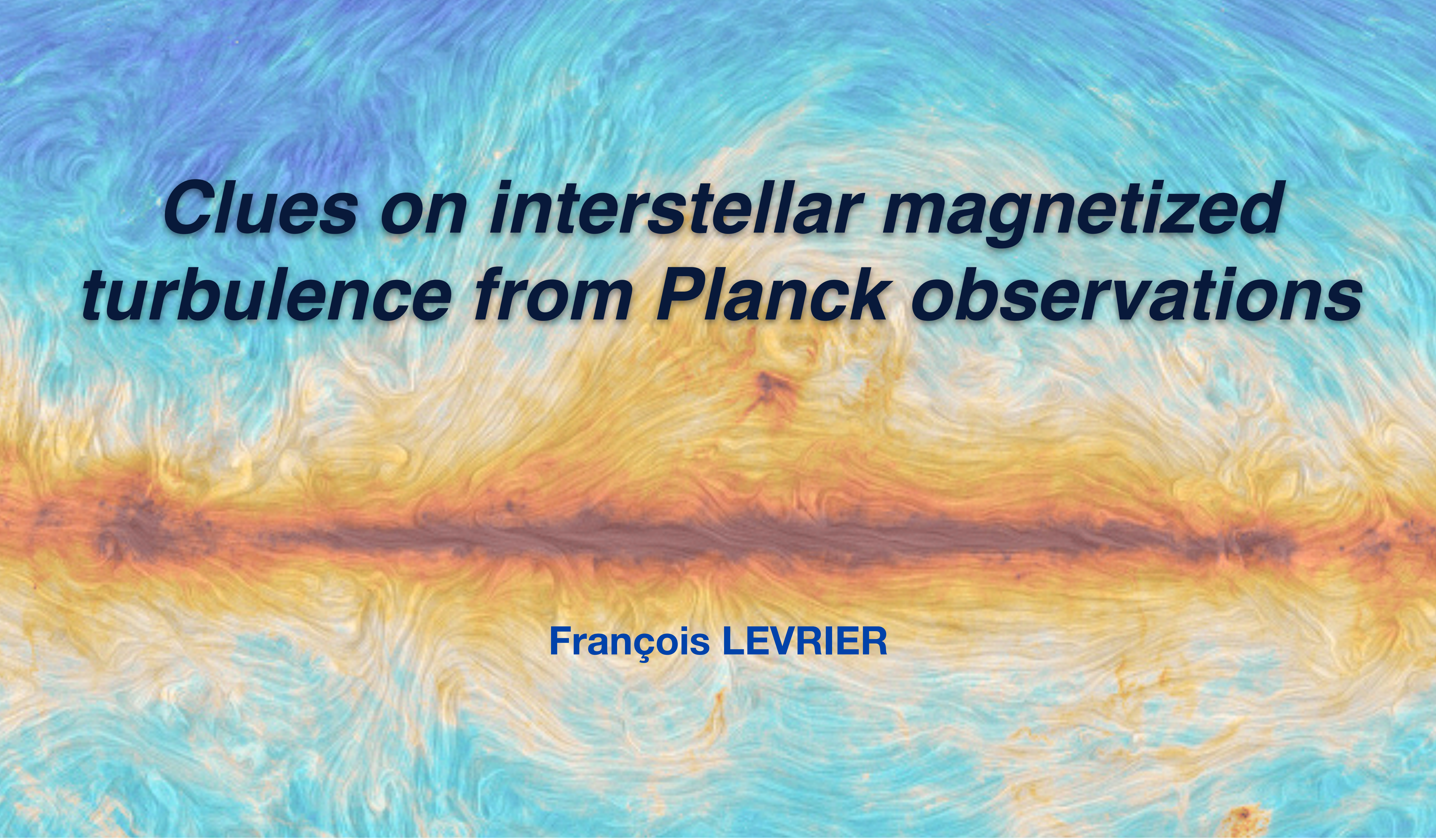
Clues on interstellar magnetized turbulence from Planck observations

François LEVRIER



Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

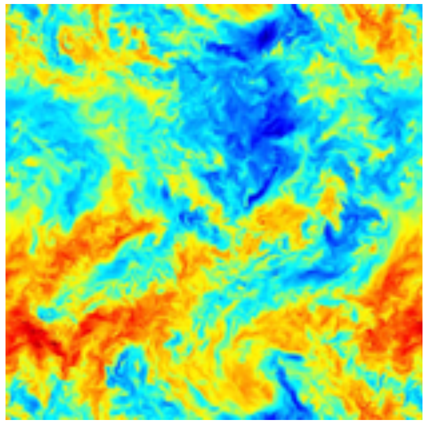
ISM Jamboree, ENS Paris, 18.11.2016

Talk outline

- Lightning-fast introduction…

- Planck thermal dust polarization and MHD turbulence

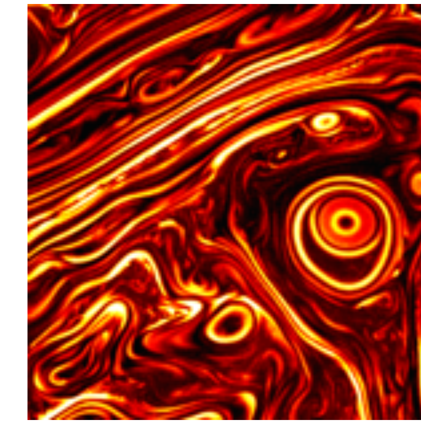
- Current work (also talk by F. Boulanger)



Vorticity (JHU)

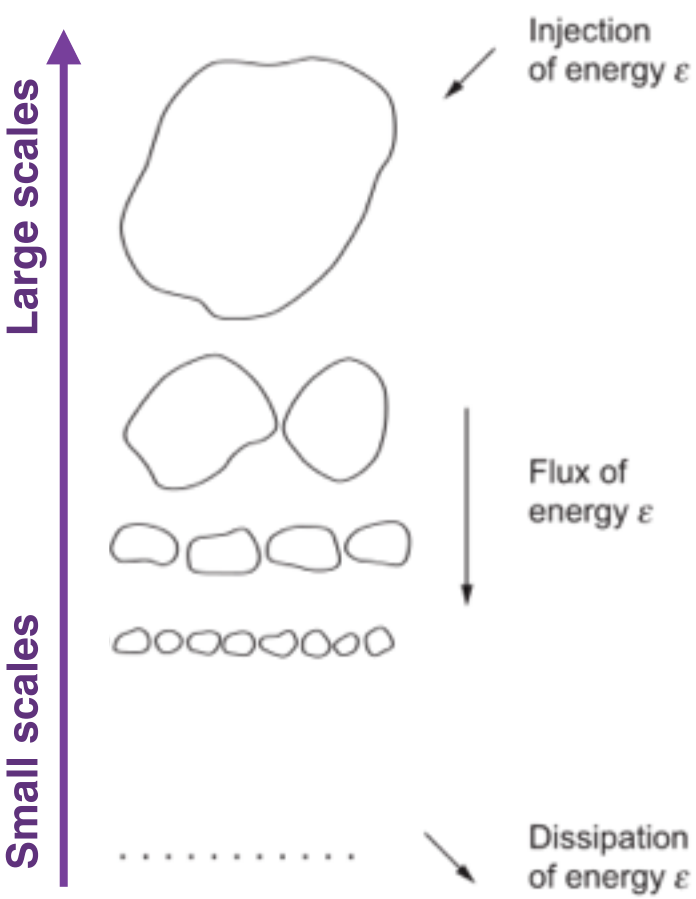
Turbulence

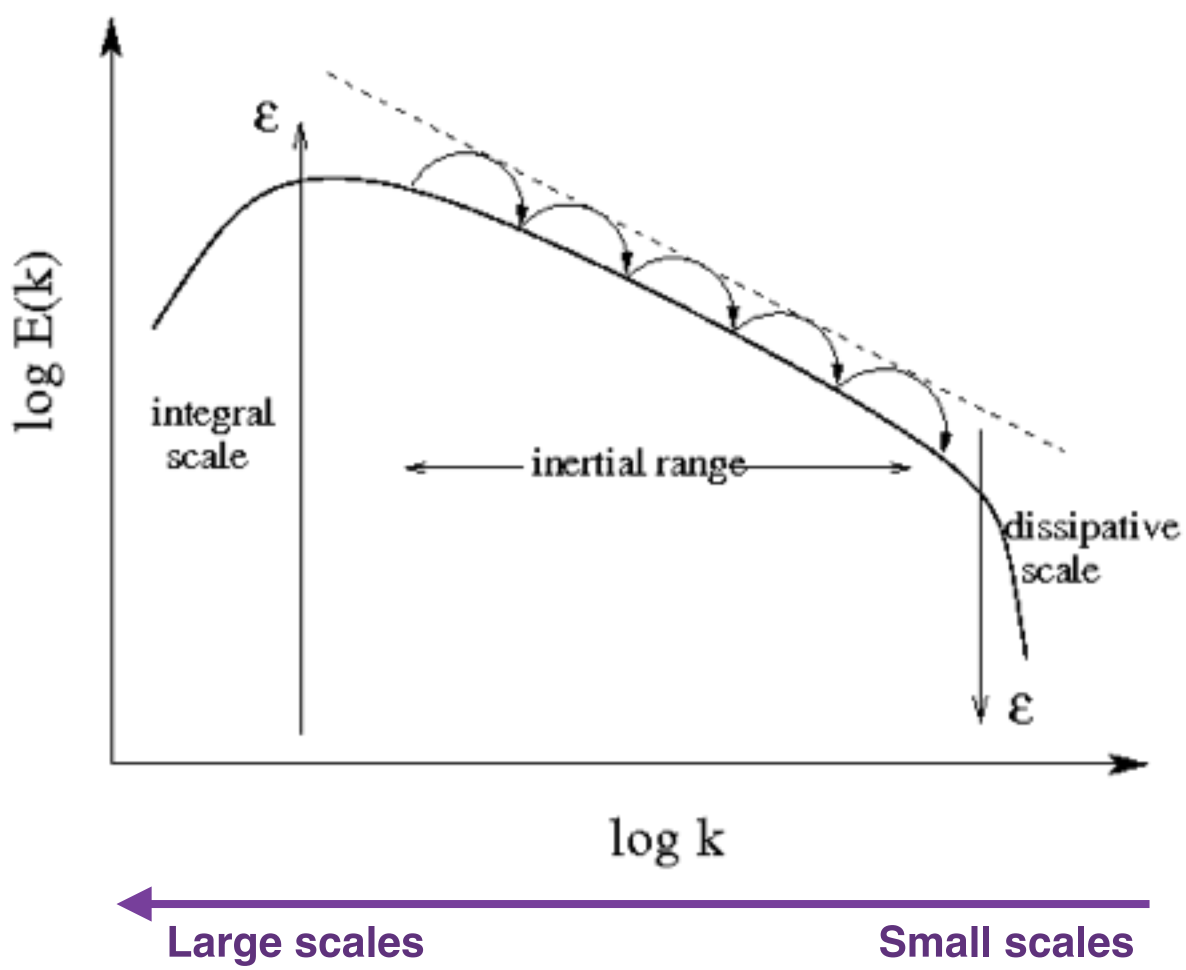
« Big whirls have little whirls
that feed on their velocity,
and little whirls have lesser whirls
and so on to viscosity. »
Lewis Fry Richardson (1920)



Current (UCSD, Berkeley Lab)

- Kolmogorov's K41 theory for HD turbulence : incompressible, homogeneous, isotropic cascade
- 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

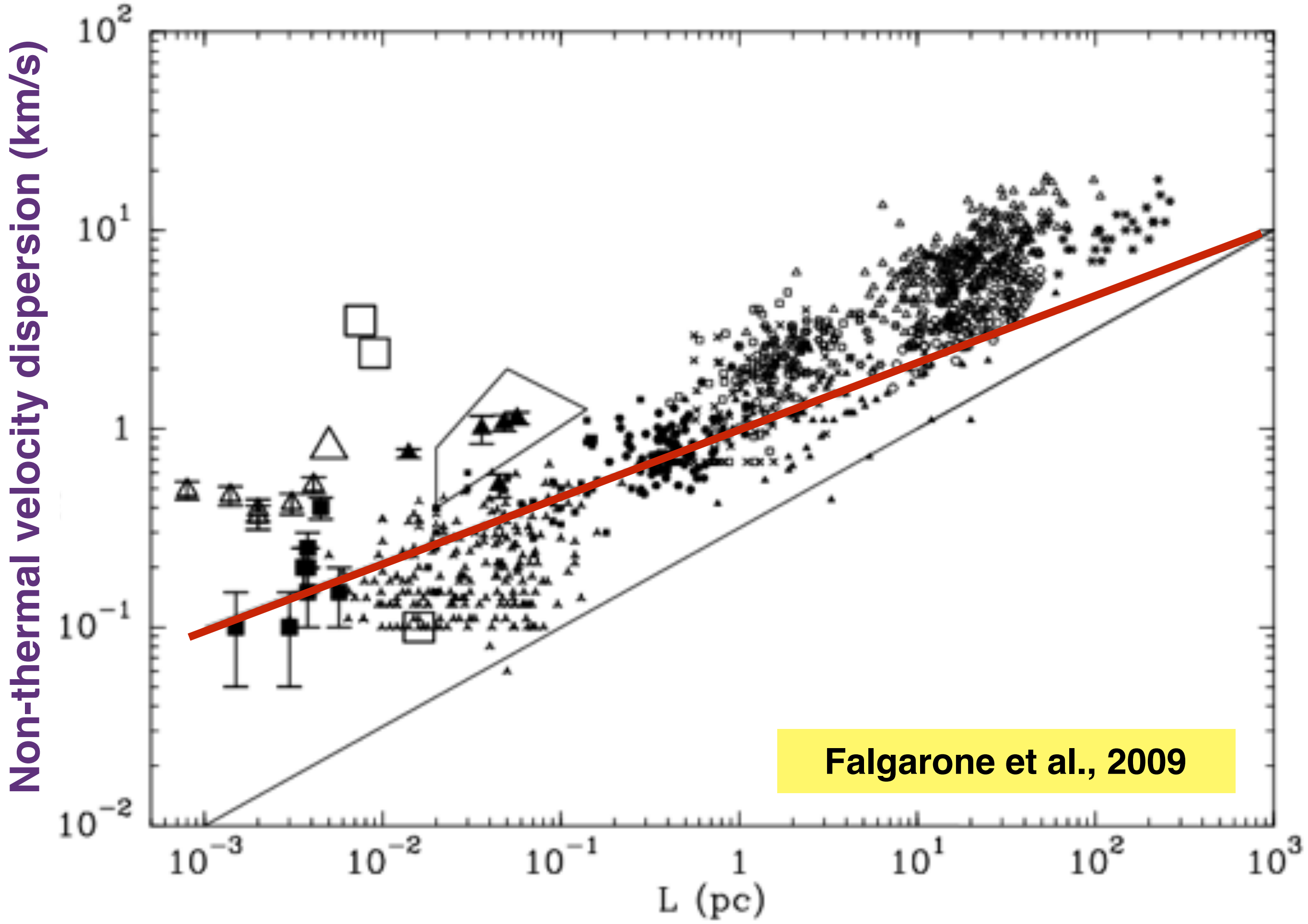
$$P_{v_\perp}(k) \propto k_\perp^{-5/3}$$

Kowal & Lazarian 2007

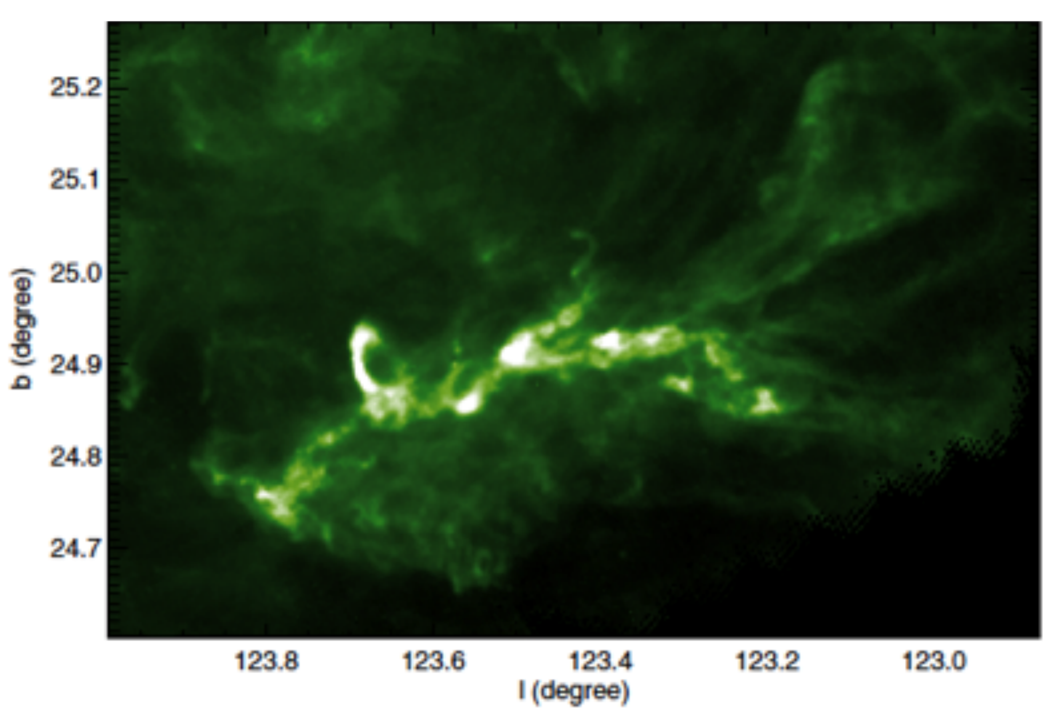
$$P_{\rho^{1/3} v}(k) \propto k^{-5/3}$$

Turbulence in the ISM

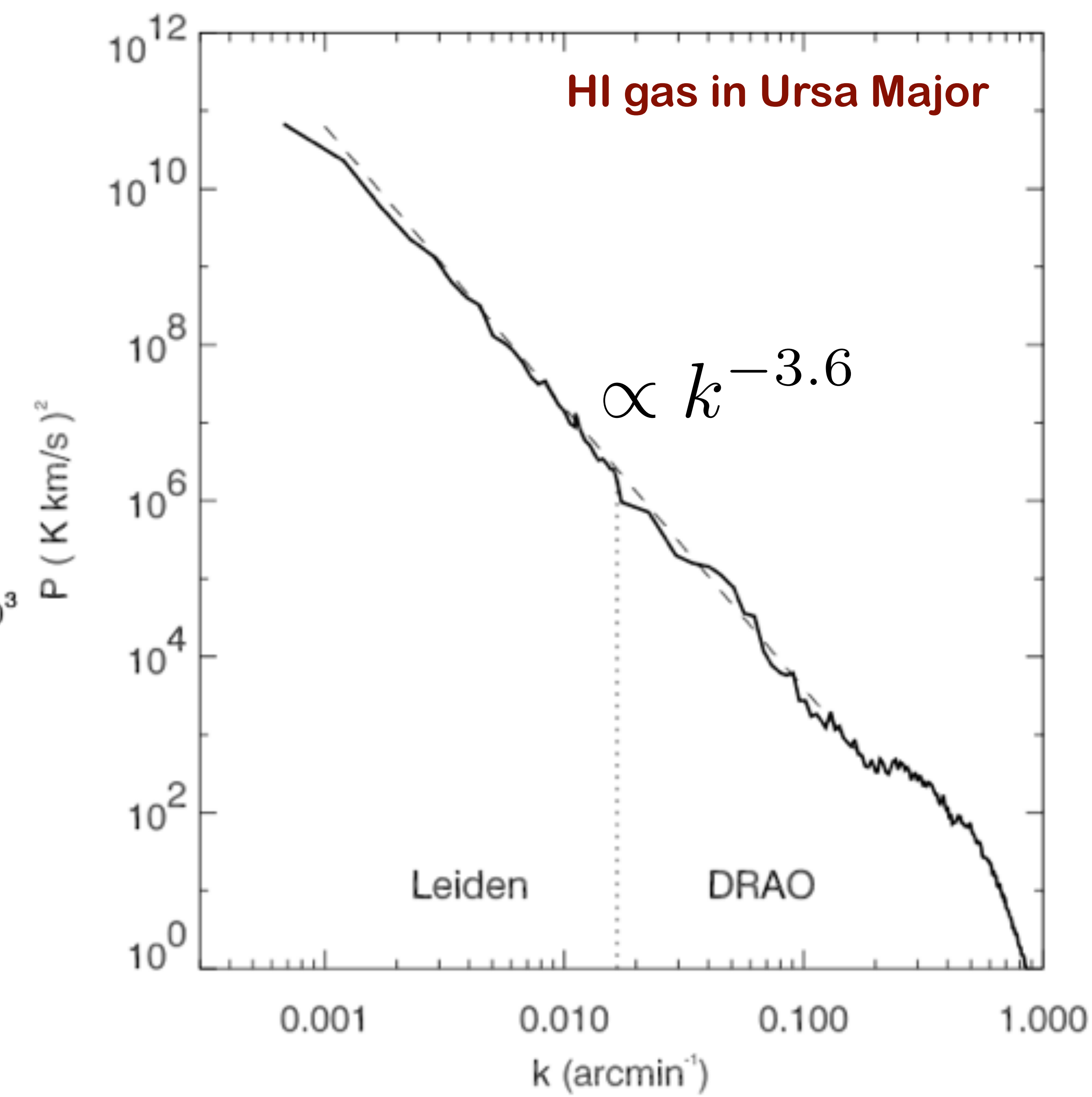
- Suprathermal linewidths, scaling with the size of structures
- Self-similarity of structures across many scales
- Intermittency at small scales : non-Gaussian wings in distributions of centroid velocity increments



Falgarone et al., 2009



Miville-Deschênes et al., 2010

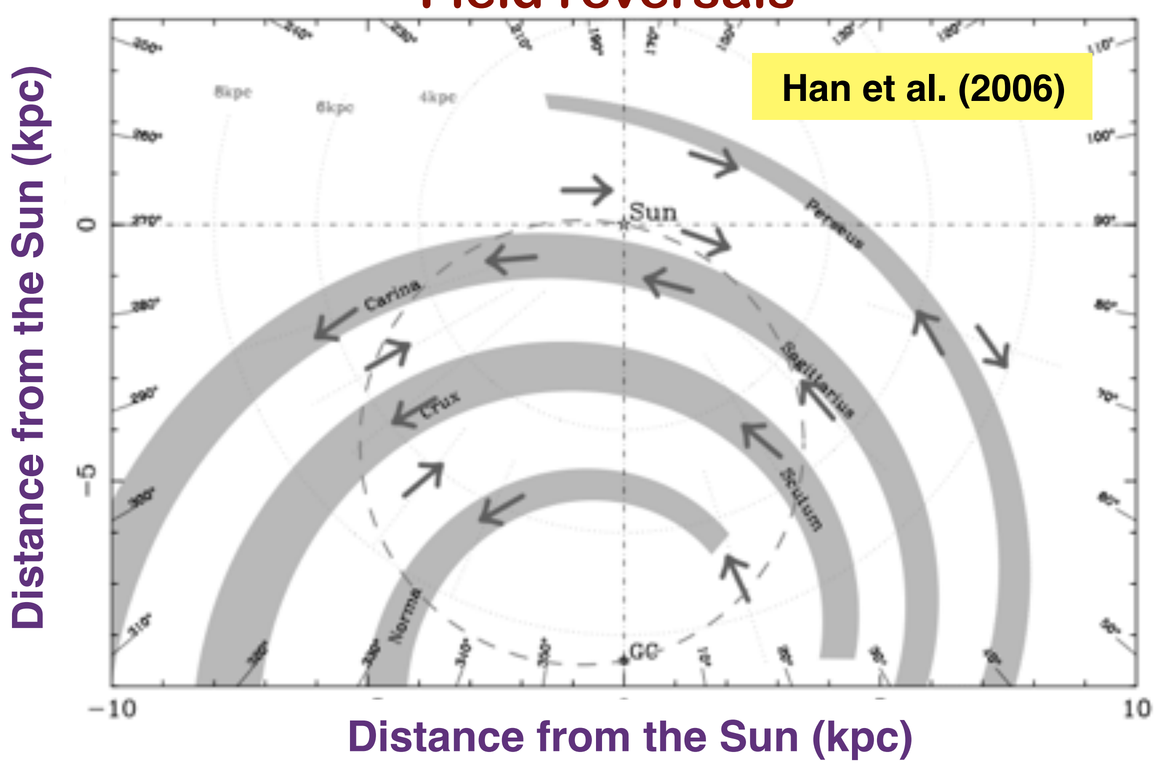


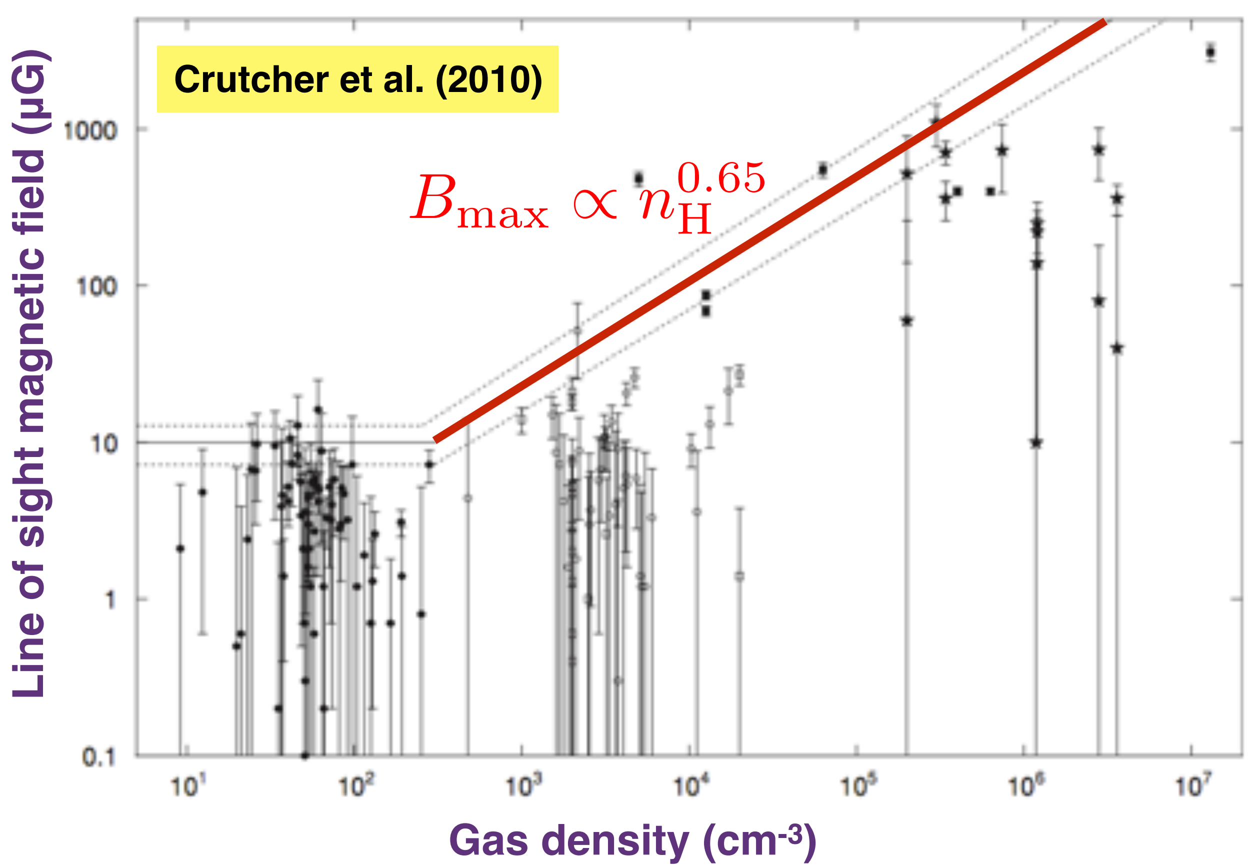
Miville-Deschênes et al., 2003

Magnetic fields in the Milky Way

- 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





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

$\sim$ a few μG $\qquad$ $\sim$ a few μG

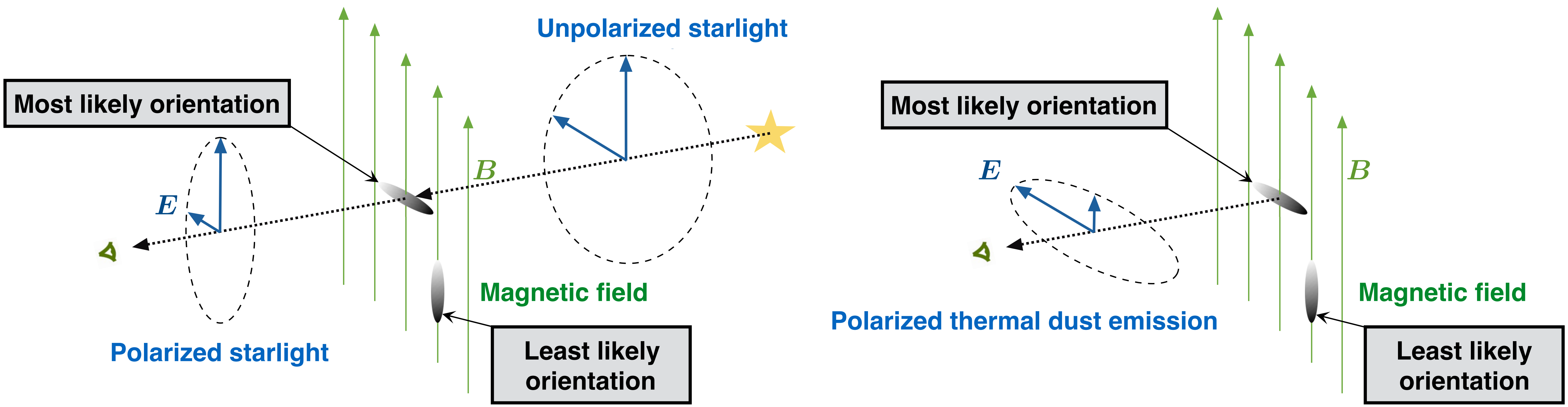
Haverkorn et al. (2008)

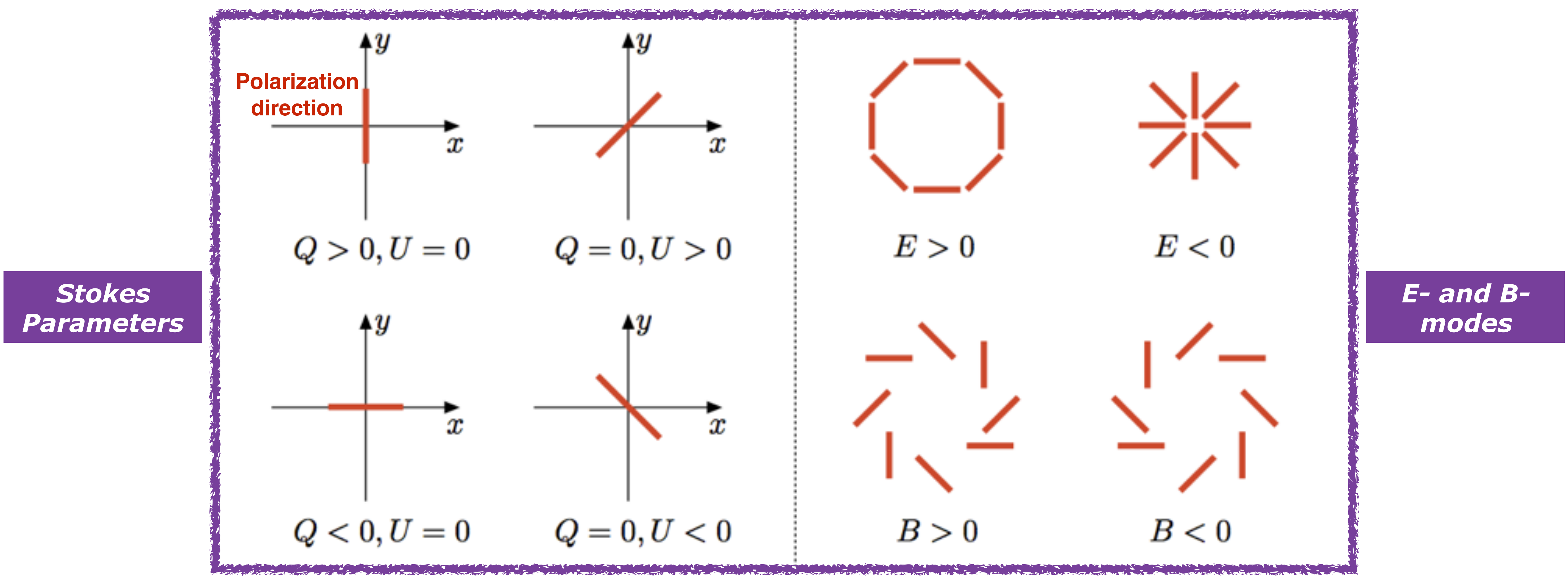
Measurement methods

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

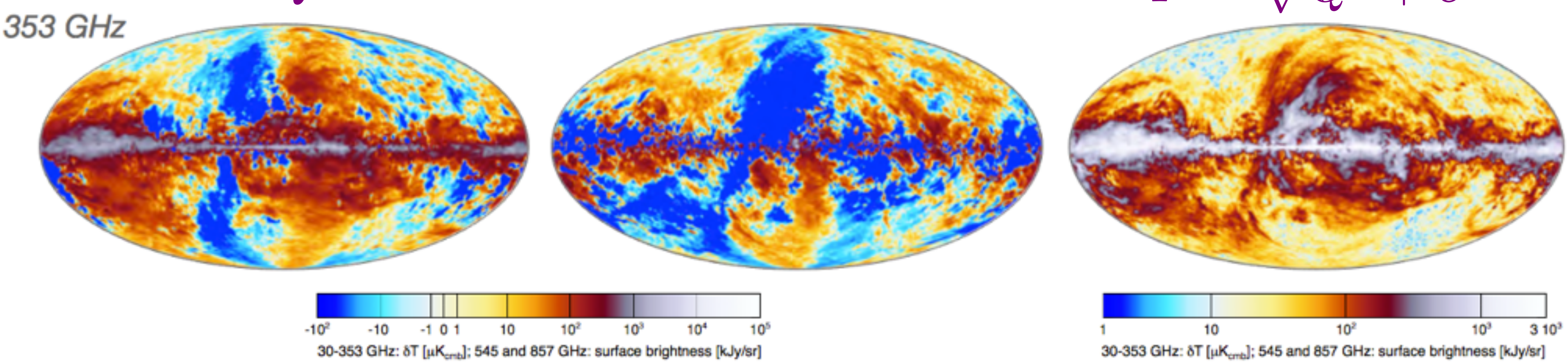
- Aspherical, charged, rotating dust grains statistically align in the local magnetic field
- Background starlight emerges polarized parallel to the magnetic field
- Polarized thermal dust emission arises perpendicularly to the magnetic field



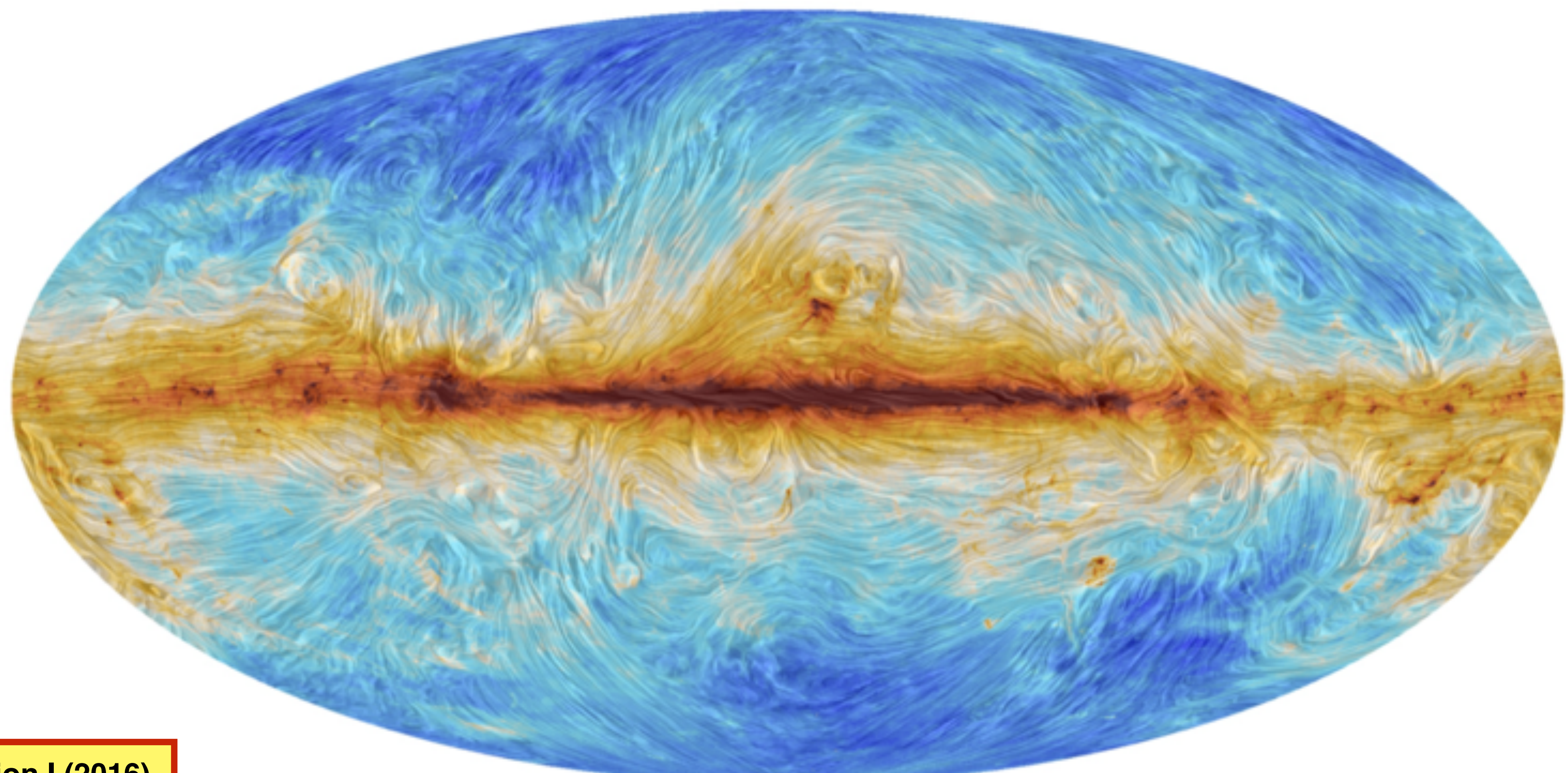


The Planck view of the Galactic magnetic field

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



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



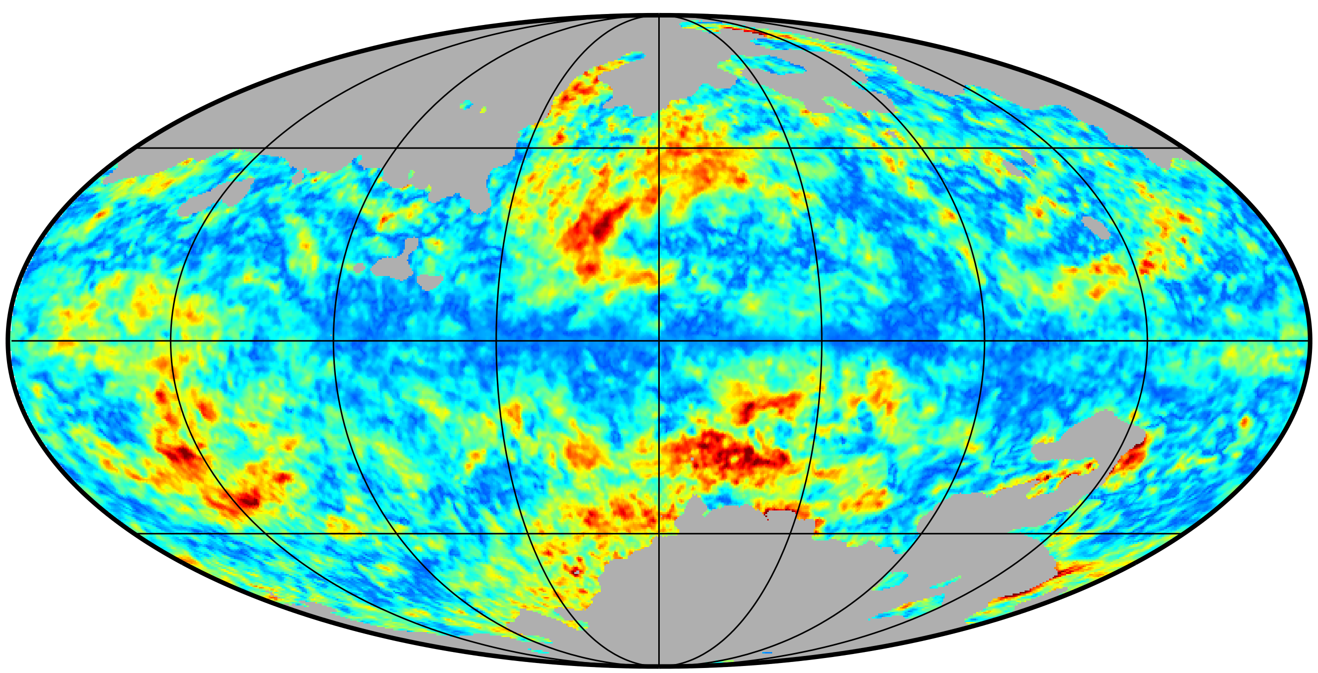
Planck Collaboration I (2016)

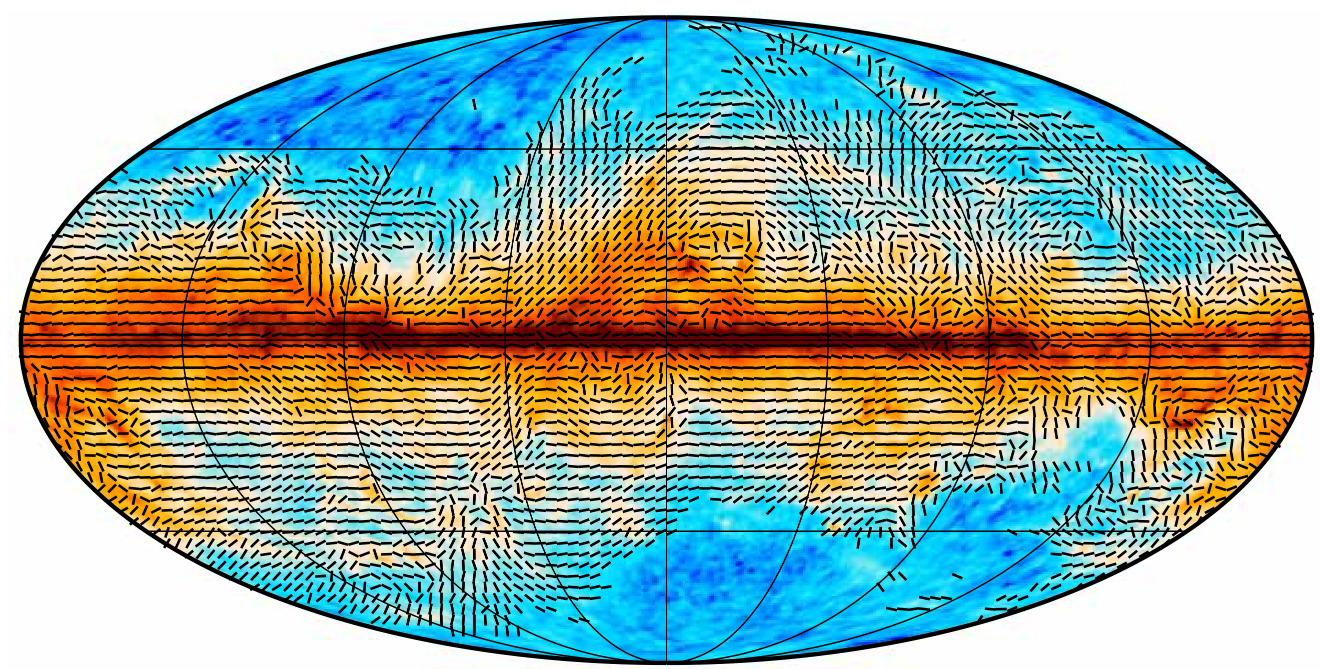
Properties of large-scale thermal dust polarization

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





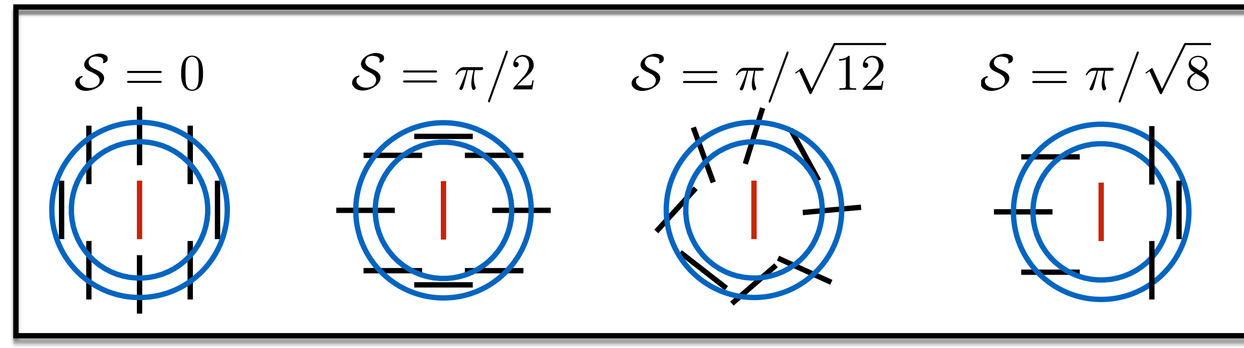
Update in early 2017…

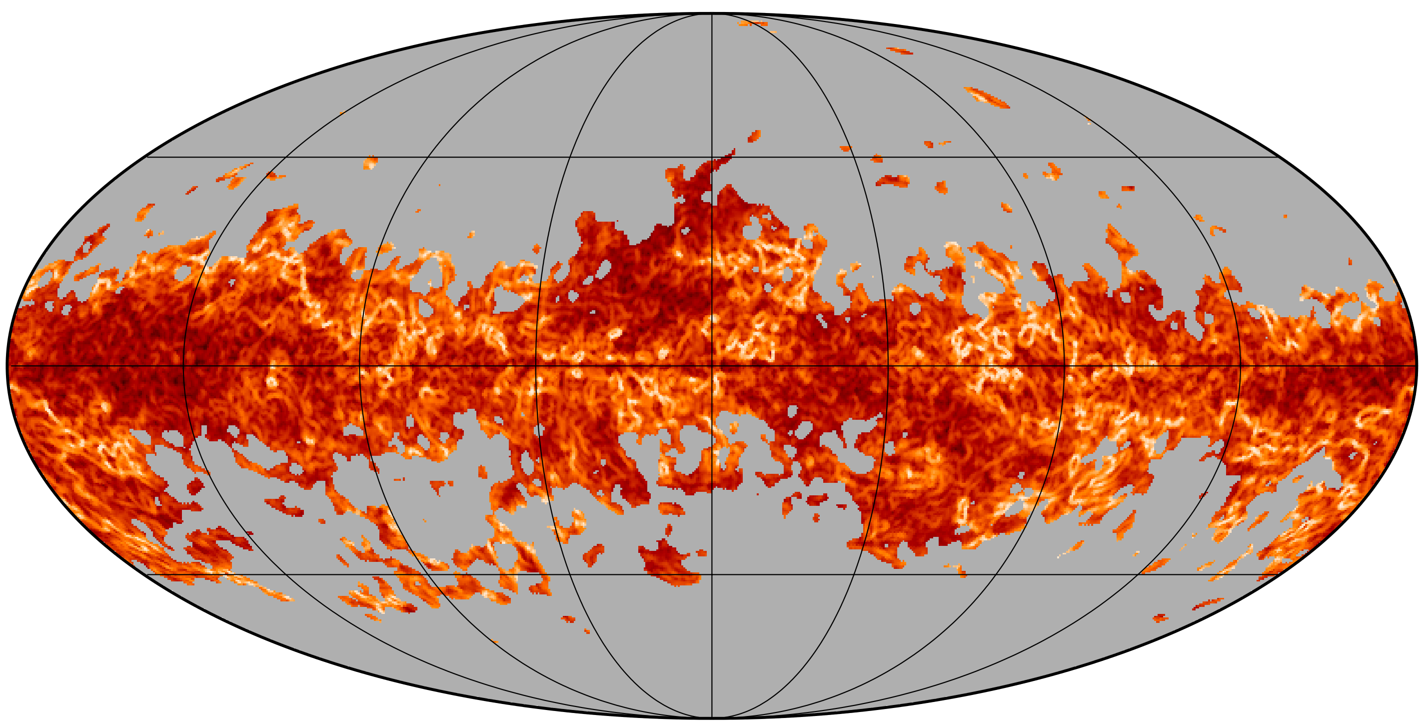
Planck Collaboration Int. XIX (2015)

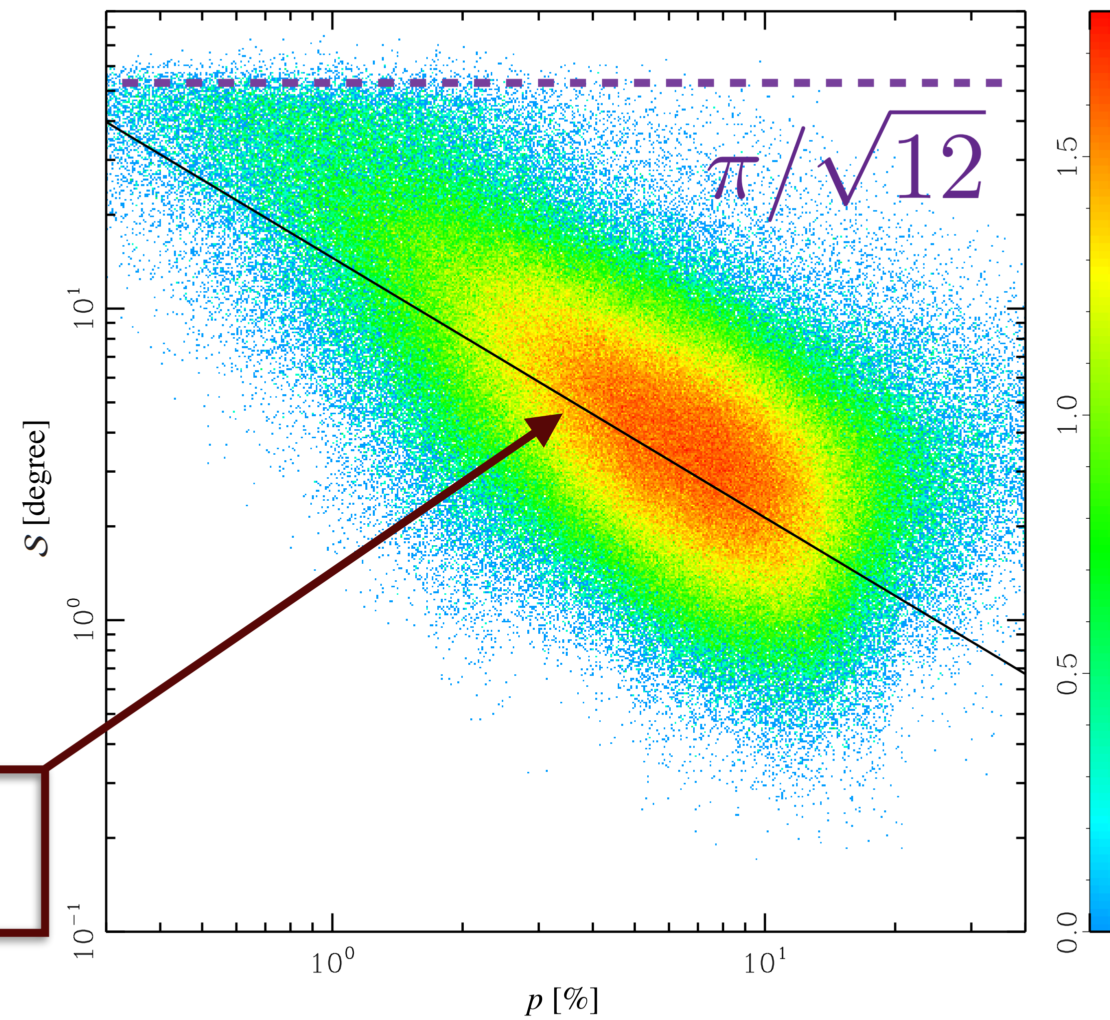
Spatial structure of the polarization angle map

Polarization angle dispersion function

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





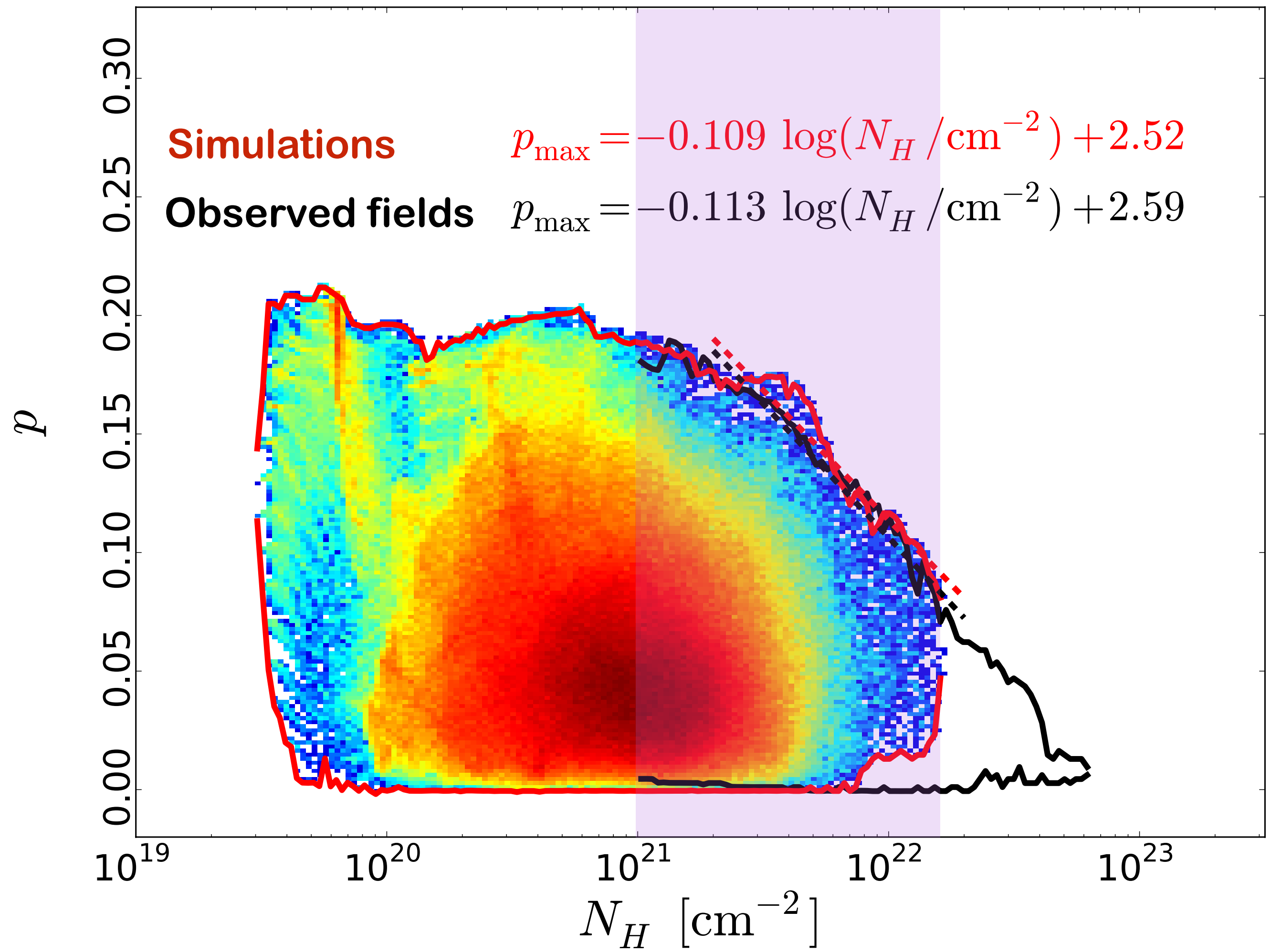


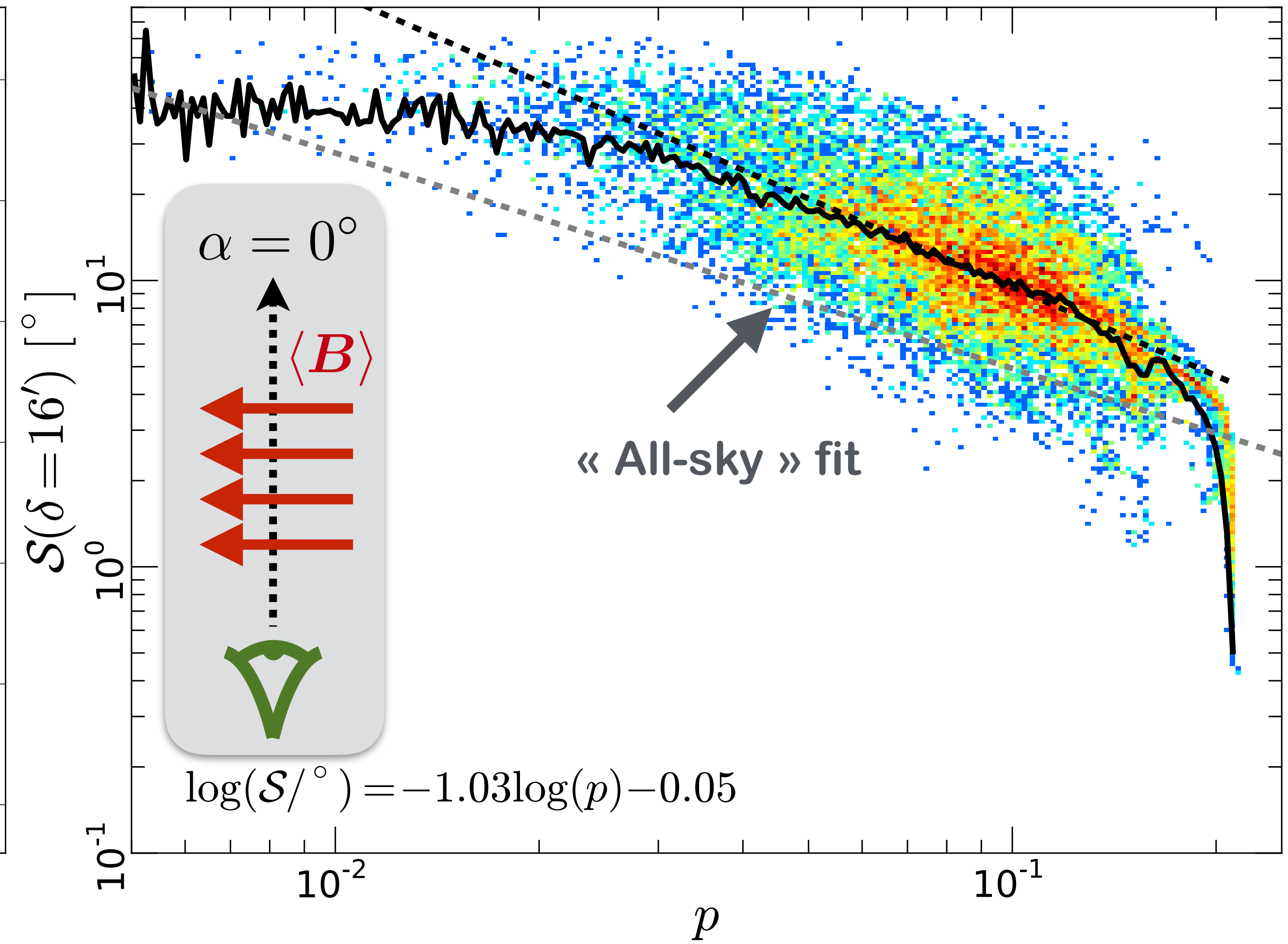
$$\log(\mathcal{S}/\,\mathrm{deg}) = -0.834\log p - 0.504$$

- 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)

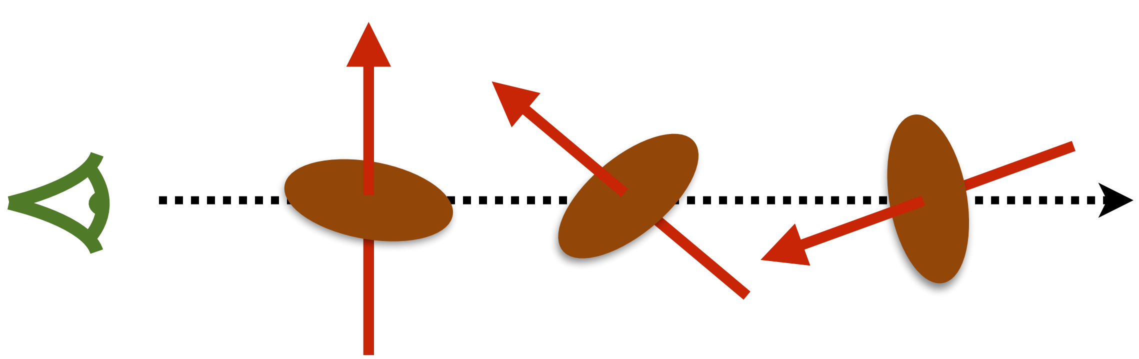
Comparison with a simulation of anisotropic MHD turbulence

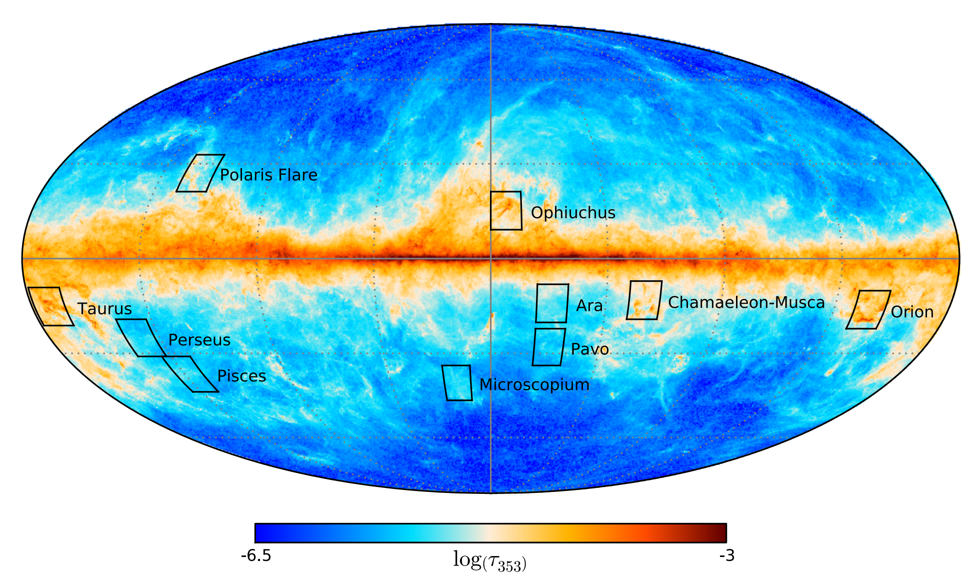




- Simulations reproduce the decrease of the maximum polarization fraction with N_H in that range
- The global anti-correlation with the polarization angle dispersion function is reproduced, with a shift

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



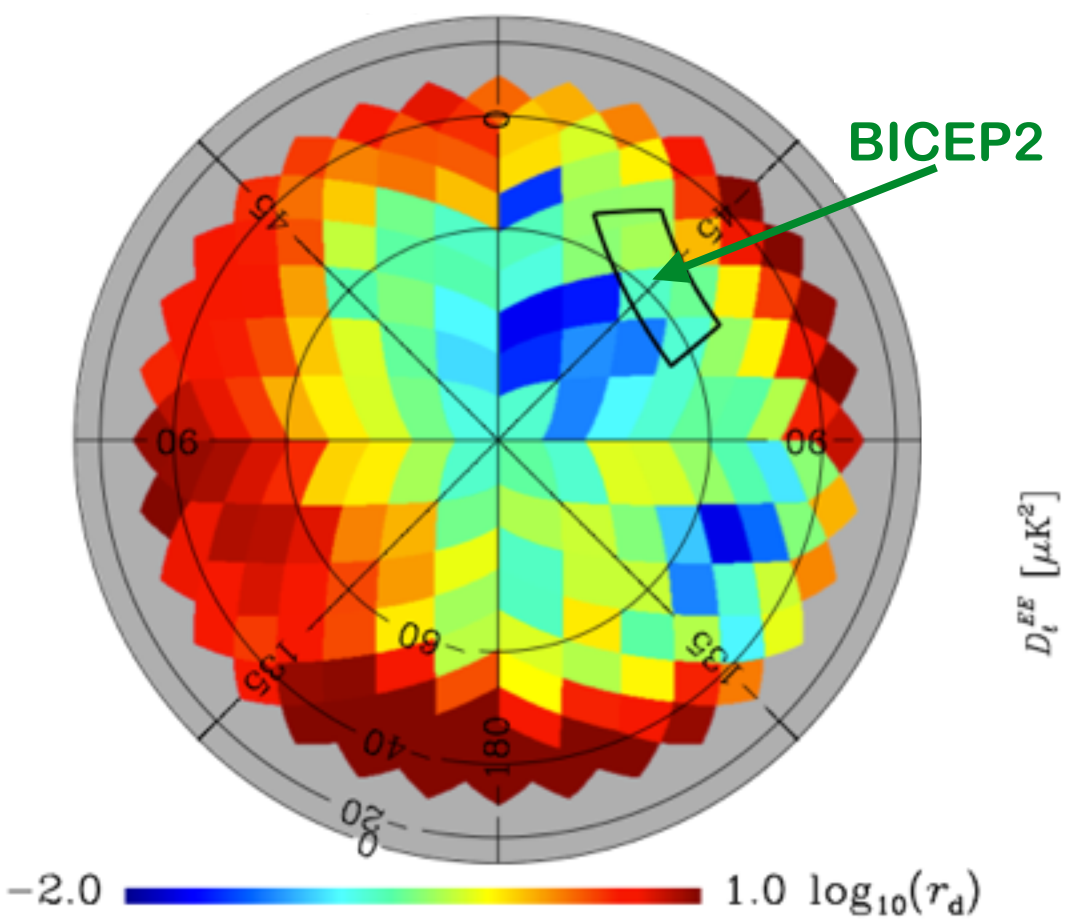


Planck Collaboration Int. XX (2015)

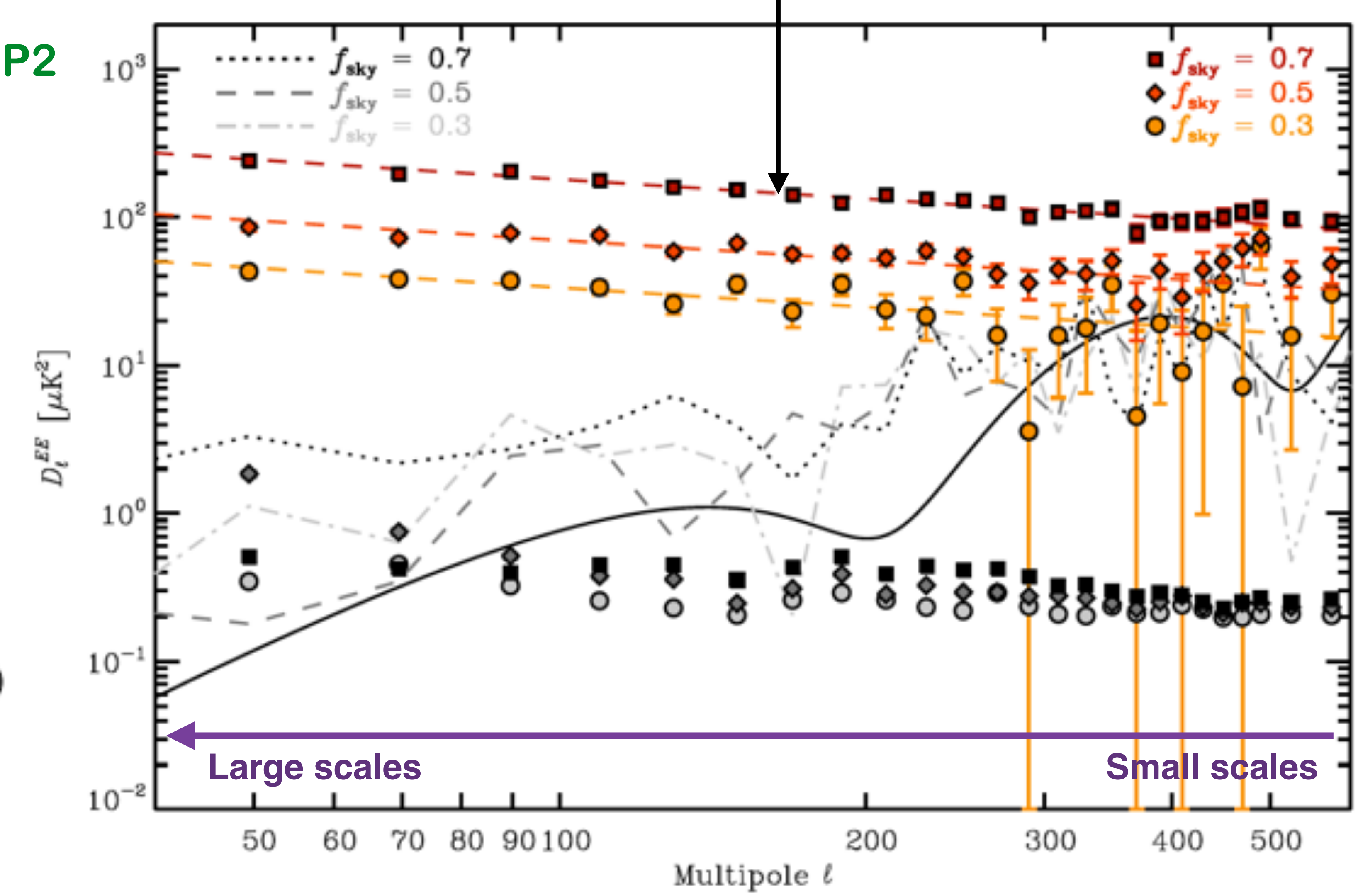
The angular power spectrum of polarized thermal dust emission

- E and B thermal dust emission angular power spectra outside the Galactic plane well fit by power laws
- B mode power attributable to dust in the BICEP2 field compatible with reported detection

BICEP2 Collaboration (2014)



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



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

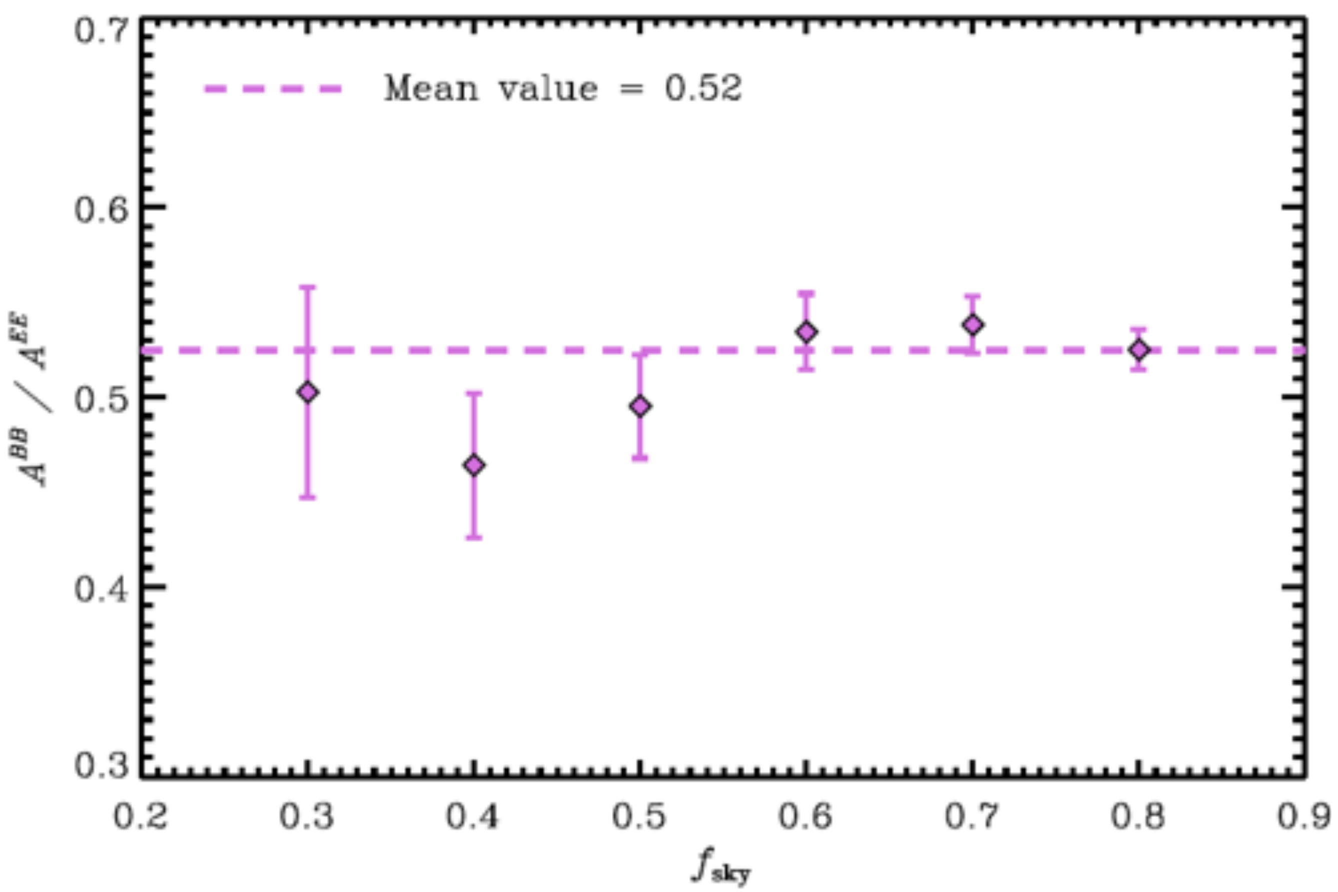
$$\alpha_{EE,BB} = -2.42 \pm 0.02$$

Planck Collaboration Int. XXX (2016)

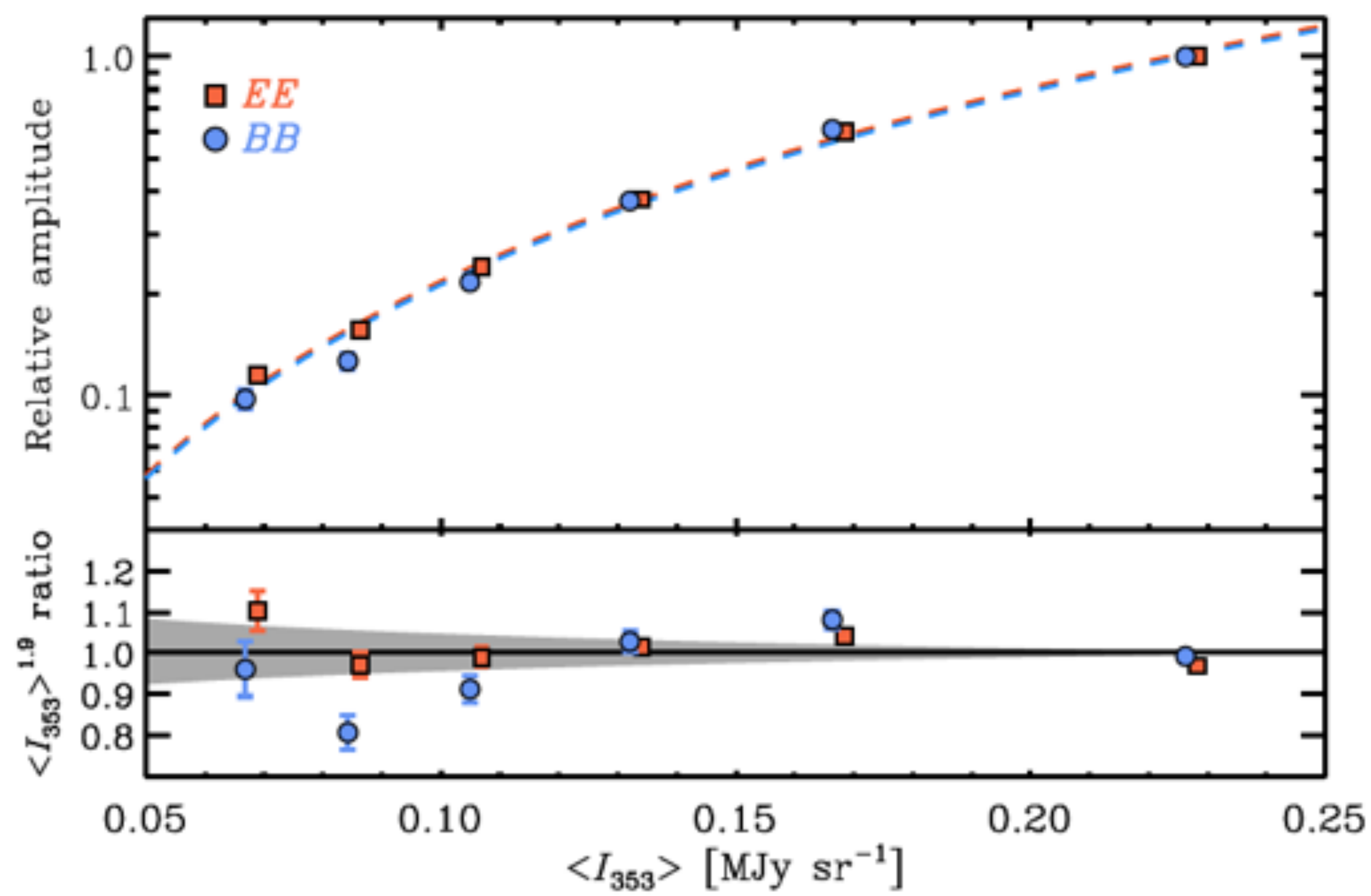
The angular power spectrum of polarized thermal dust emission

- 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/E asymmetry



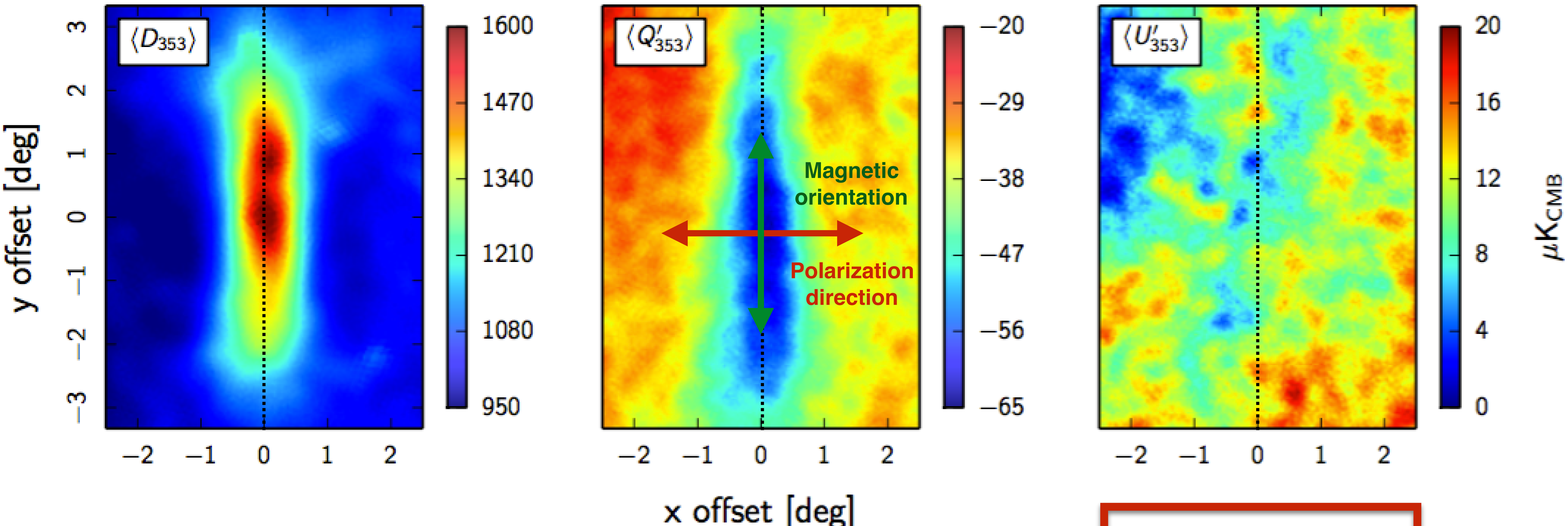
Scaling with dust emission intensity



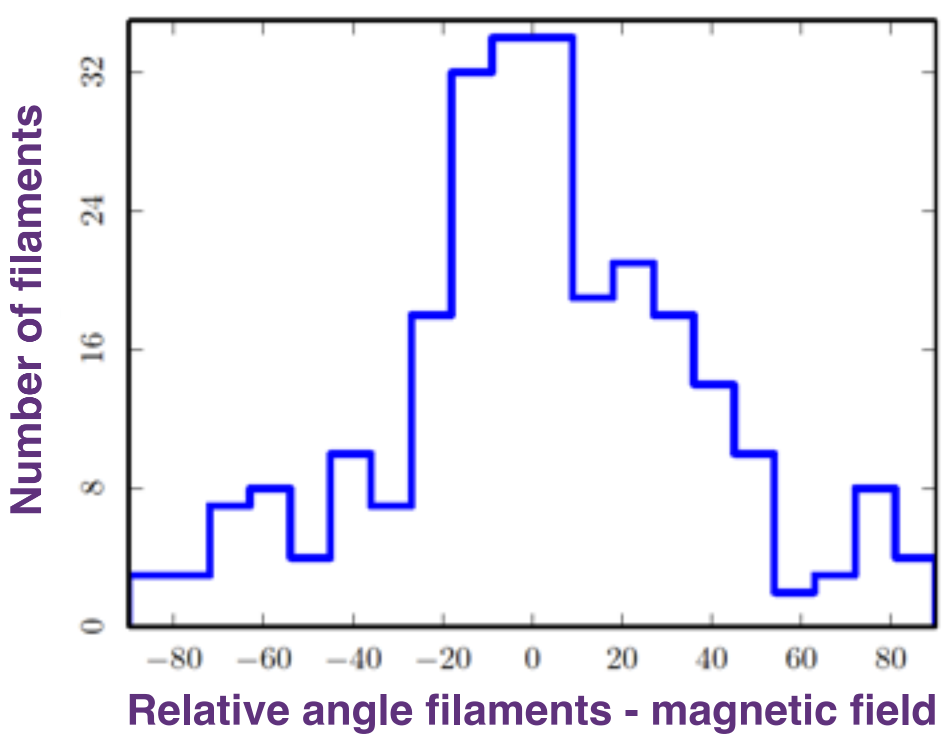
Planck Collaboration Int. XXX (2016)

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



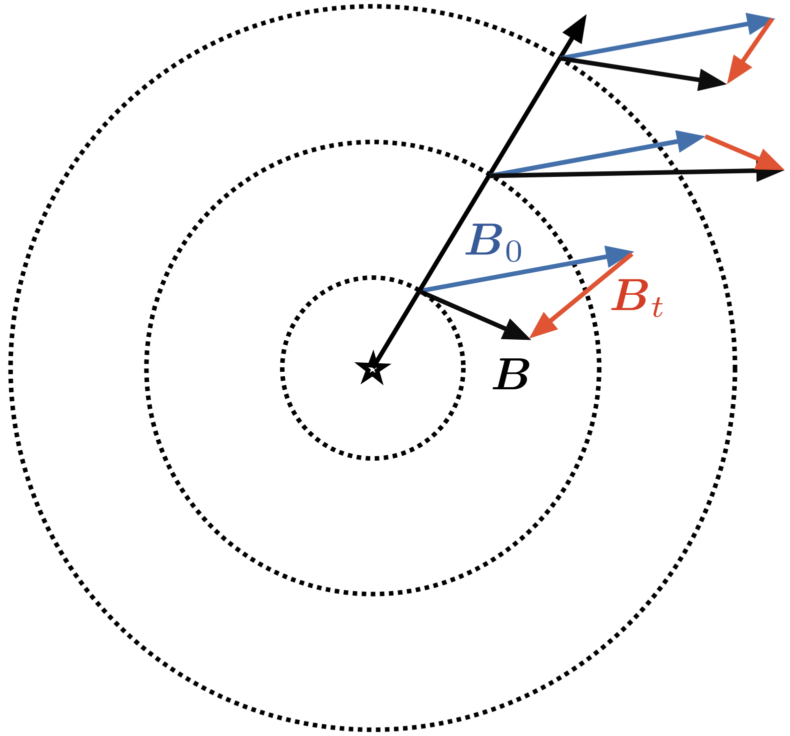
$$\langle p \rangle = 11\%$$



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

Planck Collaboration Int. XXXVIII (2016)

A Gaussian model of the polarized sky



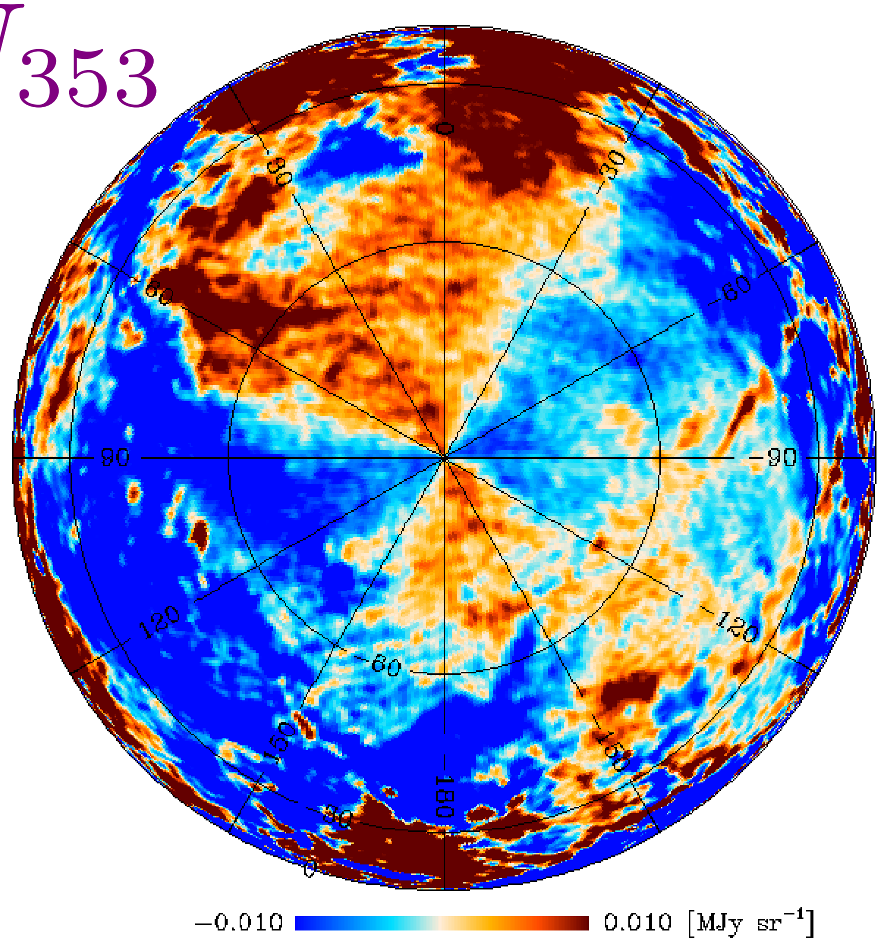
Magnetic field $B = B_0 + B_t$

Uniform field — Turbulent field

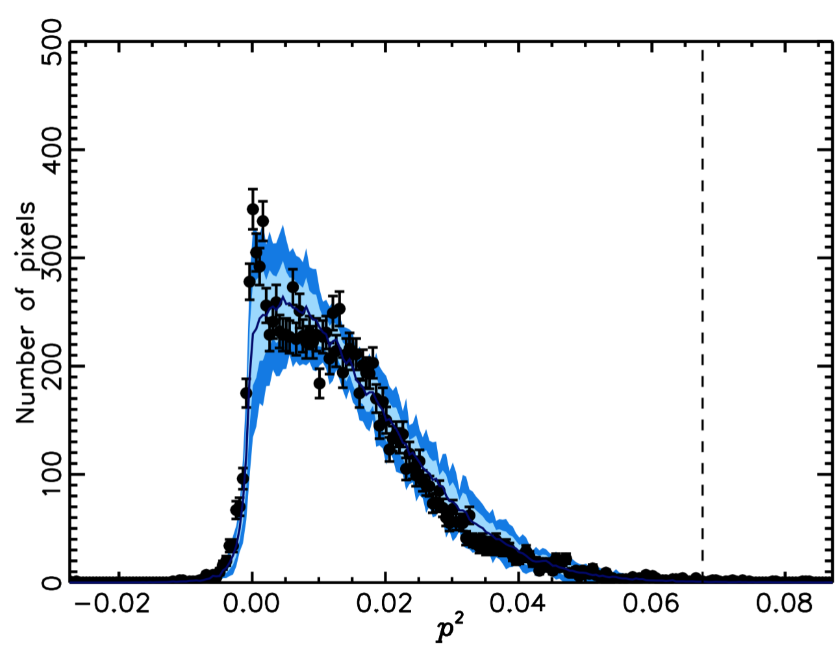
- A superposition of variously polarized layers (turbulent cells ?)
- Turbulent field : 3D Gaussian random variable
- Analysis of the Southern Galactic cap

  - 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 $p_0 = 26 \pm 3\%$

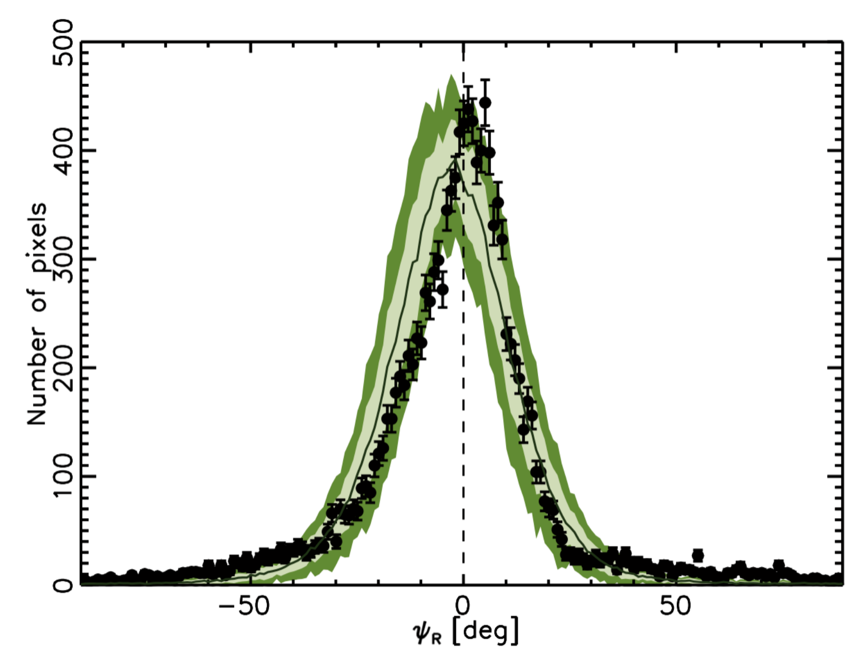
U_{353}



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



Polarization fraction

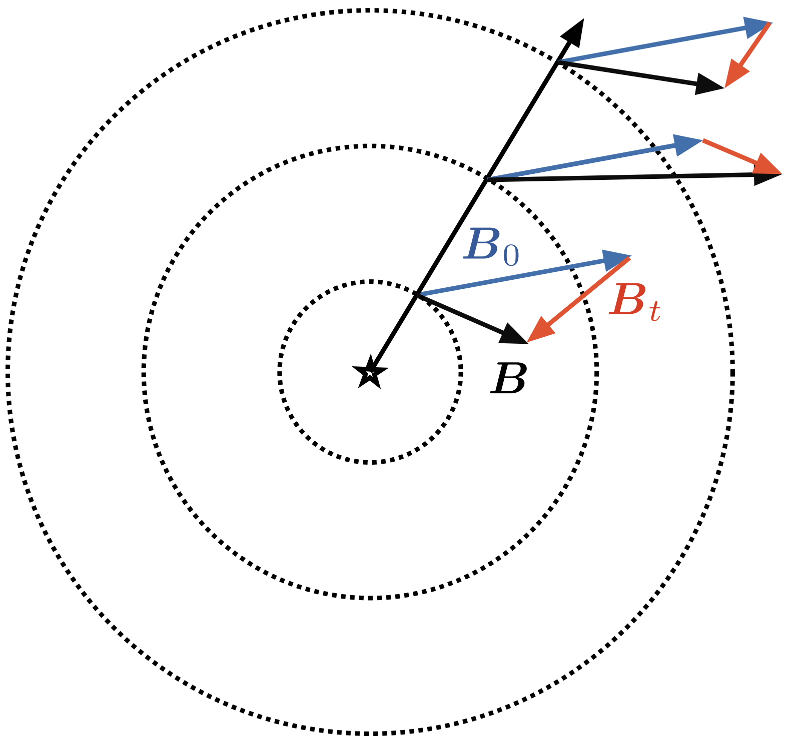


Polarization angle relative to the large-scale field

Planck Collaboration Int. XXXII, XLIV (2016)

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 $f_{\rm M} = \frac{\sigma_B}{B_0}$

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

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

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

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

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

- 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)

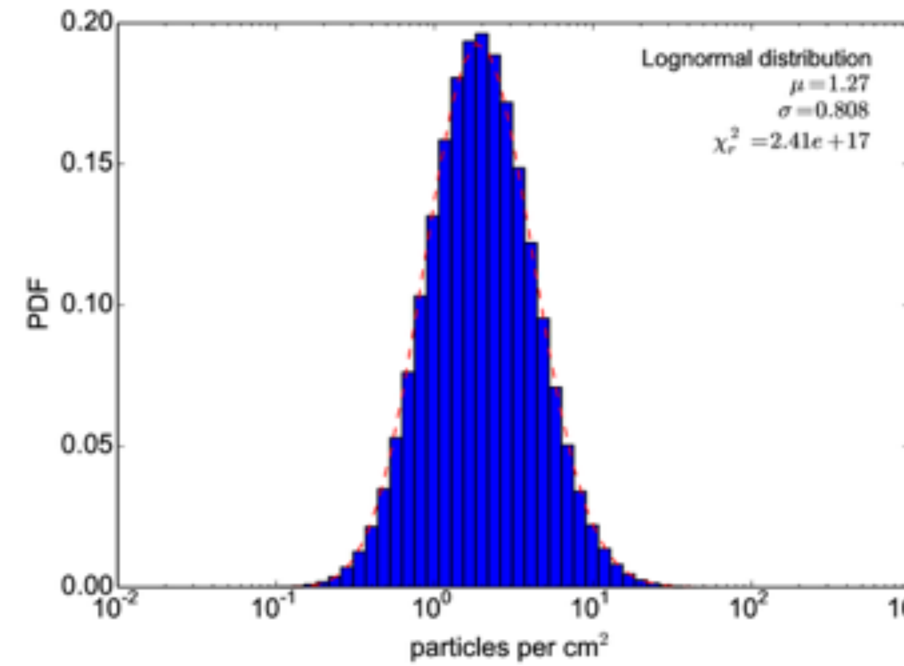
Modelling polarized thermal dust emission with fBm fields

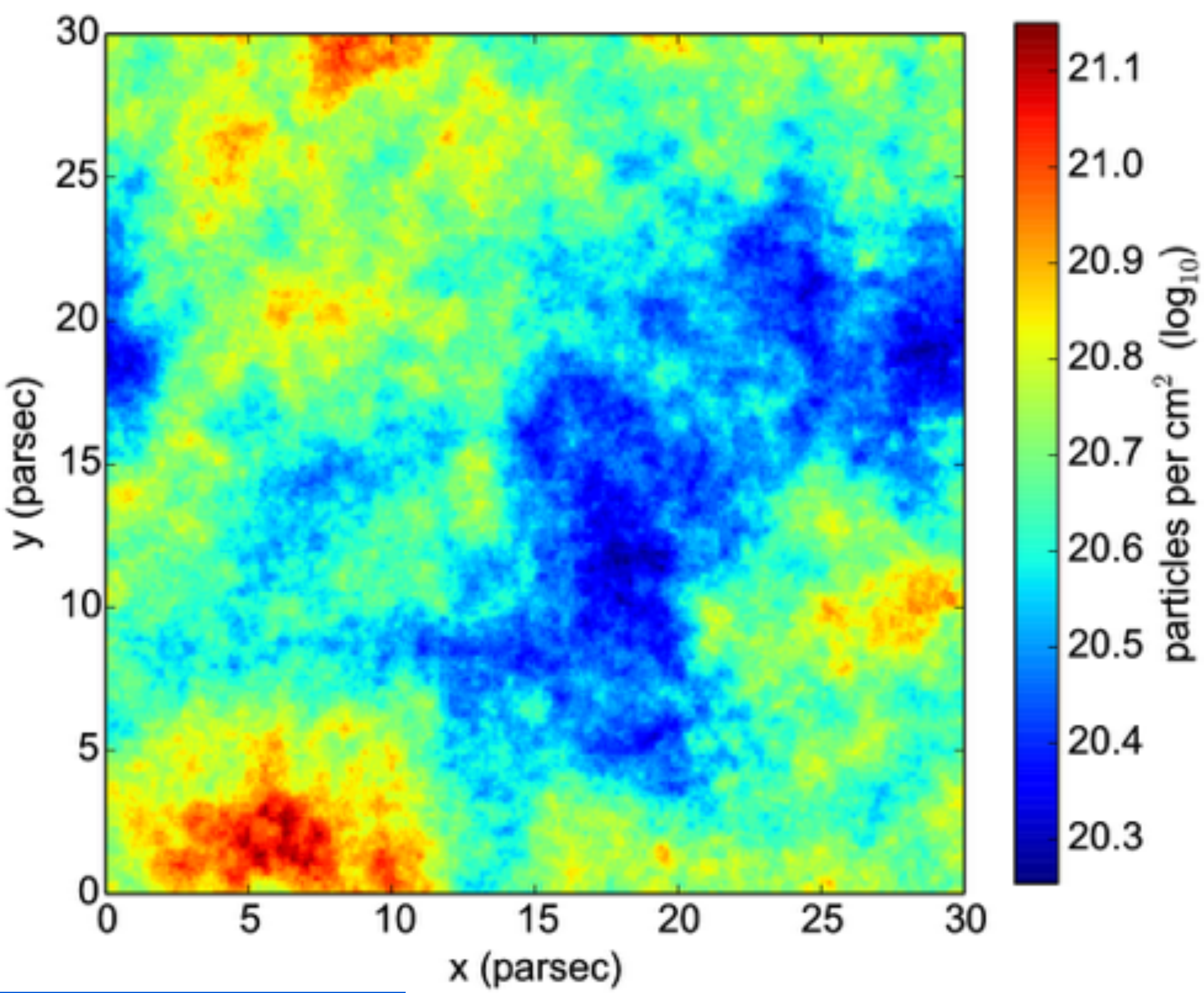
We wish to constrain the statistical properties of the interstellar B field

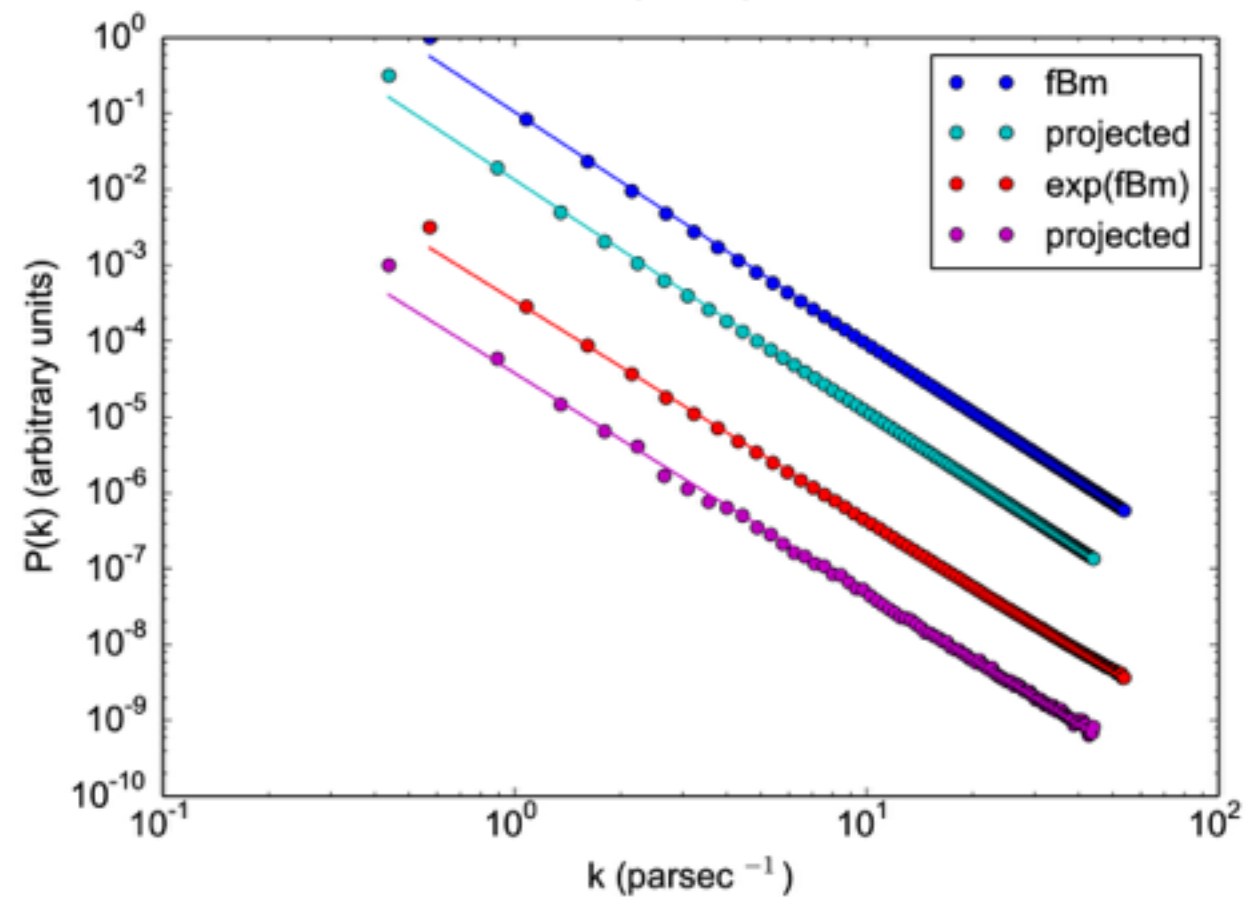
Dust density : exponentiated fractional Brownian motion field (fBm)

$$n_{\mathrm{d}} = n_0 \exp\left(\frac{X}{X_r}\right)$$

- Power-law power spectrum with index β_n
- Log-normal distribution
- Possibly large fluctuations $\frac{\sigma_n}{n_{\mathrm{d}}} > 0.3$







Levrier et al. (in prep)

Modelling polarized thermal dust emission with fBm fields

Magnetic field from fBm vector potential components

$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$$

Input Fourier phase map

$$\widetilde{B_\lambda}(\boldsymbol{k}) = \epsilon_{\lambda\mu\nu} i k_\mu \mathcal{F}_0 |\boldsymbol{k}|^{-\beta_A/2} \exp\left[i\phi_{A_\nu}(\boldsymbol{k})\right]$$

Levi-Civita tensor

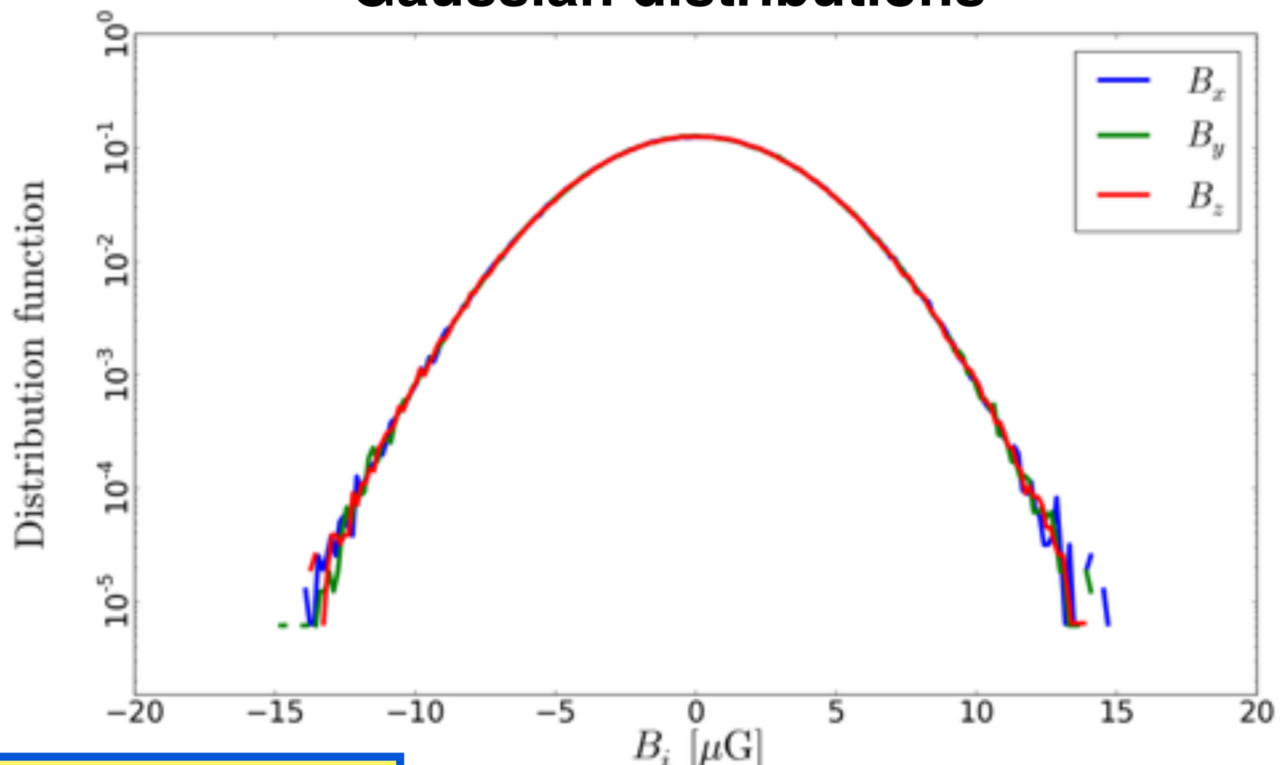
Input spectral index

Component of the B field in Fourier space

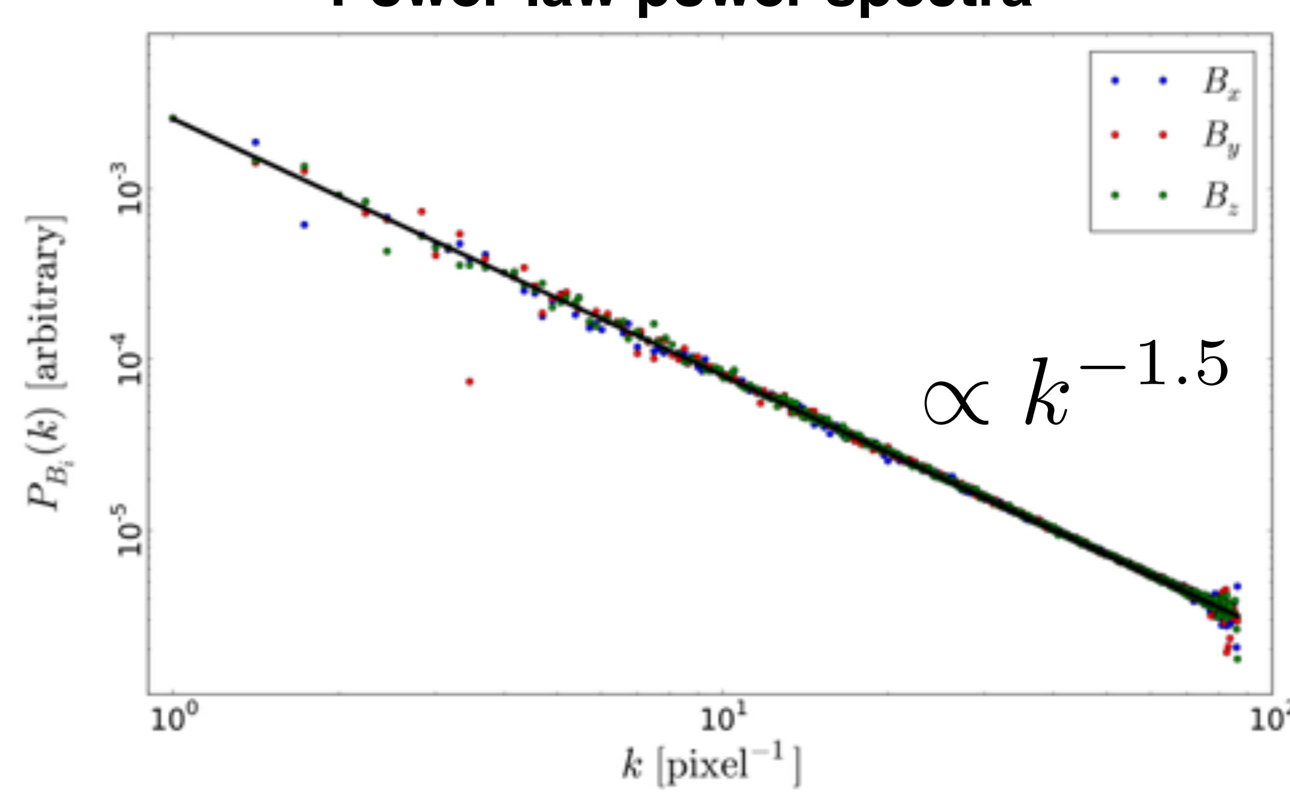
- Power-law power spectrum with index $\beta_B = \beta_A - 2$
- Divergence-free by construction
- Gaussian distribution with zero mean
- Possibility to add a large-scale uniform field

$\widetilde{A_\nu}(\boldsymbol{k})$ **fBm fields**

Gaussian distributions

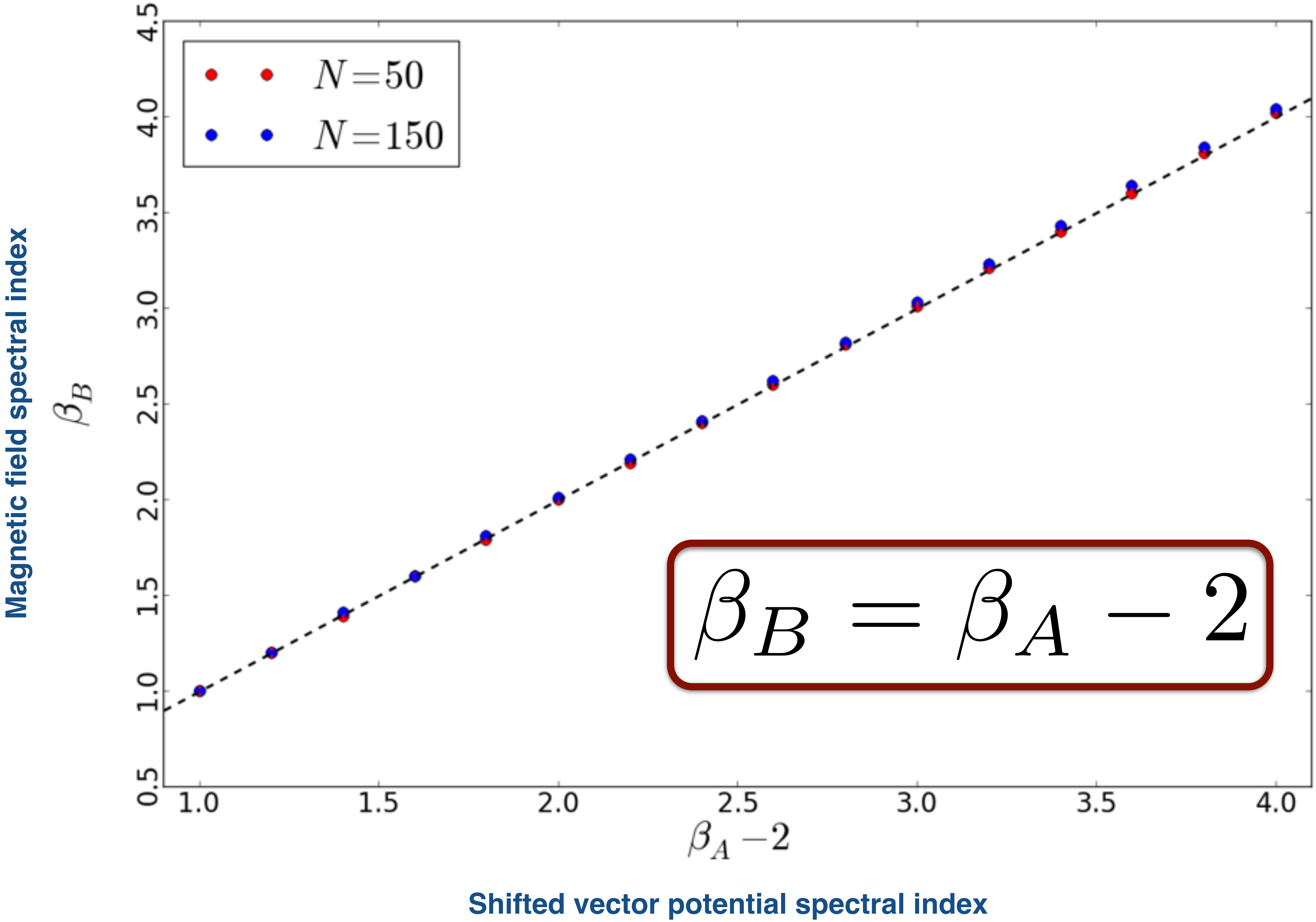


Power-law power spectra



Levrier et al. (in prep)

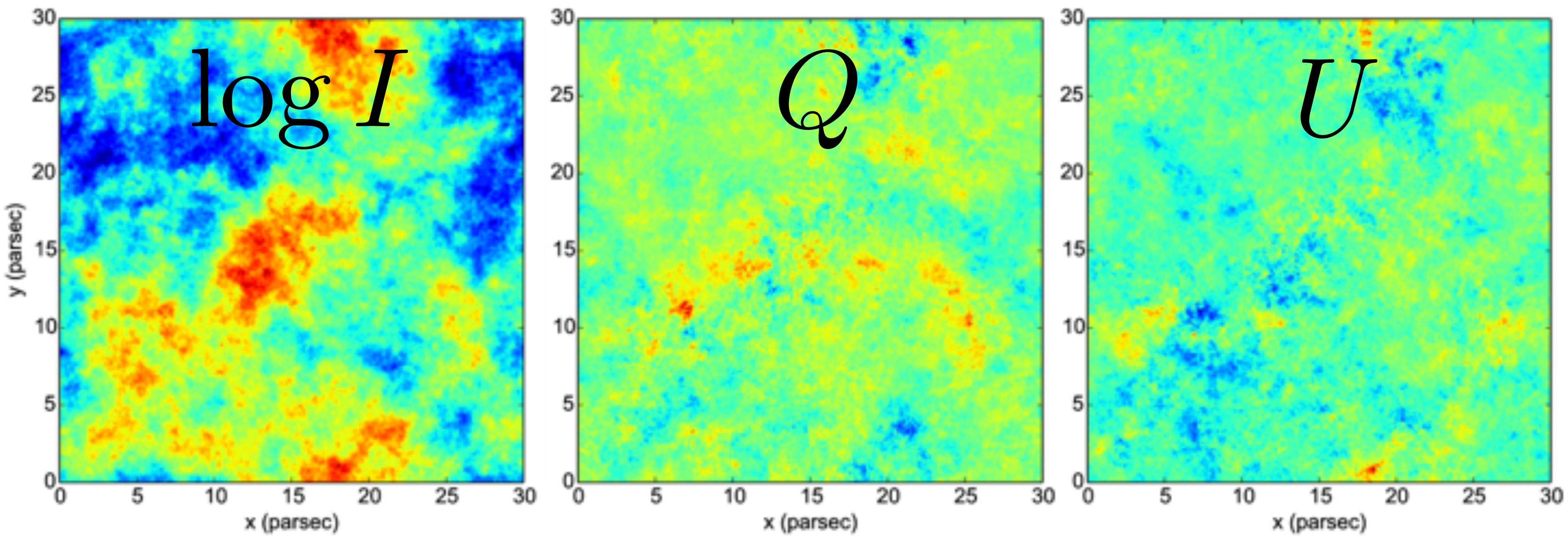
Synthetic magnetic field spectral index



Parameter space exploration

- 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

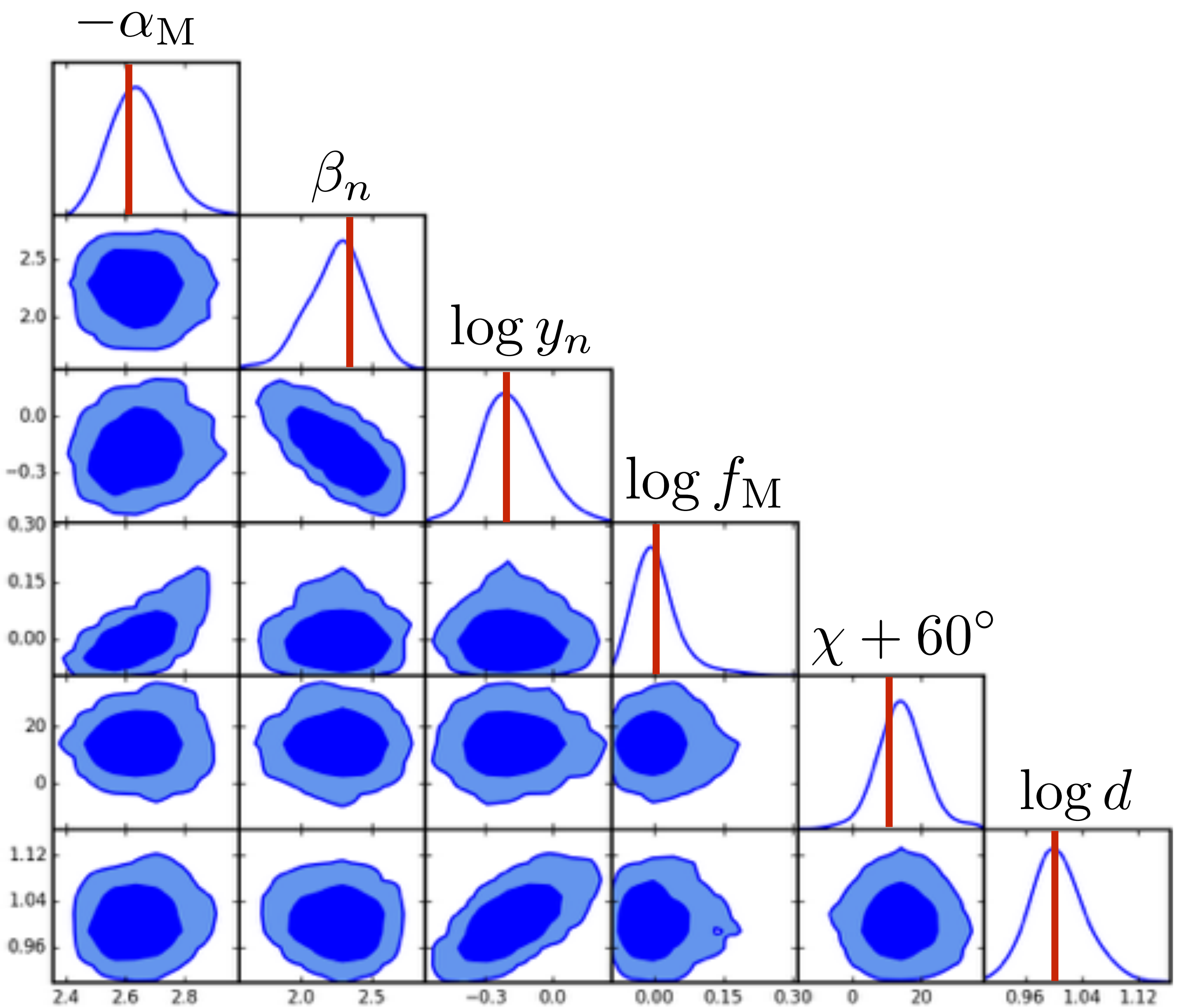
Parameter	Prior
β_B	$[1, 4]$
β_n	$[1, 5]$
$\log_{10} y_n$	$[-1, 1]$
$\log_{10} y_B^{\mathrm{POS}}$	$[-1, 1]$
χ	$[-90°, 90°]$
$\log_{10}(d/1\,\mathrm{pc})$	$[-0.3, 1.5]$



Type	From	Method
PDF	$i, q, u, p_{\mathrm{MAS}}, \psi, \mathcal{S}$	Bin by bin fit of the histogram
Power spectrum	$I_{\mathrm{m}}, Q_{\mathrm{m}}, U_{\mathrm{m}}$	Bin by bin fit of the power spectrum
Correlation	$\{\mathcal{S}, p_{\mathrm{MAS}}\}$	Bin by bin fit of the scatter plot

Validation of the method

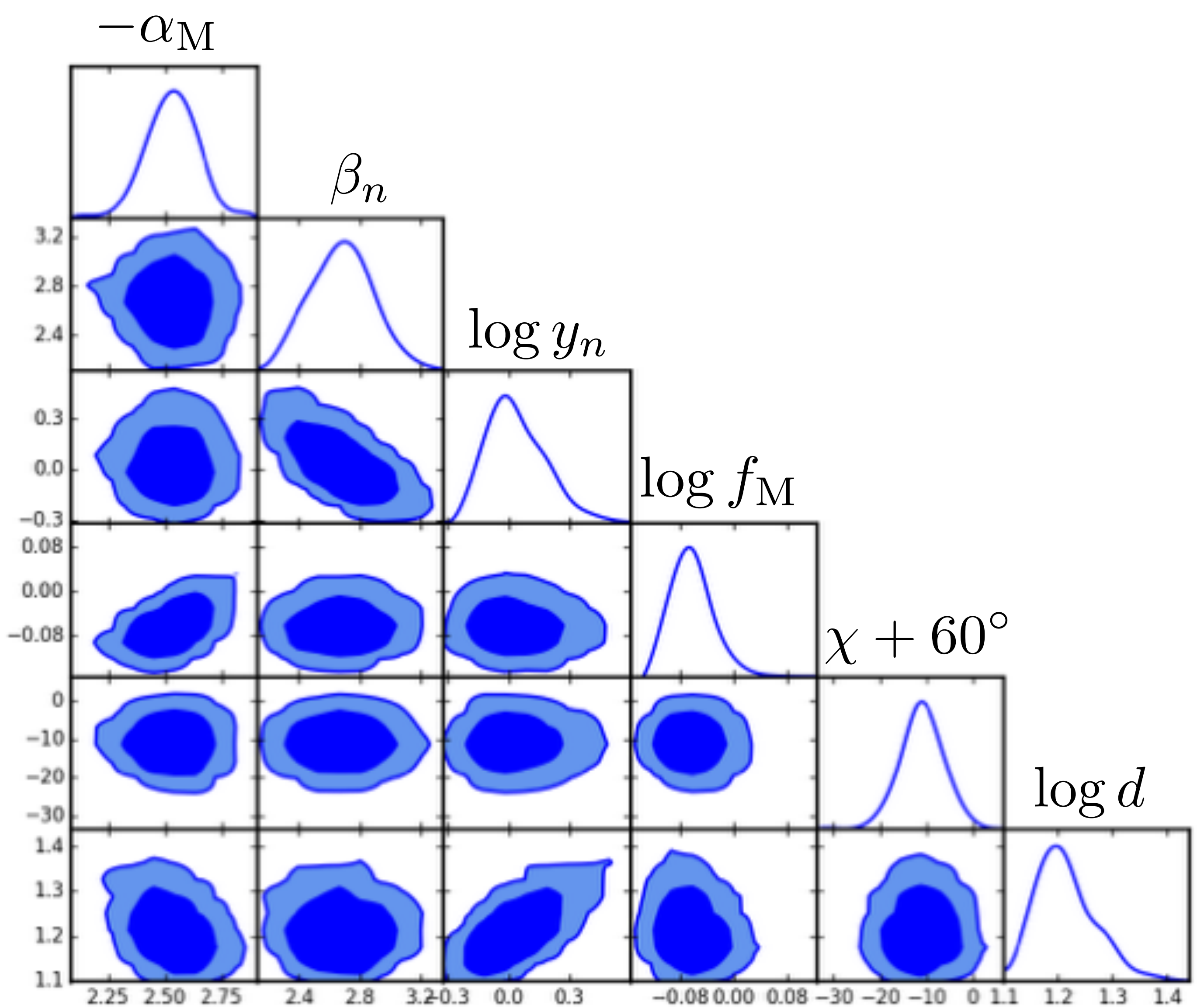
Levrier et al. (in prep)



Parameters	β_B	β_n	$\log_{10} y_n$	$\log_{10} y_B$	χ [°]	$\log_{10}(d/1\ \mathrm{pc})$	$\langle\chi^2_{\rm best}\rangle$
Simulation D							
Input parameters	2.6	2.31	0.0	-0.05	−70	1.18	
Best fit values	$2.57^{+0.13}_{-0.11}$	$2.45^{+0.46}_{-0.31}$	$-0.02^{+0.14}_{-0.18}$	$-0.02^{+0.03}_{-0.05}$	$-68.6^{+6.1}_{-5.8}$	$1.20^{+0.05}_{-0.06}$	8.7

Application to Planck data on the Polaris Flare

Levrier et al. (in prep)



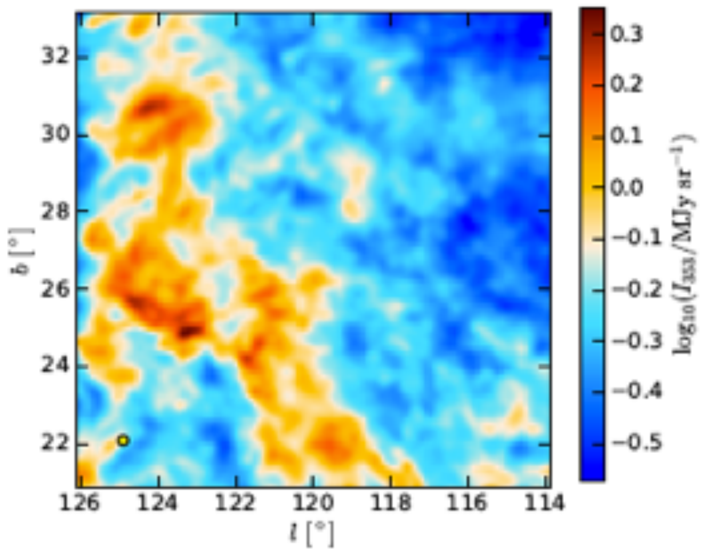
$$\alpha_M = -2.53^{+0.13}_{-0.12}$$

$$f_M = 0.87^{+0.06}_{-0.08}$$

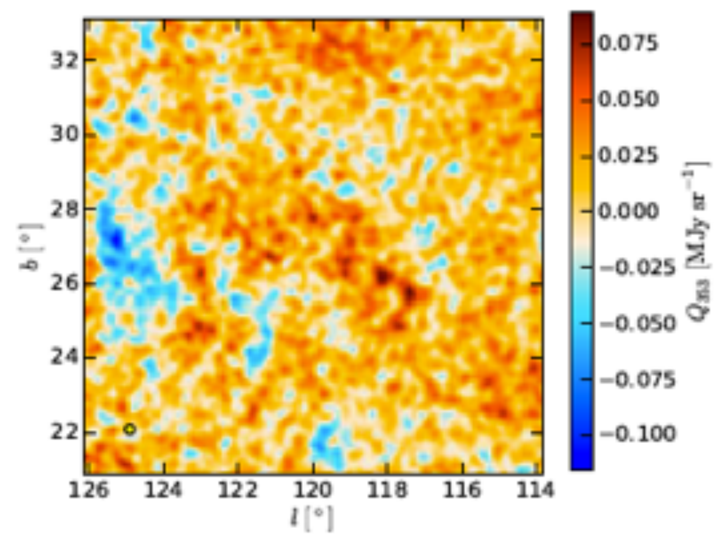
Parameters	β_B	β_n	$\log_{10} y_n$	$\log_{10} y_B$	χ [°]	$\log_{10}(d/1\,\mathrm{pc})$	$\langle \chi^2_{\mathrm{best}} \rangle$
Polaris Flare – no CIB correction							
Best fit values	$2.54^{+0.13}_{-0.13}$	$2.33^{+0.46}_{-0.35}$	$0.04^{+0.15}_{-0.19}$	$-0.06^{+0.03}_{-0.04}$	$-71.3^{+5.4}_{-5.7}$	$1.21^{+0.06}_{-0.07}$	16.3
Polaris Flare – CIB correction							
Best fit values	$2.43^{+0.12}_{-0.12}$	$2.44^{+0.44}_{-0.31}$	$-0.07^{+0.13}_{-0.18}$	$-0.02^{+0.04}_{-0.04}$	$-71.1^{+5.2}_{-5.0}$	$1.19^{+0.06}_{-0.07}$	15.4

Planck Polaris Flare maps

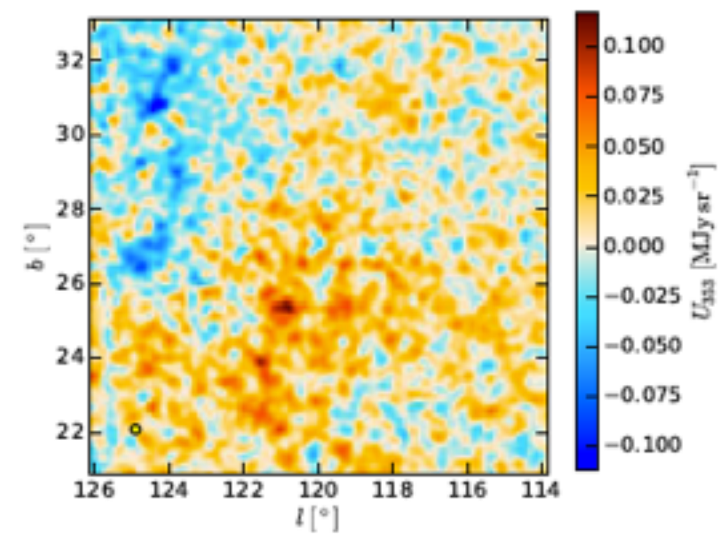
Total intensity



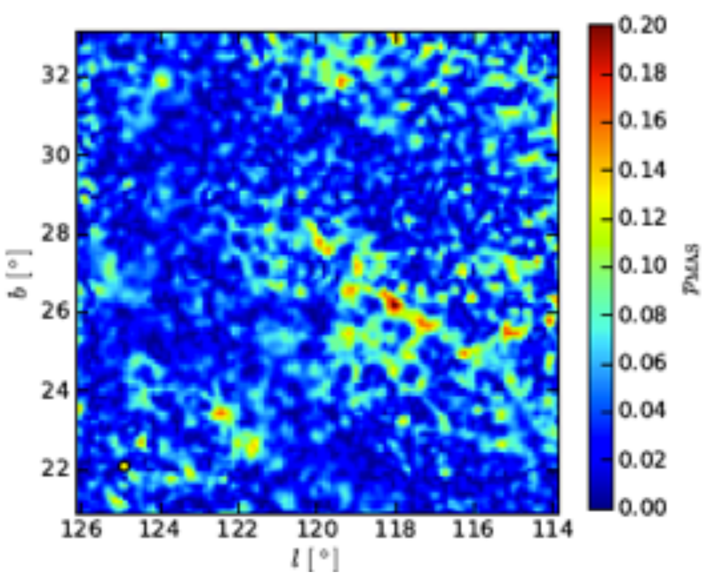
Stokes Q



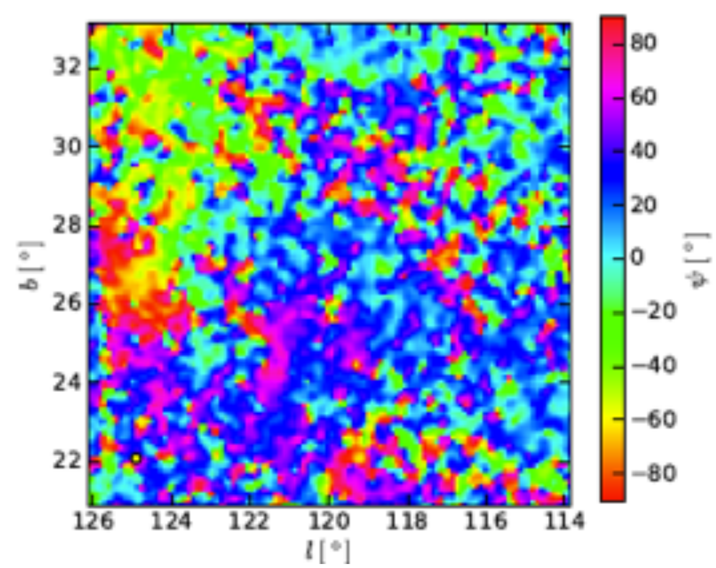
Stokes U



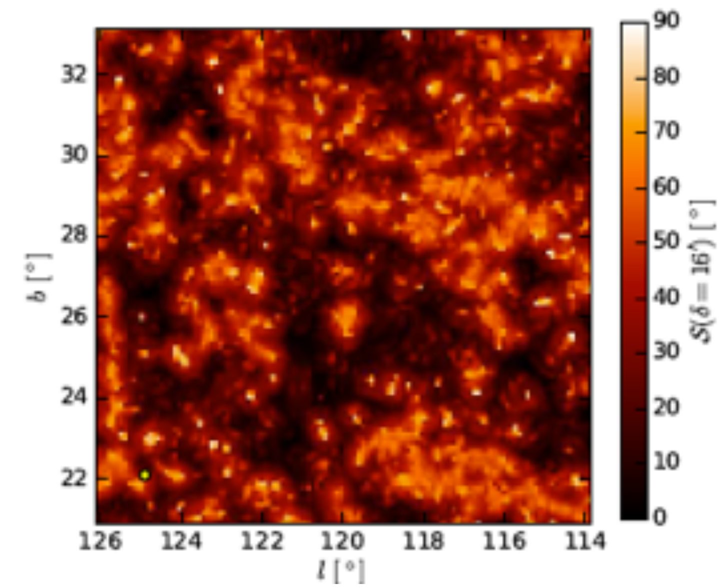
Polarization fraction



Polarization angle



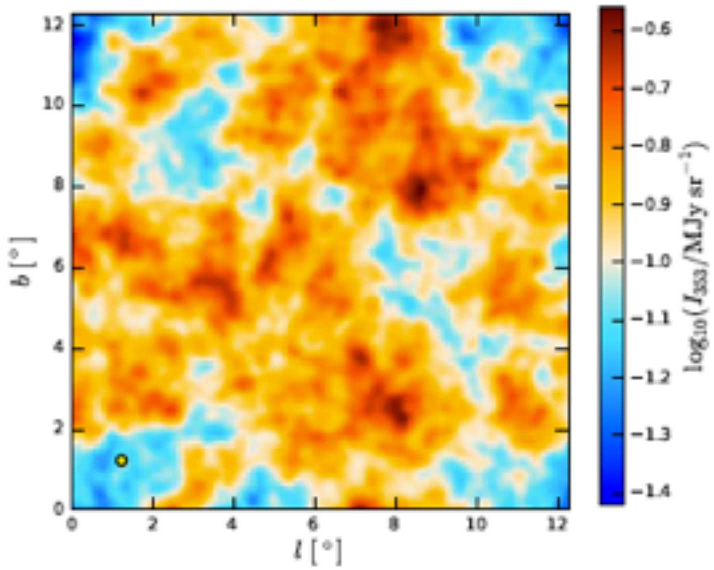
Angular dispersion



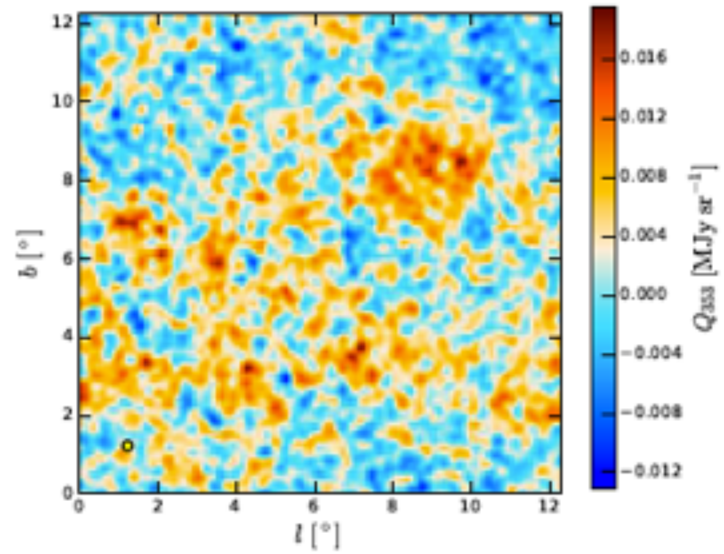
Levrier et al. (in prep)

Simulations maps with best fitting parameters

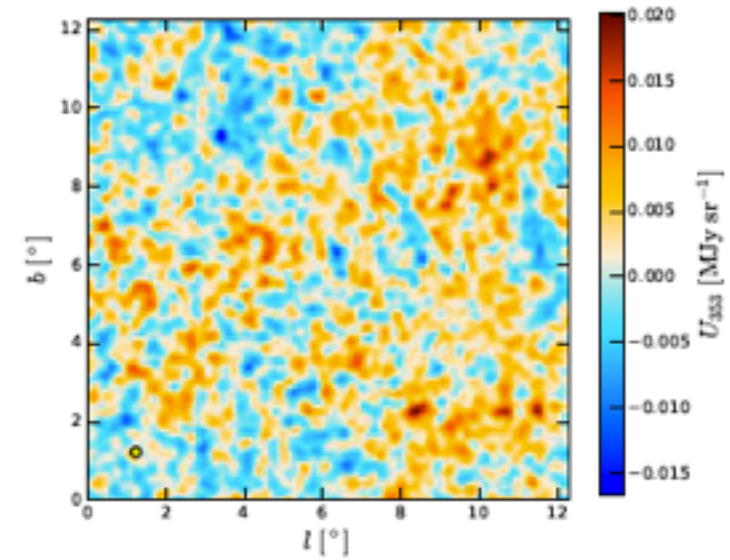
Total intensity



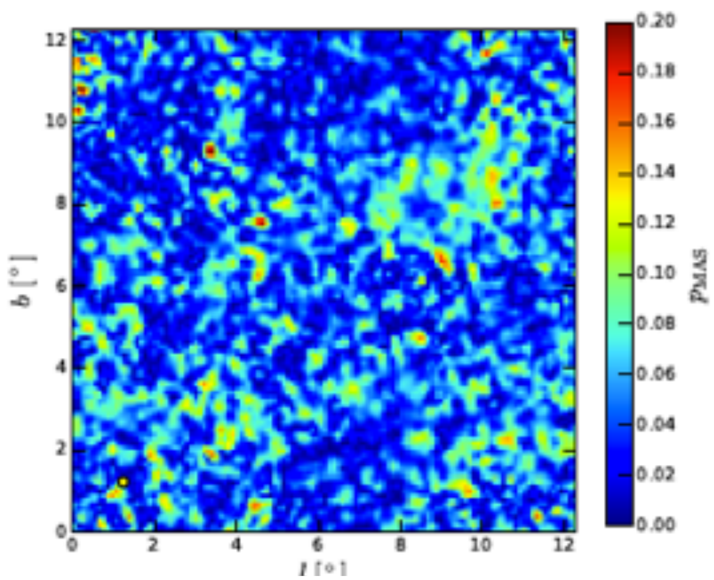
Stokes Q



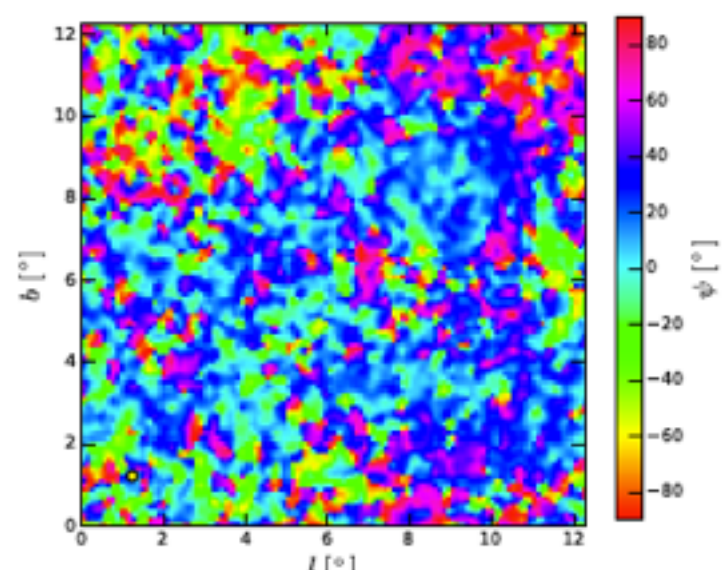
Stokes U



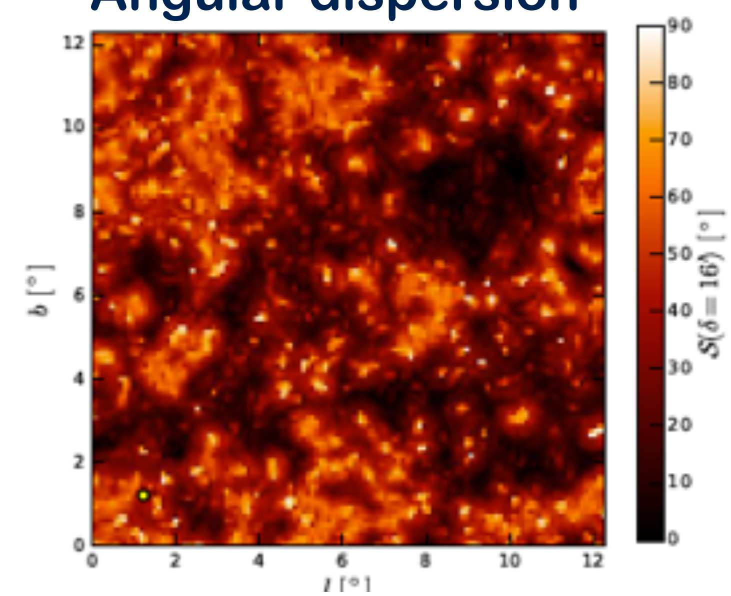
Polarization fraction



Polarization angle



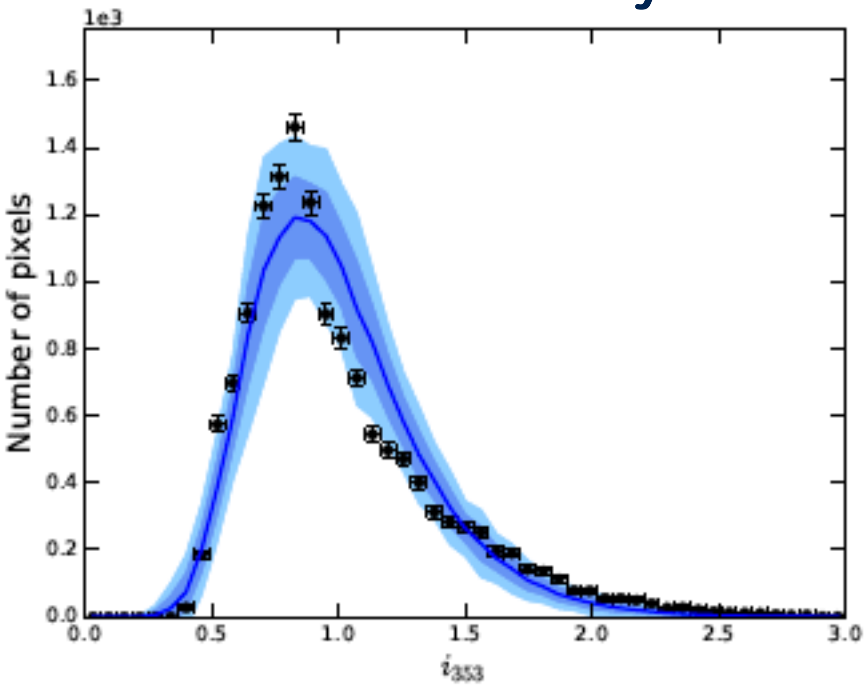
Angular dispersion



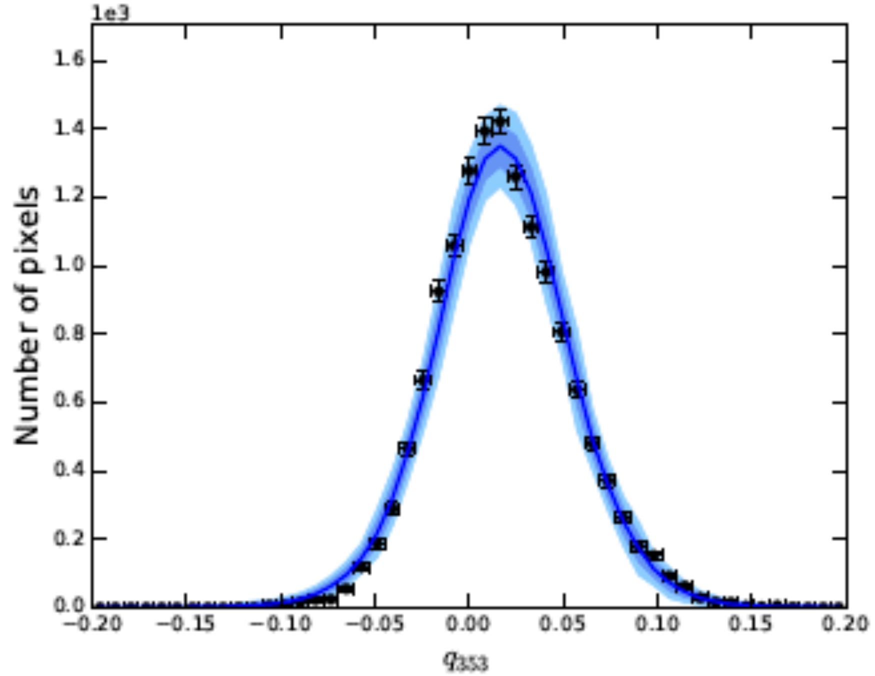
Levrier et al. (in prep)

PDFs of observables (Polaris and best-fit model)

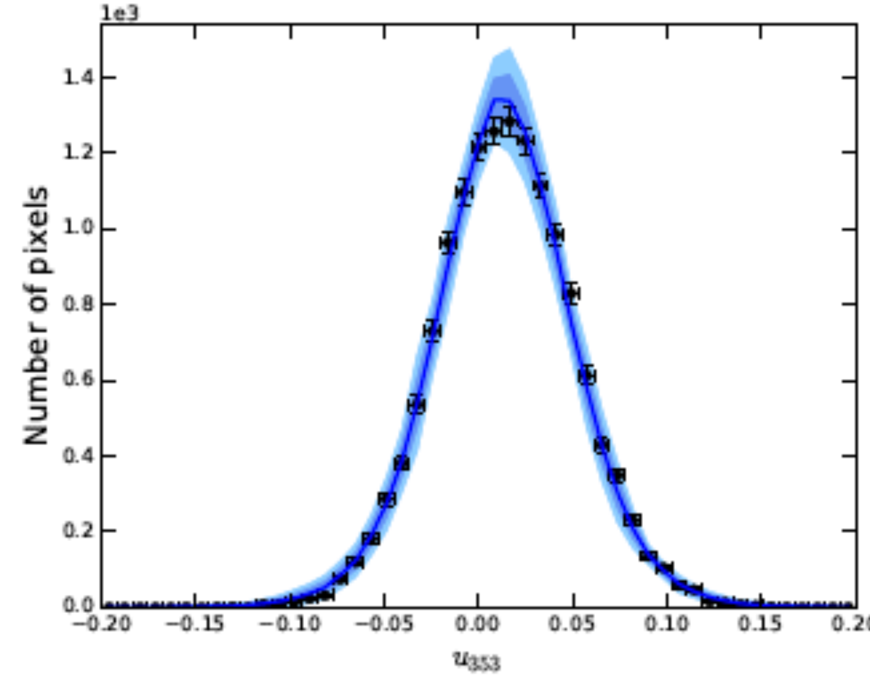
Total intensity

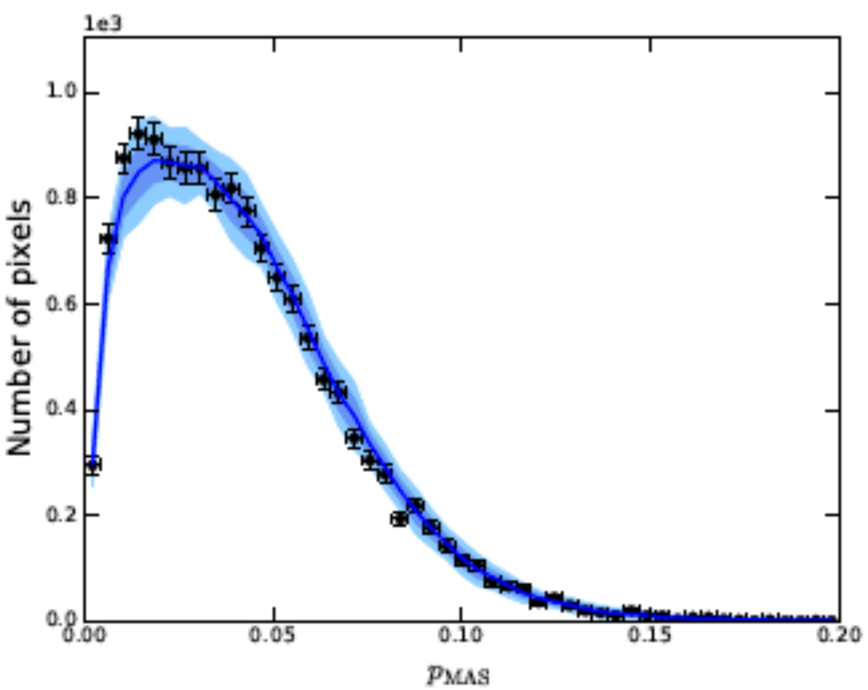


Stokes Q

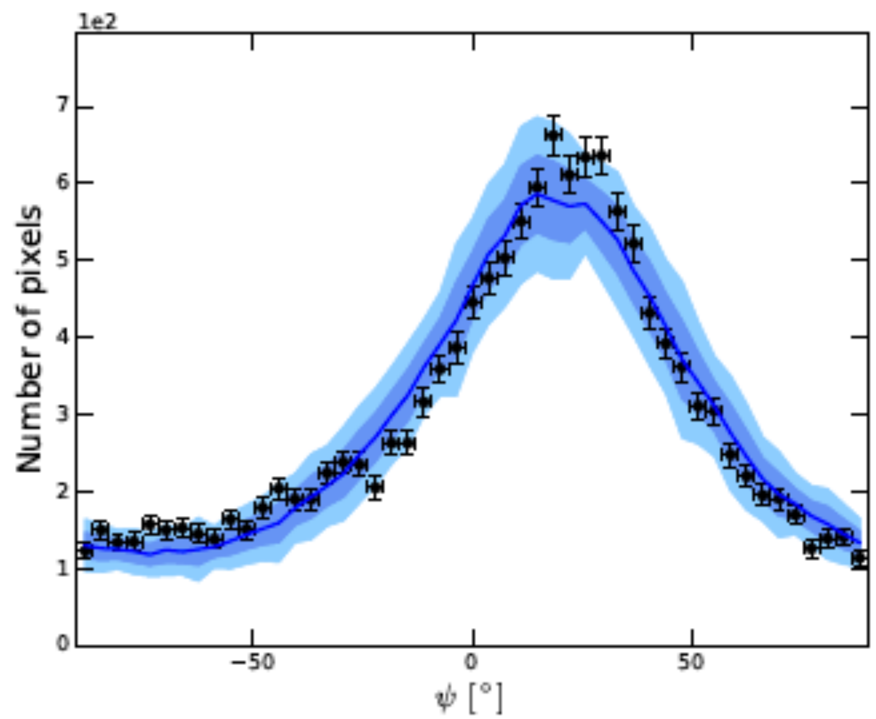


Stokes U

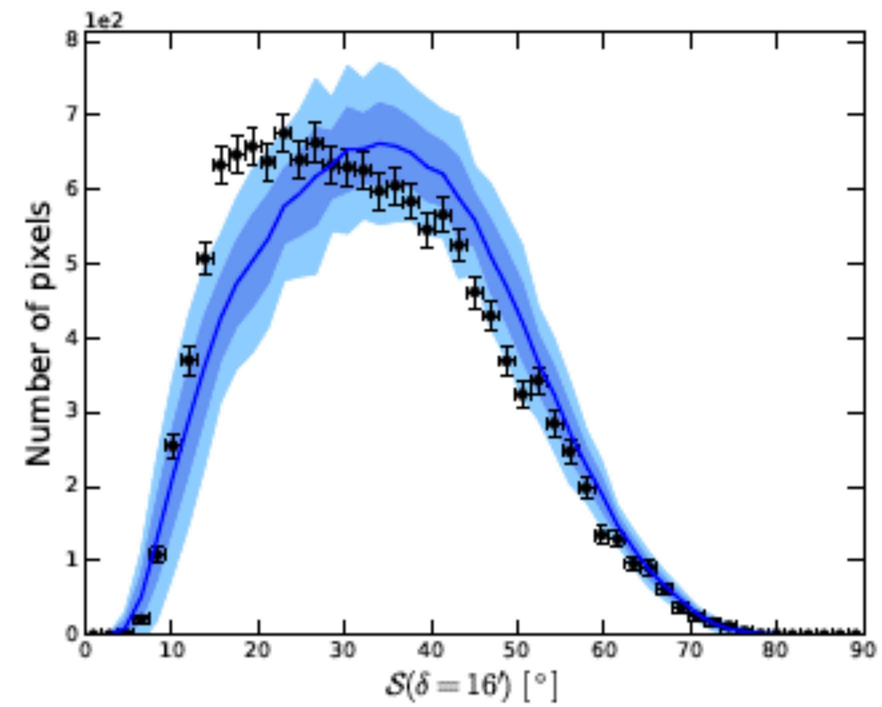




Polarization fraction



Polarization angle

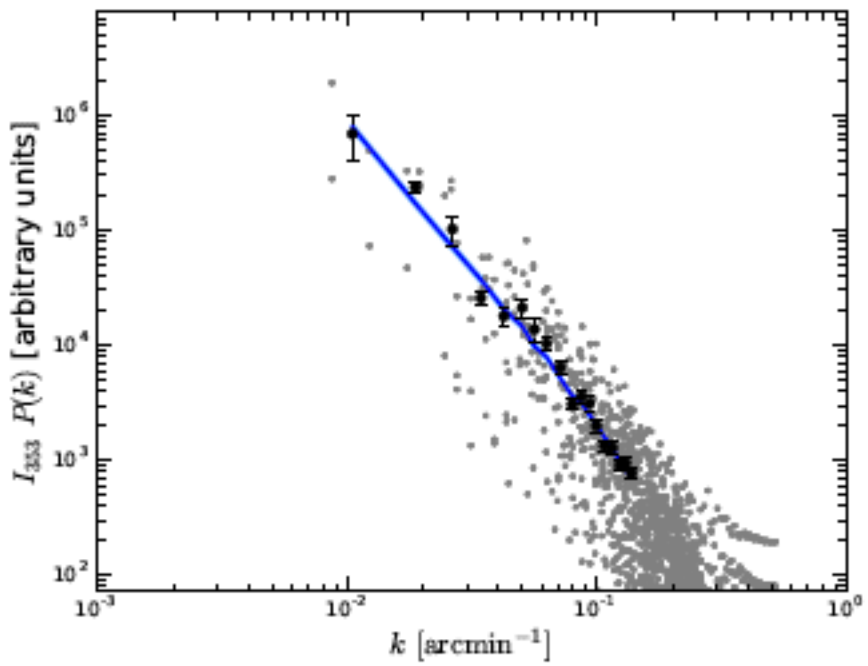


Angular dispersion

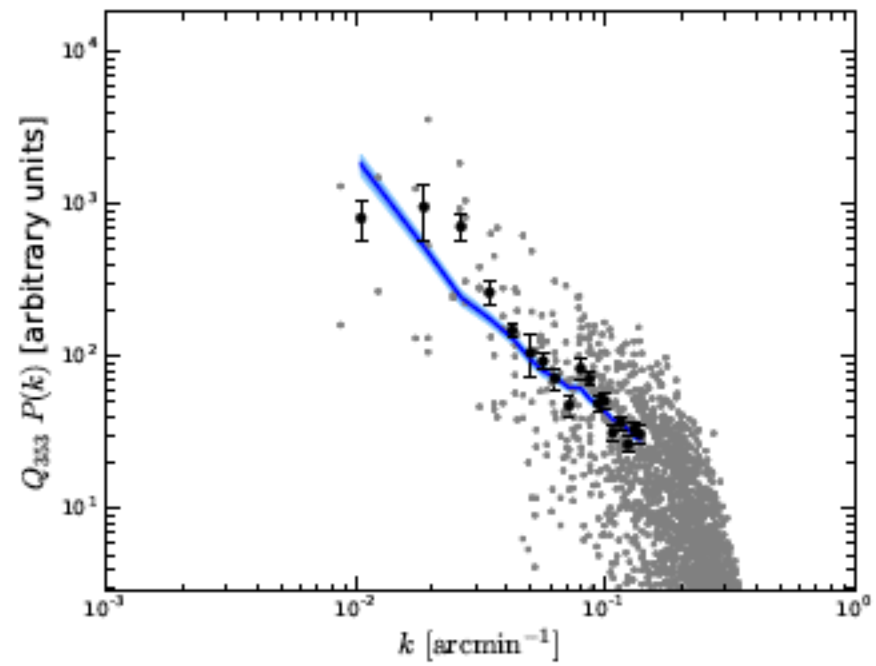
Levrier et al. (in prep)

Power spectra of observables (Polaris and best-fit model)

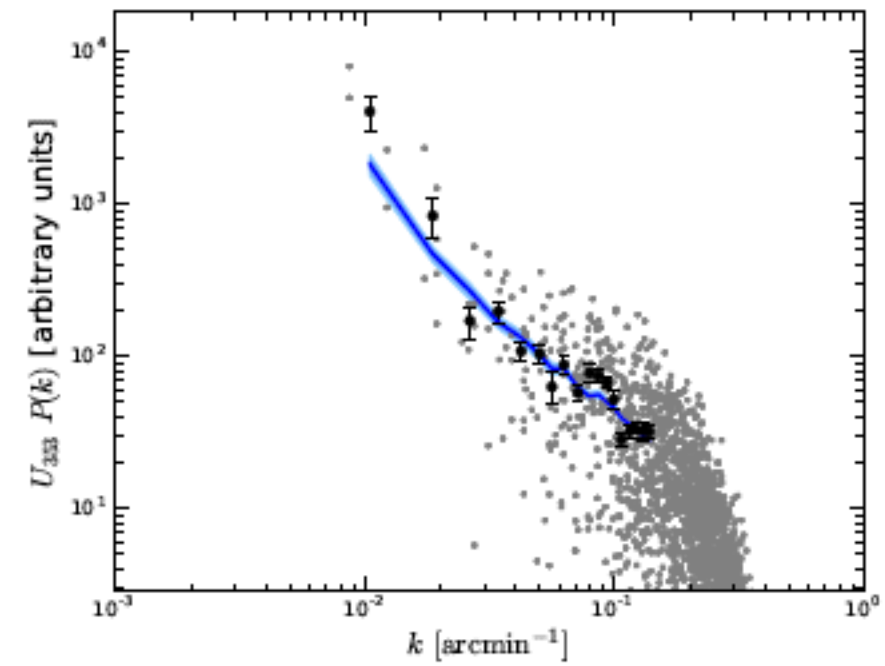
Total intensity



Stokes Q

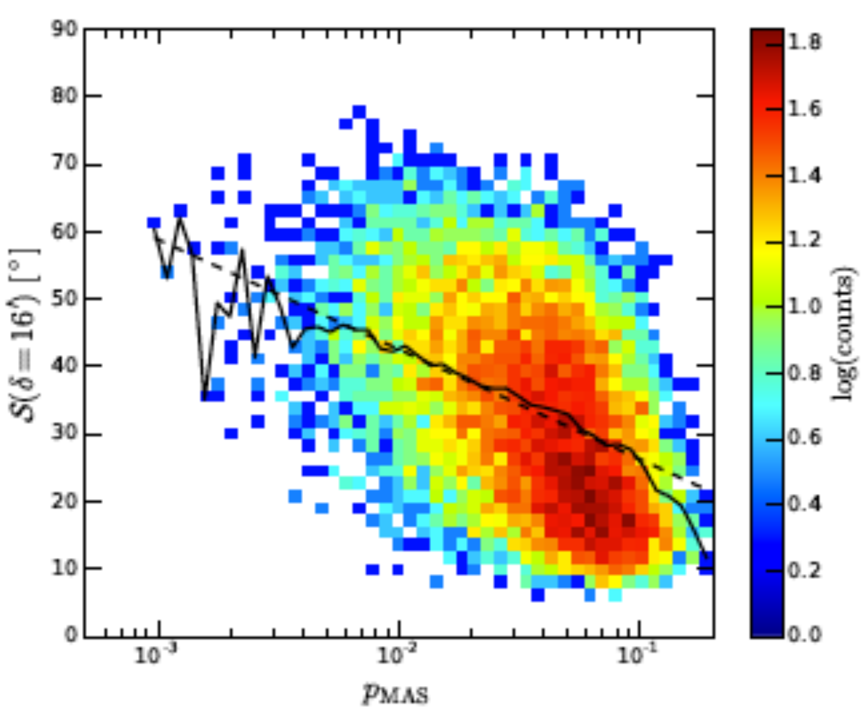


Stokes U

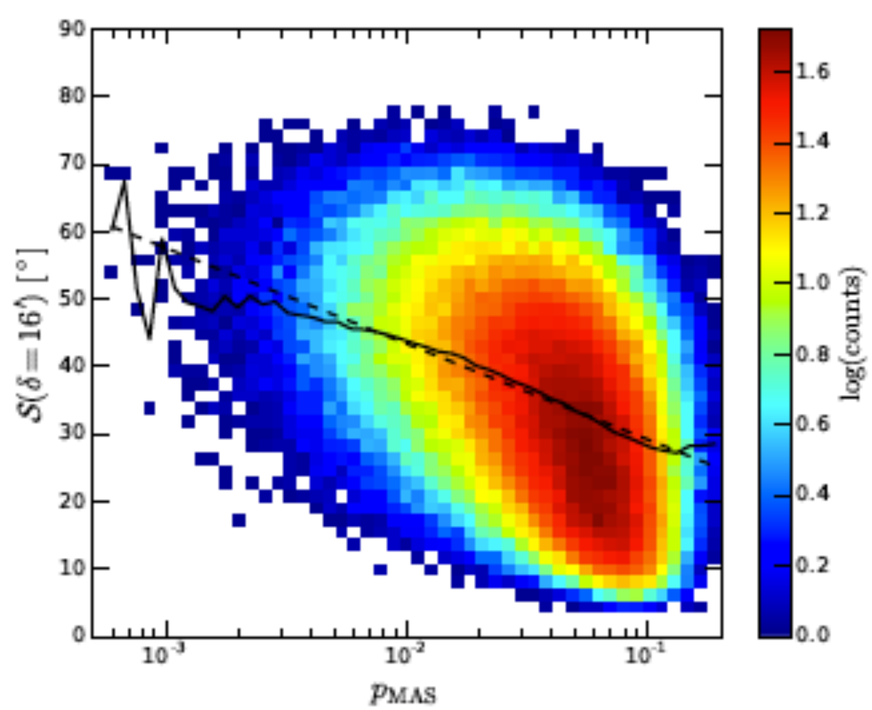


Correlation polarization fraction - angular dispersion

Polaris Flare



Best-fit model



Residuals