Magnetic Fields in Molecular Clouds

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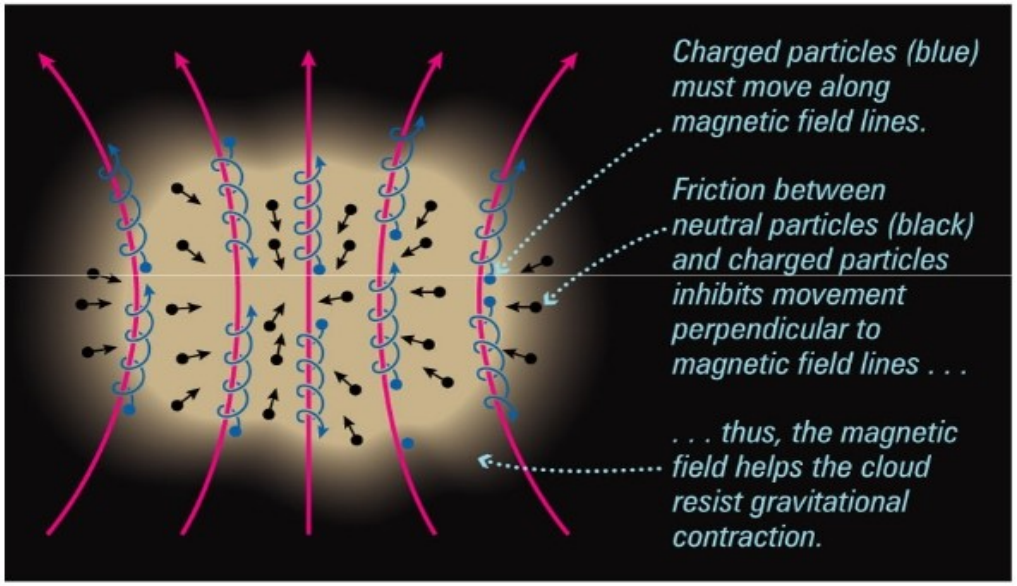
Cosmic Magnetism – From Stellar to Intergalactic scales
7-11 June 2010

Talk Outline

- Overview of magnetic field in molecular clouds
  - Cloud support (recent Crutcher-Mouschovias debate)
- MHD Turbulence
  - Velocity anisotropy (Goldreich-Sridhar Effect)
  - Velocity anisotropy in the Taurus Molecular Cloud

Cloud Support



Mestel & Spitzer (1956)
Mouschovias & Spitzer (1976)
Nakano (1978)
Lizano & Shu (1988)

$$M_{crit} = (1/63G)^{1/2}\ \Phi$$
$$= 10^3\ M_{sun}\ (B/30\ \mu G)\ (R/2\ pc)^2$$
$$\Sigma_{crit} = 80\ M_{sun}/pc^2\ (B/30\ \mu G)$$

$$\mu = \Sigma/\Sigma_{crit}$$

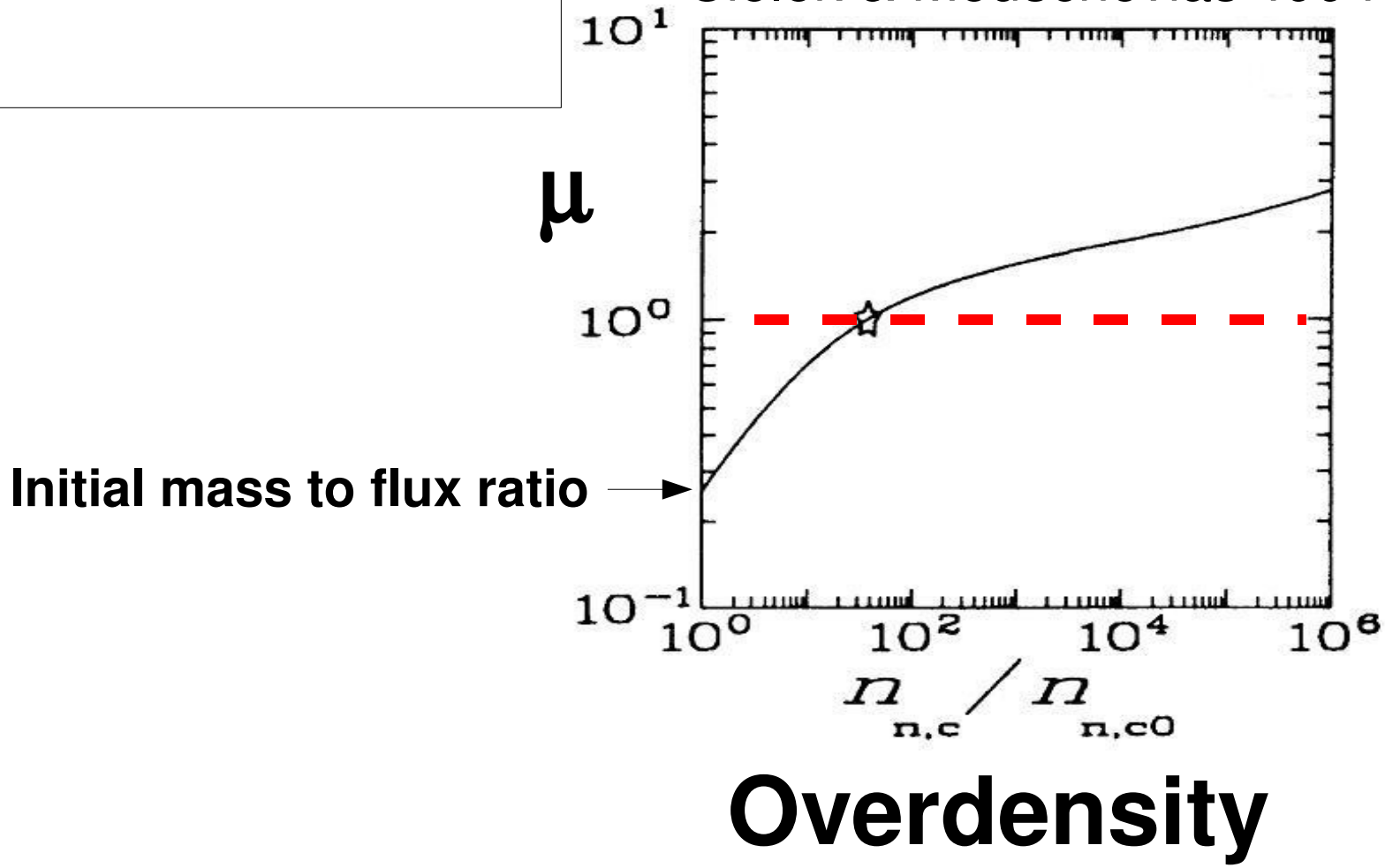
if $\mu > 1$ supercritical

if $\mu < 1$ sub-critical

Ambipolar Diffusion

Allows the development of supercritical cores and star formation

Ciolek & Mouschovias 1994



Observations of Magnetic support

Challenges in measuring μ:

B --> Σ_{crit}

Zeeman Measurements: OH 1665/1667 MHz

- Large single dish OH beams
- Measure los field component --> Correct for inclination

Σ

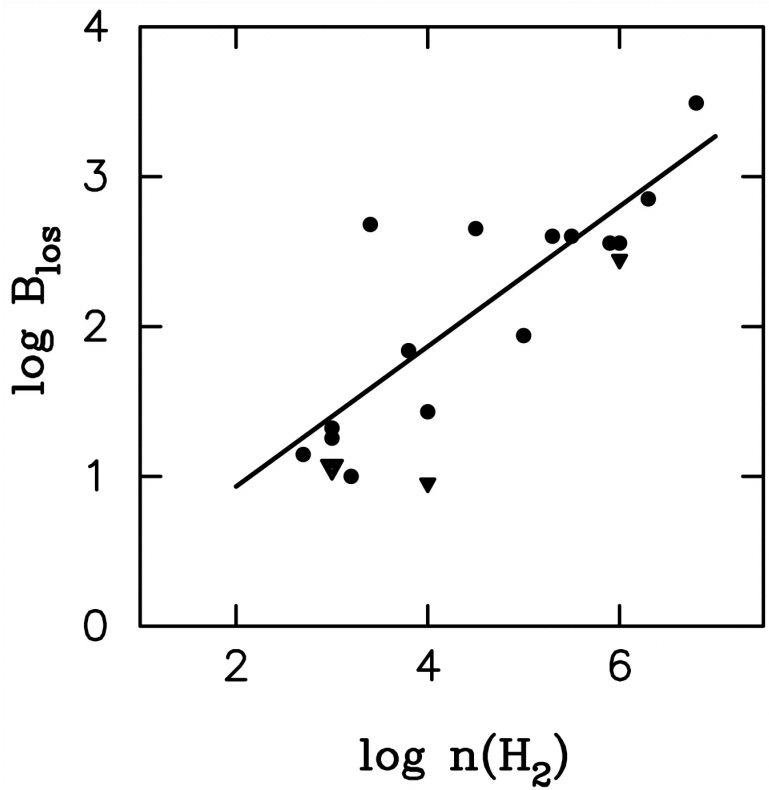
- Compile Σ from same volume responsible for Zeeman splitting
- Correct for inclinations to obtain central surface density

OH Zeeman towards Molecular Clouds

Crutcher (1999) compiled OH Zeeman measurements and molecular cloud properties

- $(c/v_A)^2 \sim 0.04$
- $T \sim M \sim W/2$
- $B \sim n^{1/2}$
- $\langle\mu_{obs}\rangle \sim 4$;

  $\langle\mu\rangle_{corr}$ less than 2

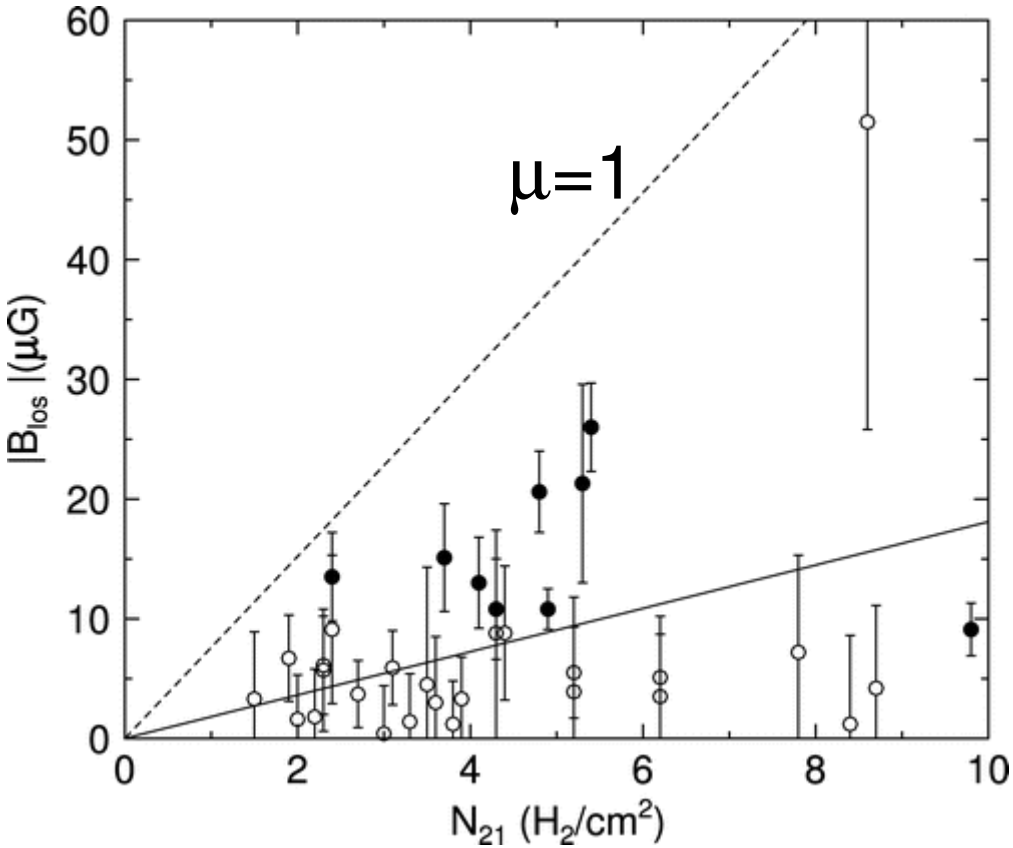


OH Zeeman towards Dark Clouds

$\langle\mu_{obs}\rangle = 4.8 +/- 0.4$

$\langle\mu\rangle_{corr} \sim 2$

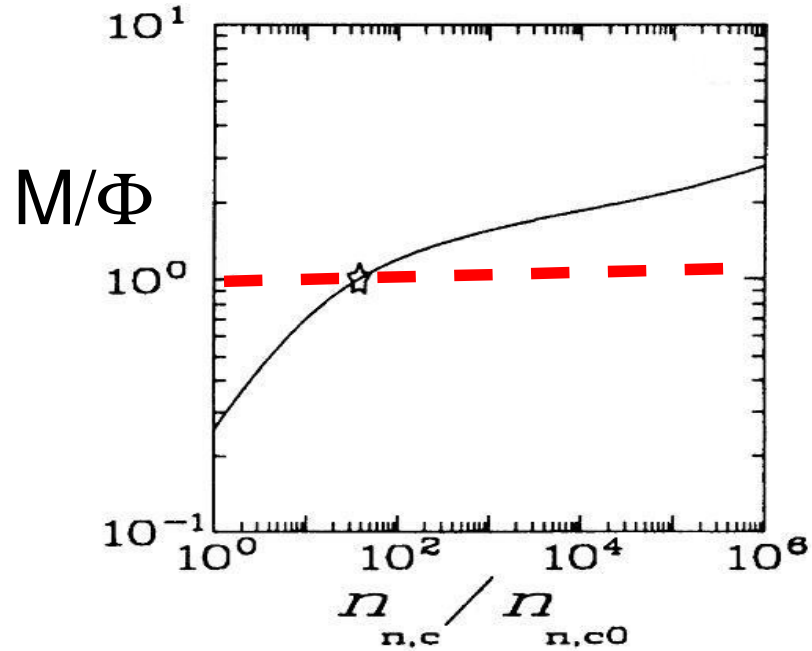
Troland & Crutcher 2008



Testing Magnetic Field Star Formation Theory
Crutcher, Hakobian, Troland (2009, 2010)

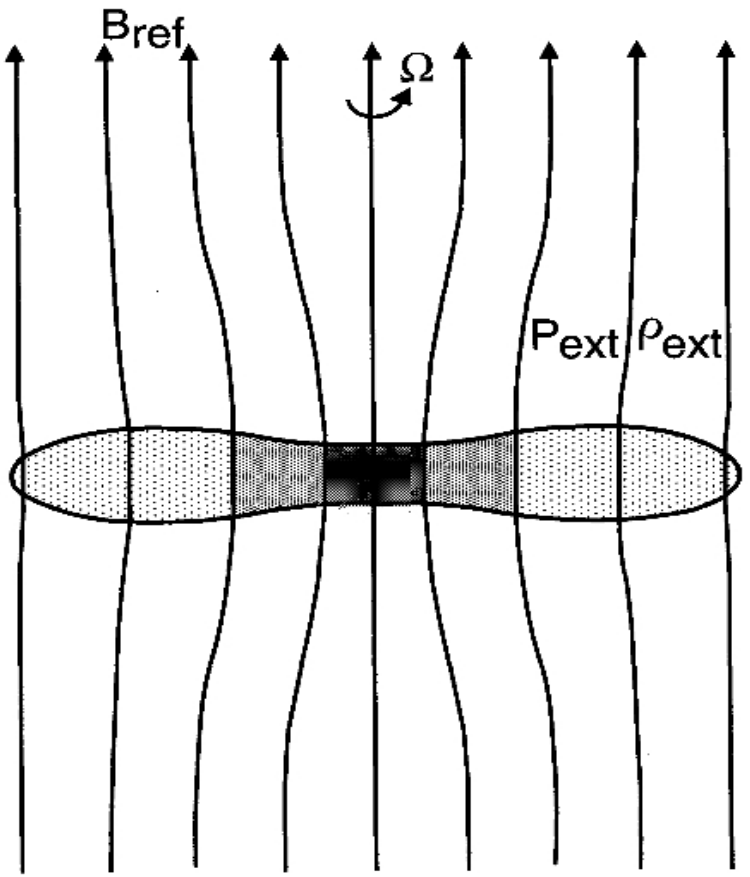
Ciolek & Mouschovias 1994

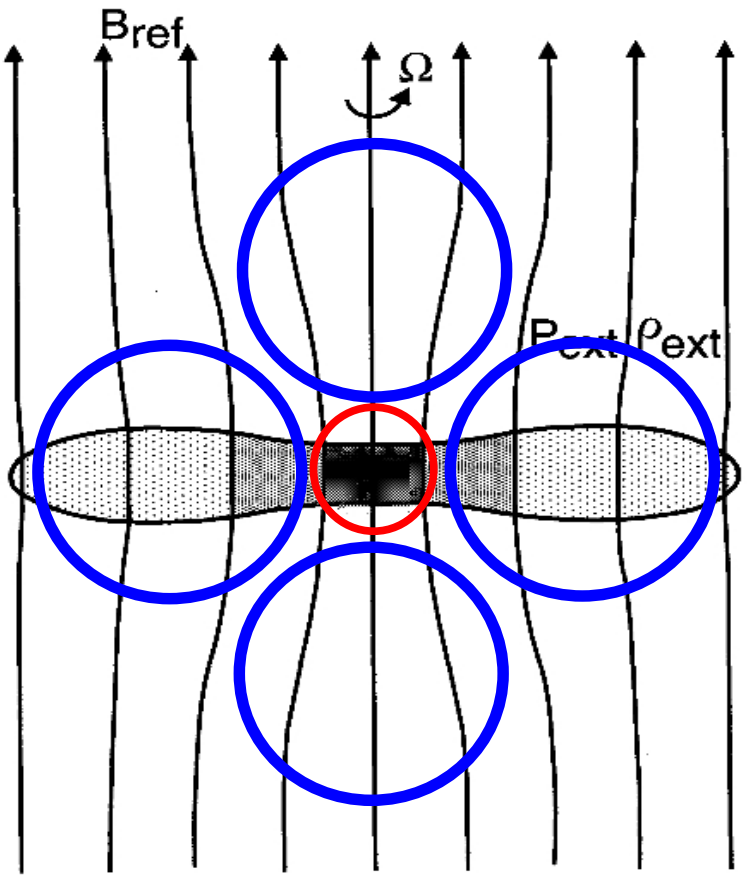
Prediction: $[M/\Phi]_{core} > [M/\Phi]_{envelope}$



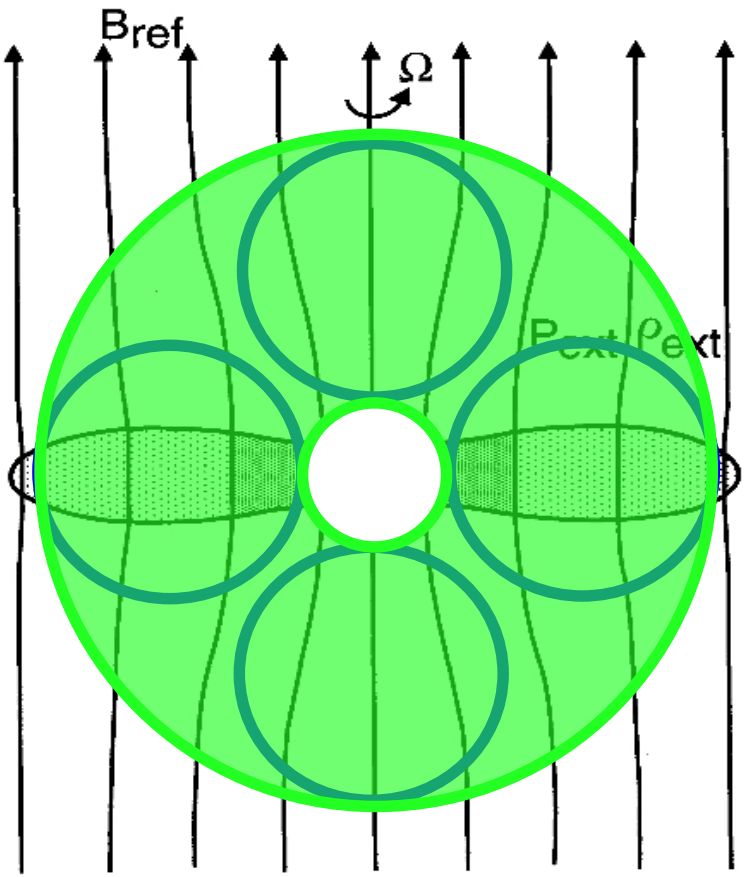
Assumption:"Idealized" case with straight field lines over core/envelope

$$R = \frac{[M/\Phi]_{core}}{[M/\Phi]_{envelope}} = \frac{[T_{line}\,\Delta V / B_{los}]_{core}}{[T_{line}\,\Delta V / B_{los}]_{envelope}}$$


B_{ref}
Ω
P_{ext} ρ_{ext}


B_{ref}
Ω
P_{ext} ρ_{ext}

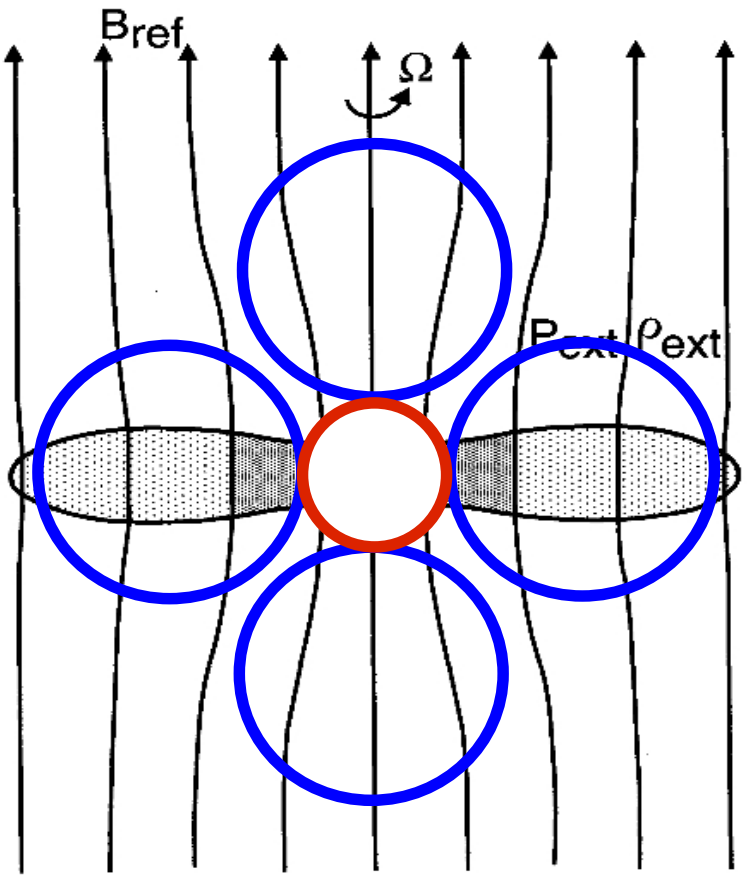
Toroidal beam for envelope



Toroidal beam for envelope

Results: mostly non-detections

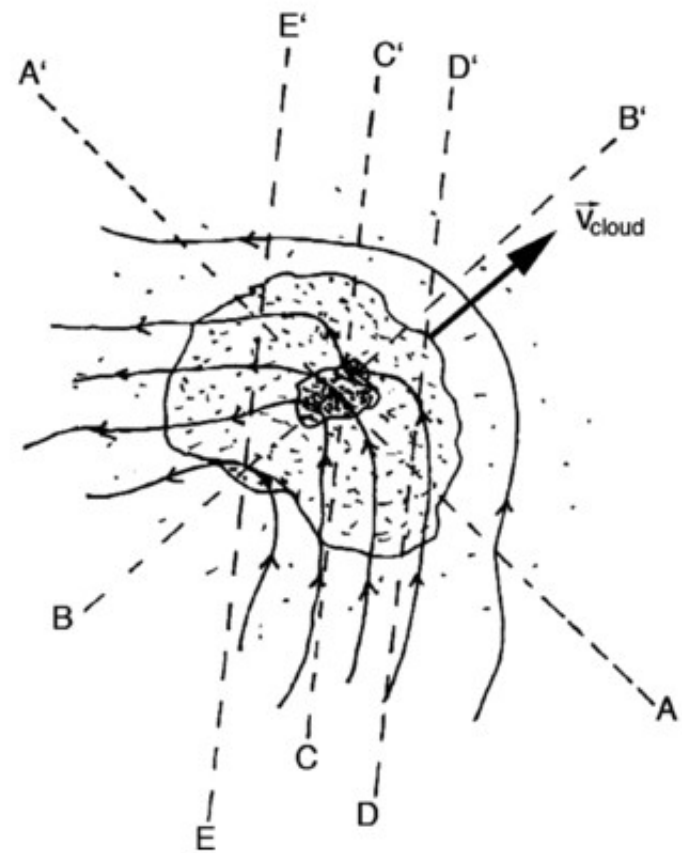
Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010



Mouschovias & Tassis (2009)

Must account for measured variations of B between envelope beams:

- Variations in field strength
- Variations in field orientation along line of sight



Relax CHT assumption of straight field lines to derive 2σ upper limits

Cloud	$B_{mean} \pm \sigma_{mean}$	$B_{max\mathcal{L}} \pm \sigma_{\mathcal{L}}$	$\lvert B_{env}\rvert\ (\leq 2\sigma)$	$\lvert R\rvert\ (\leq 2\sigma)$
L1448CO	0 ± 5	-4^{+9}_{-8}	27	2.0
B217-2	$+2 \pm 4$	$+2^{+7}_{-7}$	22	2.9
L1544	$+2 \pm 3$	$+4^{+10}_{-8}$	29	5.0
B1	-8 ± 3	-8^{+5}_{-5}	20	1.1

Summary 1

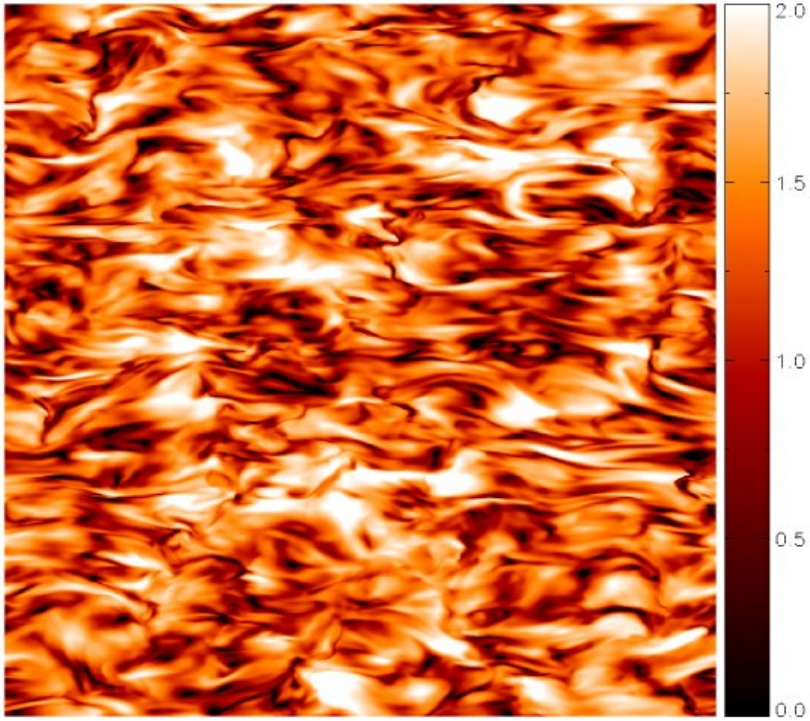
- Magnetic support of molecular clouds remains observationally ill-defined
- Interstellar clouds are complicated!

MHD Velocity Anisotropy (Goldreich & Sridhar 1995)

- Energy is distributed <u>differentially</u> along directions parallel and perpendicular to magnetic field
- Longer velocity correlation lengths <u>along</u> magnetic field:

$$k_{||} \sim (k_{perp})^{2/3}$$

Vestuto, Ostriker, & Stone 2003

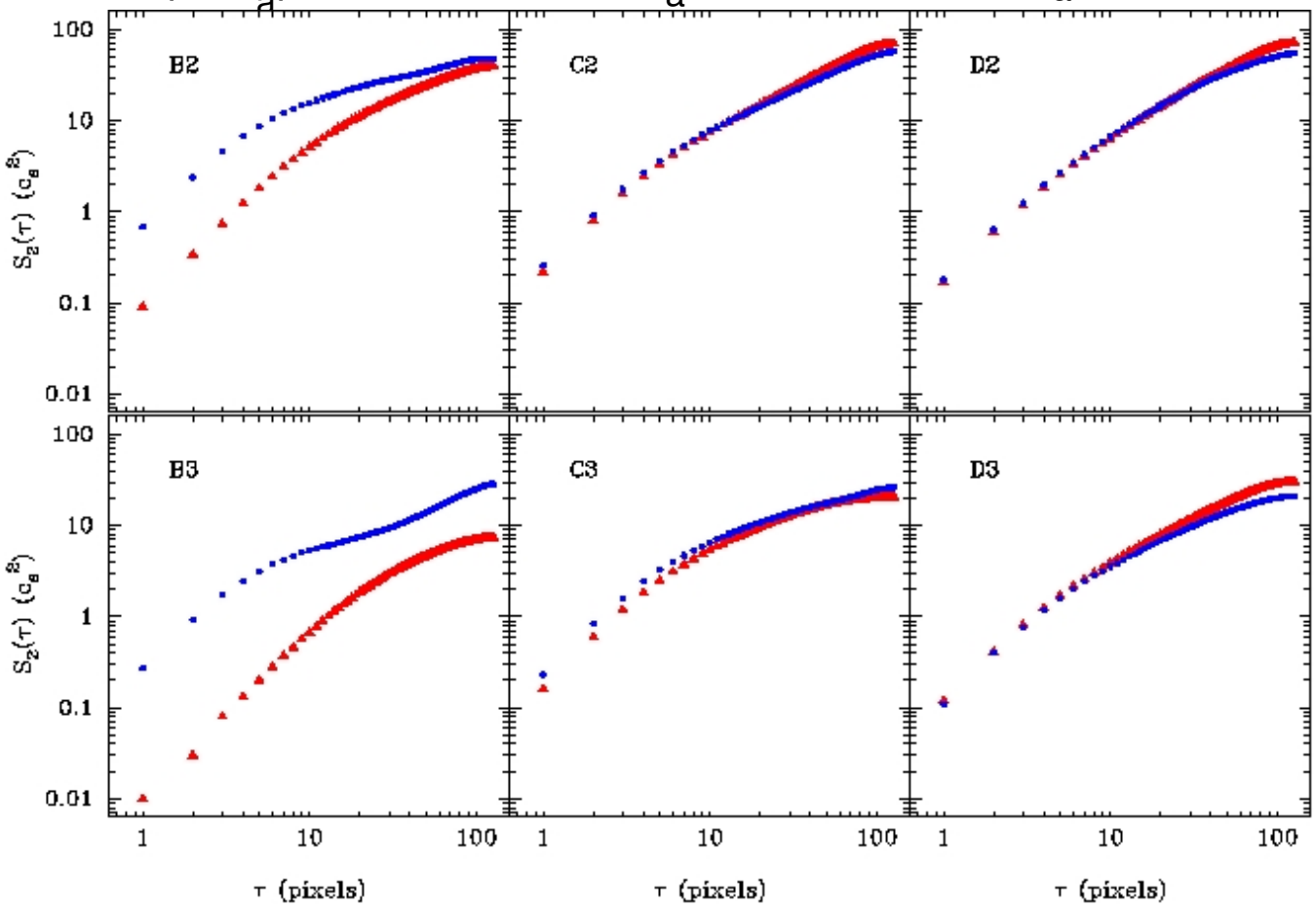


B →

Structure Functions (Ostriker, Stone & Gammie (2001)

RED: PARALLEL to B_0 **BLUE: PERPENDICULAR to B_0**

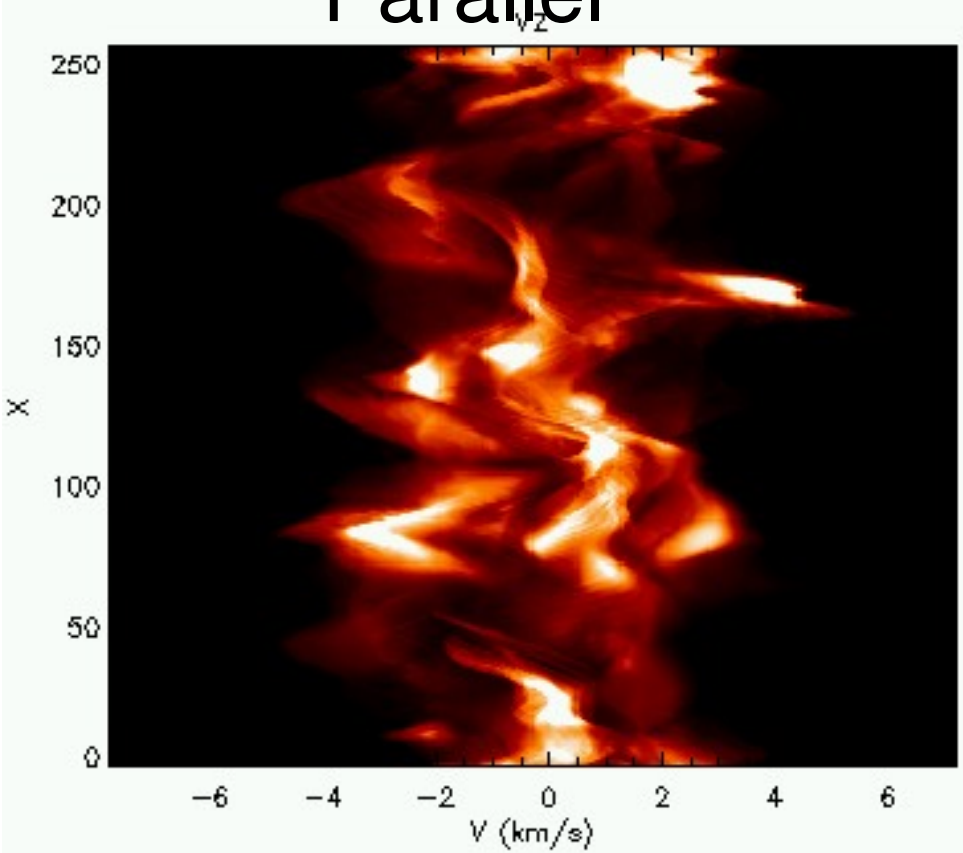
$(c/v_a)^2=0.01$ $(c/v_a)^2=0.1$ $(c/v_a)^2=1.0$



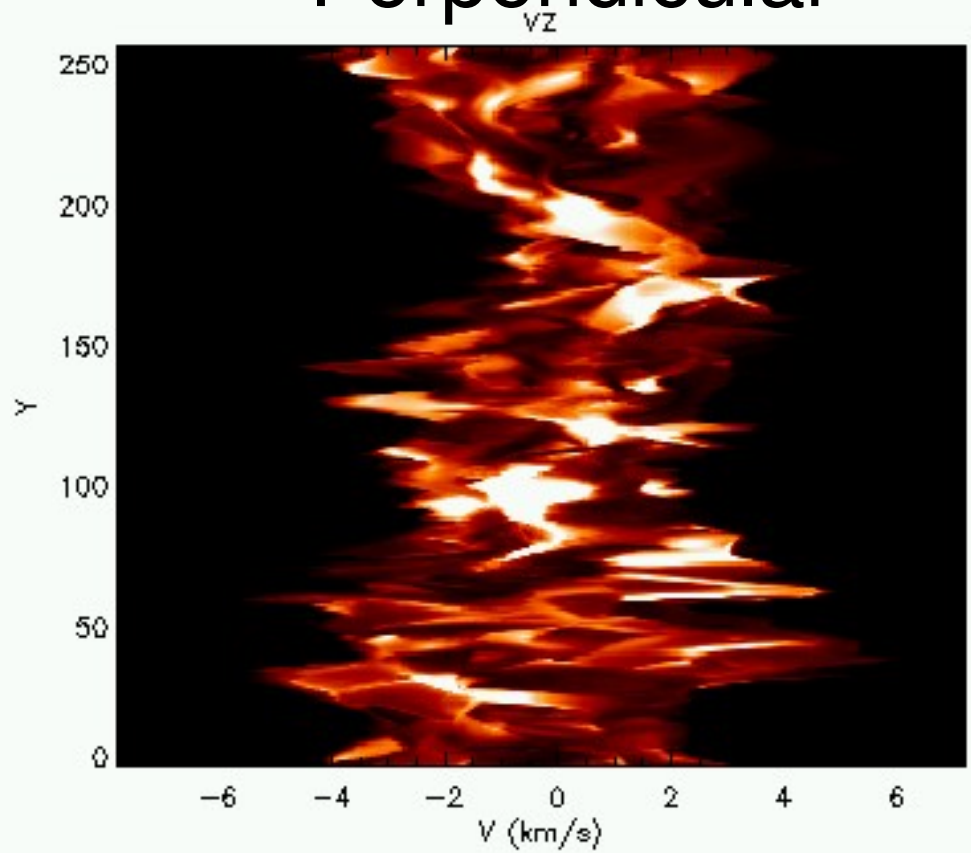
Simulated Observations of models:

$n(x,y,z), v(x,y,z) \dashrightarrow T_A(x,y,V_{LSR})$

Parallel



Perpendicular



Observational Expectations of the G-S Effect (Heyer etal 2008)

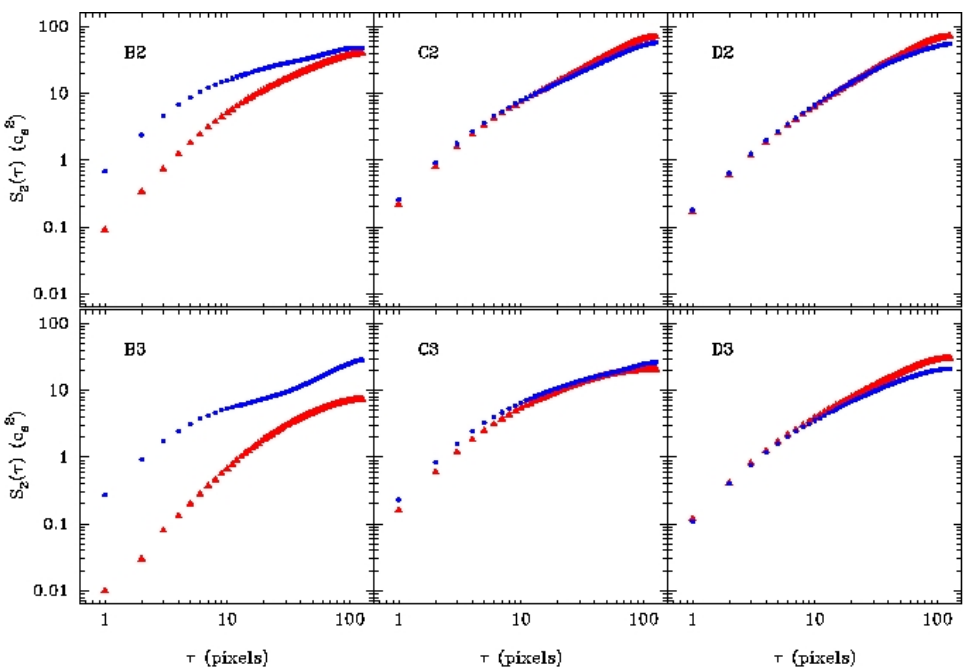
Measures structure function along two perpendicular axes within data cube, $T_A(x,y,V_{LSR})$:

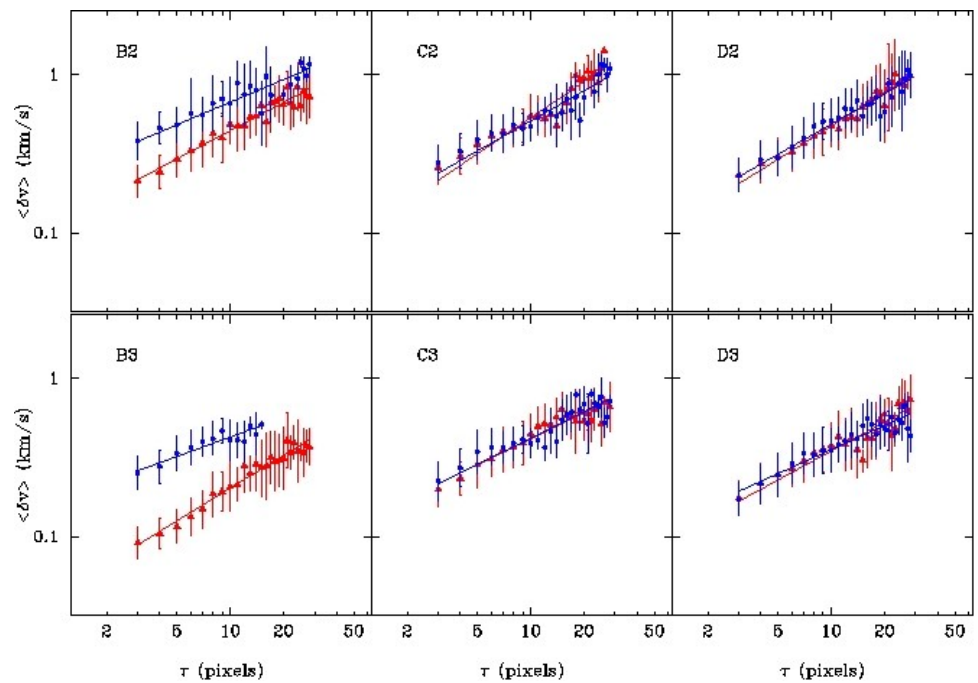
Eigenvectors: $\delta v(\tau)$

Eigenprojections: τ

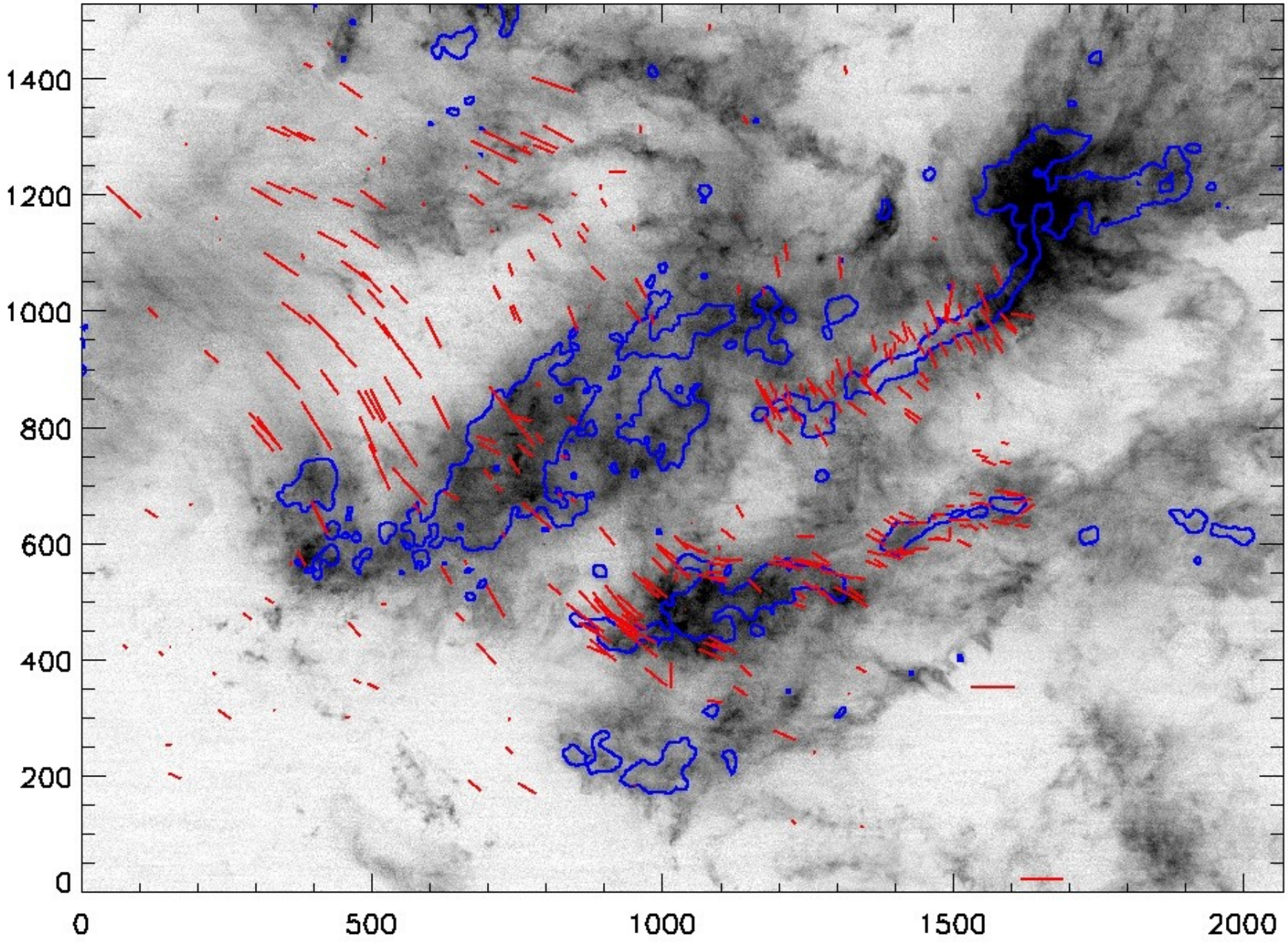
$$\delta v_x = v_{0x} L_x^{\gamma x}$$

$$\delta v_y = v_{0y} L_y^{\gamma y}$$





Red: optical polarization vectors Blue contour: Av=5 mag. (2MASS)



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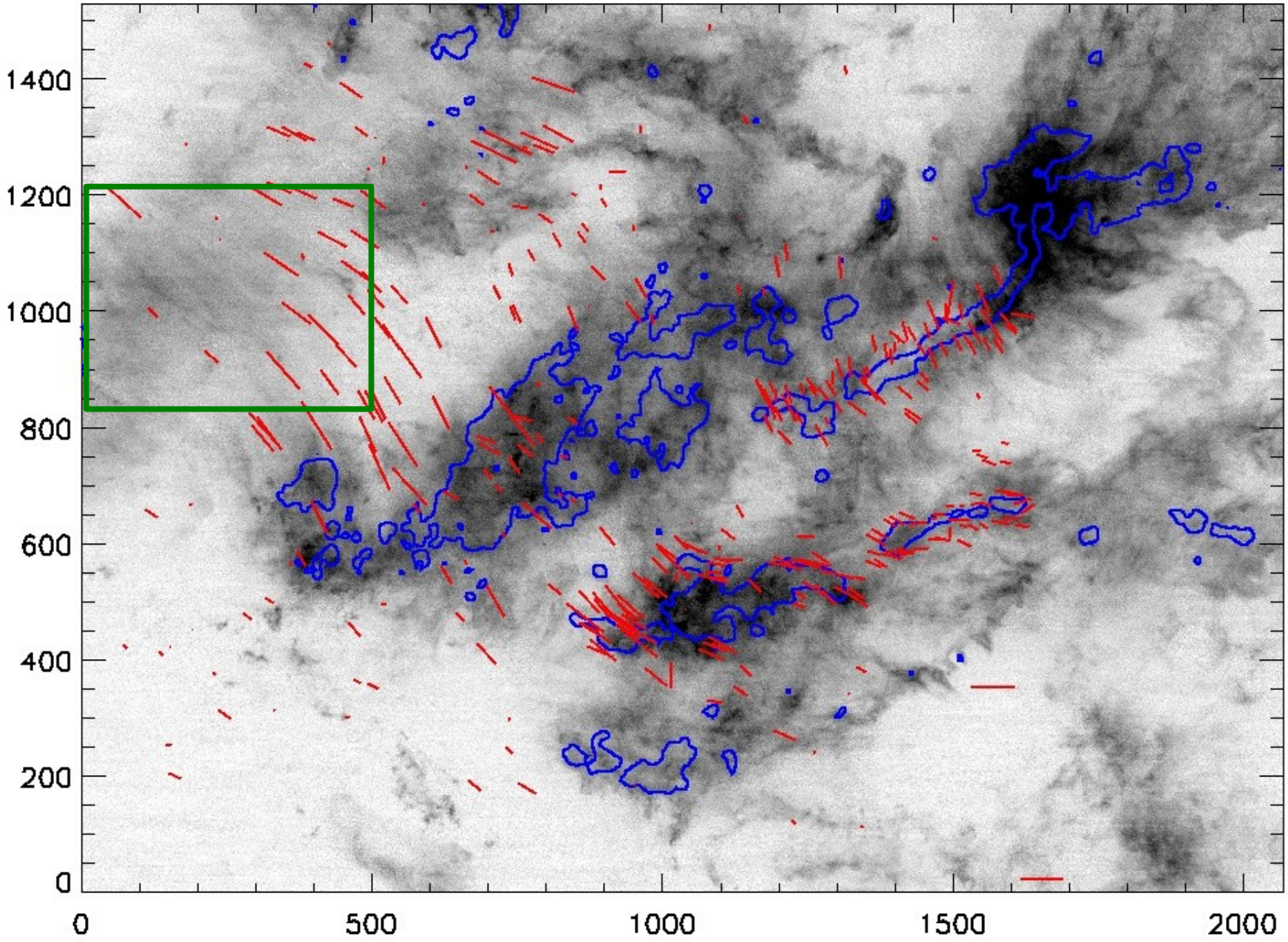
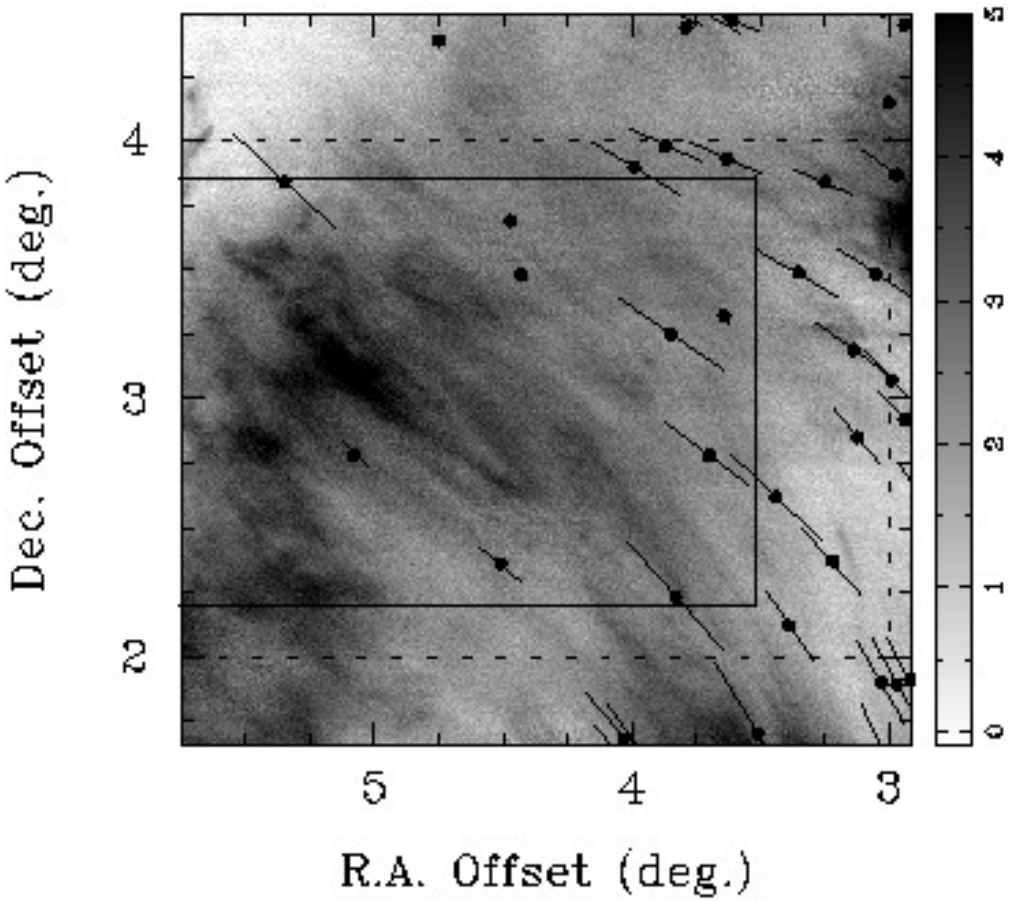
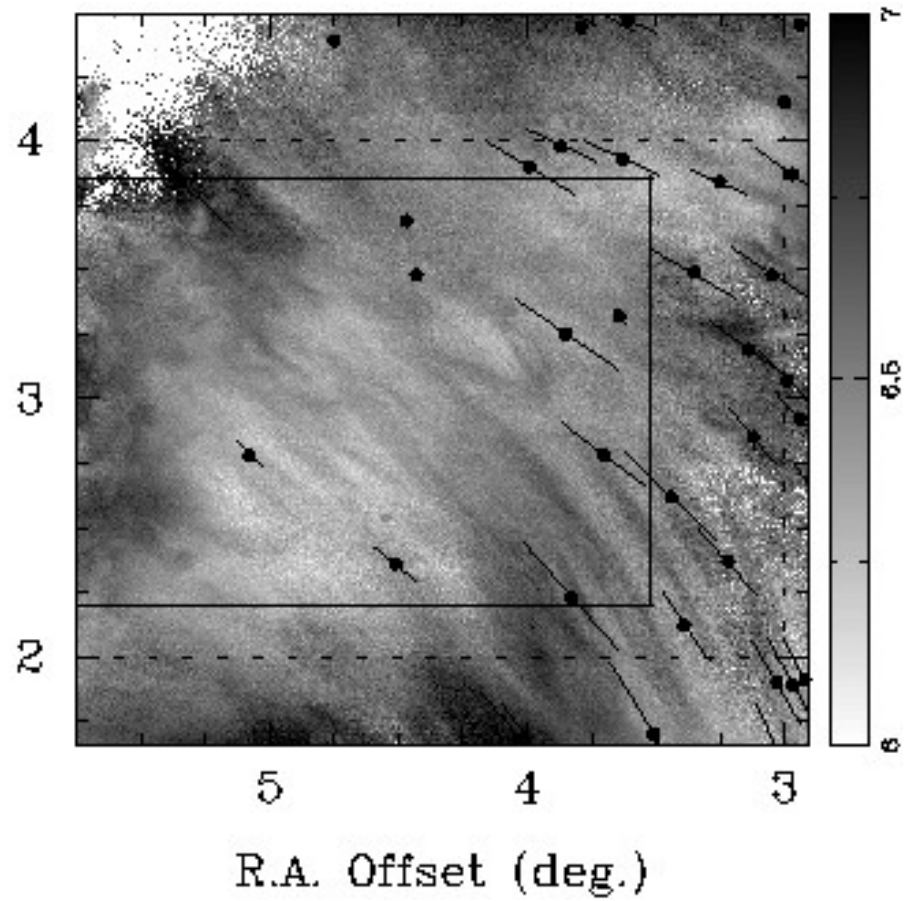


Taurus Sub-field

Integrated Intensity



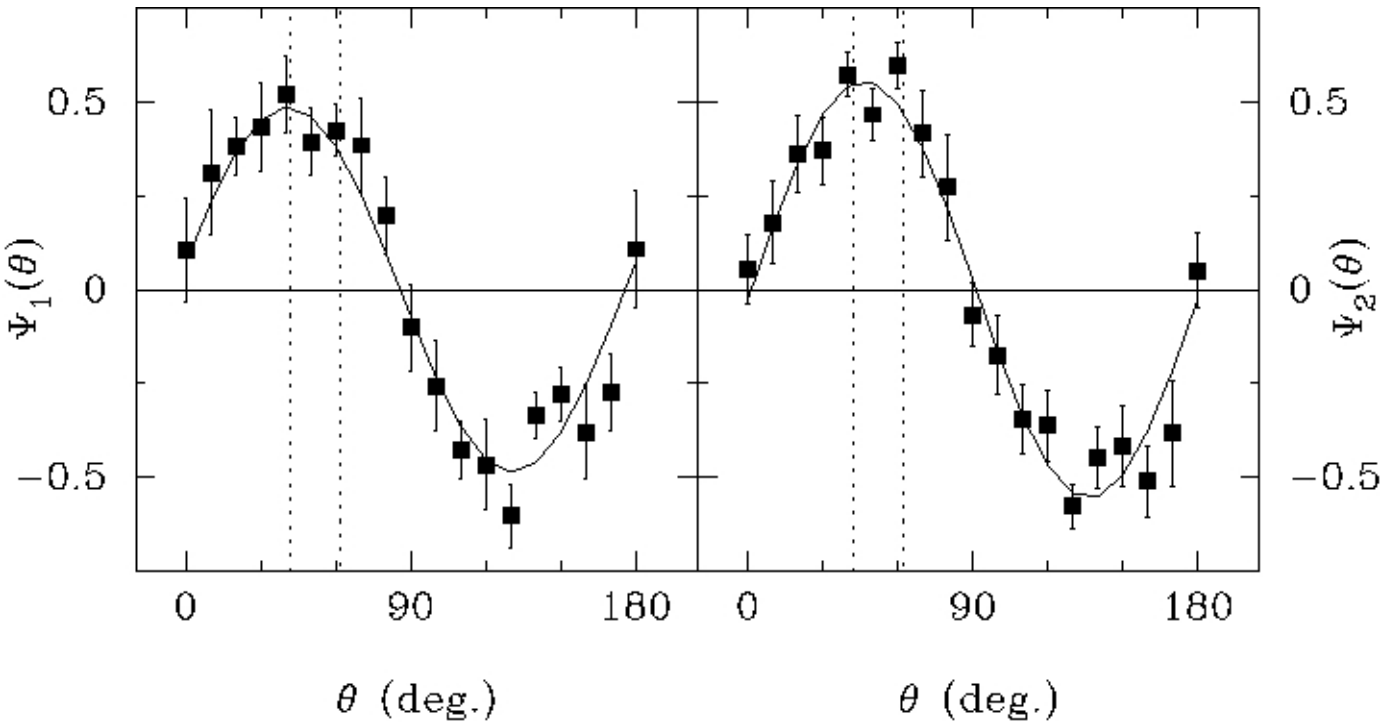
Centroid Velocity



Anisotropy Measures from Structure function parameters

$\Psi_1 = (\gamma_x - \gamma_y)/(\gamma_x + \gamma_y)$ (power law indices)

$\Psi_2 = (v_{0y} - v_{0x})/(v_{0x} + v_{0y})$ (amplitudes)



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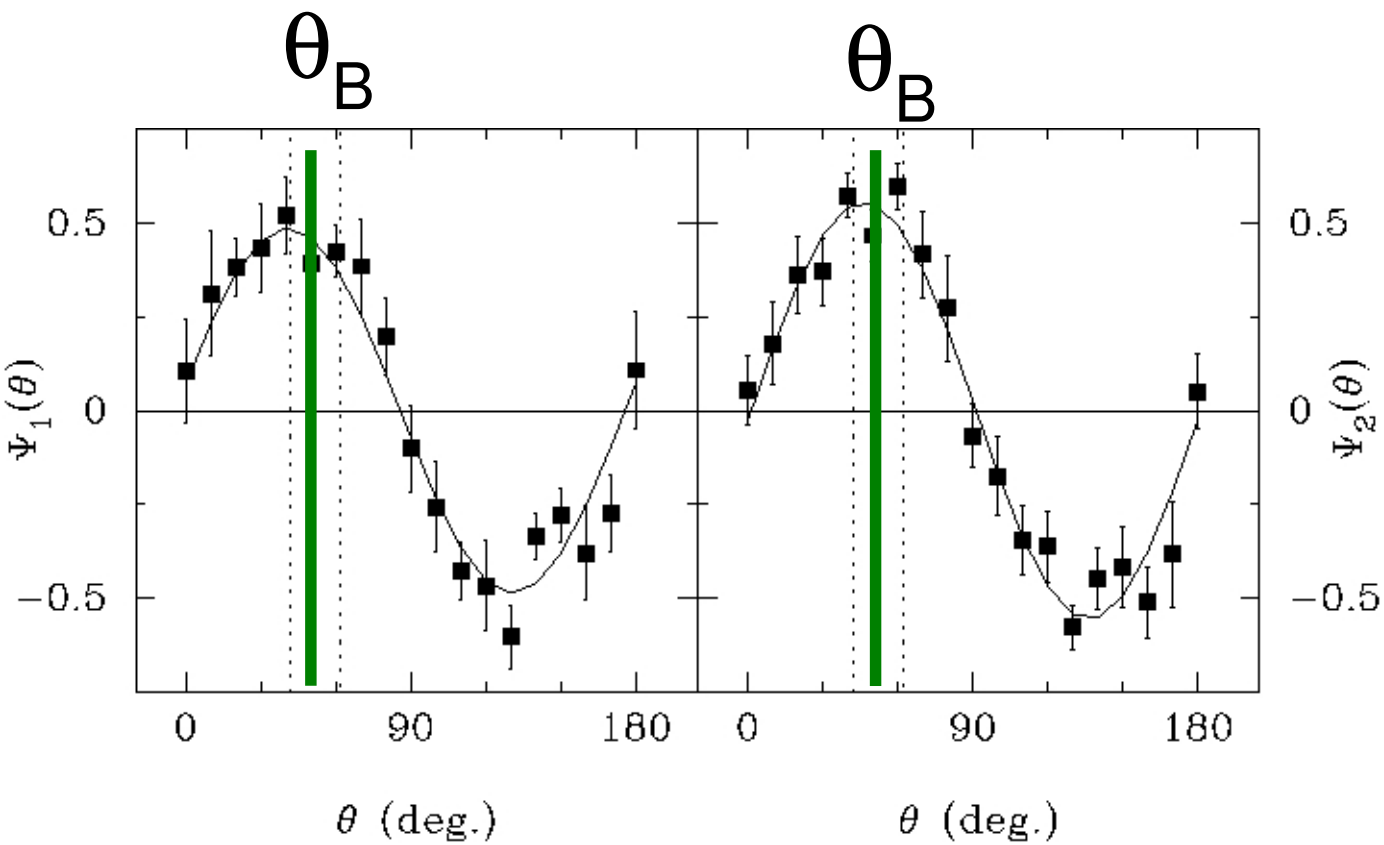
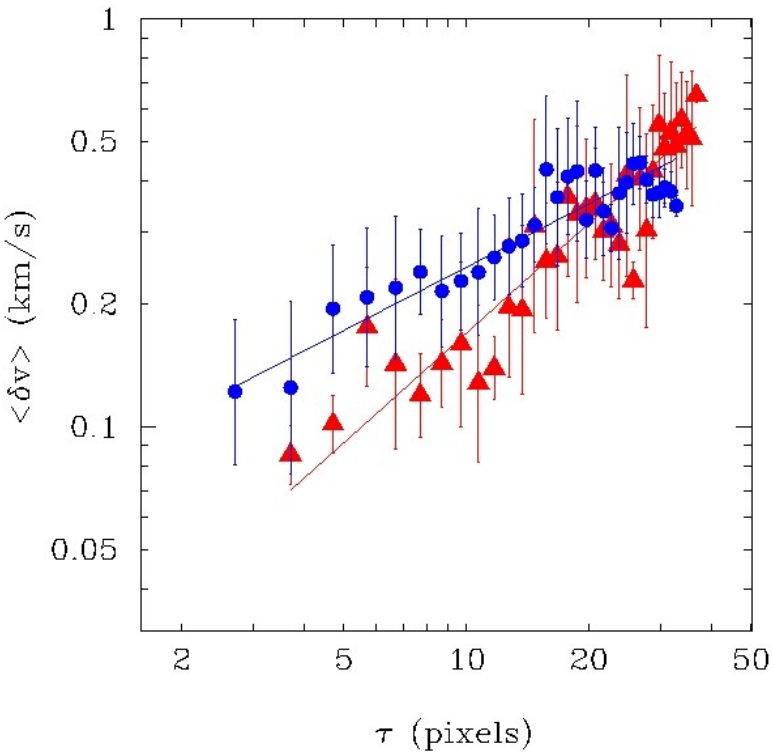


At angle of max. anisotropy



Models

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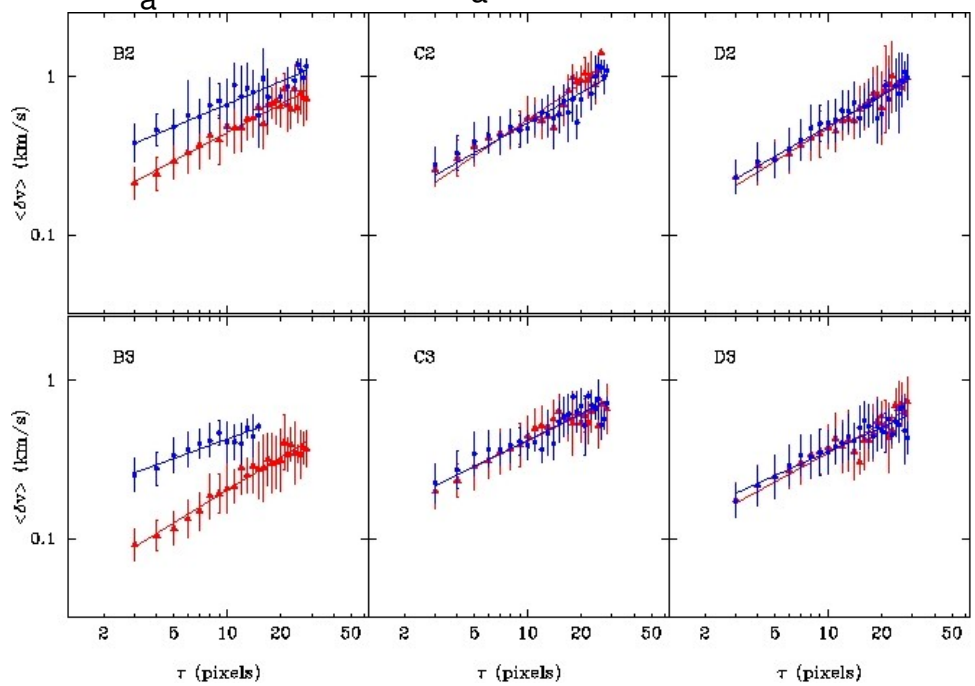
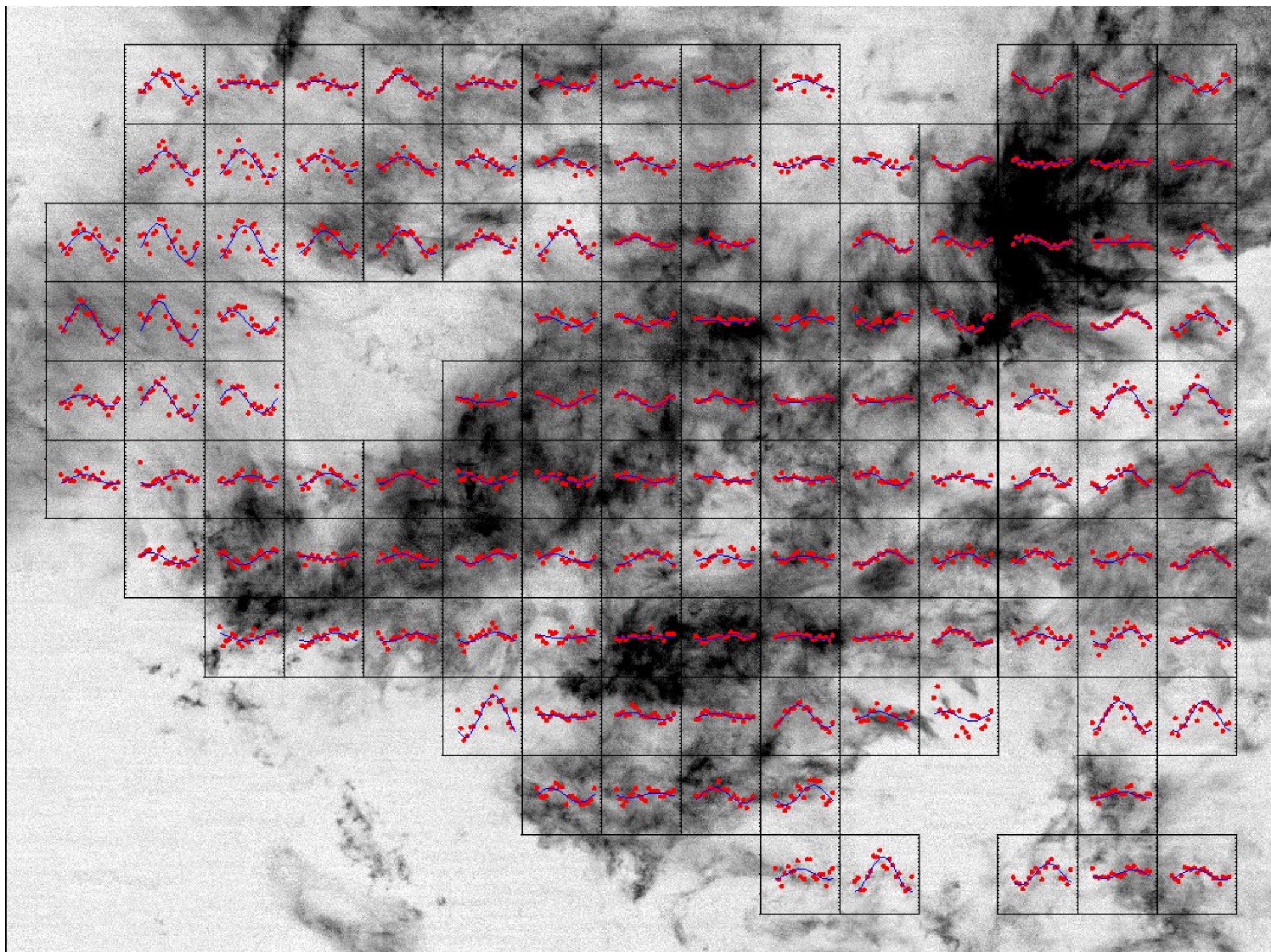
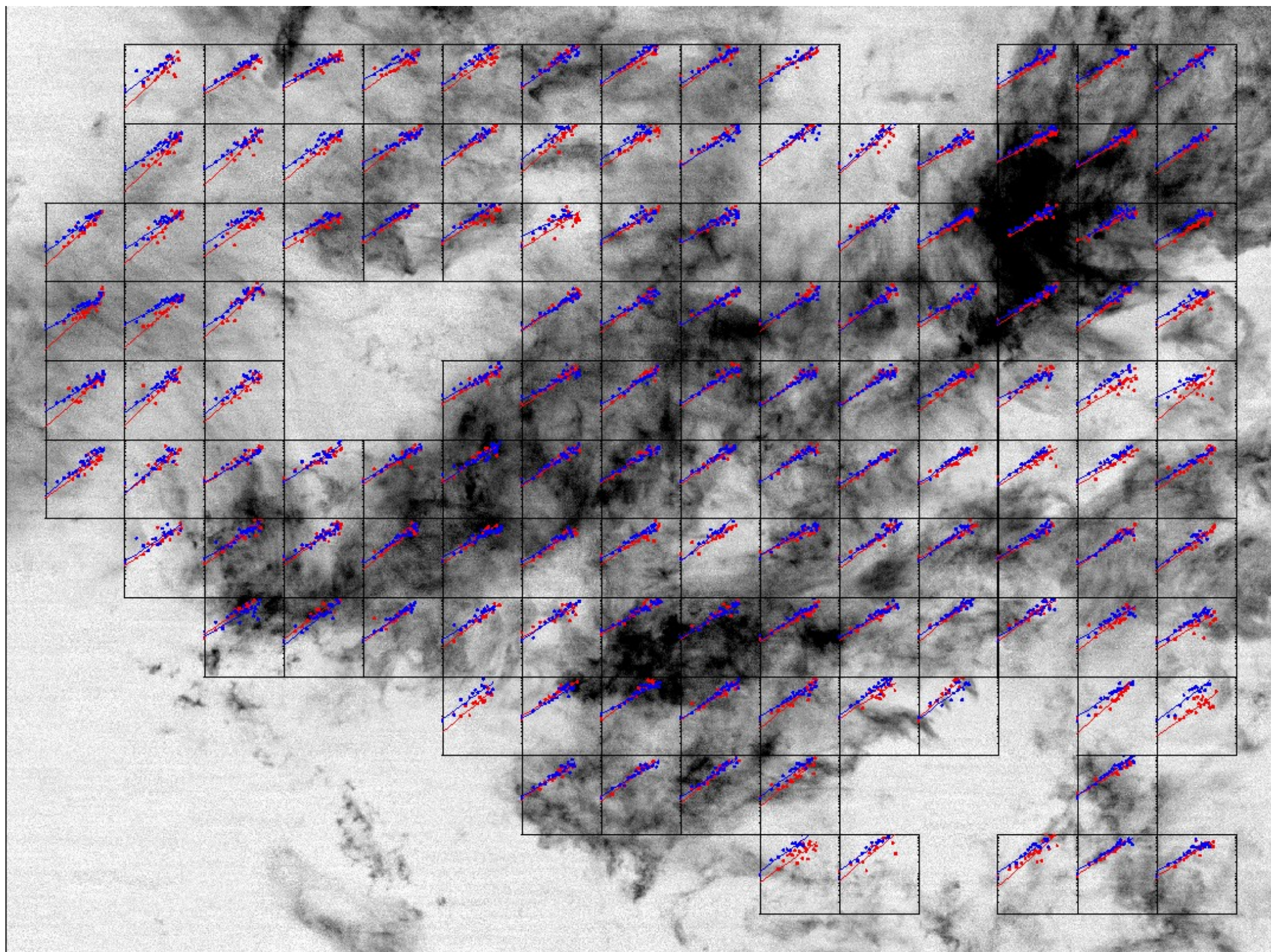


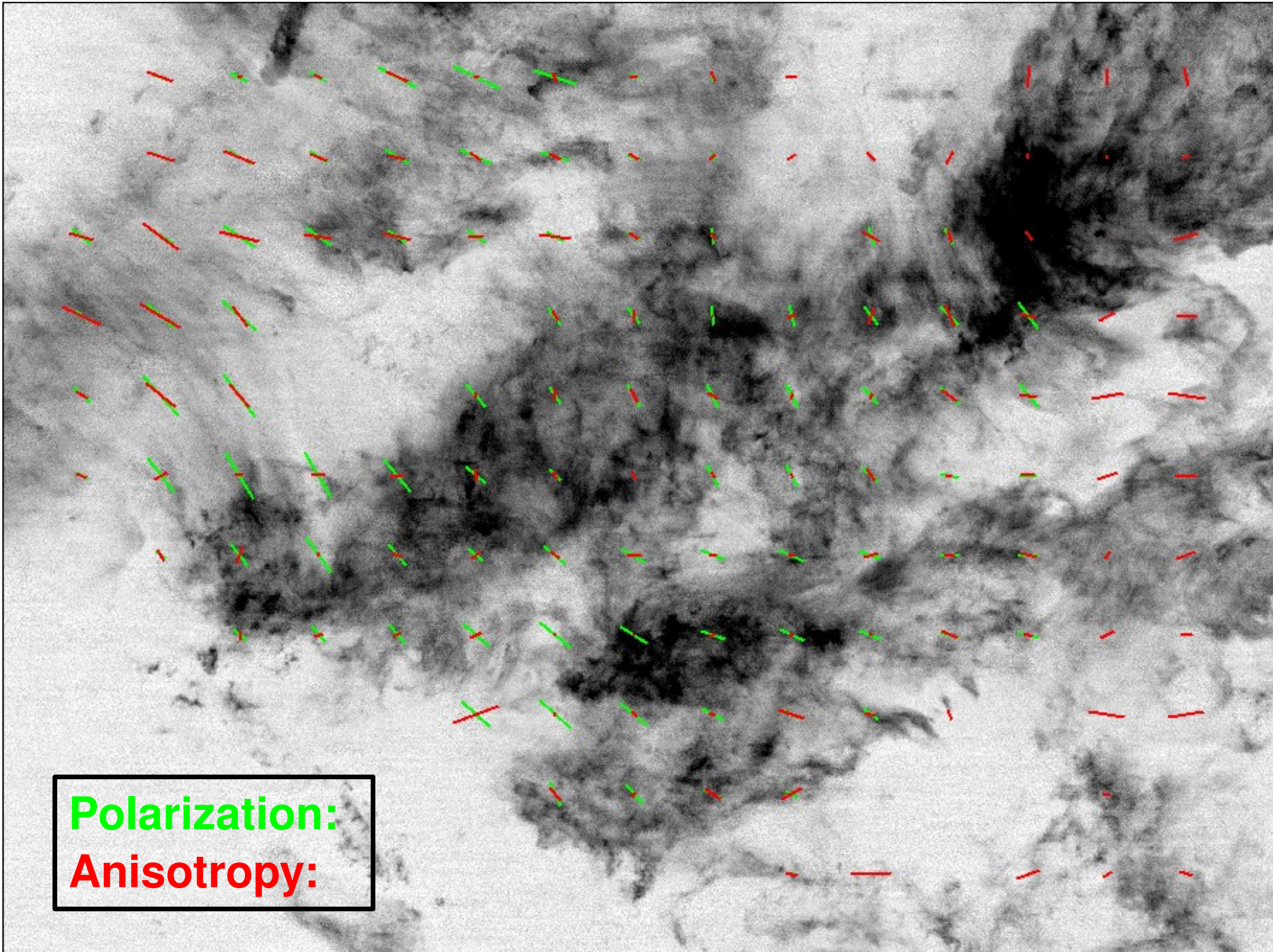
$(c_s/v_A)^2 \sim 0.03 = c_s^2\,(4\pi\rho)/B_0^2$

T=15 K, <n>=250 cm^{-3} ---> $B_0 = 14\ \mu G$

$N(H_2) \sim 1.5\times10^{21}\ cm^{-2}$ → $\mu_{obs} = N_{obs}/N_{cr} = 0.8$

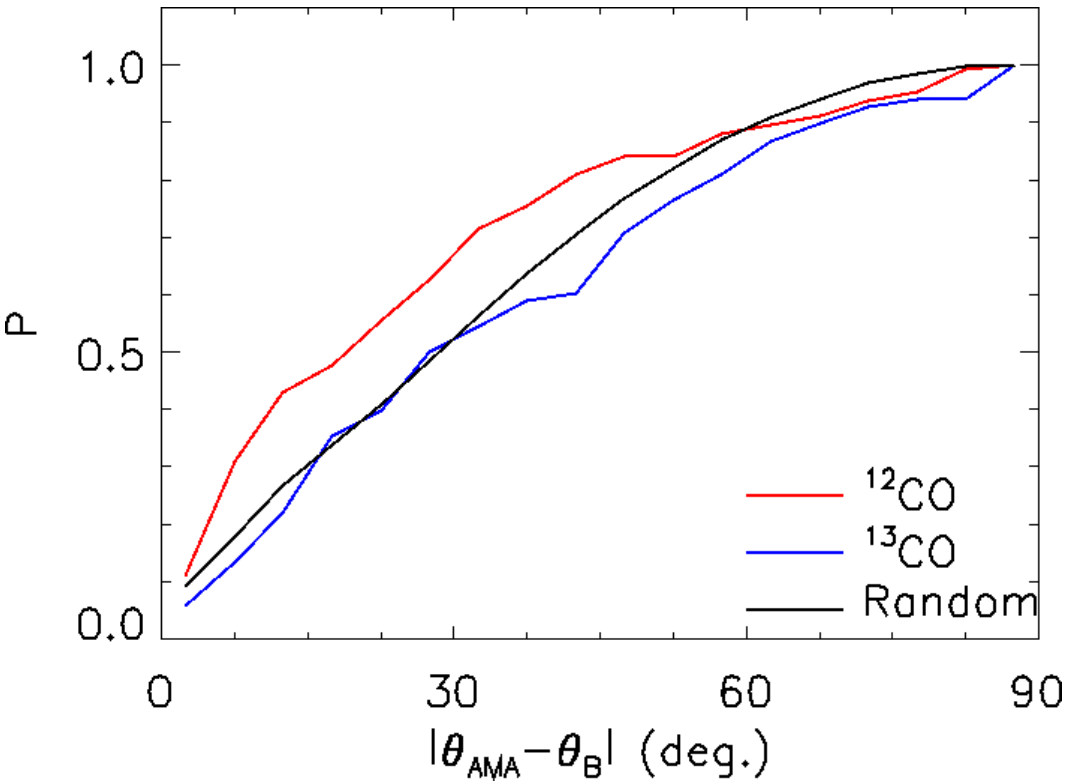





Polarization:
Anisotropy:

Ambipolar Diffusion?

Distribution of angle offsets



Ambipolar Diffusion?

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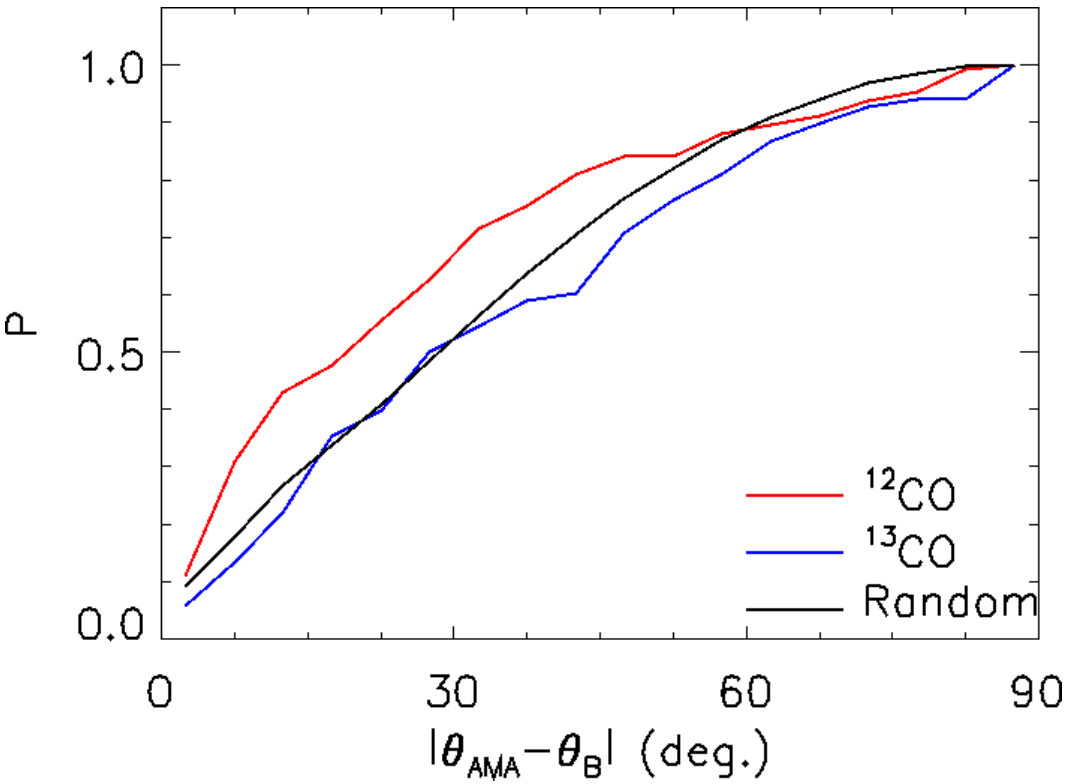
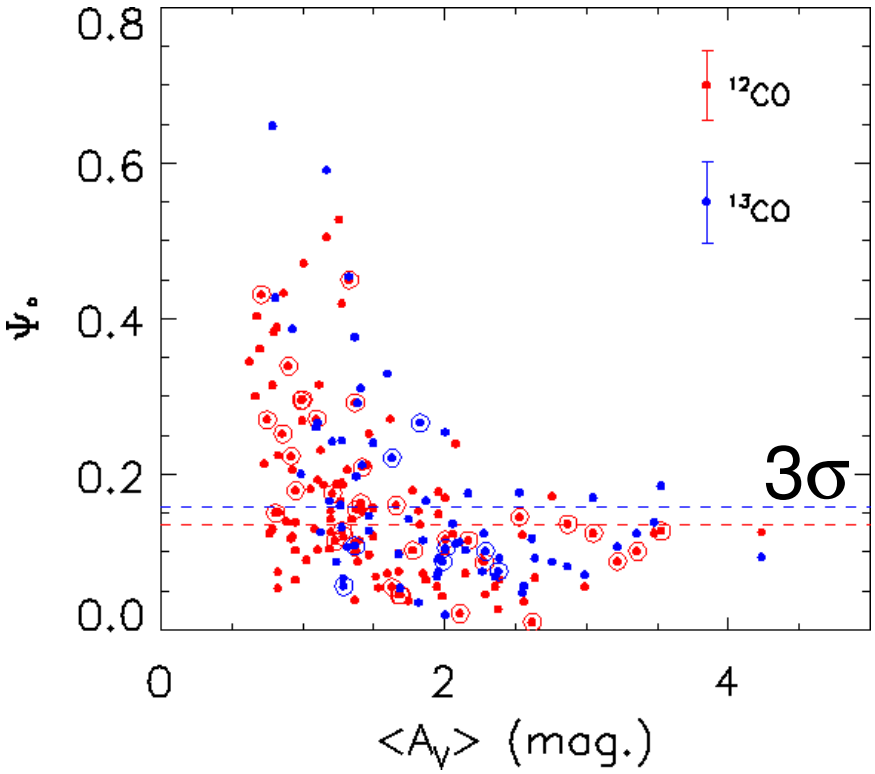


Amplitude vs Av



Summary

- Observational evidence does not exclude an important role of the interstellar magnetic field in cloud support

Measuring M/Φ is challenging

- Velocity anisotropy induced by strong MHD turbulence can provide a coarse measure of $(c_s/v_A)^2$
- Taurus molecular cloud envelope appears sub-critical
- Velocity anisotropy is reduced or non-existent in high column density regions

Axis Constrained PCA

$$W_y(x,v) = \frac{1}{\Delta}\sum_{j=j1}^{j2} T(x, y_j, v)$$

Position Velocity image along x axis

$$C^x_{kl} = \frac{1}{n_x}\sum_{i=1}^{n_x} W(x_i, v_k)W(x_i, v_l),$$

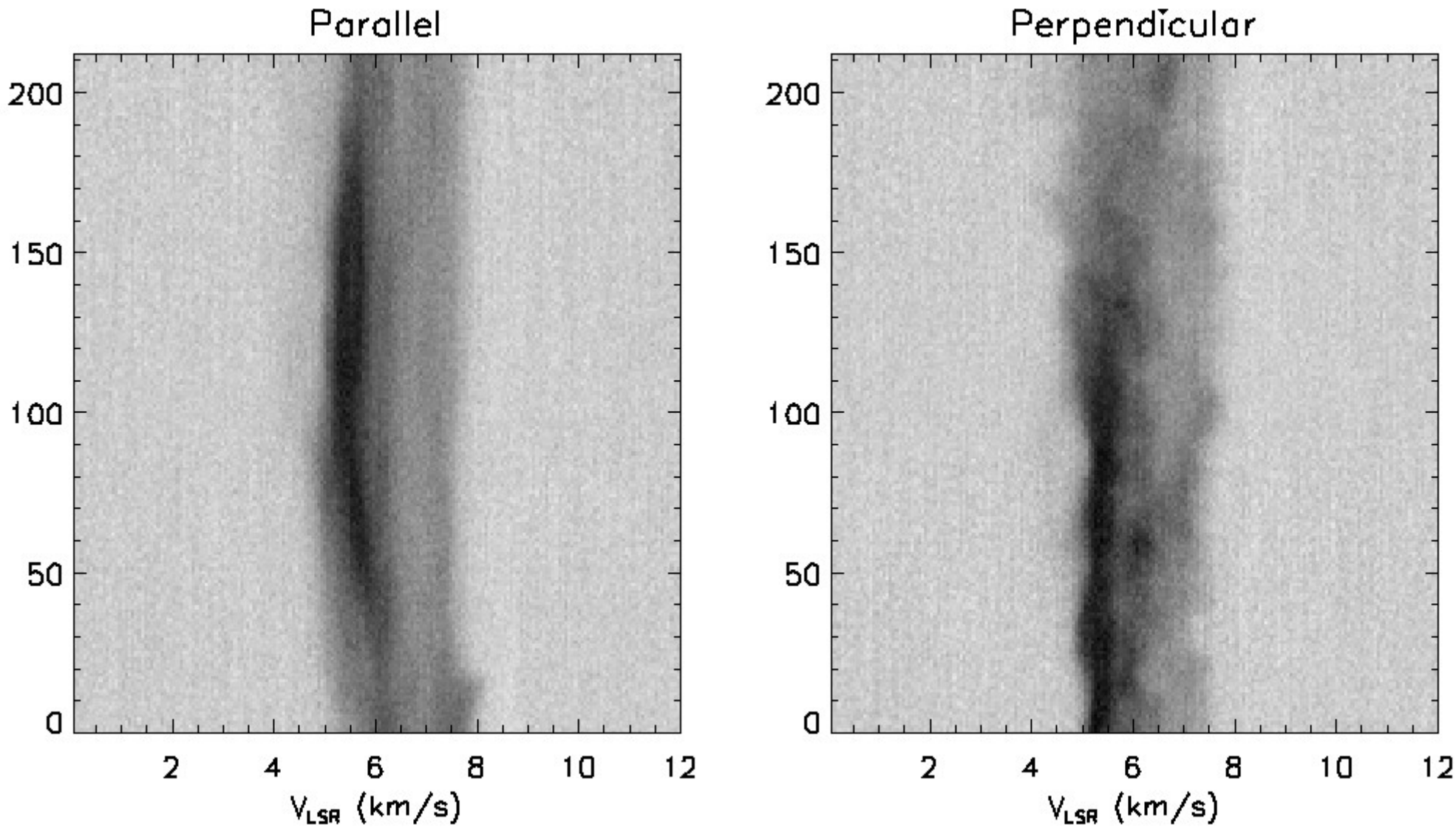
Covariance matrix

$$\mathbf{C}^x u_x = \lambda_x u_x$$

Eigenvalue Equation:
solve for λ, u: ---> δv_x for i=0,1,2,...

$$I_x(x_i) = \sum_{k=1}^{n_v} W(x_i, v_k) u_x(v_k)$$

Eigenimage (1D): --> L_x for i=0,1,2,...


Parallel
Perpendicular
200
150
100
50
0
2
4
6
8
10
12
V_{LSR} (km/s)