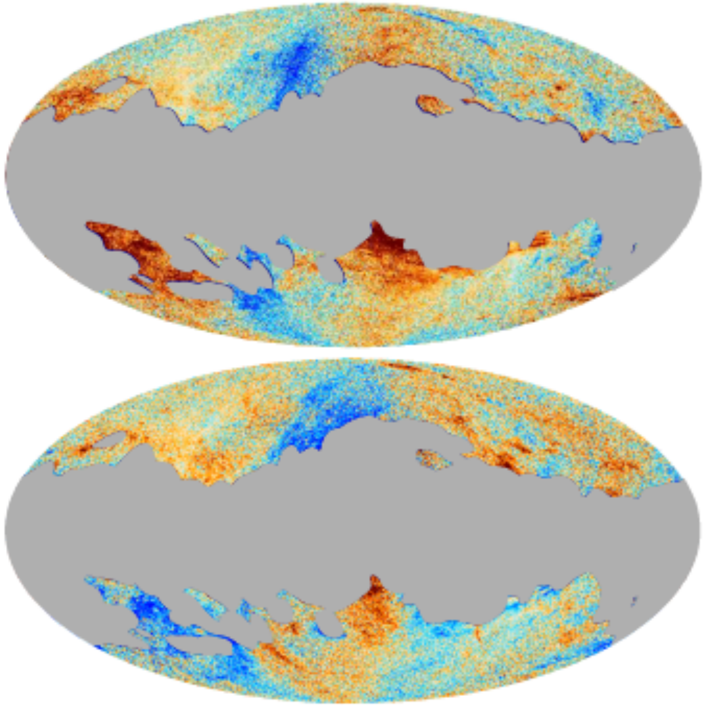
Polarized dust SED without 353 GHz correlated synchrotron emission

polarization fraction is normalized to 353 GHz



[Planck Intermediate XXII 2014, arXiv:1406.0874]

General methodology



Q and U maps at 353 GHz

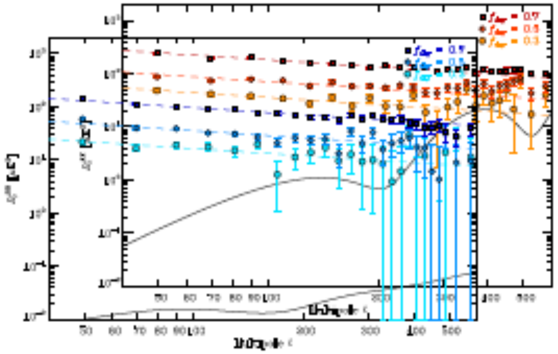
XPOL

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

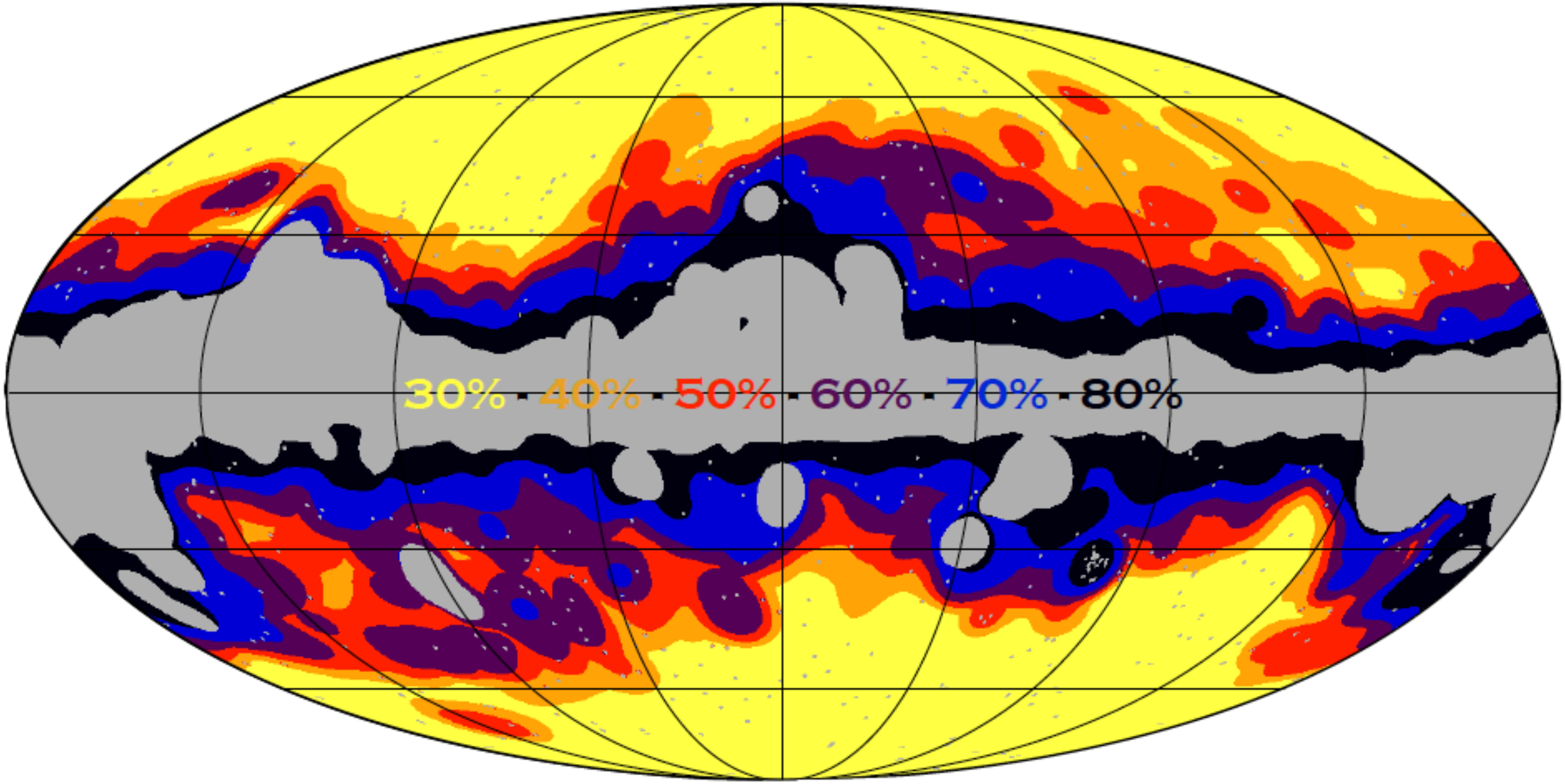
$$C_\ell(\nu \times \nu) \equiv C_\ell(D_\nu^1 \times D_\nu^2).$$

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



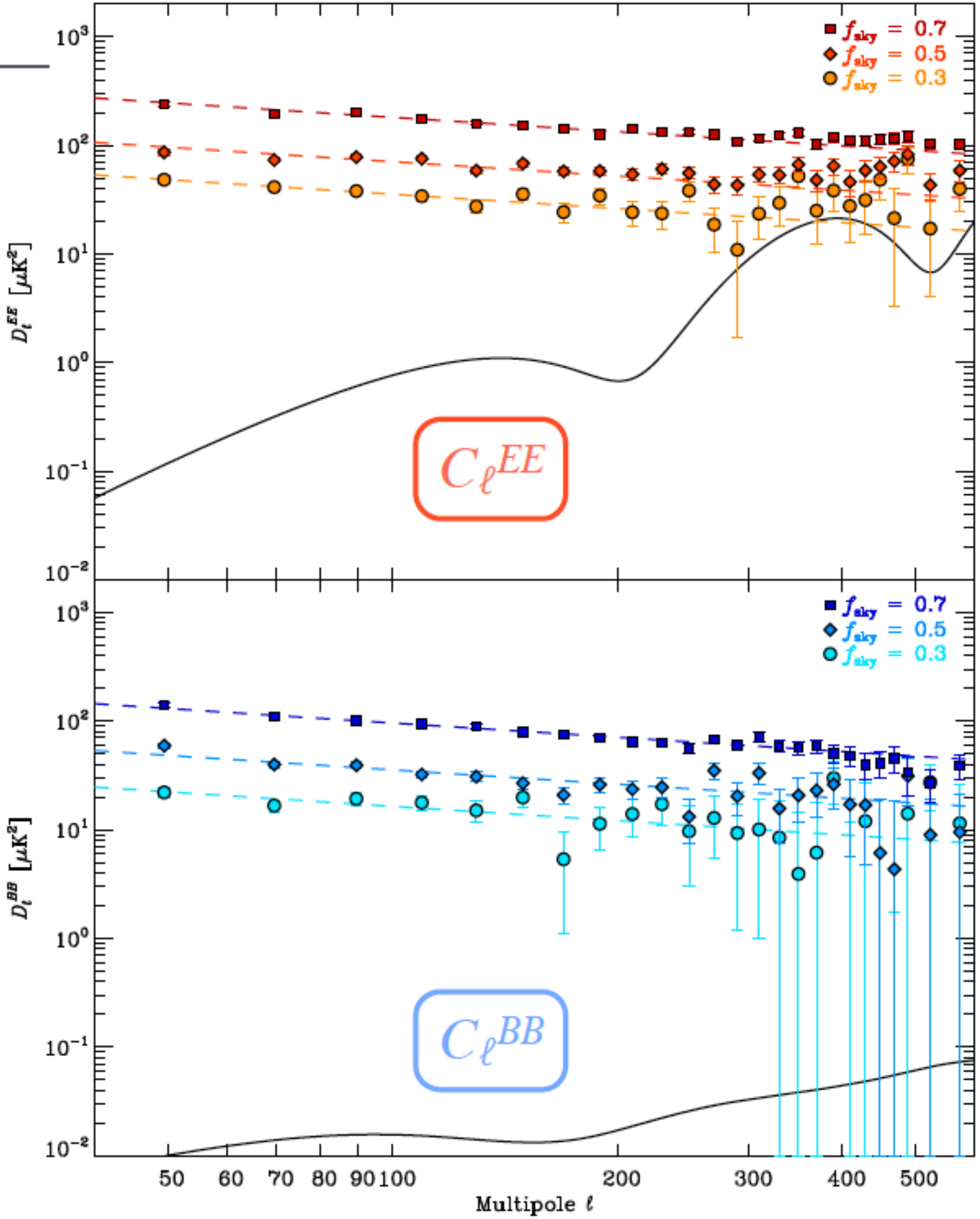
+ CO + radio point sources mask + apodization (5 degrees)

[Planck Intermediate XXX 2014, arXiv 1409.5738]

Results

- First detection of the dust polarized angular power spectra at $\ell>10$
- Even on 30% of the sky, the dust polarized emission dominates the CMB, at all scales

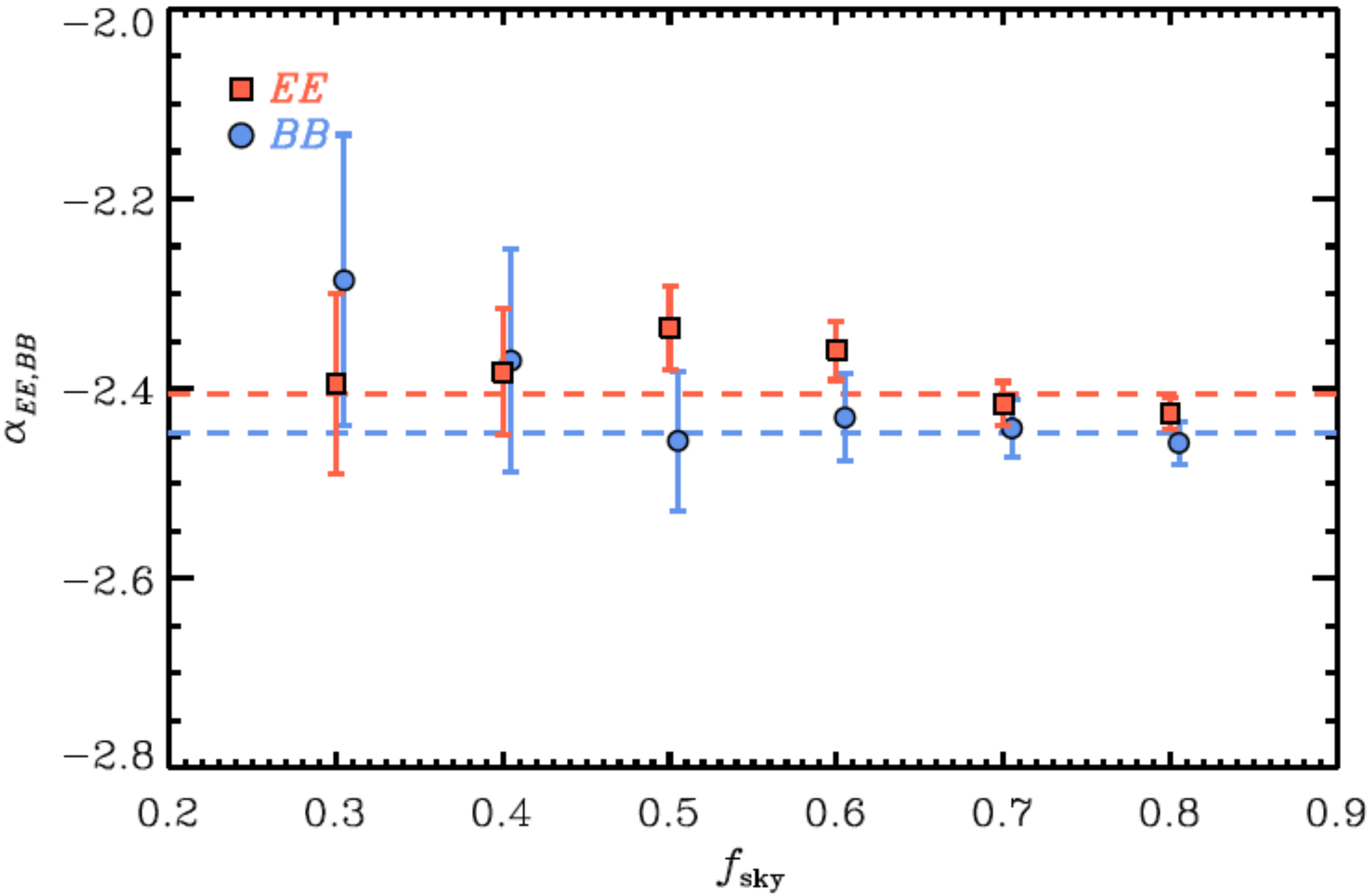
1. Shape of the spectra?
2. Variation of their amplitudes with respect to the mask?
3. *BB*/*EE* ratio?
4. Amplitudes at other frequencies?



[Planck Intermediate XXX 2014, arXiv 1409.5738]

Shape of the spectra?

Power-law: $C_\ell^{EE,BB} \equiv A^{EE,BB} \ell^{\alpha_{EE,BB}}$



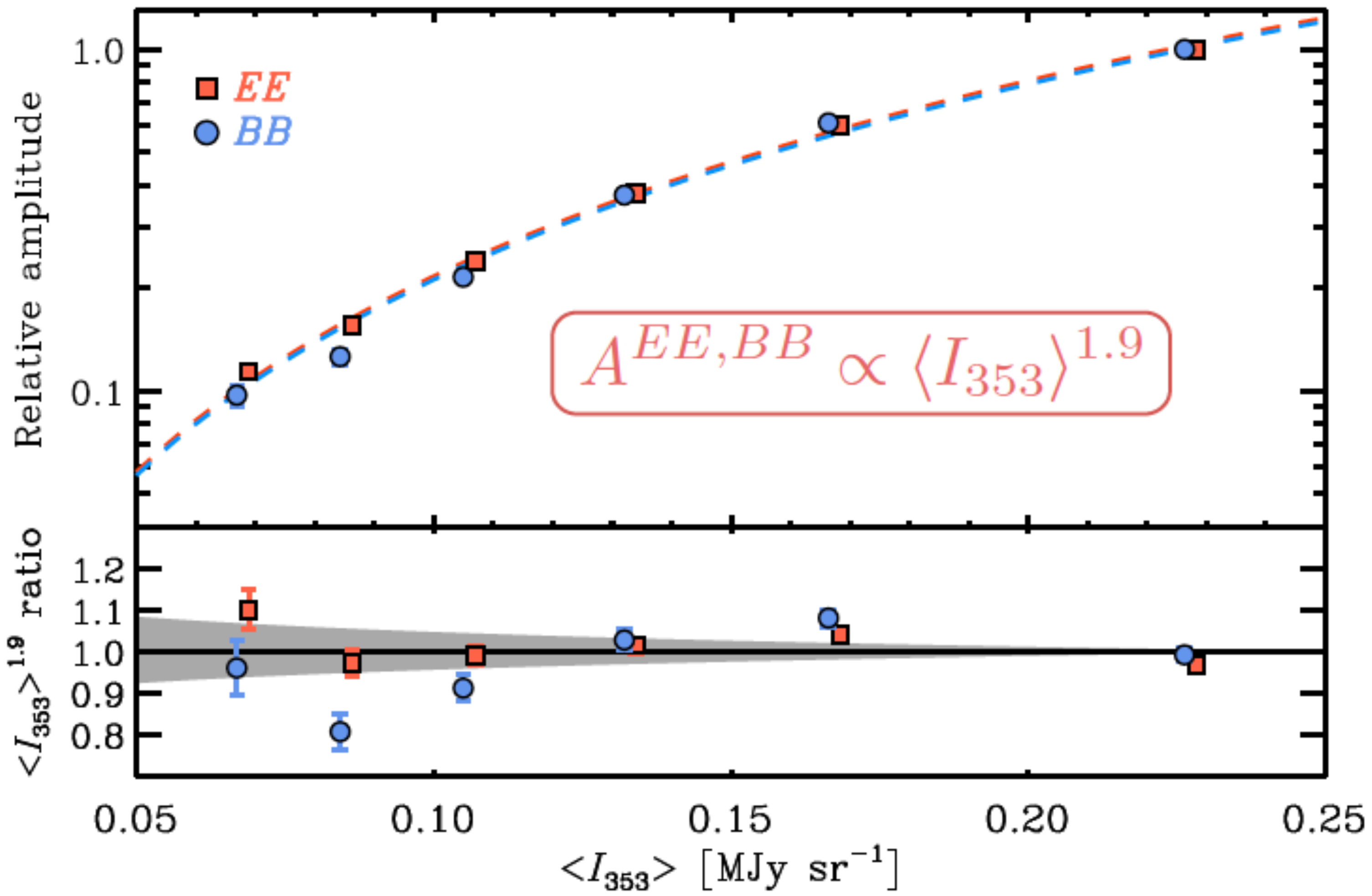
[Planck Intermediate XXX 2014, arXiv 1409.5738]

- ★ The spectra are compatible with power-laws with a -2.42 slope
- ★ No significant difference between *EE* and *BB*

Amplitude as a function of the mask

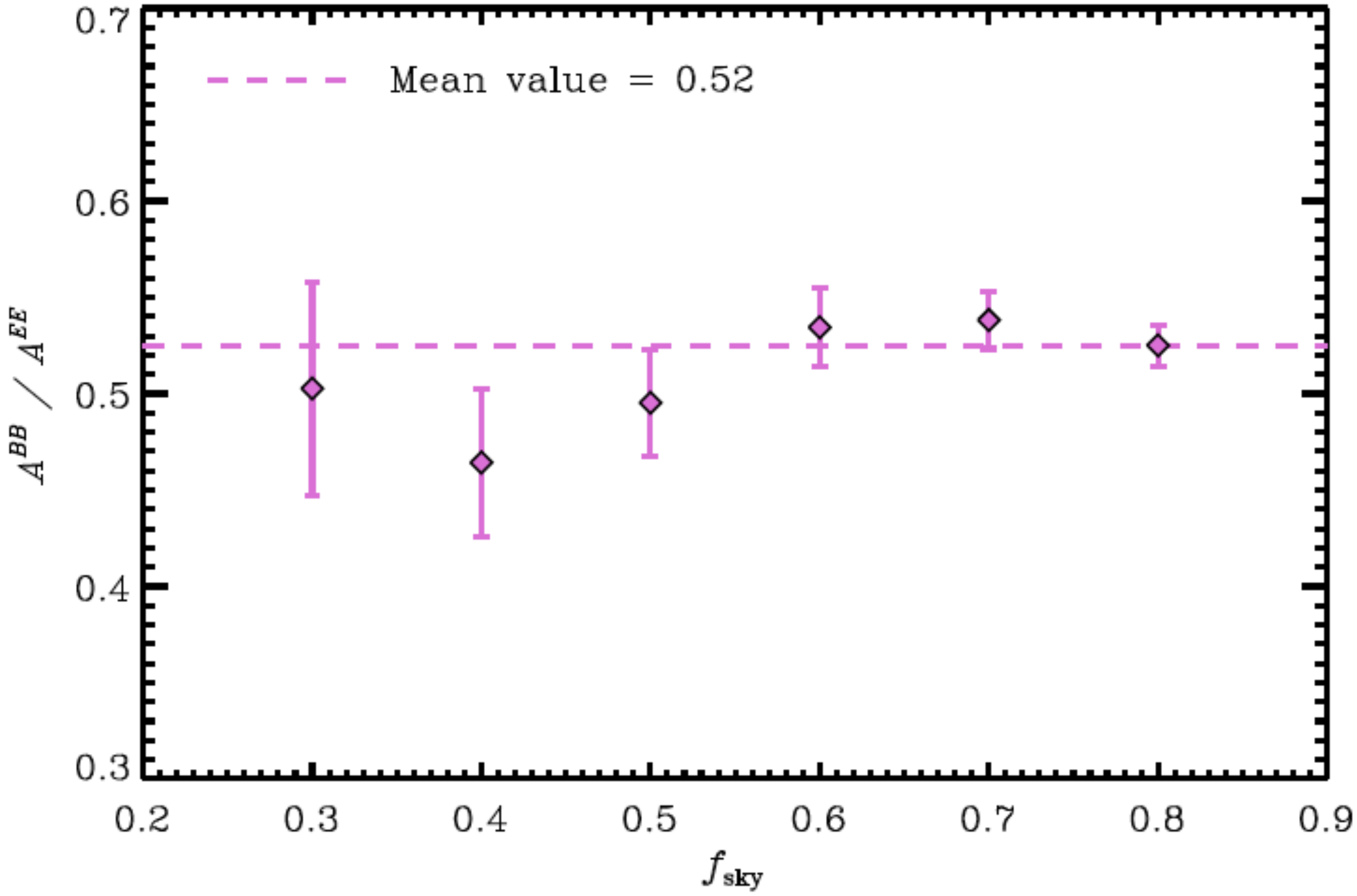
$$C_\ell^{EE,BB} \equiv A^{EE,BB} \ell^{-2.42}$$

[Planck Intermediate XXX 2014, arXiv 1409.5738]



★ There is an empirical relation between the amplitude and the mean dust intensity on the considered region

BB/EE ratio?

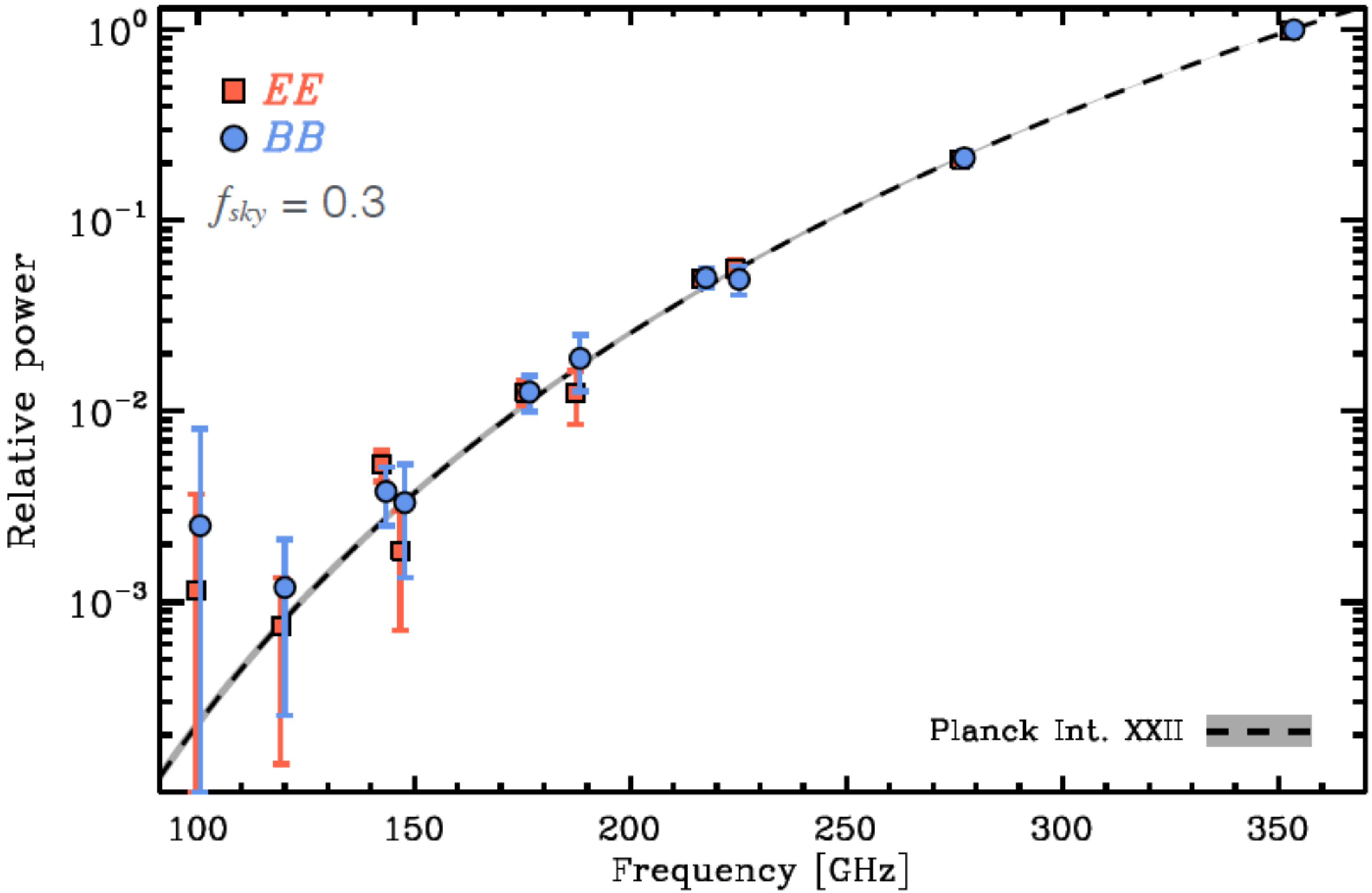


[Planck Intermediate XXX 2014, arXiv 1409.5738]

- ★ The dust polarized emission produces twice as much EE than BB
- ★ The existing dust models give $BB/EE\sim1$

Amplitude as a function of the observing frequency?

[Planck Intermediate XXX 2014, arXiv 1409.5738]
[Planck Intermediate XXII 2014, arXiv 1405.0874]

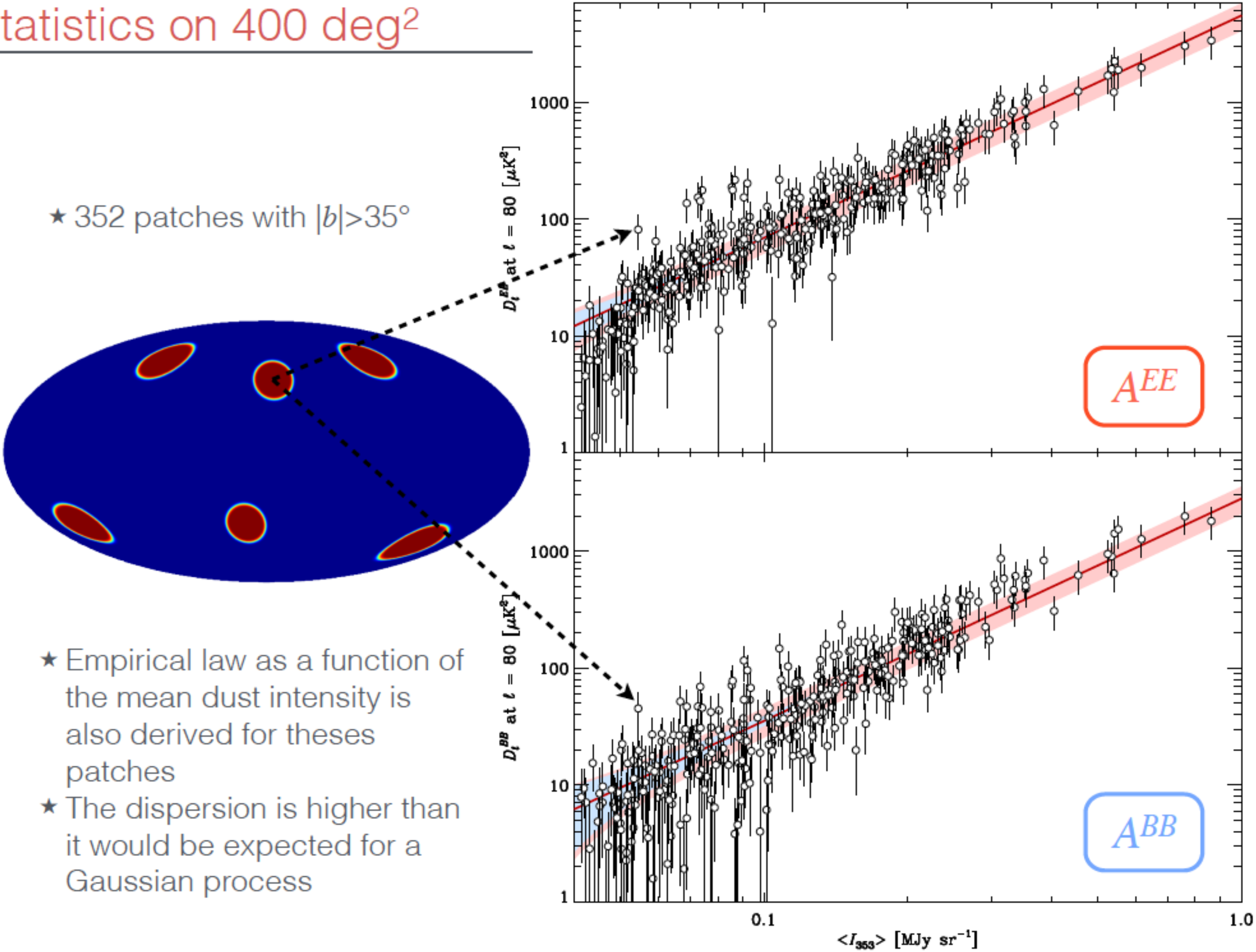


- ★ The spectra amplitudes follow the frequency dependence of the dust polarization for both *EE* and *BB*

Statistics on 400 deg²

[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

Conclusions

Planck observations of light emitted by interstellar dust are revealing a new sky for Galactic astrophysics and cosmology.

These map provide astrophysicists with the most detailed view yet at the Galactic magnetic field, unveiling its role in creating the filamentary, web-like, structures where stars form.

The spectral dependence of the polarized signal from dust furthers our understanding of the nature of interstellar dust

Planck data characterize dust polarization as a foreground to CMB polarization.

The CMB B-mode signal from primordial gravity waves will not be detected without removal of the dust polarization with high accuracy and confidence.This requirement ties the search from primordial B-modes to the astrophysics of the dusty magnetized interstellar medium.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

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