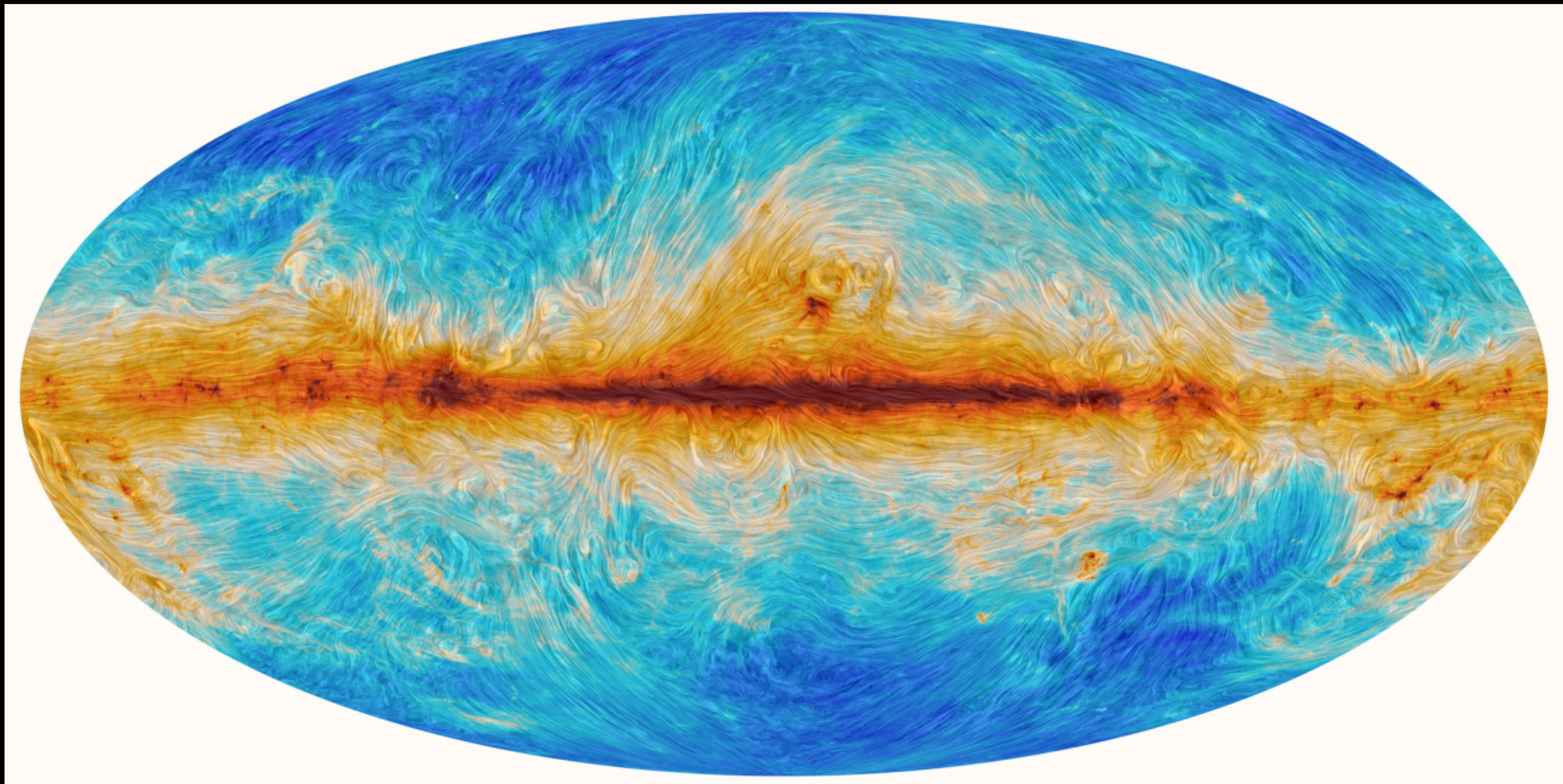
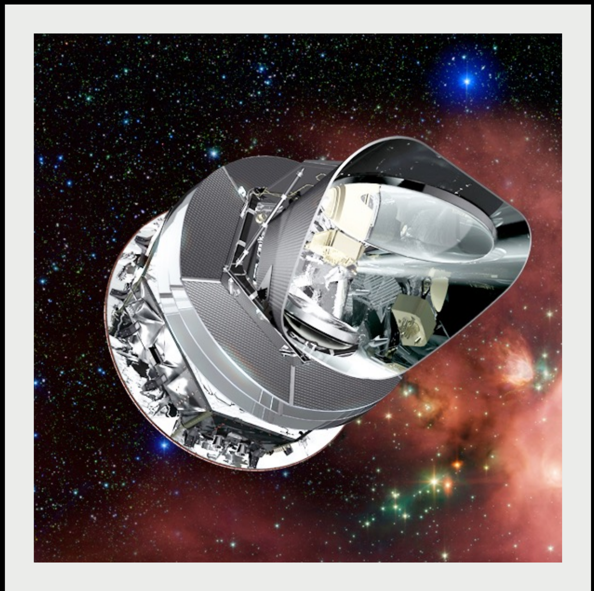
Planck view at Galactic magnetic fields

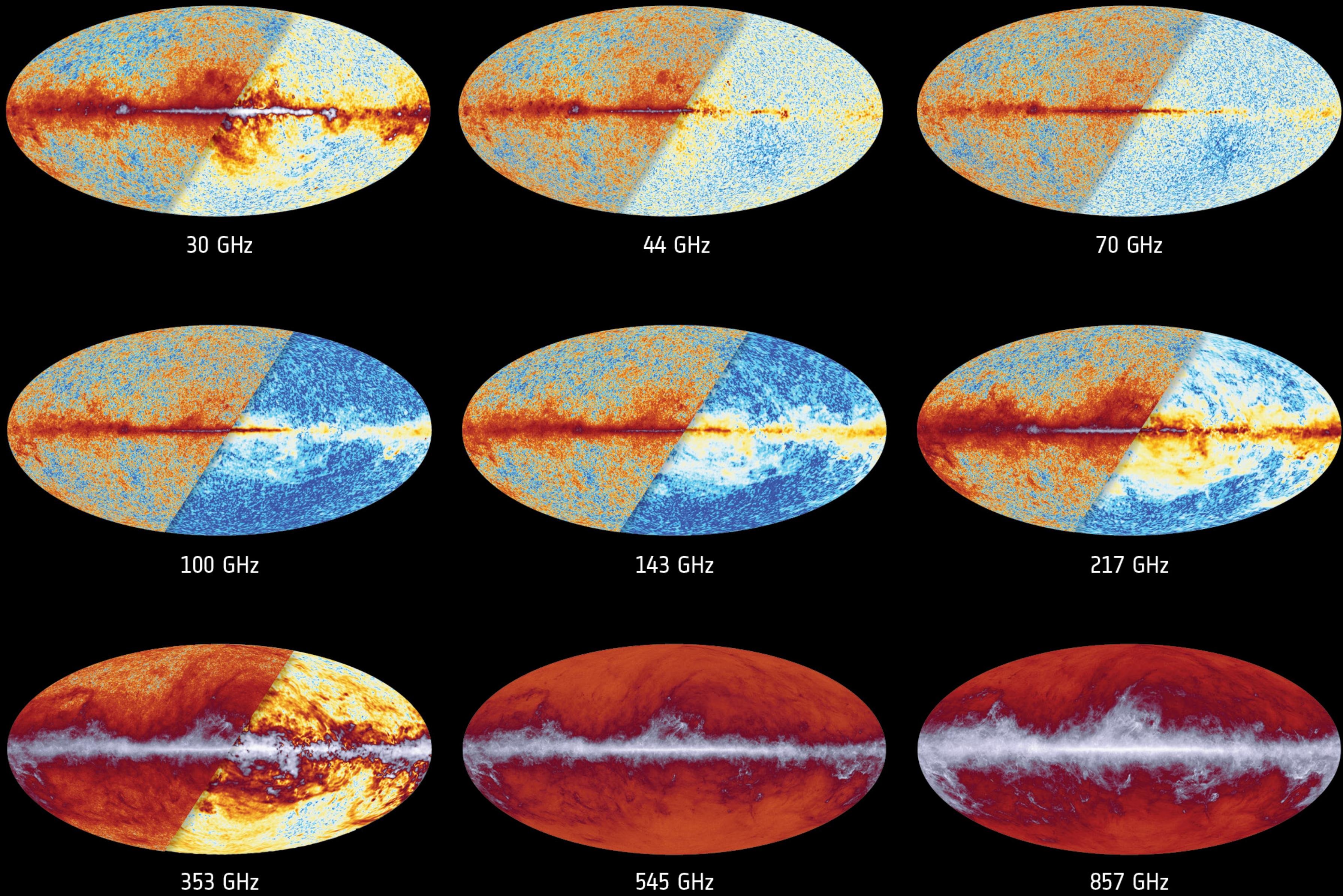


François Boulanger
Institut d'Astrophysique Spatiale



- ★Polarization at microwave frequencies
- ★Dust polarization
- ★Insight on the interplay between magnetic fields and interstellar matter

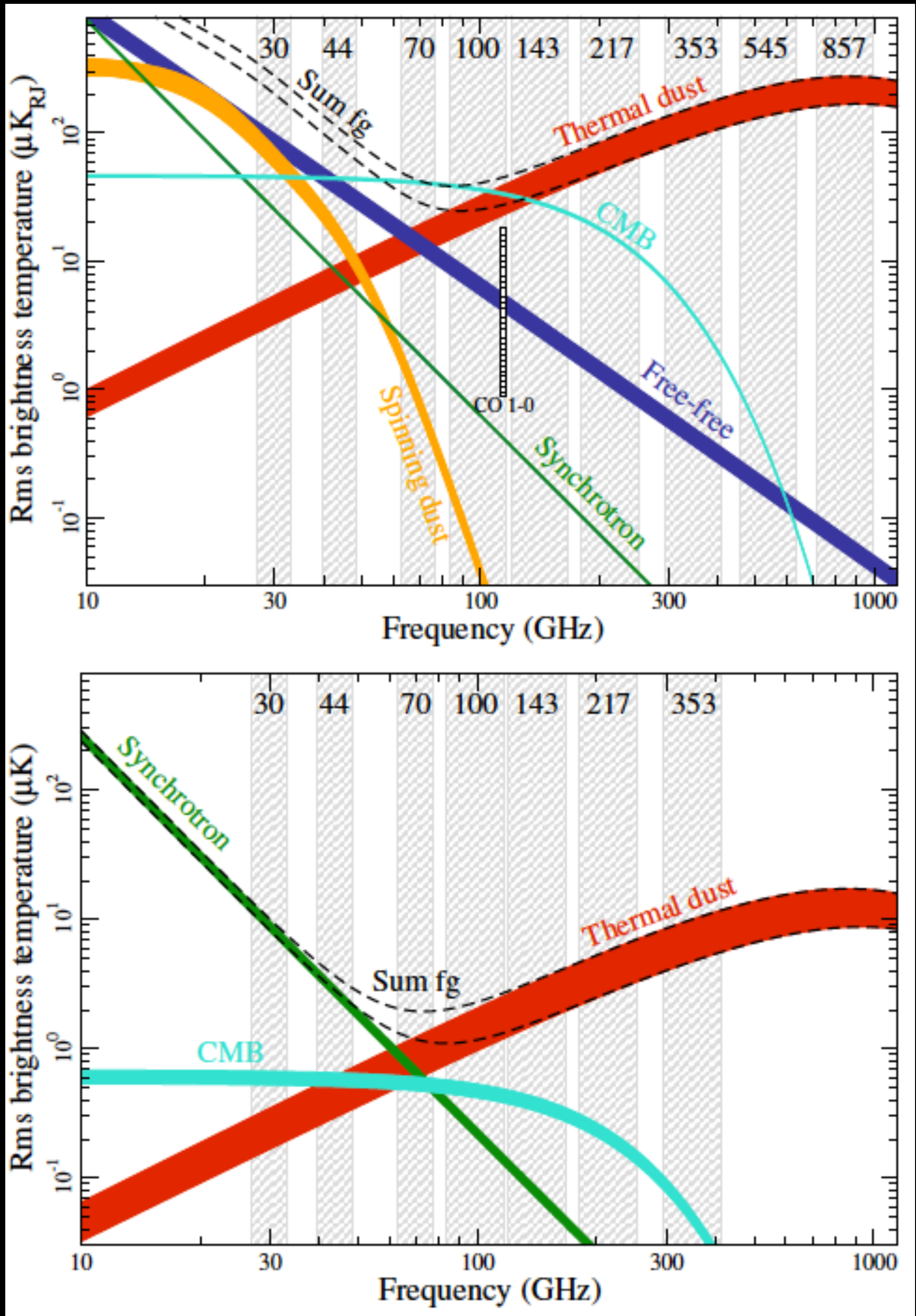
Intensity/Polarization sky



Galactic *Foregrounds*

rms for $0.8 < f_{sky} < 0.9$

Planck Collaboration X 2016



Temperature

- ➡ *Several* Galactic *components* but CMB dominant signal at microwave frequencies
- ➡ Synchrotron emission is difficult to separate from anomalous microwave emission

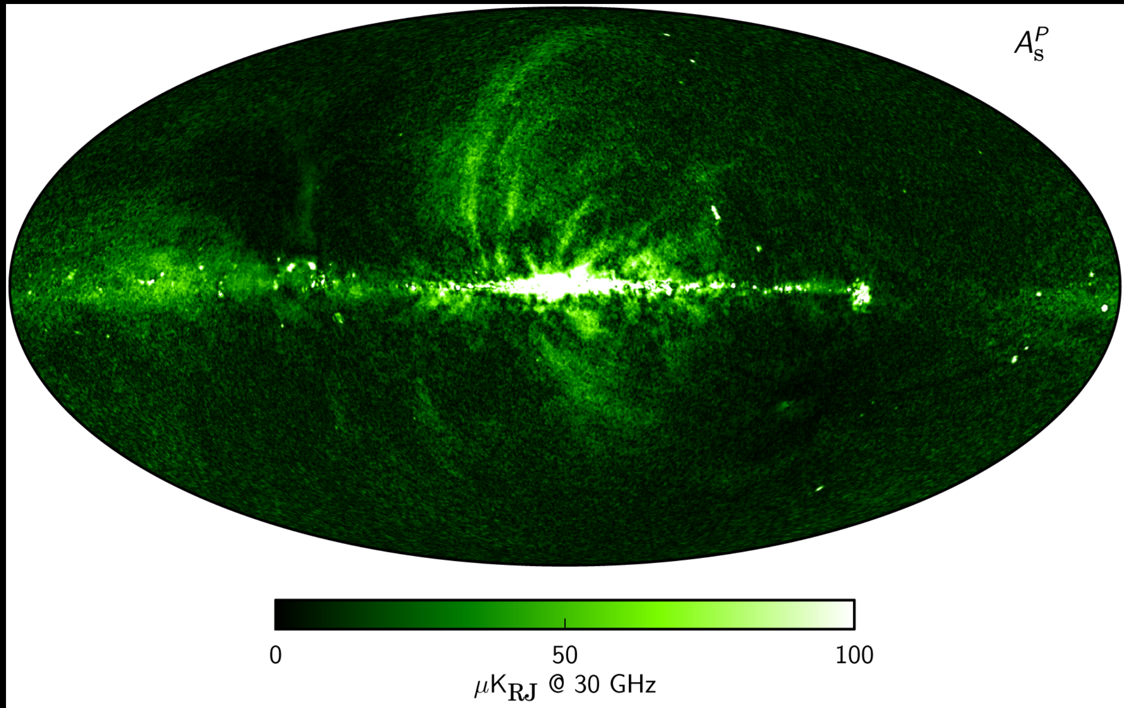
Polarization

- ➡ Two Galactic polarized components: dust and synchrotron

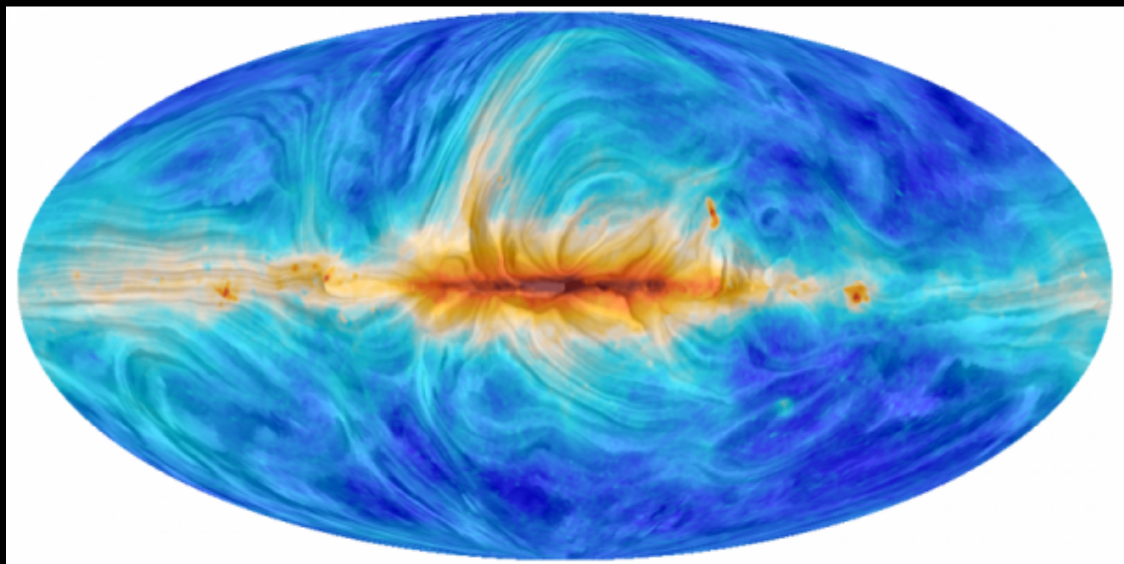
Synchrotron Polarization

Planck results XXV. 2016: A&A 594, 25
Planck results X. 2016: A&A 594, 10

Polarized Intensity



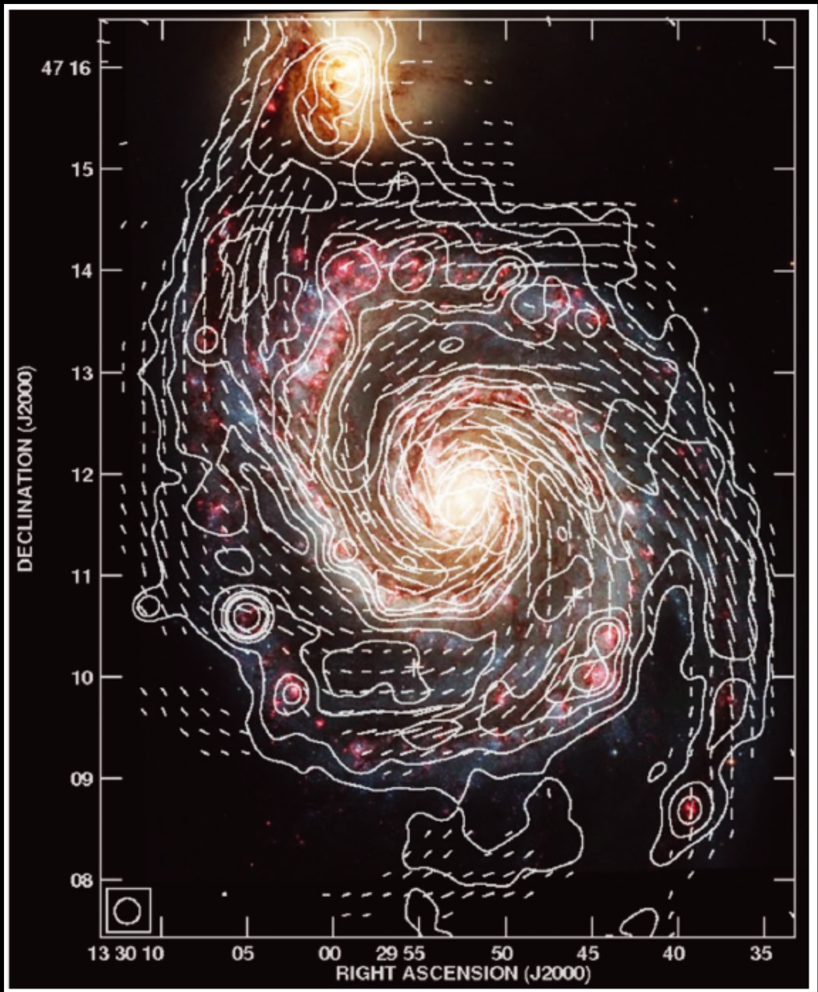
B field orientation



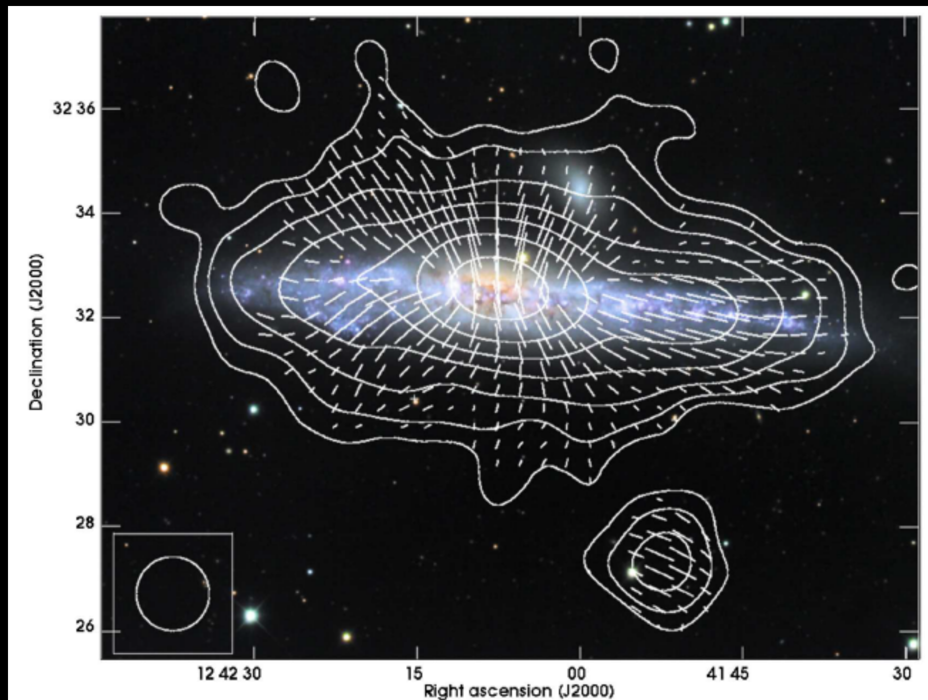
- Complementary to radio observations because Faraday rotation is negligible at Planck frequencies
- Comparison with existing models of large scale Galactic magnetic field in Planck intermediate results. XLII 2016, arXiv:1601.00546

Magnetic fields on Galactic scales

The ordered magnetic field on Galactic scales is best displayed by radio observations of external Galaxies



Fletcher+ 2011



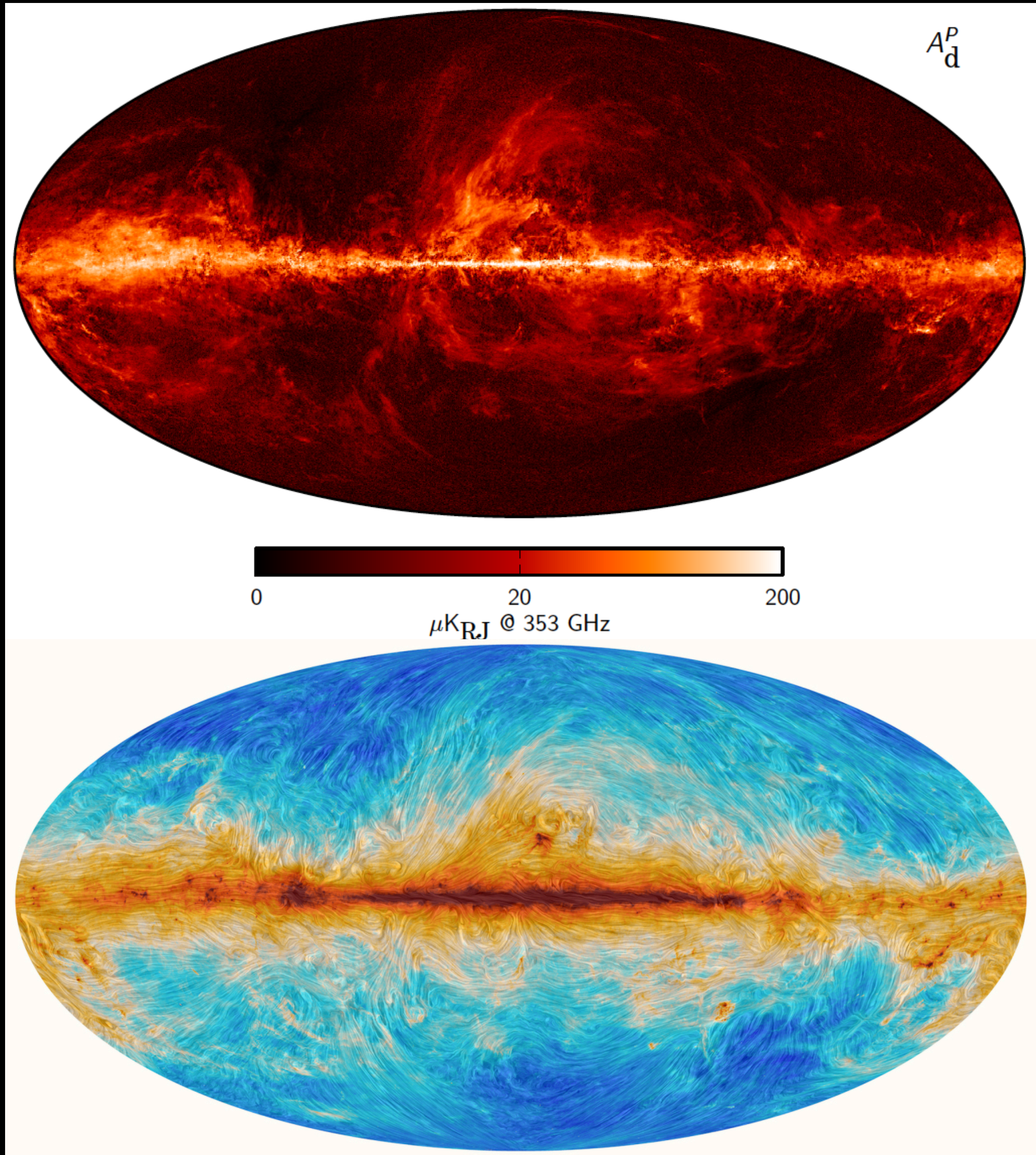
Mora & Krause 2013

Dust Polarization

Planck intermediate results XIX. 2016: A&A 576, 104
Planck results I. 2016: A&A 594, 1

Polarized Intensity

B-field Orientation



- Huge step forward in terms of sensitivity and sky coverage
- The Planck data have allowed us to carry the first statistical study of the interplay between interstellar matter and magnetic fields

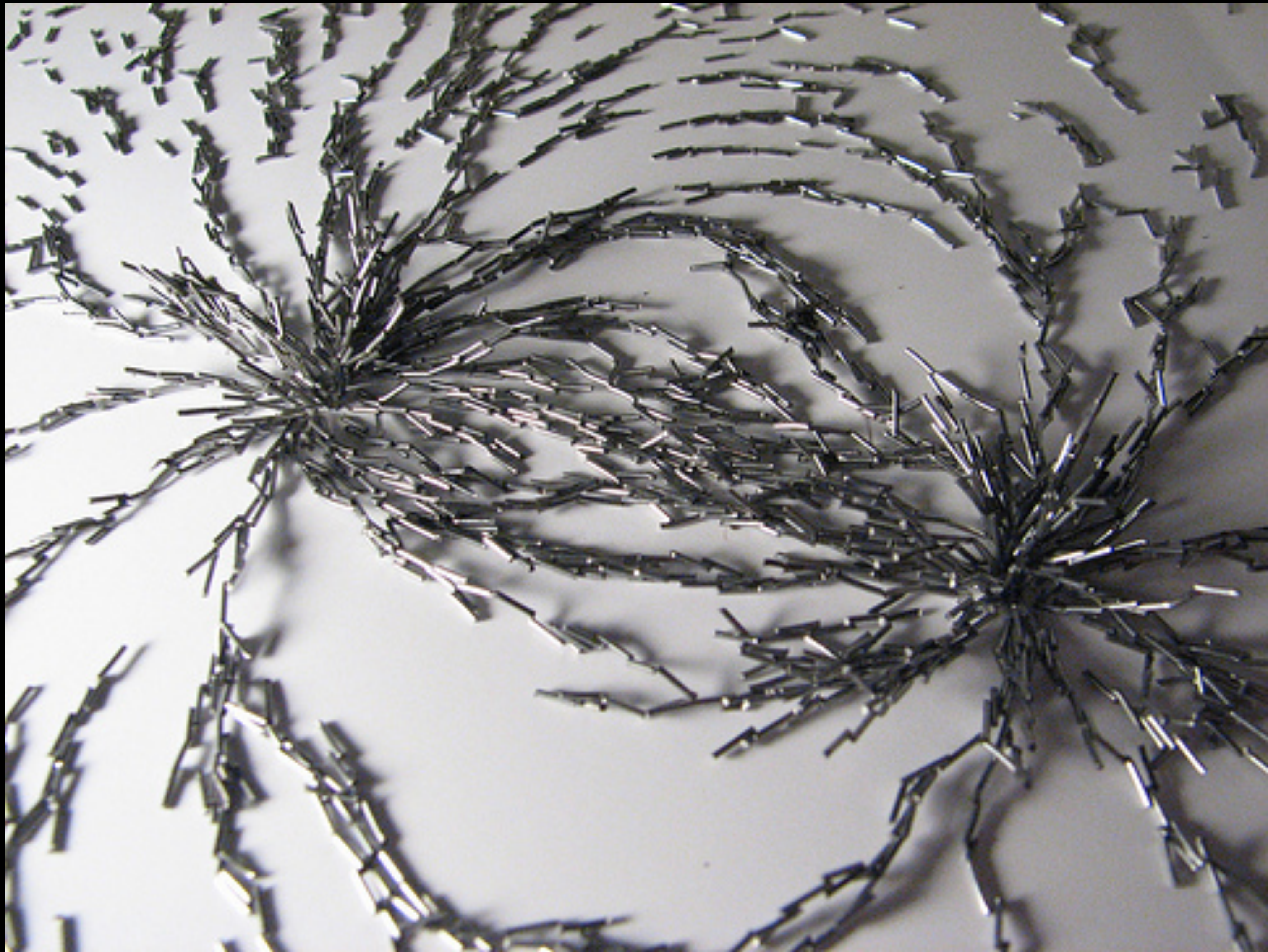
Dust emission is a tracer of the column density of interstellar matter

★ Dust polarisation traces the magnetic field over the thin disk where matter is concentrated. The volume emissivity scales as n_H. The contribution from dust in the thick Galactic disk is minor. Observed polarization is the sum of two contributions:

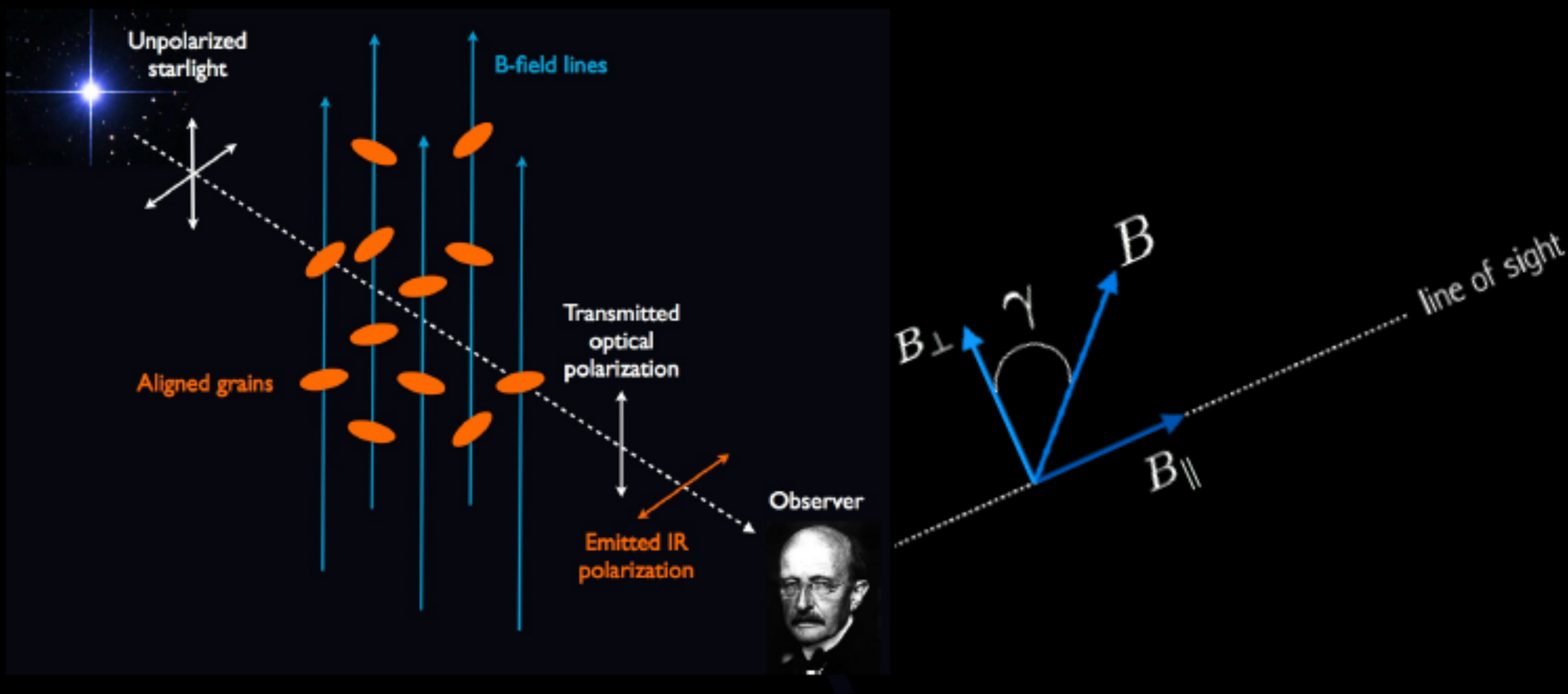
- The warm medium (WNM/WIM) with a significant volume filling factor ($f_{WNM/WIM} \gtrsim 0.2$). This contribution traces the mean direction/structure of the field averaged along the line of sight.
- The cold medium (CNM) with a small volume filling factor ($f_{CNM} \lesssim 0.01$). This contribution 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

The interplay between magnetic field and interstellar matter



Dust polarization



Credit: Andrea Bracco

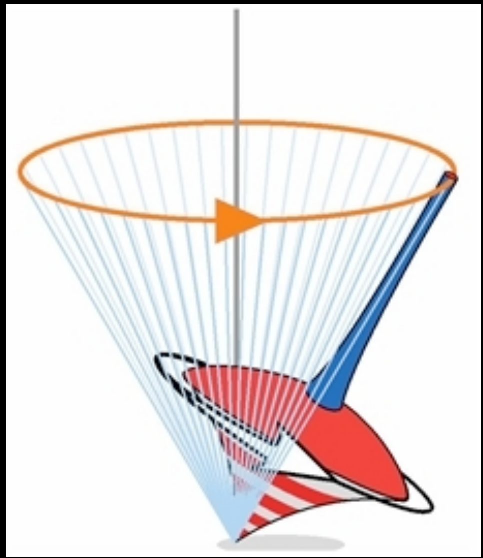
- Aspherical dust grains align their axis of maximal inertia with the local magnetic field orientation

- The polarization fraction depends on the angle (ɣ) between the local magnetic field and the plane of the sky

➡ Both the polarization fraction (p) and angle (ψ) trace the magnetic field structure

Why are grains aligned with the field?

- Interstellar grains spin like tops around their axis of maximal inertia. Their rotation axis precesses around the magnetic field lines.
- Alignment may be associated with paramagnetic relaxation or radiative torques. H_2 formation can also locally contribute.



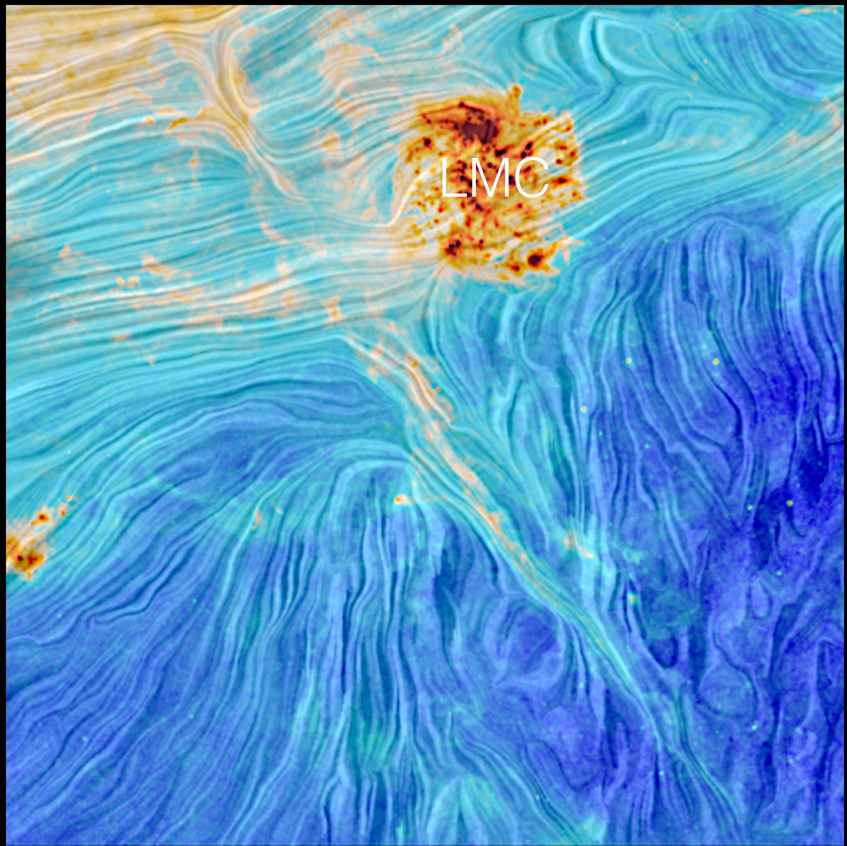
Hoang+ 2016

➡The degree of grain alignment may vary, but it is difficult to discriminate this possibility from magnetic field structure

➡We assume that the degree of grain alignment is homogeneous

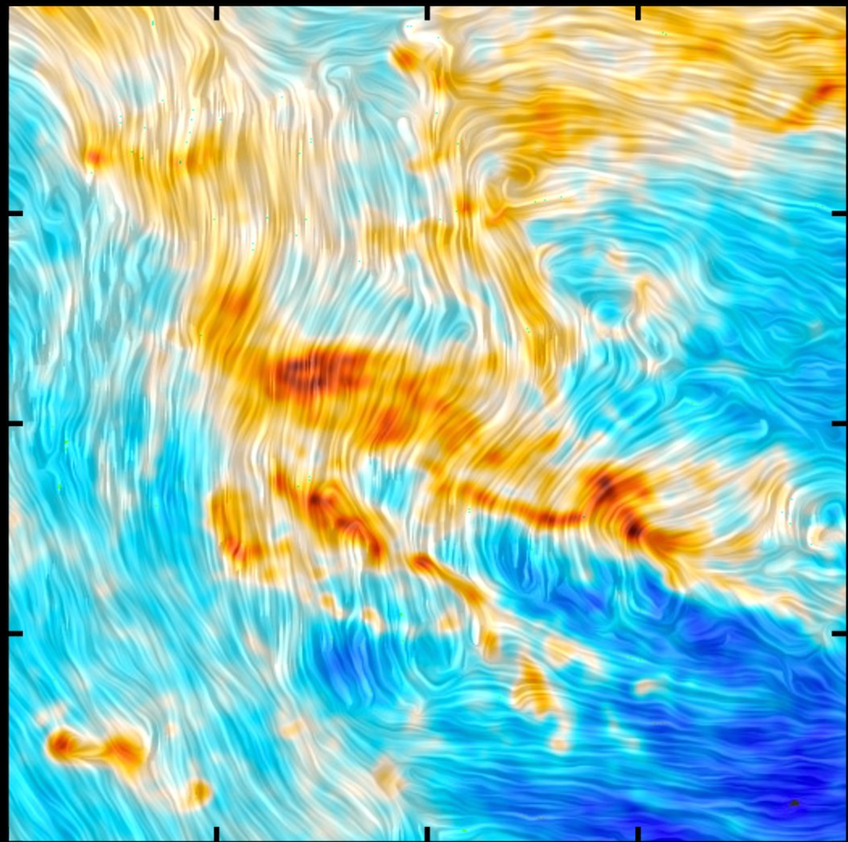
The interplay between magnetic field and interstellar matter

Diffuse ISM



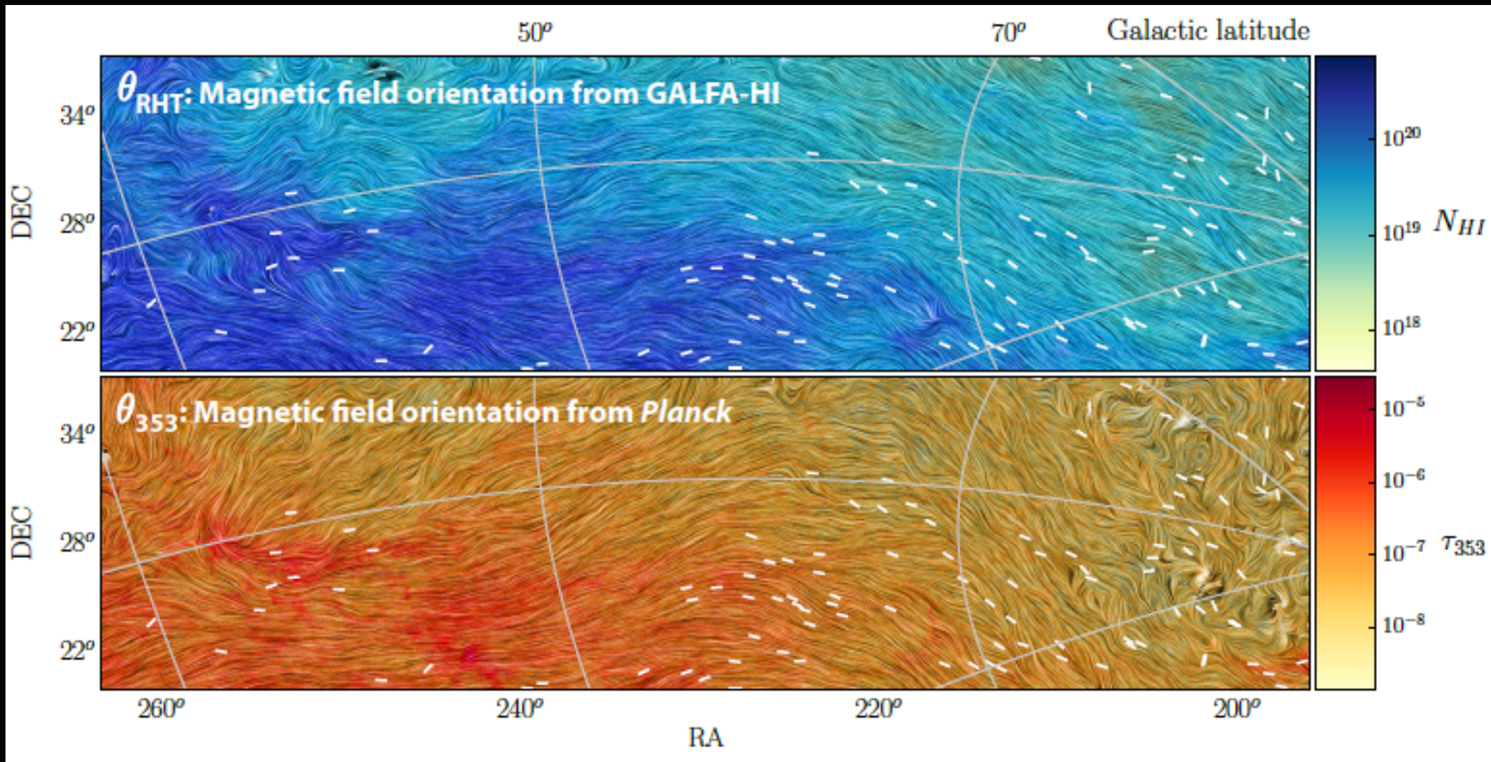
Matter/Magnetic field alignment

Taurus molecular cloud



Magnetic field perpendicular to matter

Correlation with HI filamentary structure



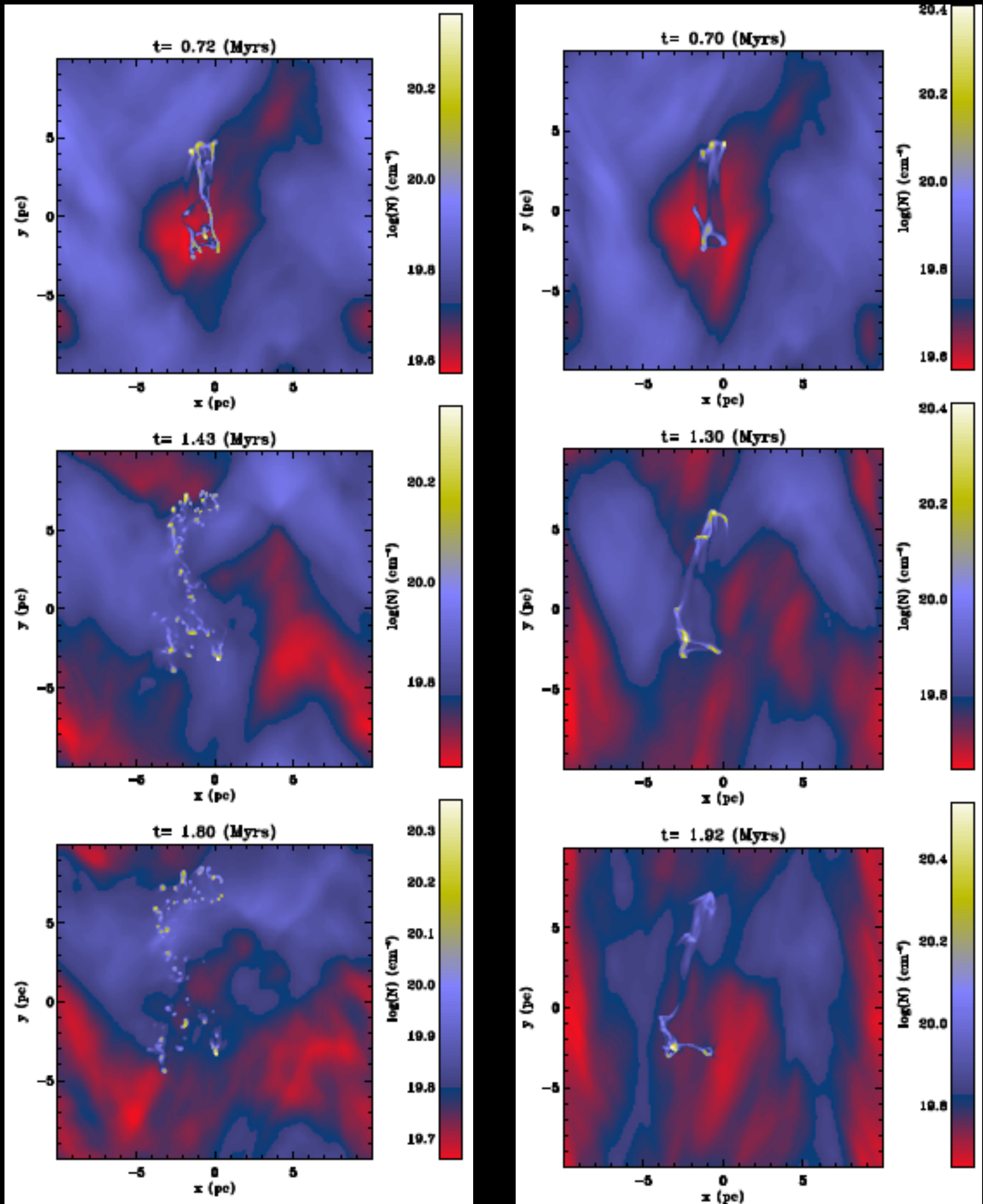
HI

Planck

Clark+ 2015

➡ The orientation of magnetic field is encoded in the anisotropy of the matter distribution

HD MHD



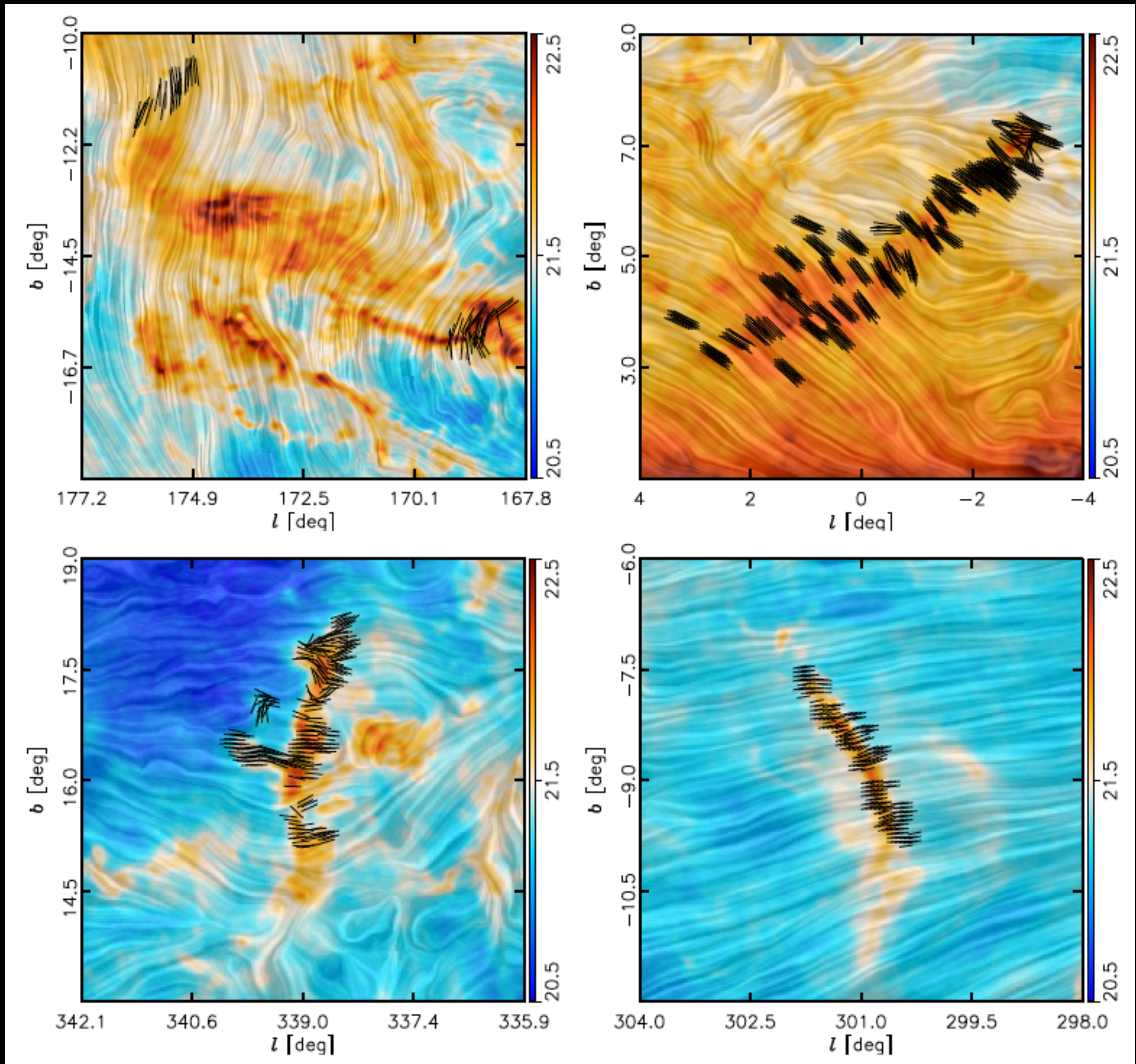
Formation of a filament through shear

- ★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

Magnetic fields in molecular clouds

Planck and stellar polarization



- Magnetic field tends to be perpendicular to star forming filaments
- This is interpreted as a signature of the formation of gravitationally bound structures for a dynamically important magnetic field.

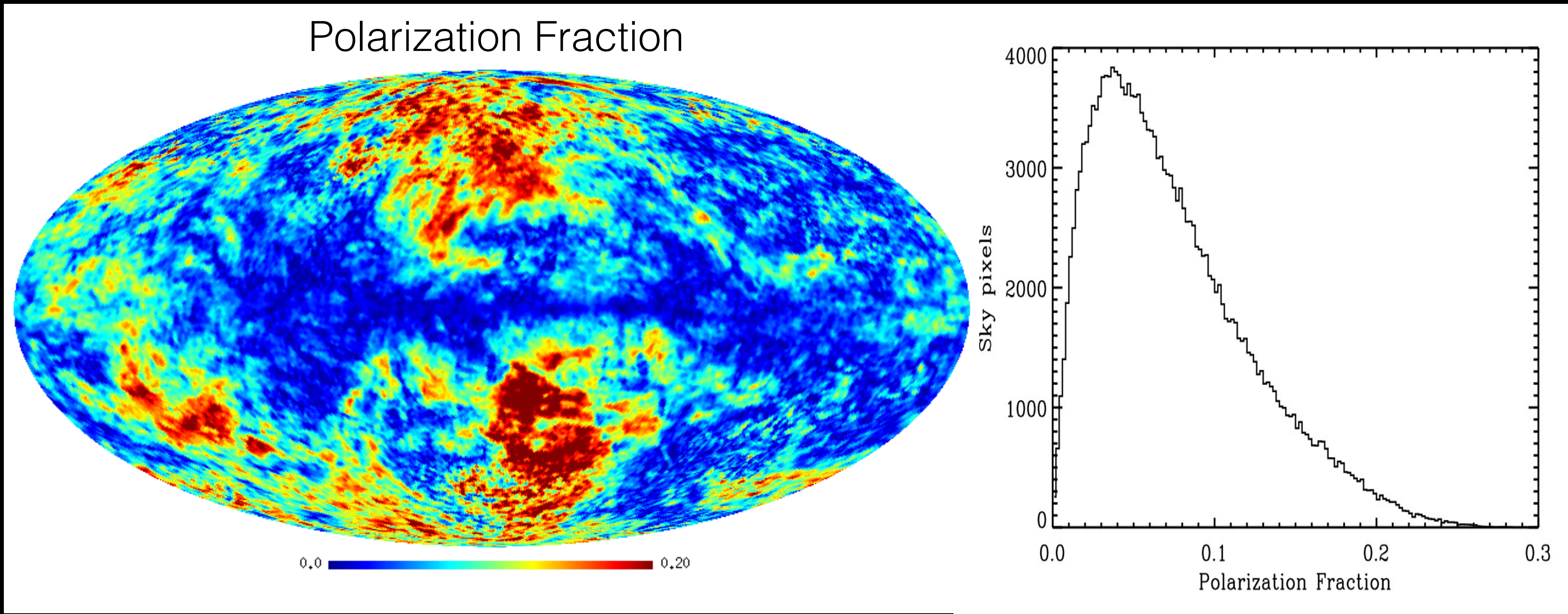
Planck Intermediate XXXV 2014, arXiv:1502.04123
Soler+2016 arXiv:1605.09371

Data Modelling

- Modelling is required to disentangle the contribution of magnetic fields and ISM structure to the observed polarization
- Phenomelogical approach in parallel to comparison with MHD simulations

Polarization Fraction

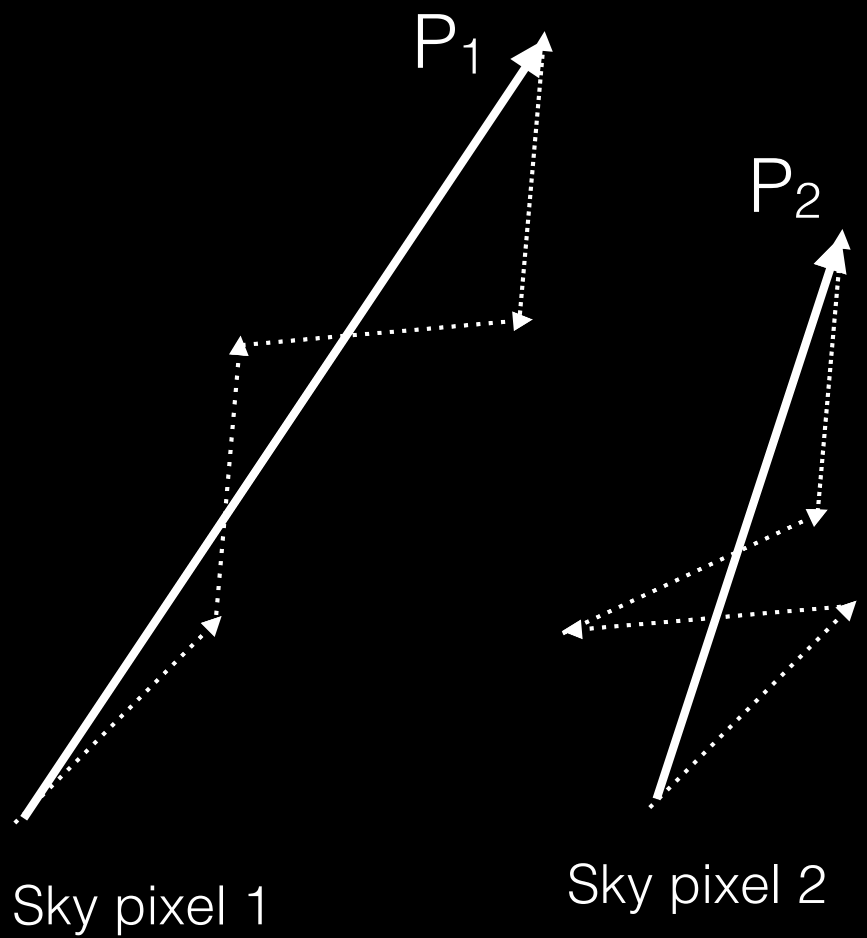
Overview paper dust polarization by Planck collaboration (2014)



- 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

Schematic explanation

Dust polarization may be viewed as a random walk in the Q,U plane about a mean direction



Same I but different polarized intensity and polarization angle

- The magnetic field orientation sets the direction of each step about a mean orientation set by its ordered component.
- Dust polarized intensity sets the length
- The large variance of p implies that the number of steps is small
- Steps account for

➡ Multiphase structure of the ISM

➡ Correlation length of interstellar magnetic field

Modeling of dust polarization

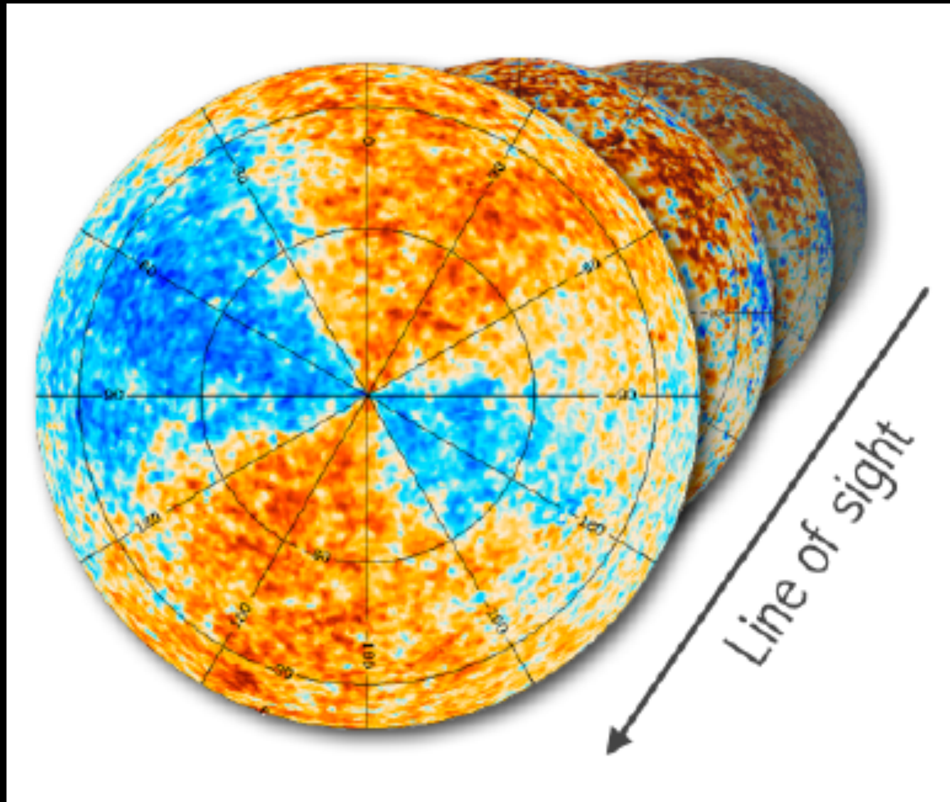
- Magnetic field
  - Uniform + random

$$B = |B_0| \, (\hat{B}_0 + f_M \, \hat{B}_t)$$

  - Power-law spectrum

$$C_\ell \propto \ell^{\alpha_M} \text{ for } \ell \geq 2$$

- Matter
  - Distribution of matter from total intensity maps
  - Correlation between magnetic field and matter
- A number N of emitting layers

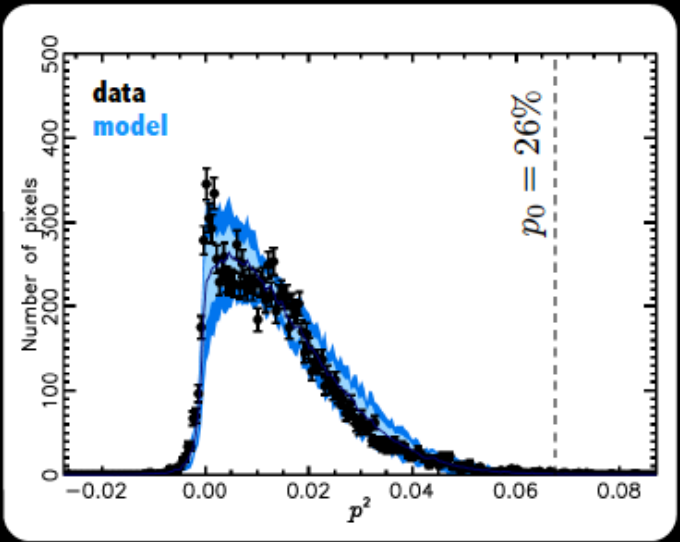


[Planck int. res. XLIV. arXiv:1604.01029]

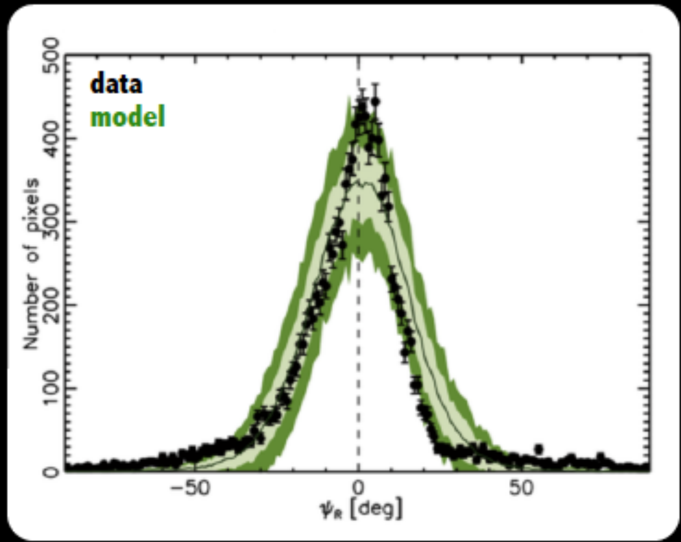
Model parameters constrained by data fitting: large scale patterns in Q and U maps, 1-point statistics of p and ψ, and power spectra

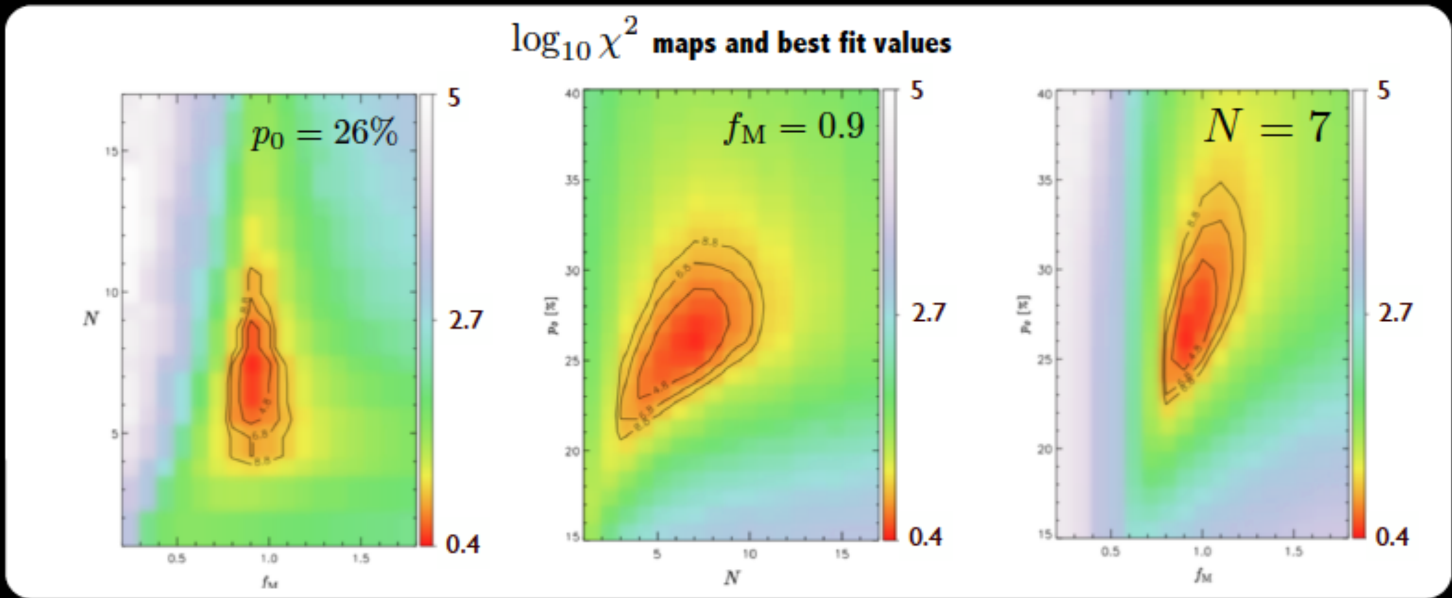
Dust polarization statistics

Polarization fraction



Polarization angle



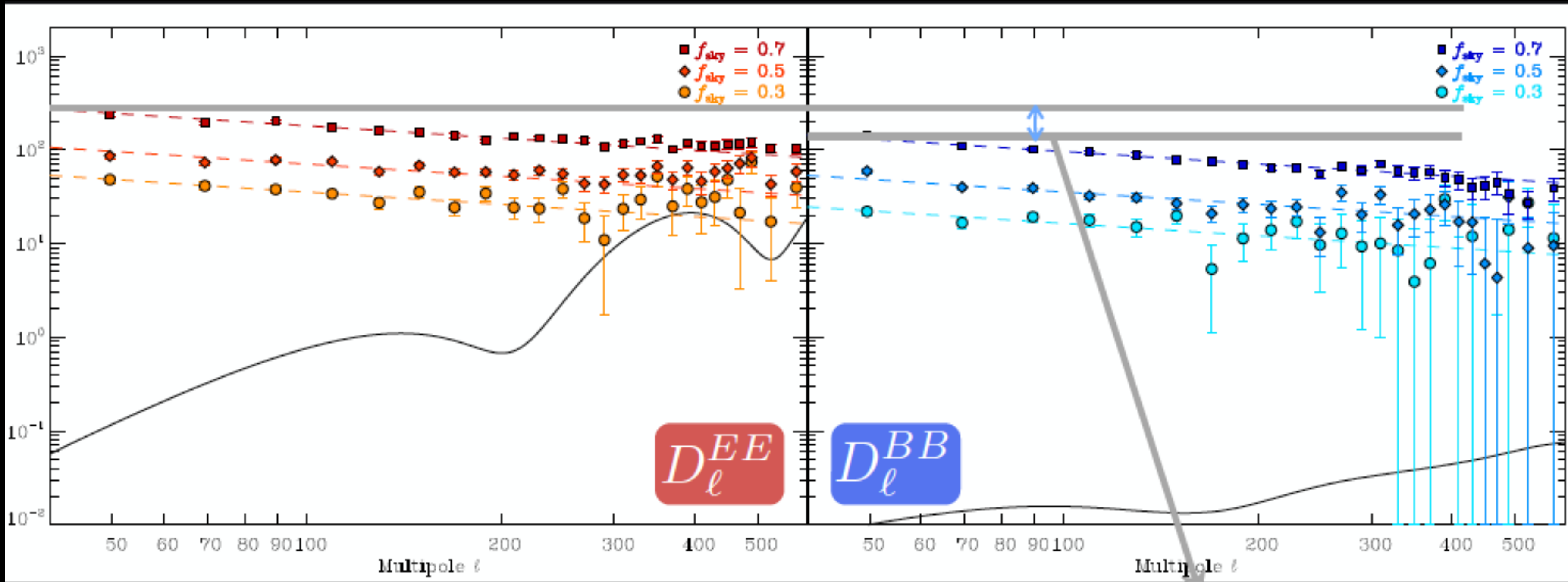


- High dust polarization fraction (p_0=0.26)
- Turbulence is sub/trans-Alvenic (f_M ~0.9)
- Small number of structures/turbulent cells along the line of sight

[Planck int. res. XLIV. arXiv:1604.01029]

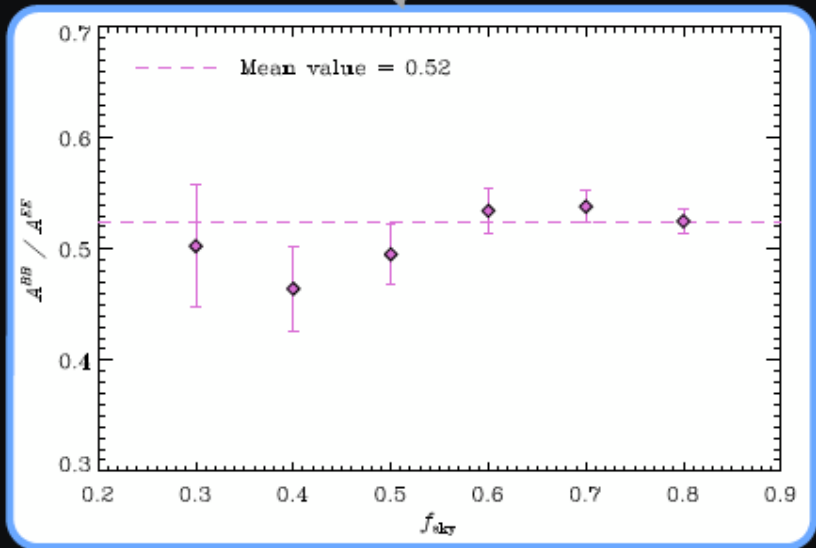
Power spectra of dust polarization

Gradient-like E modes | Curl-like B modes



[Planck Intermediate 2014 XXX]
[Planck Intermediate 2014 XXXVIII]

- ★ Dust polarization spectra follow power-laws of ℓ with a -2.42 slope
- ★ Spectra scale as a function of the mean intensity of the mask ($<I_{dust}>^{1.9}$)
- ★ *BB/EE* ~ 0.5
- ★ $TE/(EE*TT)^{0.5}$ ~ 0.35



Modeling of power spectra

The exponent of power spectra is that of the magnetic field orientation

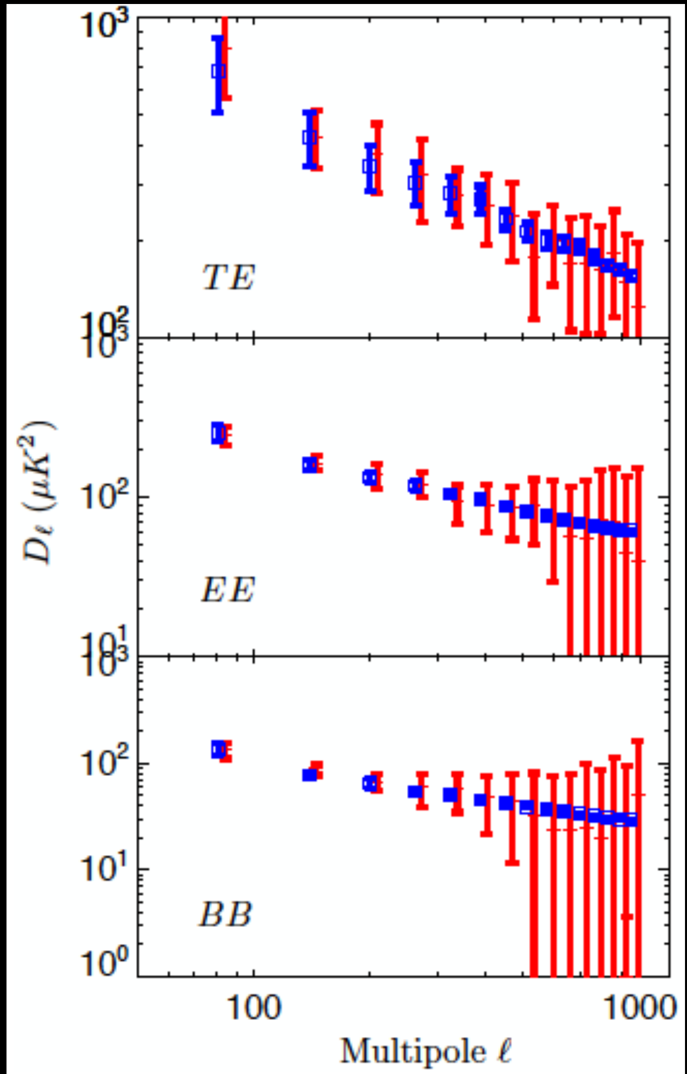
Alignment of magnetic field and filamentary structures accounts for both the TE correlation and E/B asymmetry

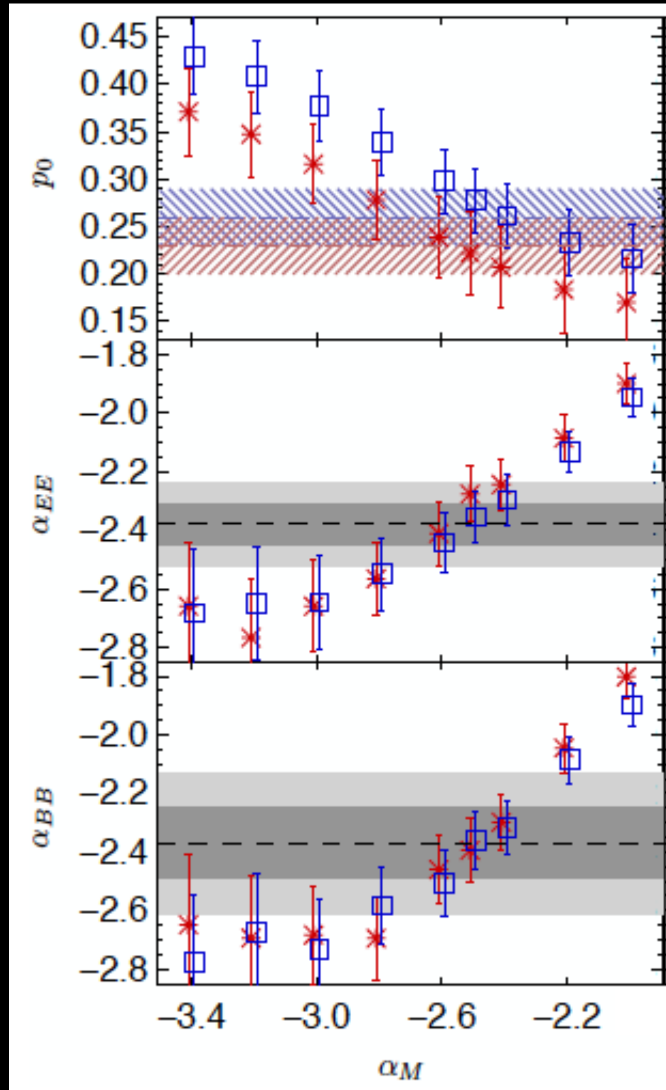
Planck int. res. XXXVII, A&A 2016 586, 141

Vansyngel+ 2016, arXiv: 1611.02577

Ghosh+16: arXiv:1611.02418

Magnetic Field power spectrum

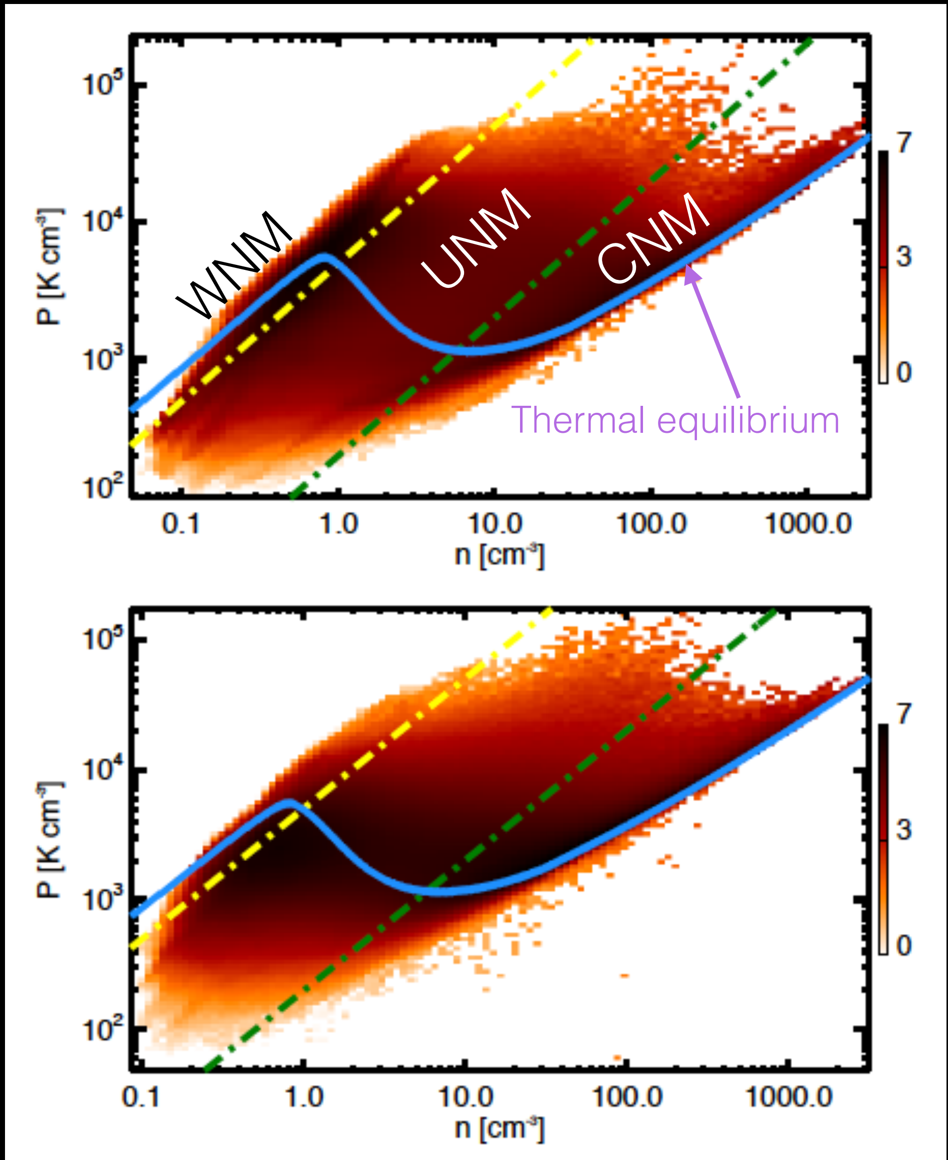




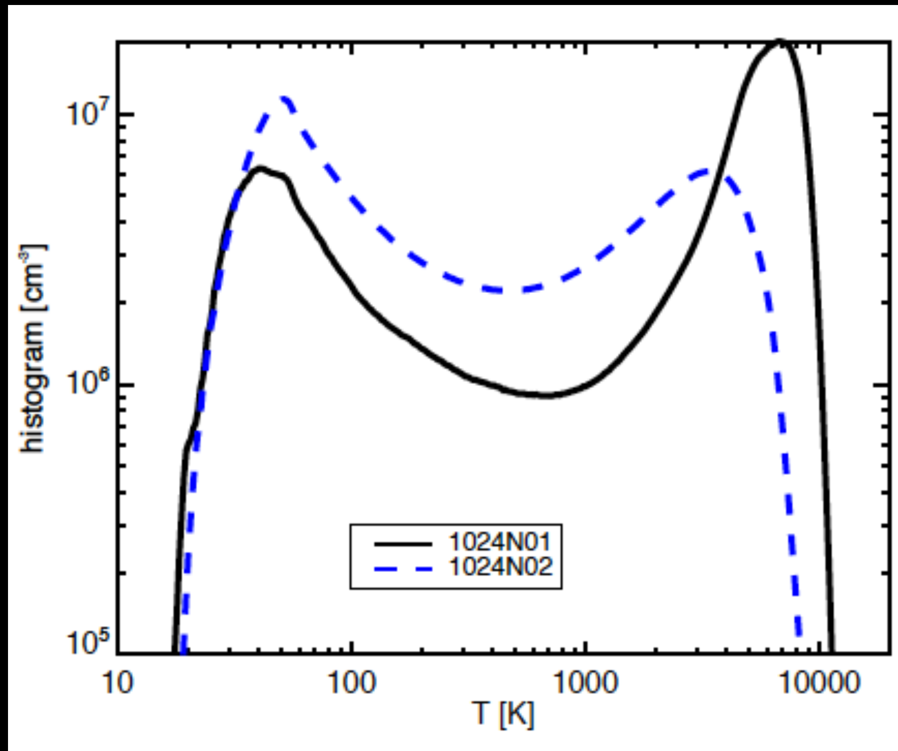
Vansyngel+ 2016, arXiv:1611.02577

The slopes of power-spectra are matched for a magnetic field power spectrum index α_M = -2.5

Two hydro simulations with distinct initial conditions



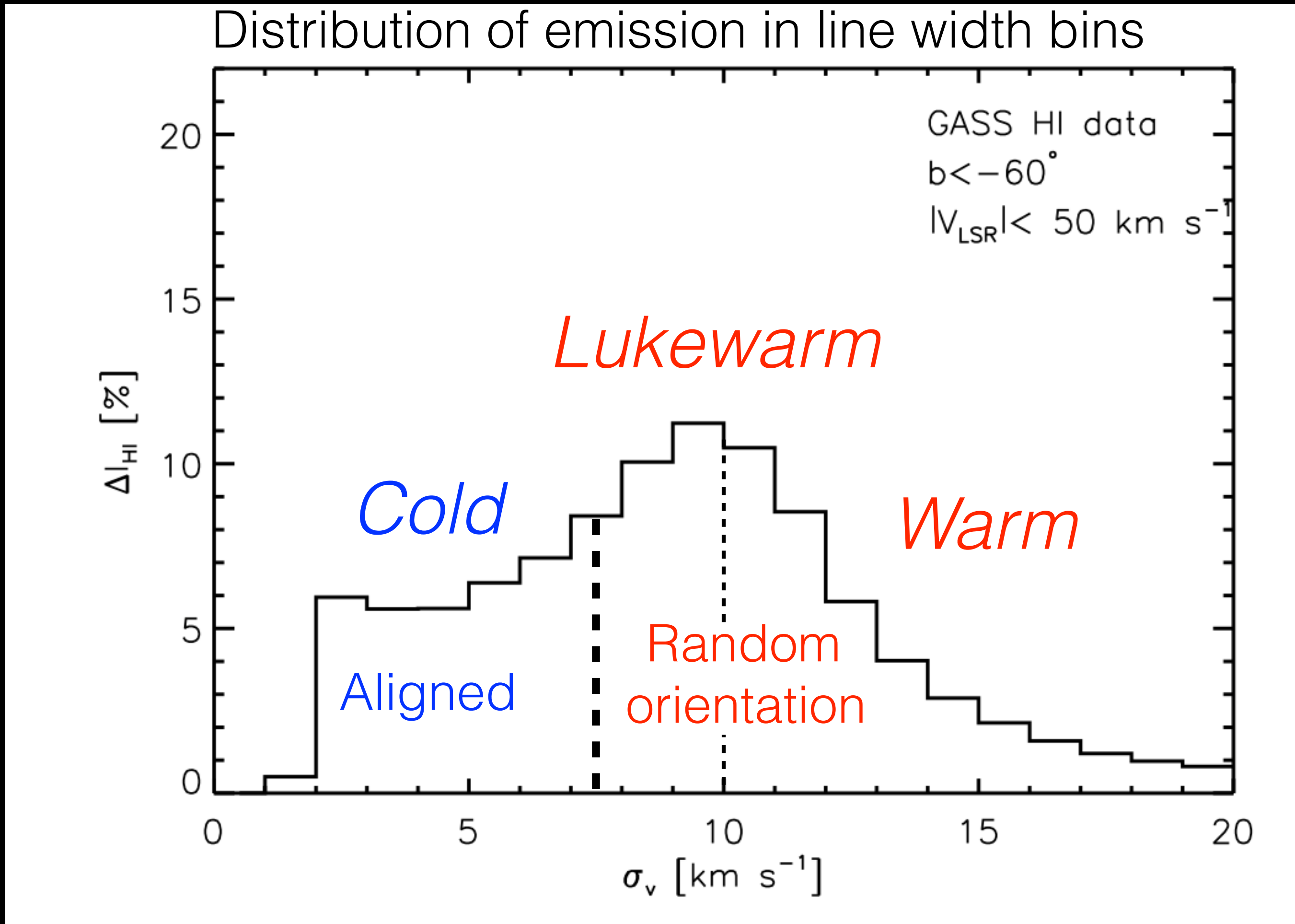
The presence of a significant gas fraction at intermediate temperatures between the two stable cold and warm phases testify of the **dynamical** nature of the **diffuse ISM structure** with **$t_{dyn} \sim t_{cool}$ (WNM, a few 10^6 yrs)**

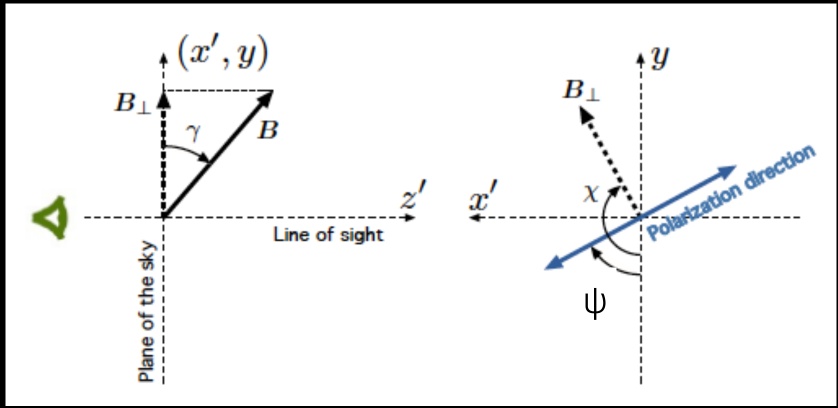


Saury+14

Gaussian decomposition of HI spectra (Haud & Kalberla 07) used to produce to sky maps of ISM *phases*

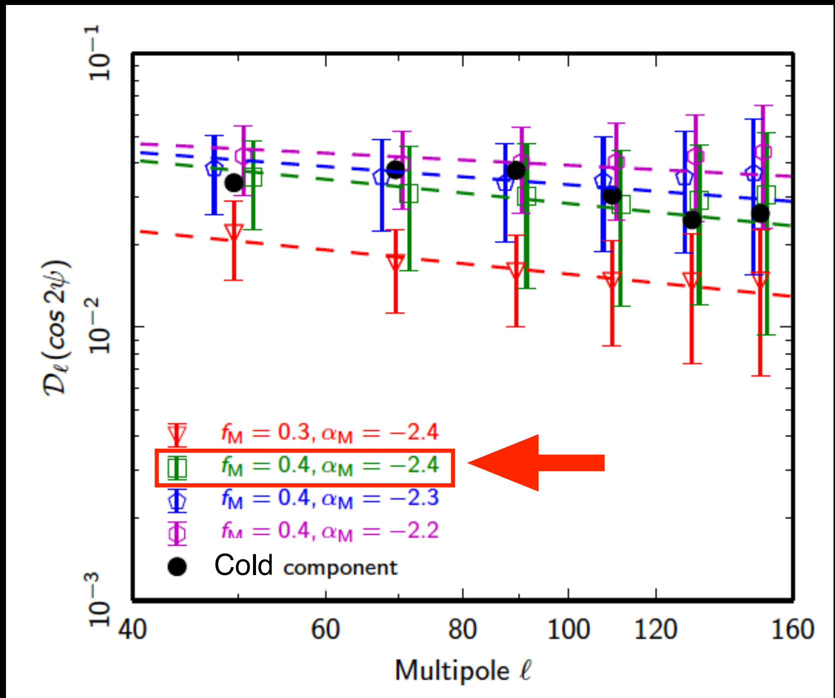
Ghosh+16: arXiv:1611.02418



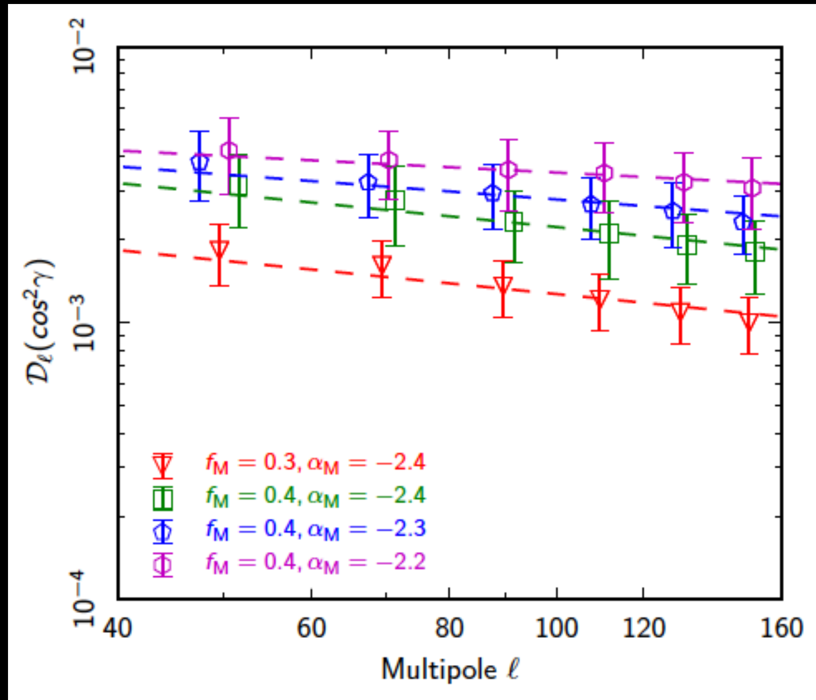


The anisotropy of HI filamentary structures matches the spectral exponent of dust polarization power spectra

HI Cold map



Gaussian simulation



Ghosh + 2016

Summary

Planck data has allowed us to carry out the first statistical study of dust polarization providing new insight into the structure of Galactic magnetic fields and their interplay with matter

- ★ Planck dust polarization maps reveal the imprint of interstellar magnetic fields on matter on scales (0.5-100 pc) relevant to the formation of the ISM filamentary structure.
- ★ Spectral exponent of magnetic field power spectrum is -2.5 +/- 0.1. This value is larger than the -11/3 Kolmogorov value.
- ★ The spectral exponent reflects the correlation between magnetic field and the filamentary structure of the cold neutral medium
- ★ Interstellar turbulence is sub/trans-Alfvenic in all models ($f_M < 1$)