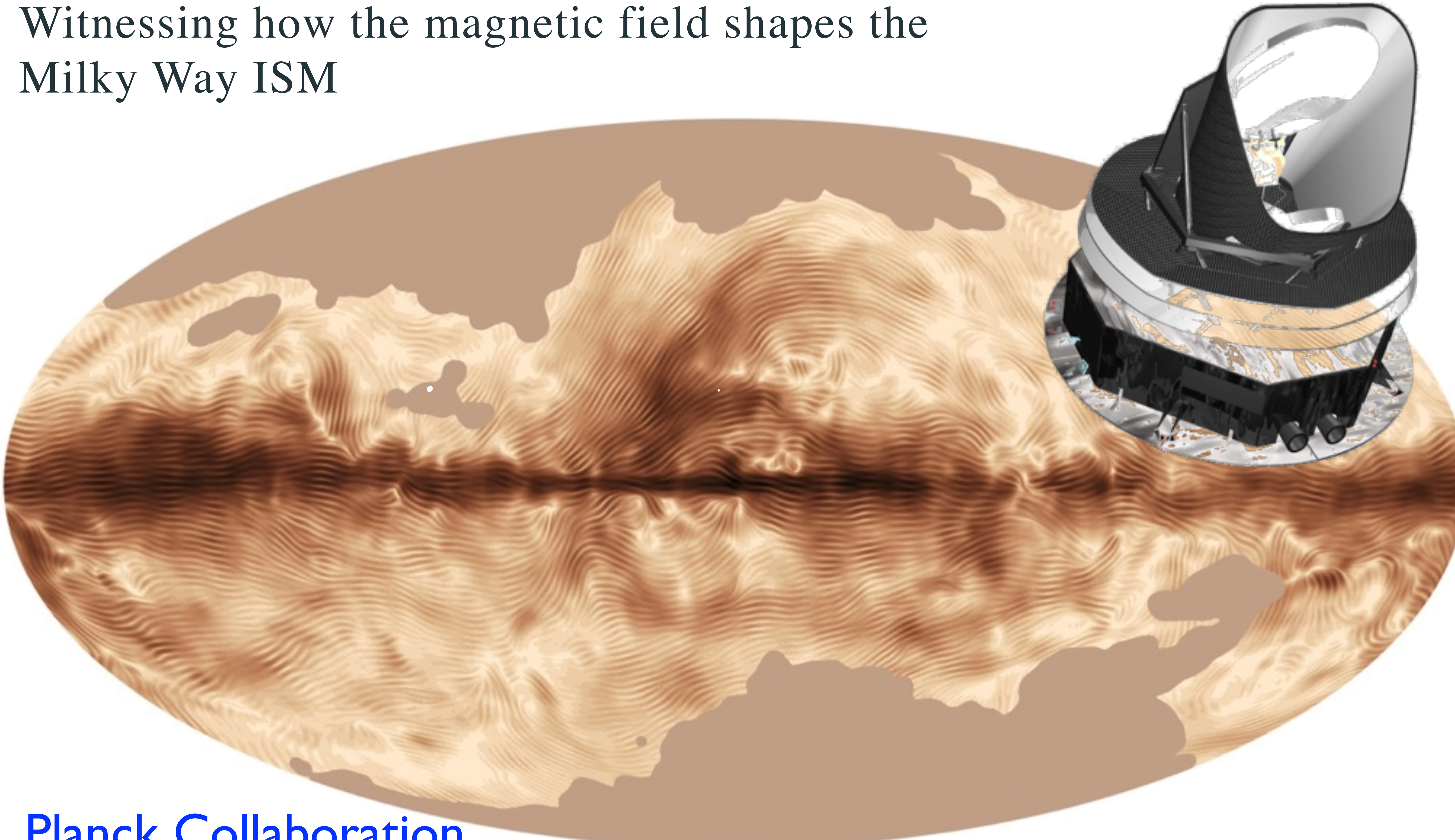
Planck all-sky thermal dust Polarization

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 *This presentation*
- **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 *See Talk by Bracco*
The relative orientation between the magnetic field and structures traced by interstellar dust
- **Planck intermediate results. XXXIII.** arXiv:astro-ph 1411.2271 *See Talk by Arzoumanian*
Signature of the magnetic field geometry of interstellar filaments in dust polarization maps
- **Planck intermediate results. XXXIV.** arXiv:astro-ph 1501.00922 *See Talk by Alves*
The magnetic field structure in the Rosette Nebula
- **Planck Collaboration Planck intermediate results. XXXV.** arXiv:astro-ph 1502.0412 *See Talk by Soler*
Probing the role of the magnetic field in the formation of structure in molecular clouds

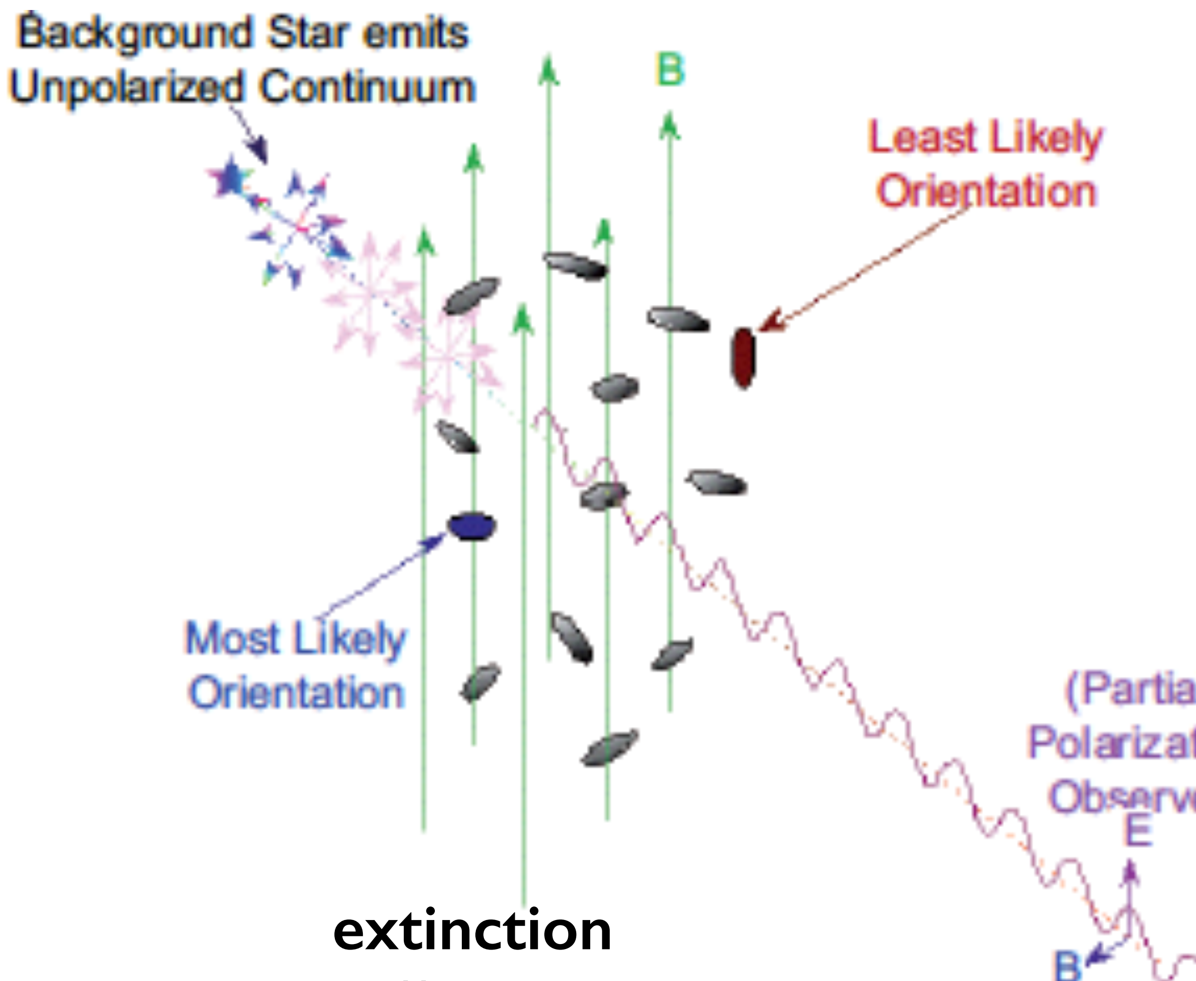
---

- **Montier et al.** 2015 A&A 574, 135, **Montier et al.** 2015 A&A 574, 136 *See Talk by Montier*
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

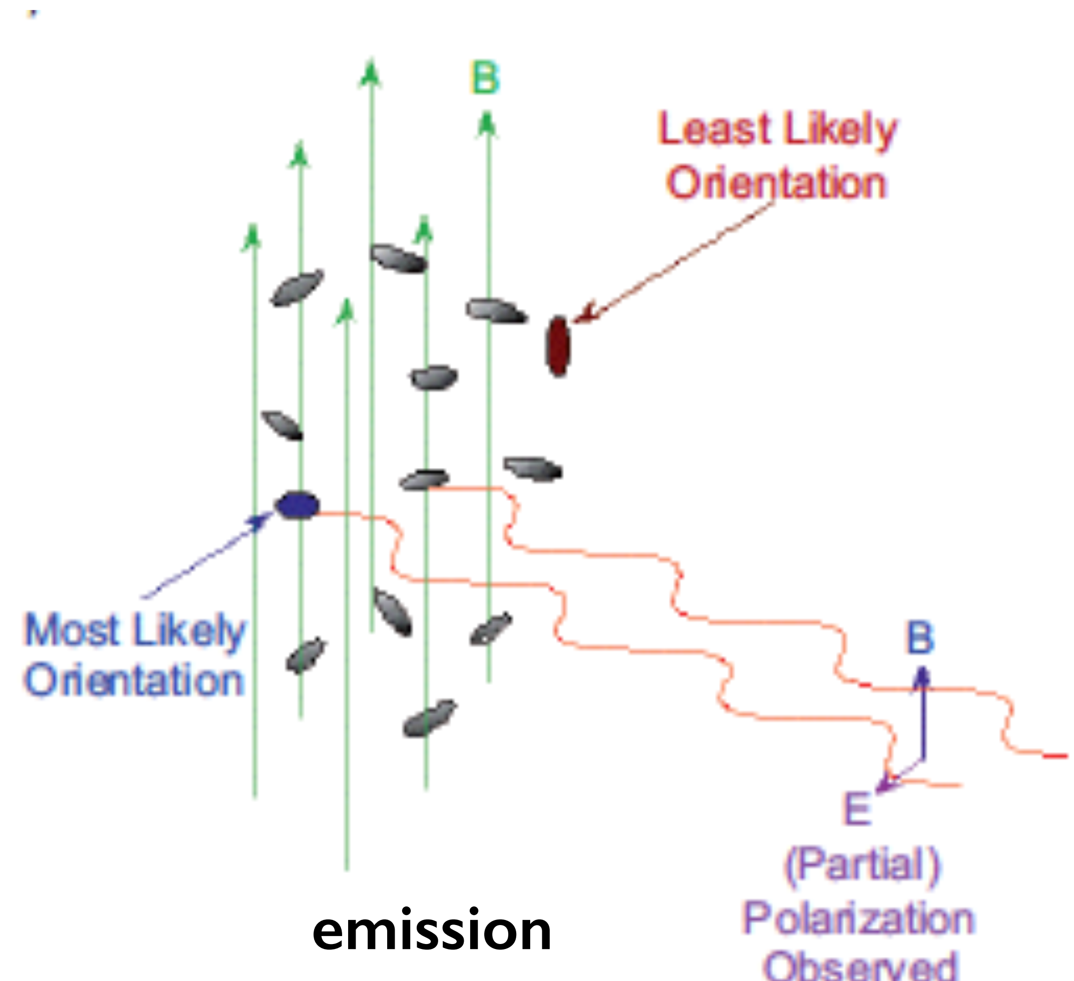
---

- **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 *See Talk by Ghosh*

Dust Polarization

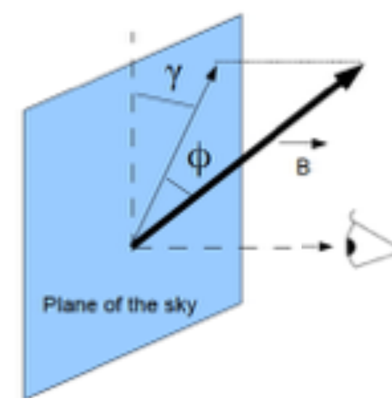


extinction
// to B



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)

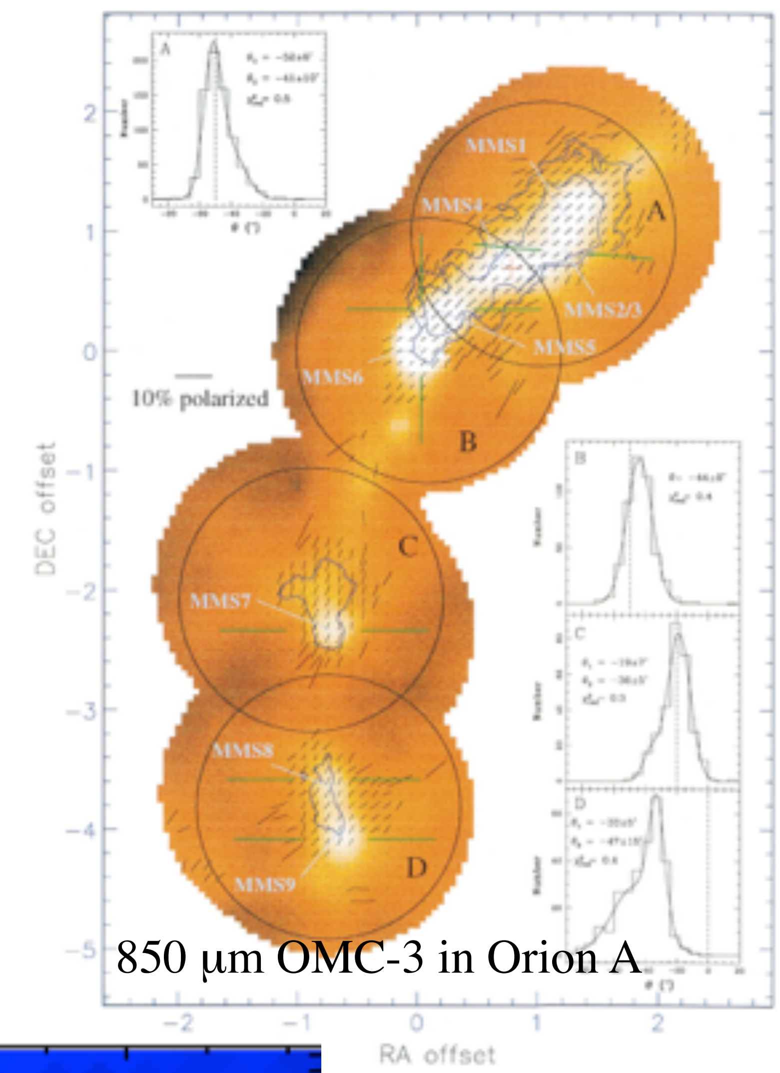


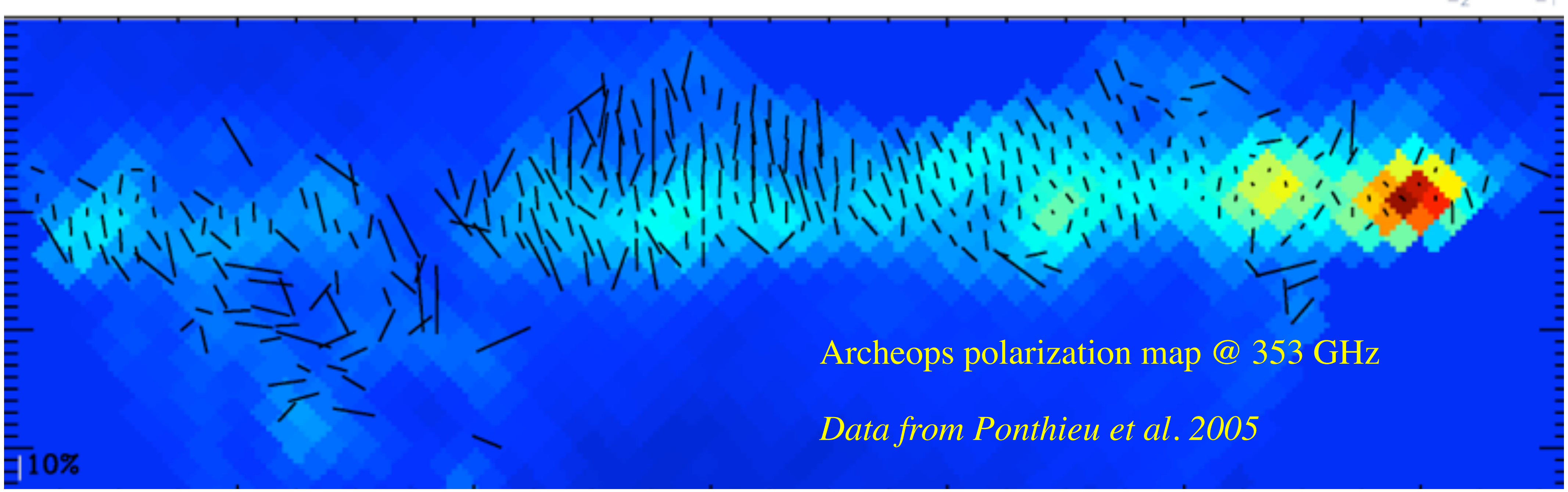
$$P = \sqrt{(Q^2+U^2)} \propto \cos^2\phi$$

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

Before Planck: emission

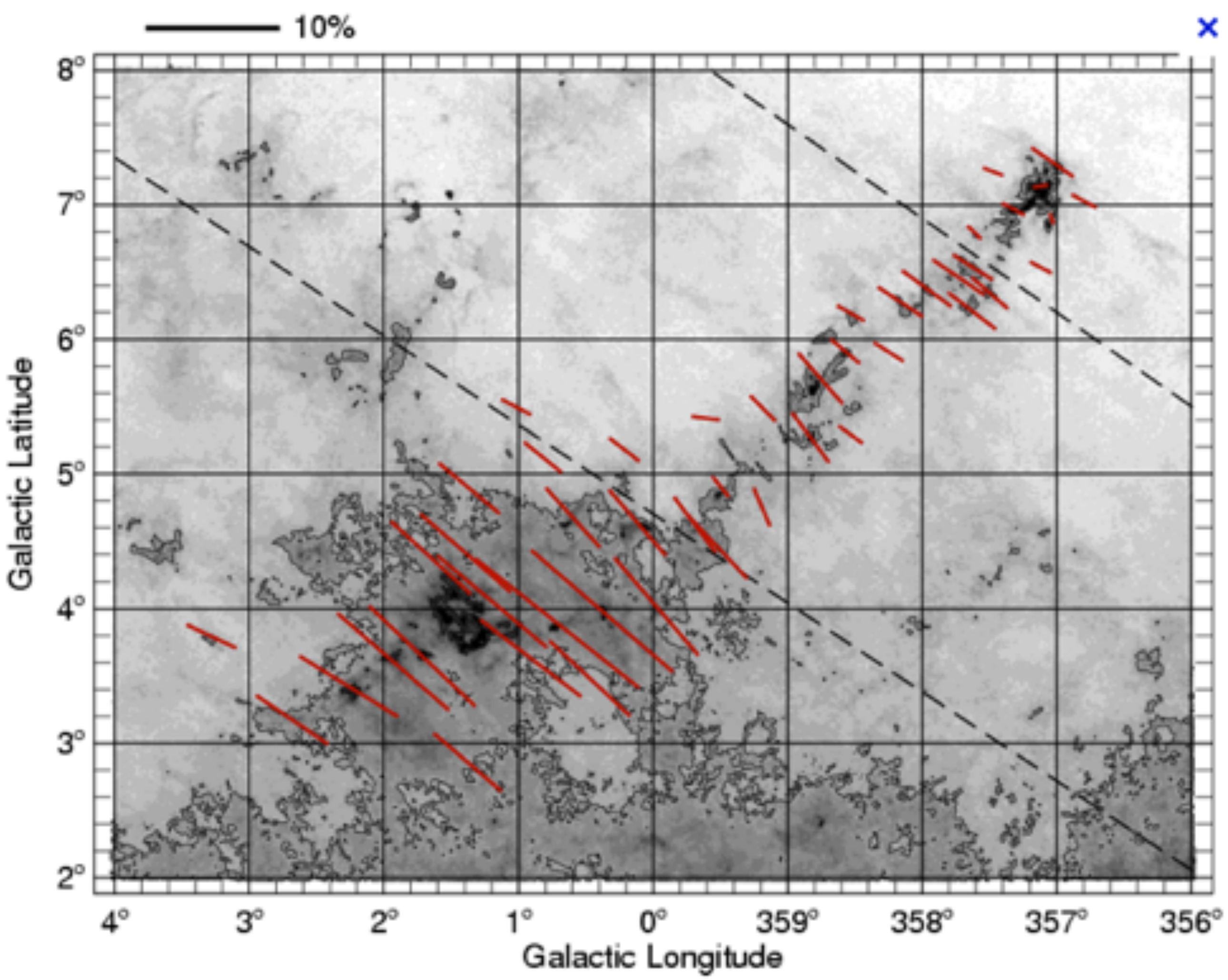
- Ground submm measurements (restricted to bright regions) indicate low p values (a few %)
- Archeops claimed 10-15% off the plane (2nd Galactic Quadrant)

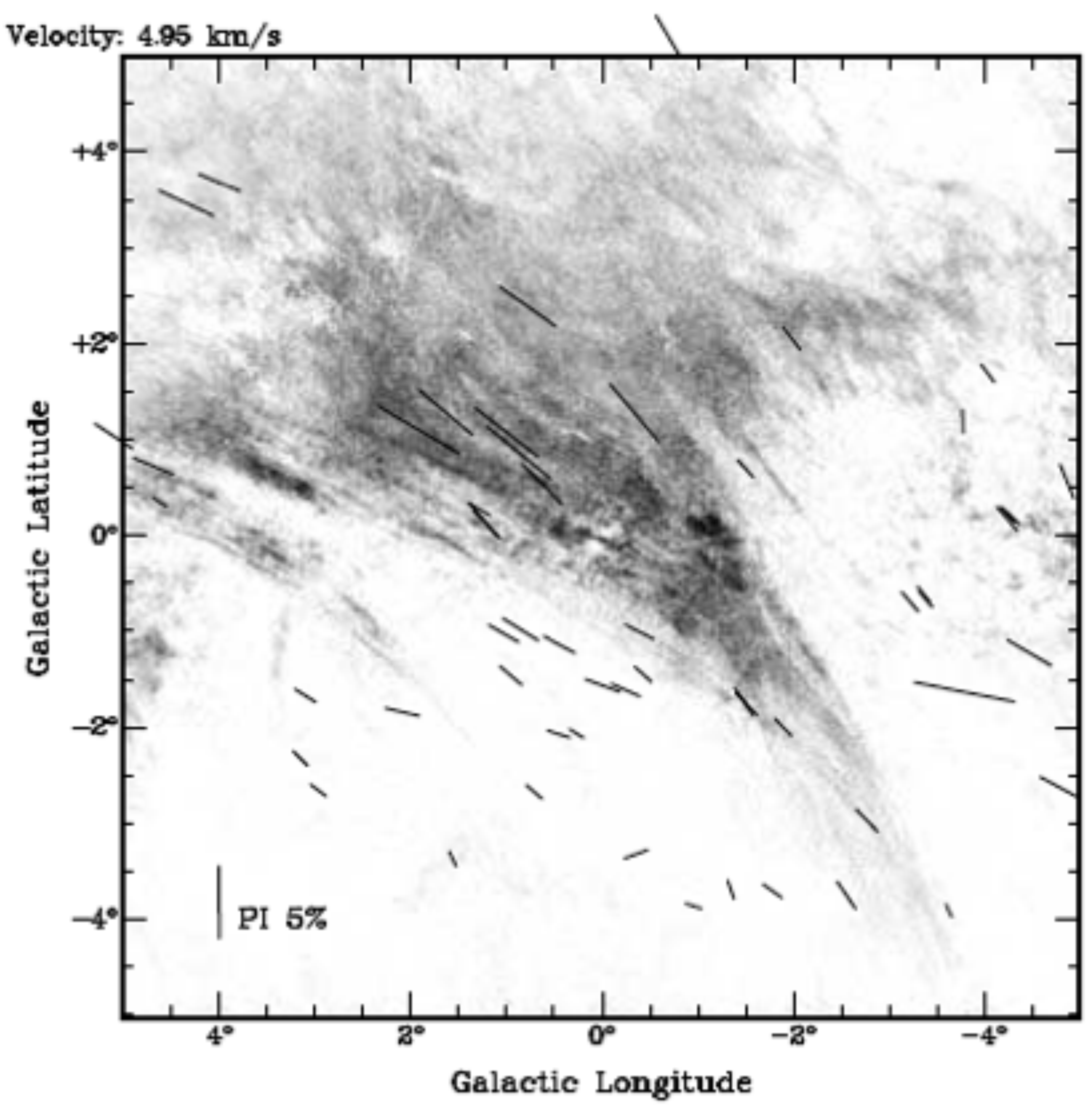




Before Planck: Extinction

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

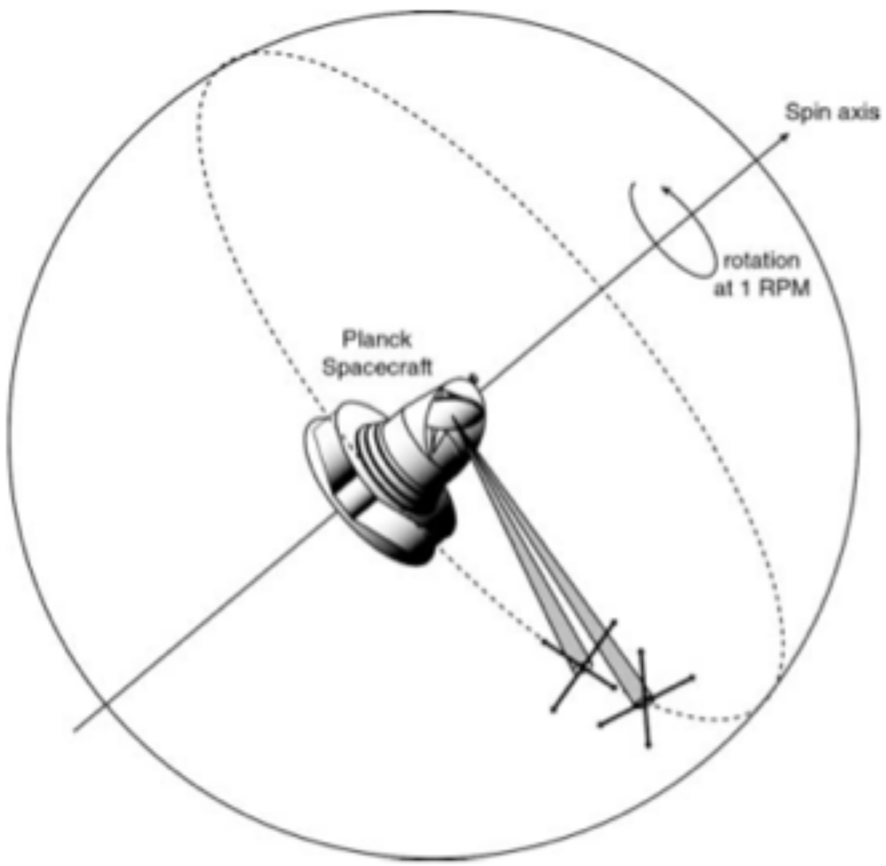




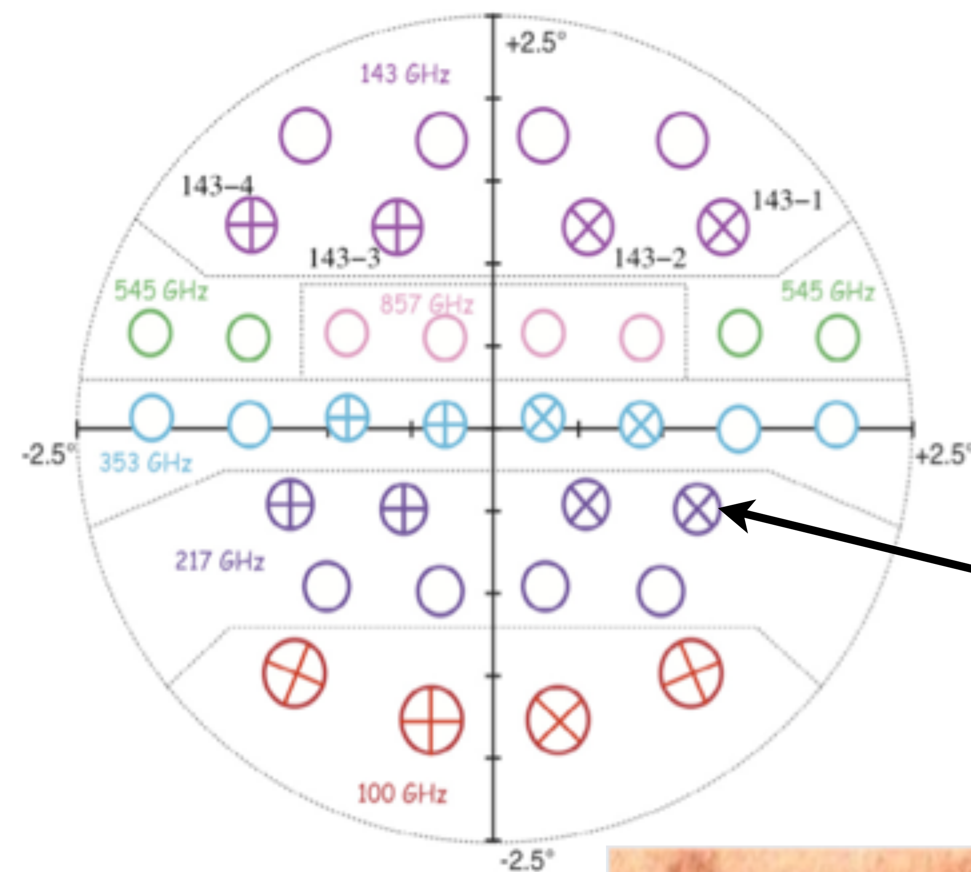
... although the two examples shown here (only a few degrees apart on the sky) give opposite filament orientation w.r.t. B field

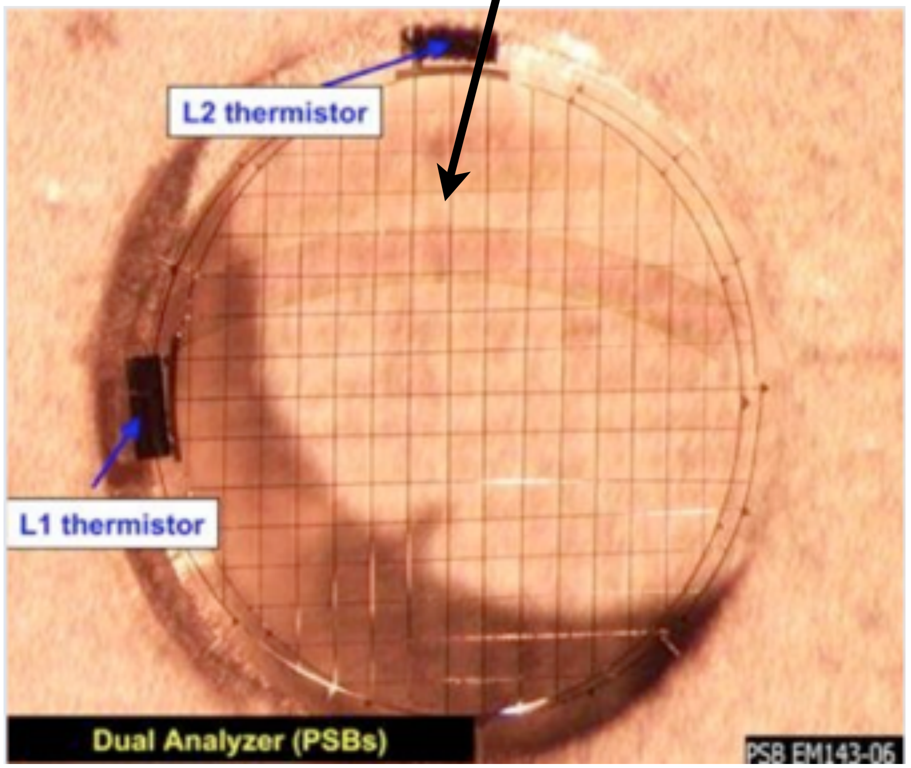
How Planck measures polarization

Planck scanning the sky



Planck/HFI focal plane





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

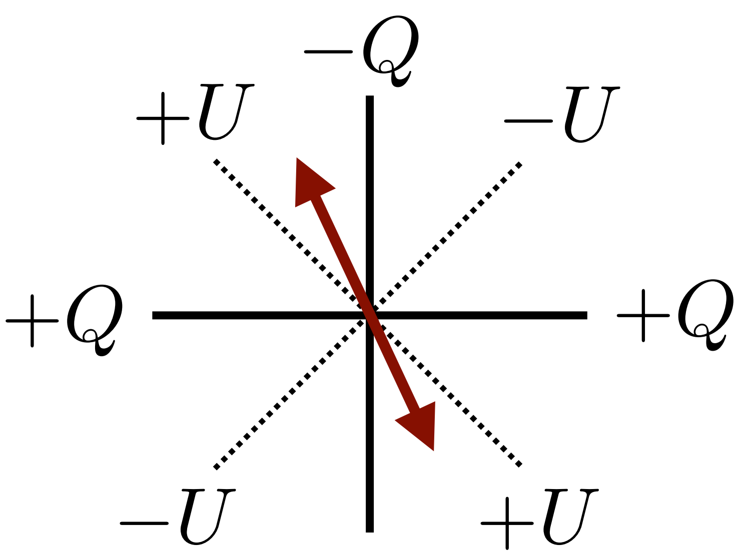
$$s_1 - s_2 = Q\ cos(2\alpha) + U\ sin(2\alpha)$$
$$s_3 - s_4 = Q\ sin(2\alpha) - U\ cos(2\alpha)$$

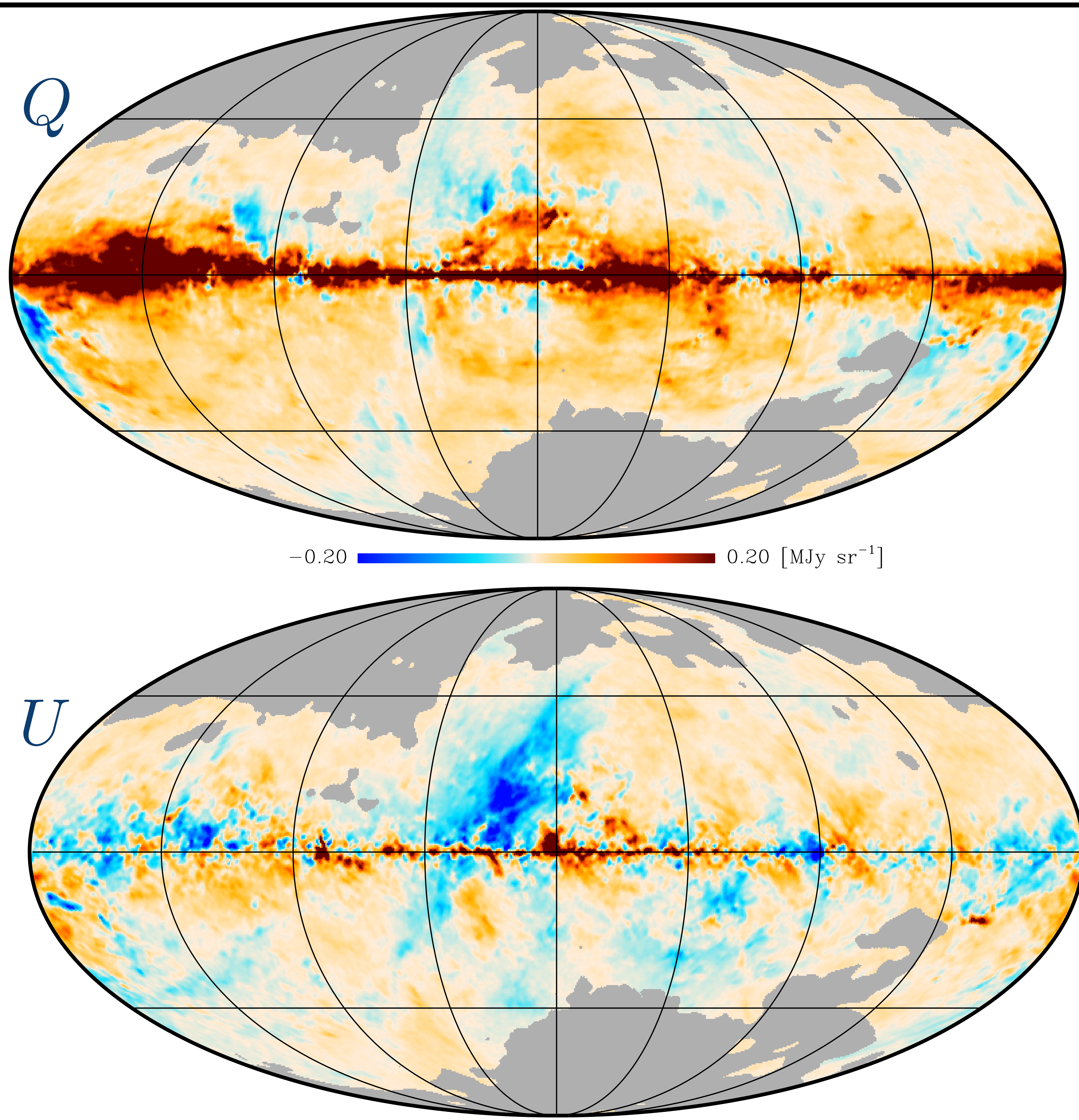
Multiple scans provide Q and U with different a orientation.
Maps of Q and U and their standard deviations are derived.

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

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

noise cov. matrix →

	$\varepsilon = 1$, $\rho = 0$	$\varepsilon = 1/2$, $\rho = 0$	$\varepsilon = 2$, $\rho = 0$	$\varepsilon = 1$, $\rho = -1/2$	$\varepsilon = 1$, $\rho = 1/2$

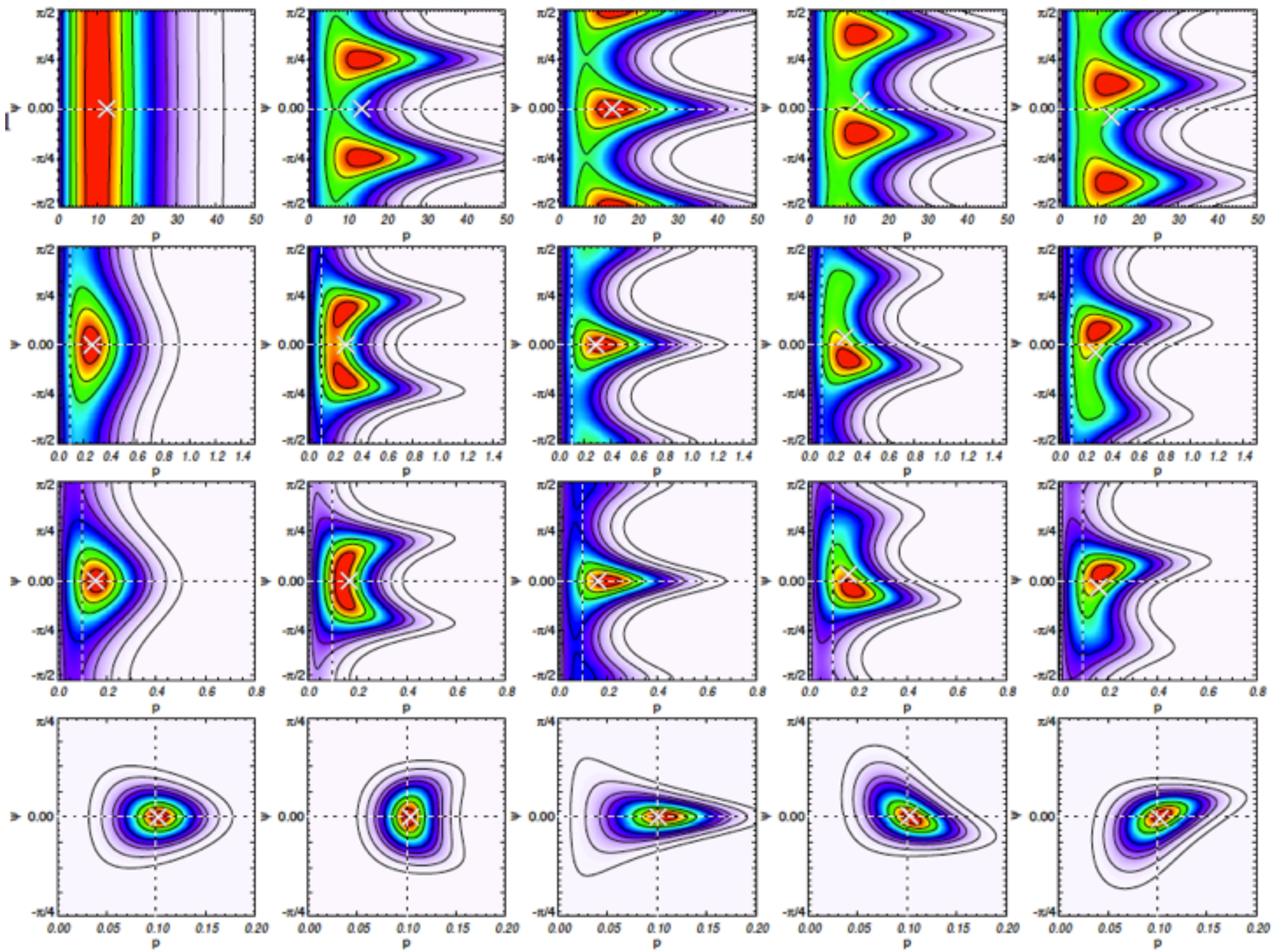
p_0/σ_p ↓

0.01

0.5

1

5



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

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

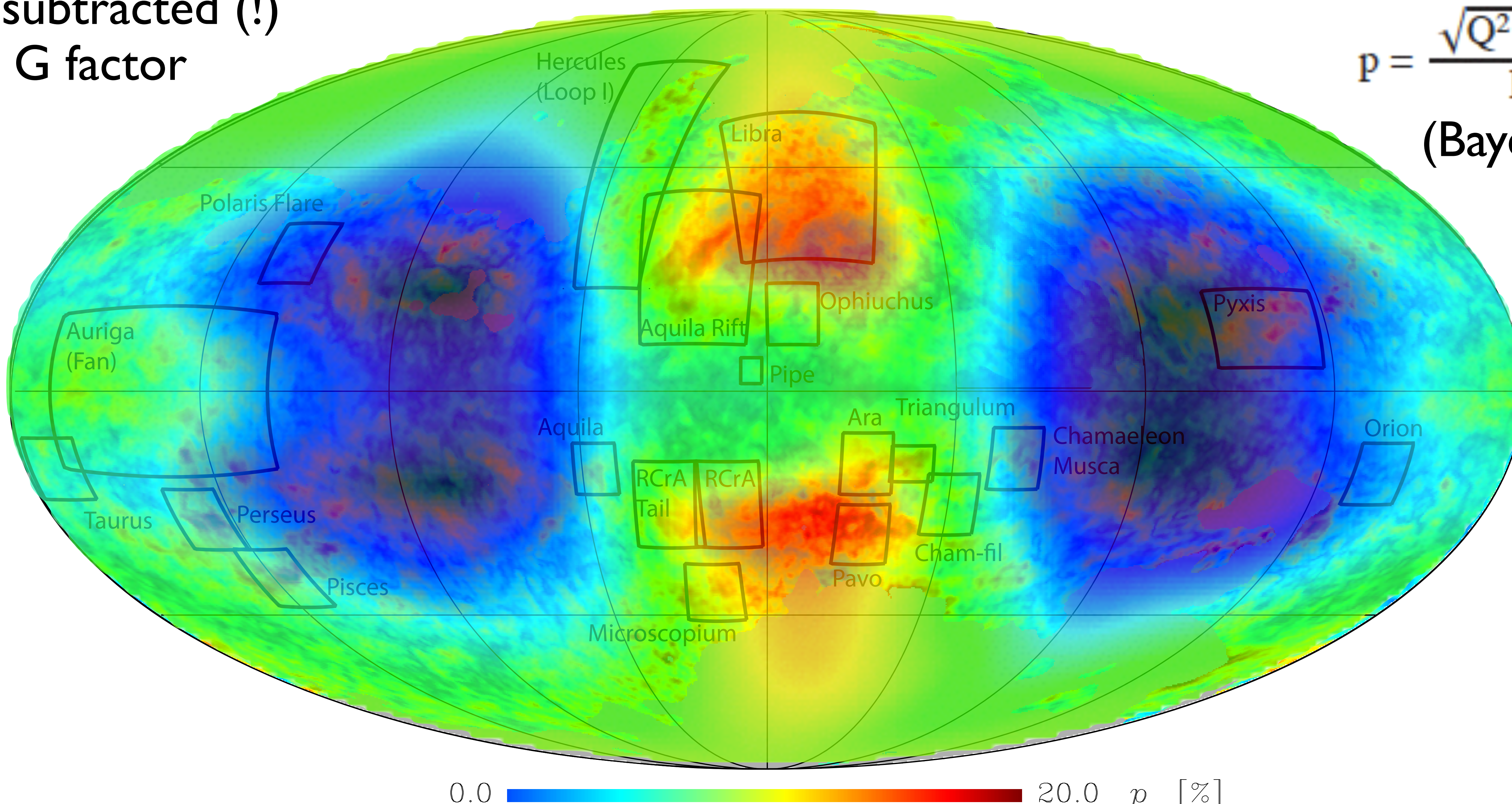
Montier et al. 2015a, 2015b

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

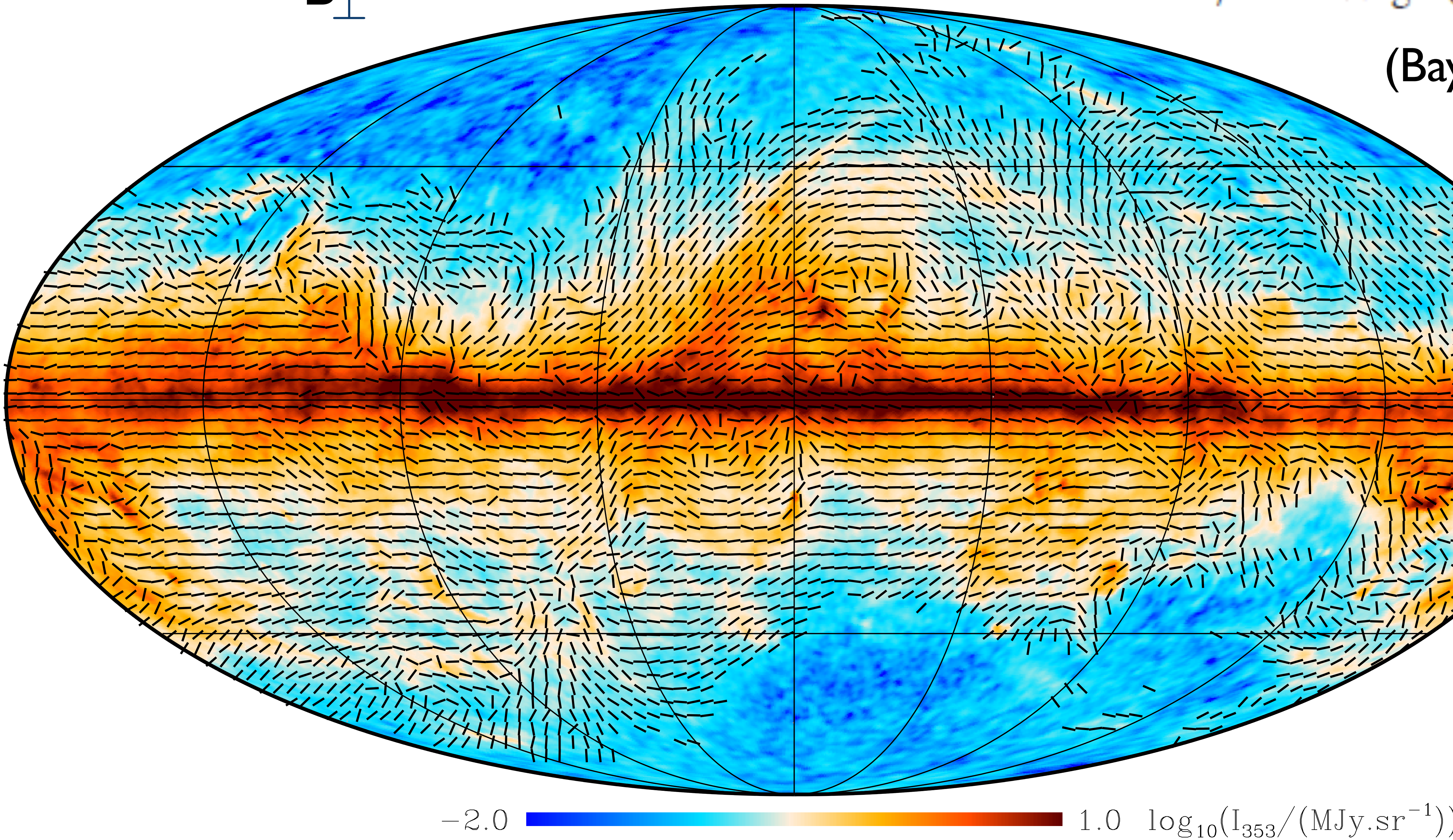
The sky looks different in polarization !!

Polarization angle

rotated 90° ⟶ $\mathbf{B}_{\perp}$

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

(Bayesian)



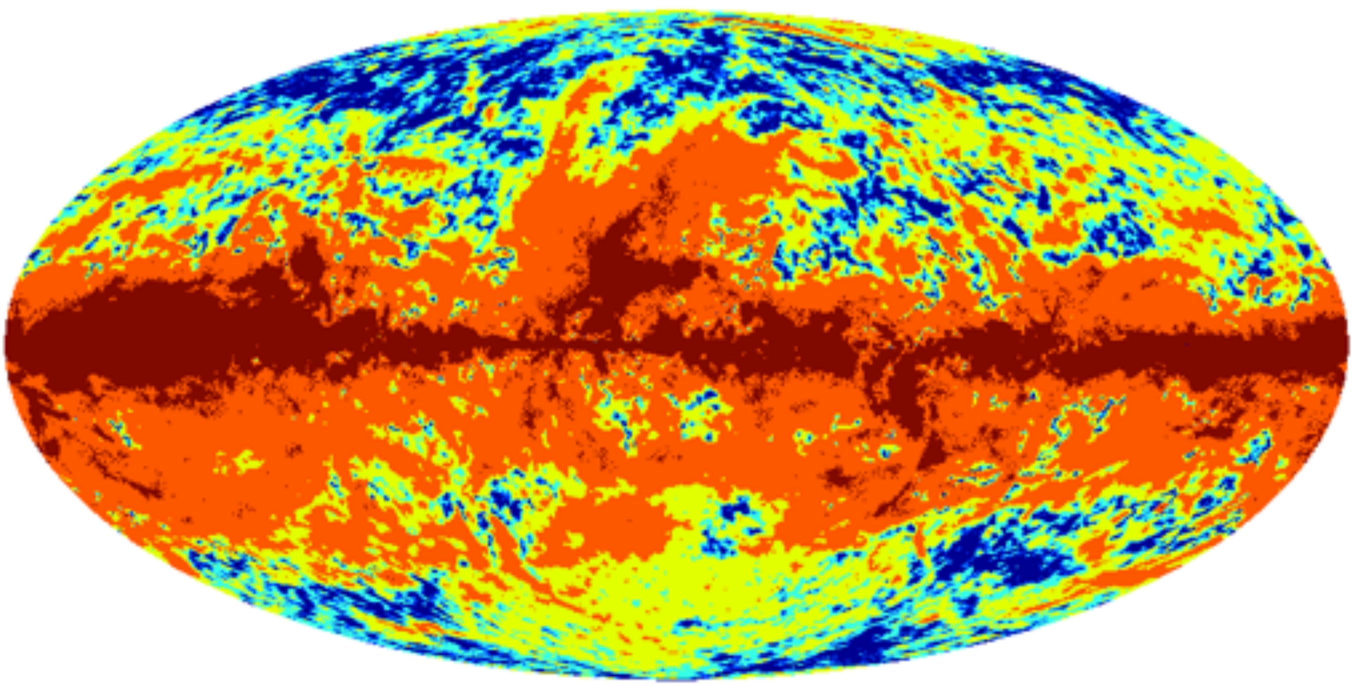
Color: Intensity at 353 GHz

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

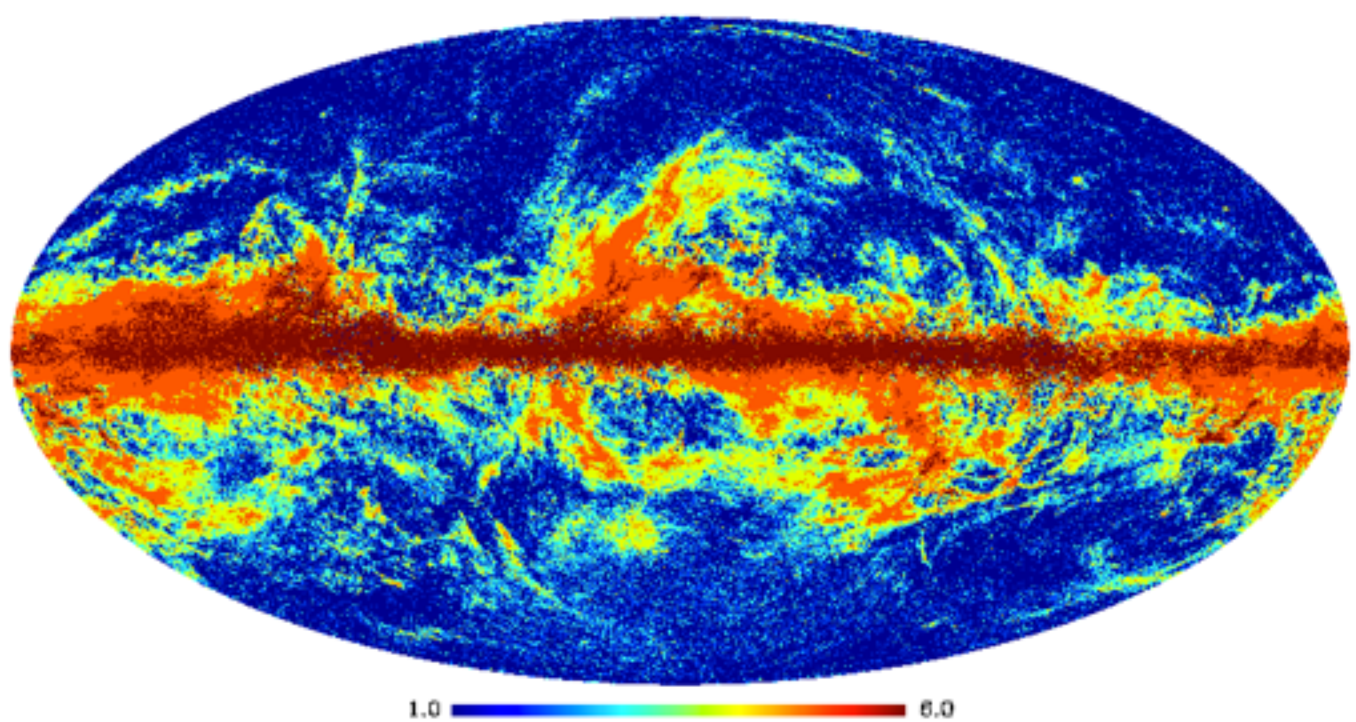
Uncertainties

maps of SNR on p

1° resolution



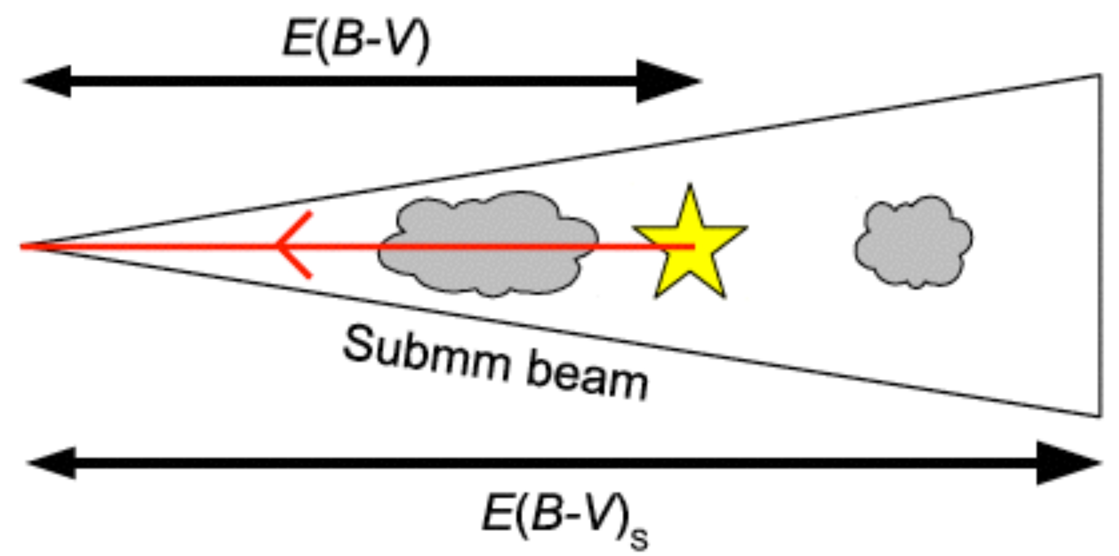
30’ resolution



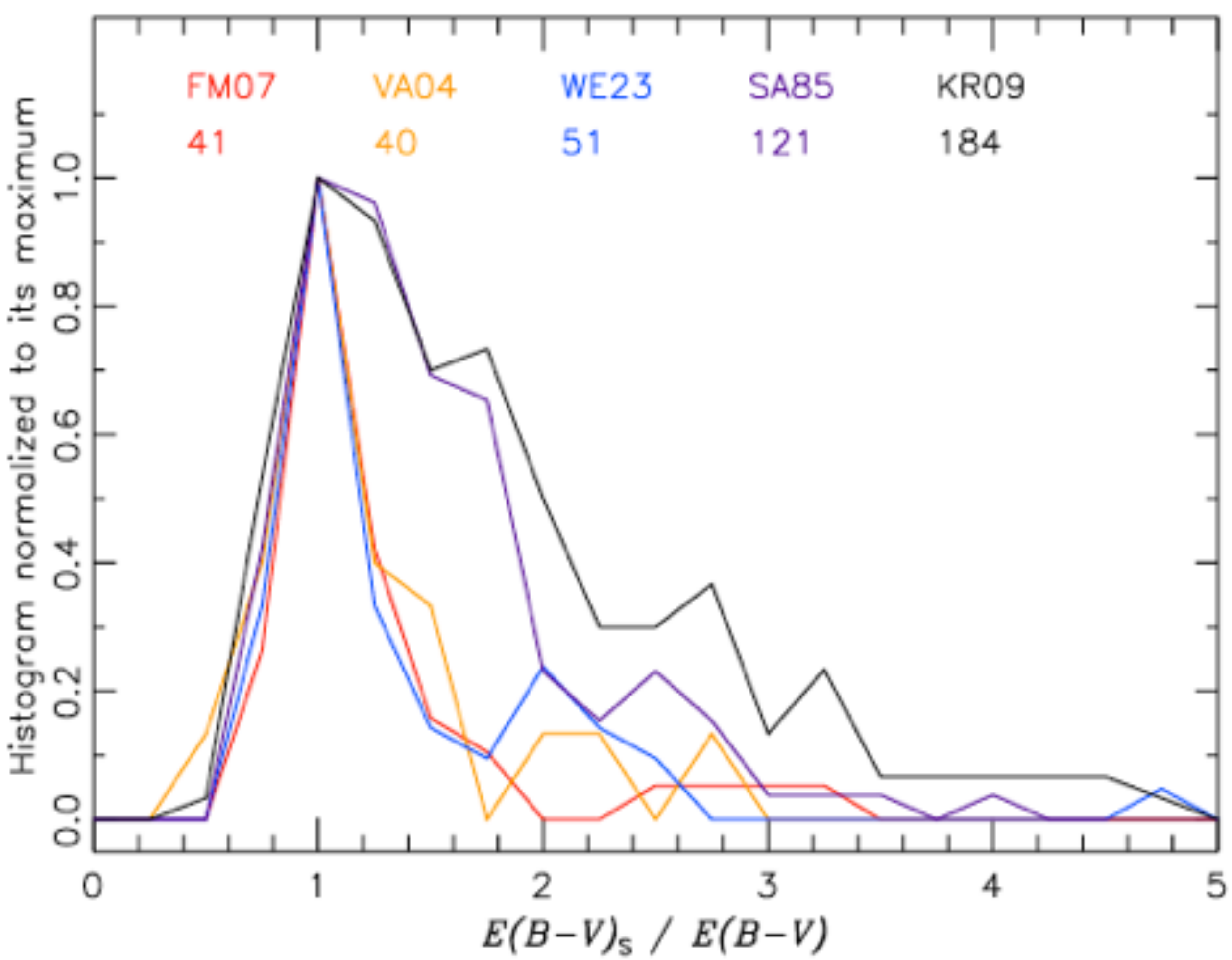
- Computed from mean likelihood
- Basically reflect Intensity and sky coverage

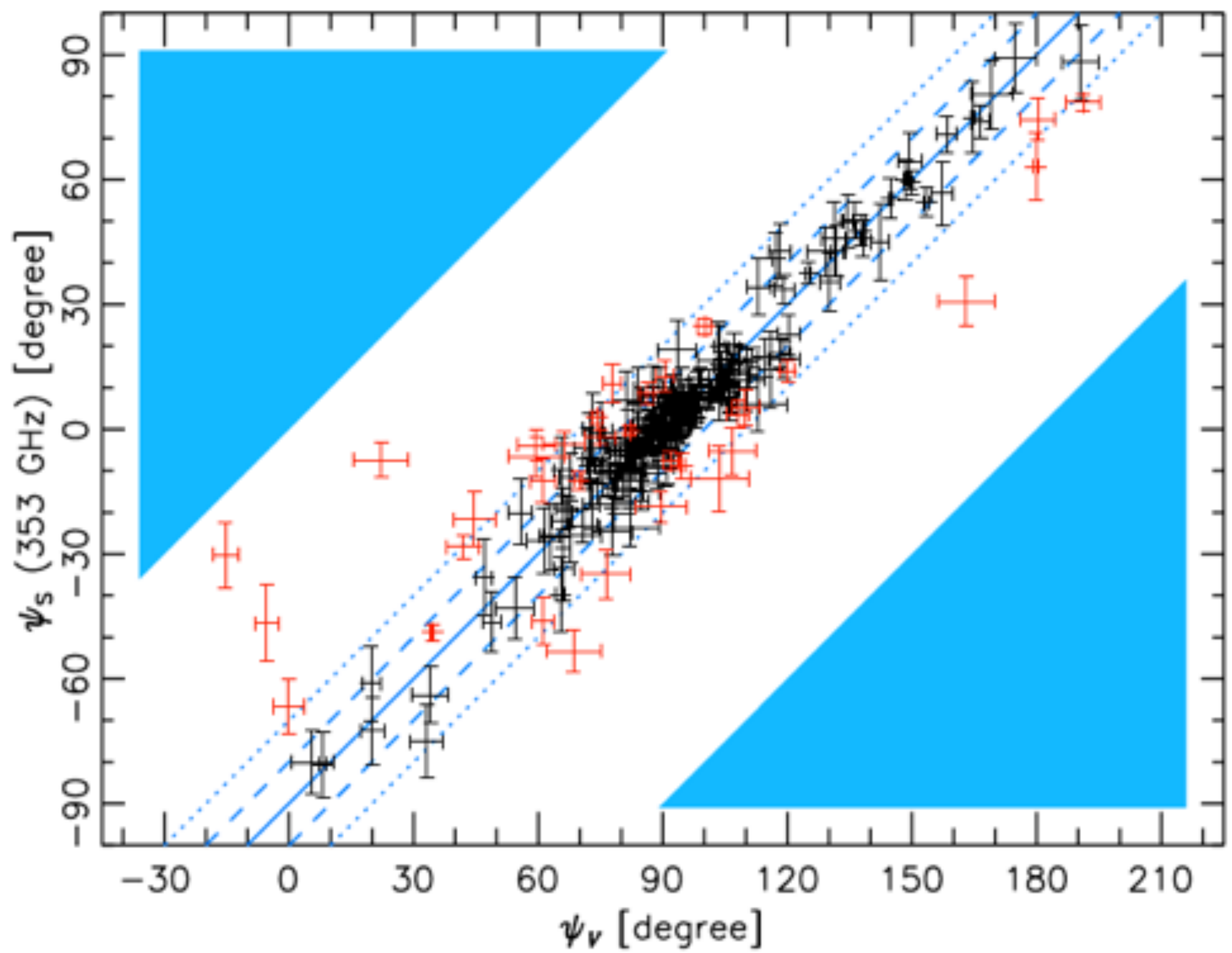
	1°	30’	15’
SNR>2	93 %	82 %	61 %
SNR>3	89 %	72 %	48 %
SNR>5	77 %	55 %	33 %
SNR>10	53 %	34 %	19 %

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



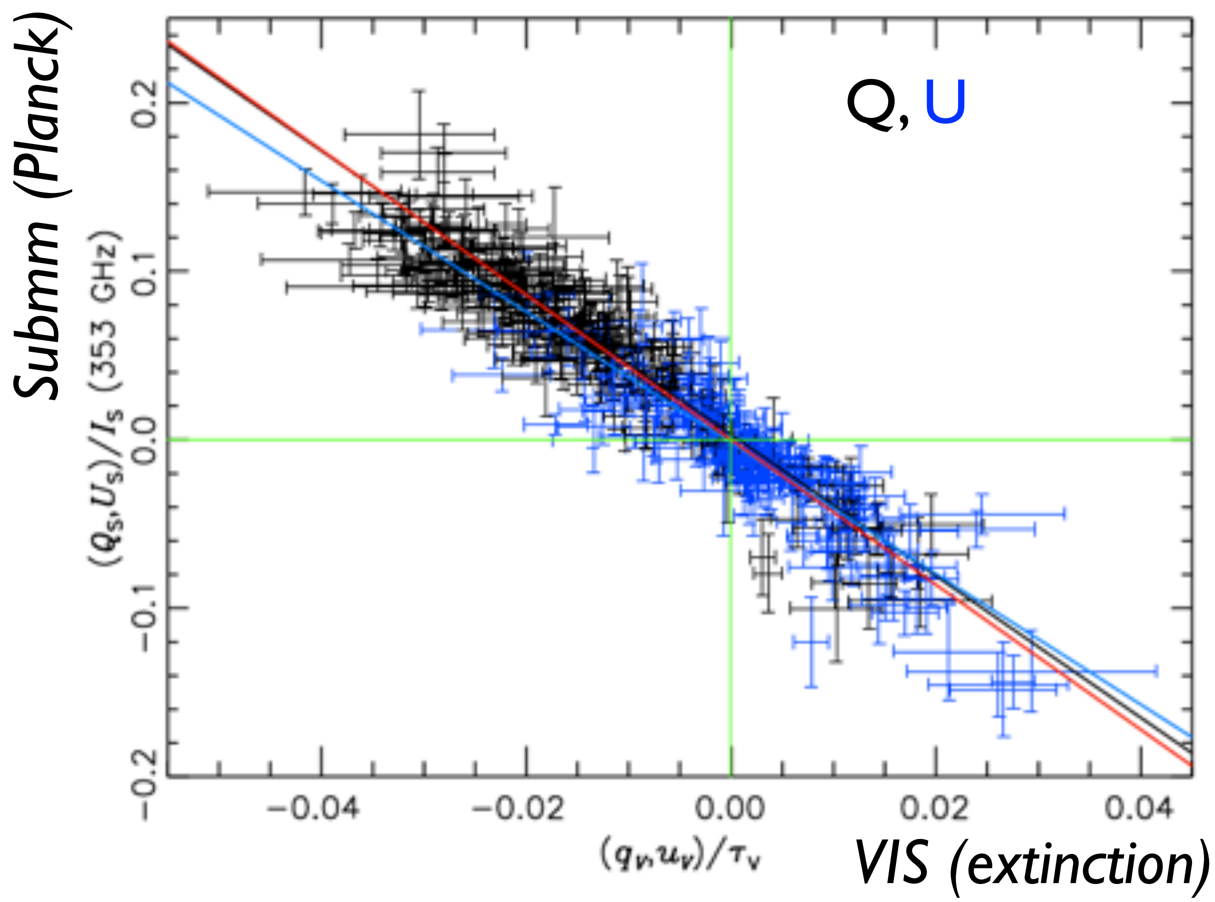
- Selected 255 stars with:
    - high S/N in both vis and submm
    - $E(B\text{-}V)_s \leq 1$ and $W_{CO} < 2$ K km s^{-1}
    - similar column densities $E(B\text{-}V)_s / E(B\text{-}V)_V < 1.6$
    - similar polarization angles $\Psi_V \sim \Psi_S - 90$

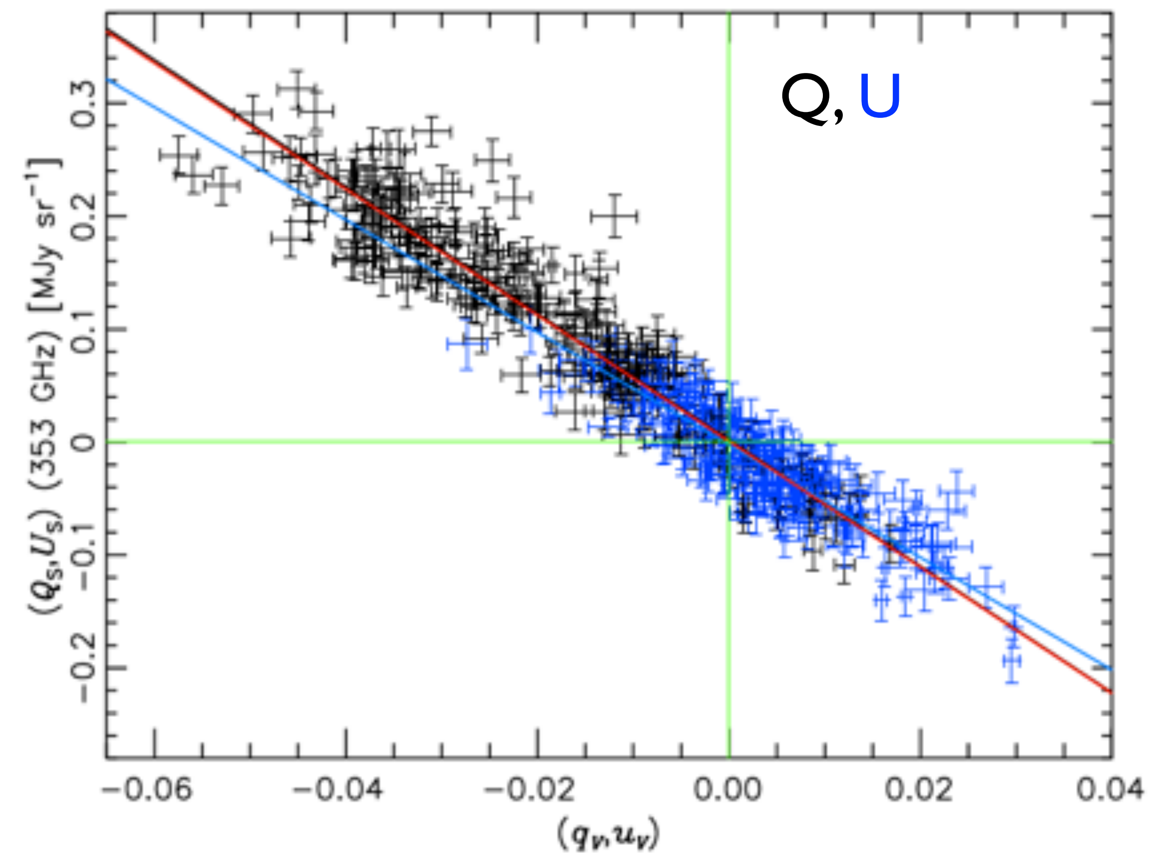




Planck intermediate results. XXI.

Emission vs Extinction

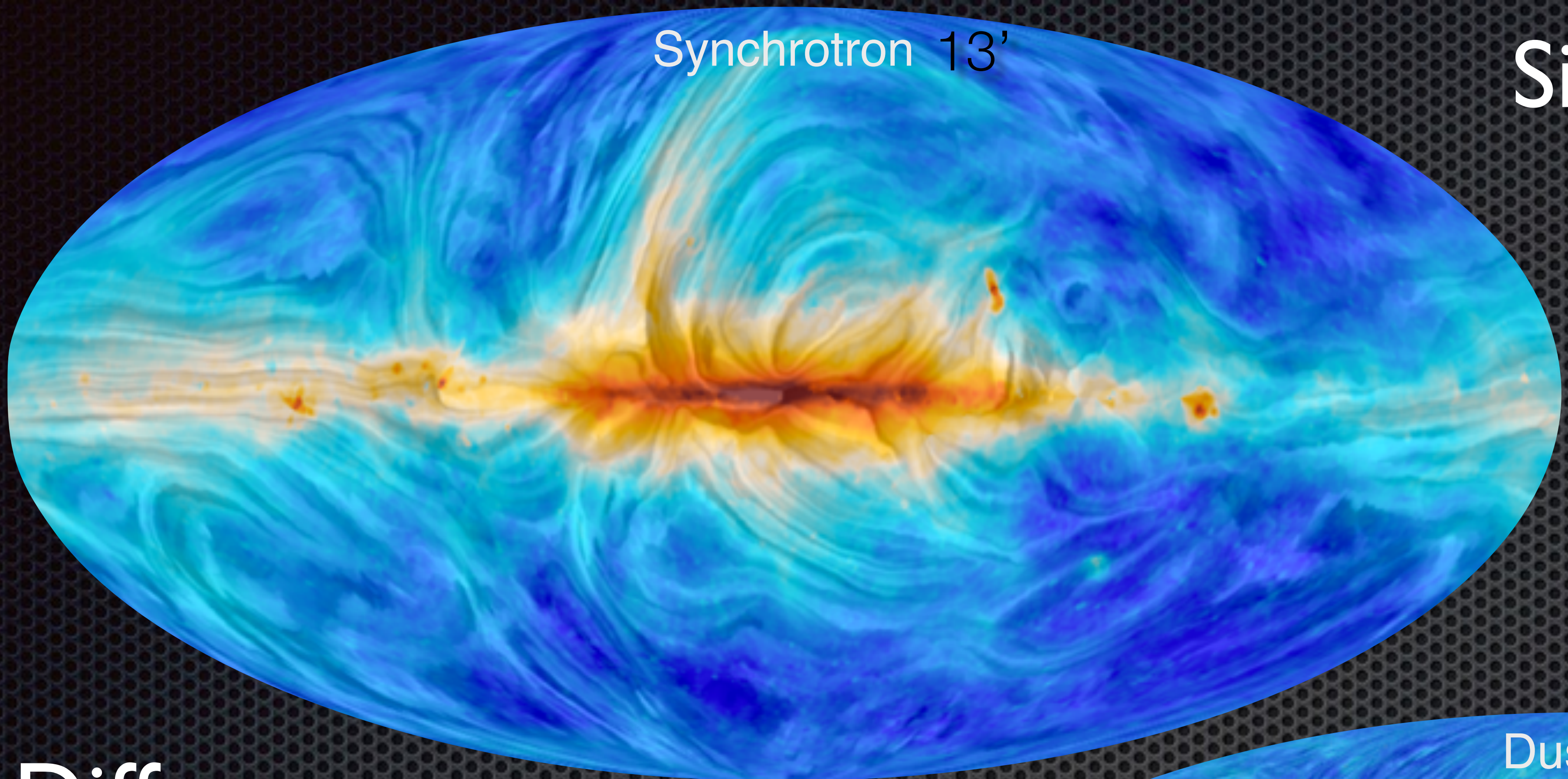




- Polarization efficiency ratio: $R_{S/V} = (P_S/I_S)/(p_V/\tau_V) = 4.3 \pm 0.2\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.})$
- $R_{S/V}$ compatible with a range of dust models, not very discriminatory.
- Polarized emission ratio: $R_{P/p} = P_S/p_V = 5.6 \pm 0.2$ (stat.) ± 0.4 (syst.) MJy sr^{-1}
-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

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

Planck Polarization maps

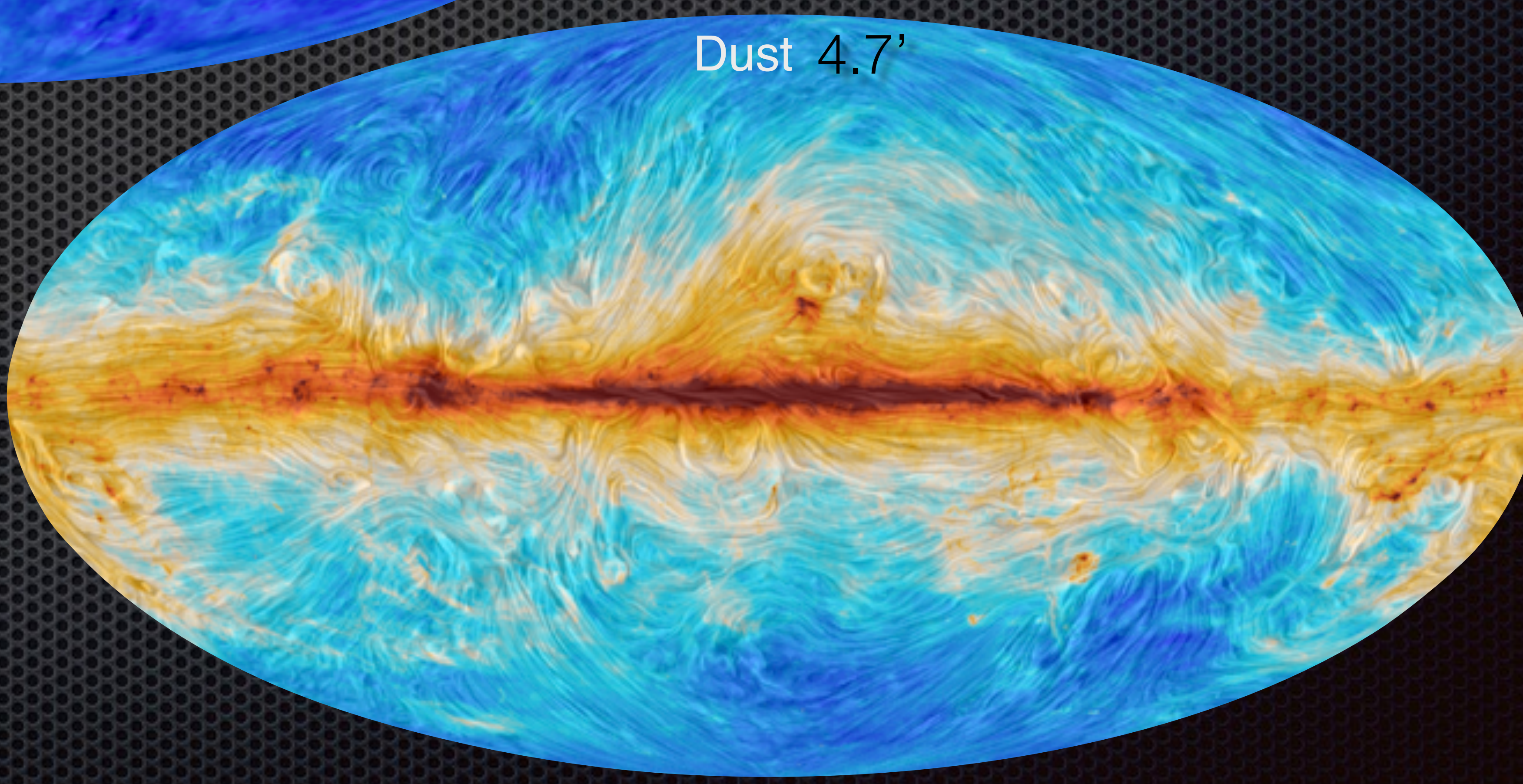


Similarities:

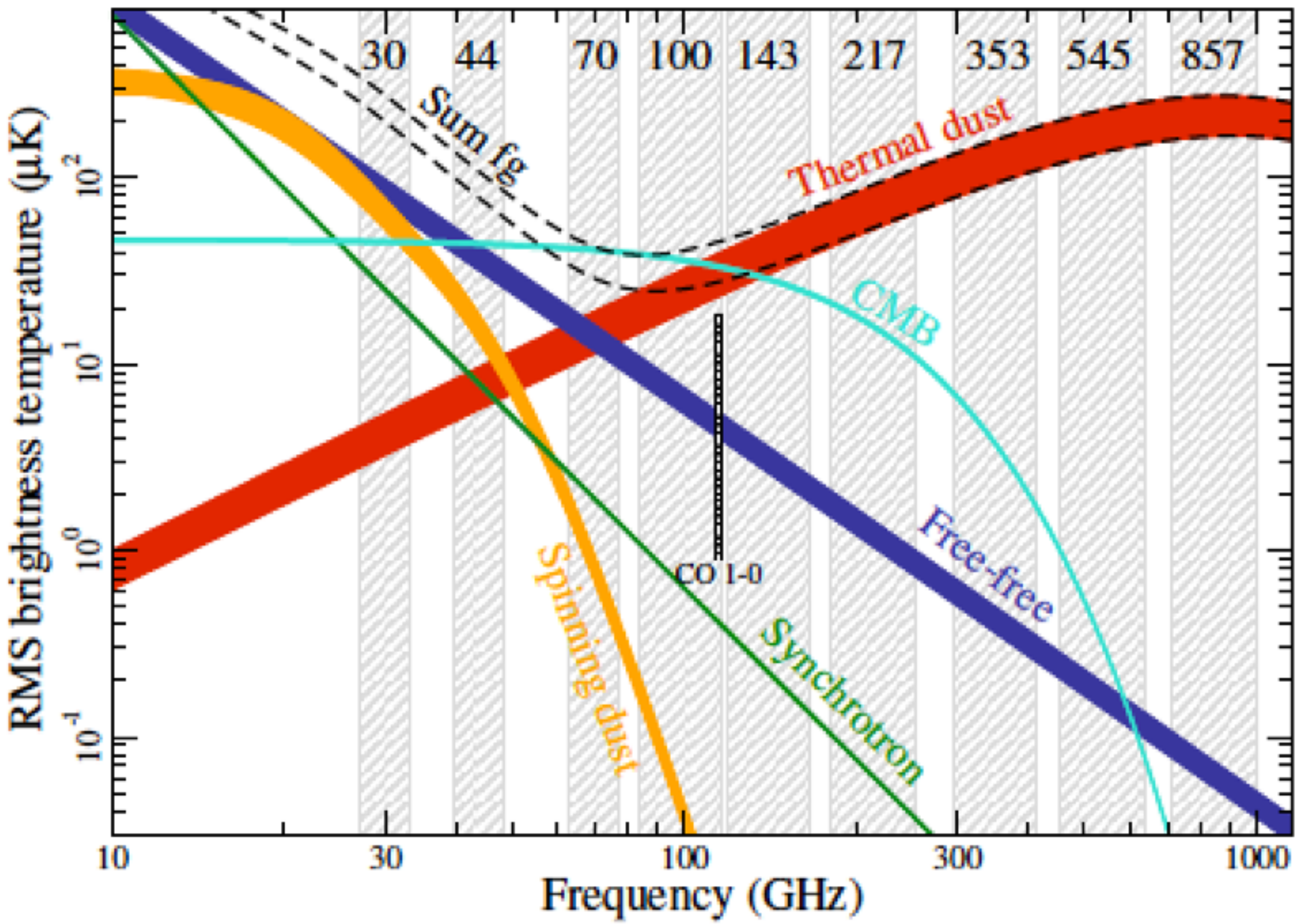
- Measure direction of the same component of **B**
- Same beam and LOS depolarization effects

Differences:

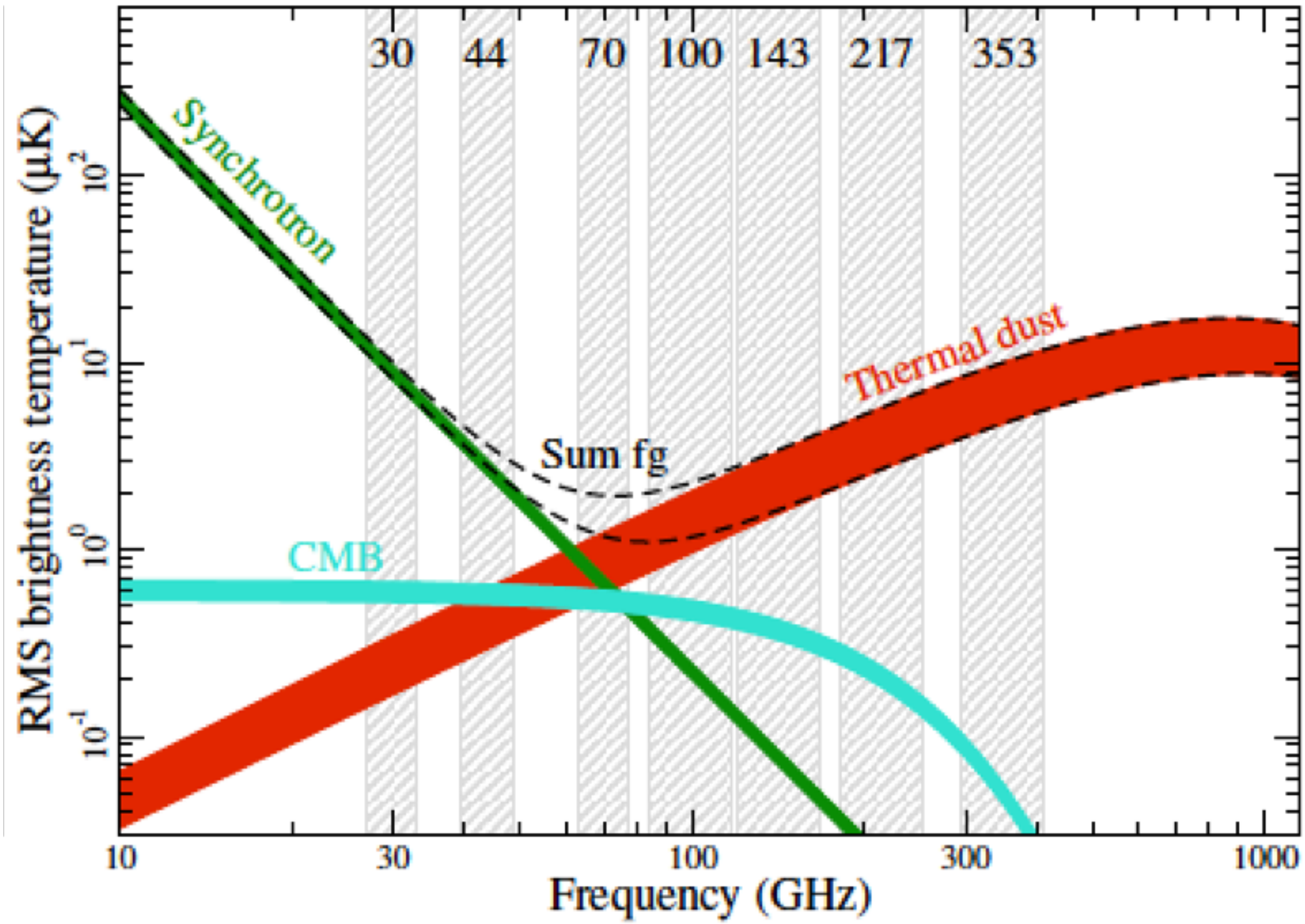
- Faraday rotation negligible !
- Planck measures all scales : no filtering of I,Q,U like with interferometers
- Dust is distributed in the thin disk of the MW (comparable to neutral HI + molecular)
- Dust polarization mostly insensitive to |**B**|



Astrophysical components in Planck bands

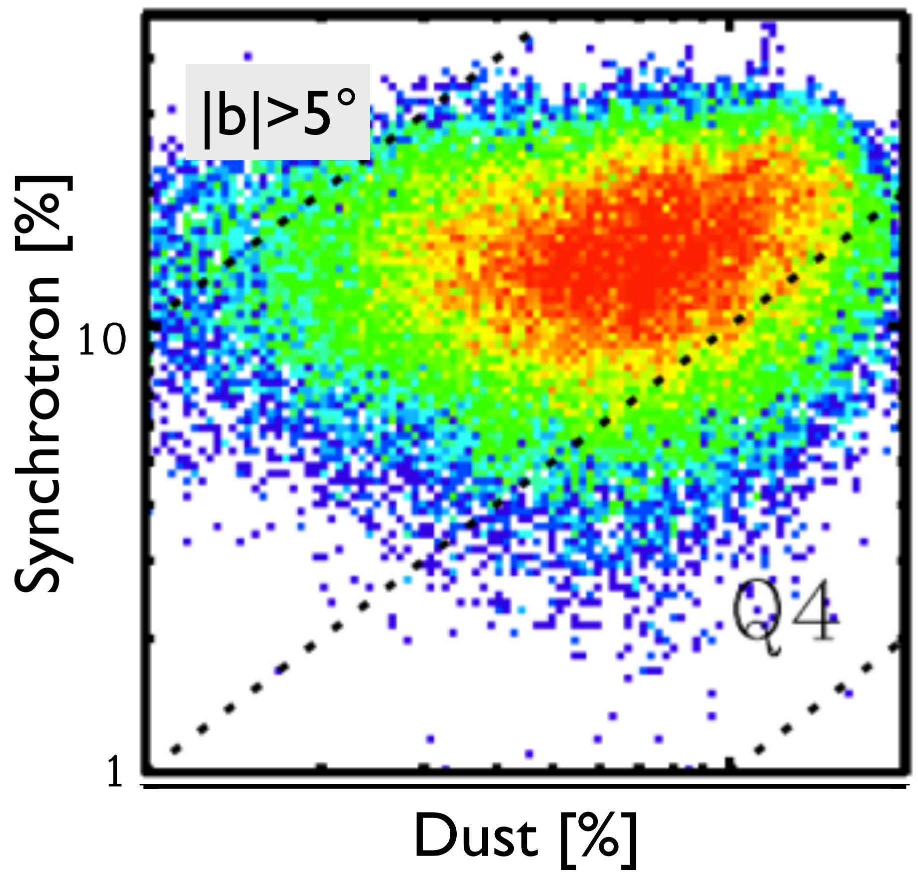


Astrophysical components in Planck bands

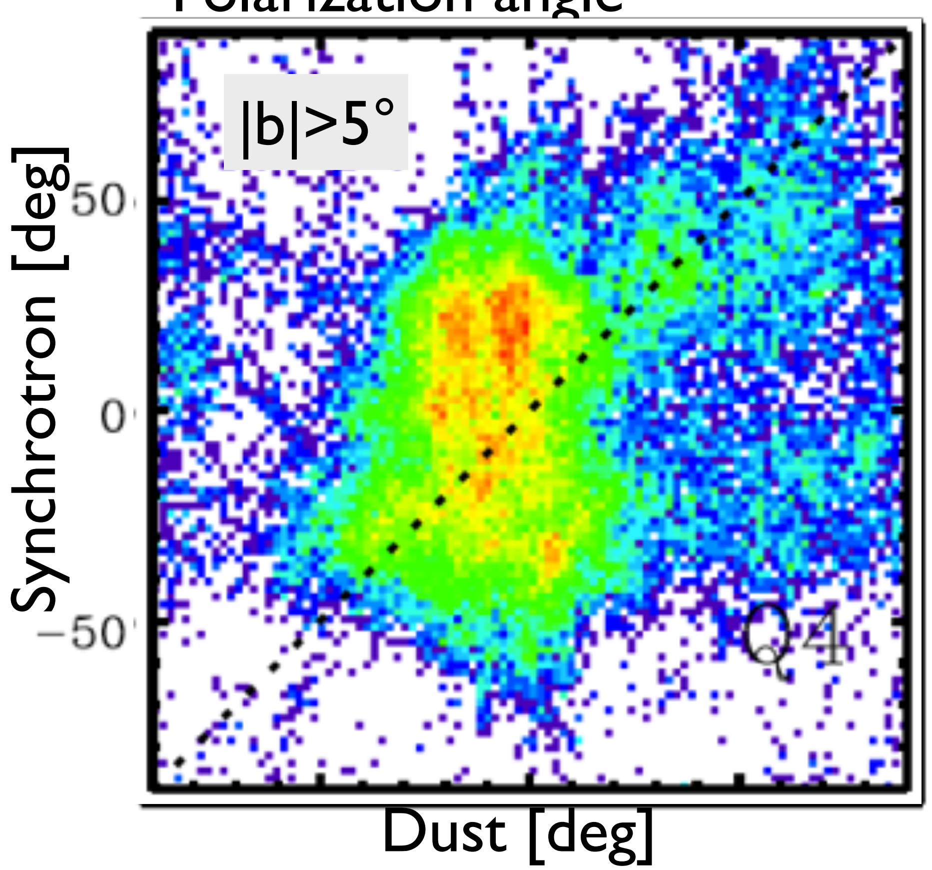


Synchrotron (30 GHz) vs Dust (353 GHz)

Polarization fraction



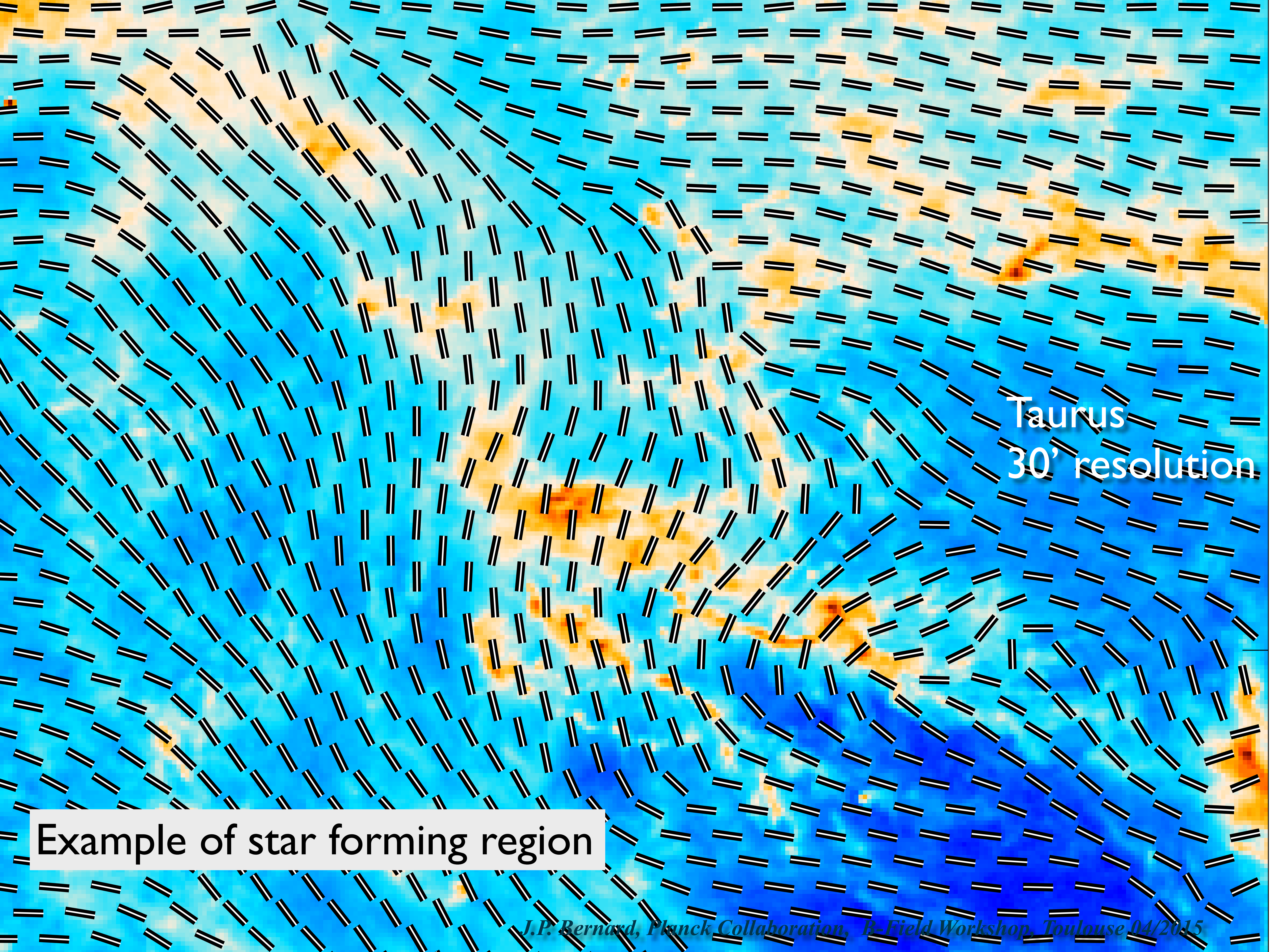
Polarization angle

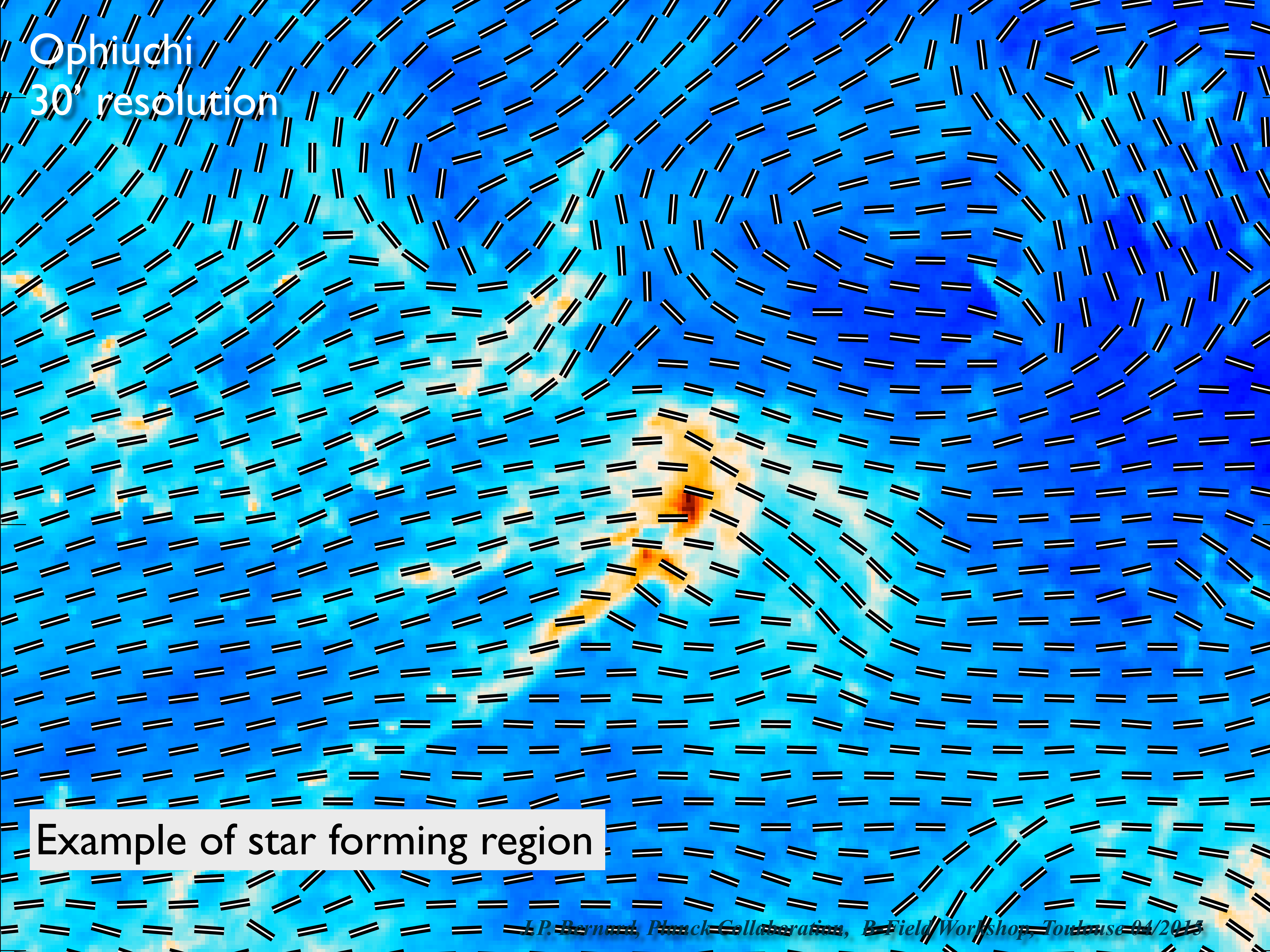


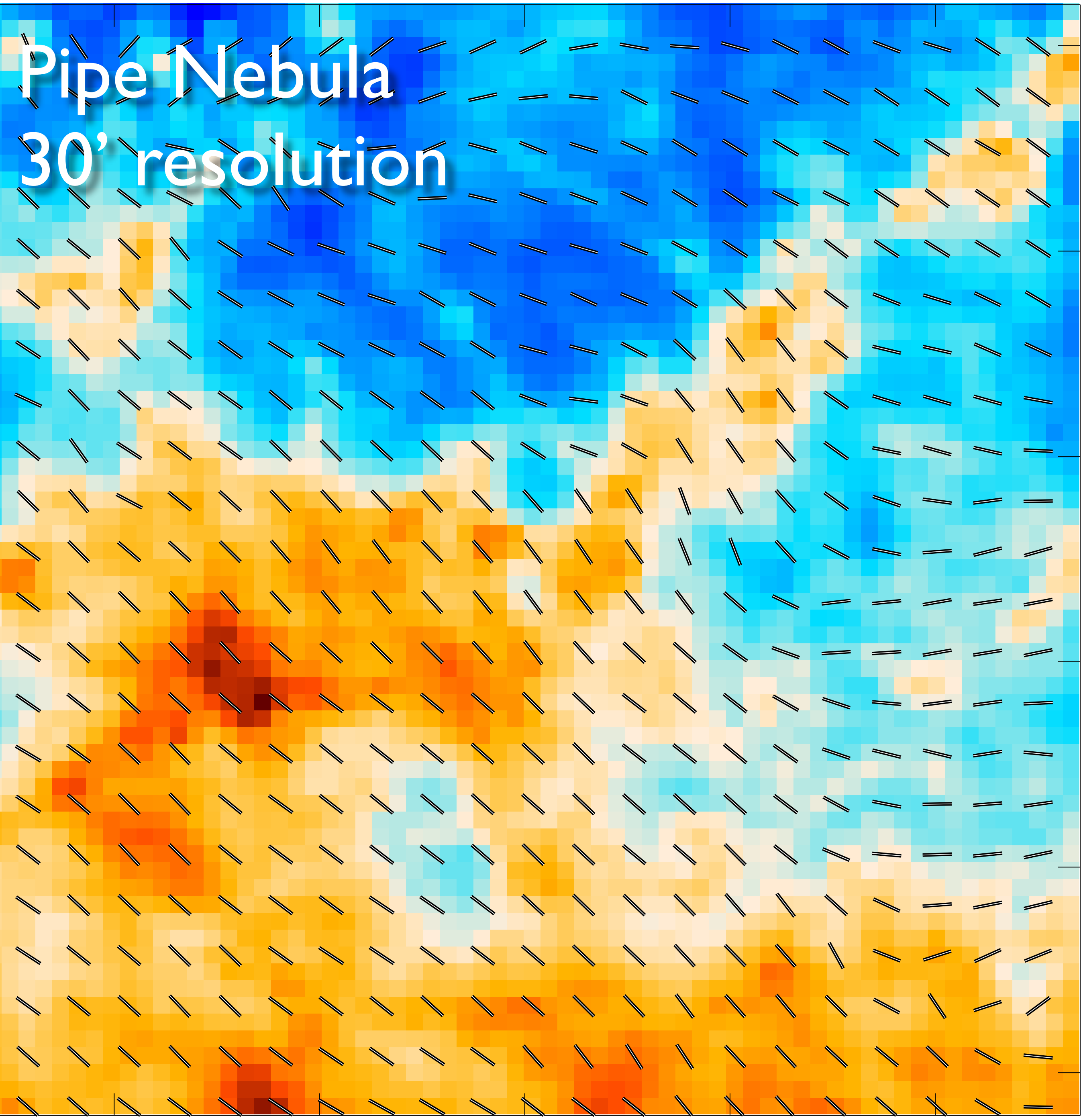
- Polarization fraction:
  - Measurable correlations in-plane
  - Weaker correlations off-plane
- Angles :
  - Around 0° in plane but not well correlated
  - Correlate over some regions (Fan, North Polar Spur)

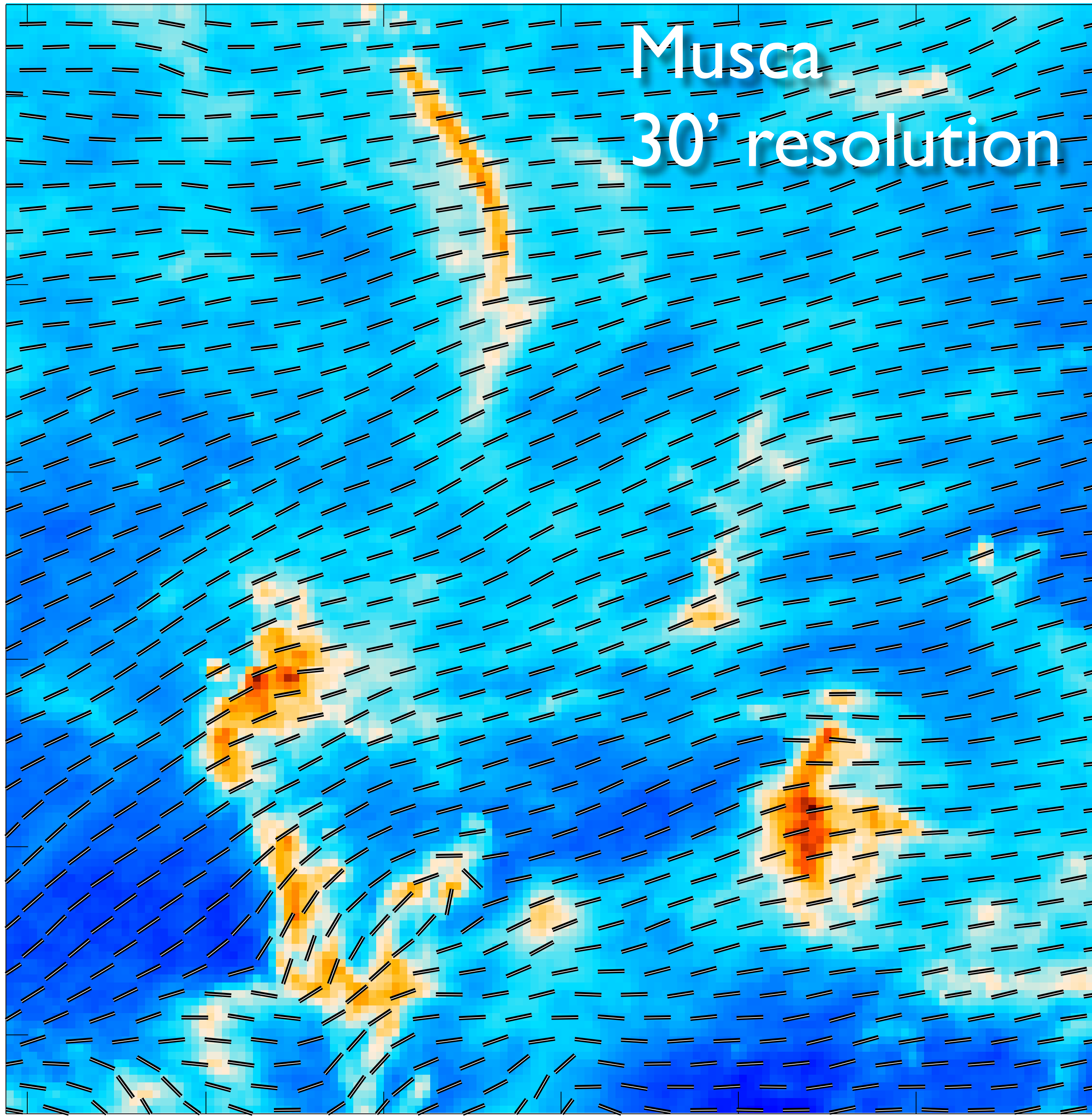
Significant scatter:
Synchrotron and dust not generally trace the same regions of LOS

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

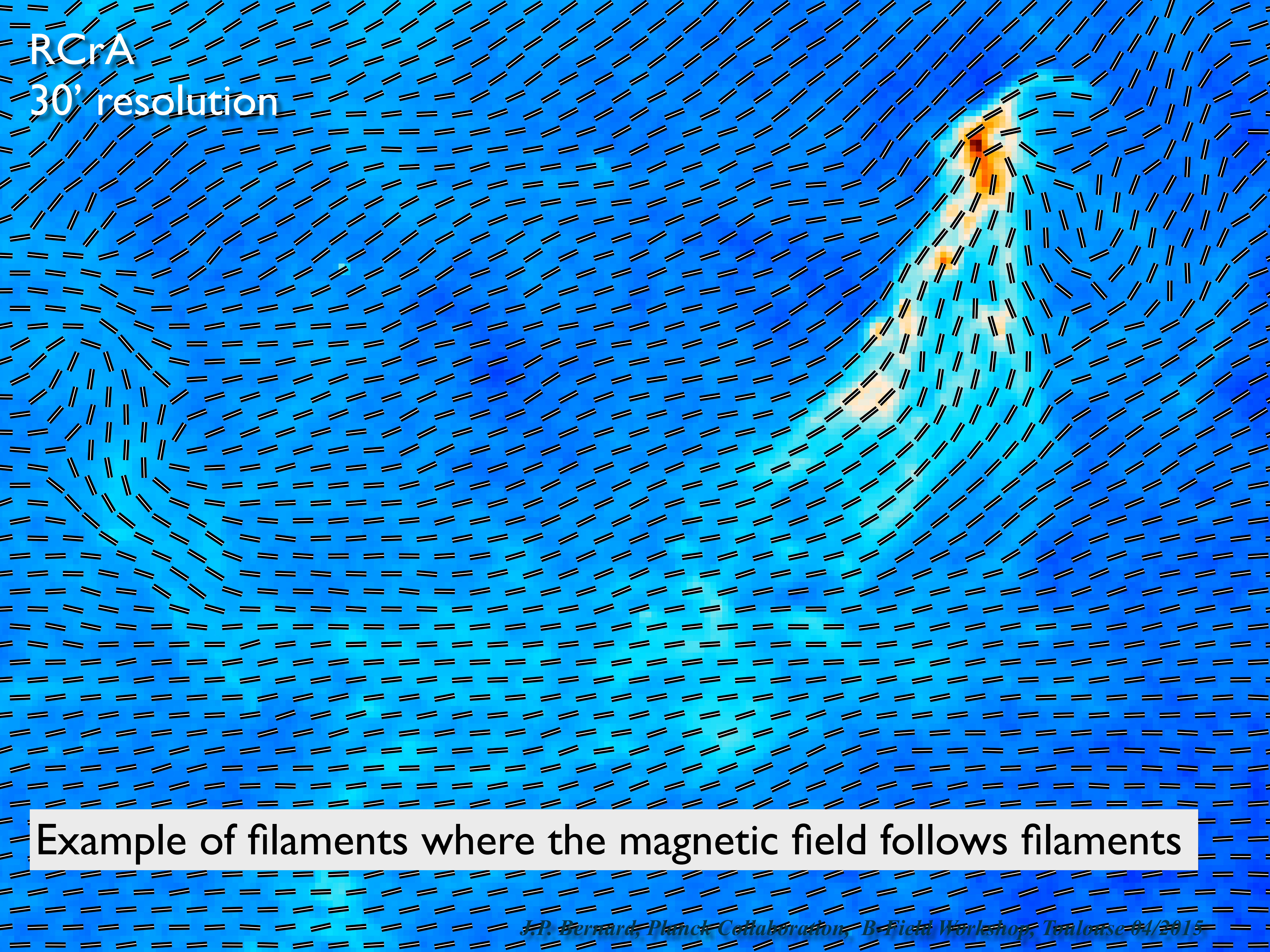

Taurus
30' resolution
Example of star forming region
J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015

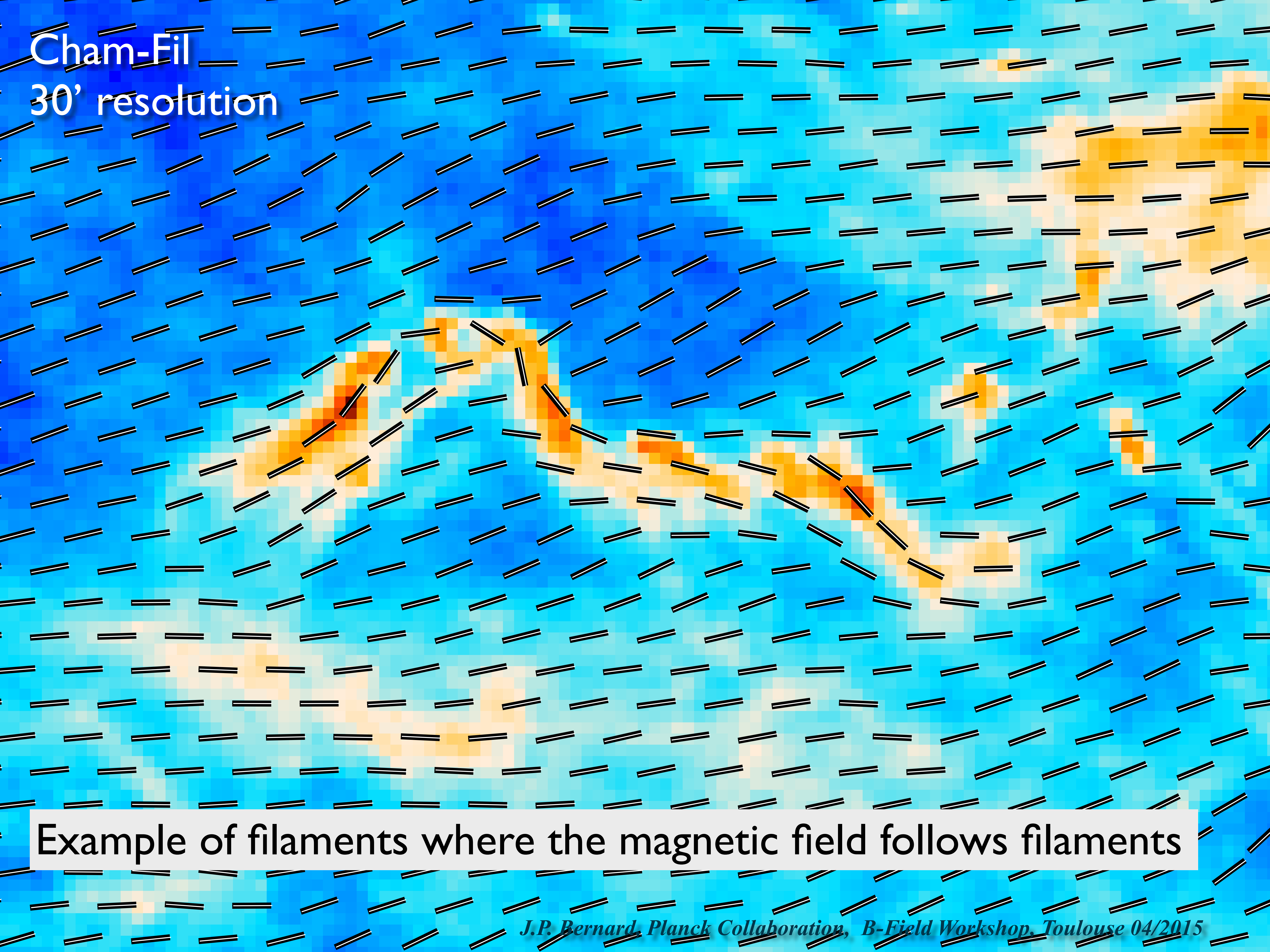

Ophiuchi
30' resolution
Example of star forming region
J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015





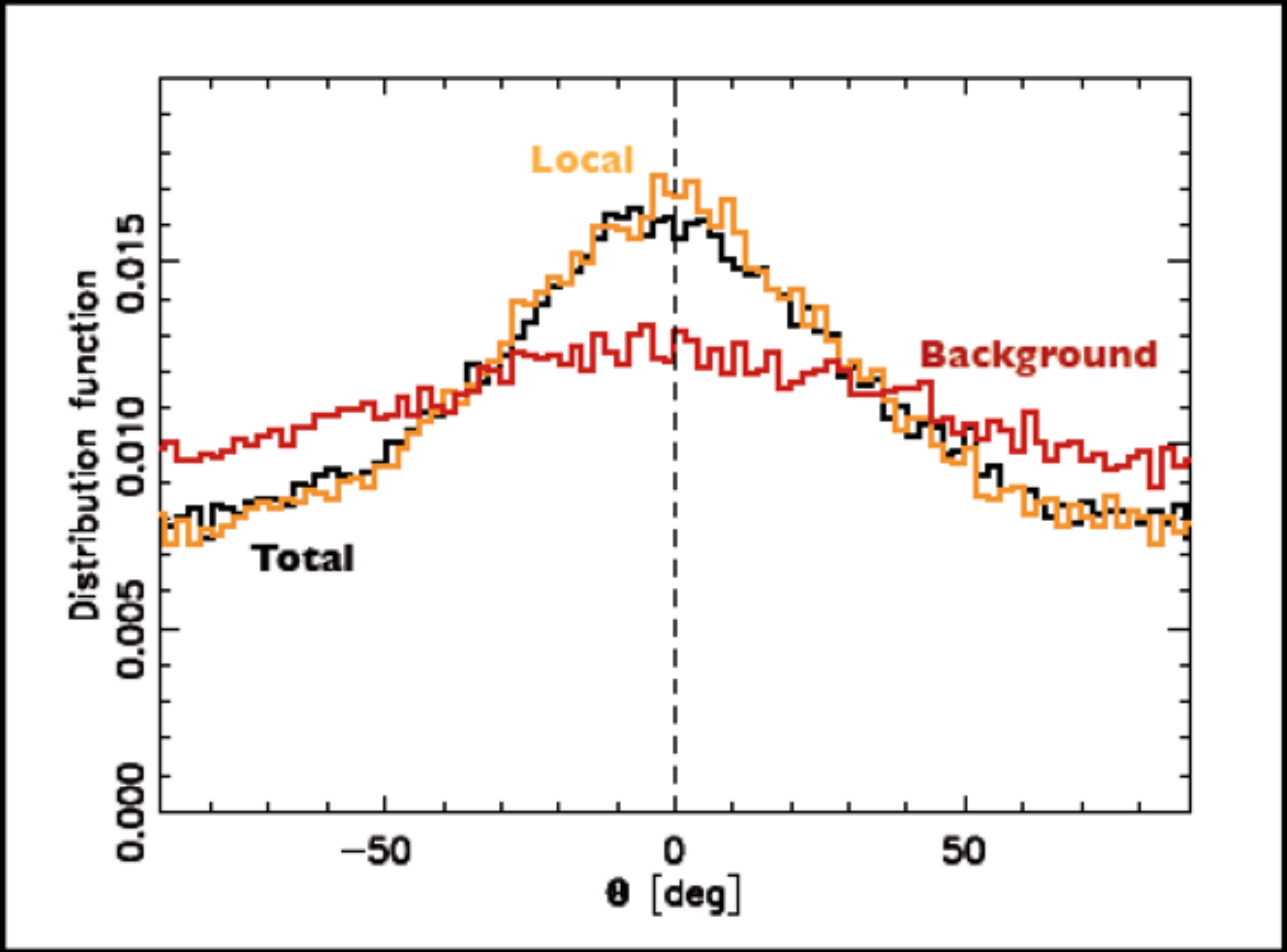
Example of filaments where the magnetic field ⊥ to filaments

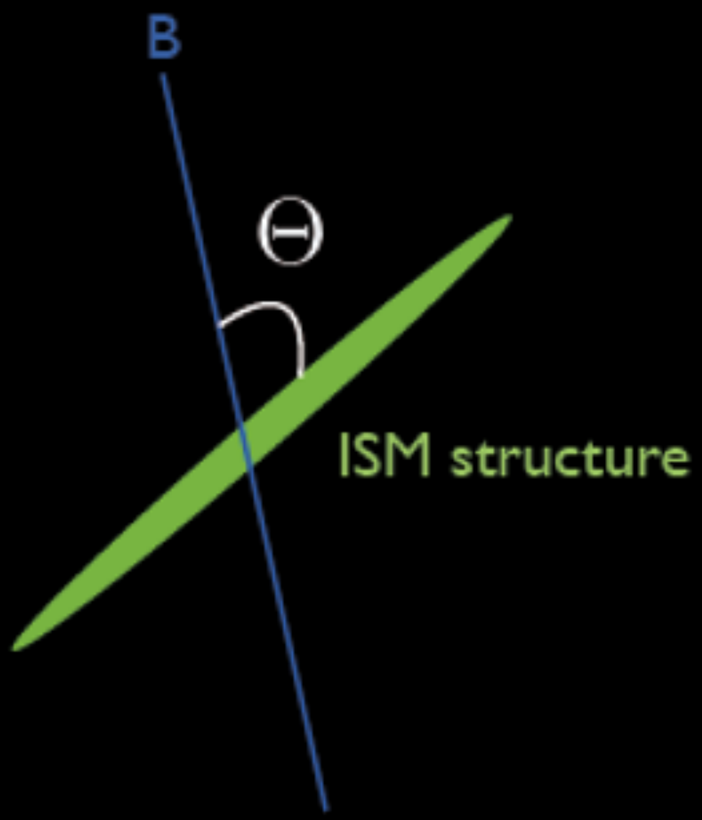

RCrA
30' resolution
Example of filaments where the magnetic field follows filaments
J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015


Cham-Fil
30’ resolution
Example of filaments where the magnetic field follows filaments
J.P. Bernard, Planck Collaboration, B-Field Workshop, Toulouse 04/2015

B orientation vs filaments

Planck Collaboration *Planck intermediate results. XXXII*





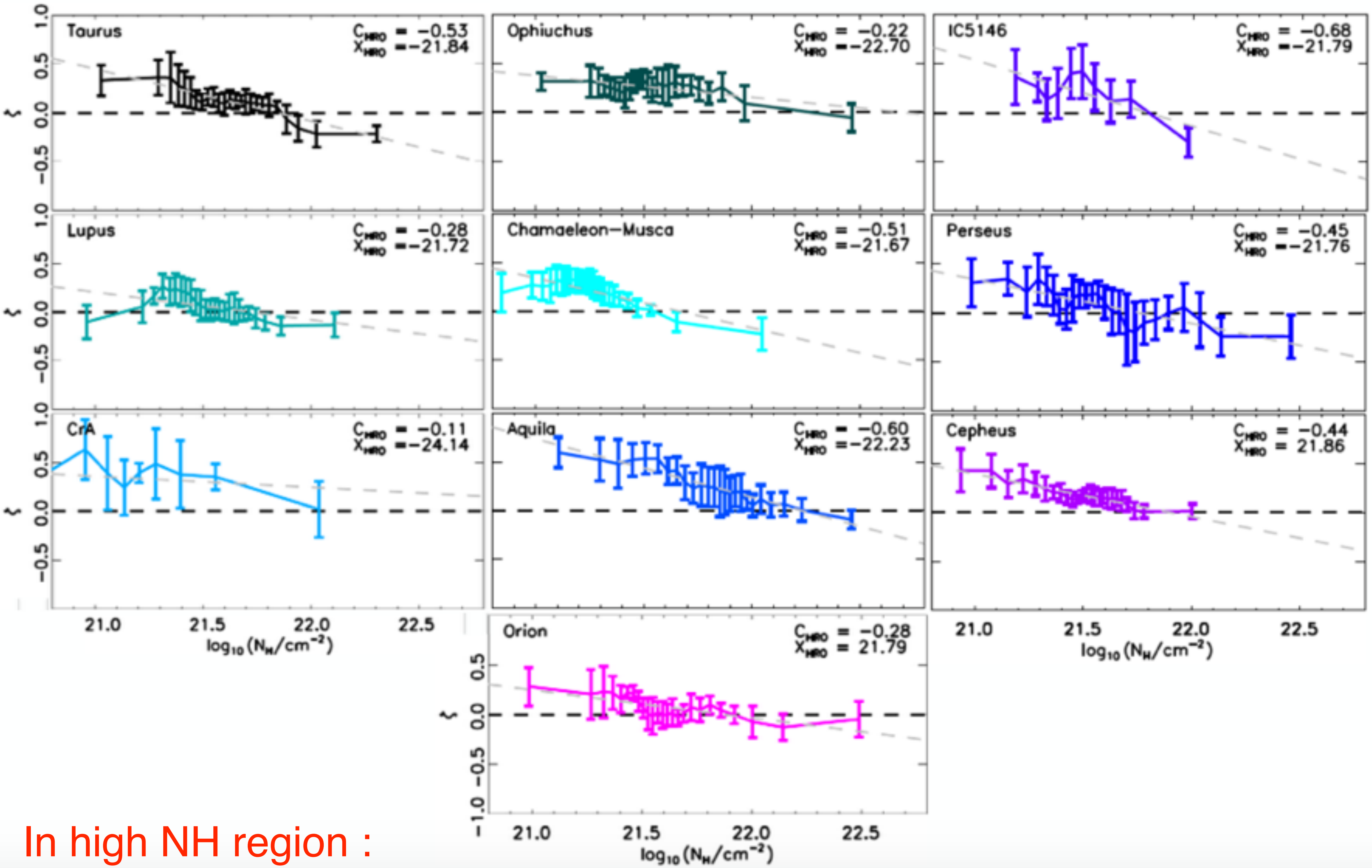
In low NH region :

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!

B orientation vs filaments

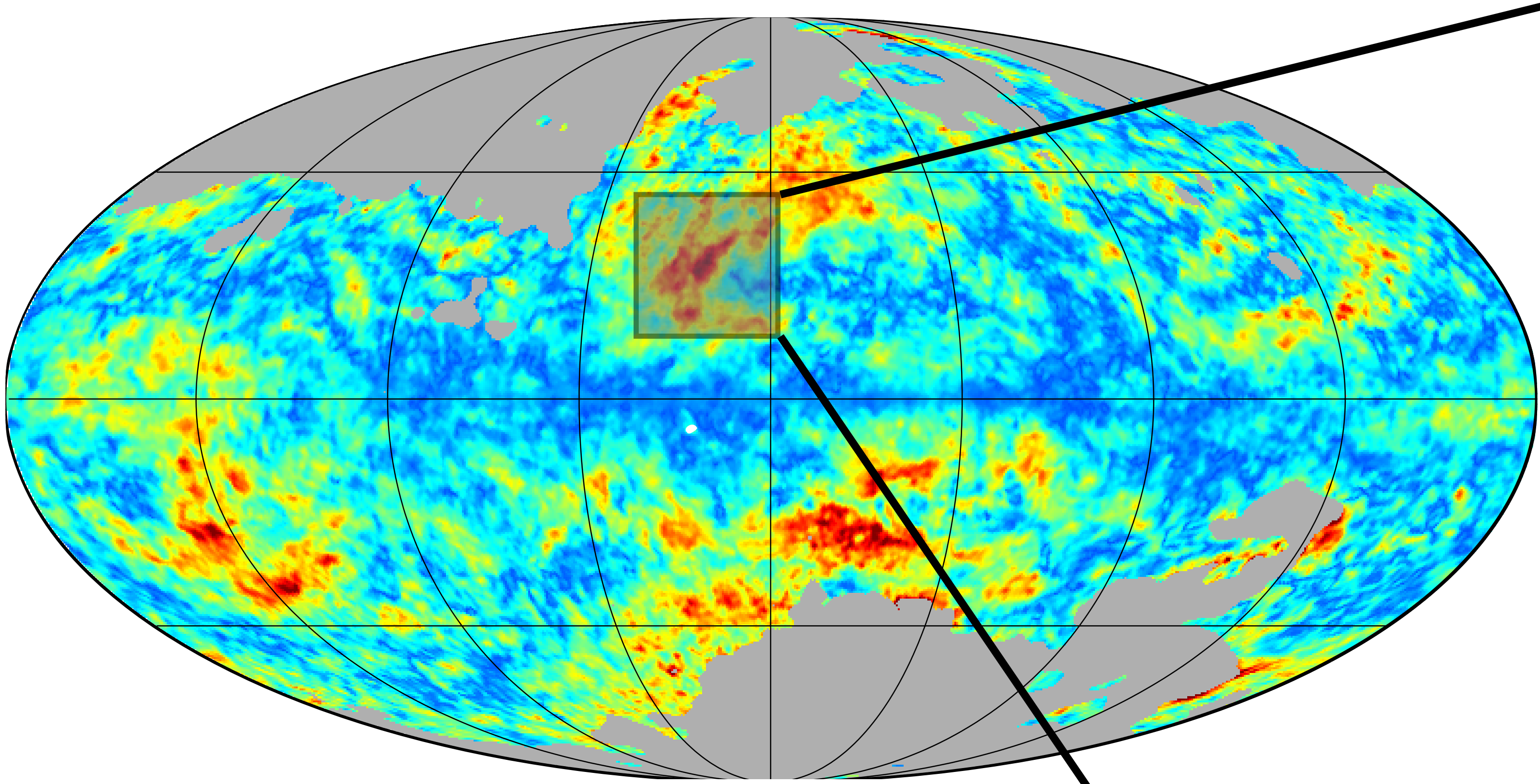
Planck Collaboration Planck intermediate results. XXXV

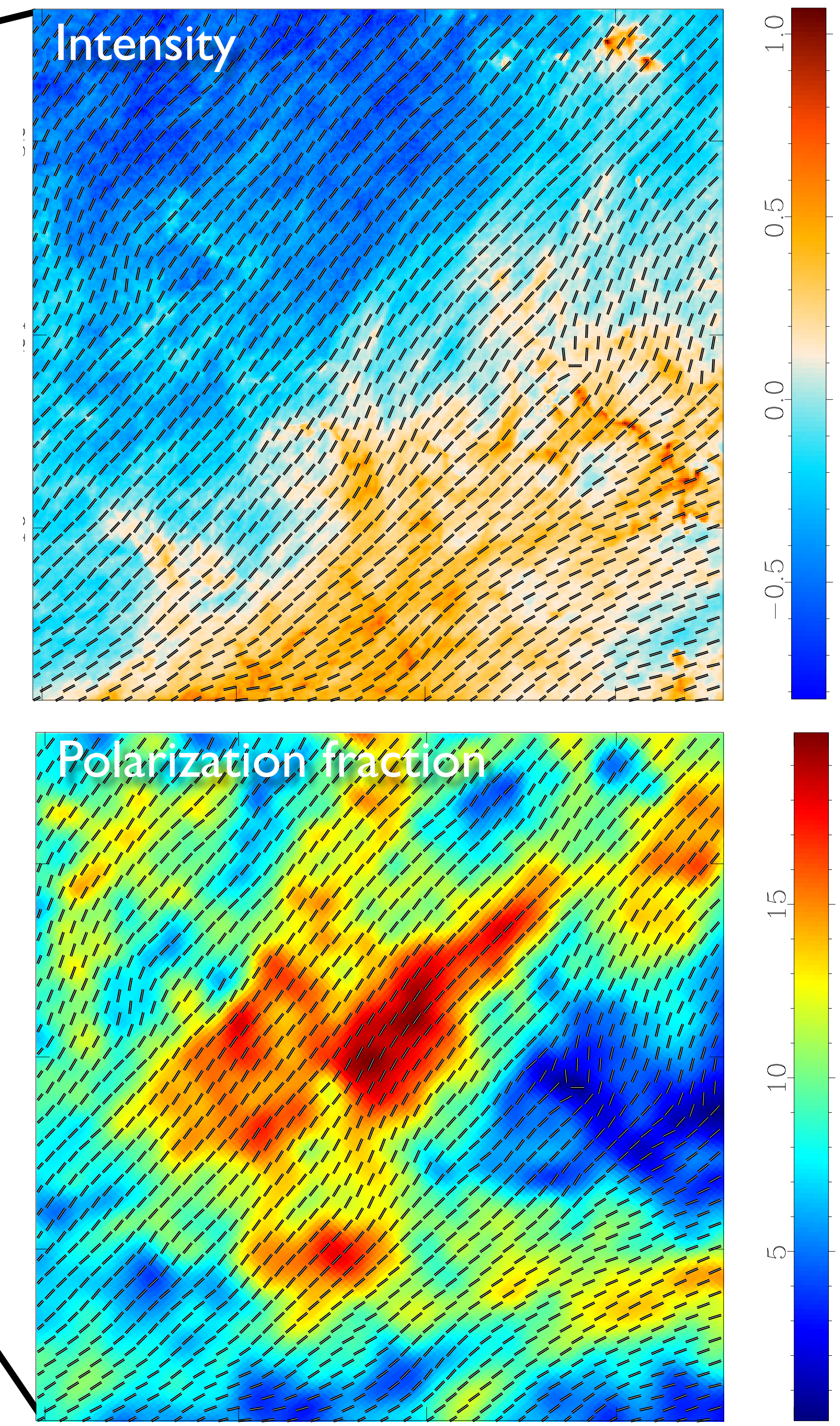


In high NH region :

The structures tend to be orthogonal to B

Polarization Fraction

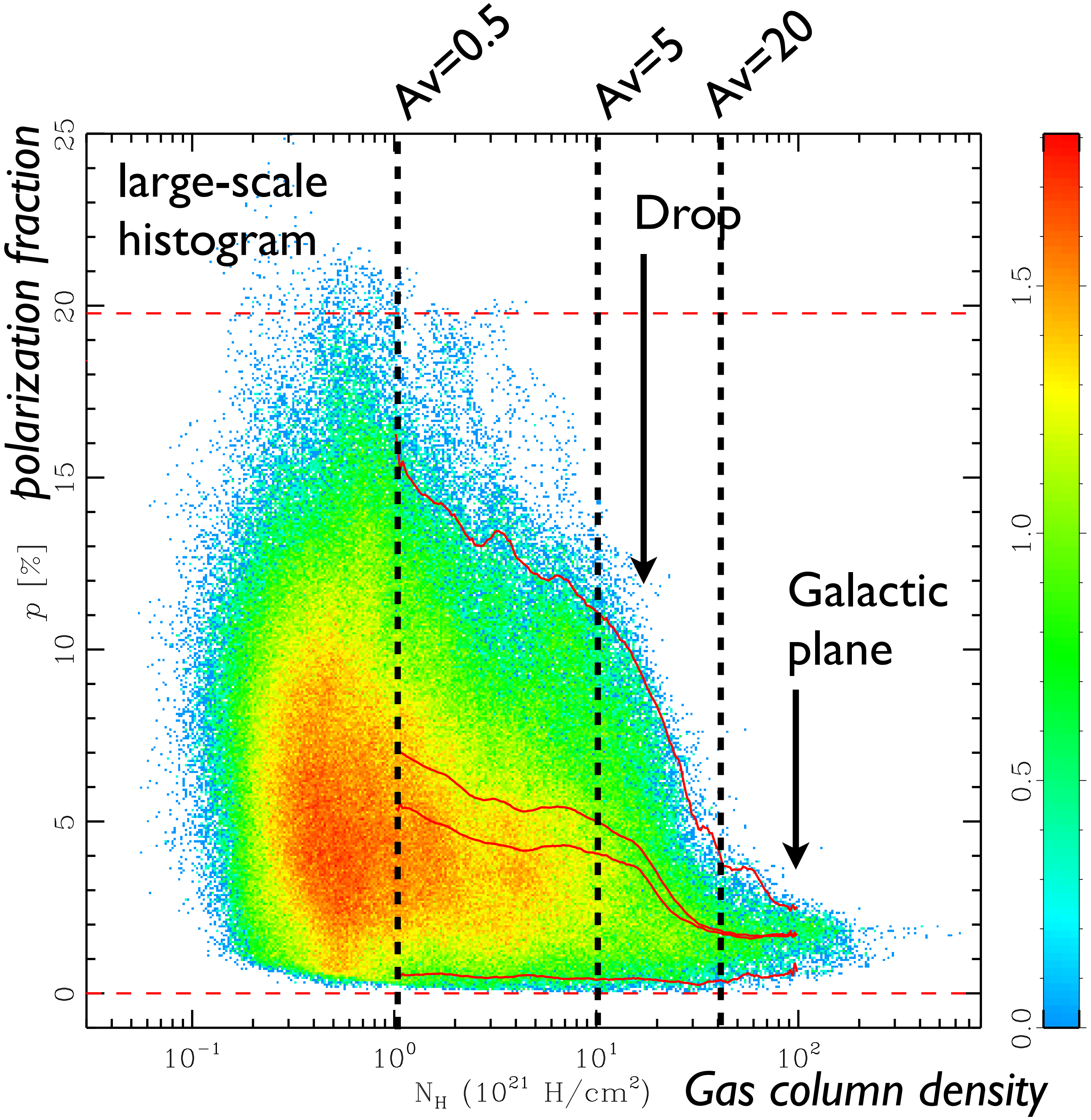


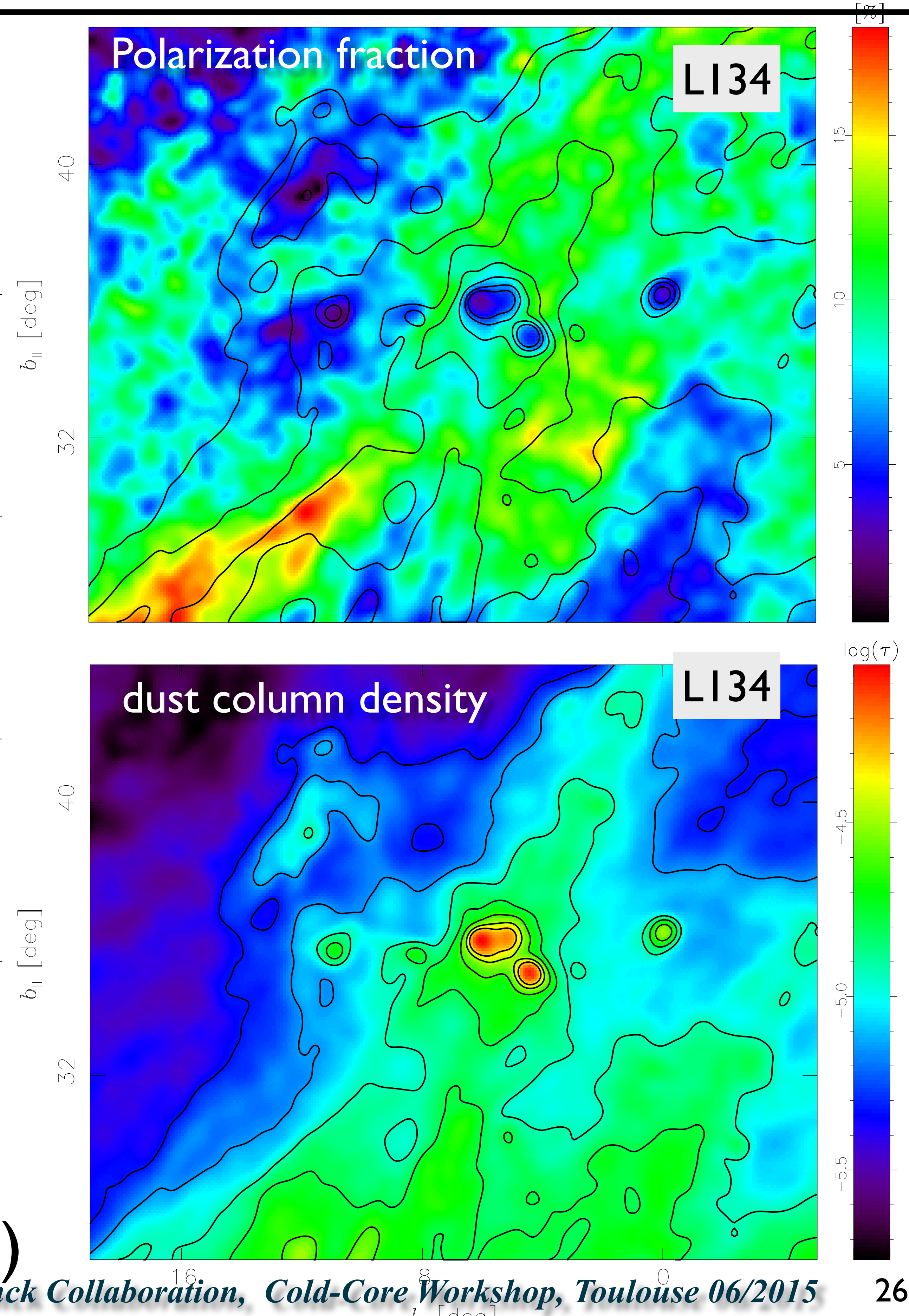


Highly polarized regions:
- Found in homogenous B field regions
- Often at edges of intensity structures

Some of these have little to no intensity counterparts

Polarization fraction vs N_H



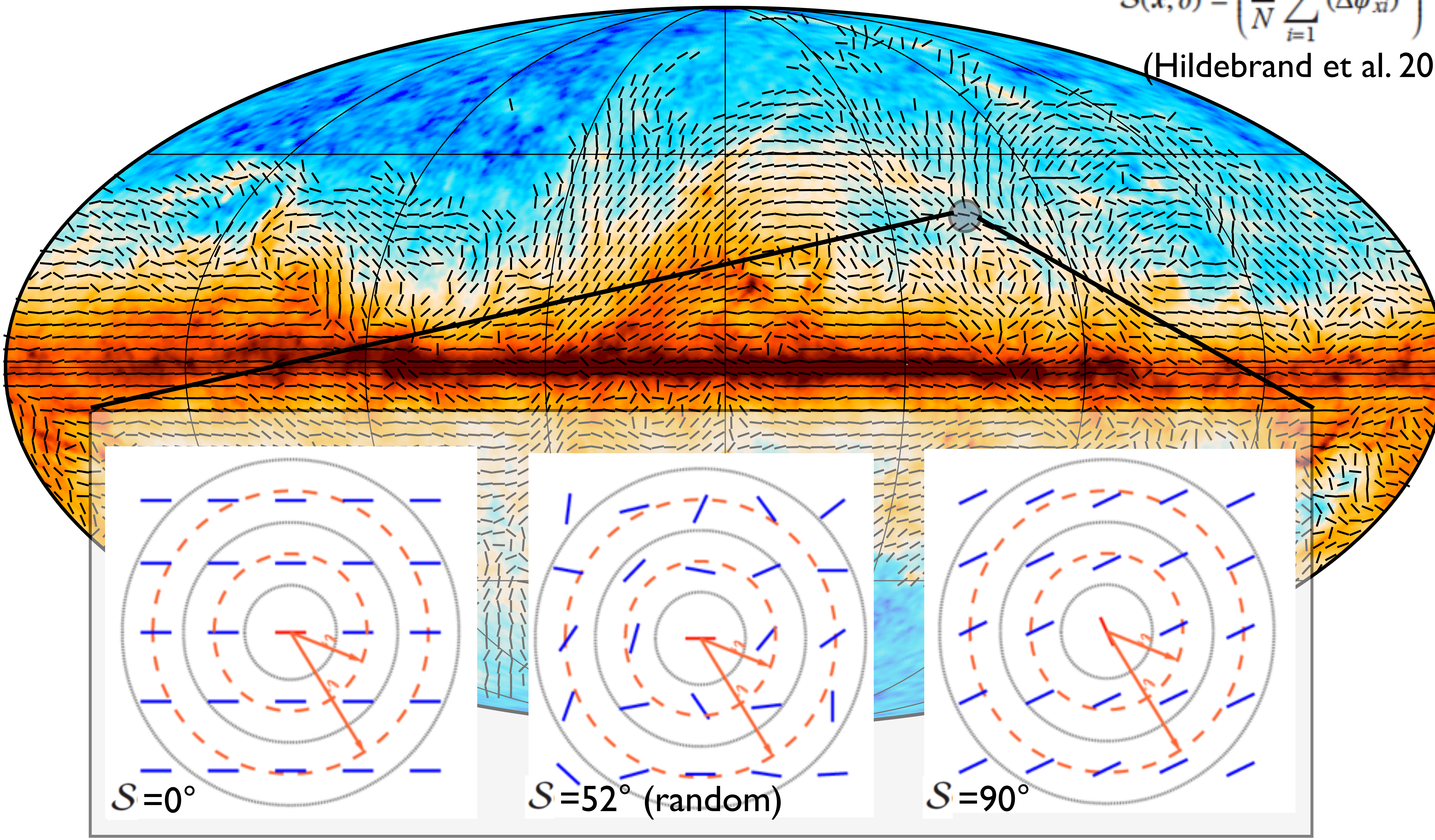


Polarization fractions drops at large column density (Galactic Plane + individual clouds)

Planck intermediate results. XIX.

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

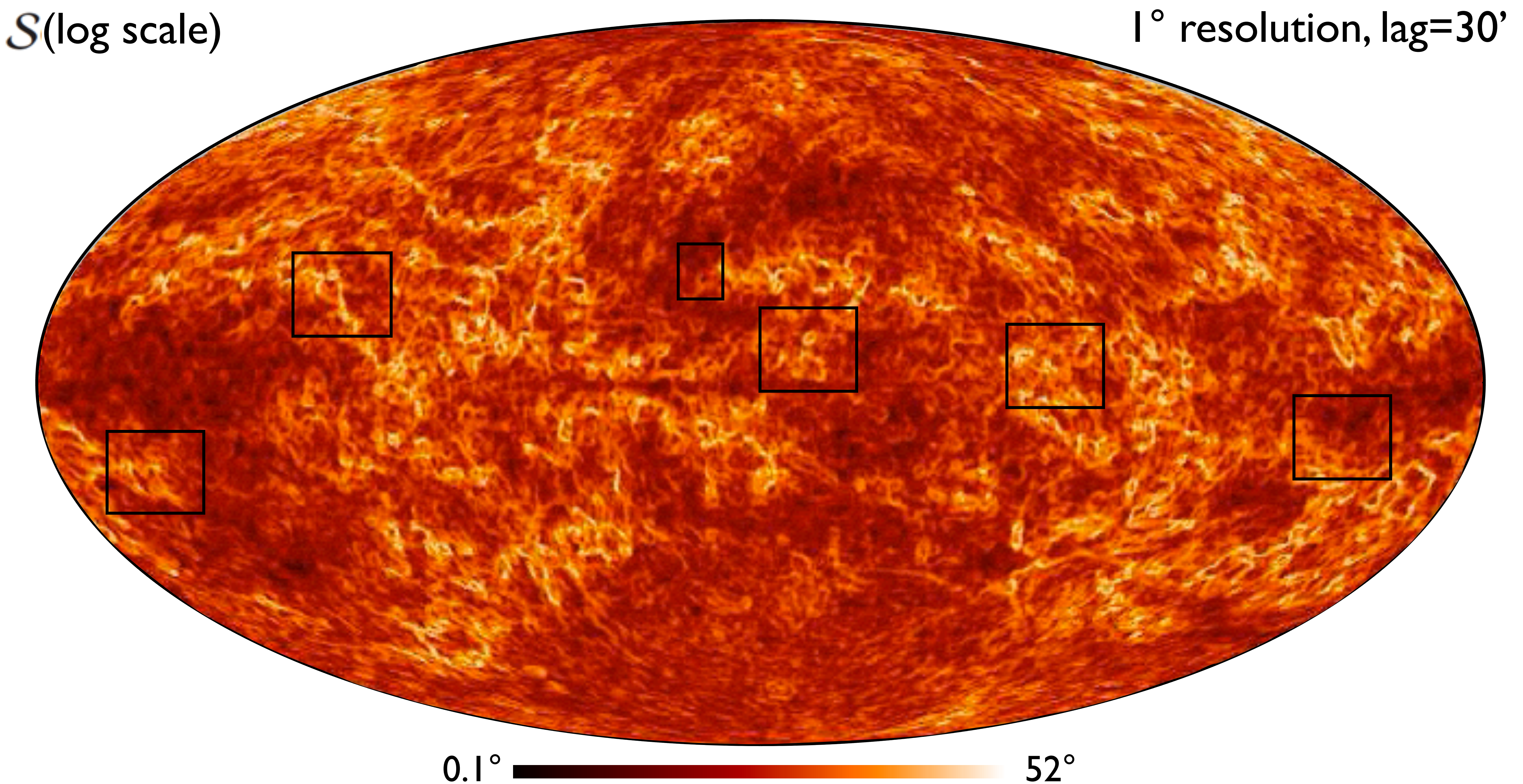
(Hildebrand et al. 2009)



$\mathcal{S}$ measures polarization direction homogeneity at given spatial scale

Planck intermediate results. XIX.

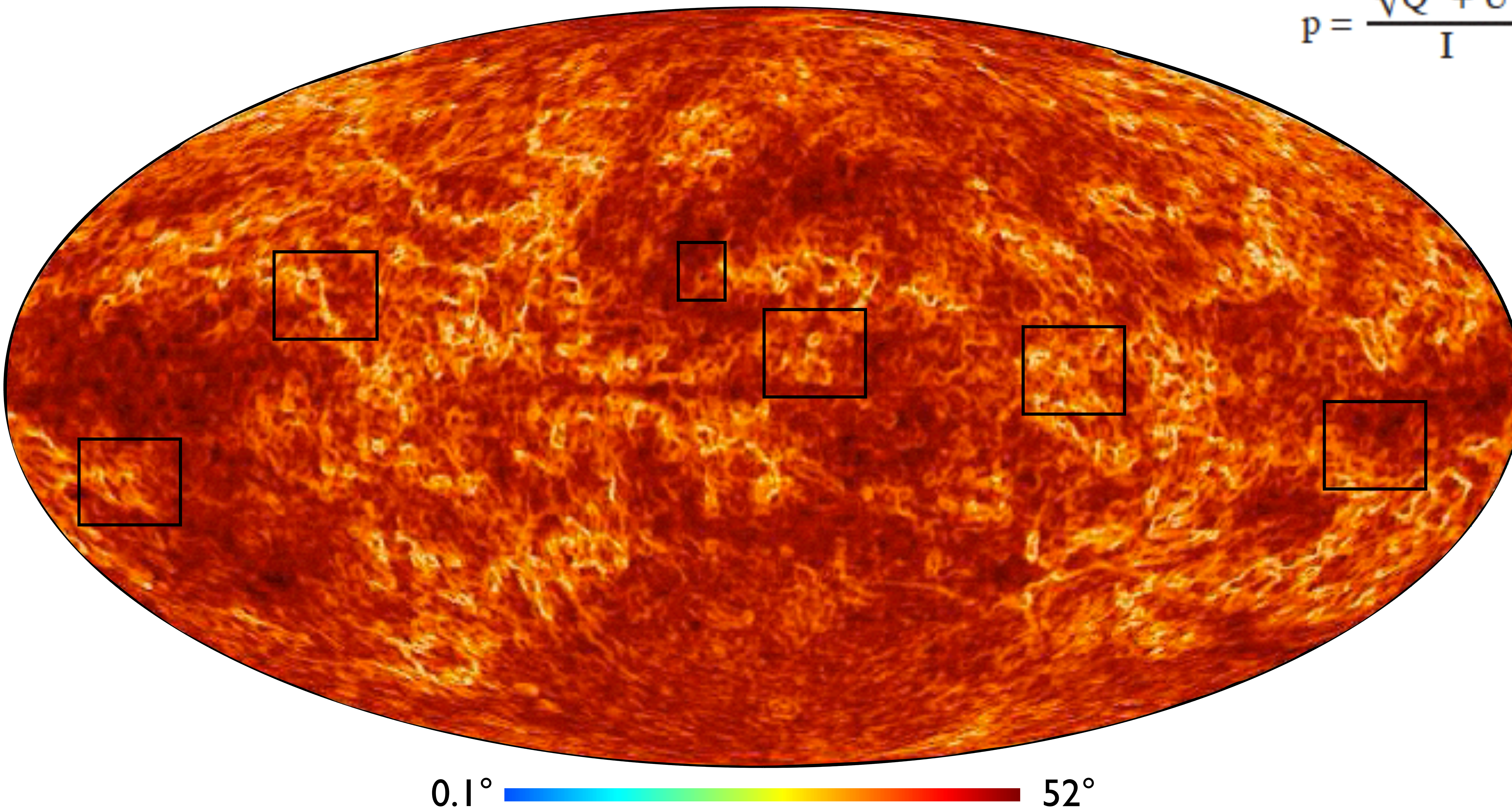
Angle Dispersion Function



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

Planck intermediate results. XIX.

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

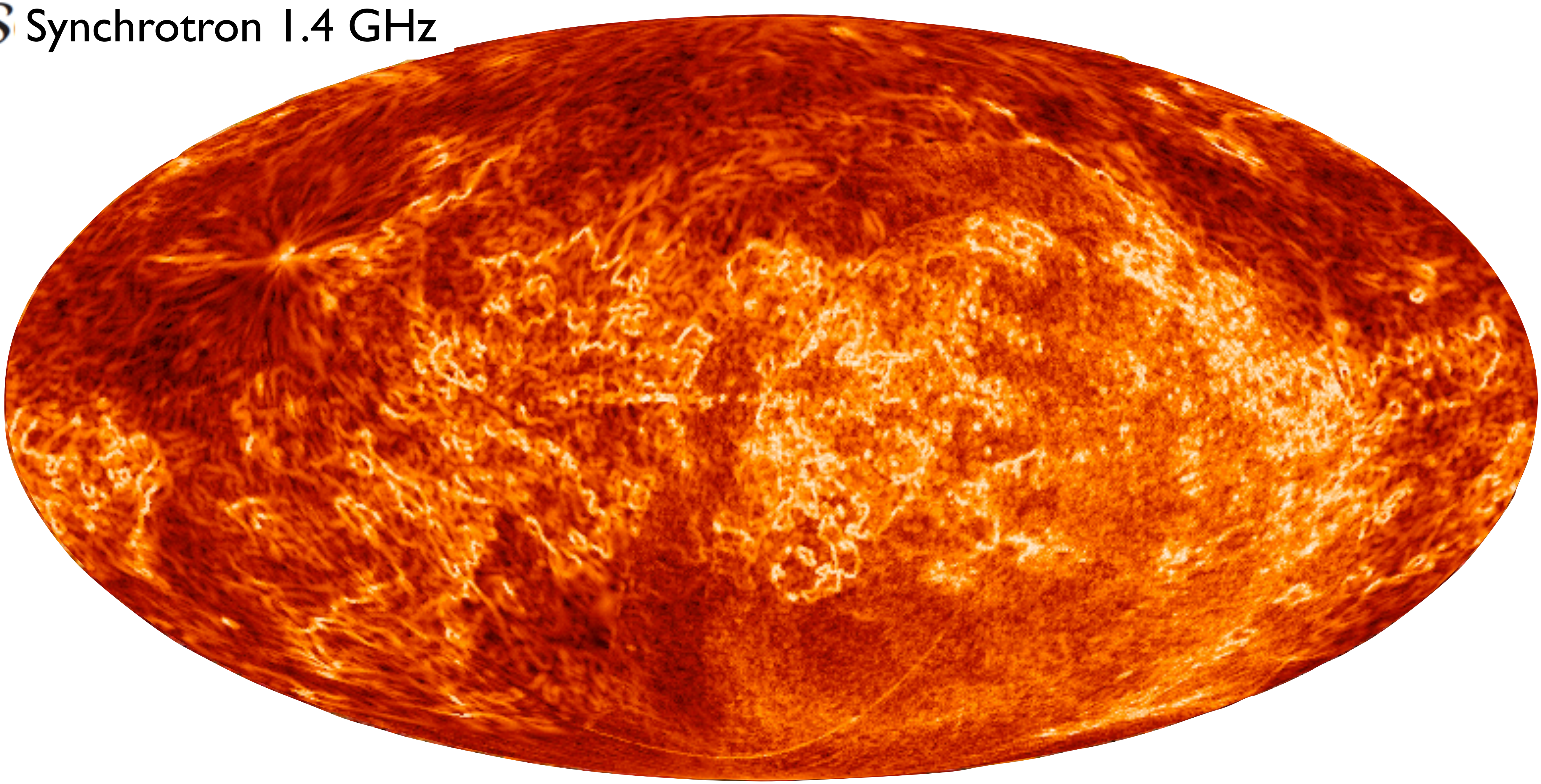


- Filamentary (Spaghetti) regions of high polarization rotation (!!)
- Correlate with low polarization

Planck intermediate results. XIX.

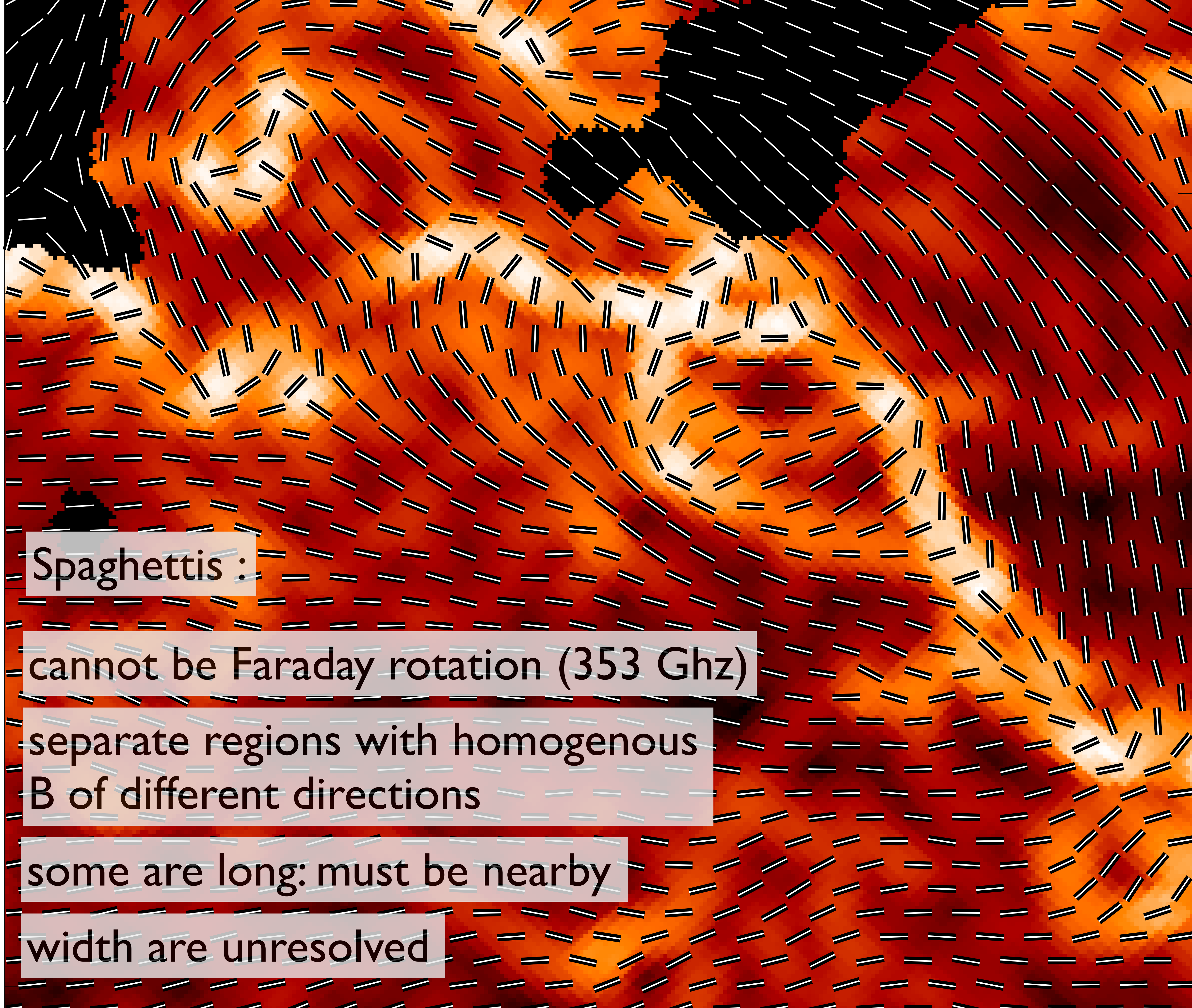
Angle Dispersion Function

$\mathcal{S}$ 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

Planck intermediate results. XIX.



Spaghettis :

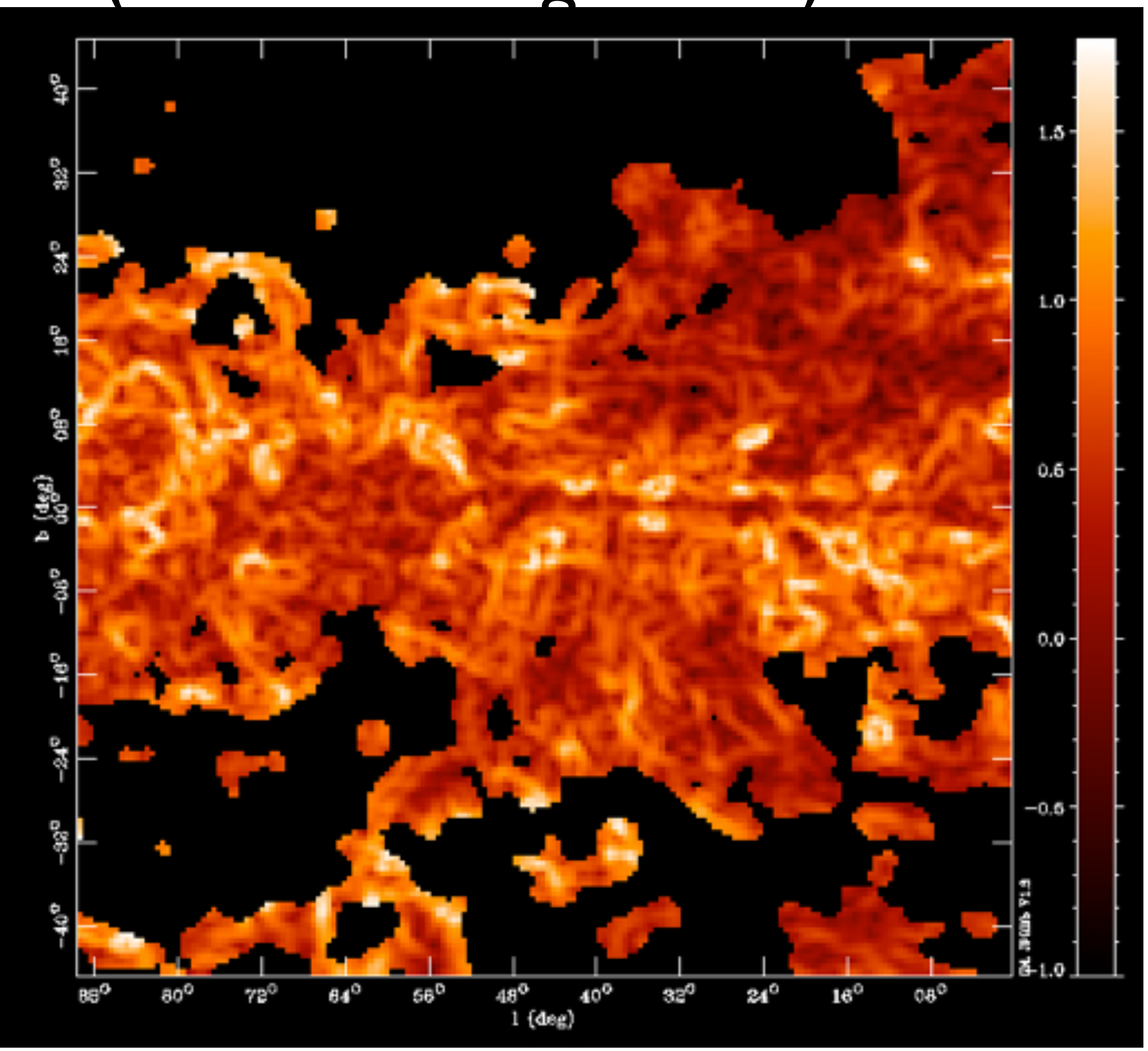
cannot be Faraday rotation (353 Ghz)

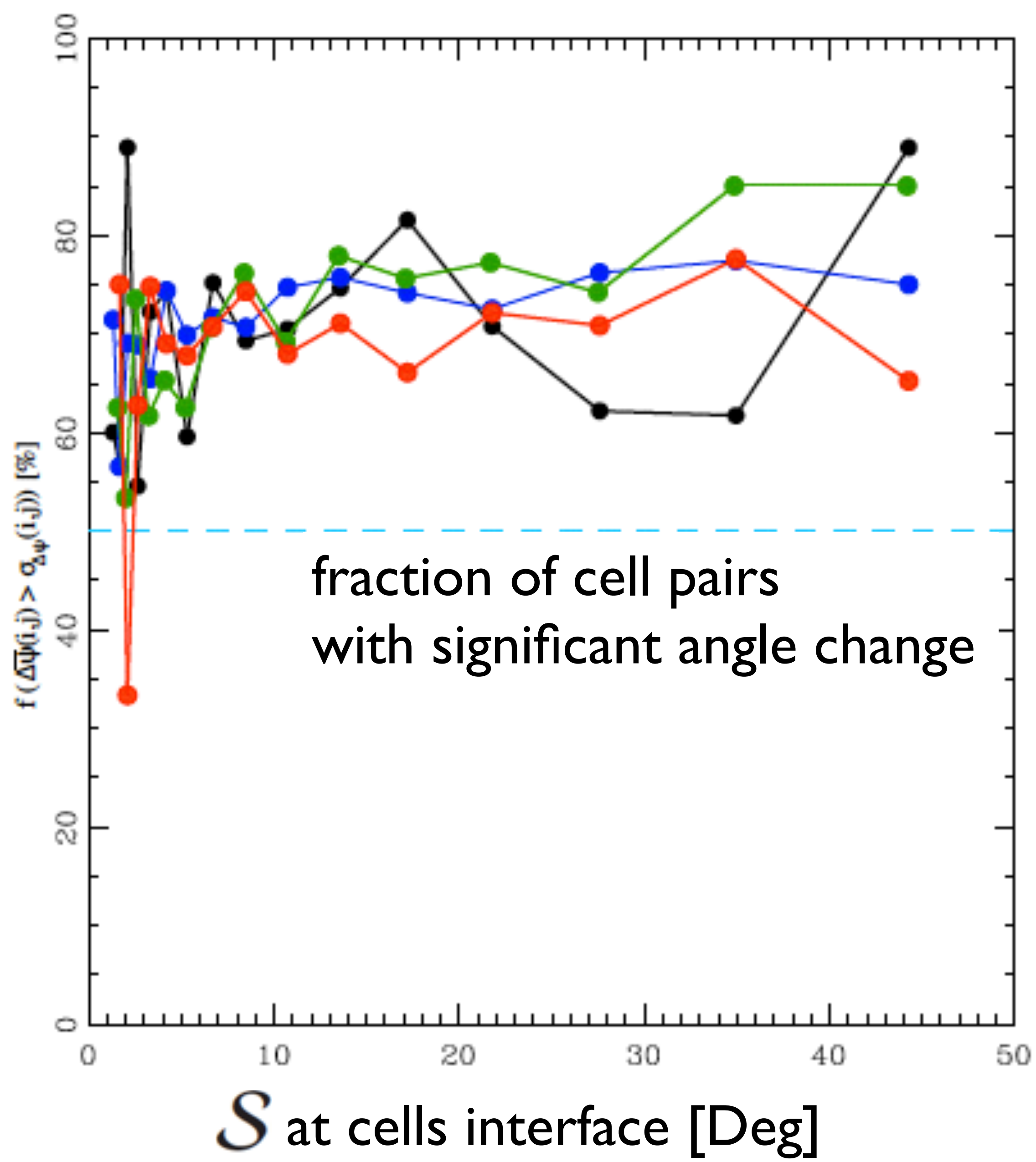
separate regions with homogenous B of different directions

some are long: must be nearby

width are unresolved

Cells separated using S
(watershed algorithm)

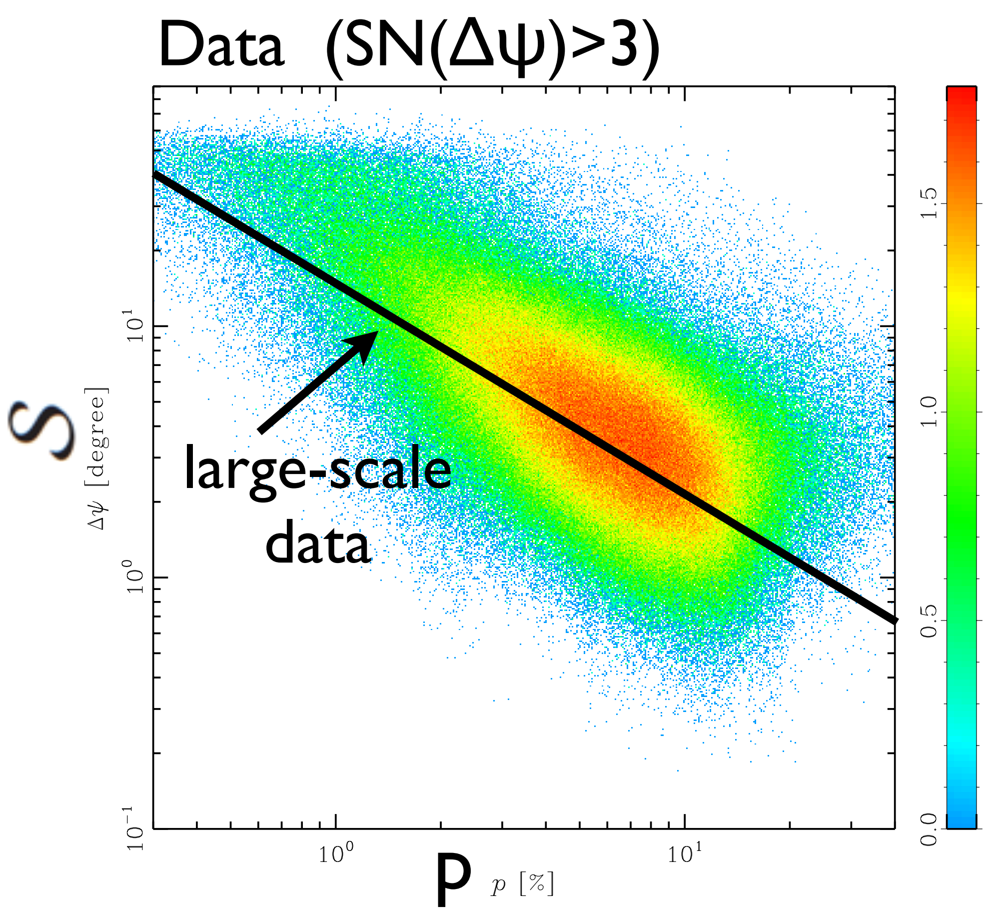


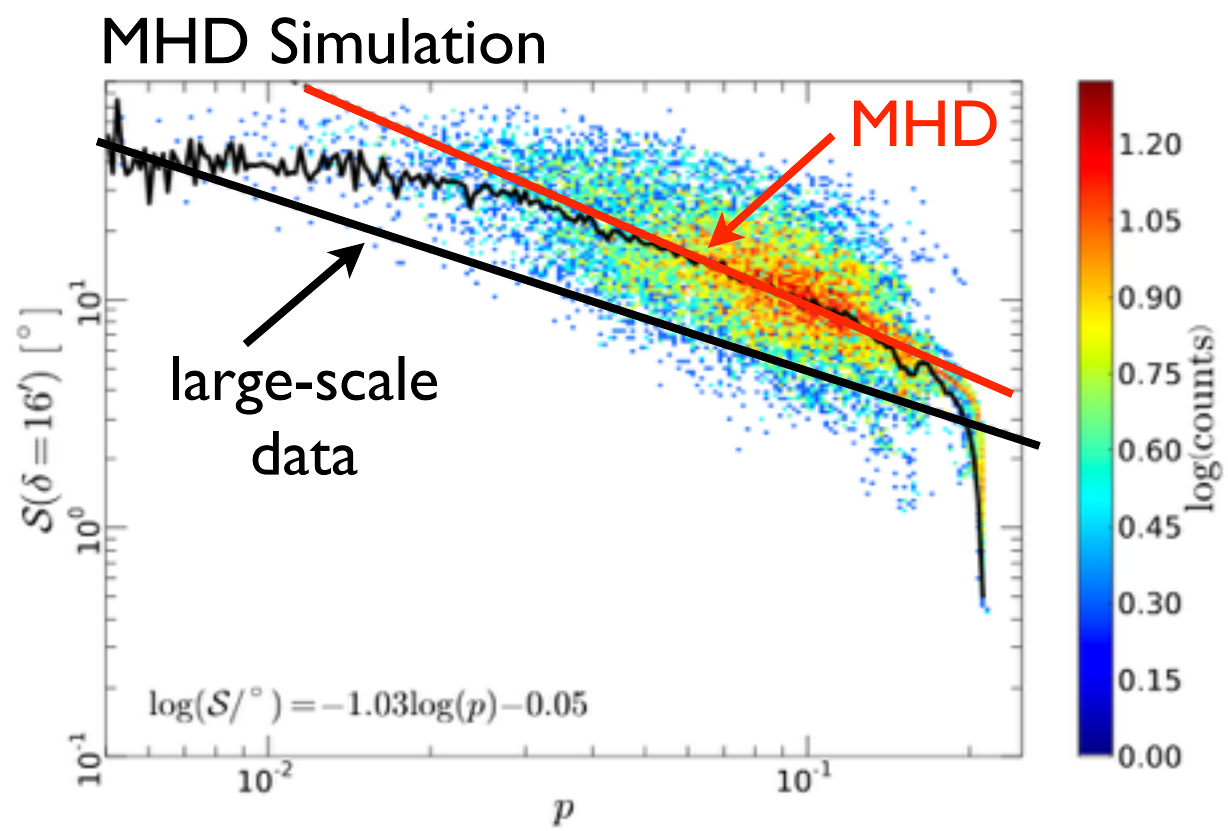


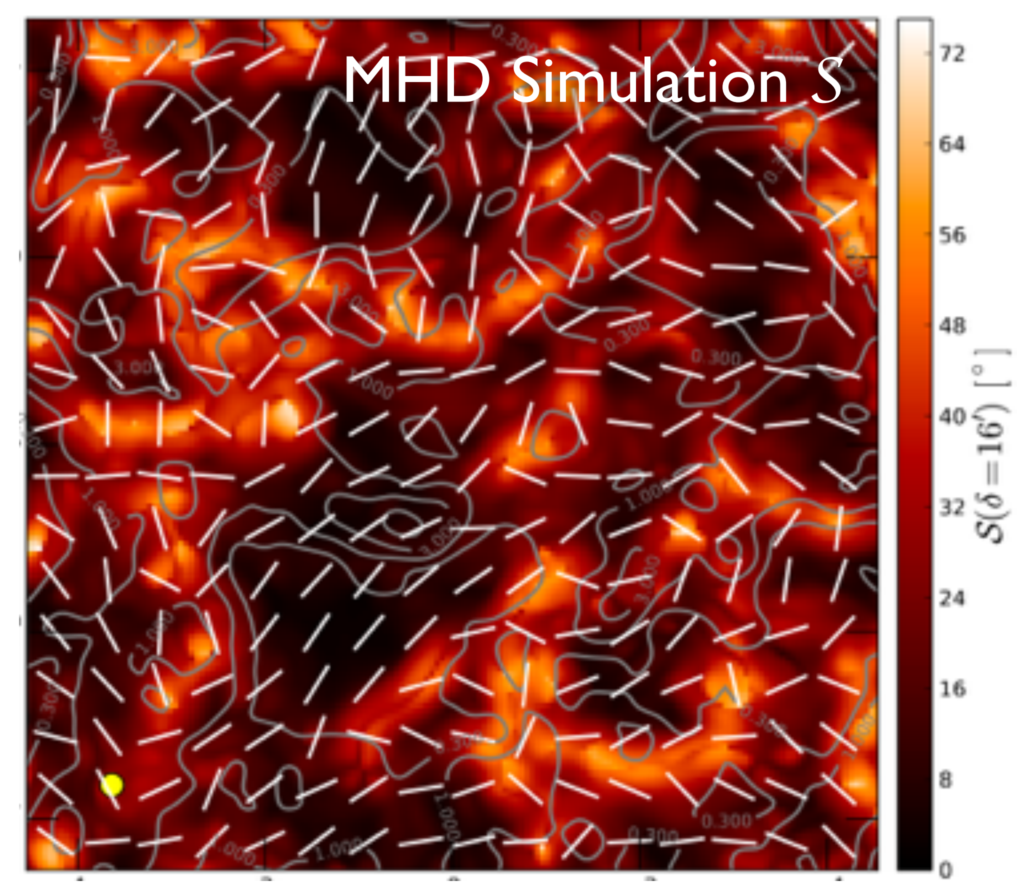
Depolarization canals separate contiguous connex regions with homogenous B, but of different directions

Planck intermediate results. XIX.

Comparison to MHD simulations



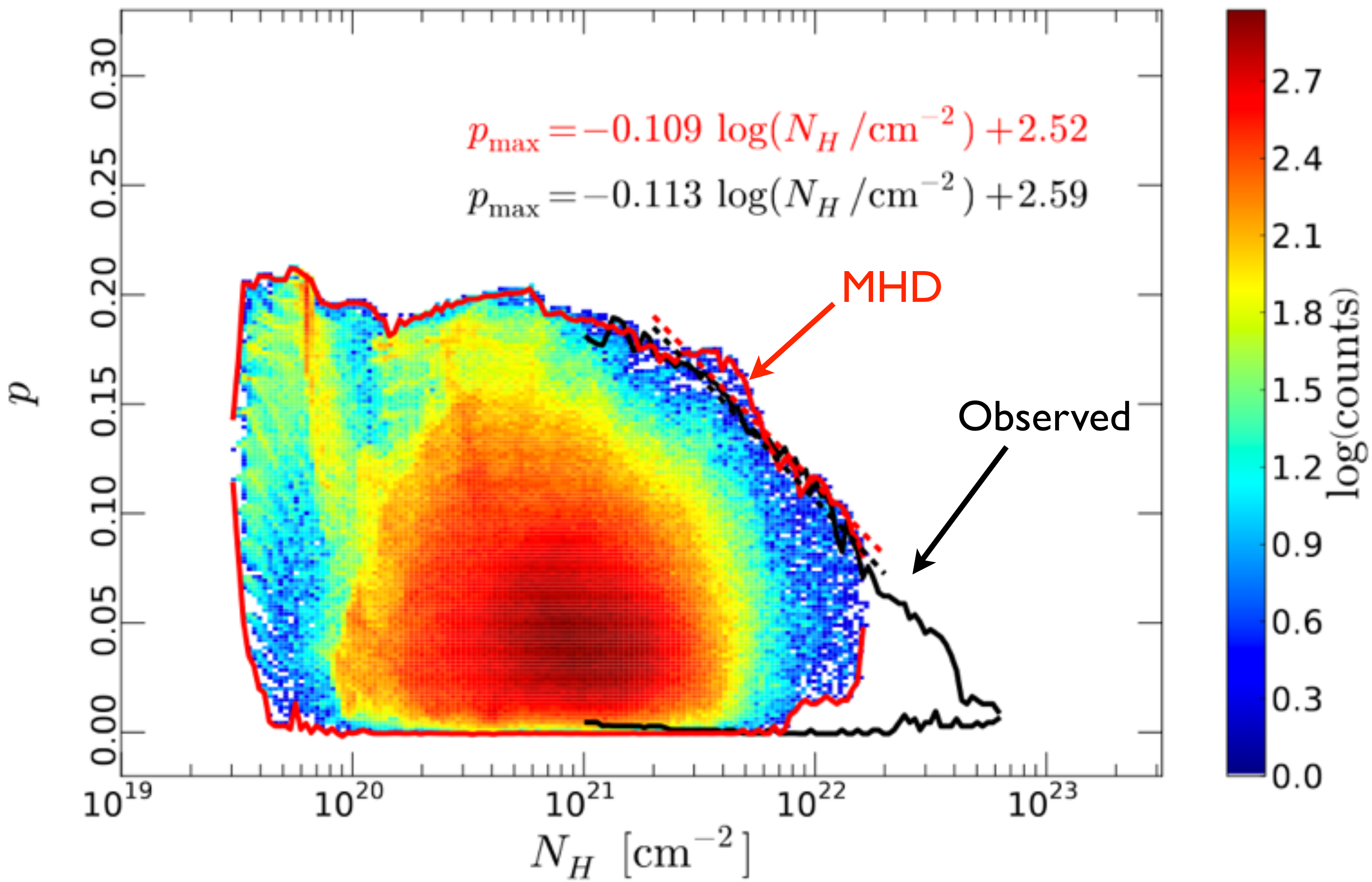




- Similar behaviour of $\mathcal{S}$ observed in MHD simulations
- MHD shows similar $\mathcal{S}$ filamentary structure
- Some differences in absolute $\mathcal{S}$ level ...

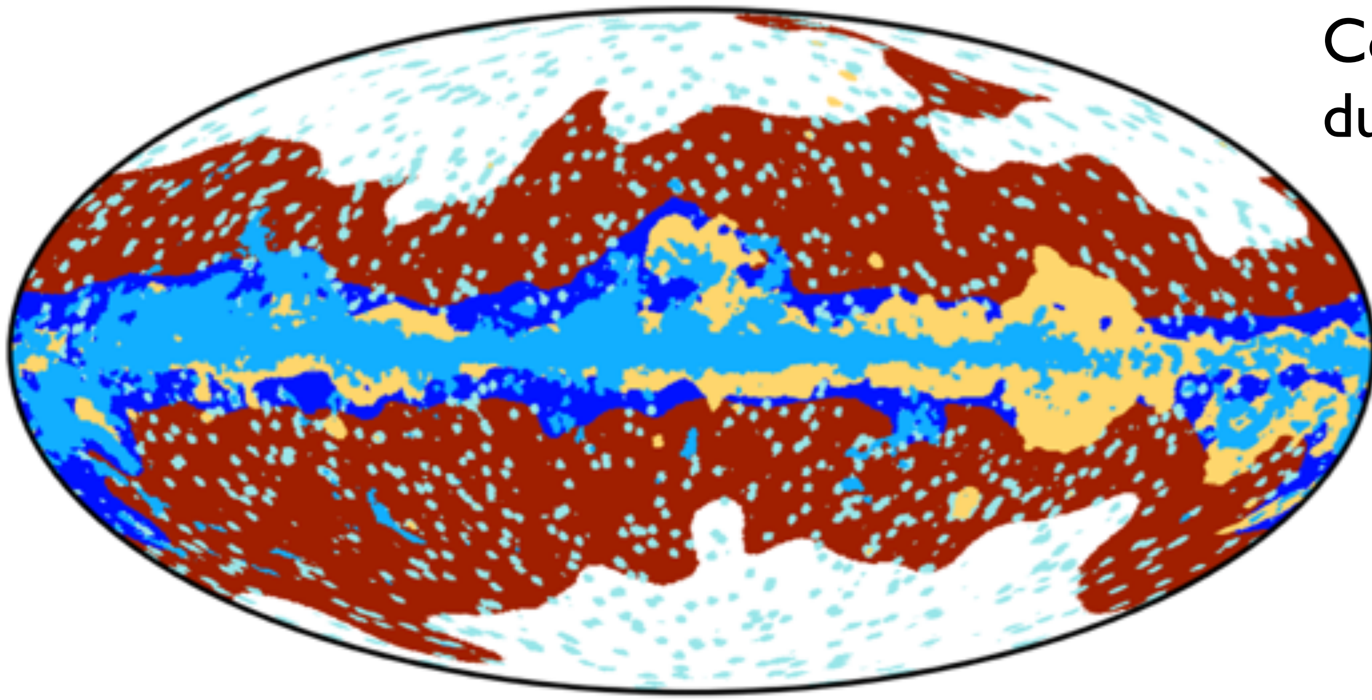
Planck intermediate results. XX.

Polarization fraction vs column density



Simulations reproduce well the decrease of p_{max} with N_H in the range 10^{21} to 2×10^{22} cm^{-2}

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

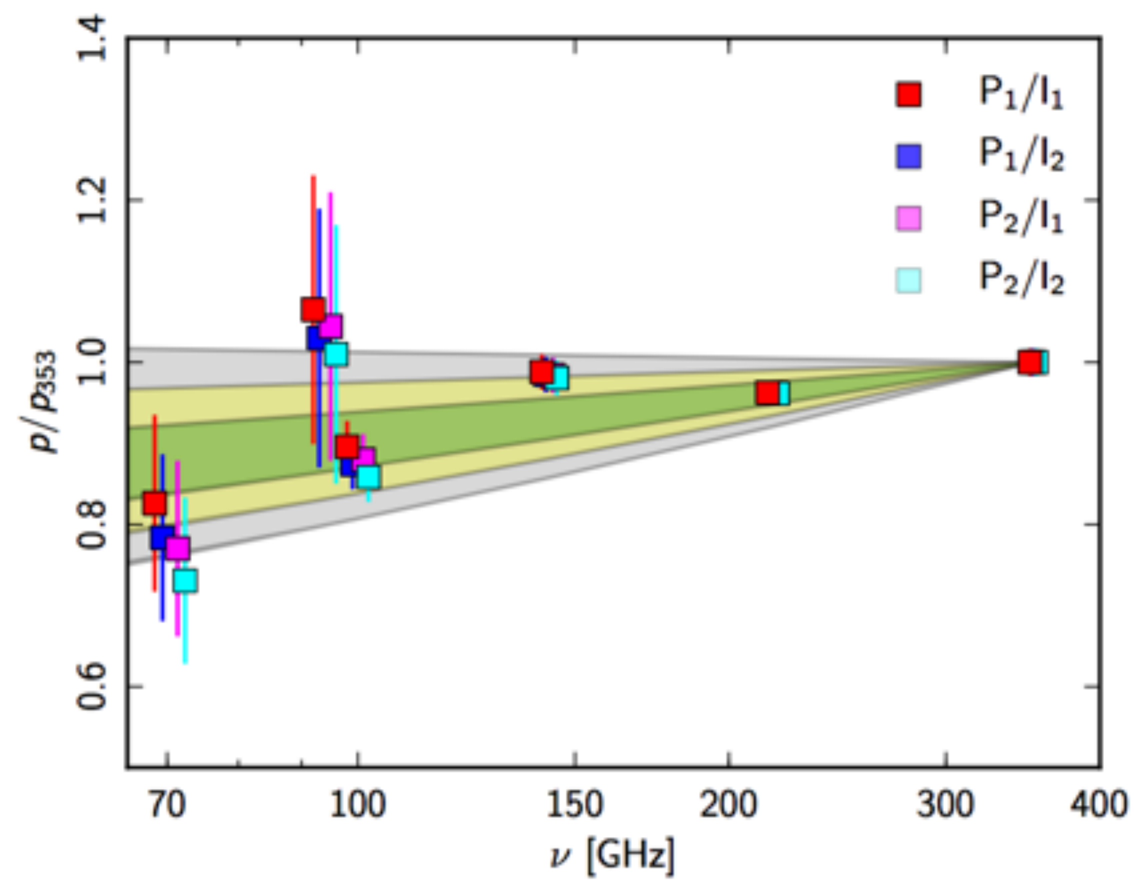
Indications for polarization SED steeper than Intensity SED :

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

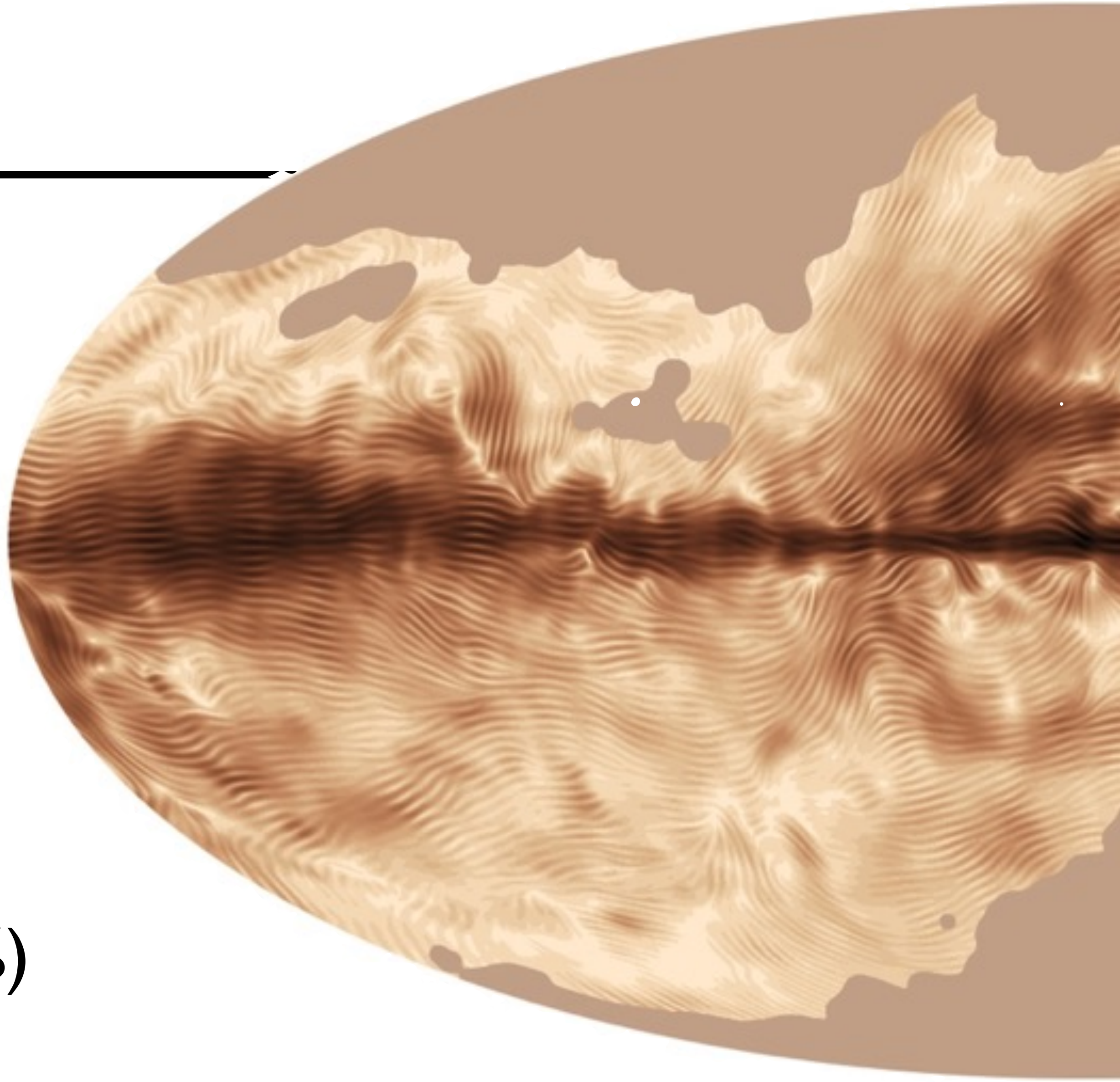
(unaccounted for component ? ferro-magnetic grains ? Carbonaceous grains ?)

New constraints on dust models and/ or component separation

Polarization fraction vs frequency



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

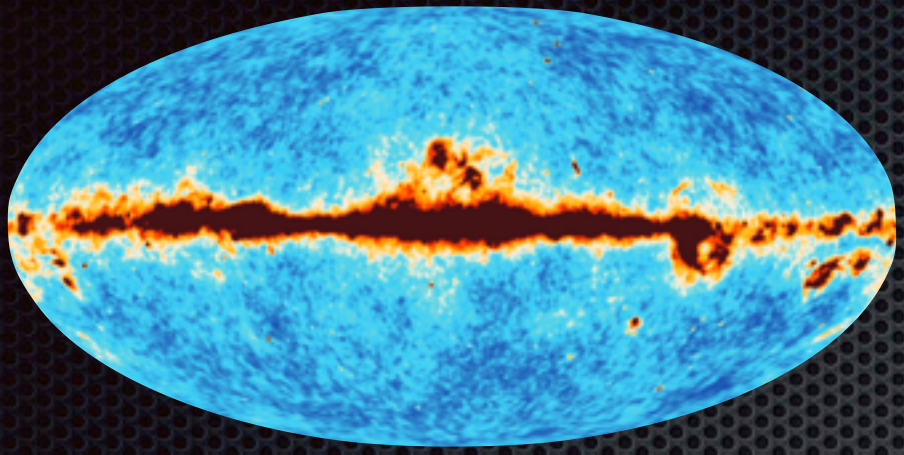
- Dust has high intrinsic polarization (>20%)
- p decreases with N_H
- We see depolarization canals, not due to Faraday rotation
- Anticorrelation between p and angle dispersion underlines importance of the field geometry.
- New constraints for dust models.

- The Analysis is only at a start

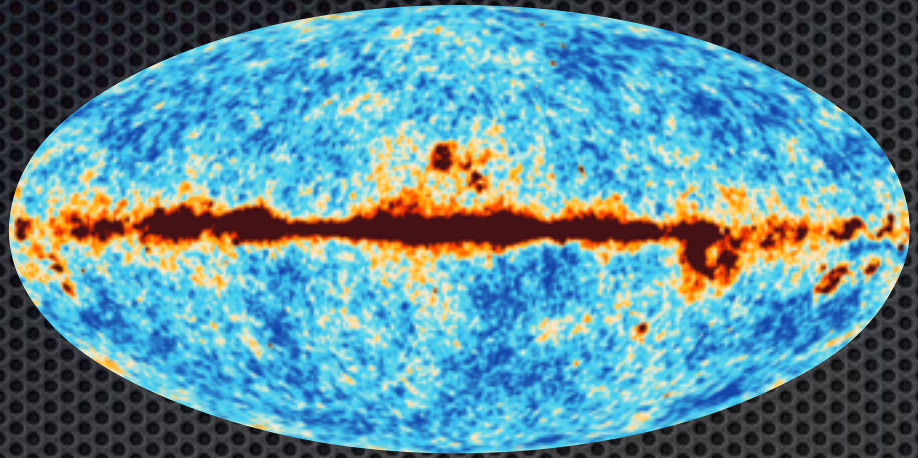
The Data is released …

Planck Intensity maps

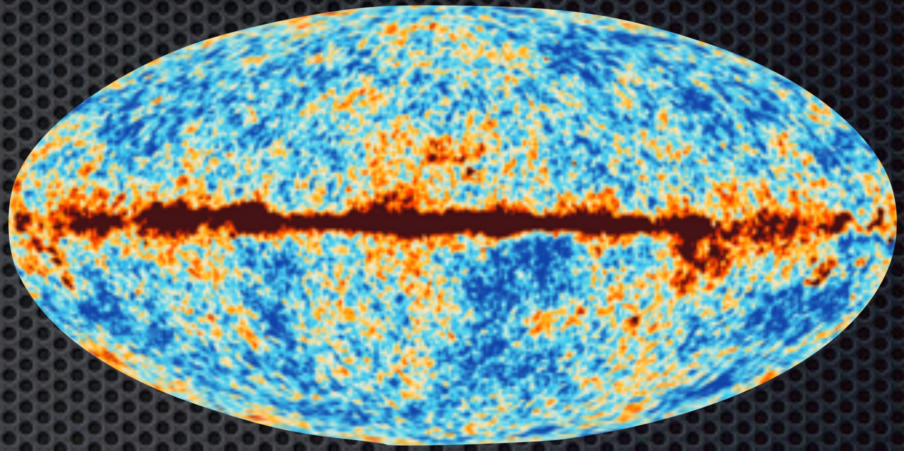
30 GHz 10 mm 32.6’



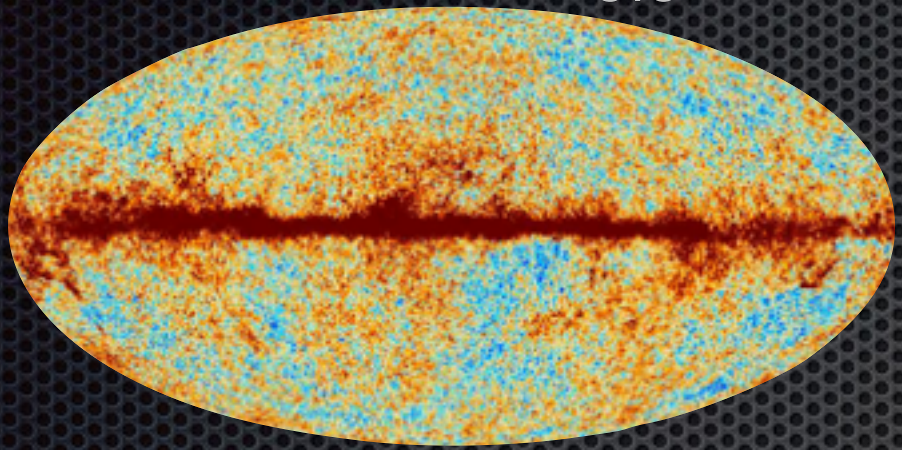
44 GHz 6.8 mm 28’



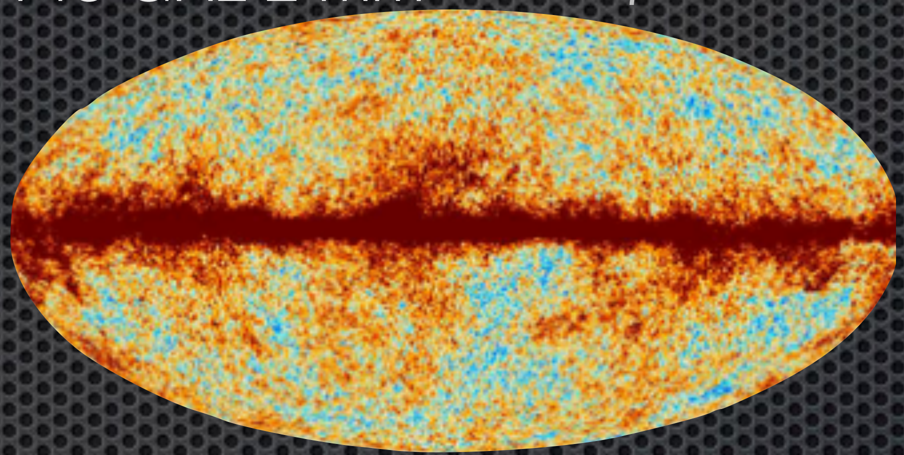
70 GHz 4.3 mm 13’



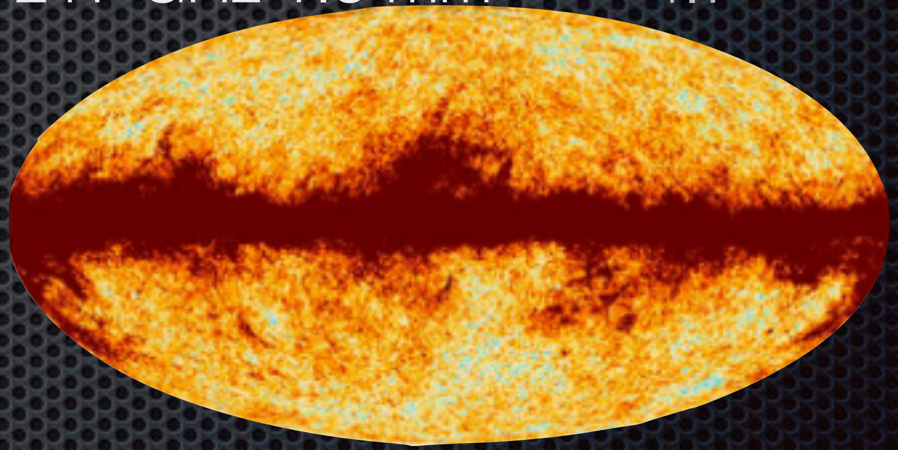
100 GHz 3 mm 9.5’



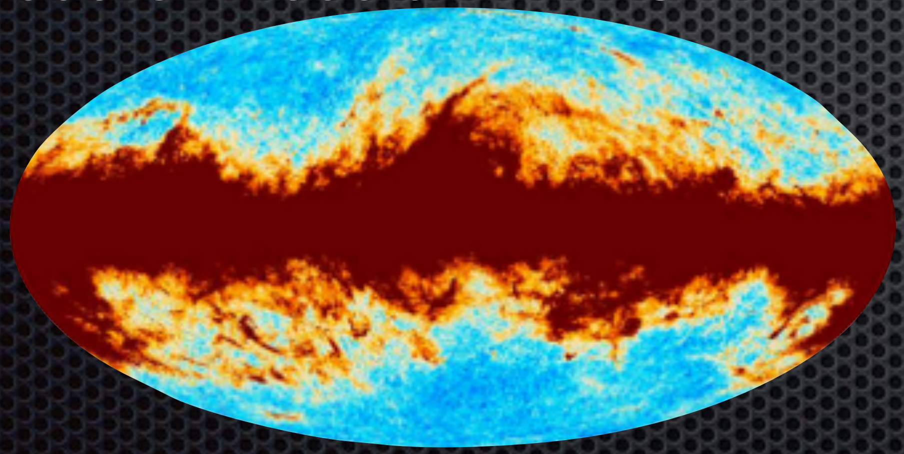
143 GHz 2 mm 7’



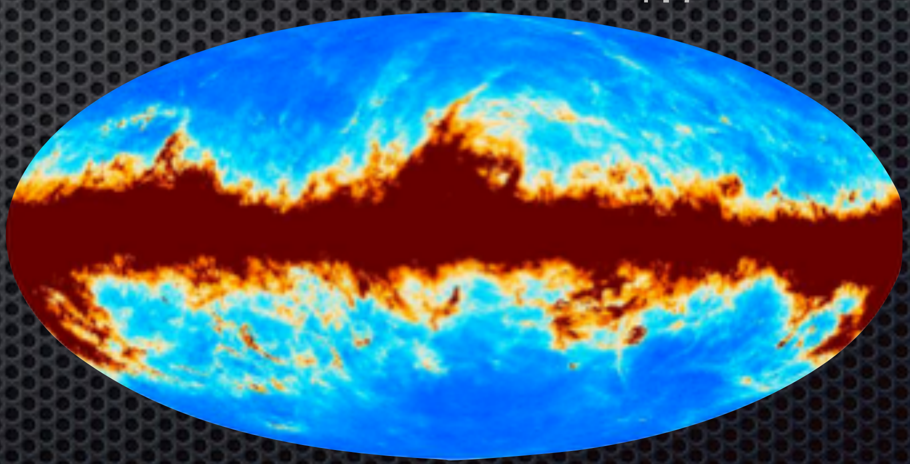
217 GHz 1.3 mm 4.7’



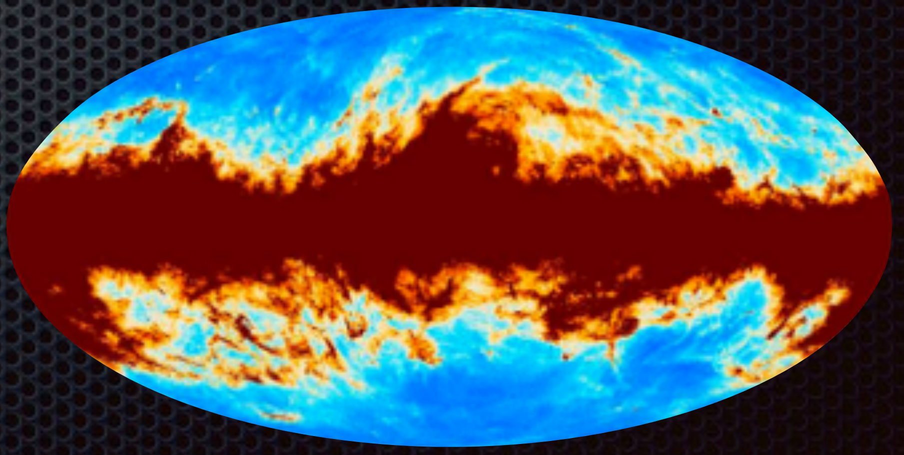
353 GHz 850 um 4.5’



545 GHz 550 um 4.7’



857 GHz 350 um 4.4’

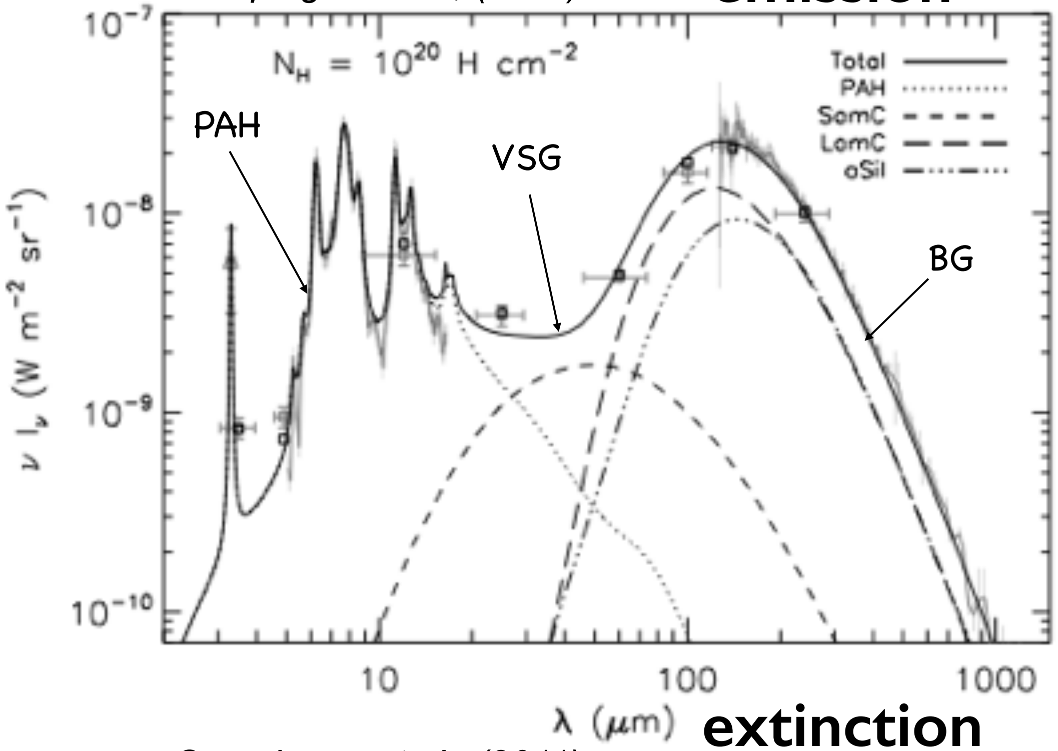


The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

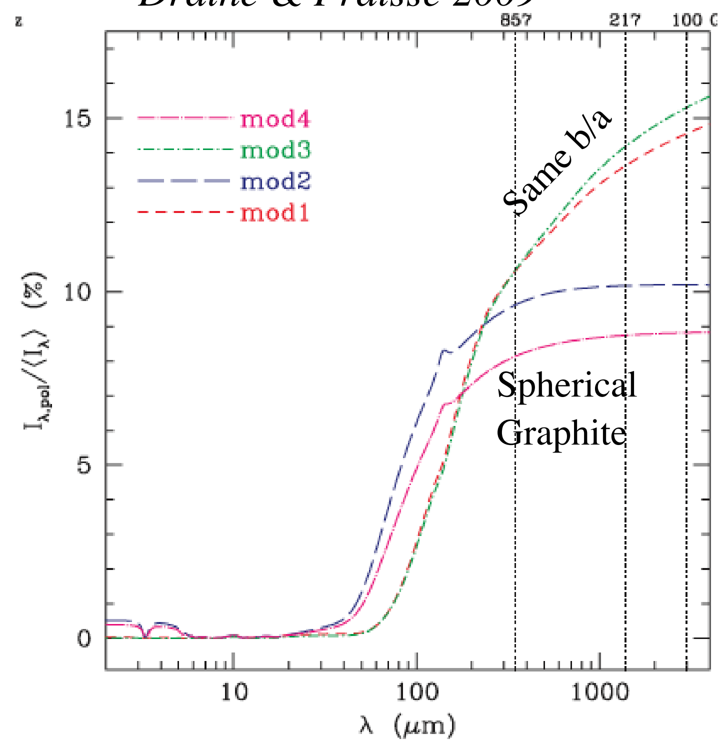
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

Dust Polarization

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



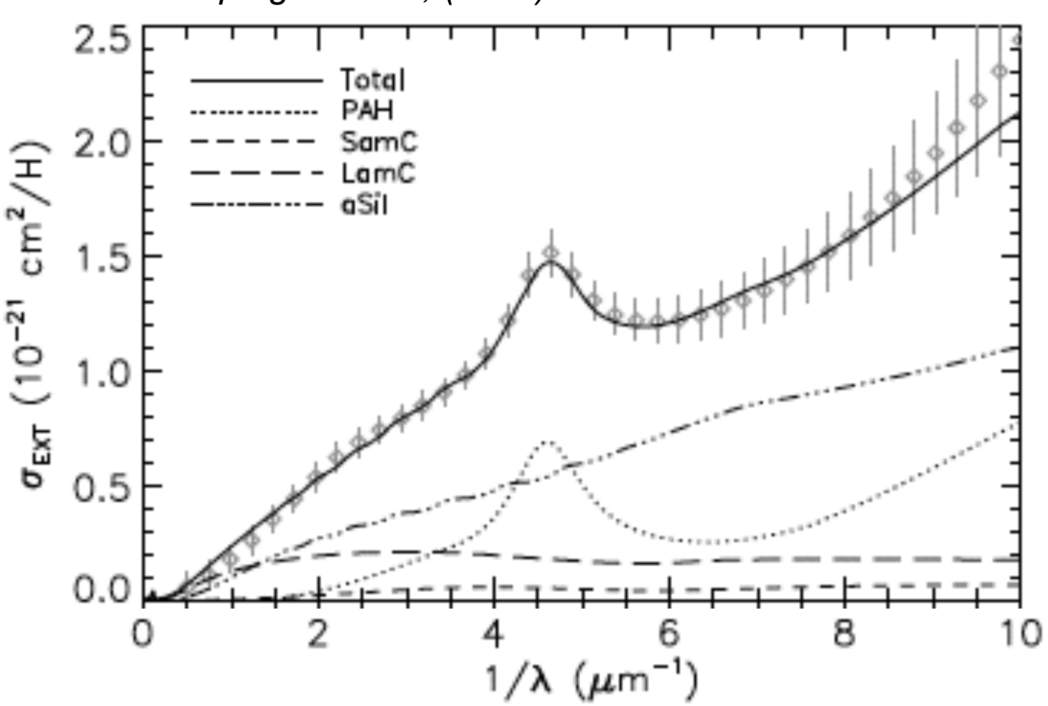
Draine & Fraisse 2009

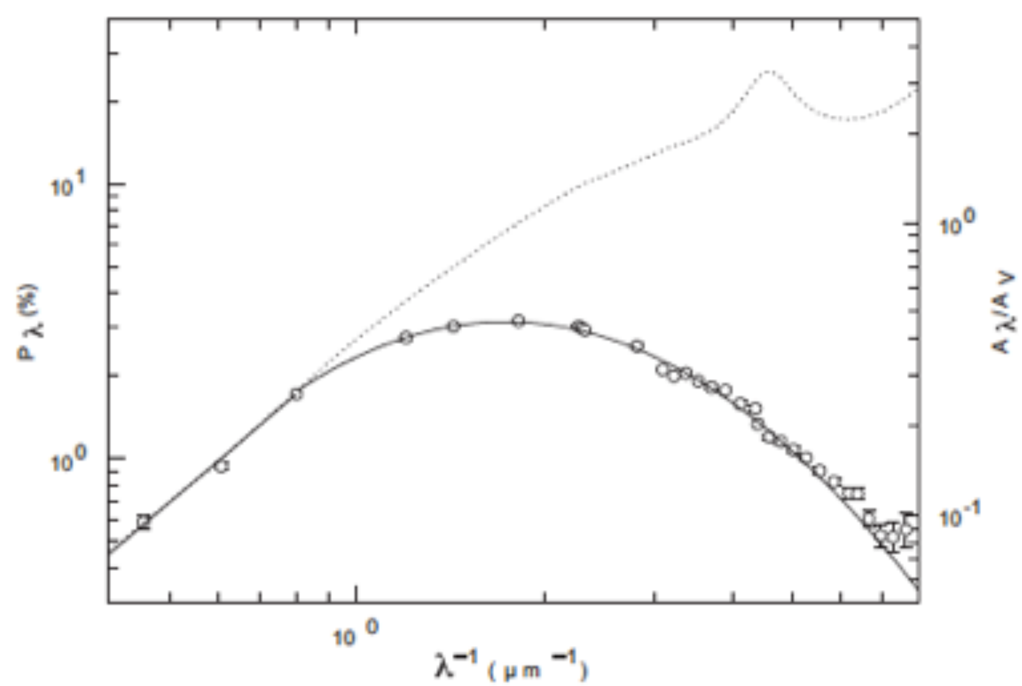


polarization in emission is predicted ~10-15%

extinction

Compiegne et al., (2011)



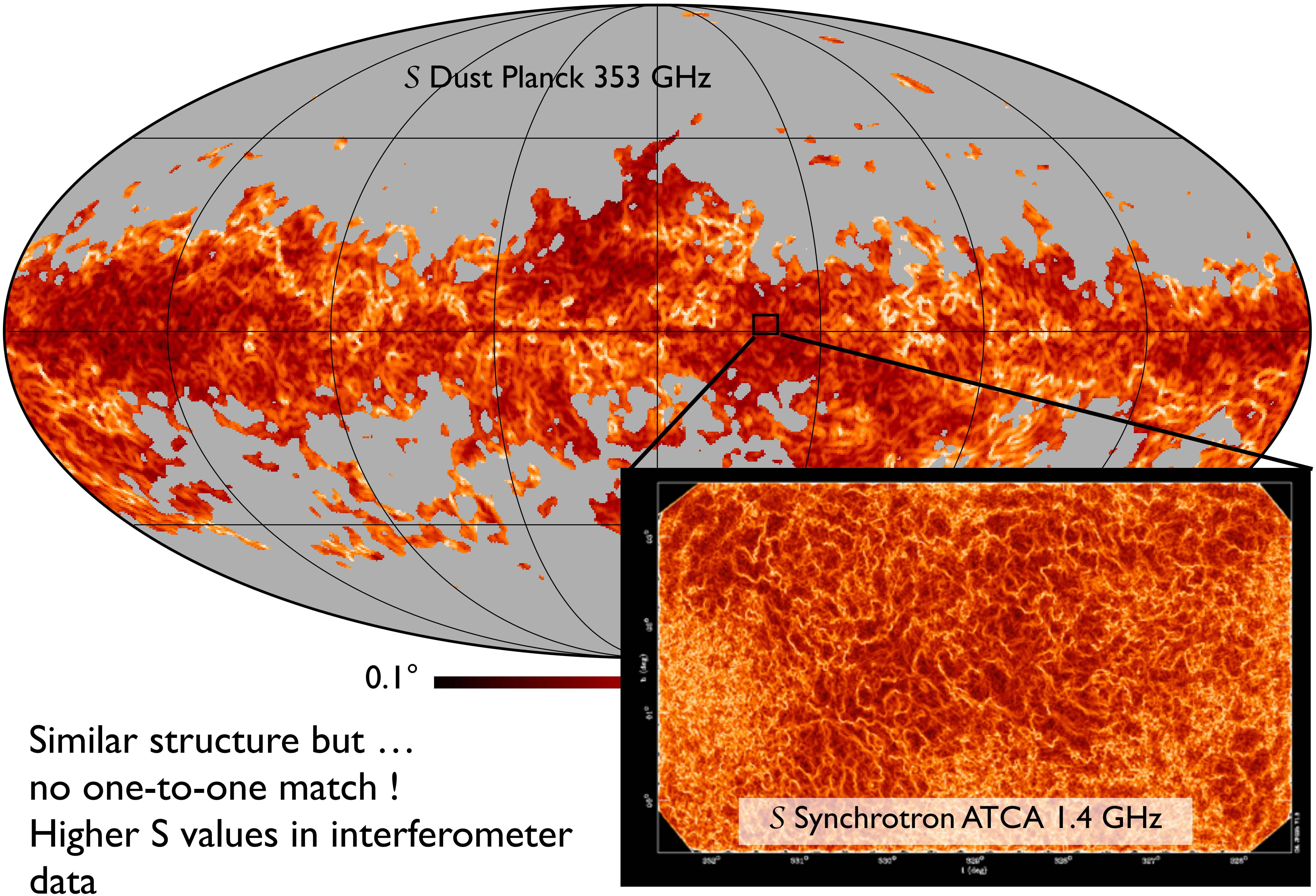


Small grains extinction not polarized:
likely not aligned

Various possible models lead to different predictions in polarization

Variations of polarization fraction with frequency will help constrain dust models

Angle Dispersion Function



Similar structure but …
no one-to-one match !
Higher S values in interferometer data

Data from Gaensler et al. 2009

Planck and CMB B Foreground


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For Au

News & Comment > News > 2014 > May > Article

NATURE | NEWS

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

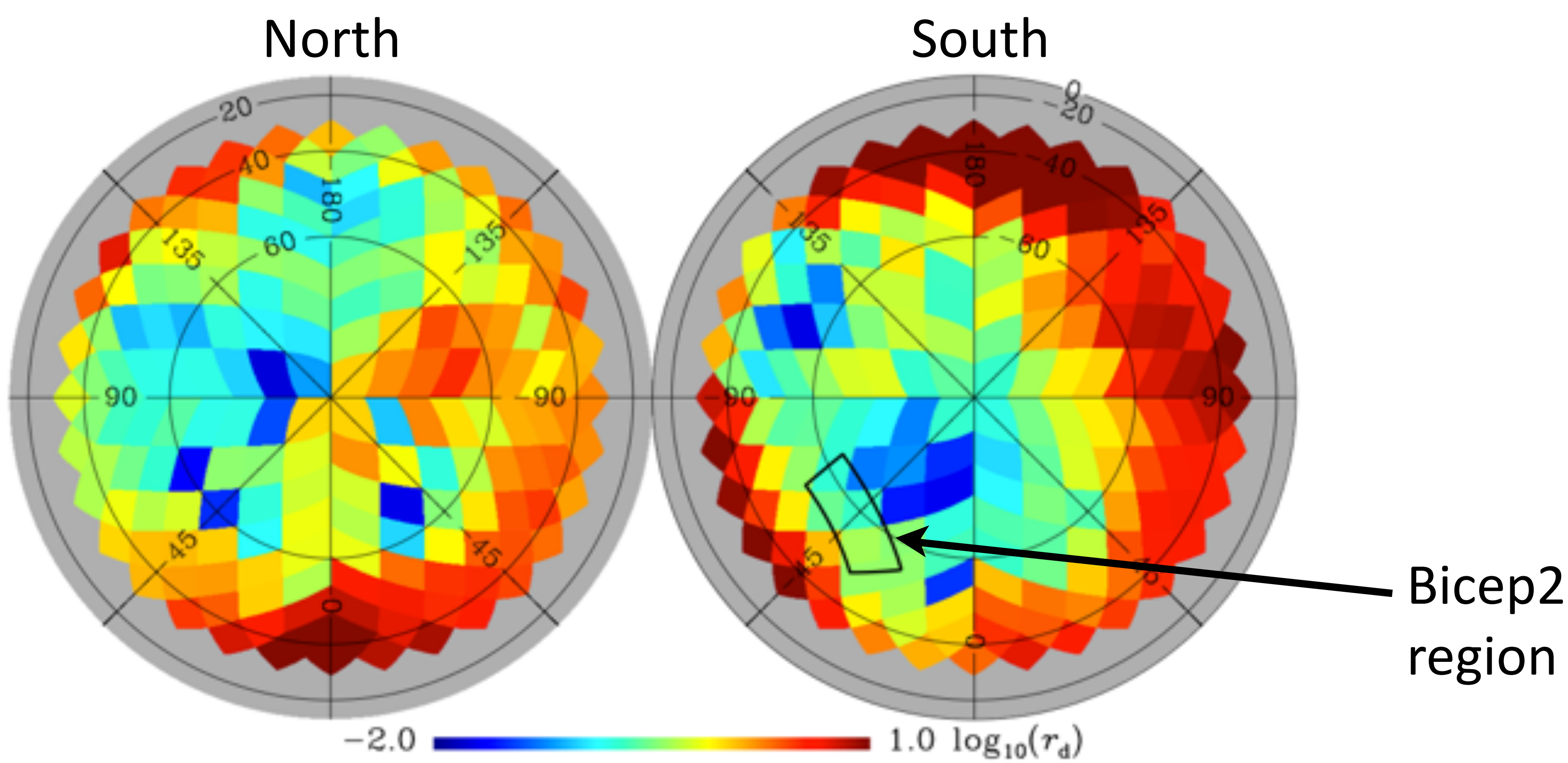
By Adrian Cho | Monday, May 19, 2014 - 6:30pm

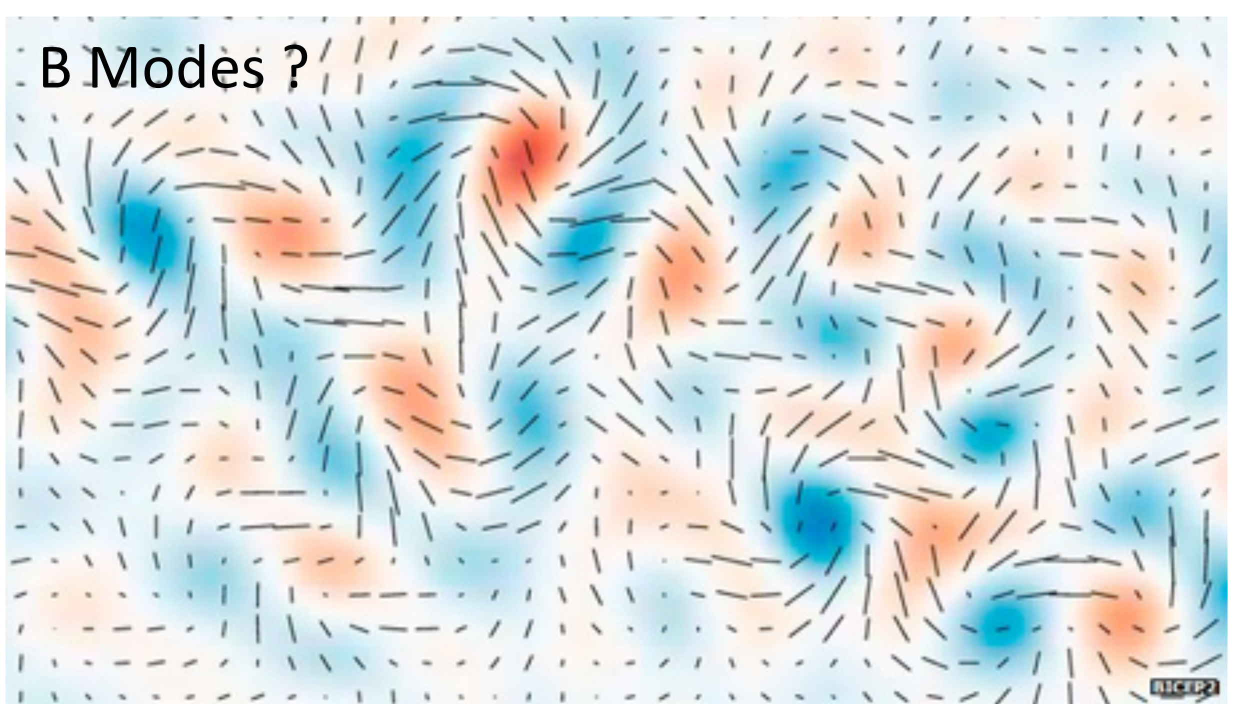
Staff Writer

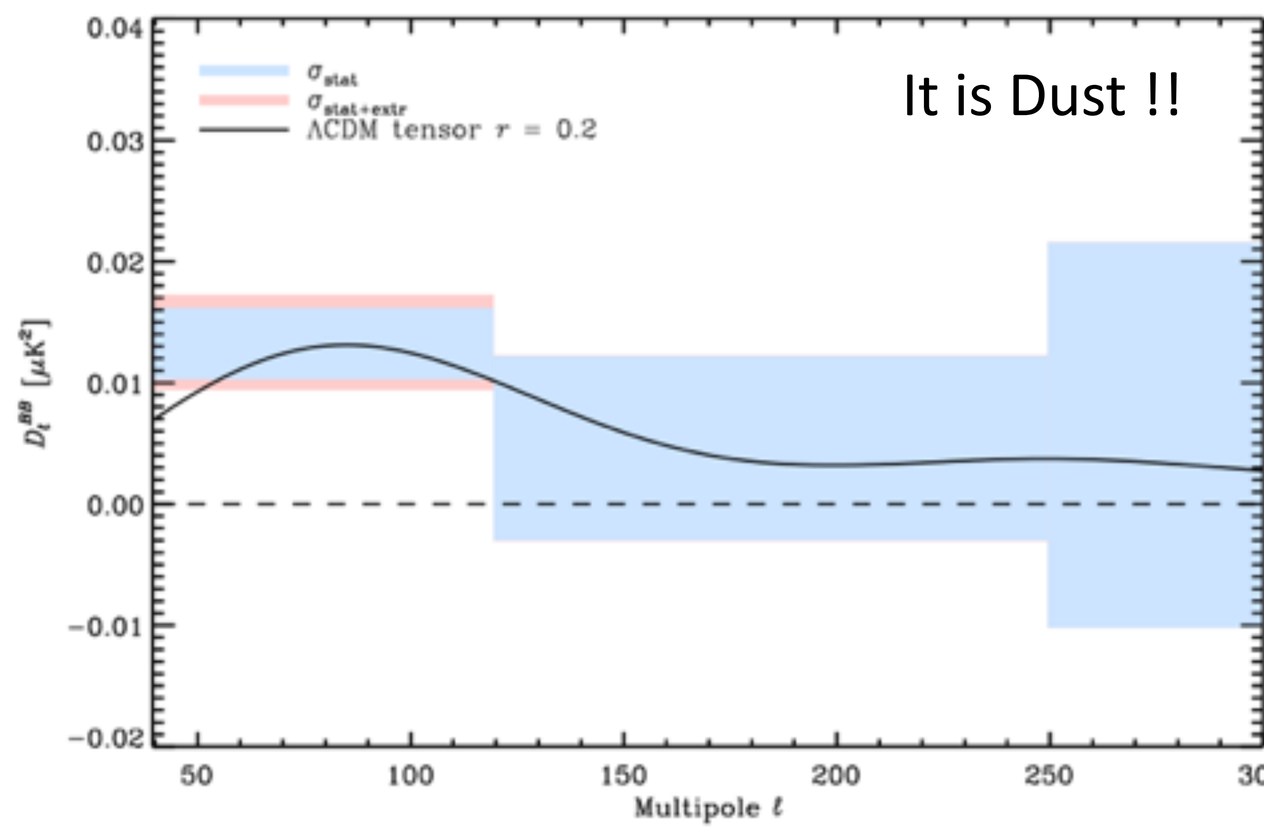
Email Adrian

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.