The Planck view of the magnetized interstellar medium

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Talk outline

- The turbulent and magnetized interstellar medium : an overview

- The Planck mission

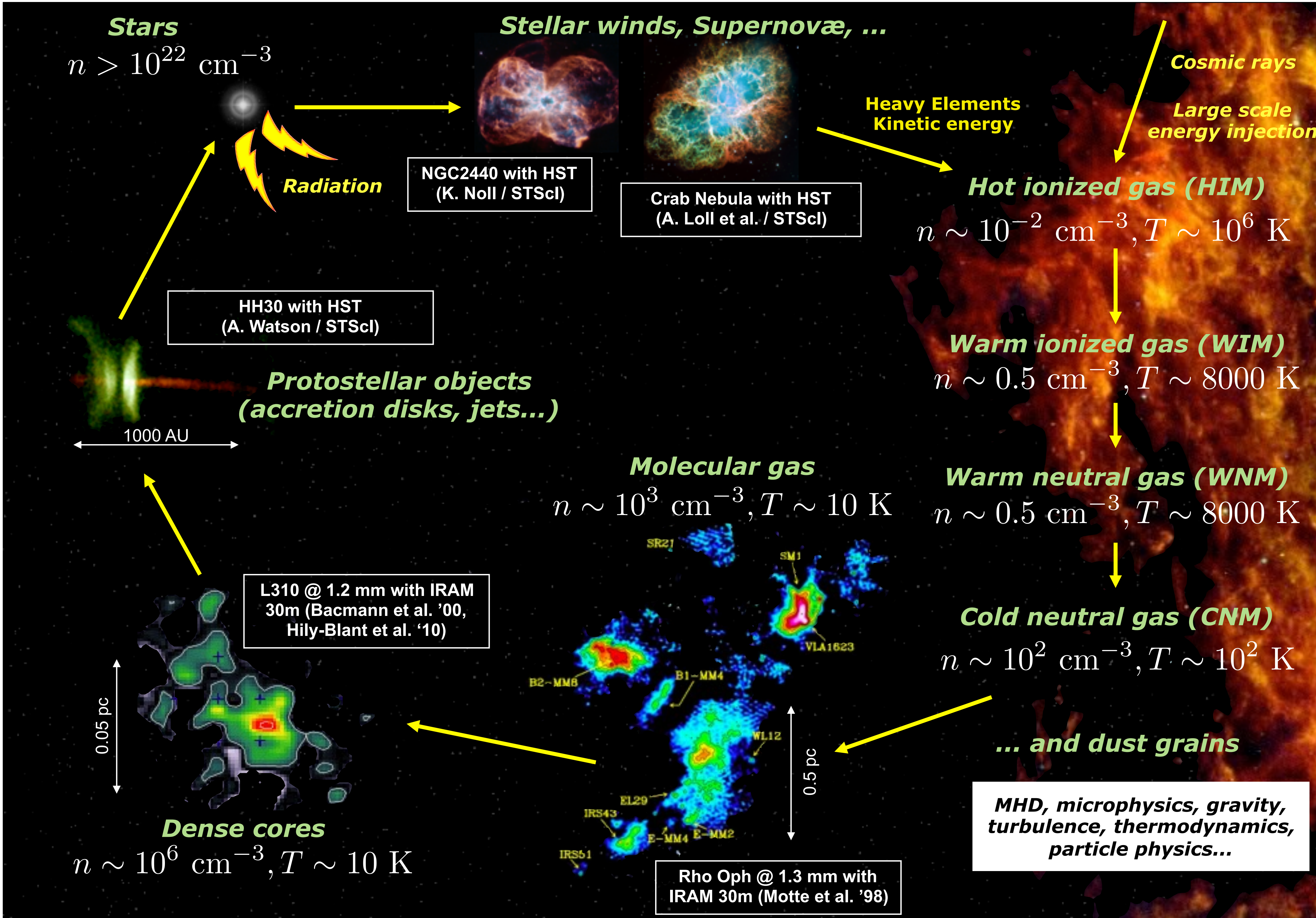
- Main Planck results on the turbulent and magnetized ISM

- Current work

The interstellar medium (ISM)

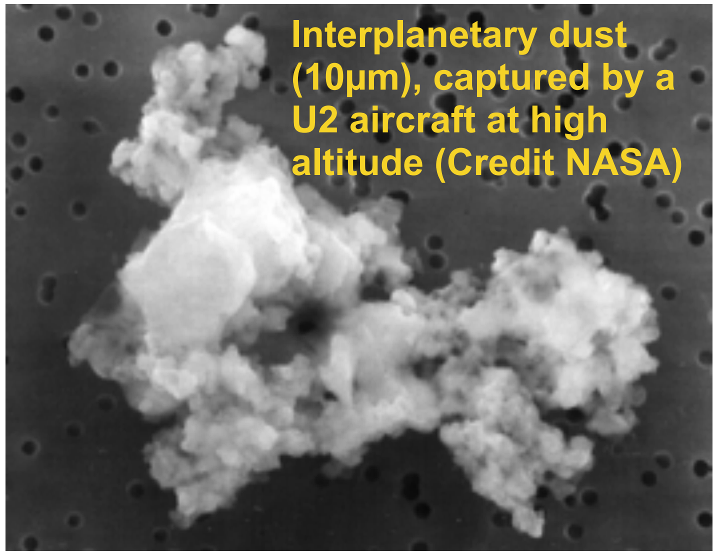
- 1% of the total mass of the Galaxy
- Gas (mainly hydrogen) and dust particles
- The locus of star formation
- Mechanical processes : turbulence and shocks
- Thermodynamical processes : gas heating and cooling
- Electromagnetic processes : radiative transfer, magnetic field
- Quantum processes : Species excitation, radiative transfer
- Chemical processes : in the gas phase and on grain surfaces

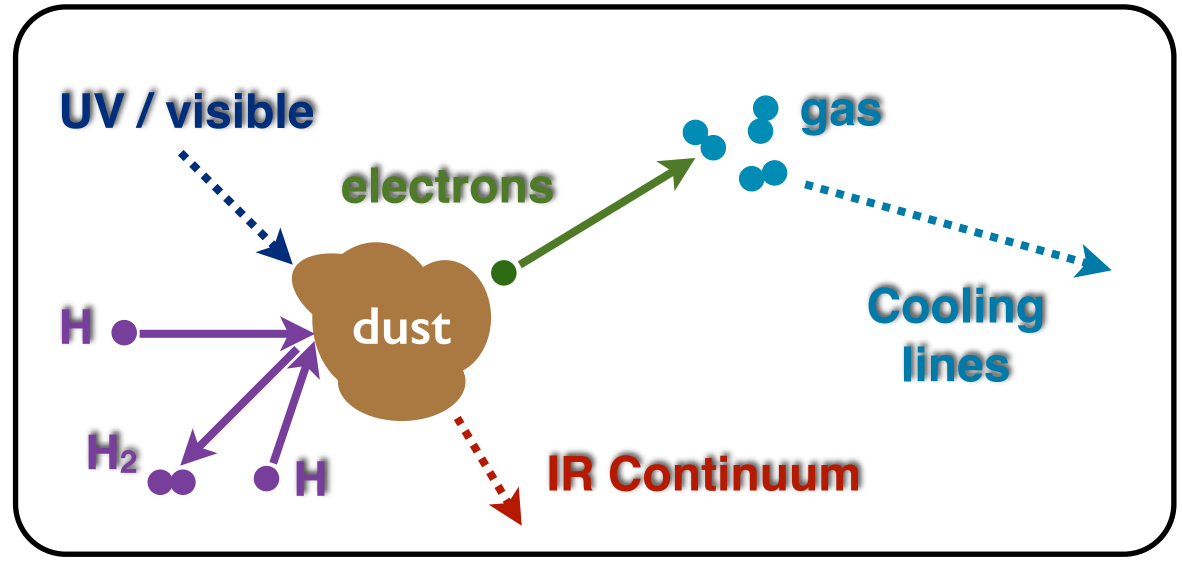
Star formation and the cycle of interstellar matter

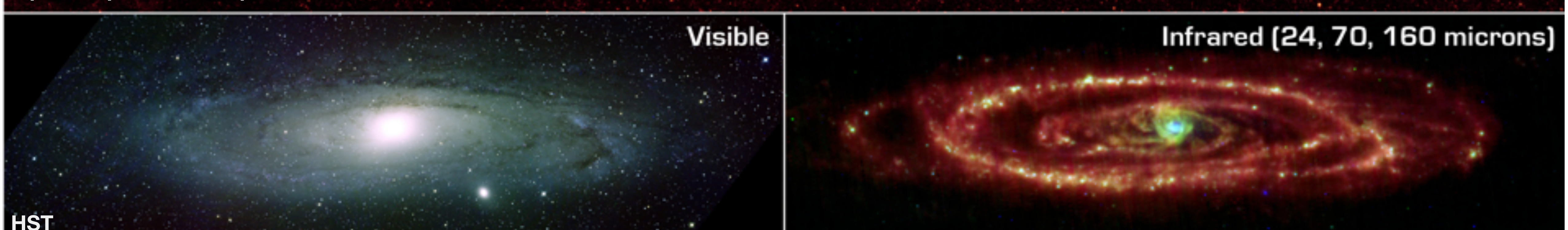


Interstellar dust grains

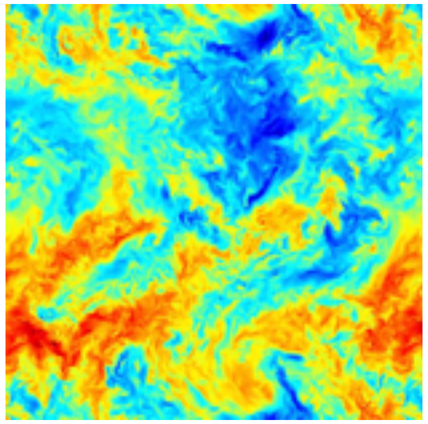
- Carbonaceous and silicate aggregates (1 nm to 10 μm)
- Starlight reprocessing from visible/UV to IR
- Chemical processes on grain surfaces
- Gas heating via photoelectric effect





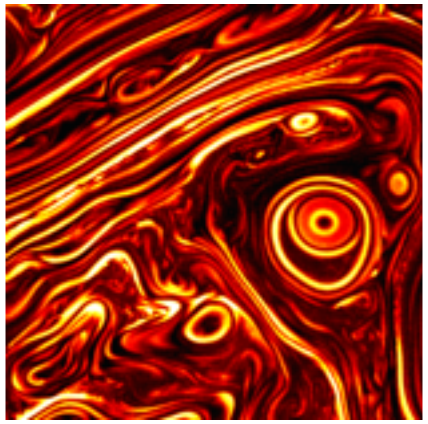


Turbulence



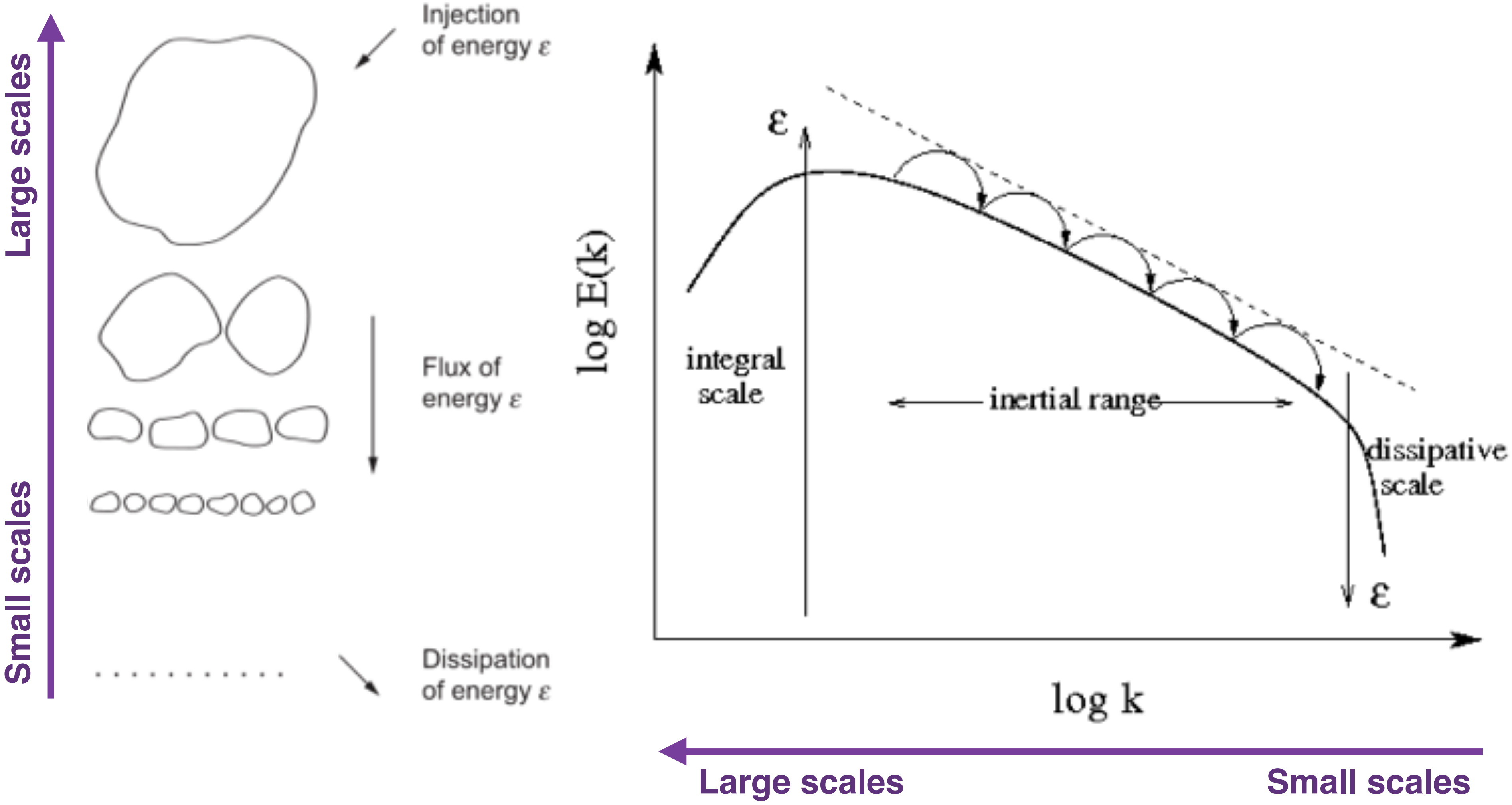
Vorticity (JHU)

« Big whirls have little whirls
that feed on their velocity,
and little whirls have lesser whirls
and so on to viscosity. »
Lewis Fry Richardson (1920)



Current (UCSD, Berkeley Lab)

- Kolmogorov's K41 theory : incompressible, homogeneous, isotropic cascade of energy
- Scaling laws and self-similarity
- Intermittency : dissipation of energy occurs in bursts, localized in time and space
- Modification of scaling laws from compressibility and magnetic fields (MHD turbulence)



Kolmogorov 1941

$$P_v(k) \propto \epsilon^{2/3} k^{-5/3}$$

Iroshnikov 1964, Kraichnan 1965

$$P_v(k) \propto (\epsilon v_A)^{1/2} k^{-3/2}$$

Sridhar & Goldreich 1994, 1995

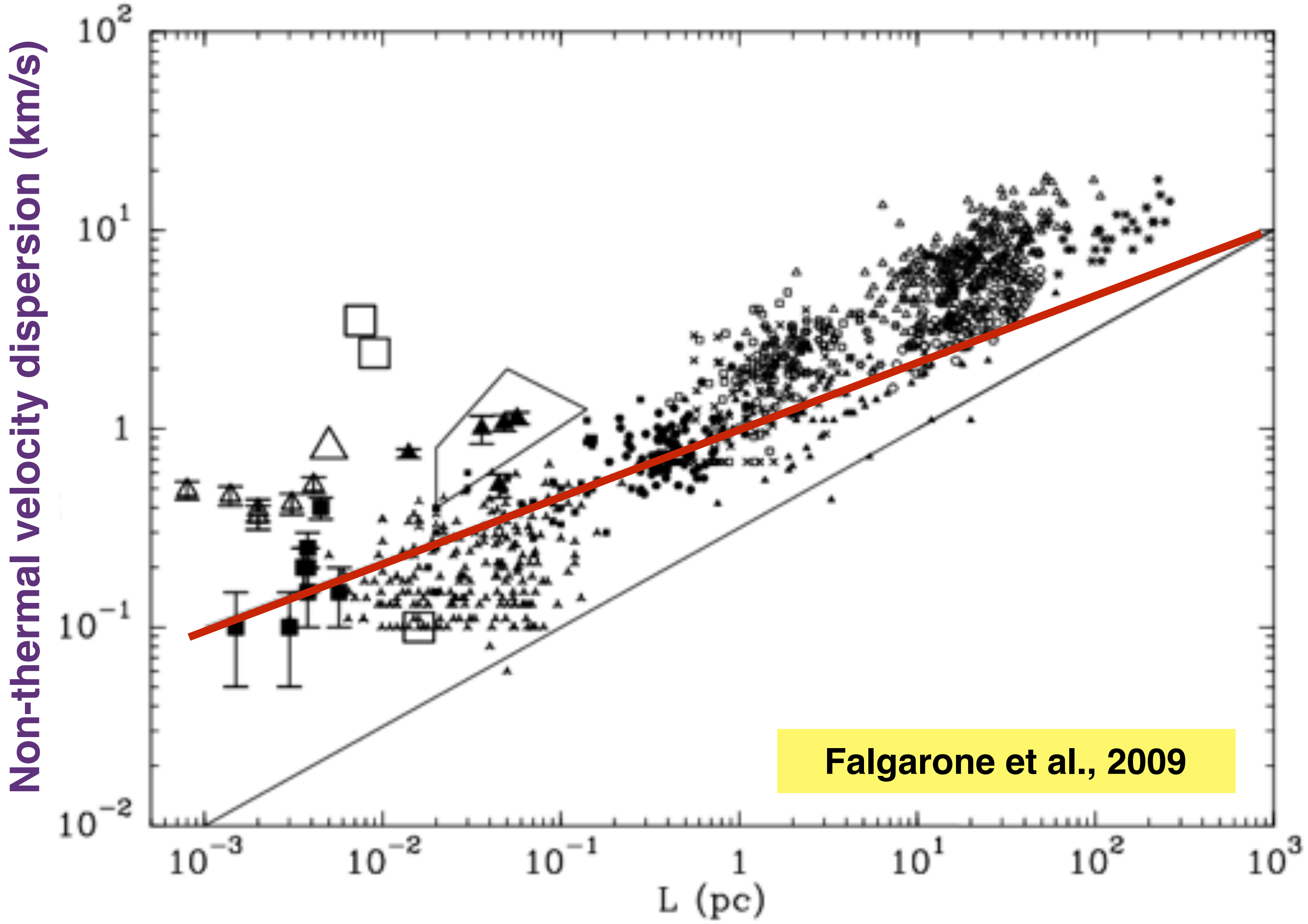
$$P_{v_\perp}(k) \propto k_\perp^{-5/3}$$

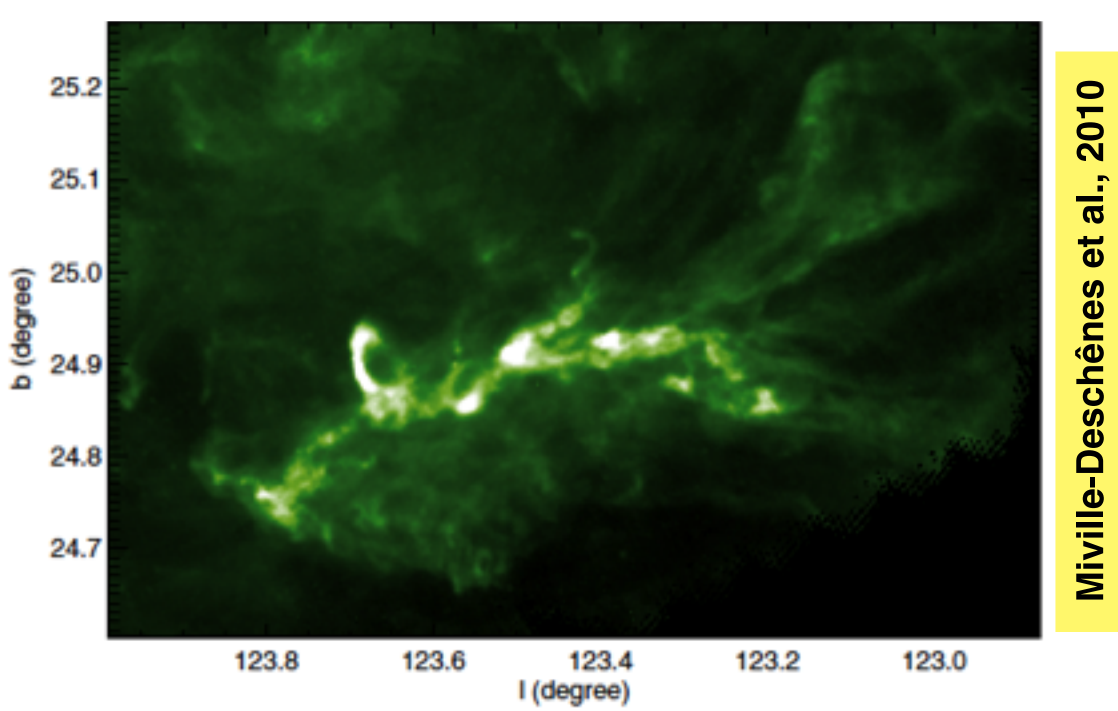
Kowal & Lazarian 2007

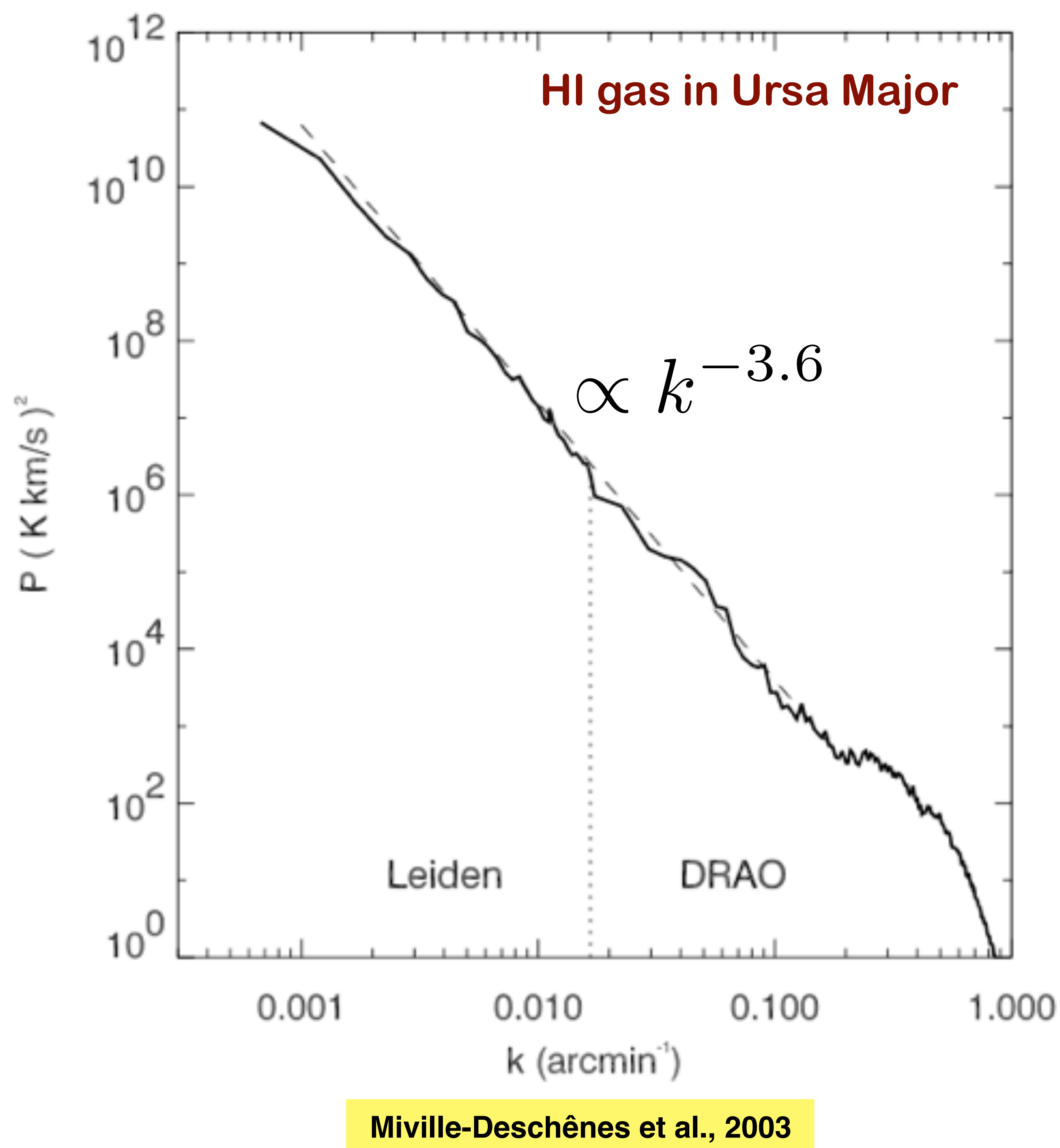
$$P_{\rho^{1/3} v}(k) \propto k^{-5/3}$$

Turbulence in the ISM

- Suprathermal linewidths, scaling with the size of structures
- Self-similarity of structures across many scales
- Intermittency at small scales : non-Gaussian wings in distributions of centroid velocity increments





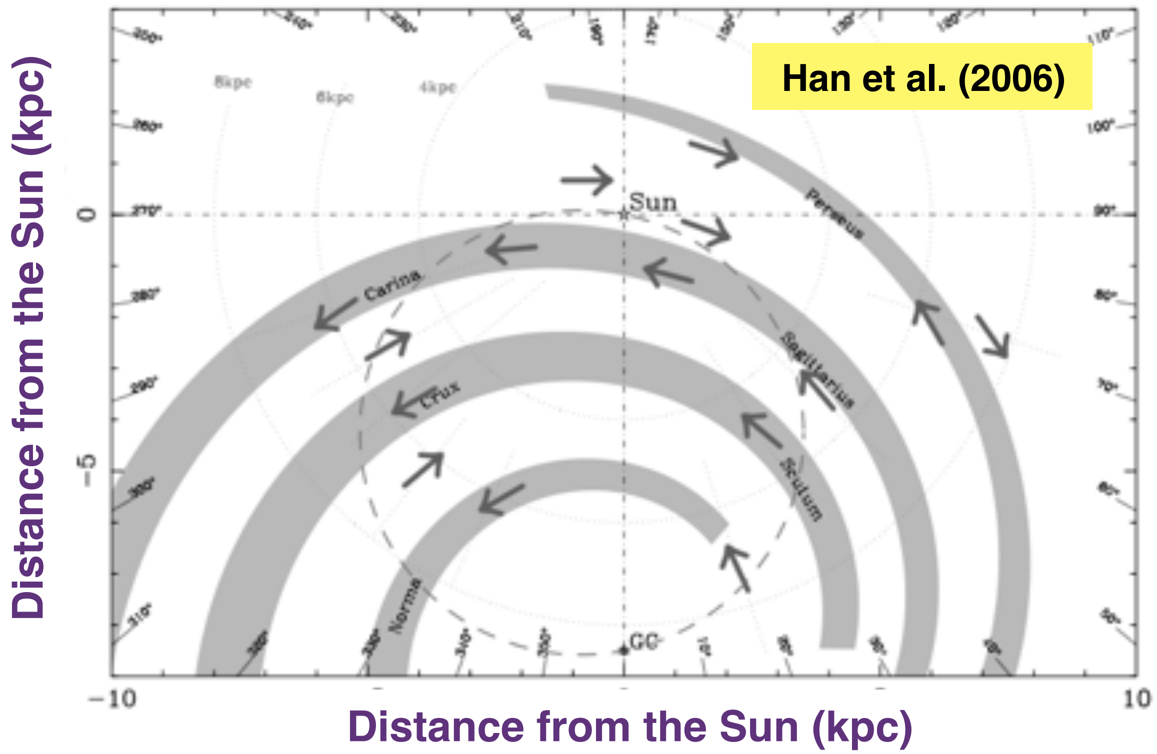


Magnetic fields in the Milky Way

Beck (2016)

- Coupled to the gas, provides balance with gravity, controls the propagation of cosmic rays
- Generated from primordial seed fields via a coupling of differential rotation and Coriolis force
- Superposition of a large-scale field following spiral arms and of a turbulent component

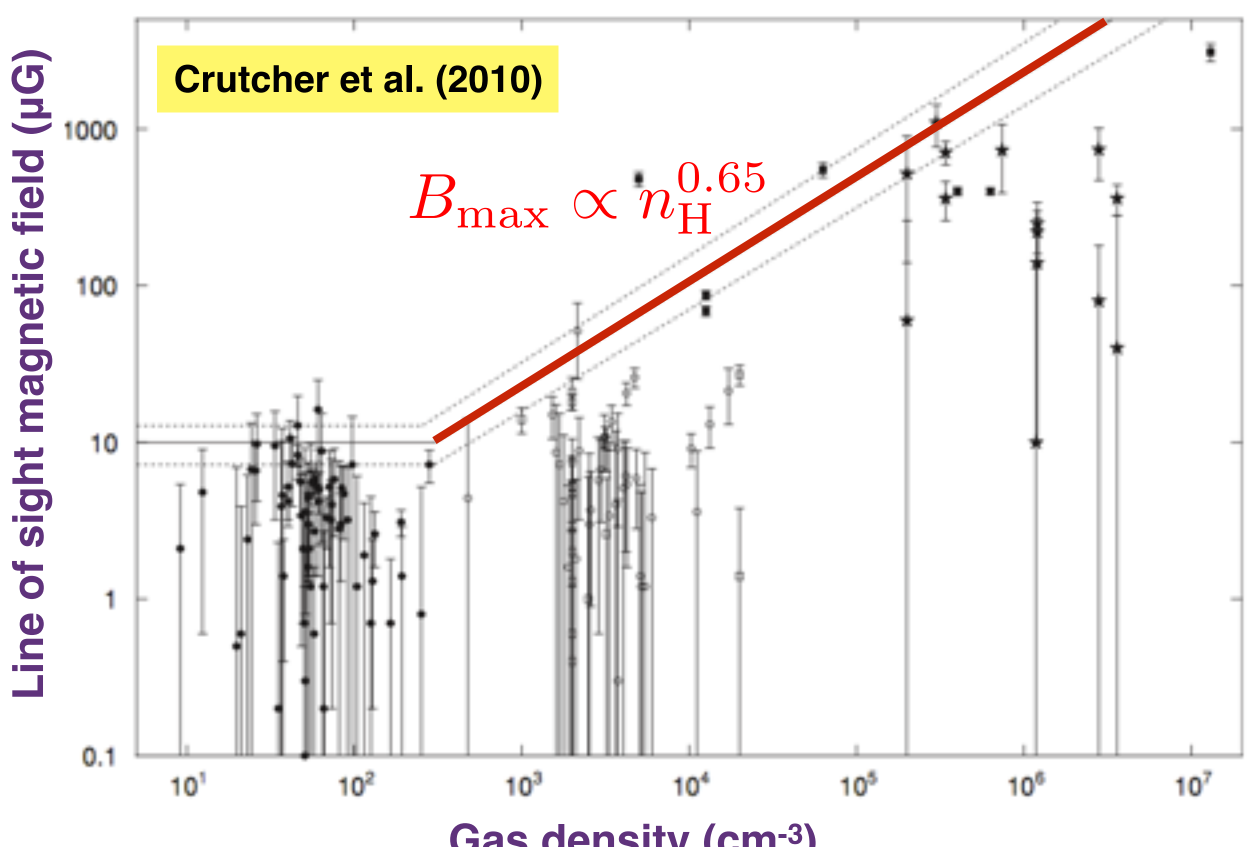
Field reversals



$$B = B_0 + B_t$$

$\sim$ a few μG $\sim$ a few μG

Haverkorn et al. (2008)

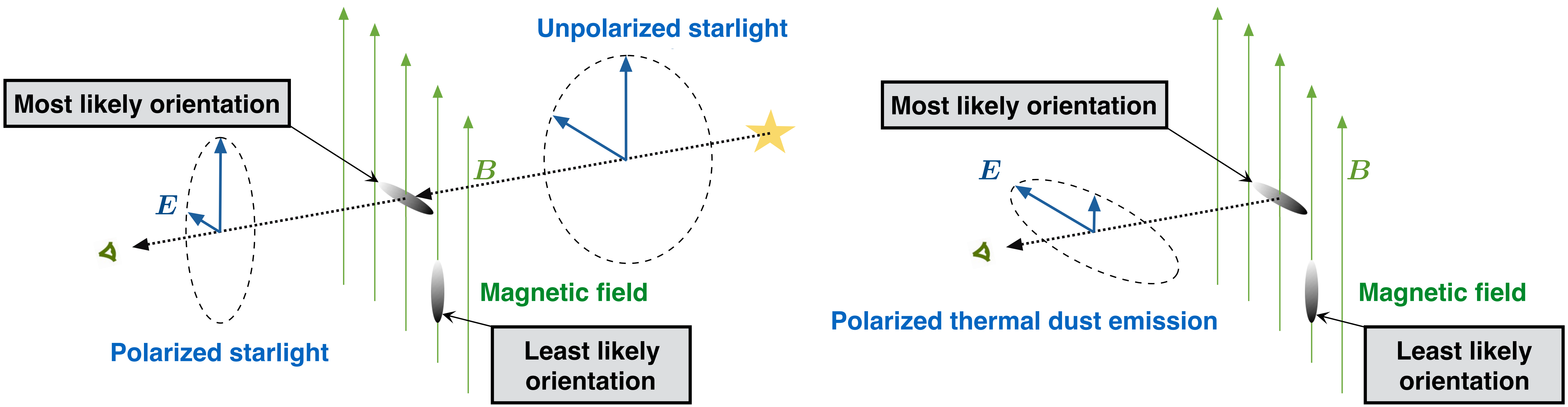


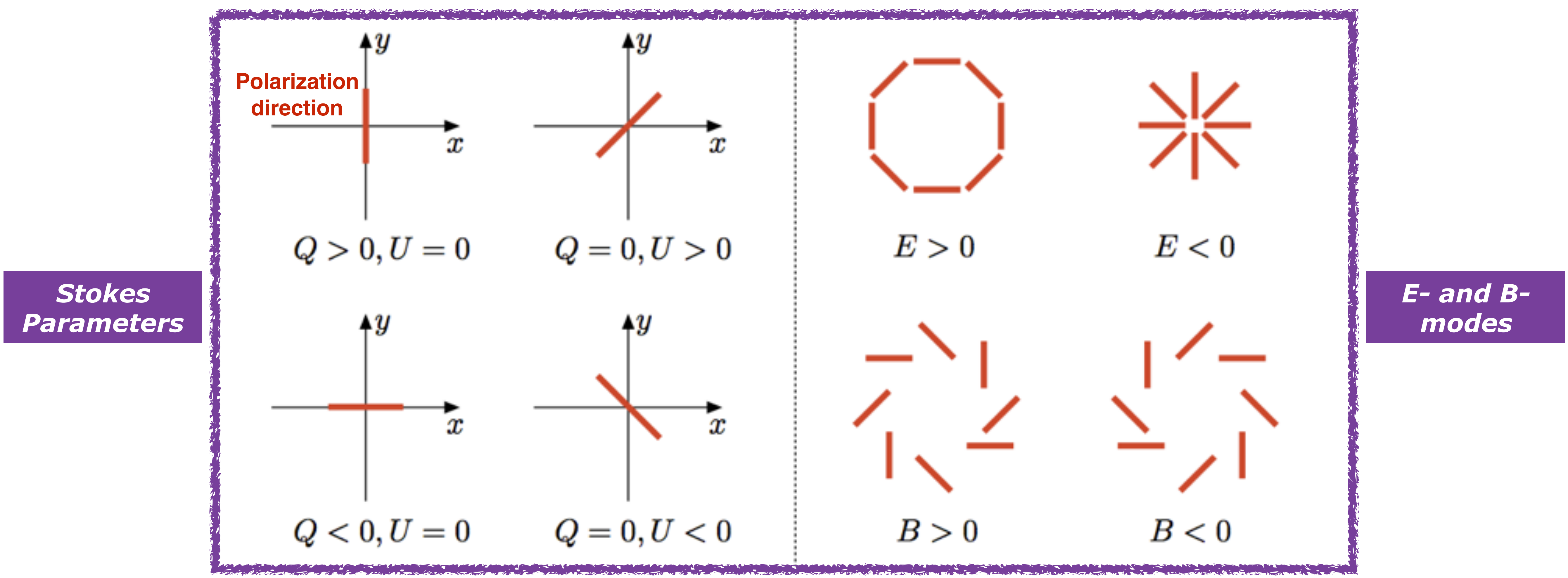
Measurement methods

Notation	Observational signatures
$B^2_{\rm tot,\perp} = B^2_{\rm turb,\perp} + B^2_{\rm reg,\perp}$	Total synchrotron intensity
$B^2_{\rm turb,\perp} = B^2_{\rm iso,\perp} + B^2_{\rm aniso,\perp}$	Total synchrotron emission, partly polarized
$B_{\rm iso,\perp}\ (= \sqrt{2/3}\,B_{\rm iso})$	Unpolarized synchr. intensity, beam depolarization, Faraday depolarization
$B_{\rm iso,\parallel}\ (= \sqrt{1/3}\,B_{\rm iso})$	Faraday depolarization
$B^2_{\rm ord,\perp} = B^2_{\rm aniso,\perp} + B^2_{\rm reg,\perp}$	Intensity and vectors of radio, optical, IR & submm pol.
$B_{\rm aniso,\perp}$	Intensity and vectors of radio, optical, IR & submm pol., Faraday depolarization
$B_{\rm reg,\perp}$	Intensity and vectors of radio, optical, IR & submm pol., Goldreich-Kylafis effect
$B_{\rm reg,\parallel}$	Faraday rotation + depol., longitudinal Zeeman effect

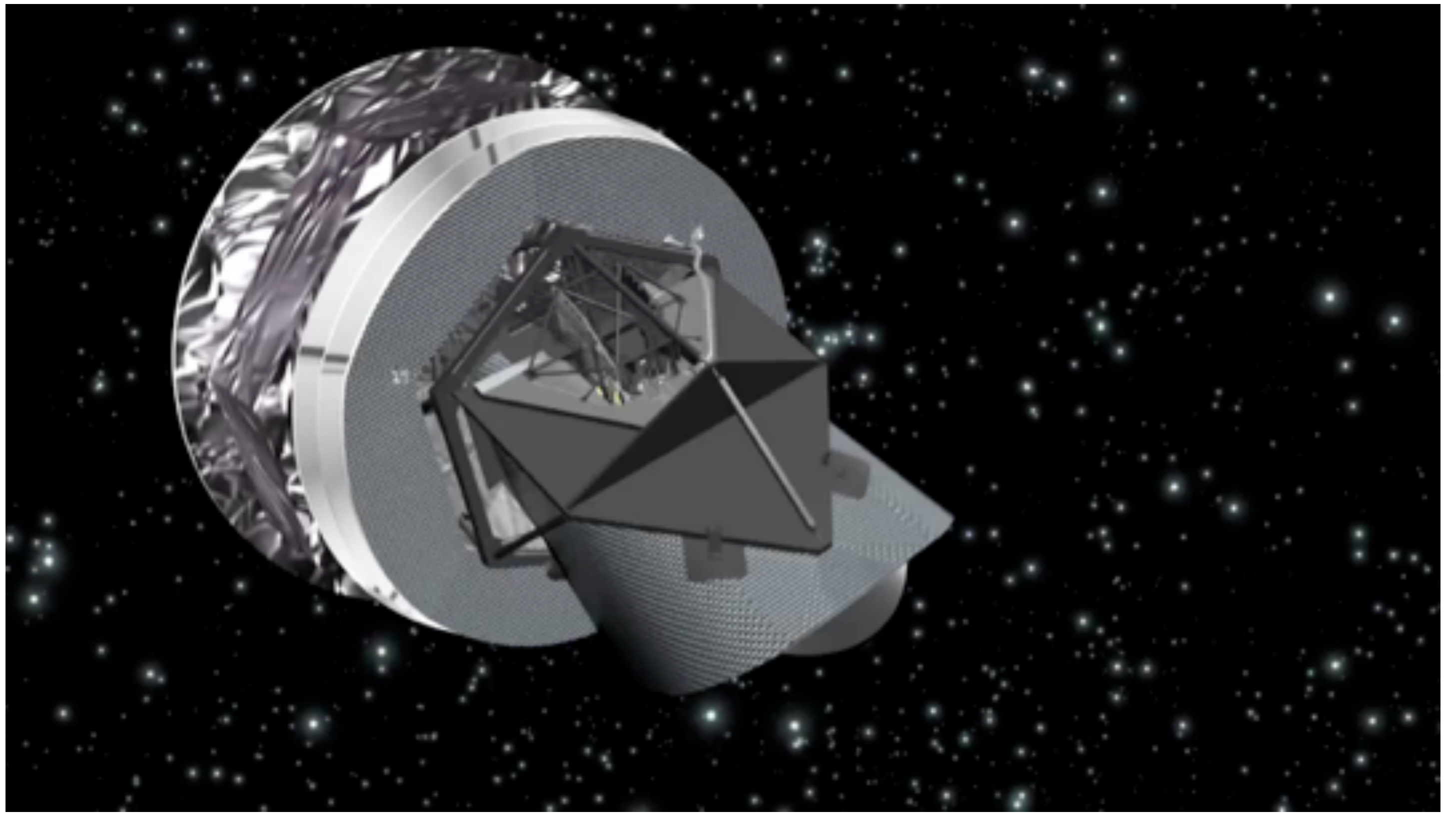
Dust, magnetic fields and polarization

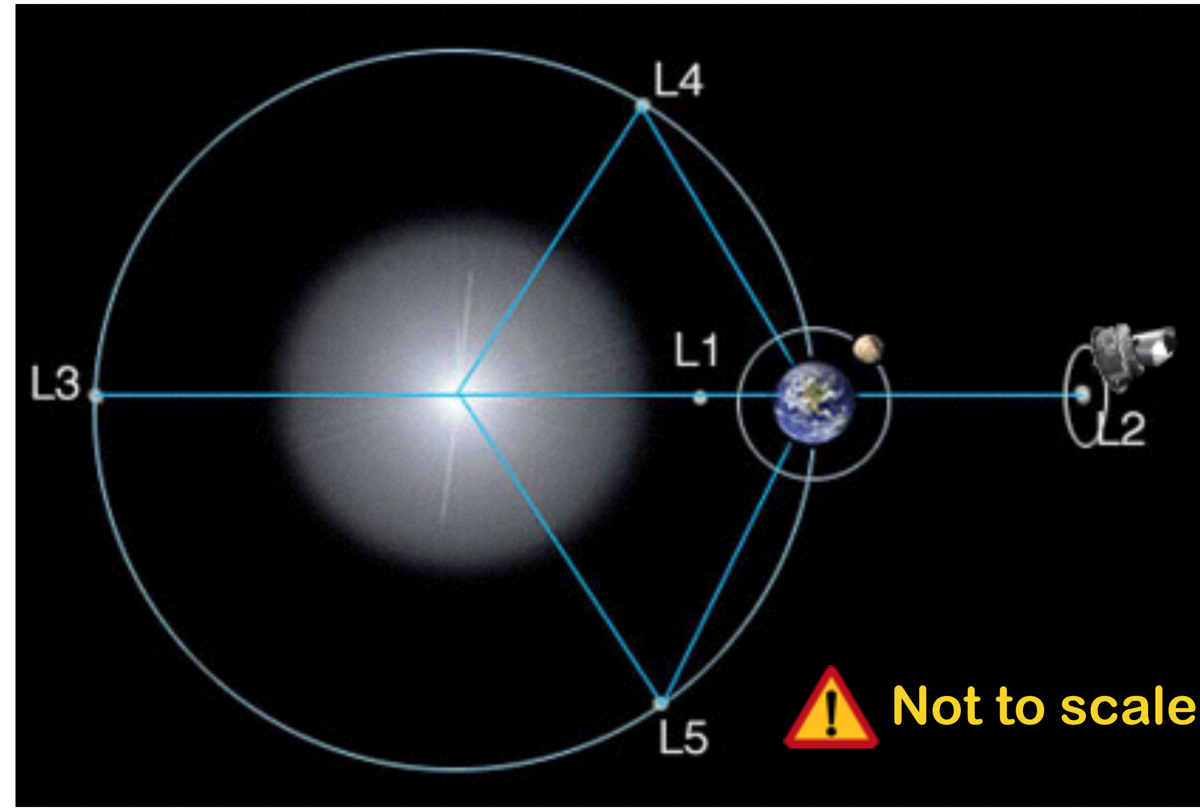
- Aspherical, charged, rotating dust grains statistically align in the local magnetic field
- Background starlight emerges polarized parallel to the magnetic field
- Polarized thermal dust emission arises perpendicularly to the magnetic field



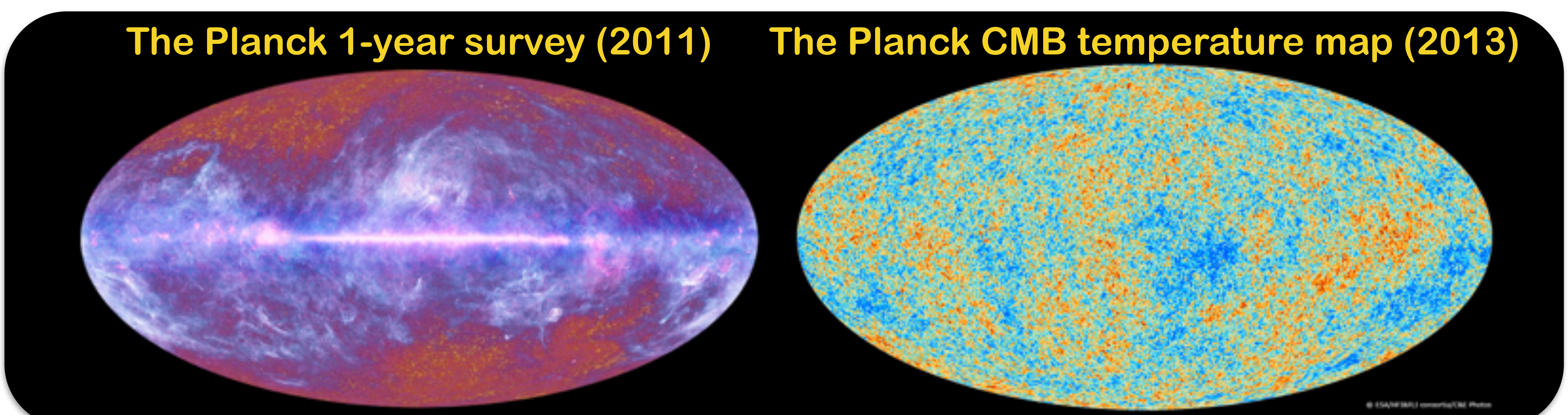


The Planck mission

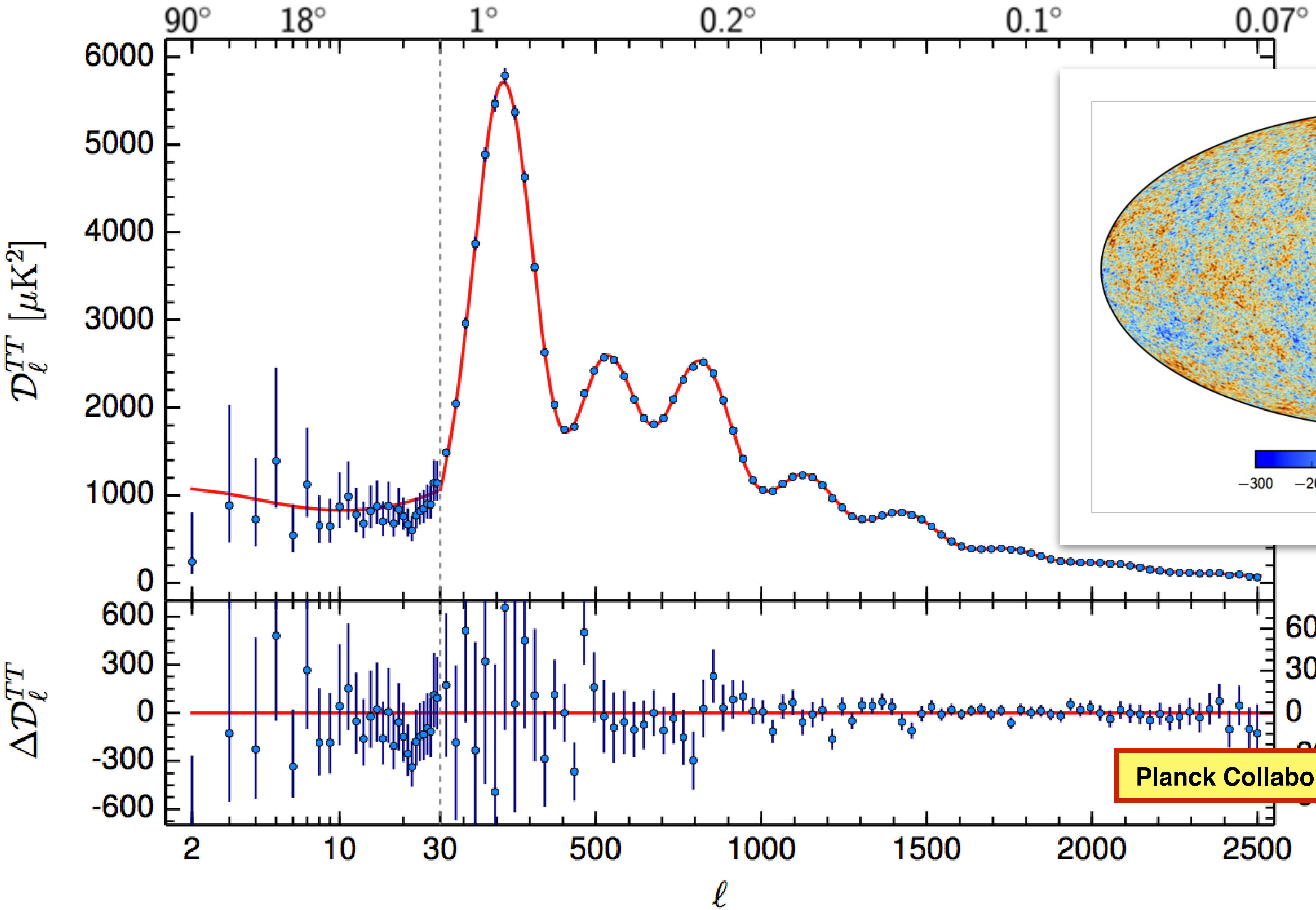


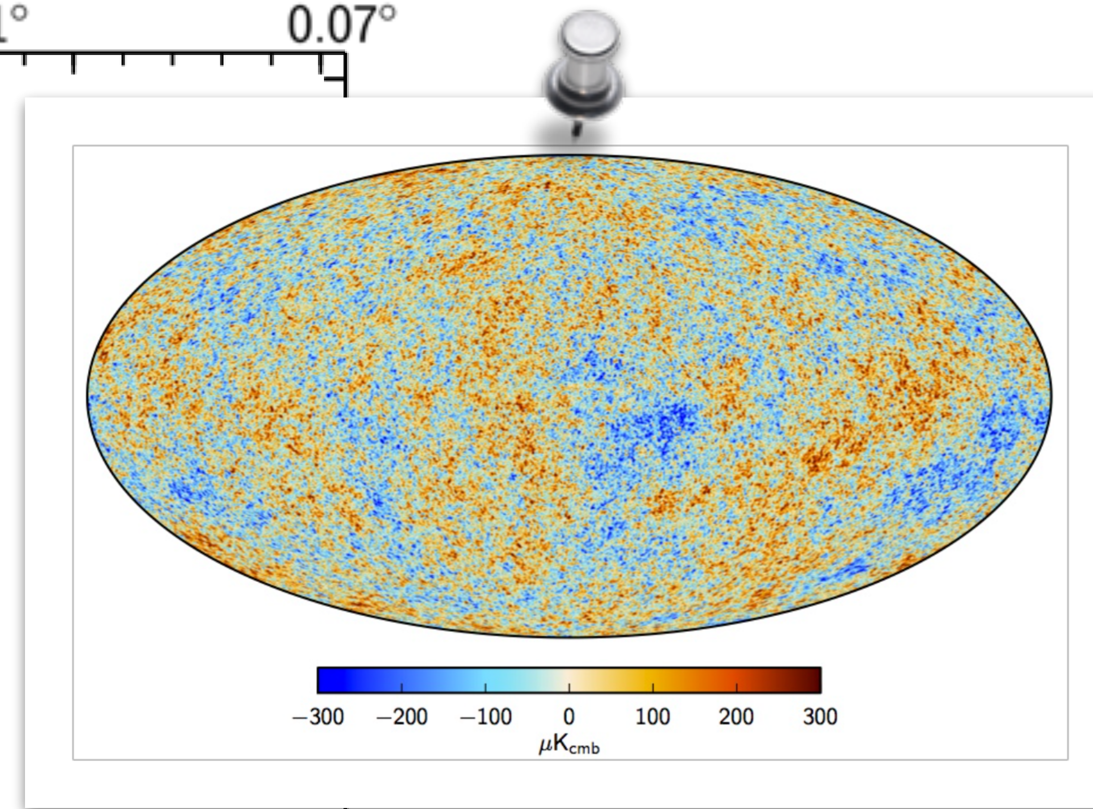


- 2009-2013 European space mission : Full survey of the microwave sky
- 30 - 857 GHz coverage in nine bands
- Measurement of Cosmic Microwave Background (CMB) anisotropies
- Mapping of the cold, dusty Milky Way
- First full-sky survey in microwave polarization



The « ultimate » CMB temperature mission





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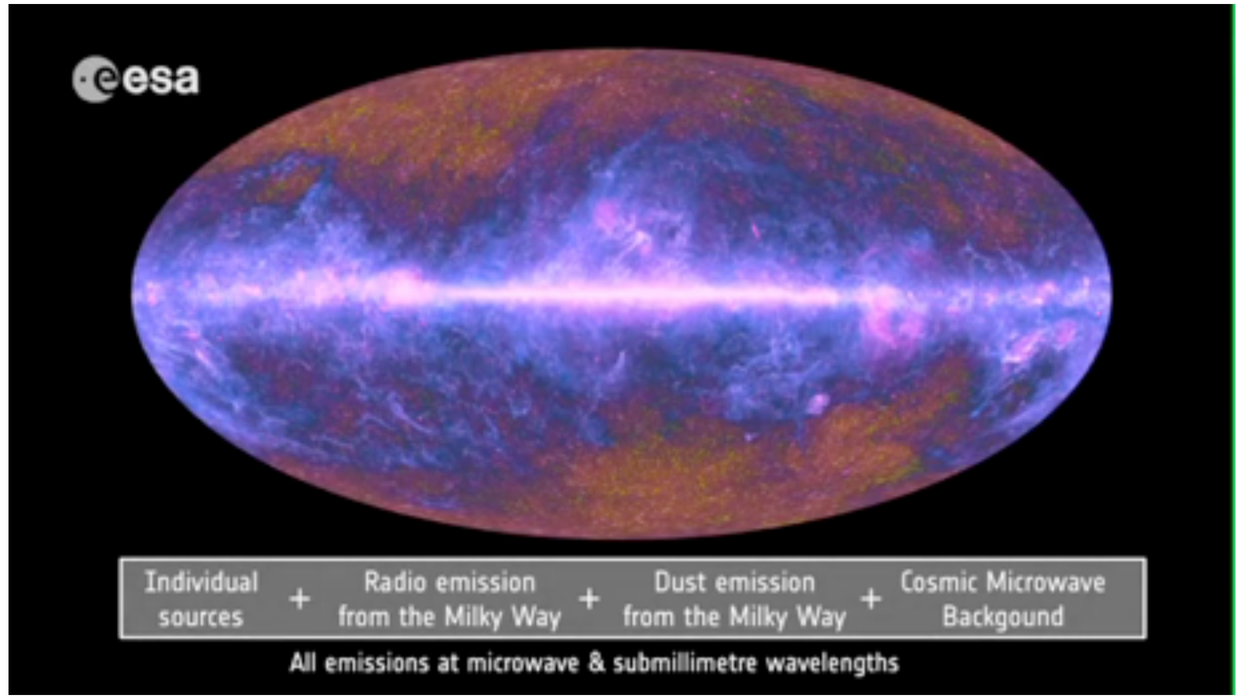
- Mapping of CMB anisotropies of order 10^{-5}
- Measurement of the power as a function of angular scale
- Excellent agreement with the 6-parameter Λ-CDM model
- No hint for a necessity to extend the model

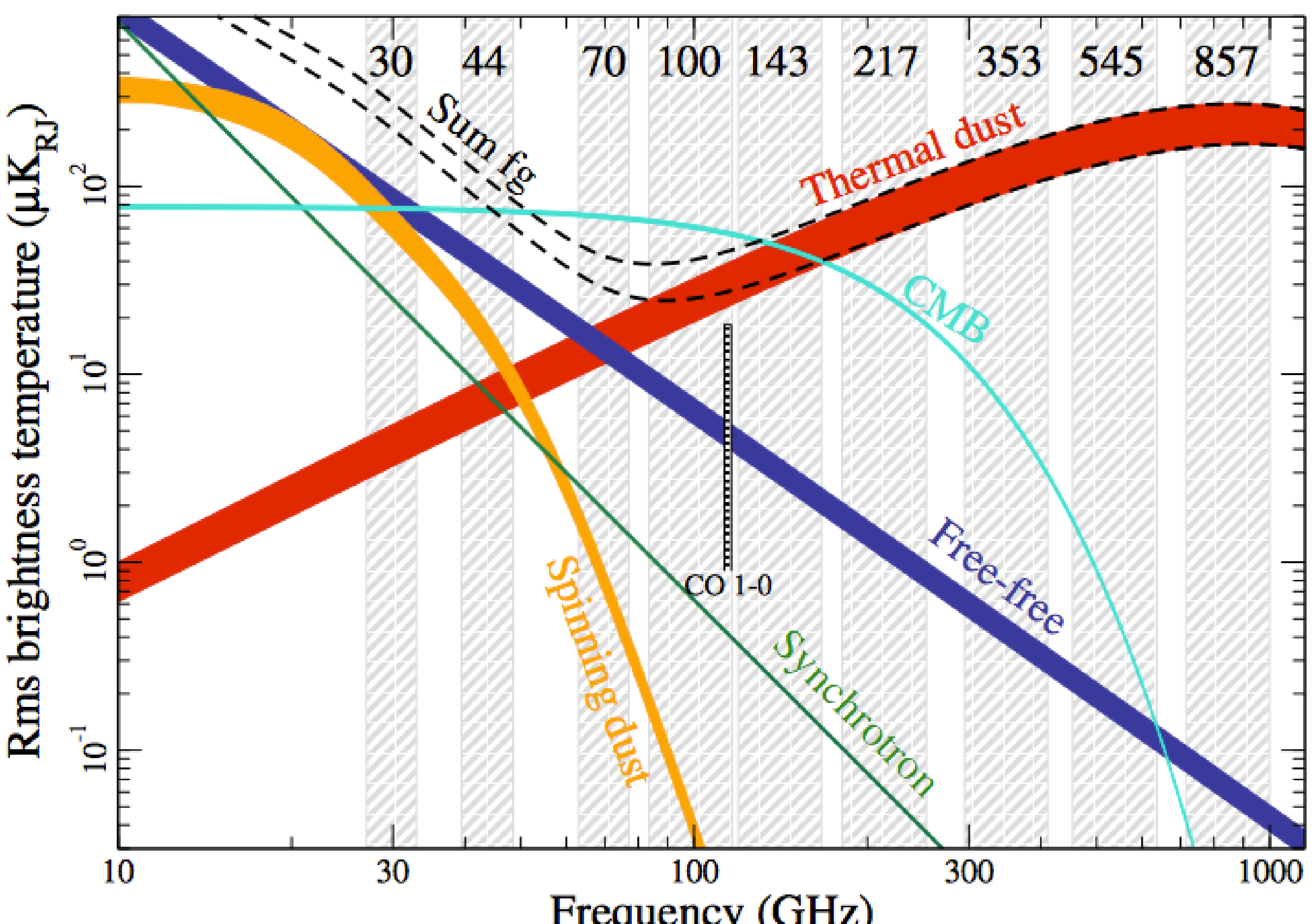
Planck Collaboration XIII (2016)

$\Omega_b h^2$	0.02230 ± 0.00014
$\Omega_c h^2$	0.1188 ± 0.0010
$100\theta_{MC}$	1.04093 ± 0.00030
τ	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.064 ± 0.023
n_s	0.9667 ± 0.0040

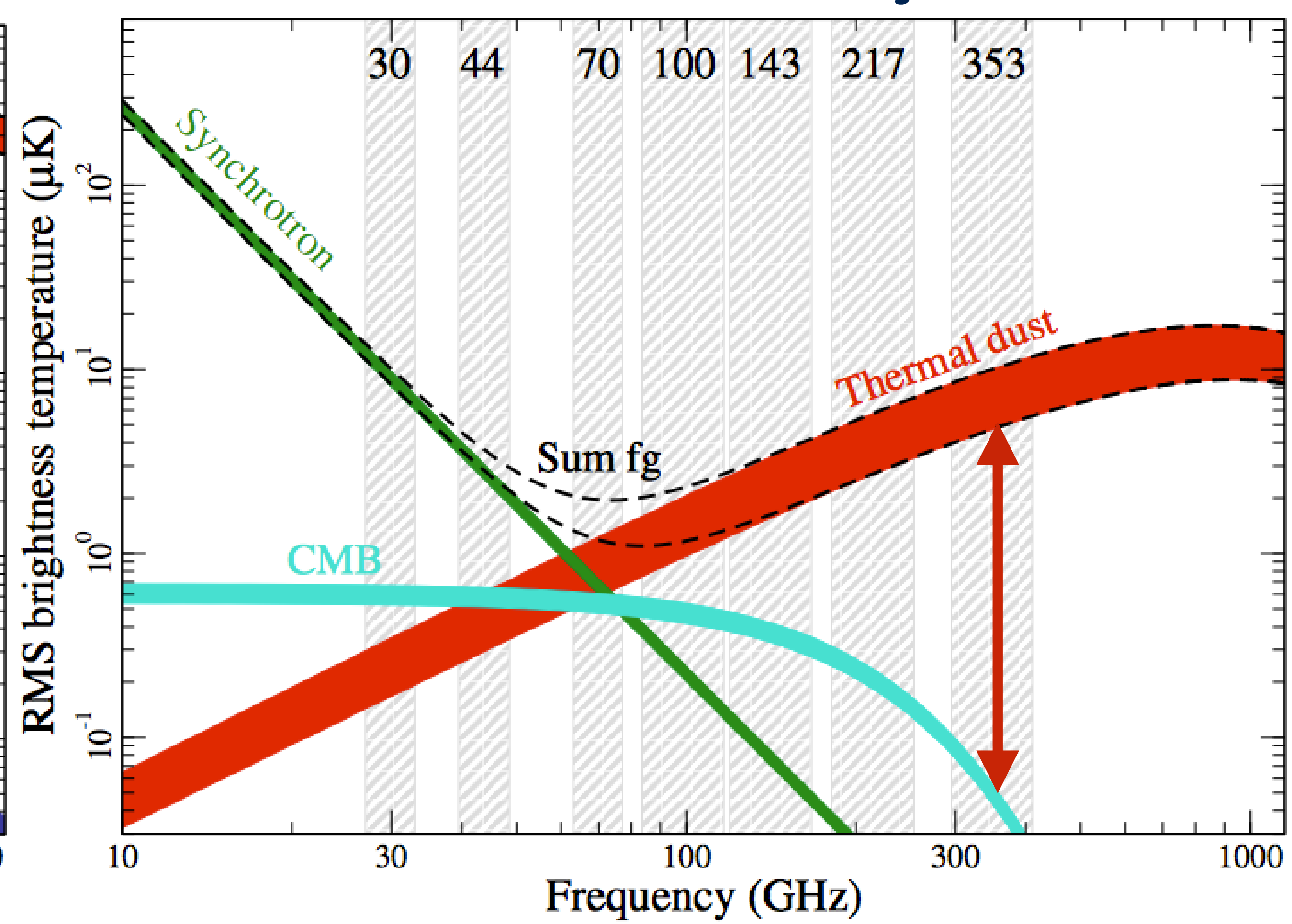
Galactic dust emission : a foreground to the CMB



Total intensity



Polarized intensity



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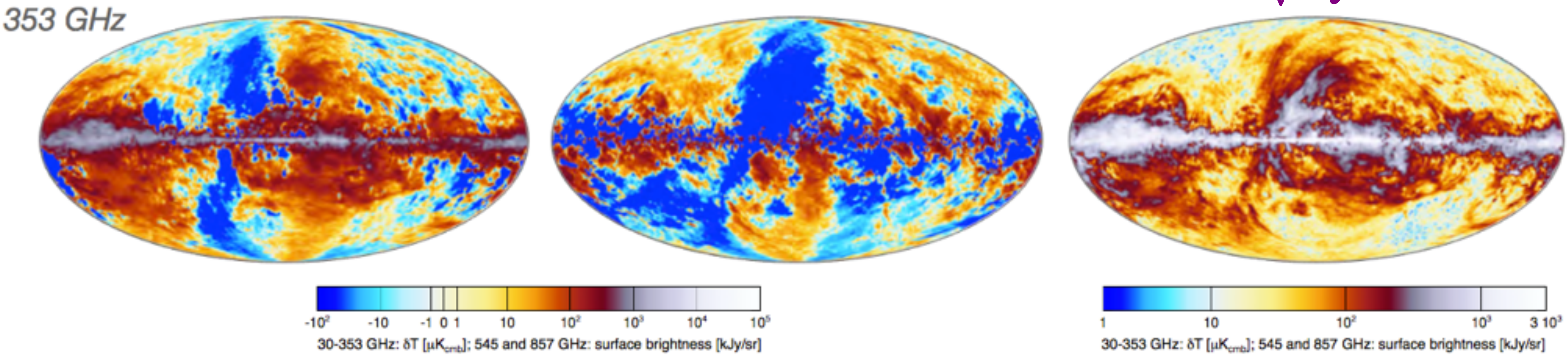
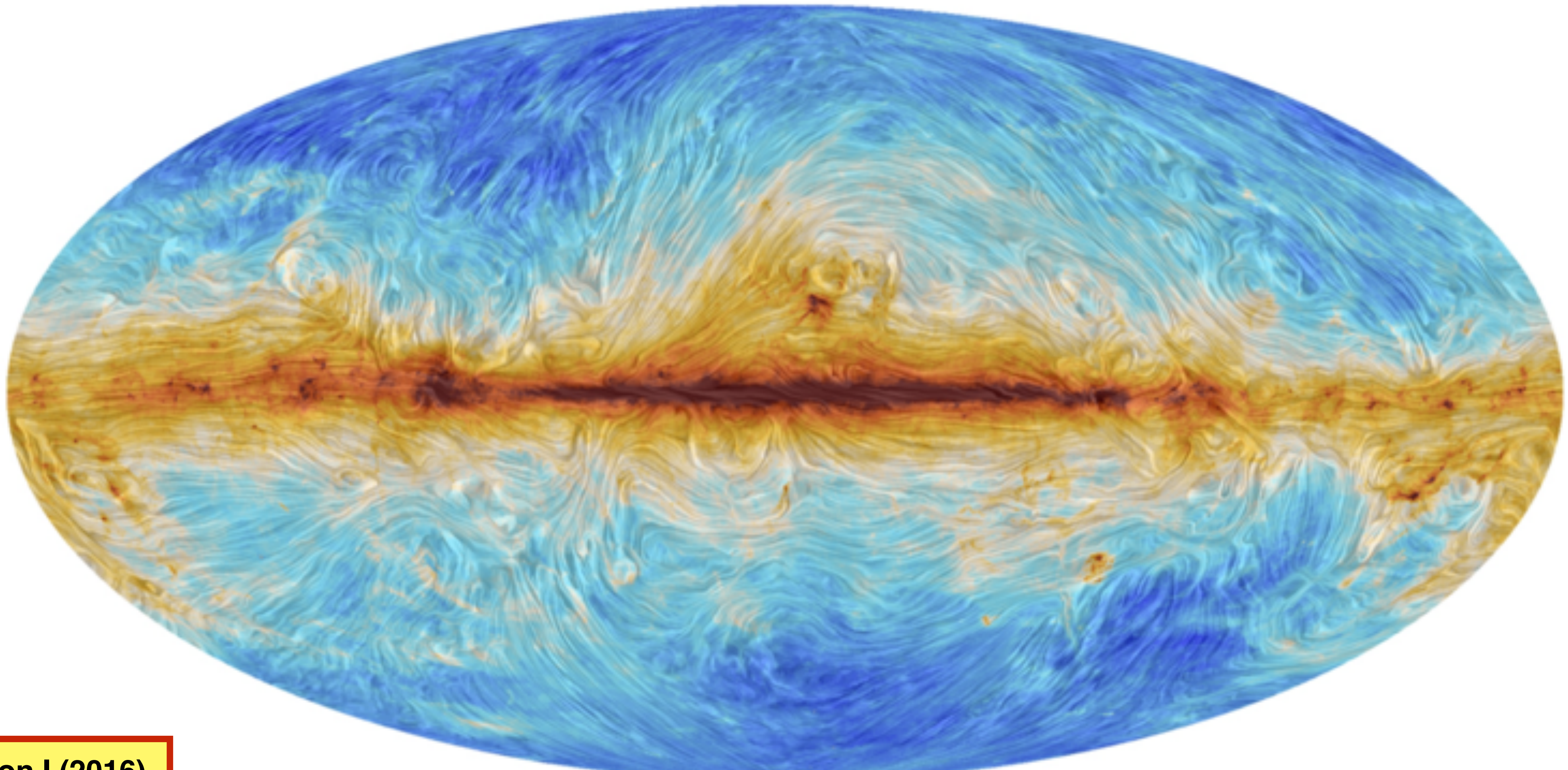
The Planck view of the Galactic magnetic field

Q U $P = \sqrt{Q^2 + U^2}$



Total intensity and « drapery » showing the direction of the magnetic field



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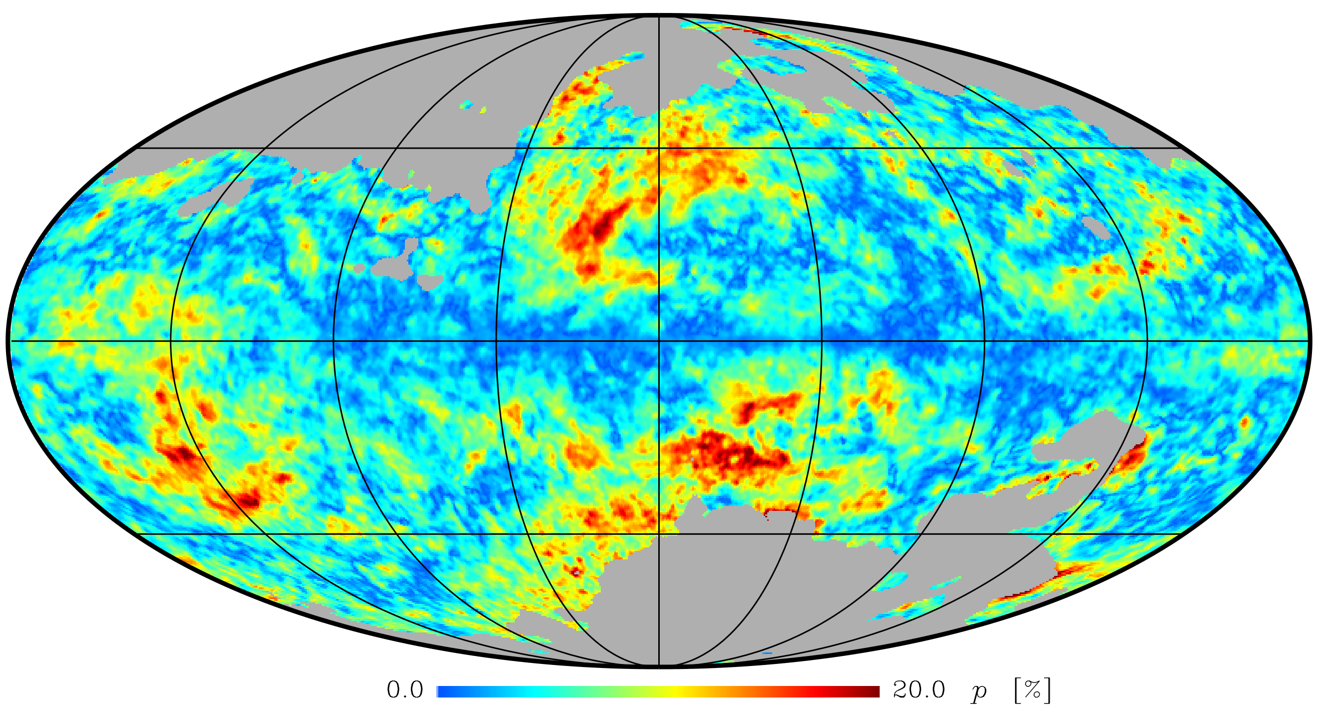
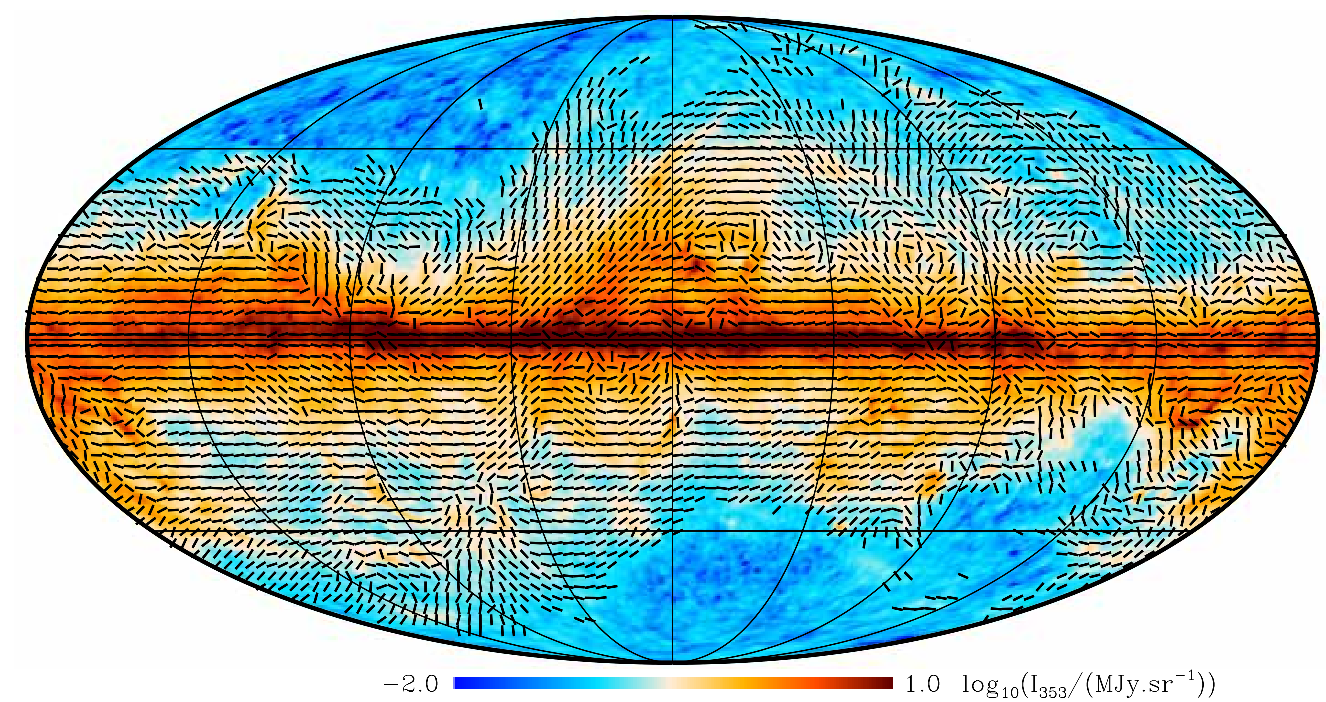
Properties of large-scale thermal dust polarization

- Low polarization fractions in the Galactic Plane and some highly polarized regions
- Thin filamentary structures of low polarization with no material counterpart

Polarization fraction $p = \frac{P}{I}$

Polarization angle $\psi = \frac{1}{2}\mathrm{atan}(U, Q)$



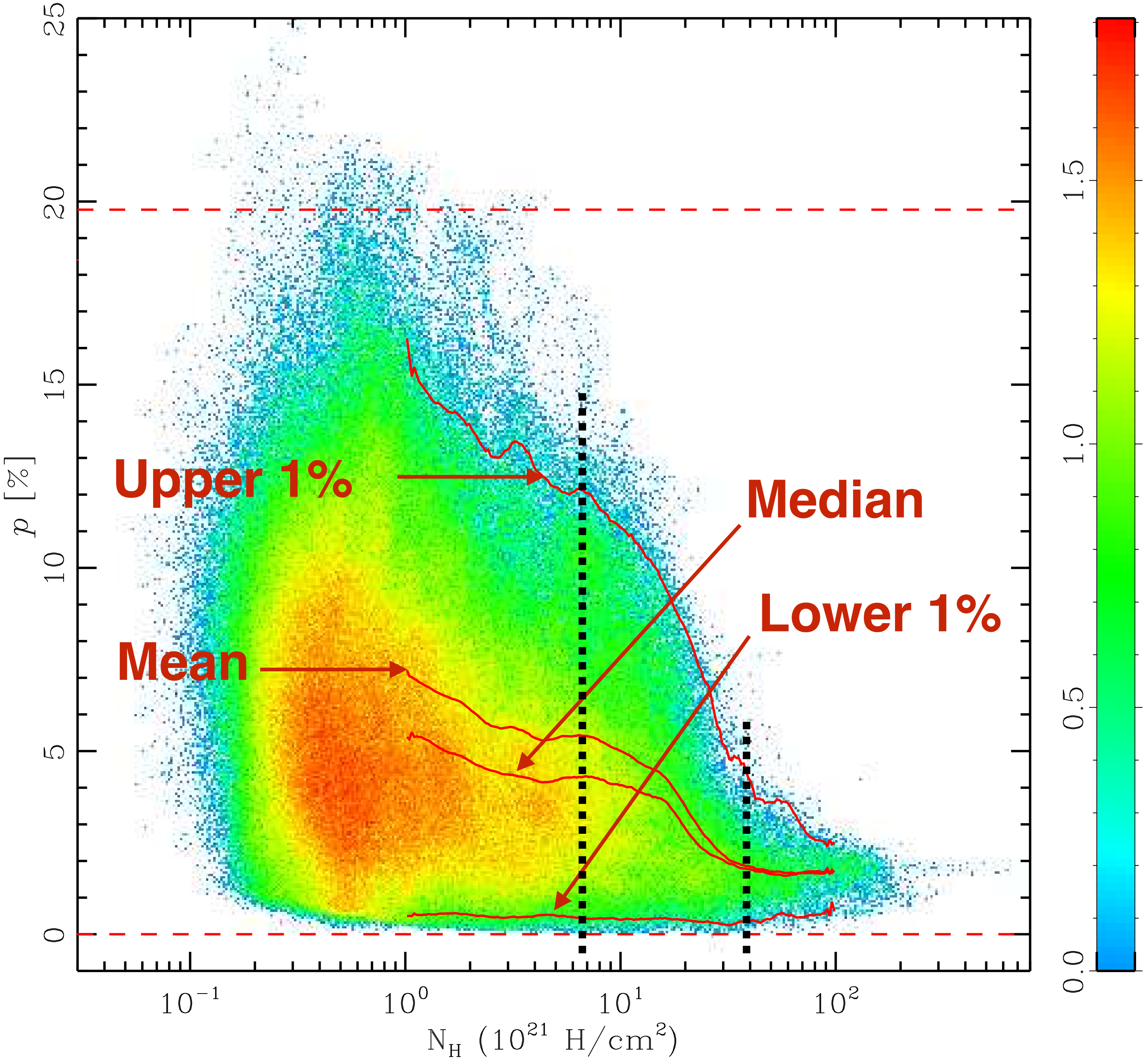


Update expected in 2017…

Planck Collaboration Int. XIX (2015)

Polarization fraction vs. column density

- Intrinsic dust polarization at least of order 20%
- Decrease of the maximum polarization fraction with increasing column density



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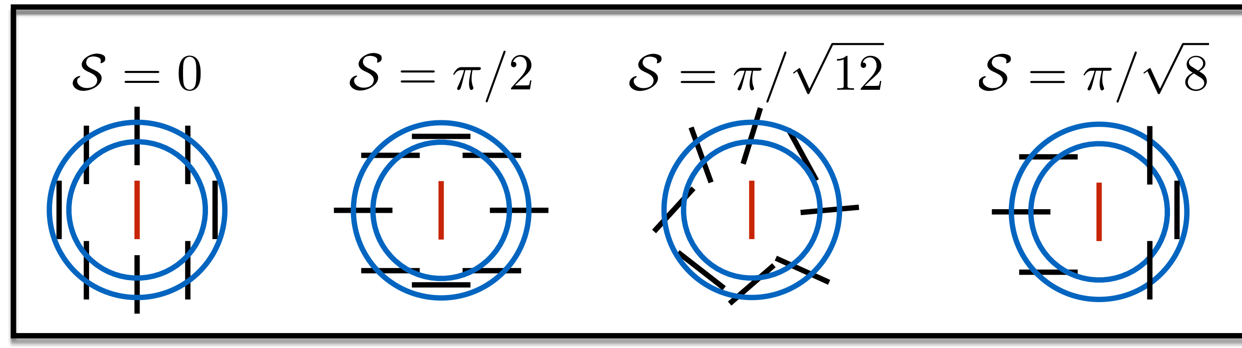
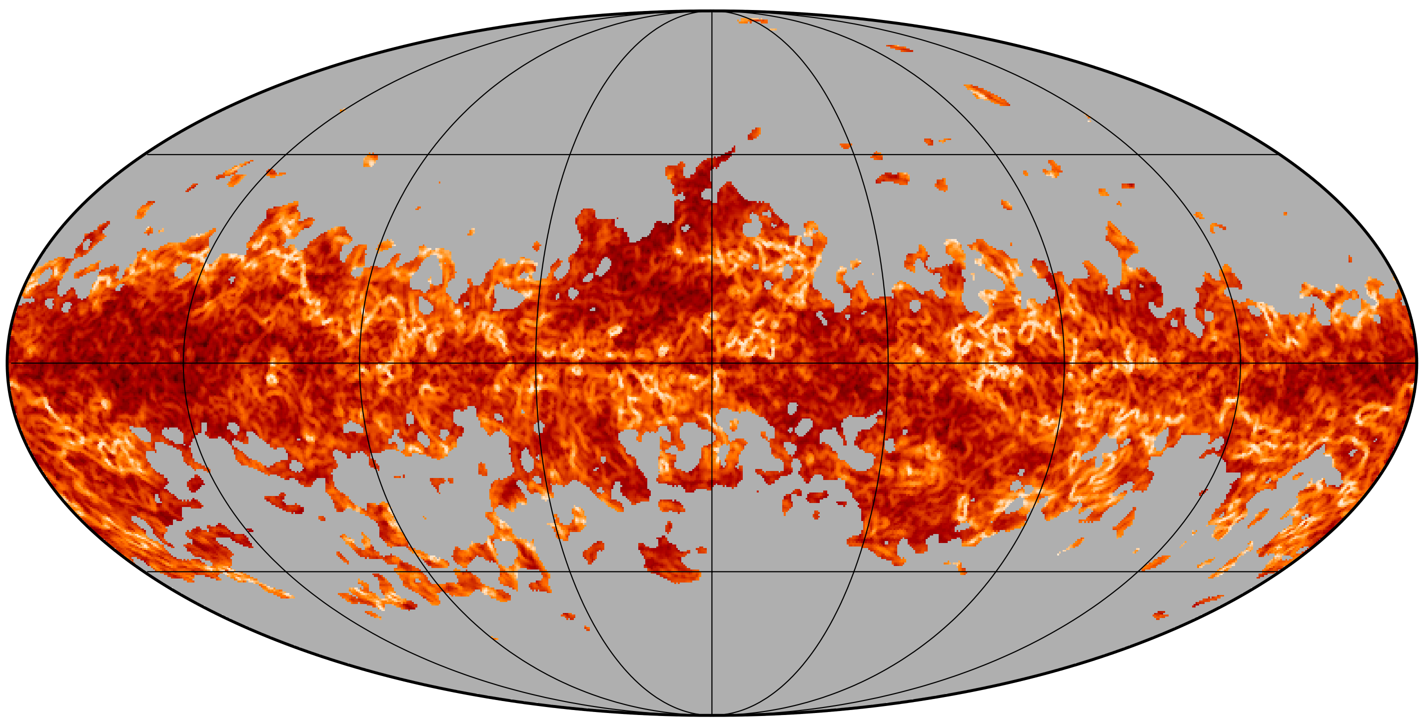
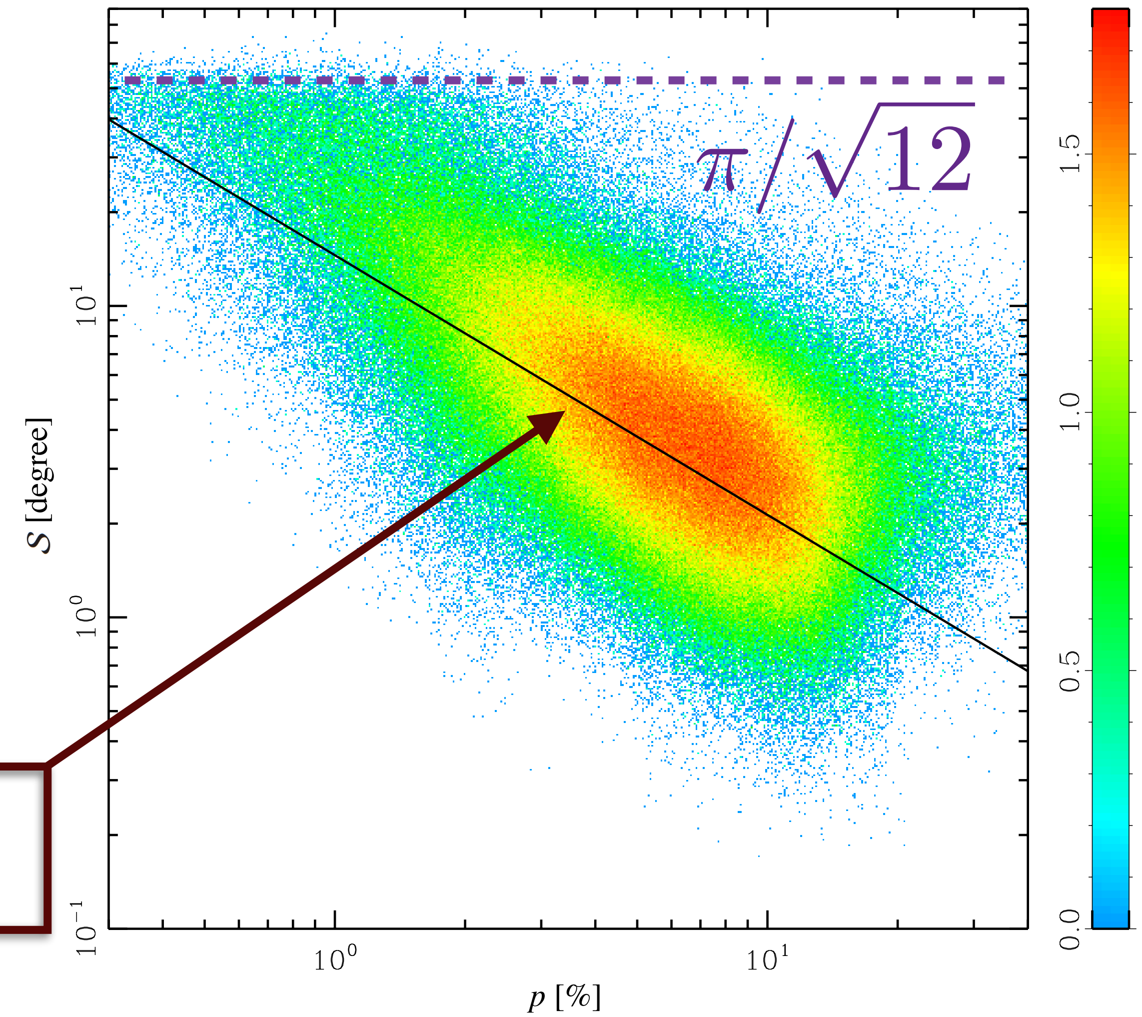
Spatial structure of the polarization angle map

Polarization angle dispersion function

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





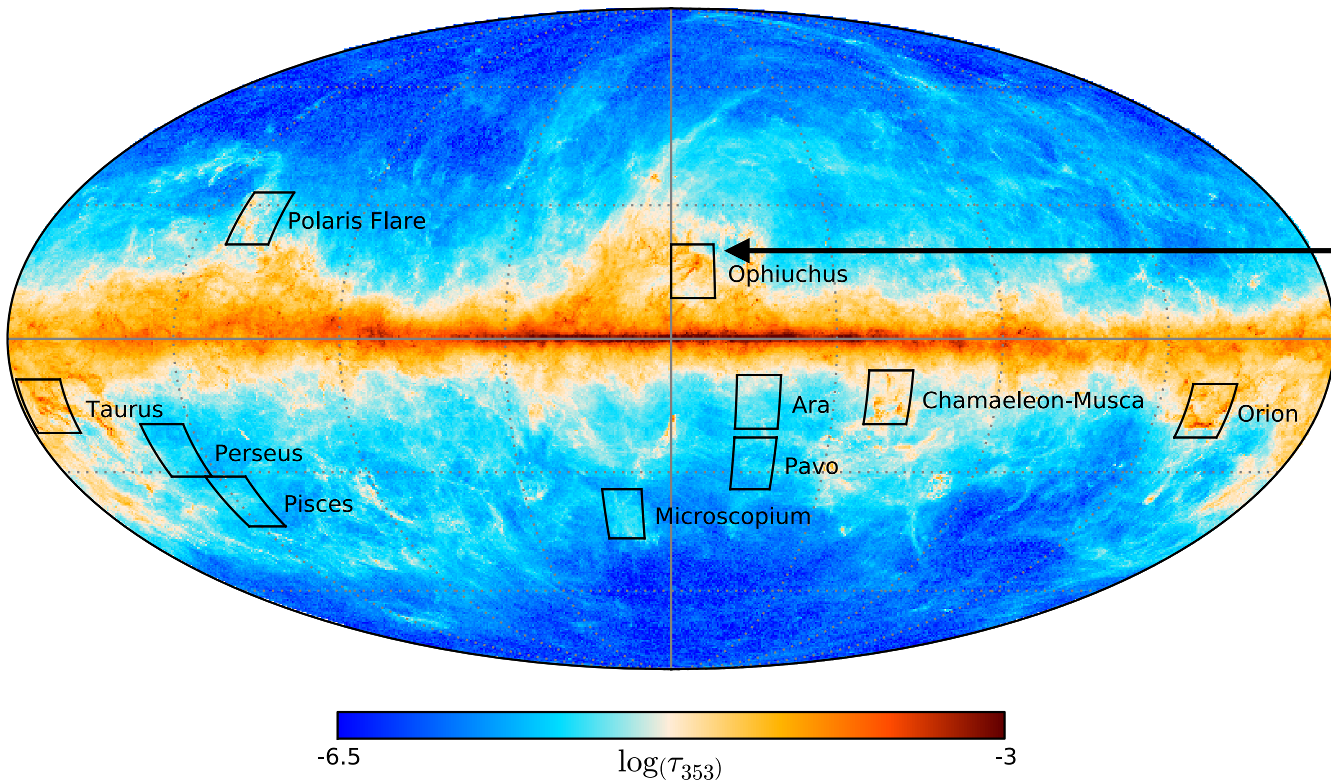


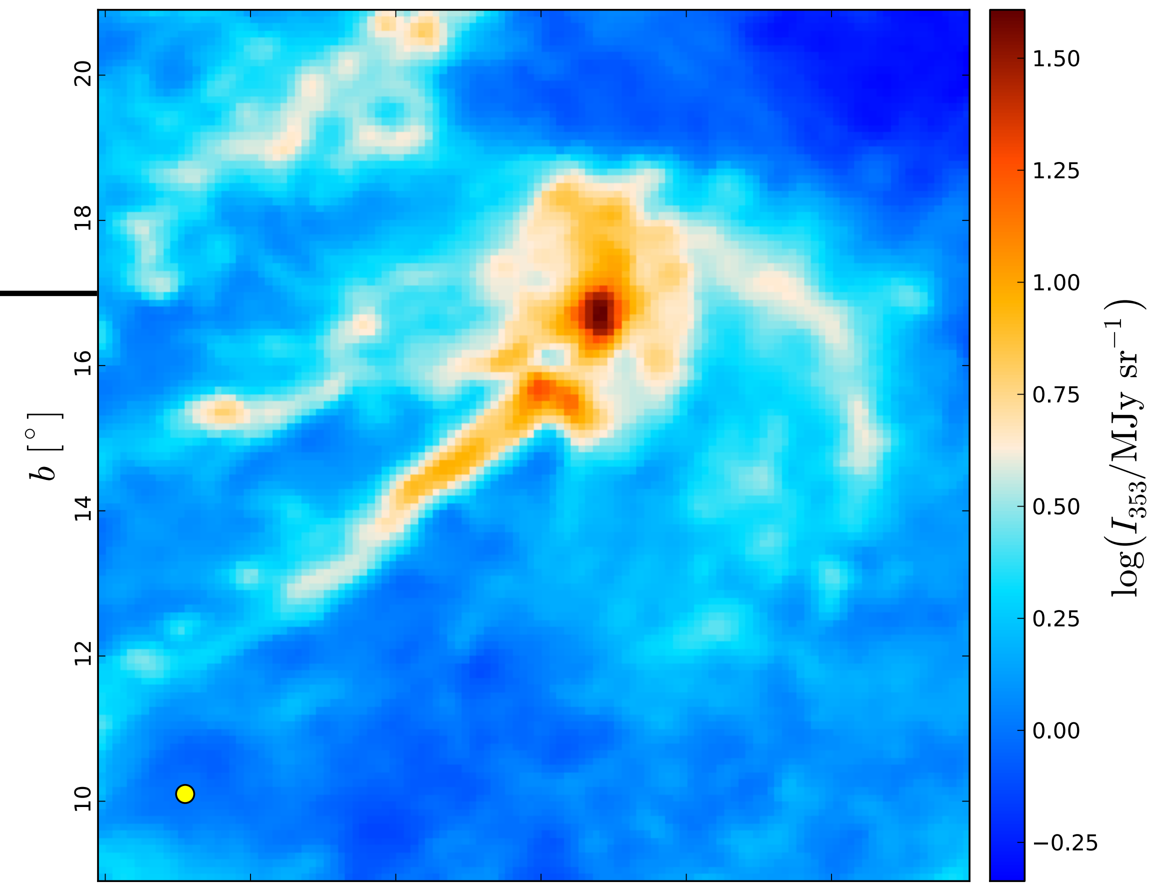
$$\log(\mathcal{S}/\,\mathrm{deg}) = -0.834\log p - 0.504$$

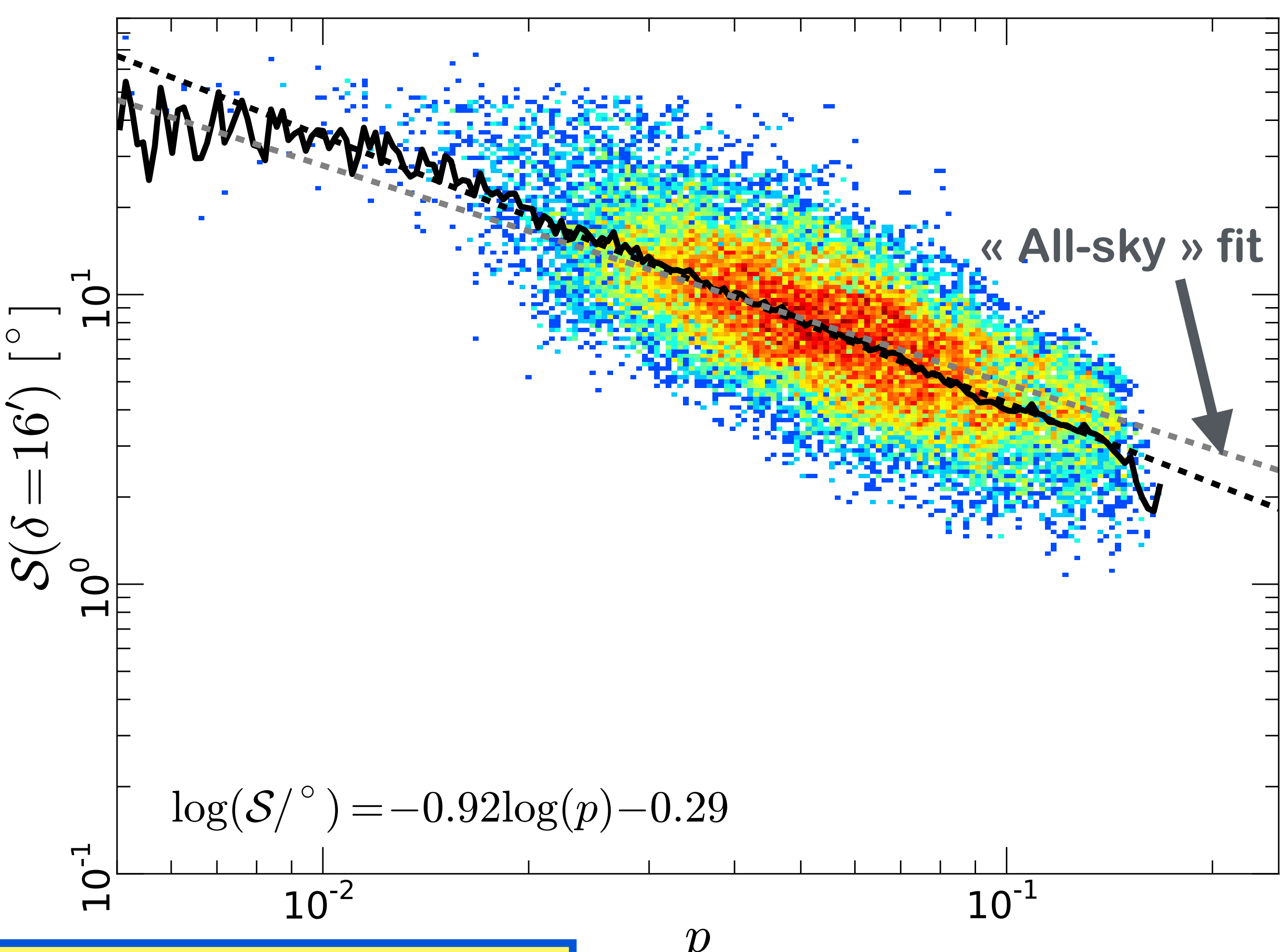
- Strongly anti-correlated with the polarization fraction
- Low polarization fractions found where the polarization angle direction changes abruptly
- Increased lag δ flattens the anti-correlation

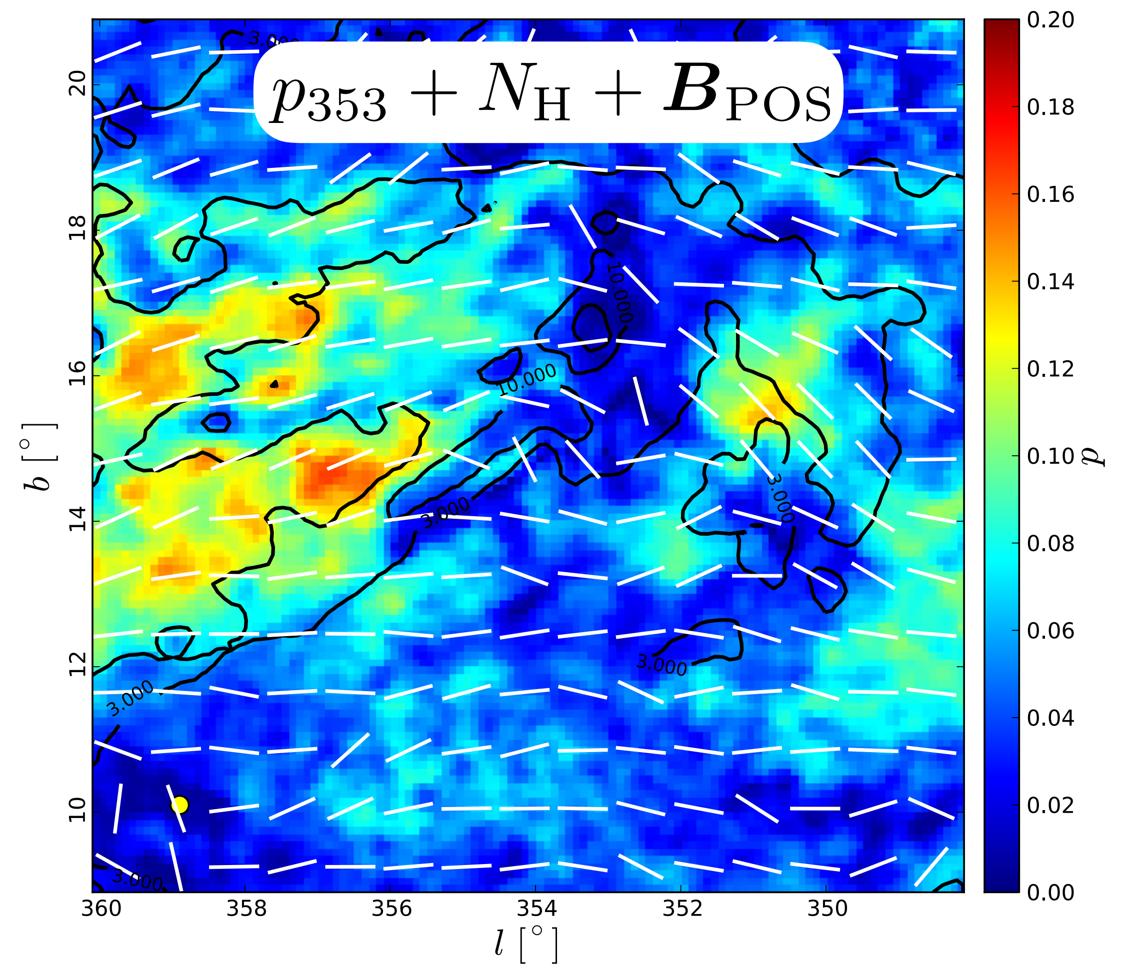
Planck Collaboration Int. XIX (2015)

Thermal dust polarization towards molecular clouds









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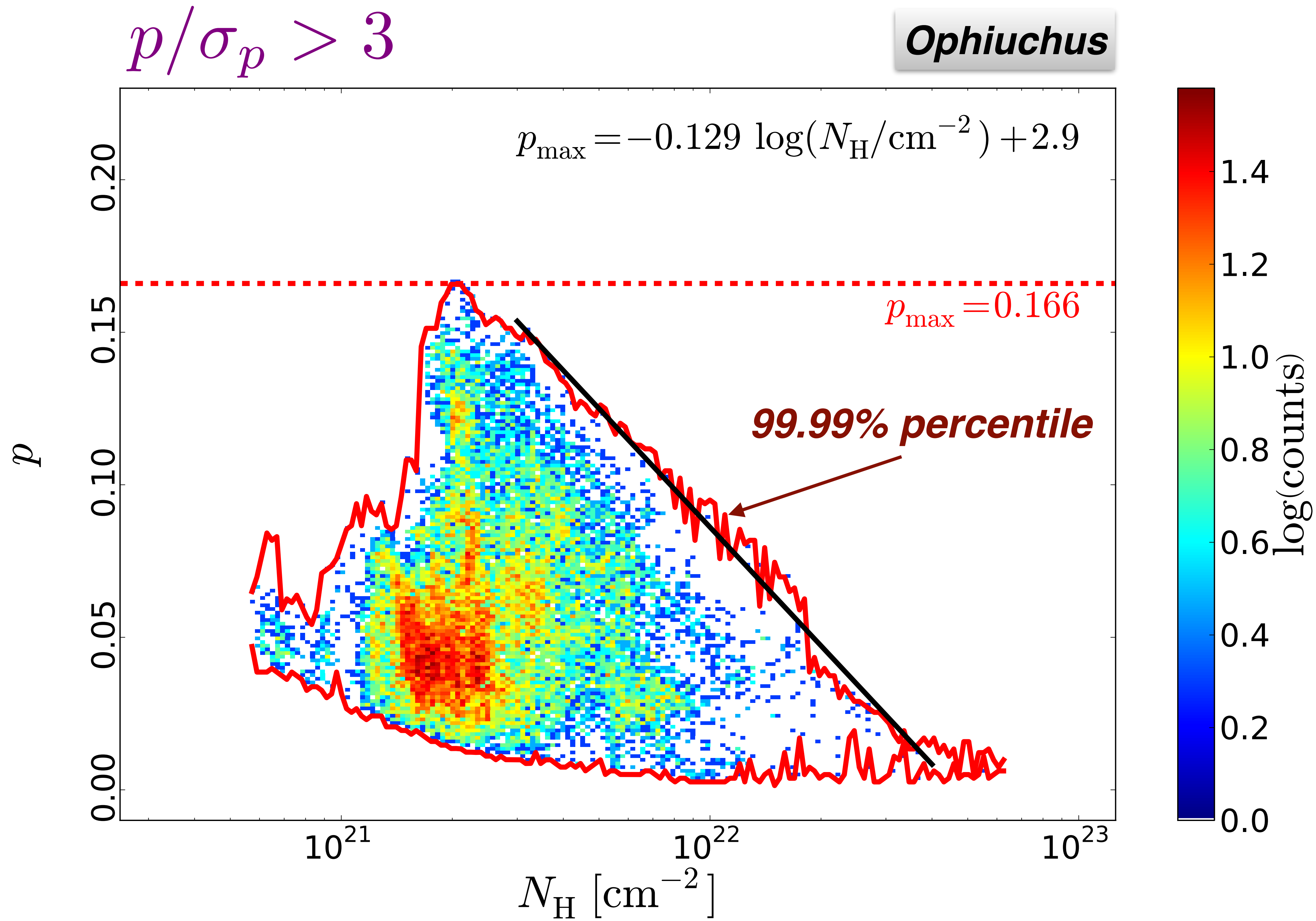
Maximum polarization fraction vs. column density



Anti-correlation robust with respect to polarization S/N

Planck Collaboration Int. XX (2015)

Comparison with a simulation of anisotropic MHD turbulence

starformat.obspm.fr

Hennebelle et al. (2008)

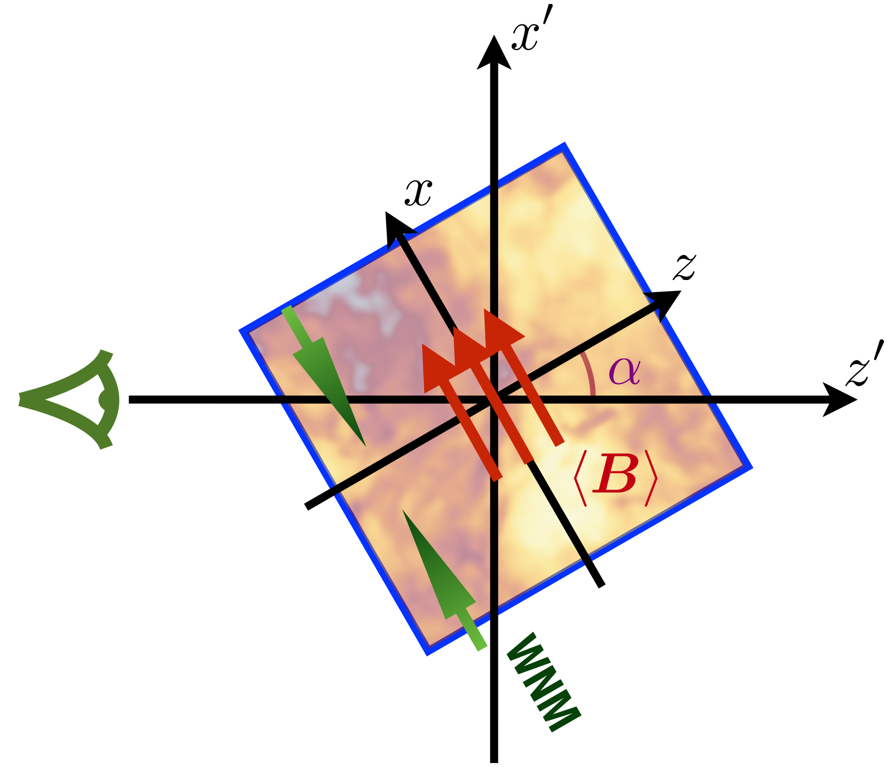
- MHD turbulence simulation with self-gravity using RAMSES
- An 18 pc subset of a 50 pc simulation cube
- Converging flows of magnetized warm gas
- Mean magnetic field along the flows
- Rotation of the cube, placed at 100 pc distance
- Uniform dust temperature and intrinsic polarization
- Simulated Stokes maps at 353 GHz smoothed at 15’

$$I = \int S_\nu e^{-\tau_\nu} \left[1 - p_0 \left(\cos^2\gamma - \frac{2}{3}\right)\right] \mathrm{d}\tau_\nu$$

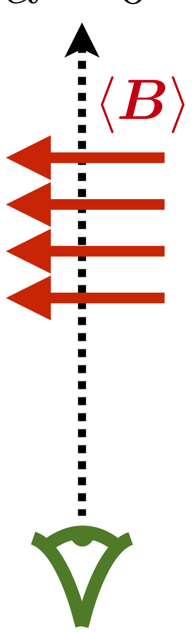
$$Q = \int p_0 S_\nu e^{-\tau_\nu} \cos\left(2\phi\right) \cos^2\gamma \mathrm{d}\tau_\nu$$

$$U = \int p_0 S_\nu e^{-\tau_\nu} \sin\left(2\phi\right) \cos^2\gamma \mathrm{d}\tau_\nu$$

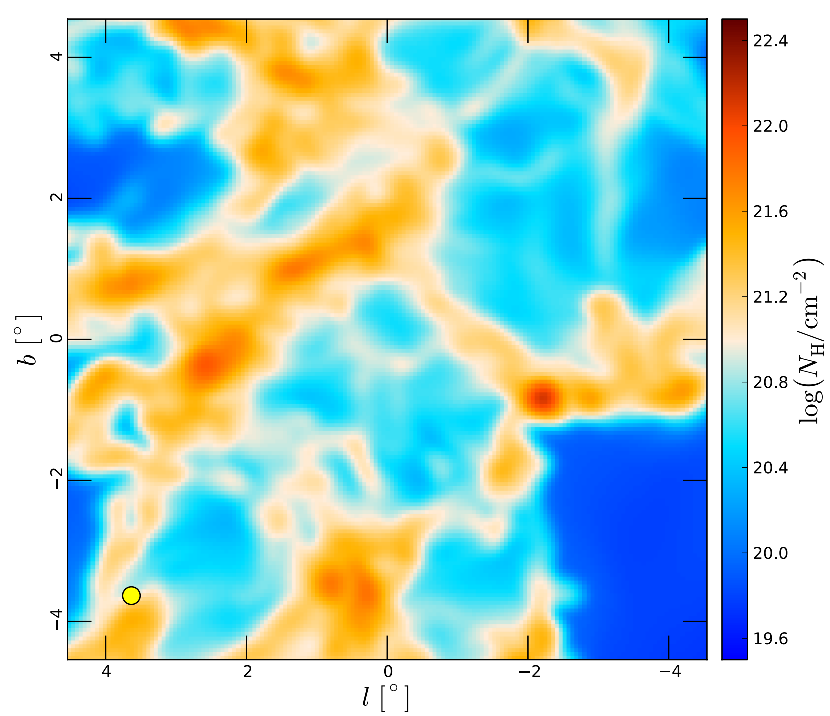
$$p_0 = 0.20$$



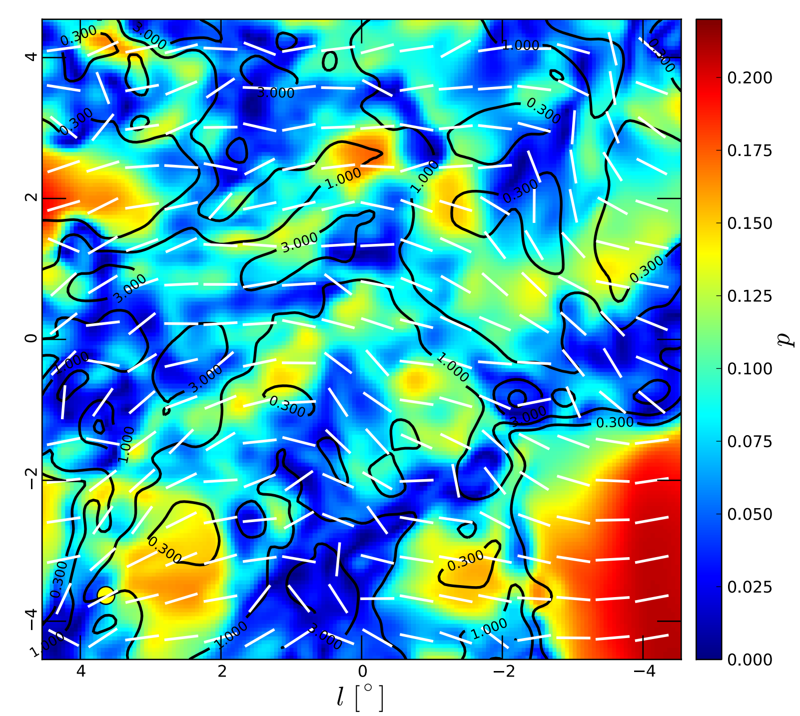
$\alpha = 0^\circ$



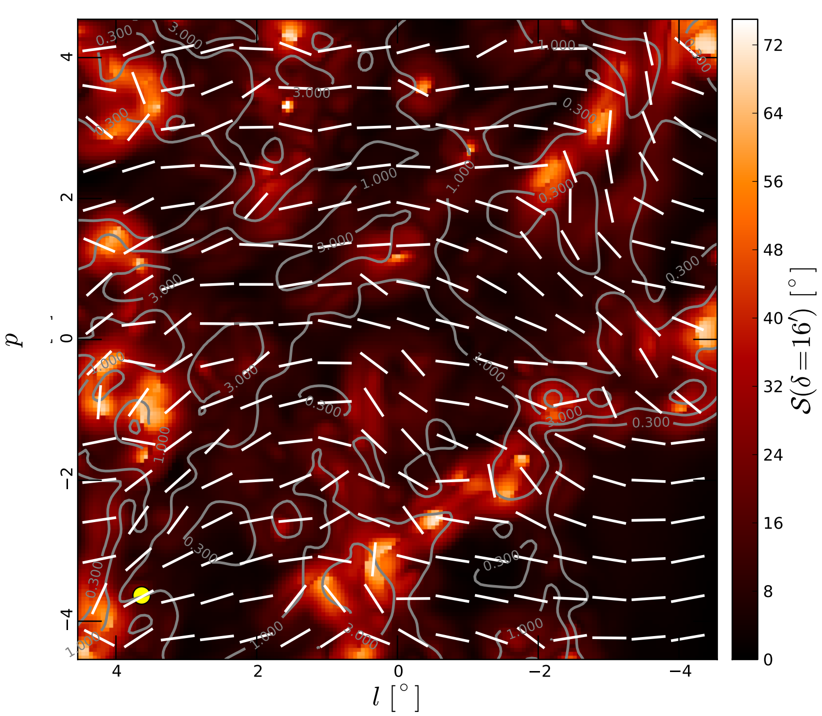
Total gas column density



Polarization fraction



Polarization angle dispersion



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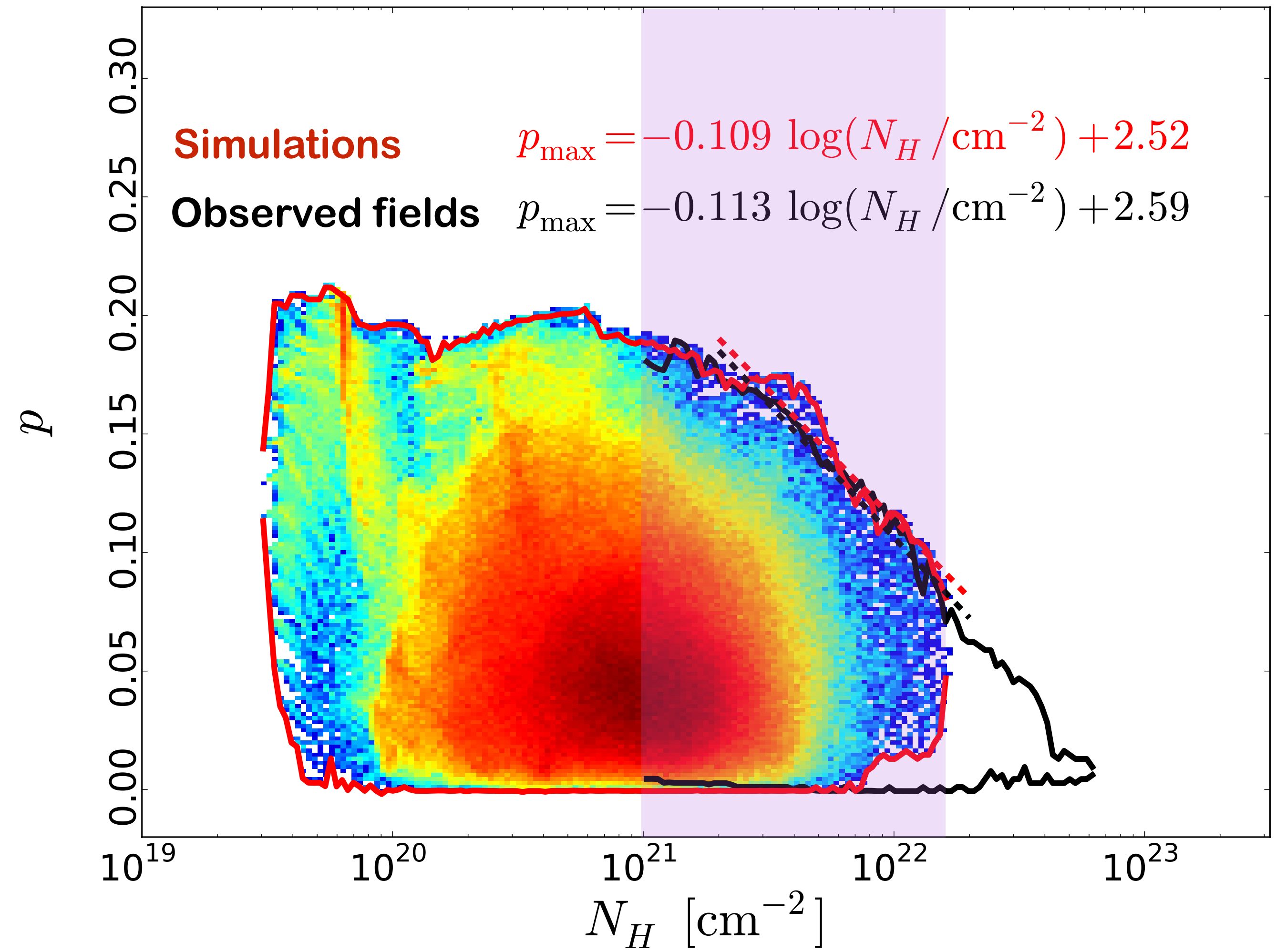
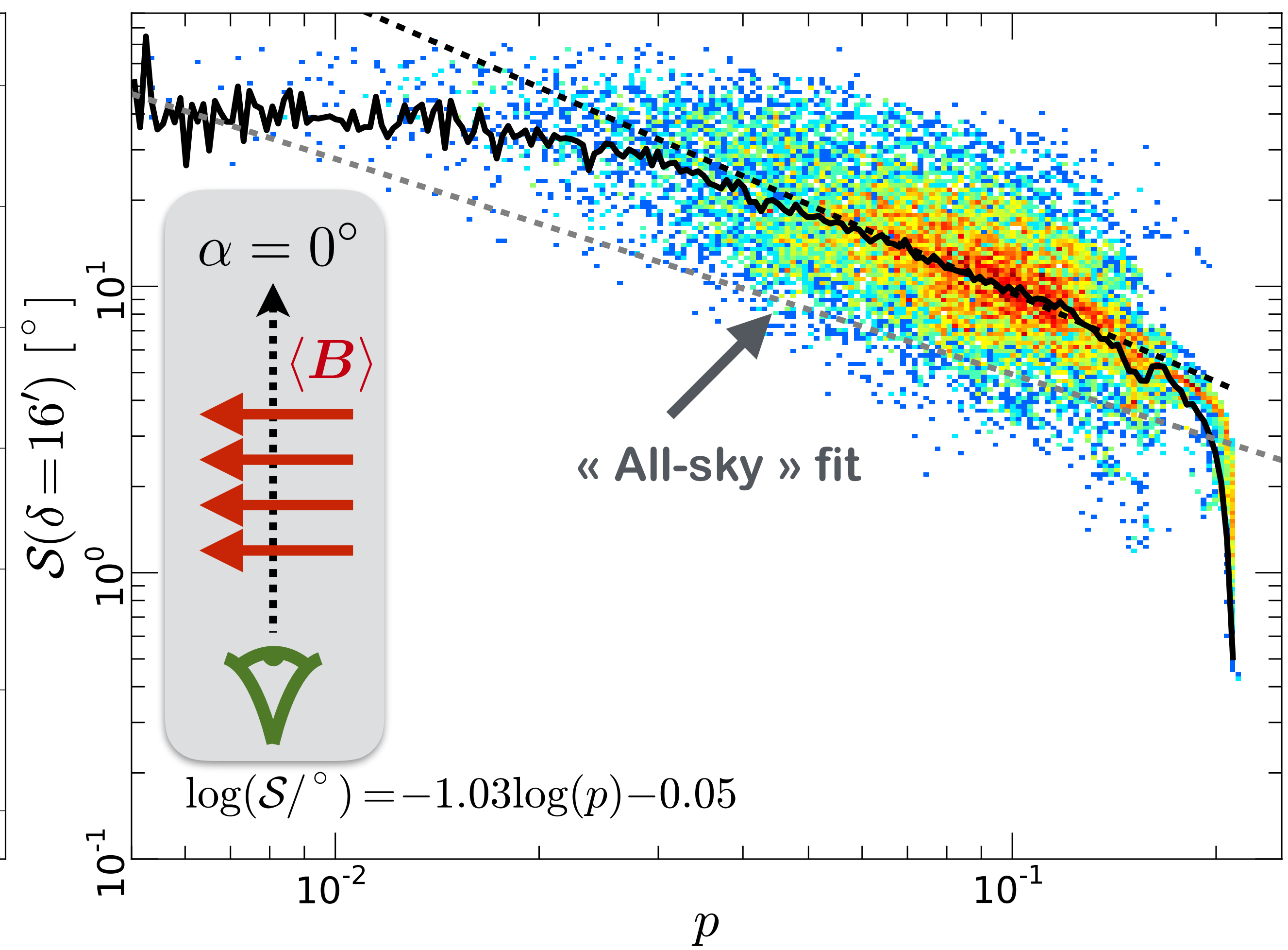
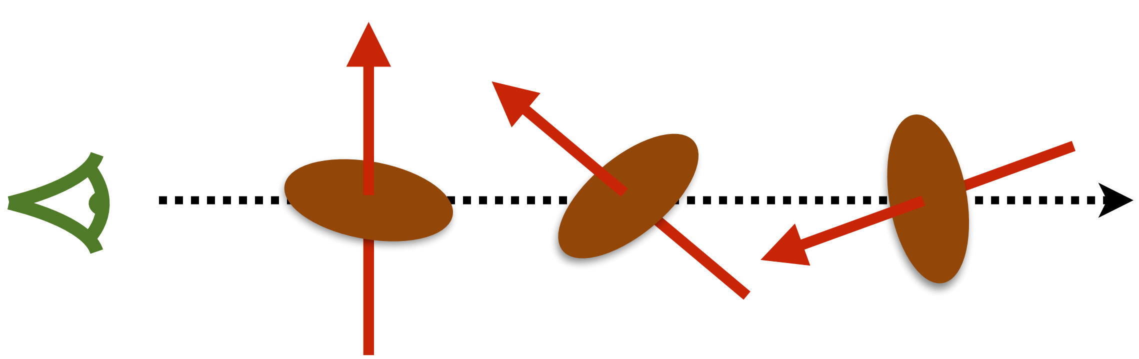
Comparison with a simulation of anisotropic MHD turbulence

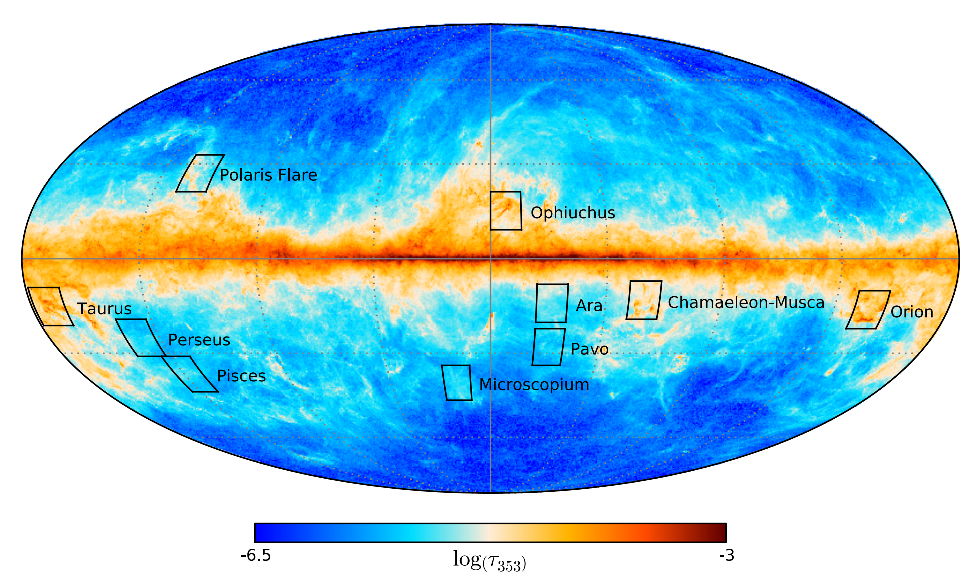




- Simulations reproduce the decrease of the maximum polarization fraction with N_H in that range
- The global anti-correlation with the polarization angle dispersion function is reproduced, with a shift

An effect of magnetic field tangling on the line of sight…



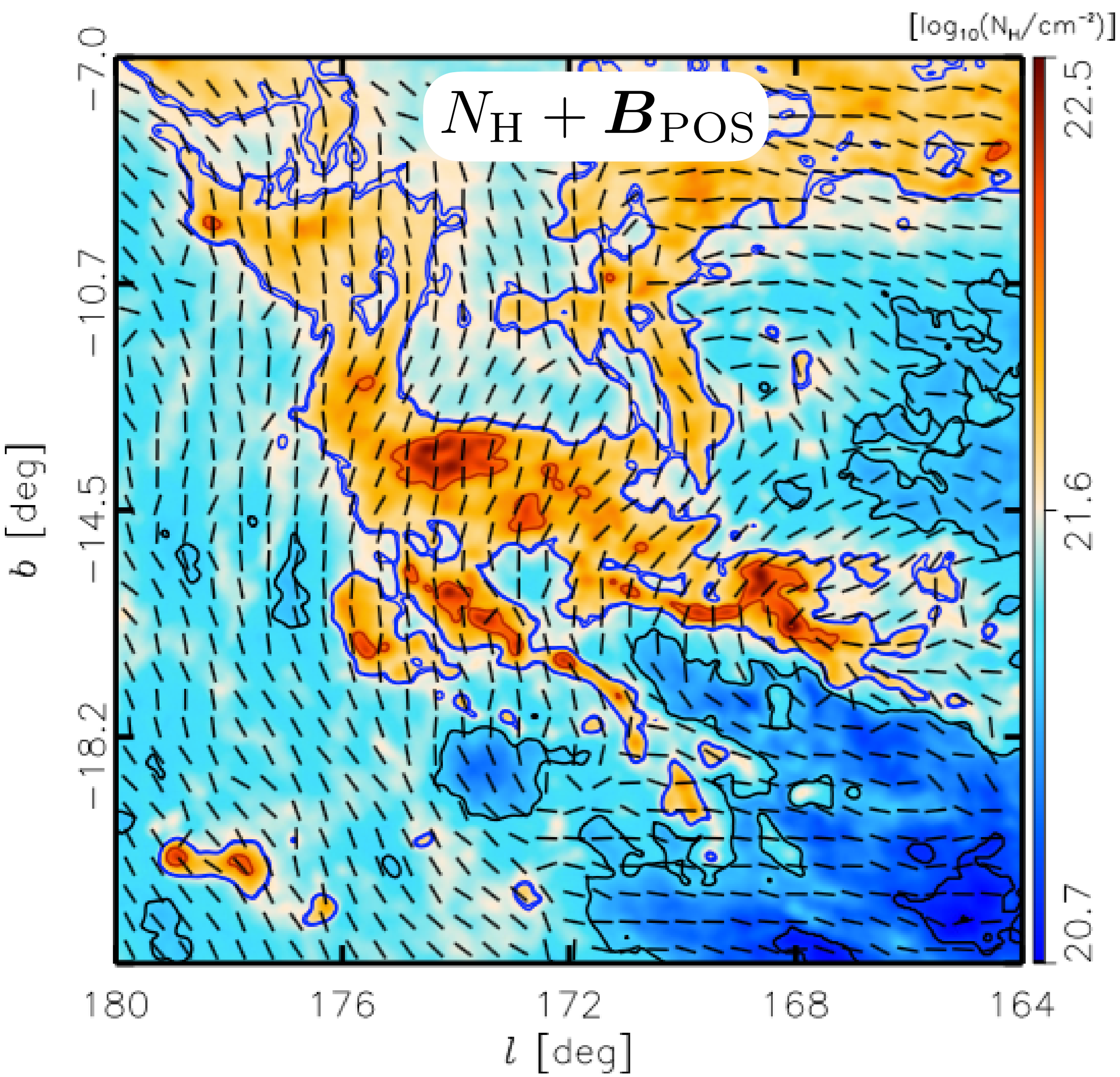


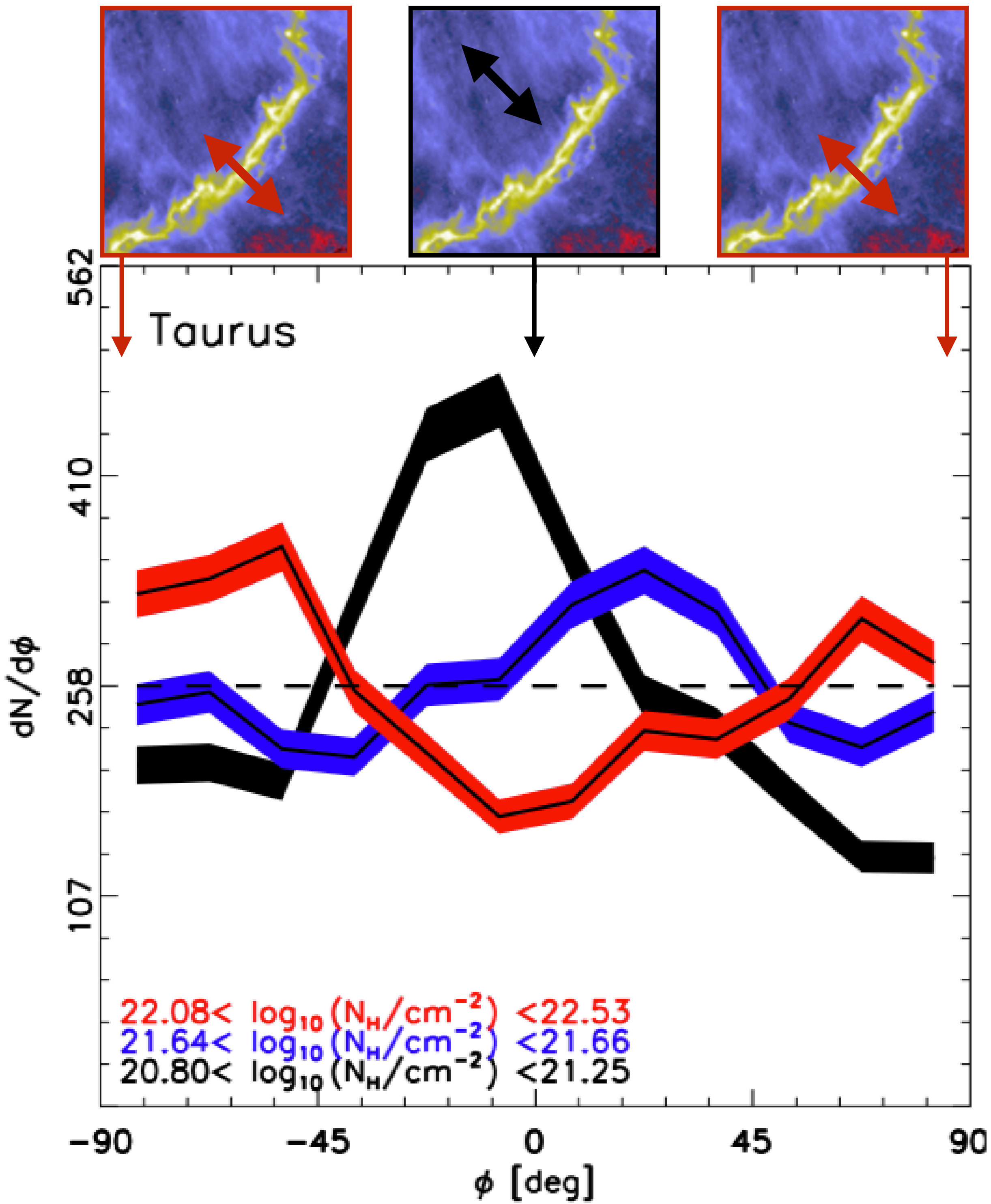
Planck Collaboration Int. XX (2015)

Magnetic field orientation with respect to structures of matter

- In nearby molecular clouds, using the Histogram of Relative Orientations (HRO) **Soler et al. (2013)**
- Change of relative orientation as column density increases
- Consistent with sub- and trans-Alfvénic simulations of MHD turbulence (strong magnetic field)
- Estimates of B from the Davis-Chandrasekhar-Fermi method **Chandrasekhar & Fermi (1953), Hildebrand et al. (2009)**

$$\boldsymbol{B}_{\mathrm{POS}} \sim 10 - 50\,\mu\mathrm{G}$$



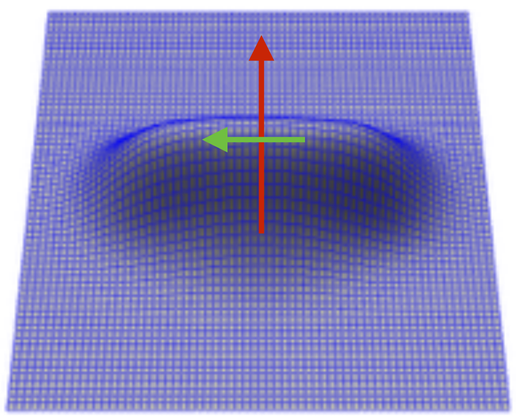


Planck Collaboration Int. XXXV (2016)

Magnetic field orientation with respect to structures of matter

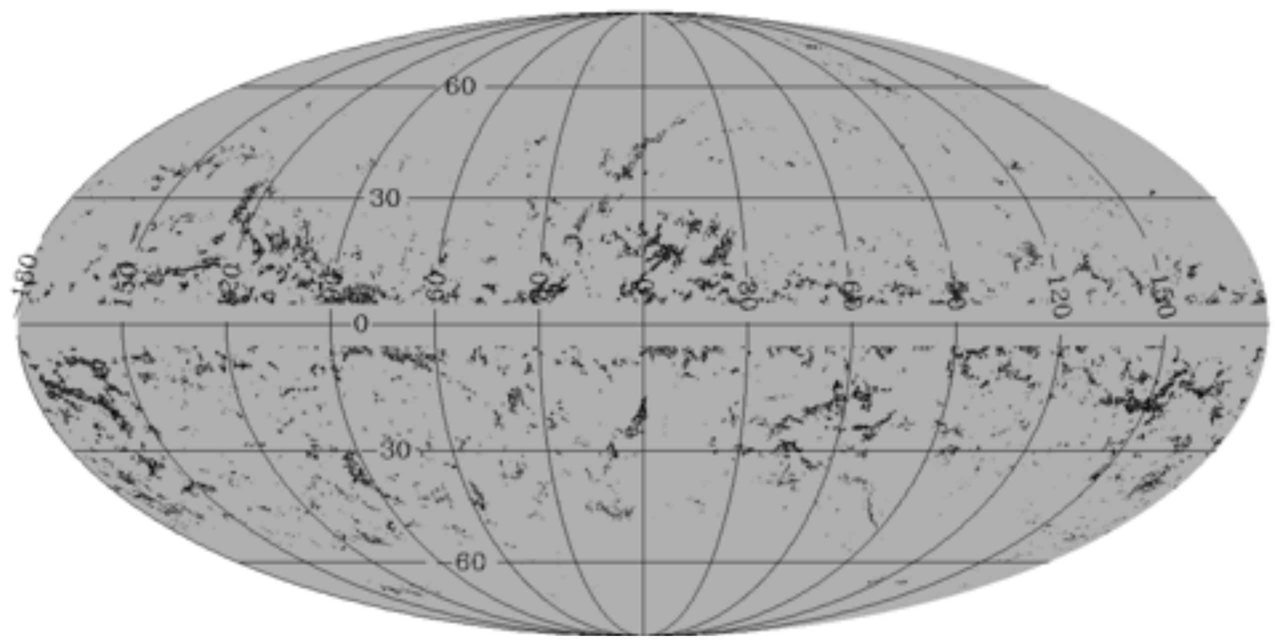
- At intermediate and high Galactic latitudes, using the eigenvalues and eigenvectors of the Hessian
- Relative angle between filaments and magnetic field shows preferred alignment

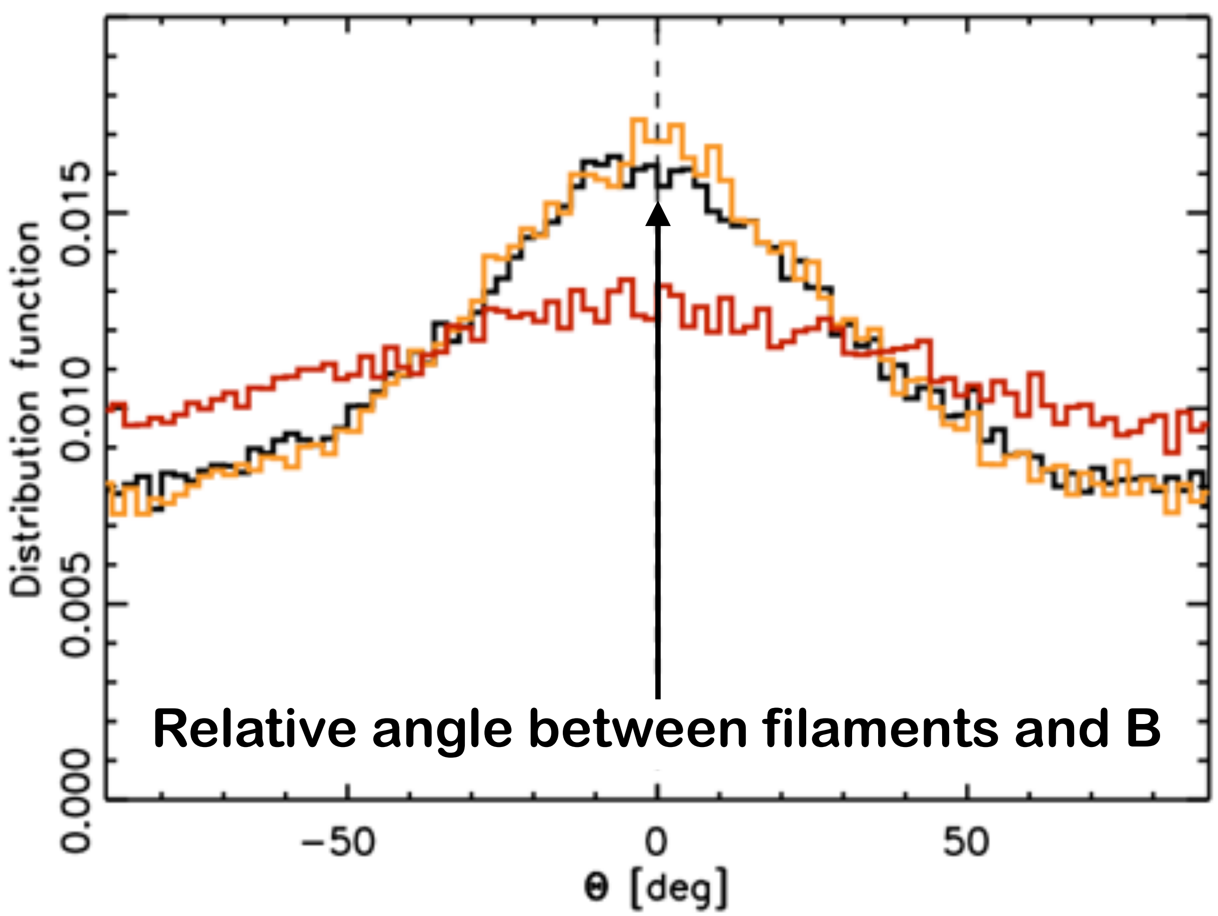
$$\mathbf{H} = \begin{bmatrix} \partial^2_{xx} D_{353} & \partial^2_{xy} D_{353} \\ \partial^2_{xy} D_{353} & \partial^2_{yy} D_{353} \end{bmatrix}$$

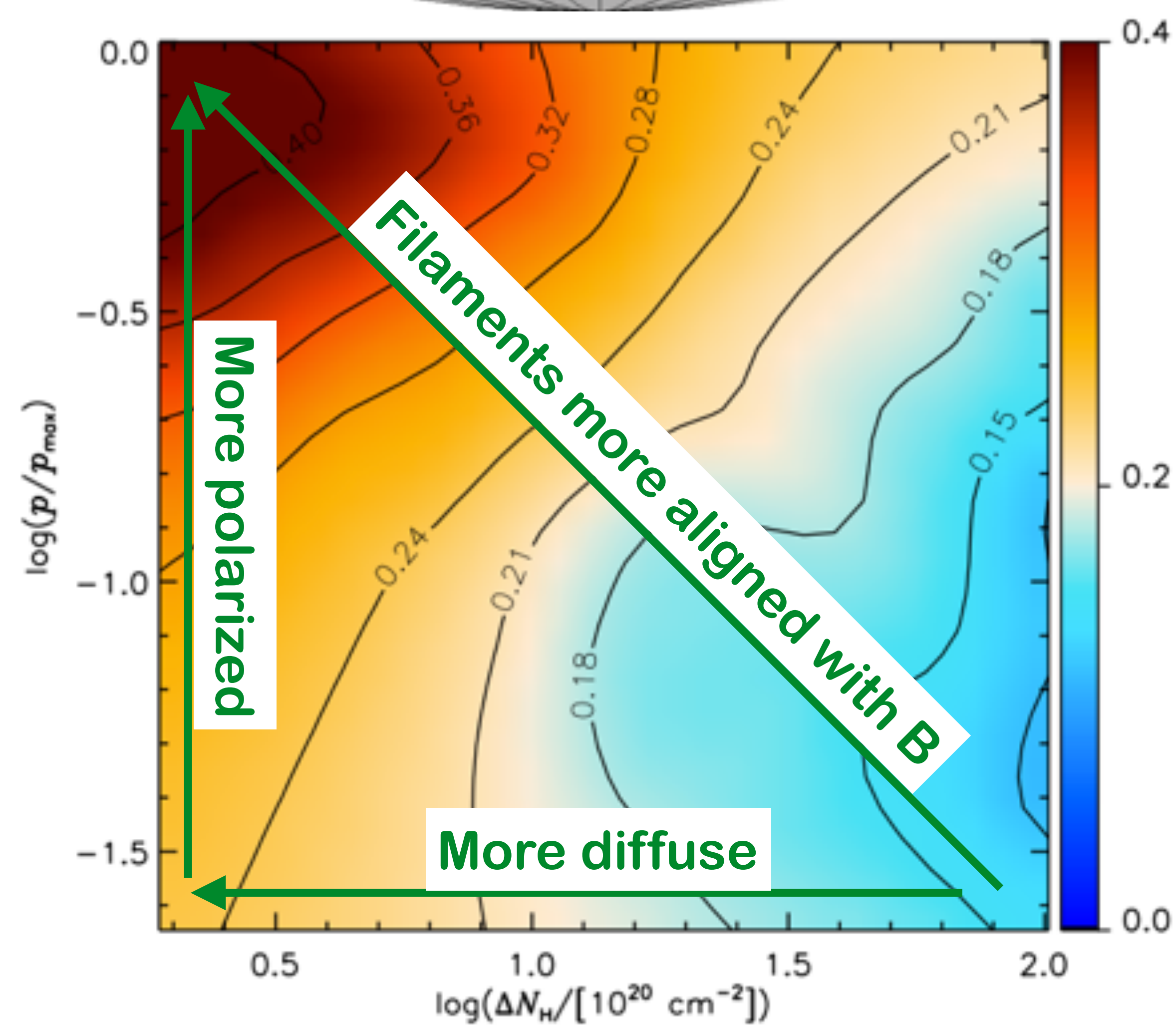


$$\langle p \rangle = 12 \pm 1\%$$

Map of the most negative eigenvalue







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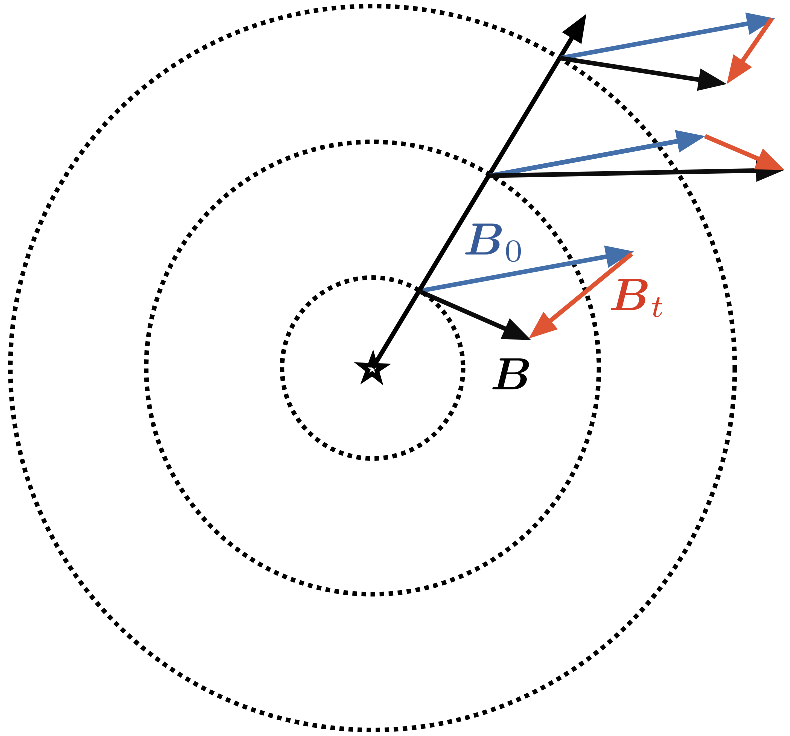
A Gaussian model of the polarized sky



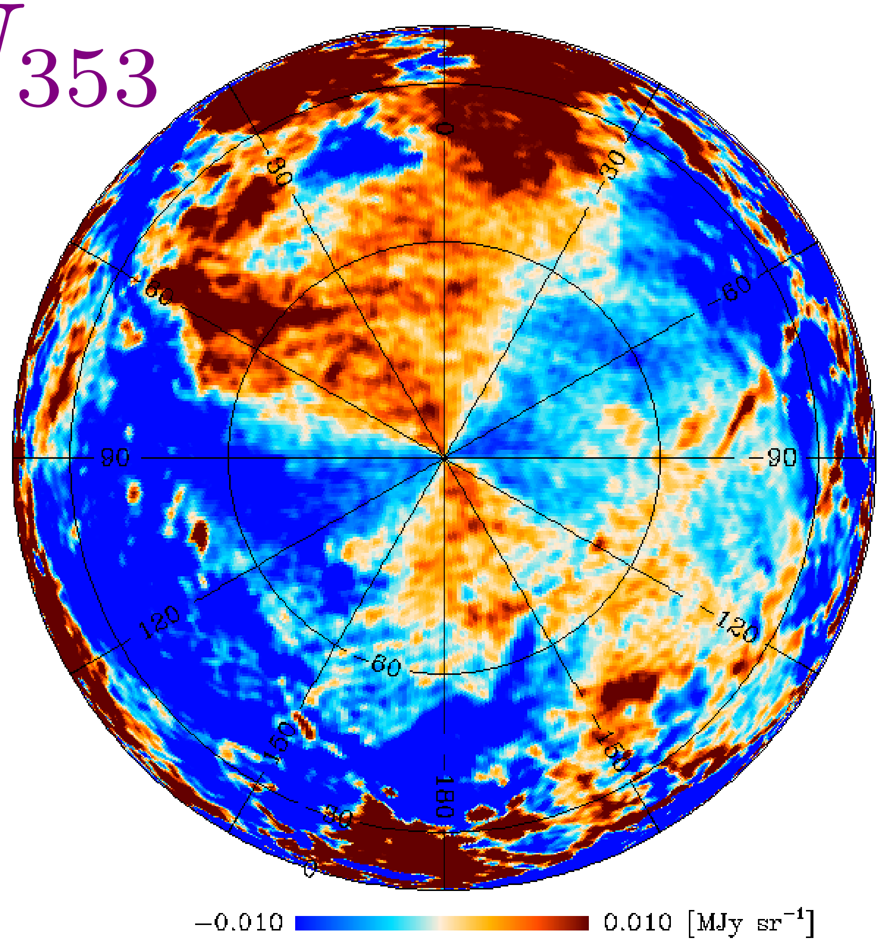
Magnetic field $B = B_0 + B_t$

Uniform field — Turbulent field

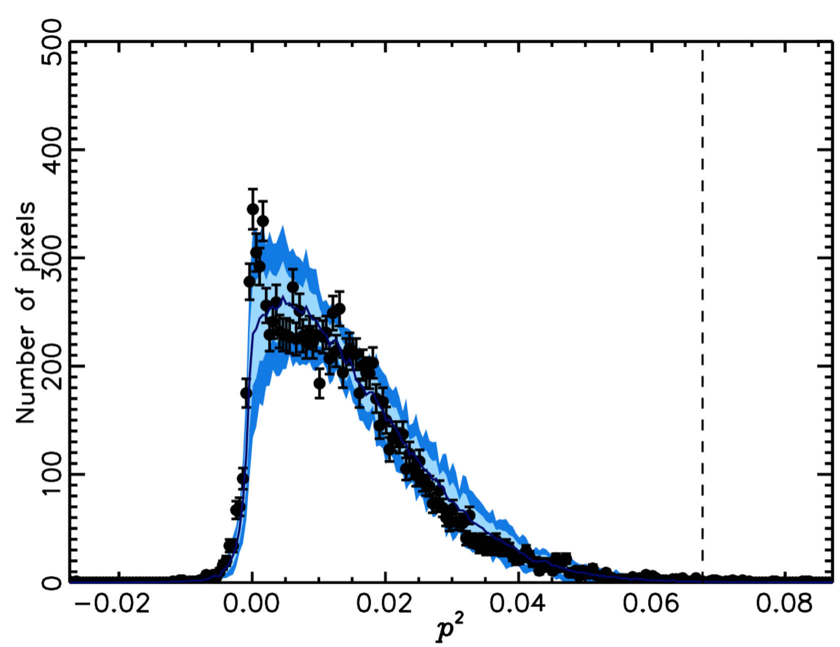
- A superposition of variously polarized layers (turbulent cells ?)
- Turbulent field : 3D Gaussian random variable (in 2D space)
- Analysis of the Southern Galactic cap

  - Spatial power spectrum unconstrained $C_\ell \propto \ell^{\alpha_M}$
  - Direction of the large-scale field $(l_0, b_0) = (70 \pm 5°, 24 \pm 5°)$
  - Turbulent-to-mean ratio $f_M = 0.9 \pm 0.1$
  - Number of layers $N = 7 \pm 2$
  - Intrinsic polarization fraction $p_0 = 26 \pm 3\%$

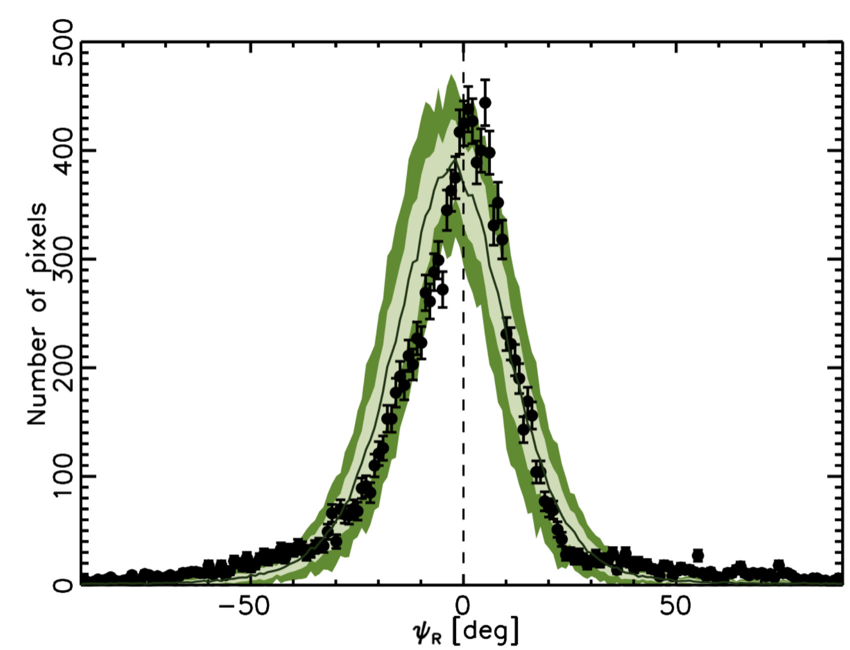
U_{353}



Observations (black dots) vs. Simulations (colored regions)



Polarization fraction

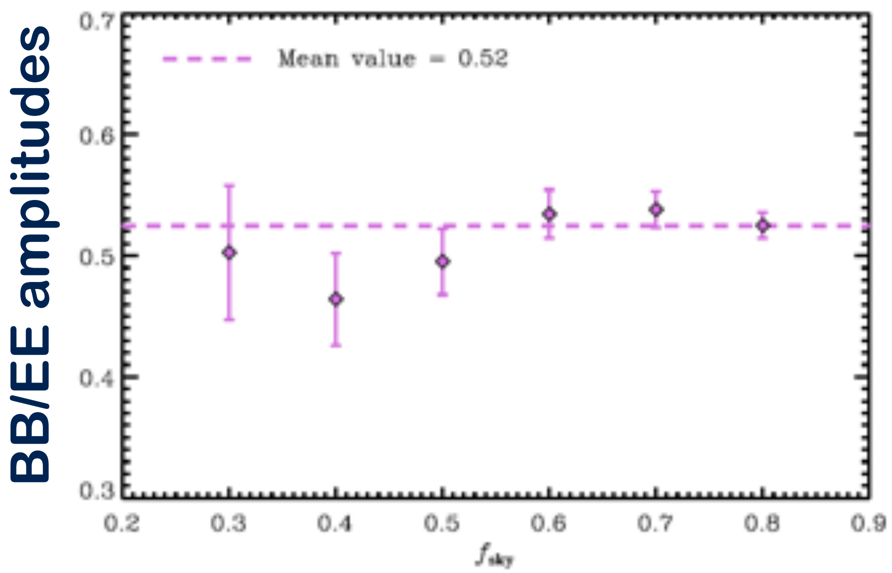


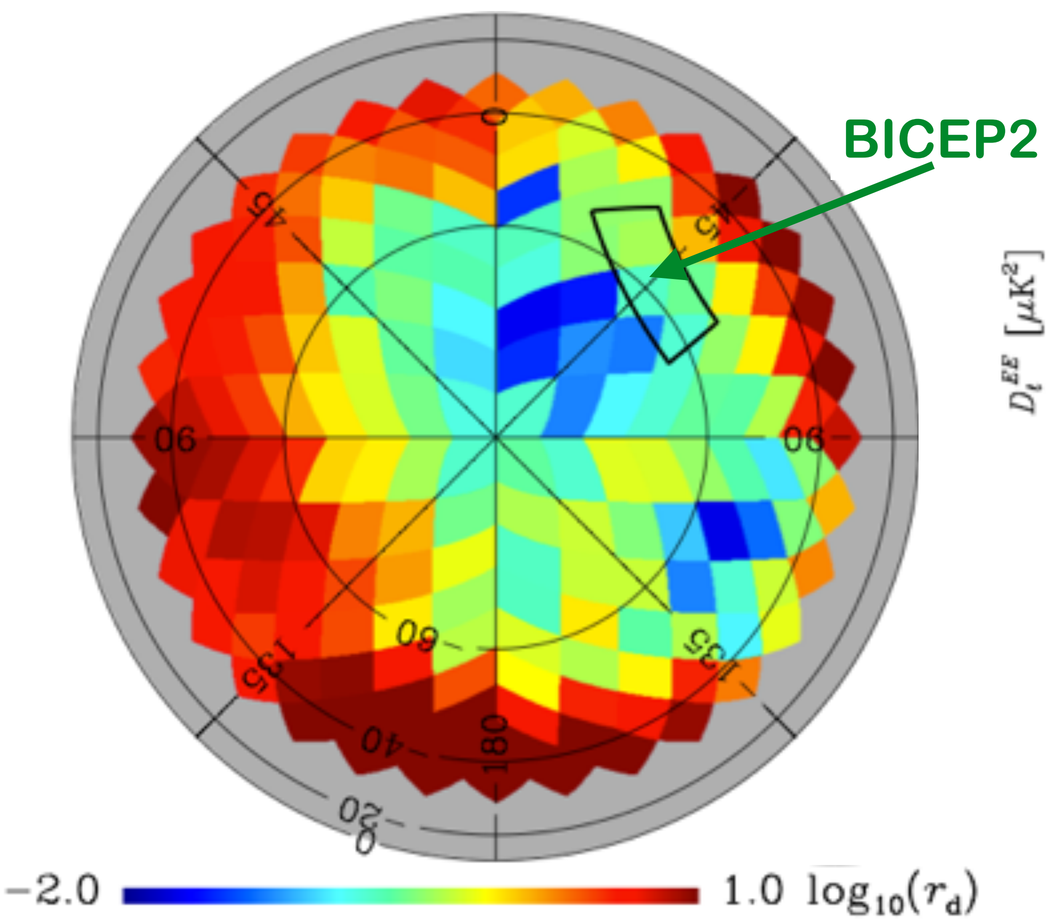
Polarization angle relative to the large-scale field

Planck Collaboration Int. XXXII, XLIV (2016)

The angular power spectrum of polarized thermal dust emission

- E and B thermal dust emission angular power spectra outside the Galactic plane well fit by power laws
- Amplitudes vary approximately as the square of average dust brightness in the selected region
- Asymmetry in the E and B modes : twice as much power in E modes
- B mode power attributable to dust in the BICEP2 field compatible with reported detection

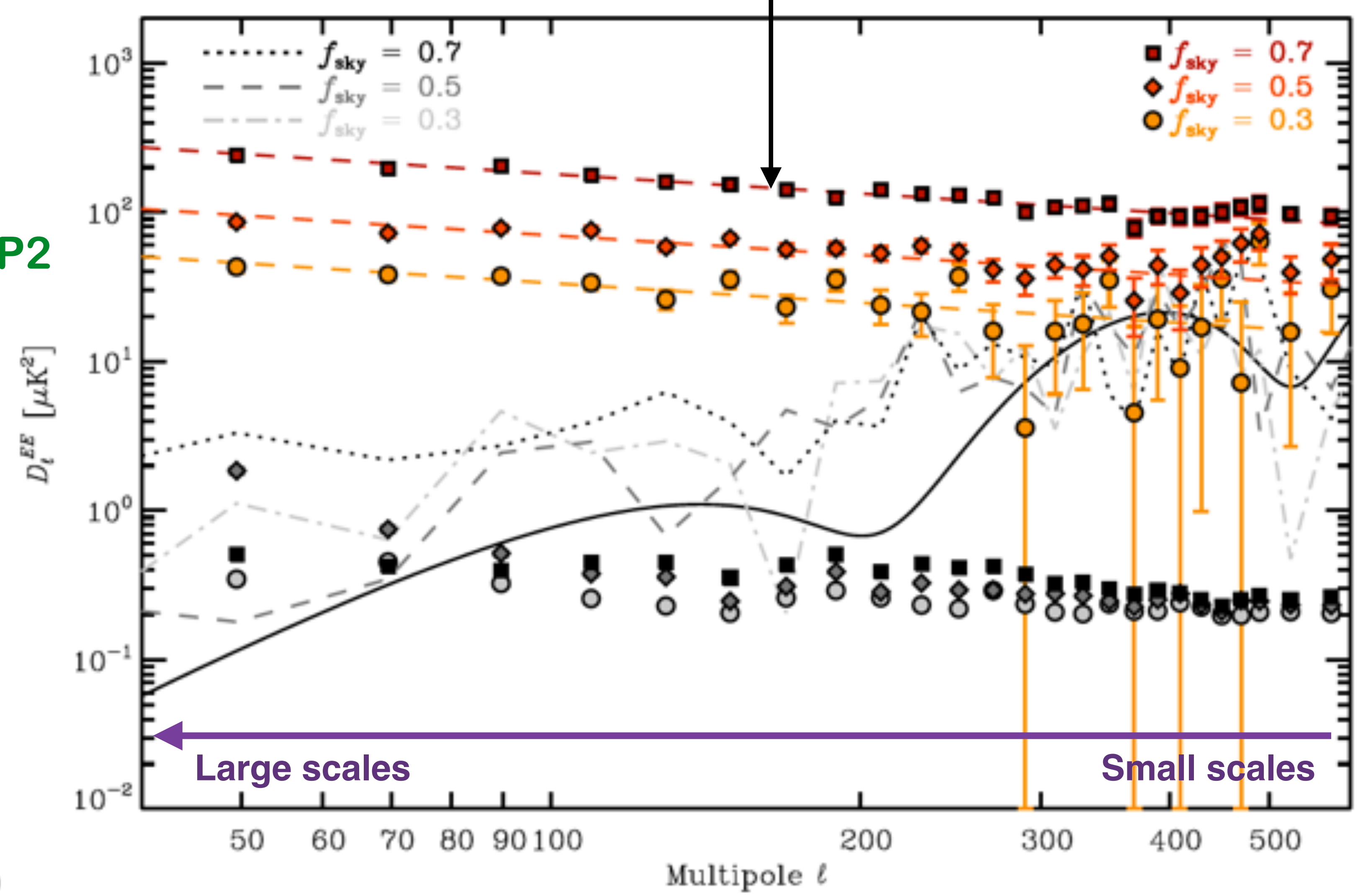




Planck Collaboration Int. XXX (2016)

BICEP2 Collaboration (2014)

$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$

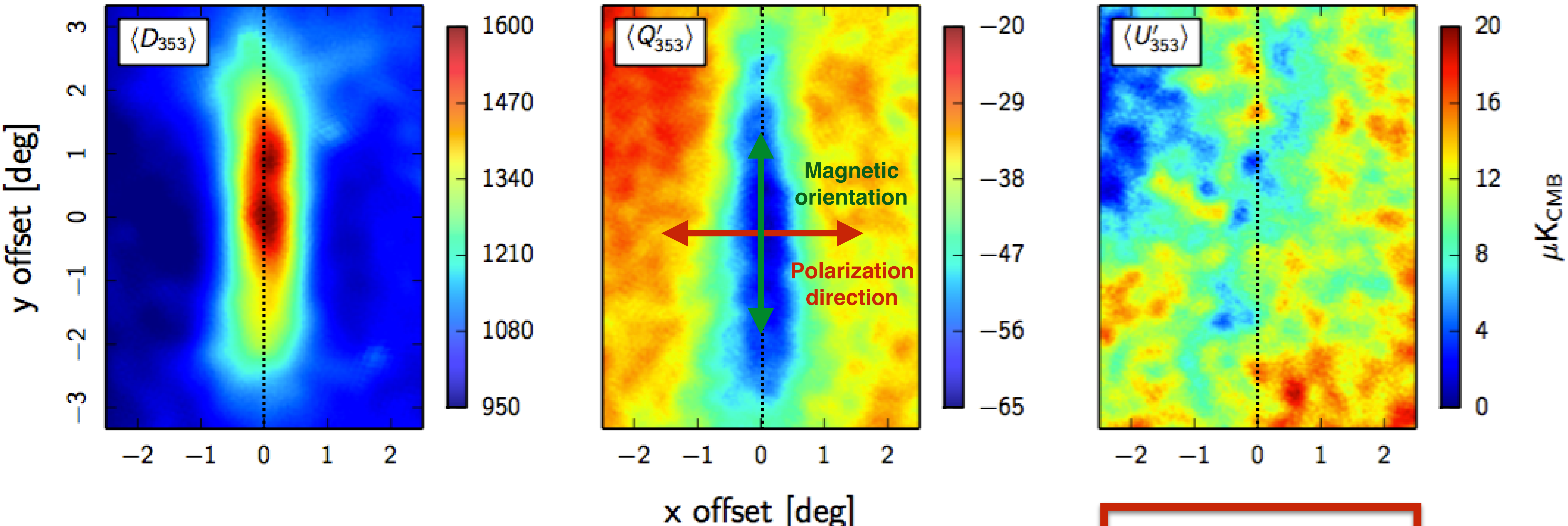


$C_\ell^{EE} \propto \ell^{\alpha_{EE}}$ $C_\ell^{BB} \propto \ell^{\alpha_{BB}}$

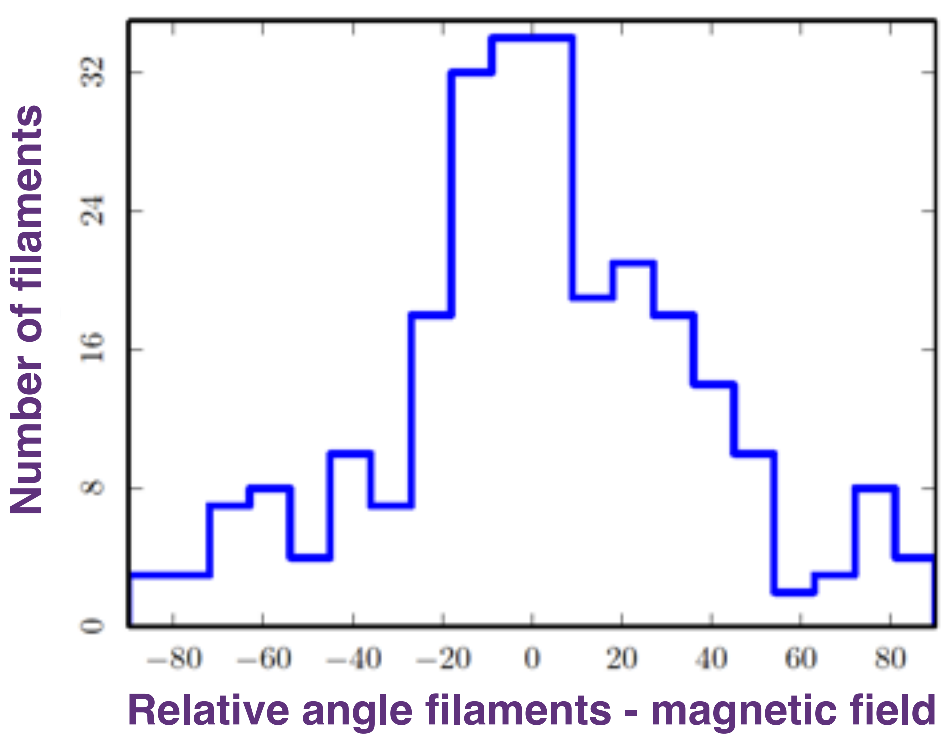
$$\alpha_{EE,BB} = -2.42 \pm 0.02$$

Origin of the E/B power asymmetry

- Identification of 259 matter filaments longer than 2° in the high Galactic latitude sky using the Hessian
- Preferential alignment of the filaments with the magnetic field
- Stacking of Stokes parameter maps rotated along the filaments leads to mean polarization fraction
- E/B asymmetry may be accounted for by this preferential alignment



$$\langle p \rangle = 11\%$$



$$\frac{A^{BB}}{A^{EE}} \simeq \frac{\langle \sin^2 \ 2\Delta^{\mathrm{F}}_{\bar{\chi}-\bar{\theta}_{-}} \rangle}{\langle \cos^2 \ 2\Delta^{\mathrm{F}}_{\bar{\chi}-\bar{\theta}_{-}} \rangle} = 0.66$$

Planck Collaboration Int. XXXVIII (2016)

Frequency dependence of dust polarized emission

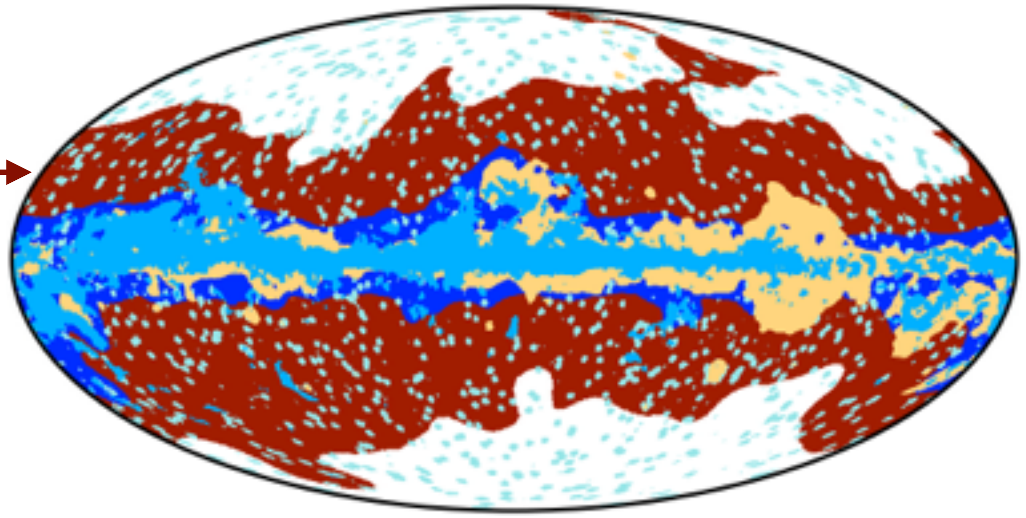
- Cross-correlation of 353 GHz Stokes maps (dust templates) with Planck and WMAP [23-353 GHz]
- Spectral indices of dust emission in total intensity and polarization over 10° radius patches
- Mean dust spectral energy distribution (SED) shows an increase below 60 GHz
- Polarization fraction of dust emission is found to decrease from 353 GHz to 70 GHz

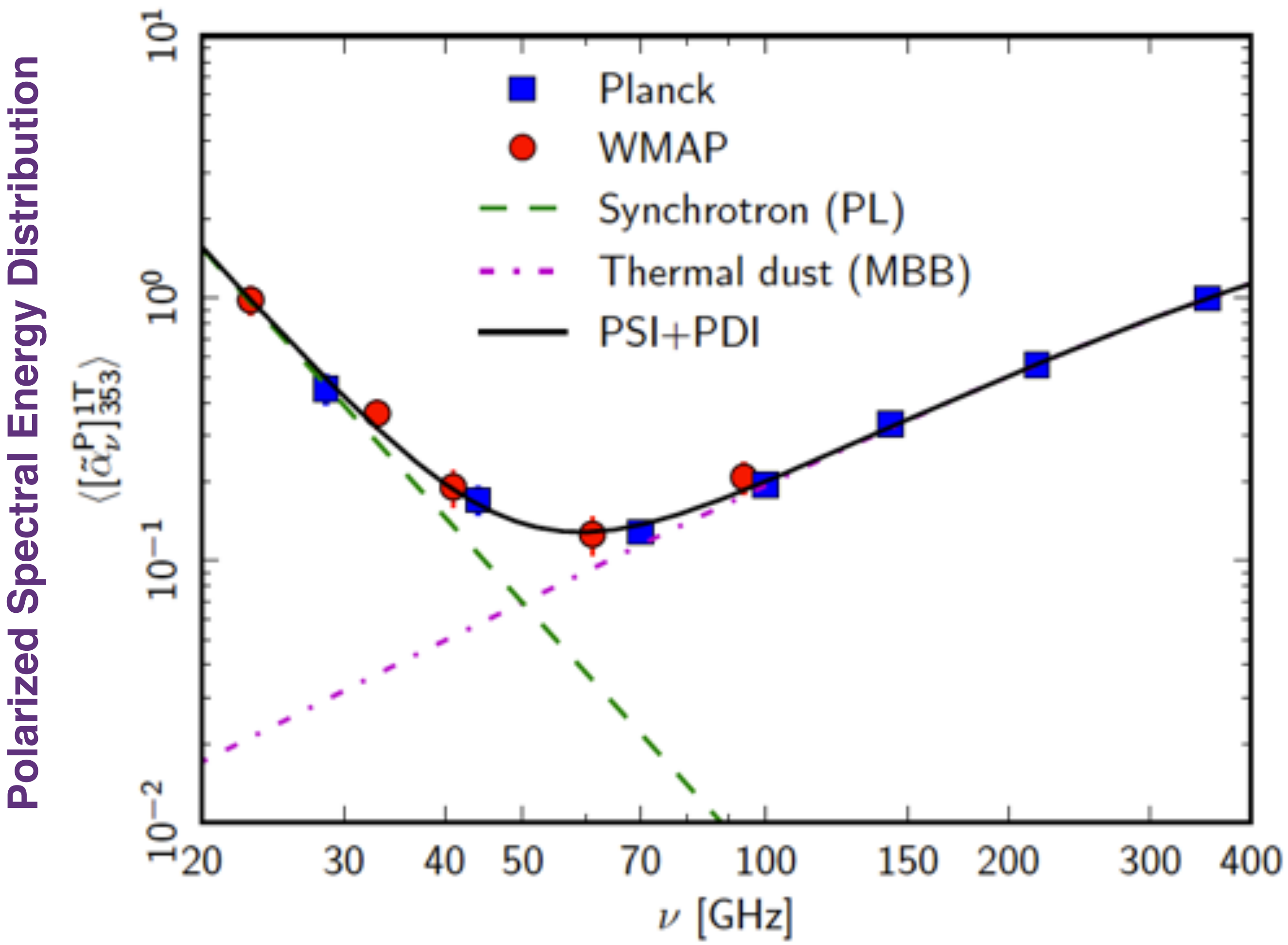
$$T_{\rm d} = 19.6\,{\rm K}$$

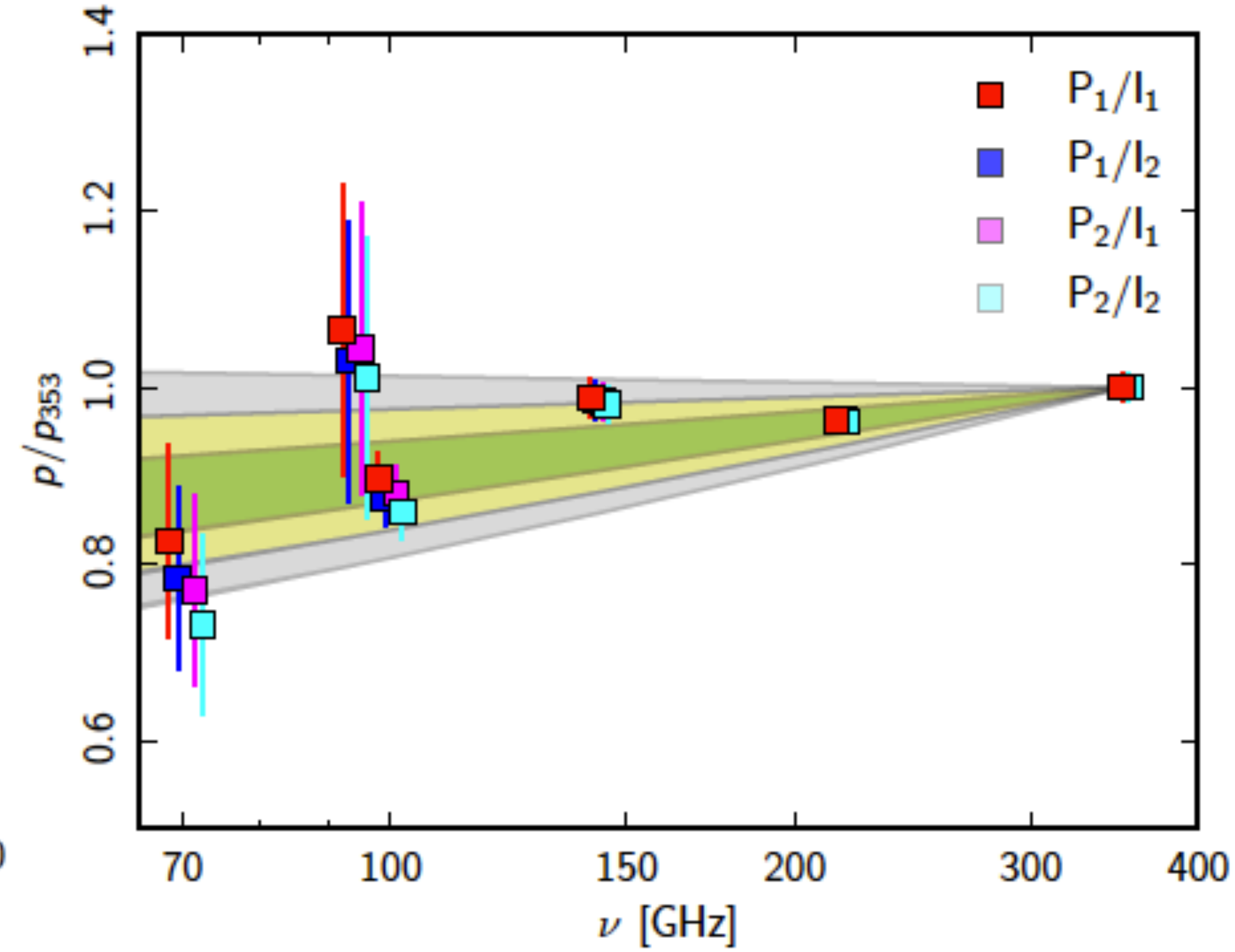
$$\beta_I = 1.51 \pm 0.01$$

$$\beta_P = 1.59 \pm 0.02$$

Regions used →







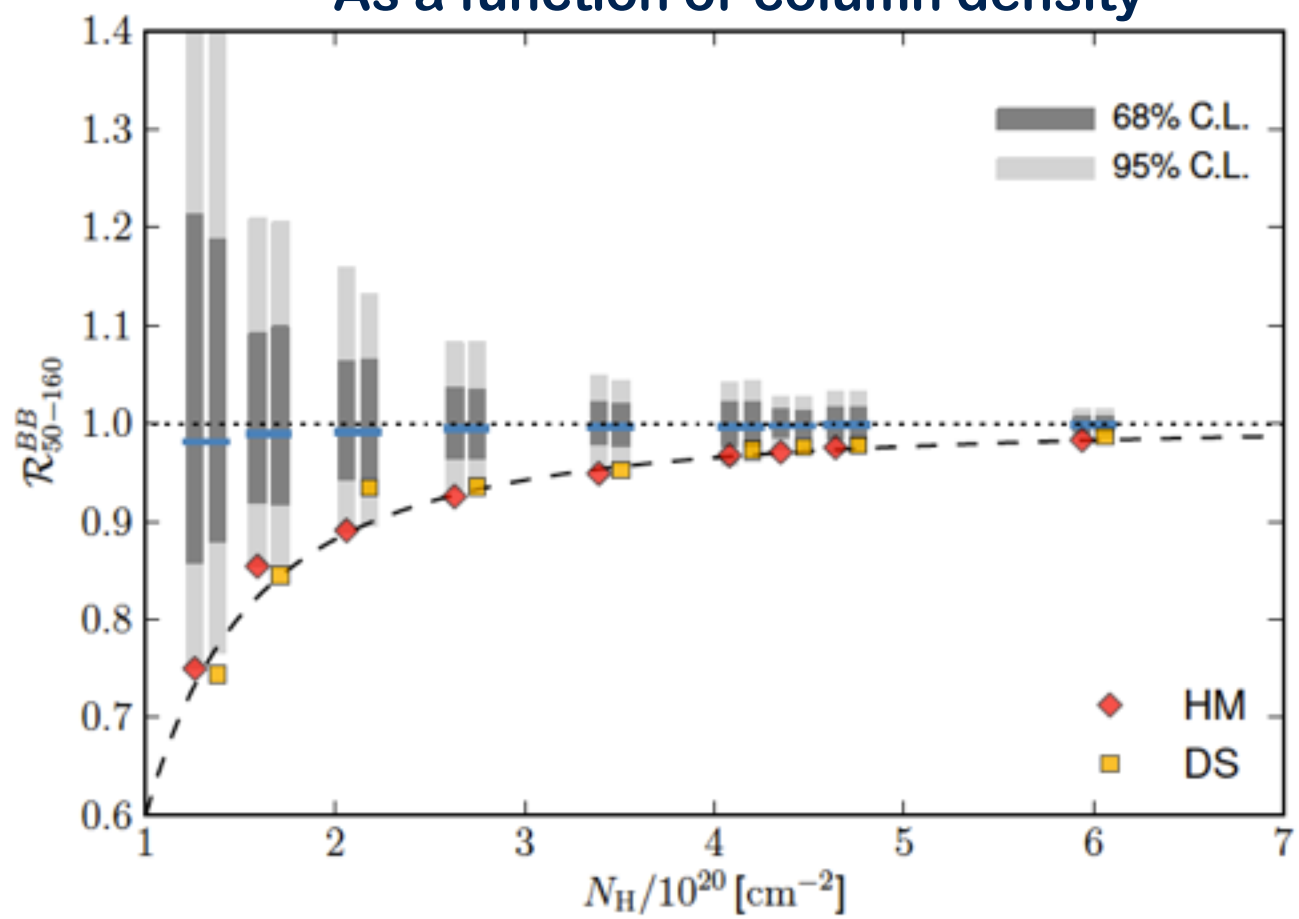
Planck Collaboration Int. XXII (2015)

Spatial decorrelation of polarized emission across frequencies

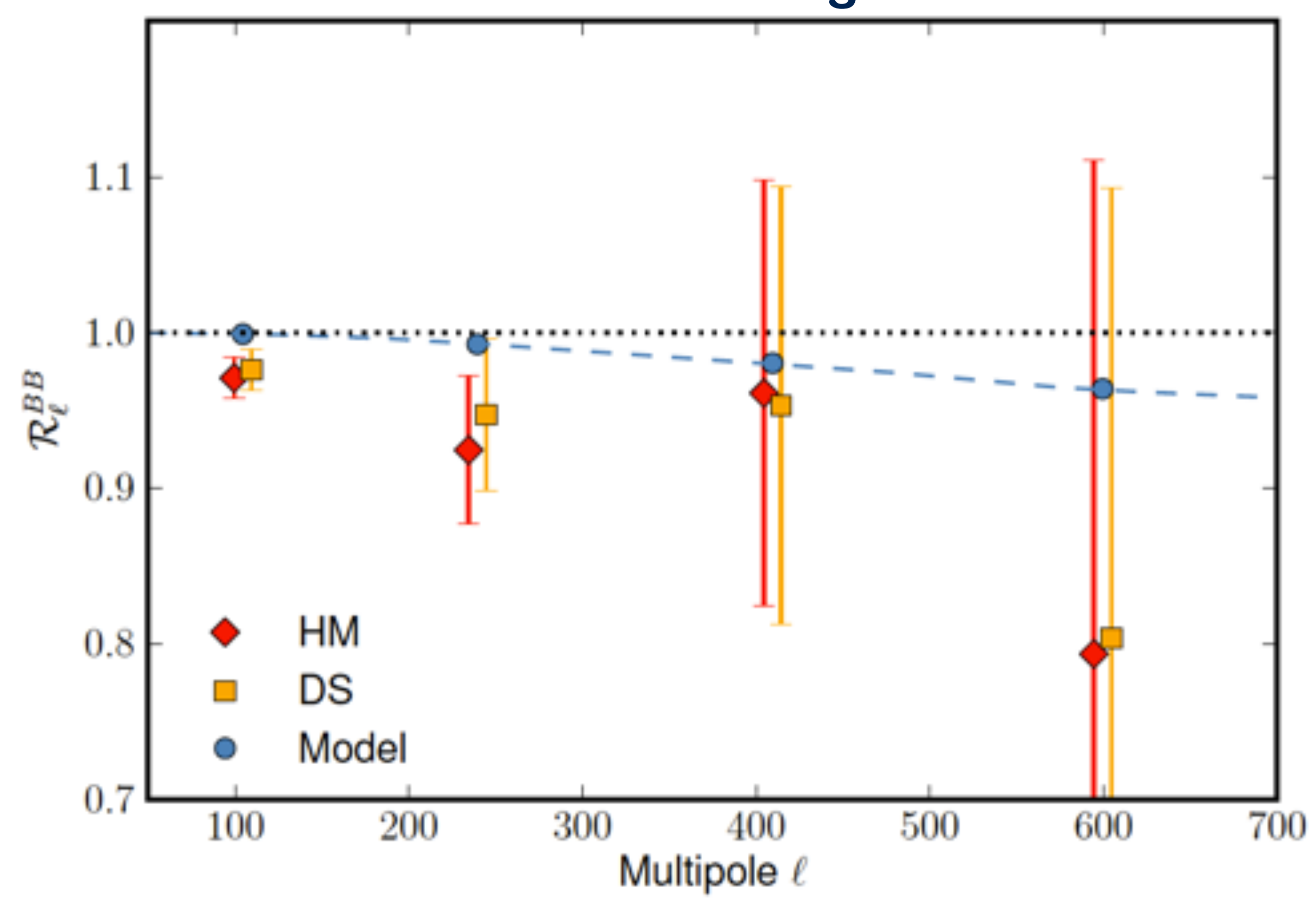
- Correlation ratio of 353 GHz and 217 GHz E and B modes lower than expected
- Decorrelation stronger in more diffuse regions and at smaller scales, possibly very variable on the sky
- Spatial variations of the polarized SED spectral index or of the polarization angle
- Fundamental issue when extrapolating dust emission templates from high frequency to CMB channels

Correlation ratio $$\mathcal{R}_\ell^{XX} \equiv \frac{C_\ell^{XX}(353 \times 217)}{\sqrt{C_\ell^{XX}(353 \times 353)\, C_\ell^{XX}(217 \times 217)}} \qquad X \in \{E, B\}$$

As a function of column density

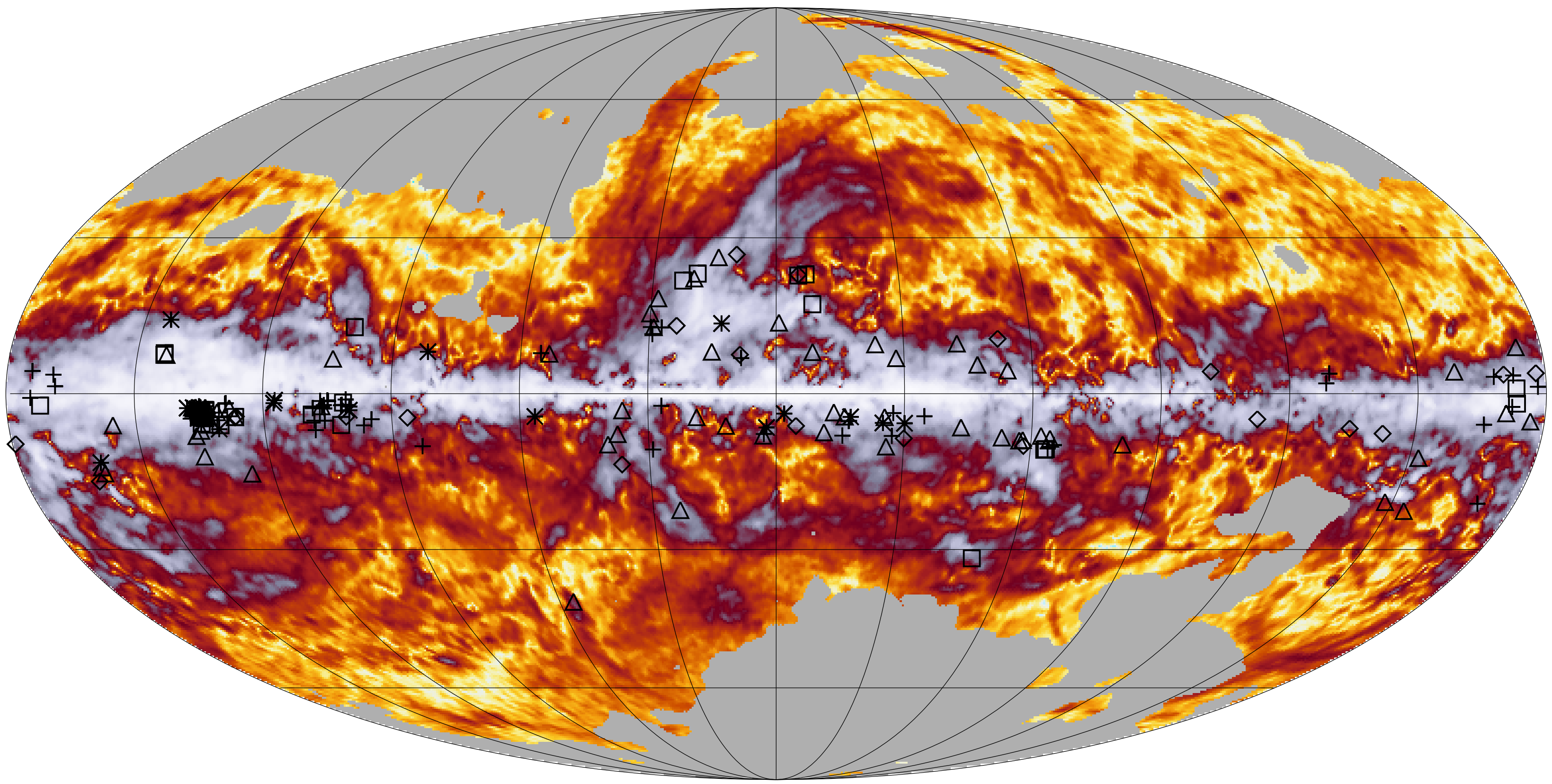


As a function of angular scale

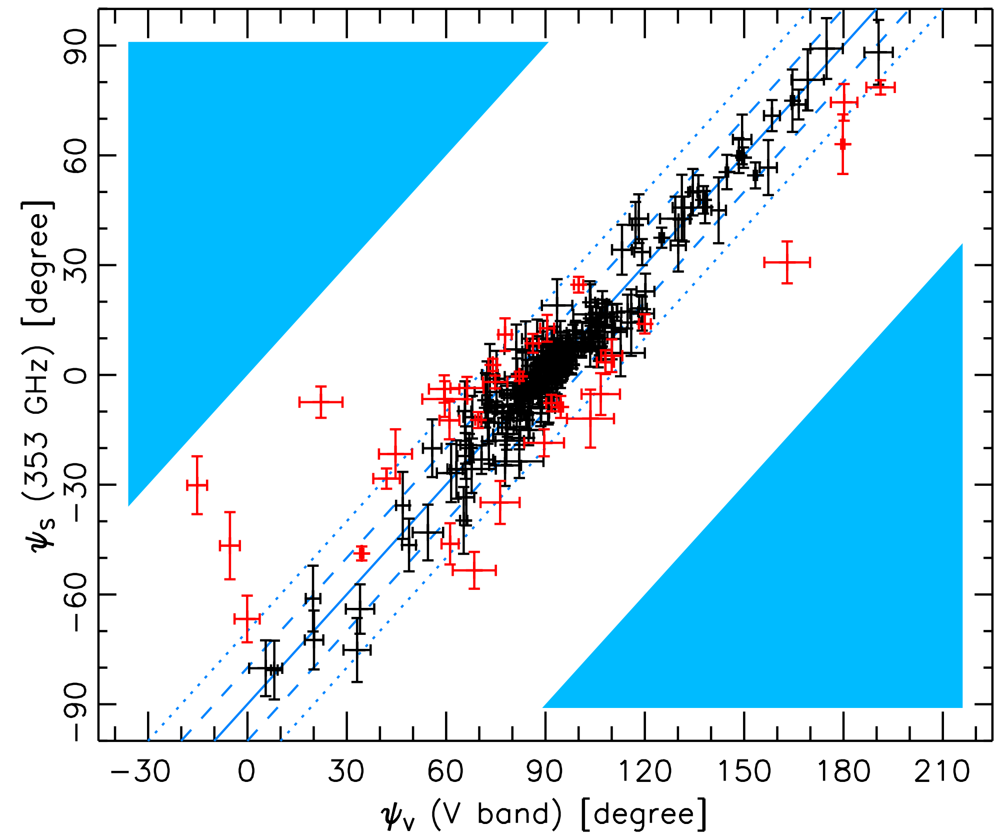


Planck Collaboration Int. L (2016)

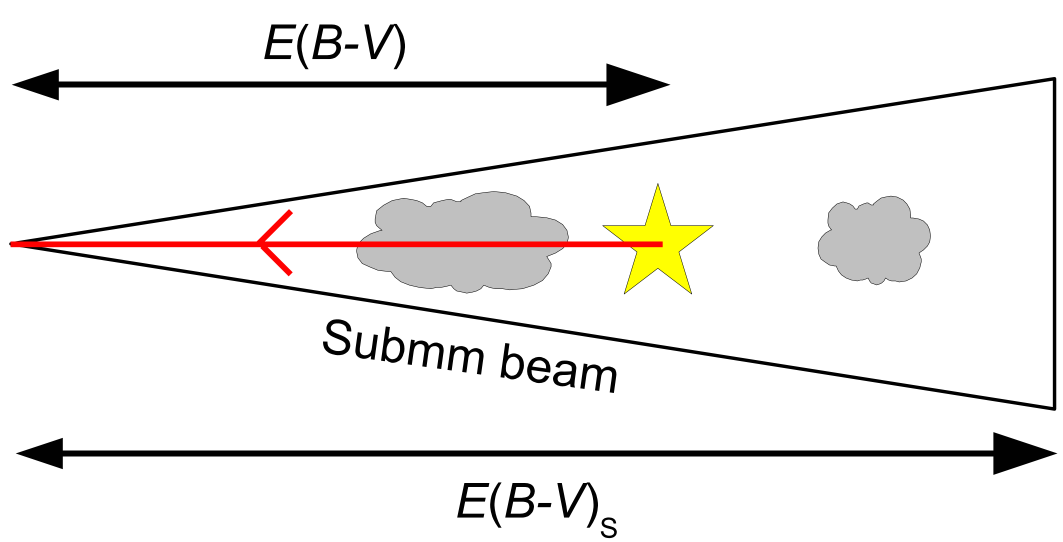
Comparison with starlight polarization in extinction



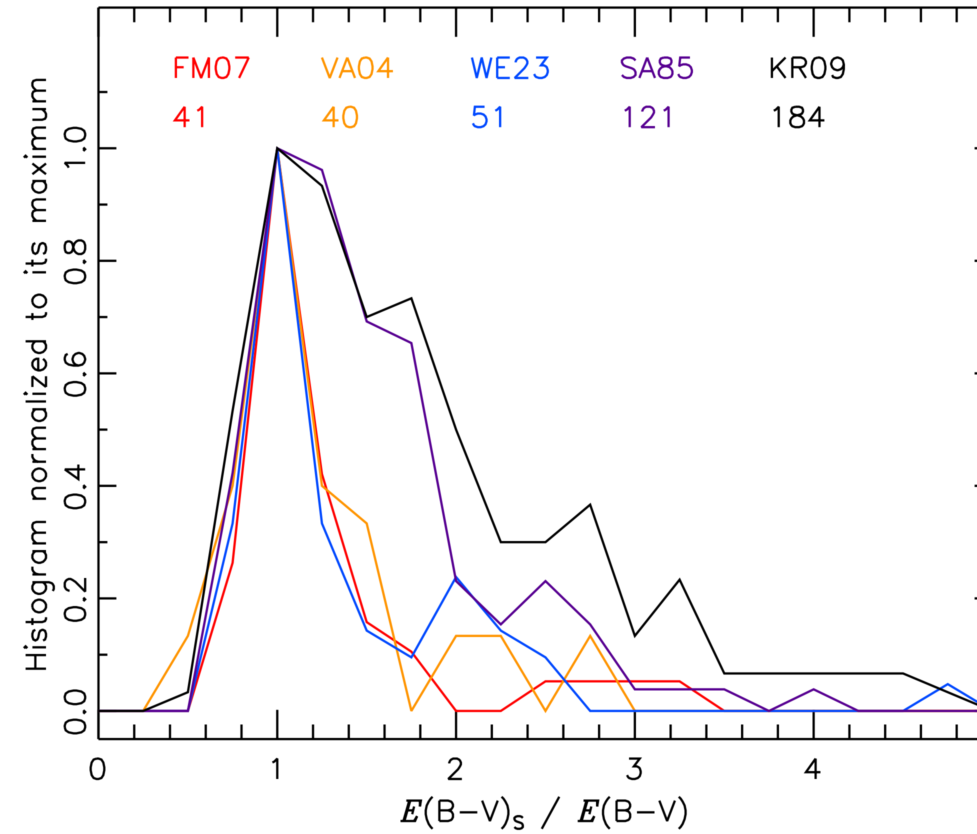
Selection on angle consistency



Selection of 206 stars with optical polarization measurements with consistent polarization angles and column densities

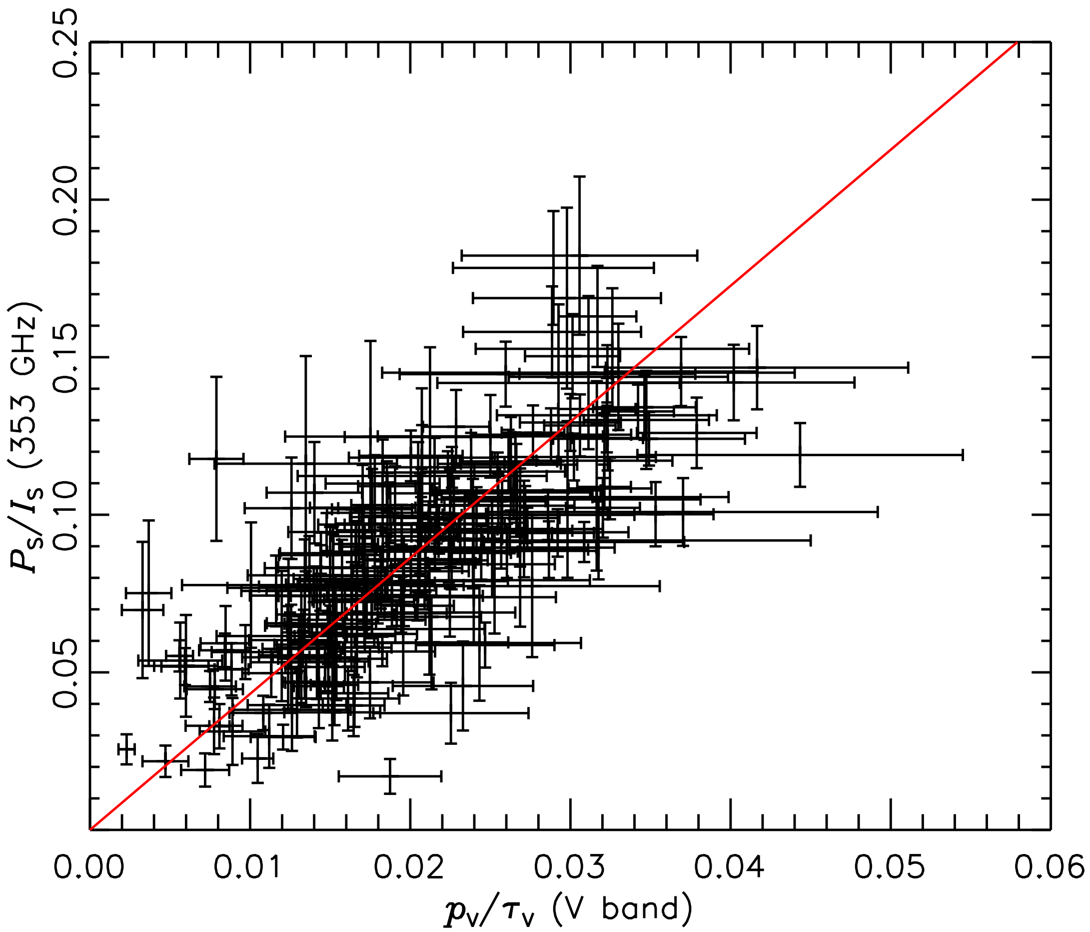


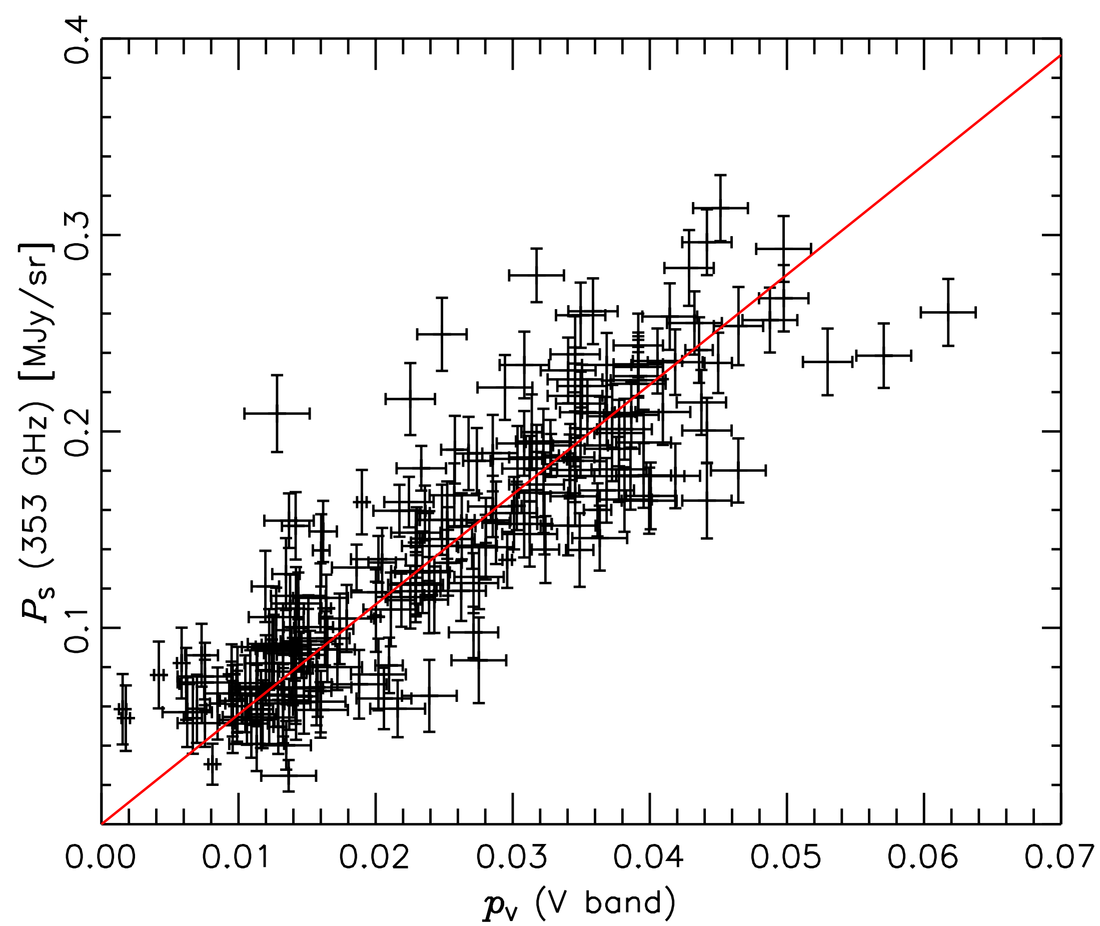
Selection on reddening ratio



Planck Collaboration Int. XXI (2015)

Comparison with starlight polarization in extinction





(Stat) (Syst)

$$R_{\mathrm{S/V}} = \frac{P_{\mathrm{S}}/I_{\mathrm{S}}}{p_{\mathrm{V}}/\tau_{\mathrm{V}}} = 4.2 \pm 0.2 \pm 0.3$$

- Reasonably compatible with current dust models
- Not very discriminating

(Stat) (Syst)

$$R_{P/p} = \frac{P_{\mathrm{S}}}{p_{\mathrm{V}}} = 5.4 \pm 0.2 \pm 0.3\,\mathrm{MJy\,sr^{-1}}$$

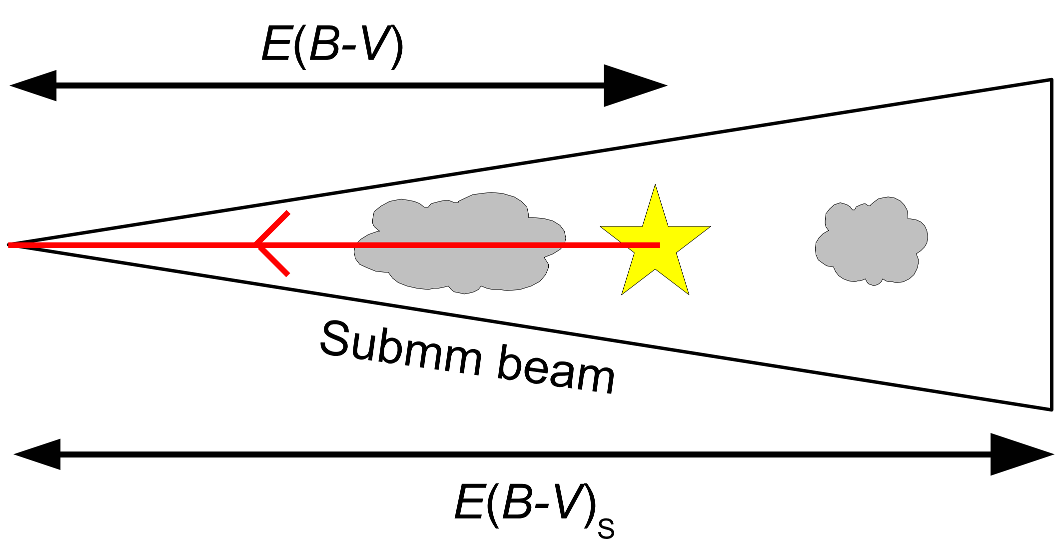
- Much more discriminating diagnostic
- Current dust models predict a value lower by a factor 2.5

Planck Collaboration Int. XXI (2015)

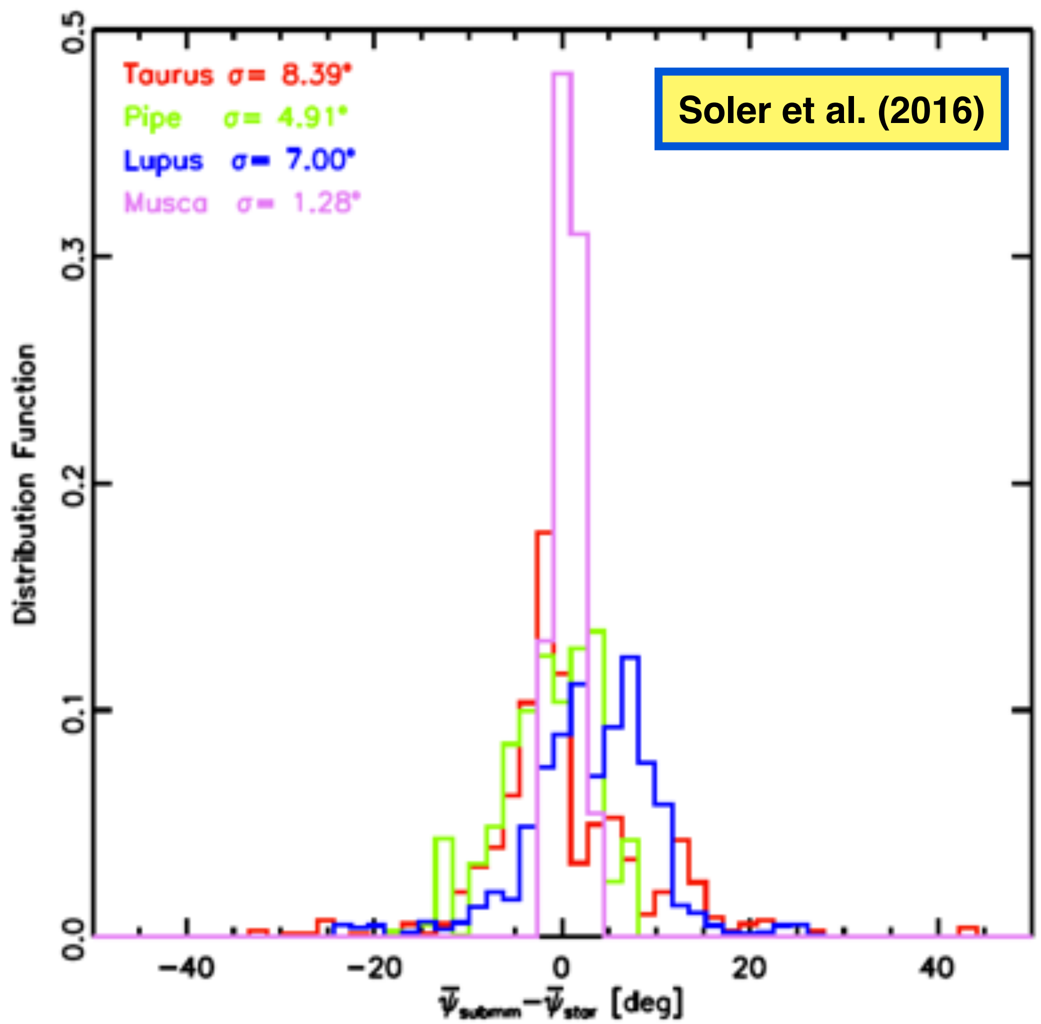
Guillet et al. (in prep)

Comparison with starlight polarization in extinction

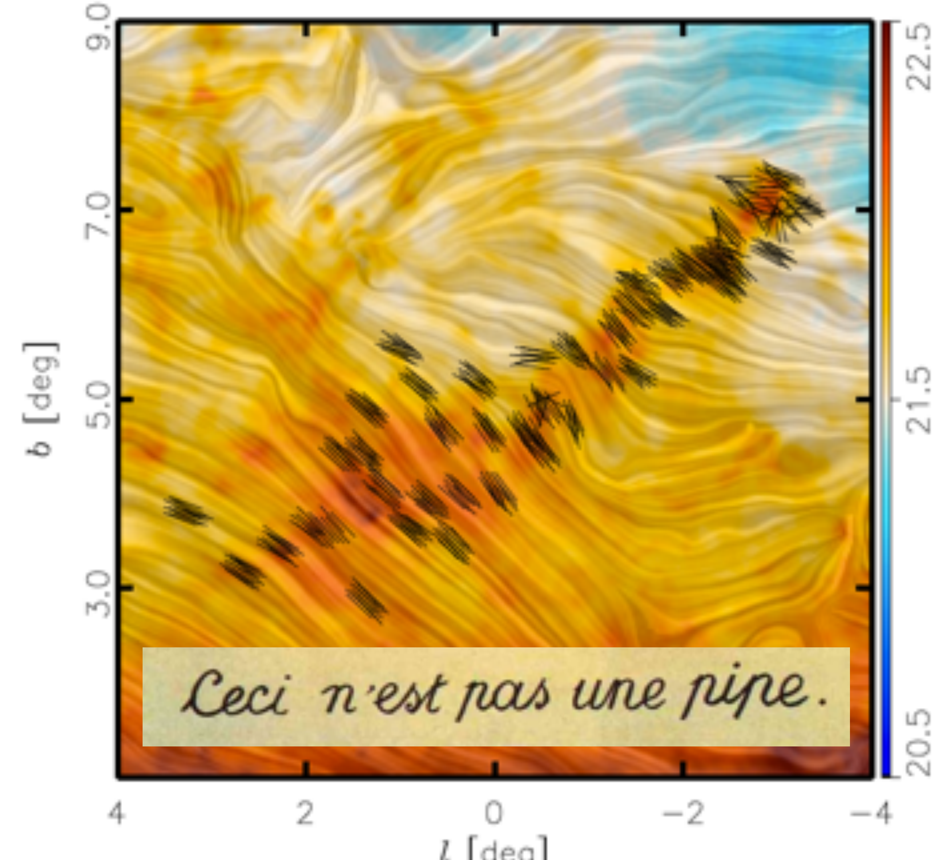
- Starlight polarization in extinction in NIR/visible probes much smaller scales than Planck data
- Differences in polarization angles are small and consistent with resolution effects

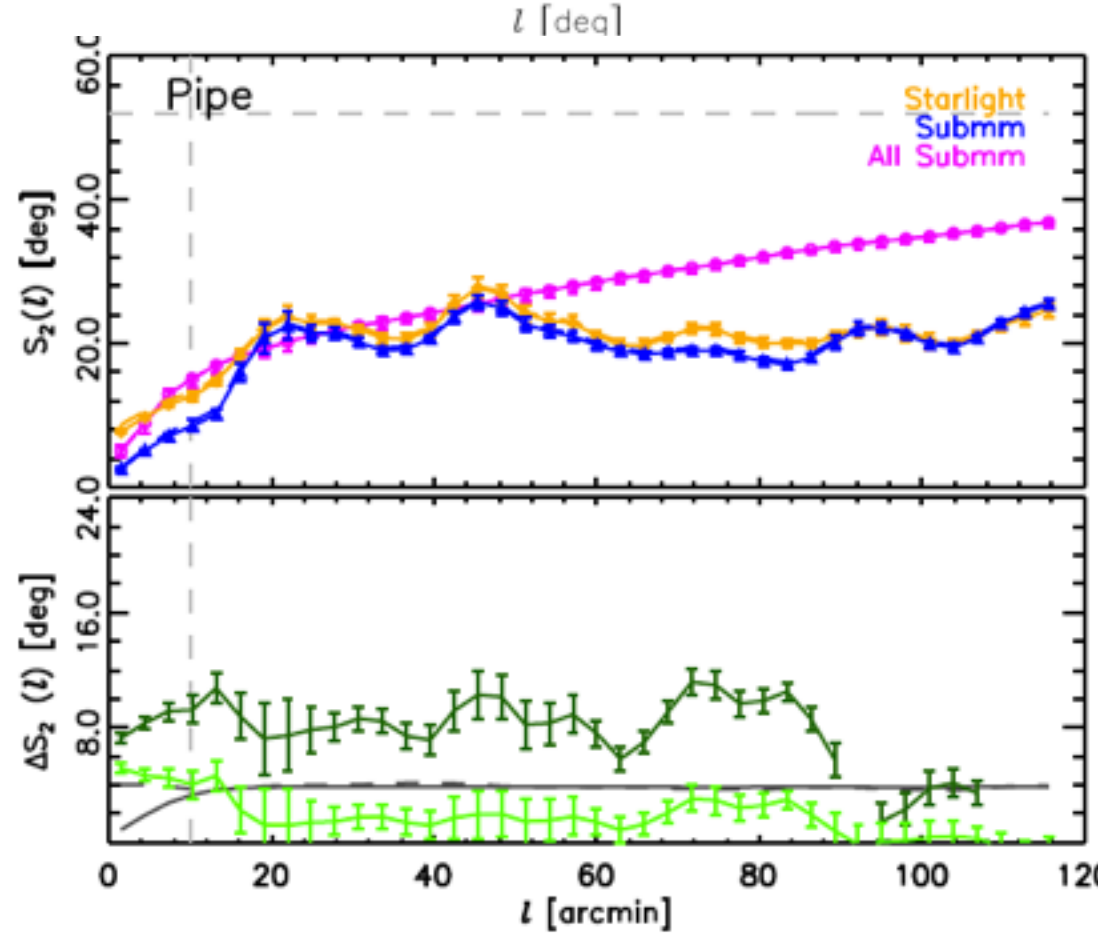


Planck Collaboration Int. XXI (2015)



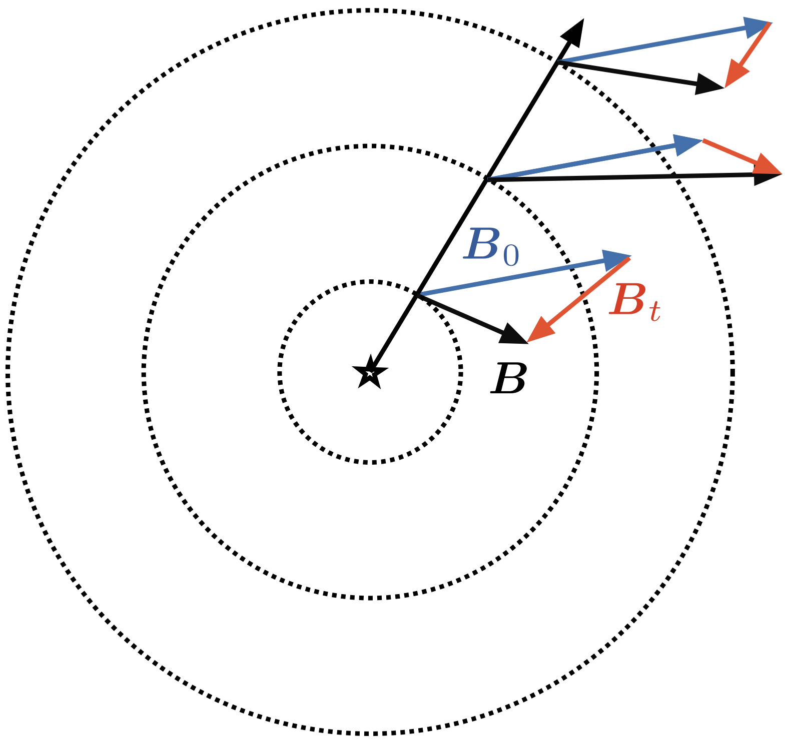
Soler et al. (2016)





Perspectives on modelling polarized thermal dust emission

- Stacking of a small number of polarized emission layers, with POS spatial correlations



Turbulent field

$$B = B_0 + B_t$$

Uniform field

Turbulent-to-mean ratio $f_{\mathrm{M}} = \frac{\sigma_B}{B_0}$

Spectral index of the turbulent component $C_\ell \propto \ell^{\alpha_{\mathrm{M}}}$

Molecular clouds $f_{\mathrm{M}} = 0.5 \pm 0.2$ — Planck Collaboration Int. XXXV (2016)

Diffuse ISM at high and intermediate latitudes $f_{\mathrm{M}} = 0.8 \pm 0.2$ — Planck Collaboration Int. XXXII (2016)

Southern Galactic cap $f_{\mathrm{M}} = 0.9 \pm 0.1$ — Planck Collaboration Int. XLIV (2016)

$\alpha_{\mathrm{M}} \in [-2, -3]$

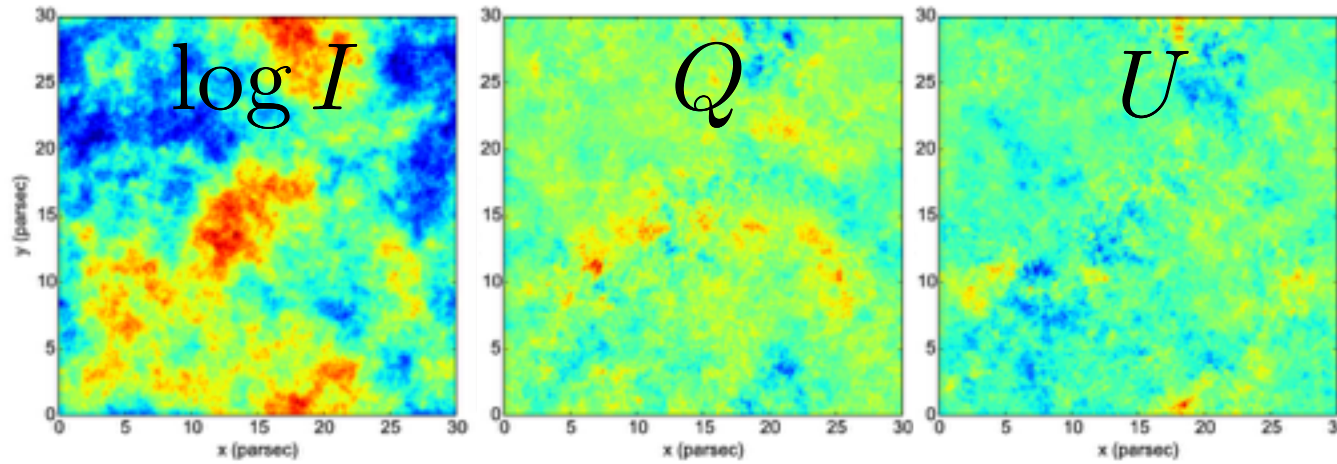
- Turbulent magnetic field modelled along the LOS, no POS correlation from pixel to pixel

WMAP 23 GHz polarized synchrotron data — Miville-Deschênes et al. (2008)

Models of polarized thermal dust emission at 150 GHz — O'Dea et al. (2012)

Modelling polarized thermal dust emission with fBm fields

- Dust density and magnetic field modelled by 3D fields with realistic spatial correlations
- Parameters are spectral indices, fluctuation levels, angle of the mean field and depth on the LOS
- Simulated polarization maps characterized by PDFs, power spectra, and correlations
- Monte-Carlo Markov Chain exploration of parameter likelihood given input polarization maps

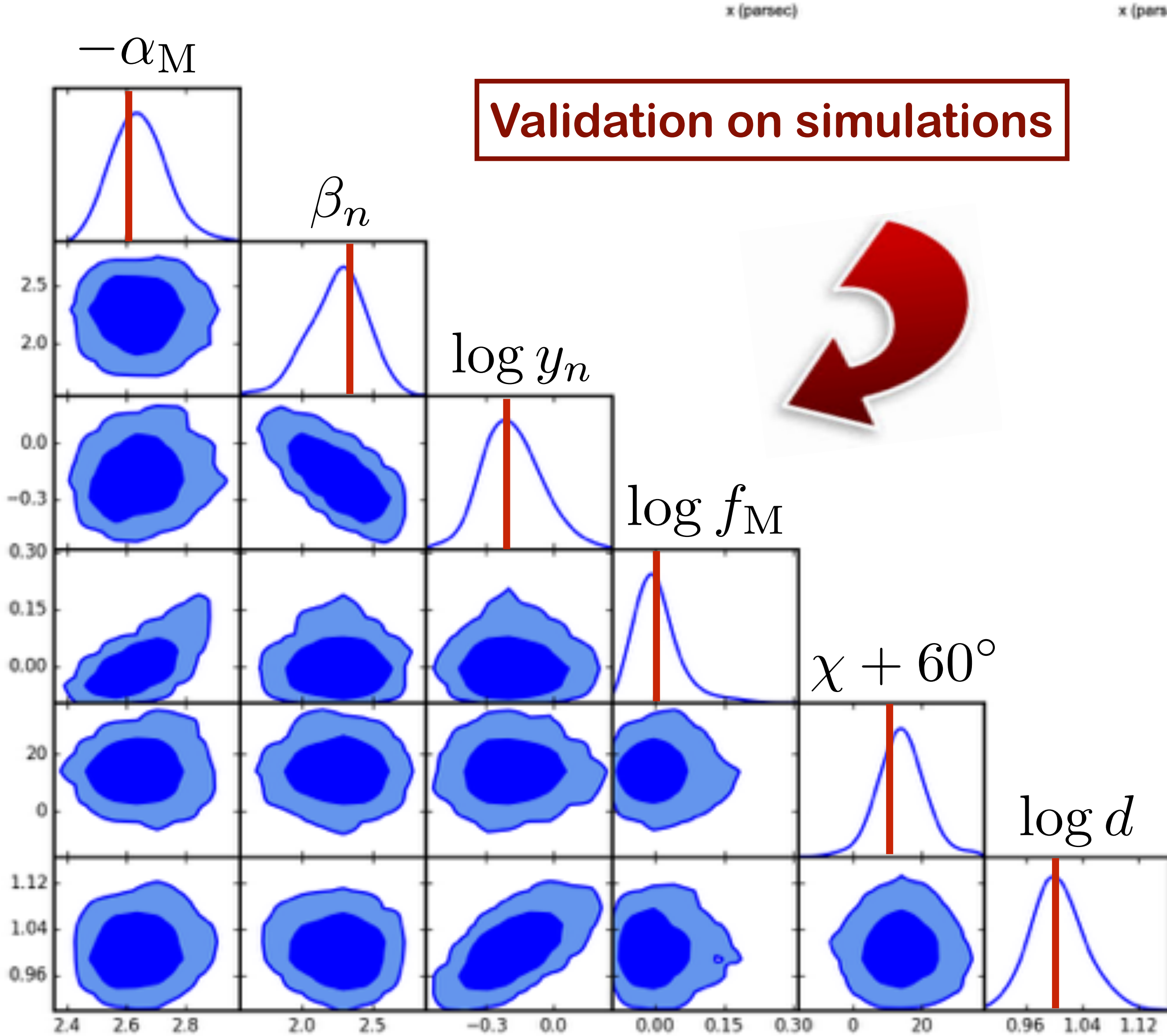


$$\alpha_{\rm M} = -2.53^{+0.13}_{-0.12}$$

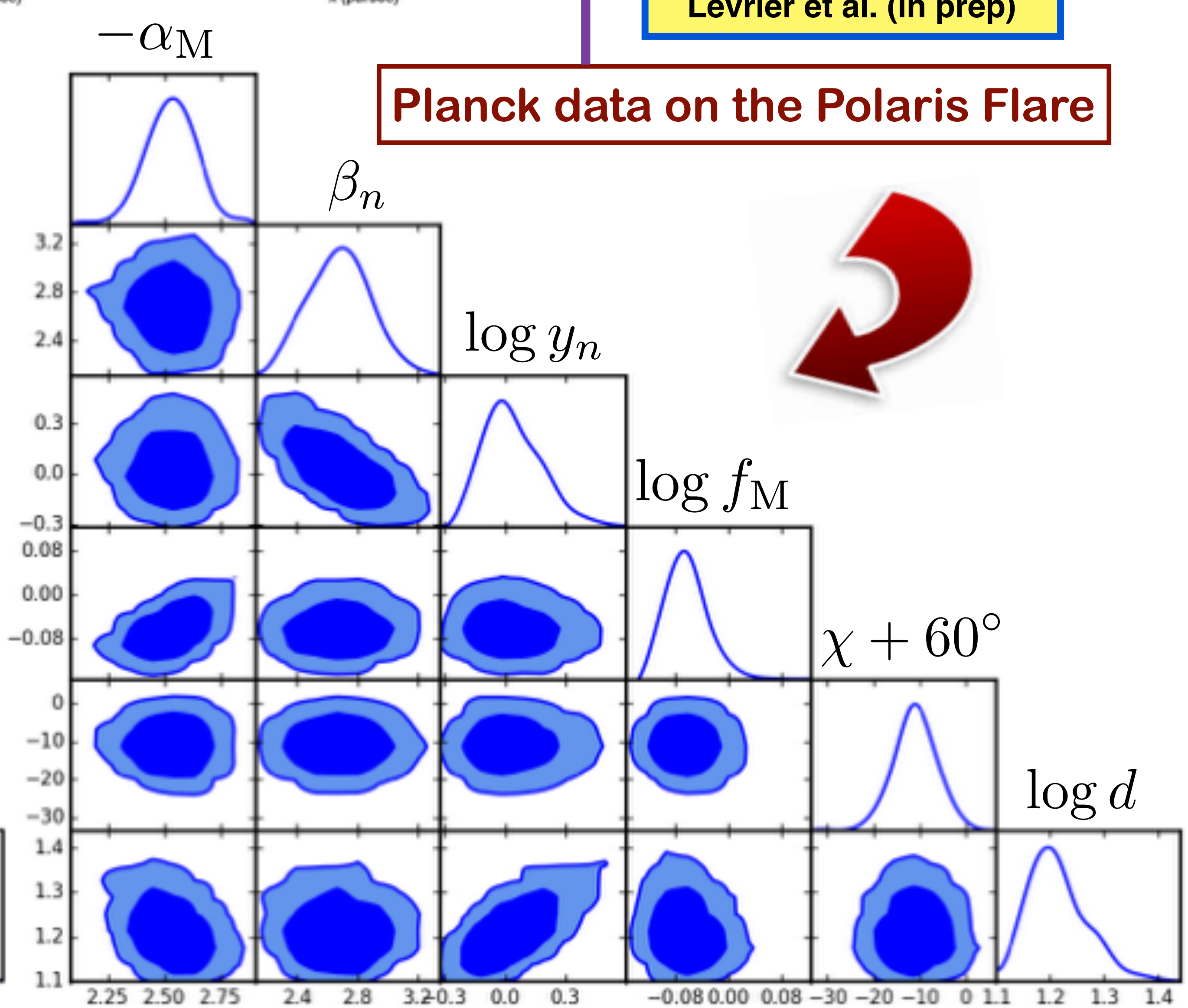
$$f_{\rm M} = 0.87^{+0.06}_{-0.08}$$

Levrier et al. (in prep)

Validation on simulations



Planck data on the Polaris Flare



Conclusions

- **First all-sky survey of polarized thermal dust emission**
- **Imprints of the Galactic magnetic field topology**
- **Dynamical role of the magnetic field in the formation of clouds**
- **Empirical models probe the turbulent magnetic field**
- **A strong foreground to primordial signals**

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