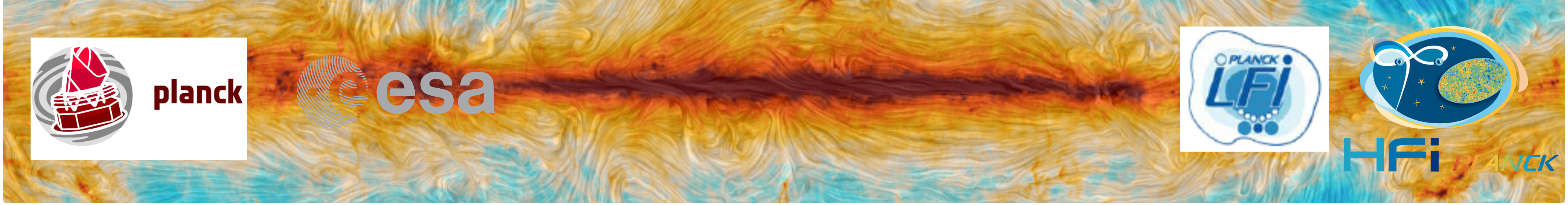
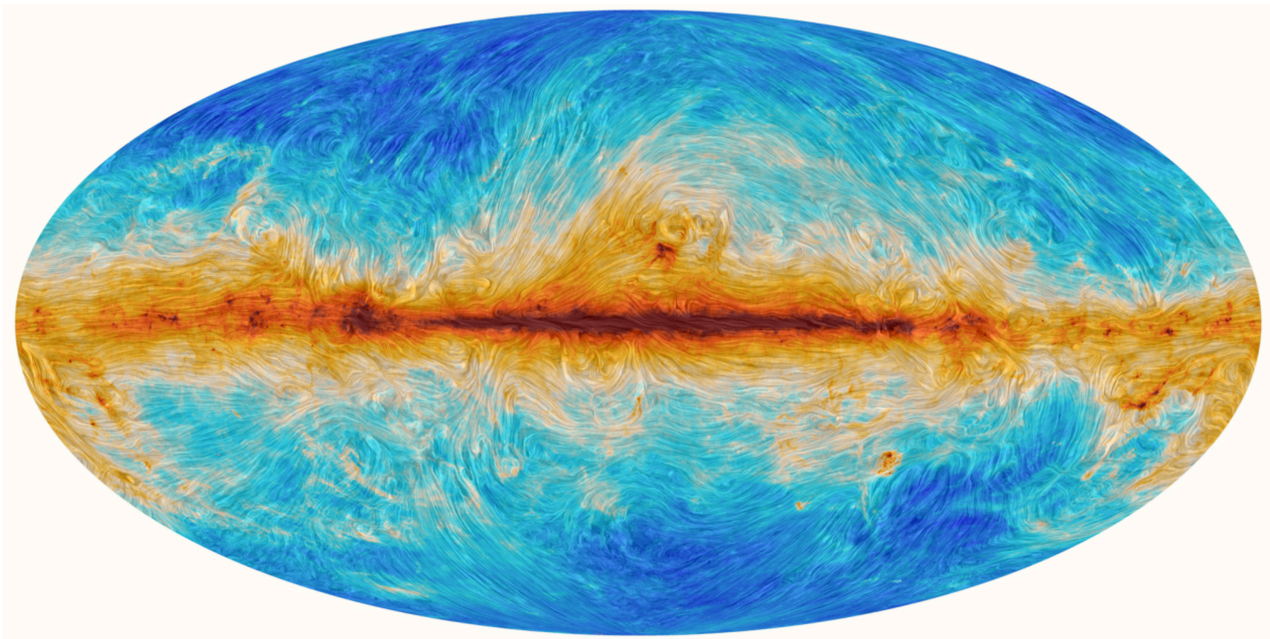


The astrophysics of Planck dust polarization



F. Boulanger (Ecole Normale Supérieure)
on behalf of the Planck Collaboration

Input Planck legacy papers

- **Planck 2018 results. XI. Polarized dust foregrounds**
  - Power spectra analysis of dust polarization maps
  - Spectral energy distribution of dust polarized emission
  - Correlation of dust polarization over microwave frequencies

- **Planck 2018 results. XII. Galactic astrophysics using polarized dust emission**
  - Statistical analysis of polarization fraction and angle
  - Correlation of dust polarization in emission (sub-mm wavelengths from Planck) and extinction (stellar optical data)

I. **The polarization properties of interstellar dust**

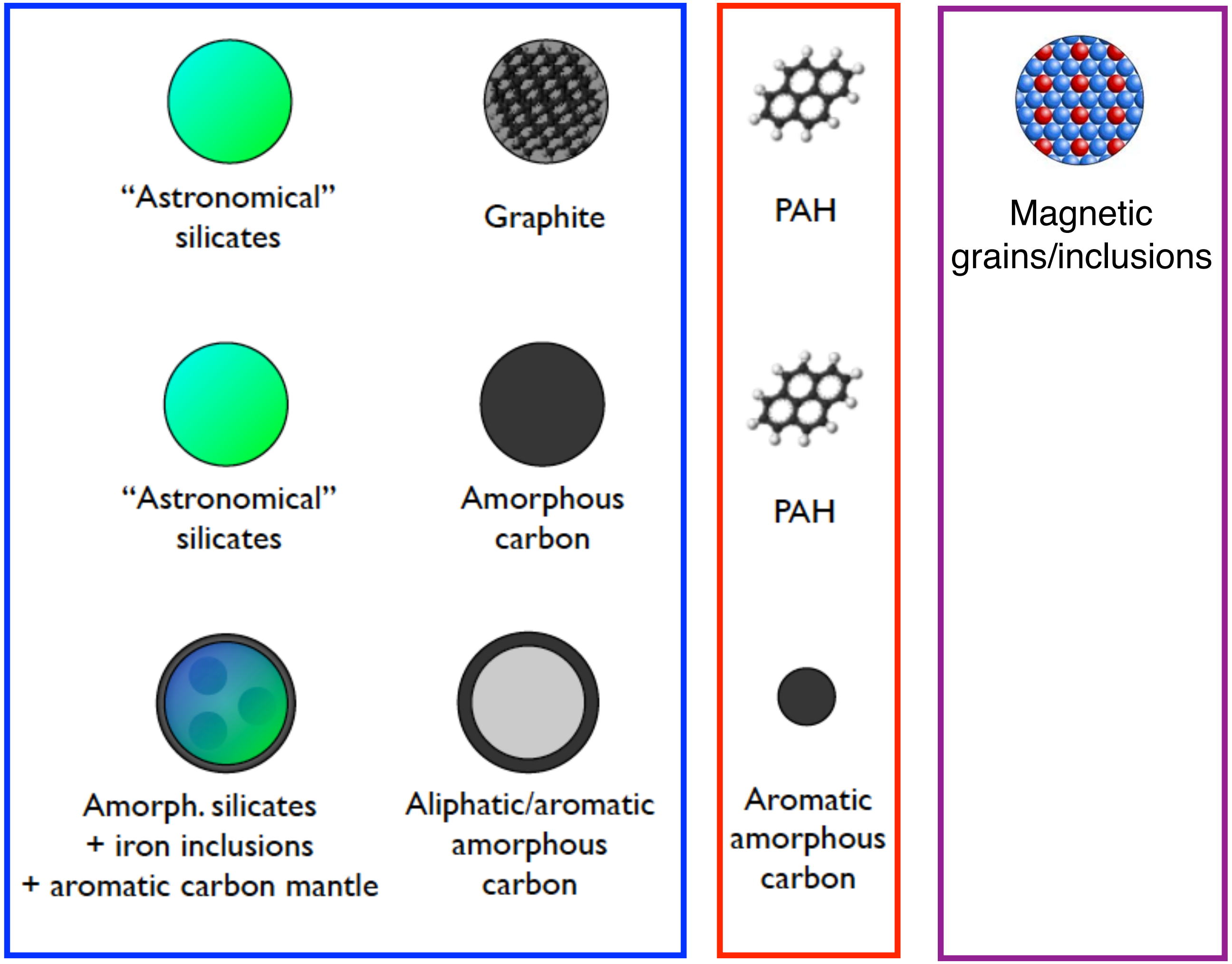
II. Galactic Magnetic field in the Solar Neighbourhood

III. Statistical modeling of dust polarization

Draine & Fraisse 2009
Draine & Hensley 2013

Compiegne et al. 2011
Guillet et al. 2018

Jones et al. 2013



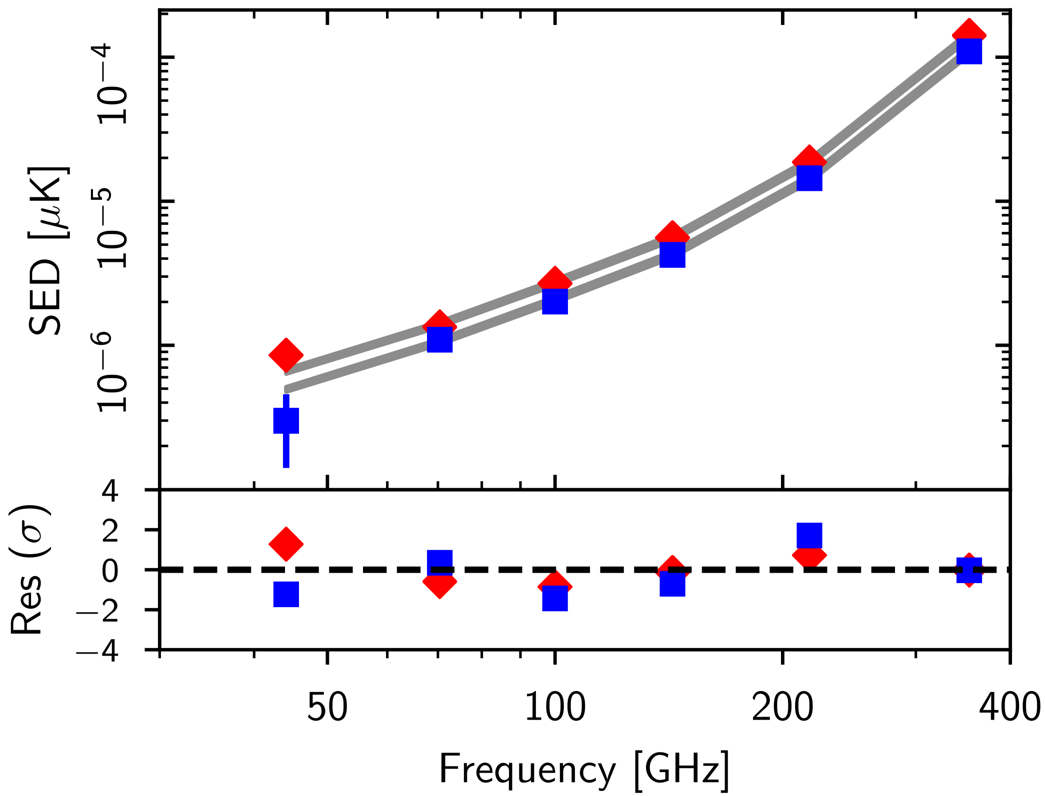
Large dust grains
Dust polarization

AME

Magnetic Dipole Emission

Dust spectral energy distribution

Dust SED in polarization

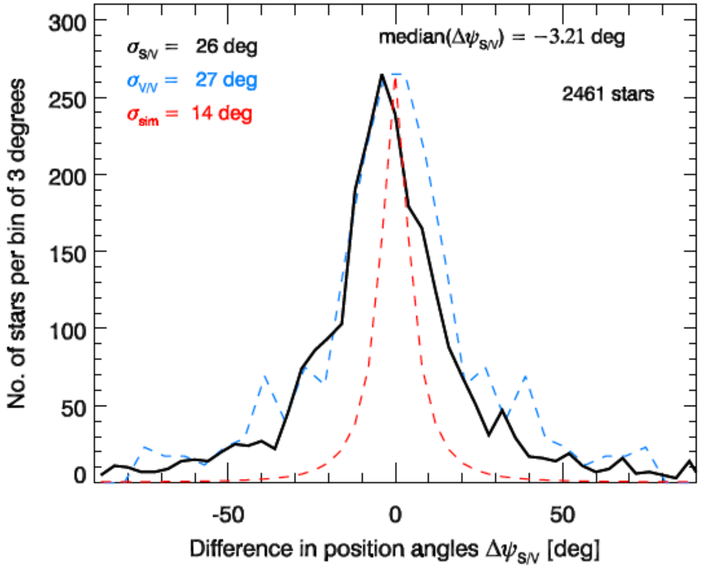


- The dust SED in polarization from blind component separation is remarkably well fit by a single temperature modified black-body emission law from 353 to 44 GHz

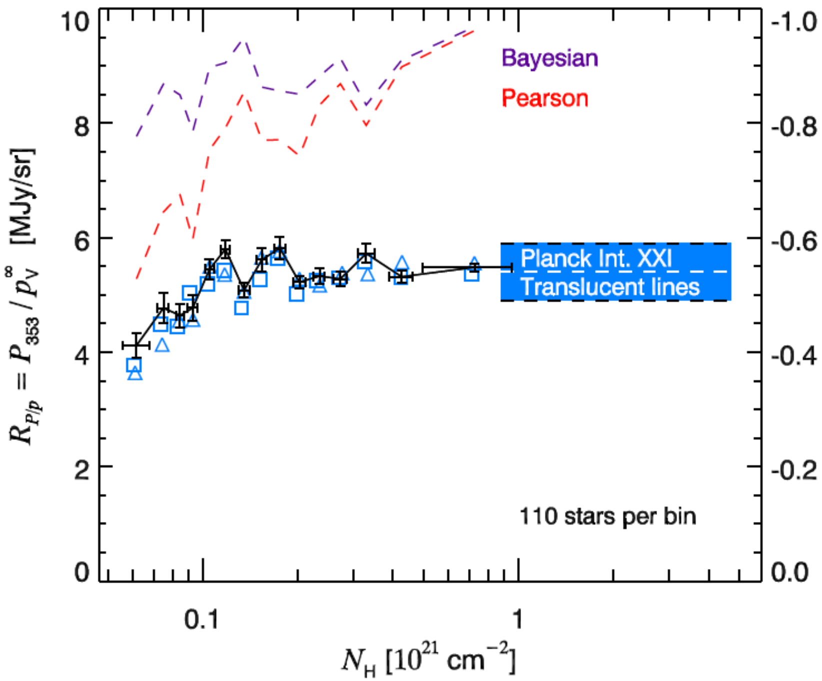
Polarization vs total intensity

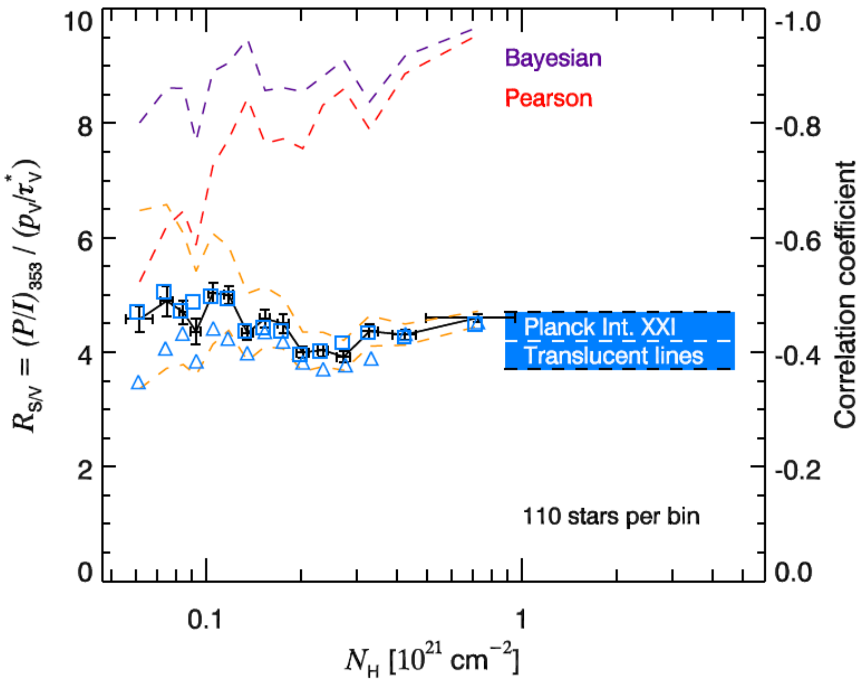
- The difference between spectral indices for polarization and total intensity is small (0.05 ± 0.03) and not of high statistical significance
- **Planck data analysis suggests that the emission from a single grain type dominates the long-wavelength emission in both polarization and total intensity.**
- It constrains dust models involving multiple dust components (e.g., separate carbon and silicate grains) and magnetic dipole emission

Dust extinction vs emission

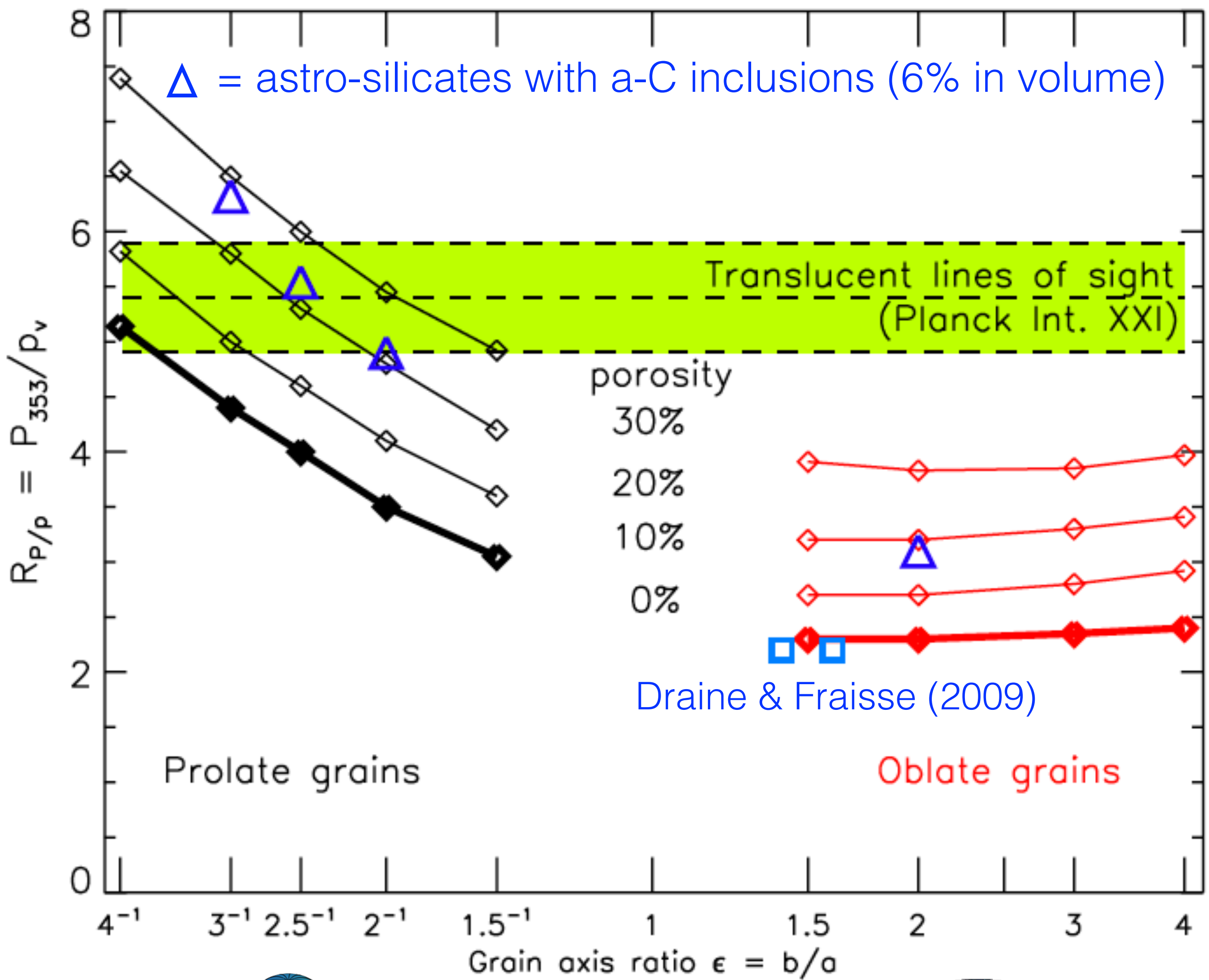


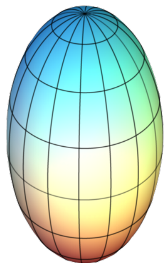
- Good correlation between Planck and stellar polarization
- The measured ratios between Stokes parameters and polarization fraction constrain dust models
- The values first determined in translucent lines of sight apply to lower column densities



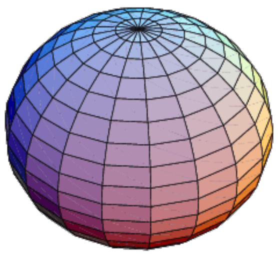


Grains shape & composition





Ratio between sizes perpendicular to and along symmetry axis



- ➡ Ratio between sub-mm and visible polarization matched by prolate astrosilicate grains, which are porous, or with a-C inclusions (Guillet et al. 2018)
- ➡ Other solutions are possible changing the dust optical properties

I. The polarization properties of interstellar dust

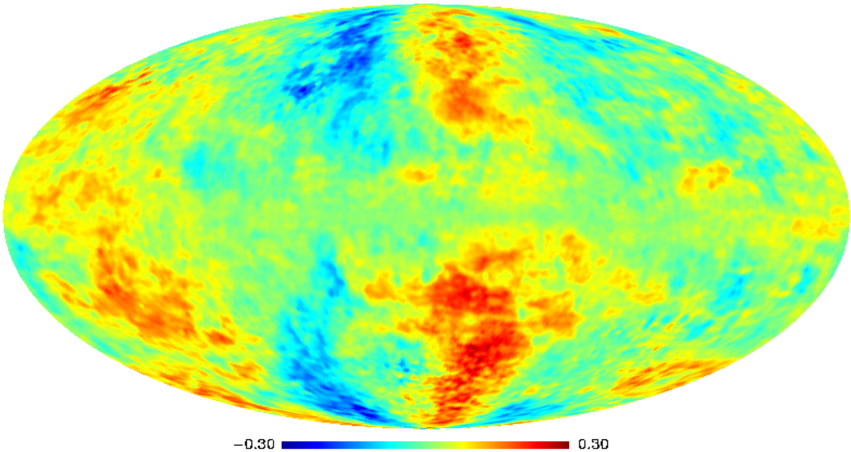
II. **Galactic Magnetic fields in the Solar Neighbourhood**

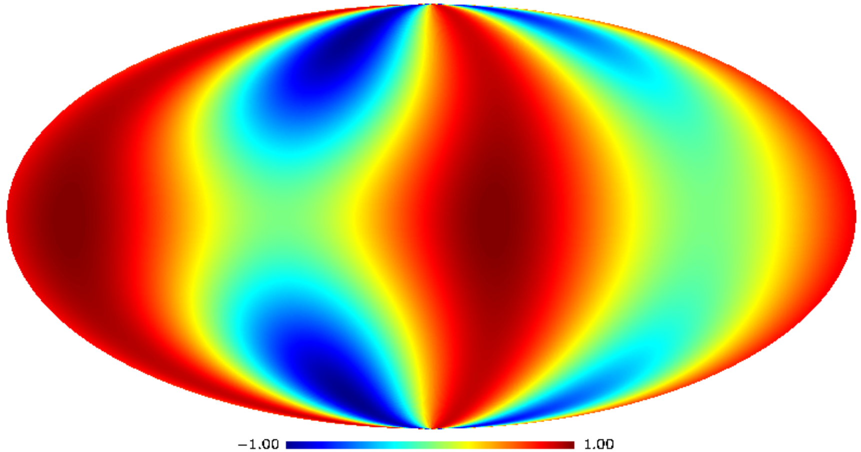
III. Statistical modeling of dust polarization

Ordered magnetic field

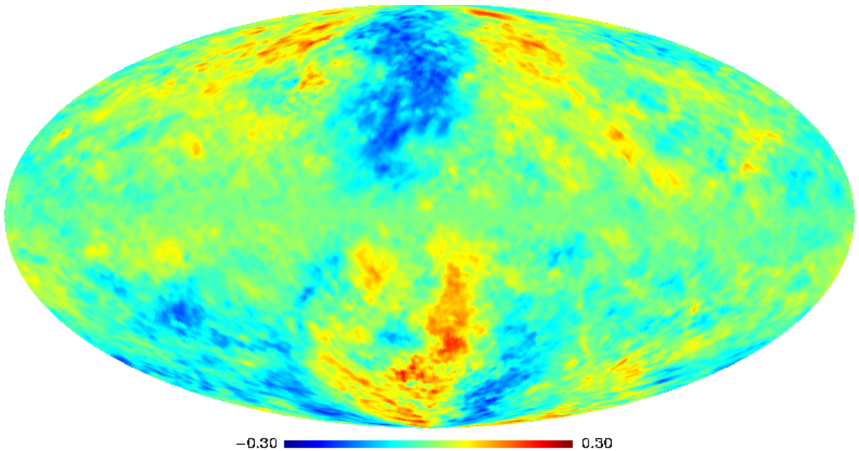
Planck maps smoothed (80' beam) | Model with no turbulence

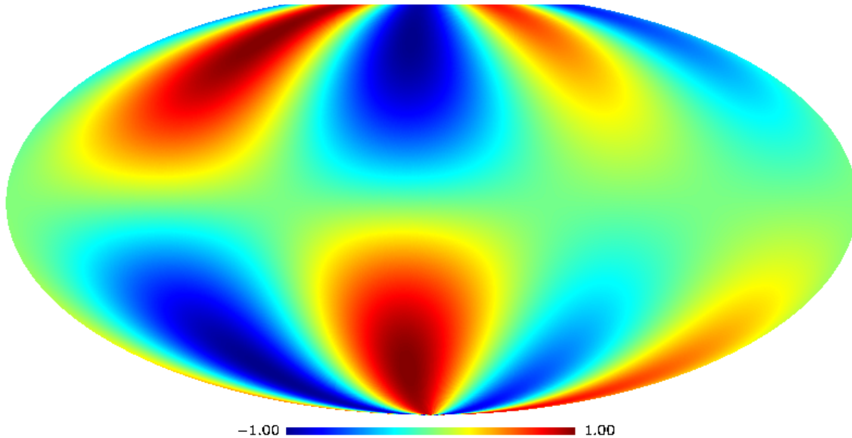
Stokes Q/I





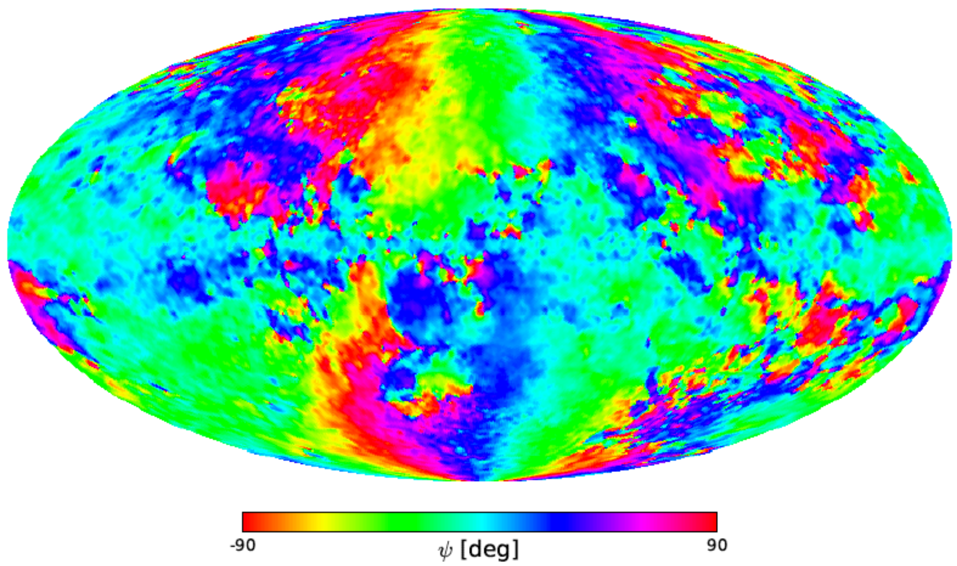
Stokes U/I



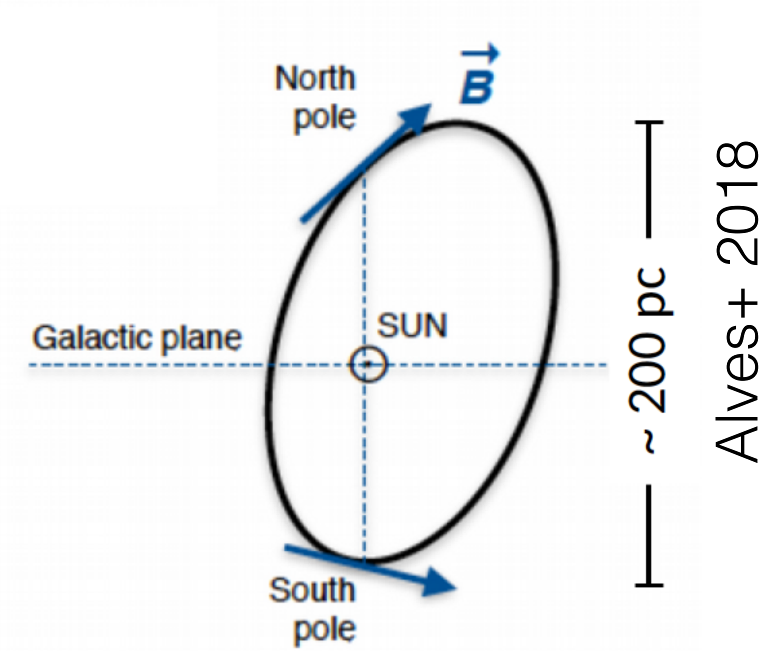


Solar Neighborhood magnetic field

Polarization angle ψ



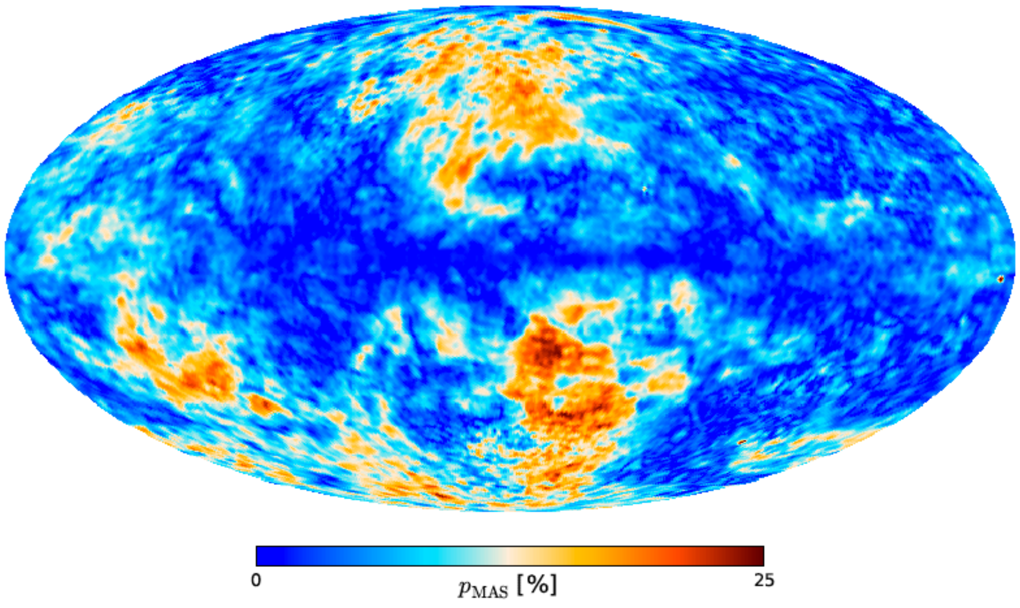
Local Bubble

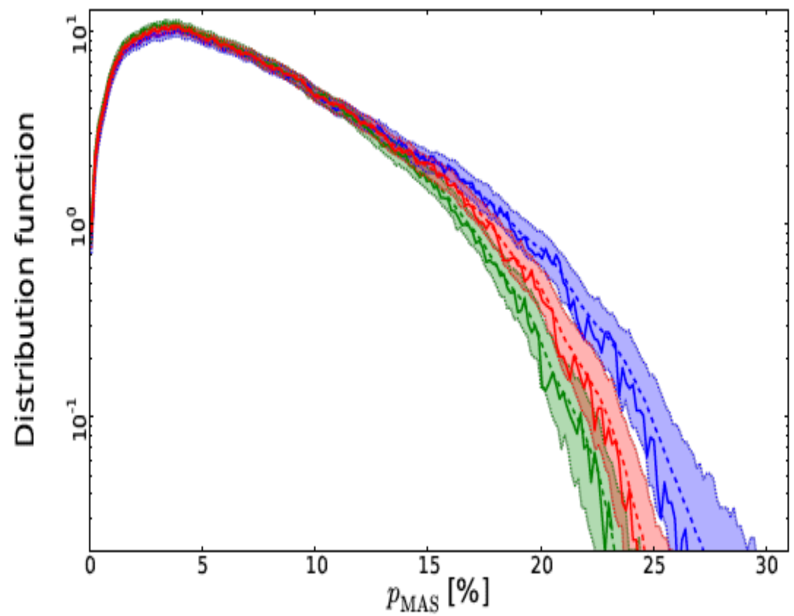


- Imprint from an ordered magnetic field is clearly apparent on the map of polarization angles
- **We may be seeing a local deformation of the Galactic magnetic field associated with the Local Bubble (Alves et al. 2018)**
- Dust, unlike synchrotron, polarization is sensitive to this because the extension of the Bubble towards the pole is comparable to the dust scale-height

Dust polarization fraction

polarization fraction p

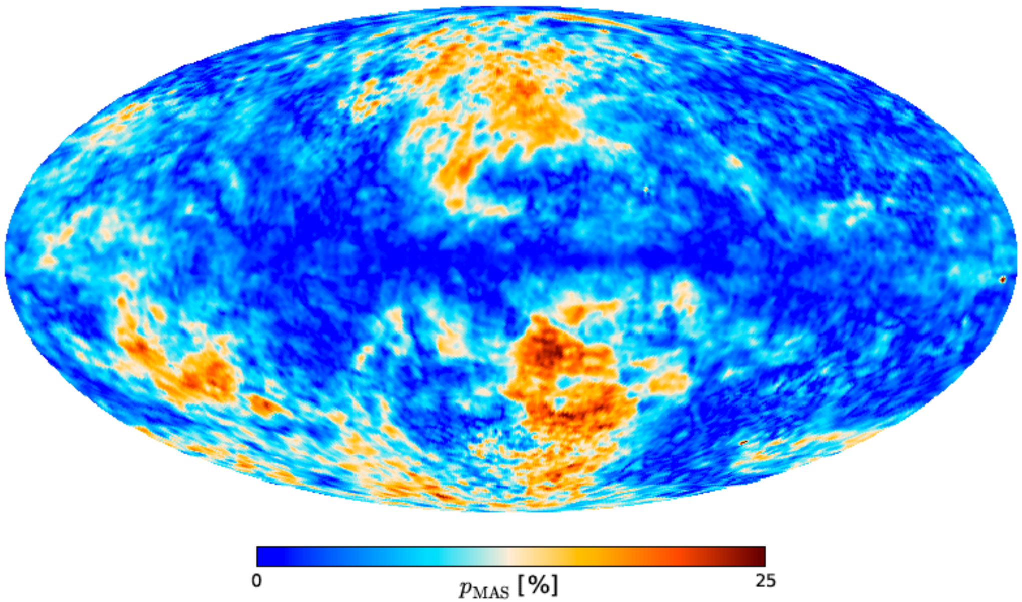




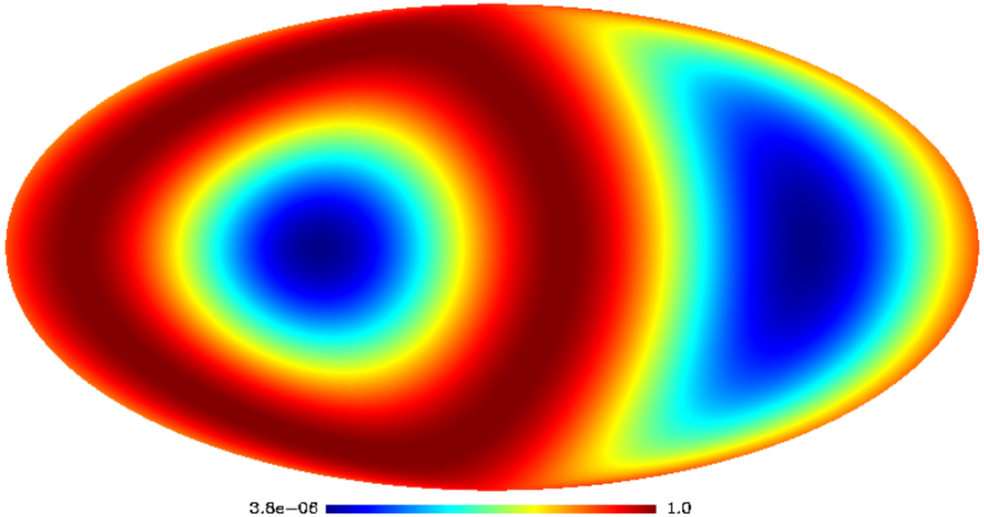
The maximal polarization fraction is large (> 20%). It is an unexpected result from Planck, which challenges dust polarization models

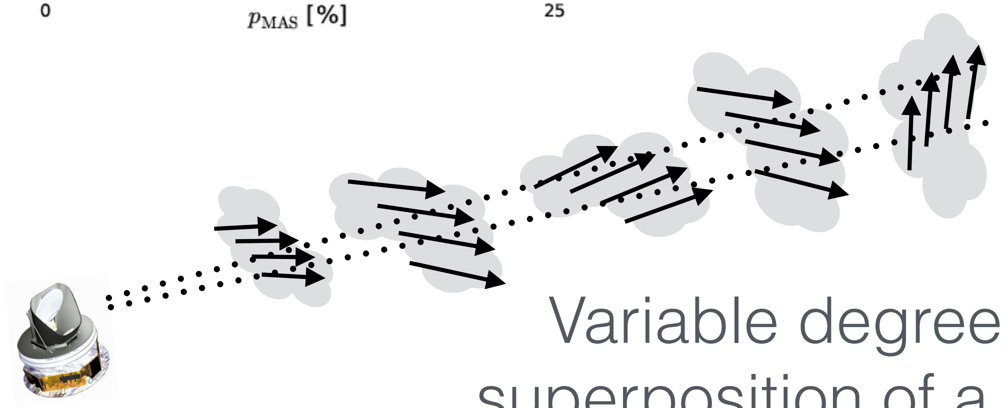
Depolarization from Turbulence

polarization fraction



Model with no turbulence



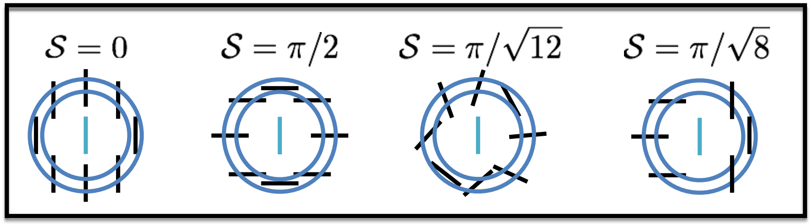


Variable degree of depolarization from the superposition of a small number of ISM *clouds*, and magnetic coherence *lengths* along the line of sight, with distinct polarization

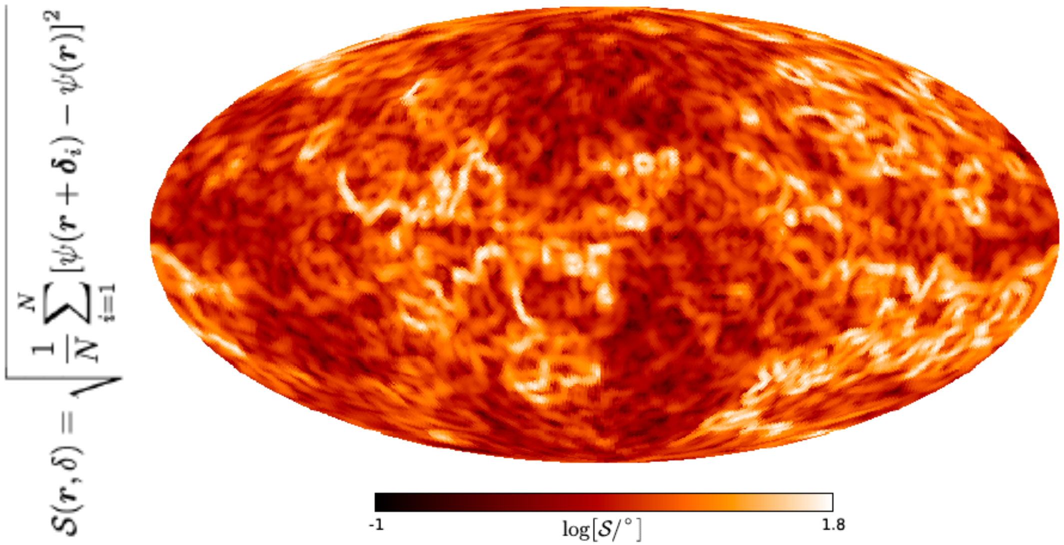
Filamentary structures

Dispersion function of polarization angles

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

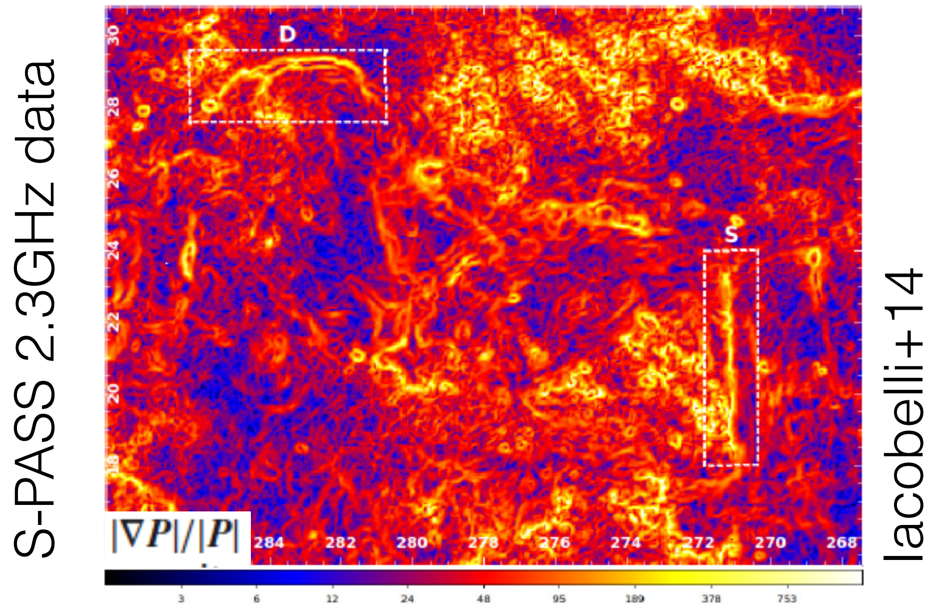


Local dispersion of ψ



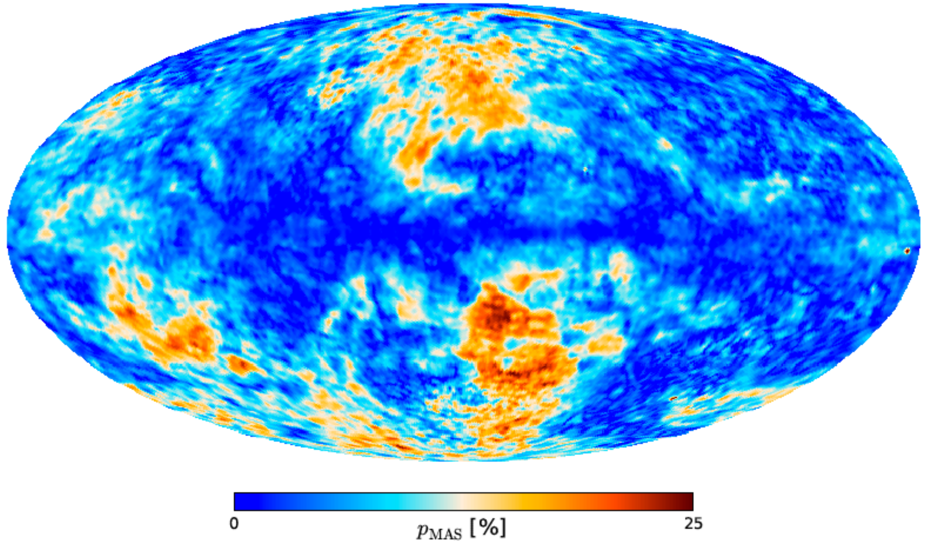
Similar filamentary structures are observed in radio data measuring Faraday rotation

They have been interpreted as signatures of magnetic shocks (Burkhart+12)



Dust polarization fraction

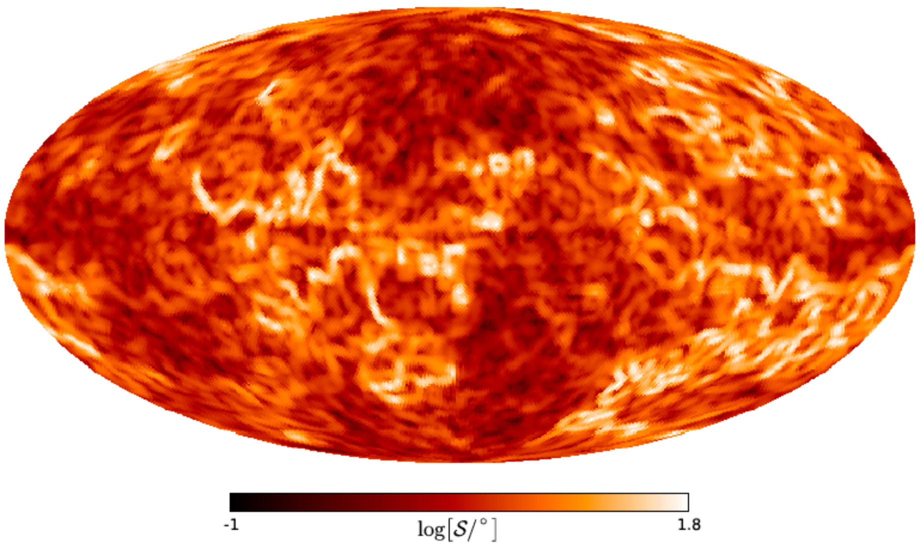
- The dust polarization maps trace magnetic field structure
- The data analysis shows no clear evidence for variations in the degree of grain alignment, nor in the intrinsic degree of dust polarization

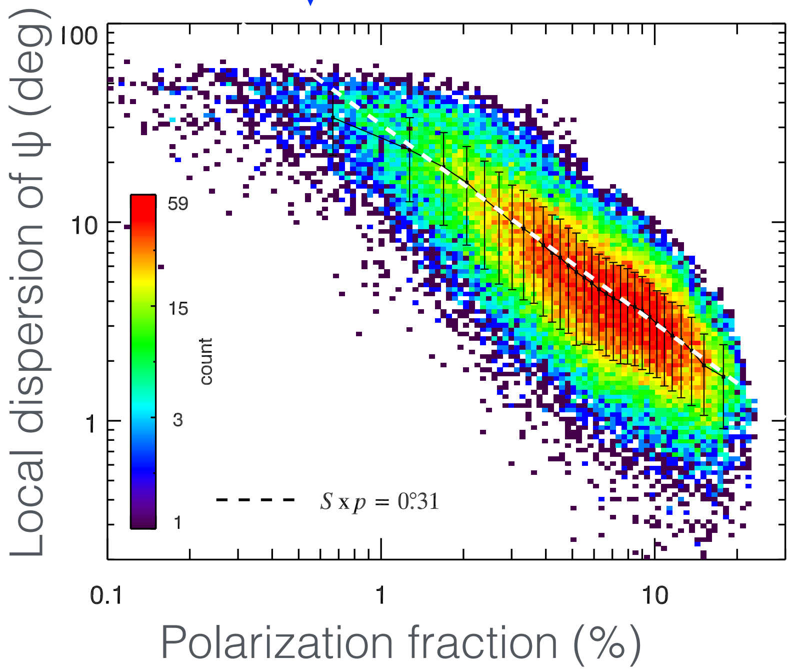


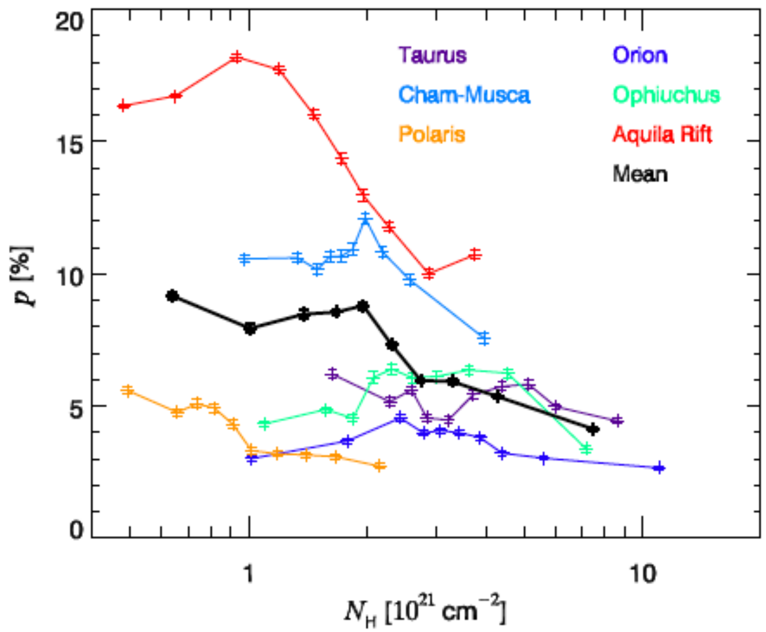
Polarization fraction

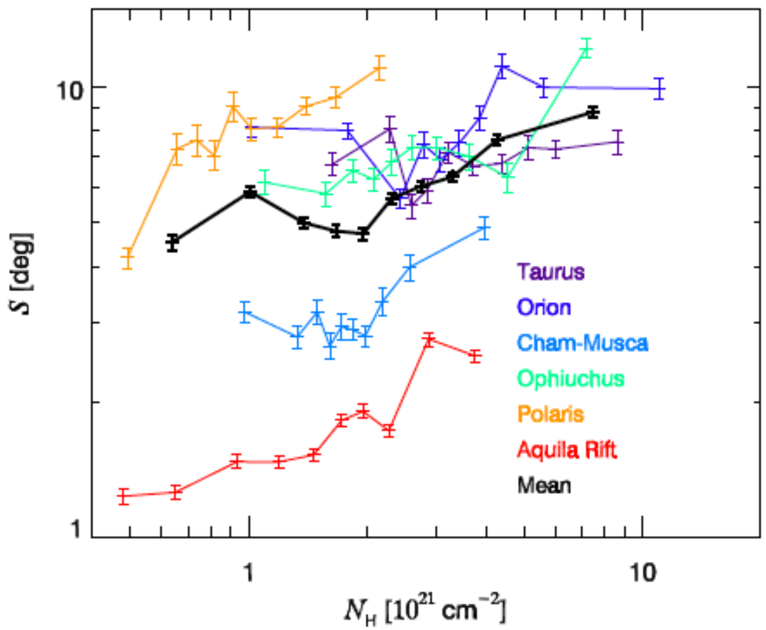
Local dispersion of ψ

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

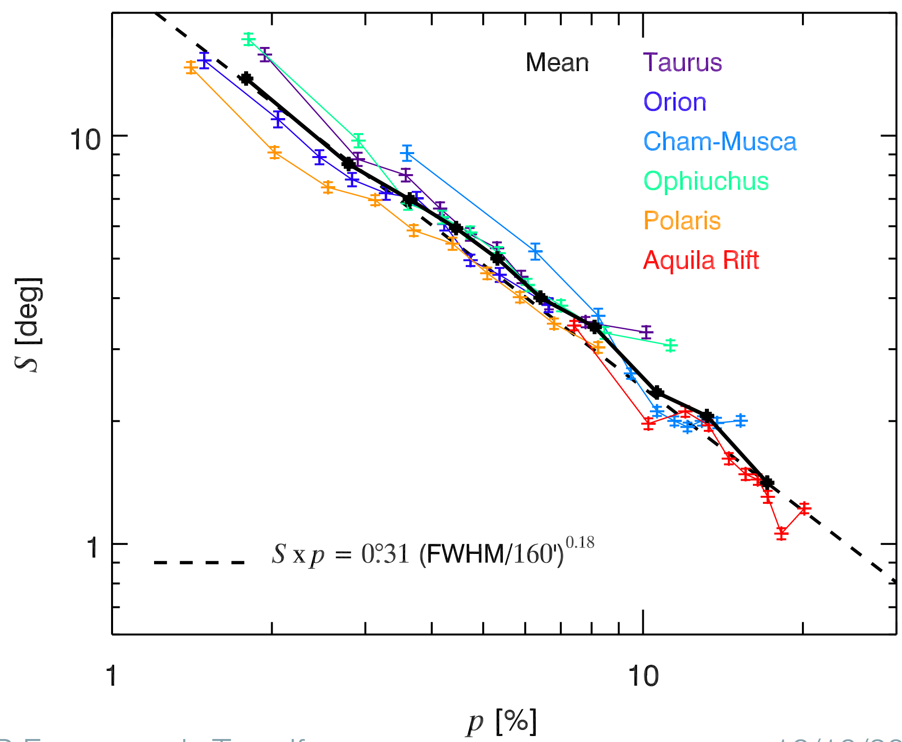








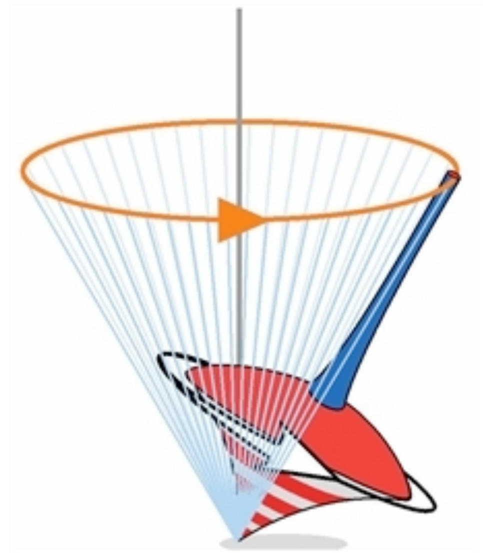
- The decrease of p for increasing N_H is compensated by a comparable increase in S
- It is a signature of the magnetic field structure and not, as often assumed, of a decrease in the degree of grain alignment



Grain Alignment

- Interstellar grains spin like tops around their axis of maximal inertia. Their rotation axis precesses around the magnetic field lines.

- Alignment of interstellar grains is thought to result from the combined action of radiative torques and paramagnetic relaxation. Alignment efficiency depends on whether interstellar silicates comprise magnetic inclusions (Hoang and Lazarian 2016).



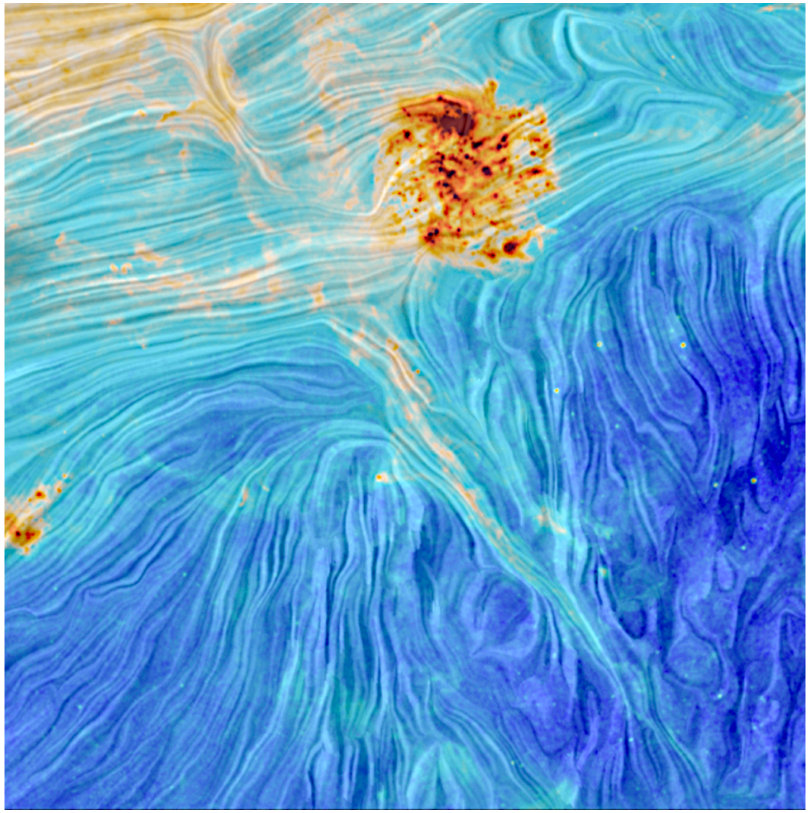
➡ The Planck data fit with a degree of grain alignment that is homogeneous in the diffuse ISM and molecular cloud envelopes

➡ This result and the high polarization fraction indicate that grain alignment is an efficient interstellar process

Magnetic fields and turbulence interplay

Diffuse ISM

$E_{mag} \sim E_{turb} >> E_{grav}$

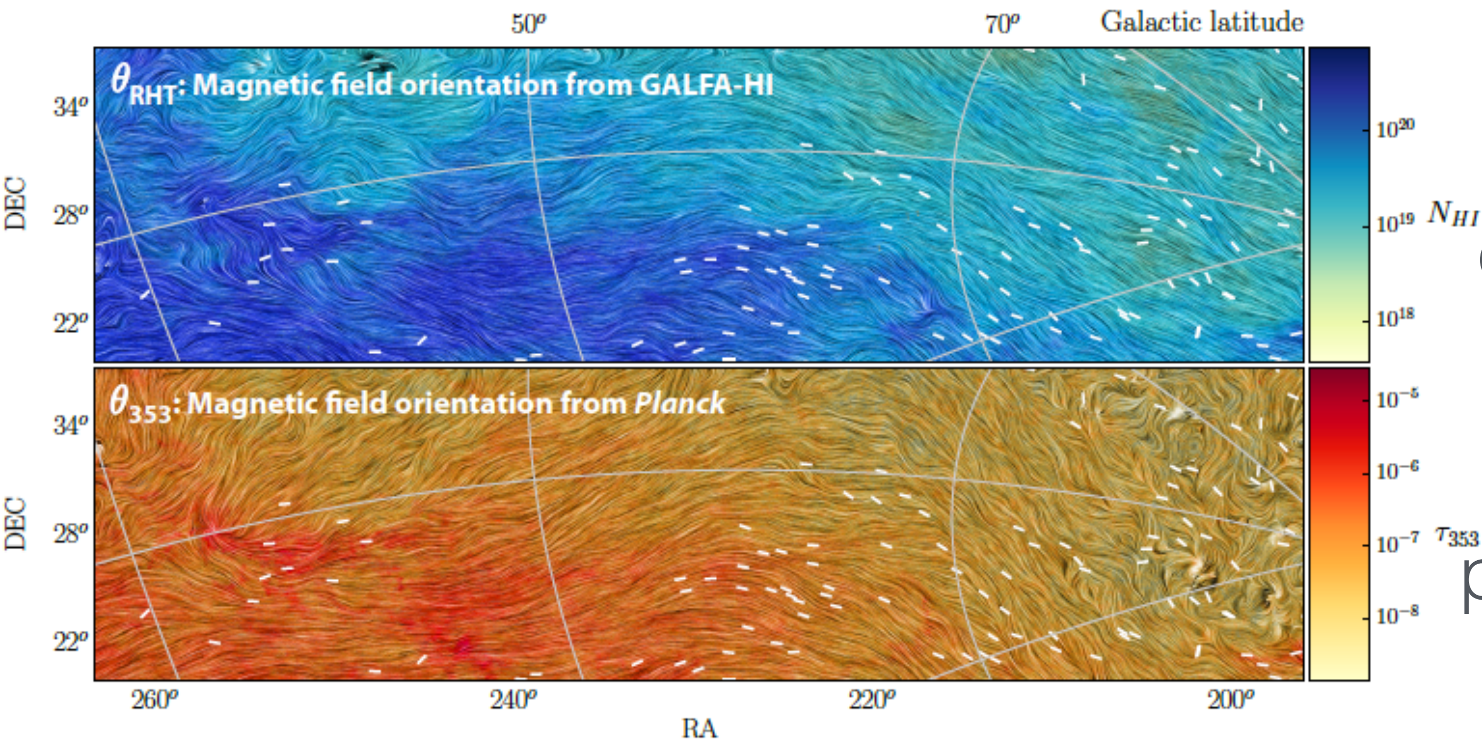


Matter/Magnetic field alignment

- Alignment of magnetic field and filamentary structures accounts for both the E/B asymmetry and TE correlation (Clark+15, Planck XXXVIII 2016)
- Change of relative orientation observed in molecular clouds where the gas self-gravity is significant (Planck XXXV 2016)

Correlation with HI filamentary structure

Clark+ 2015



HI orientation

Planck polarization

- The orientation of magnetic fields is encoded in the anisotropy of the matter distribution
- HI 21cm spectroscopic data may be used to model dust polarization (Ghosh+2017, Clark+ 2018)

I. The polarization properties of interstellar dust

II. Galactic Magnetic fields in the Solar Neighbourhood

III. Statistical modeling of dust polarization

Moving forward with foregrounds

Extending to foregrounds the statistical approach of CMB simulations

Data analysis of Planck dust polarization data

↓

Astrophysics of dust polarization

↓

Statistical modelling of dust polarization

First step

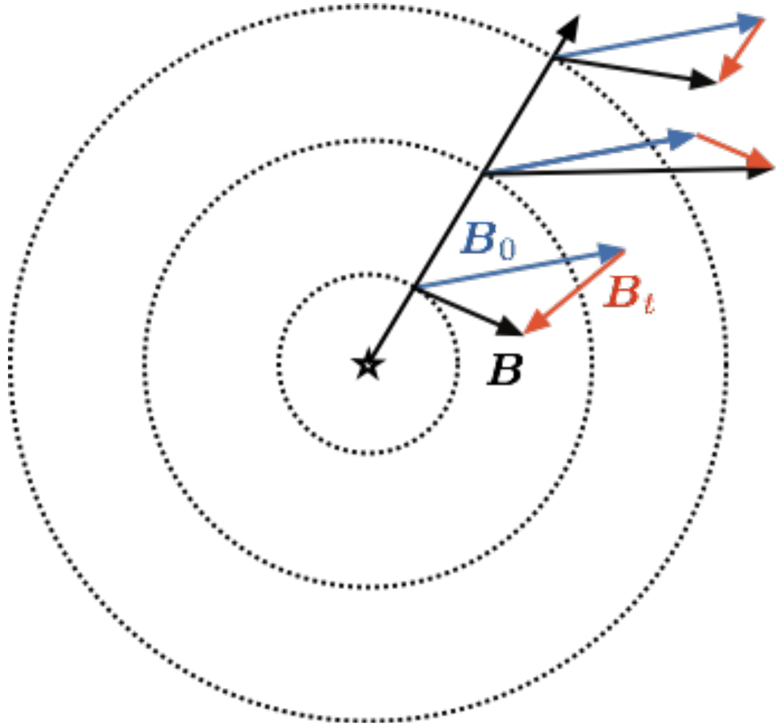
- Magnetic field
  - ordered + turbulent

$$\boldsymbol{B} = |\boldsymbol{B}_0| \, (\hat{\boldsymbol{B}}_0 + f_{\rm M} \, \hat{\boldsymbol{B}}_{\rm t}) \quad f_M \simeq 0.9$$

  - Power-law spectrum

$$C_\ell \propto \ell^{\alpha_{\rm M}} \text{ for } \ell \geq 2 \quad \alpha_M = -2.5$$

- Distribution of matter from total intensity Planck map
- Summing emission over N emitting layers (ISM structure along the line of sight)



Turbulent field

$$\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}_t$$

Ordered field

➡ **This phenomenological model, introduced in Planck Intermediate XLIV, accounts for statistical results on p and ψ in Planck Legacy XII, and the dust polarization power spectra (Ghosh+ 2017, Vansyngel+ 2017)**

Model-Data Correspondences

Magnetic fields → **Dust polarization maps**

Ordered component
- Fixed model, currently 2D must become 3D (Gaia)

- Large scale patterns
- Non-stationarity of dust polarization power

Turbulent component
- Statistical parametric model
- MHD simulations
- Correlation between B fields & matter

- Power spectra exponent & amplitude
- Depolarization
- E/B asymmetry, TE and TB correlations
- Non-Gaussianity

Dust properties → **Spectral energy distribution**

- Number of polarized components
- Variations on the sky & along the line of sight
- Correlation between dust, matter & B fields

- Dimensionality of the component separation
- Frequency decorrelation

Summary

- ★ Planck dust polarization maps reveal the imprint of interstellar magnetic fields on matter. The data probe the ordered and turbulent components of the Galactic magnetic field in the Solar Neighborhood

- ★ Polarization data set valuable constraints on dust composition, which call for new efforts in dust modeling

- ★ Planck is providing many of the inputs needed to statistically model Galactic polarized foregrounds for preparing future space missions, optimizing and assessing component separations.

- ★ Further insight on frequency decorrelation in the presentation of Anna Mangilli