Planck results on dust polarization : magnetic field and B-modes contamination

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esa

planck

cnes

asi
agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

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Consejo Superior de Investigaciones Científicas

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HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
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California Institute of Technology

ioa

KICC
Kavli Institute for Cosmology Cambridge

Cavendish Astrophysics

University of Cambridge

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Observer & comprendre

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Les deux infinis

ipac

Helsinki Institute of Physics

Instituto de Astrofísica de Canarias IAC

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

Néel institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
Data Centre for Astrophysics

JPL

LAL
Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris
LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester
MilliLab

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asdc
ASI Science Data Center

Should cosmology care about Galactic dust ?

- Up to now, dealing with Galactic foregrounds has been relatively simple to obtain the CMB Cl(TT).
  The CIB anisotropies has been more problematic

- There has been two ways for doing that :

  - multi-frequency experiment with very simple prescription for foregrounds (ILC)

  - limited number of frequency bands (even n=1) at the foreground minimum (~70-100 GHz) and no prescription for foregrounds (just go for faint regions where they are negligible)

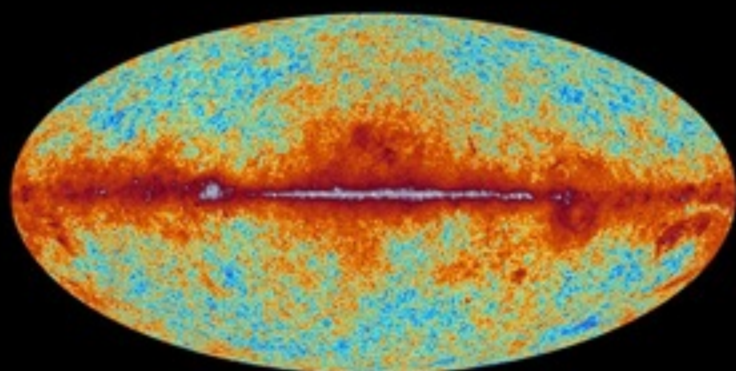
- In polarization B-modes, we learned that the second option is not available

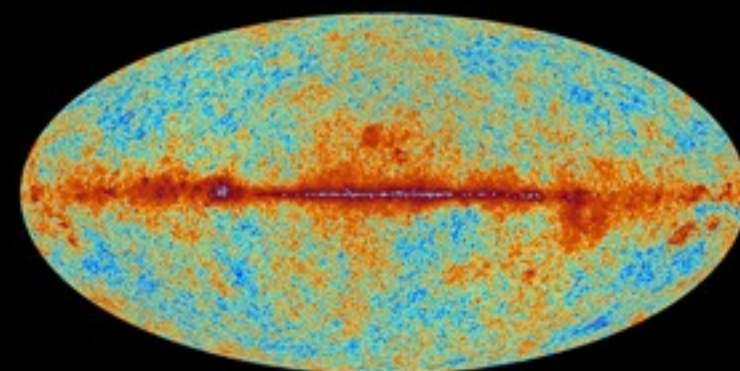
  - The quest for B-modes requires some knowledge about dust

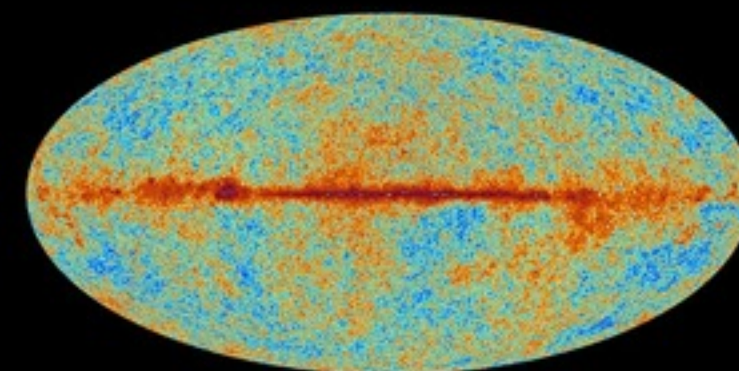
Outline

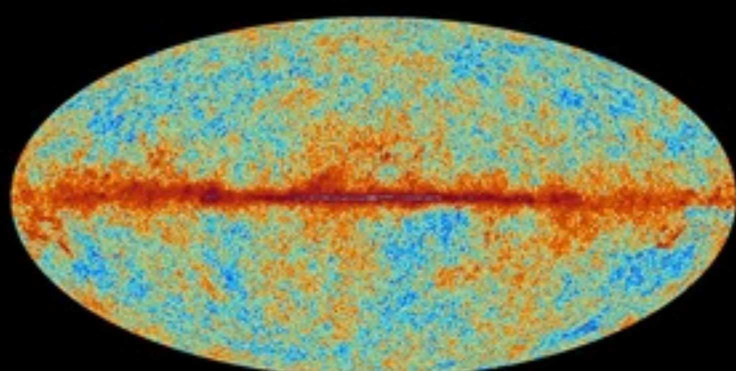
- The Planck mission
- The dust SED : how well does it scale in frequency ?
- The dust polarization sky : B-density relation
- Statistical properties of dust polarization and extrapolation to CMB type fields

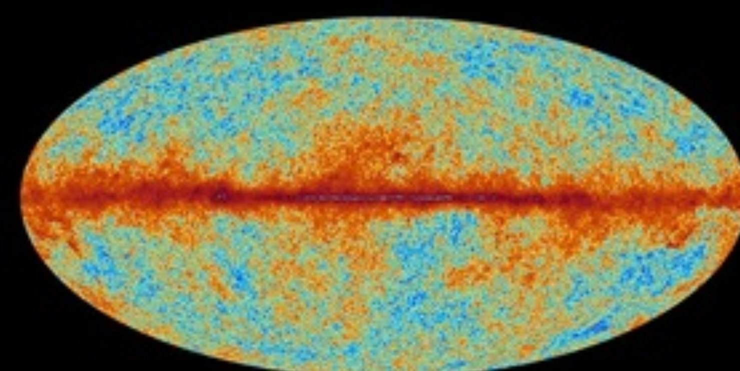
The sky as seen by Planck

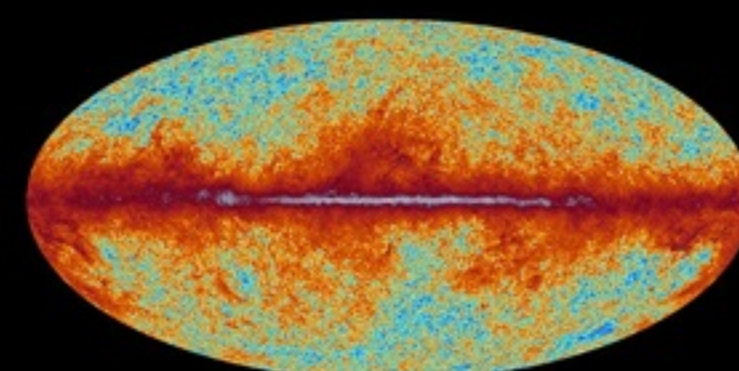

30 GHz

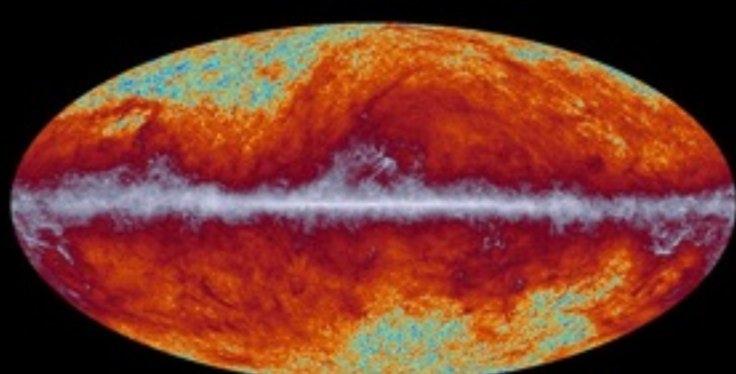

44 GHz

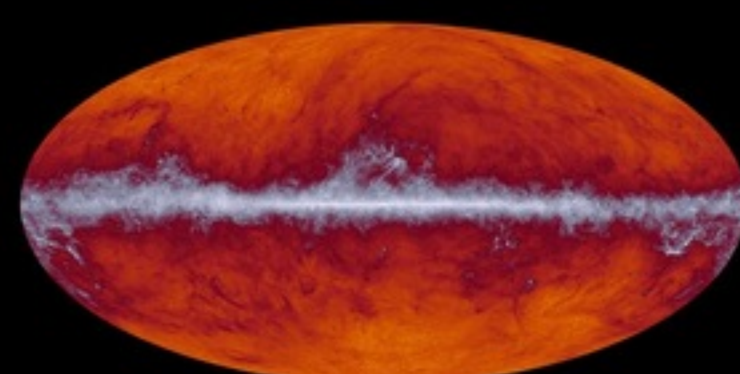

70 GHz

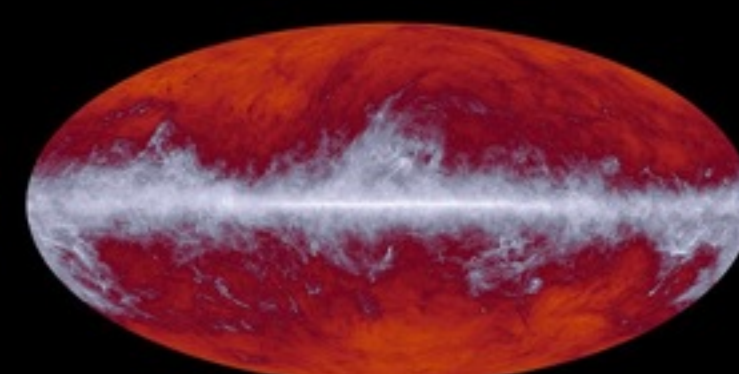

100 GHz


143 GHz


217 GHz


353 GHz

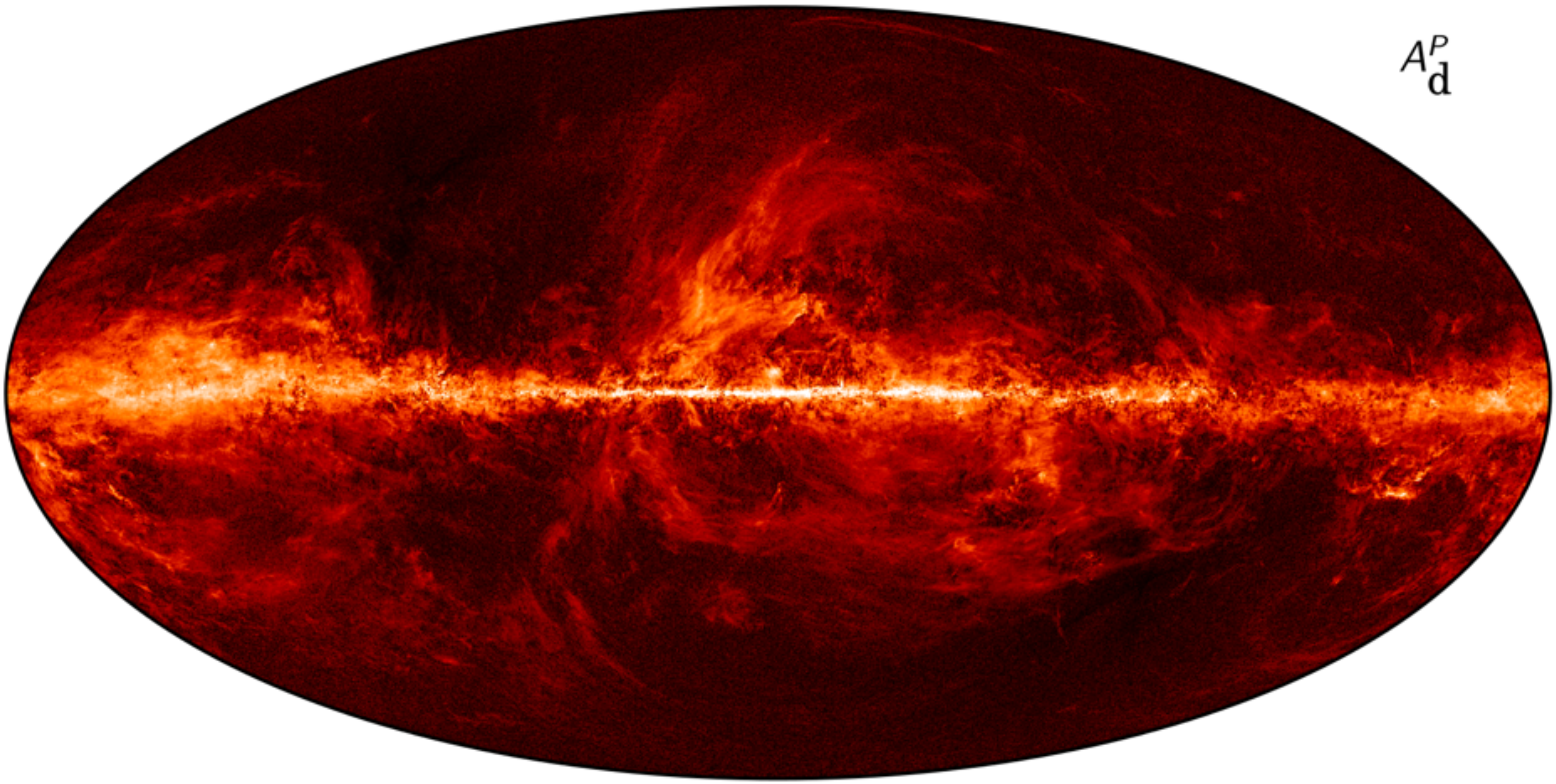

545 GHz


857 GHz

The sky as seen by Planck

- Allsky mapping in 9 frequency bands from 30 to 857 GHz
  - polarization for 7 bands from 30 to 353 GHz
- Angular resolution from 4.5 to 30 arcmin
- Photon noise limited in intensity
- Operations from August 2009 to January 2012
- First data release in March 2013 : nominal mission (14 months)
- Second data release early 2015 : full mission (2.5 years)

Planck 353 GHz polarized intensity

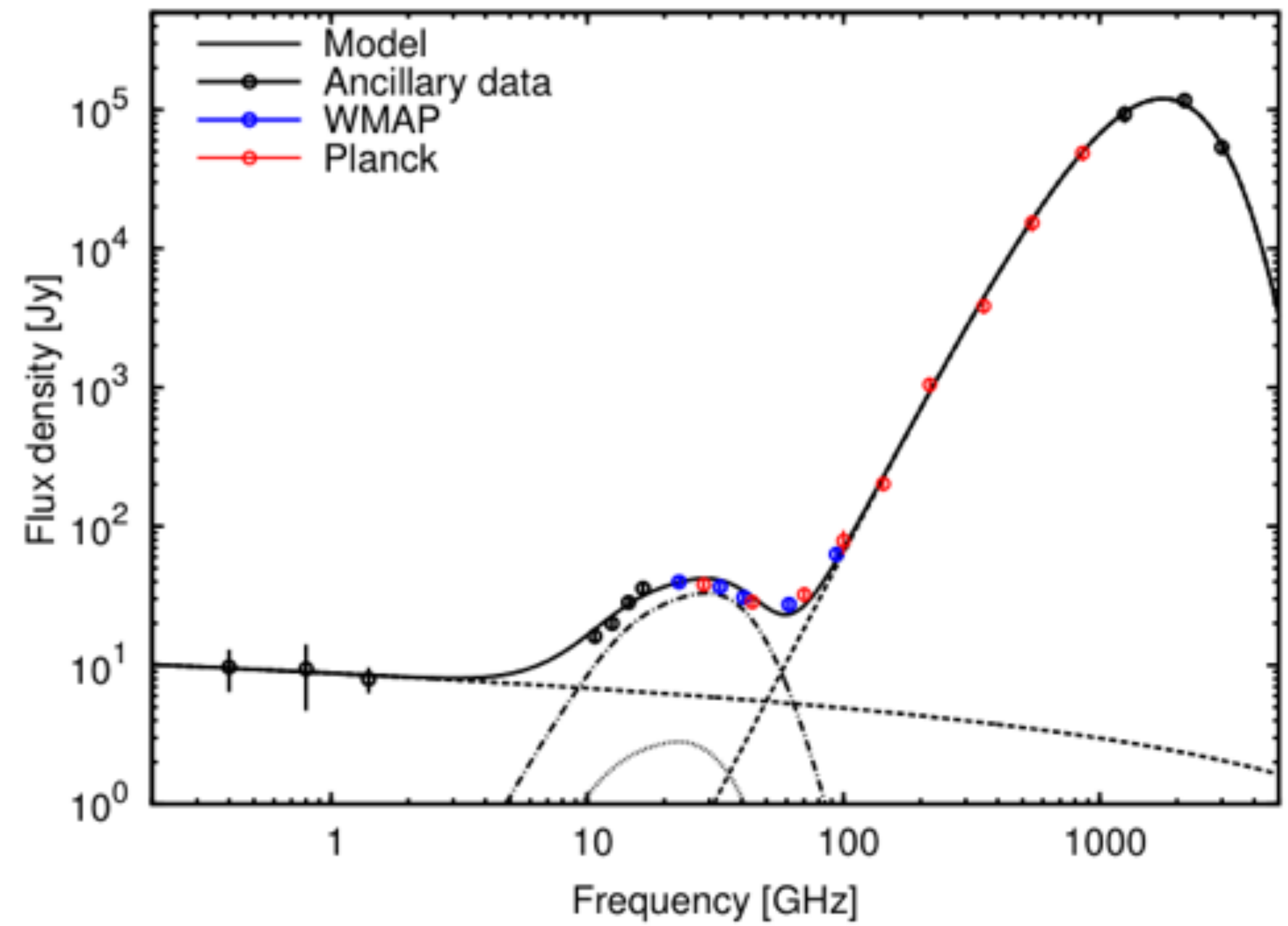


Model of dust emission

- Thermal dust emission
  - Model as a modified black body
  - COBE-FIRAS era : flattening of the SED in the nu < 350 GHz Finkbeiner et al. (1999)

- Challenges in the Planck-HFI range
  - CO
  - Free-free
  - CMB anisotropies
  - CIB anisotropies

Perseus molecular cloud

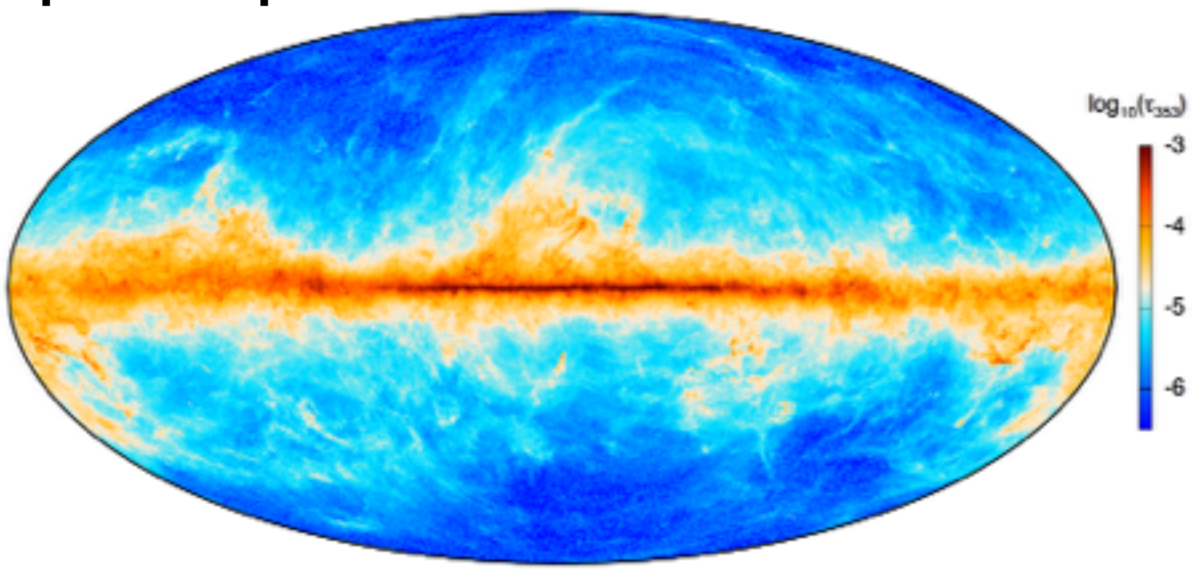


$$I_\nu = N_H \, B_\nu(T) \, \alpha \nu^\beta$$

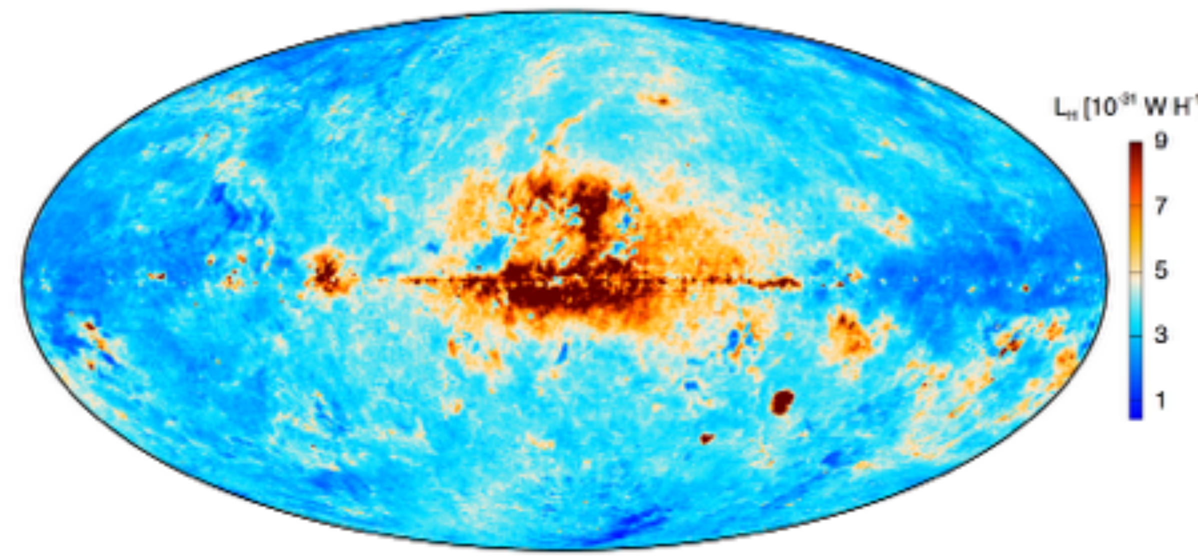
All-sky model of dust emission using Planck (2013 data release) + IRAS

all-sky maps at 5 arc min resolution
frequencies : 353, 545, 857 and 3000 GHz

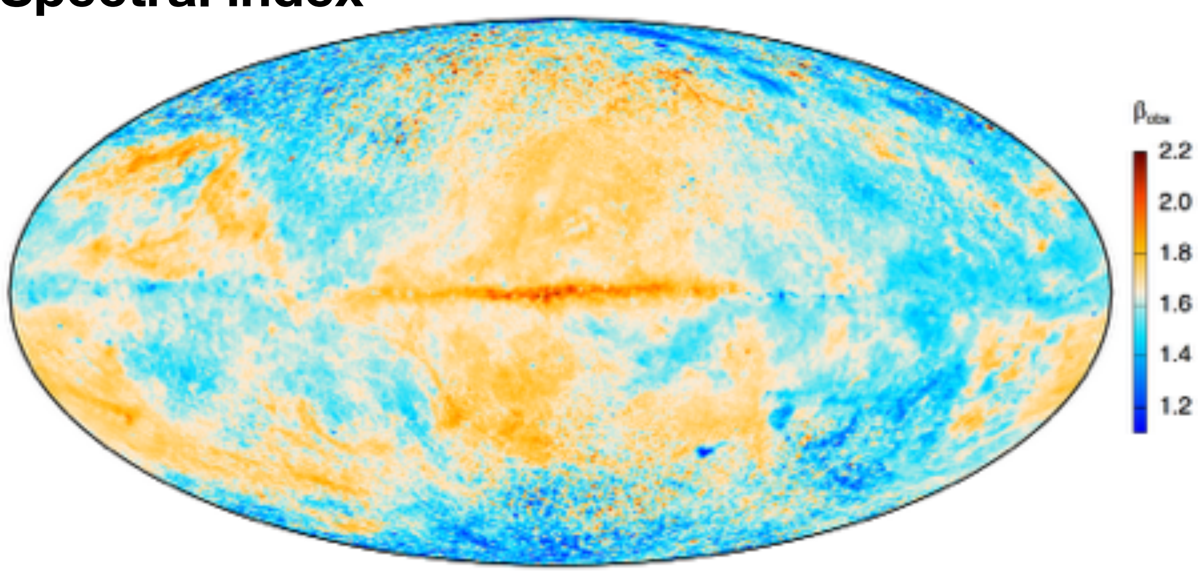
Optical depth at 850 micron - 353 GHz



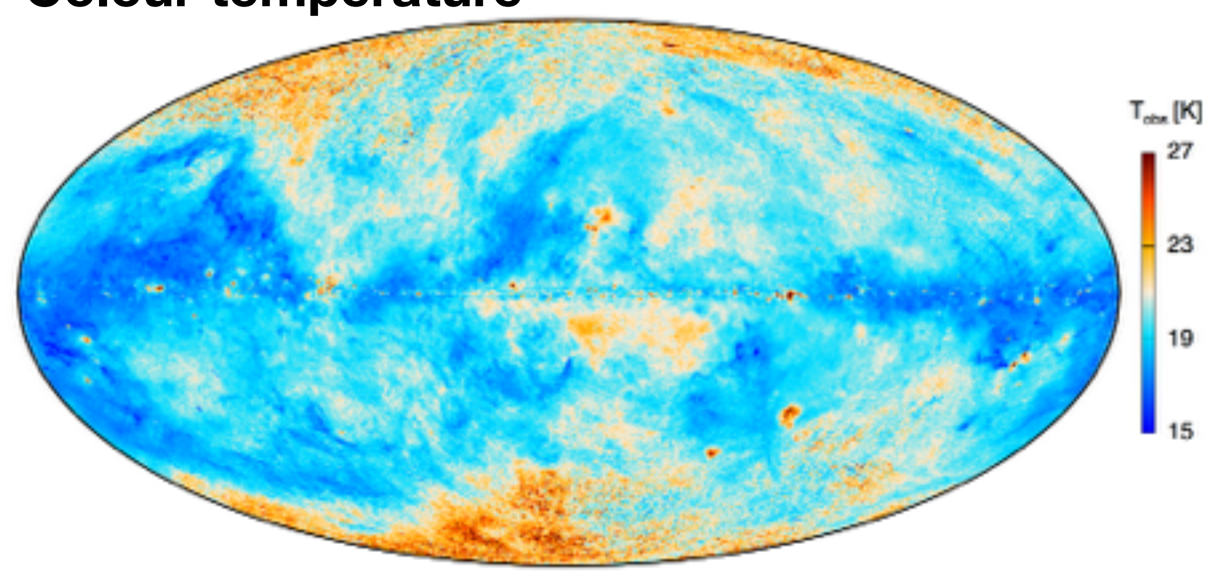
Radiation field strength : L_{dust} / N_H



Spectral index



Colour temperature



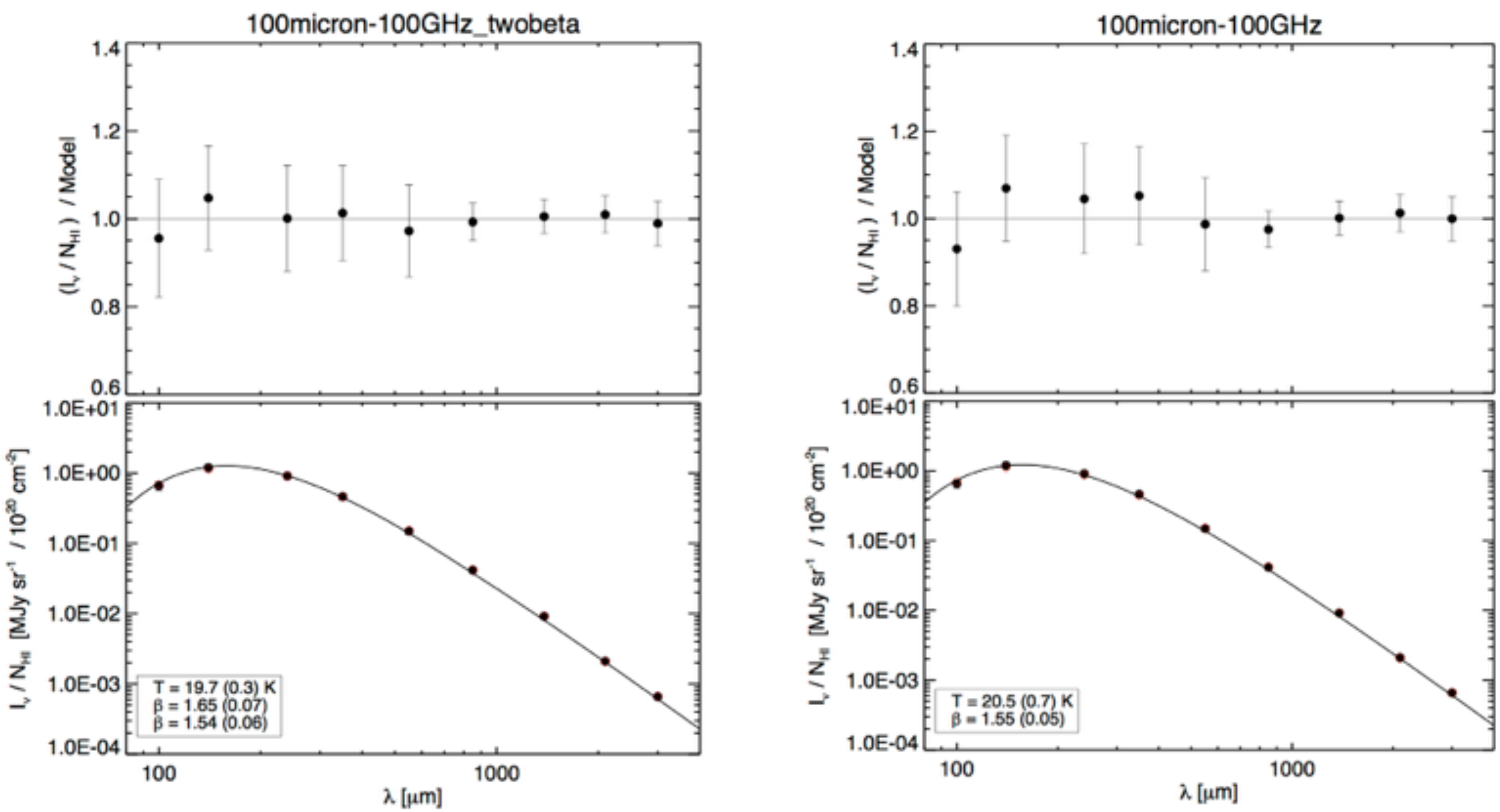
dust spectral index is 1.55-1.65
also : all-sky map of dust reddening : E(B-V)

Planck collaboration 2013 results. XI (2014)

Dust SED down to CMB frequencies —Planck 2013 data release —

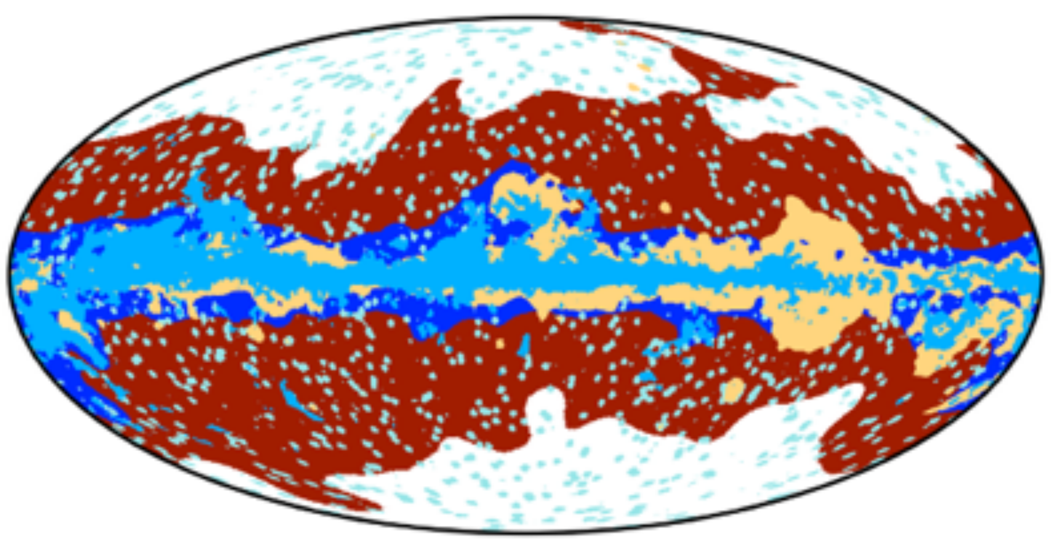
Beta_FIR = 1.65
Beta_mm = 1.54

- Fit of the fiducial high Galactic latitude dust SED
- Obtained by a correlation of Planck and DIRBE data with HI in the diffuse ISM towards the south ecliptic pole (15% of the sky)
  - Correlation done on 136 patches of 180 sq. deg.

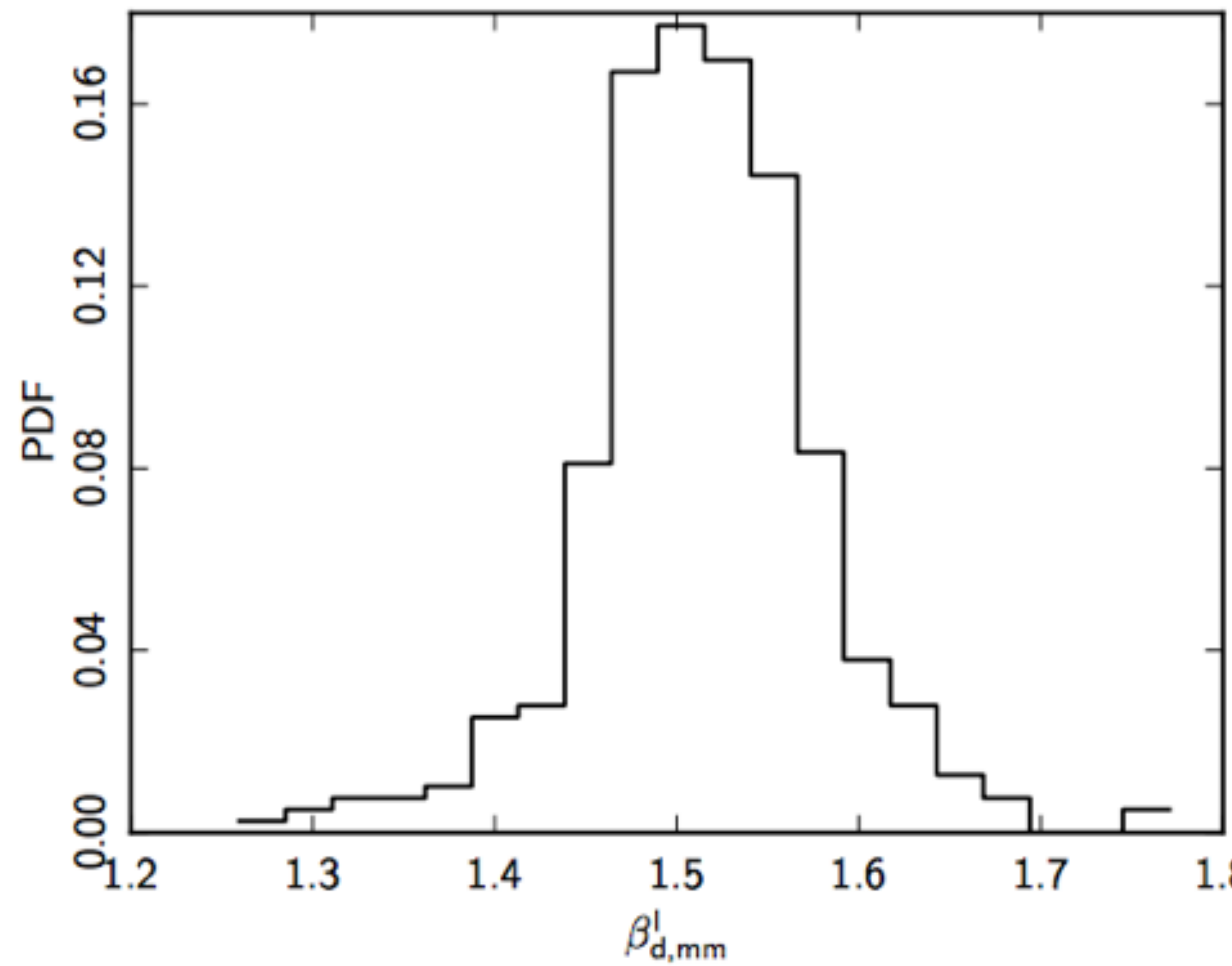


Dust spectral index : 217-353 GHz

- Cross-correlation of 217 with 353 in 10 deg. patches
- Intermediate latitude (39% of the sky) to reduce the effects of CMB, CIB, CO and free-free
- Assumes Td derived at high frequencies (3000/857 GHz).



Intensity

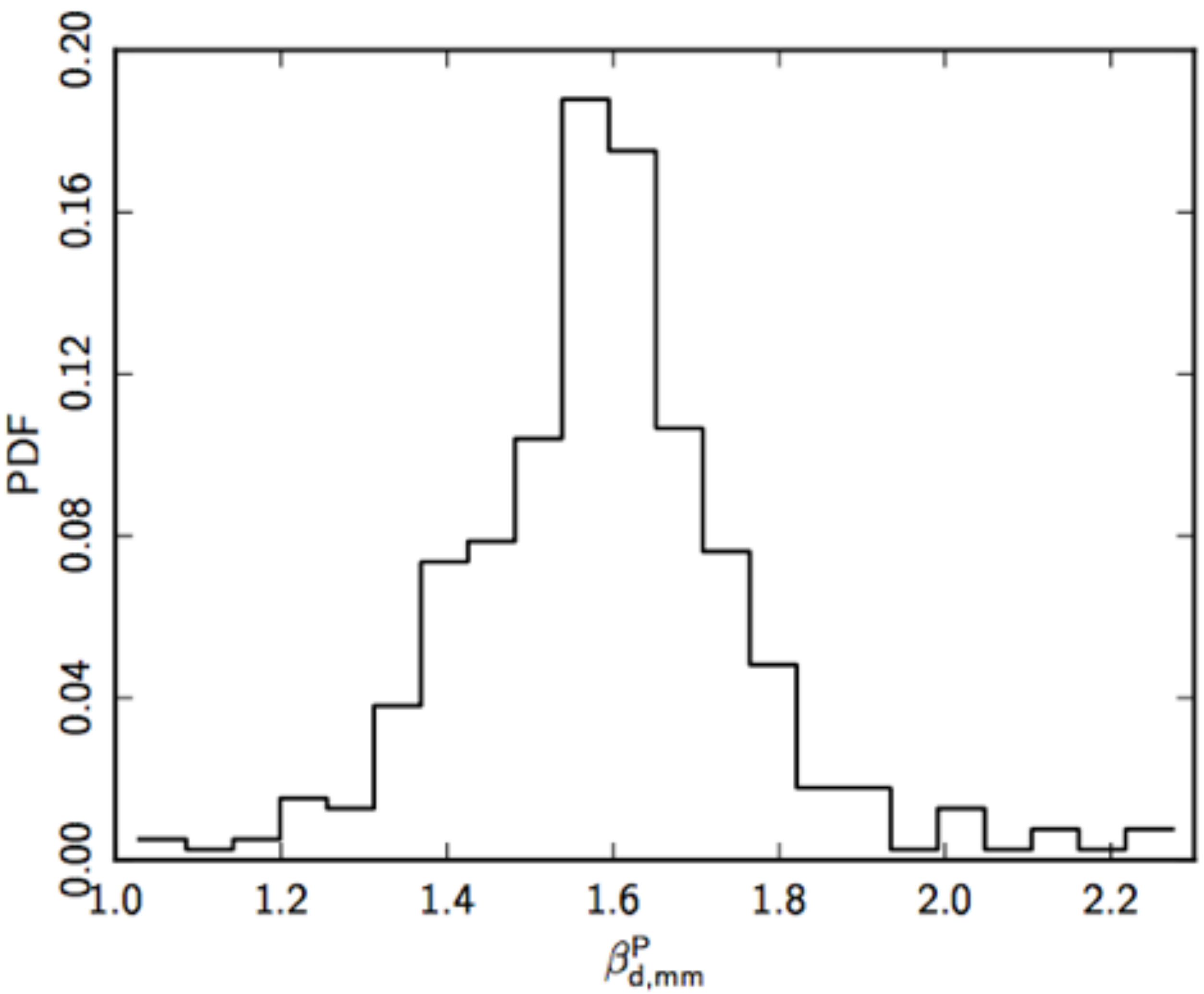


average = 1.51
1 sigma = 0.07
noise contribution is +- 0.01

Planck intermediate results. XXII. (2014)

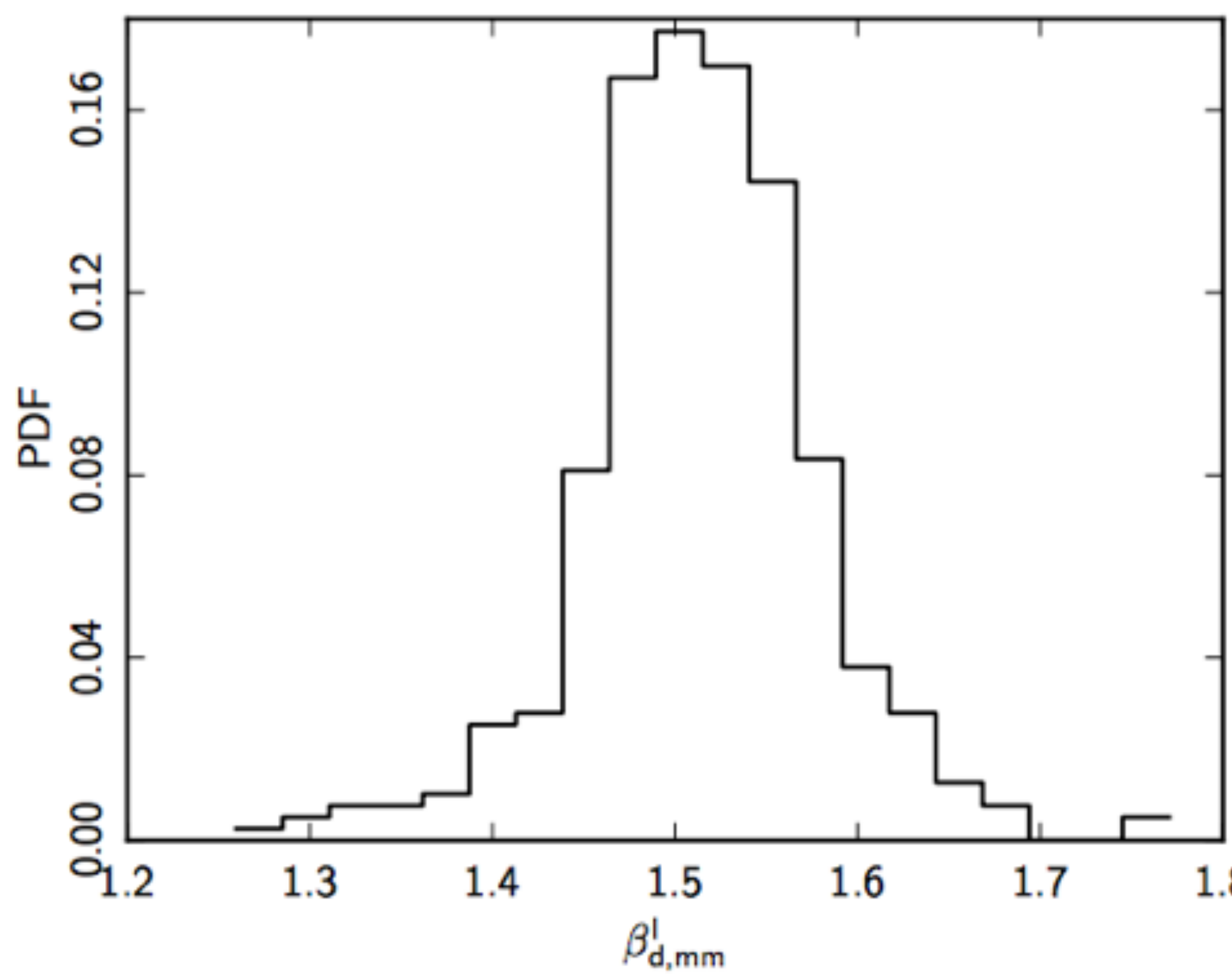
Dust spectral index : 217-353 GHz

Polarization



average = 1.59
1 sigma = 0.17
noise contribution is +- 0.01

Intensity



average = 1.51
1 sigma = 0.07
noise contribution is +- 0.01

Difference between intensity and polarization has a 3.6 sigma significance

Planck intermediate results. XXII. (2014)

Shape of the dust SED with the Planck 2015 data release

- The flattening of the dust SED, Is there a flattening of the SED in the mm ?
  - we worked in this context since the FIRAS results (~ 1999)
  - accounted for by adding a second dust component (e.g. Finkbeiner et al. 1999 model)
  - depends strongly on the calibration of the data
- Planck Calibration vs FIRAS
  - 2013 data release
    - 545 GHz : -15% vs FIRAS (based on Planet observations)
    - 857 GHz : -7% vs FIRAS (based on Planet observations)
  - 2015 data release
    - 545 GHz : -19% vs FIRAS (based on Solar dipole and Planet observations : both agree within 1%)
    - 857 GHz : -10% vs FIRAS (based on Planet observations)
    - 353 GHz : +2% vs 2013 data release (improvement of dipole measurement)
- Planck 2015 : **no significant change in Beta from FIR to submm**
  - **Beta dust ~ 1.5 across the whole Planck frequency range**
  - **High Galactic latitude : Tdust ~ 19.6K**

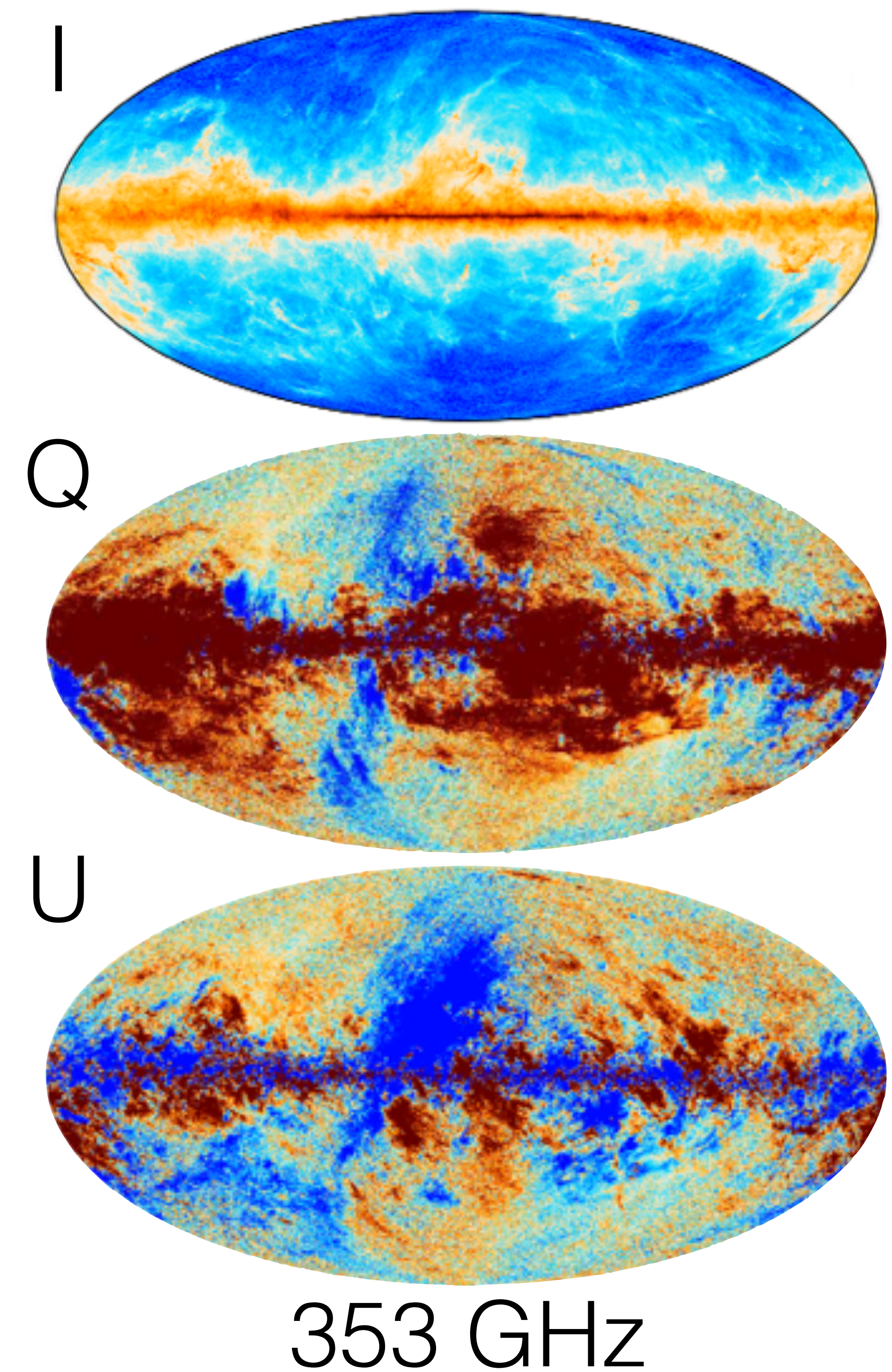
Dust polarization

$$I_\nu \propto \int n_z\, B_\nu(T_z)\, dz$$

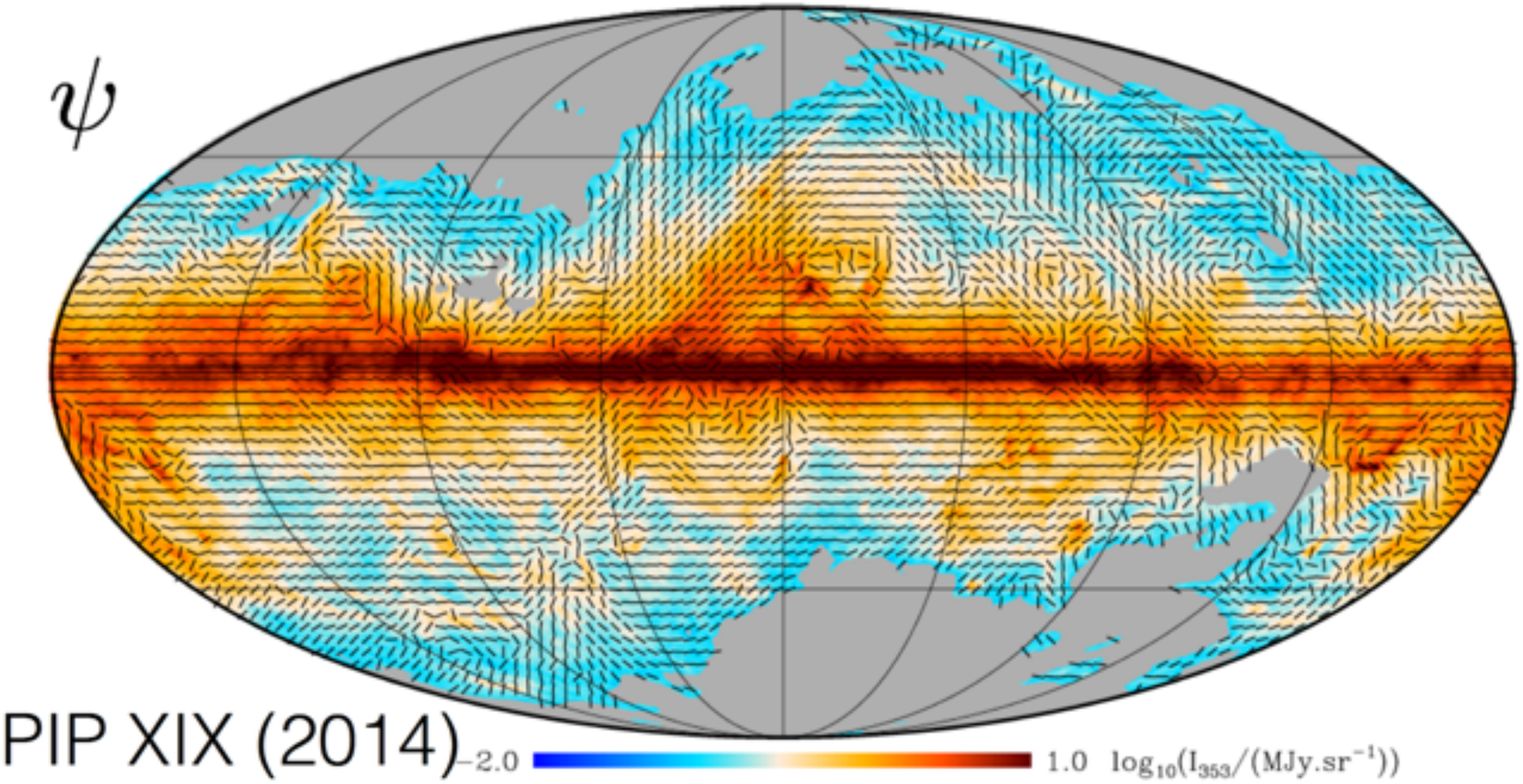
$$Q_\nu \propto \int n_z\, B_\nu(T_z)\, \cos(2\phi_z)\, \cos^2\gamma_z\, dz$$

$$U_\nu \propto \int n_z\, B_\nu(T_z)\, \sin(2\phi_z)\, \cos^2\gamma_z\, dz$$

- Fluctuation in I is dominated by column density
- Fluctuation in Q and U traces column density and magnetic field orientation variations
- The large scale sky in Q and U is modulated by a simple geometrical effect, not present in I, due to the magnetic field of the local spiral arm

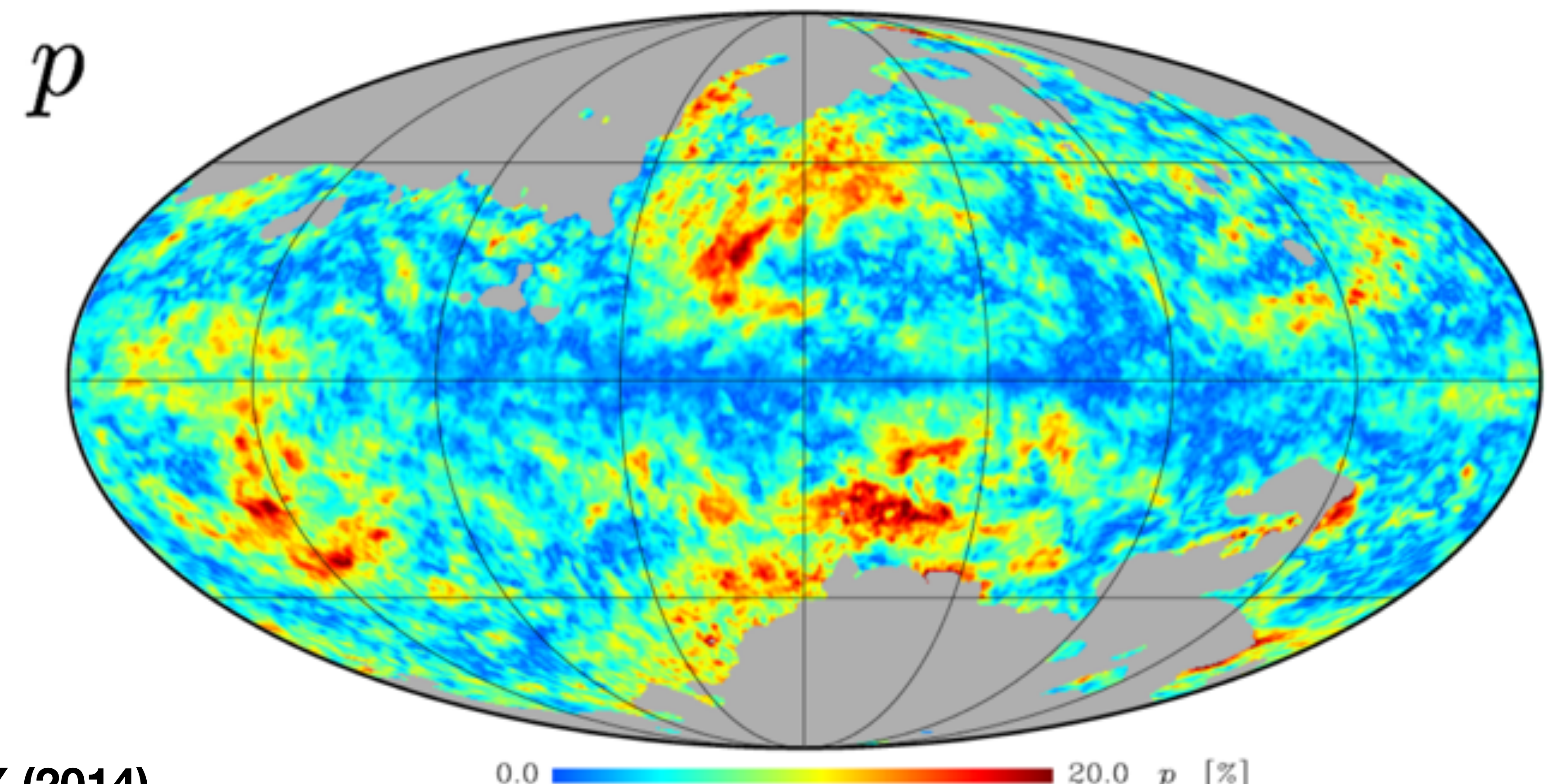


Polarization angle



PIP XIX (2014)

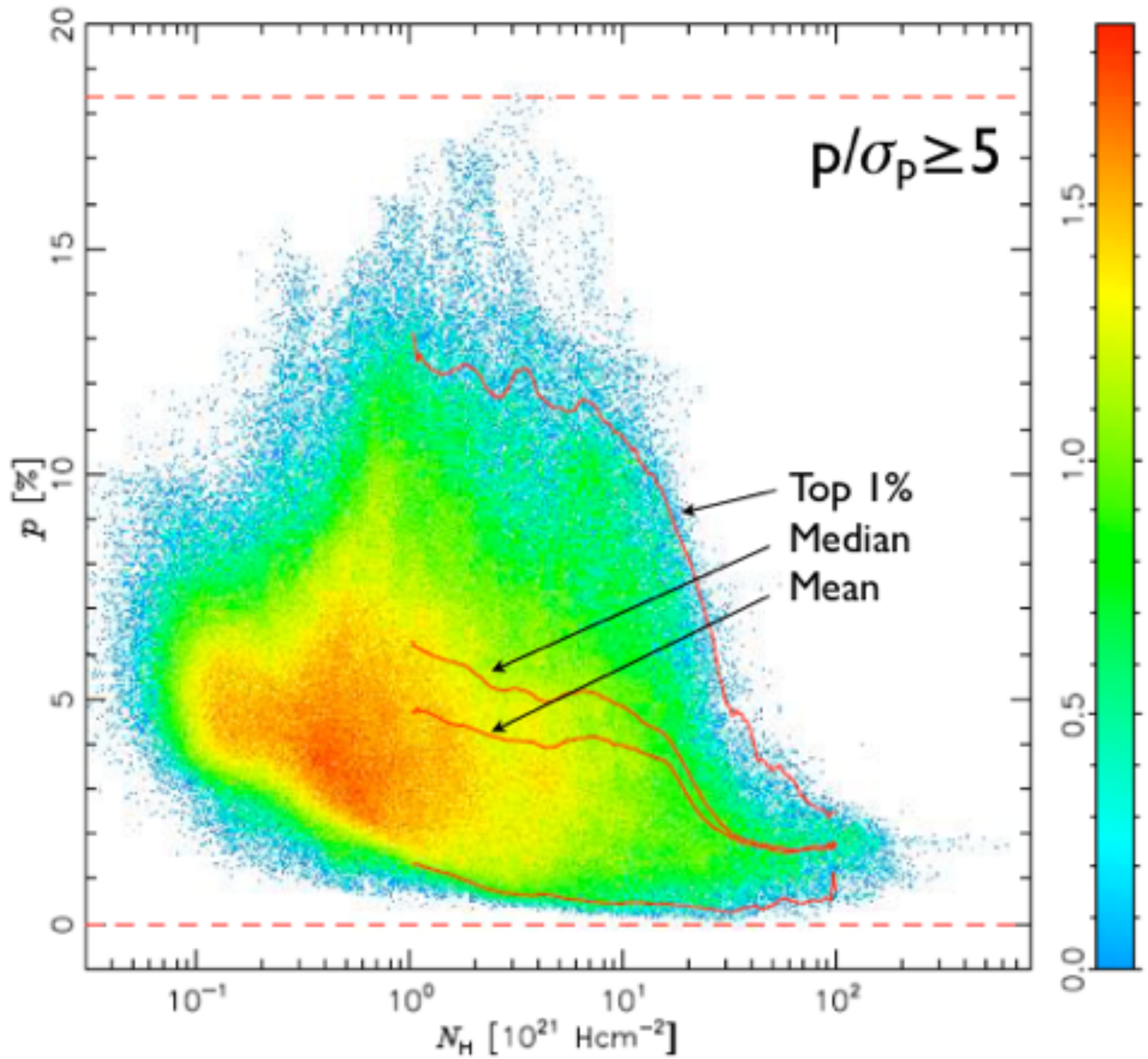
Polarization fraction



Planck intermediate results XIX (2014)

Polarization fraction vs NH

Whole sky



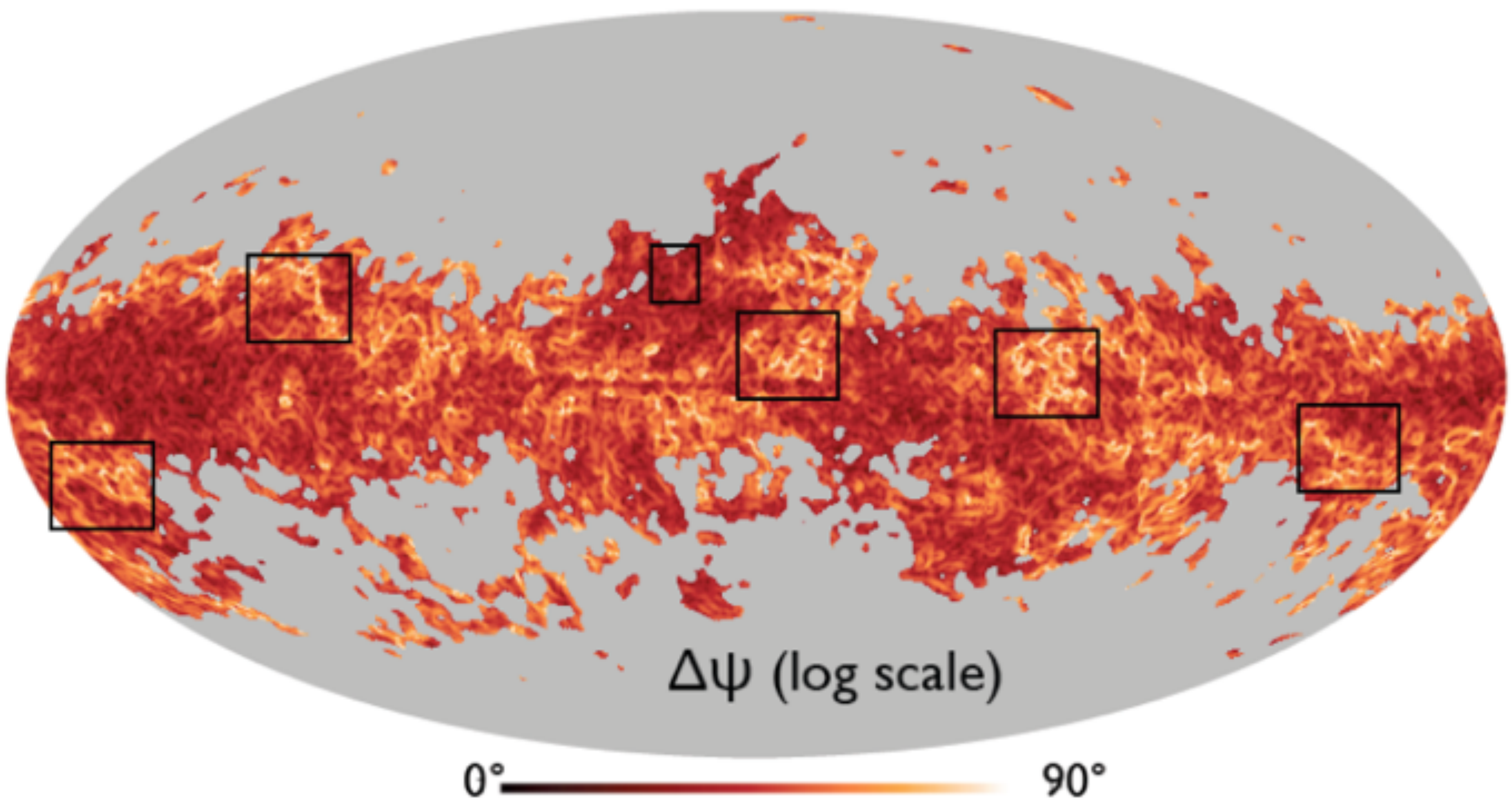
- General decrease of p versus column density. Consistent with results from earlier observations in extinction.
- Seen over the whole sky and on the scale of clouds.
- This result has been interpreted by a loss of grain alignment in the shielded interior of clouds. Planck data challenge this intepretation.

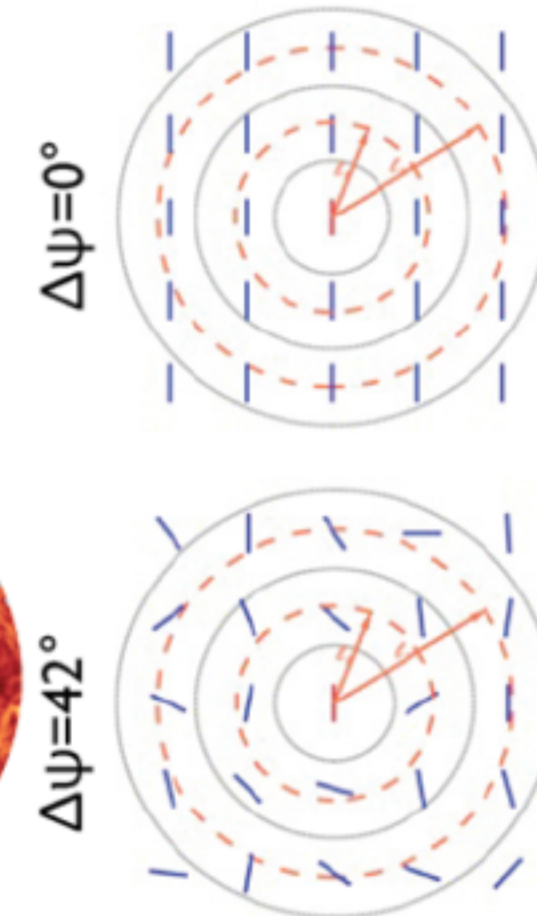
Planck intermediate results XIX (2014)

Local dispersion of polarization angles

Measure of polarization direction homogeneity at scale ℓ :

$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}\left[\psi(\mathbf{r}) - \psi(\mathbf{r}+\mathbf{l}_i)\right]^2$$ (Hildebrand et al. 2009)



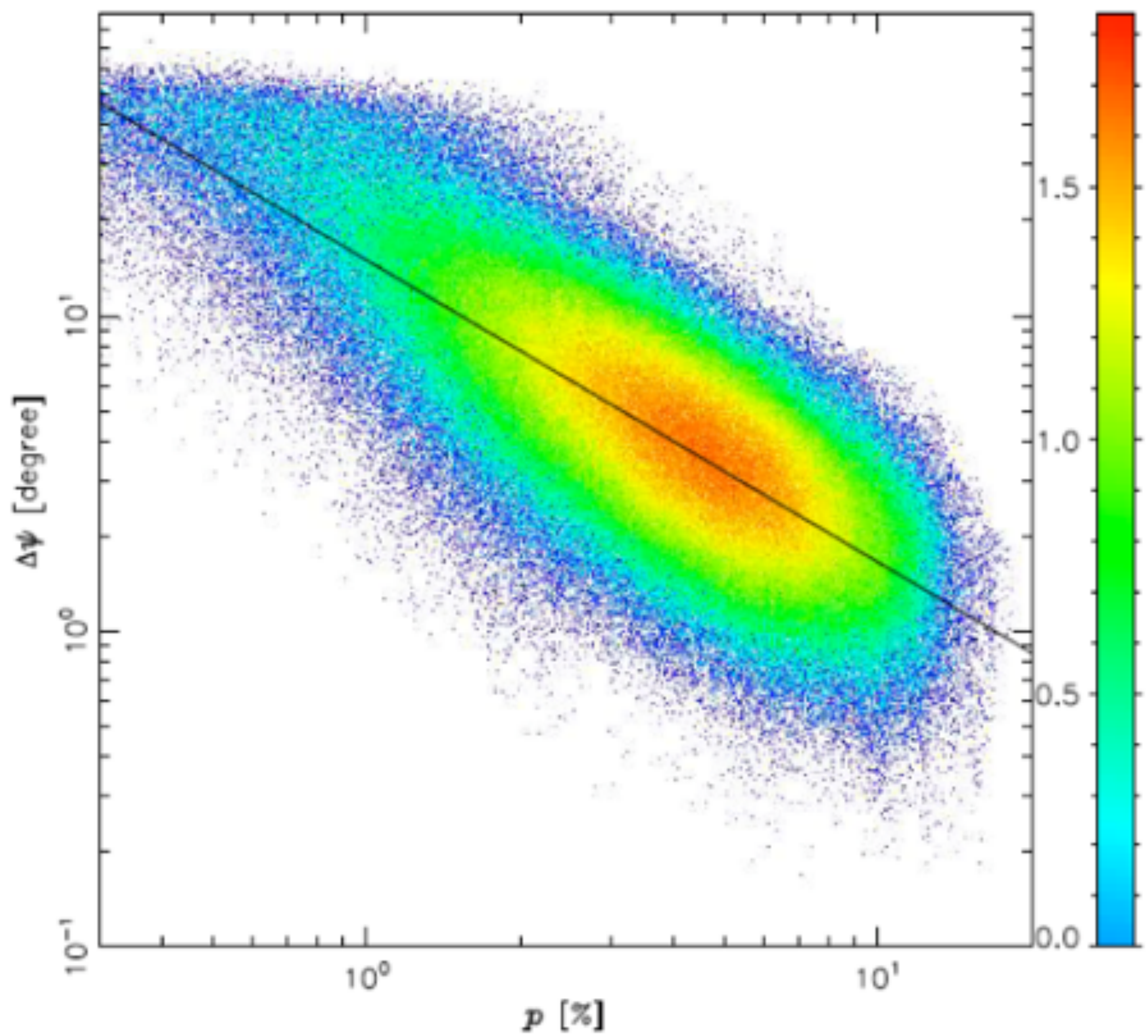


- Computed on Full survey on 1° resolution map at ℓ=30'.
- Masked where SN(Δψ)<3 (uncertainties using MC)
- Similar maps for all 5 individual surveys and 2 half-ring surveys

Planck intermediate results XIX (2014)

Anticorrelation $\Delta\Psi$ and p

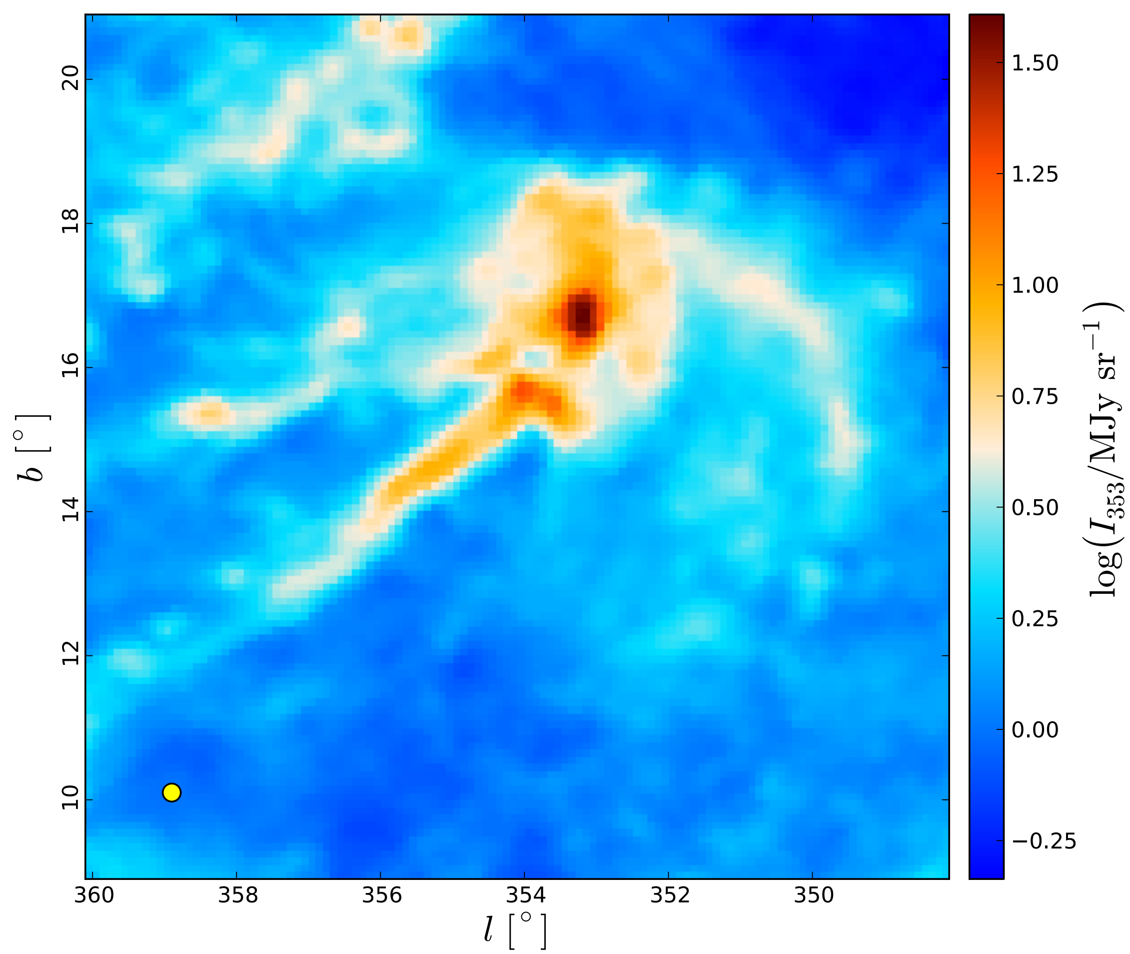
$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}[\psi(\mathbf{r}) - \psi(\mathbf{r}+\mathbf{l}_i)]^2$$

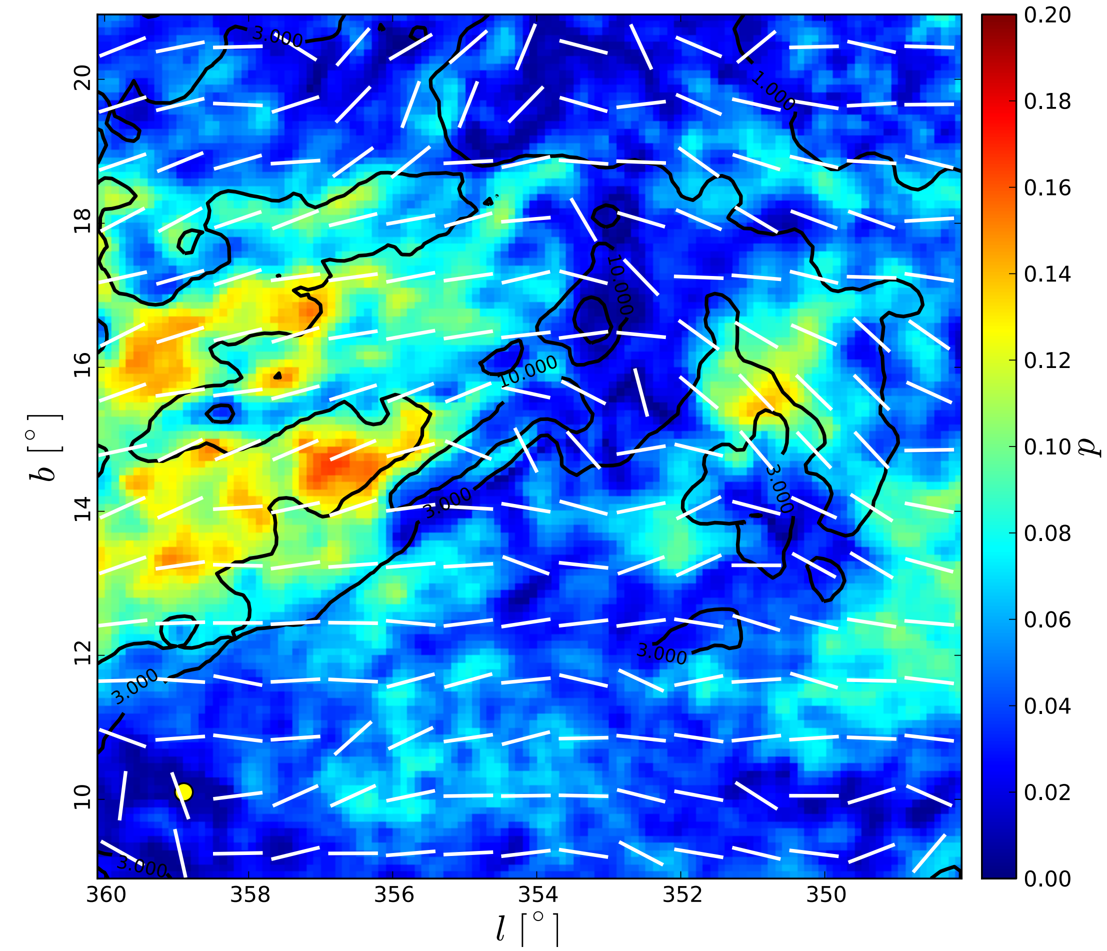


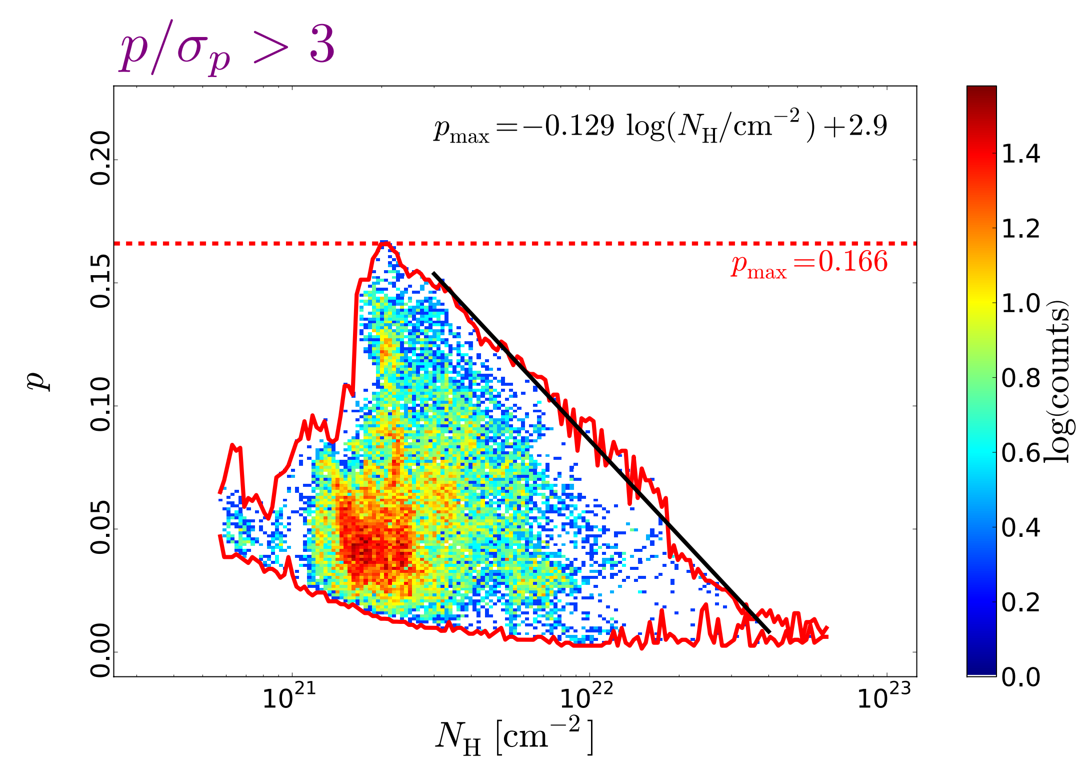
The Planck data suggests that depolarization in the diffuse ISM mainly results from superposition of signals with different polarization directions. Within this interpretation variations in p are primarily related to the field structure

Planck intermediate results XIX (2014)

Polarization fraction versus column density





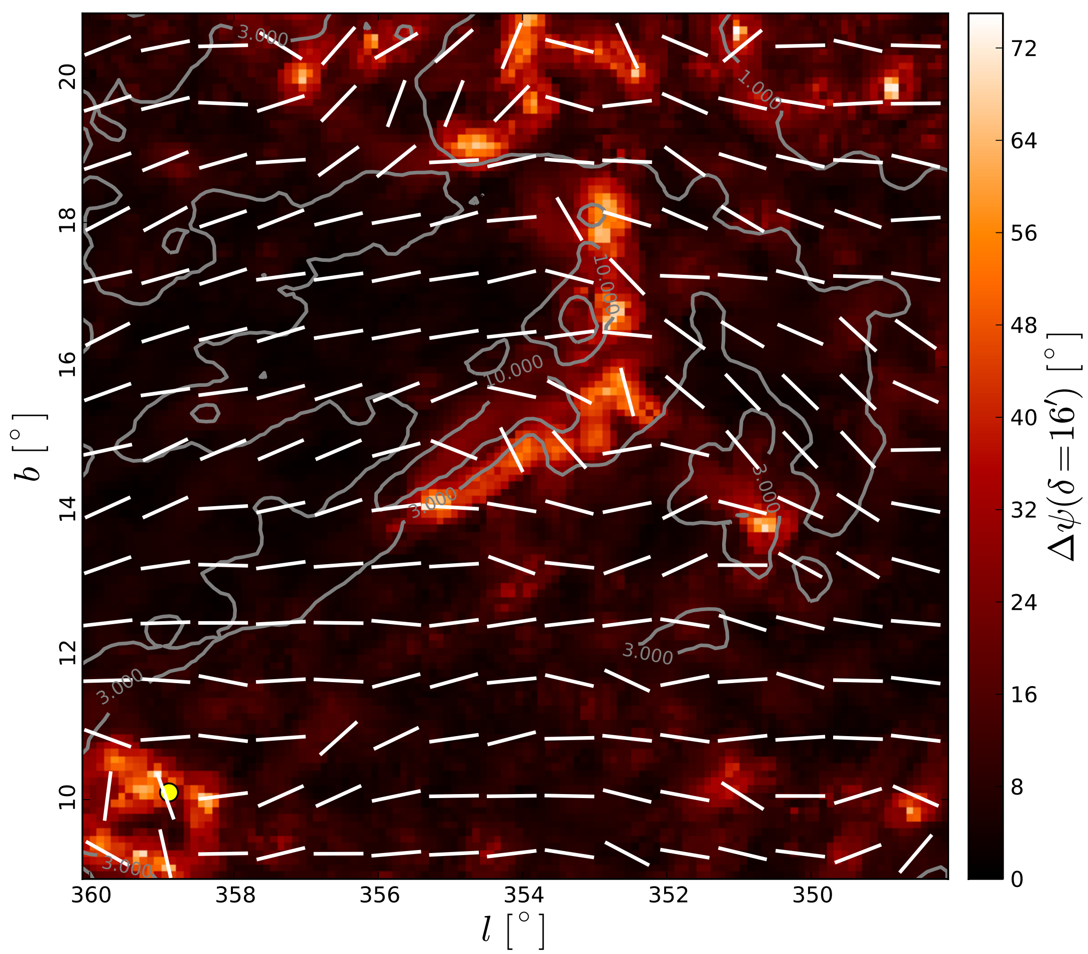


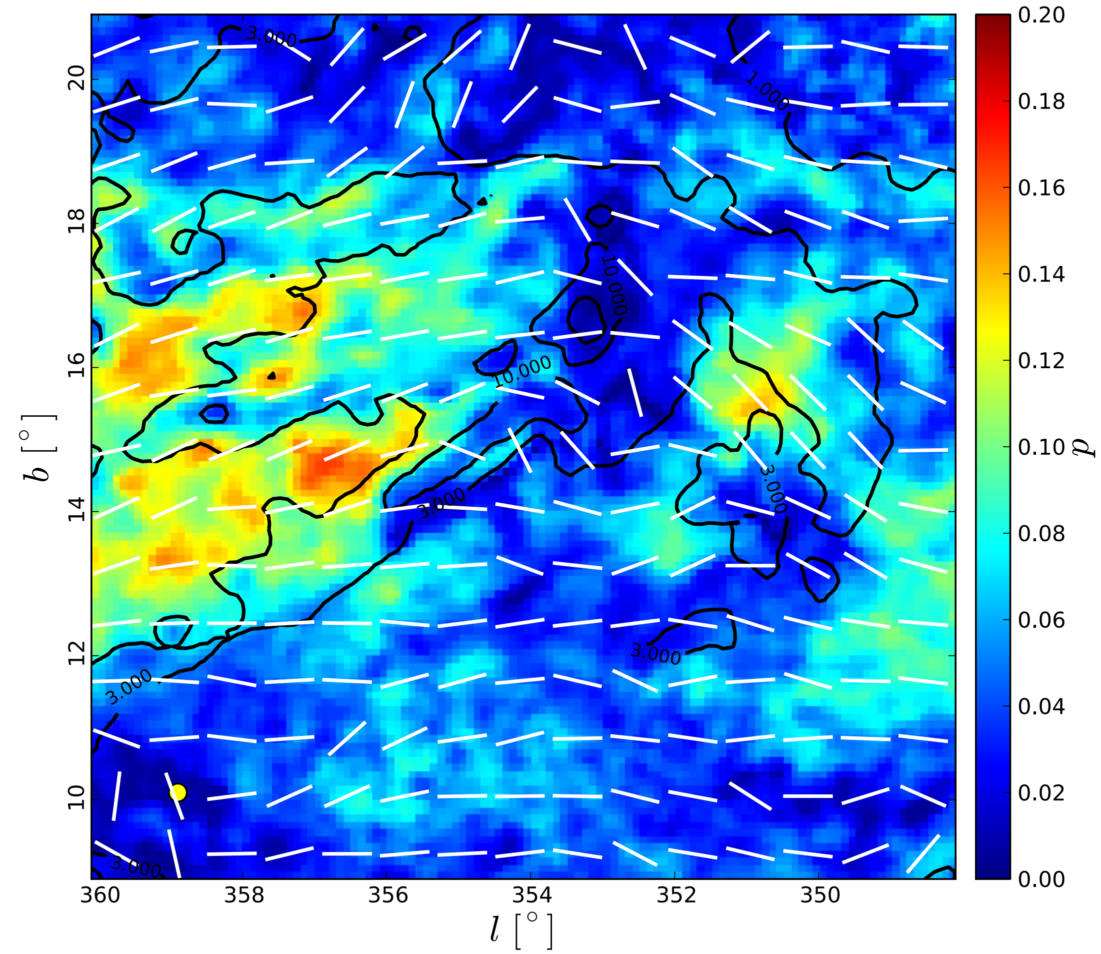
Ophiuchus

Contours : column density (units of 10^{21} cm^{-2})
Segments : mean orientation of *B* in the plane of the sky

Planck intermediate results. XX. (2014)

Polarization fraction and angle dispersion

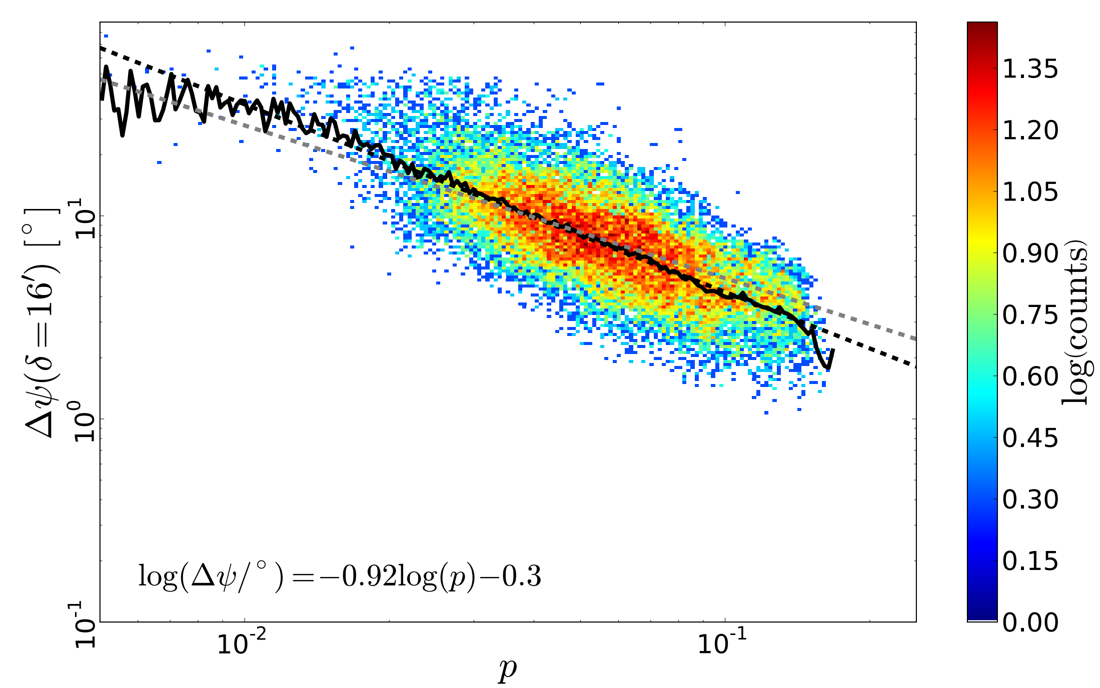




Ophiuchus

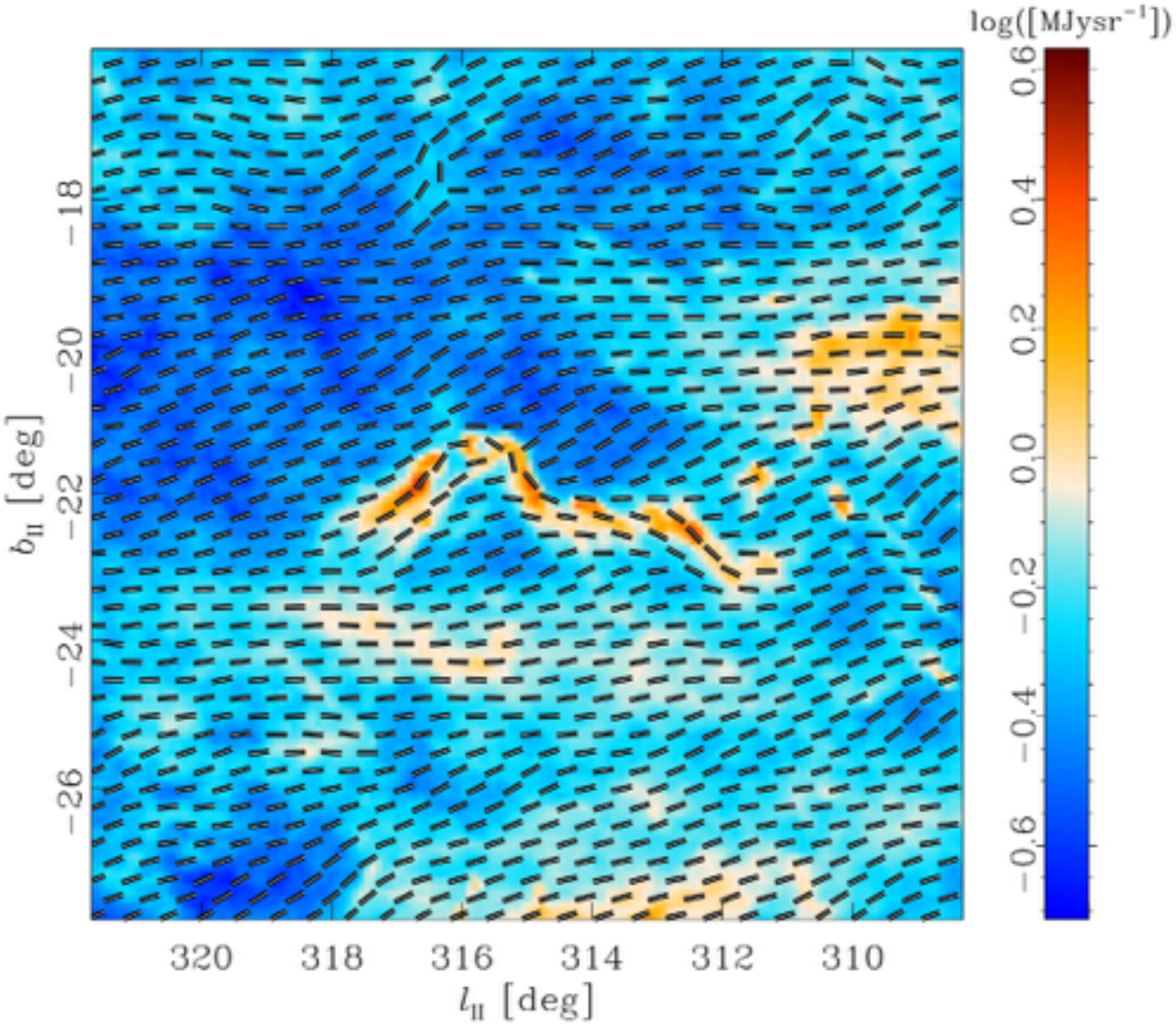
15' resolution

16' lag

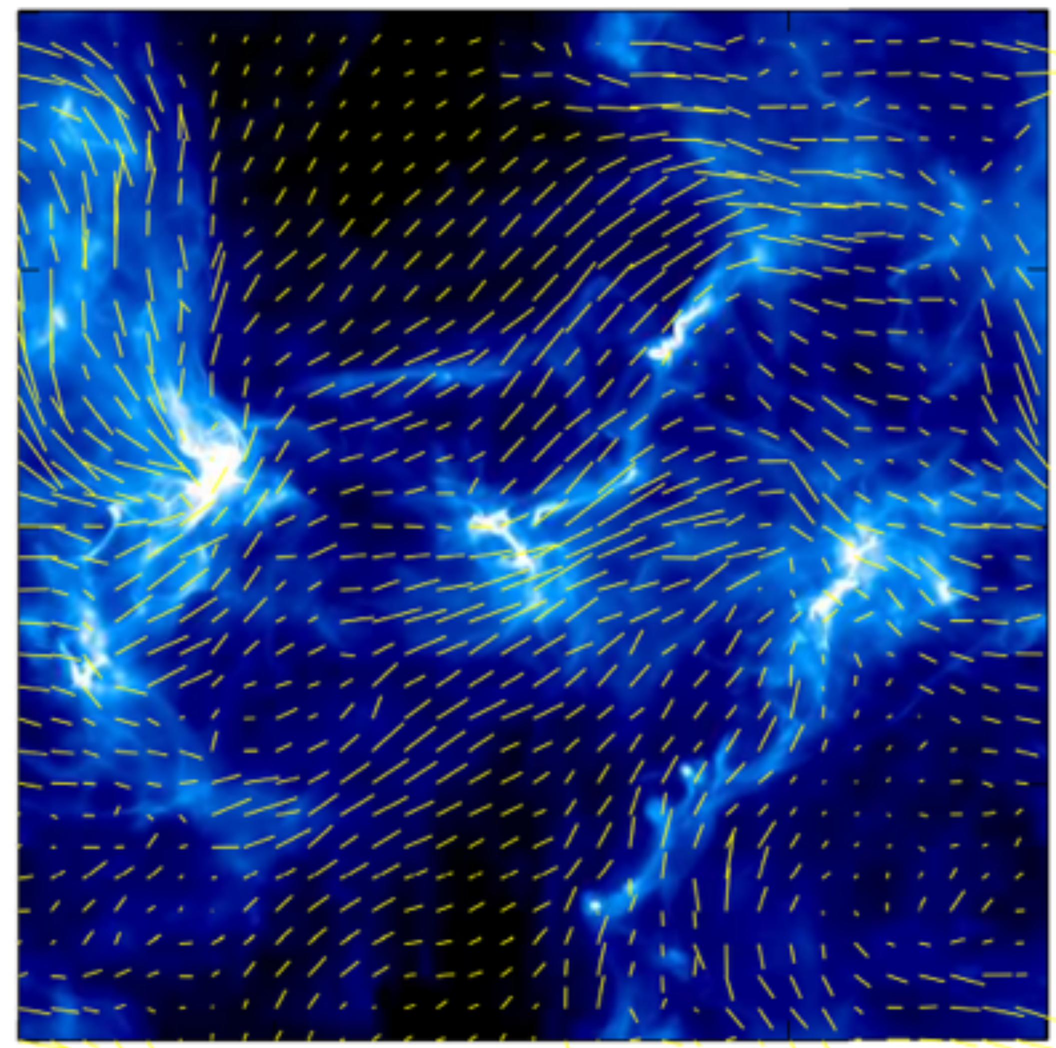


Planck intermediate results. XX. (2014)

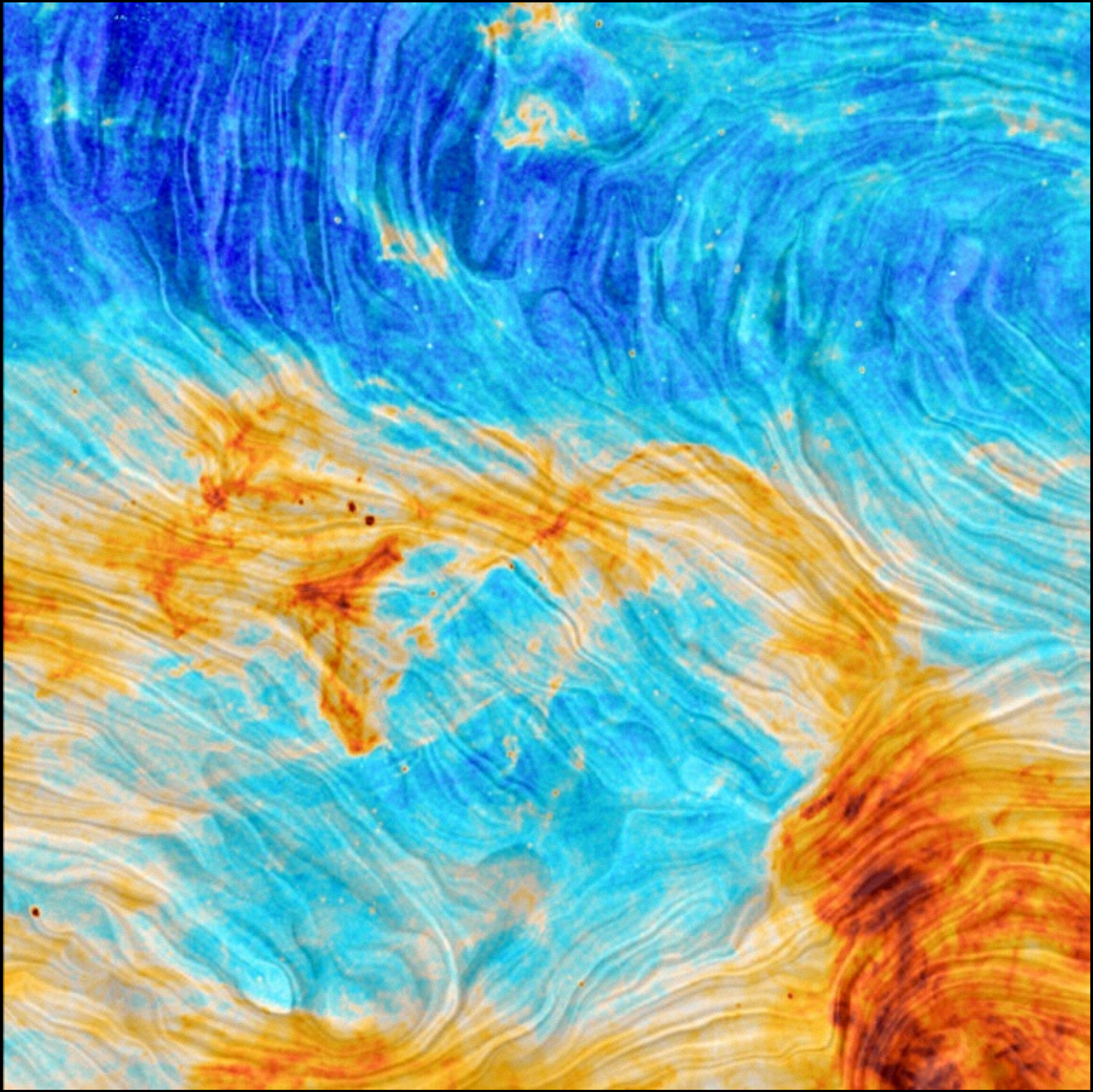
What is the role of the magnetic field in the structure of the ISM ?

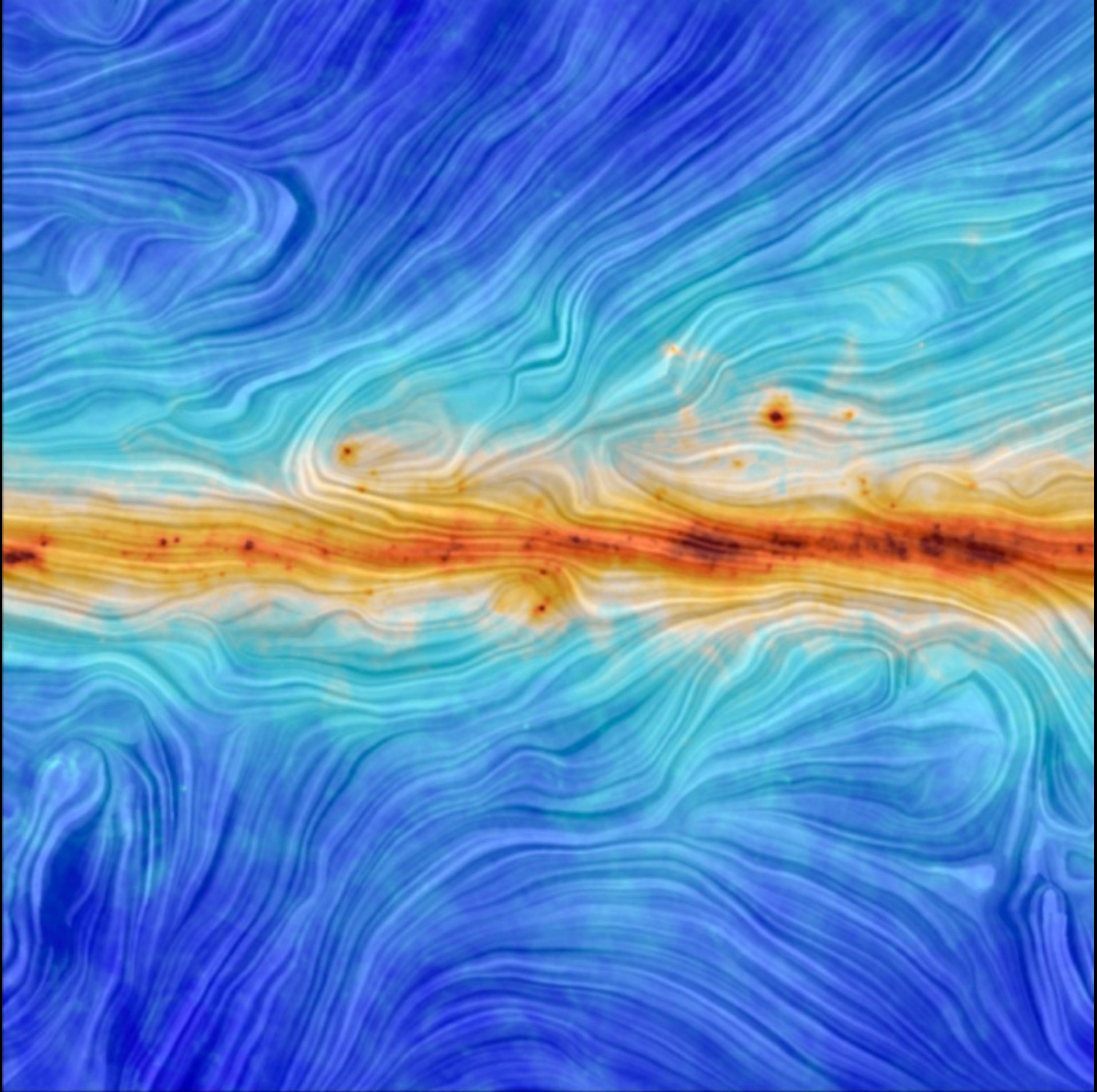


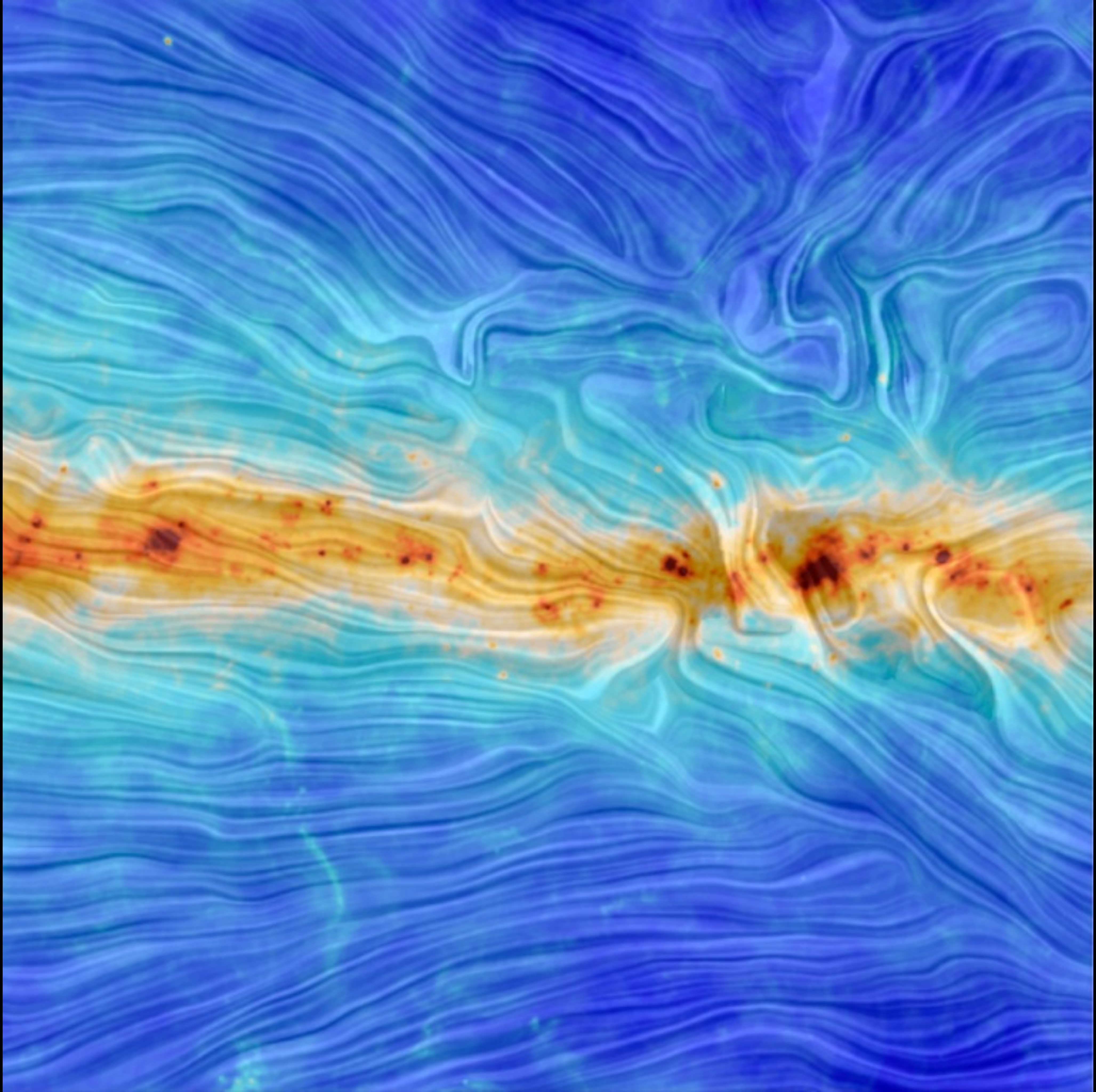
Chamaeleon molecular cloud
Planck 353 GHz (850 micron) optical depth
with polarization vectors overlaid
Planck intermediate results XIX (2014)

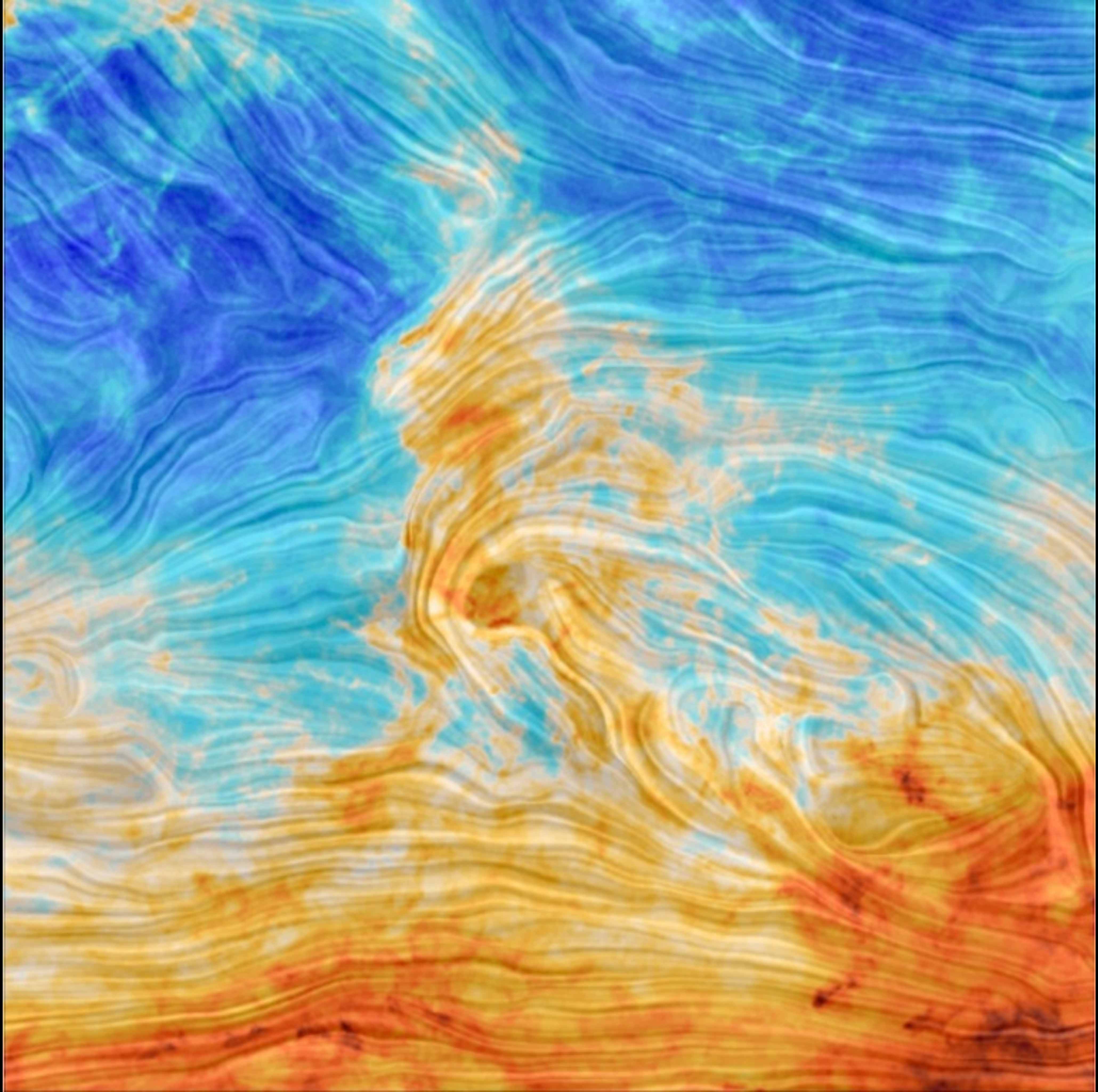


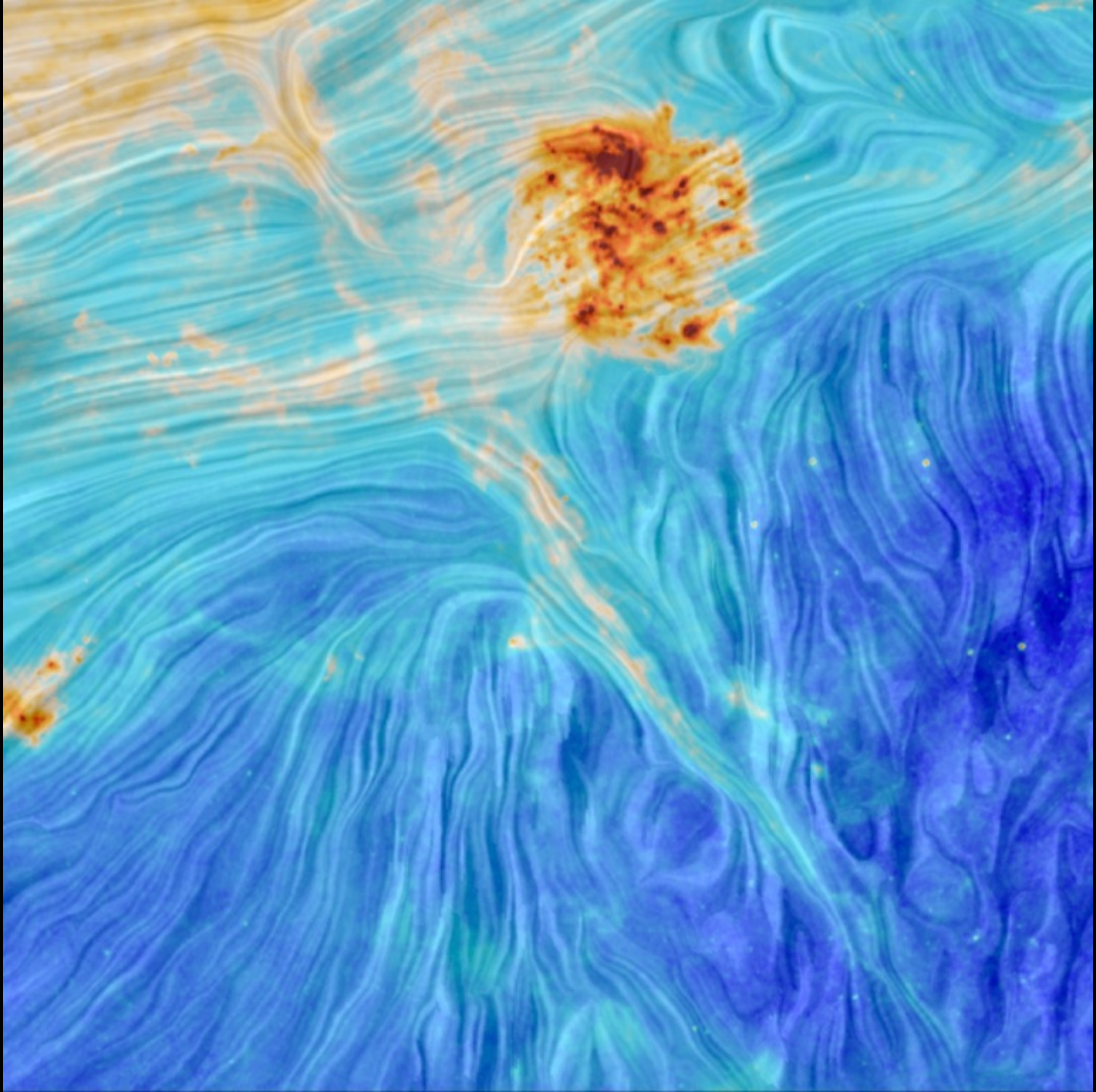
MHD simulations: link between structure and magnetic field in a molecular cloud.
Soler et al. (2013)





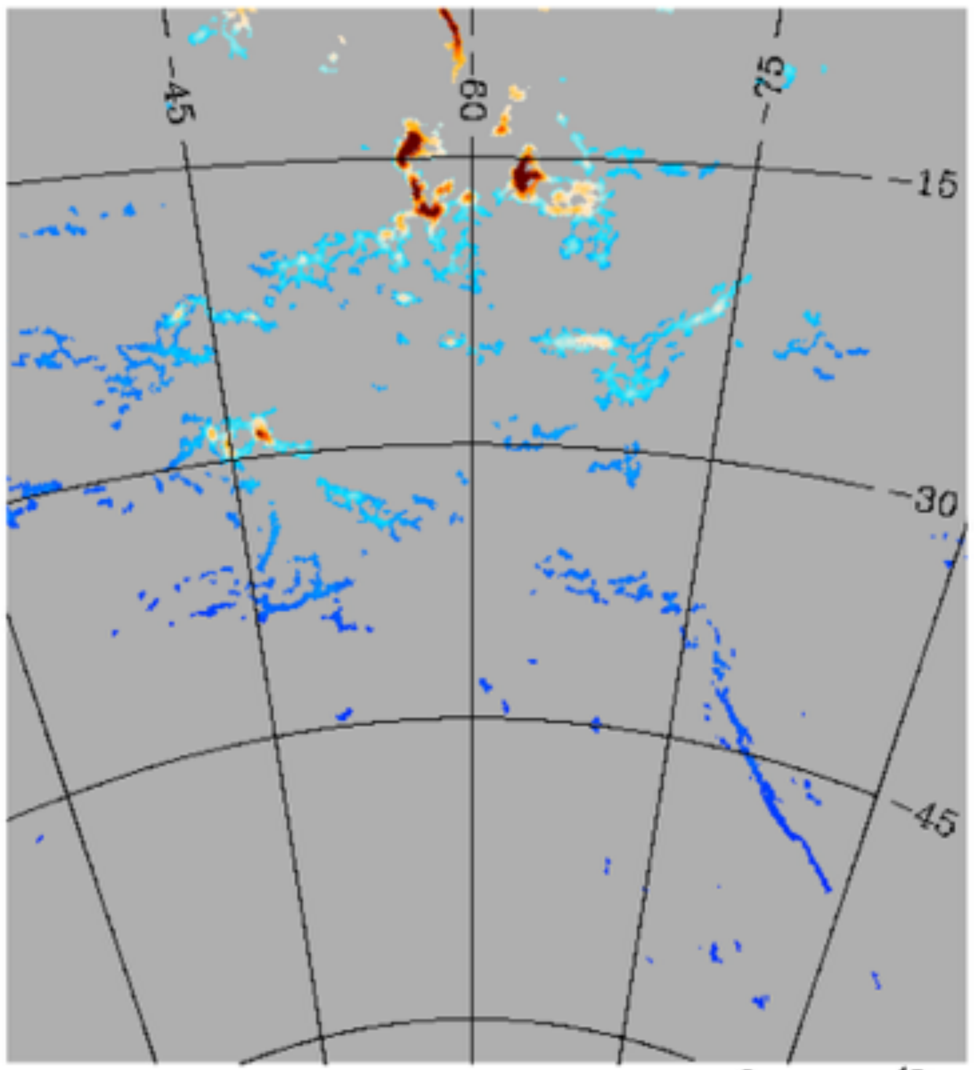


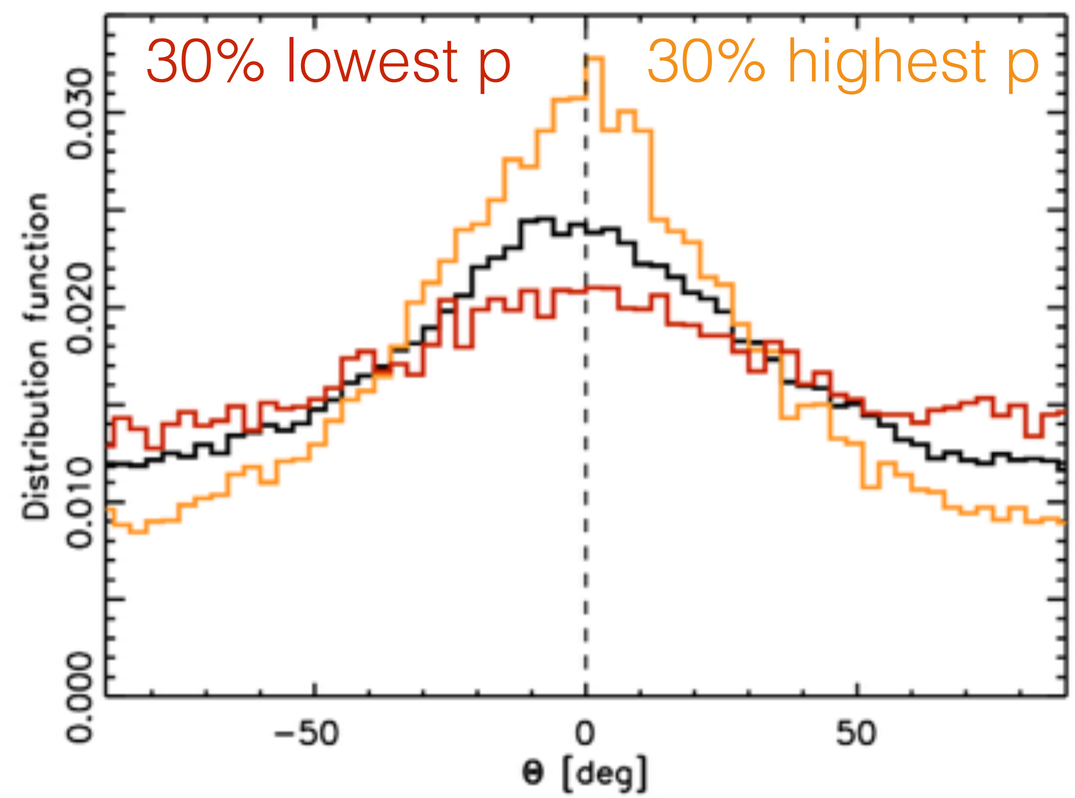




Planck intermediate results. XXXII. The relative orientation between the magnetic field and structures traced by interstellar dust

arXiv:1409.6728



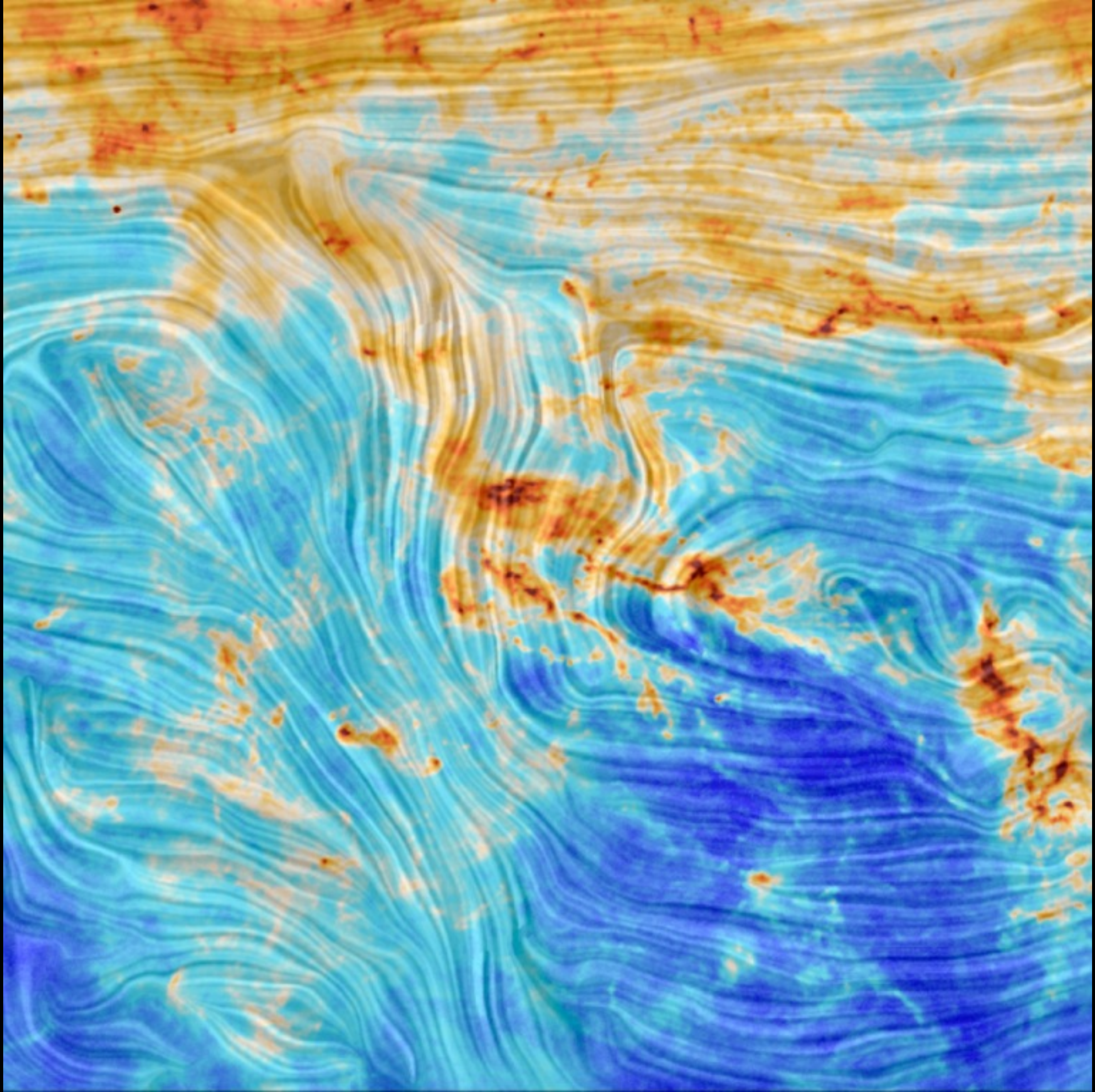


Methodology : angle between polarization and matter for ridges at intermediate and high Galactic latitude.

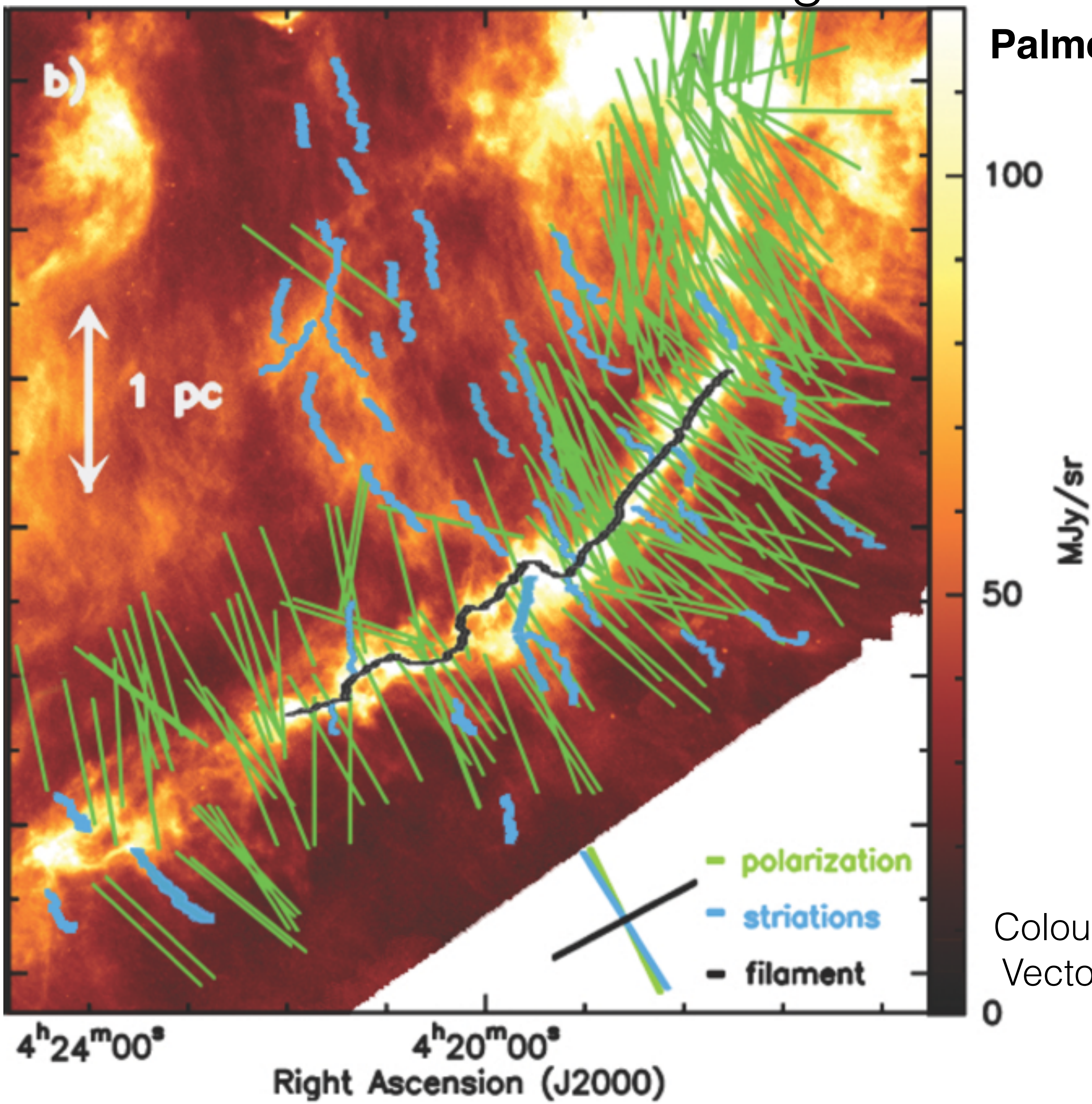
Result : Matter and B are parallel in the diffuse ISM.

Weaker correlation for higher N_H and lower p : projection effects.

$B_{turbulent}$ / $\langle B \rangle = 0.8$



Taurus - B211/B213/L1495 region

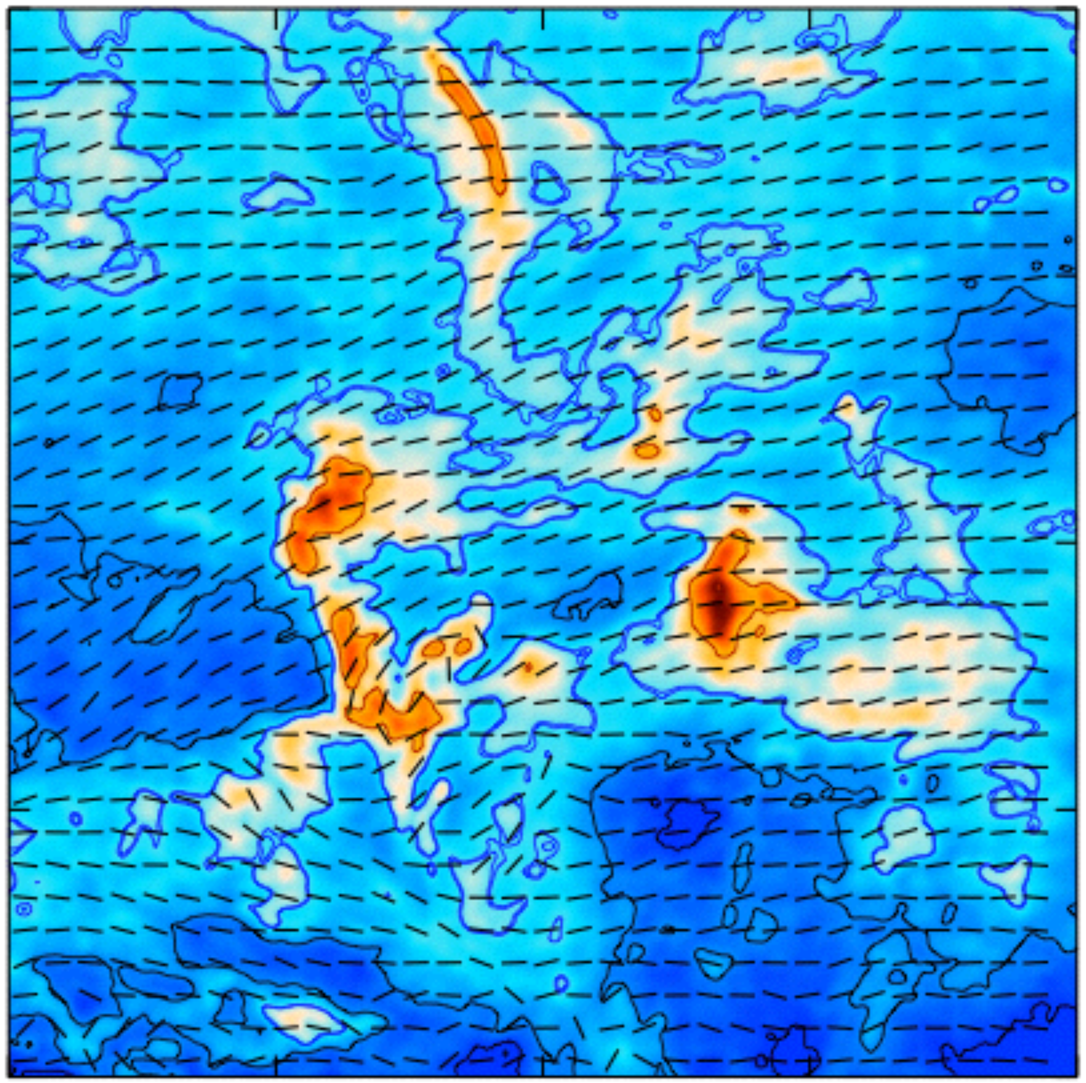


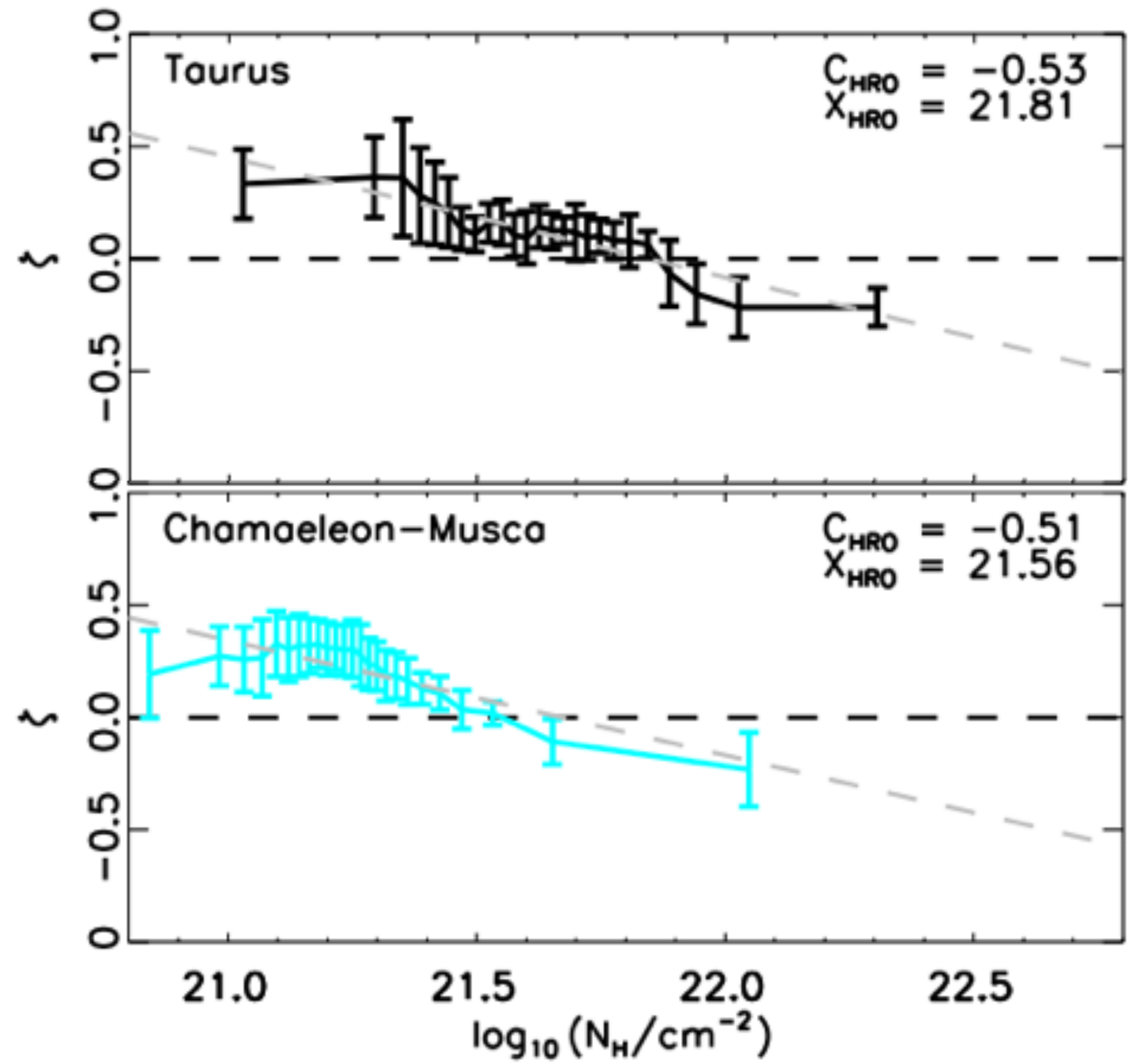
Palmeirim et al. (2013)

Colour : Herschel 250 micron
Vectors : optical polarization

Planck intermediate results. Probing the role of the magnetic field in the formation of structure in molecular clouds

The *Planck* collaboration **preliminary**

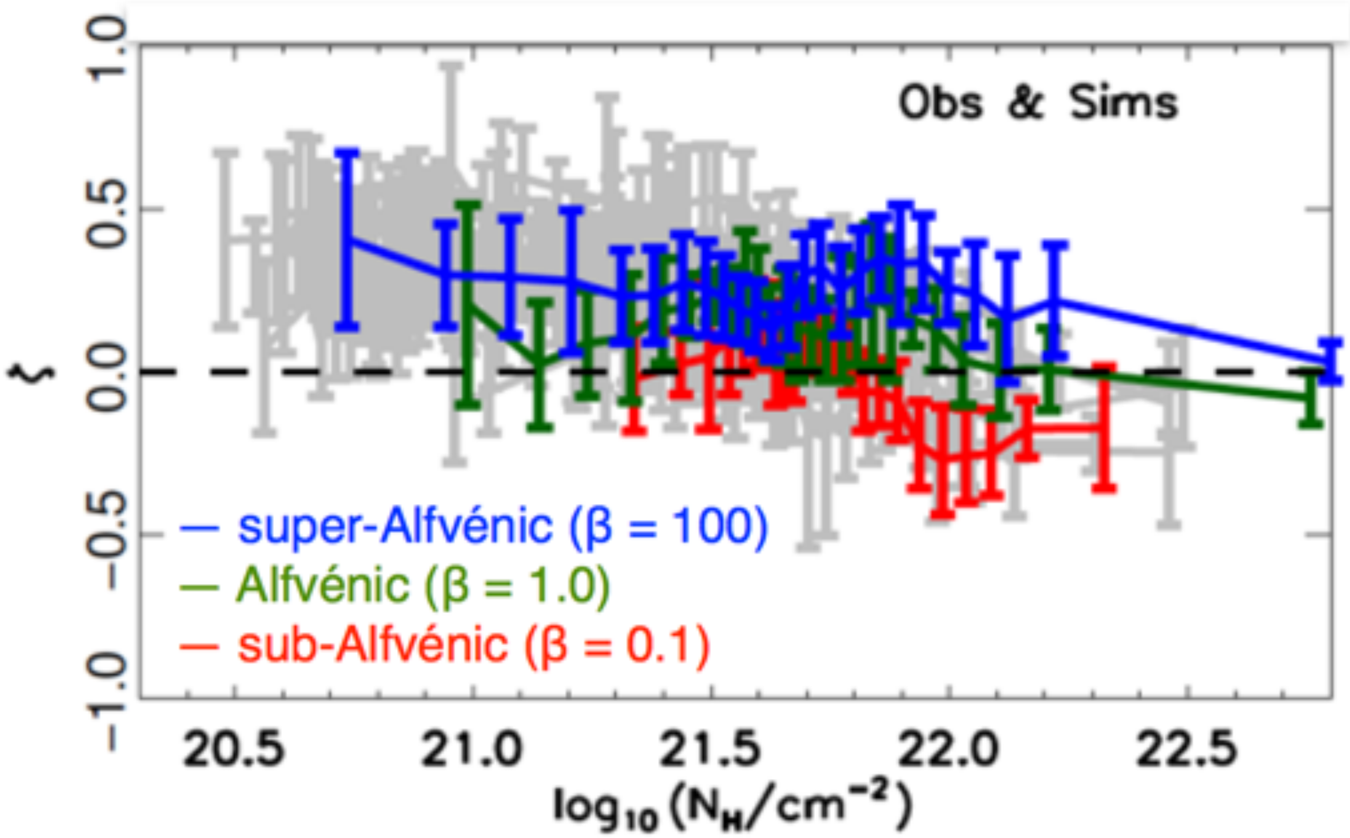




Methodology : Histogram of Relative Orientation (HRO) applied on 10 nearby molecular clouds

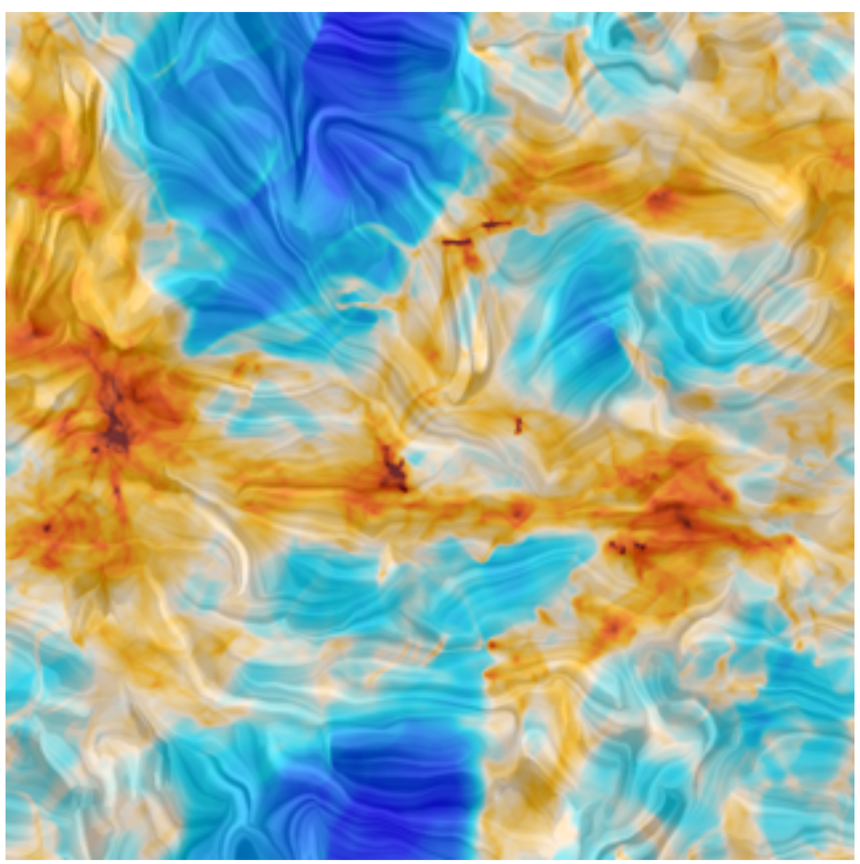
Result : Matter and B are parallel in the diffuse ISM

Matter and B are perpendicular in the dense ISM



Beta = kinetic / magnetic pressure

Soler et al. (2013)
Planck collaboration, in prep. (2015)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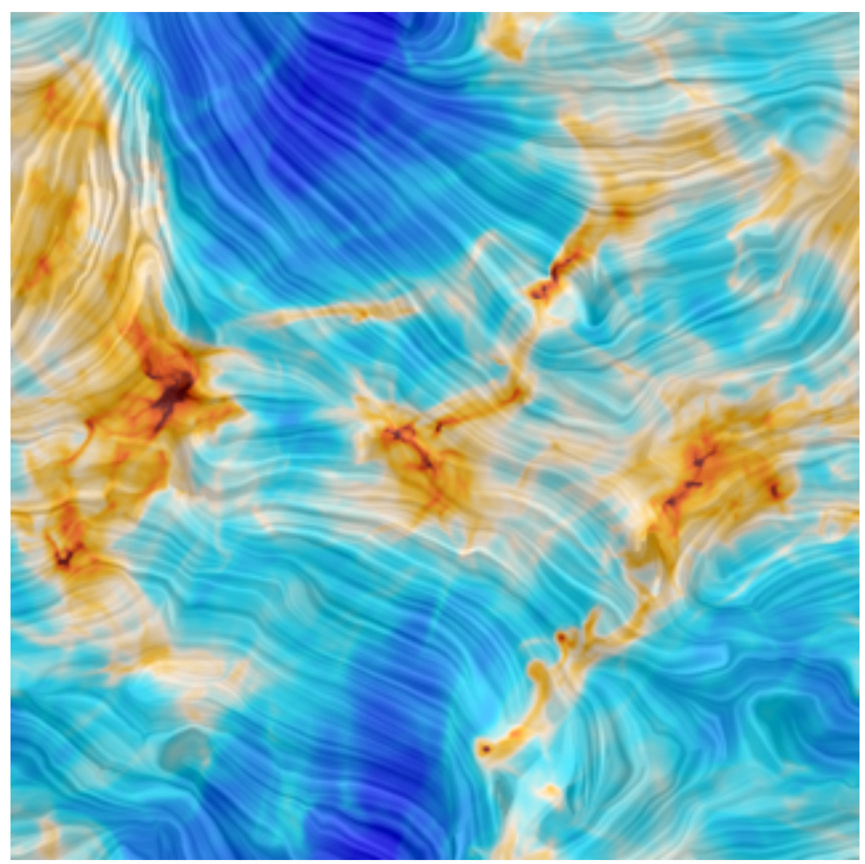
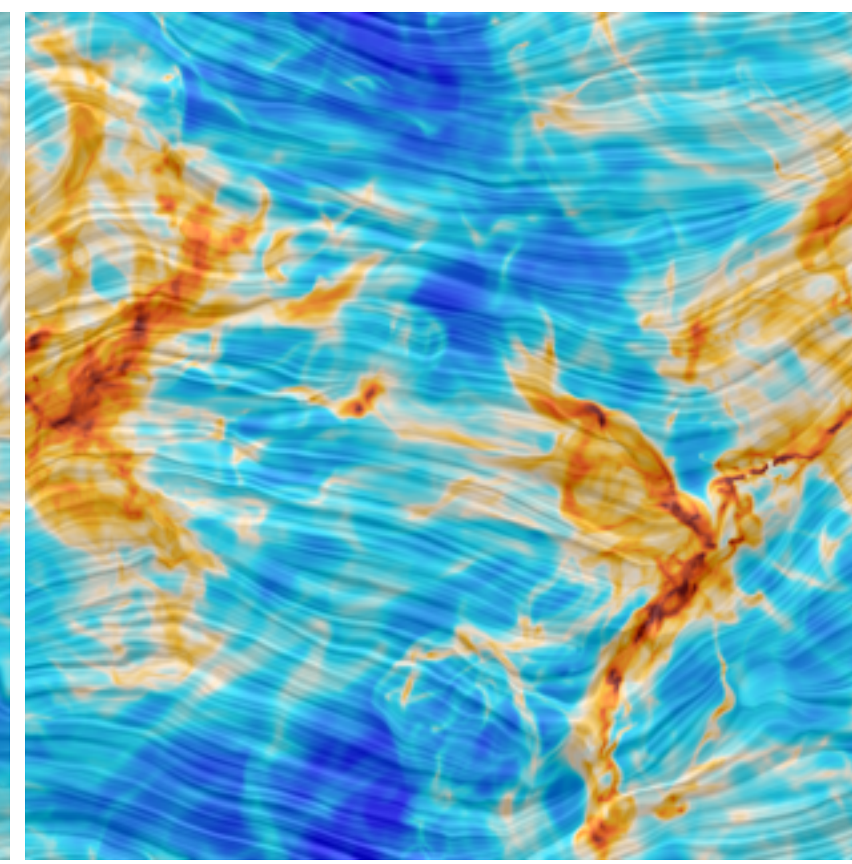
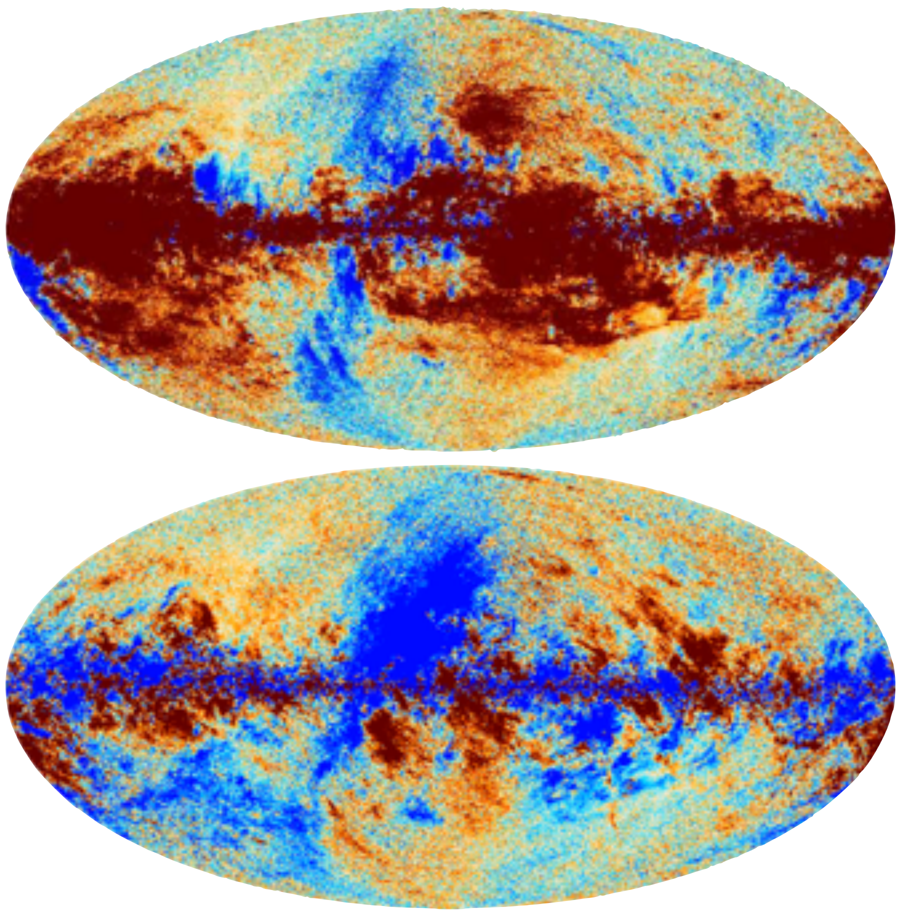

Beta=1


Beta=0.1

Measuring the dust polarization power spectrum



Planck

Q and U maps at 353 GHz

Xpol

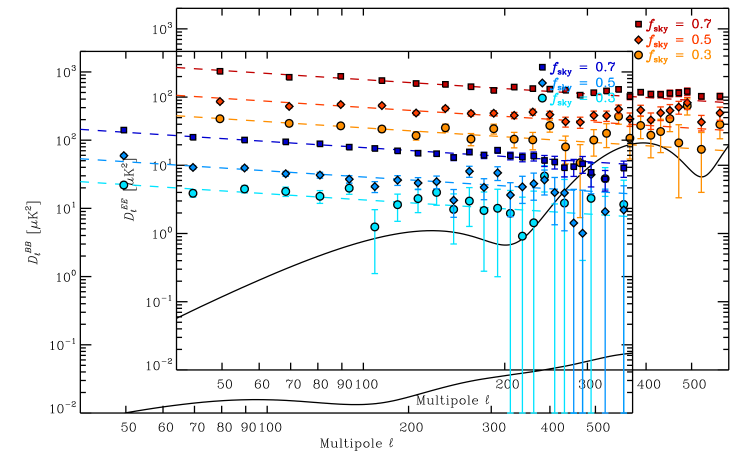
pseudo-C_ℓ estimator

based on **Xspect**

[Tristram et al. 2005]

Corrects for incomplete sky coverage, pixel and beam window functions

[Planck Intermediate XXX 2014, arXiv 1409.5738]



Angular power spectra

C_ℓ^{EE} and C_ℓ^{BB}

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

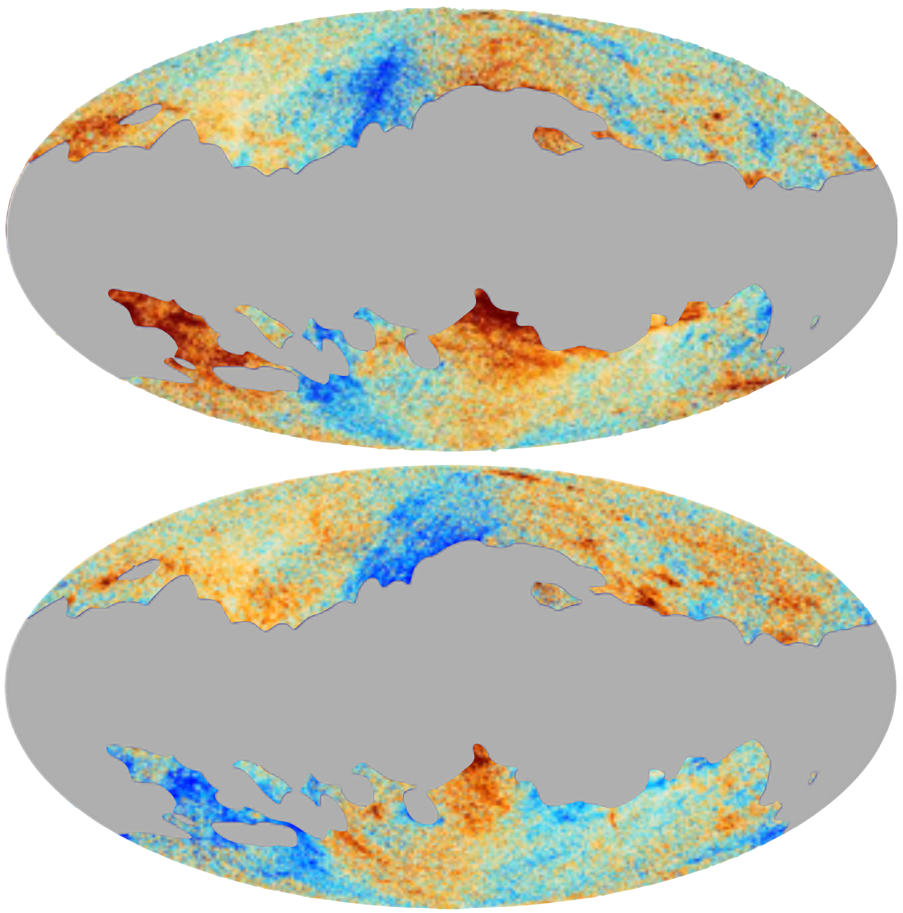
$$C_\ell(\nu \times \nu) \equiv C_\ell(D_\nu^1 \times D_\nu^2)$$

The CMB C_ℓ^{EE} best fit model is removed

[Planck Collaboration XIV 2014]

General methodology

[Planck Intermediate XXX 2014, arXiv 1409.5738]



Planck
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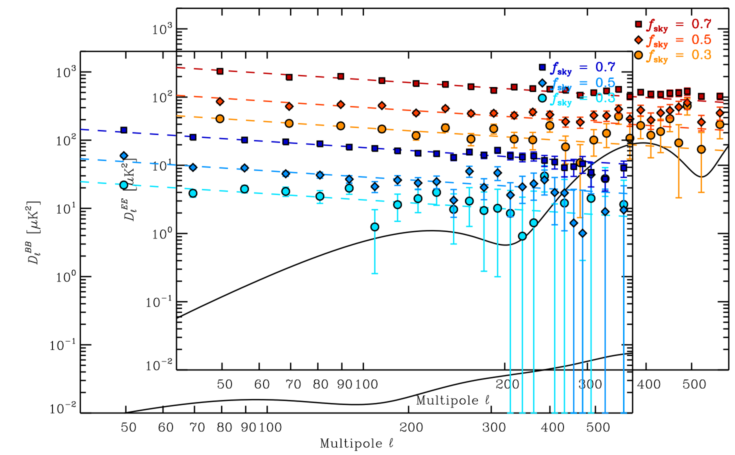

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[Planck Collaboration XIV 2014]

Results

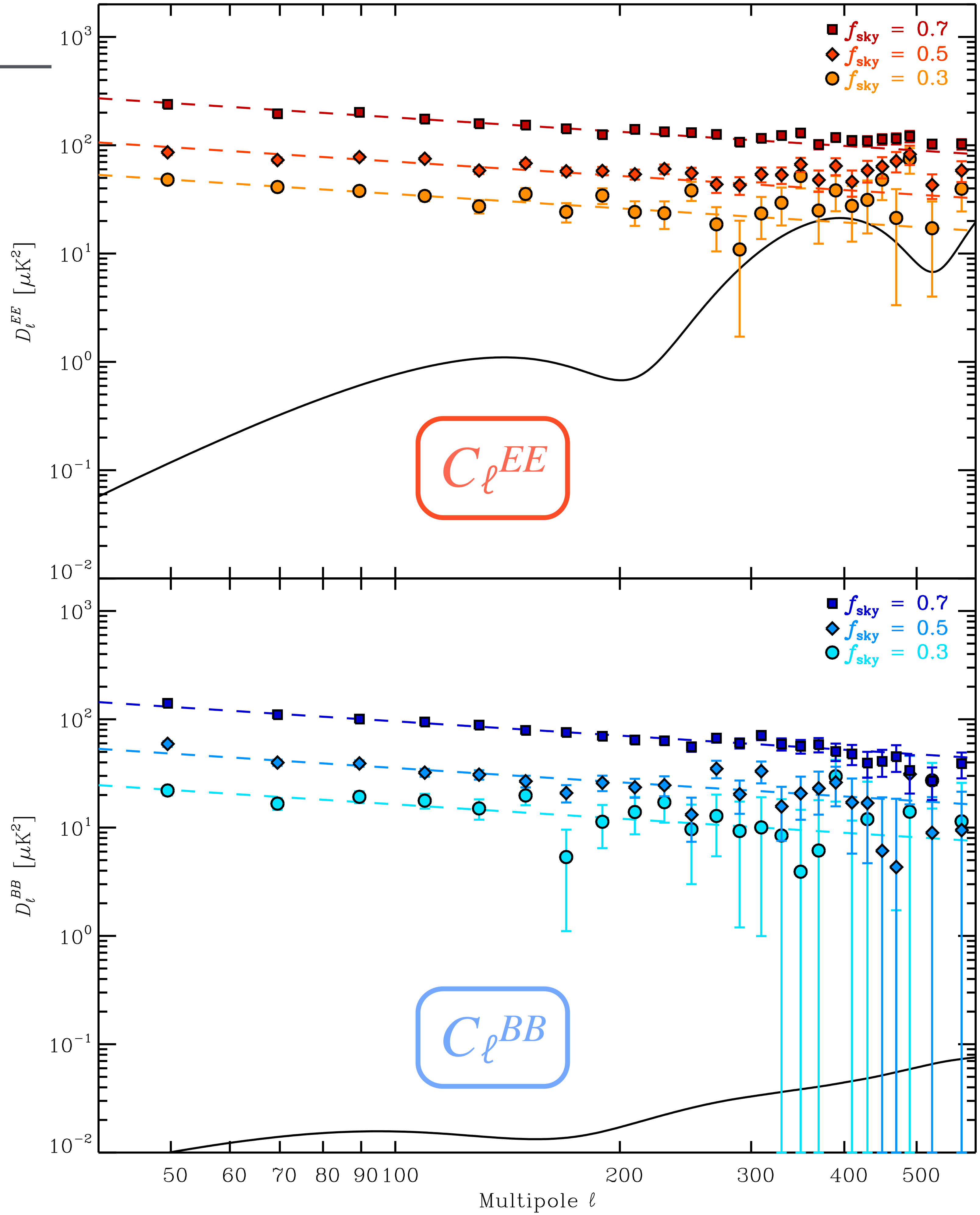
★ 353 GHz *EE* and *BB* angular power spectra

★ First detection of the dust polarized angular power spectra at ℓ>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?

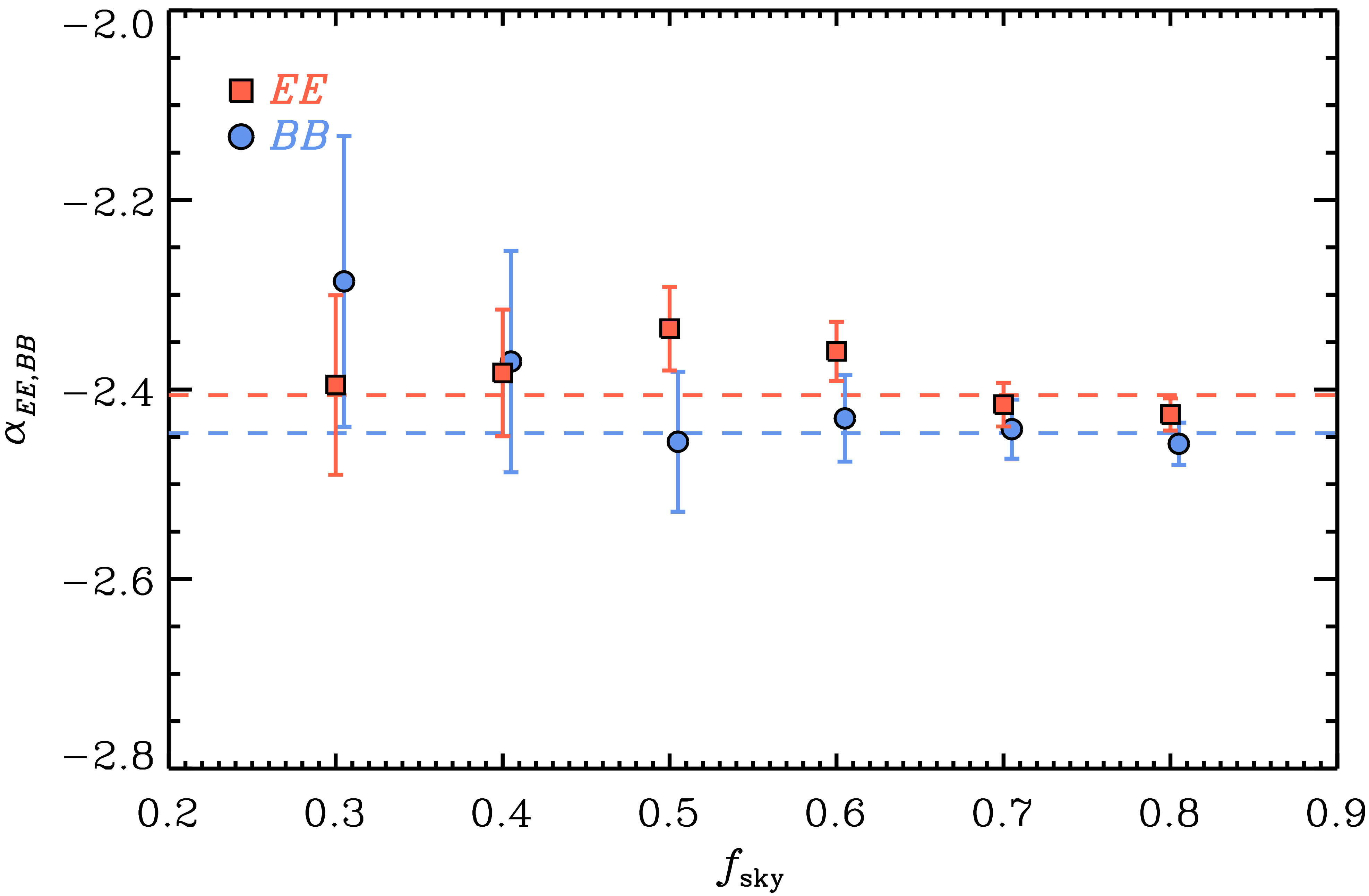
[Planck Intermediate XXX 2014, arXiv 1409.5738]



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]



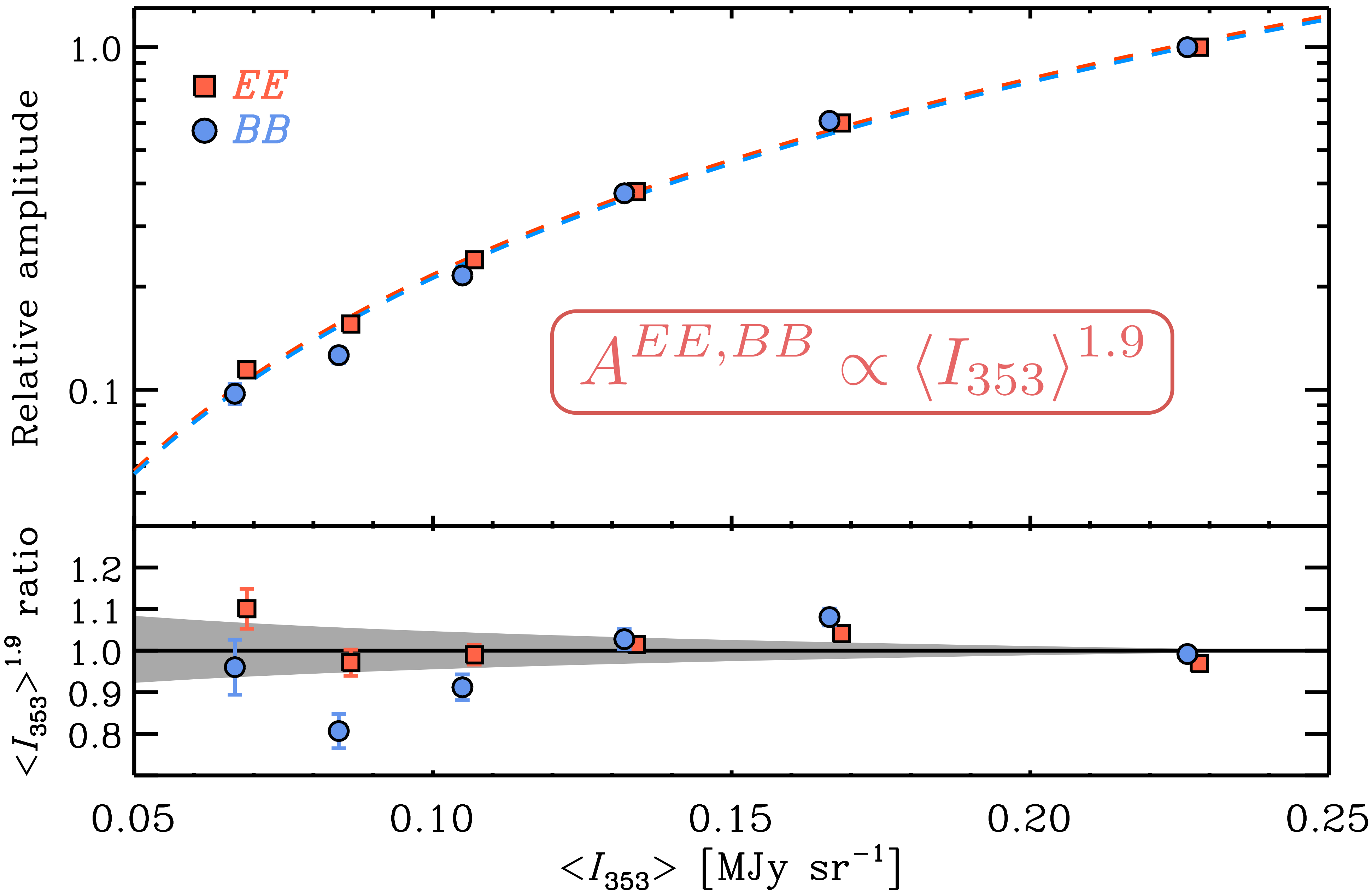
★ The spectra are compatible with power-laws with a -2.42 slope

★ No significant difference between *EE* and *BB*

Amplitude as a function of the mask

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

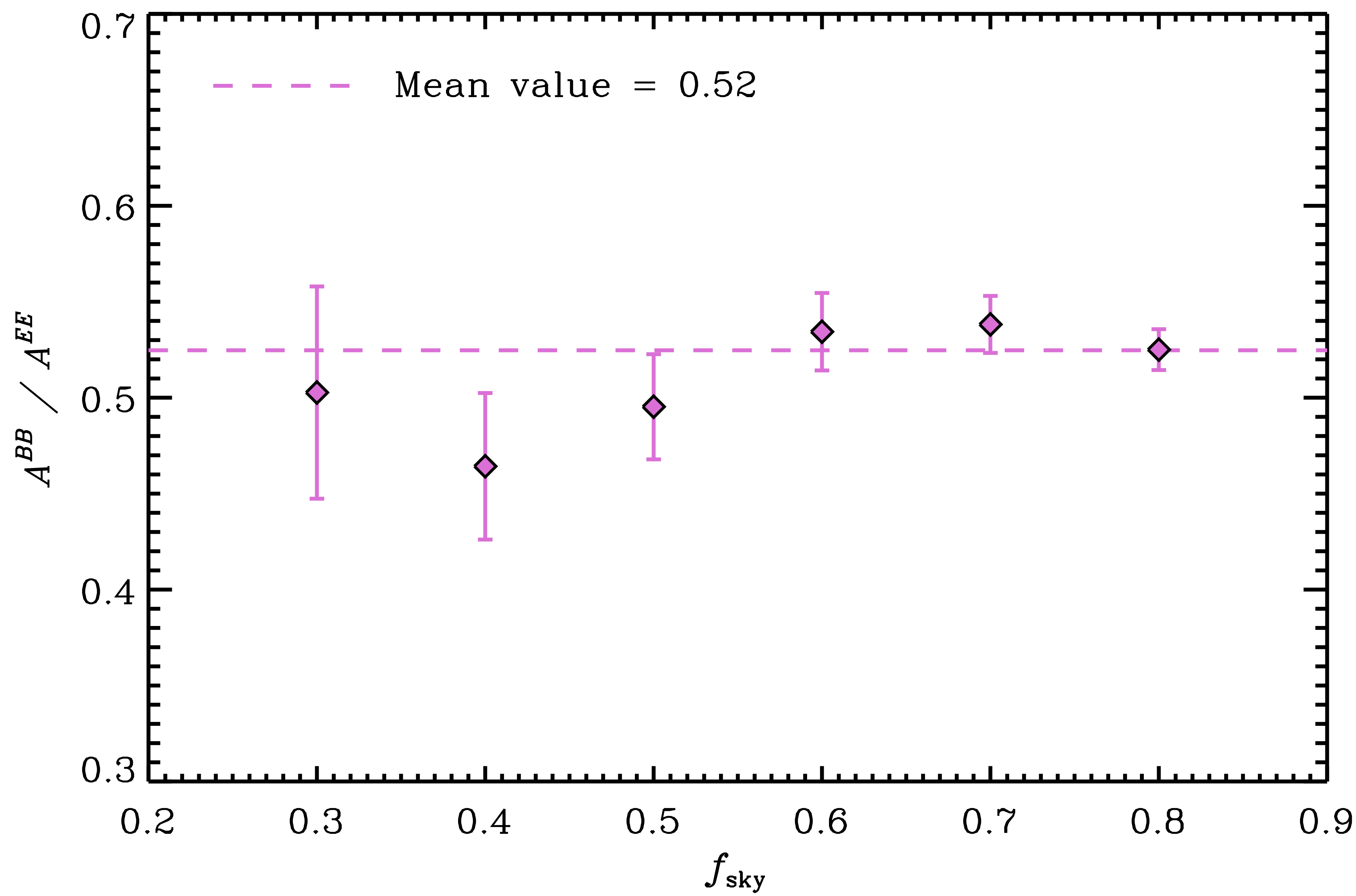
[Planck Intermediate XXX 2014, arXiv 1409.5738]



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

BB/*EE* ratio?

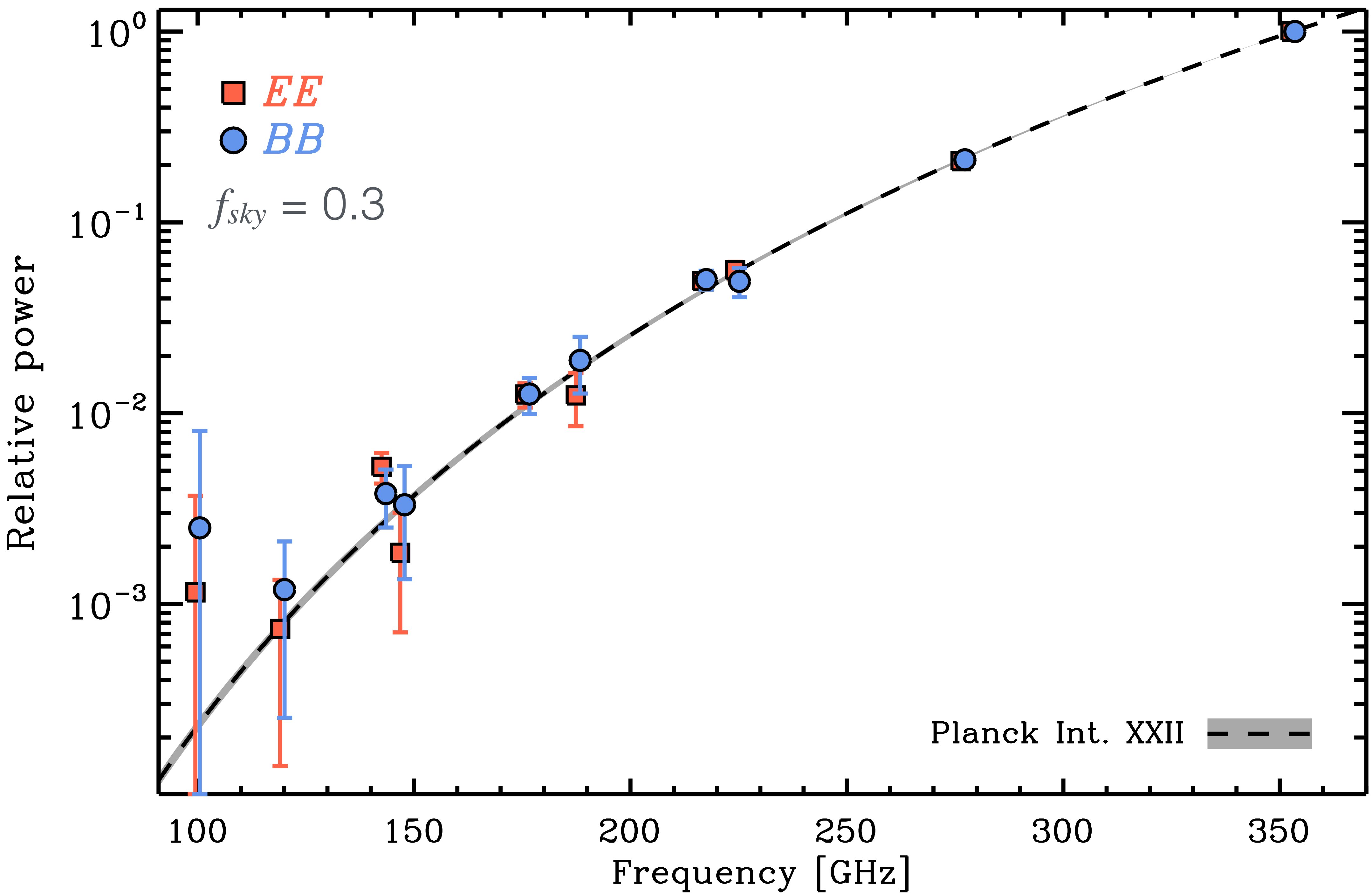
[Planck Intermediate XXX 2014, arXiv 1409.5738]



★ The dust polarized emission produces twice as much *EE* than *BB*
★ The existing dust models give *BB*/*EE*~1

Amplitude as a function of the observing frequency?

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

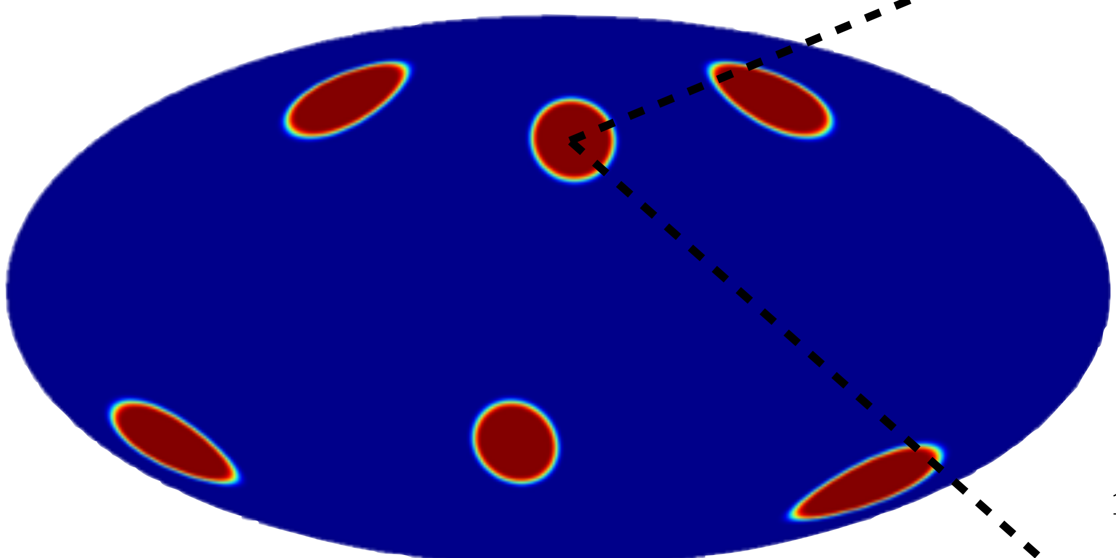


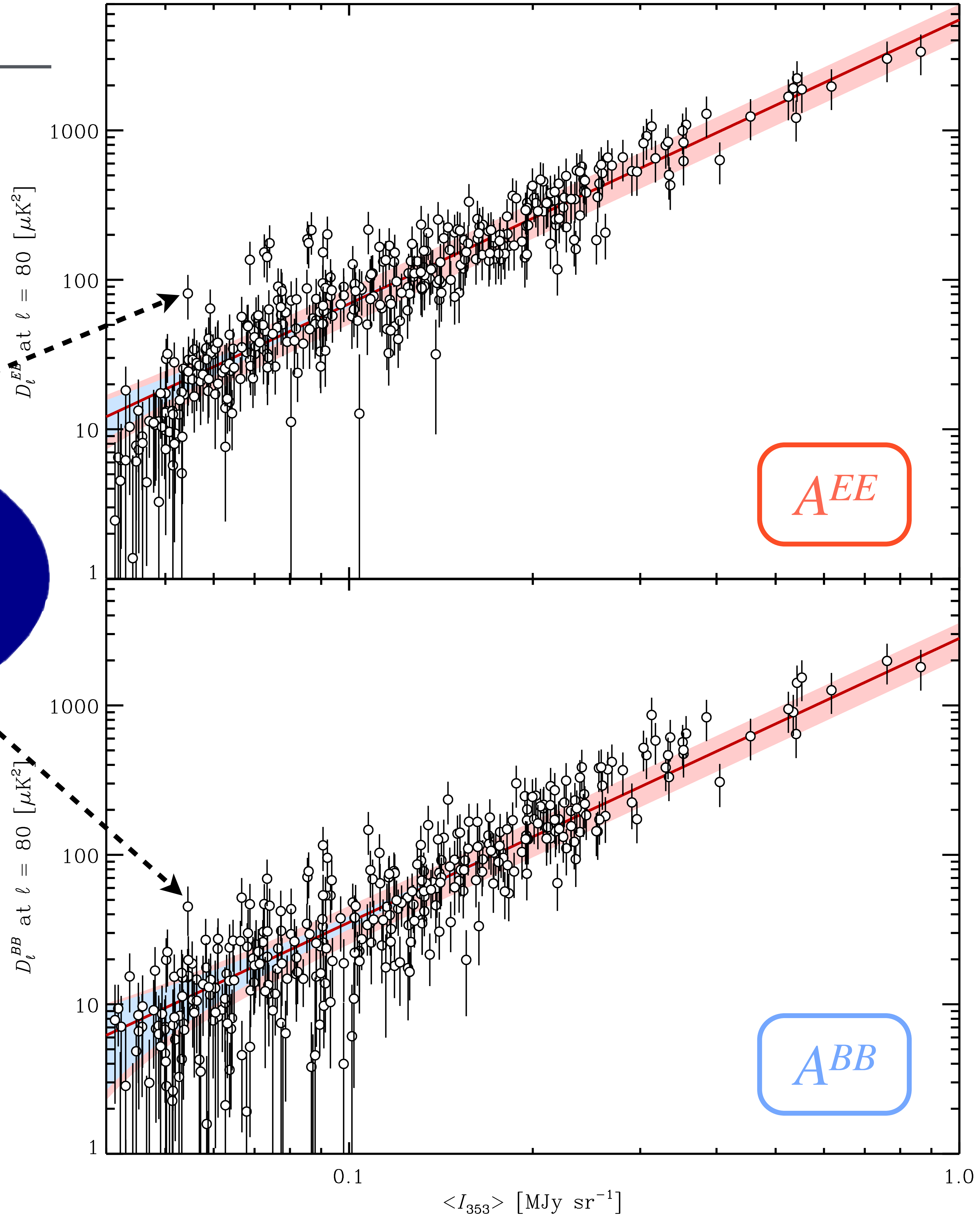
★ The spectra amplitudes follow the frequency dependence of the dust polarization for both *EE* and *BB*

Statistics on 400 deg²

[Planck Intermediate XXX 2014, arXiv 1409.5738]

★ 352 patches with $|b|>35°$





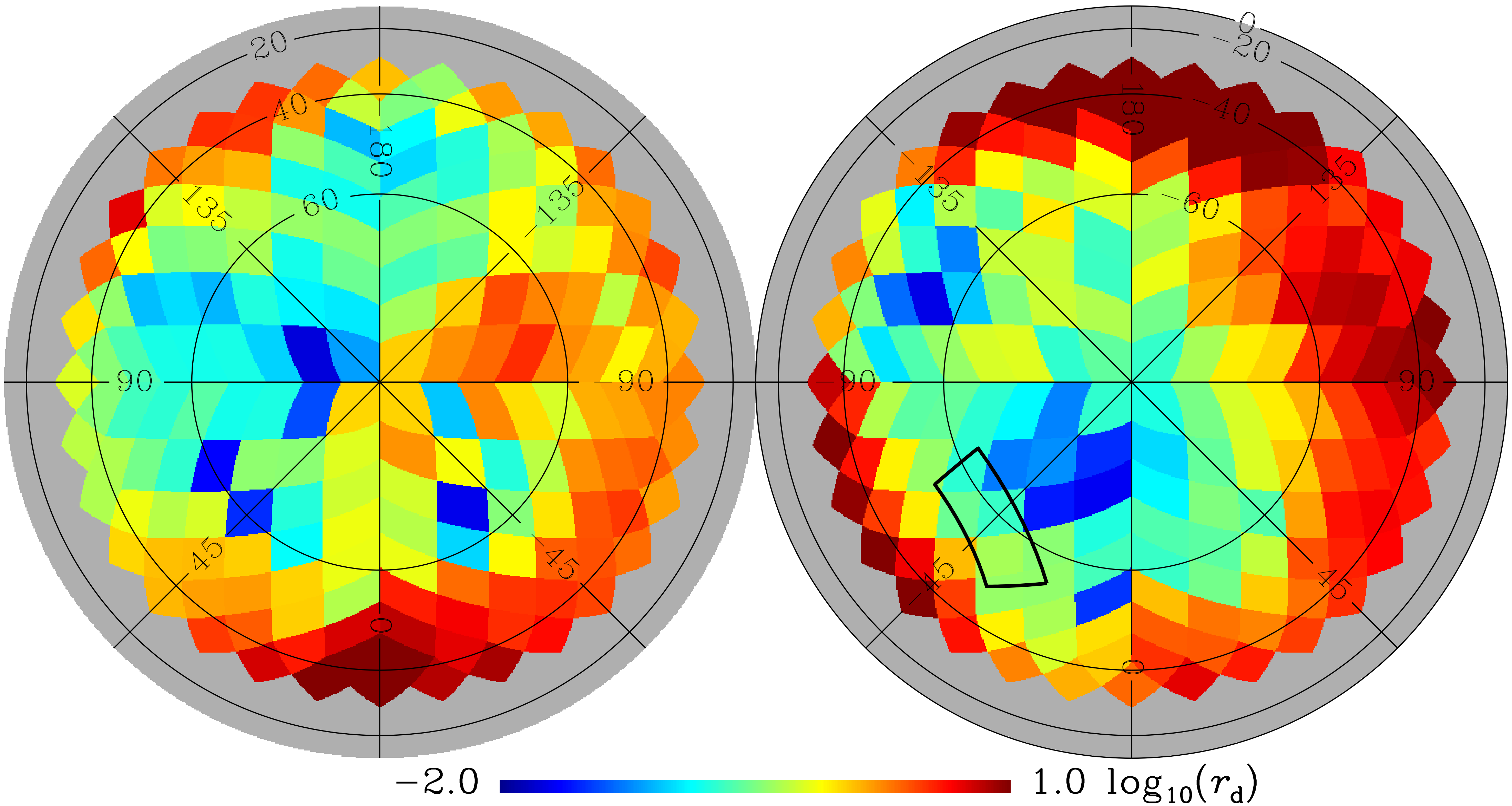
★ Empirical law as a function of the mean dust intensity is also derived for theses patches

★ The dispersion is higher than it would be expected for a Gaussian process

Statistics on 400 deg²

- ★ Extrapolation of the *BB* amplitudes at 150 GHz
- ★ Amplitudes expressed in units of r_d (*e.g.* r_d = 0.2 means that the dust has the same level as the CMB r = 0.2 à ℓ=80)

[Planck Intermediate XXX 2014, arXiv 1409.5738]

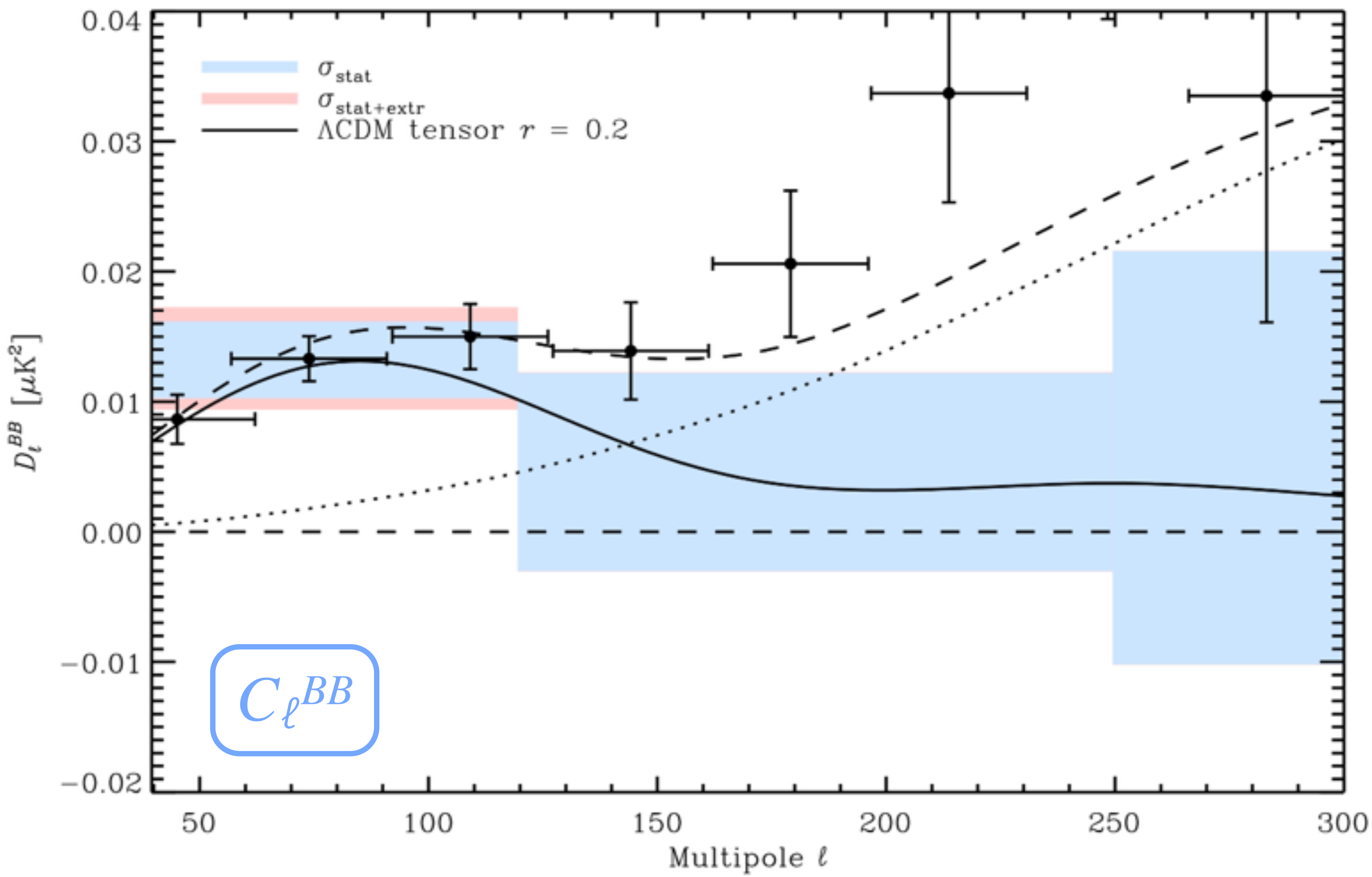


- ★ The cleanest regions of the sky have r_d~0.01±0.06
- ★ In no region the dust polarization can be neglected if one wants to measure the CMB primordial *B*-modes

Measurement of the dust in the BICEP2 field

★ Computation of the BB spectrum at 353 GHz in the BICEP2 region
★ Extrapolation to 150 GHz

[Planck Intermediate XXX 2014, arXiv 1409.5738]
[BICEP2 Collaboration 2014]



★ 4.5σ detection of the dust at 353 GHz

★ 3.6σ prediction at 150 GHz

★ Prediction of the dust level similar to the B-modes measured by BICEP2

Conclusion

- Planck measured the dust SED from 100 to 857 GHz
  - Disagreement with the FIRAS calibration up to 19% at 545 GHz
  - Dust model got simpler : only one dust component in the Planck range (Beta=1.50, T=19.6K)
  - Low variation of dust spectral index at high Galactic latitudes (intensity and polarization)
  - Maximum dust polarization fraction is high (20%)
- Planck reveals the projected structure of the Galactic magnetic field
  - Striking relationship between density and magnetic field structure.
  - B is a major player of the dynamics
- CMB foregrounds : there is no dust free window in polarization
  - The level of dust polarized foreground is higher than what was expected, by a factor 1.5.
  - Power spectrum of dust : Cl ~ l^-2.42
  - The amplitude of the dust Cl (EE and BB) scales with local average brightness (I^1.9) —> dust polarization is non-stationary, like its emission
  - Dust BB/EE ~ 0.5
  - The small spatial variations of the dust polarized SED give hope that foreground subtraction can be done with multi-frequencies experiment.