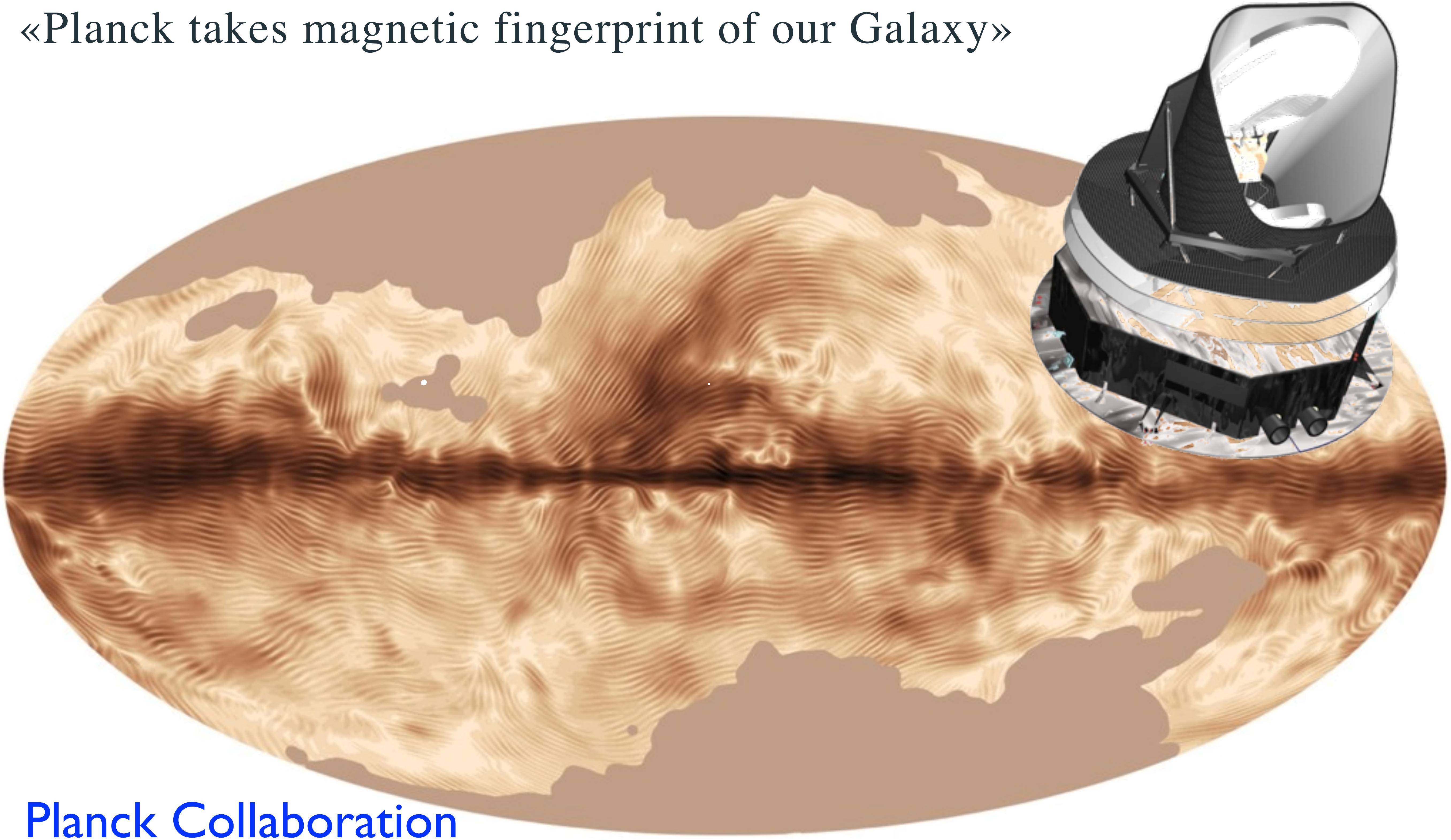
The Thermal Dust Polarization as Observed with Planck

«Planck takes magnetic fingerprint of our Galaxy»



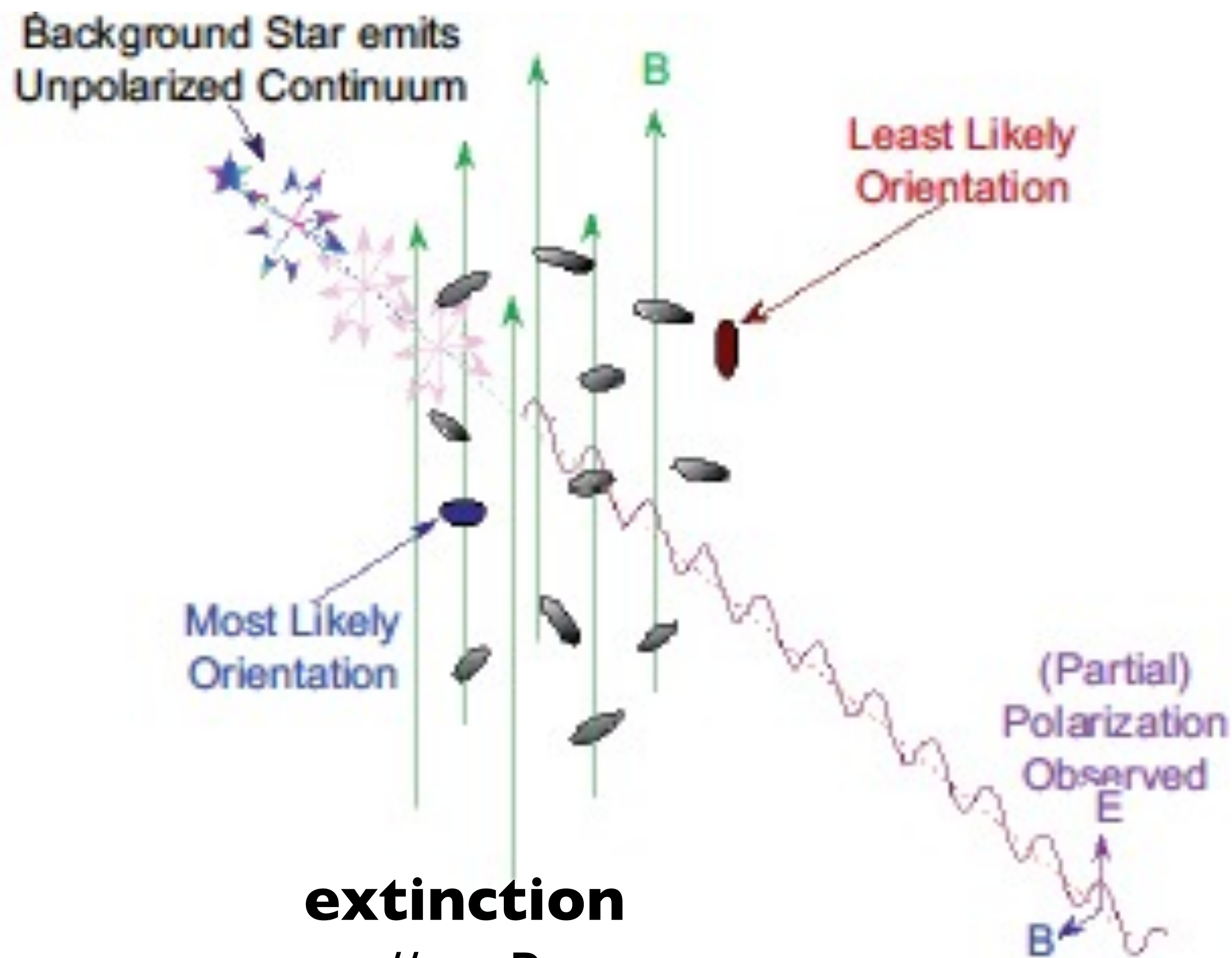
Planck Collaboration

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

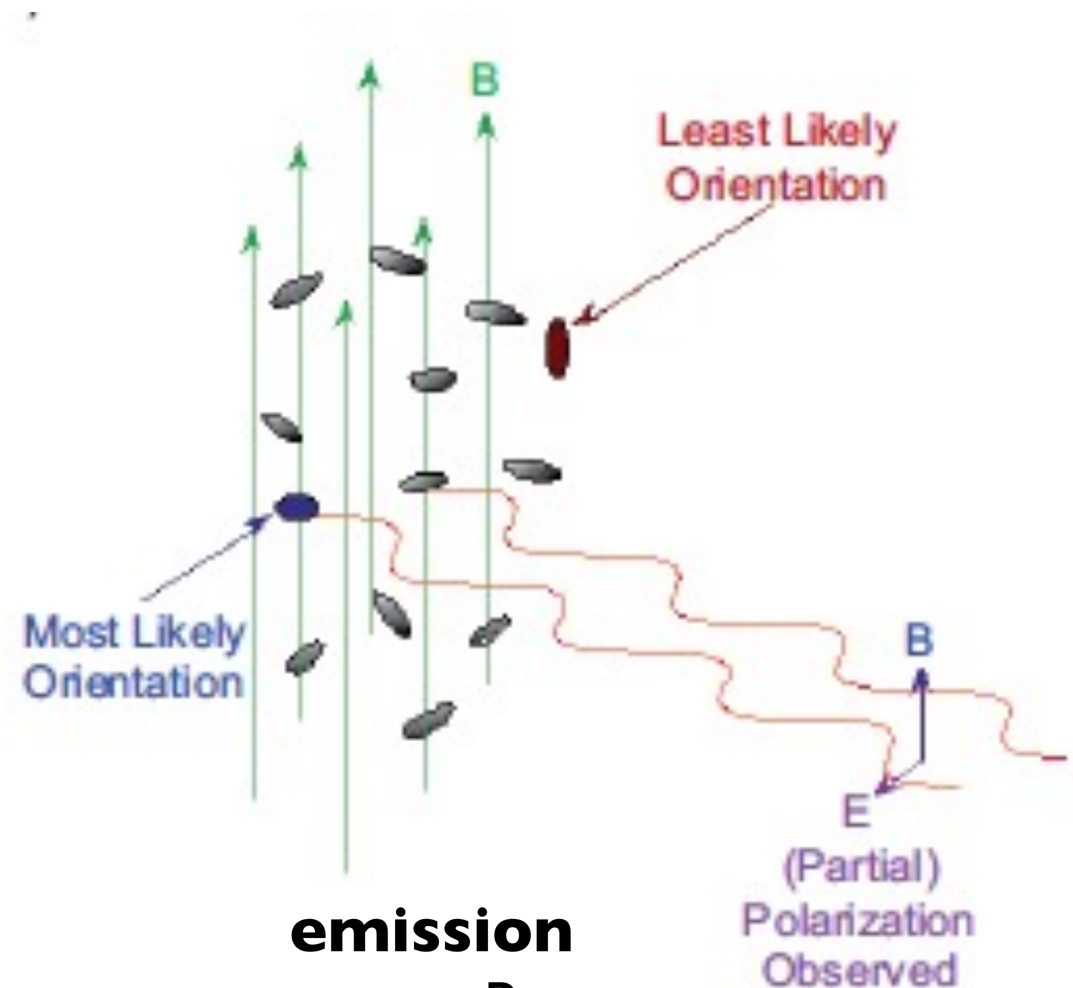
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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.

Dust Polarization

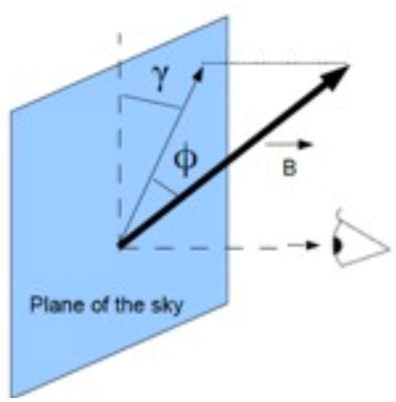


extinction
// to B



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)

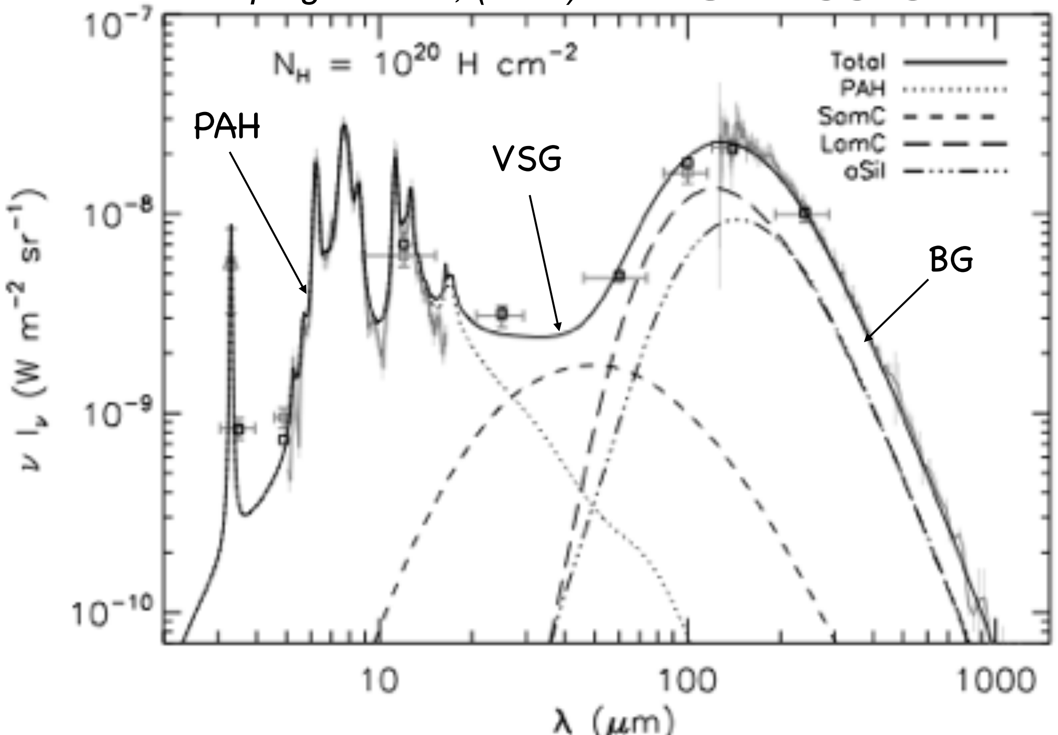


$$P = \sqrt{(Q^2+U^2)} \propto \cos^2\phi$$

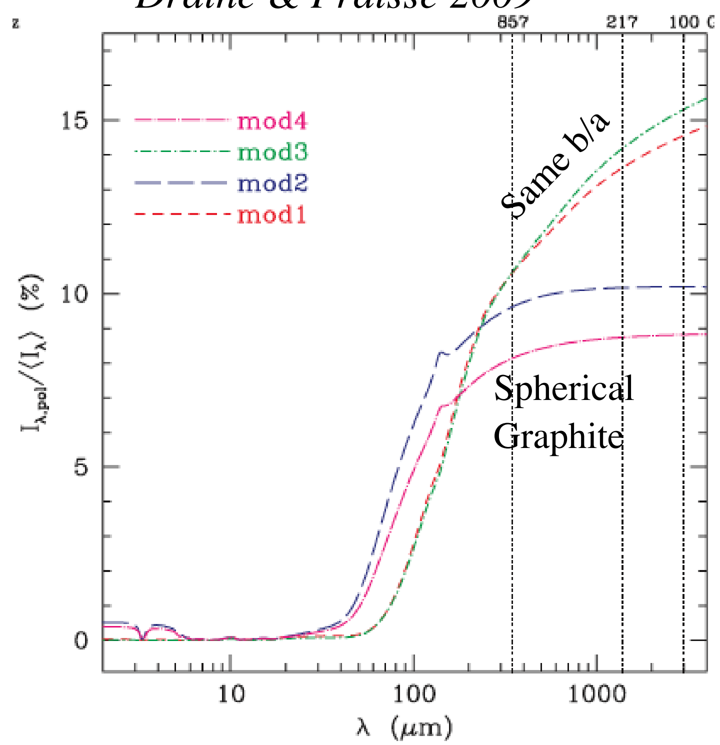
Stein 1966, Andersson 2012, Draine & Fraisse 2009, Hoang & Lazarian 2008, Martin 1975, 2007

Dust Polarization

Compiegne et al., (2011) **emission**

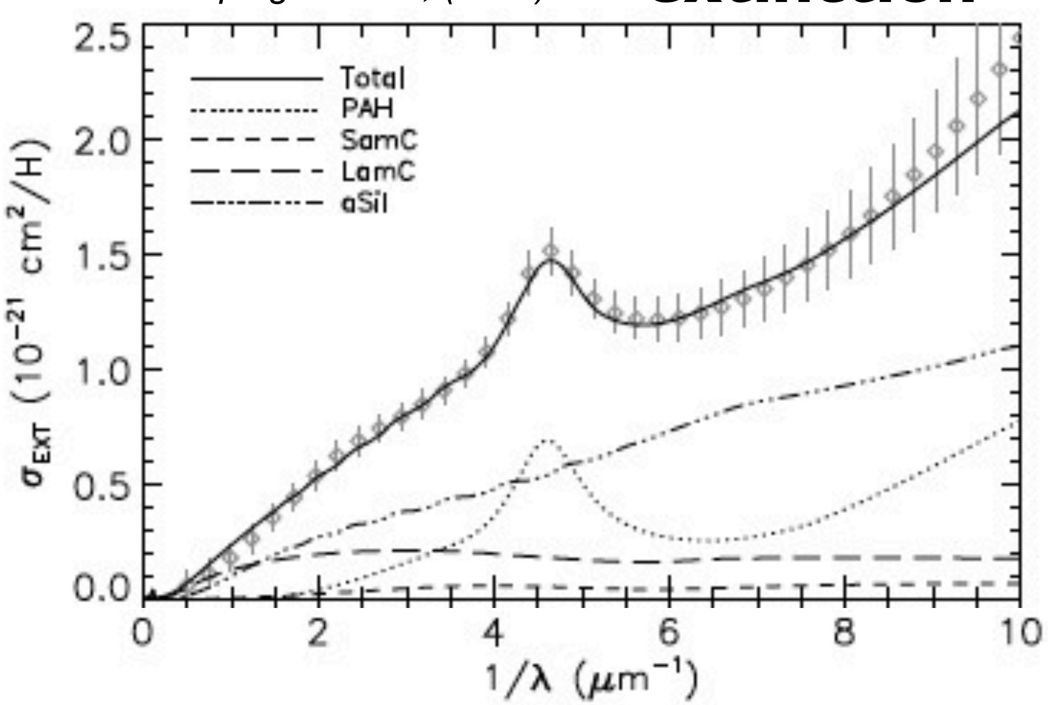


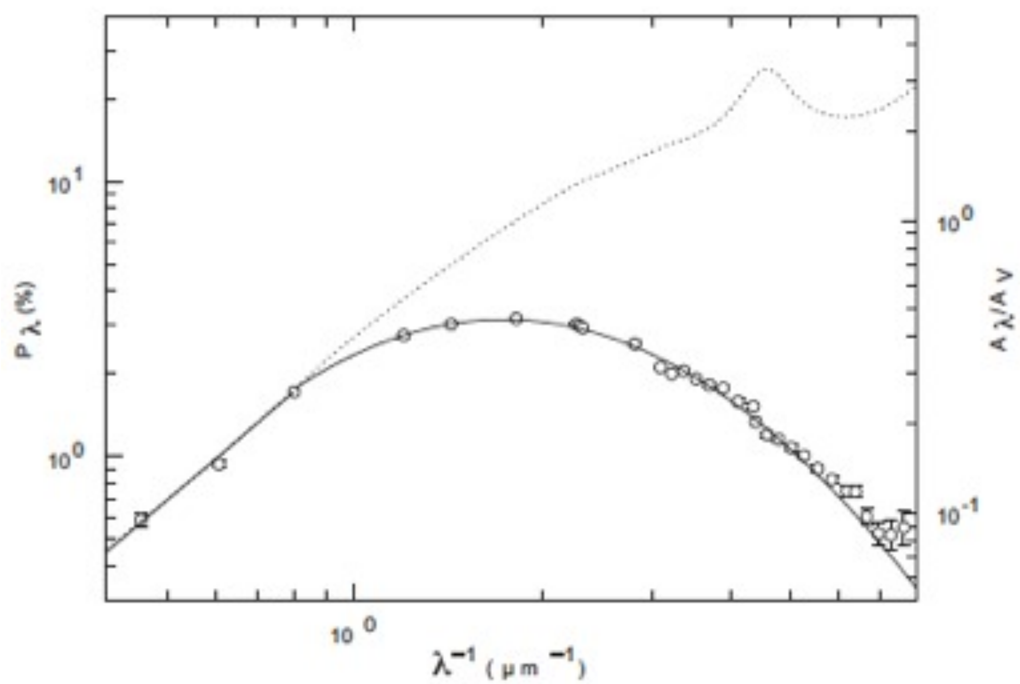
Draine & Fraisse 2009



polarization in emission is predicted ~10-15%

Compiegne et al., (2011) **extinction**





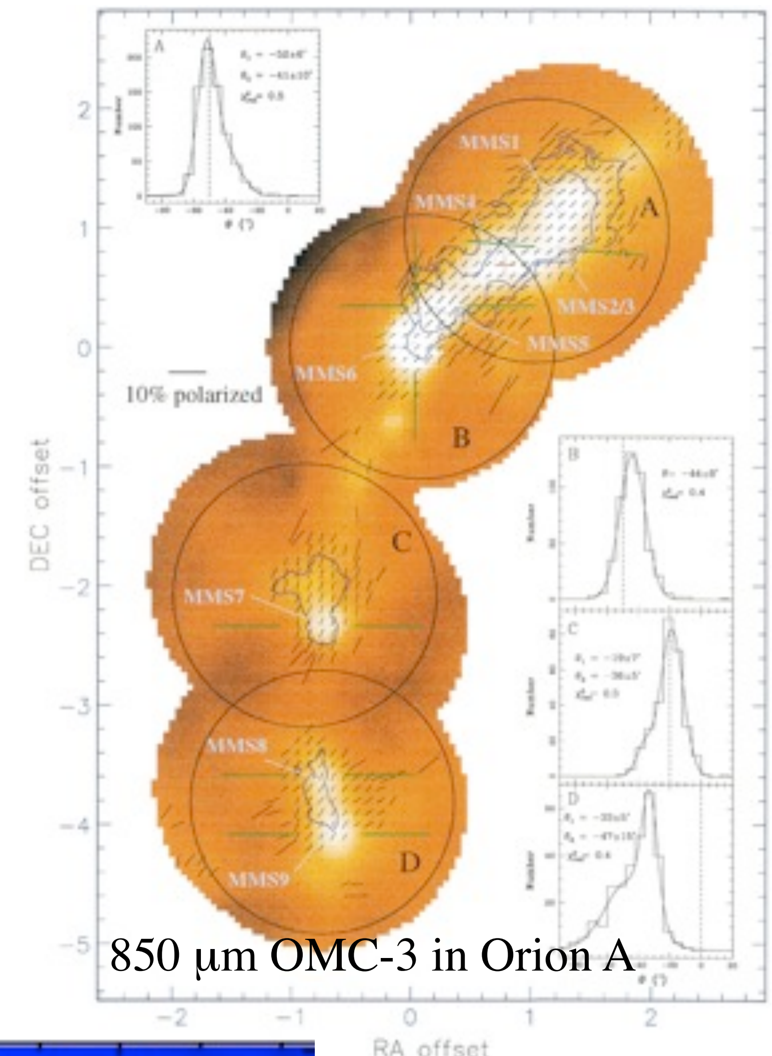
Small grains extinction not polarized:
likely not aligned

Various possible models lead to different predictions in polarization

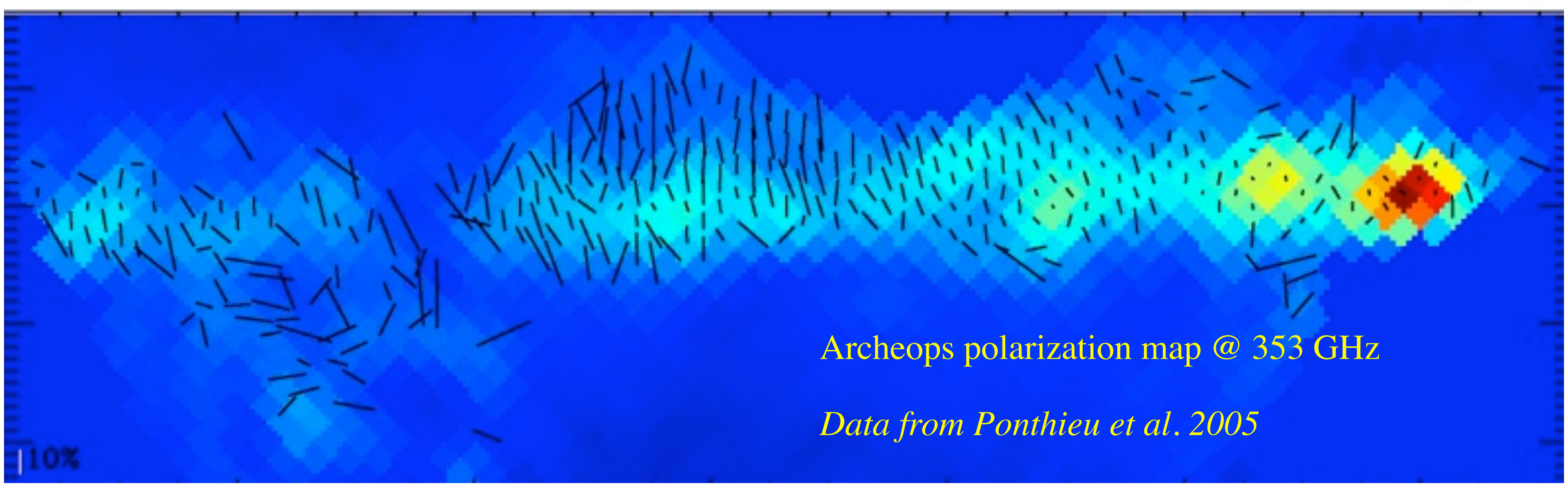
Variations of polarization fraction with frequency will help constrain dust models

Before Planck: emission

- Ground submm measurements (restricted to bright regions) indicate low p values (a few %)
- Archeops claimed 10-15% in the plane (2nd Galactic Quadrant)



850 µm OMC-3 in Orion A

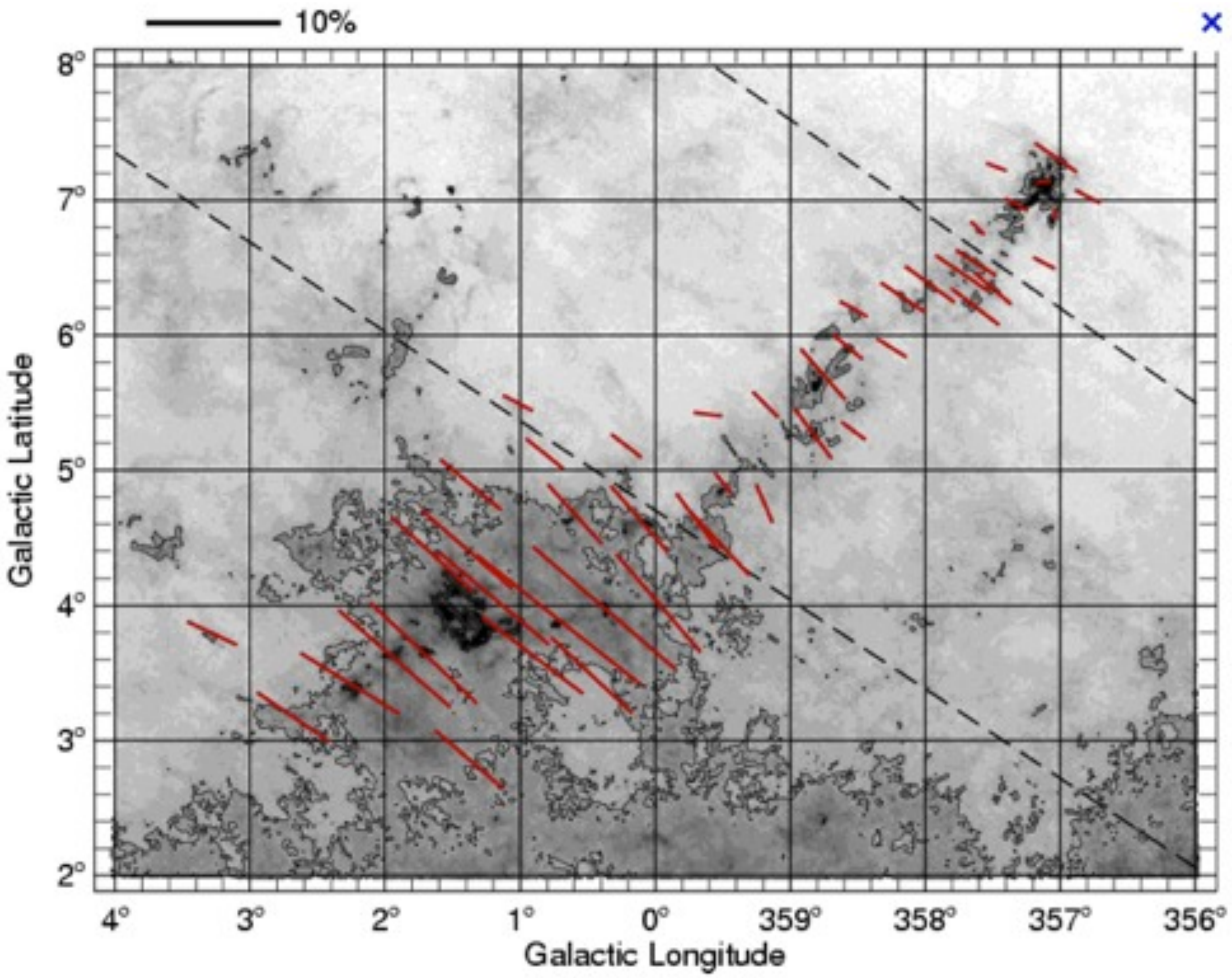


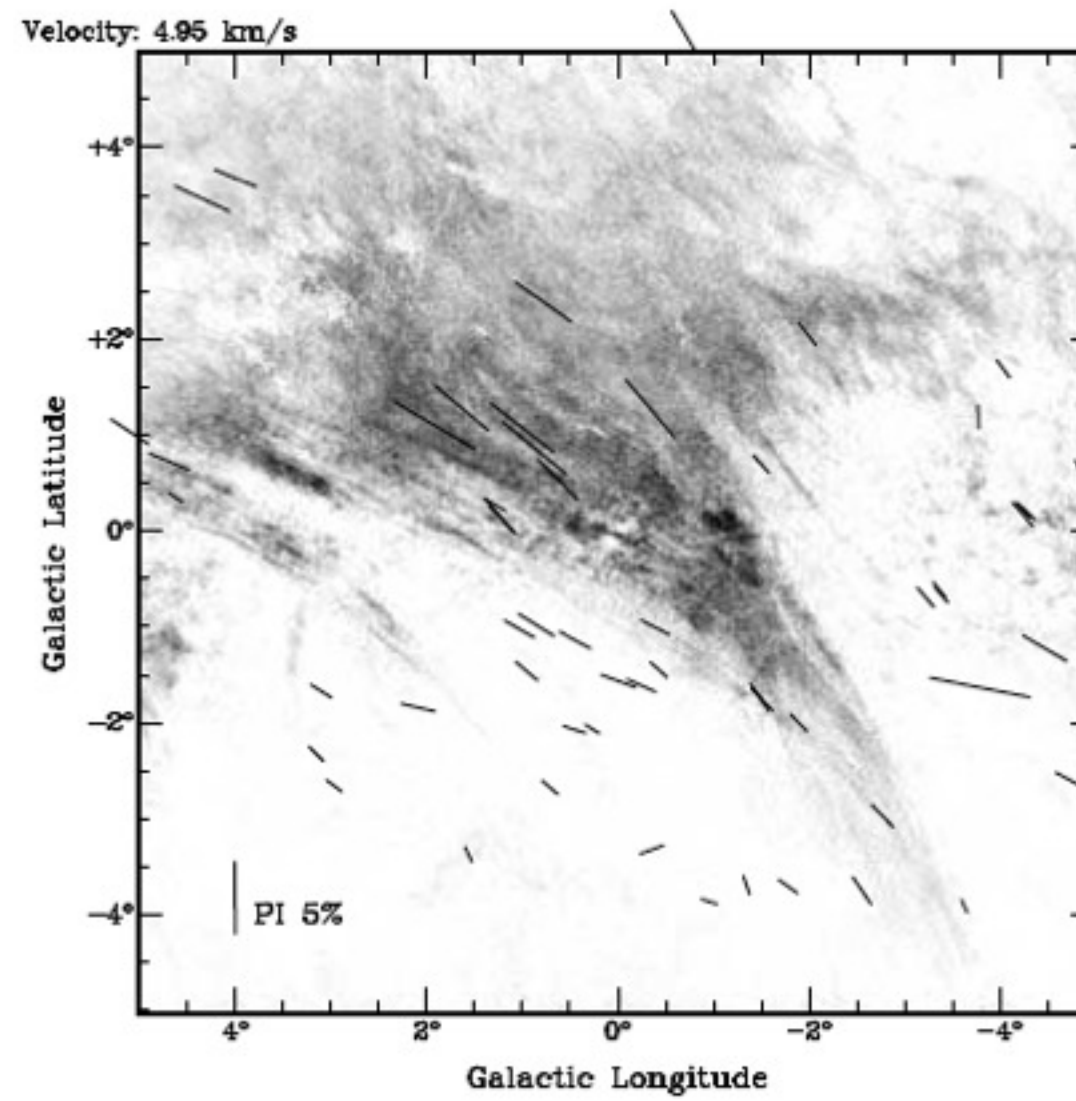
Archeops polarization map @ 353 GHz

Data from Ponthieu et al. 2005

Before Planck: Extinction

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





... although the two examples shown here (only a few degrees apart on the sky) give opposite filament orientation w.r.t. B field

Dust vs Synchrotron

Similarities:

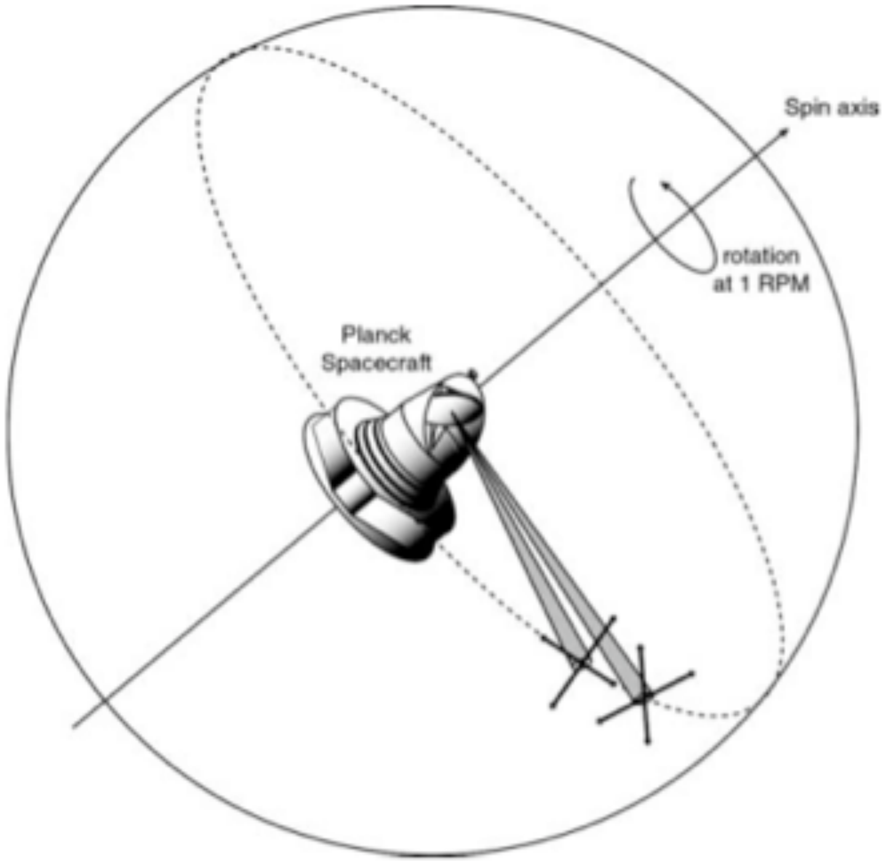
- Measure direction of the same component of the **B** field
- Same beam and LOS depolarization effects

Differences:

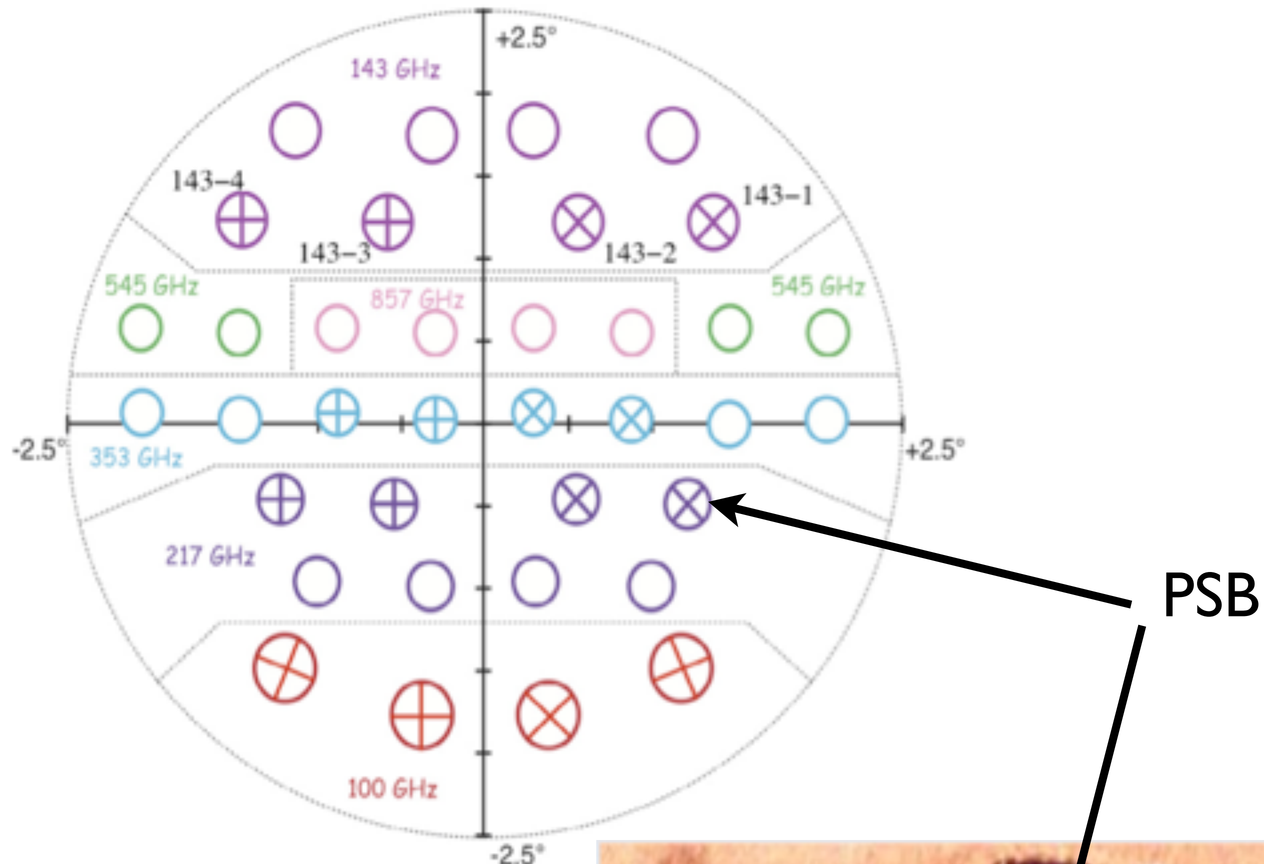
- At 353 GHz, Faraday rotation is totally negligible !
- Planck is all sky and measures all scales :
no filtering of I,Q,U like with interferometers
- Dust is distributed in the thin disk of the MW
  (comparable to neutral HI + molecular)
- Dust polarization mostly insensitive to |**B**|

How Planck measures polarization

Planck scanning the sky



Planck/HFI focal plane

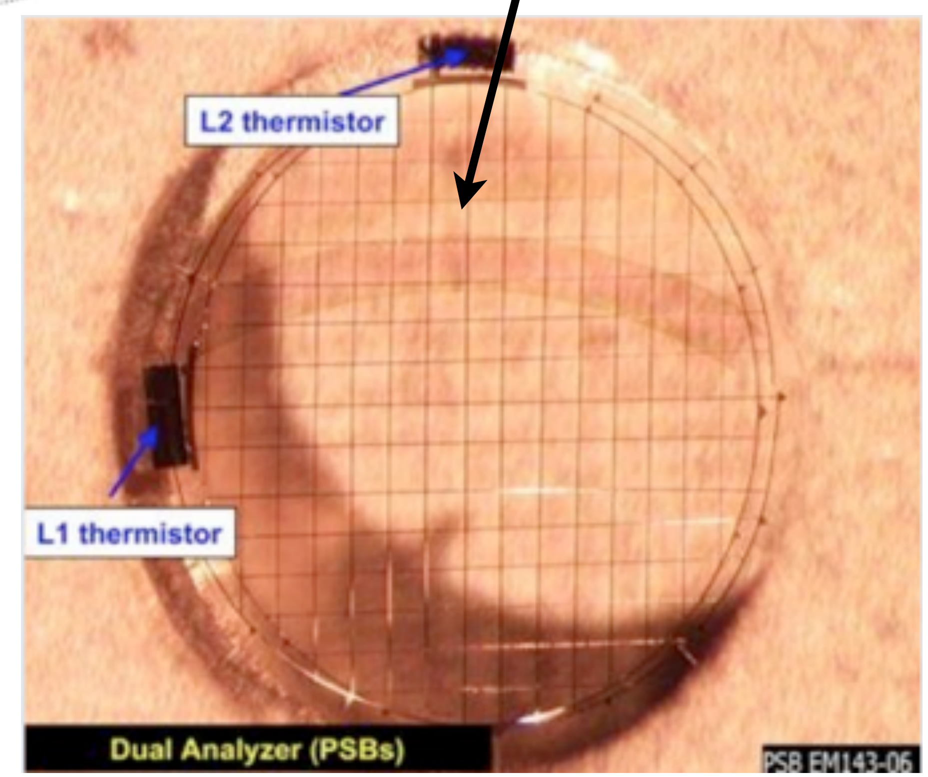


Combination of two pairs of PSB bolometers rotated by 45°
observing the same sky positions

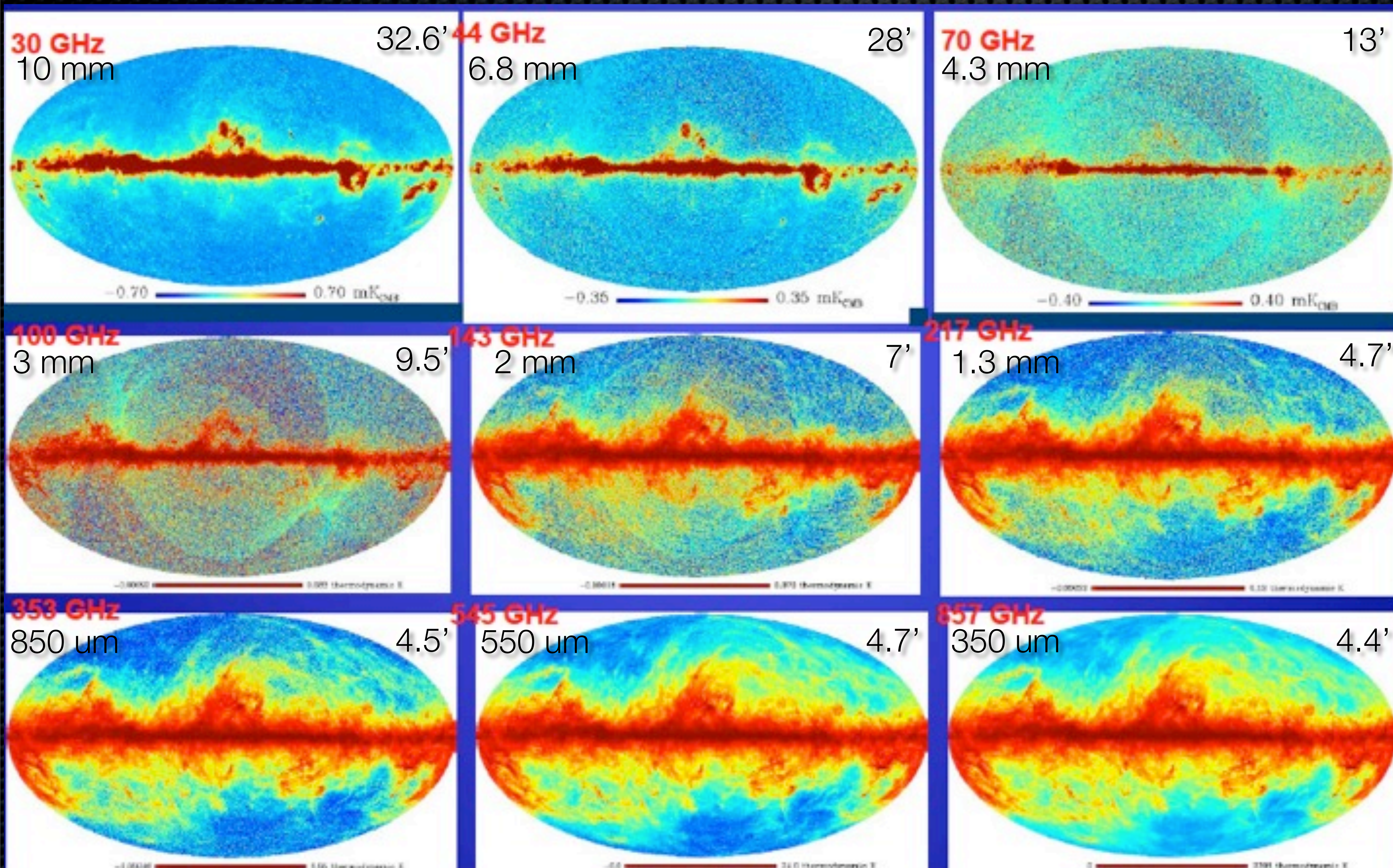
$$s_1 - s_2 = Q\ cos(2\alpha) + U\ sin(2\alpha)$$
$$s_3 - s_4 = Q\ sin(2\alpha) - U\ cos(2\alpha)$$

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

5 independent sky surveys



Planck Intensity maps



The first Planck papers in polarization

Published on arXiv since last May

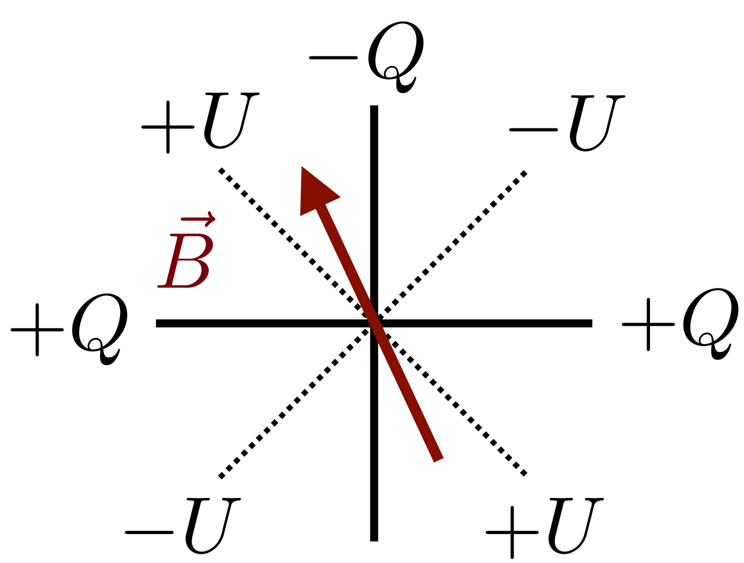
- **Planck Collaboration** ***Planck intermediate results. XIX.*** arXiv:astro-ph 1405.0871
An overview of the polarized thermal emission from Galactic dust
- **Planck Collaboration** ***Planck intermediate results. XX.*** arXiv:astro-ph 1405.0872
Comparison of polarized thermal emission from Galactic dust with simulations of MHD turbulence
- **Planck Collaboration** ***Planck intermediate results. XXI.*** arXiv:astro-ph 1405.0873
Comparison of polarized thermal emission from Galactic dust at 353 GHz with optical interstellar polarization
- **Planck Collaboration** ***Planck intermediate results. XXII.*** arXiv:astro-ph 1405.0874
Frequency dependence of thermal emission from Galactic dust in intensity and polarization

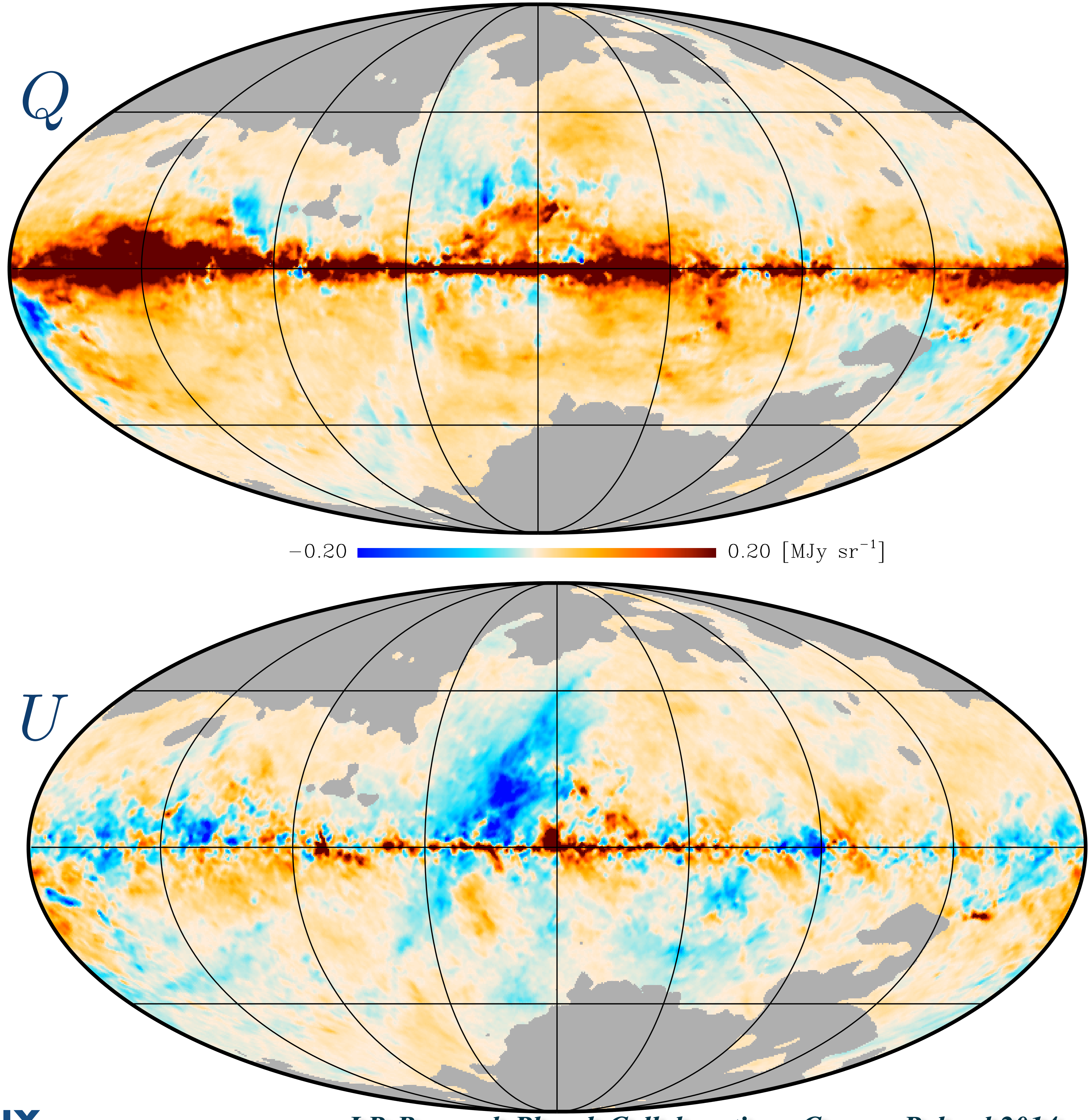
- **Planck Collaboration** ***Planck intermediate results. XXX.*** arXiv:astro-ph 1409.5738
The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes
- **Planck Collaboration** ***Planck intermediate results. XXXII.*** arXiv:astro-ph 1409.6728
The relative orientation between the magnetic field and structures traced by interstellar dust

- **Montier et al.** arXiv:astro-ph 1406.6536
Polarization measurements analysis I: Impact of the full covariance matrix on polarization frcation and angle measurements
- **Montier et al.** arXiv:astro-ph 1407.0178
Polarization measurements analysis II: Best estimators of polarization fraction and angle

The Planck Polarization sky

353 GHz





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

Resolution 1°

Planck intermediate results. XIX.

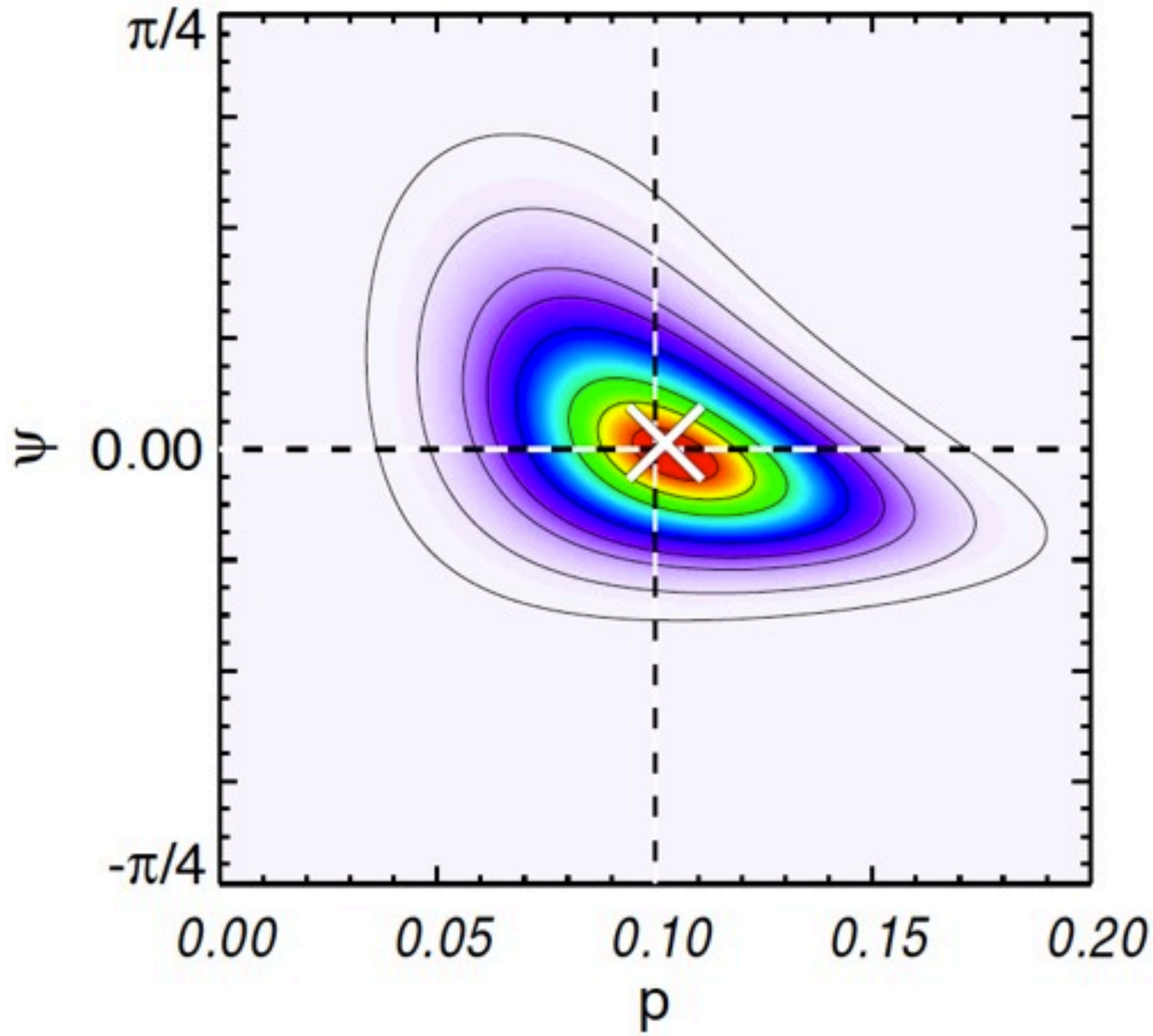
Noise and Bias

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

Bayesian inference in 3D
Using maximum likelihood
and the full noise covariance matrix

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

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



Montier et al. 2014a, 2014b

Noise and Bias

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

noise cov. matrix →

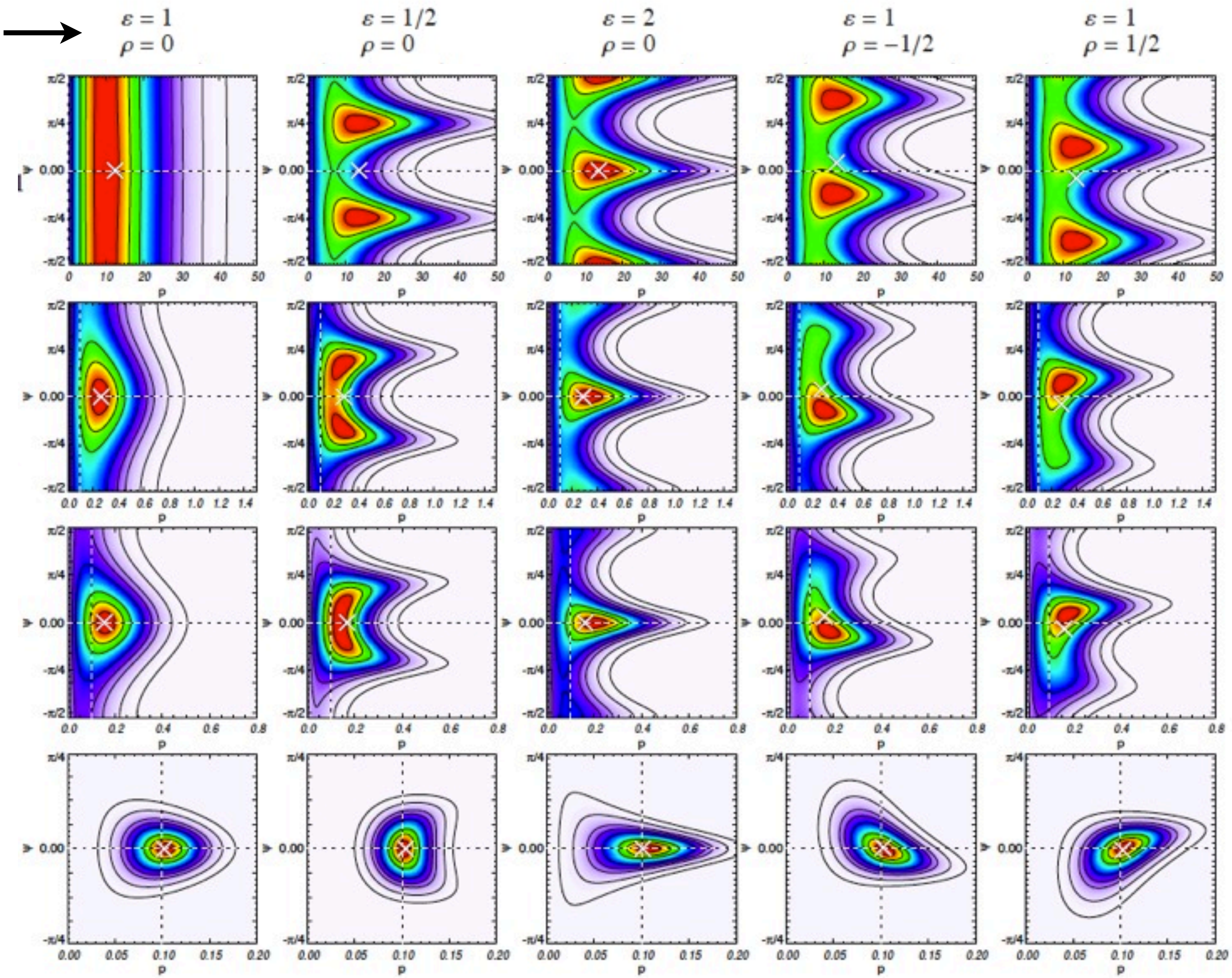
$p0/\sigma p$ ↓

0.01

0.5

1

5



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

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

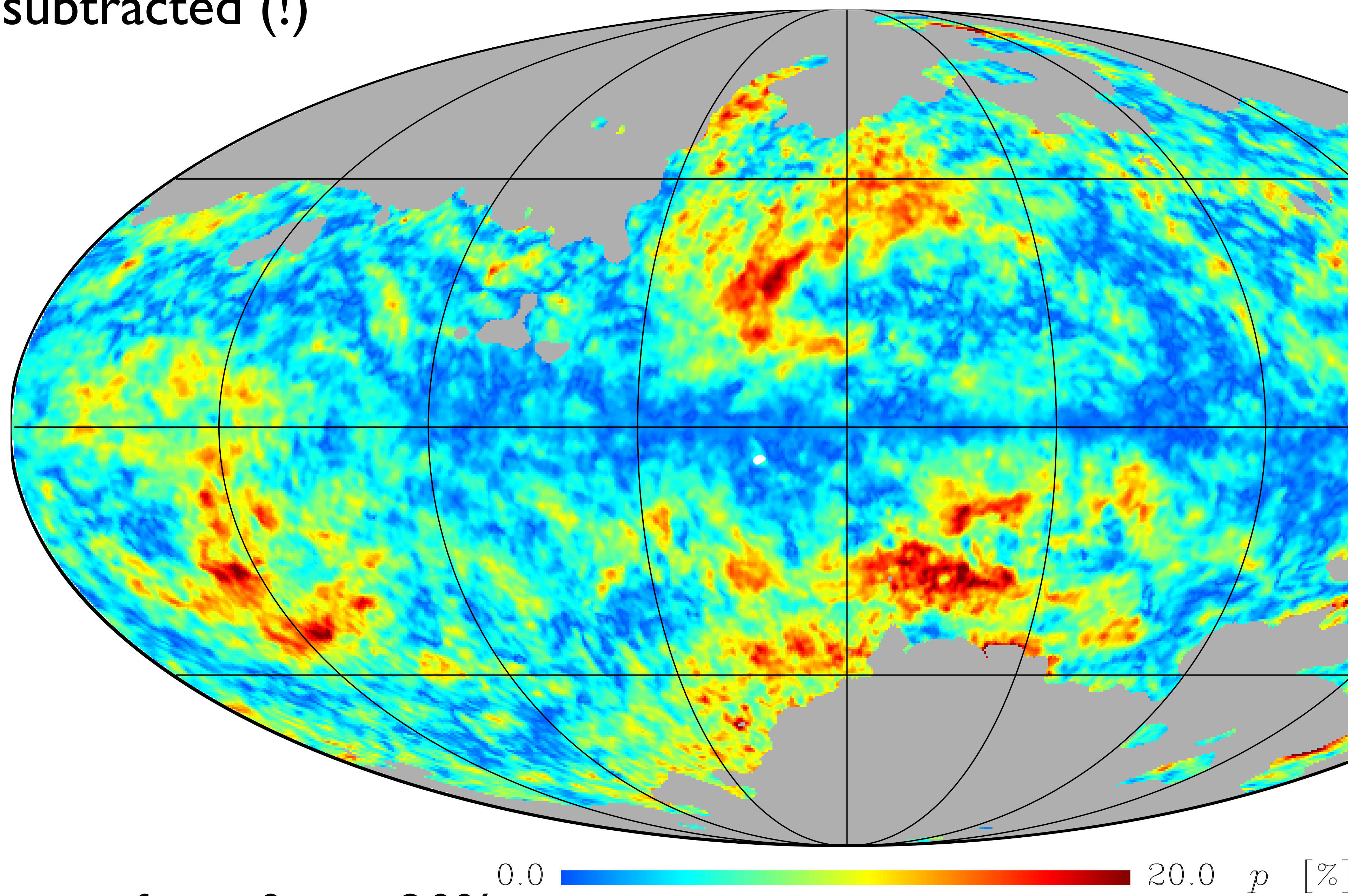
Montier et al. 2014a, 2014b

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

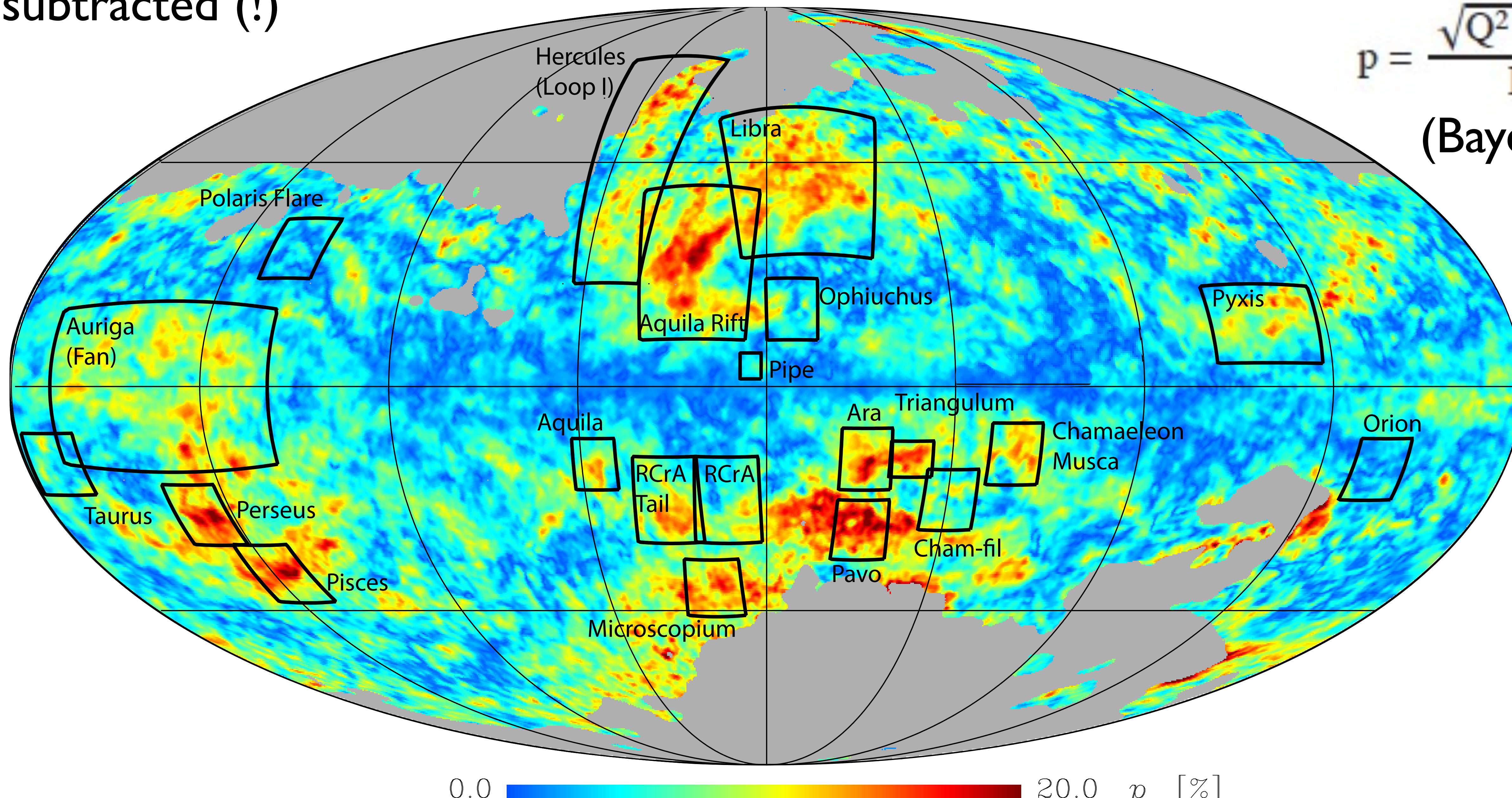
The sky looks different in polarization !!

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

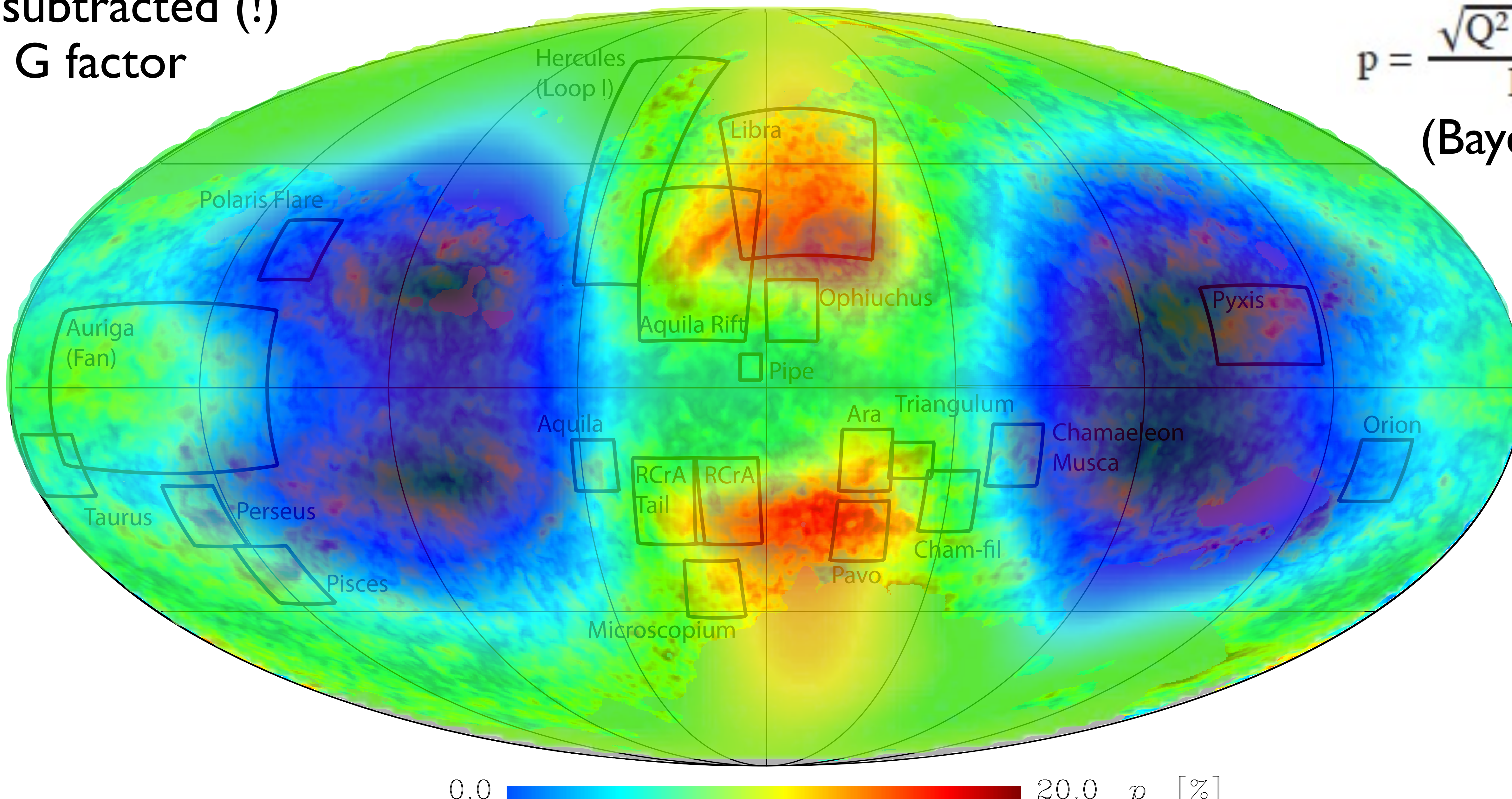
The sky looks different in polarization !!

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

CIB subtracted (!)
PSM G factor

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

(Bayesian)



p ranges from 0 to ~20%
Low p values in inner MW plane
Large p values in outer plane and intermediate latitudes
Large scale variations similar to MW B-field structure

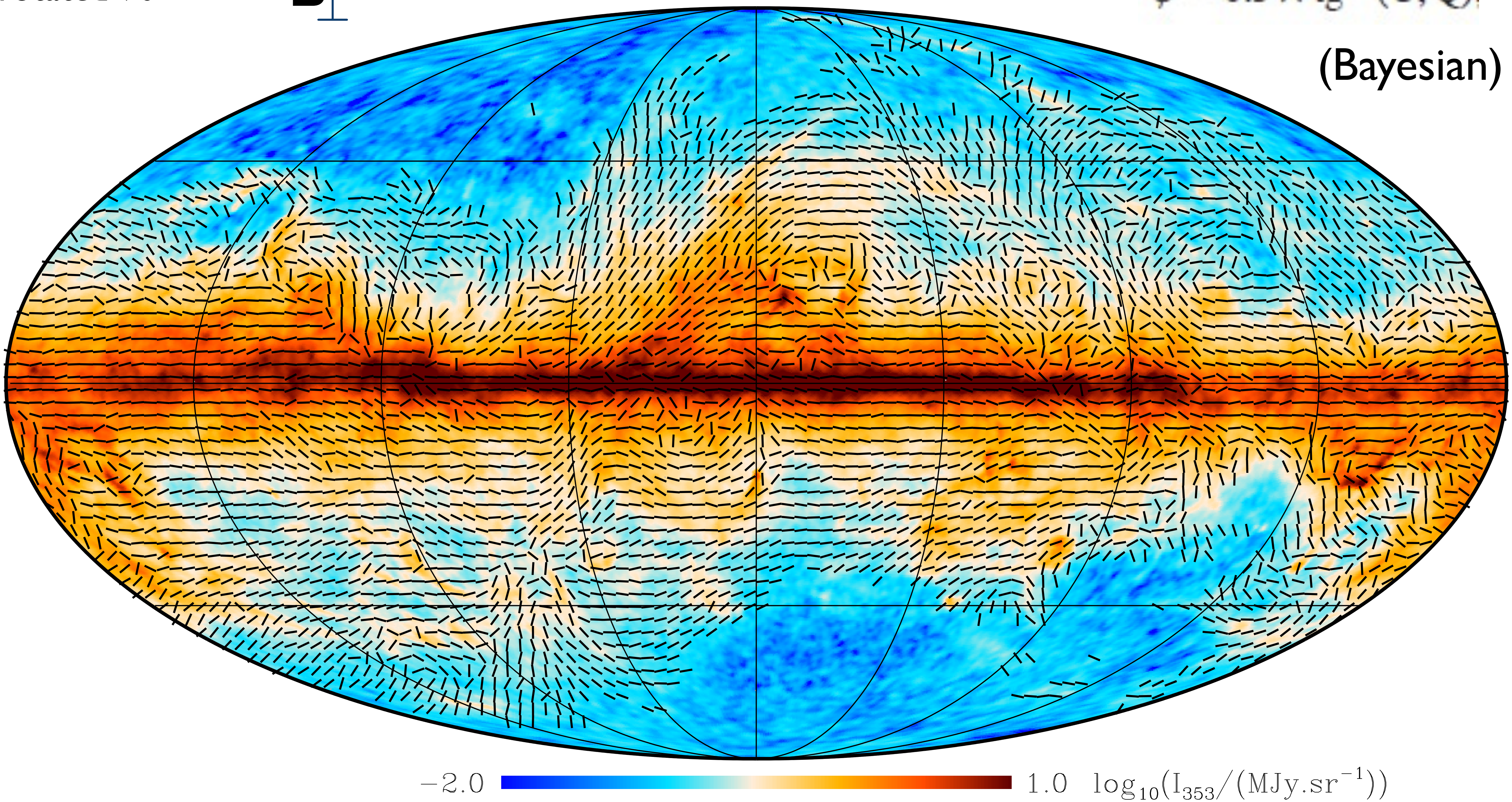
The sky looks different in polarization !!

Polarization angle

rotated 90° → $\mathbf{B}_\perp$

$\psi = 0.5 \times tg^{-1}(U,Q)$

(Bayesian)



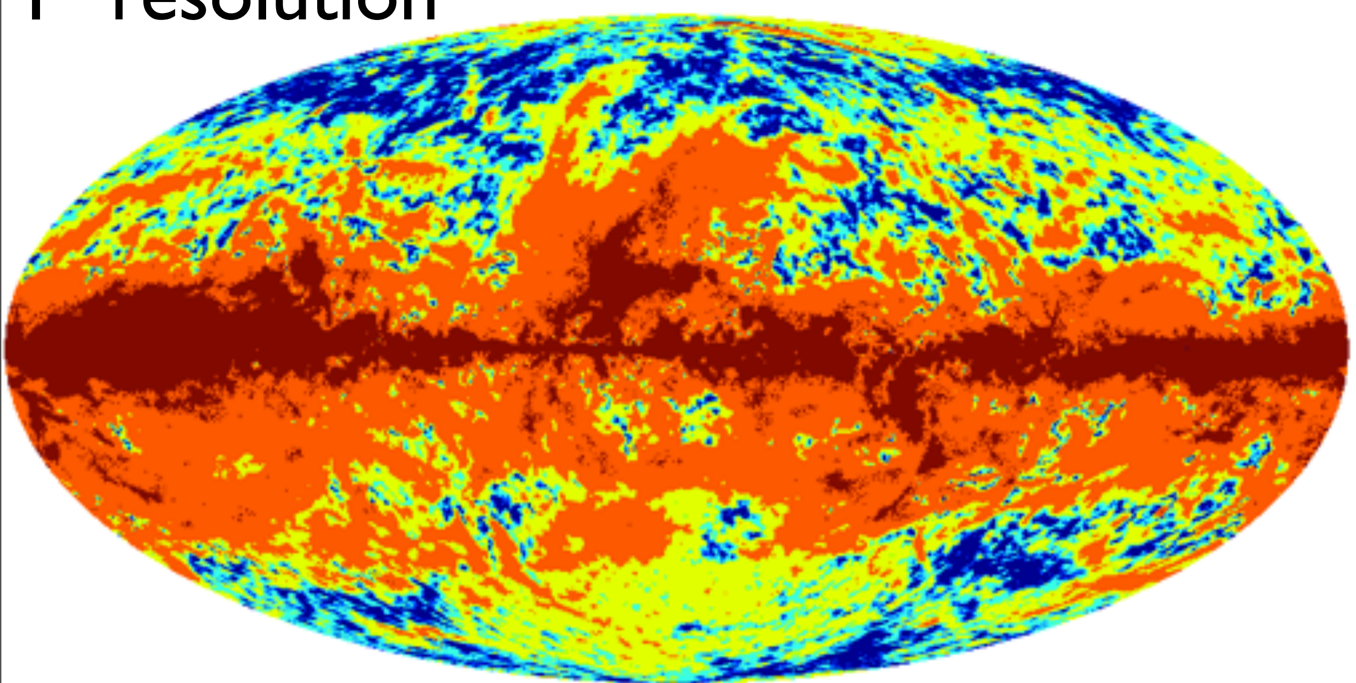
Color: Intensity at 353 GHz

Lines: Direction of magnetic field as projected on the sky. Normalized length.

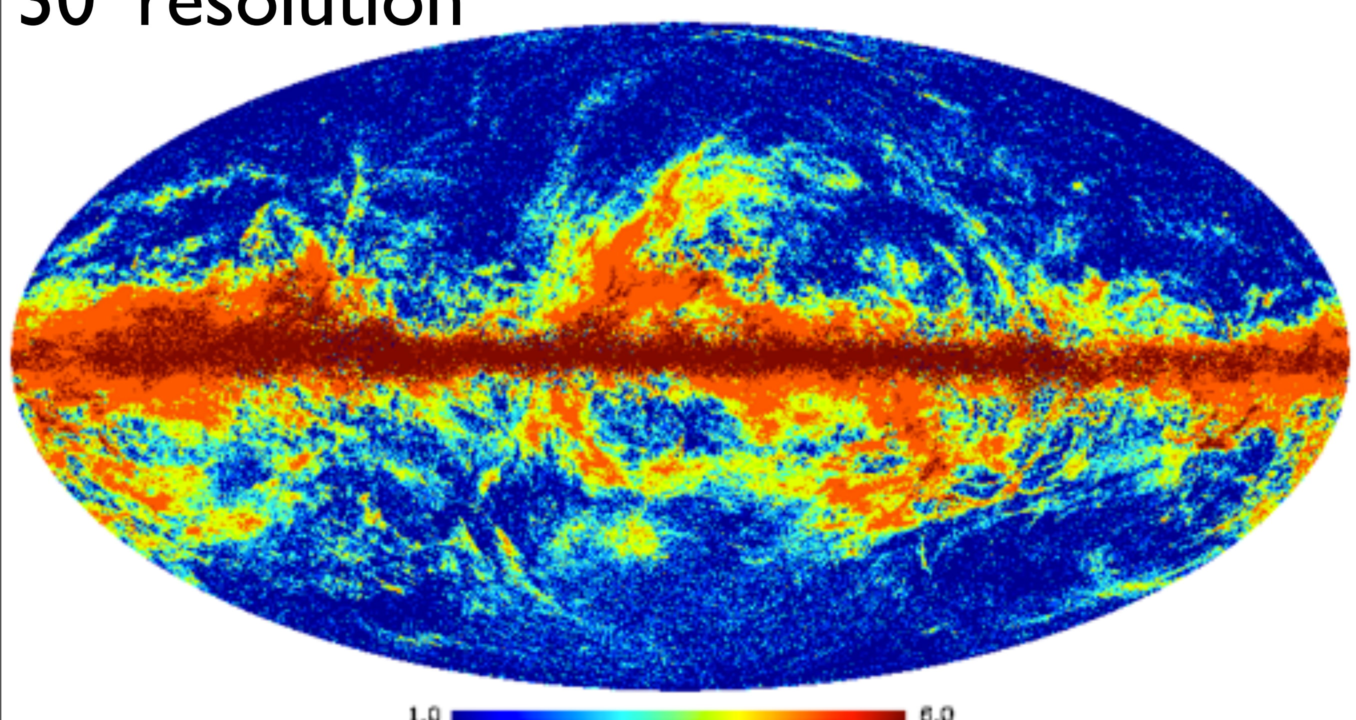
Uncertainties

maps of SNR on p

1° resolution



30' resolution



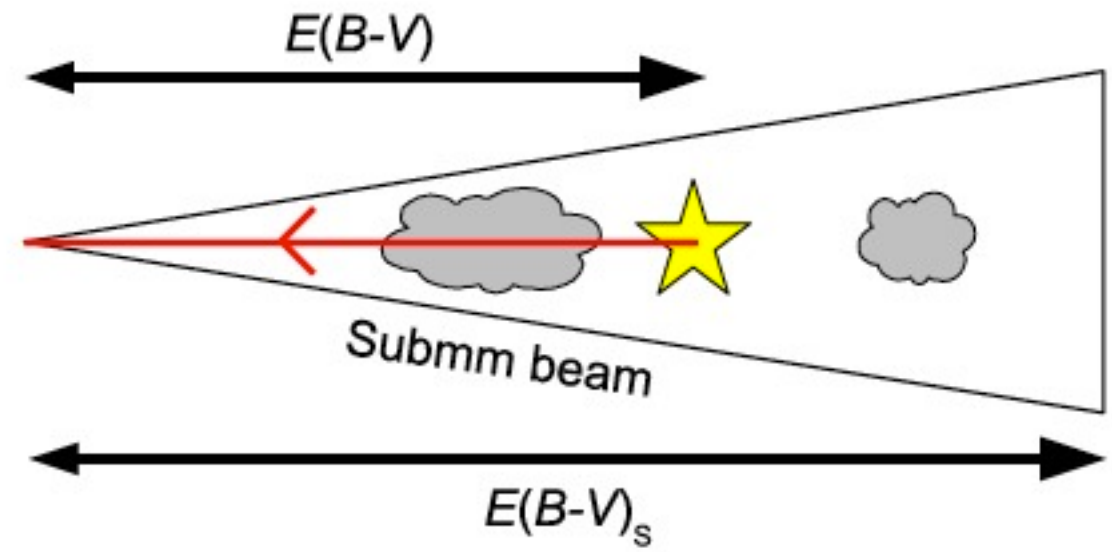
- Computed from mean likelihood
- Basically reflect Intensity and sky coverage

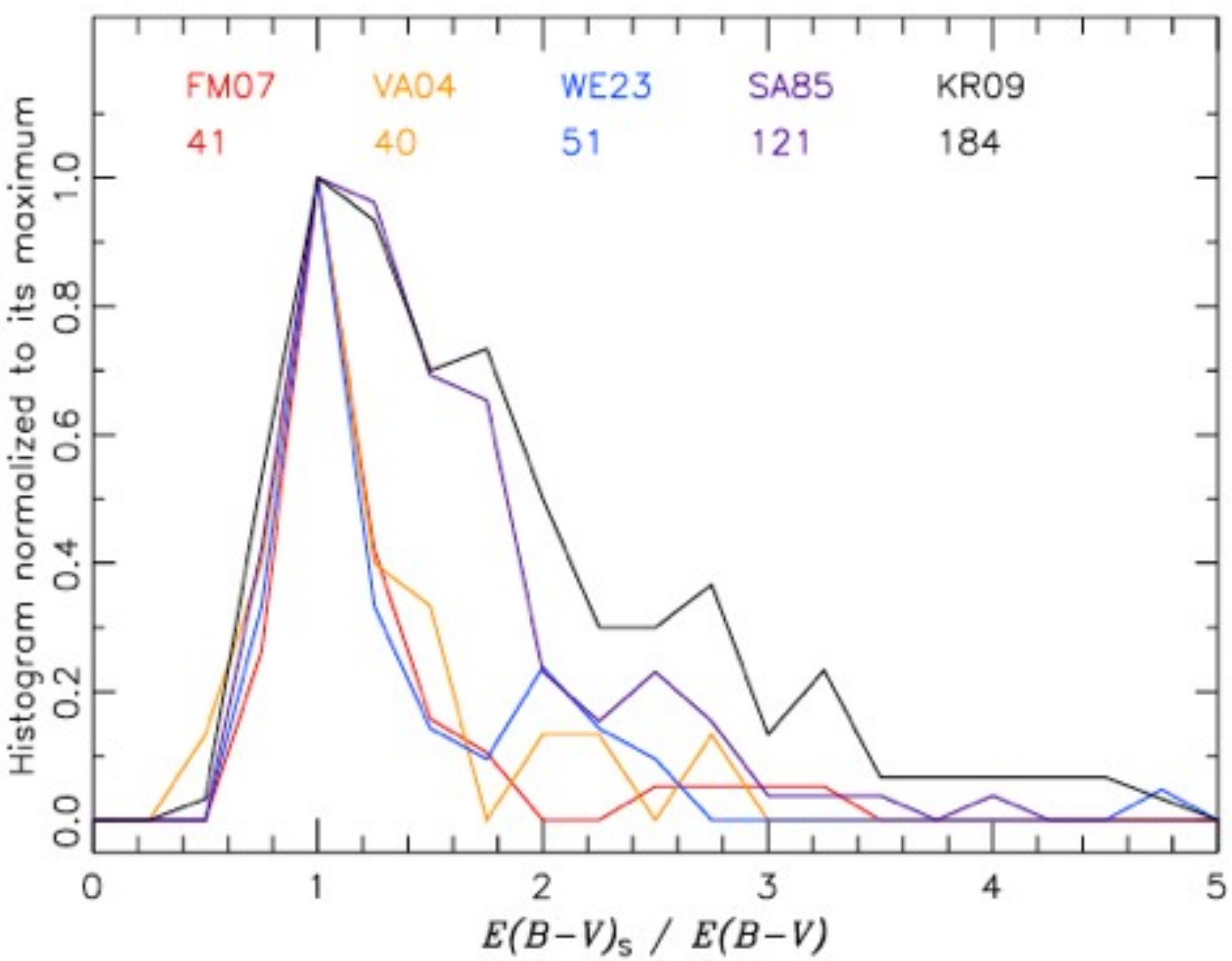
	1°	30'	15'
SNR>2	93 %	82 %	61 %
SNR>3	89 %	72 %	48 %
SNR>5	77 %	55 %	33 %
SNR>10	53 %	34 %	19 %

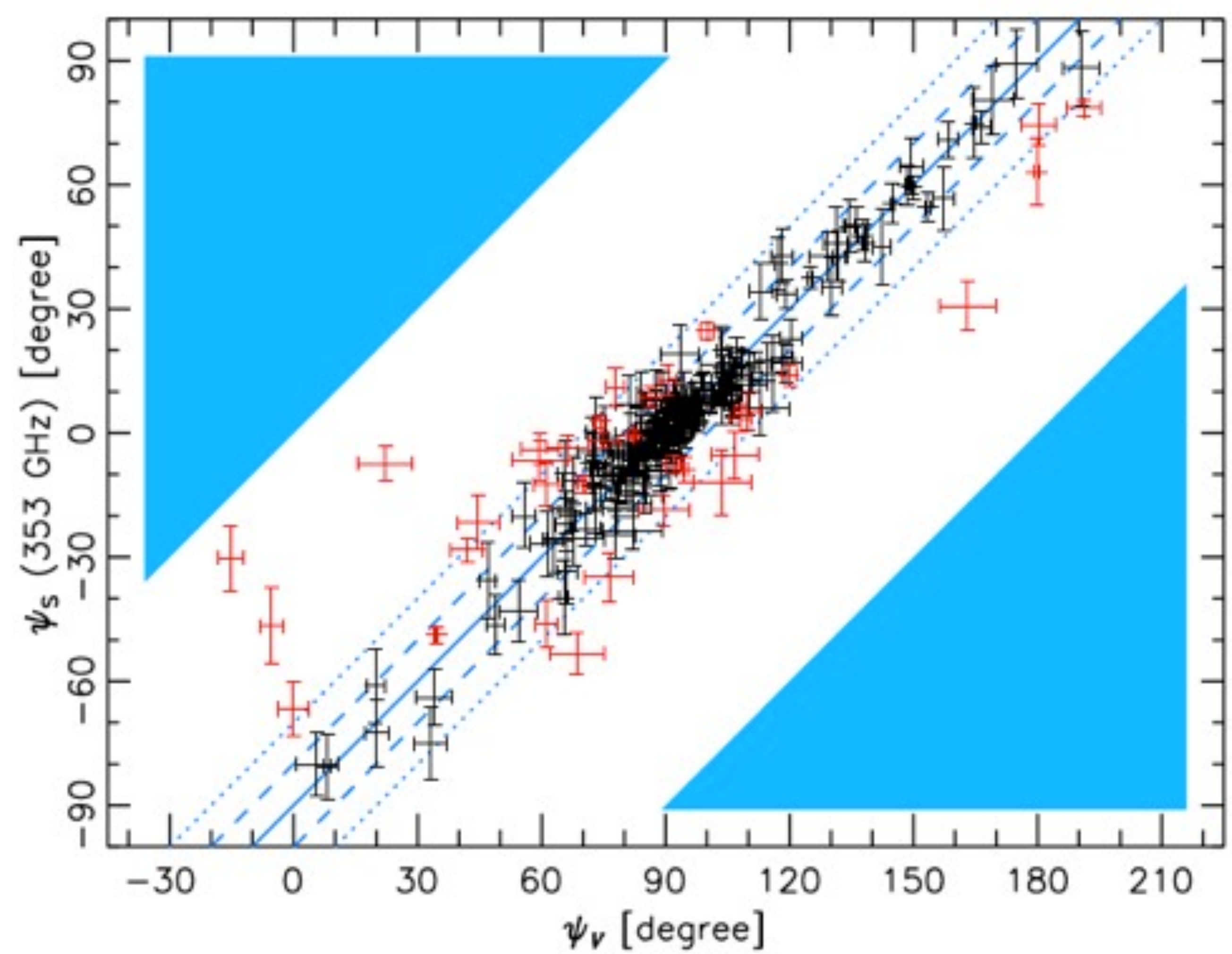
- Work at 1° resolution to lower noise (also 7', 14', 30')
- Smoothed noise cov. matrix using MC simulations

Emission vs Extinction

- Selected 255 stars with:
  - high S/N in both
  - $E(B\text{-}V)_s \leq 1$ and $W_{CO} < 2$ K km s^{-1}
  - similar column densities $E(B\text{-}V)_s/E(B\text{-}V)_V < 1.6$
  - similar polarization angles $\Psi_V \sim \Psi_S$ - 90



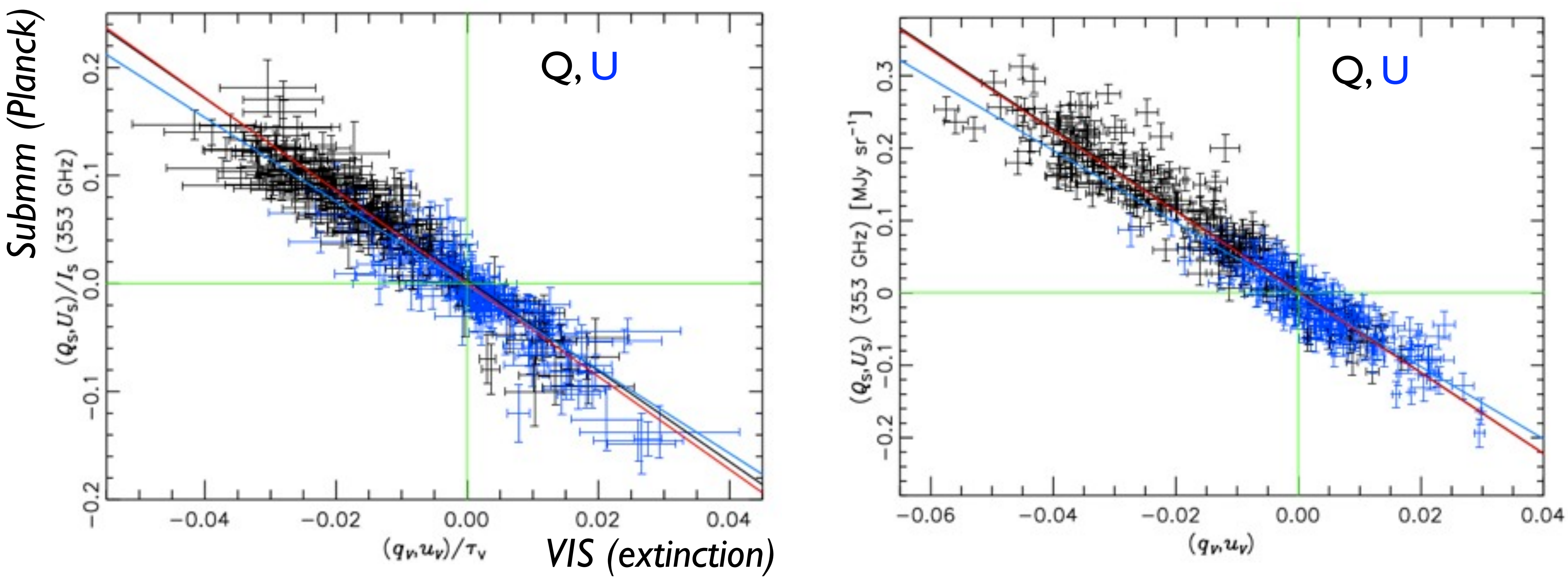




Planck intermediate results. XXI.

J.P. Bernard, Planck Collaboration, Cracow Poland 2014

Emission vs Extinction

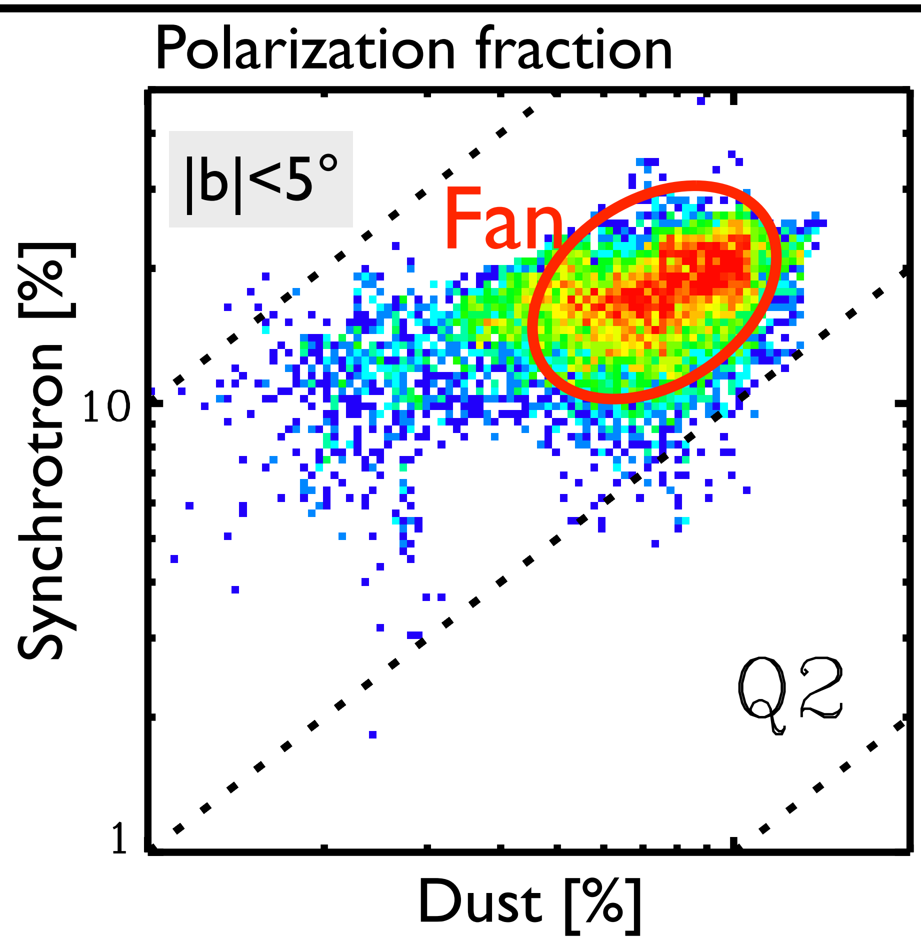


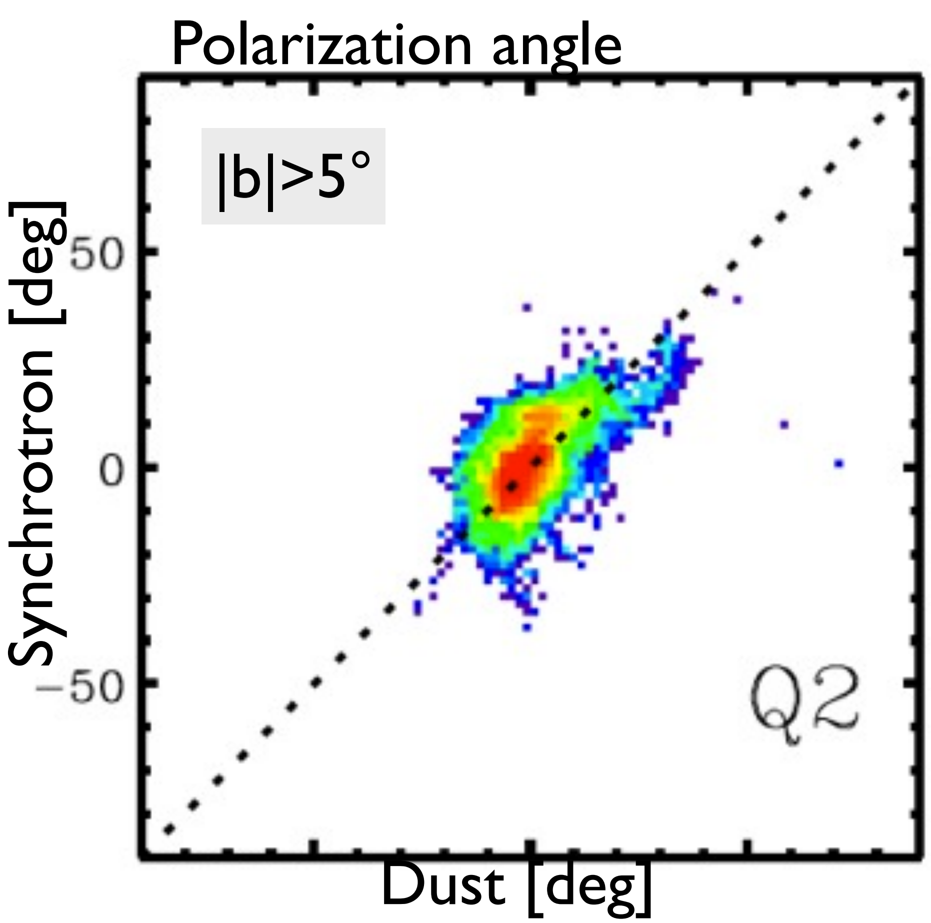
- Polarization efficiency ratio: $R_{S/V} = (P_S/I_S)/(p_V/\tau_V) = 4.3 \pm 0.2(\text{stat.}) \pm 0.4(\text{syst.})$
- $R_{S/V}$ compatible with a range of dust models, not very discriminatory.
- Polarized emission ratio: $R_{P/p} = P_S/p_V = 5.6 \pm 0.2$ (stat.) ± 0.4 (syst.) MJy sr^{-1}
- $R_{P/p}$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

More theoretical work is needed to understand the implications for dust grain physics.

Planck intermediate results. XXI.

Synchrotron (30 GHz) vs Dust (353 GHz)

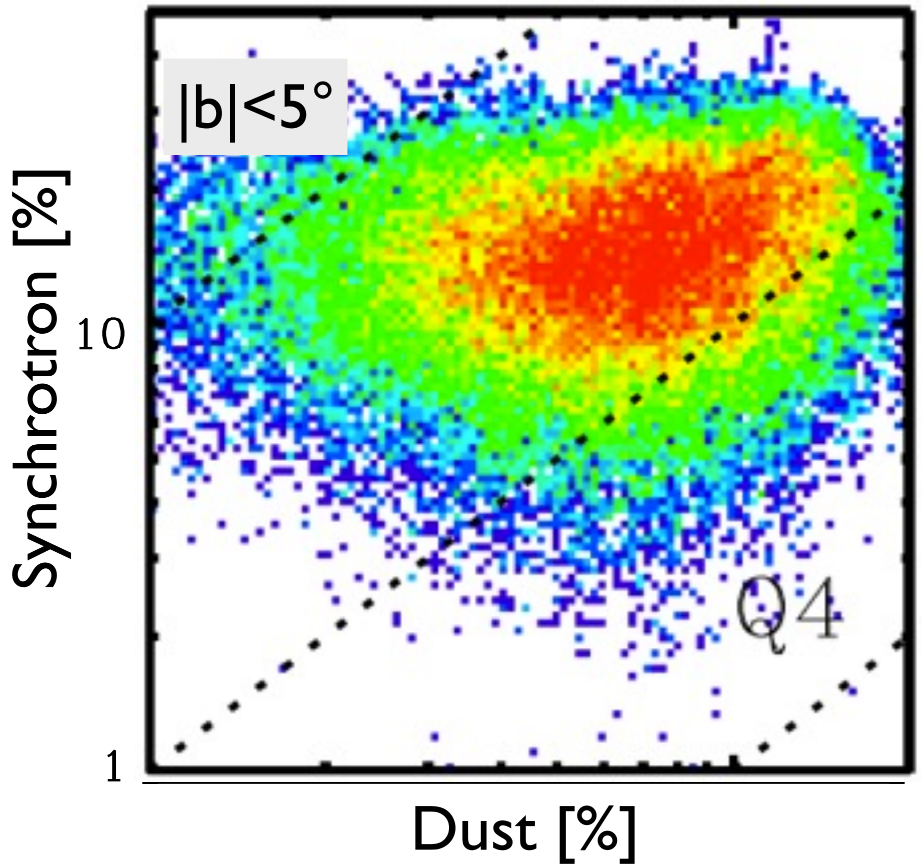




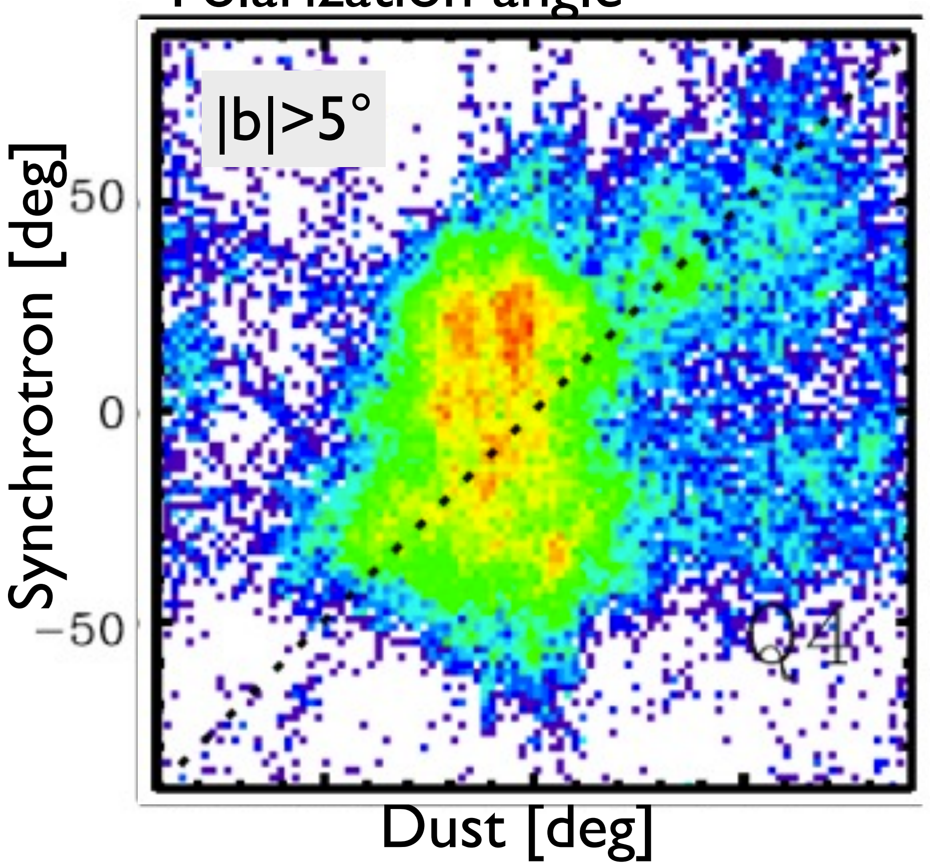
- Polarization fraction:
  - Measurable correlations in-plane
  - Weaker correlations off-plane
- Angles :
  - Around 0° in plane but not well correlated
  - Correlate over some regions (Fan, North Polar Spur)

Synchrotron (30 GHz) vs Dust (353 GHz)

Polarization fraction



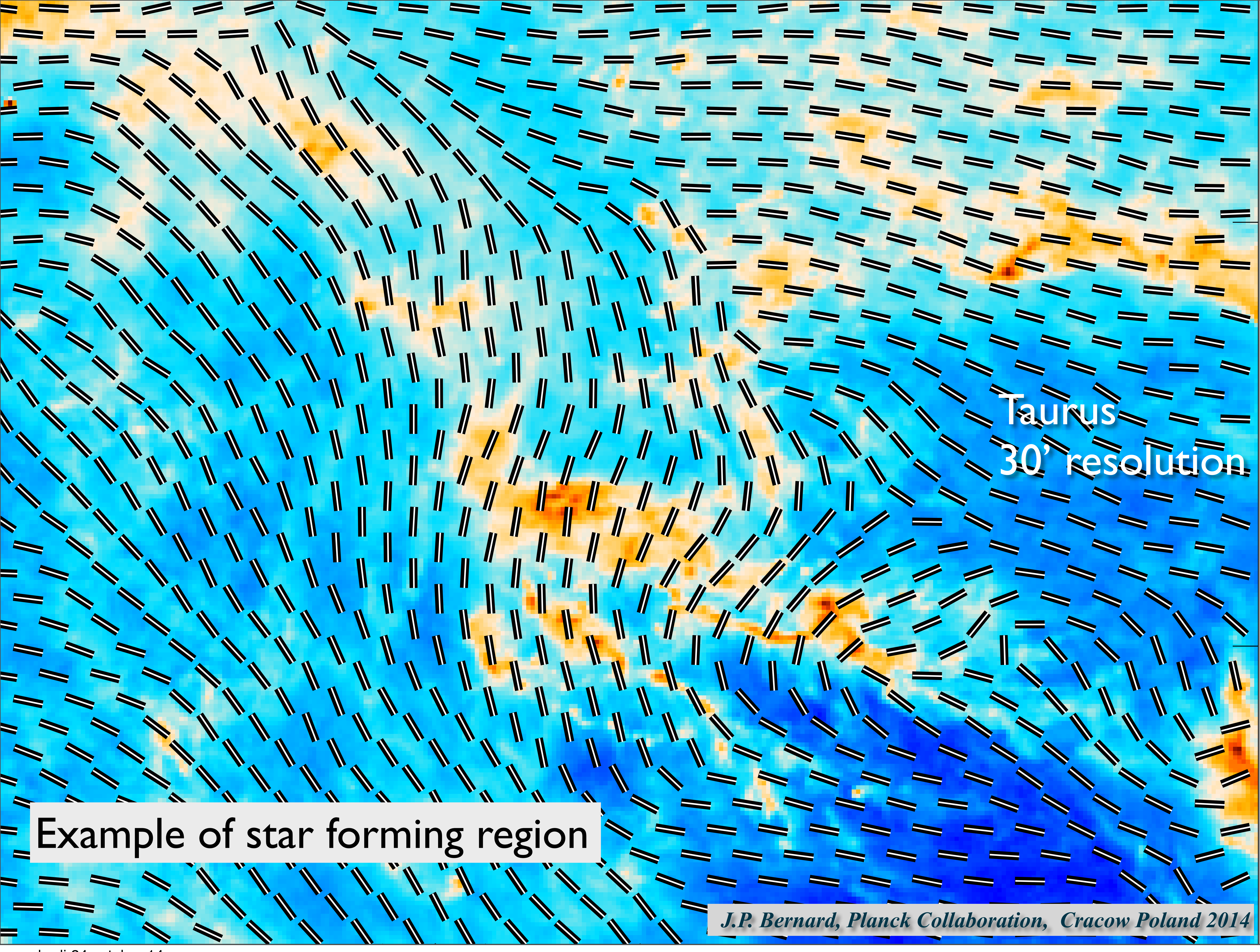
Polarization angle

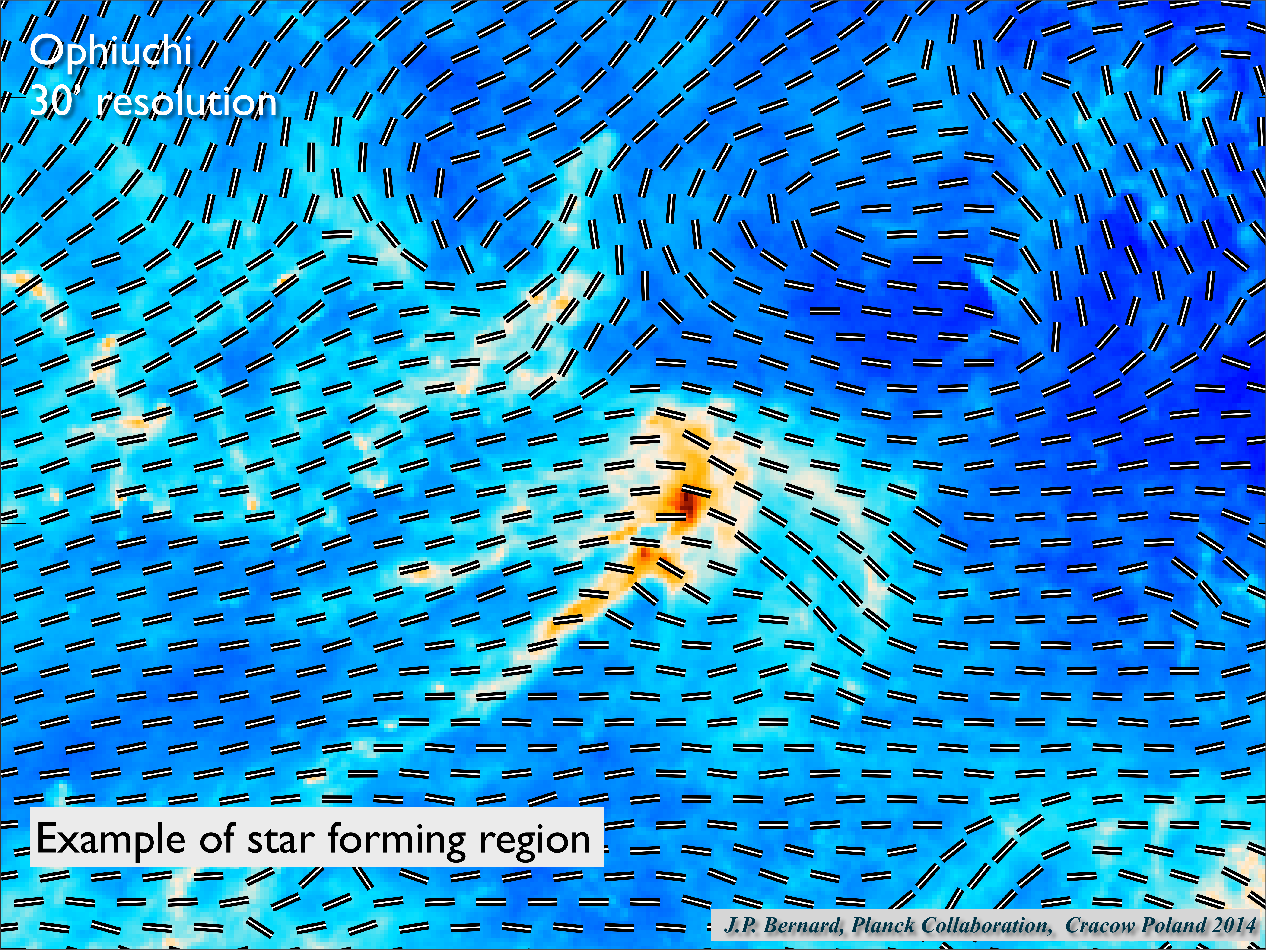


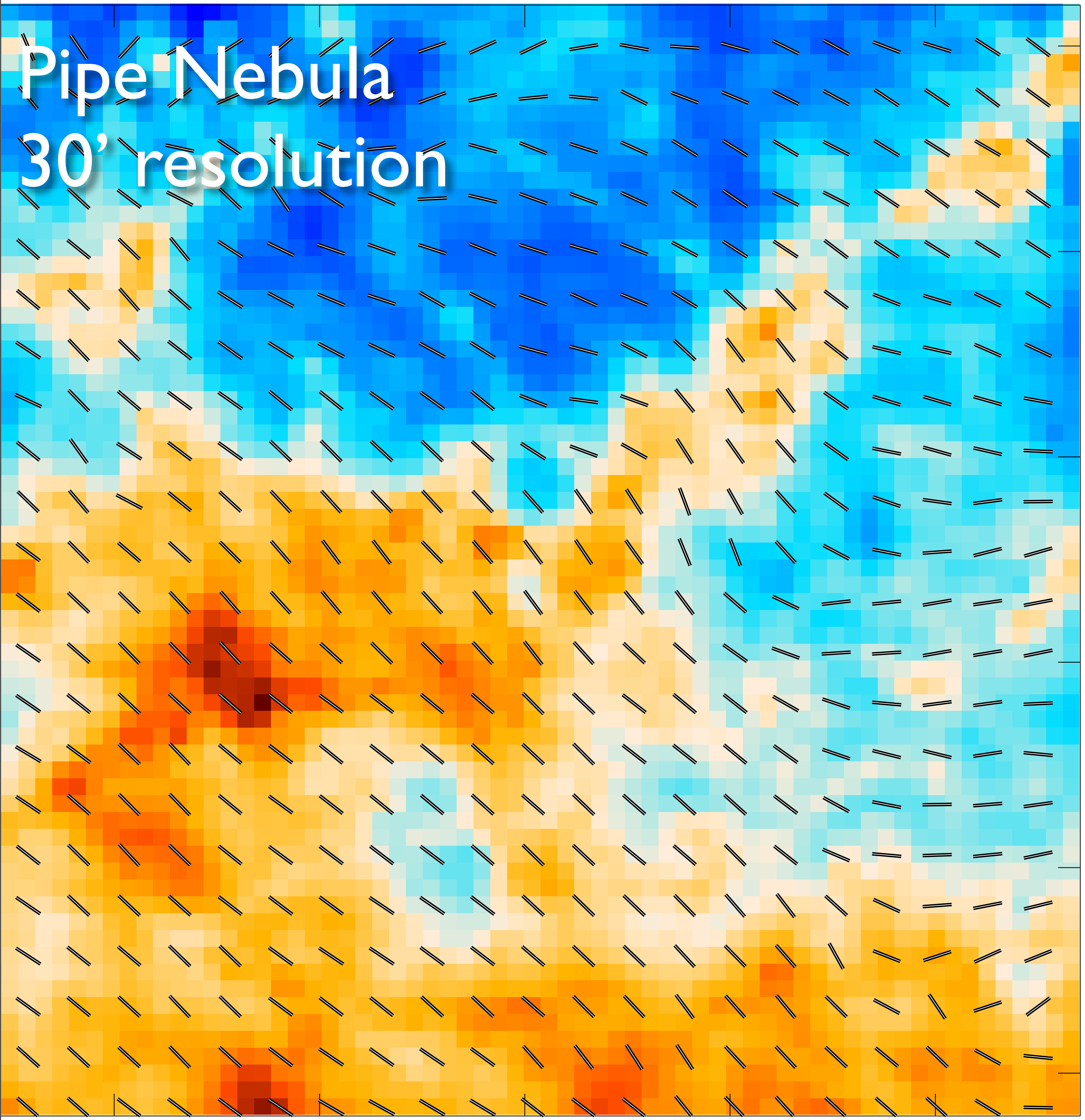
- Polarization fraction:
  - Measurable correlations in-plane
  - Weaker correlations off-plane
- Angles :
  - Around 0° in plane but not well correlated
  - Correlate over some regions (Fan, North Polar Spur)

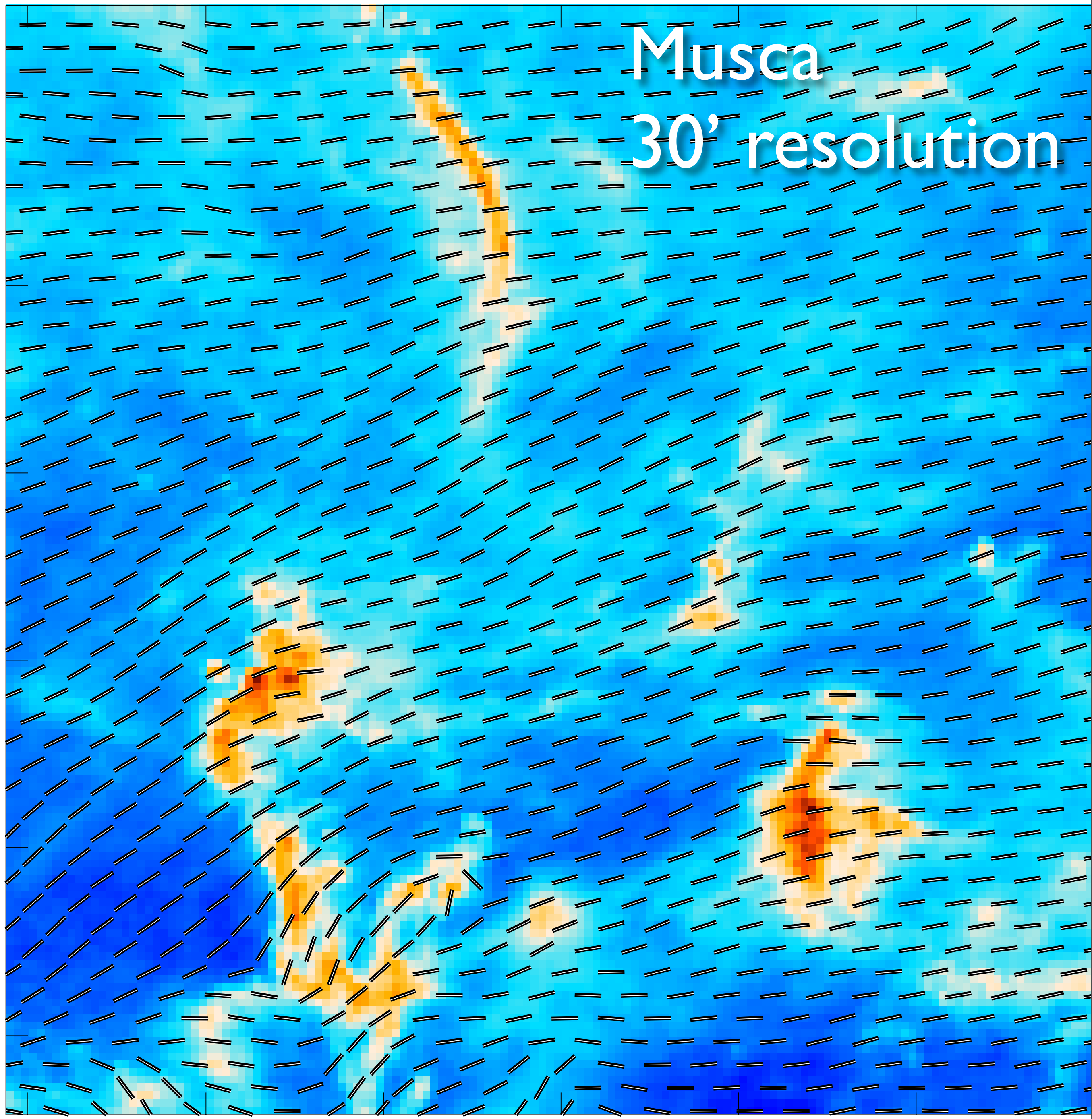
Significant scatter:
Synchrotron and dust not generally trace the same regions of LOS

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

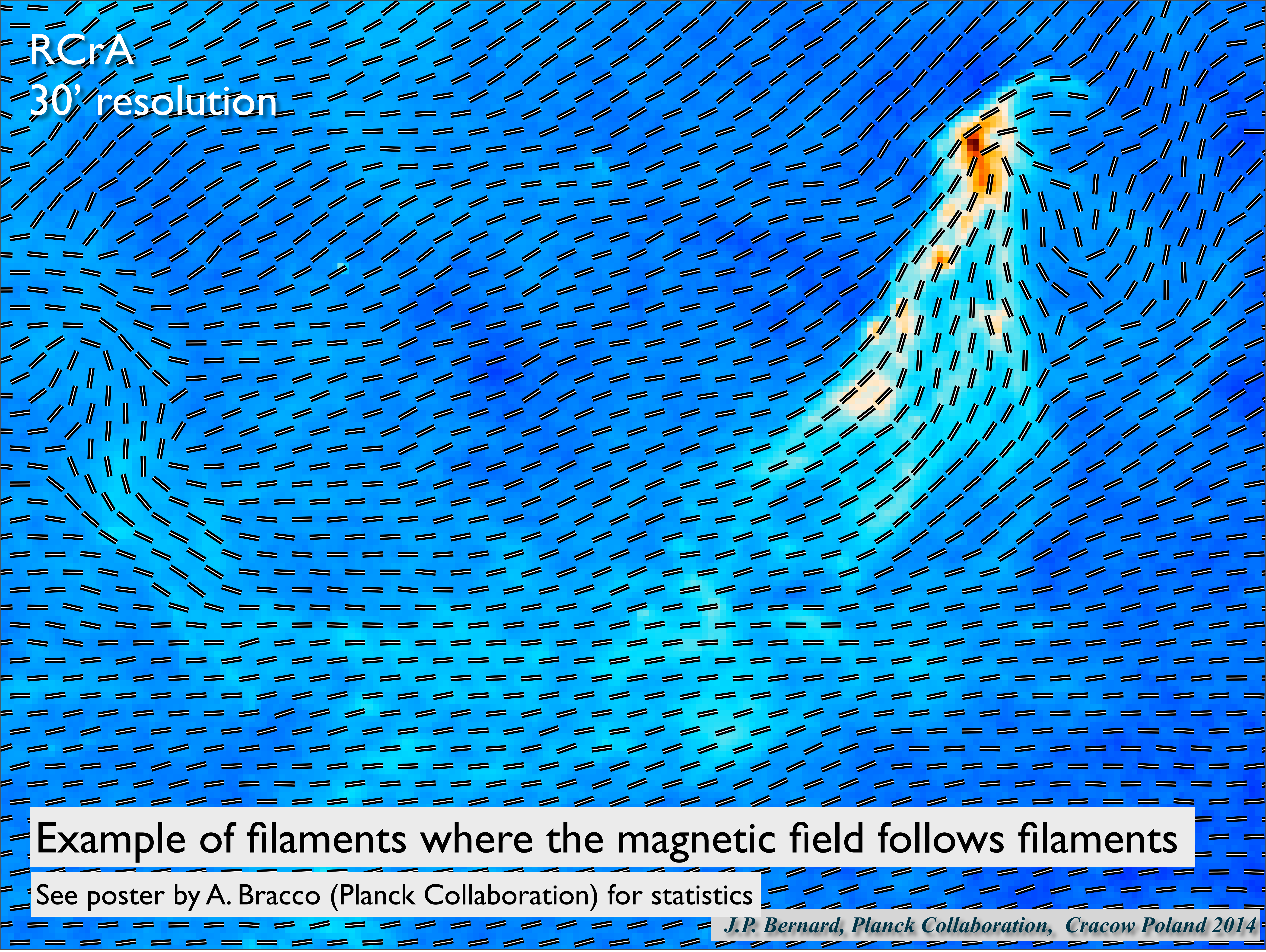

Taurus
30' resolution
Example of star forming region
J.P. Bernard, Planck Collaboration, Cracow Poland 2014


Ophiuchi
30' resolution
Example of star forming region
J.P. Bernard, Planck Collaboration, Cracow Poland 2014





Example of filaments where the magnetic field $\perp$ to filaments



Example of filaments where the magnetic field follows filaments

See poster by A. Bracco (Planck Collaboration) for statistics

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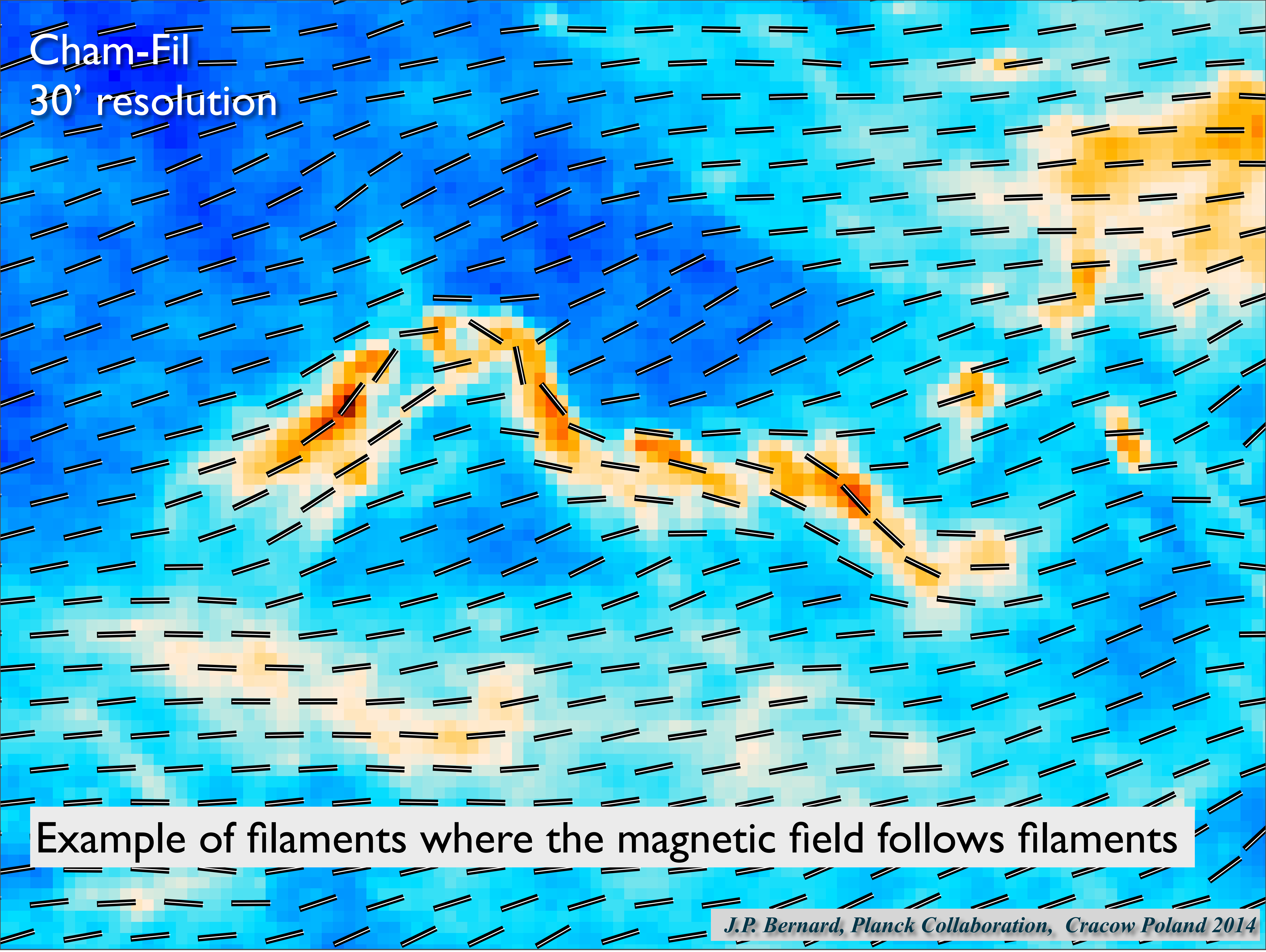
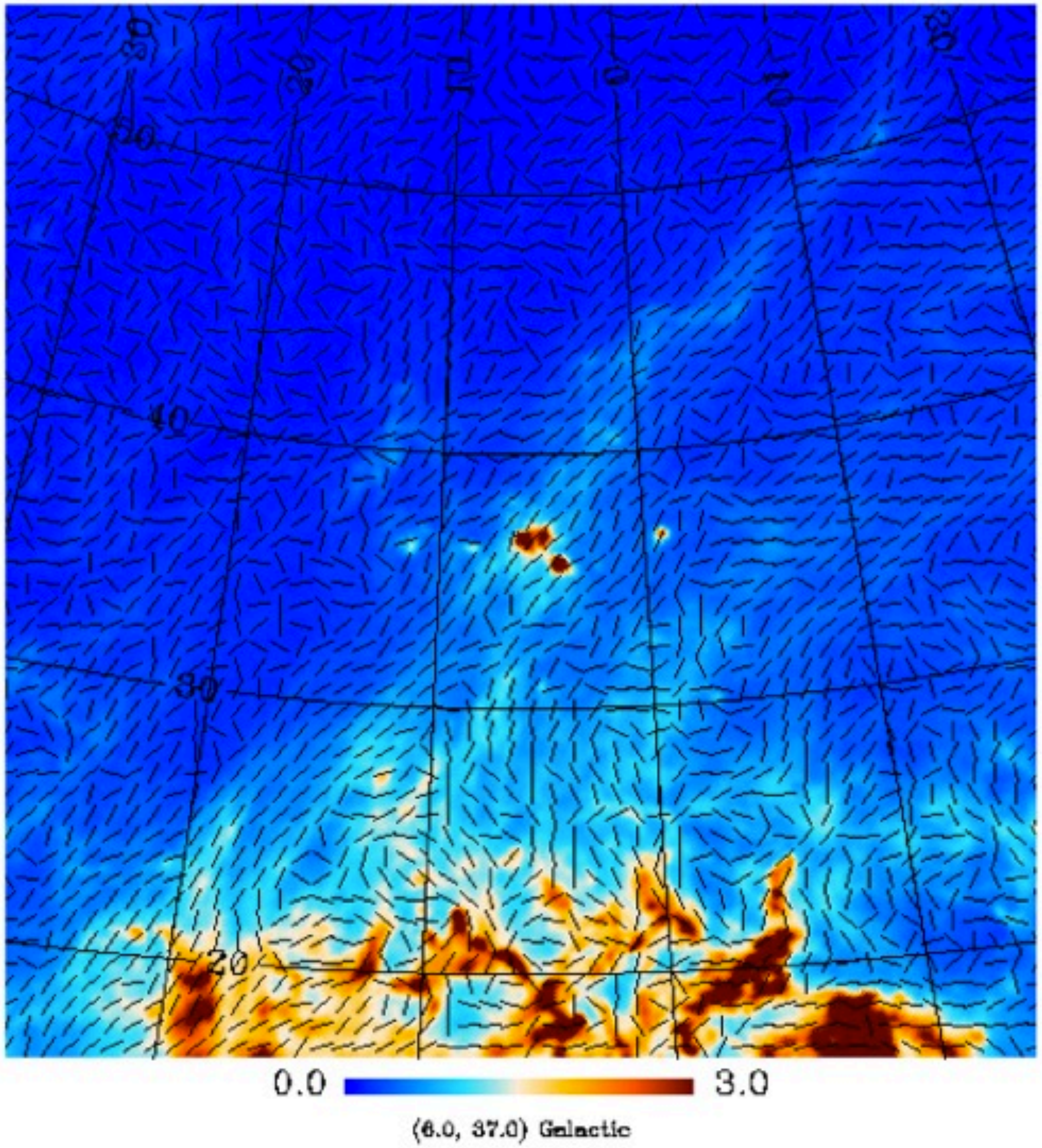
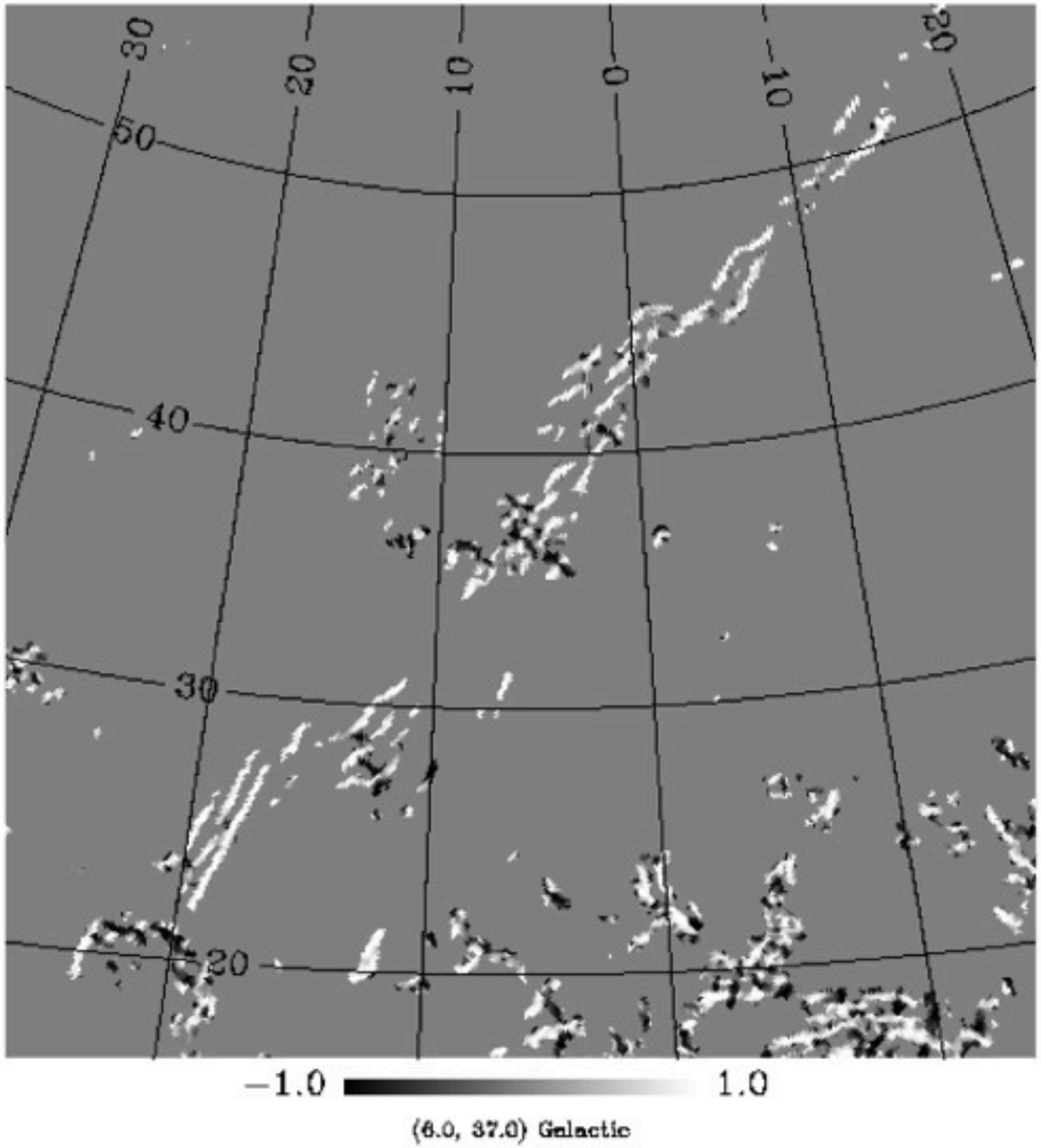


Example of filaments where the magnetic field follows filaments

B vs matter





Planck intermediate results. XXXII.

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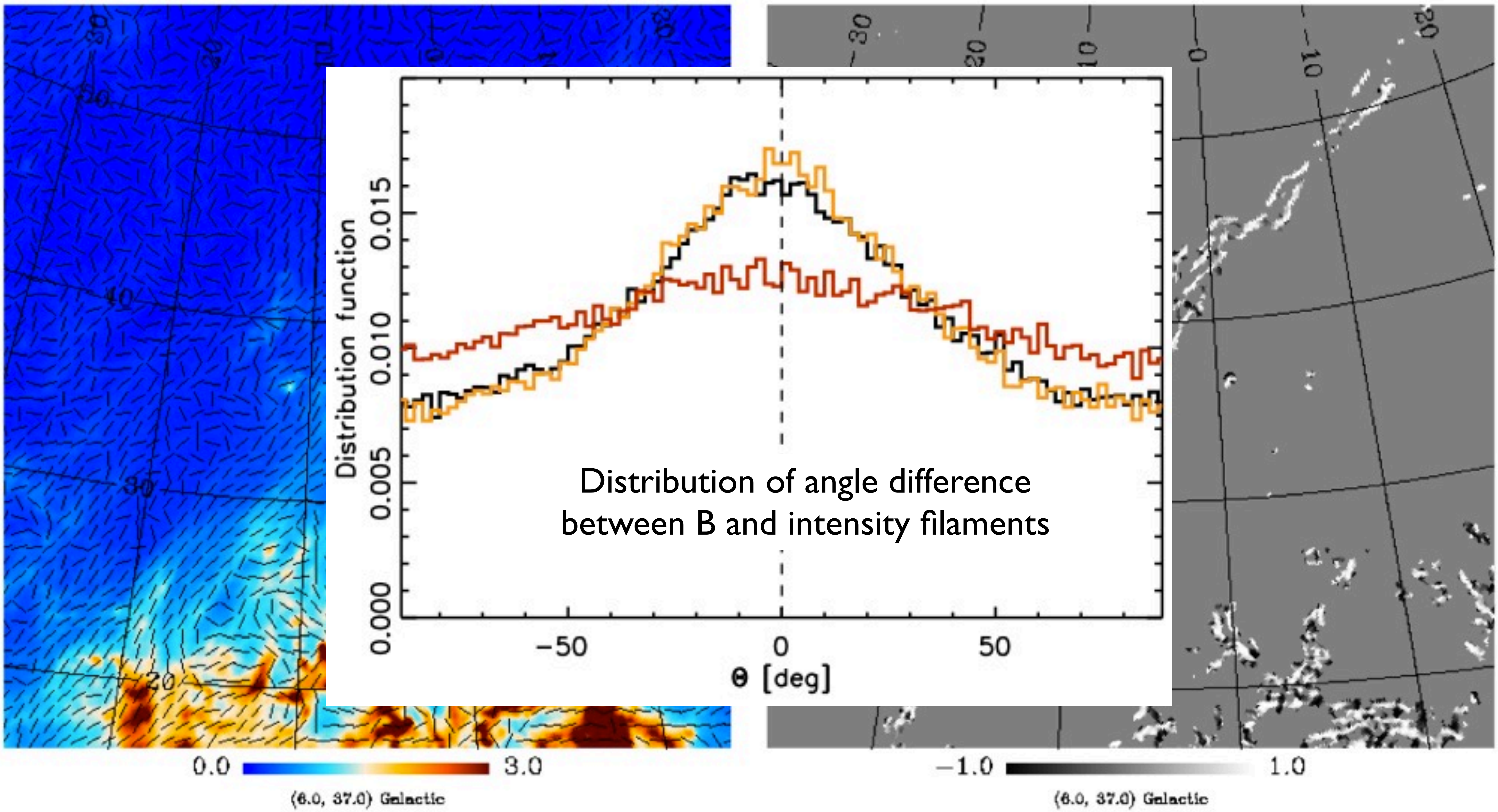
B vs matter



Magnetic field direction more often aligns with ISM filamentary structures

Planck intermediate results. XXXII.

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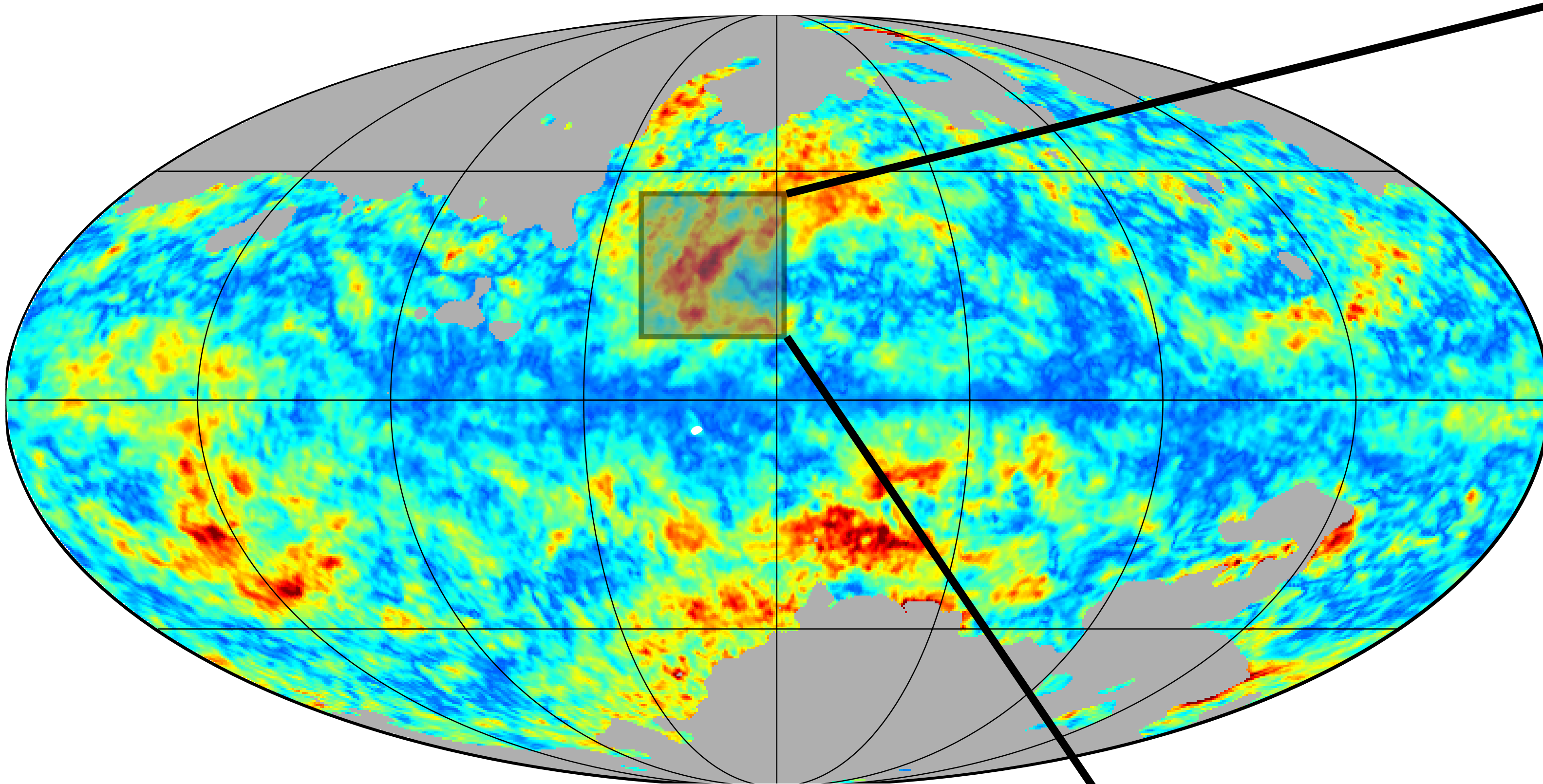
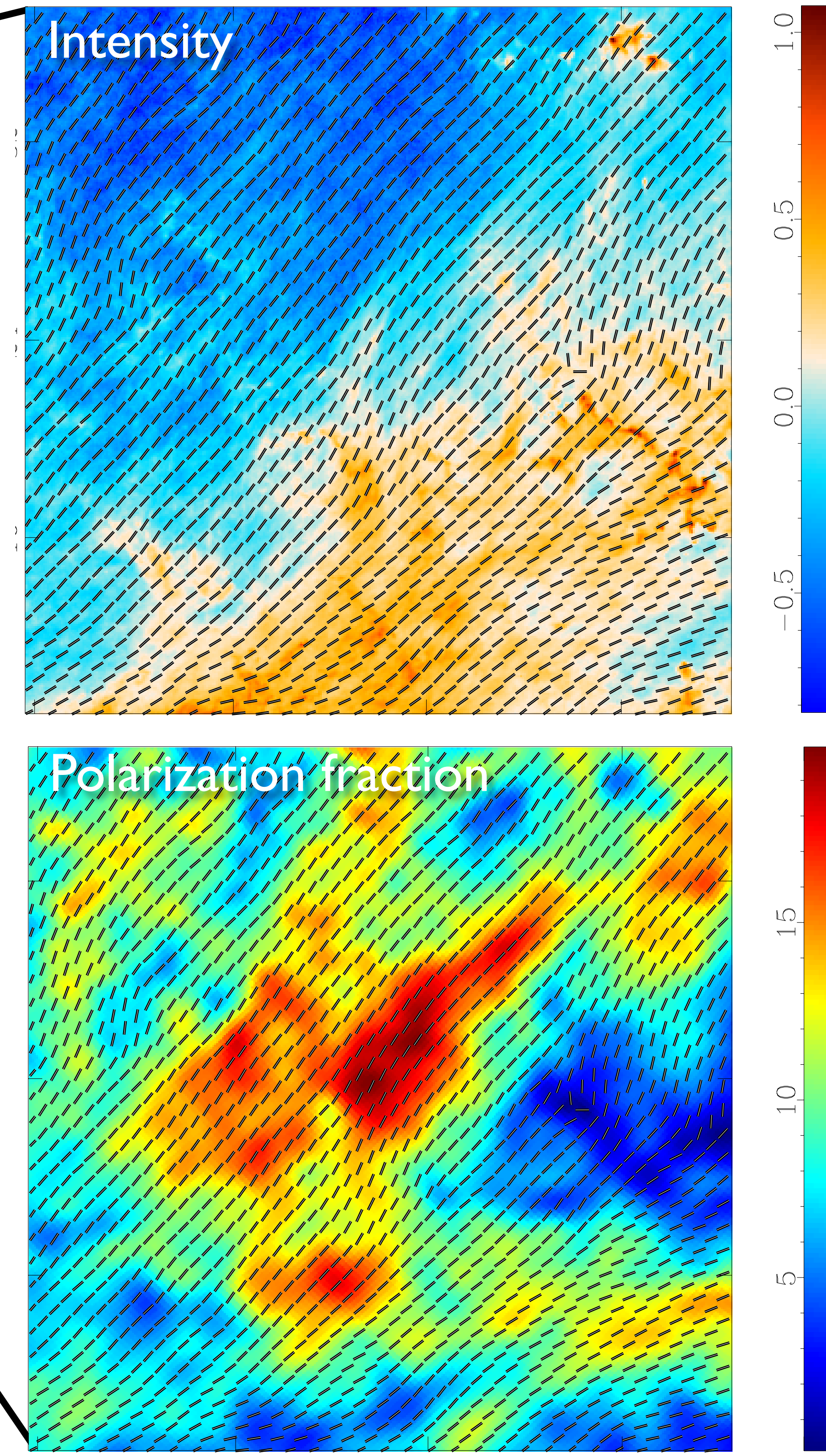
Polarization Fraction

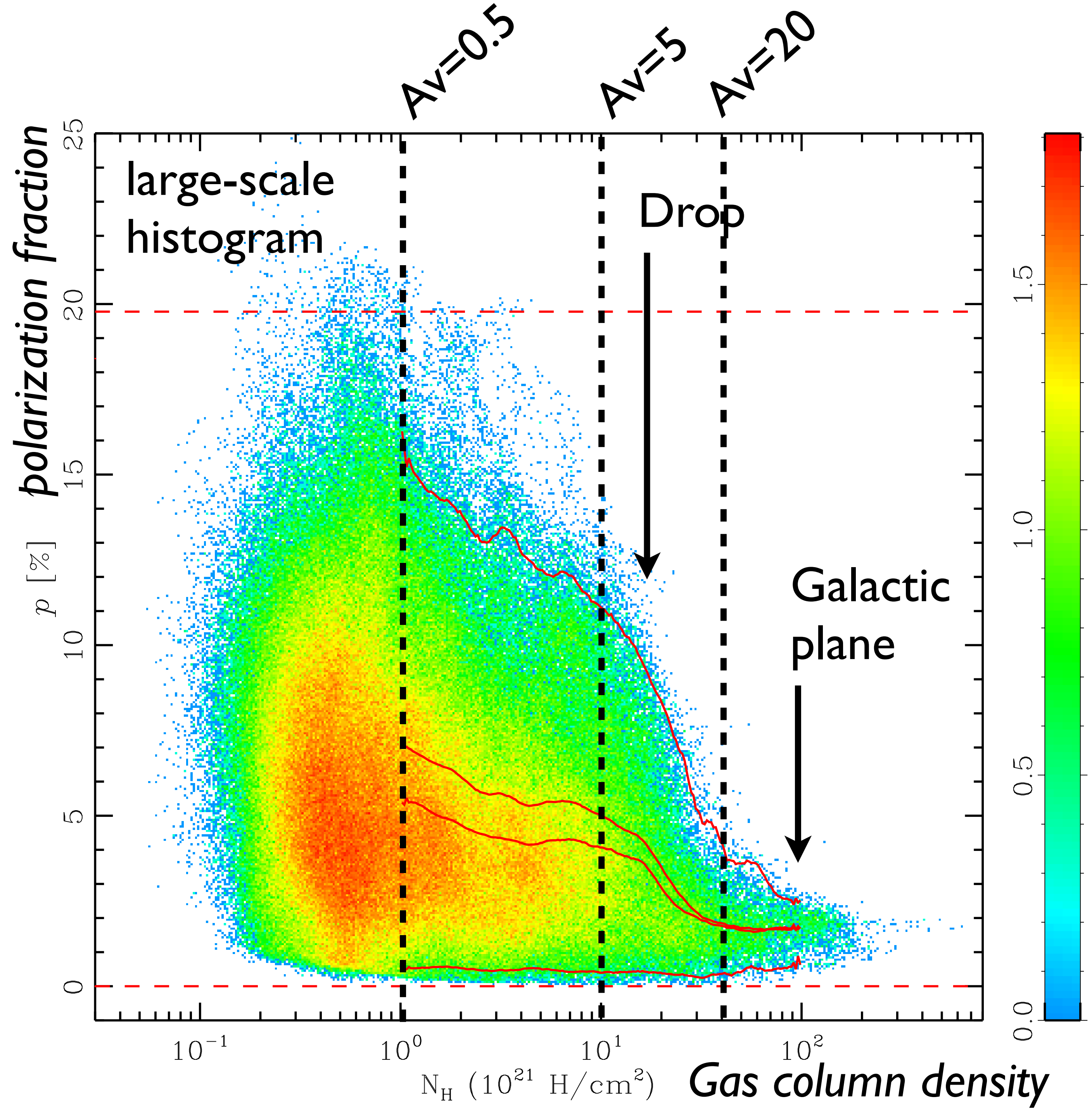


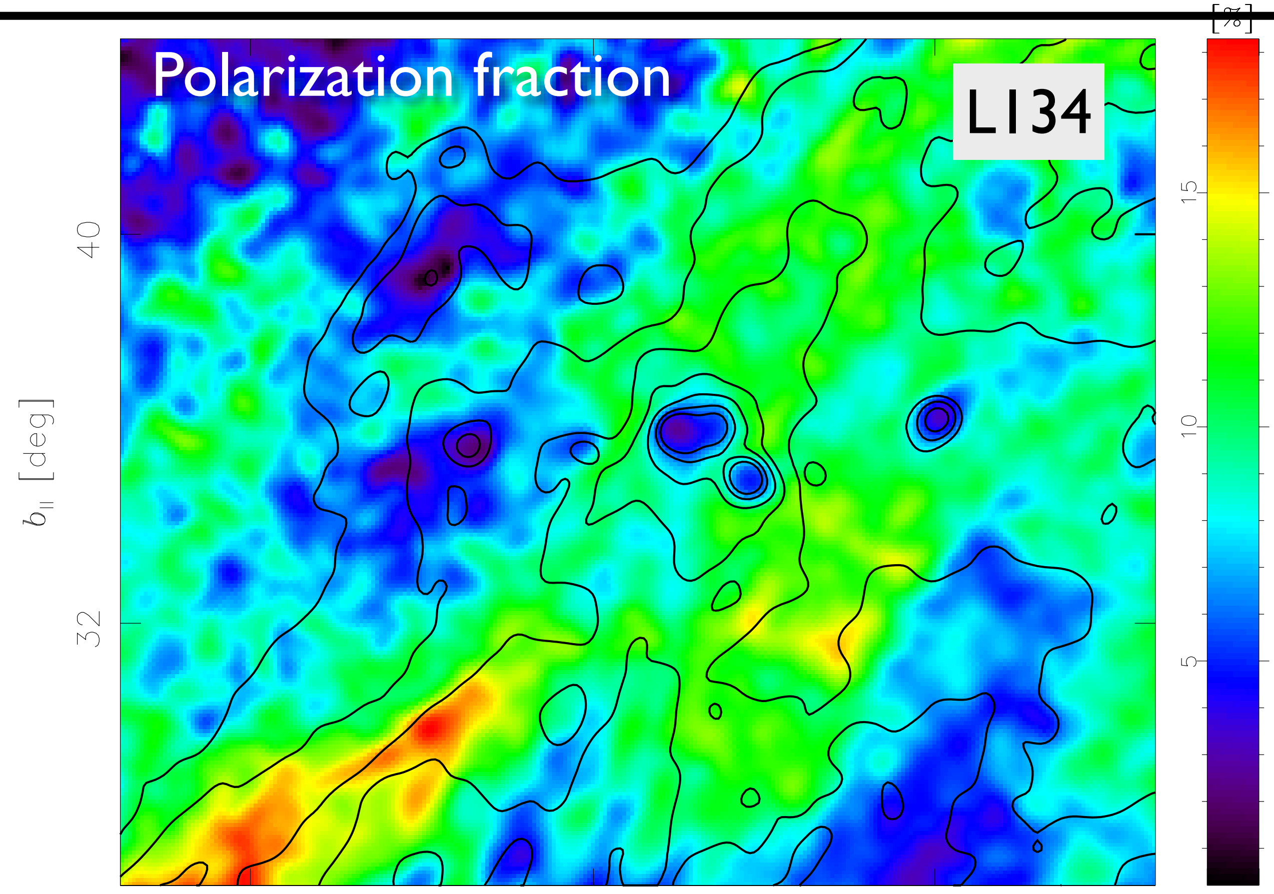


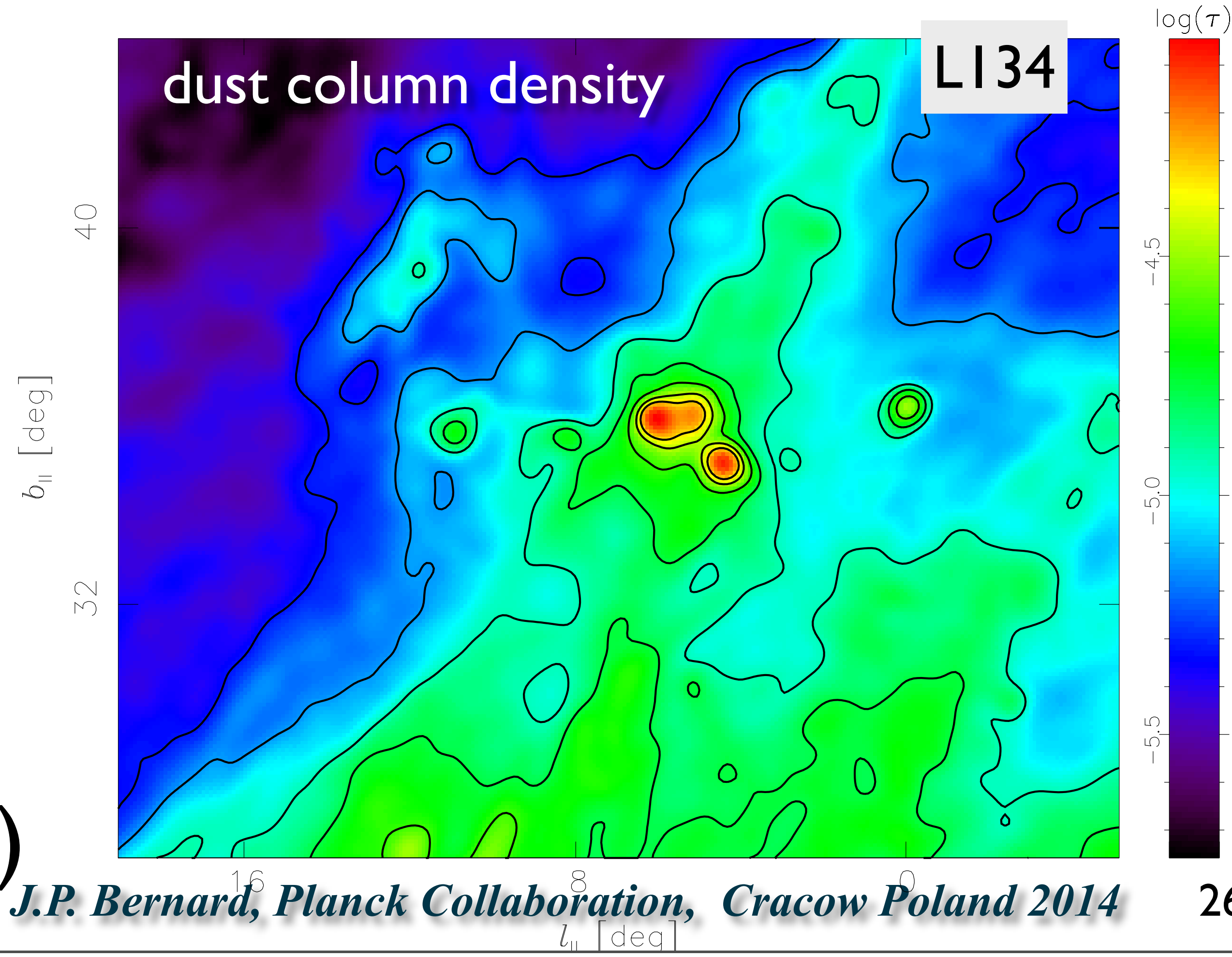
Highly polarized regions:
- Found in homogenous B field regions
- Often at edges of intensity structures

Some of these have little to no intensity counterparts

Polarization fraction vs N_H







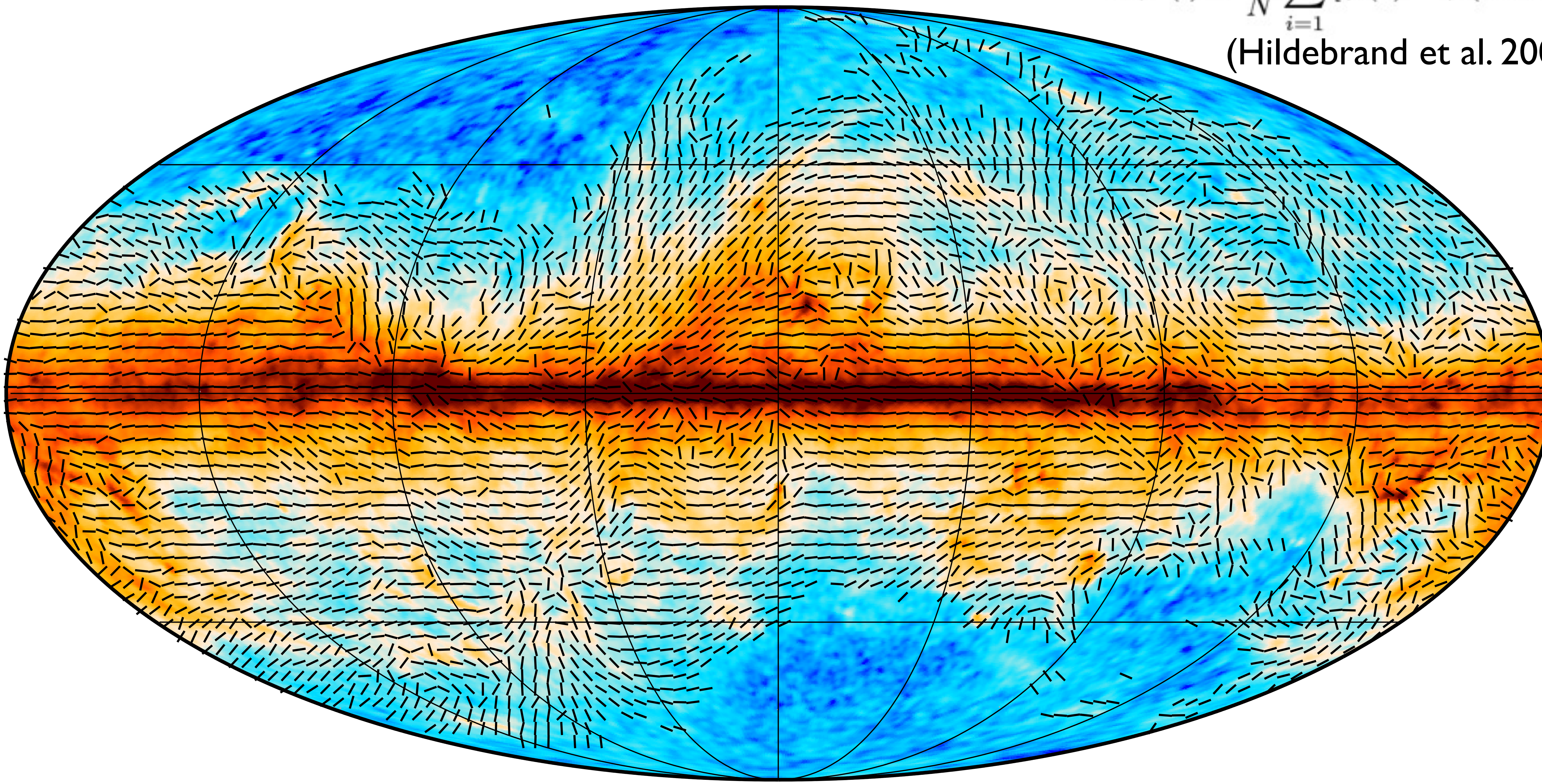
Polarization fractions drops at large column density
(Galactic Plane + individual clouds)

Planck intermediate results. XIX.

Angle Dispersion Function

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

(Hildebrand et al. 2009)



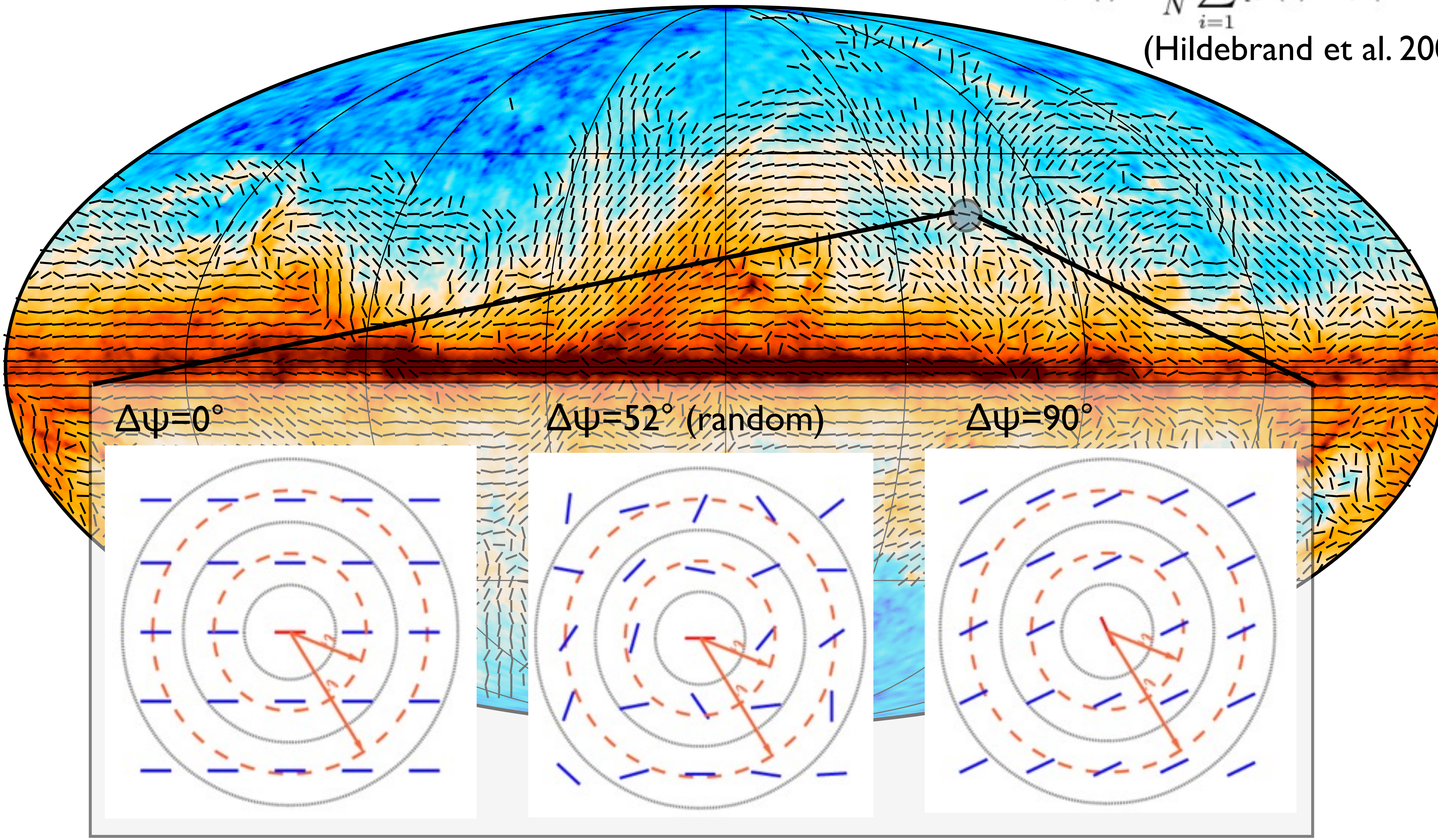
$\Delta\psi$ measures polarization direction homogeneity at given spatial scale

Planck intermediate results. XIX.

Angle Dispersion Function

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

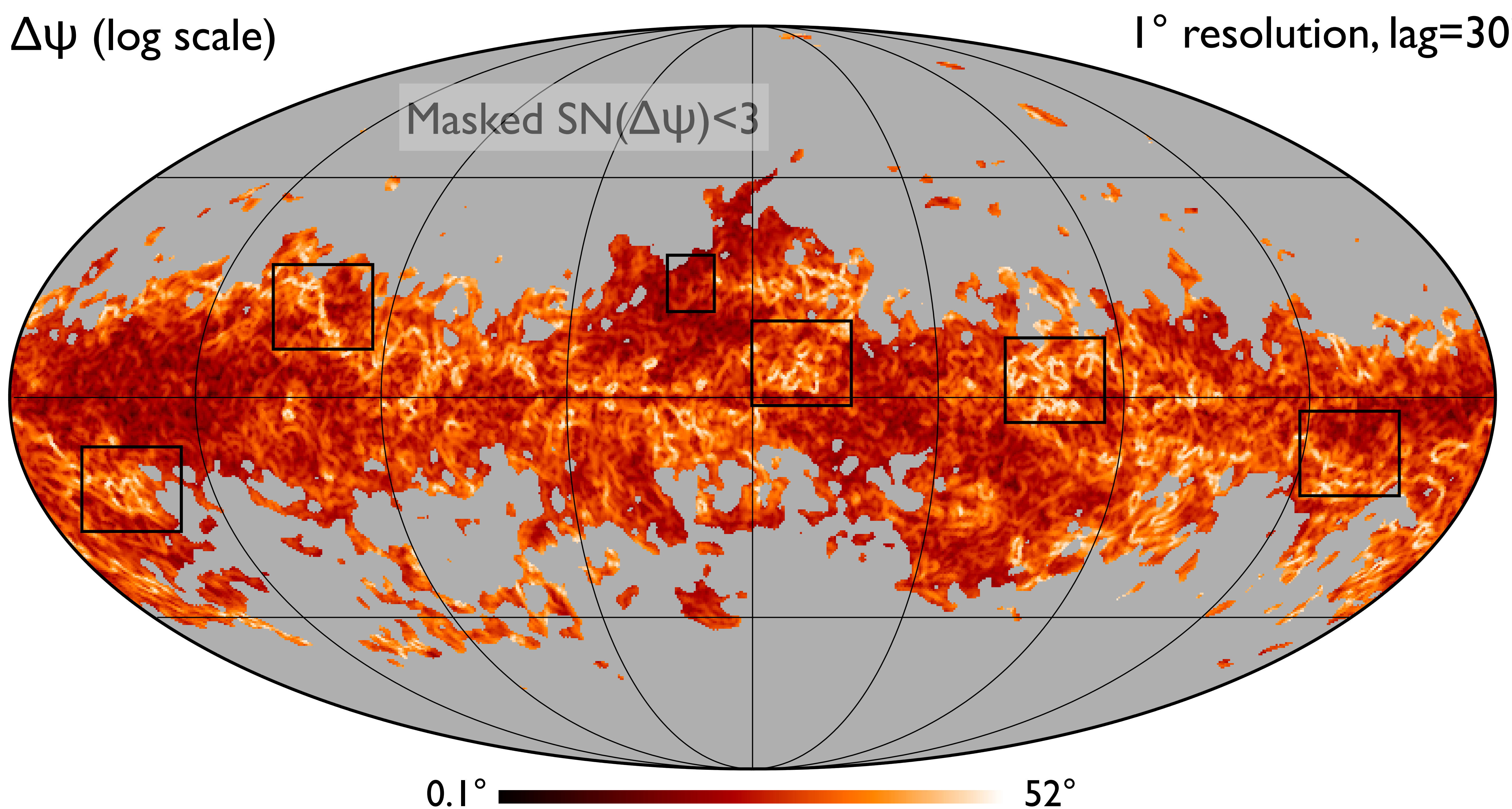
(Hildebrand et al. 2009)



Δψ measures polarization direction homogeneity at given spatial scale

Planck intermediate results. XIX.

Angle Dispersion Function

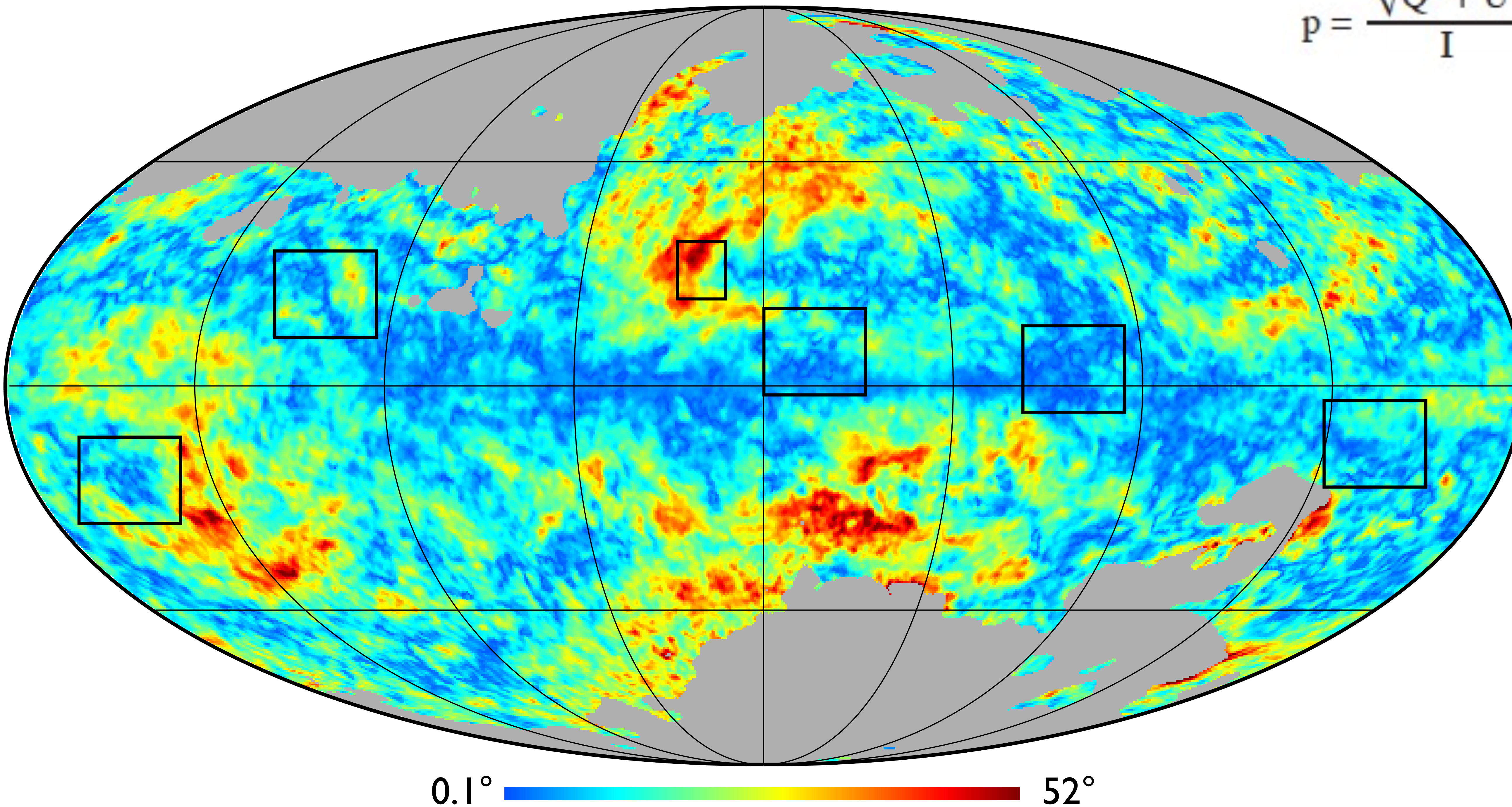


- Filamentary (Spaghetti) regions of high polarization rotation (!!)
- Some extend over large areas (must be nearby)

Planck intermediate results. XIX.

Angle Dispersion Function

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

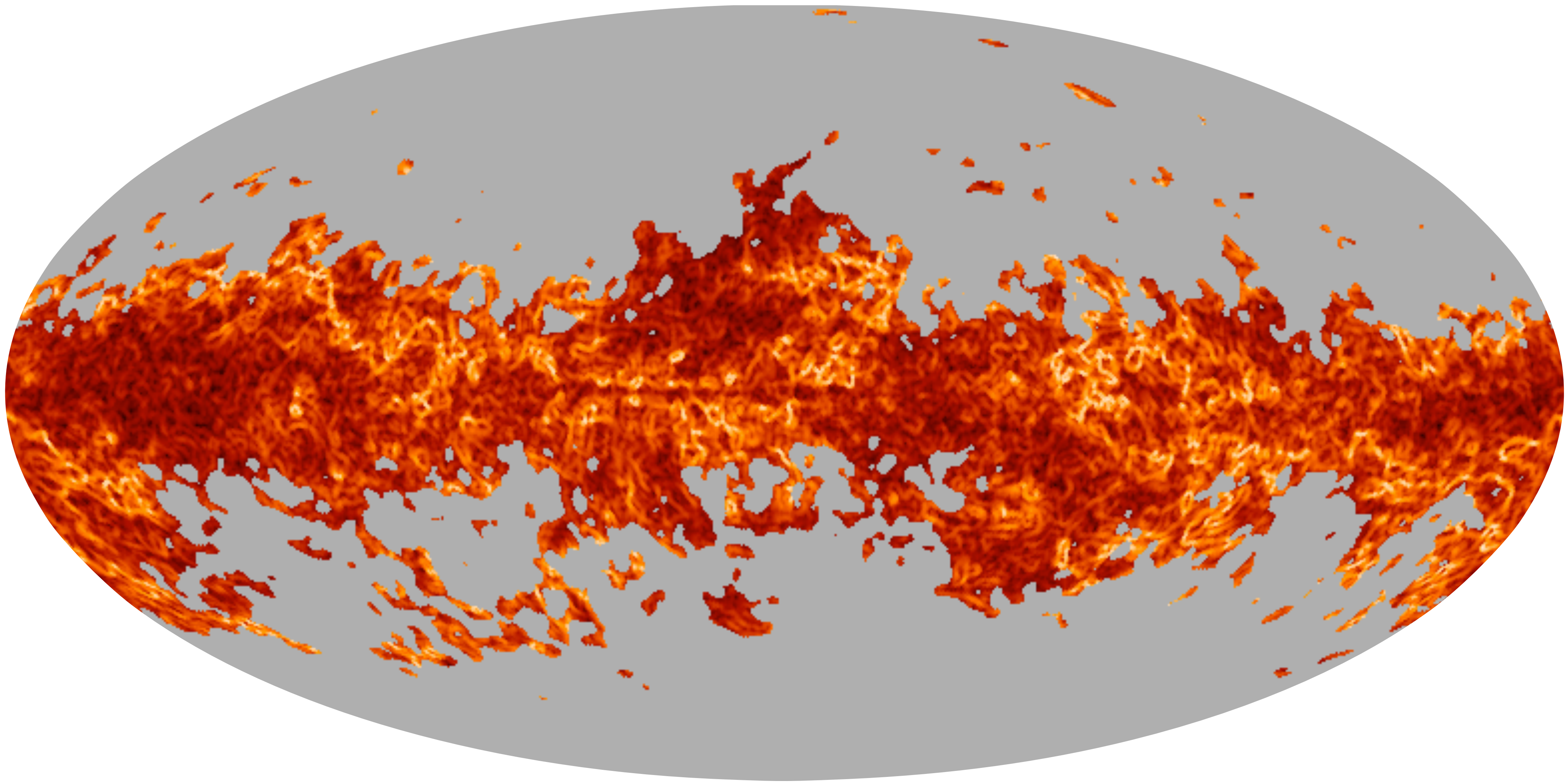


- Filamentary (Spaghetti) regions of high polarization rotation (!!)
- Correlate with low polarization

Planck intermediate results. XIX.

Angular Structure Function

$\Delta\psi$ Dust 353 GHz

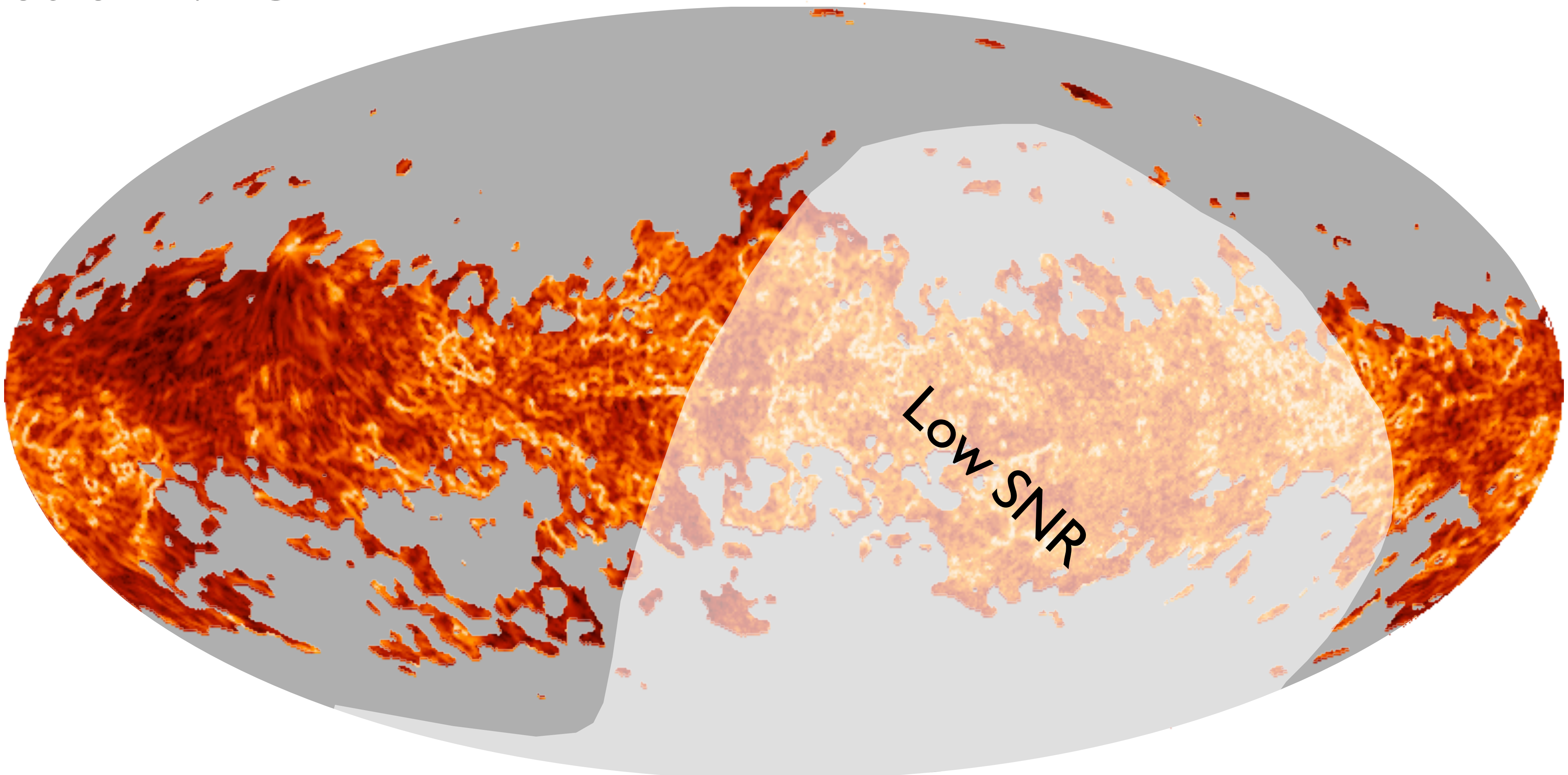


Synchrotron data (Reich 82, Reich & Reich 86) shows similar structures
These structures also correspond to low p (depolarization canals)
Those are likely due to Faraday rotation (not present at 353 GHz)
The structures in the dust and synchrotron $\Delta\psi$ do not match

Planck intermediate results. XIX.

Angular Structure Function

Δψ 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)
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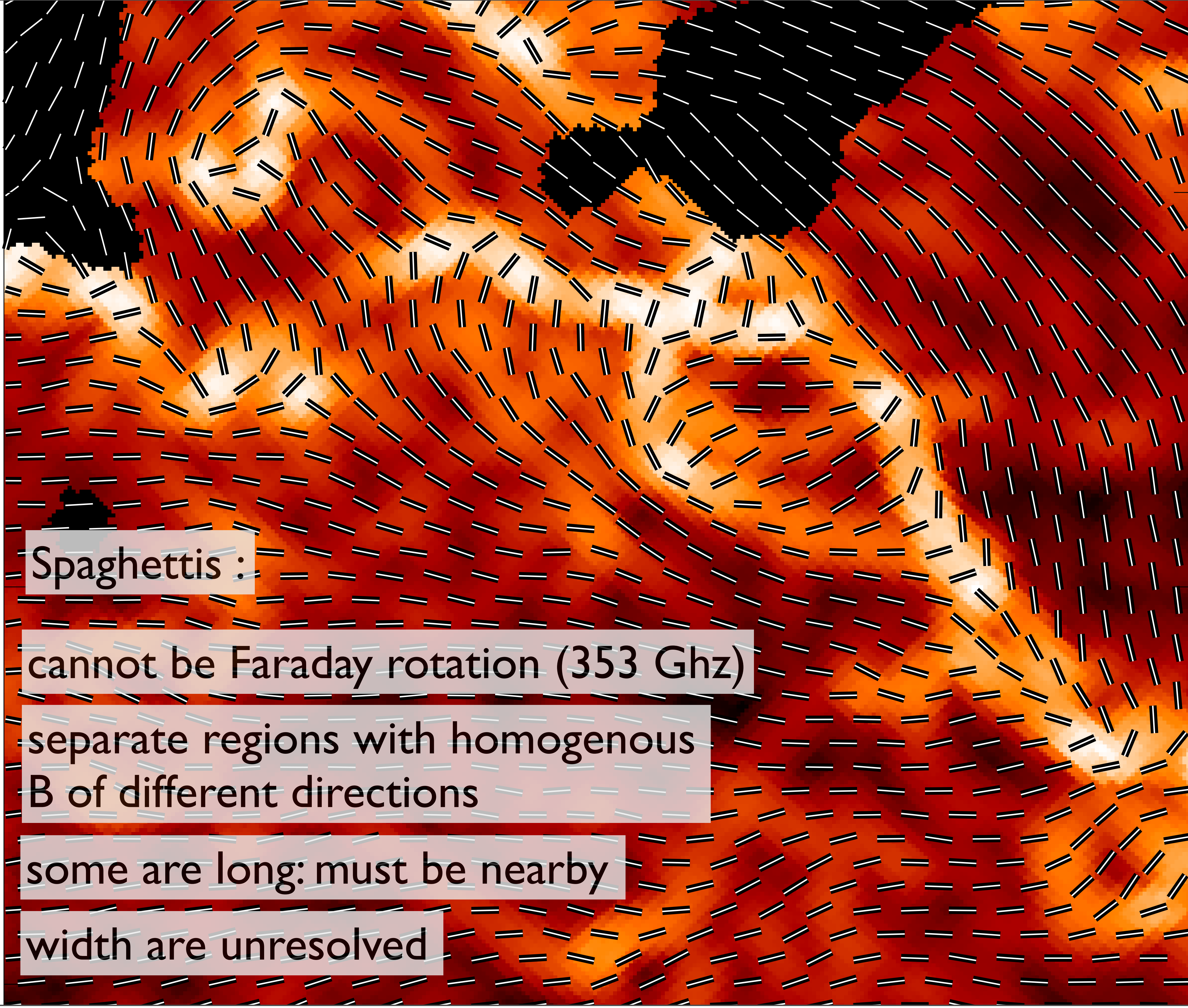
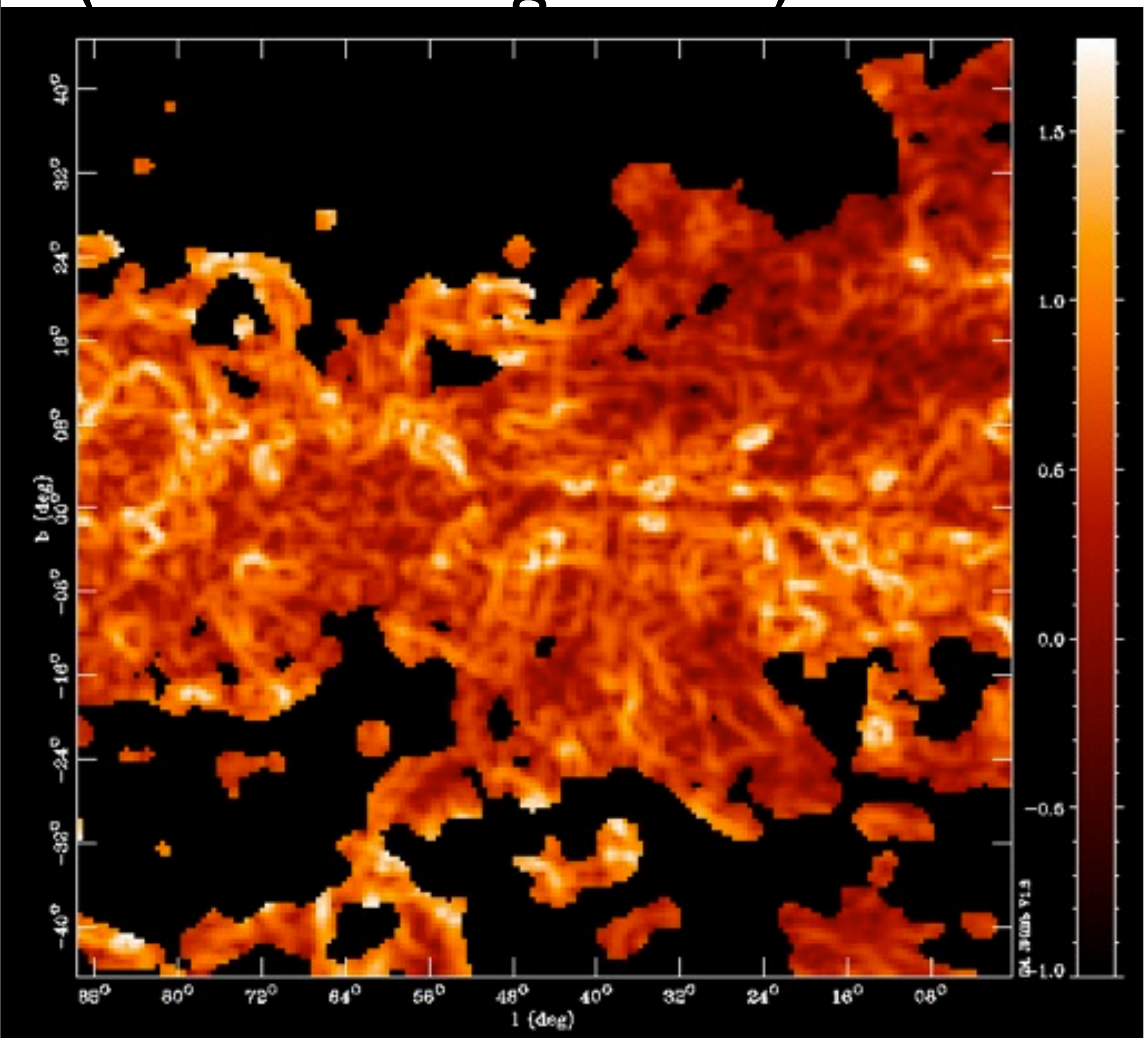
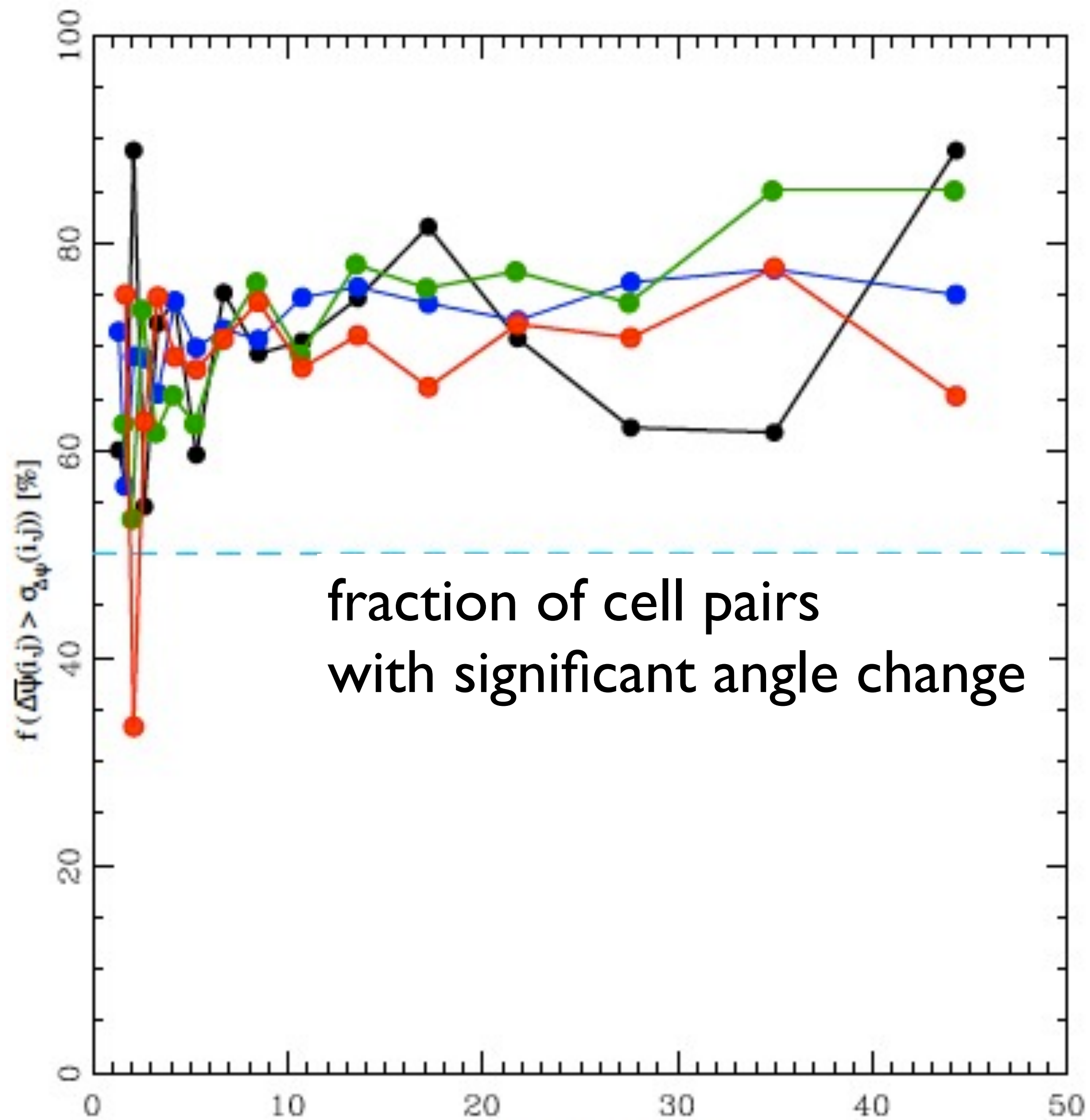

Spaghettis :
cannot be Faraday rotation (353 Ghz)
separate regions with homogenous B of different directions
some are long: must be nearby
width are unresolved
d 2014

Cells separated using Δψ (watershed algorithm)





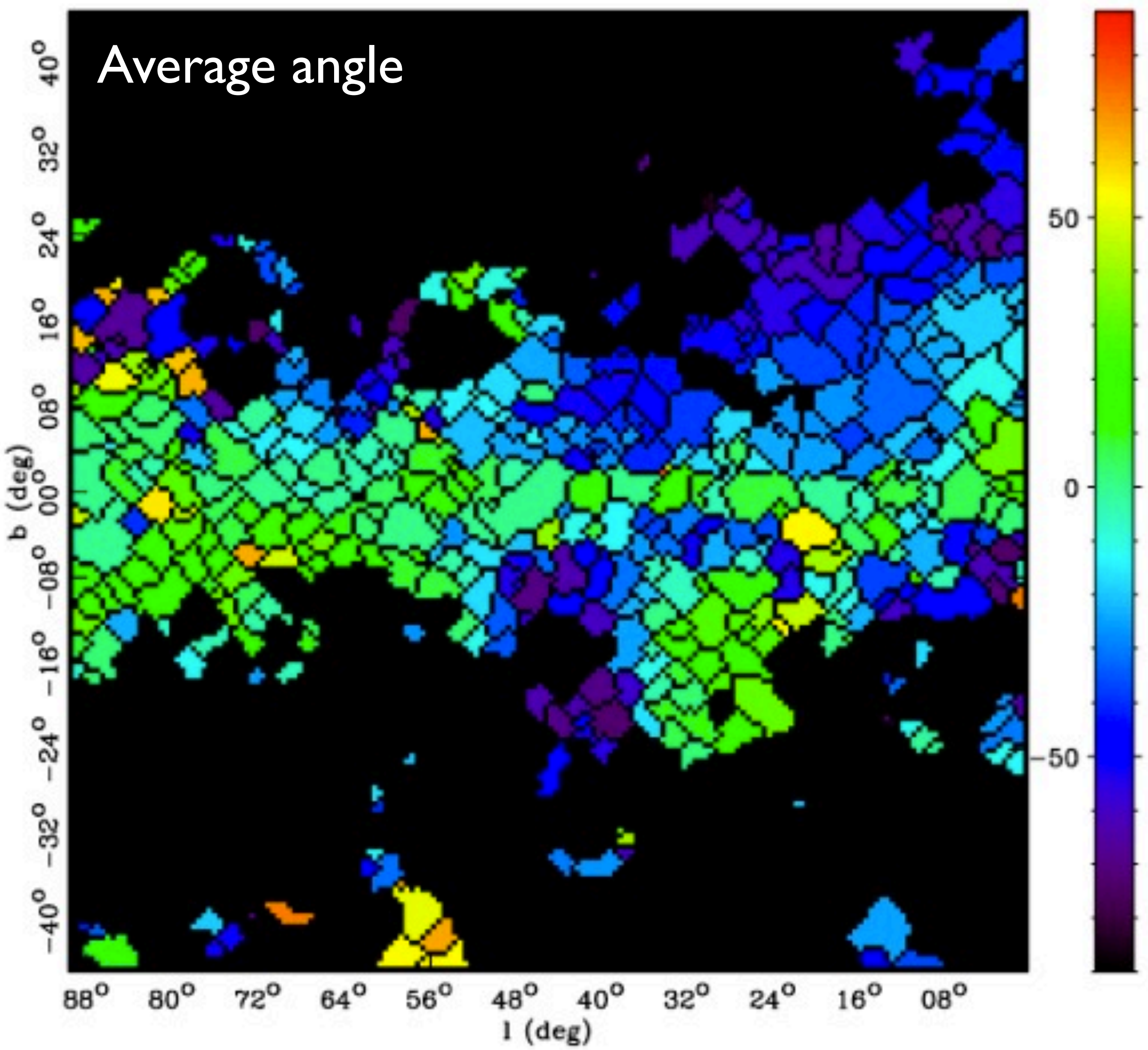
Depolarization canals separate contiguous connex regions with homogenous B, but of different directions

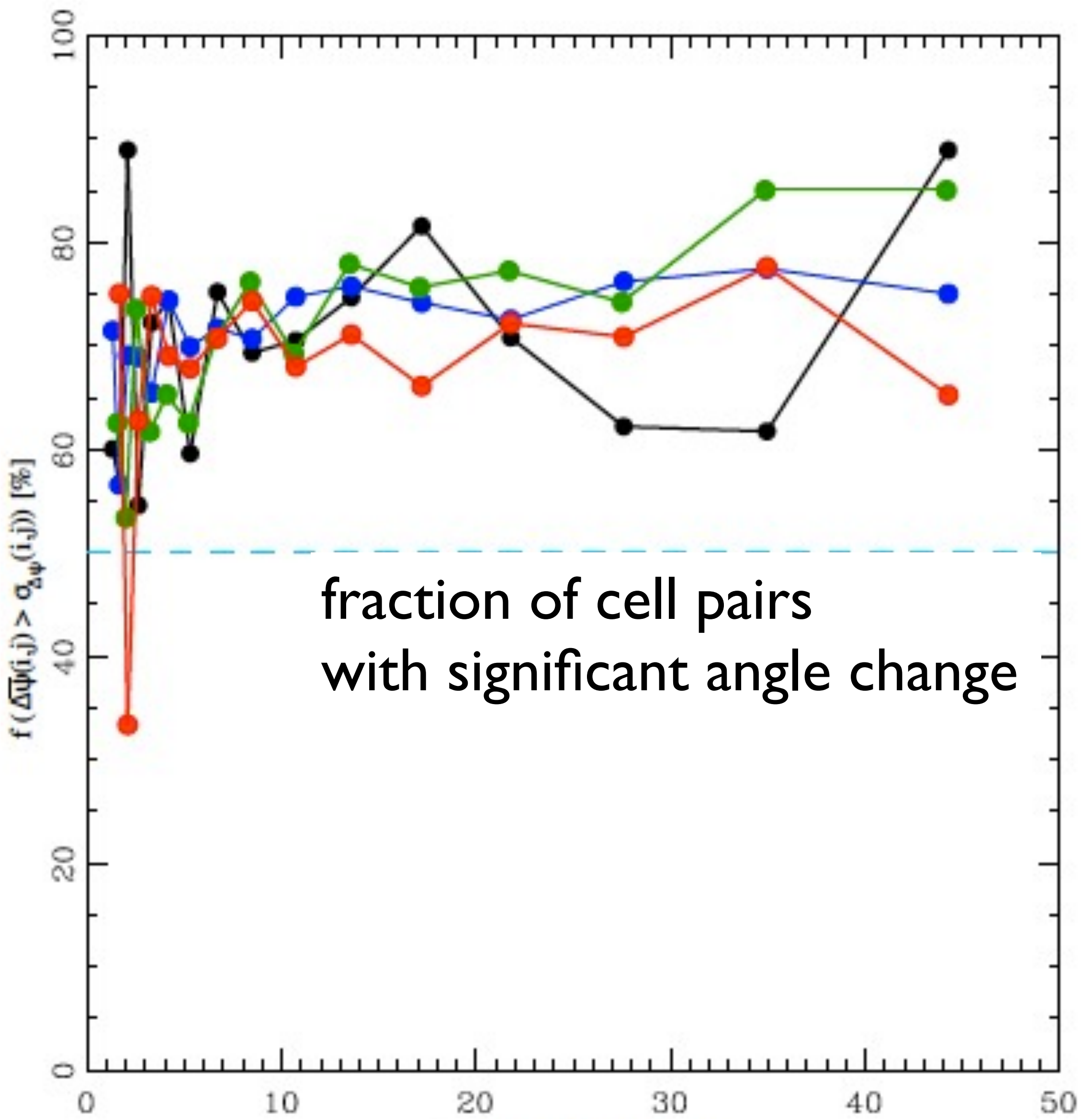
Planck intermediate results. XIX.

J.P. Bernard, Planck Collaboration, Cracow Poland 2014

Angle Dispersion Function

Cells separated using Δψ (watershed algorithm)





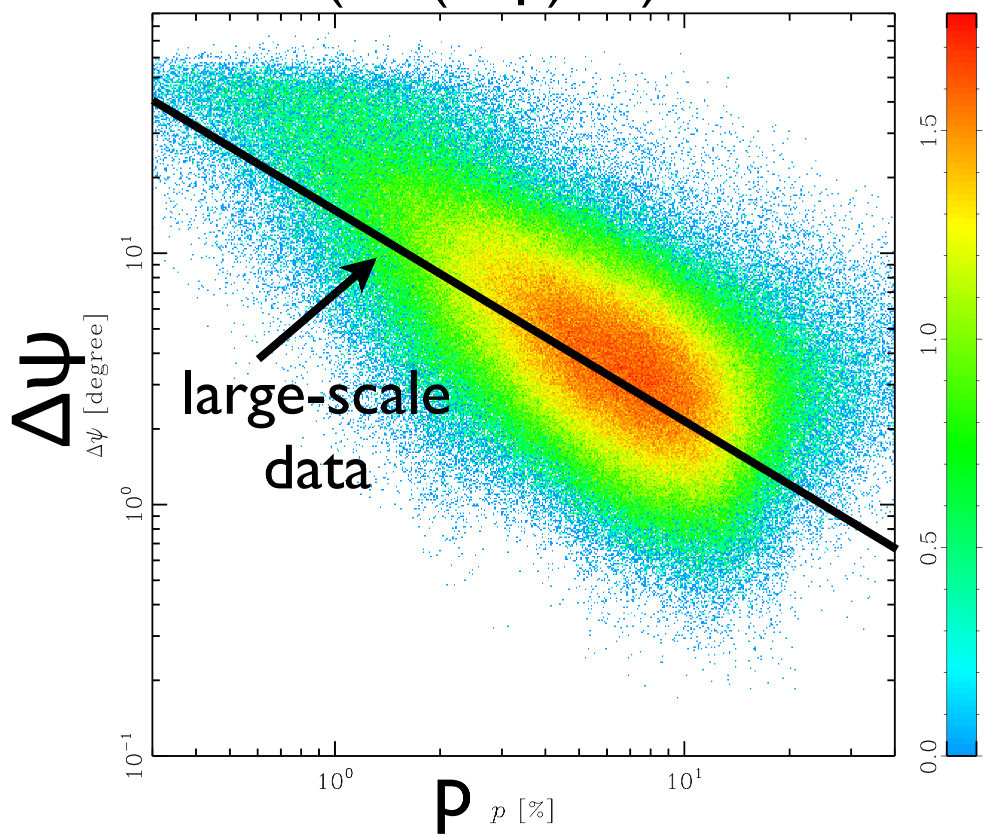
Depolarization canals separate contiguous connex regions with homogenous B, but of different directions

Planck intermediate results. XIX.

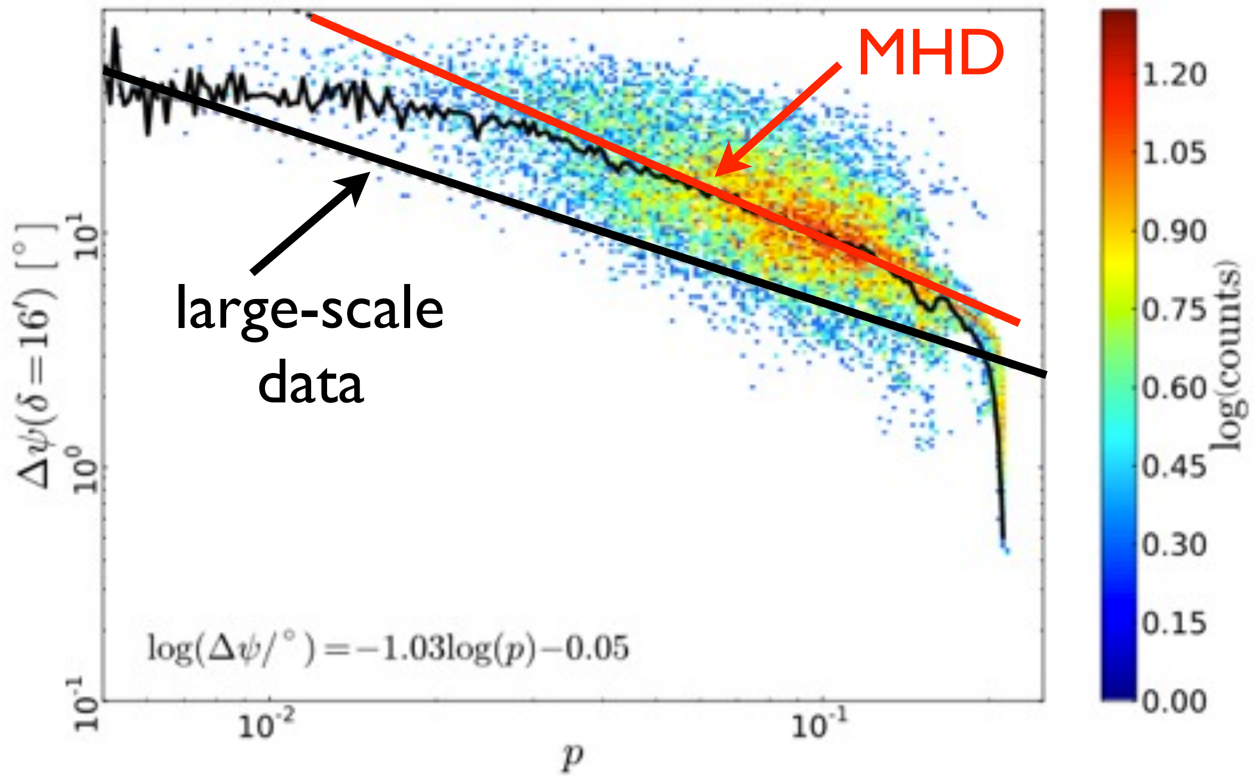
J.P. Bernard, Planck Collaboration, Cracow Poland 2014

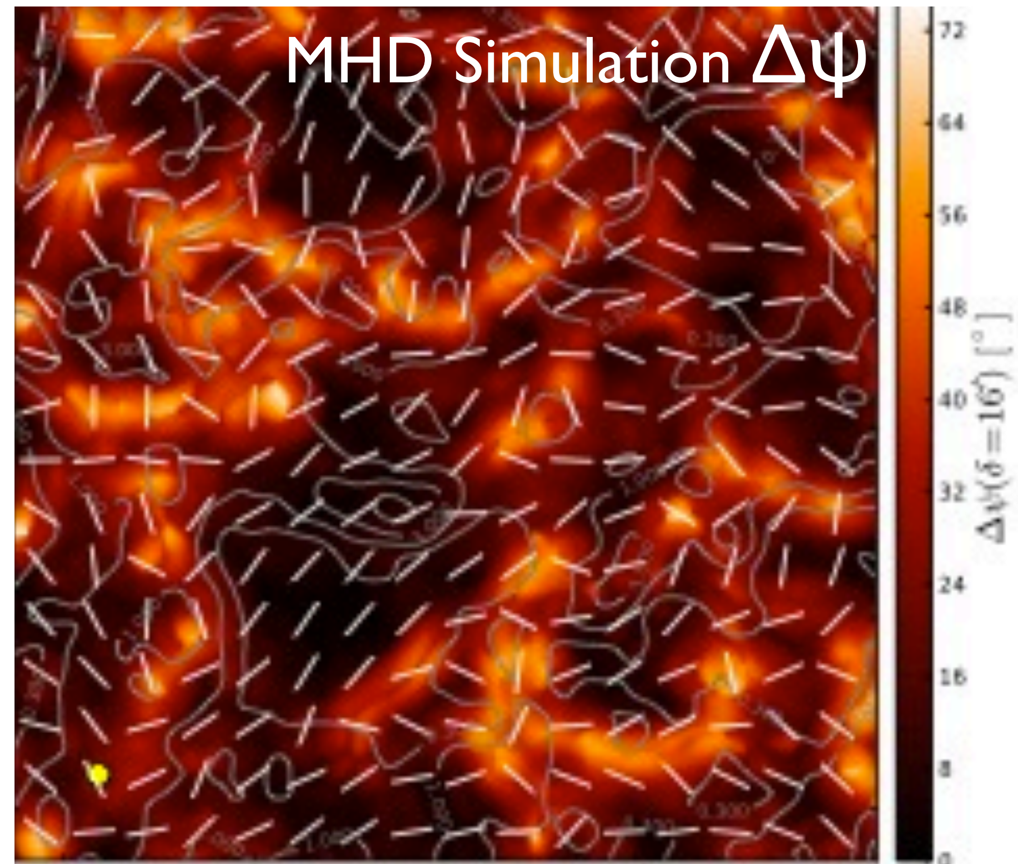
Comparison to MHD simulations

Data (SN(Δψ)>3)



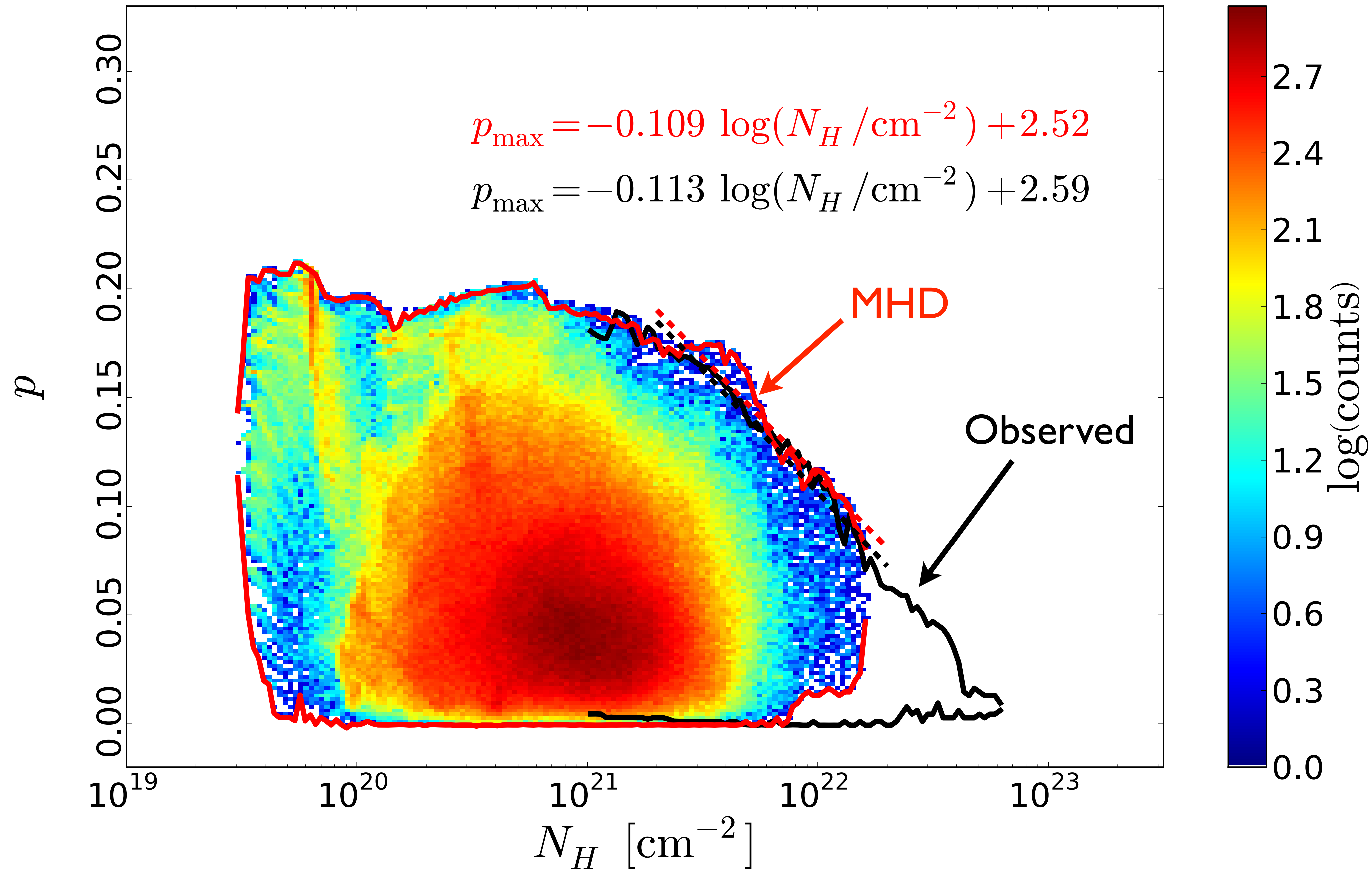
MHD Simulation





- Similar behaviour observed for Δψ in MHD simulations
- MHD Δψ shows similar filamentary structure
- Some differences in absolute Δψ level ...

Polarization fraction vs column density

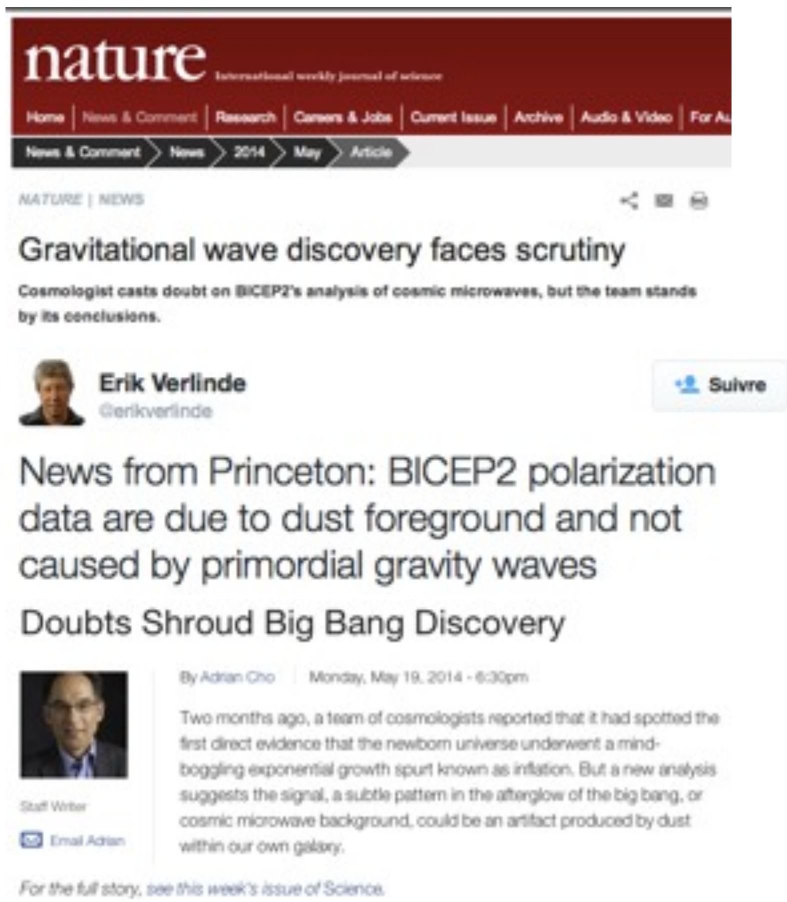


Simulations reproduce well the decrease of $p_{\rm max}$ with $N_{\rm H}$ in the range 10^{21} to 2×10^{22} cm^{-2}

Planck intermediate results. XX.

J.P. Bernard, Planck Collaboration, Cracow Poland 2014

Planck and CMB Foreground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Gravitational wave discovery faces scrutiny

Cosmologist casts doubt on BICEP2's analysis of cosmic microwaves, but the team stands by its conclusions.

Erik Verlinde
@erikverlinde
Suivre

News from Princeton: BICEP2 polarization data are due to dust foreground and not caused by primordial gravity waves

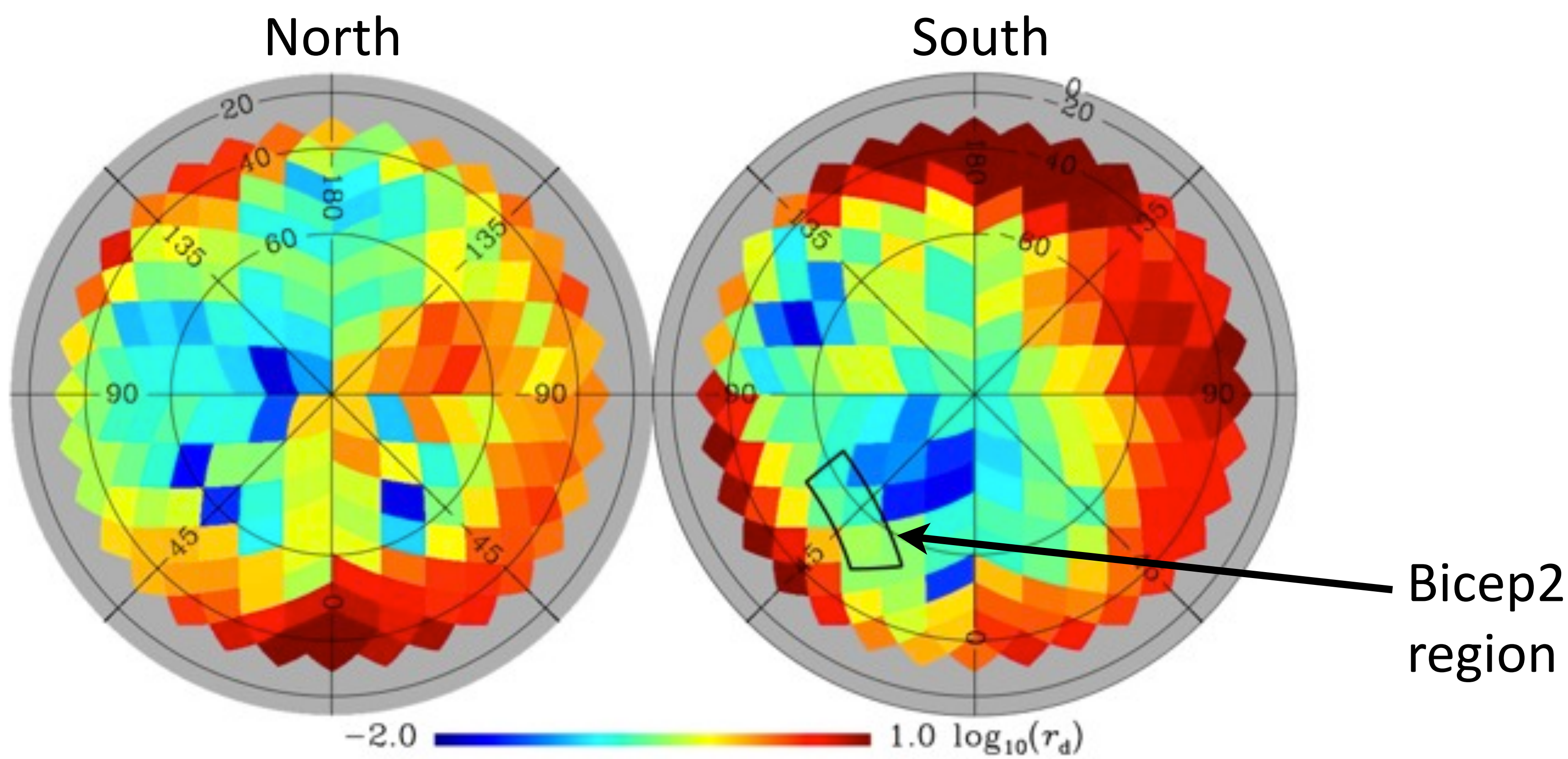
Doubts Shroud Big Bang Discovery

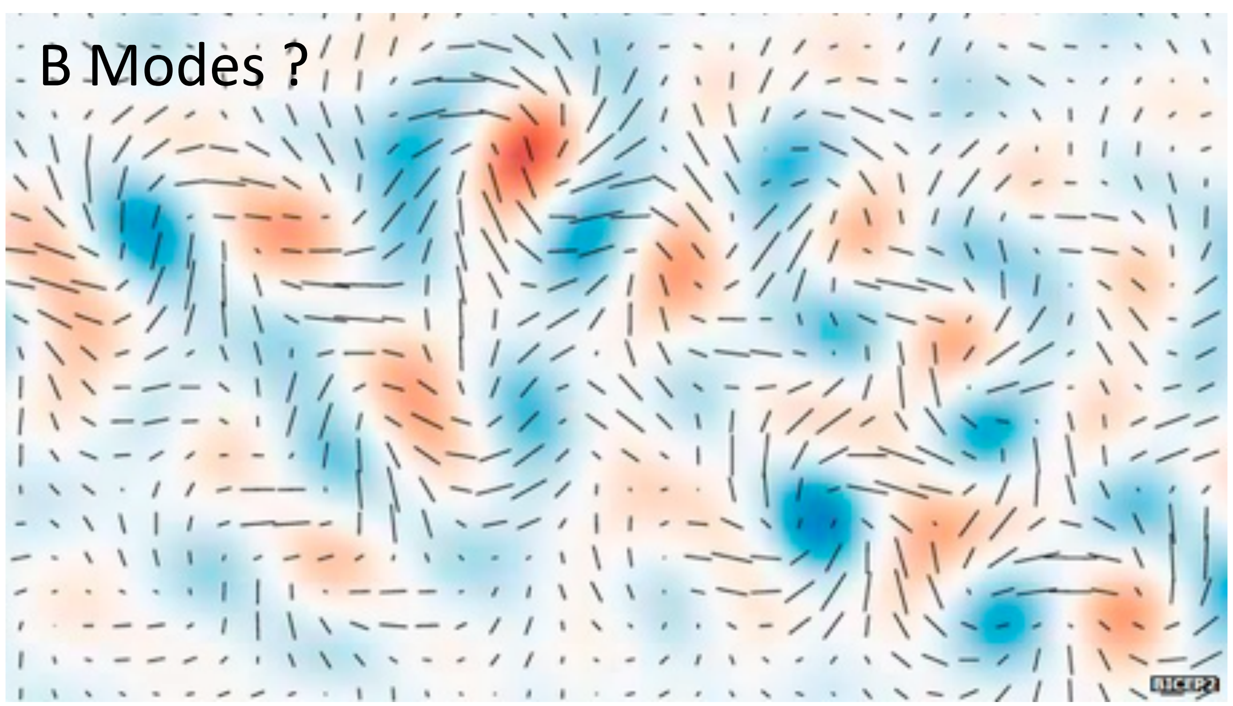
By Adrian Cho | Monday, May 19, 2014 - 6:30pm

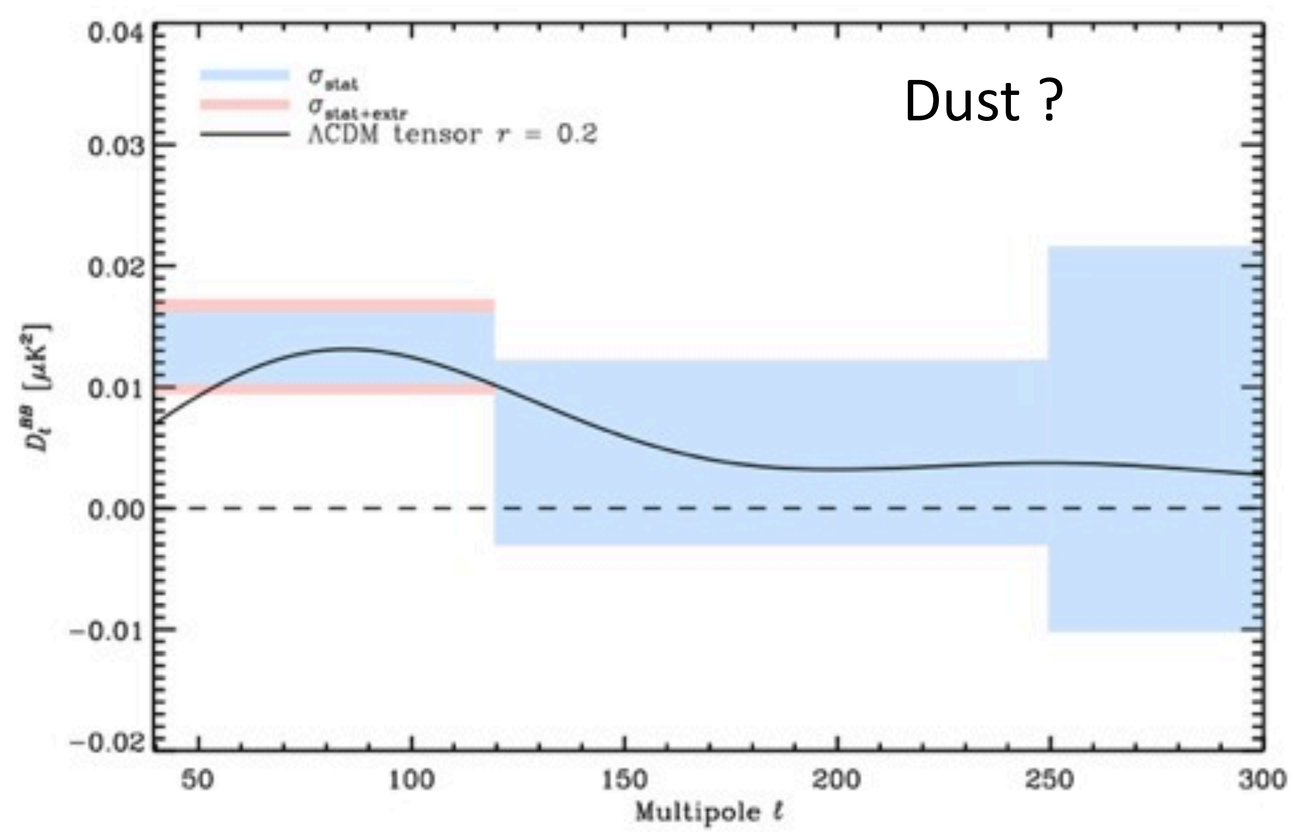
Staff Writer
Email Adrian

Two months ago, a team of cosmologists reported that it had spotted the first direct evidence that the newborn universe underwent a mind-boggling exponential growth spurt known as inflation. But a new analysis suggests the signal, a subtle pattern in the afterglow of the big bang, or cosmic microwave background, could be an artifact produced by dust within our own galaxy.

For the full story, see this week's issue of Science.

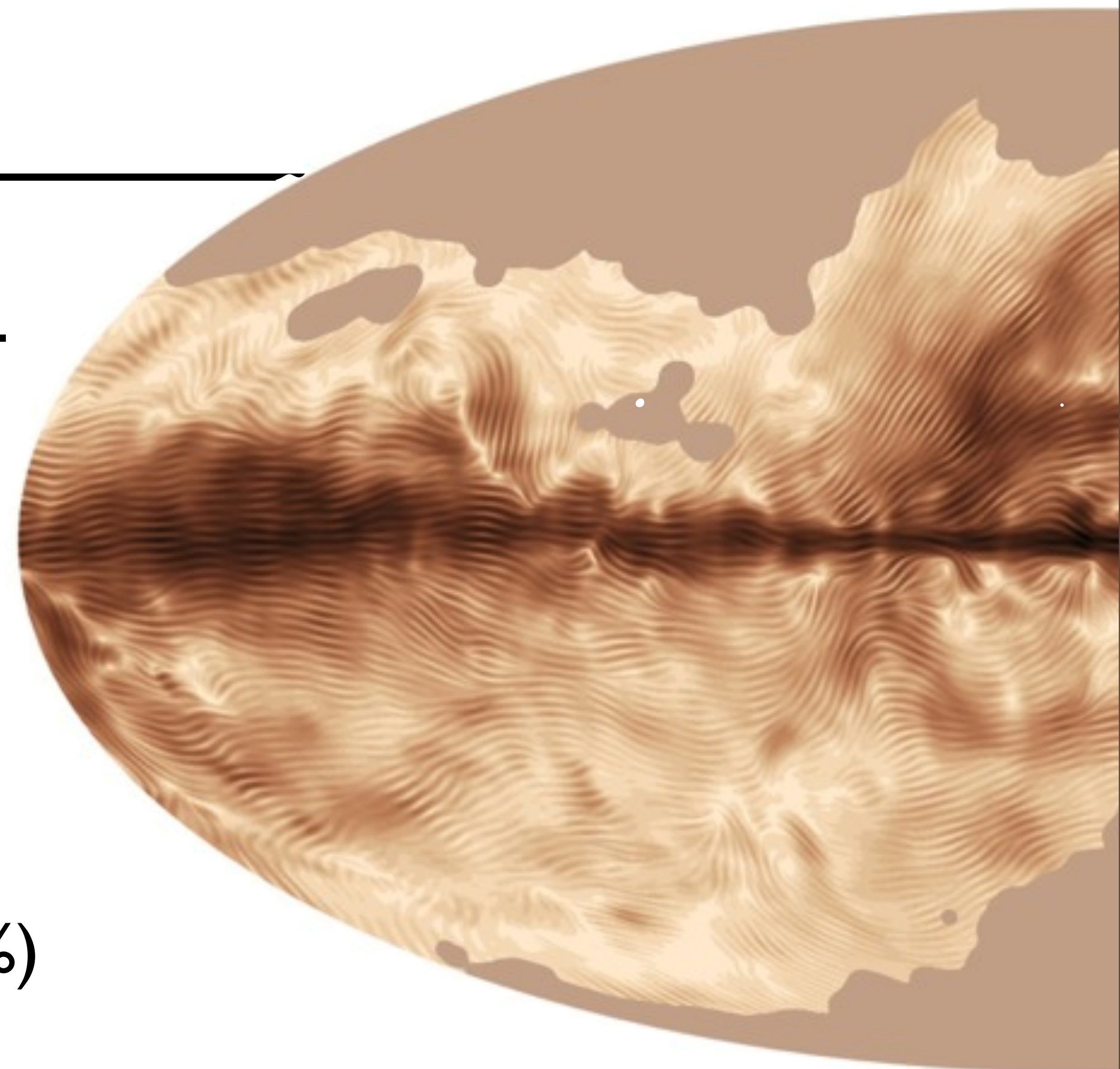






Planck intermediate results. XXX.

Conclusions



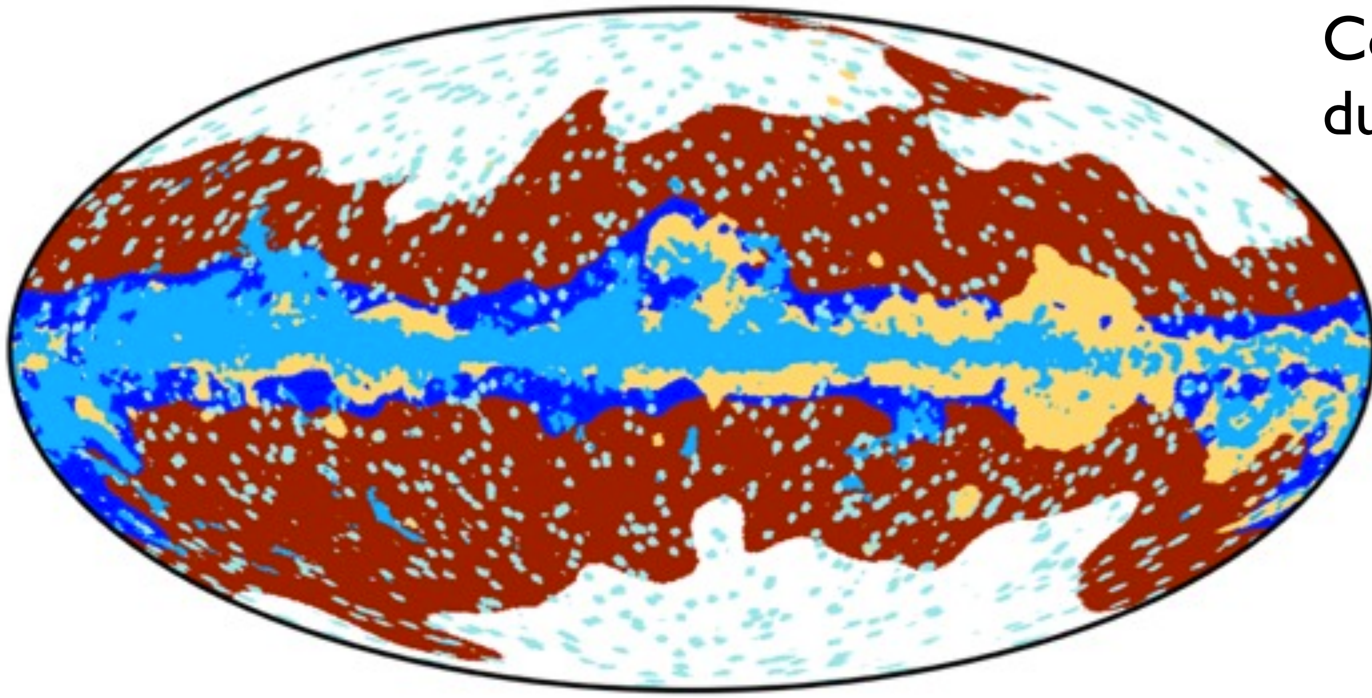
- Planck is providing completely new large-scale information on dust polarization

- This is revealing both the magnetic field geometry of our galaxy and new properties of dust emission

- Dust has high intrinsic polarization (>20%)
- p decreases with N_H
- We see depolarization canals, not due to Faradat rotation
- Anticorrelation between p and angle dispertion underlines importance of the field geometry.
- New constraints for dust models.

- The Analysis is only at a start

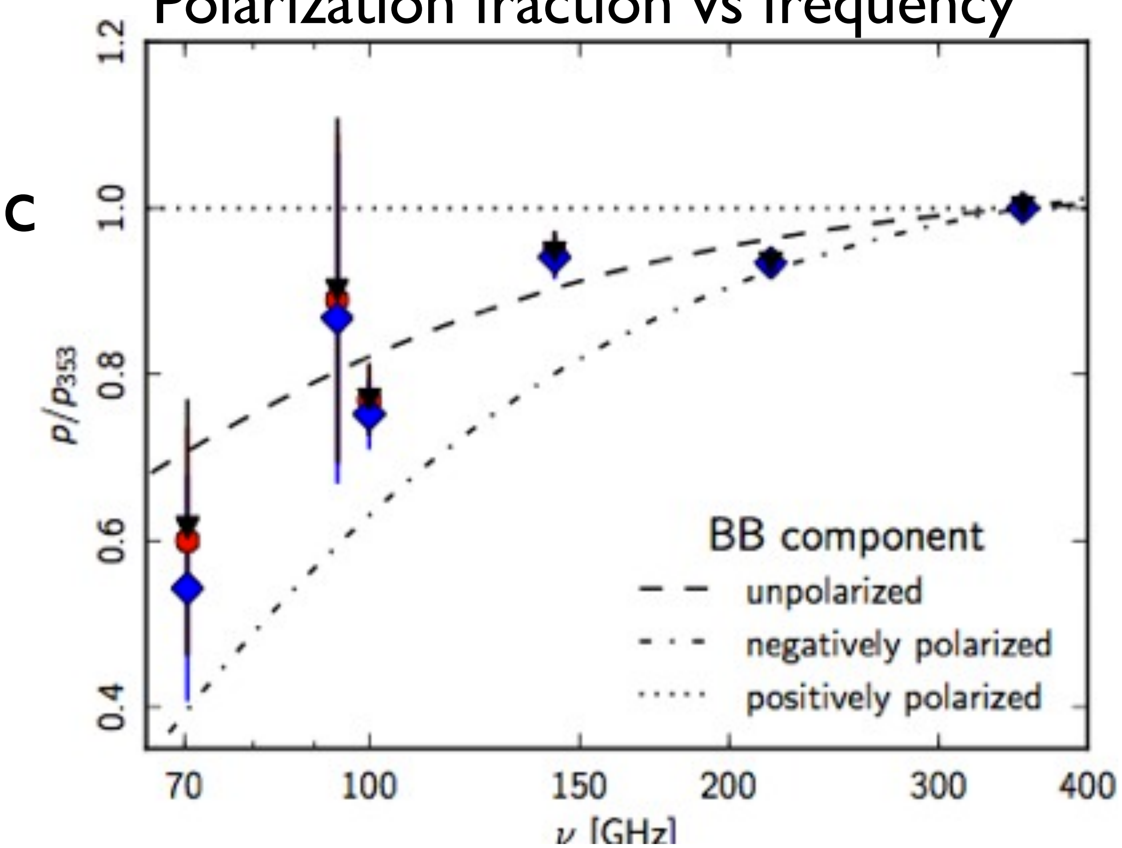
Data to be released in the fall



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

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

Polarization fraction vs frequency

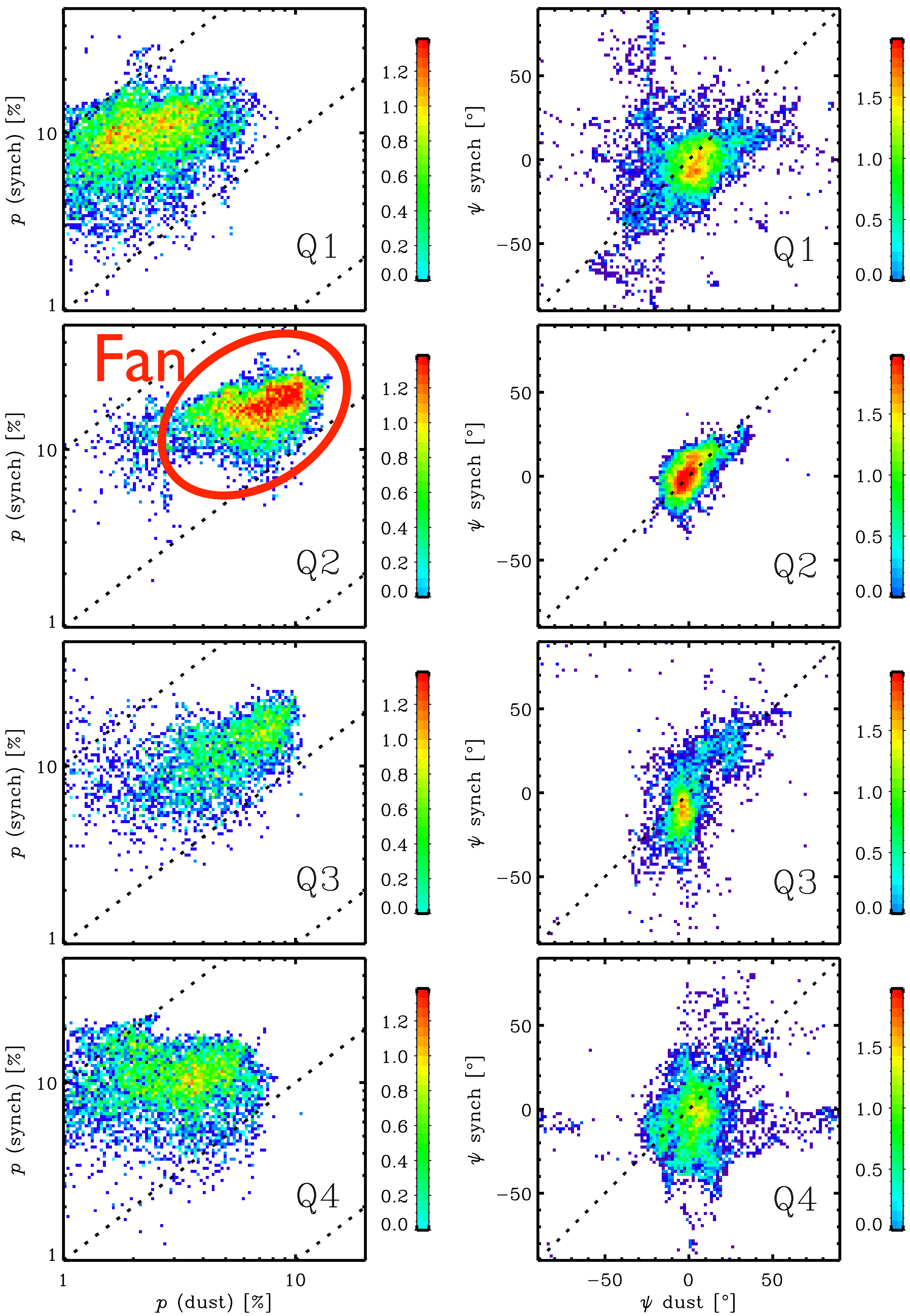


Evidences lower p at long wavelengths

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

New constraints on dust models and/or component separation

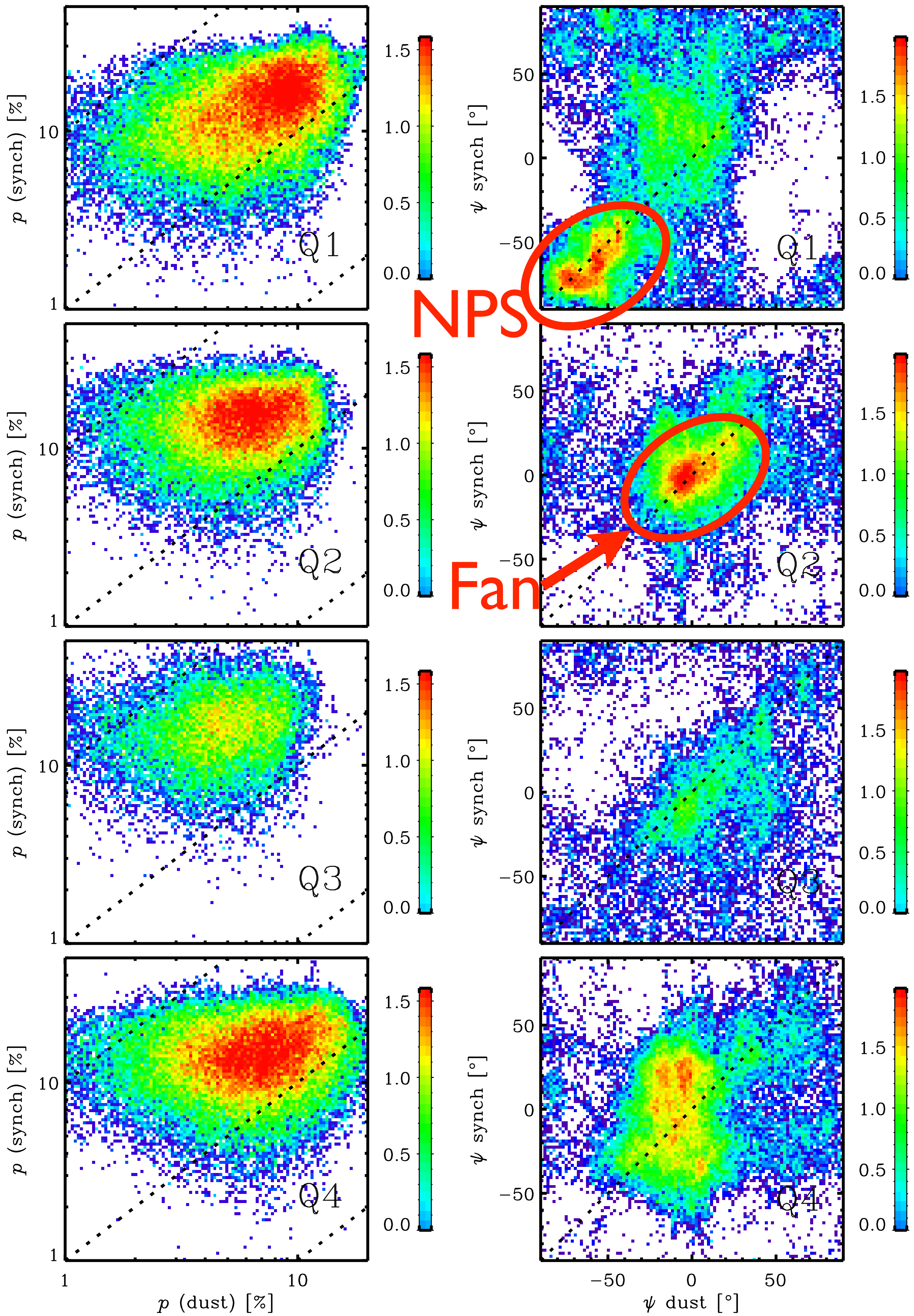
Synchrotron vs Dust



- p:
  - 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

Synchrotron vs Dust

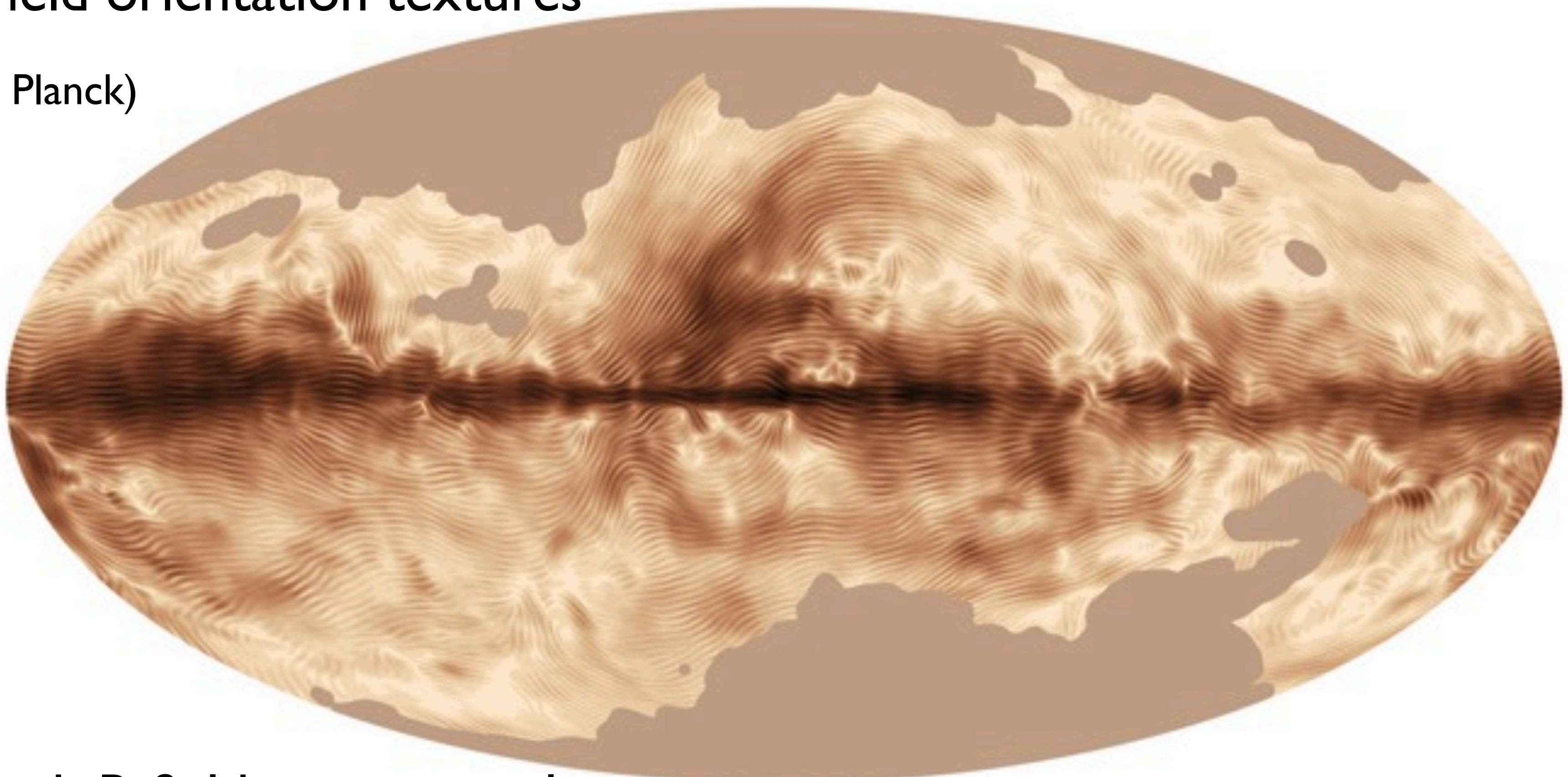


|b|>5°

- Off the plane, weaker signal, more scatter. Little measured correlation except in Q1.
- In angles, two things to note:
  - Correlation in Q1 due to North Polar Spur region
  - Angles still zero off the plane in Fan region. I.e., field remains coherent and parallel to the plane over a large region of that quadrant in both observables.
- Significant scatter otherwise, synchrotron and dust not generally tracing the same fields.

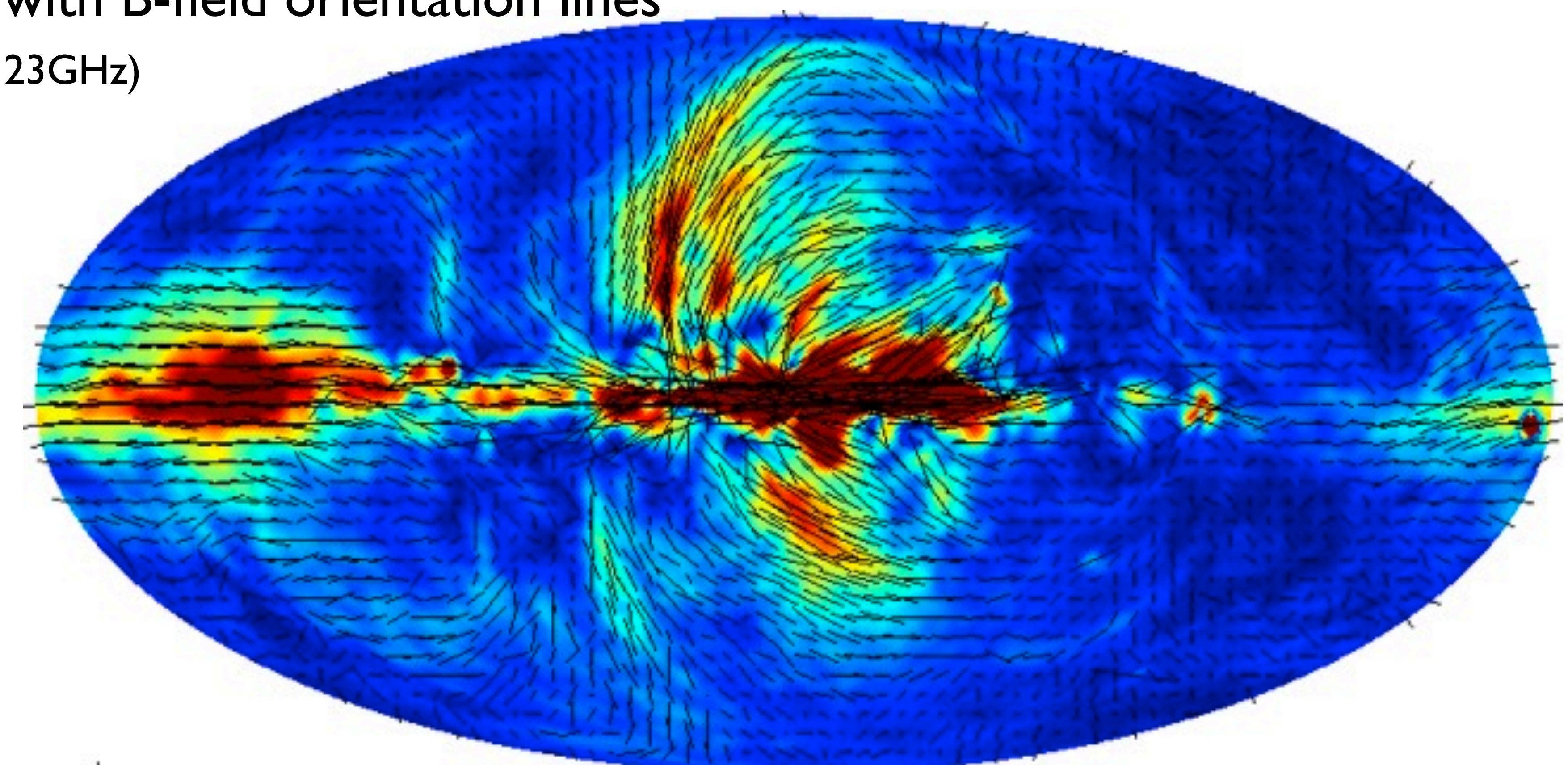
Dust *PI* with B-field orientation textures

(Image ESA Planck)



Synchrotron *PI* with B-field orientation lines

(WMAP 23GHz)

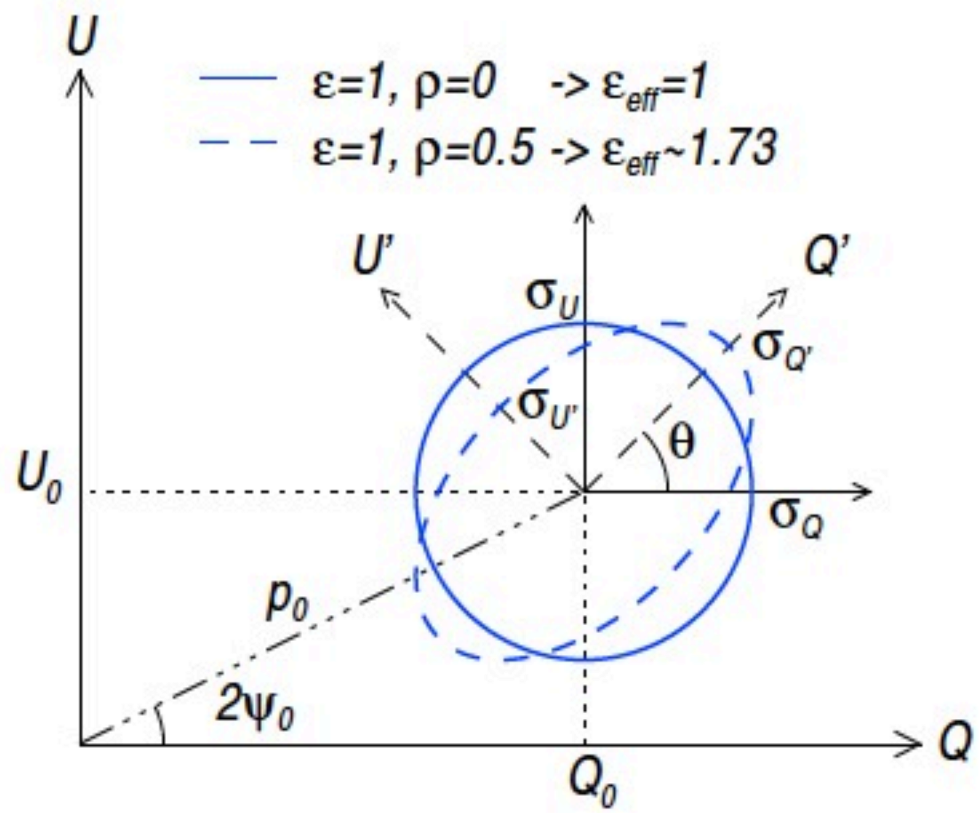


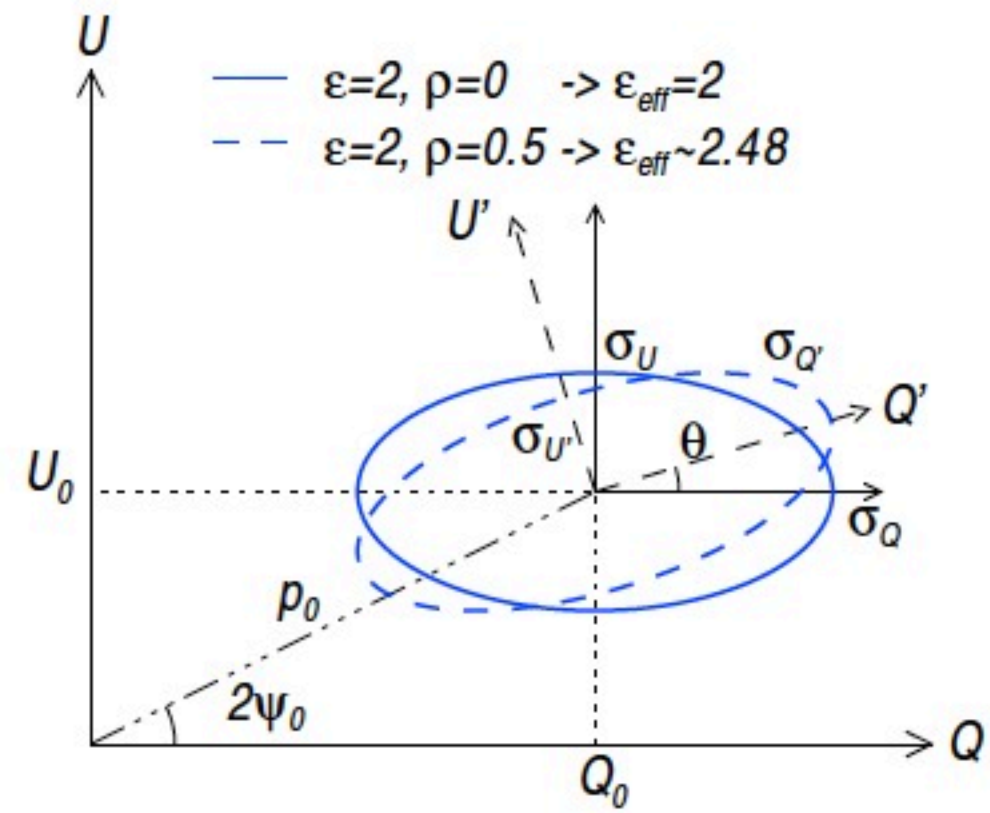
Noise and Bias

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

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

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





Montier et al. 2014a, 2014b