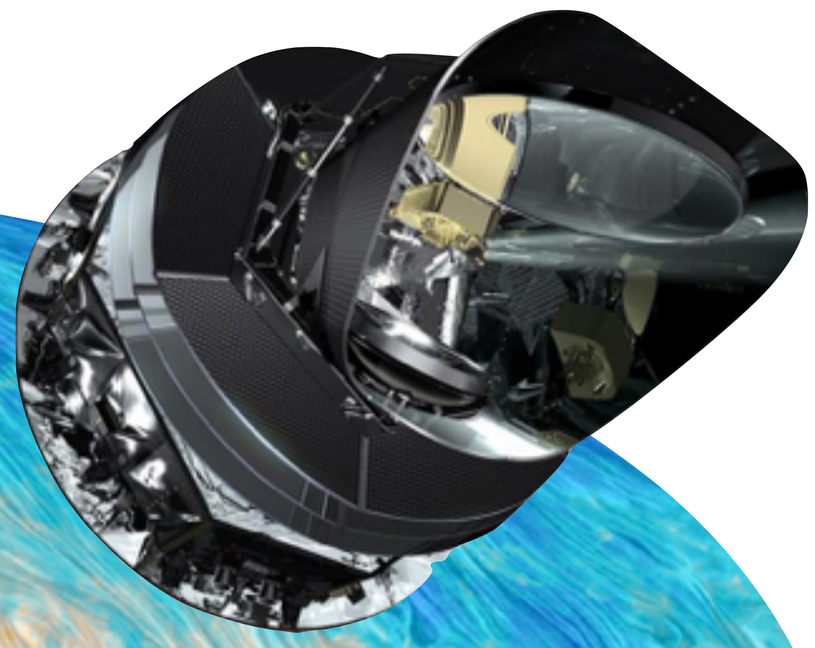
Planck all-sky thermal dust Polarization

Witnessing how the magnetic field shapes the Milky Way ISM



Planck Collaboration
Presented by J.-Ph. Bernard (IRAP) Toulouse, France

The first Planck papers in polarization

- **Planck Collaboration** ***Planck intermediate results. XIX.*** 2015 A&A 576.104
An overview of the polarized thermal emission from Galactic dust
- **Planck Collaboration** ***Planck intermediate results. XX.*** 2015 A&A 576.105
Comparison of polarized thermal emission from Galactic dust with simulations of MHD turbulence
- **Planck Collaboration** ***Planck intermediate results. XXI.*** 2015 A&A 576.106
Comparison of polarized thermal emission from Galactic dust at 353 GHz with optical interstellar polarization
- **Planck Collaboration** ***Planck intermediate results. XXII.*** 2015 A&A 576.107
Frequency dependence of thermal emission from Galactic dust in intensity and polarization

- **Planck Collaboration** ***Planck intermediate results. XXXII.*** arXiv:astro-ph 1409.6728
The relative orientation between the magnetic field and structures traced by interstellar dust

- **Planck intermediate results. XXXIII.** arXiv:astro-ph 1411.2271
Signature of the magnetic field geometry of interstellar filaments in dust polarization maps

- **Planck intermediate results. XXXIV.** arXiv:astro-ph 1501.00922
The magnetic field structure in the Rosette Nebula

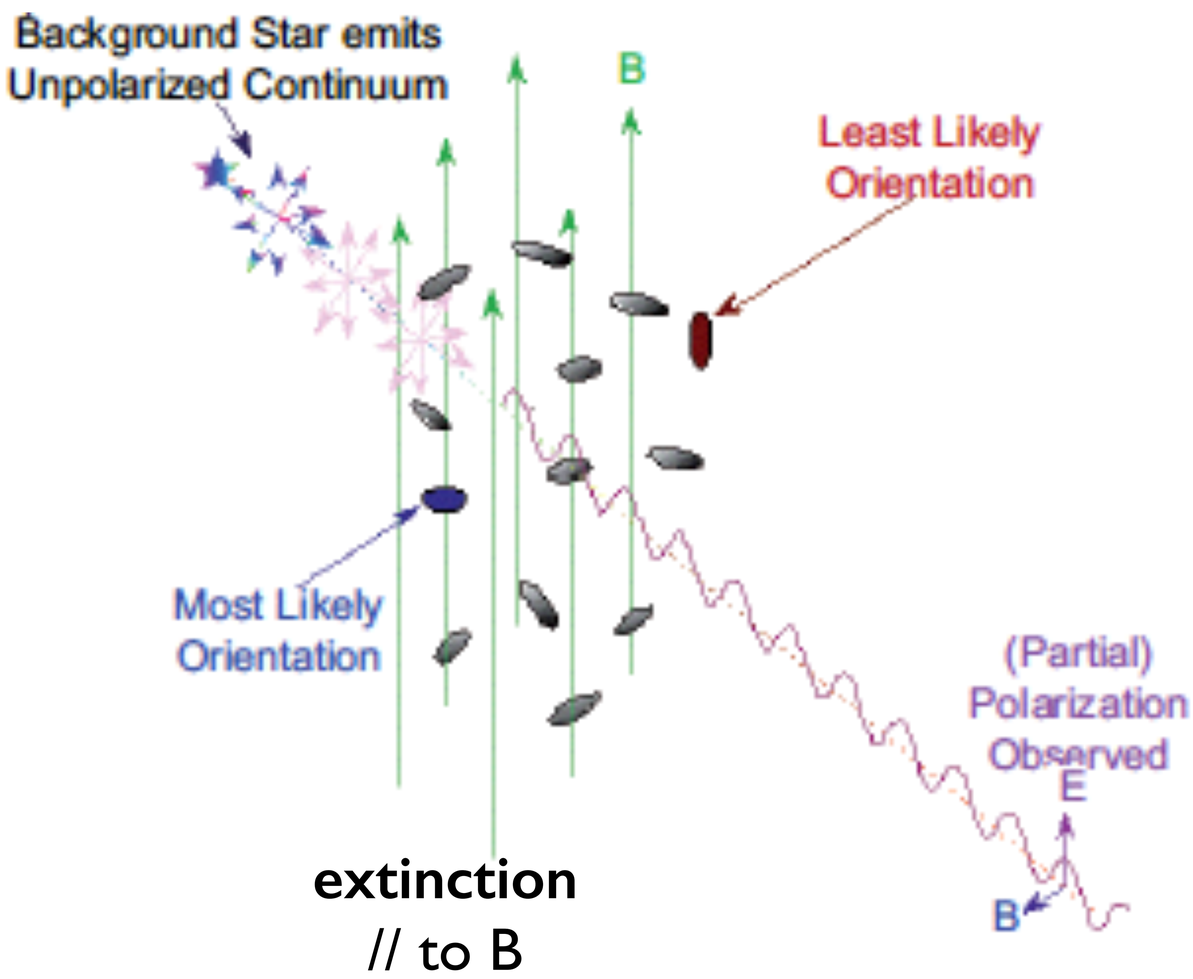
- **Planck Collaboration Planck intermediate results. XXXV.** arXiv:astro-ph 1502.0412
Probing the role of the magnetic field in the formation of structure in molecular clouds

- **Montier et al.** 2015 A&A 574, 135, **Montier et al.** 2015 A&A 574, 136
Polarization measurements analysis I: Impact of the full covariance matrix on p and ψ
Polarization measurements analysis II: Best estimators of polarization fraction and angle

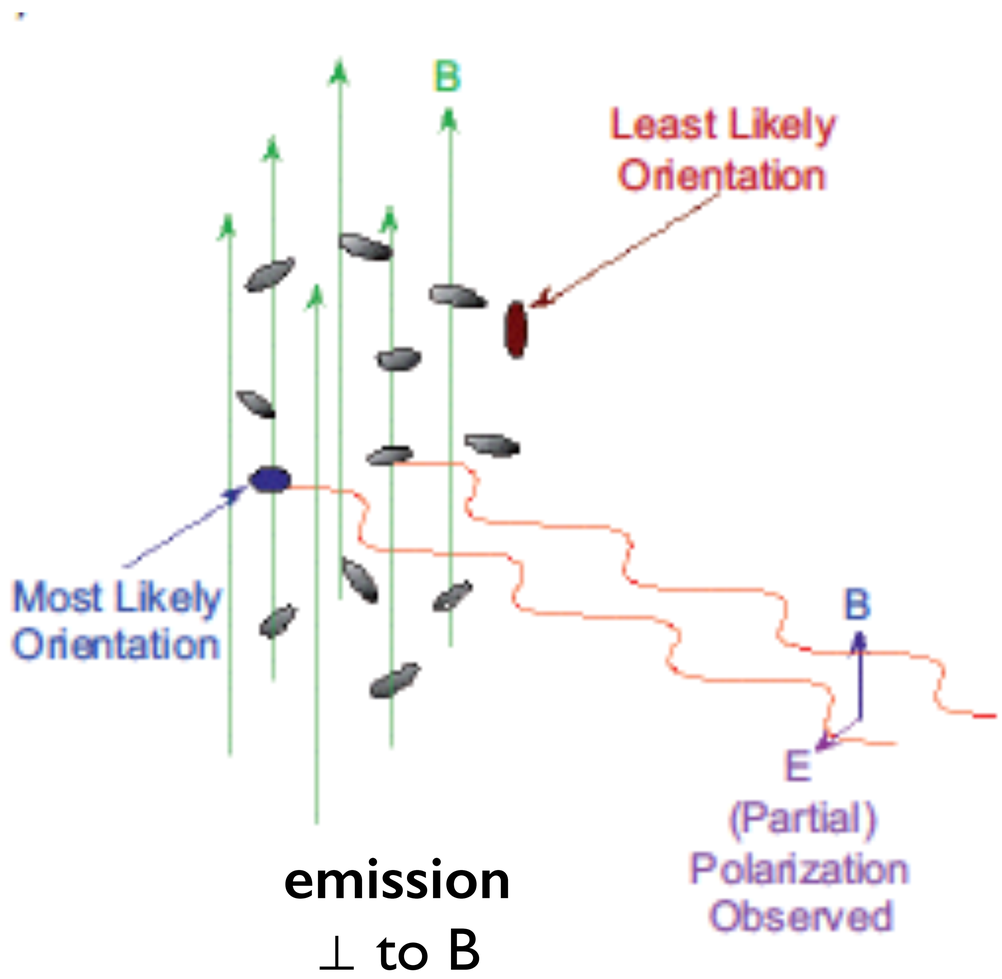
- **Planck Collaboration** ***Planck intermediate results. XXX.*** arXiv:astro-ph 1409.5738
The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

- **BICEP2/Keck & Planck Collaboration** arXiv:astro-ph 2015 PhRvL. 114, 1301
Joint Analysis of BICEP2/Keck Array and Planck data

Dust Polarization

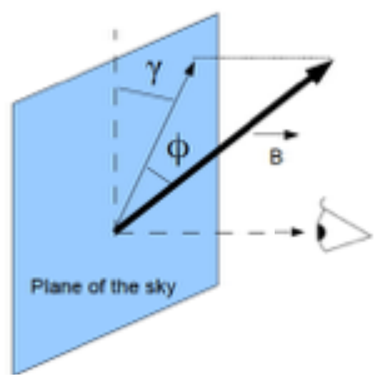


extinction
// to B



emission
⊥ to B

- Grains are rotating, elongated
- Grains align partially on B
- Cross sections α grains size,
  so polarization in extinction and emission
- Trace magnetic field direction projected on the sky
  (just like Synchrotron emission)



$$P = \sqrt{(Q^2+U^2)} \propto \cos^2\phi$$

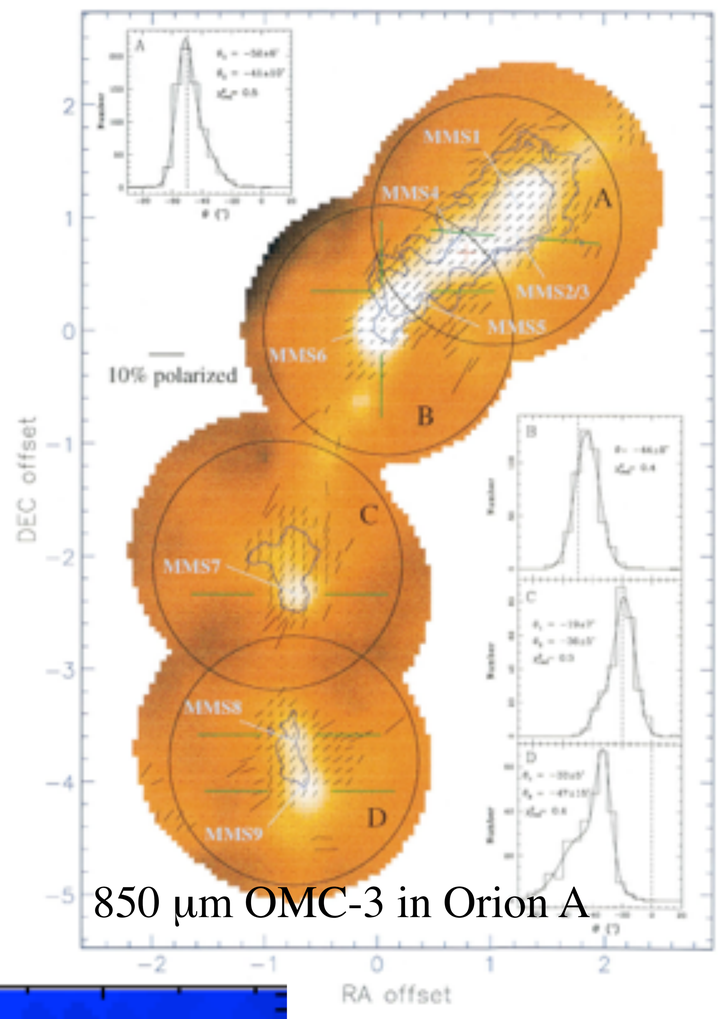
Stein 1966, Andersson 2012, Draine & Fraisse 2009, Hoang & Lazarian 2008, Martin 1975, 2007

Dust Polarization

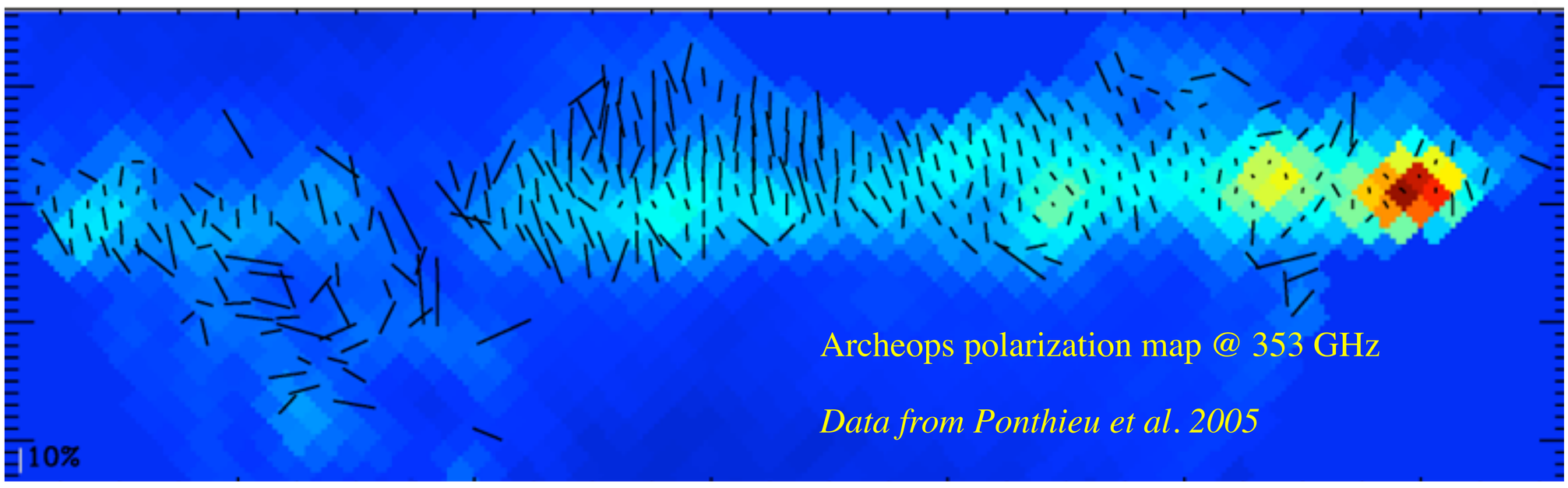
Before Planck: emission

- Ground submm measurements (restricted to bright regions) indicate low p values (p= few %)

- Archeops claimed p=10-15% off the plane (2nd Galactic Quadrant)



850 μm OMC-3 in Orion A



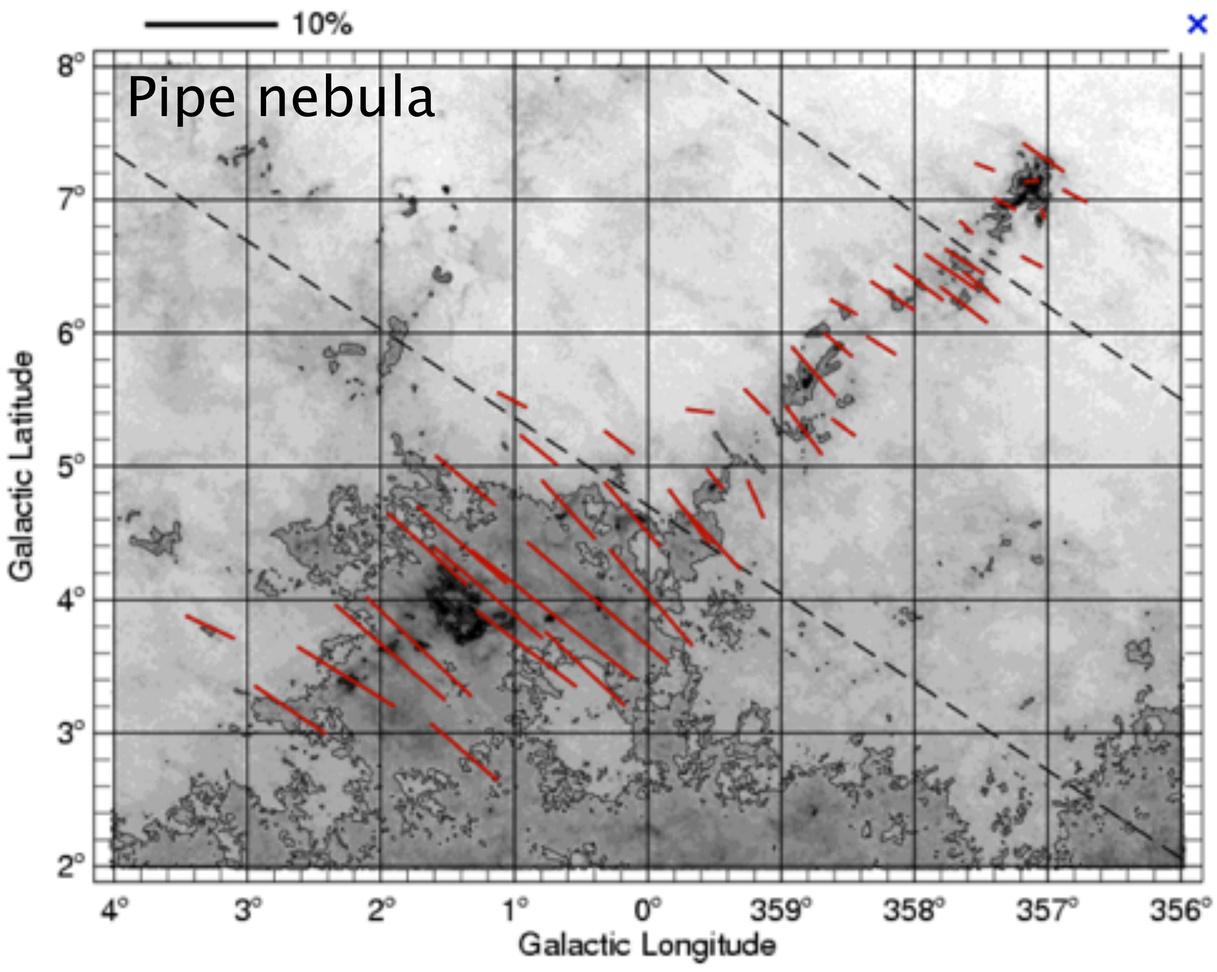
Archeops polarization map @ 353 GHz

Data from Ponthieu et al. 2005

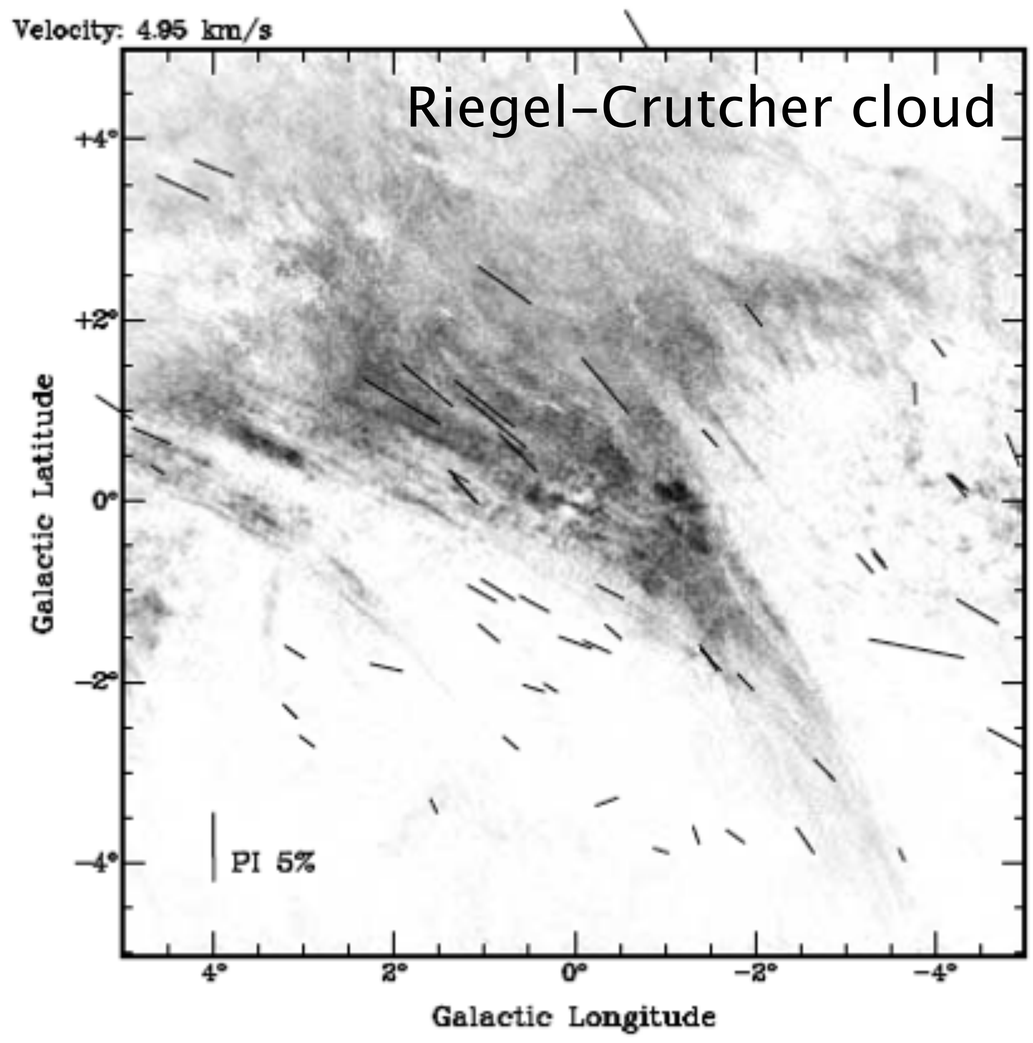
Before Planck: Extinction

Dust Polarization

Some ISM filamentary structures show apparent connection with magnetic field ...



B ⊥ to pipe filament

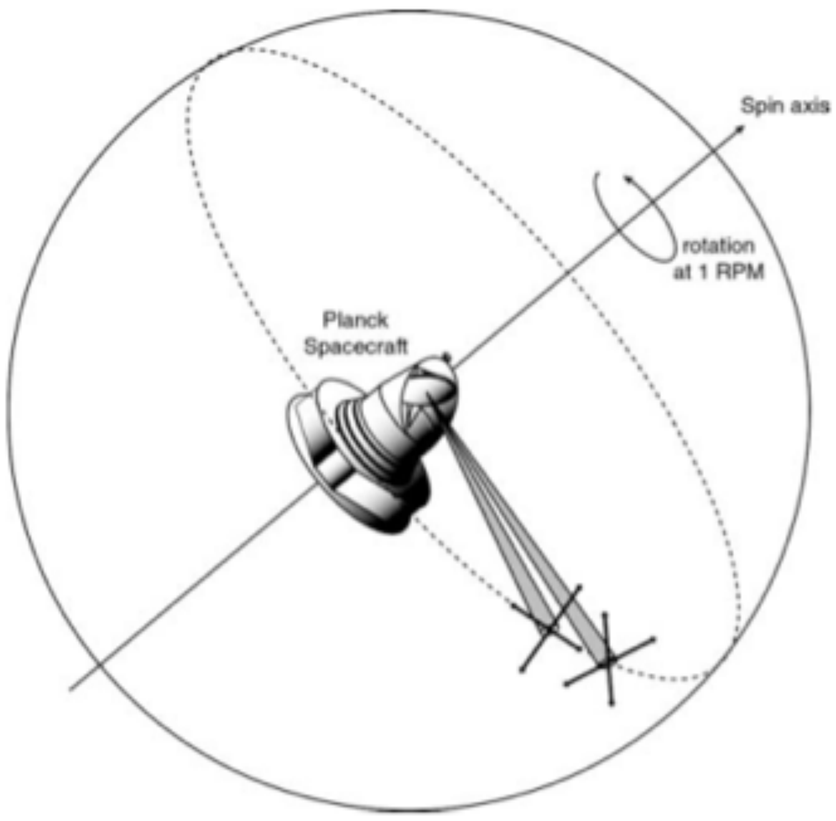


B // to HI filaments

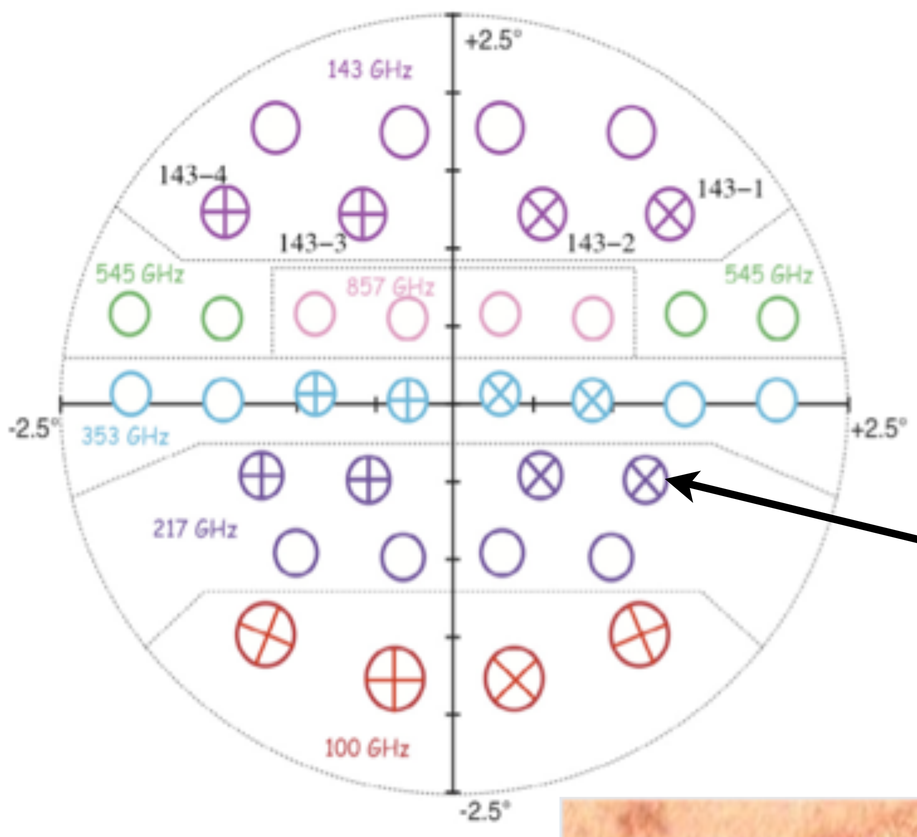
… but sparse data prevents statistics

How Planck measures polarization

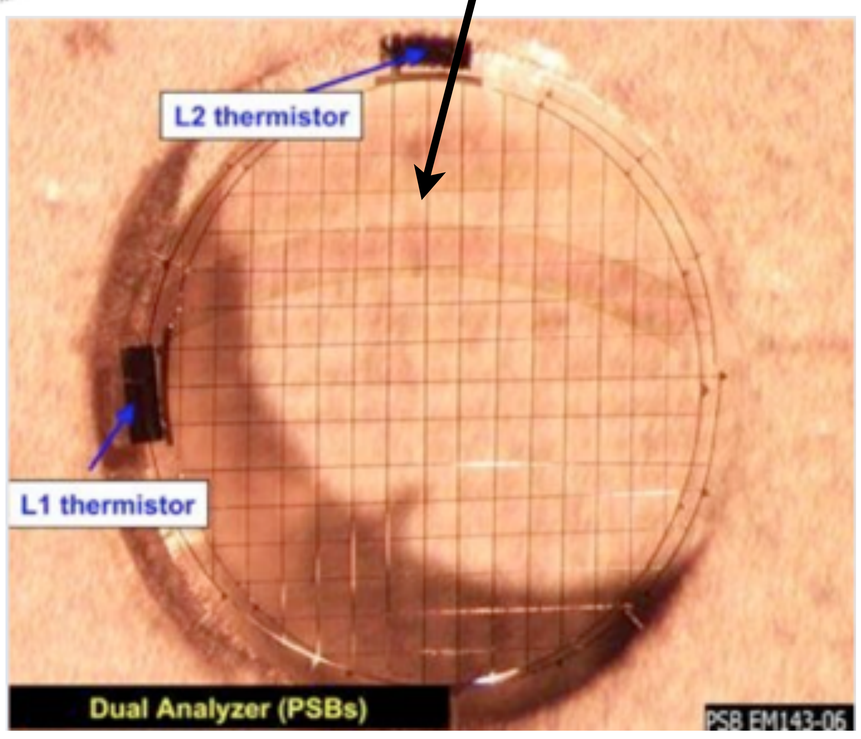
Planck scanning the sky



Planck/HFI focal plane



PSB



Combination of two pairs of PSB bolometers rotated by 45° observing the same sky positions

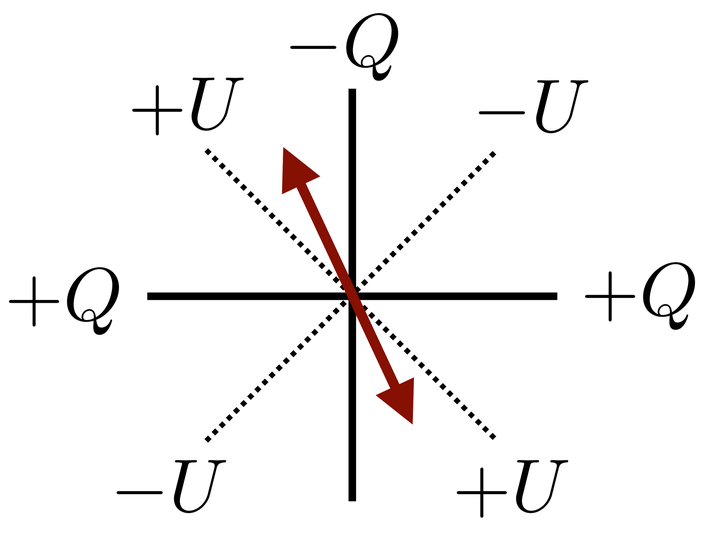
$$s_1 - s_2 = Q\ cos(2\alpha) + U\ sin(2\alpha)$$
$$s_3 - s_4 = Q\ sin(2\alpha) - U\ cos(2\alpha)$$

Multiple scans provide Q and U with different a orientation.
Maps of Q and U and their standard deviations are derived.

5 independent sky surveys

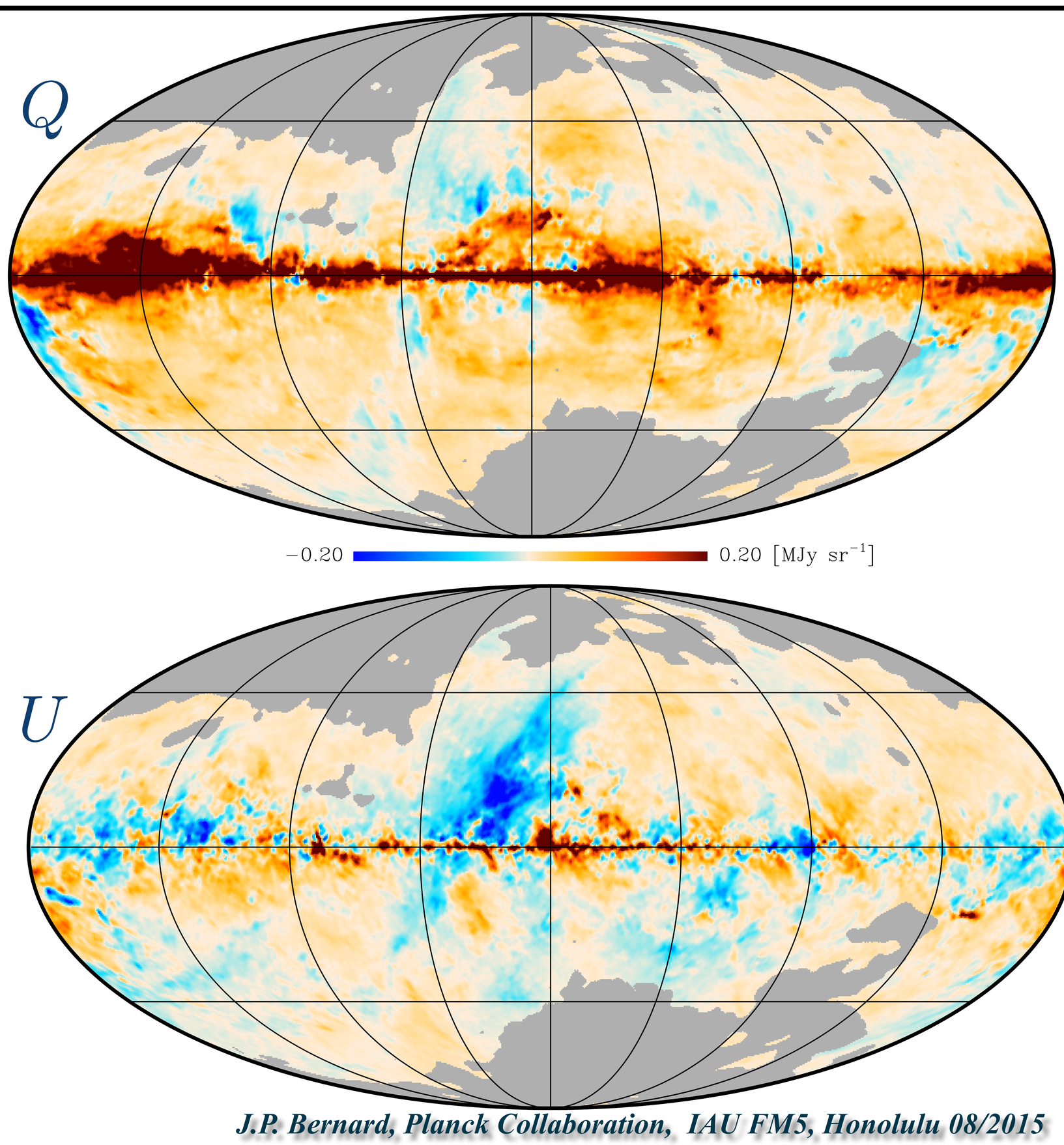
The Planck Polarization sky

353 GHz



Masked regions :
I_{353} < 0.1 MJy/sr + σ_P<3%

Resolution 1°



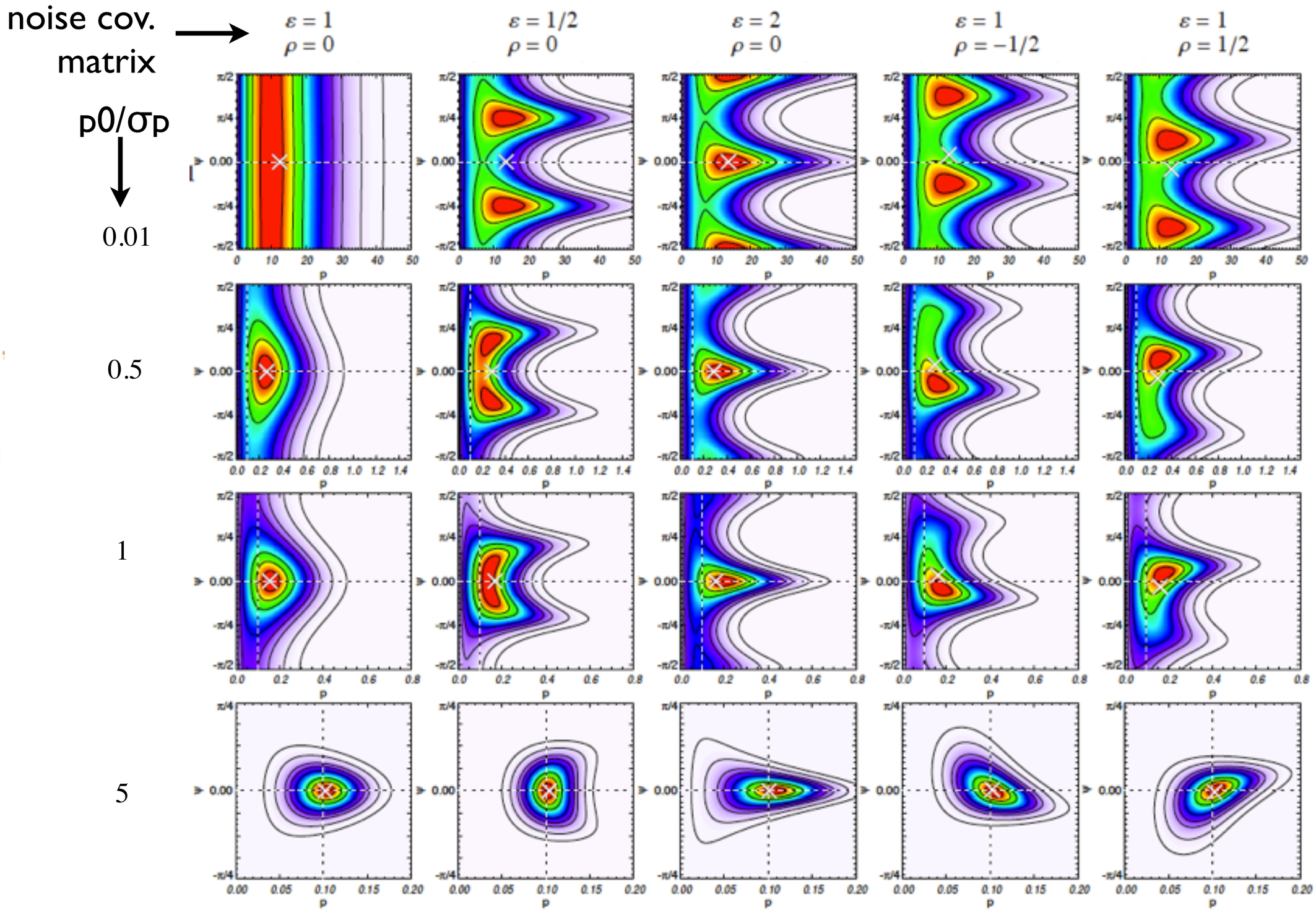
Planck intermediate results. XIX.

Noise and Bias

$$\Sigma \equiv \begin{pmatrix} \sigma_{II} & \sigma_{IQ} & \sigma_{IU} \\ \sigma_{IQ} & \sigma_{QQ} & \sigma_{QU} \\ \sigma_{IU} & \sigma_{QU} & \sigma_{UU} \end{pmatrix} = \begin{pmatrix} {\sigma_I}^2 & \rho_Q \sigma_I \sigma_Q & \rho_U \sigma_I \sigma_U \\ \rho_Q \sigma_I \sigma_Q & {\sigma_Q}^2 & \rho \sigma_Q \sigma_U \\ \rho_U \sigma_I \sigma_U & \rho \sigma_Q \sigma_U & {\sigma_U}^2 \end{pmatrix} \qquad \varepsilon \equiv \frac{\sigma_Q}{\sigma_U}; \quad \rho \equiv \frac{\sigma_{QU}}{\sigma_Q \sigma_U}$$

$$p \equiv \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\psi \equiv \frac{1}{2} \mathrm{atan}\left(\frac{U}{Q}\right)$$

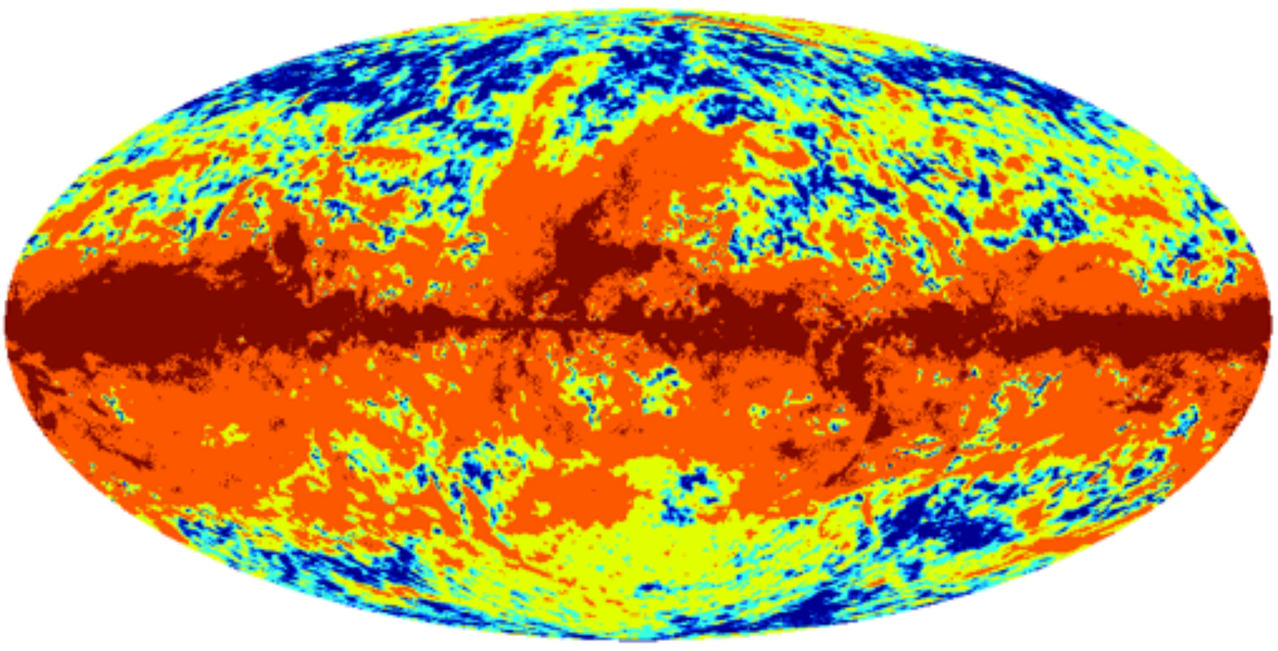


Montier et al. 2015a, 2015b

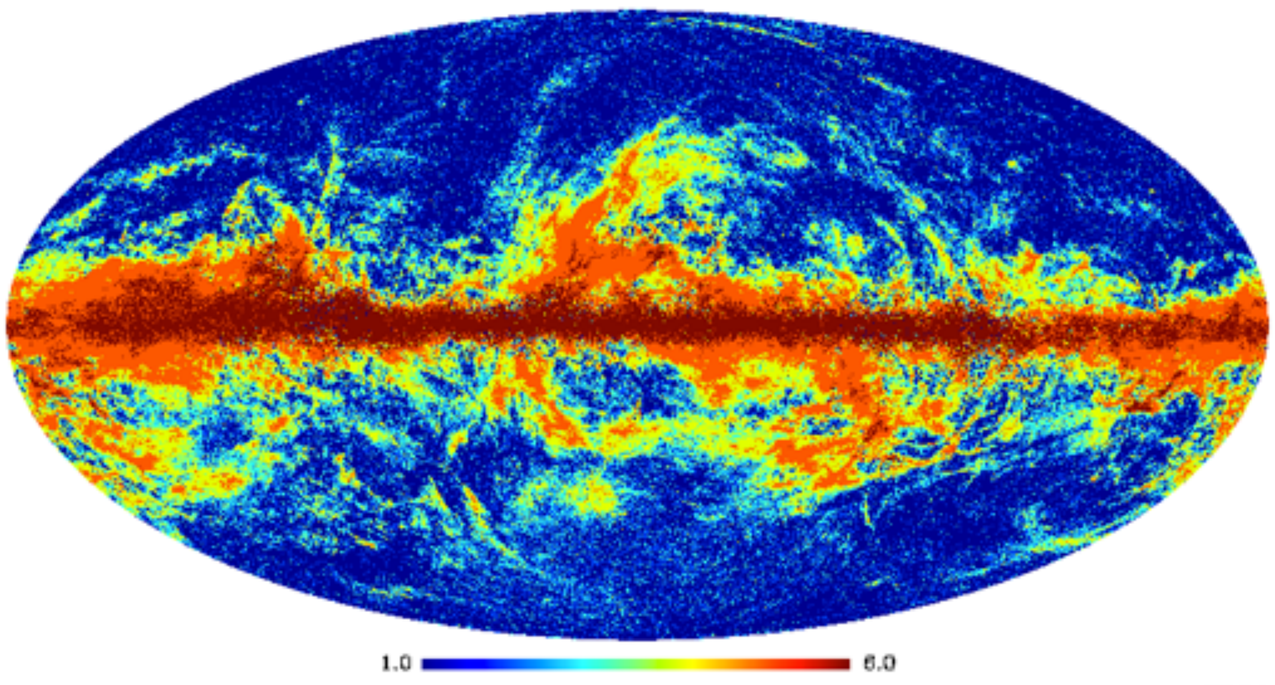
Uncertainties

maps of SNR on p

1° resolution



30’ resolution



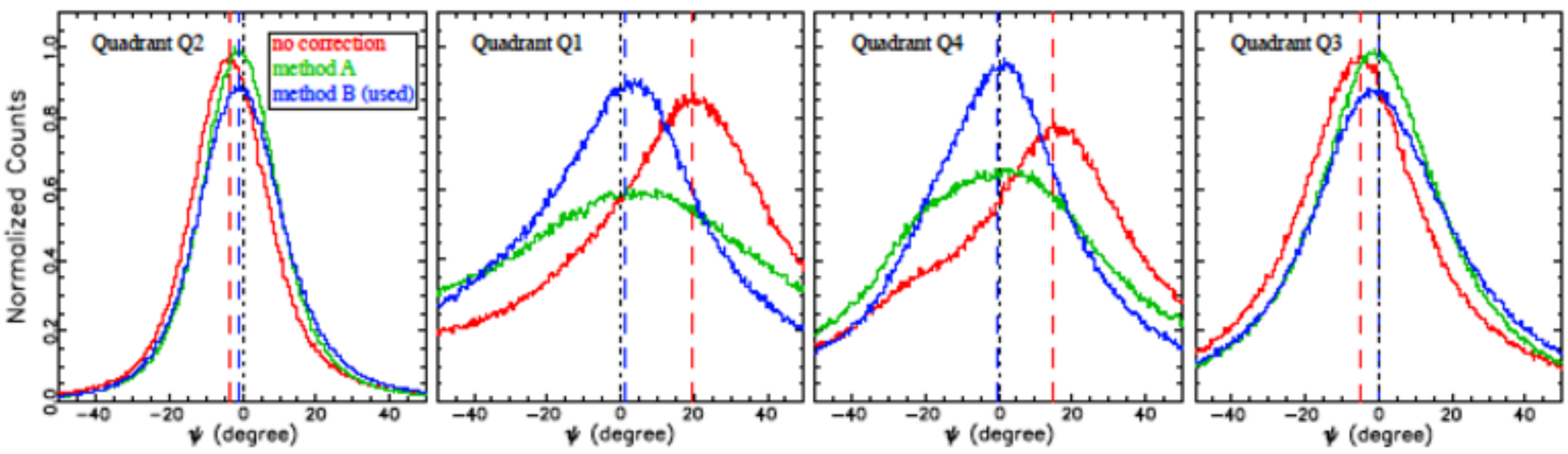
- Computed from mean likelihood
- Basically reflect Intensity and sky coverage

	1°	30’	15’
SNR>2	93 %	82 %	61 %
SNR>3	89 %	72 %	48 %
SNR>5	77 %	55 %	33 %
SNR>10	53 %	34 %	19 %

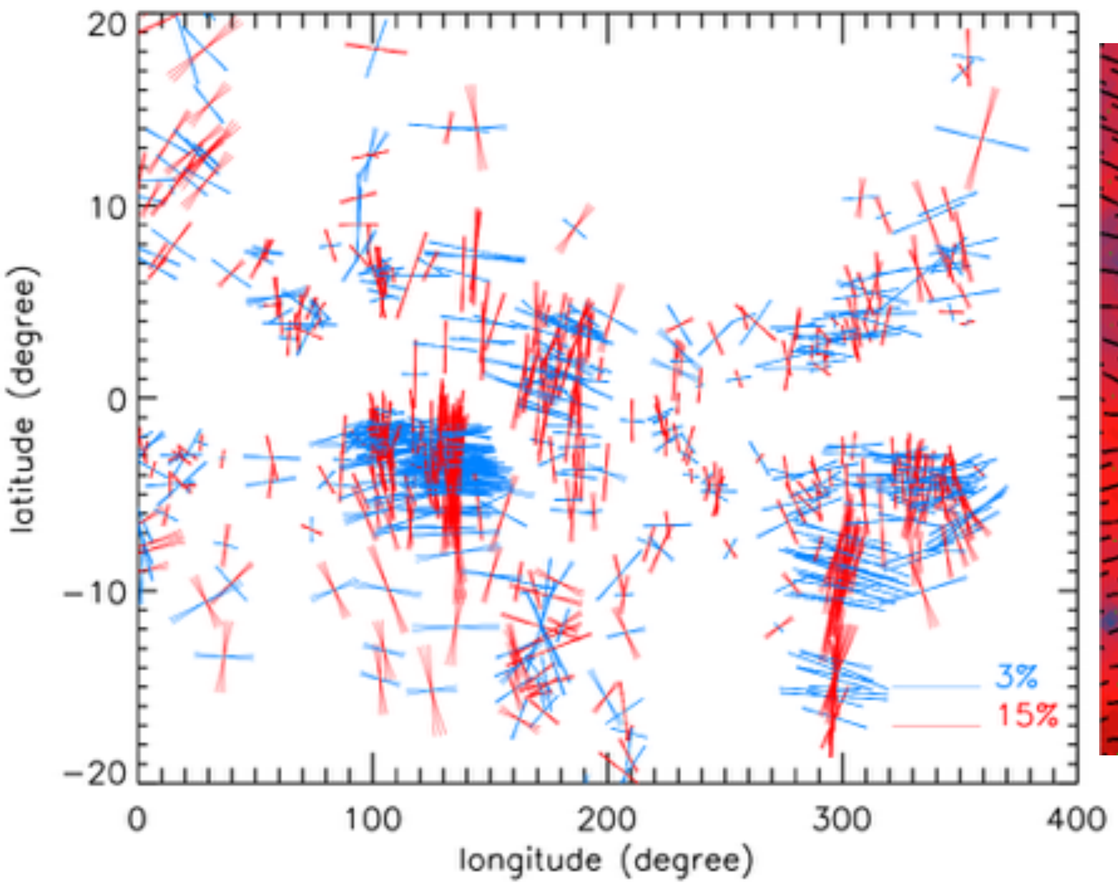
- Work at 1° resolution to lower noise (also 7’, 14’, 30’)
- Smoothed noise cov. matrix

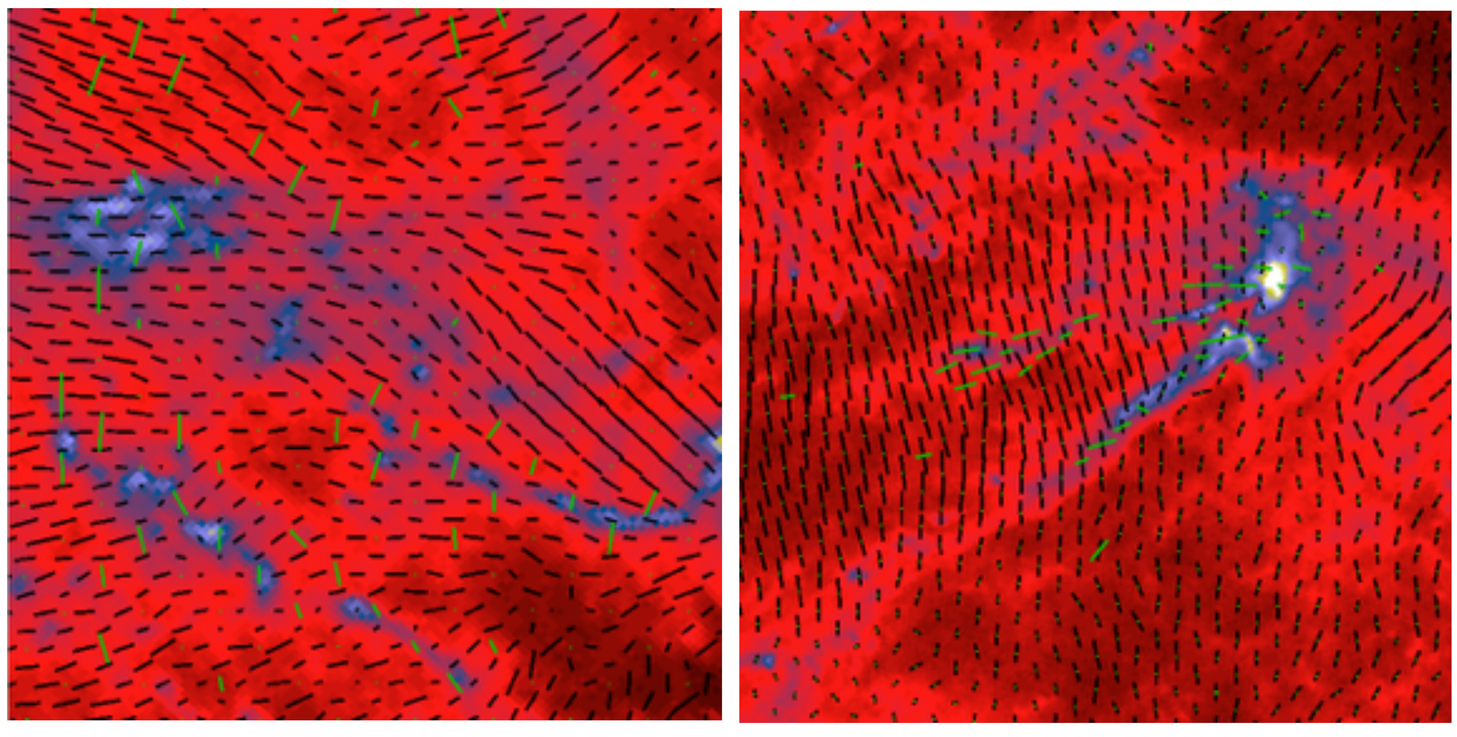
Emission vs Extinction

Bandpass mismatch could be checked using B direction along the Galactic Plane



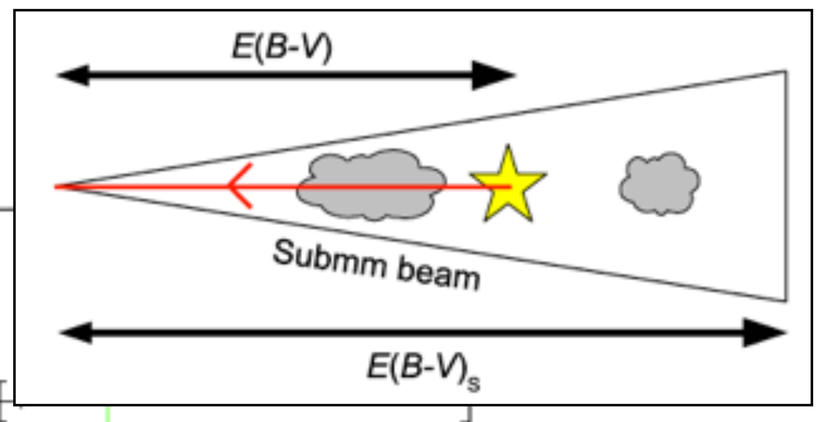
Stellar extinction polarization (Heiles Catalog) and Planck Submm extinction match beautifully

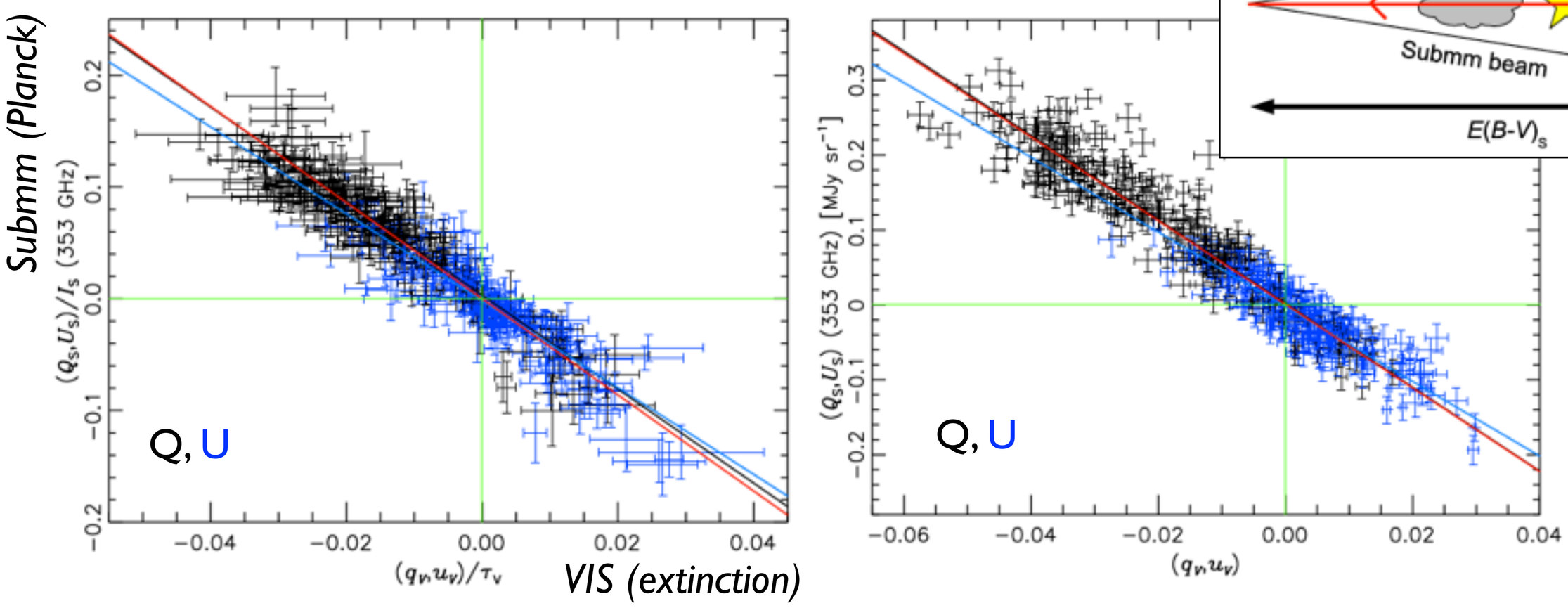




Emission vs Extinction

star selection based on angle, extinction, …



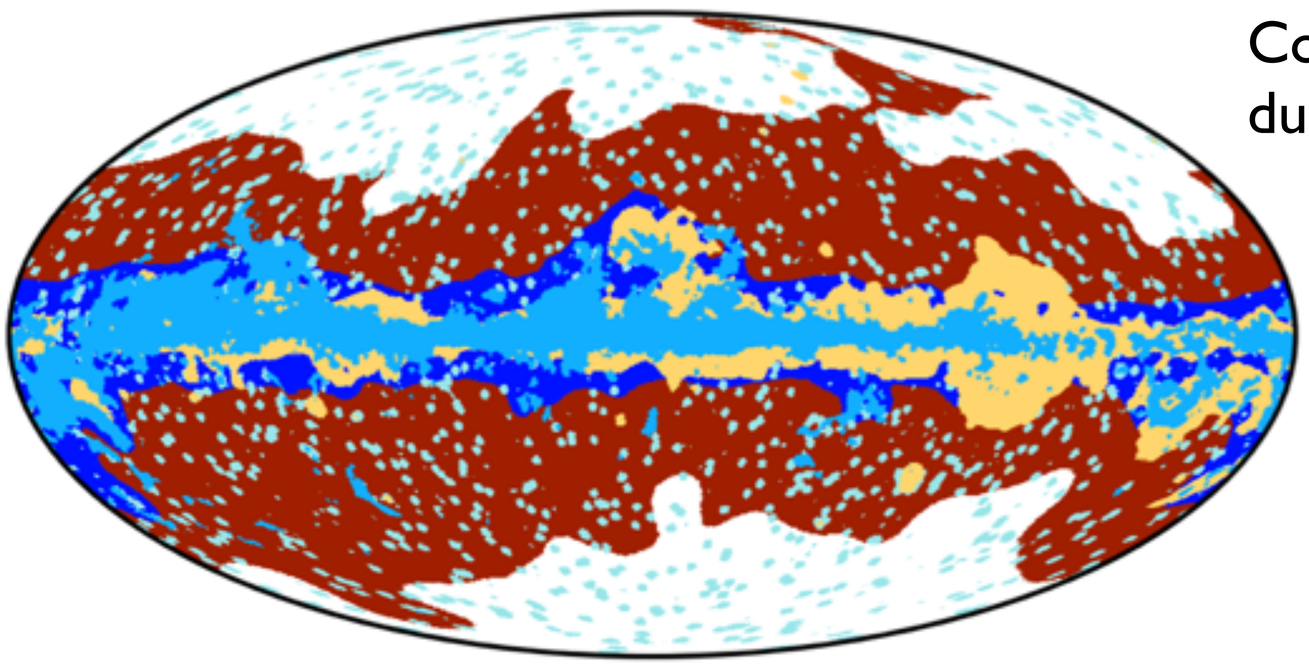


- Polarization efficiency ratio: $R_{S/V} = (P_S/I_S)/(p_V/\tau_V) = 4.3 \pm 0.2(\text{stat.}) \pm 0.4(\text{syst.})$
- $R_{S/V}$ compatible with a range of dust models, not very discriminatory.
- Polarized emission ratio: $R_{P/p} = P_S/p_V = 5.6 \pm 0.2\ (\text{stat.}) \pm 0.4\ (\text{syst.})$ MJy sr^{-1}
- $R_{P/p}$ higher than model predictions by ~ 2.5.

New constraint for dust grain physics.

Planck intermediate results. XXI.

p vs wavelength



Correlation analysis using I,Q,U at 353 GHz as dust template)

over 39% of the sky. Excluding most free-free, CO, ... contaminated regions

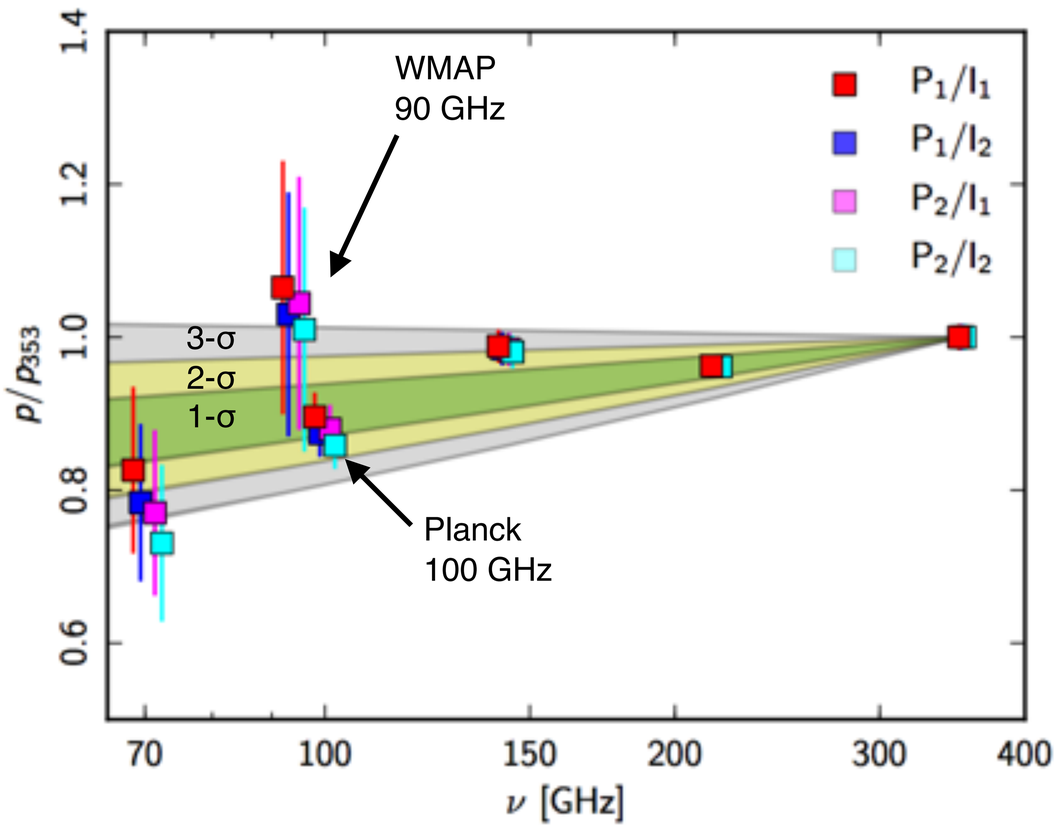
Indications for polarization SED steeper than Intensity SED :

$$\beta^I = 1.52 \pm 0.01$$
$$\beta^P = 1.59 \pm 0.02$$

(unaccounted for component ? ferro-magnetic grains ? Carbonaceous grains ?)

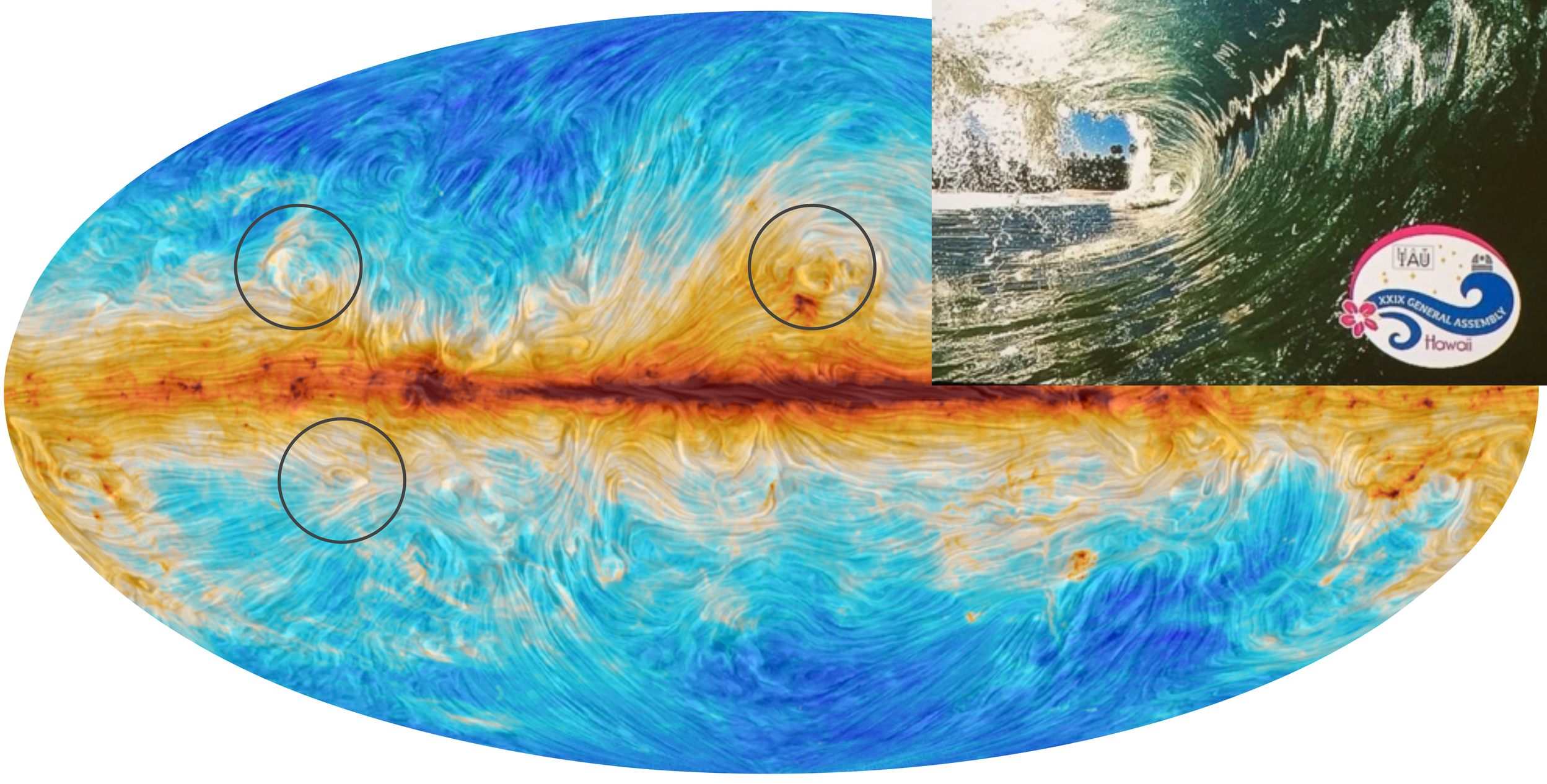
New constraints on dust models and/ or component separation

Polarization fraction vs frequency

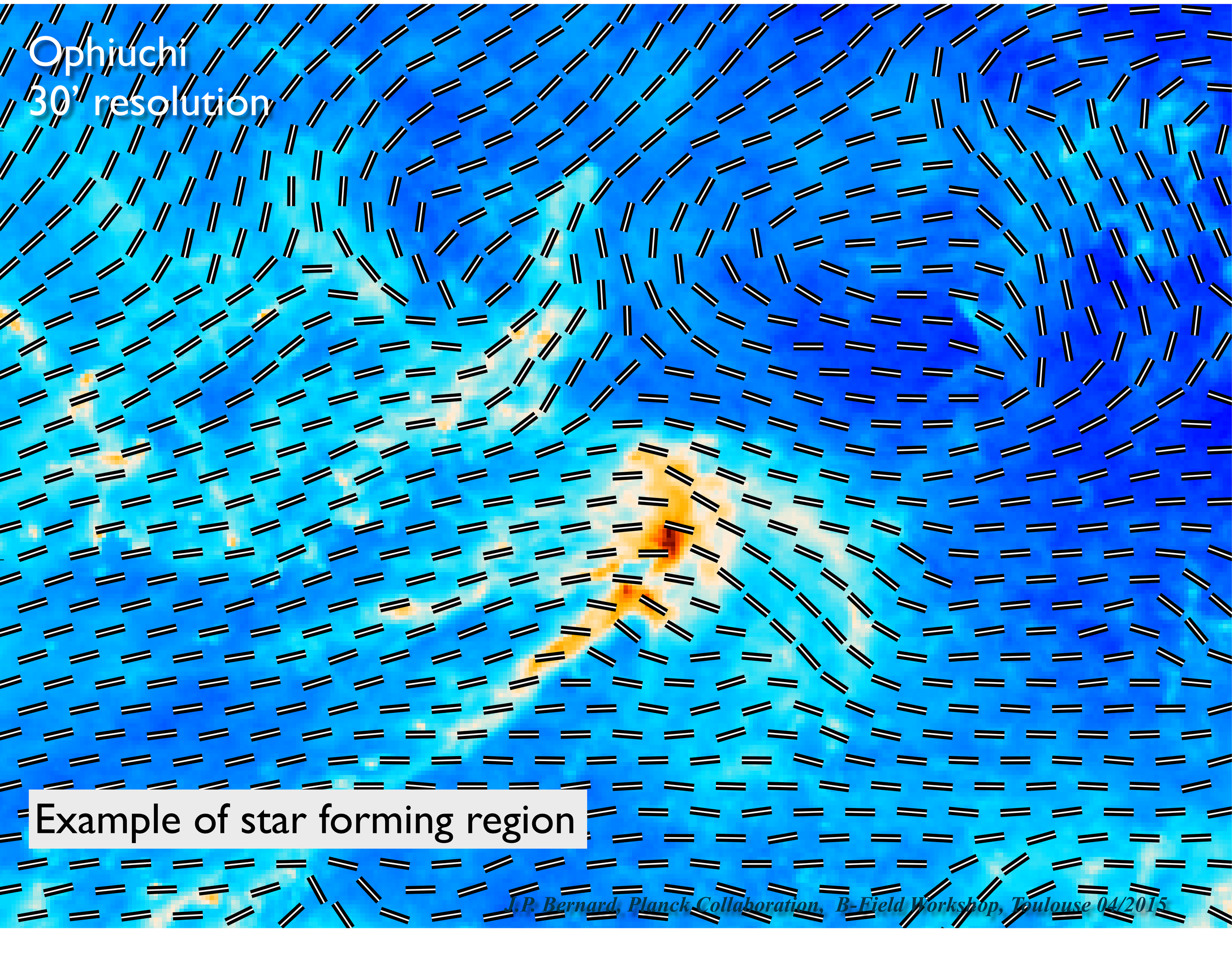


Polarization angle

353 GHz rotated 90° ⟶ $\mathbf{B}_{\perp}$



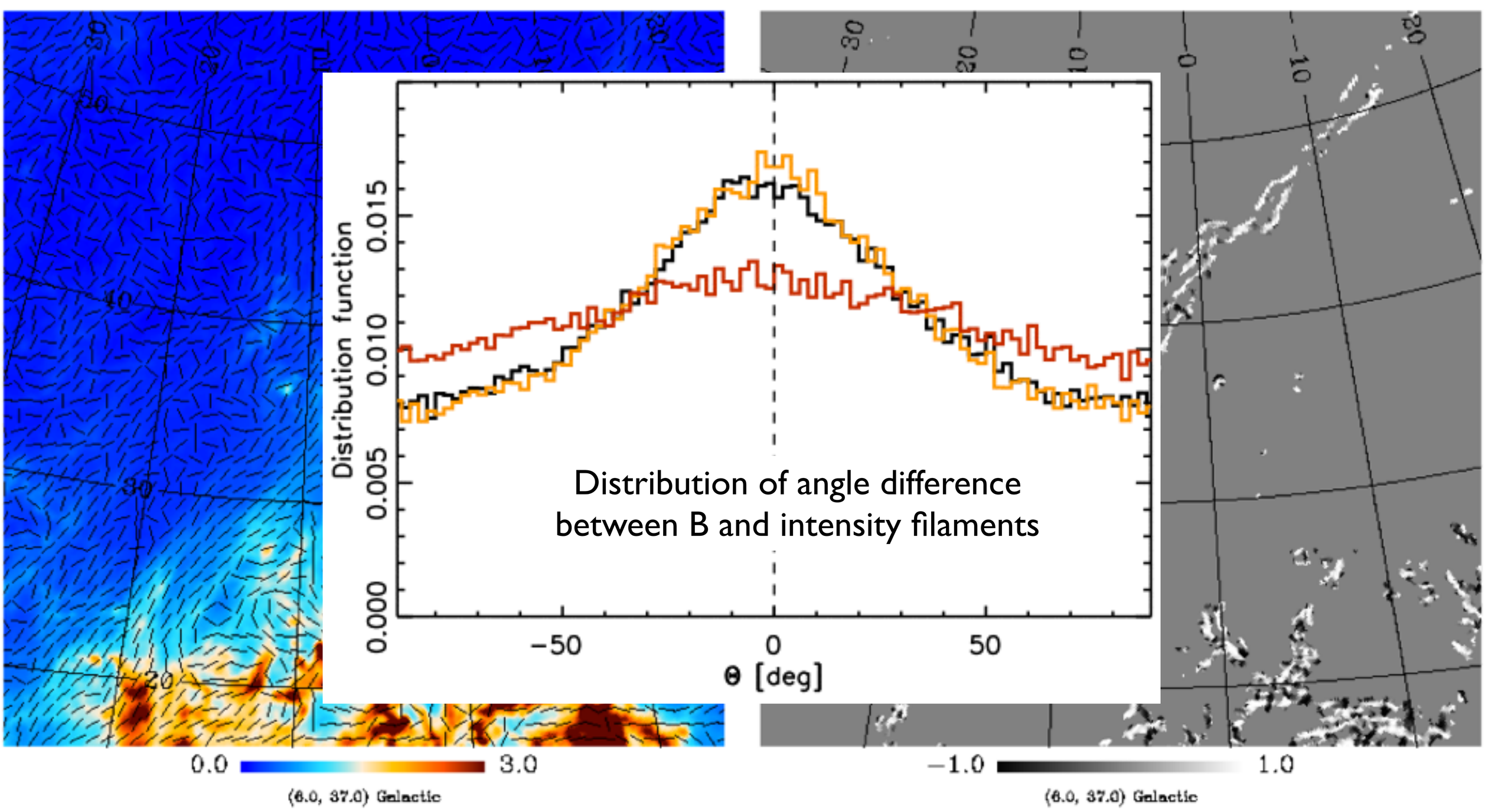
Color: Intensity at 353 GHz
Texture: Direction of magnetic field as projected on the sky (Line Integral Convolution)


Ophiuchi
30’ resolution
Example of star forming region
J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015

Example of filaments where the magnetic field follows filaments

J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015

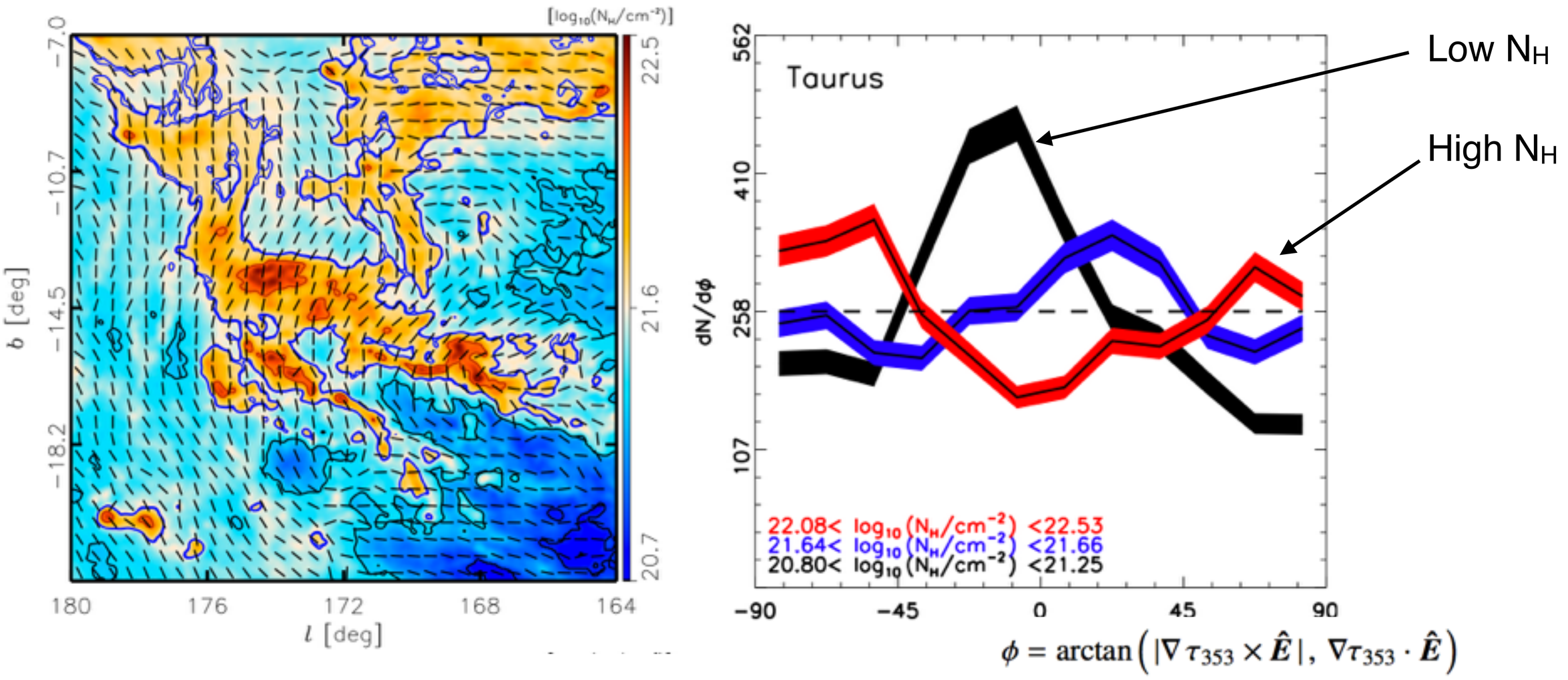
B vs filaments



at low N_H : B // ISM filamentary structures

Planck intermediate results. XXXII.

B vs filaments



at low N_H : B // ISM filamentary structures

at high N_H :B ⊥ to ISM filamentary structures

ressembles predictions of sub-Alfvenic turbulence

See talk by J. Soler

Planck intermediate results. XXXII.

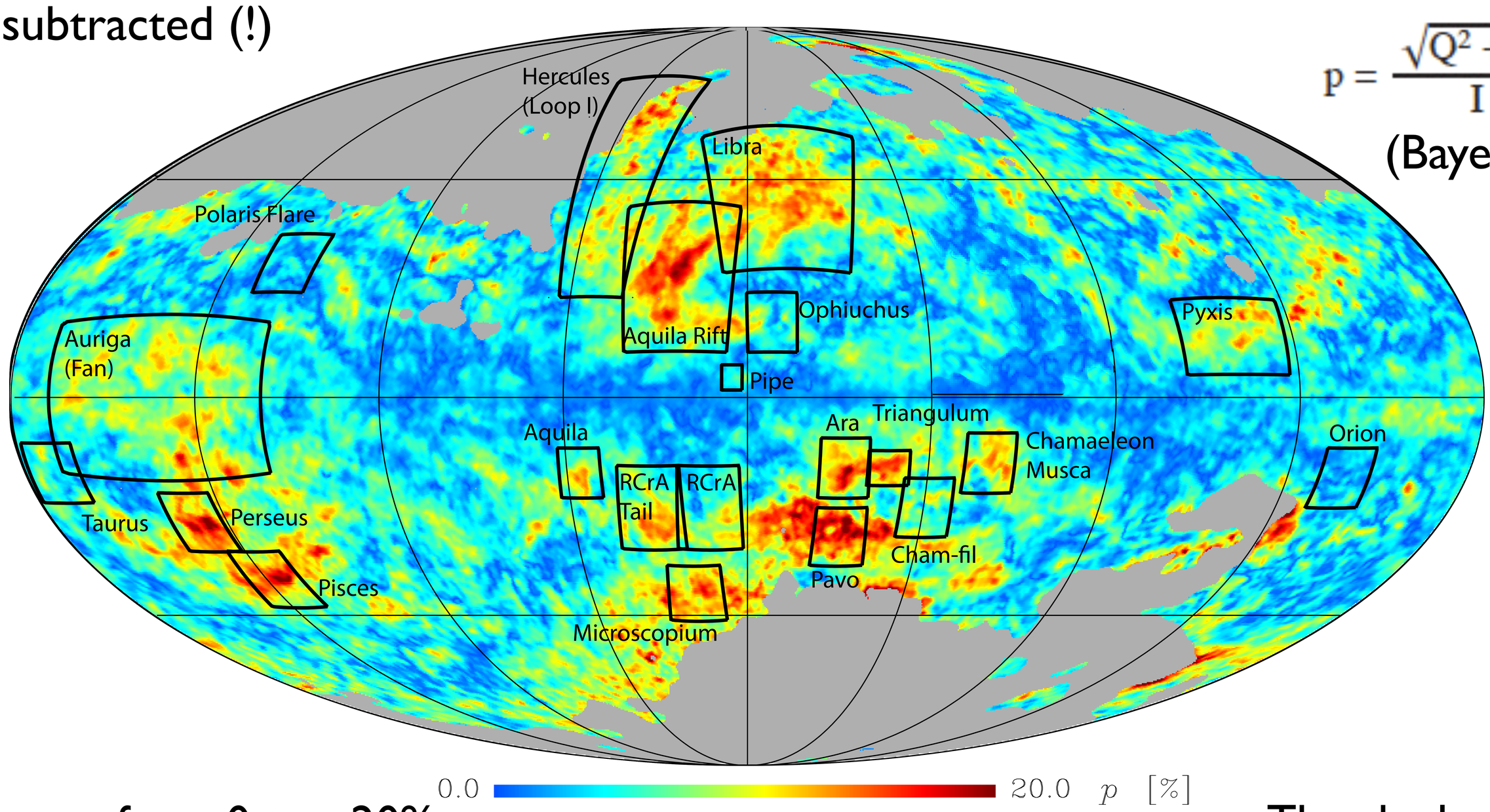
Planck intermediate results. XXXV.

Dust polarization fraction (p) at 353 GHz, 1° resolution

CIB subtracted (!)

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$

(Bayesian)



p ranges from 0 to ~20%

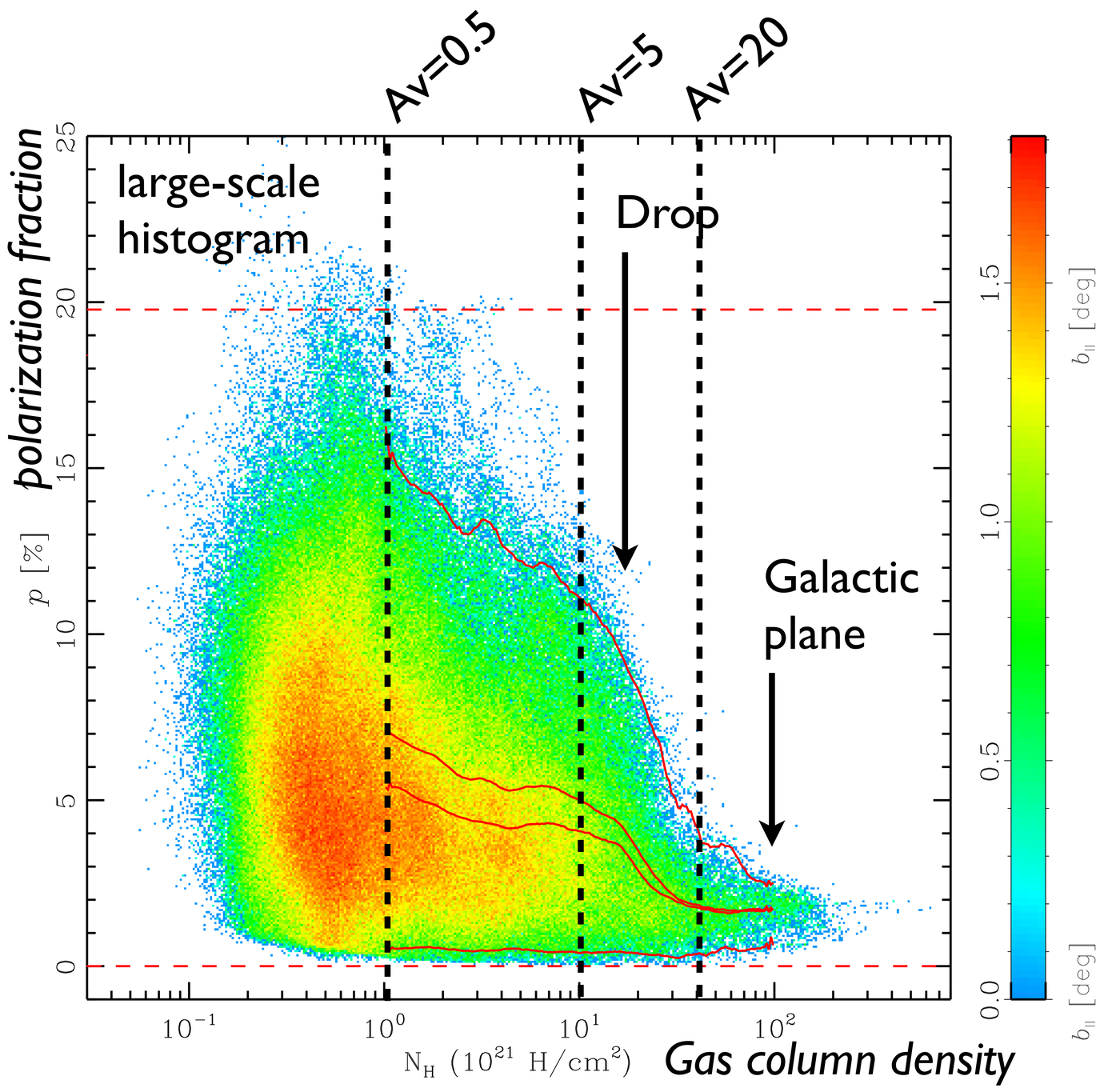
Low p values in inner MW plane

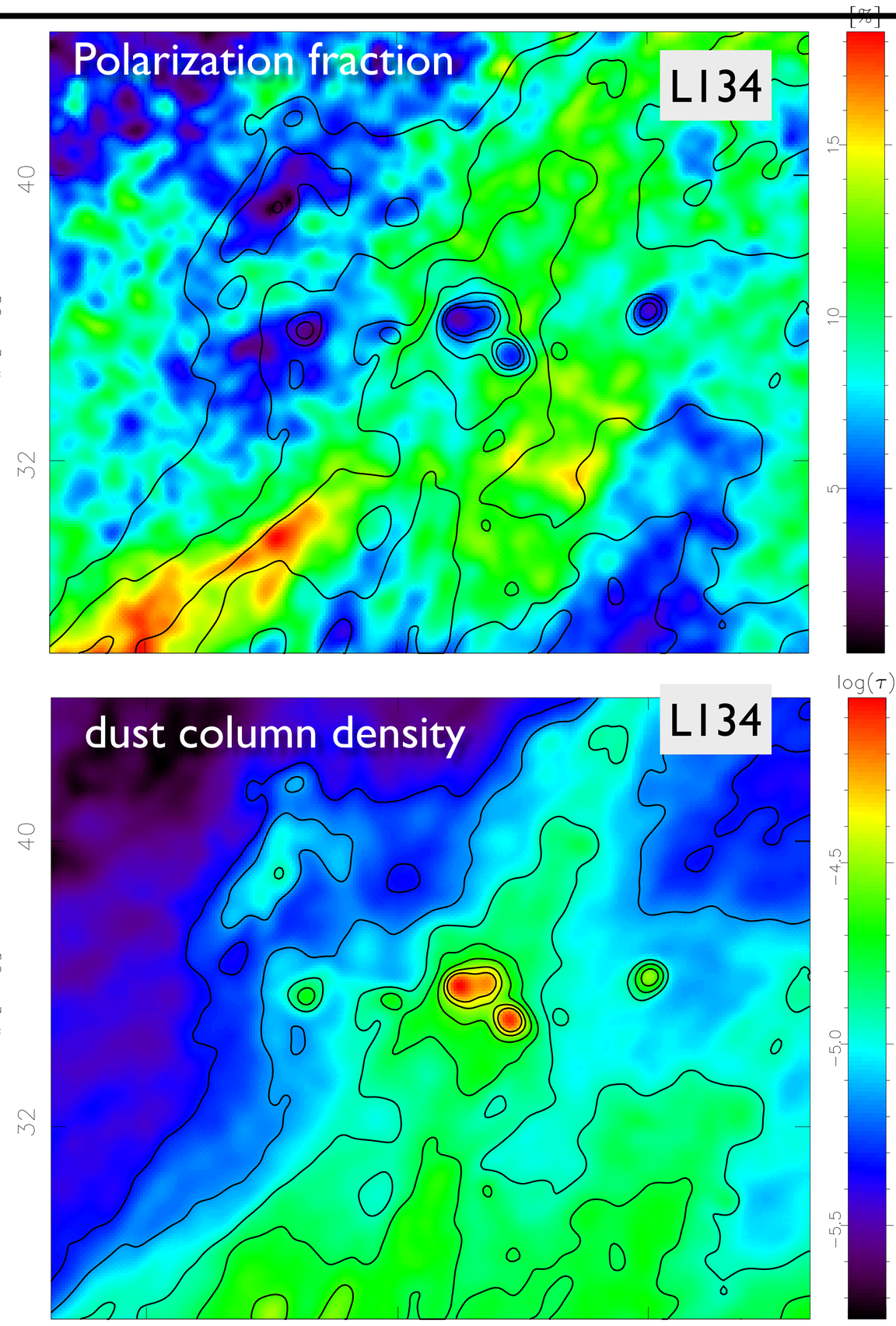
Large p values in outer plane and intermediate latitudes

The sky looks different in polarization !!

Planck intermediate results. XIX.

Polarization fraction vs N_H

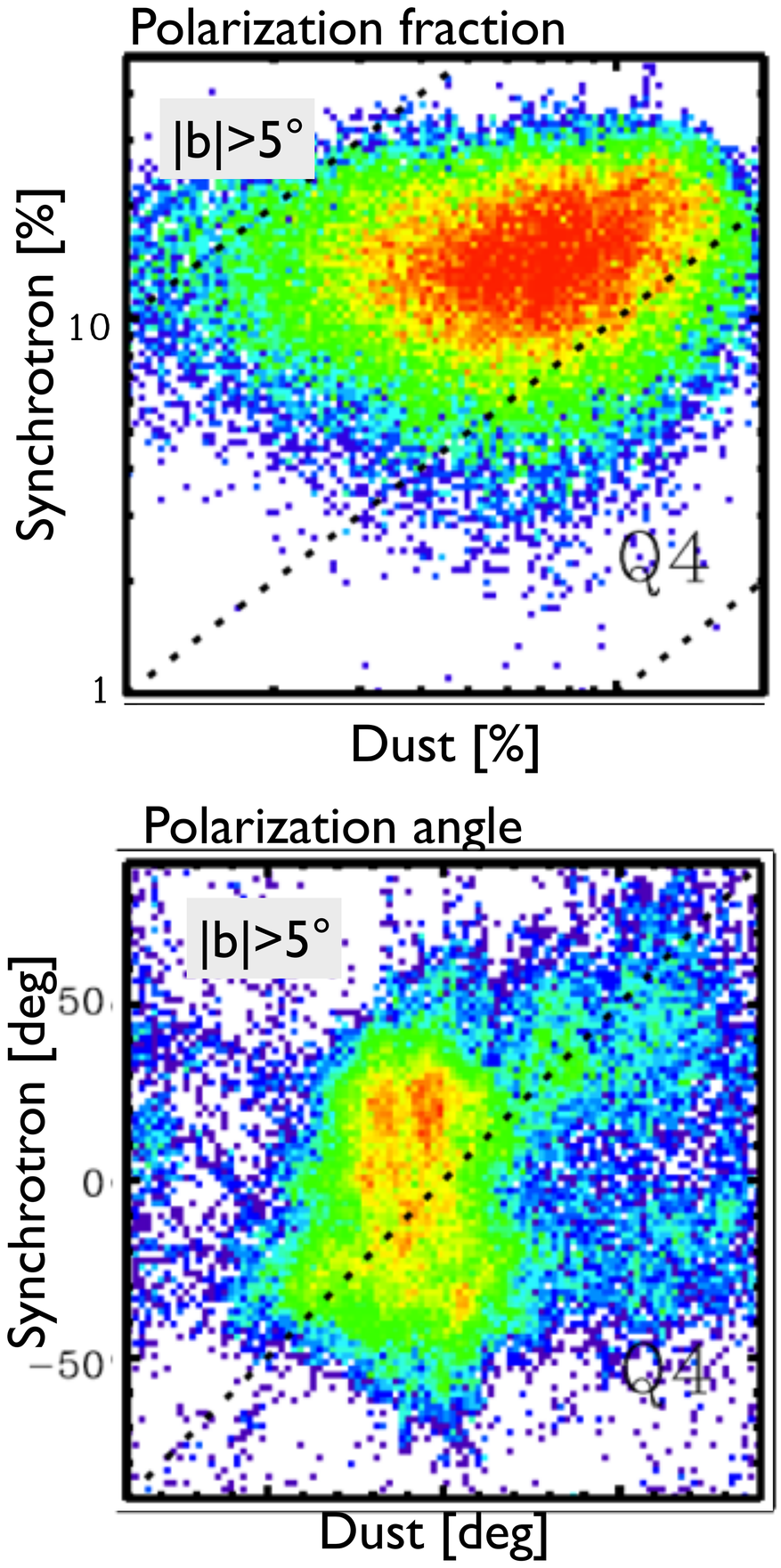




Polarization fractions drops at large column density (Galactic Plane + individual clouds)

Planck intermediate results. XIX.

Synchrotron (30 GHz) vs Dust (353 GHz)



- Polarization fraction:
  - Measurable correlations in-plane
  - Weaker correlations off-plane
- Angles :
  - Around 0° in plane but not well correlated
  - Correlate over some regions (Fan, North Polar Spur)

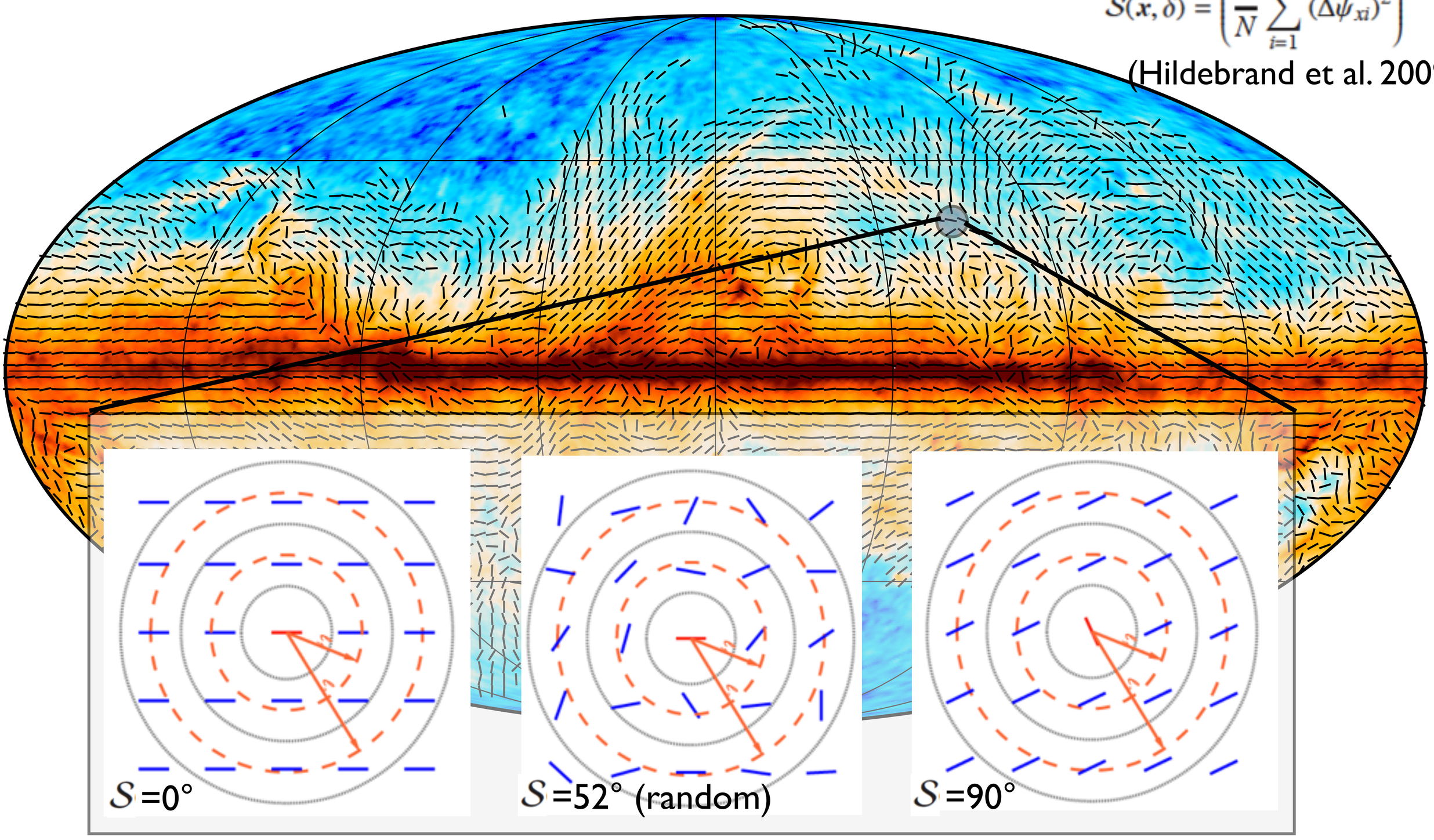
Significant scatter:
Synchrotron and dust not generally trace the same regions of LOS

The Planck data is unique in tracing B field in the dust disk of the MW.

Angle Dispersion Function

$$S(x,\delta) = \left(\frac{1}{N} \sum_{i=1}^{N} (\Delta\psi_{xi})^2 \right)^{1/2}$$

(Hildebrand et al. 2009)



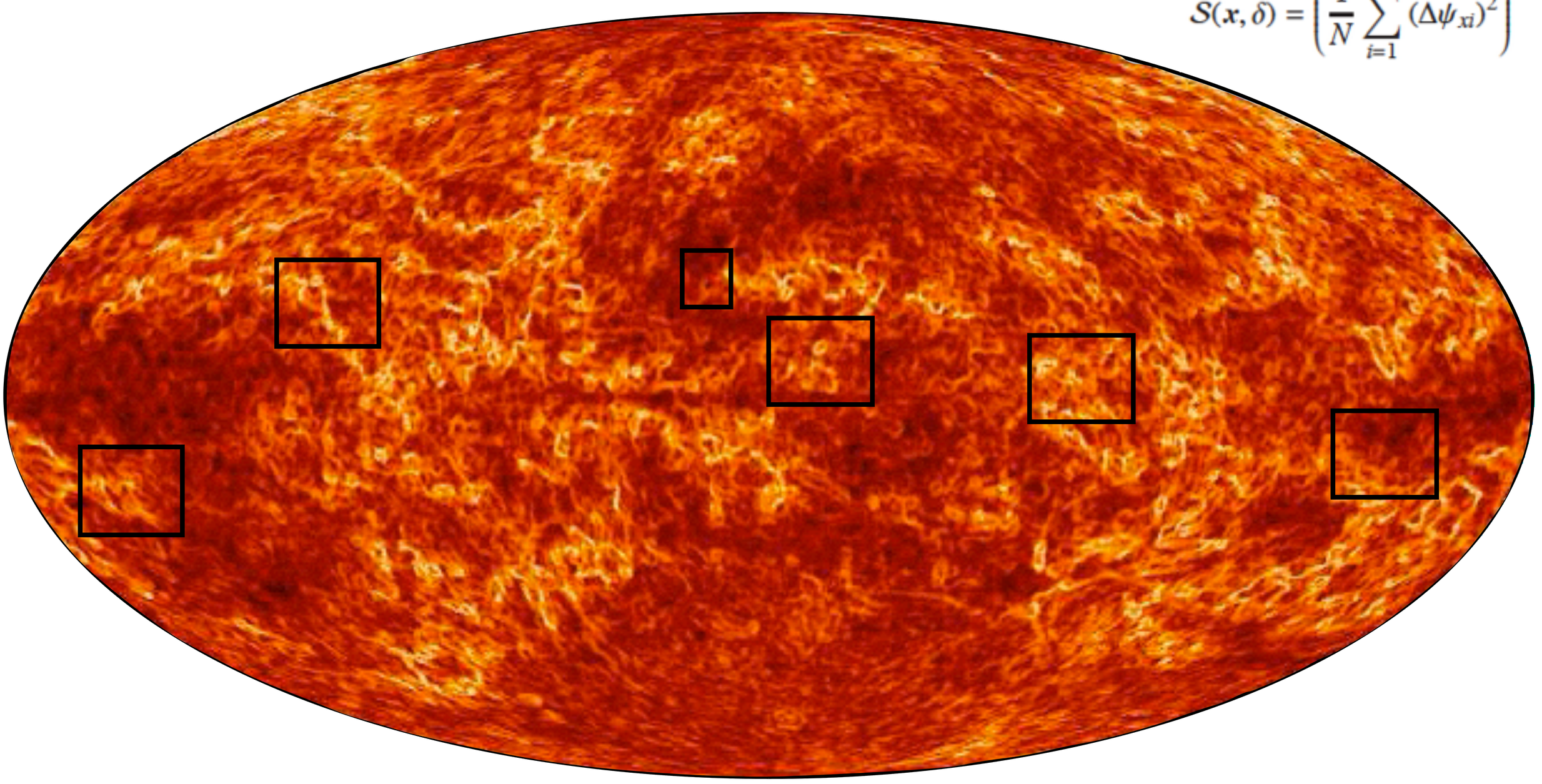
S measures polarization direction homogeneity at given spatial scale

Planck intermediate results. XIX.

Angle Dispersion Function

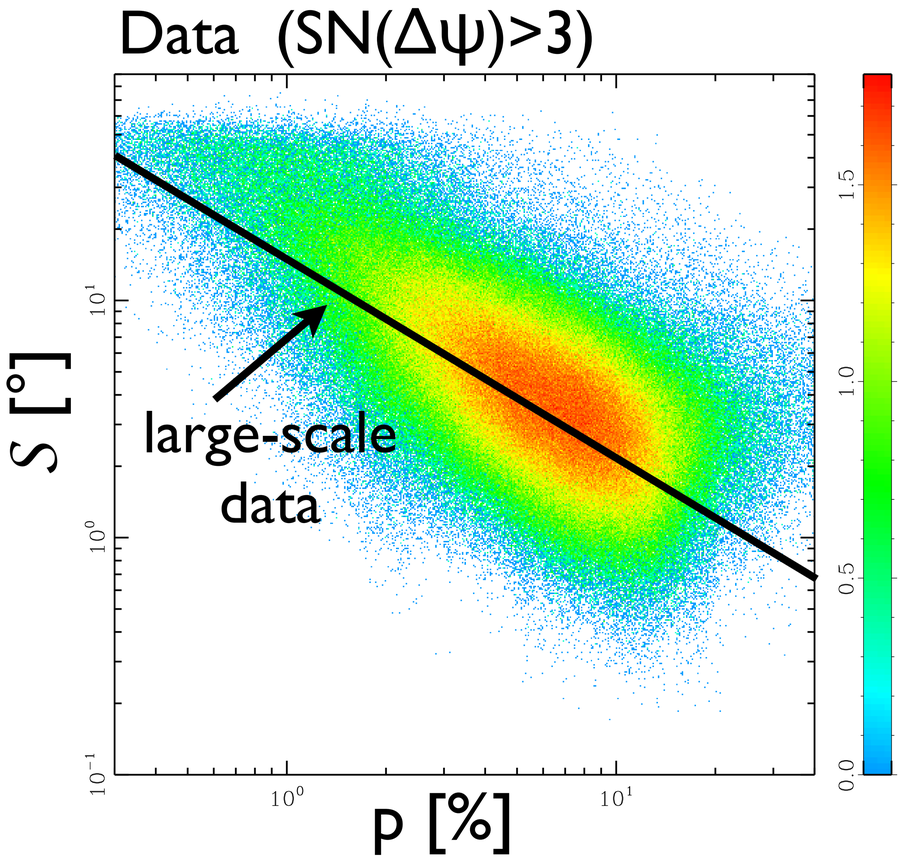
Planck intermediate results. XIX.

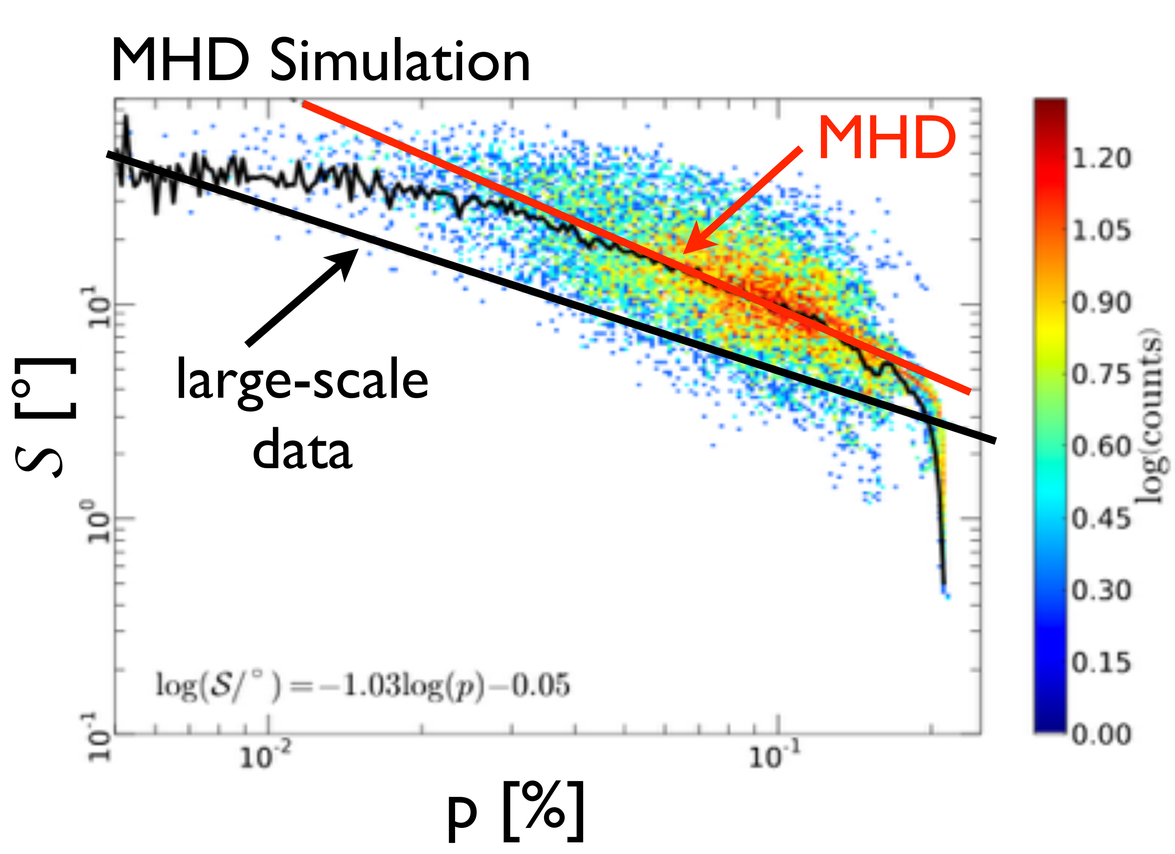
$$S(x,\delta) = \left(\frac{1}{N} \sum_{i=1}^{N} (\Delta\psi_{xi})^2 \right)^{1/2}$$

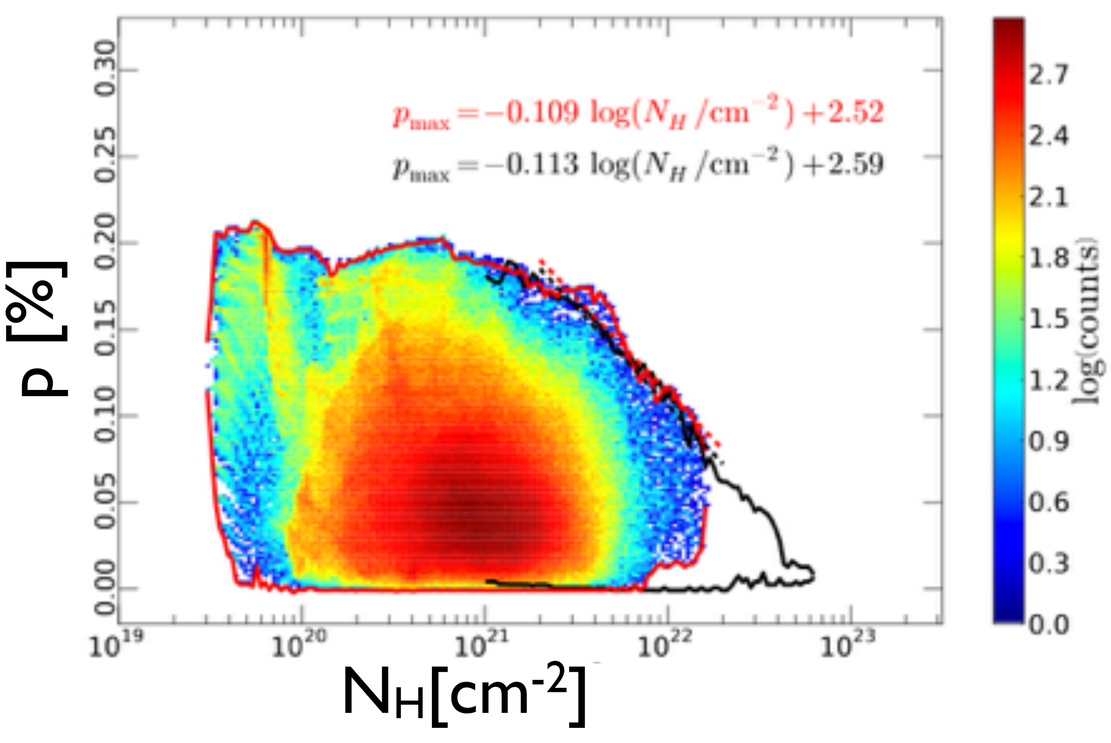


- Filamentary (Spaghetti) regions of high polarization rotation (!!)
- Correlate with low polarization
- No direct link with intensity structures

Comparison to MHD simulations







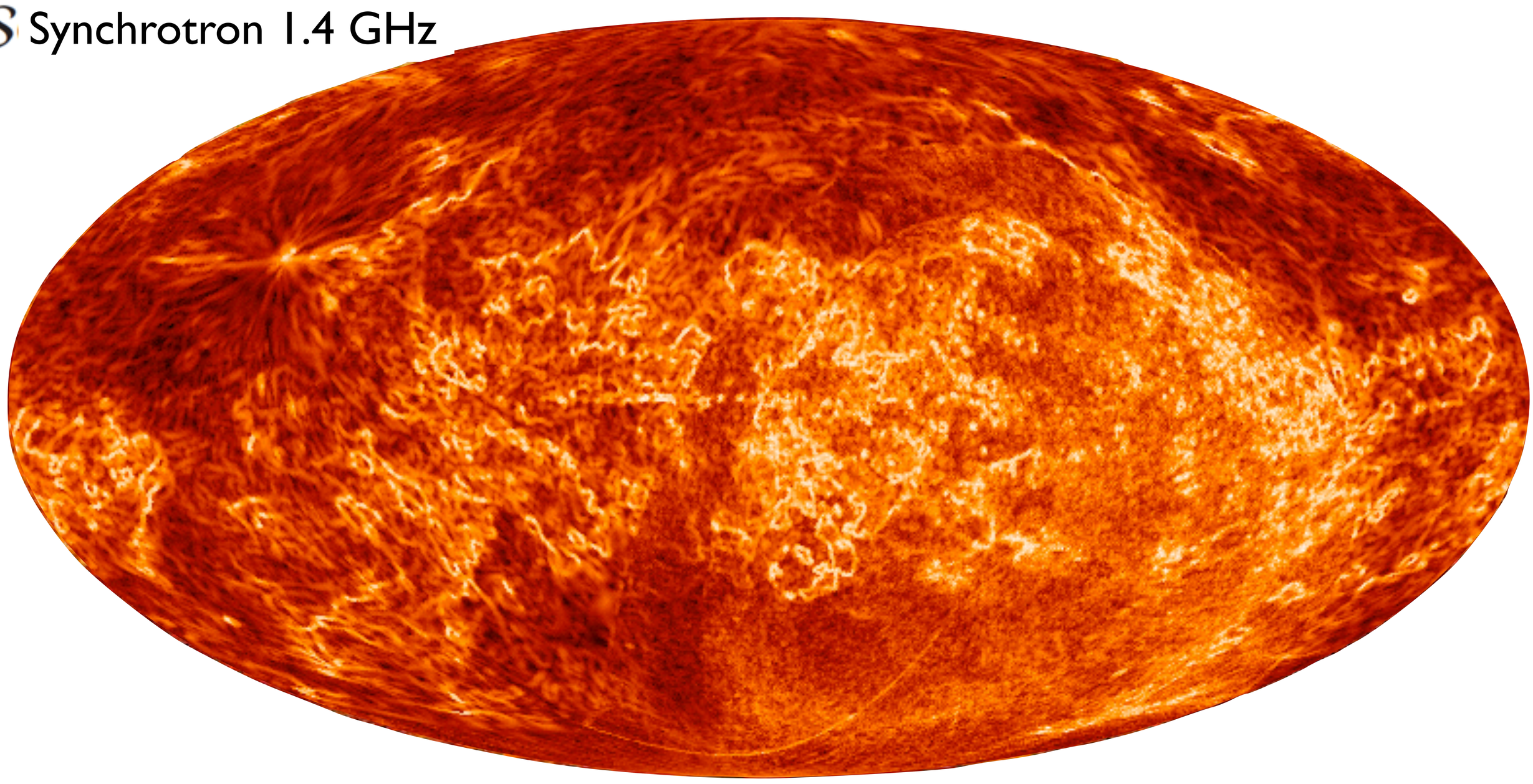
- Similar S(p) in MHD simulations
- Similar $p_{max}(N_H)$ in MHD simulations

Planck intermediate results. XX.

See talk by F. Levrier

Angle Dispersion Function

S Synchrotron 1.4 GHz

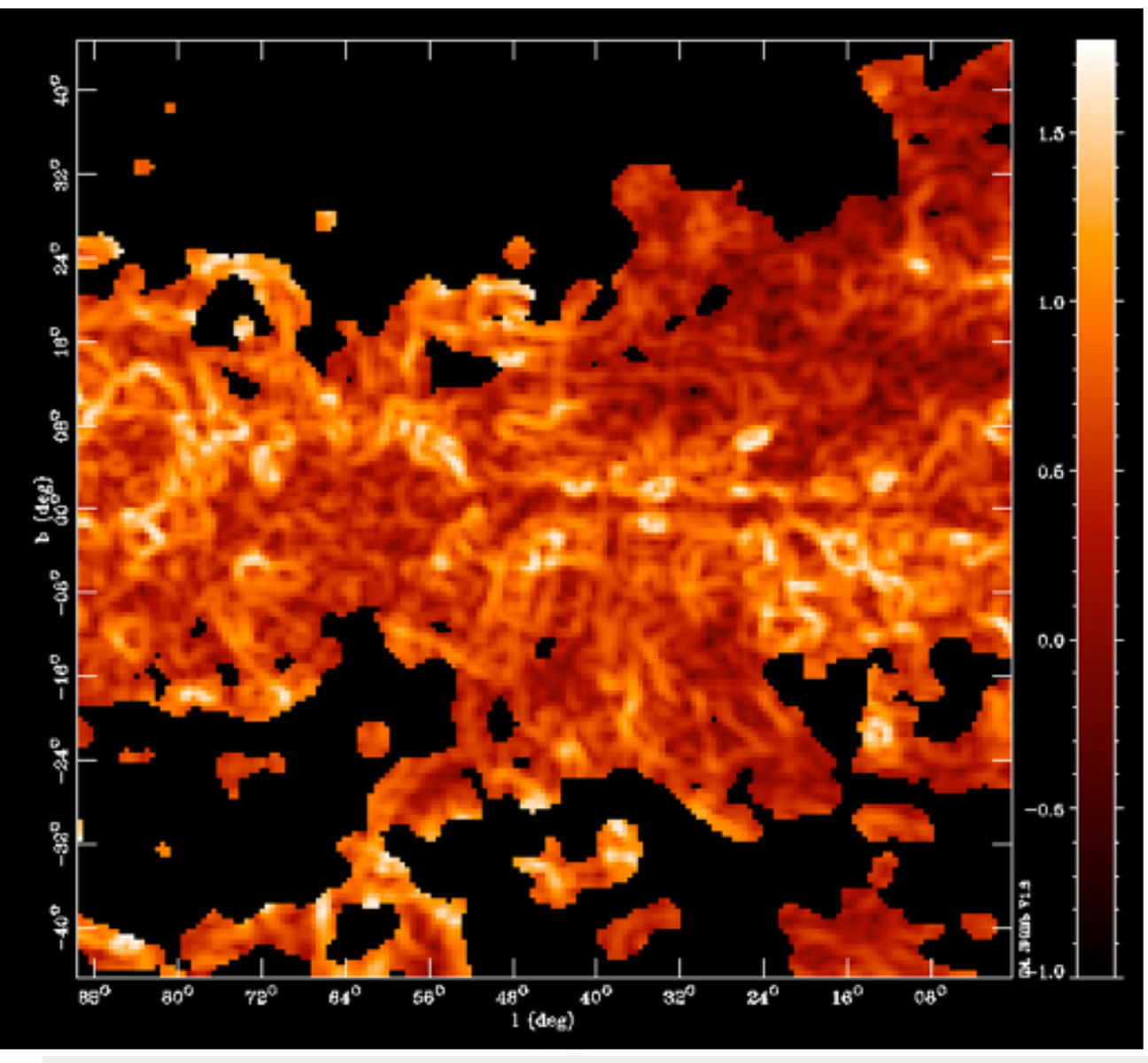


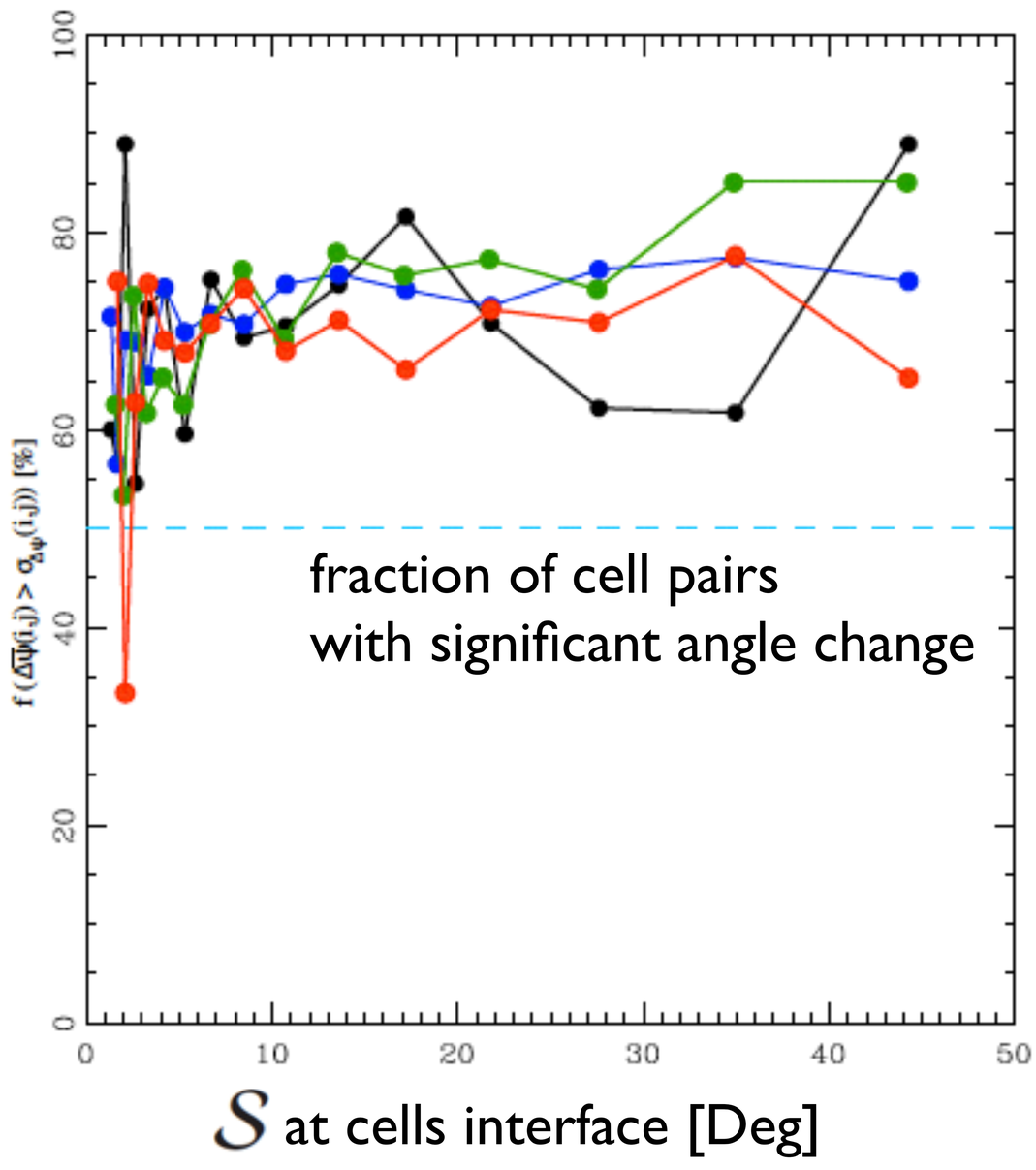
Synchrotron data (Reich 82, Reich & Reich 86) shows similar structures
These structures also correspond to low p (depolarization canals)
Those are likely due to Faraday rotation (not present at 353 GHz)
The structures in the dust and synchrotron S do not match in positions

Planck intermediate results. XIX.

Angle Dispersion Function

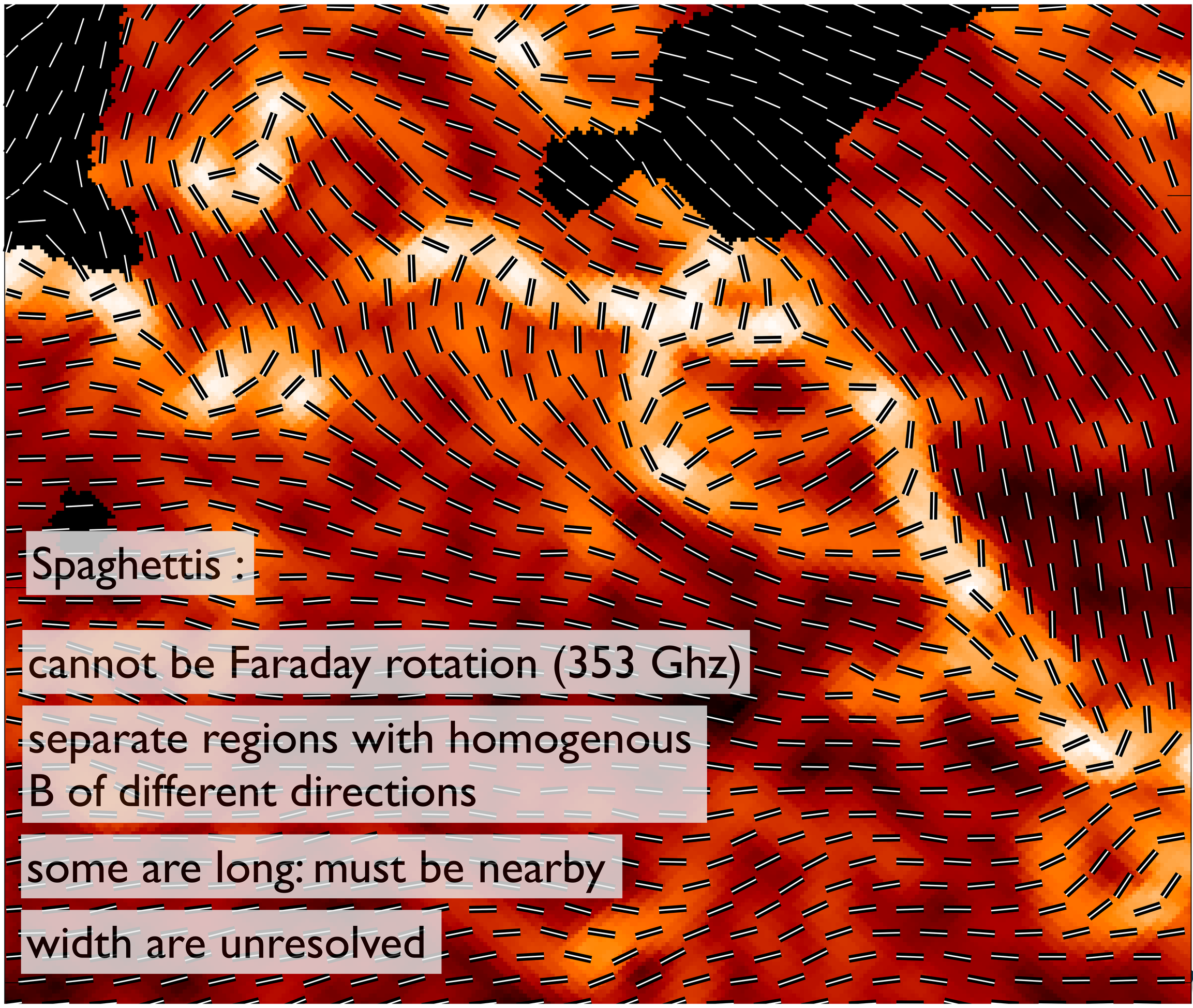
Cells separated using S (watershed algorithm)





Depolarization canals separate contiguous connex regions with homogenous B, but of different directions

Planck intermediate results. XIX.


Spaghettis :
cannot be Faraday rotation (353 Ghz)
separate regions with homogenous
B of different directions
some are long: must be nearby
width are unresolved

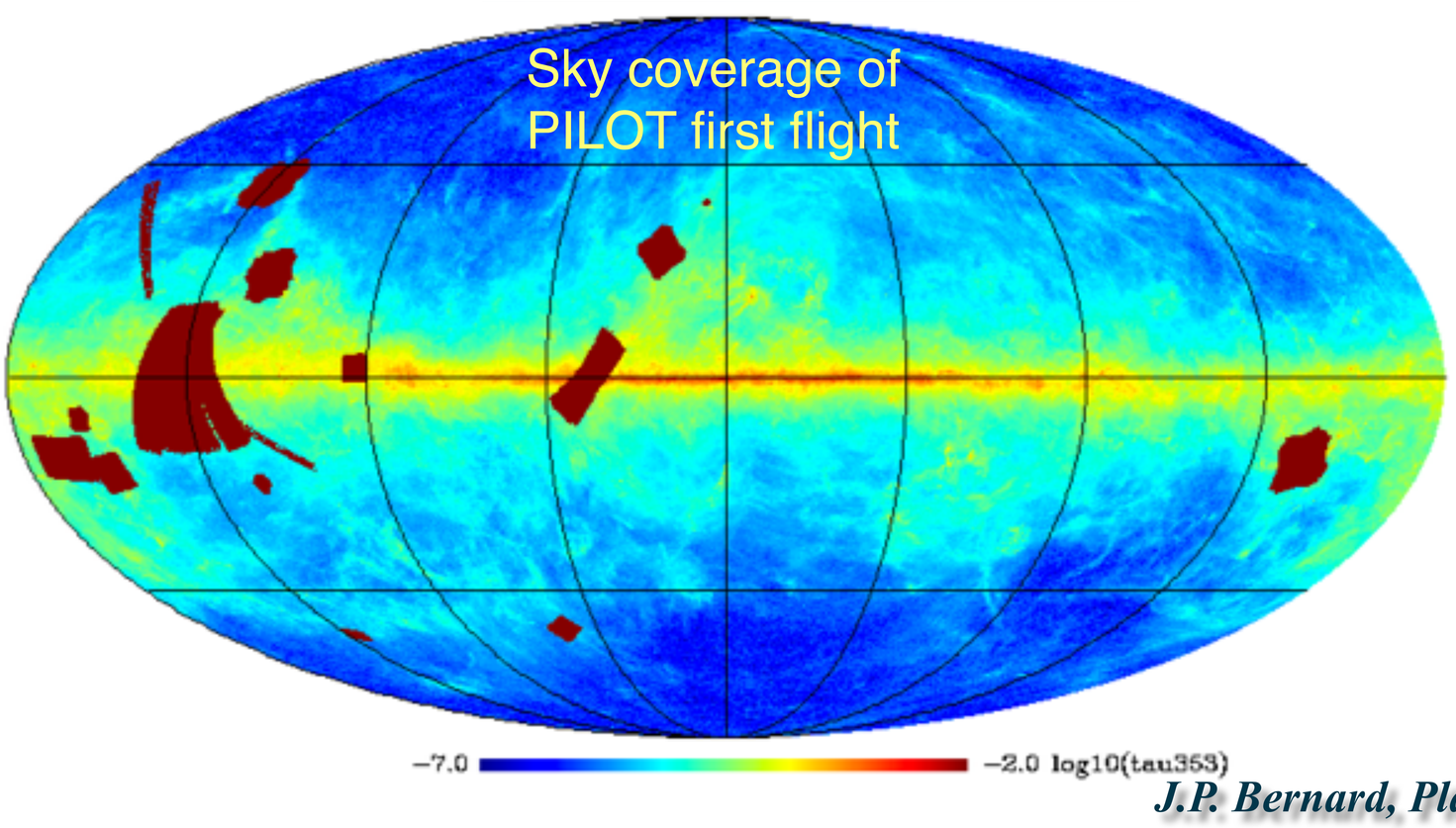
Future: polarization in MW

http://pilot.irap.omp.eu/

the PILOT experiment:
Measuring polarization at 240 μm
2048 bolometers
1.4’ resolution
Large FOV ~ 1°
Sensitivity to dust column density similar or exceeding that of Planck

PILOT 1st flight in Sept 2015, from Timmins Ontario, Canada.

PILOT 2nd flight April 2017, from Alice Springs, Australia.



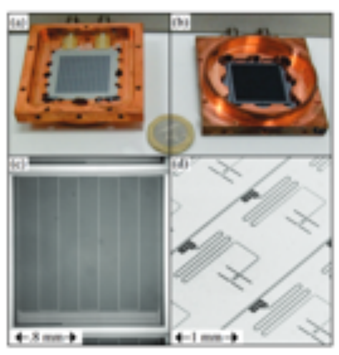
Observing plan includes
- MW regions (Fan, CygOB7, inner MW)
- Nearby star forming regions (Taurus, Orion)
- Cold cores (e.g. L183, California neb.)
- Deep fields (Polaris).

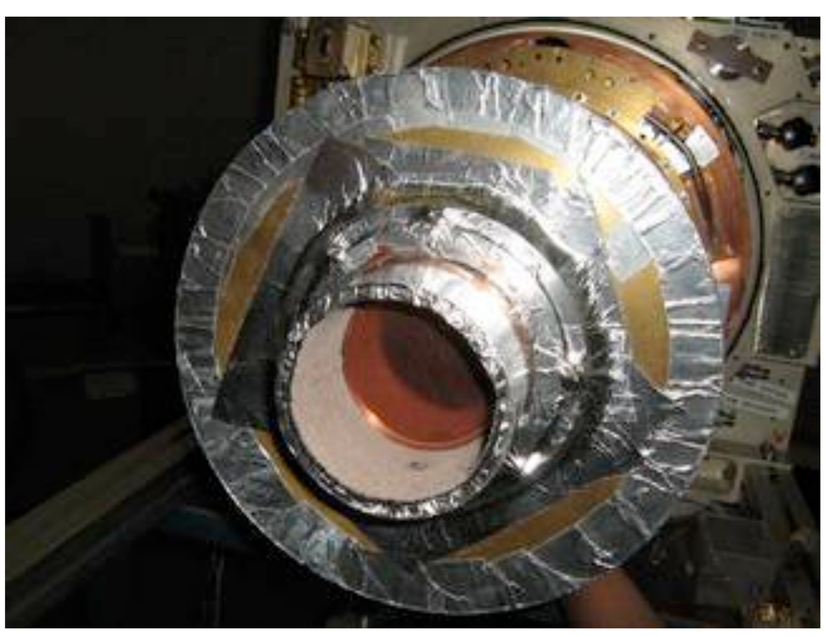
Future balloon experiments for polarization measurements of CMB foreground under development in the US and Europe

Future: polarization in external galaxies

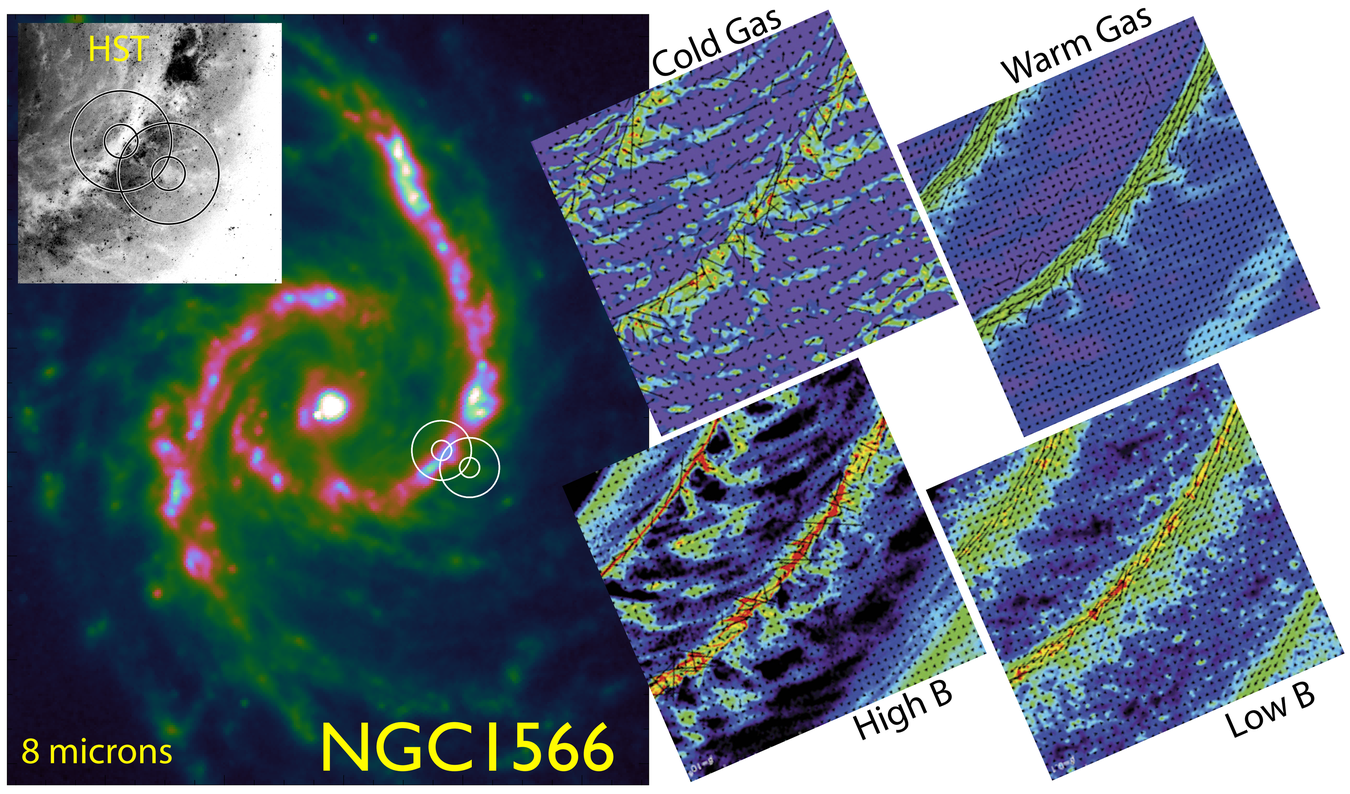
NIKA2 on IRAM 30m

Polarization at 1 and 2 mm
KIDS detectors
Resn: 12”





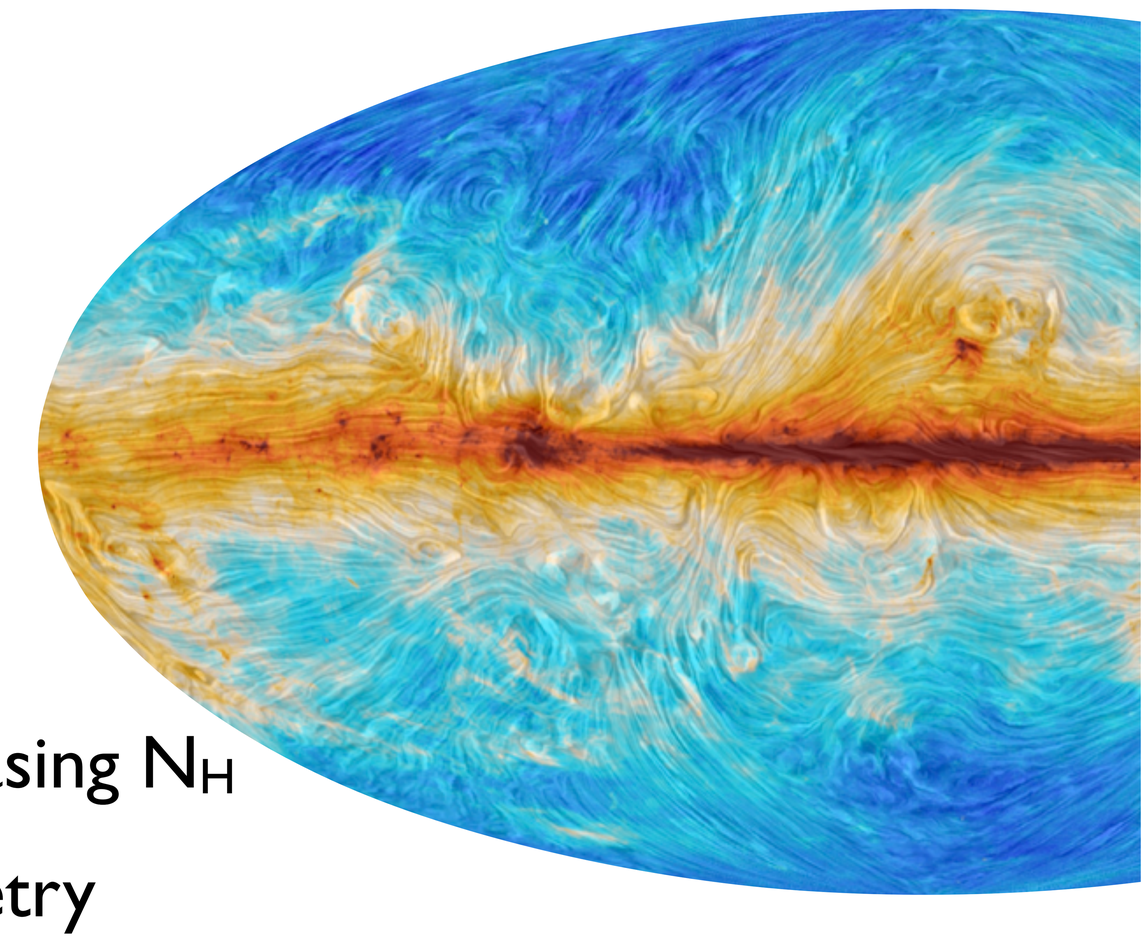
ALMA is starting to get polarization data



e.g. ALMA accepted Cycle 3 (PI Hughes):

2 fields (arm, interarm spur)
350 GHz (Band 7)
Resn: 1.4” (60pc)
Usable FoV: 5.7” (250pc)
grand-design spiral NGC1566
distance 9 Mpc

Conclusions



- Planck is providing completely new all-sky information on galactic B field

- Unlike Synchrotron, dust polarization traces B in star forming regions

- ISM filaments generally sensitive to B direction

- p as high as 20% but decreases with increasing N_H

- Variations of p largely due to B field geometry

- Spaghetti structures in B field geometry remain to be understood

- The Analysis is only at a start

The Planck polarization Data is released …

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

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