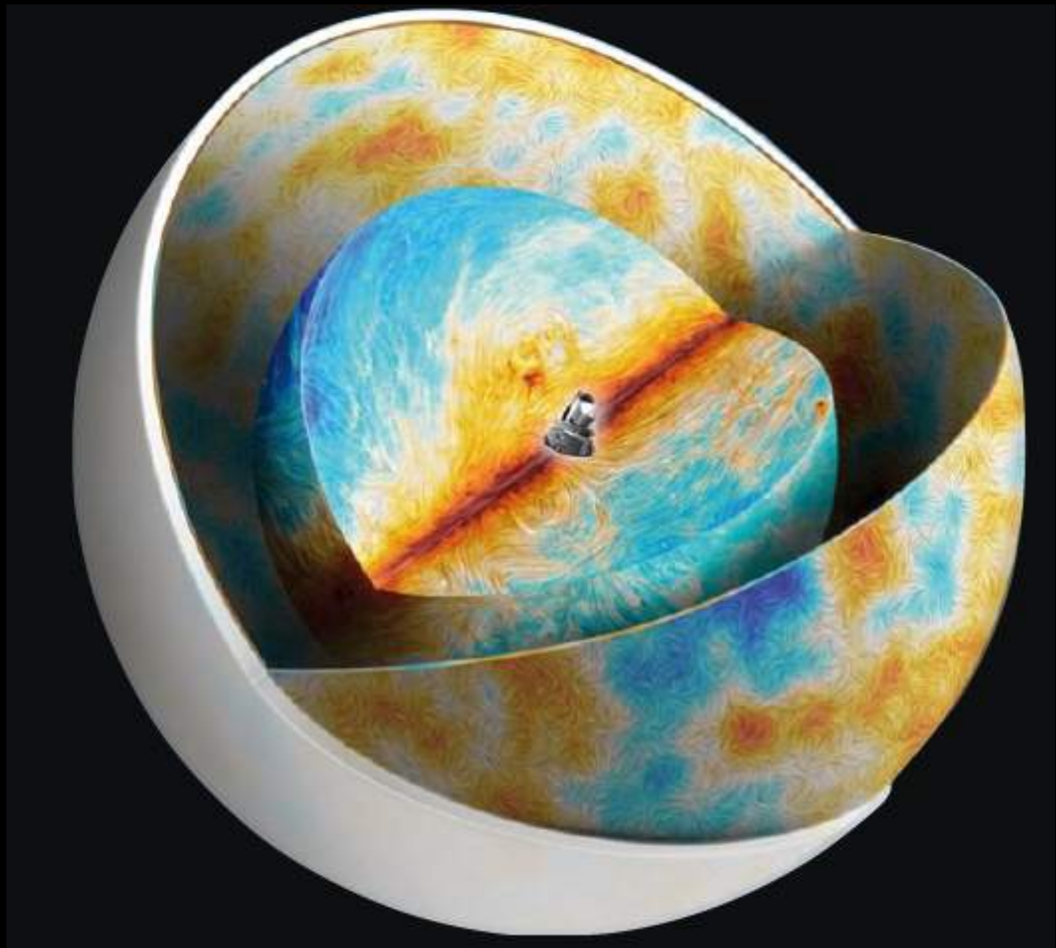
Magnetic field structure from Planck polarization observations of the diffuse Galactic ISM



François Boulanger
Institut d'Astrophysique Spatiale
on behalf of the Planck Consortium

Outline

★The Planck data and science

★Dust polarization and magnetic fields

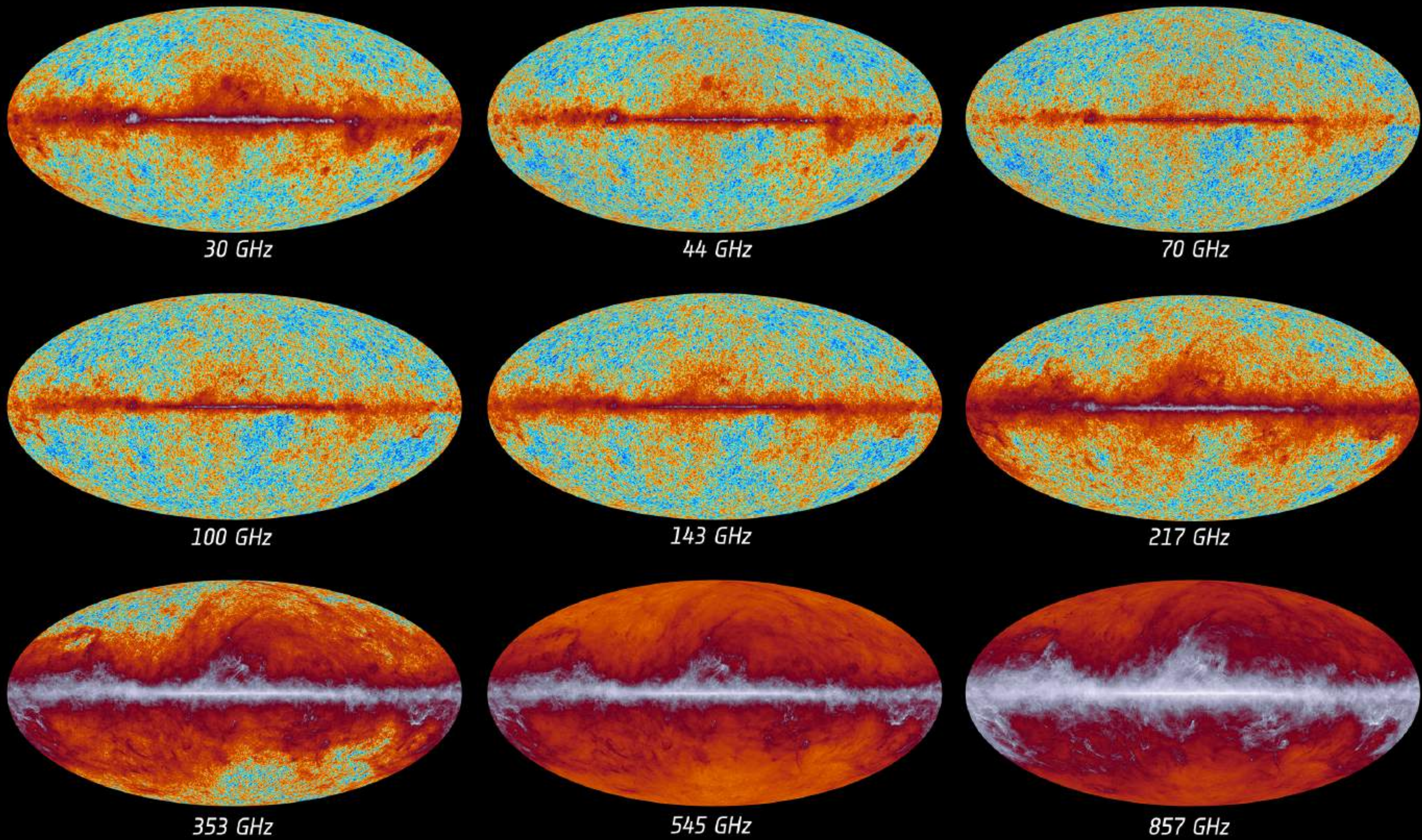
★Focus on three specific results

- The correlation between matter and magnetic field in the diffuse ISM
- The ratio between the strengths of the coherent and turbulent components of the magnetic field in the CNM and WNM.
- The power spectrum of the turbulent component of the magnetic field

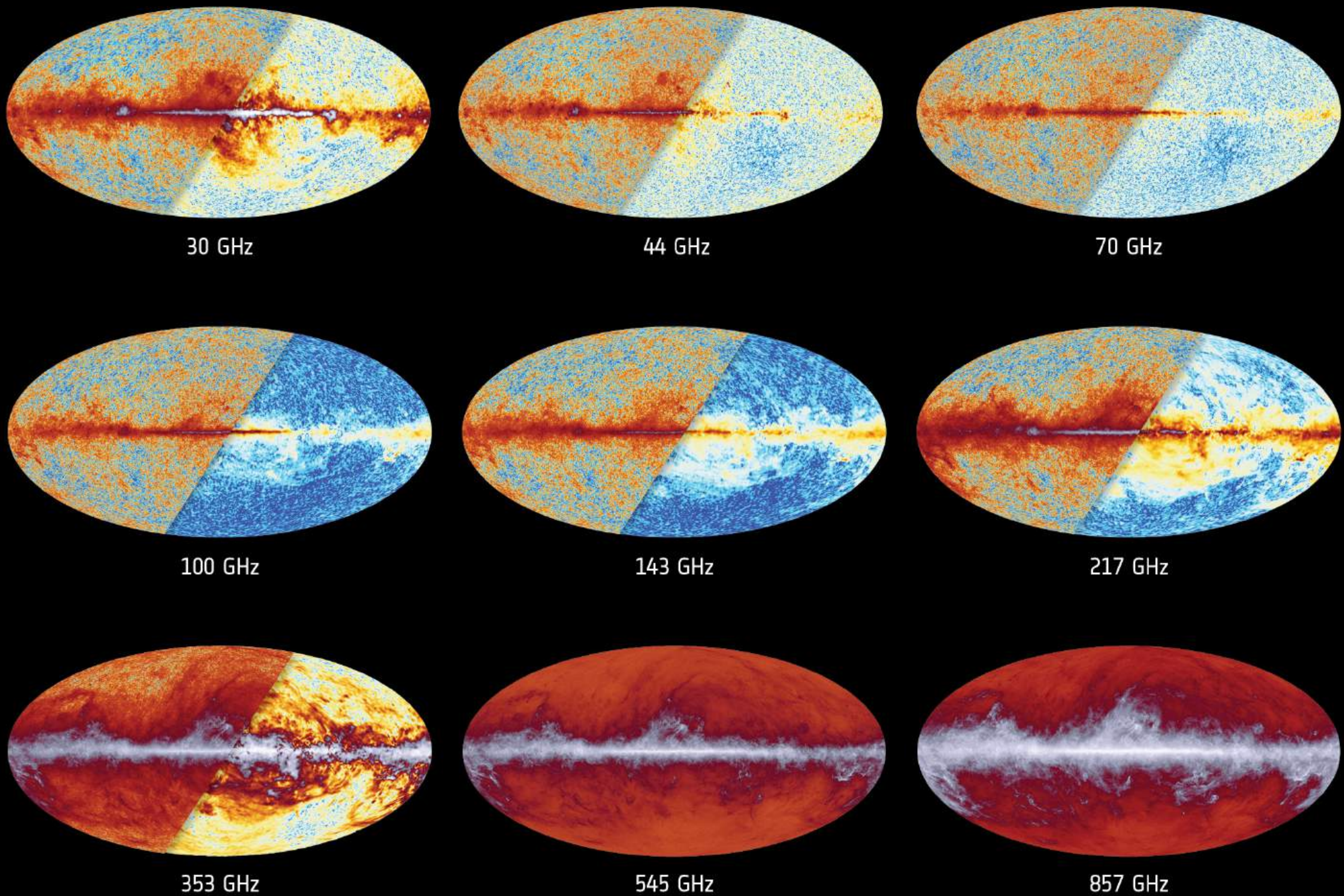
Additional perspectives on subsequent talks and the posters of Andrea Bracco and Flavien Vansyngel

➡ See also www.planckandthemagneticfield.info

The sky as seen by Planck



Intensity / Polarization Sky



Cosmology

- Characterizing and testing the standard Bib-Bang model (ΛCDM)
- Large scale structure of the universe (CMB lensing)
- Hot baryons in the universe (the Sunyaev-Zeldovitch effect)
- Star formation is its cosmological context (the cosmic far-infrared background)

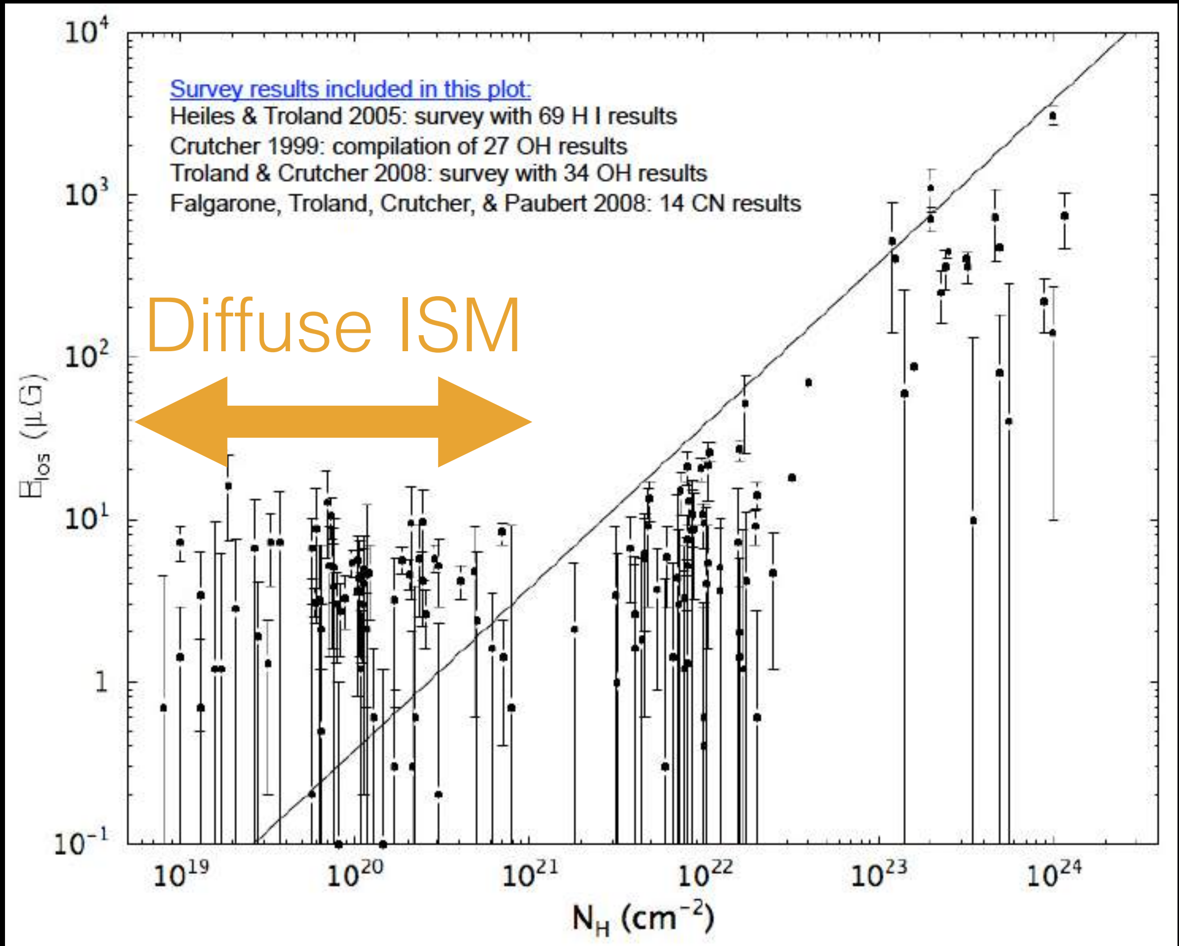
Galactic science

- ISM physics from several emission components: thermal dust, synchrotron, free-free, dipolar emission from small dust particules, CO line emission
- Dust polarization properties

➡Galactic magnetic field from polarization data (dust and synchrotron)

➡Modelling of the Galactic polarized foregrounds to CMB polarization

Zeeman plot from Dick Crutcher's talk



The diffuse ISM comprise gas over a wide range of temperature including its cold and warm phases (CNM and WNM/WIM)

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

Observations of the Galactic magnetic field

★ **Synchrotron emission** traces the field over the whole volume of the Galaxy including the thick disk and Galactic halo. The volume emissivity scales as $n_{cr} \times B_{\perp}^2$.

★ **Faraday rotation** traces the amplitude of $B_{//}$ in ionized gas. The rotation measure scales as $\int n_e \times B_{//}\, ds$.

★ Zeeman observations measure $B_{//}$ in neutral atomic and molecular gas (difficult observations on a discrete set of line of sights).

★ **Dust polarisation** traces the magnetic field where matter is concentrated because dust sub-mm emission is a tracer of the interstellar matter column density. Observed polarization is the sum of two contributions:

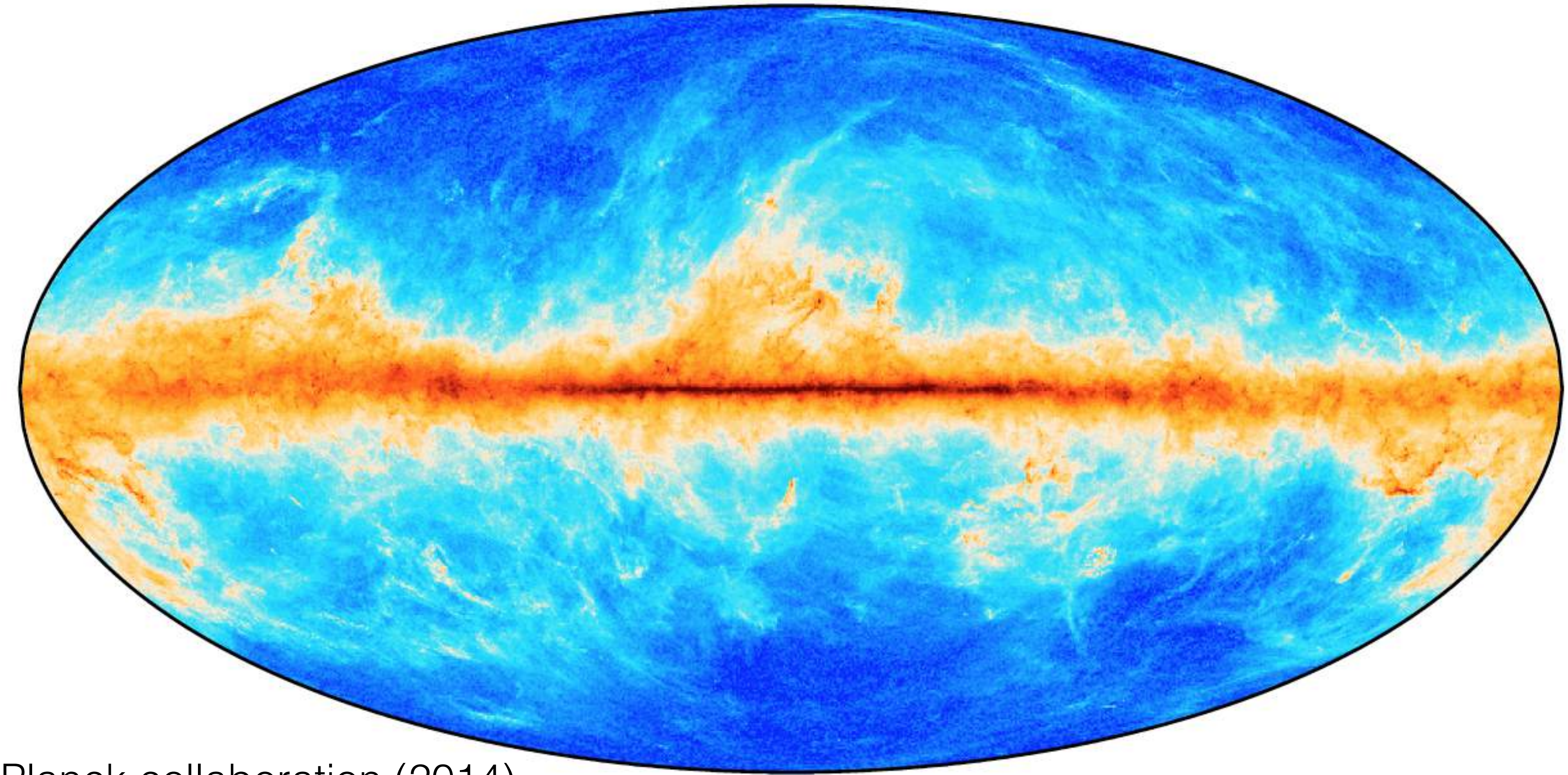
- The warm medium (WNM/WIM) with a significant volume filling factor ($f_{WNM/WIM} \gtrsim 0.2$). This contribution traces the mean direction/structure of the field averaged along the line of sight.

- The cold medium (CNM) with a small volume filling factor ($f_{CNM} \lesssim 0.01$). This contribution traces the direction/structure of the field within localized clouds.

➡ **Dust polarization is best suited to characterize the interplay between the structure of the Galactic magnetic field and that of interstellar matter**

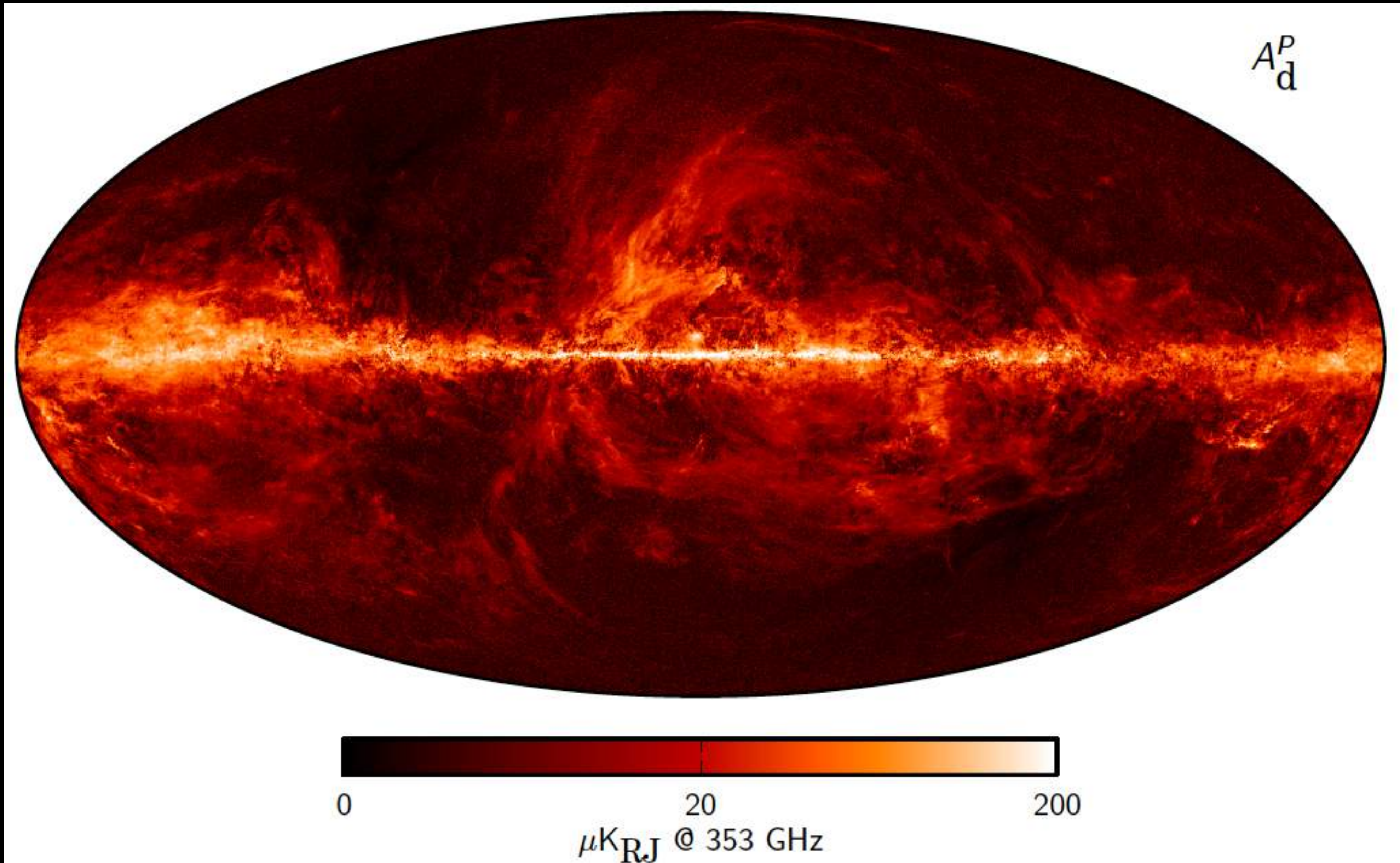
Dust opacity

Dust opacity traces dust mass



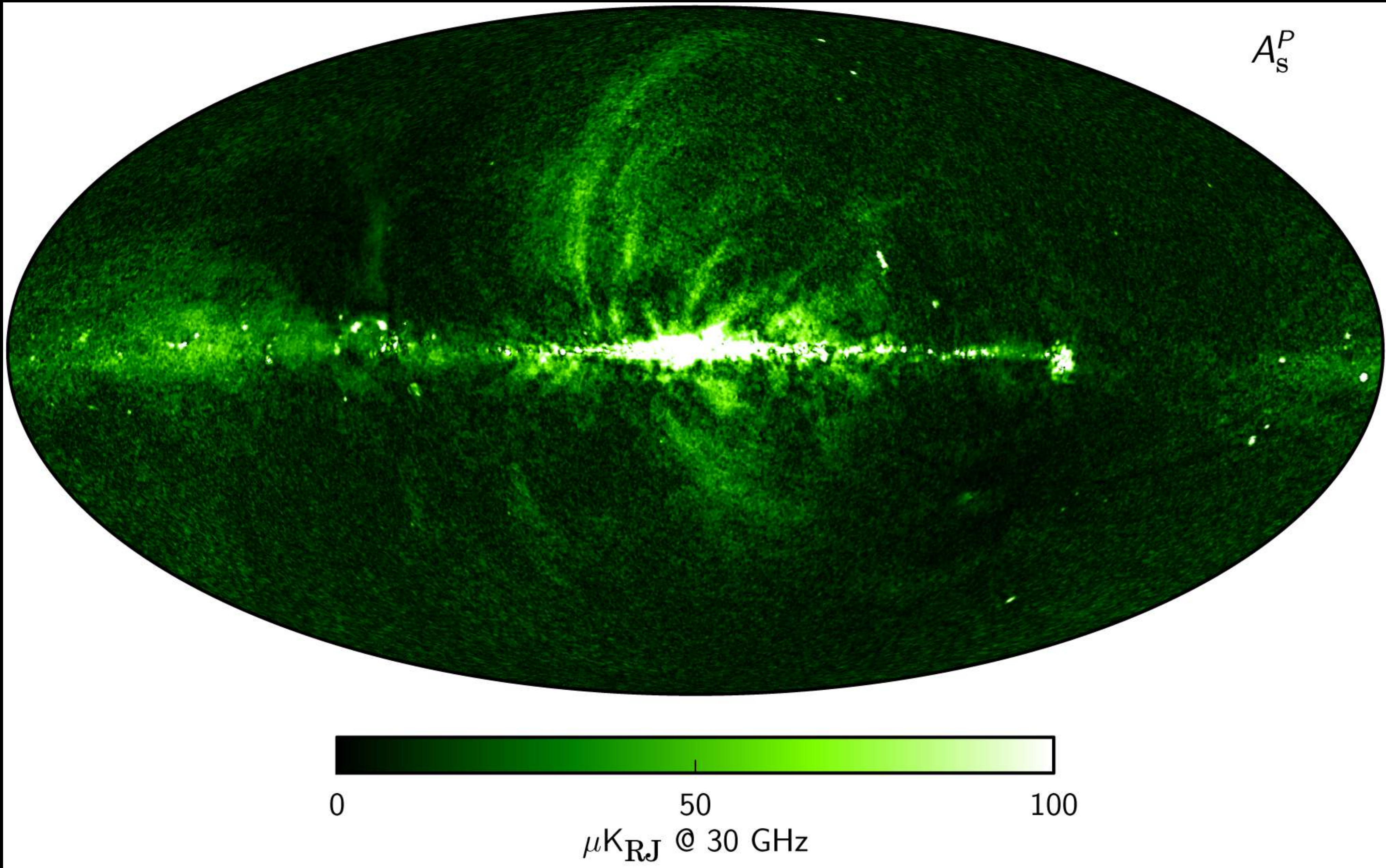
Planck collaboration (2014)

Polarized dust emission

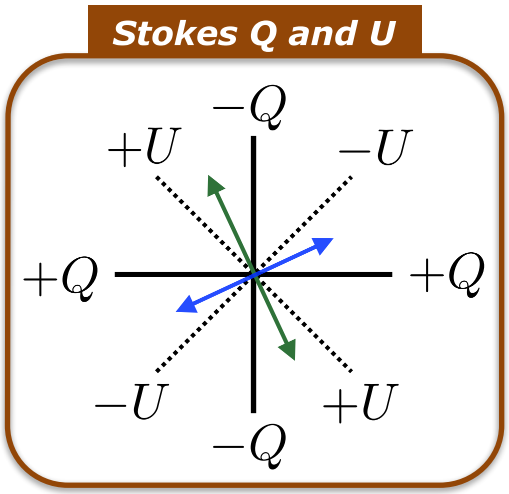


Planck collaboration (2015)

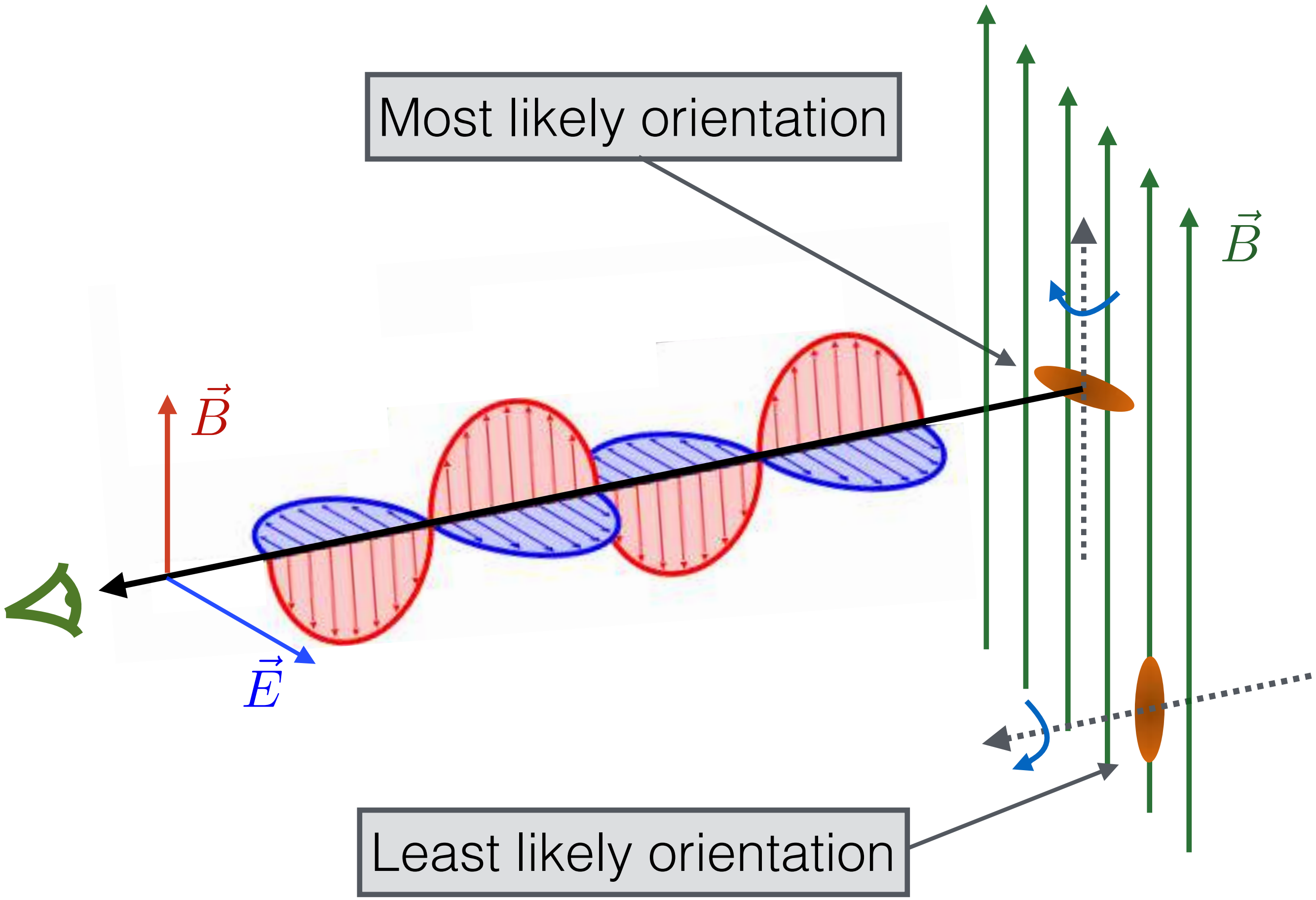
Synchrotron Polarization



Polarized thermal dust emission essentials



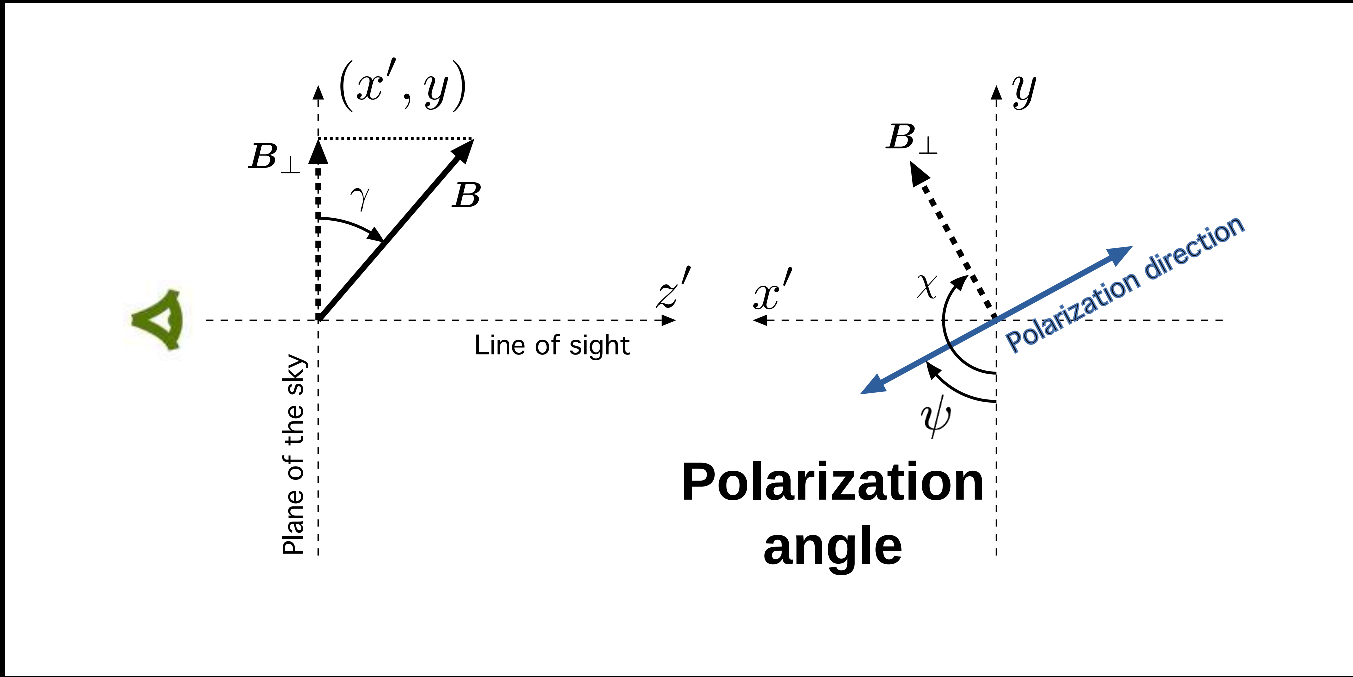
Polarization orientation
Magnetic field orientation



- Grains are aspherical, charged, rotating, and aligned preferentially perpendicularly to the local magnetic field
- Cross sections are proportional to the size, so grains emit more radiation parallel to their long axes
- Polarized thermal emission arises, with an orientation perpendicular to the local magnetic field

Remember Thiem Hoang's talk

What are we measuring?



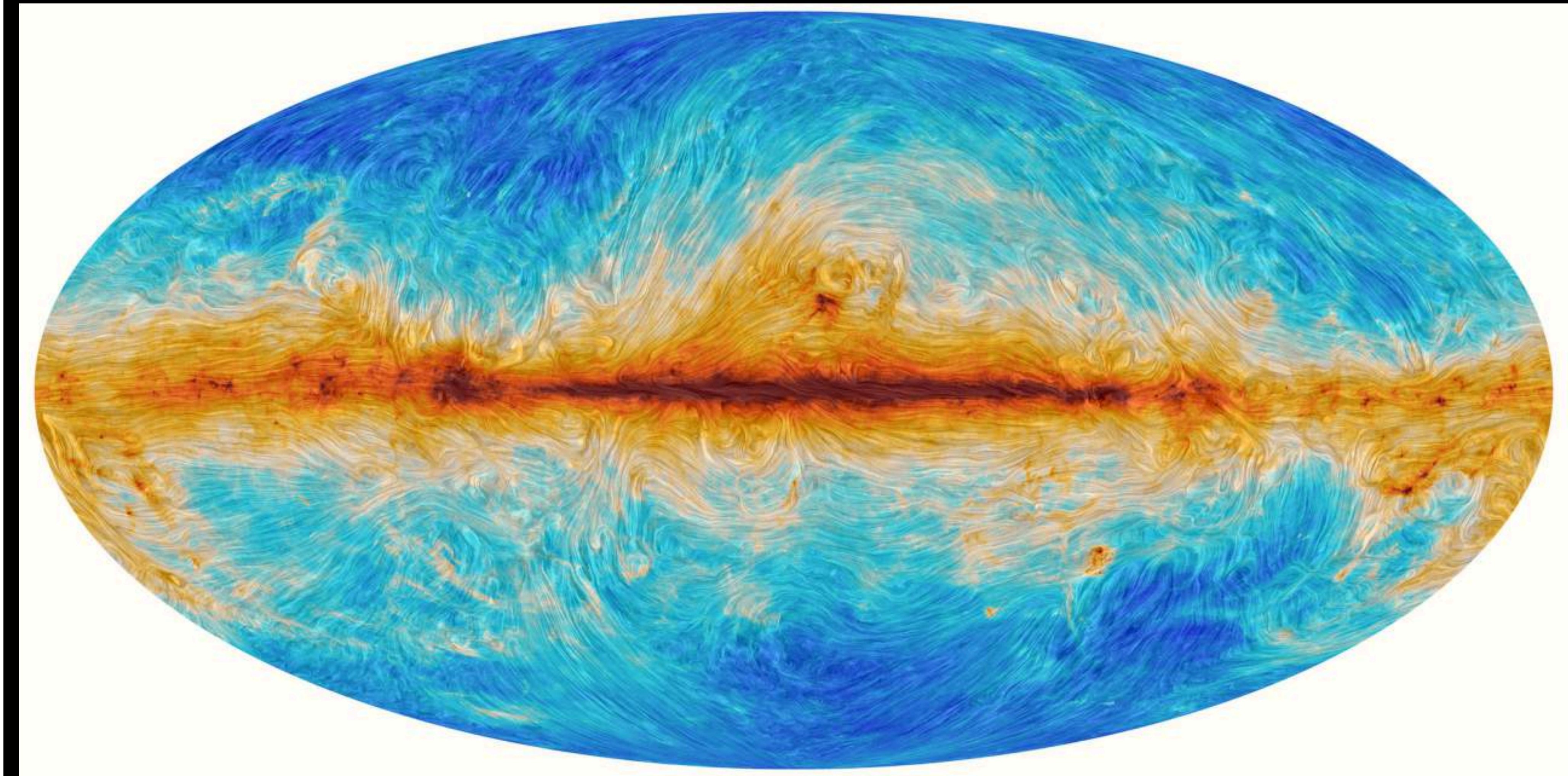
$$Q = \int p_{\max} R\, cos(2\psi)\, cos^2\gamma\, dI$$
$$U = -\int p_{\max} R\, sin(2\psi)\, cos^2\gamma\, dI$$

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

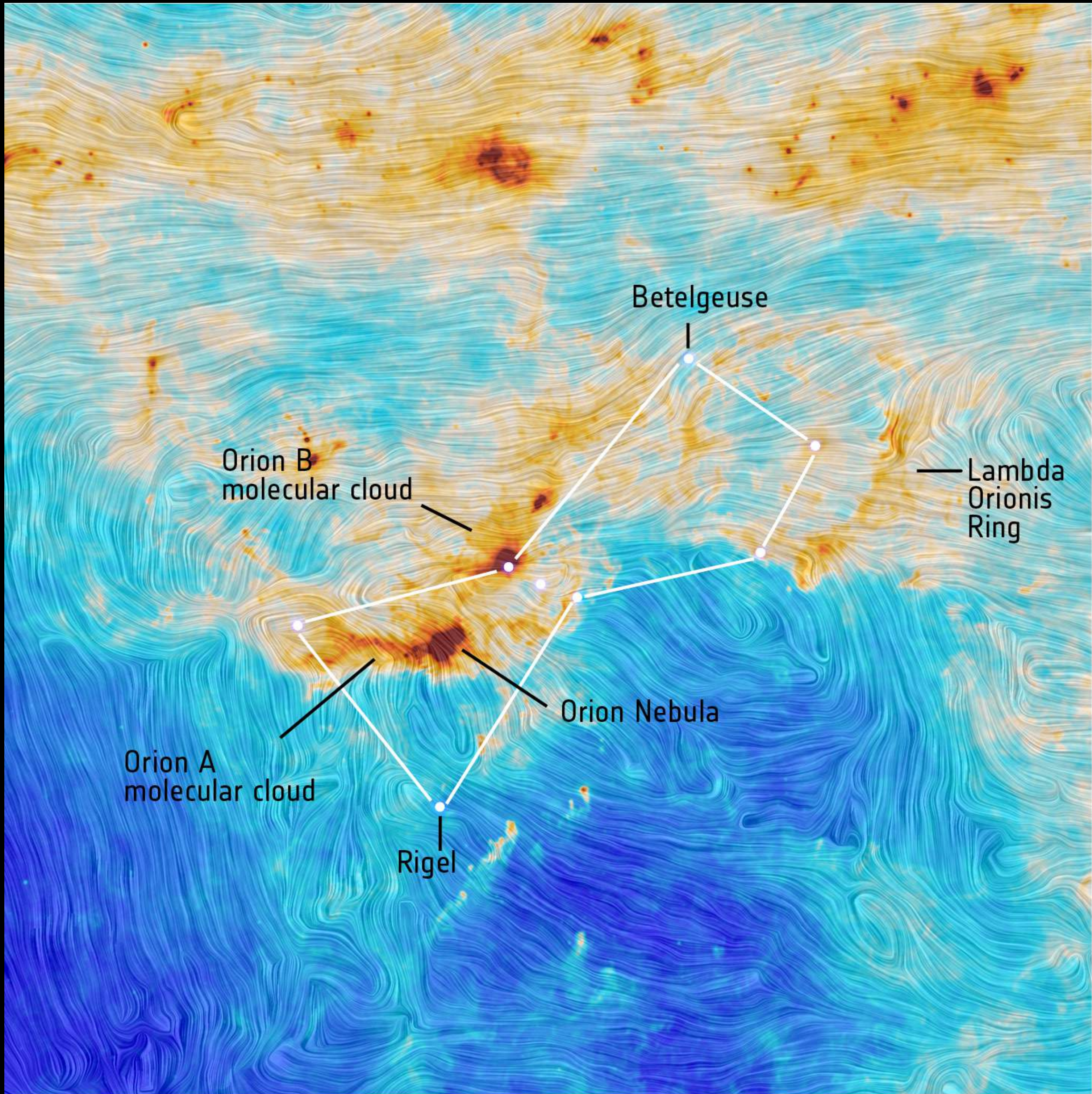
★To the extent that grain polarization properties, including alignment, are homogeneous, dust polarization (both ψ and p) track the magnetic field structure.

★This hypothesis is widely accepted for the diffuse ISM but debated for molecular clouds

Magnetic field and ISM structure

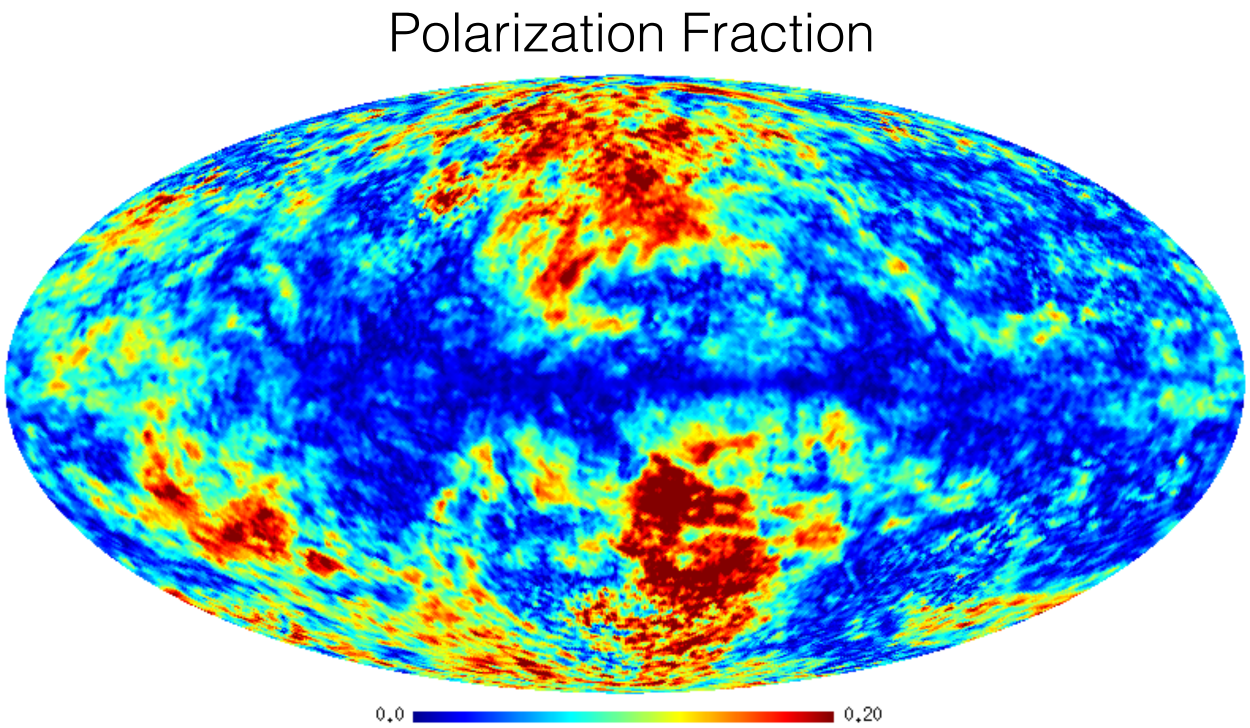


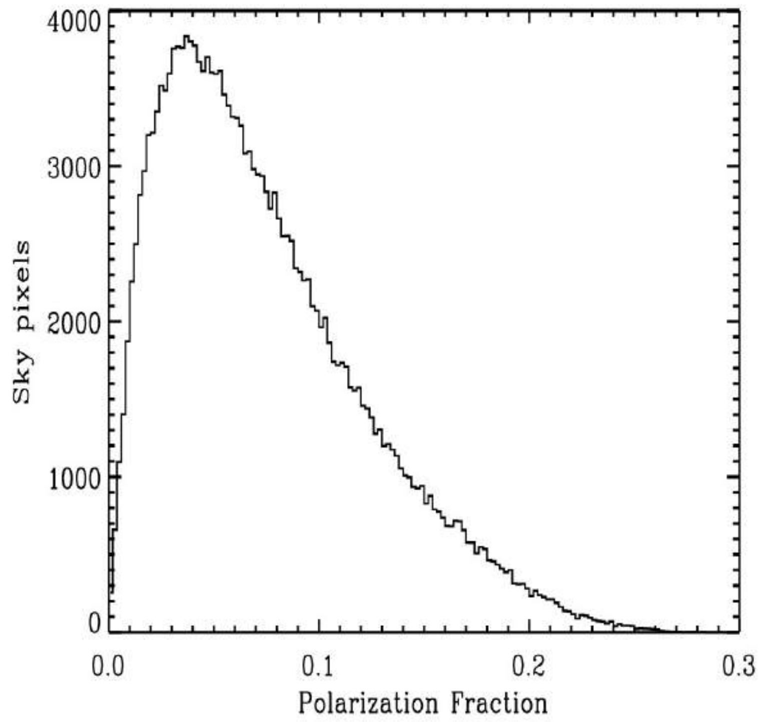
Overview paper by Planck collaboration (2015)


Betelgeuse
Orion B
molecular cloud
Lambda
Orionis
Ring
Orion Nebula
Orion A
molecular cloud
Rigel

Polarization Fraction

Overview paper dust polarization by Planck collaboration (2014)

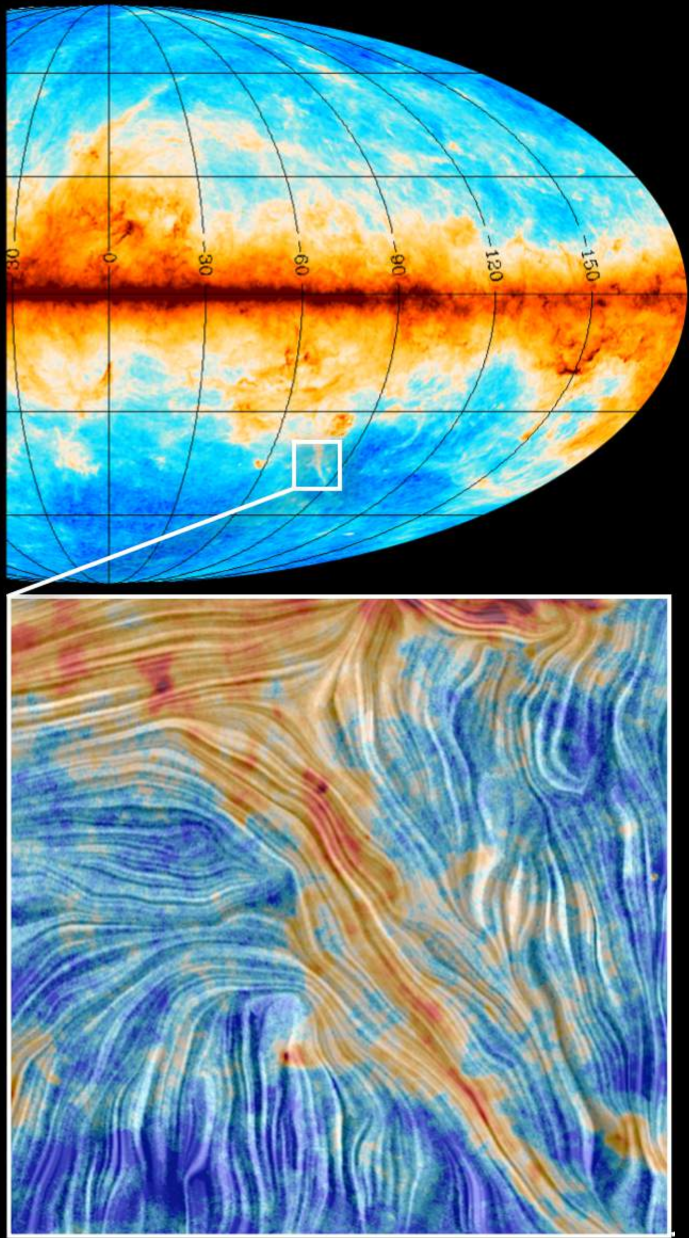




- The maximal polarization fraction is large (>20%). It is a challenge for dust models to explain such high values
- The polarization fraction shows a large scatter, which we interpret as line of sight depolarization associated with interstellar turbulence

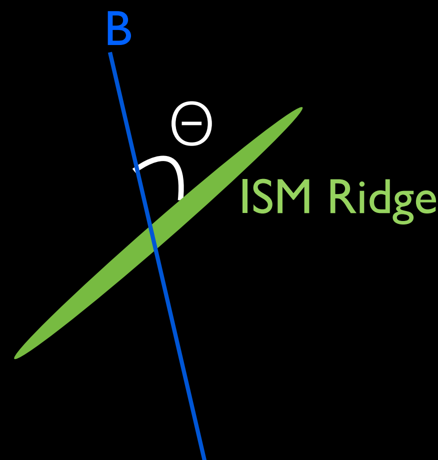
Magnetic fields and structure formation

[Planck Intermediate XXXII 2014, arXiv:1409.6728]



(*Planck* intensity 353GHz, B-field lines)

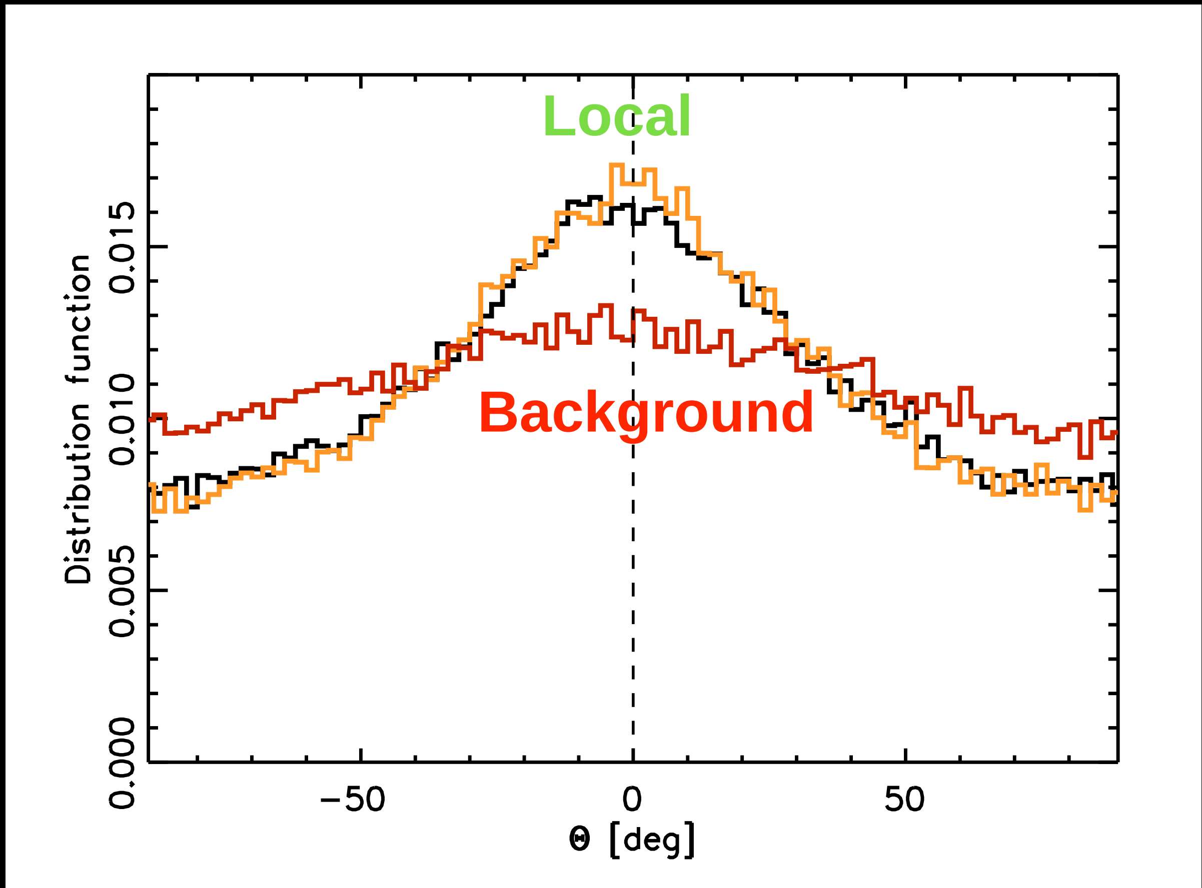
The filamentary structure of the interstellar medium

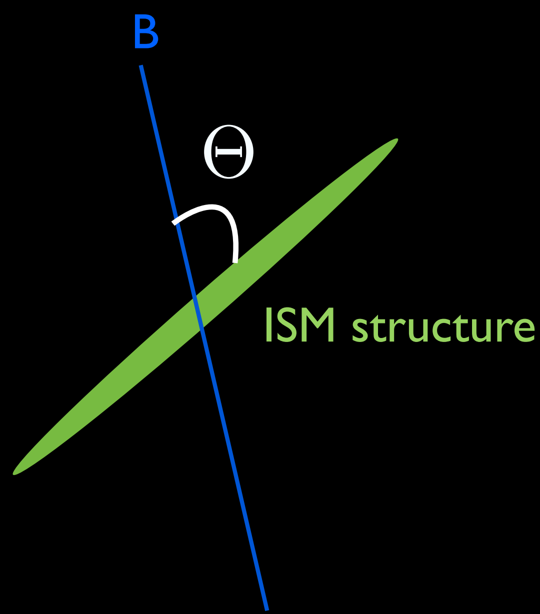


In the diffuse ISM we observe an alignment of the filamentary CNM structures with the magnetic field orientation

Matter vs Magnetic Field

[Planck Intermediate XXXII 2014, arXiv:1409.6728]
Bracco - PhD 2014, Université Paris-Sud, Orsay



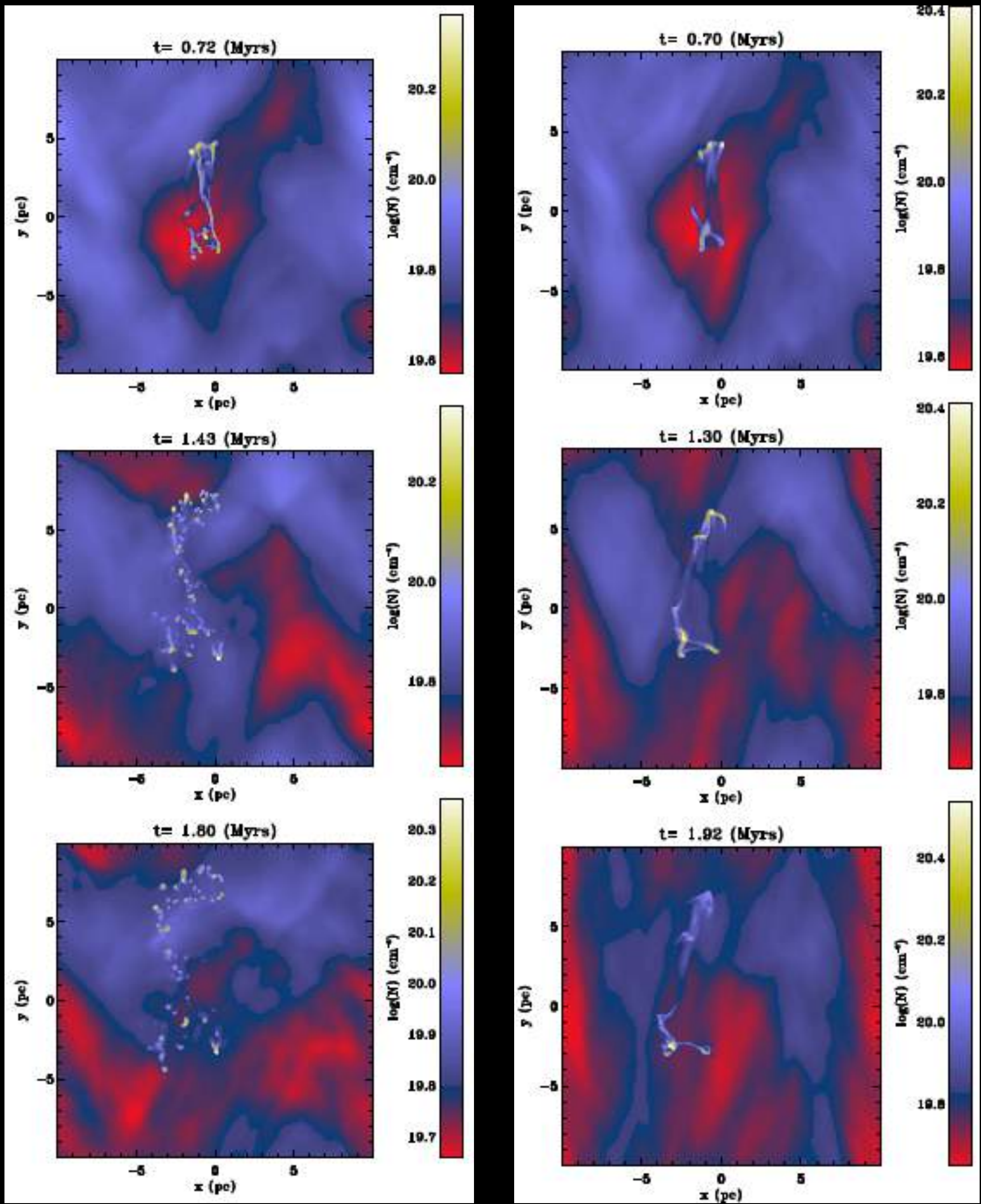


The structures tend to be aligned with the local magnetic field

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

see also Susan Clark’s presentation

HD MHD



Formation of a filament through shear

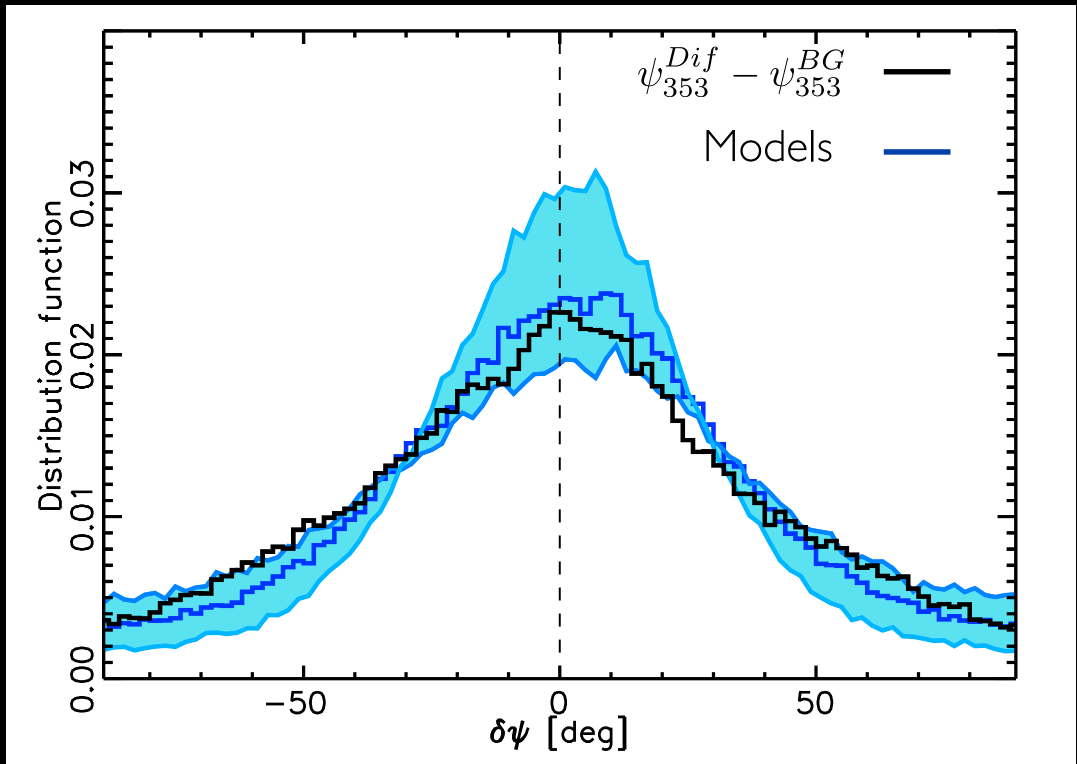
- ★In both experiments, the gas condensation is stretched into a filamentary structure by the velocity shear, but in the HD case the structure is broken up by instabilities, while in the MHD case it remains coherent.

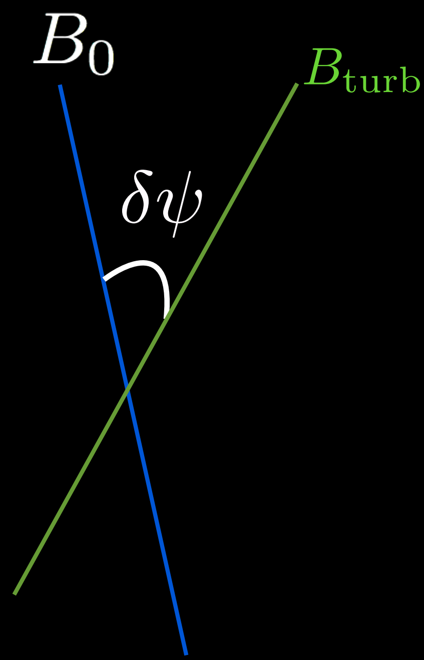
- ★Filamentary structures may result from turbulent shear (rather than shocks) that stretches both CNM gas condensations and the magnetic field.

Hennebelle 2013

Turbulent and coherent fields

$$\vec{B} = \vec{B}_0 + \vec{B}_{turb} \qquad (< \vec{B}_{\rm turb} >= 0)$$



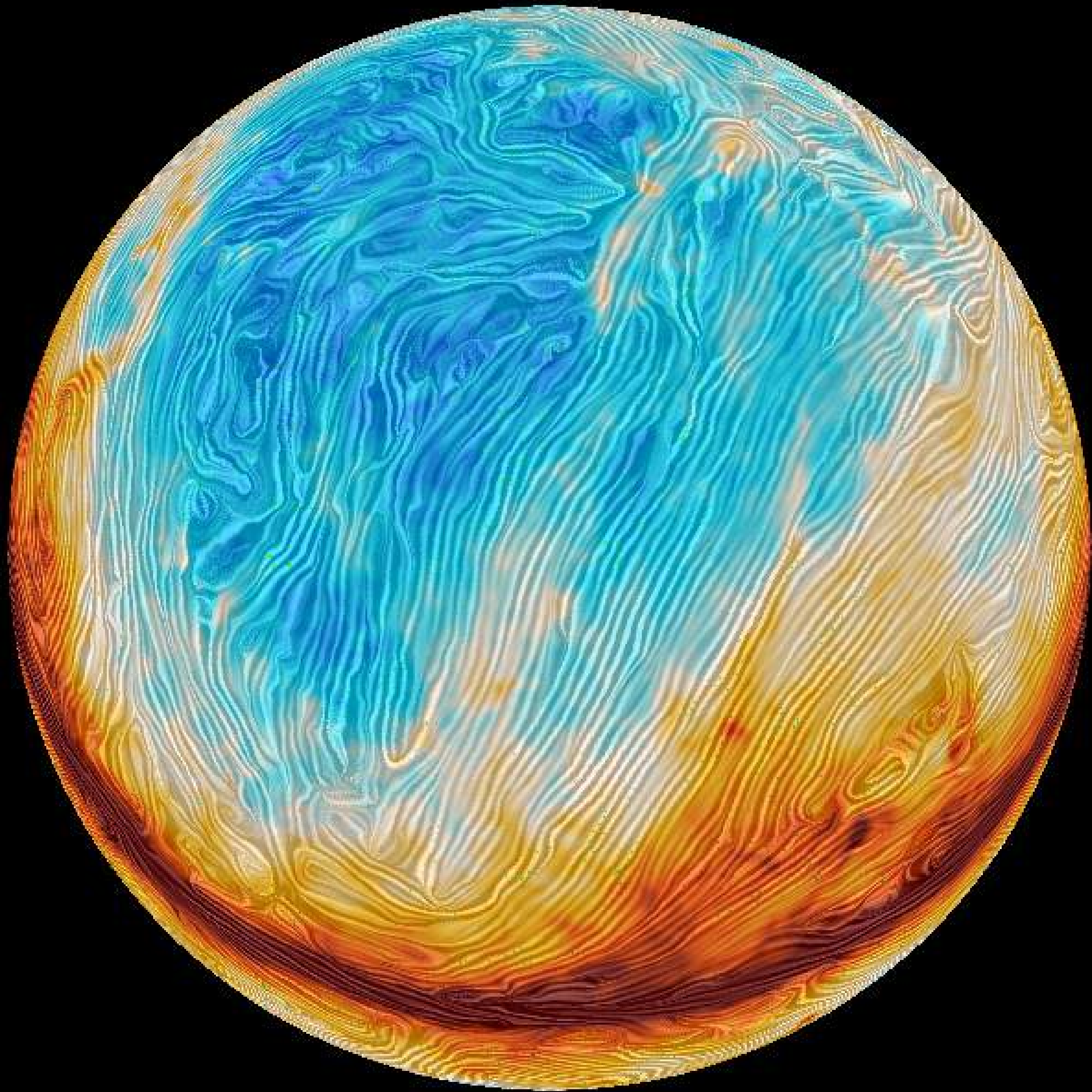


[Planck Intermediate XXXII 2014, arXiv:1409.6728]

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

- Models quantifying the ratio between the strengths of the turbulent and mean components of the magnetic field. Best fit model for : $B_{turb}/B_0 = 0.8 \pm 0.2$ (trans-Alfvenic turbulence)

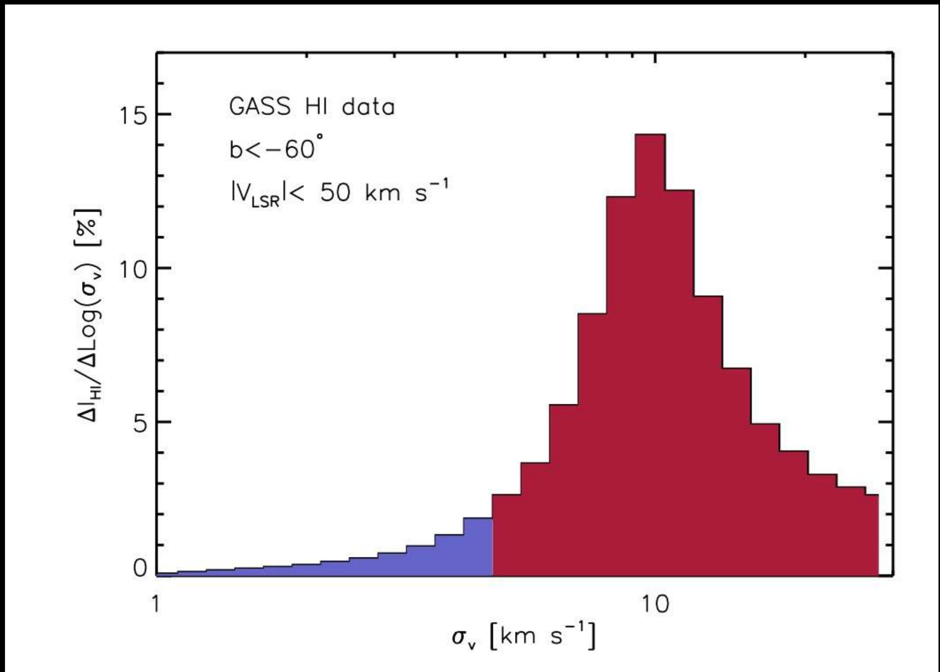
Looking towards the Galactic poles …



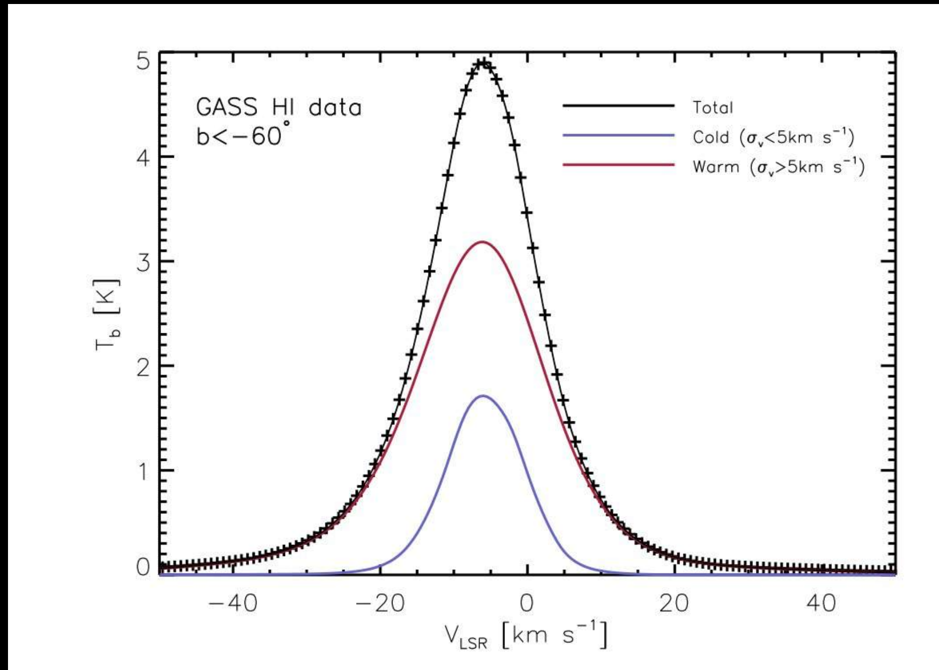
Diffuse ISM towards the southern Galactic pole

Turbulence from Gaussian decomposition of HI GASS spectra done by Haud and Kalberla

Histogram of line emission



Integrated spectra



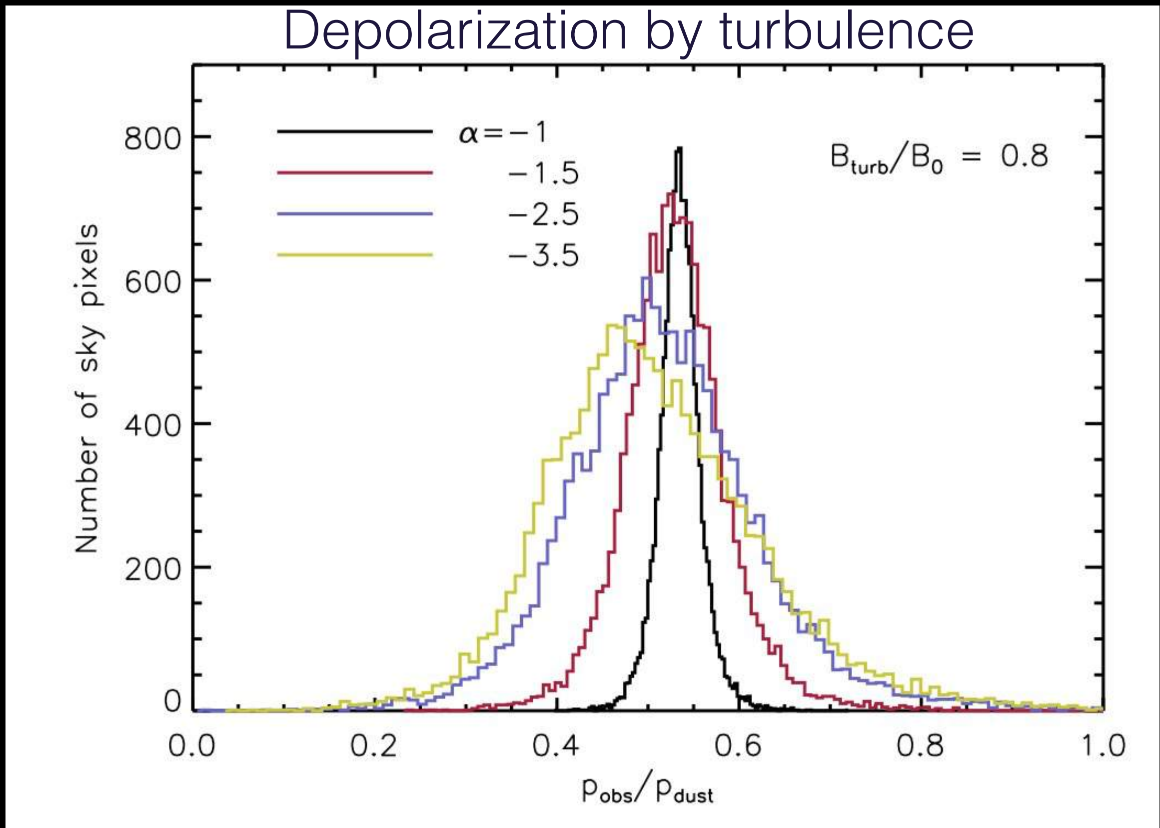
★Most of the emission comes from the WNM gas traced by broad Gaussian components ($\boldsymbol{\sigma}_V > 5$ km/s)

★*Cold* and W*arm* HI spectra have line widths $\boldsymbol{\sigma}_V = 5$ km/s and 9.5 km/s

➡Turbulence is subsonic in the WNM and supersonic in the CNM

Spectral index of the power spectrum of B_{turb}

Depolarization due to turbulence is quantified for power spectra realizations of B_{turb} along each line of sight (spectral index α)

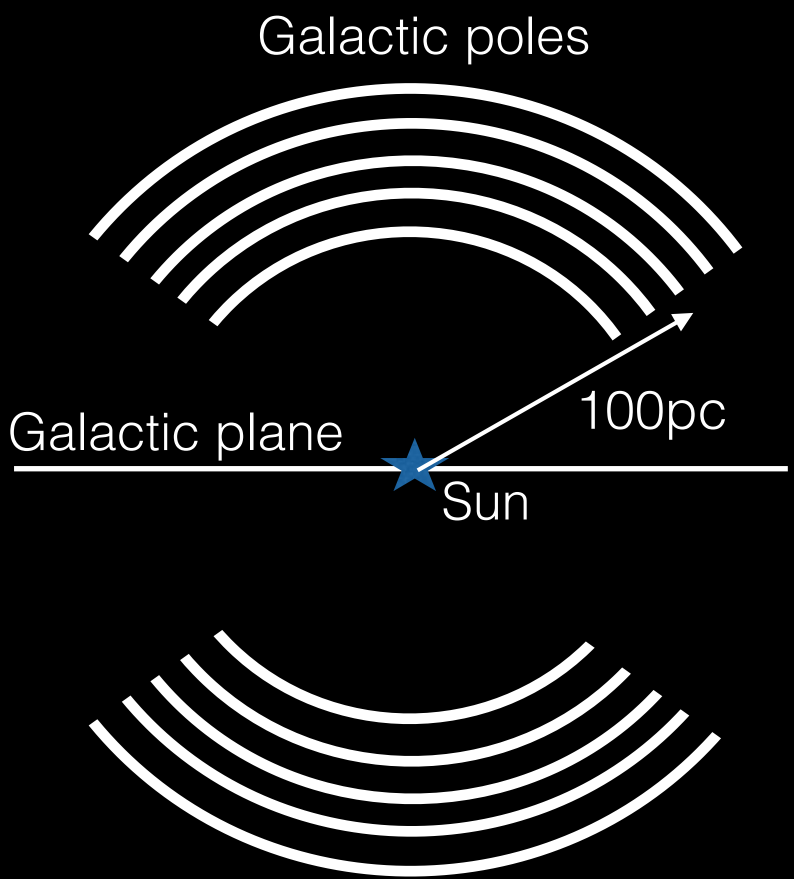


★The large dispersion of p values we observe is accounted for if the power spectrum spectrum is steep (α< -2.5)

★In this case turbulence fluctuations are dominated by large scale modes (i.e. a small number of *turbulent cells* along the line of sight)

➡More on this in François Levrier's talk (next one)

Dust polarization model



$$\vec{B} = \vec{B}_0 + \vec{B}_{turb} \qquad (< \vec{B}_{\mathrm{turb}} >= 0)$$

★The mean field is characterized by a fixed orientation (l_0 and b_0)

★The turbulent component is characterized by the ratio B_{turb}/B_0 and the spectral index of the power spectrum (α)

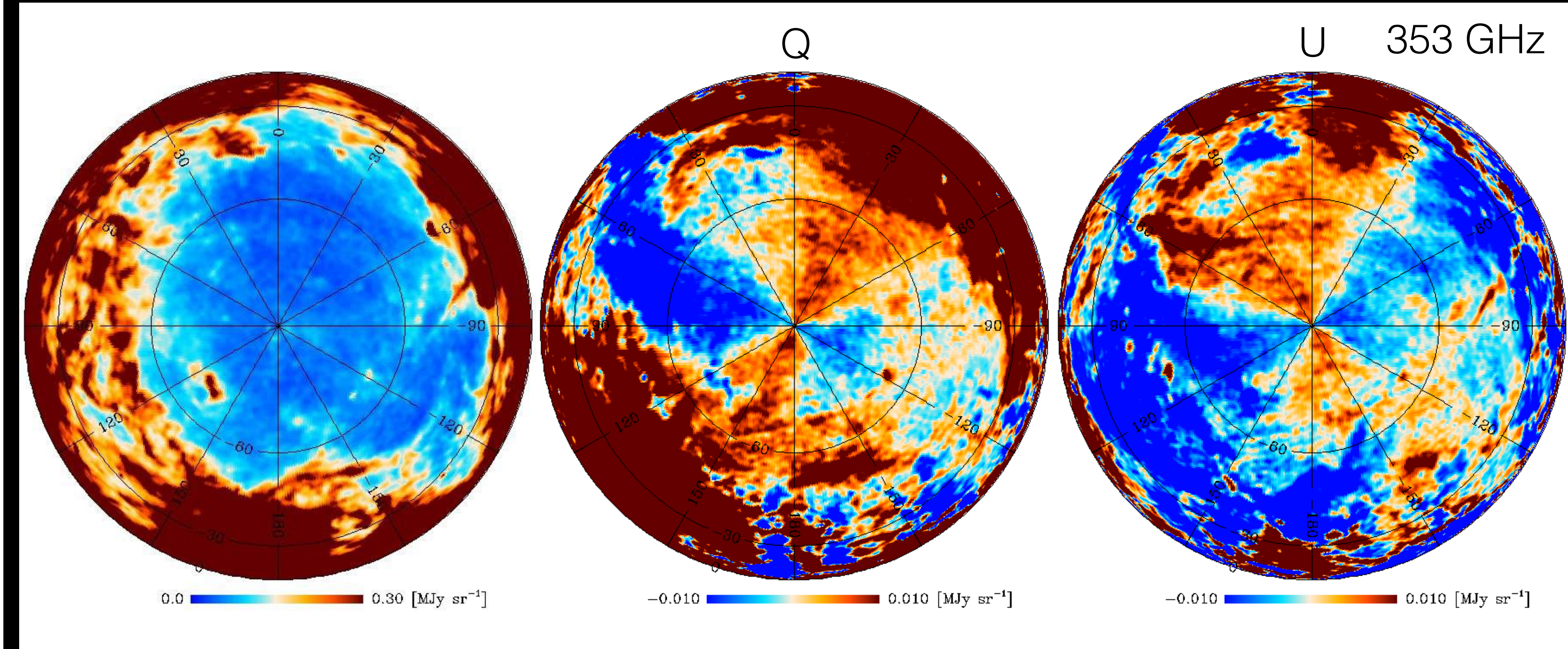
★We model the line of sight depolarization summing the emission over a small number of layers with independent realizations of turbulence. This simplification allows us to compute the model on the sphere.

★The model provides maps of Q/I and U/I that are combined with the observed I map from dust to produce simulated Q and U maps.

Poster Flavien Vansyngel: fit of Planck power spectra for dust polarization

Mean Magnetic Field

Planck data towards southern Galactic cap



- Polarization patterns towards Galactic caps allow us to measure the direction of the mean magnetic field in the Solar Neighborhood

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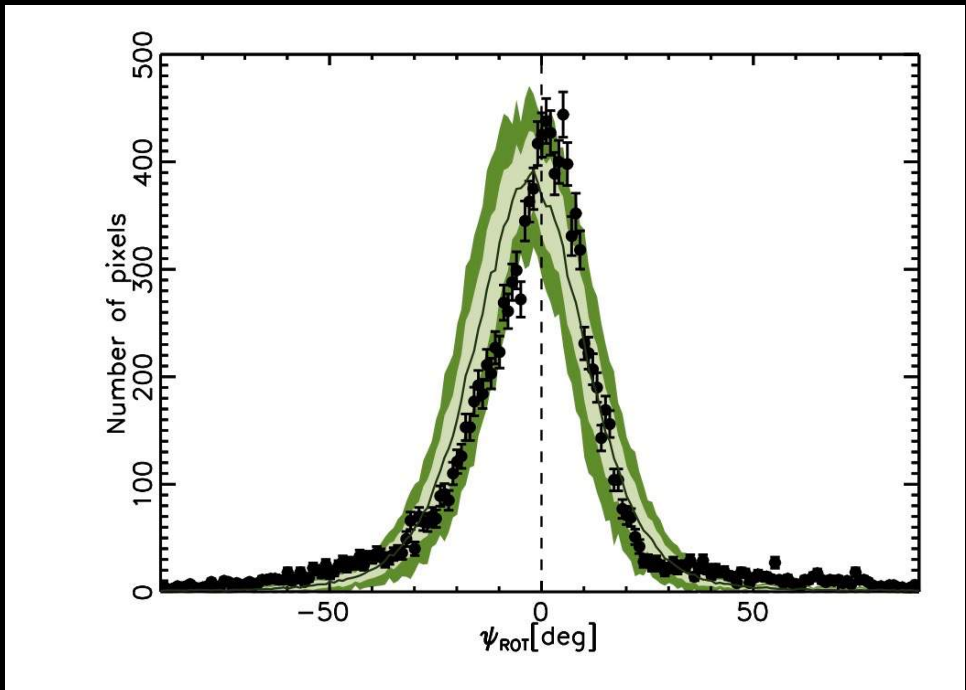
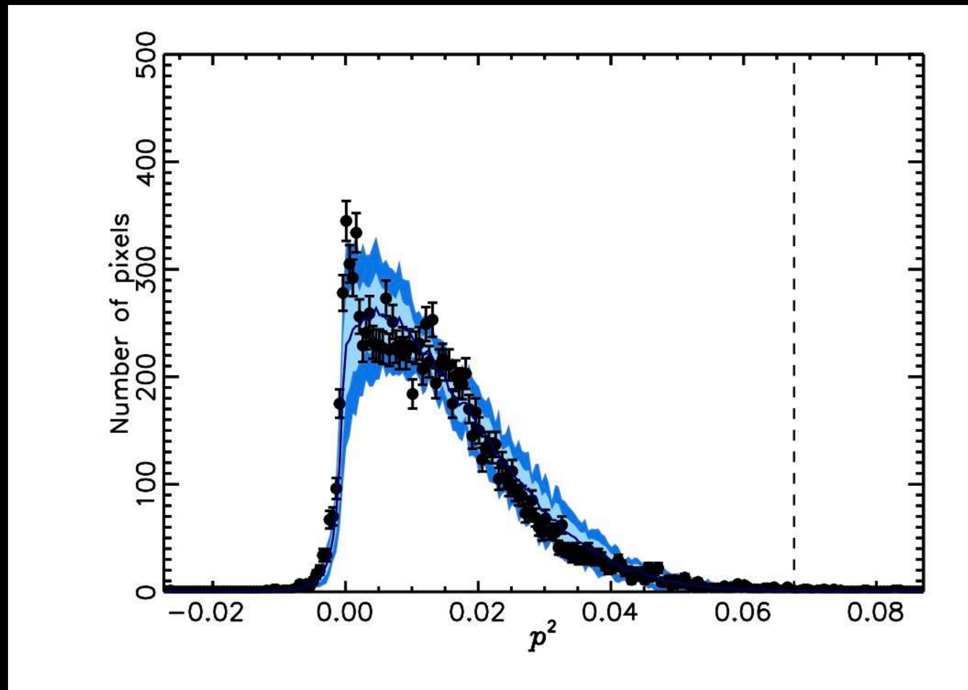
Histograms of polarization angle and fraction





- Model fit of the histograms (polarization angle and fraction) indicates that B_{turb}/B_0 ~0.8 (sub/trans-Alfvenic turbulence).
- The same model fits polarization power spectra within constrains on the magnetic energy spectrum (steeper than $k^{-2.5}$)

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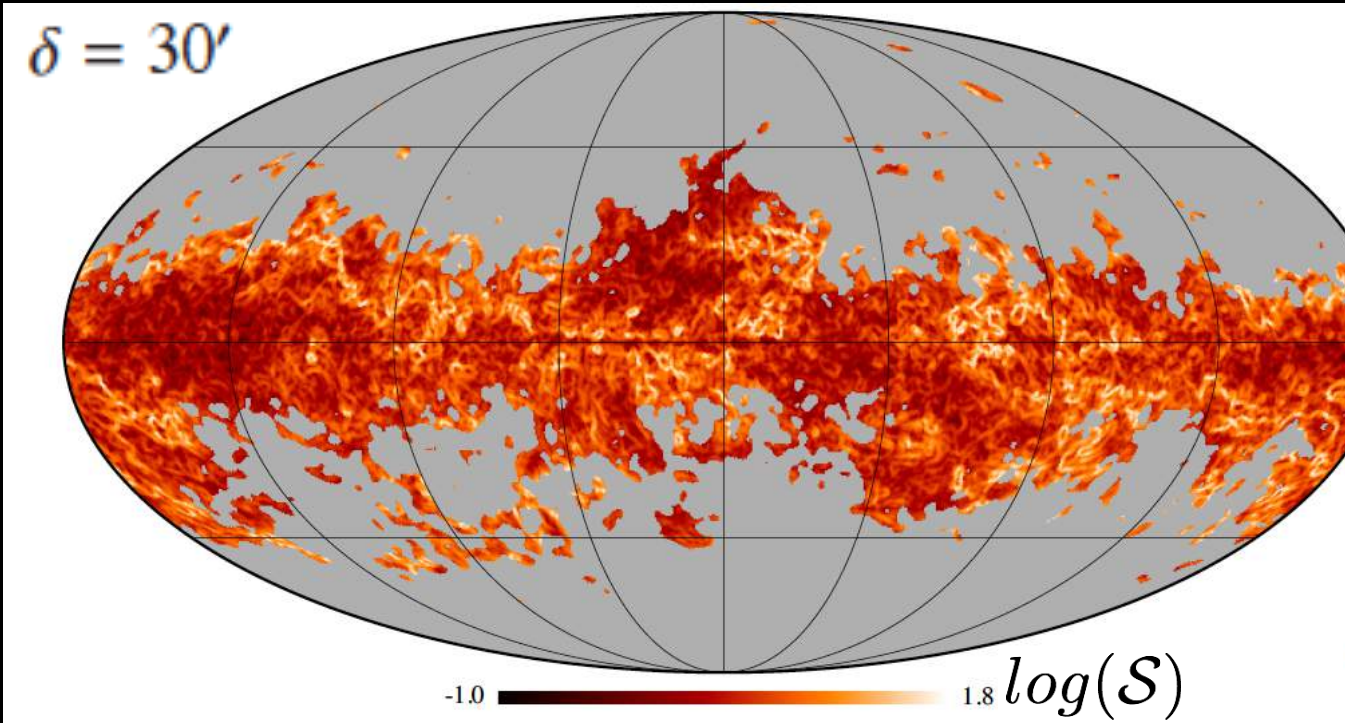
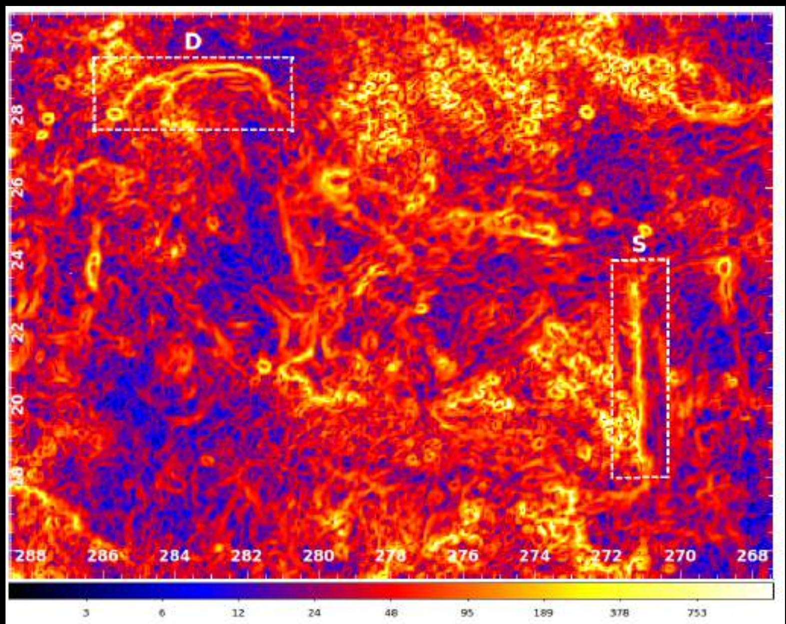
[Planck Intermediate XIX 2014, arXiv:1405.0871]



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

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

Iacobelli+14



Filamentary structures are observed in dust polatization as in synchrotron polarization

Remember Blakesley Burkhart's talk

Summary

★Planck observations of dust polarization provide us with the most detailed view yet at the Galactic magnetic field, which may be used to study interstellar turbulence and the formation of the filamentary structure of interstellar matter.

★Several observational results on the diffuse ISM (power spectra and histograms of the polarization angle and fraction) may be accounted for with a simple model of the turbulent component of the magnetic field with Bturb/B0 ~ 0.8 and a steep power spectrum.

★Dust polarization is the dominant foreground to CMB B-mode polarization. The search from primordial B-modes is now tied to the astrophysics of the dusty magnetized interstellar medium.

★A new polarization space project (*The Cosmic Origins Explorer*) will be submitted to the M5 call of ESA. We are preparing a white paper on magnetic field science. Your inputs and support will be welcome.