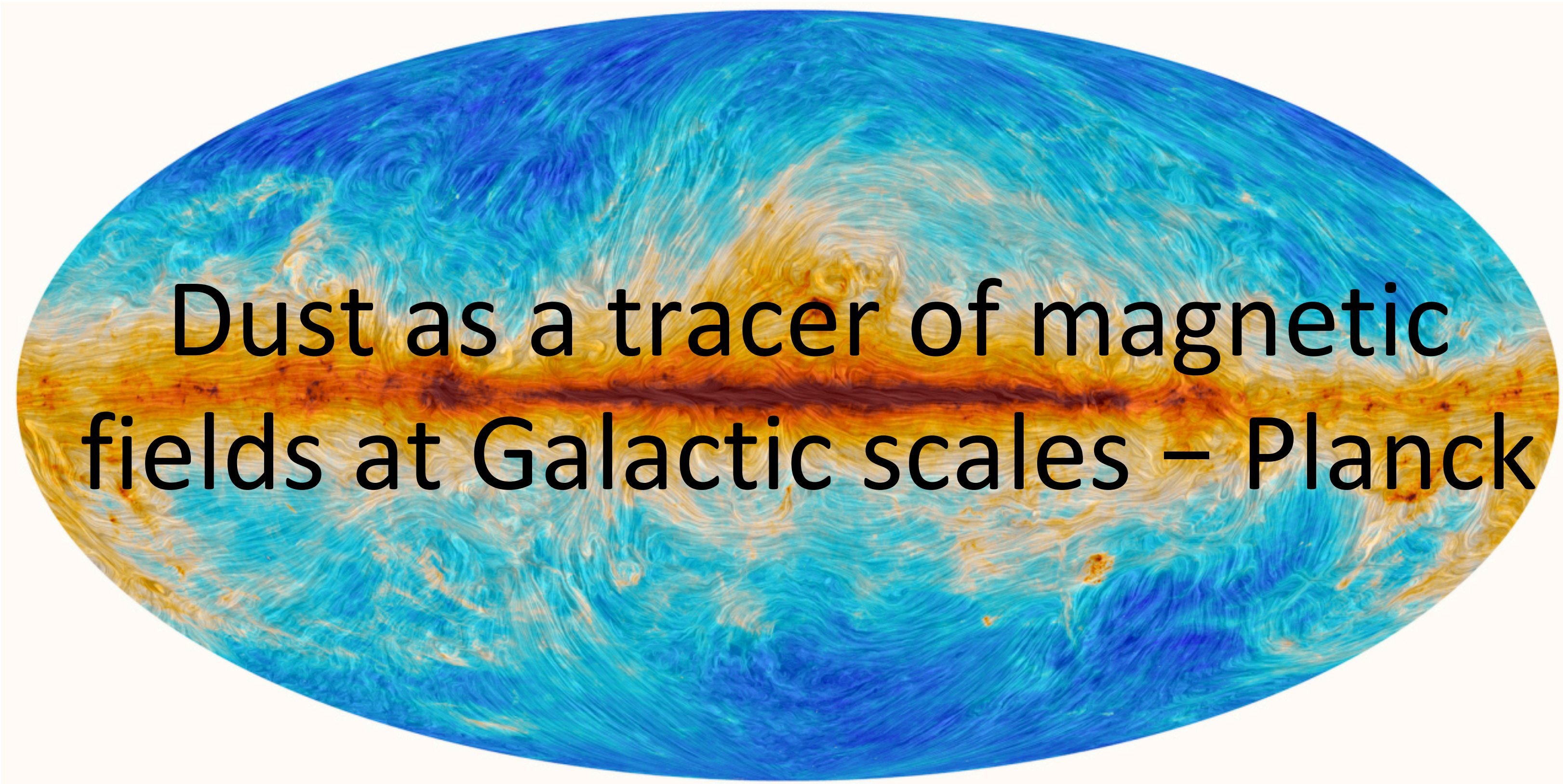

Dust as a tracer of magnetic fields at Galactic scales – Planck

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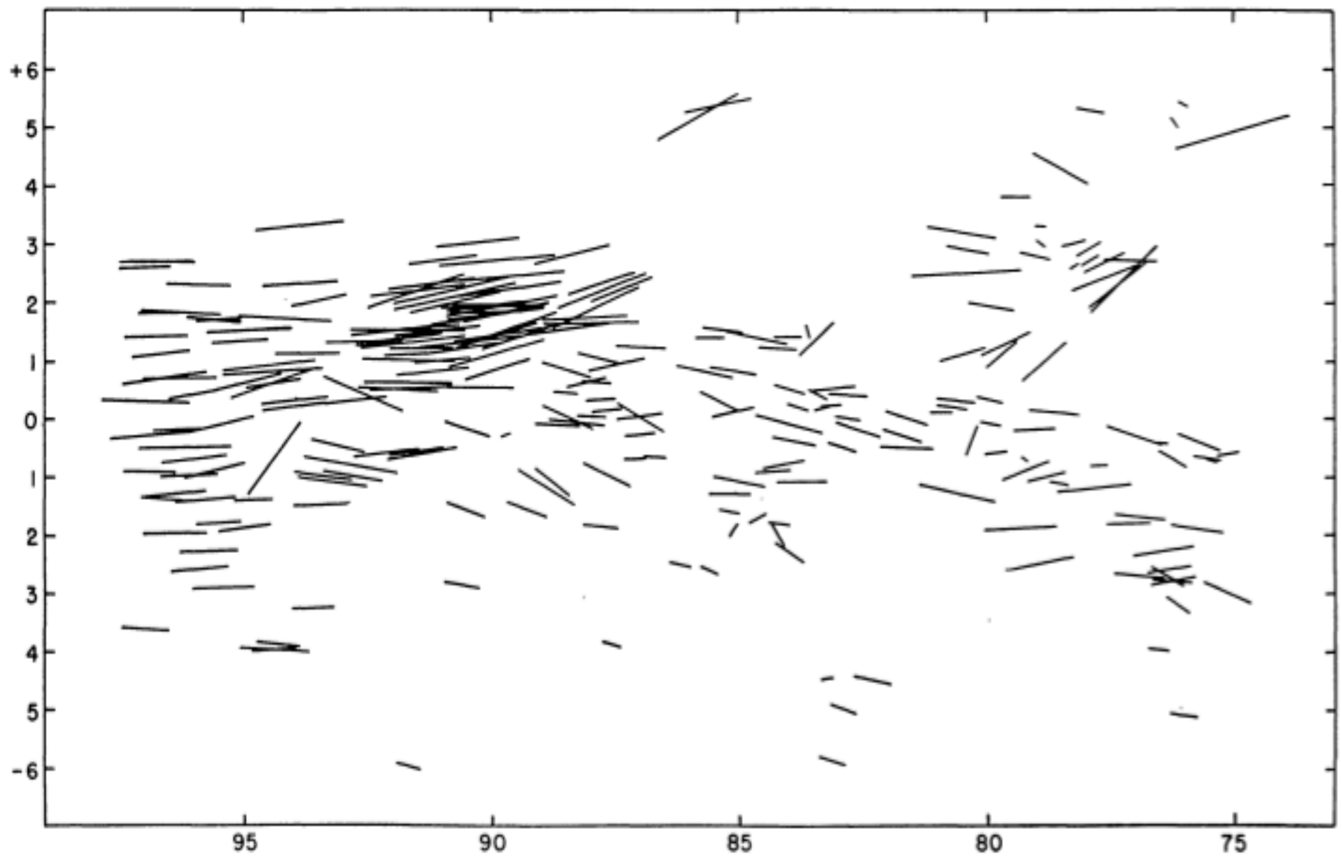
Outline

1. Starlight polarization
    a) Observations
    b) Interpretation
2. Grain alignment theories
    a) Disalignment by collisions with gas particles
    b) Alignment by magnetic torques
    c) Stabilisation by H_2 torques
    d) Alignment by Radiative Torques (RATs)
    e) Alignment by Mechanical Torques (MATs)
3. Planck results on Galactic polarization
    a) Handle polarization data
    b) Statistical properties of polarization angles
    c) Maximal polarization fraction
    d) Testing RAT theory

1. Starlight polarization : a) observations

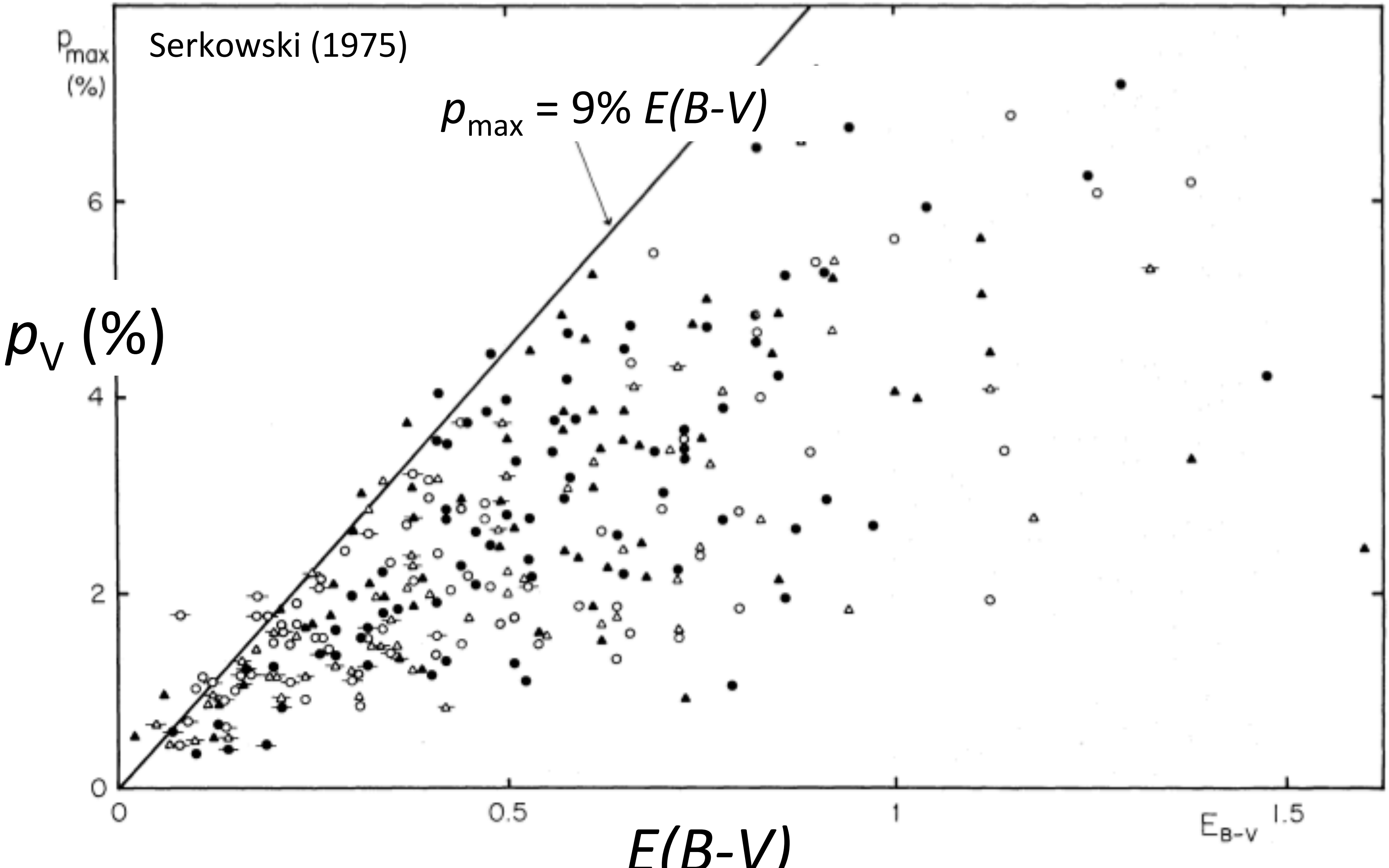
First observations of starlight polarization (Hiltner, 1949) : up to 15% ! How?



Galactic longitude

What does the polarization direction trace ?

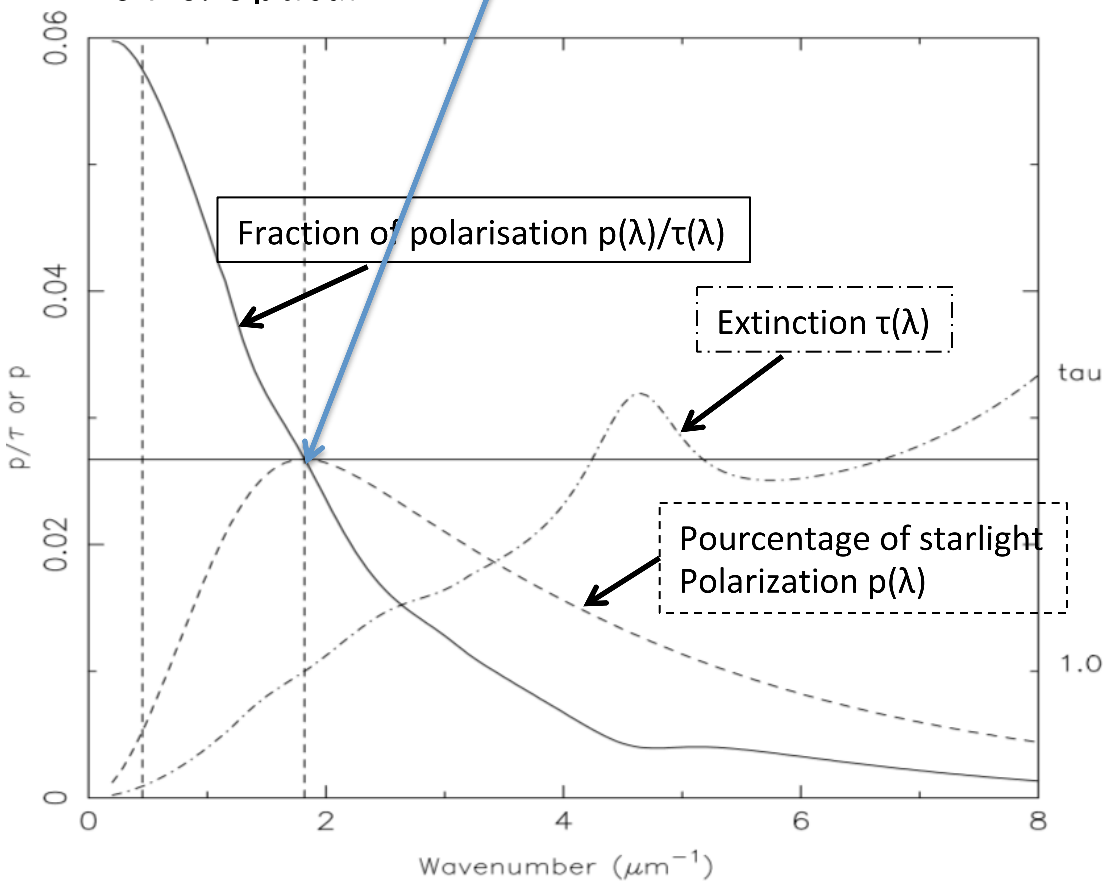
1. Starlight polarization : a) observations



1. Starlight polarization : a) observations

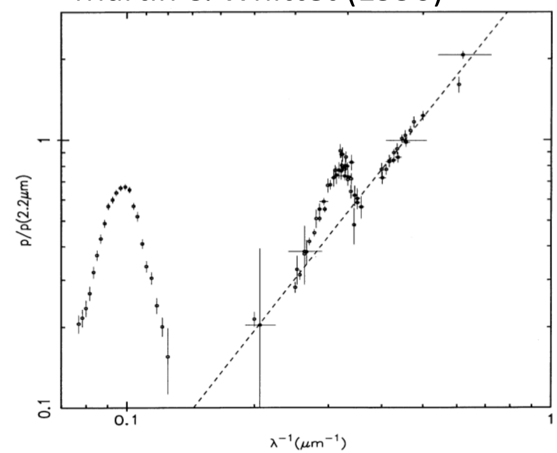
peak of polarization: λ_{max}

UV & Optical

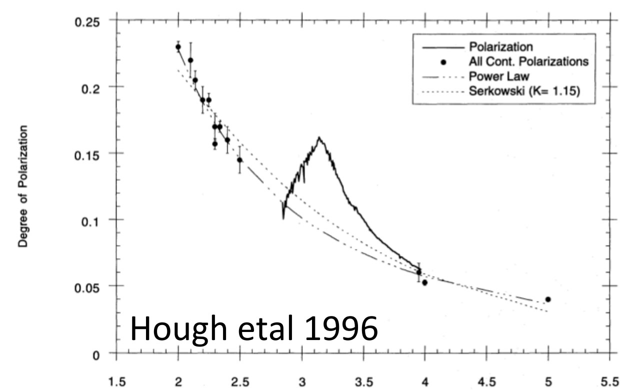


NIR bands

Martin & Whittet (1990)



1/λ (μm^{-1})

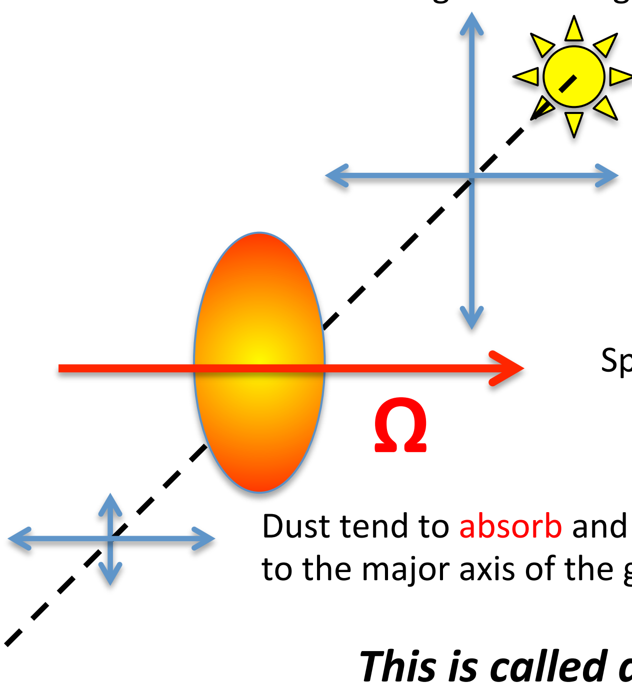


λ (μm)

1. Starlight polarization : b) interpretation

Grains are not spherical : the most simple non-spherical shape is a spheroid

Oscillating electric field **E** of the incoming electromagnetic wave



Spinning grain.

Dust tend to absorb and scatter more efficiently when **E** is parallel to the major axis of the grain than when it is parallel to the minor axis.

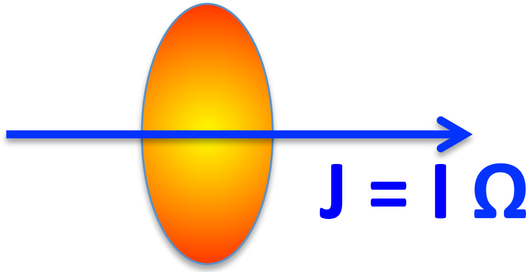
This is called dichroïc extinction

We detect a polarization parallel to the grain minor axis, i.e. parallel to the spin axis.
The polarization percentage increases with the column density of dust, i.e. with E(B-V).

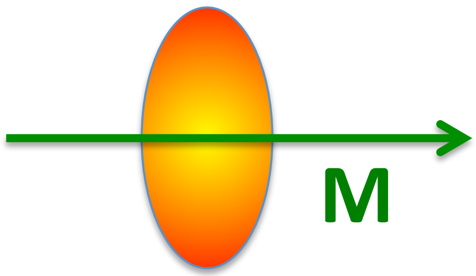
1. Starlight polarization : b) interpretation

Dust grains are **magnetic spinning tops**.

1. Dust grains rotate fast: e.g. T = 100 K => $f_{thermal} = \mathbf{\Omega}/2\pi$ ~ MHz for a = 0.1 µm.
2. Grains possess an axis of minimum inertia of moment **I**: they tend to rotate around that axis, with an angular momentum **J = I Ω**



3. Grain rotation magnetize the magnetic grain (« Barnett » effect, 1916) **even in the absence of an external magnetic field**. The magnetization **M** (magnetic moment per unit volume) is directed along the spin axis.



$$M = \chi\Omega/\gamma$$

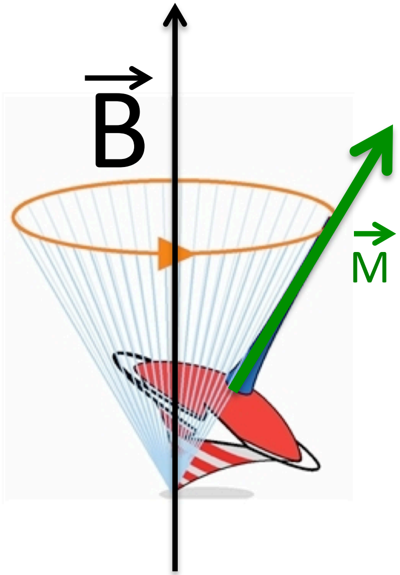
γ is the ratio of magnetic moment
to angular momentum for electrons.

Barnett effect: the rotational energy can be reduced while conserving the total angular momentum (rotation + spins) if there is a transfer from angular momentum to spins. This has an energy cost that depends on the system temperature and the energetic cost of a spin flip (Purcell 1979).

1. Starlight polarization : b) interpretation

Grain spinning dynamics is that of **gyroscopes**.

4. In the presence of an interstellar magnetic field **B**, the grain magnetization **M** produces a torque **Γ** that causes the precession (**J**'s arrow describes a circle) of the grain spin axis around the magnetic field lines.



5. To polarize starlight, the grain spin axis must be relatively stable. *Some* friction torque must rapidly (τ < 1 Myr) align interstellar grains so that grain spin axis progressively becomes aligned with the magnetic field.

To explain starlight polarization, one must find mechanisms that can align the grain spin axis on the magnetic field lines.

1. Starlight polarization : b) interpretation

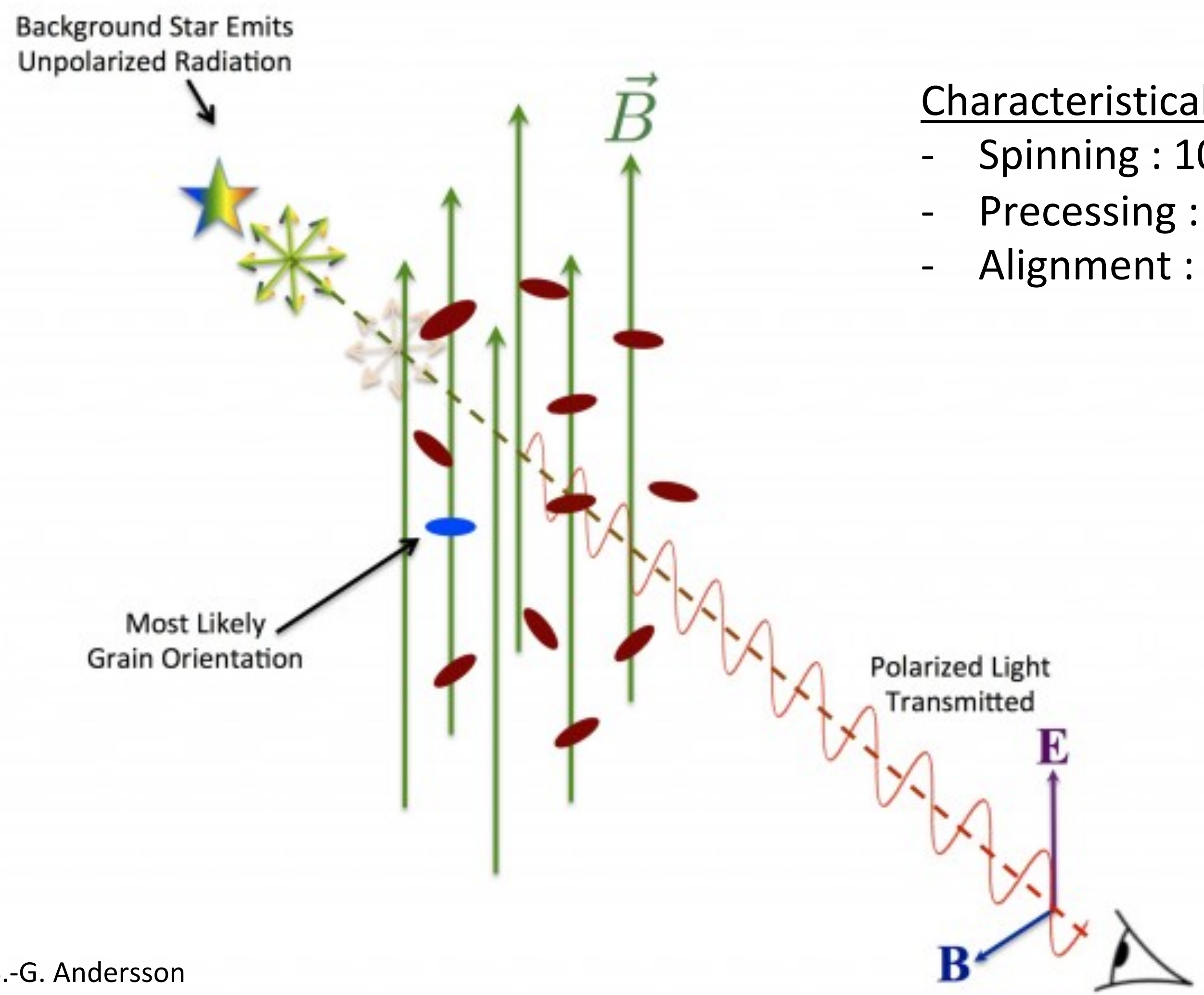
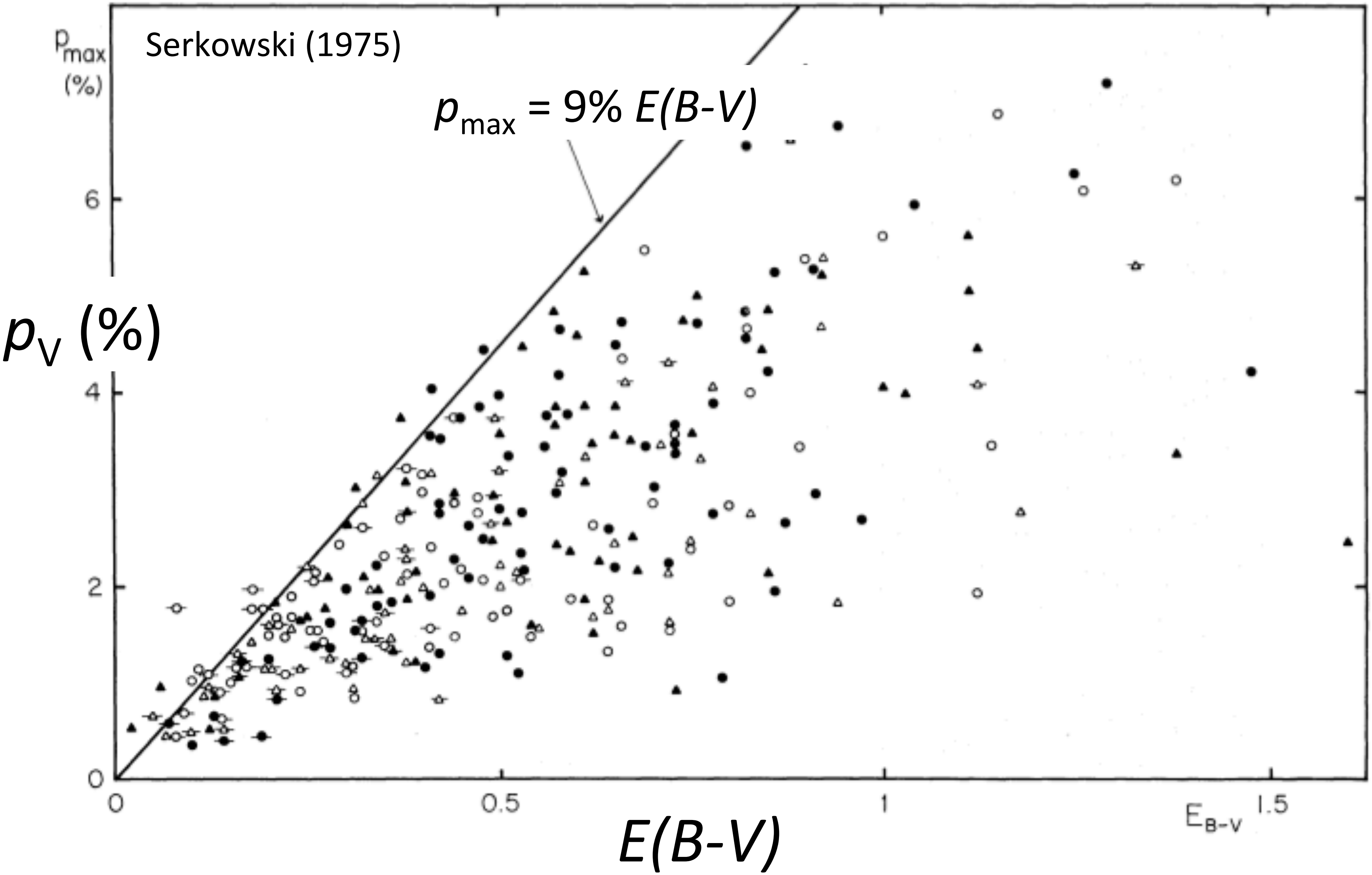


Image credit: B.-G. Andersson

Characteristical timescales

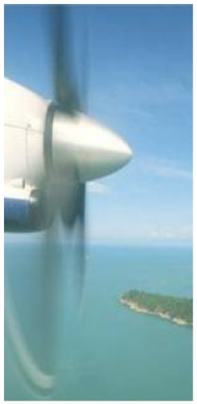
- Spinning : 10^{-8} s
- Precessing : 1 yr
- Alignment : < 10^{5-6} yr

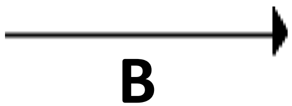
1. Starlight polarization : b) interpretation



1. Starlight polarization : b) interpretation

Orientation effects





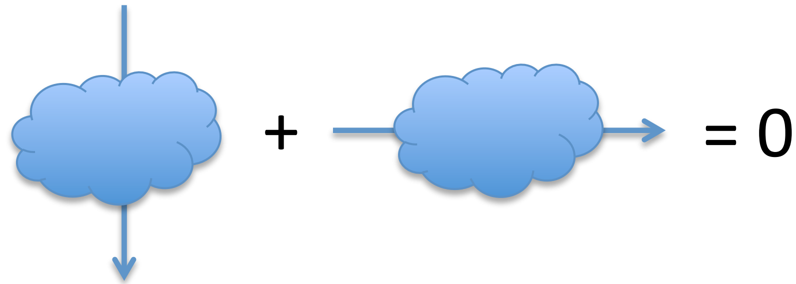
Polarization fraction is maximal

⊙

B

No polarization observed

Line of sight integration effects



1. Line of sight integration differs from Intensity

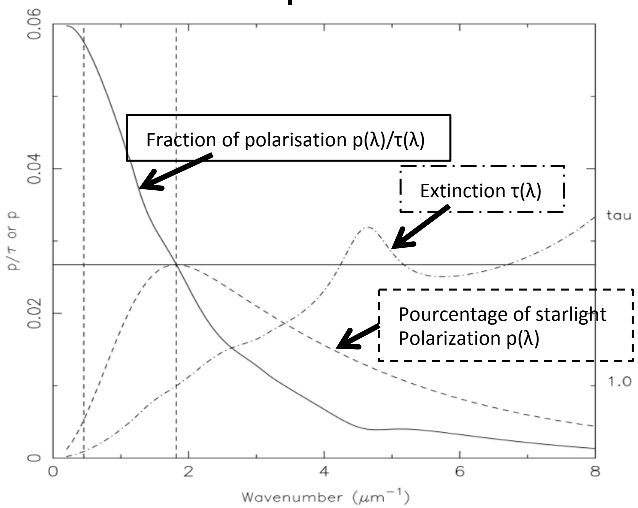
The magnetic field orientation must be coherent on large scales to observe dust polarization.

2. The polarization percentage per unit reddening can not exceed a certain value : $p/E(B\text{-}V) \leq 9\%$.

This maximal value is observed when the magnetic field is uniform and in the plane of the sky.

1. Starlight polarization : b) interpretation

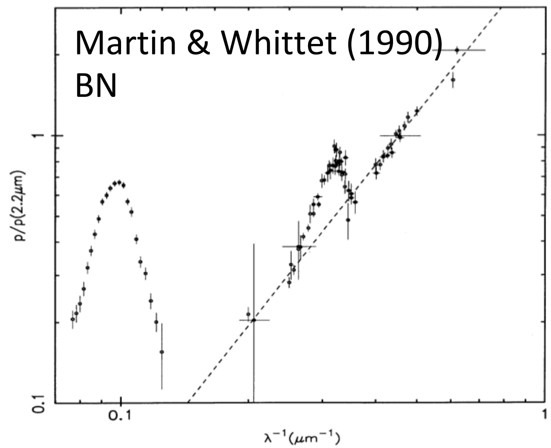
UV & Optical



1/λ (μm^{-1})

Small grains are not aligned
Large grains (0.1 μm) are aligned

NIR bands

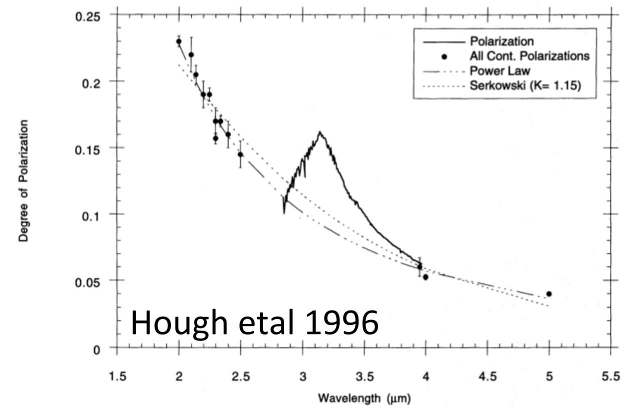


1/λ (μm^{-1})

9.7 μm band polarized : silicate grains (paramagnetic) are aligned

Not clear if carbon grains (diamagnetic) are aligned (3.4 μm aliphatic band very weak if not zero, Chiar+2006)

H_2O ice line polarized
=> Grains still aligned at $A_v > 3$



CO (4.67 μm) ice line polarized

Grains are aligned even deep in dense clouds.

2. Grain alignment theories : a) gas bombardment

Random bombardment of gas surface by atoms and molecules tend to suppress grain alignment.

<u>This effect is stronger as the density increases.</u>

Any theory of grain alignment will first need to explain why the proposed alignment mechanism is more efficient than the desalignment by gas collisions, at any given density.

NB: For most of grain alignment theories, we should expect grain alignment to drop as the density increases, unless the efficiency of the alignment increases with the density (at least as fast as disalignment does)

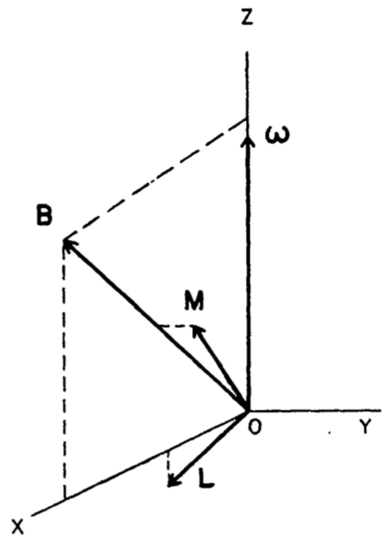
2. Grain alignment theories : b) alignment by magnetic torques

Davis & Greenstein (1951) : alignment of grains by paramagnetic absorption

➔ a kind of friction that delays the alignment of atomic magnetic dipoles (spins) by an applied B-field.

The magnetization **M** follows **B** with a delay being dragged by grain rotation, and is therefore not aligned with **B.**
The component of **M** perpendicular to **B** is

$$\boldsymbol{M} = \chi''\omega^{-1}(\boldsymbol{\omega} \times \boldsymbol{B})$$



where χ’’ is the imaginary part of the complex magnetic susceptibility. If 1/100 of atoms is iron (large magnetic moment), the material becomes paramagnetic

$$\chi'' = 2.5 \times 10^{-12}\,\frac{\omega}{T_g}$$

The magnetic moment is V**M** where V is the volume of the grain
The magnetic torque on this magnetic dipole is :

$$\boldsymbol{L} = V\boldsymbol{M} \times \boldsymbol{B} = V\chi''\omega^{-1}(\boldsymbol{\omega} \times \boldsymbol{B}) \times \boldsymbol{B}$$

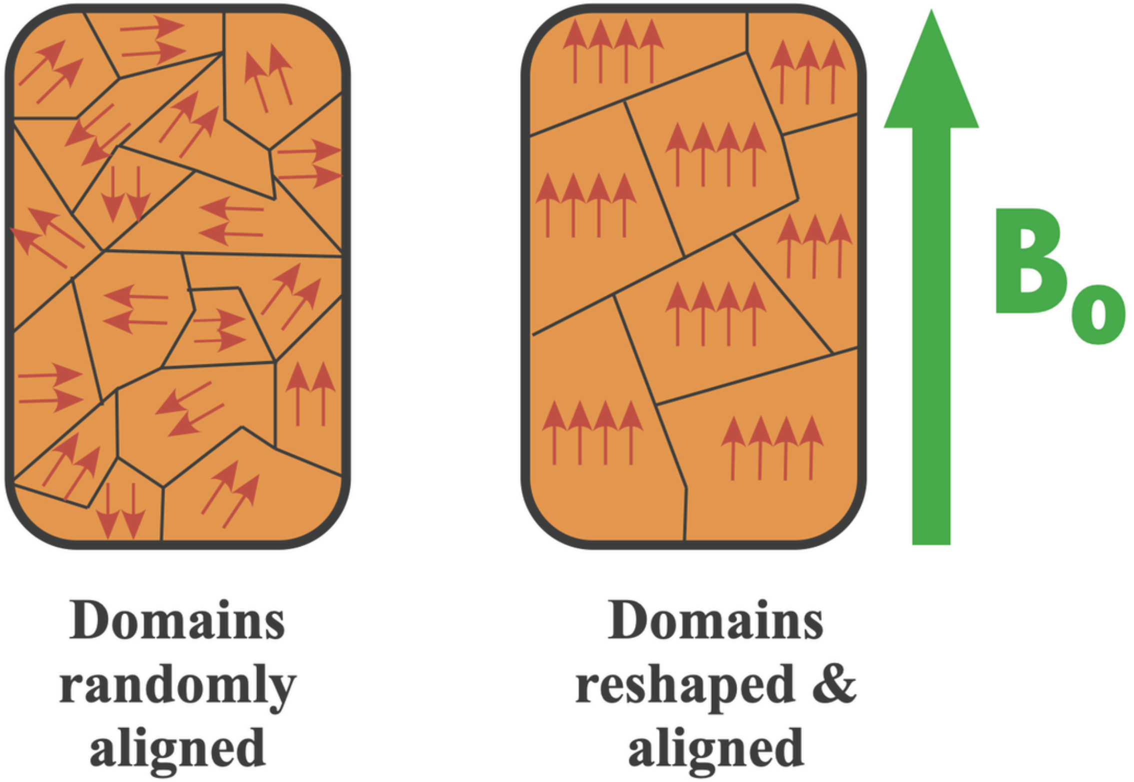
This torque tends to align the grain spin axis on **B** on $\tau \sim 10^{13}$ s ~ **1 Myr : a slow process (NB : τ ~ 1/χ’’).**

Till now, collisions of the grain with gas particles (which tend to randomize the grain orientation) were ignored. Including gas bombarment, the B-field needed to reproduce the level of grain alignment is 10-100 µG, much higher than the one observed.

➔ the historical classical theory of paramagnetic alignment can not explain the level observed of starlight polarization (p/E(B-V) up to 9%).

2. Grain alignment theories : b) alignment by magnetic torques

<u>**Jones & Spitzer (1967)**</u> : super-paramagnetic materials (paramagnetic grains with ferromagnetic domains)



➔ increase the value of χ'' by orders of magnitude.

2. Grain alignment theories : c) stabilisation by H_2 torques

Purcell (1979) : H_2 formation (releases 4.5 eV) on the surface of grains can stochastically accelerate grain rotation to suprathermal velocities, thereby stabilizing it (gyroscope effect) against disaligning effect of gas bombardment.

➔ rocket effect

H_2 formation sites on the grain surface:

- If they are randomly spread on the grain surface, the mean torque is <**L**> = 0, and we get a random walk acceleration to an effective temperature $T_{eff}(H_2) > T$.
- If they are not purely random (as one expecte from surface irregularities), <**L**> ≠ 0, and the grain can reach very high suprathermal rotational temperature. Grain alignment becomes perfect : the spin axis remains along **B.**

➔ the grain behaves like a heat engine, extracting work from two reservoirs at different temperatures (gas & dust).

Limit: What will happen if the position of H_2 formation sites slowly evolve with time ? This could occasionnaly decrease grain rotation and invert it (« cross-overs » : Spitzer & McGlynn 1979). How often does this happen ?

Other consequence : suprathermal rotation could prevent grain from forming aggregates, through its centrifugal disruption (see also Hoang+2021).

2. Grain alignment theories : d) alignment by radiative torques

The alignment mechanism does not have to be magnetic to align grains along B !

- Draine & Weingartner 1996: photons can spin up grains to suprathermal rotation
- Draine & Weingartner 1997: photons can align grains spin axis with the magnetic field.
- Lazarian & Hoang 2007 : analytical model for radiative torques (RATs).
- Hoang & Lazarian 2016: unified model for grains with ferromagnetic inclusions

In the radiative torques theory:

- The radiative source must be at least partially anisotropic.
- Grains, like windmills are spin-up and aligned by radiative torques
- Grains are well aligned if they rotate suprathermally
- Photons of wavelength λ better align grains of size $a \sim \lambda$

Success of the RATs theory (which has now become the reference theory)

- RATs can align superparamagnetic (Hoang & Lazarian 2016) but also paramagnetic grains (Herranen+2021)
- Larger grains are better aligned by RATs than smaller grains, as observed.
- Large grains can be aligned by RATs deep in dense clouds owing to the penetration of IR photons.

The direction of alignement is predicted to be

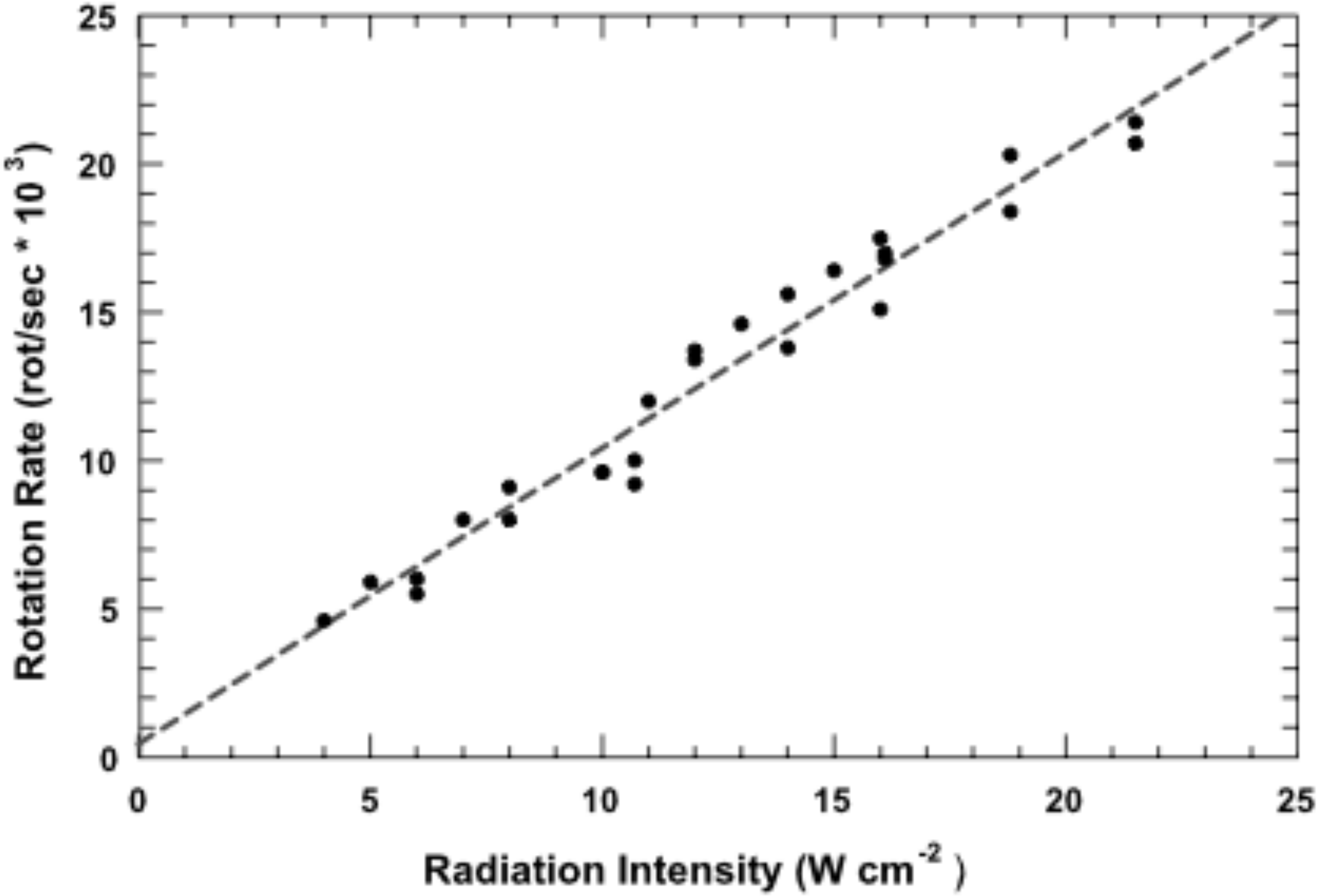
- Along the magnetic field lines if magnetic precession torque > radiative precession torque
- Along the radiation anisotropy if magnetic precession torque < radiative precession torque

Important prediction :

- grain alignment must increase with grain temperature.

2. Grain alignment theories : d) alignment by radiative torques

Laboratory study of grain spinning acceleration with a laser beam (Abbas+2004).



2. Grain alignment theories : e) alignment by mechanical torques

Gold (1952) had presented the possibily of alignment by & along supersonic flows. Never clearly observed.

Hoang, Cho & Lazarian (2018) : an approach similar to RATs has been developed with mechanical torques (MATs) generated by **anisotropic** gas bombardment. Unlike in Gold, this lead to alignment with **B**, as observed.

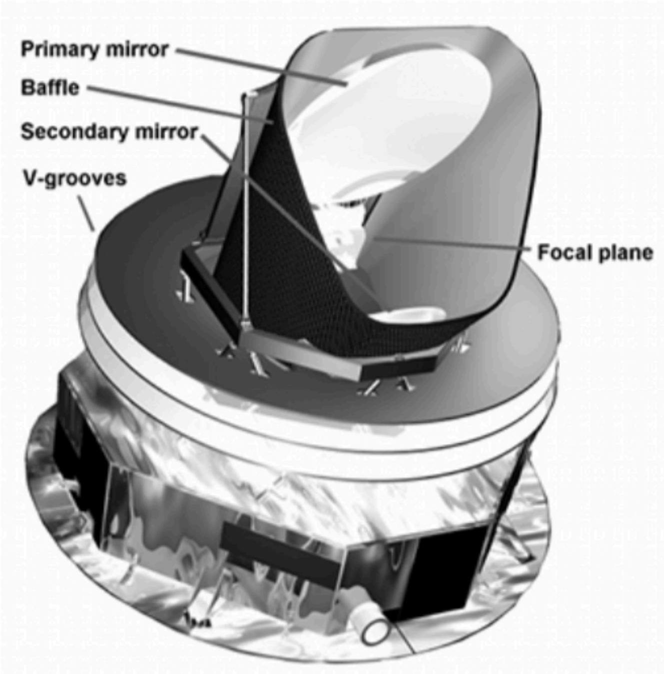
NB n°1: isotropic bombardment tend to disalign grains, anistropic bombardment can align them.

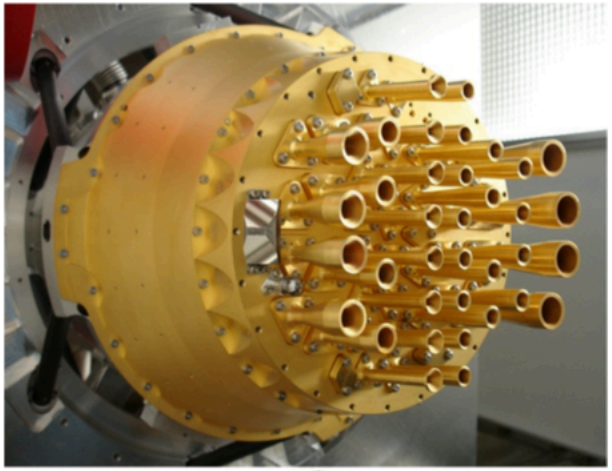
NB n°2: alignment by MATs should not depend on the gas density !

3. Planck results : a) Handle polarization data

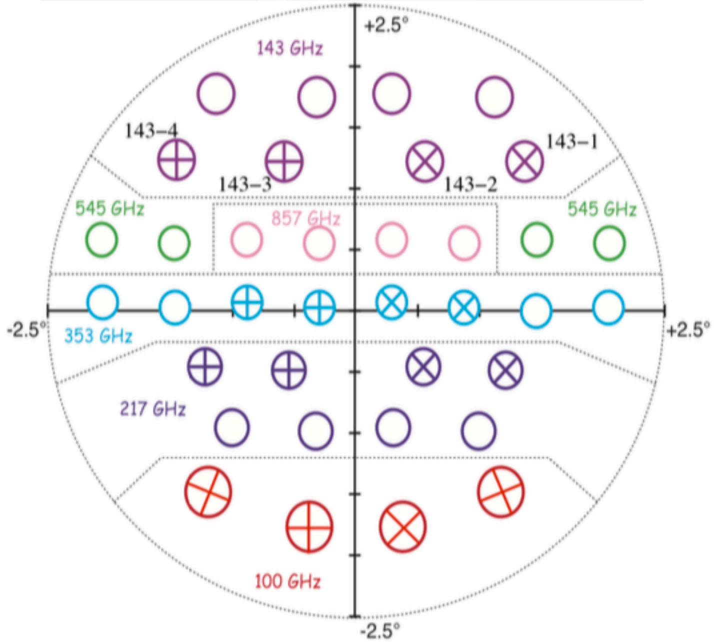
4 polarized channels : 353, 217, 143 & 100 GHz
2 PSB bolometers, rotated by 45°, x 2

Map making => 3 Stokes parameter maps : I, Q, U
+ 3x3 covariance matrix



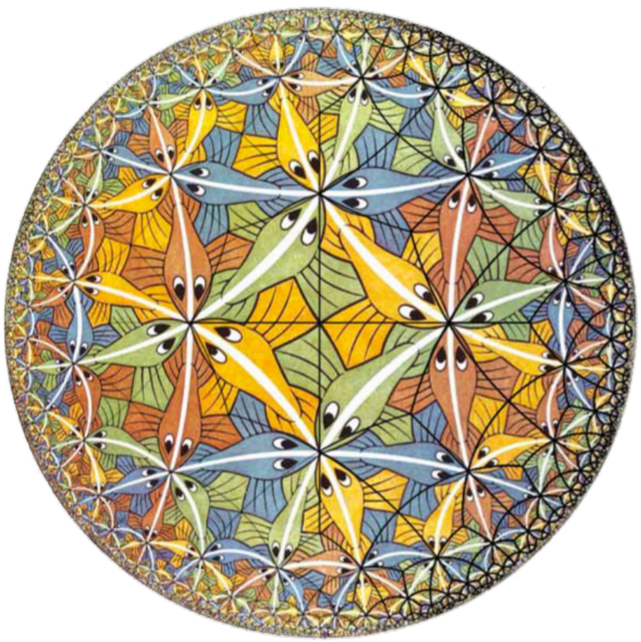


HFI
Focal
Plane



3. Planck results : a) Handle polarization data

What lies within the beam of a telescope observing dust polarized emission ?



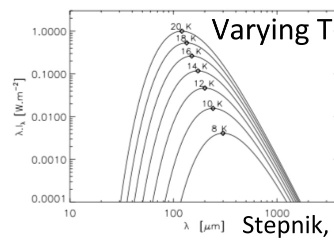
The observed polarized SED is a mix of all contributions within the beam.

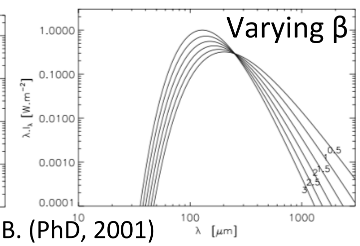
- Multiple components :
  - Line-of-sight integration (3D, Tassis 2015, Planck IR XLIV 2016)
  - Velocity integration (HI velocity, Clark & Hensley 2019)
  - ISM Phases integration (Ghosh+2017)

- Each component may be characterized by uniform properties
  - ***Dust physics***: modified blackbody (temperature T, spectral index β)

$$I_\nu = \tau_{\nu_0} B_\nu(T) \left(\frac{\nu}{\nu_0}\right)^\beta$$

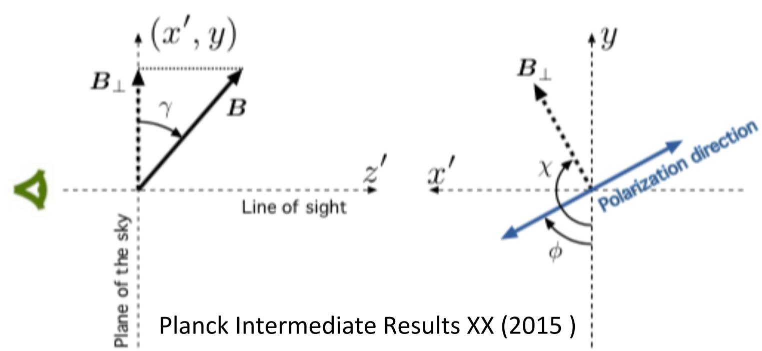
$$P_\nu = P_{\nu_0} \frac{B_\nu(T)}{B_{\nu_0}(T)} \left(\frac{\nu}{\nu_0}\right)^\beta$$





Stepnik, B. (PhD, 2001)

  - ***B-field geometry*** : Magnetic field properties (angles ψ and γ)



Planck Intermediate Results XX (2015)

3. Planck results : a) Handle polarization data

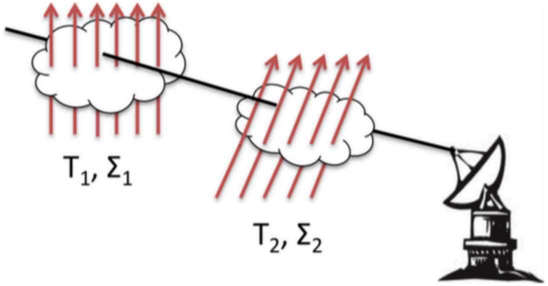
Effect of mixing the various dust polarized SEDs in the beam

1) Depolarization

A systematic decrease of the polarization fraction with the number of independent components present within the beam.

2) Decorrelation (of polarization angles) : $\psi = \psi(\nu)$

- If dust properties are homogeneous in the beam, we should observe no decorrelation
- **Tassis (2015)** : effect of a variation of dust temperature (and B-field) along the line of sight.

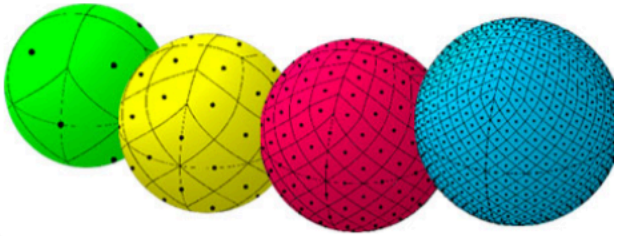


➔ We can not extrapolate the dust polarized SED

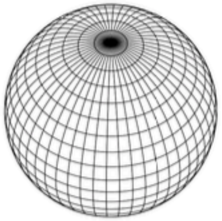
(⇔ we observe two distinct, distorted, SEDs in Q_ν and U_ν, which deviate from a MBB)

3. Planck results : a) Handle polarization data

- Stokes parameters I, Q, U, with associated 3x3 covariance matrix



- Healpix sphere mapping : resolution dependent



- Polarization angle : ψ = 0.5*atan(-U,Q),
  - measured in a local frame (parallel, meridian)
- Polarization intensity : $P = \sqrt{Q^2 + U^2}$
  - Noise-biased quantity

Simons & Stewart 1985

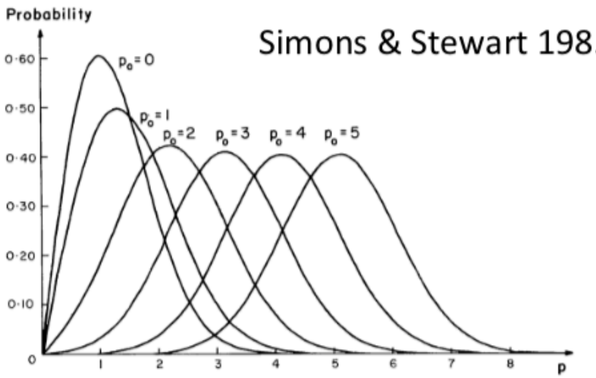
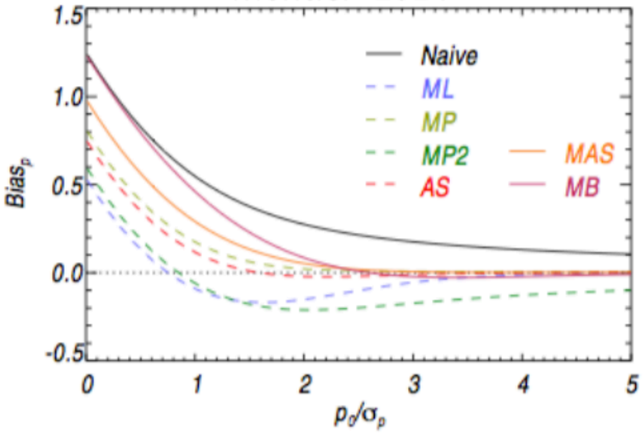


Fig. 1. The Rice distribution $F(p, p_0)$ as a function of p displayed for values of $p_0 = 1, 2, 3, 4$ and 5

Montier+2014

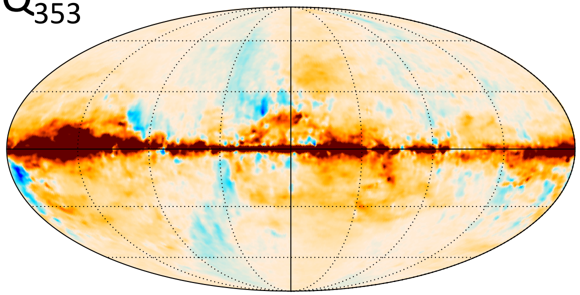


3. Planck results : a) Handle polarization data

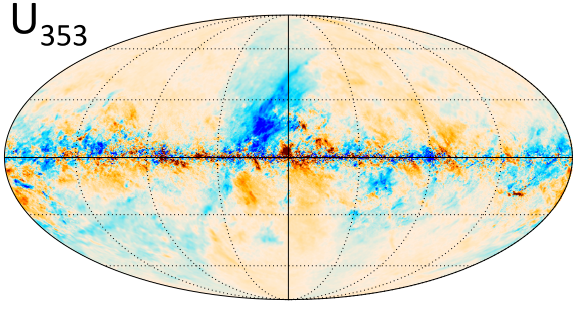
Planck full-sky maps

PR3-2018: http://pla.esac.esa.int/pla

Q_{353}



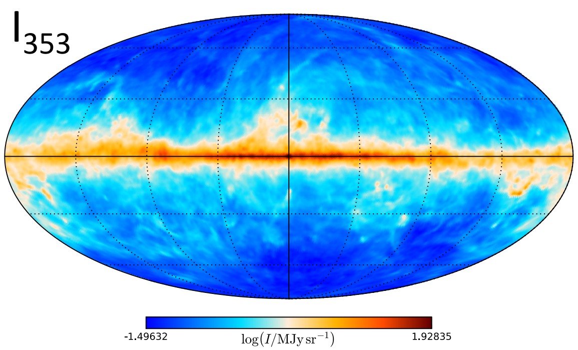
U_{353}



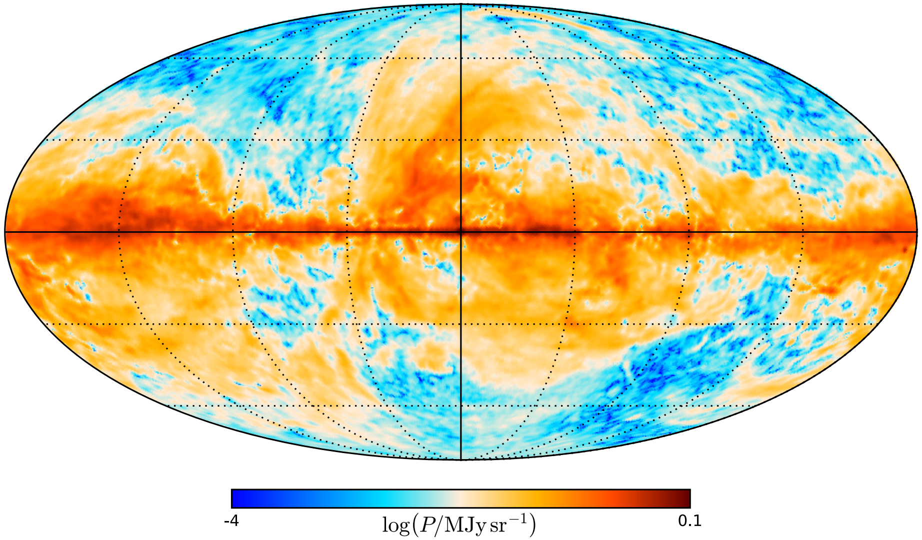
GNILC Intensity map

Generalized Internal Linear Combination (Remazeilles+2011)

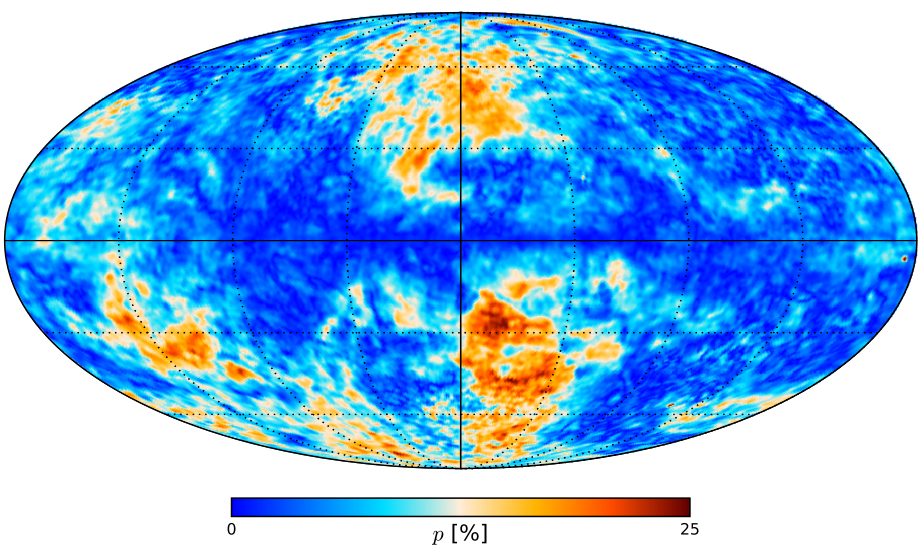
I_{353}



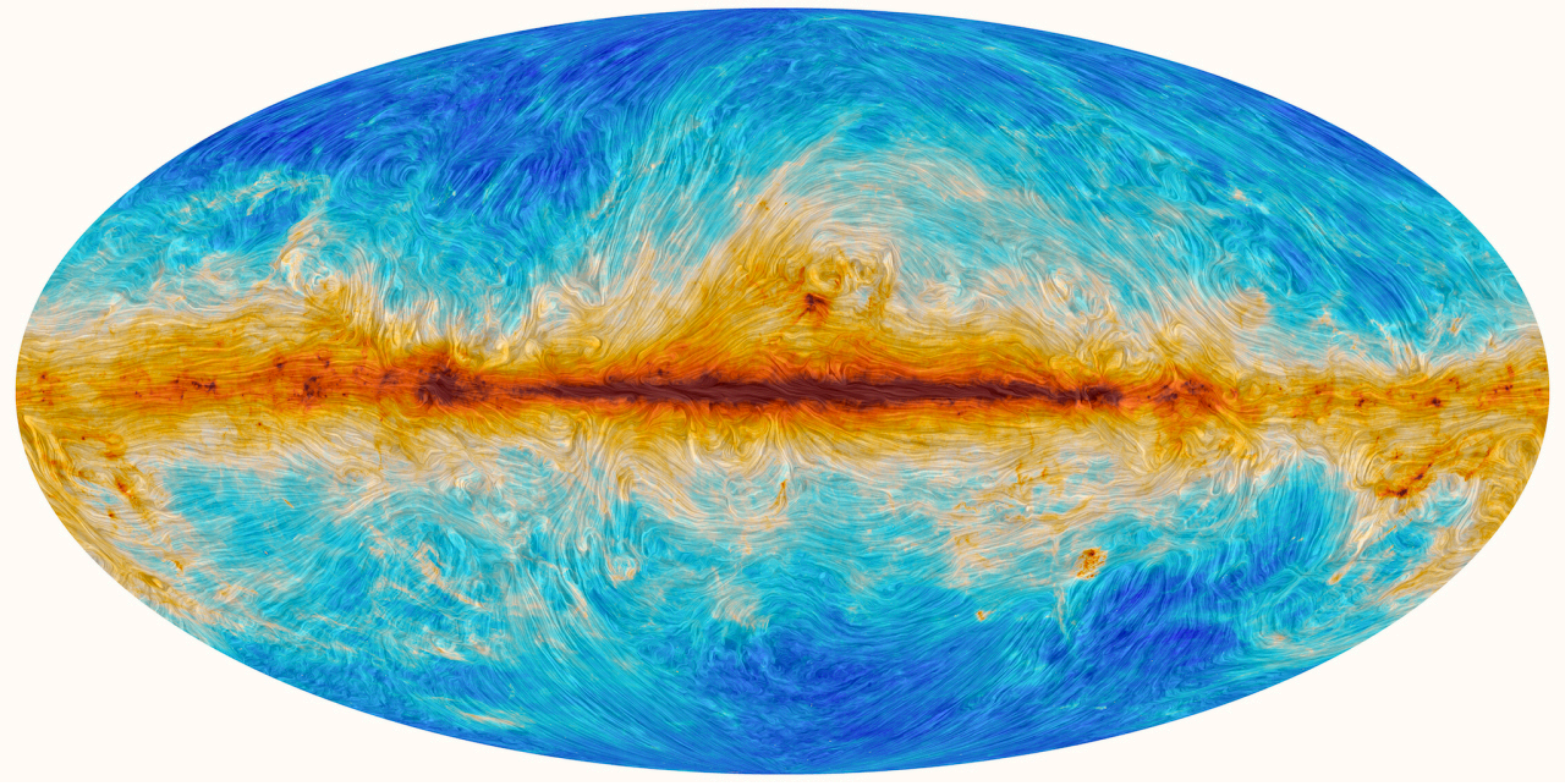
Polarized intensity P_{353}



Polarization fraction $p = P_{353}/I_{353}$



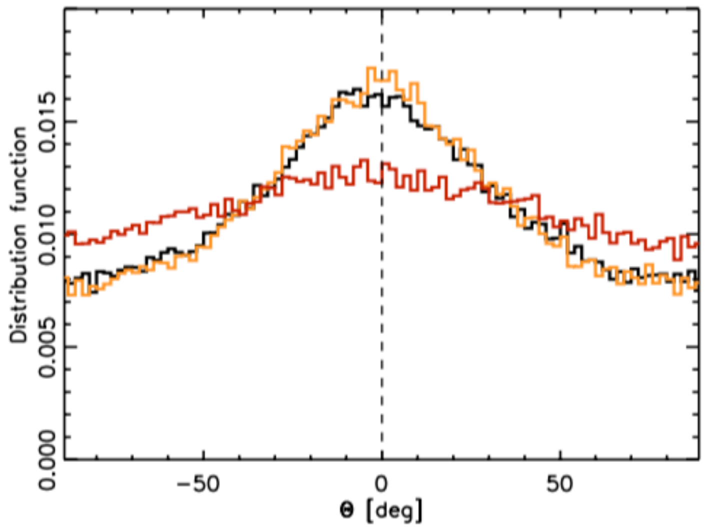
3. Planck results : b) Statistical properties of polarization angles

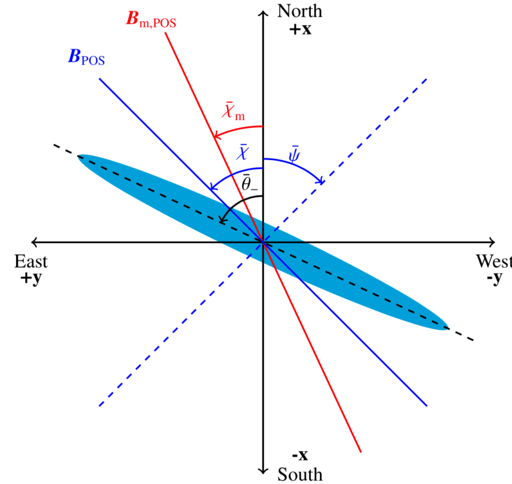


3. Planck results : b)) Statistical properties of polarization angles

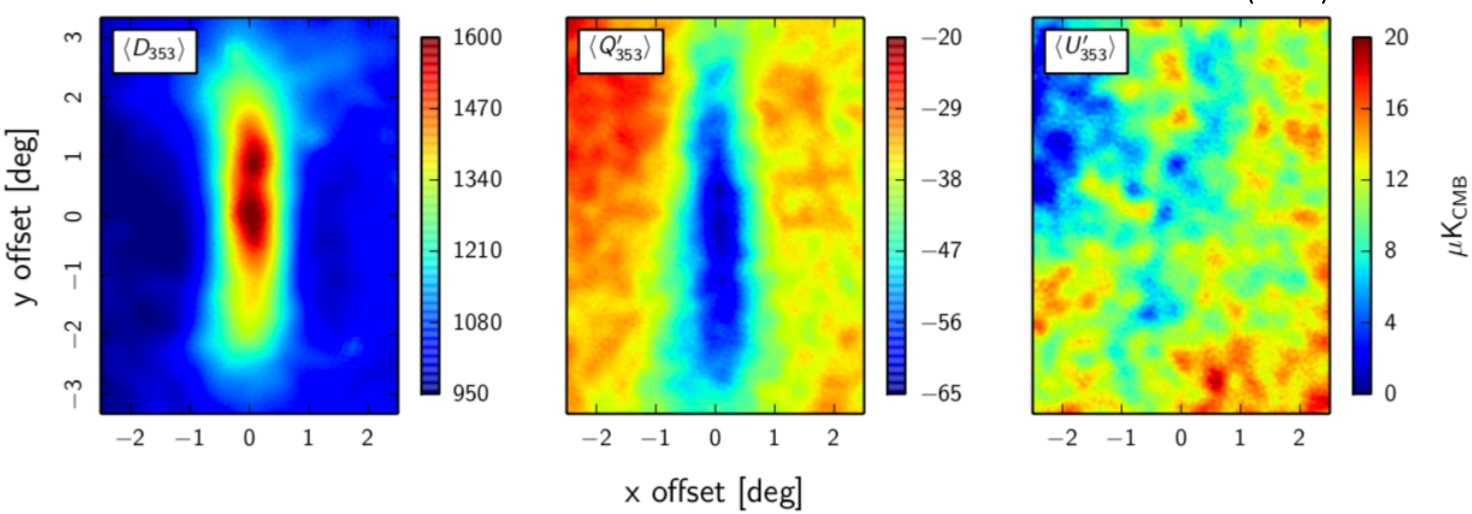
In the diffuse ISM, filaments are along the magnetic field

Planck Intermediate Results XXXII (2016)





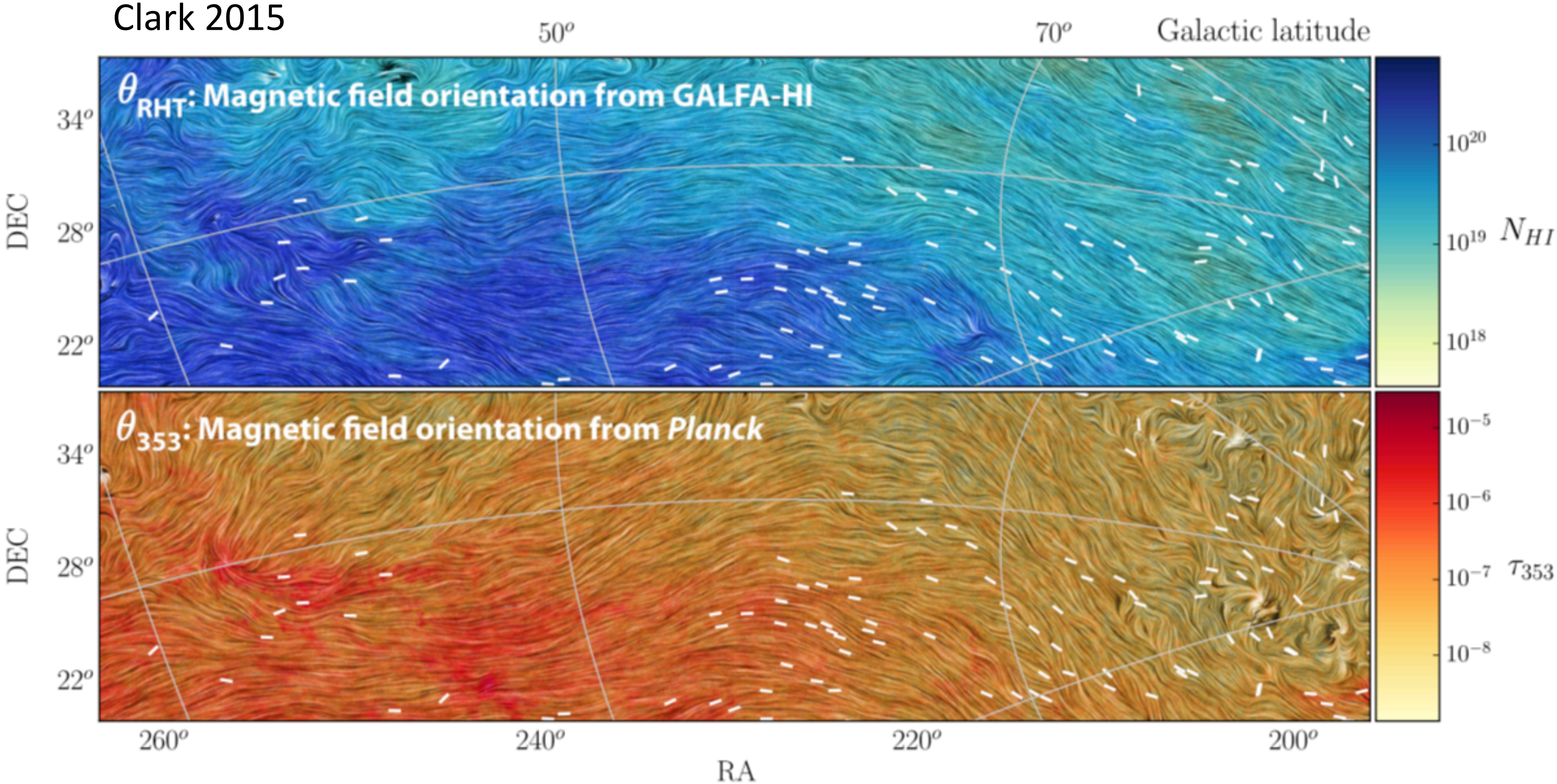
Planck Intermediate Results XXXVIII (2016)



3. Planck results : b)) Statistical properties of polarization angles

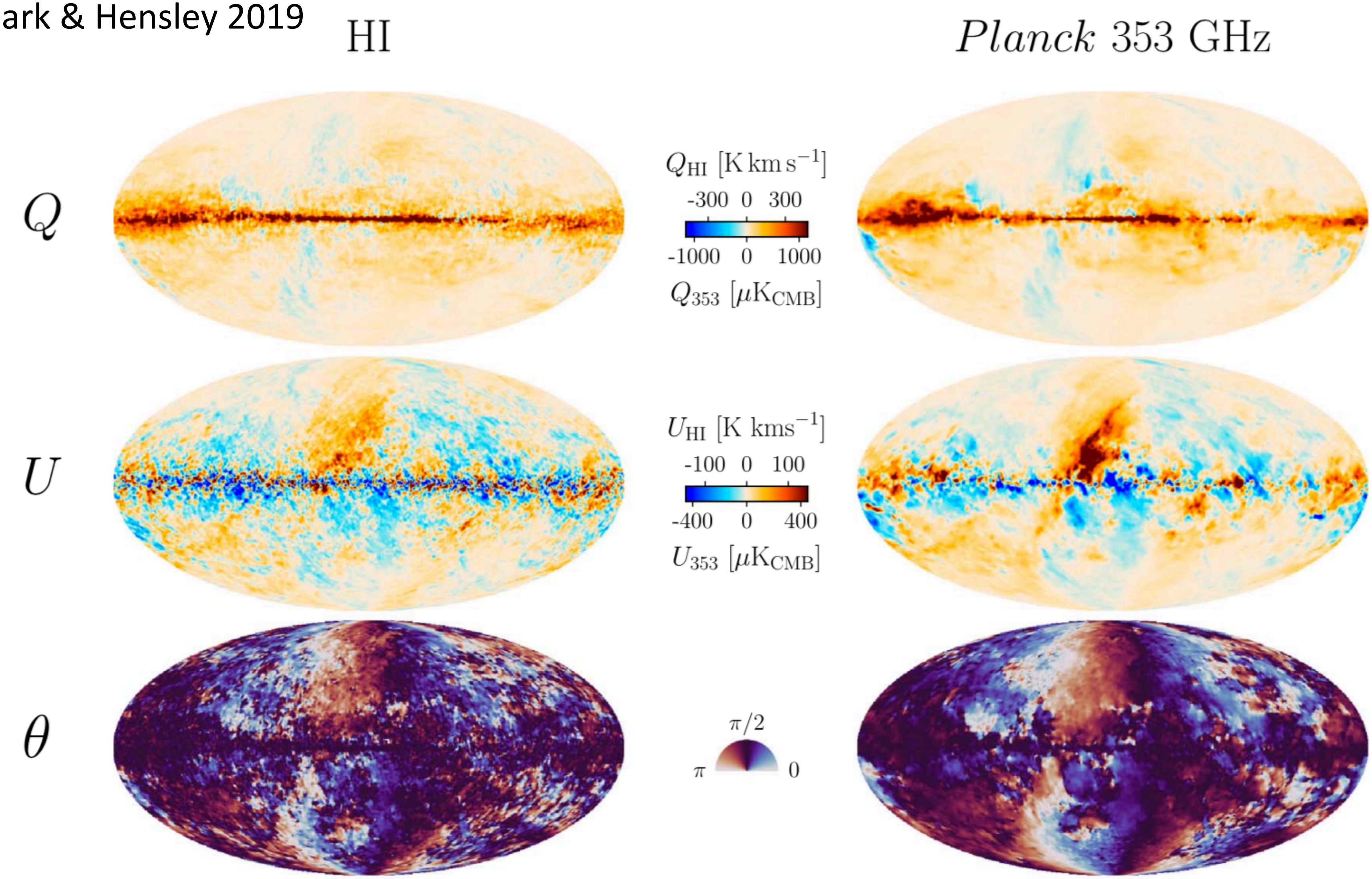
Excellent correlation with HI filaments

Clark 2015



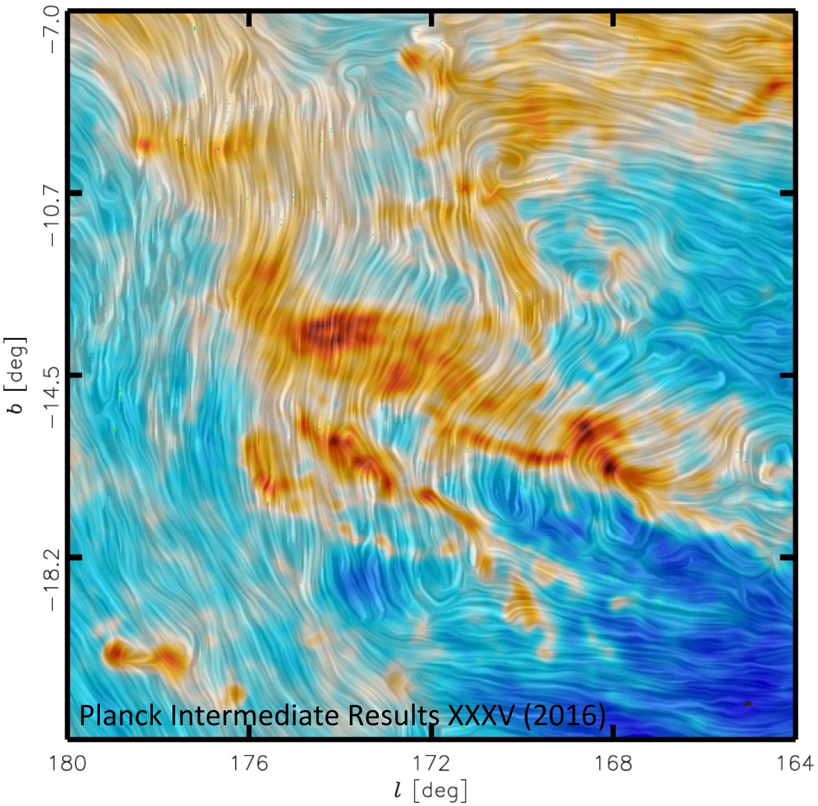
3. Planck results : b)) Statistical properties of polarization angles

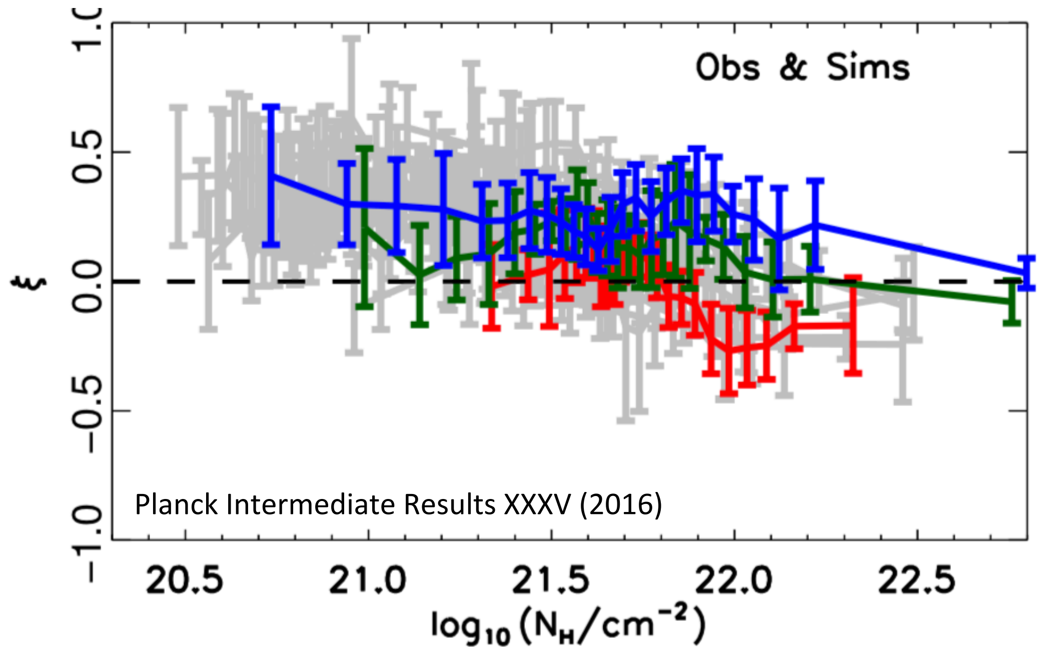
Clark & Hensley 2019



3. Planck results : b)) Statistical properties of polarization angles

Transition from the diffuse ISM to the dense ISM



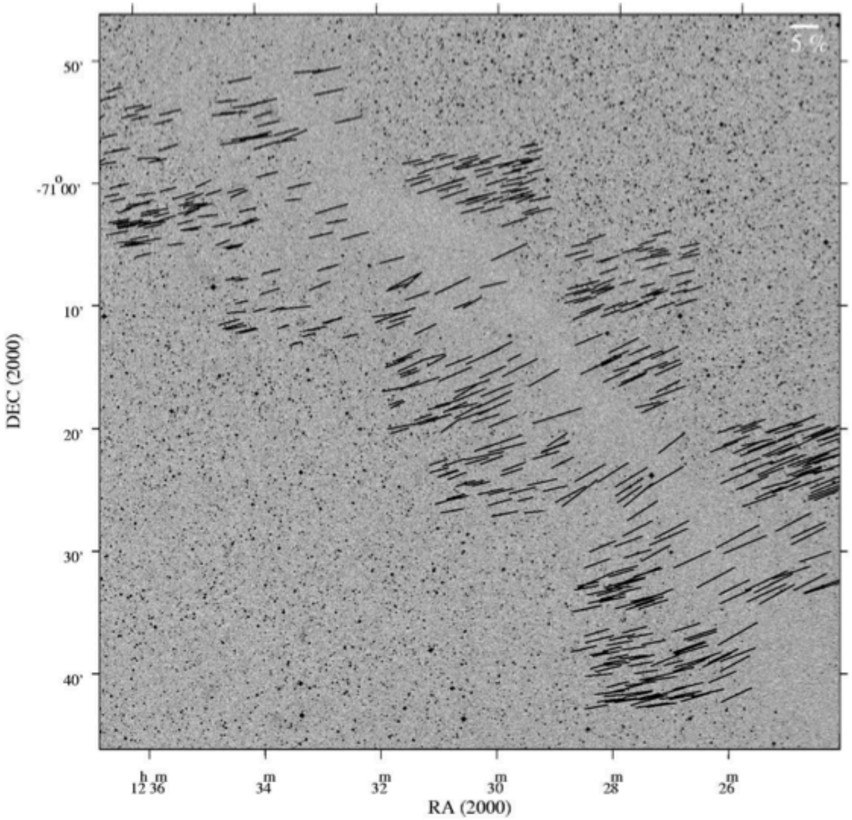


Alignment of filaments with the magnetic field tend to change from being parallel at low N_H to being perpendicular at high N_H (Planck IR XXXV 2016)

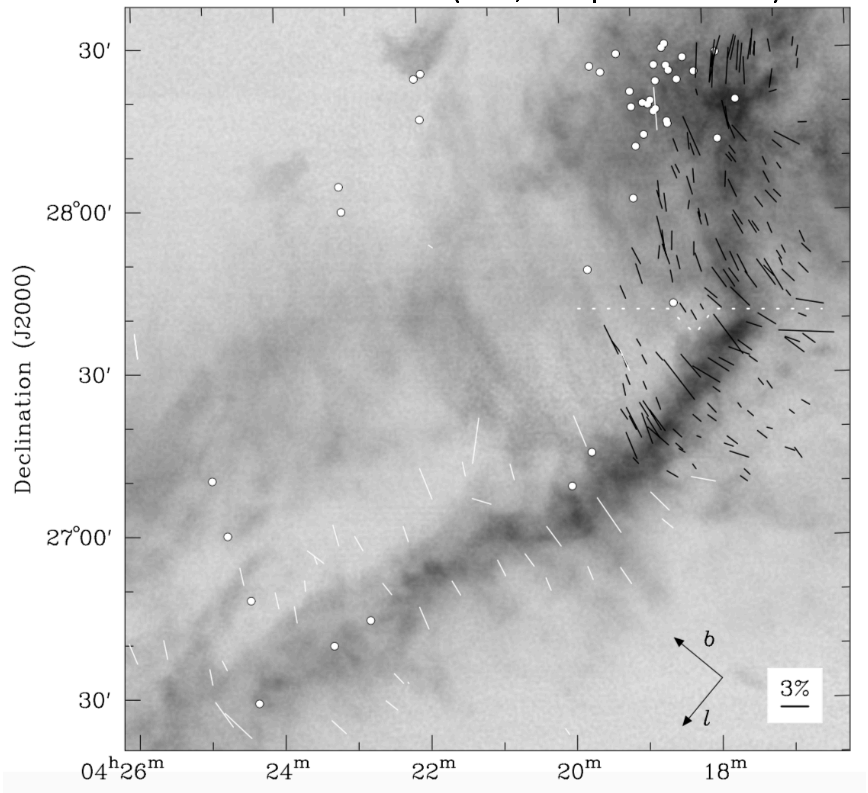
3. Planck results : b)) Statistical properties of polarization angles

A trend also observed in starlight polarization

Musca filament (optical, Pereyra & Magalhaes 2004)

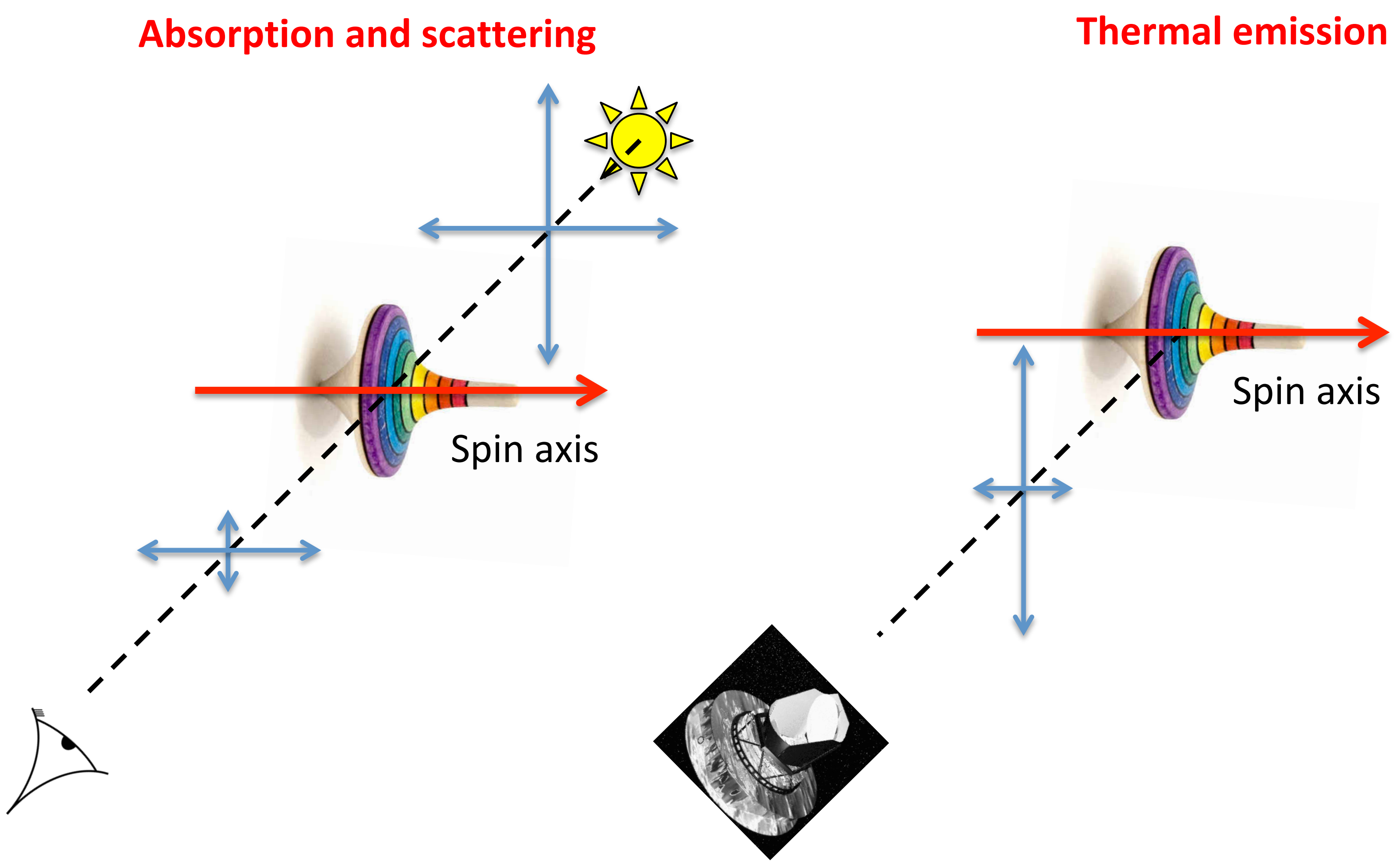


Taurus filament (NIR, Chapman+2011)



Optical (white) and NIR (black) polarization vectors.
Background = ^{13}CO emission.

3. Planck results : b)) Statistical properties of polarization angles

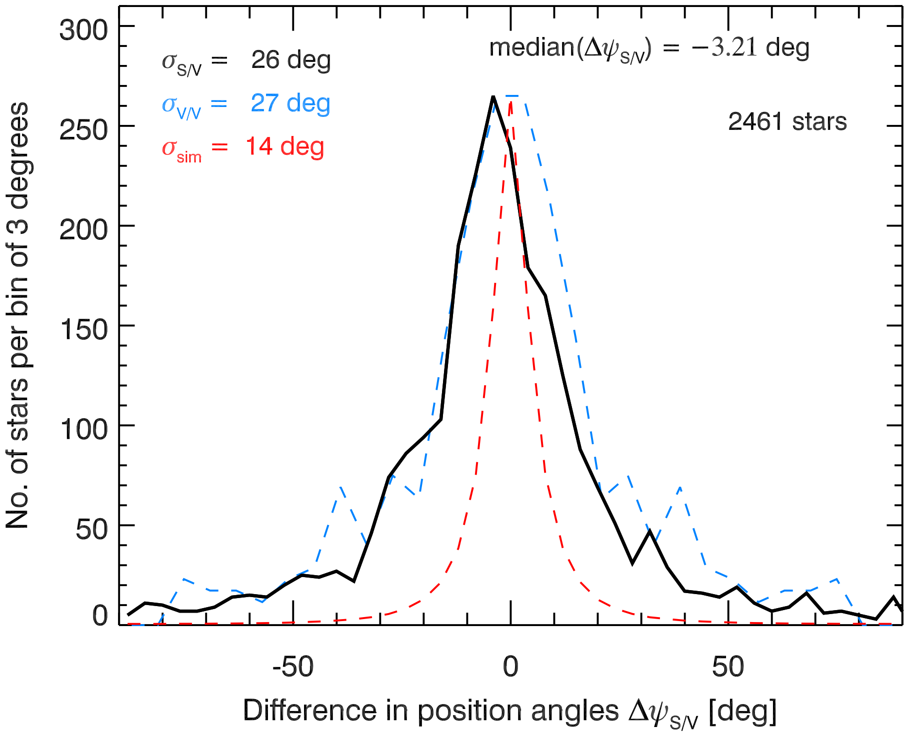


The polarization direction for thermal emission by aligned grains is perpendicular to **B**

3. Planck results : b) polarization angles

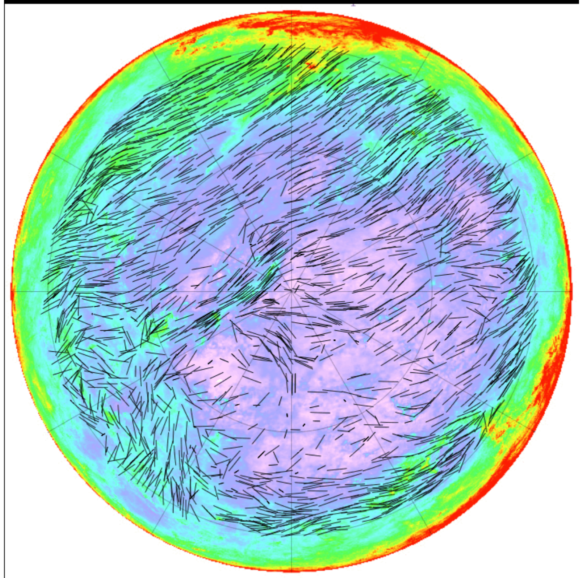
Starlight polarization data from a series of Papers by Berdyugin et al., published between 2001 and 2014.

- North : 2075 stars with b > 30 °
- South : 316 stars with b < - 60°

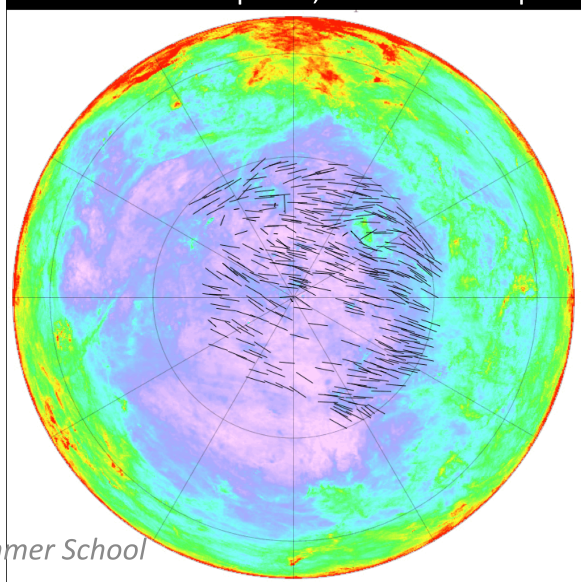


- Remarkable agreement (despite no selection)
- Width of histogram explained by noise & dispersion of starlight polarization angles within the *Planck* beam
- Unexplained systematic shift of ~ 3° deg.

Northern Hemisphere, seen from the pole



Southern hemisphere, seen from the pole



Starlight polarization data from a series of Papers by Berdyugin et al., published between 2001 and 2014.

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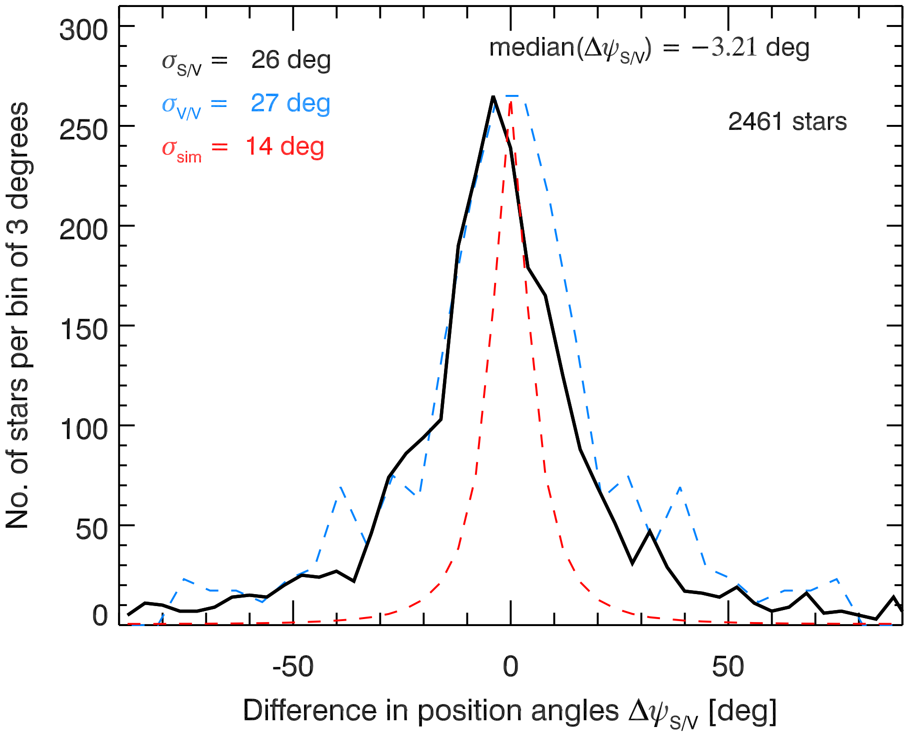
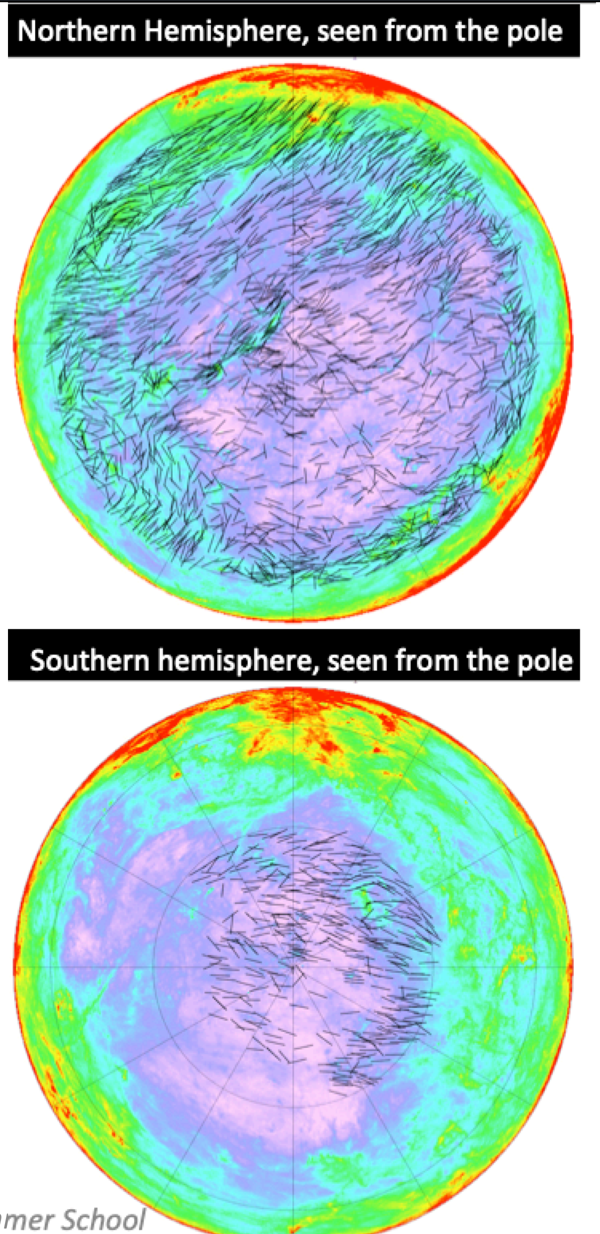
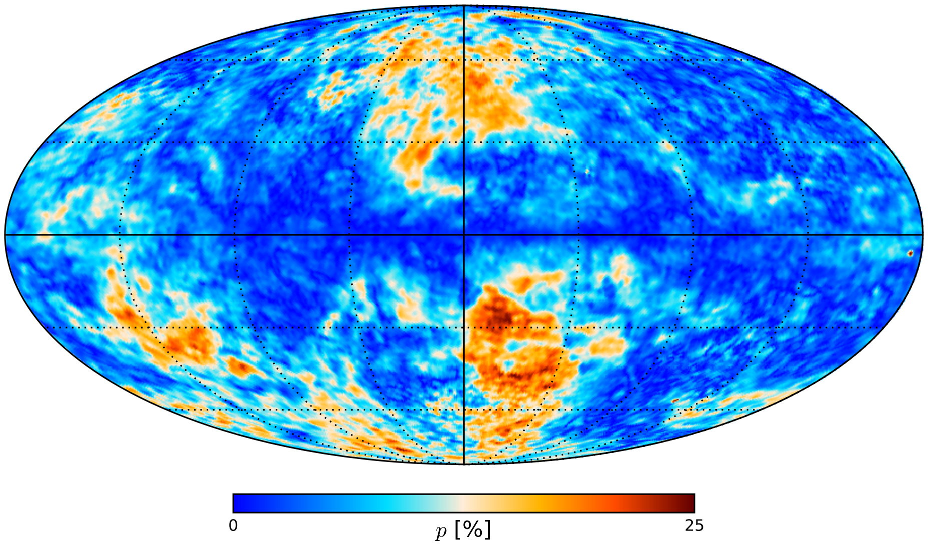


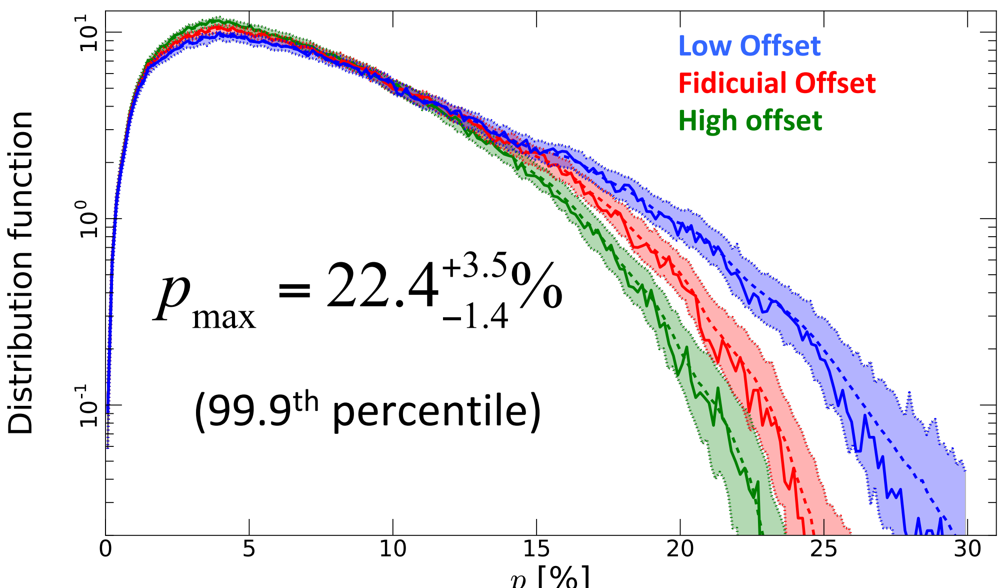


- Remarkable agreement (despite no selection)
- Width of histogram explained by noise & dispersion of starlight polarization angles within the *Planck* beam
- Unexplained systematic shift of ~ 3° deg.

3. Planck results : c) Maximal polarization fraction



At FWHM = 80 arcmin of resolution, we have ~ 2.10^5 pixels



CAN DUST MODELS ACHIEVE THIS ?

IS THIS COMPATIBLE WITH STARLIGHT POLARIZATION ?

p / $E(B\text{-}V)$ < 9% (Serkowski+1975) ?

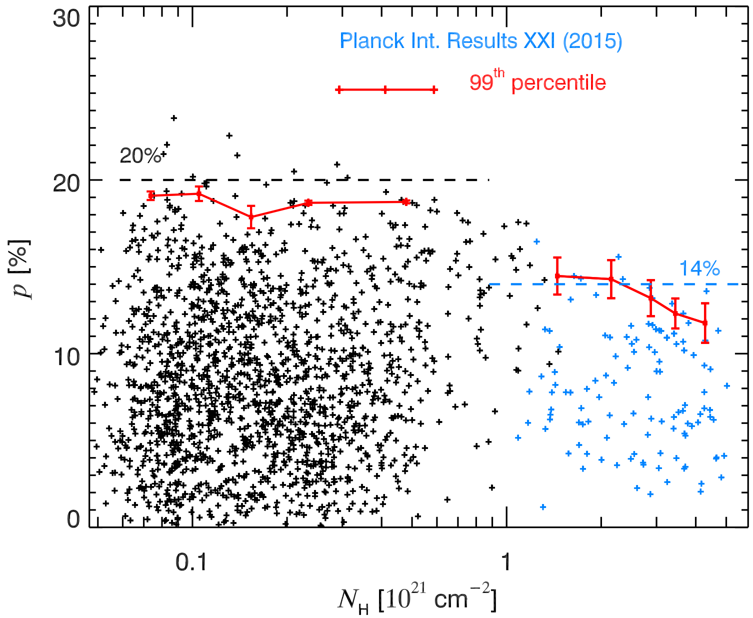
3. Planck results : c) Maximal polarization fraction

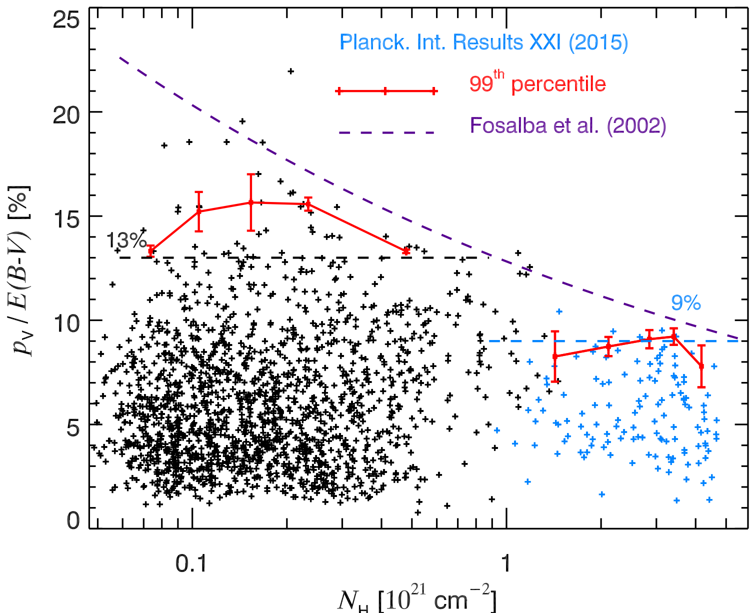
1) One can not directly compare the maximal polarization fraction in emission and in extiction

	Planck 2018 Results XII	Serkowski 1975
Maximal polarization fraction	P/I = 22%	$p_V/E(B\text{-}V)$ = 9%
N_H range	$5.10^{19} - 5.10^{20}$ cm^{-2}	> 10^{21} cm^{-2} ($E(B\text{-}V)$ > 0.15 mag)
Percentile	99.9 %	95 %

2) Fitting a percentile is difficult with low statistics: here 99th percentile

➔ **We use our knowledge of $R_{S/V}$ to estimate the max of $p_V/E(B\text{-}V)$ at low N_H**





We find:

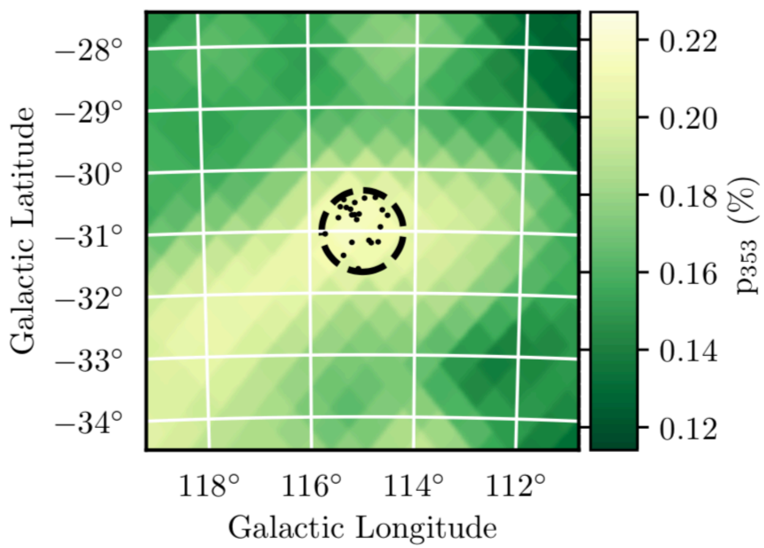
$p_V/E(B\text{-}V)$ < 13%

3. Planck results : c) Maximal polarization fraction

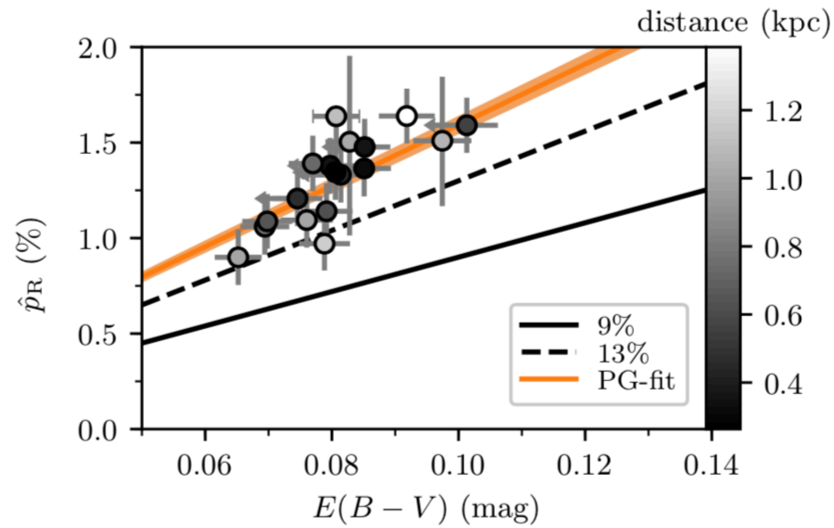
Follow-up in the optical of a *Planck* polarization peak

Panopoulou+2019

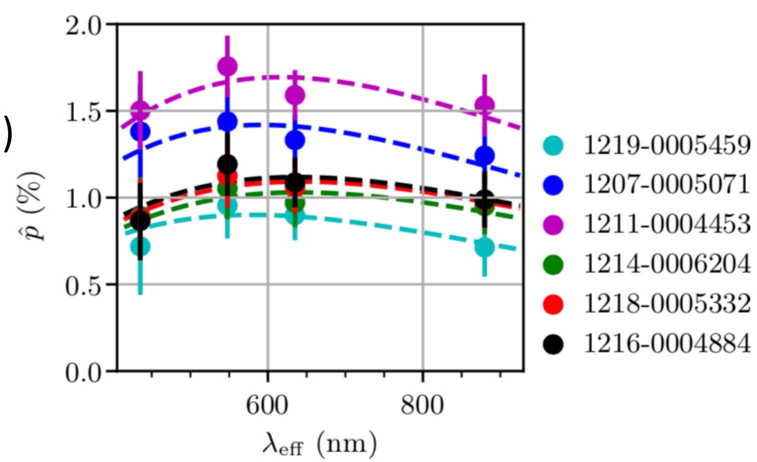
Planck polarization fraction : 20-22%



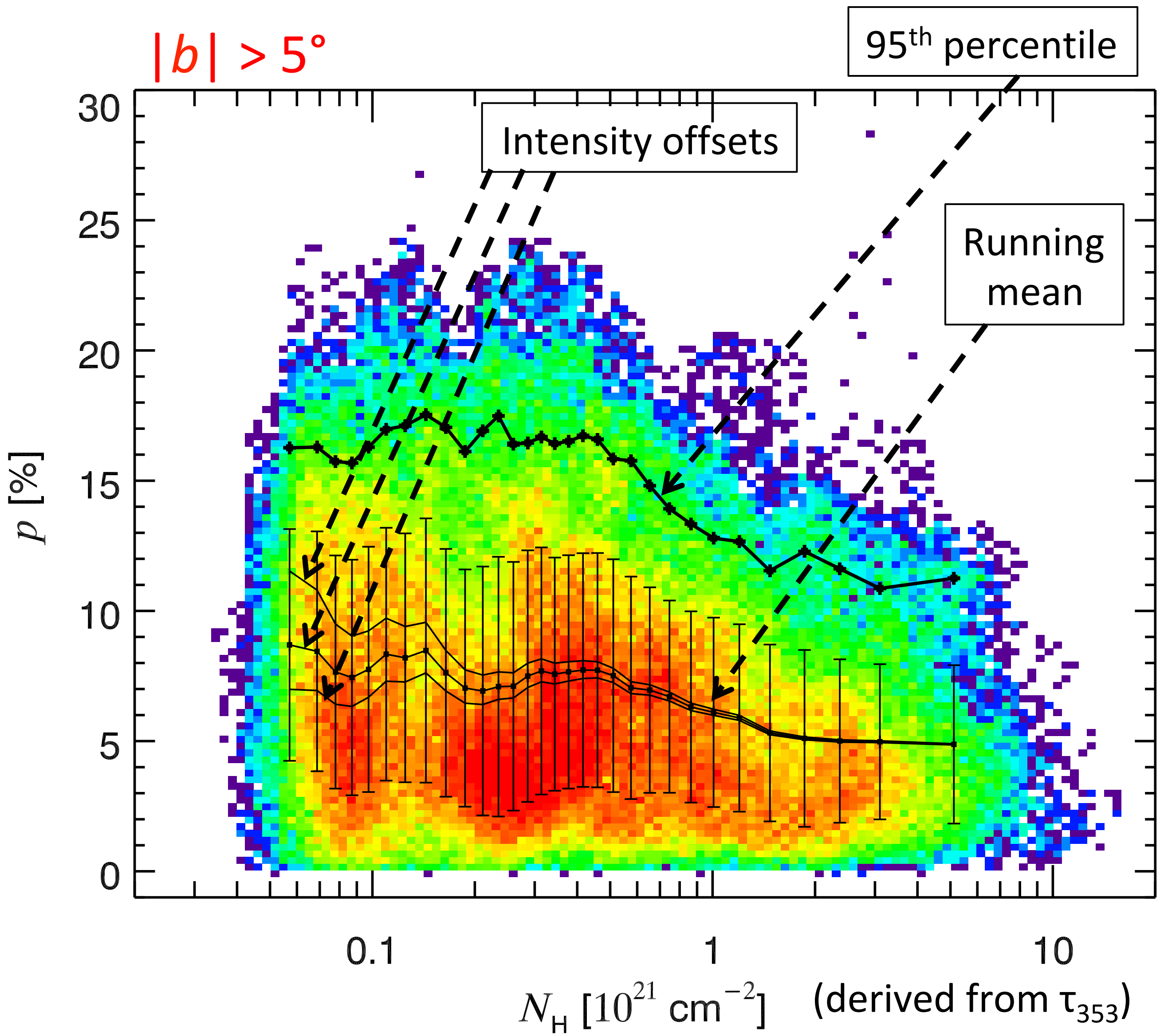
Very high polarization fraction in the optical (**R-band**):
p/E(B-V) = 13-18%, depending on the *E(B-V)* map.



Peak of polarization normal (close to diffuse ISM mean value)
⇒ **Is NOT to a peak of the alignment efficiency**



3. Planck results : d) Testing the RAT theory



A drop long observed and discussed in starlight polarization (optical, NIR):

- Hiltner (1956)
- Serkowski+1975
- Vrba+1981
- Jones (1989)
- Goodman+1992
- Whittet+1994
- Gerakines+1995
- Fosalba+2002
- Andersson+2007
- Whittet+2008
- Alves+2014
- …

WHAT IS CAUSING THE RANDOM AND SYSTEMATIC VARIATIONS OF *P/I* ?

37

3. Planck results : d) Testing the RAT theory

In emission (Rayleigh approximation when $a \ll \lambda$) :

$$p = p_{\max} R F \cos^2 \gamma$$

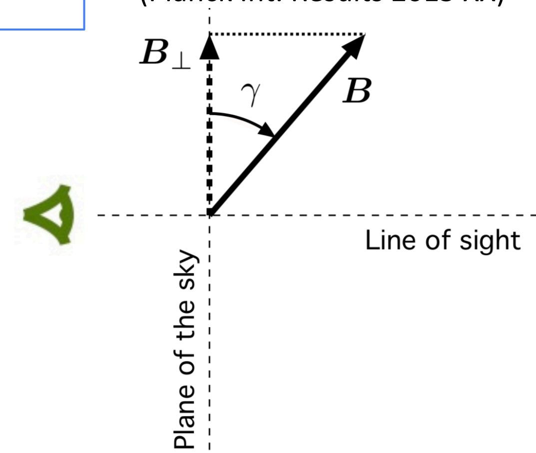
Magnetic field inclination

Magnetic field disorder (line of sight, beam)

Grain shape & composition

Grain alignment (Rayleigh reduction factor)

(Planck Int. Results 2015 XX)



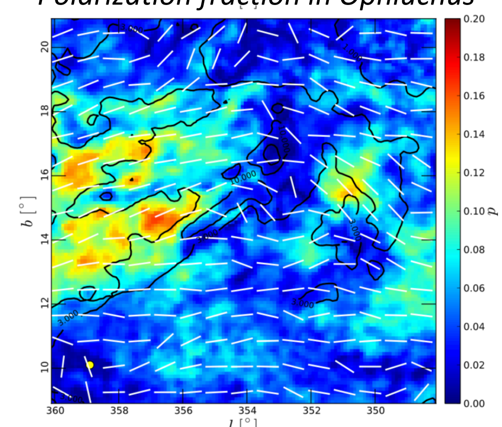
Angle structure function S

(Planck Int. Results 2015 XIX)

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

S DEPENDS ON THE STRUCTURE OF THE MAGNETIC FIELD.
S DOES NOT DEPEND ON ALIGNMENT

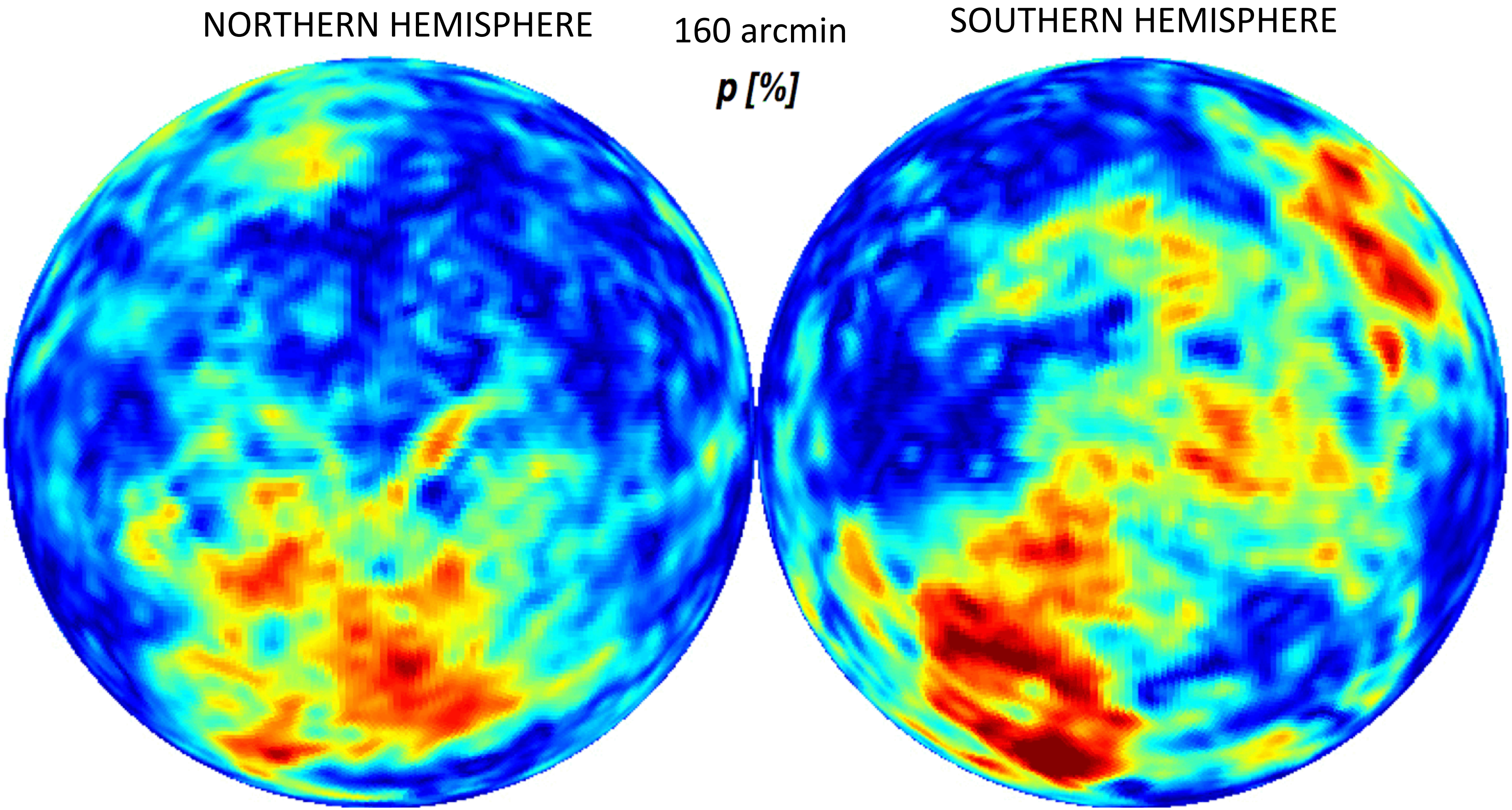
Polarization fraction in Ophiuchus



(Planck Int. Results 2015 XIX)

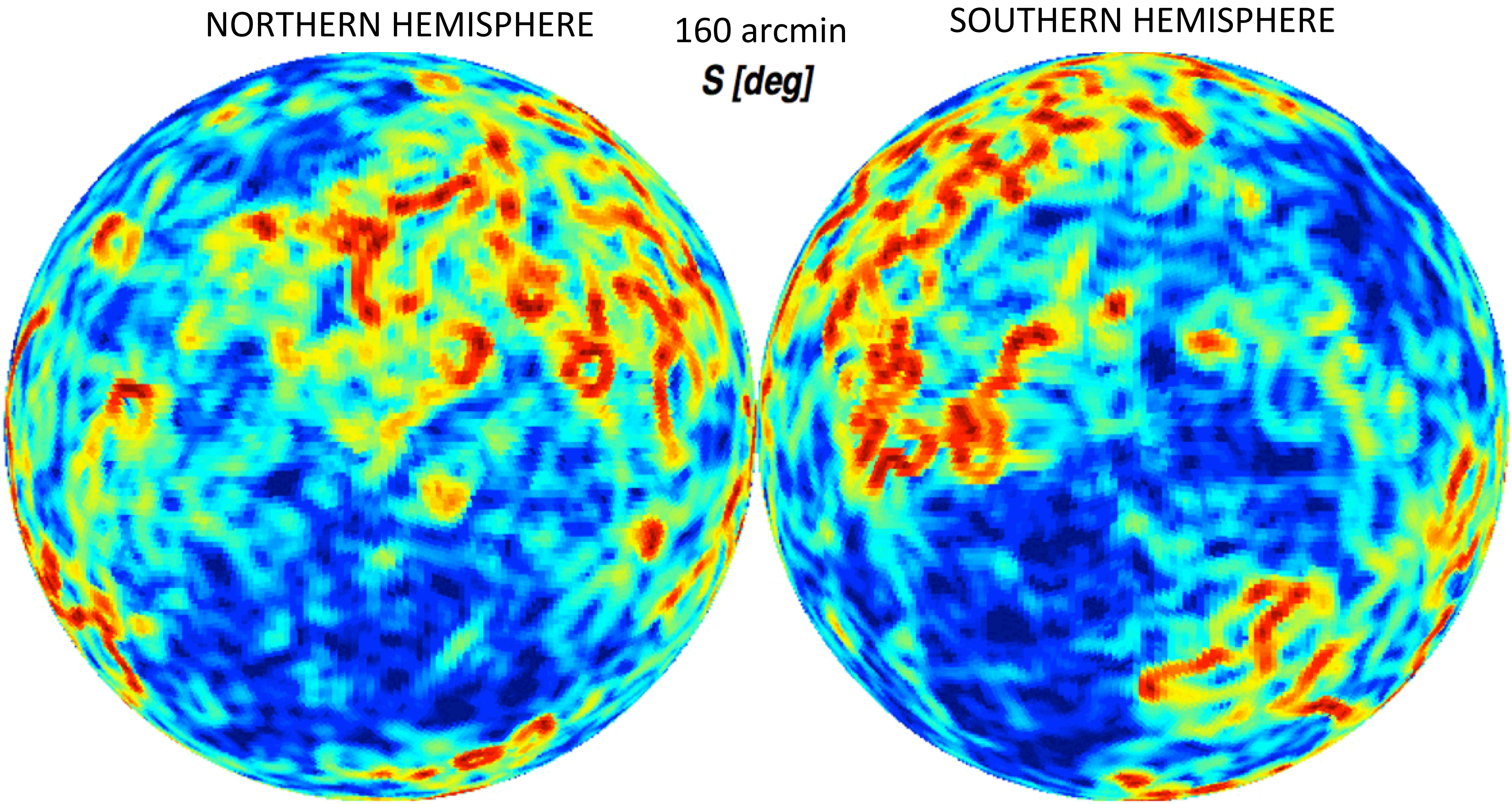
3. Planck results : d) Testing the RAT theory

Anticorrelation of S with p also observed at high latitude



3. Planck results : d) Testing the RAT theory

Anticorrelation of S with p also observed at high latitude



3. Planck results : d) Testing the RAT theory

Heiles (1996)
Hatano+2013
Planck Int. Results 2015 XIX
BlastPOL : Fissel+2016

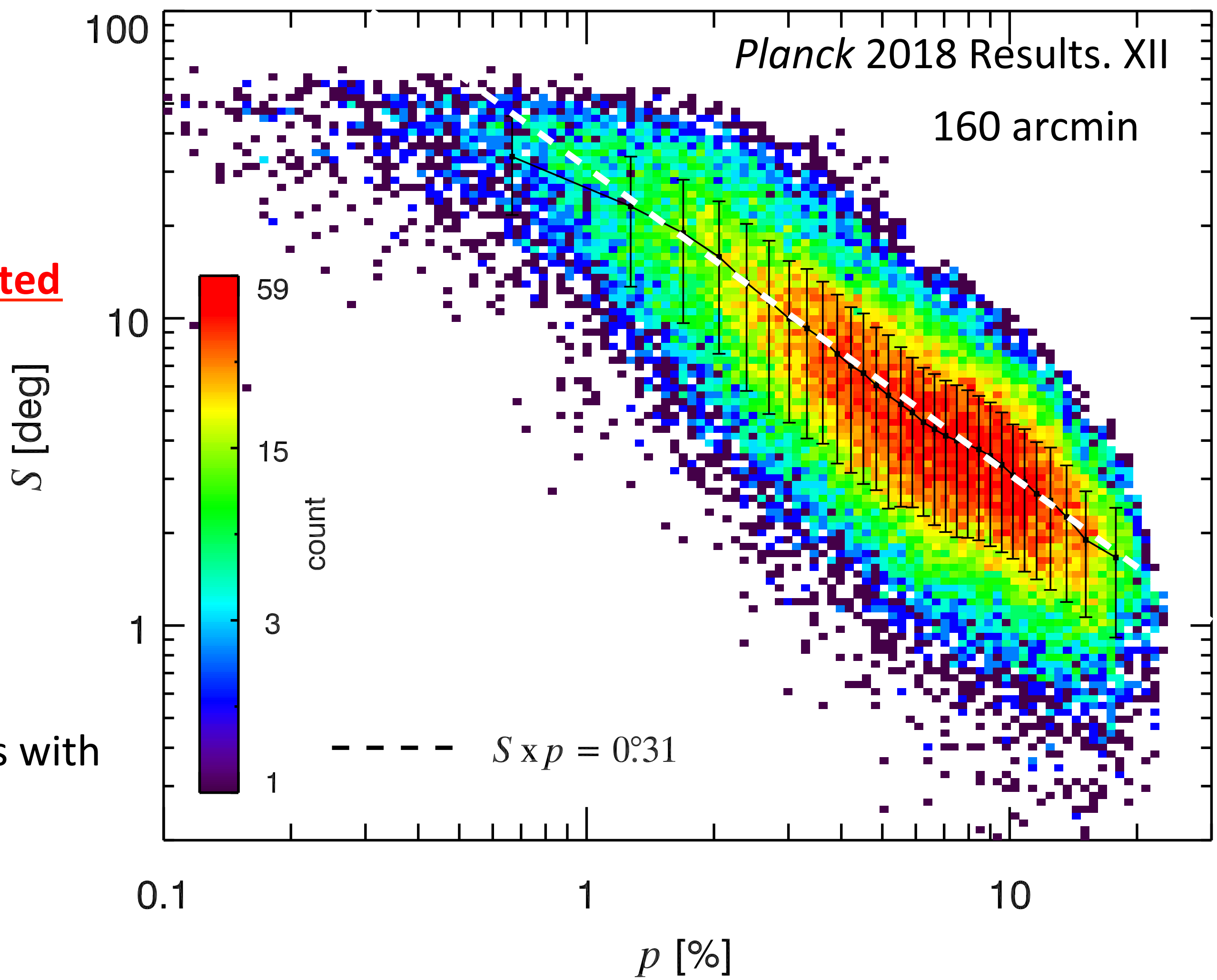
<u>*S* and *p* are anticorrelated</u>

<u>*Planck* 2018 Results XII</u>

$$\left\langle S \times p \right\rangle_p = C^{te}$$

<*S* x *p*> shows less variations with
- the column density
- the latitude
- the longitude

than <*p*> alone.



3. Planck results : d) Testing the RAT theory

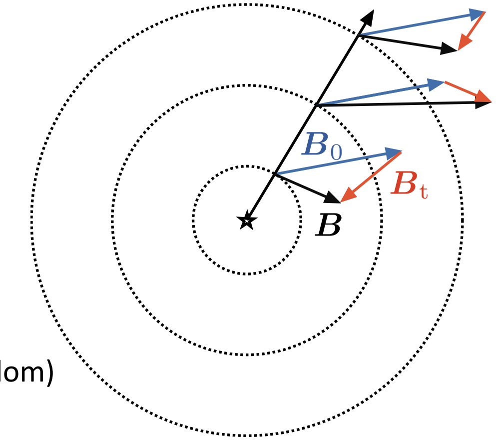
Model (*Planck* Intermediate Results XLIV 2016)

- Inspired by Jones+1992 model
- $f_M = B_t / B_0$ is the ratio of turbulent to ordered B
- p_{max} is the maximal polarization fraction
- Each of the N layers has the same column density
- α_M is the slope of the turbulence power spectrum

Ordered (uniform)

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

Turbulent (random)



Best fit : $f_M = 0.9$, $\alpha_M = -2.5\pm0.1$, $p_{max} = 0.26$, N=7

We demonstrate (*Planck* 2018 result XII)

$$\langle S \times p \rangle = 0.164 f_M \left(\frac{p_{max}}{\sqrt{N}}\right)\left(\frac{\omega}{160'}\right)^{-1-\alpha_M/2}$$

with ω the resolution (in arcmin)

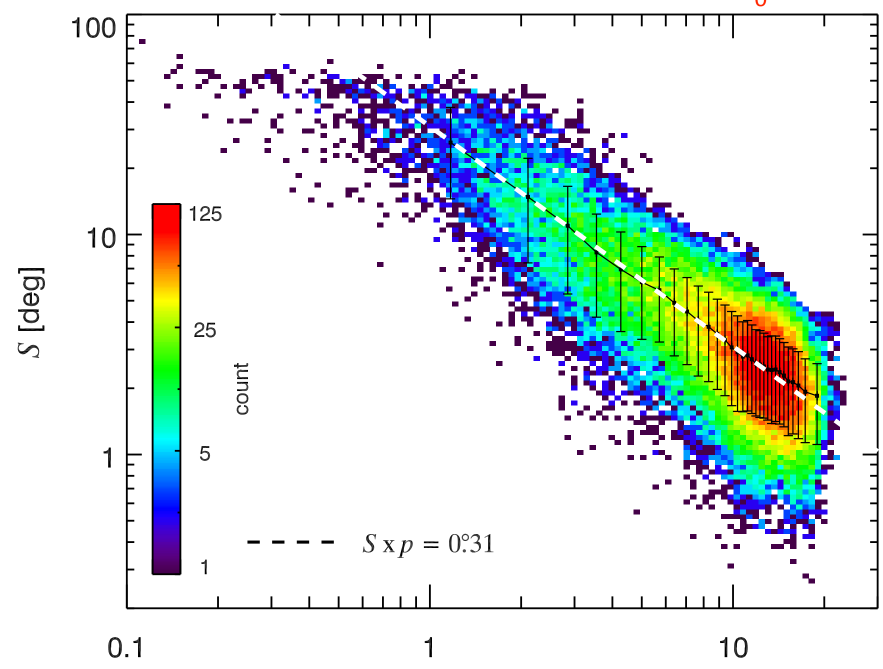
➔ **PROXY FOR GRAIN ALIGNMENT ?**

Applied to *Planck* data :

$\alpha_M = -2.38$ (measured on Q and U maps)

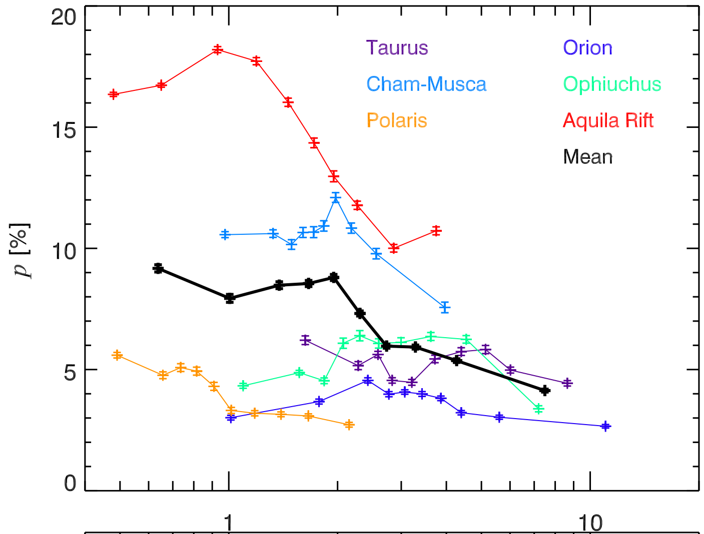
$$\langle S \times p \rangle = 0°.31\left(\frac{\omega}{160'}\right)^{0.18}$$

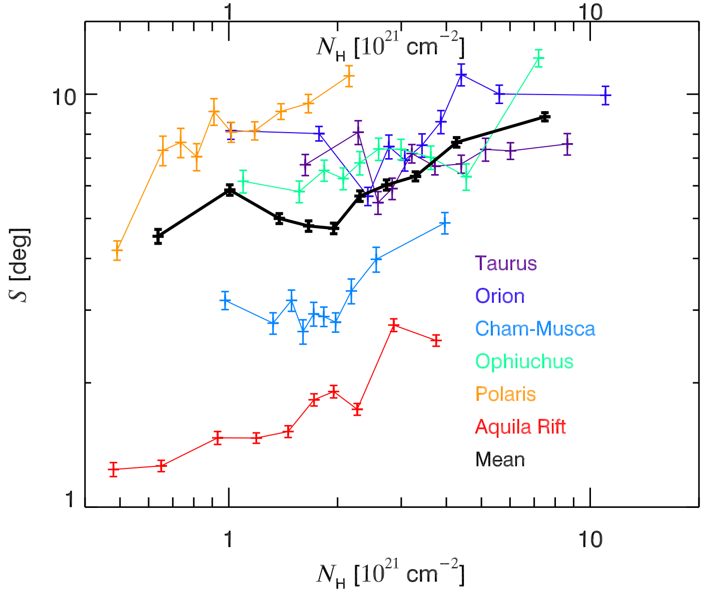
Planck XLIV model with uniform B_0

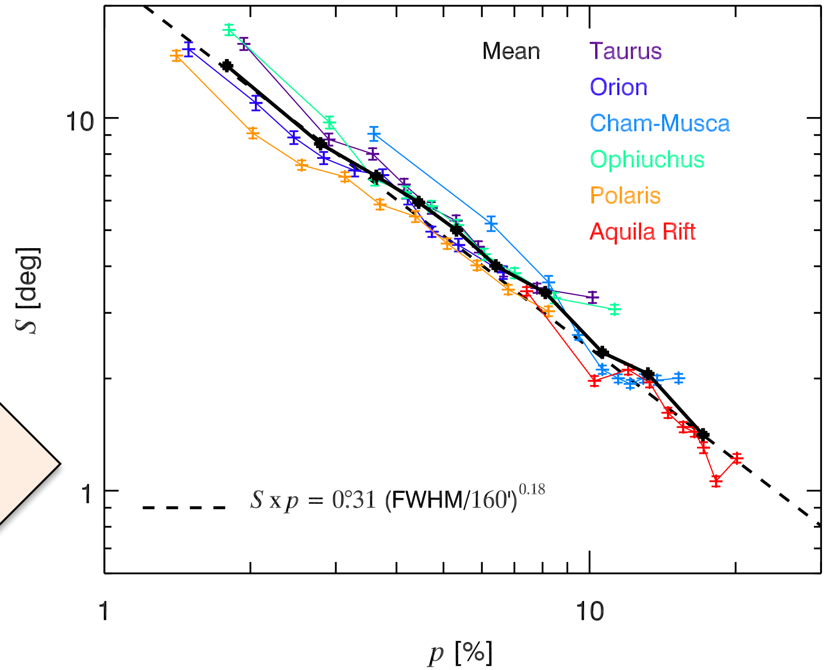


3. Planck results : d) Testing the RAT theory

Study at 40' of resolution

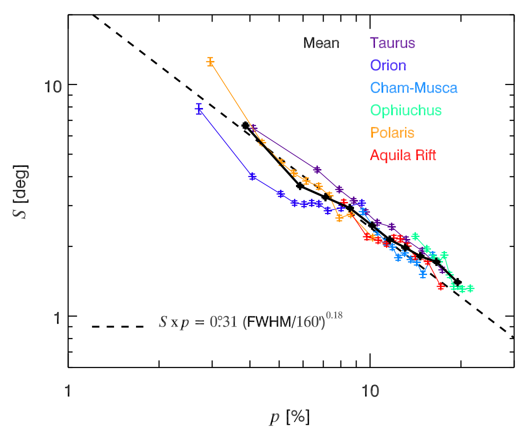






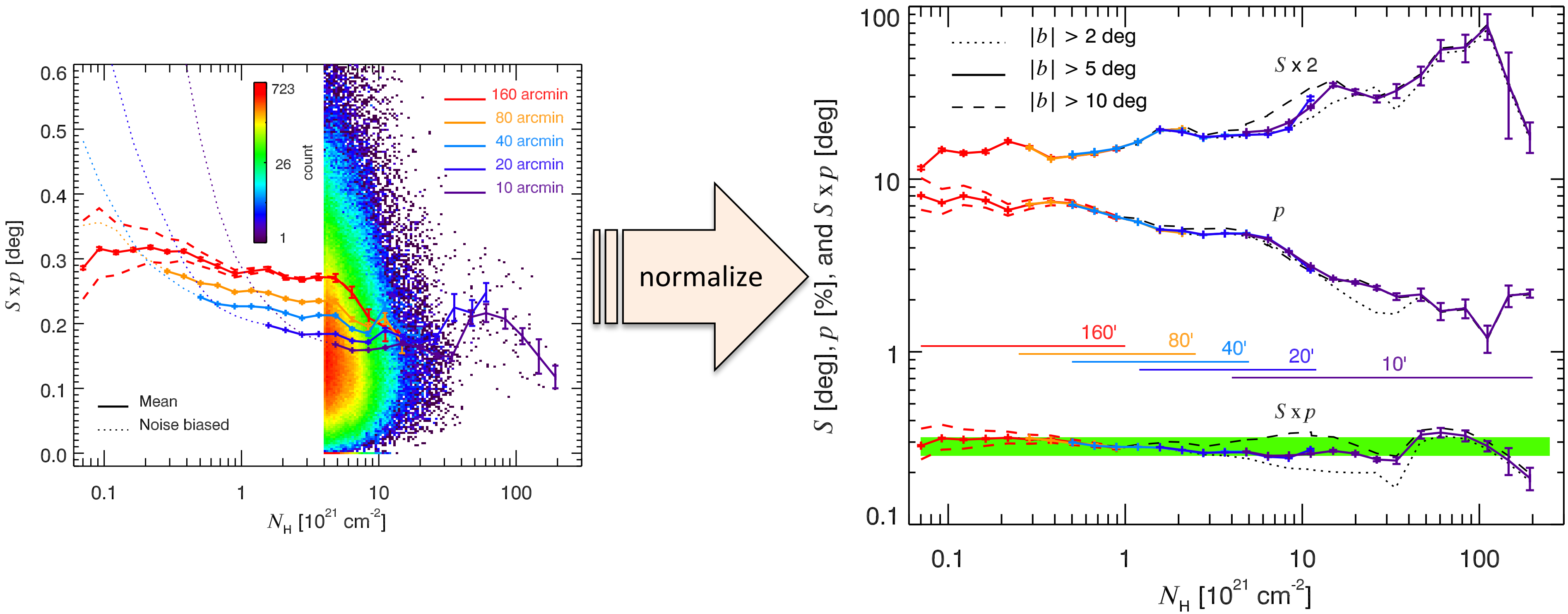
All regions fall on the same line.
Equipartition everywhere ?

Well reproduced by the model: not related to the large-scale field.



3. Planck results : d) Testing the RAT theory

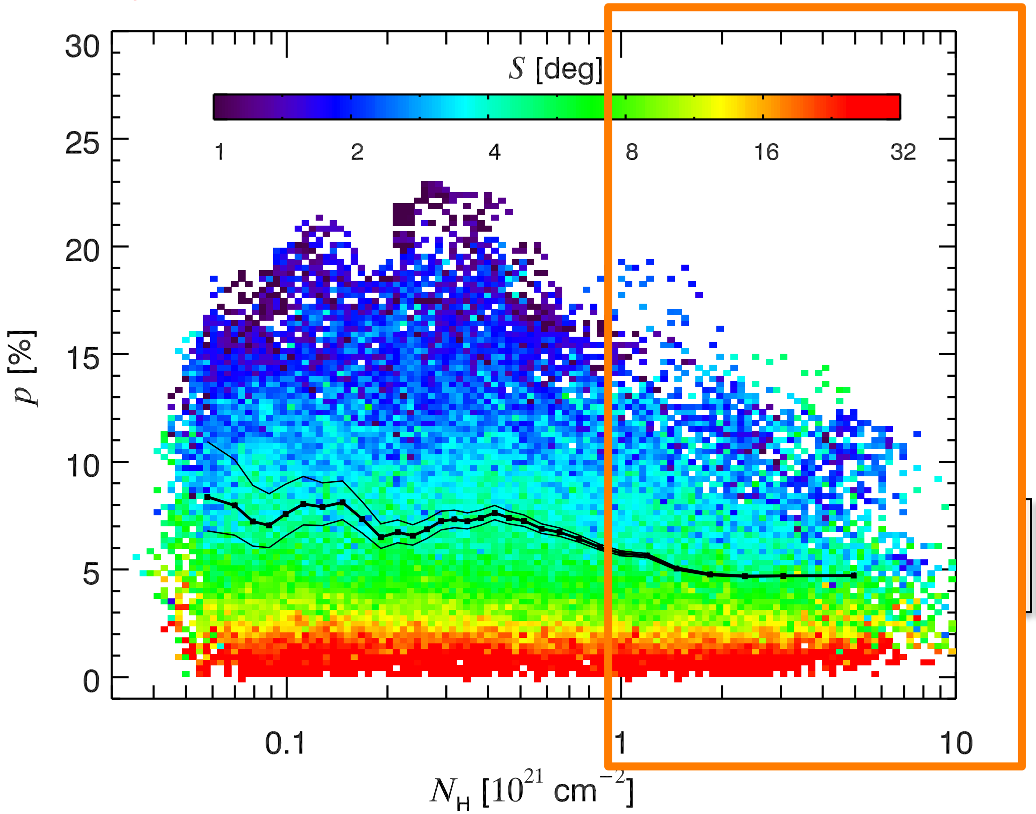
By merging results with increasing resolution (from 160' down to 10'), we probe the polarization properties of all environments observed by *Planck*



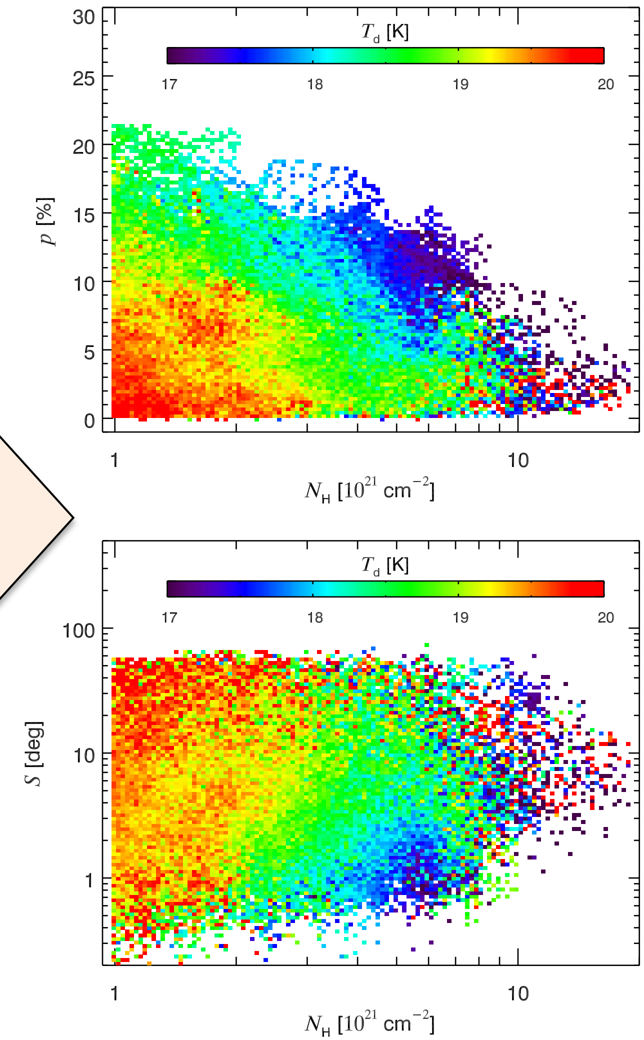
- We provide an upper limit of **25%** on the systematic drop of p with N_H that is ***NOT*** explained by the magnetic field structure.
- The drop of S x p seems to be more related to the latitude than to the column density.

3. Planck results : d) Testing the RAT theory

Study at 80' of resolution



Study at 40' of resolution



➔ Evidence against RATs, or against variation in grain alignment efficiency in the diffuse ISM.

3. Planck results : d) Testing the RAT theory

How to reconcile this with the RATs theory ?

Hoang (2020) : Rotational disruption of astrophysical dust (RATD)

- RATs spin-up grain's rotation
- If grains spin too fast, they can be destroyed (teared apart) by centrifugal force
- This will decrease the mass of aligned grains, therefore p.

After integrating RATD in the RATs theory, p is not predicted to increase with T anymore.

RATD could explain the maximal size of grains in a given environment.

Summary

Summary on the grain alignment theories

- The classical (magnetic) theory of grain alignment can not explain the observed level of polarization.
- The modern theory of grain alignment is the Radiative Torque Theory : alignment by starlight photons.
- The RATs theory has evolved a lot:
  - Integrating the Rotational Disruption Theory (RATD)
  - Extending the Mechanical alignment theory (MAT)
- One should not forget a major actor in alignment theory : the gas.

Planck results have shown:

- Dust polarization is a reliable tracer of **B** in the diffuse ISM.
- HI filaments are parallel to B => it was possible to reproduce Planck polarization maps from the knowledge of HI filaments !
- Dense filaments tend to be statistically preferentially perpendicular to B.
- No correlation found favouring RATs were found. In particular, the grain alignment efficiency has been demonstrated to be statistically constant with N_H in the diffuse ISM, independent of dust temperature.
- **Variations in the polarization fraction in the diffuse ISM are driven by the GEOMETRY of B (structure and orientation).**
- The maximal polarization is P/I=22% at 353GHz, and maximal p/E(B-V) is revised to 13% (not 9%) in the optical.

Planck results have also forced towards a maojor revision of all dust models : cf. Hensley & Draine 2023.