Characterizing Magnetized Turbulence in Molecular Clouds (and Galaxies)

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M51 project

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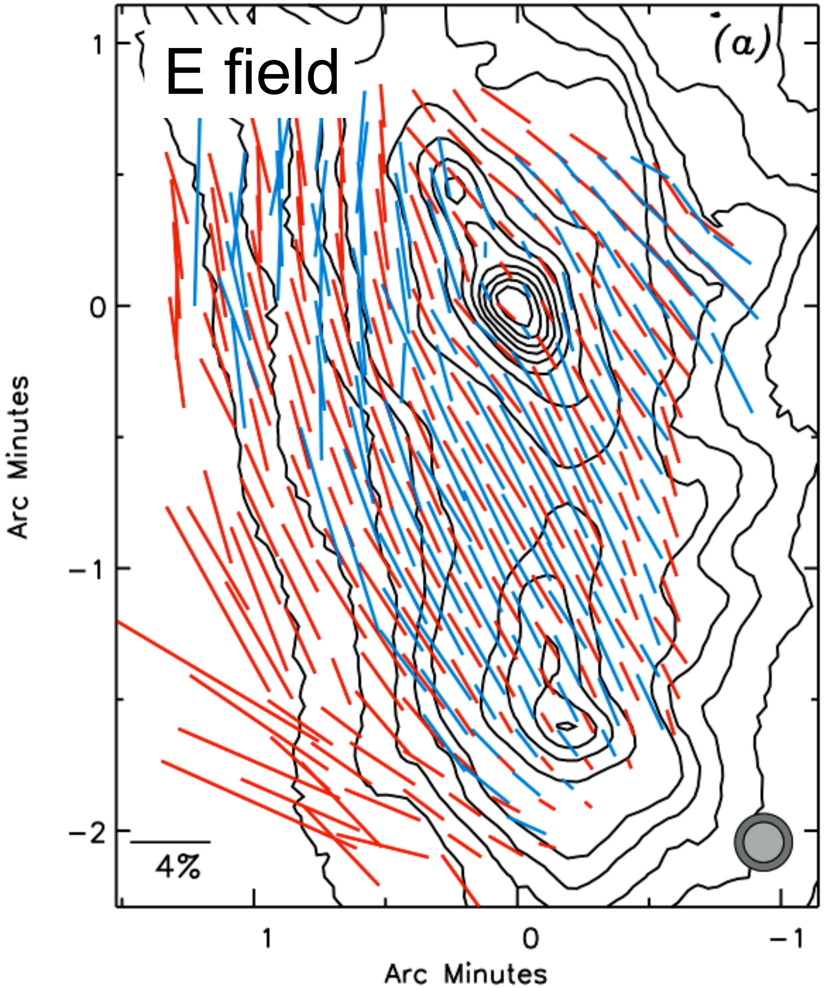
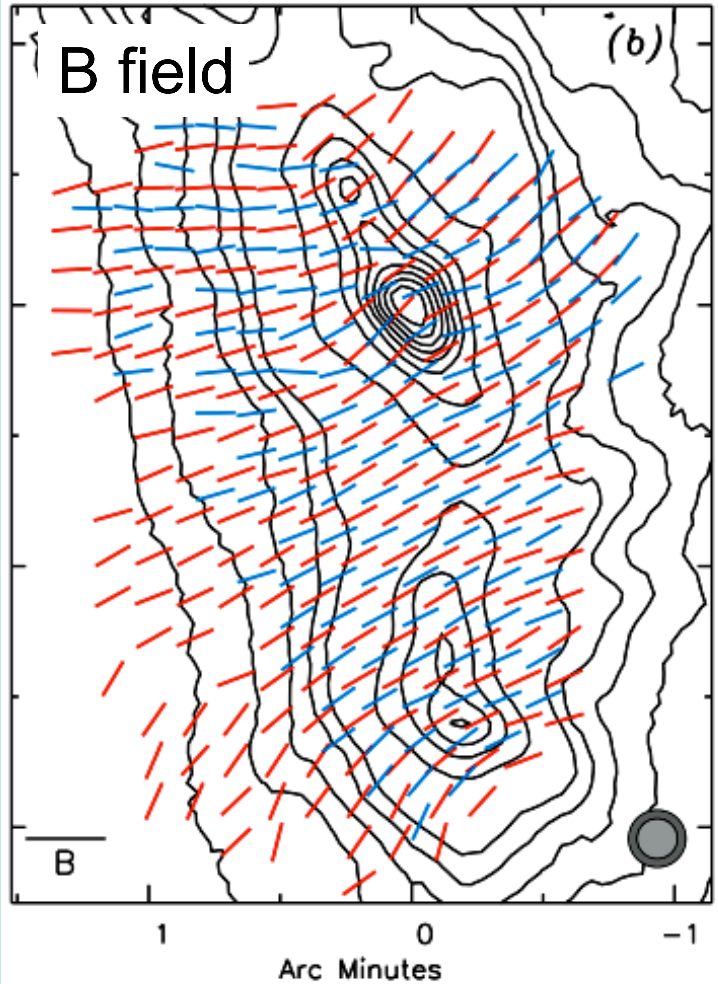
Outline

- Dispersion of magnetic fields
  - Separation of turbulent and large-scale fields through structure functions
  - Example: the Chandrasekhar-Fermi technique
- Application/results
  - Single-dish - OMC-1, CSO/SHARP
    - Turbulence correlation length
    - Turbulent/ordered field energy ratio (CF equation)
  - Interferometry - SMA
    - Magnetized turbulent power spectrum
    - Ambipolar diffusion scale
  - Single-dish (Effelsberg) + Interferometry (VLA)
    - M51 - Anisotropic turbulence

Polarization Maps - what are they good for?

OMC-1 - SHARP, 350 and 450 μm





Vaillancourt et al., 2008, ApJ, 679, L25

Structure Functions

- Common for studying turbulence
  - Nice properties for power-law power spectra with stationary signals
- Have been used in astrophysics for some time
  - Molecular clouds
    - Dotson (1996, ApJ, 470, 566) → M17 SW with KAO at 100 μm (polarization angles)
    - Falceta-Gonçalves et al. (2008, ApJ,) → simulations
  - Radio Astronomy
    - Beck et al. (1999) → Intensity maps (Stokes I, Q, and U)

Structure Functions

Given a polarization map

Angle $\Phi(\mathbf{r}) \rightarrow \mathbf{B}$ (plane of the sky)

The Angular Structure Function (stationarity and isotropy)

$$\left\langle \Delta\Phi^2(\ell) \right\rangle = \frac{1}{N(\ell)} \sum_{N(\ell)\text{ pairs}} \left[\Phi(\mathbf{r}) - \Phi(\mathbf{r} + \boldsymbol{\ell}) \right]^2$$

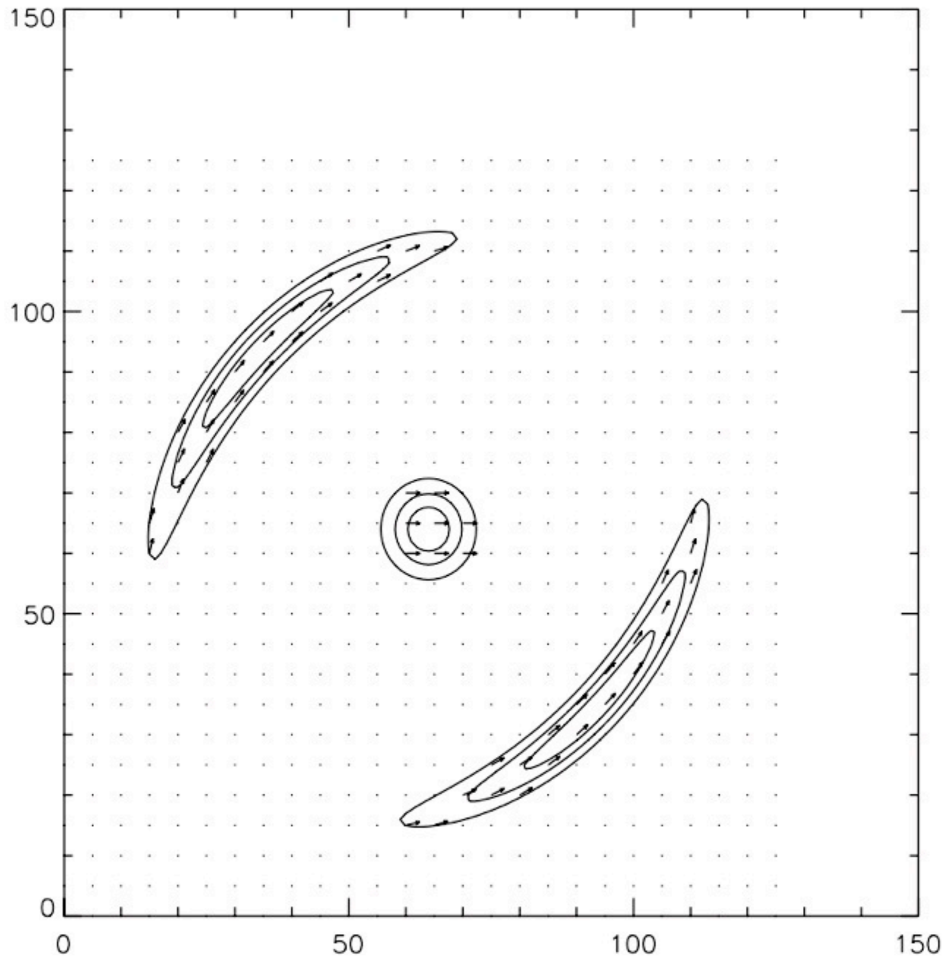
If $\mathbf{B} = \mathbf{B}_\mathrm{t} + \mathbf{B}_0$ (turbulent and ordered (large-scale) components)

$$\Rightarrow \left\langle \Delta\Phi^2(\ell) \right\rangle = \left\langle \Delta\Phi_\mathrm{t}^2(\ell) \right\rangle + \left\langle \Delta\Phi_0^2(\ell) \right\rangle$$

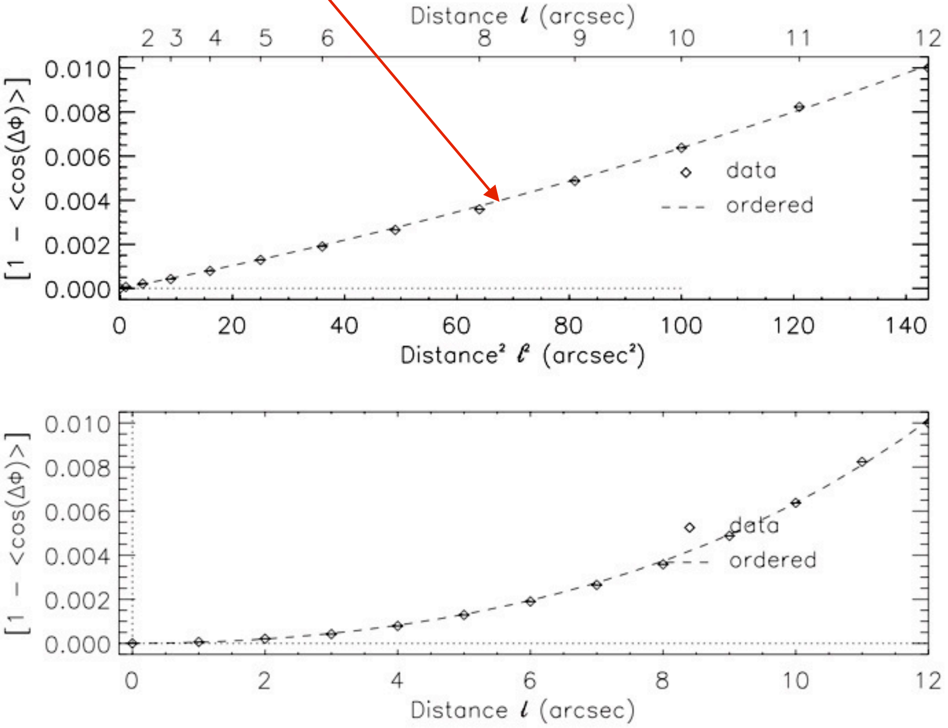
with statistical independence.

$$\Rightarrow 1 - \left\langle \cos\left[\Delta\Phi(\ell) \right] \right\rangle \simeq \frac{\left\langle \Delta\Phi^2(\ell) \right\rangle}{2} \Leftarrow$$

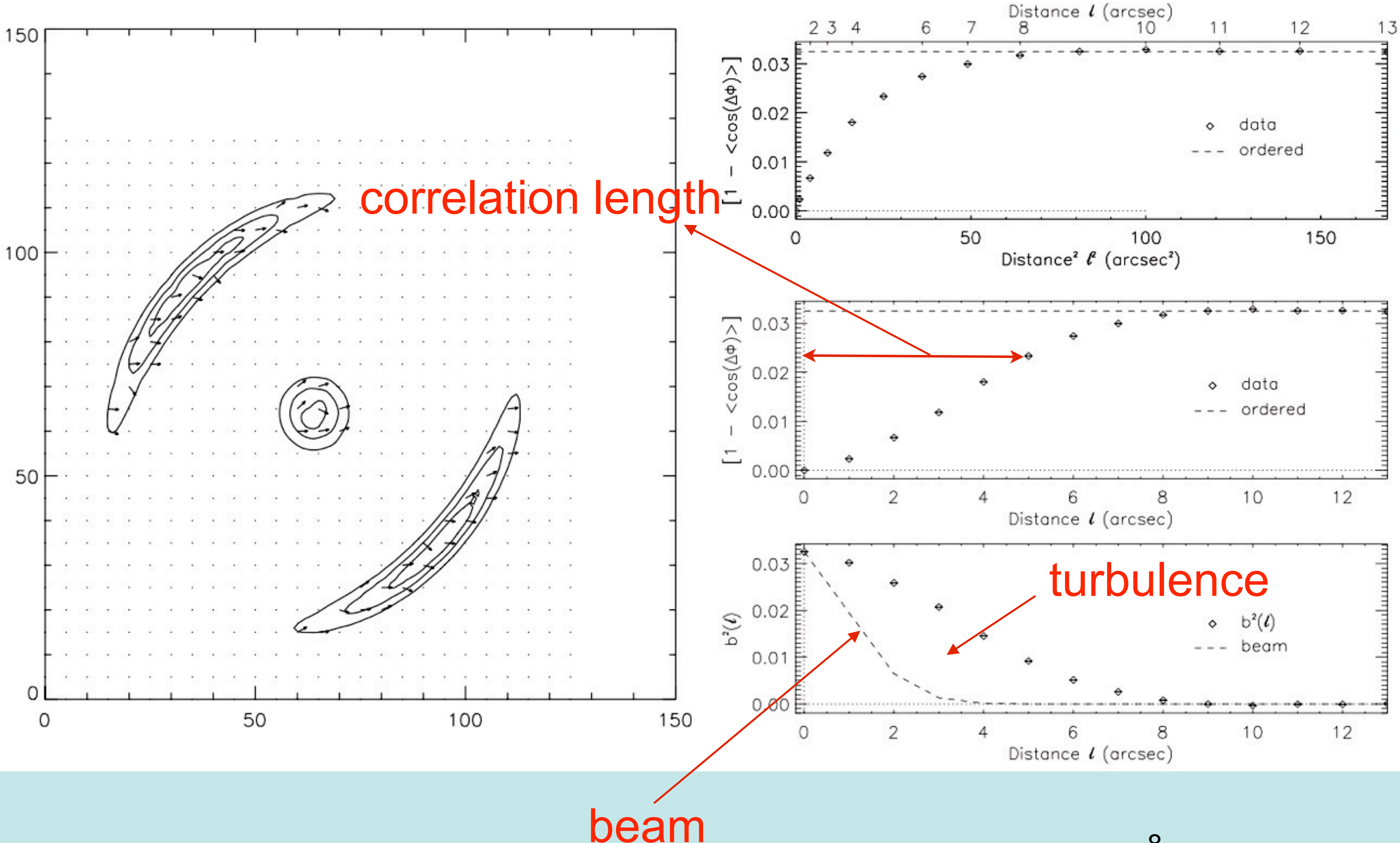
Structure Functions - Large-scale



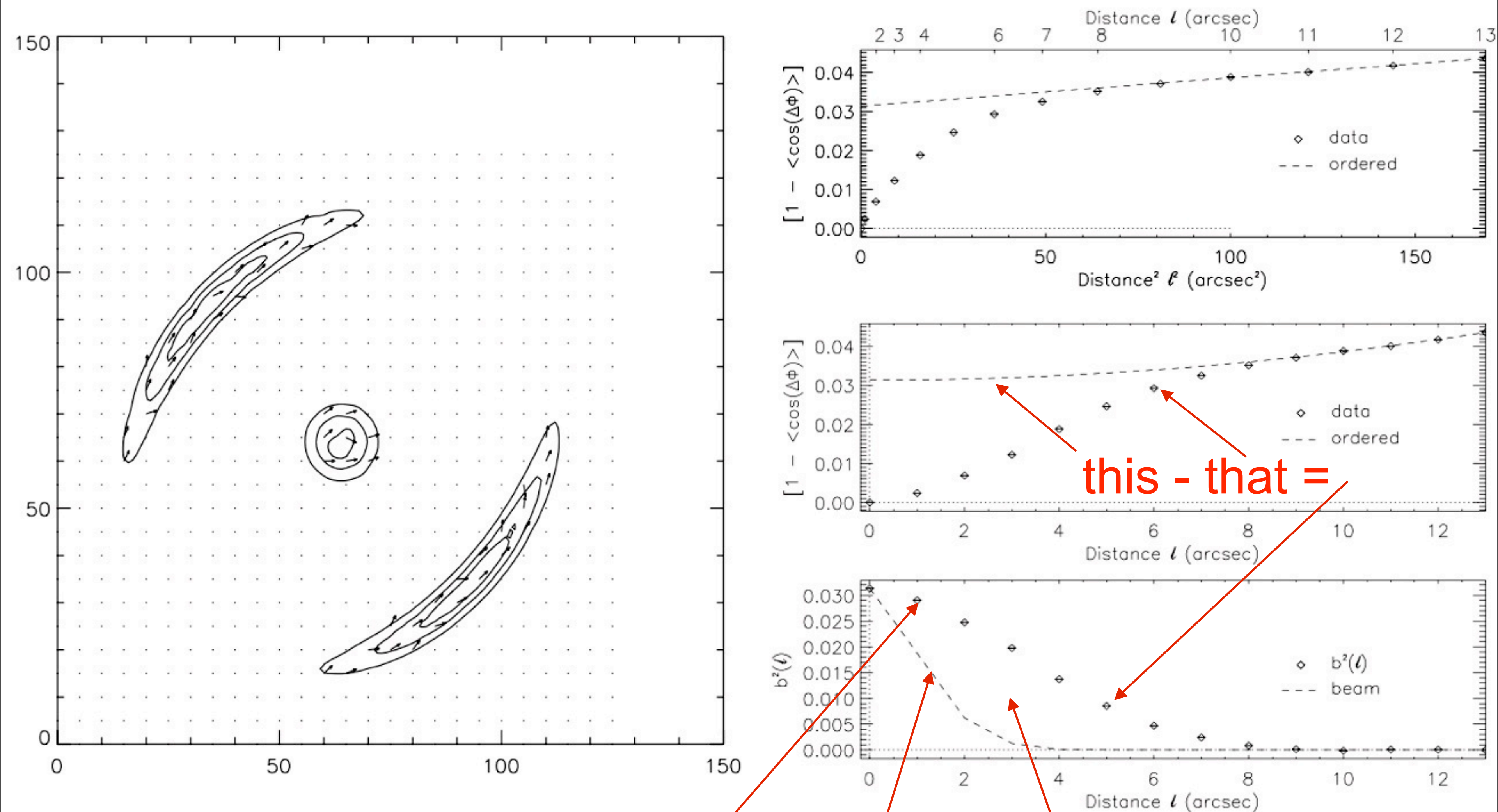
polynomial fit (even powers)



Structure Functions - Turbulence



Structure Functions - Turb.+large-scale



beam-broadened autocorrelation

beam

turbulence

Example - Chandra-Fermi Equation

$$B_0 \simeq \sqrt{4\pi\rho}\,\sigma(v)\left[\frac{\langle B_t^2\rangle}{\langle B_0^2\rangle}\right]^{-1/2}$$ (Chandrasekhar-Fermi 1953)

turbulent → $\langle B_t^2\rangle$

ordered field → $\langle B_0^2\rangle$

ρ: mass density

$\sigma(v)$: velocity dispersion (one-dimension)

But the angular dispersion $\delta\Phi$ relative to the ordered field determined with polarization maps is

$$\delta\Phi \approx \left[\frac{\langle B_t^2\rangle}{\langle B_0^2\rangle}\right]^{1/2}$$ or is it really the case?

Example - Chandra-Fermi Equation

Problems with the CF method

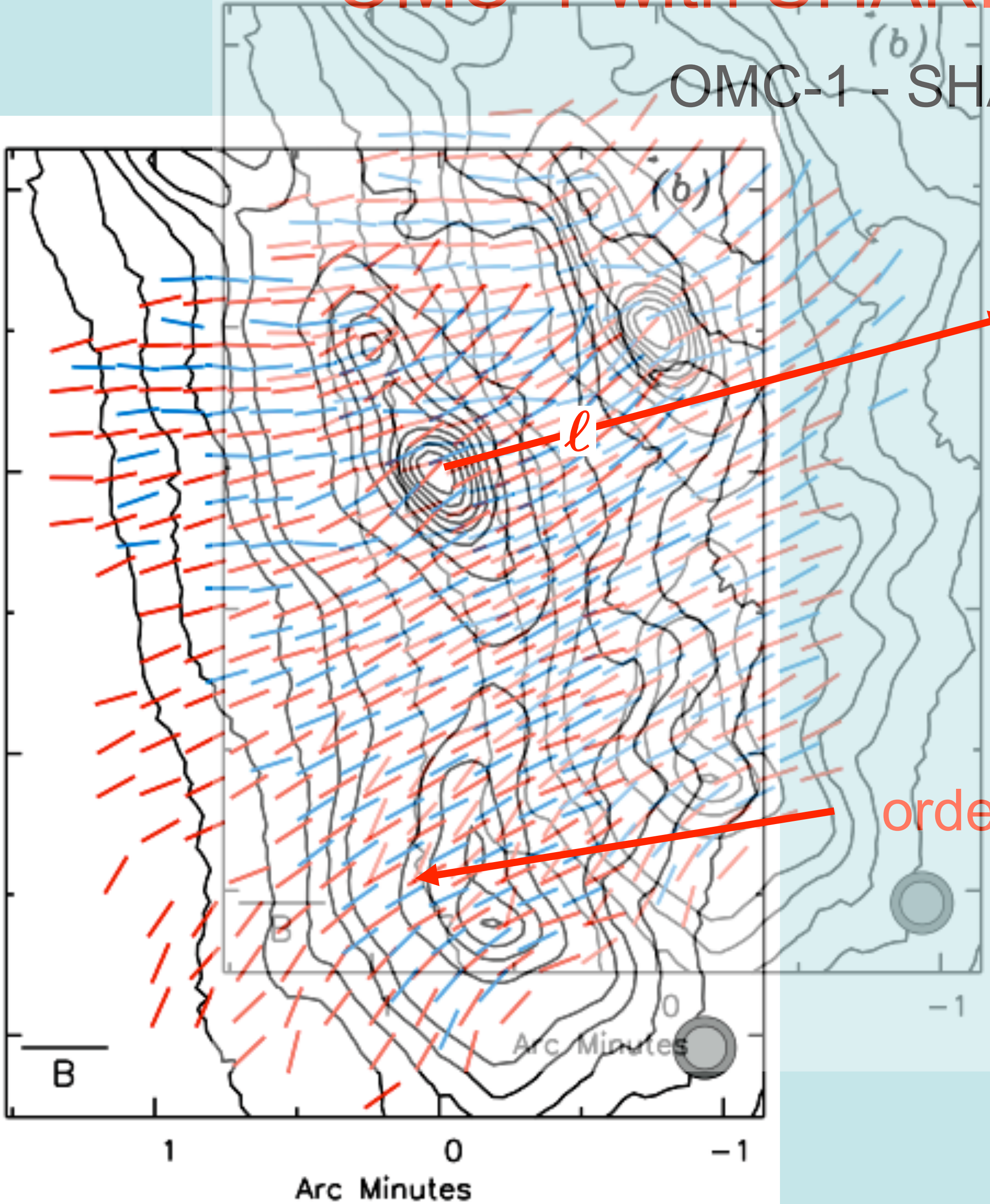
1. The models for $\mathbf{B}_0$ are imperfect and introduce more errors in the determination of $\delta\Phi$. This is solved with the structure function.

Moreover

2. Signal integration along the line of sight and across the telescope beam
   - $\langle \mathbf{B}_t^2 \rangle$ is underestimated due to averaging process
   - $\mathbf{B}_0$ is therefore overestimated

OMC-1 with SHARP at 350 μm

OMC-1 - SHARP/CSO, 350 and 450 μm



$$1 - \left\langle \cos\left[\Delta\Phi(\ell)\right] \right\rangle \simeq \frac{\left\langle \Delta\Phi^2(\ell) \right\rangle}{2}$$

ordered + turbulent fields

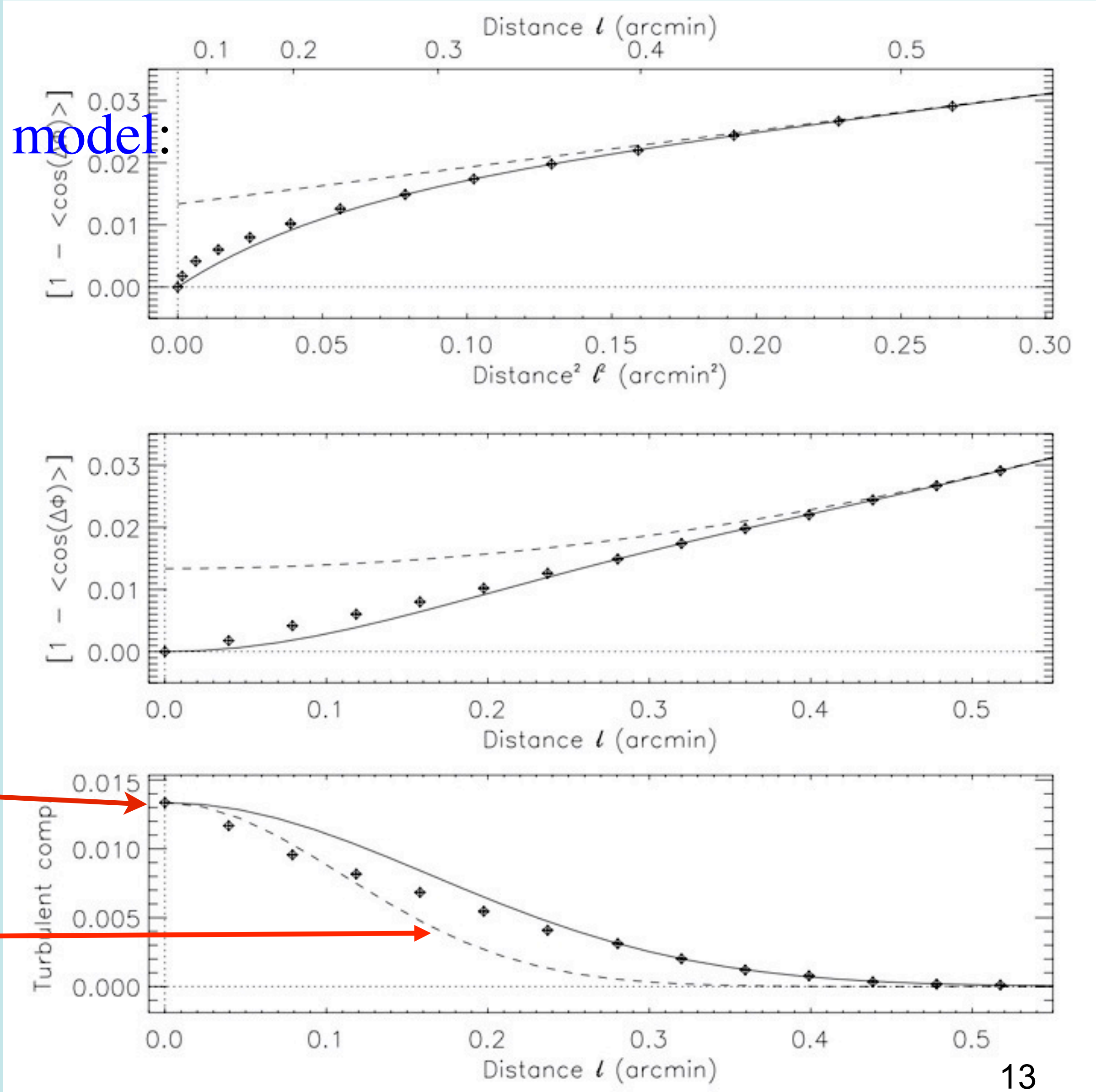
$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_t$$

Vaillancourt et al., 2008, ApJ, 679, L25

OMC-1 with SHARP at 350 μm

χ^2 fit to Gaussian model:

$\delta, \langle \bar{B}_t^2 \rangle / \langle \bar{B}_0^2 \rangle.$



$$(\delta\Phi)^2 \approx \frac{\langle \bar{B}_t^2 \rangle}{\langle \bar{B}_0^2 \rangle}$$

beam

13

Houde et al. 2009, ApJ, 706, 1504

OMC-1 / SHARP - Results

$\delta \simeq 7.3'' = 16\ \text{mpc}$ turbulent correlation length

$$N = \frac{\left(\delta^2 + 2W^2\right)\Delta'}{\sqrt{2\pi}\,\delta^3} \simeq 21$$ number of turbulent cells

$$\frac{\left\langle \overline{B}_{\mathrm{t}}^2 \right\rangle}{\left\langle \overline{B}_0^2 \right\rangle} = \frac{1}{N}\frac{\left\langle B_{\mathrm{t}}^2 \right\rangle}{\left\langle B_0^2 \right\rangle} \simeq 0.013$$

$$\frac{\left\langle B_{\mathrm{t}}^2 \right\rangle}{\left\langle B_0^2 \right\rangle} \simeq 0.28$$ turbulent/ordered field energy ratio

with Chandrasekhar-Fermi equation

$$B_0 \simeq \sqrt{4\pi\rho}\,\sigma(v)\left[\frac{\left\langle B_{\mathrm{t}}^2 \right\rangle}{\left\langle B_0^2 \right\rangle}\right]^{-1/2} \simeq 760\,\mu\text{G}$$ plane of the sky

with $n = 10^5\ \text{cm}^{-3}$, $A = 2.3$, and $\sigma(v) = 1.85\ \text{km s}^{-1}$

Houde et al. 2009, ApJ, 706, 1504

Turbulent Power Spectrum

$$1-\left\langle \cos\left[\Delta\Phi(\ell)\right]\right\rangle \simeq \frac{\left\langle \Delta\Phi^2(\ell)\right\rangle}{2}$$

but

$$\Rightarrow \left\langle \cos\left[\Delta\Phi(\ell)\right]\right\rangle \equiv \frac{\left\langle \overline{\mathbf{B}}\cdot\overline{\mathbf{B}}(\ell)\right\rangle}{\left\langle \overline{\mathbf{B}}\cdot\overline{\mathbf{B}}(0)\right\rangle} \Leftarrow$$

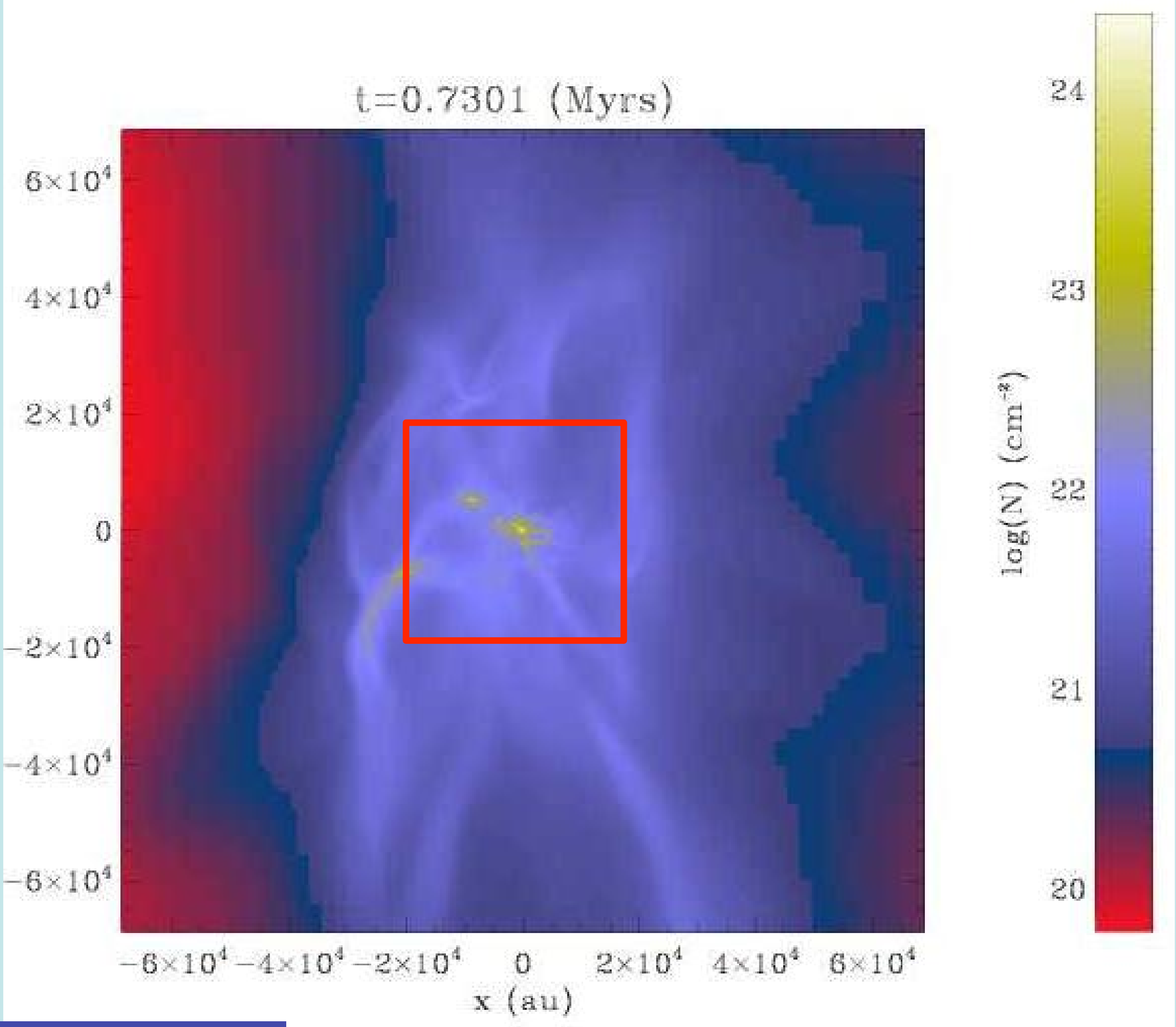
With a Fourier transform on the turbulent component

$$\frac{\left\langle \overline{\mathbf{B}}\cdot\overline{\mathbf{B}}(\ell)\right\rangle}{\left\langle \overline{B}^2\right\rangle} \rightleftharpoons \frac{1}{\left\langle \overline{B}^2\right\rangle}\left\|H\left(k_v\right)\right\|^2 R_{\mathrm{t}}\left(k_v\right)\left[\equiv b^2\left(k_v\right)\right]$$

We can determine the turbulent power spectrum $R_{\mathrm{t}}\left(k_v\right)$

by deconvolution of the beam $H\left(k_v\right)$

Turbulent Power Spectrum - simulations

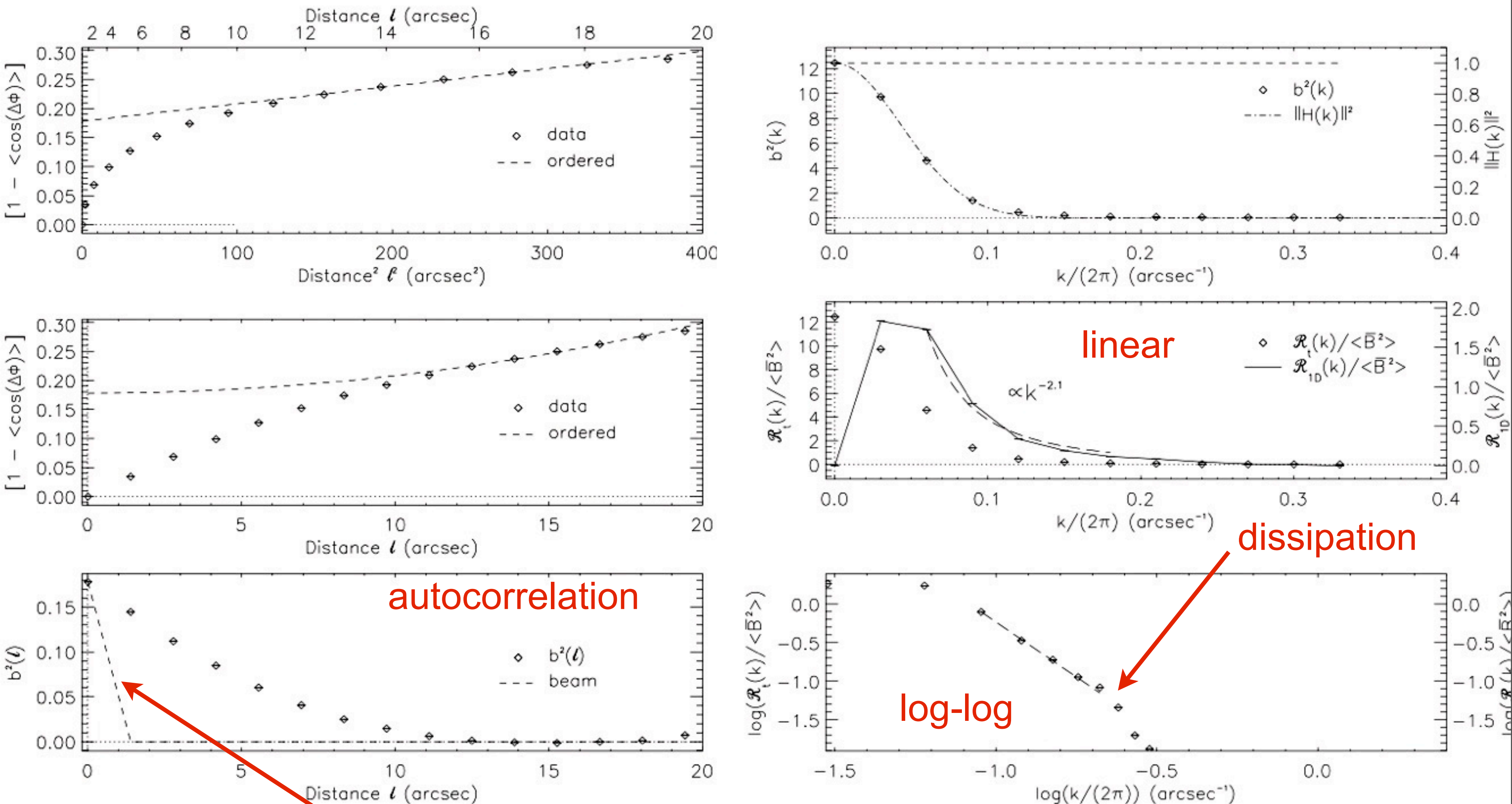


Hennebelle et al. 2011, A&A, 528, 72

Turbulent Power Spectrum - simulations

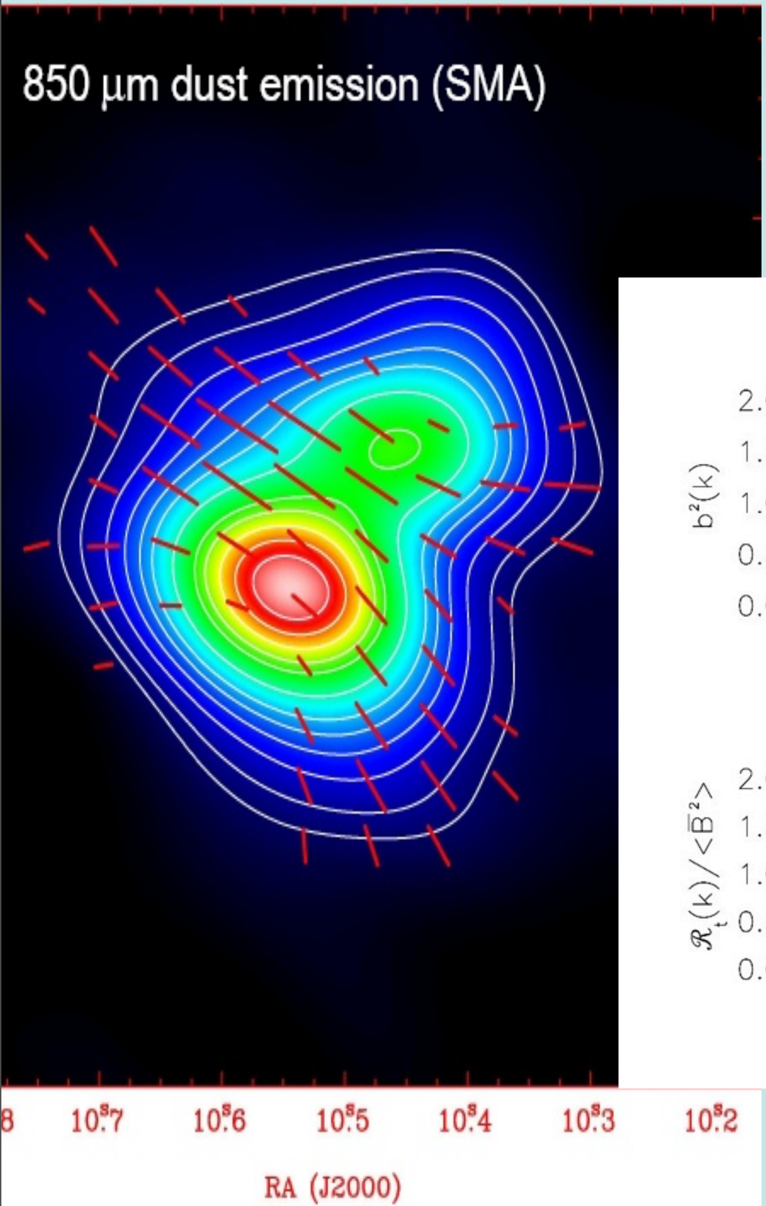
Structure Function

Power Spectrum



beam

Turbulent Power Spectrum - NGC 1333/SMA

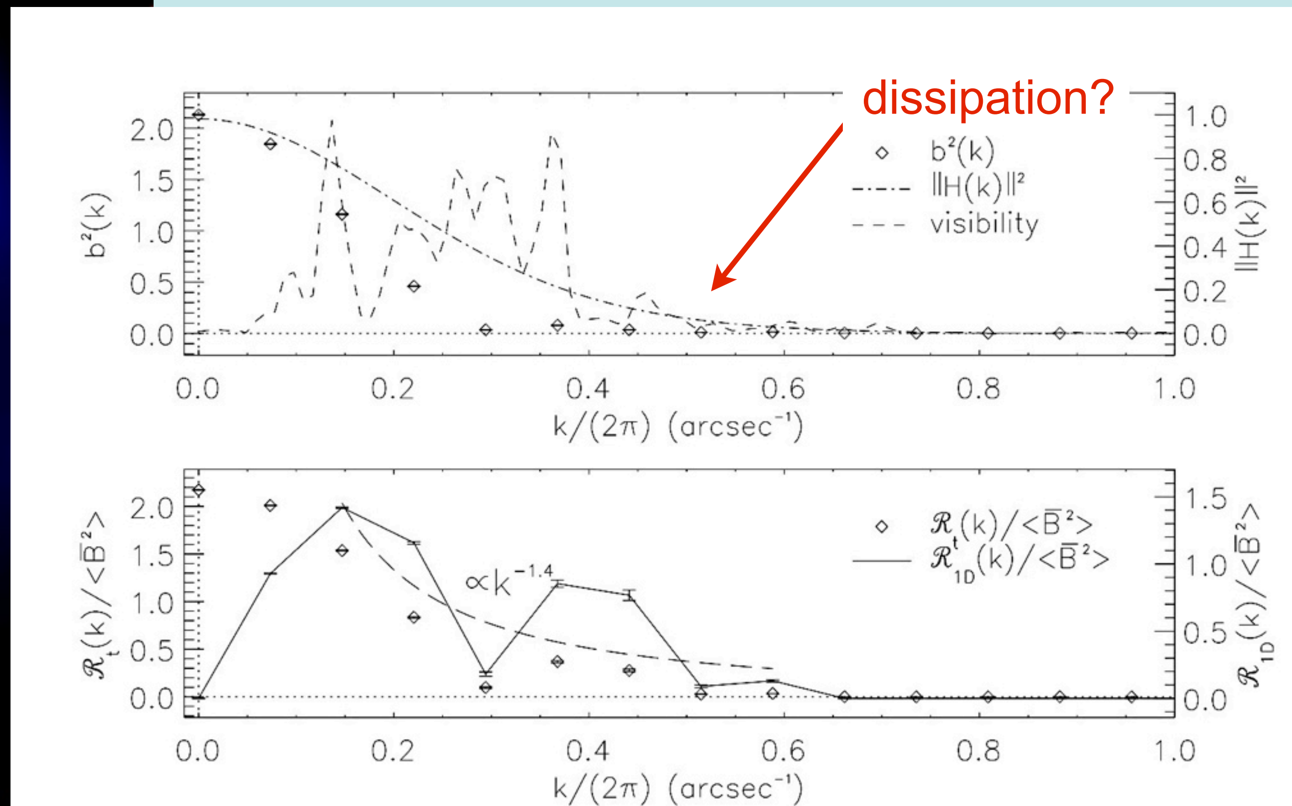


Girart, Rao, and Marrone (2006)

B-vectors

beam: 1.6”x 1.0”

sampling: 0.2”



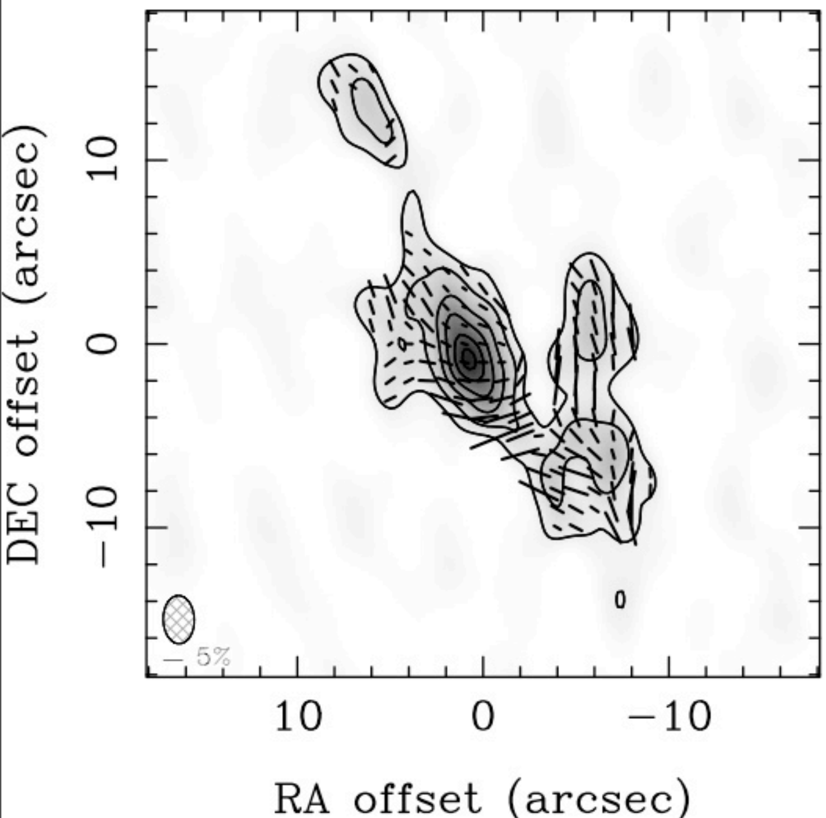
Houde et al. 2011

Turbulent Power Spectrum - Orion KL/SMA

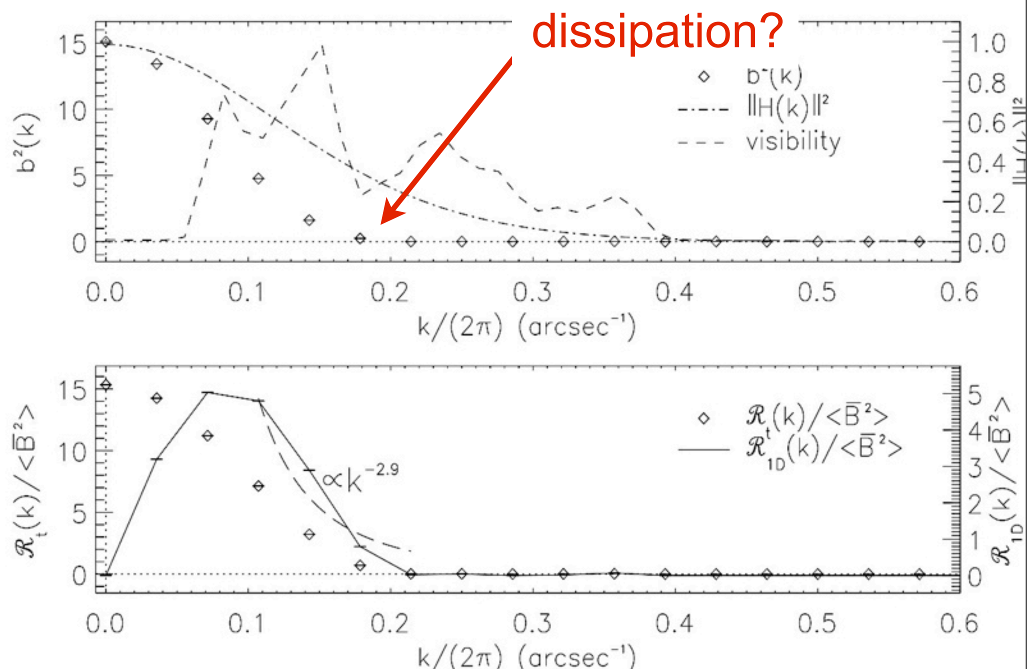
B-vectors

beam: 2.6”x 1.7”

sampling: 0.25”

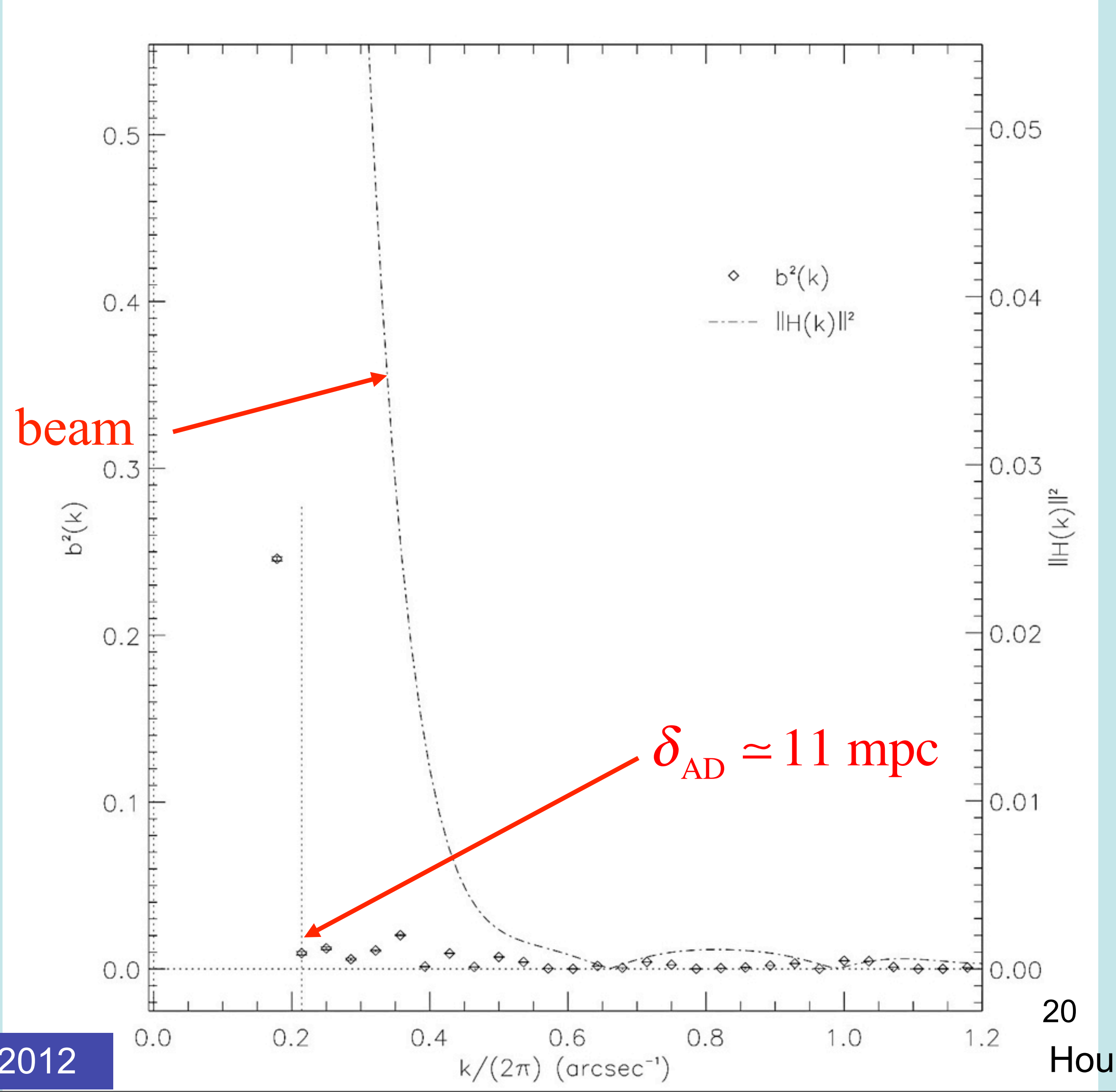


Tang et al. 2010



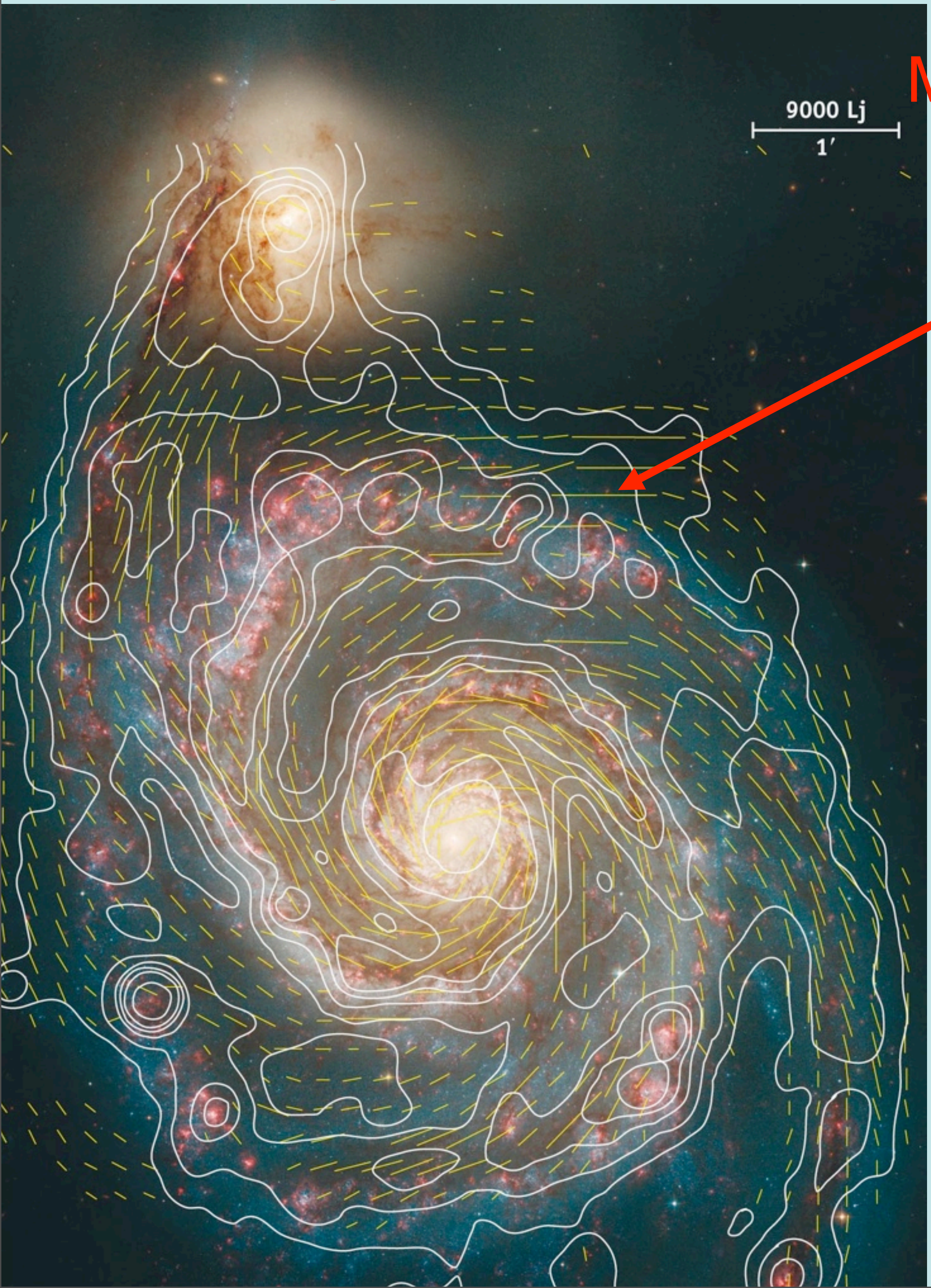
Houde et al. 2011

Ambipolar Diffusion - Orion KL/SMA



Houde et al. 2011

Magnetized Turbulence in Galaxies



M51 with Effelsberg (100m) + VLA

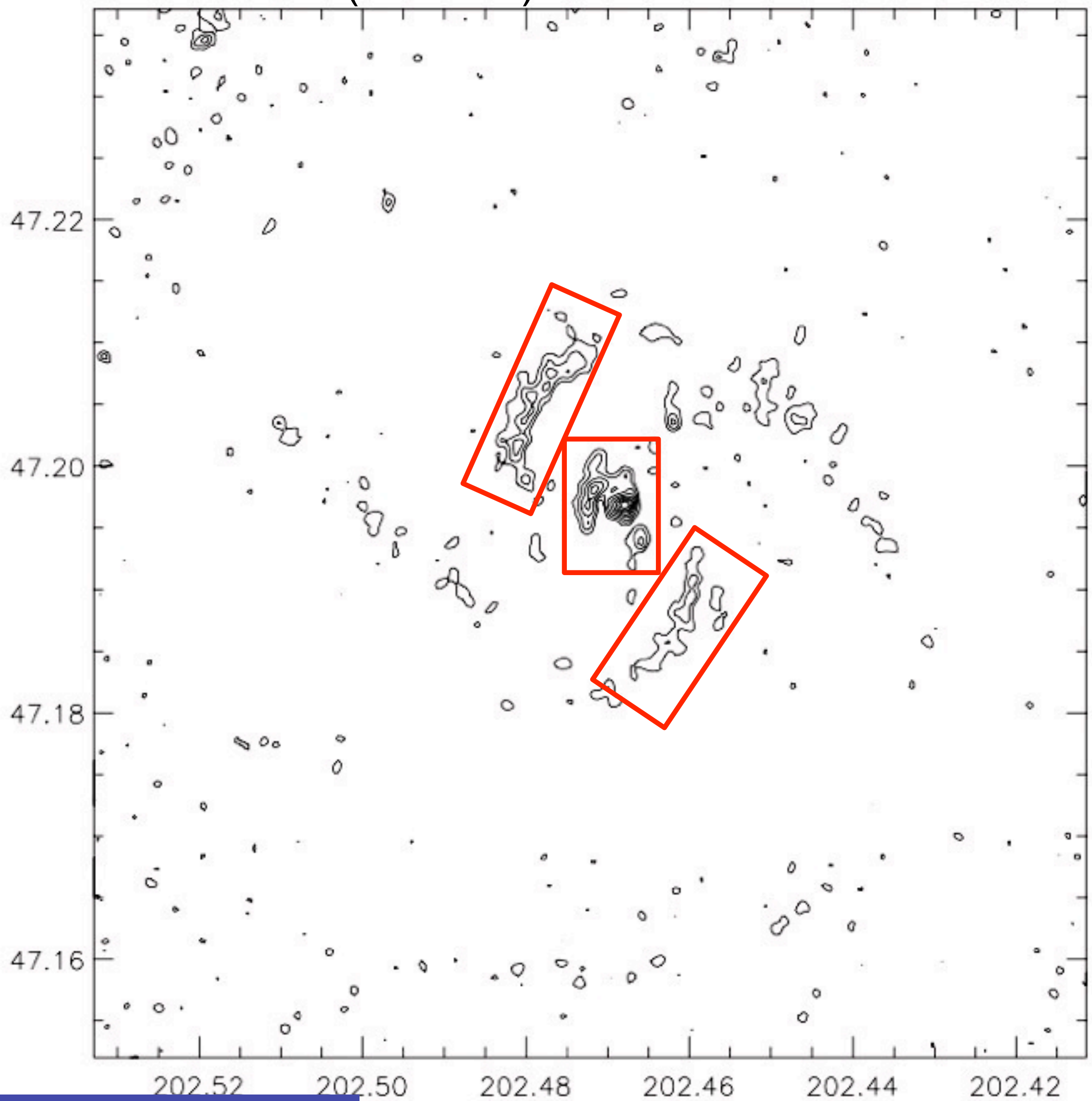
ordered + turbulent fields

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

Fletcher et al. 2011 (MNRAS)

M51 - Polarized Flux

Fletcher et al. 2011 (MNRAS)



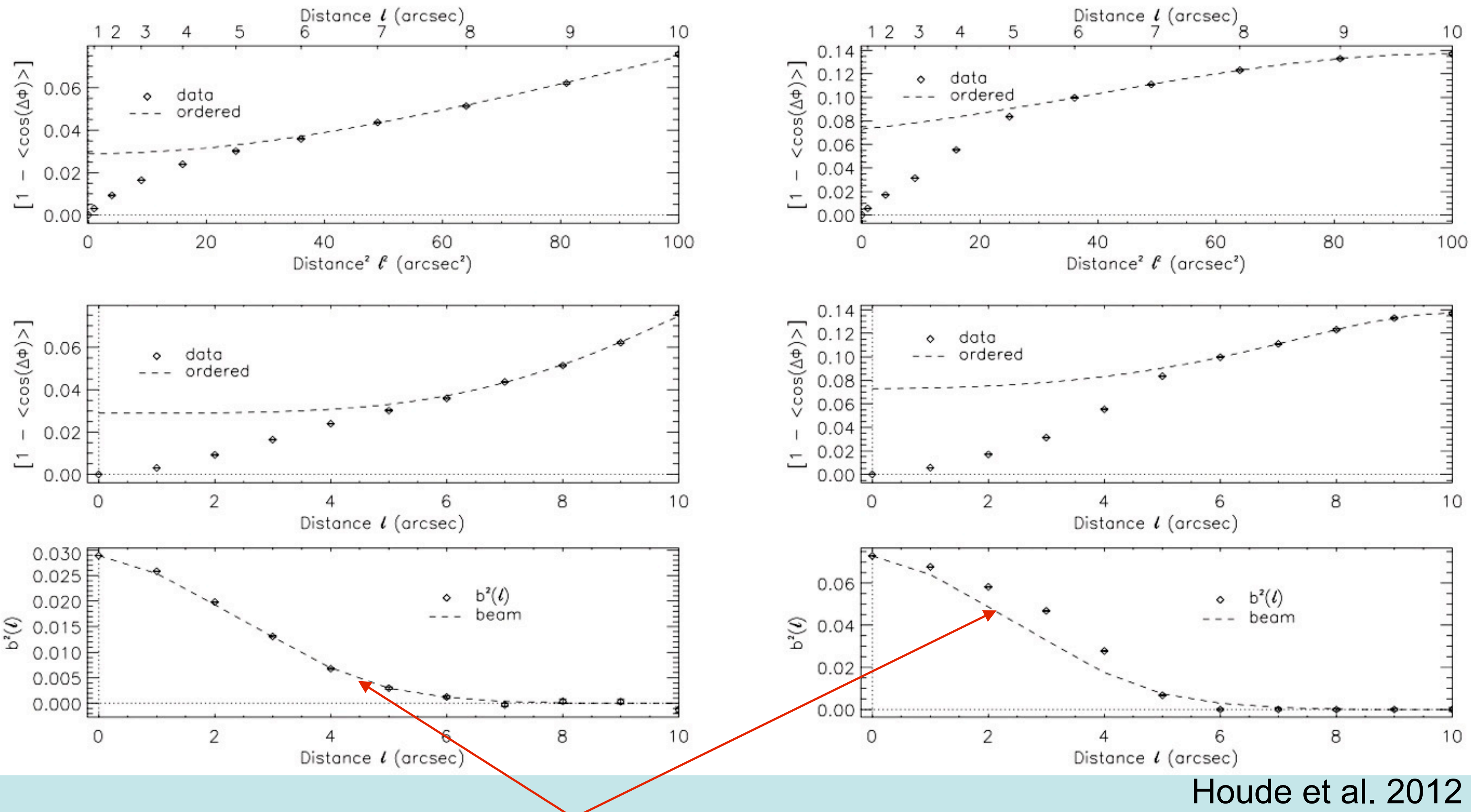
Houde et al. 2012

d = 7.6 Mpc
1" = 37 pc
λ = 6.2 cm
4" beam
1" sampling

M51 - Structure Functions

Northeast

Southwest



beam

Houde et al. 2012

M51- Isotropic Turbulence

	Northeast	Centre	Southwest
δ (pc)	$\cdots$	67 ± 7	66 ± 8
N	$\cdots$	13 ± 3	14 ± 4
$\overline{B}_{\mathrm{t}}^2 / \overline{B}^2$	0.028 ± 0.002	0.088 ± 0.026	0.072 ± 0.025
B_{t}^2 / B_0^2	$\cdots$	1.28 ± 0.29	1.08 ± 0.29
B_{t} / B_0	$\cdots$	1.13 ± 0.13	1.04 ± 0.14

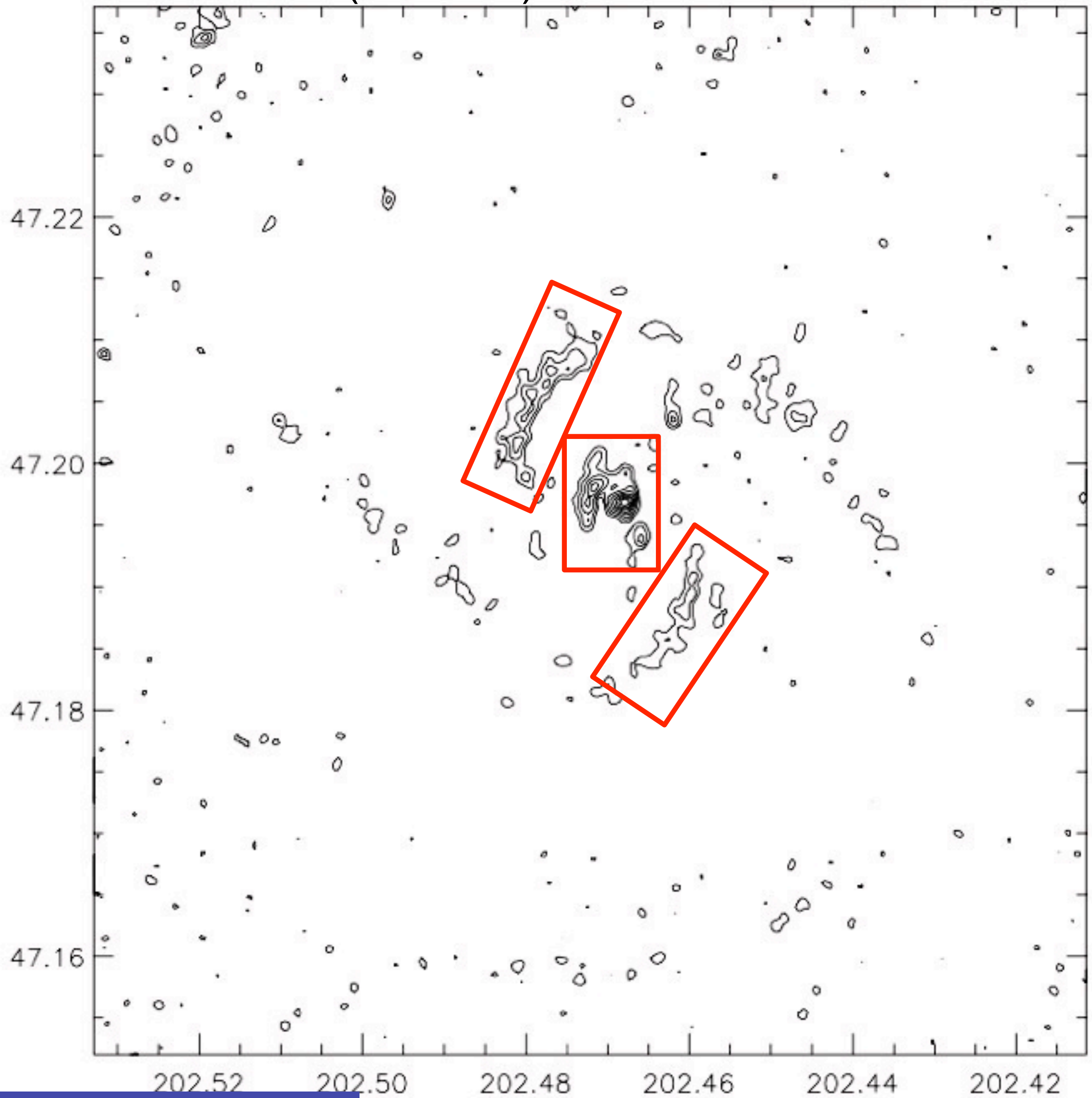
From σ_{RM} analysis, Fletcher et al. get

$$\delta \simeq 50 \text{ pc} \quad \text{and} \quad \frac{B_{\mathrm{t}}}{B_0} \simeq 1.2 - 1.5$$

Houde et al. 2012

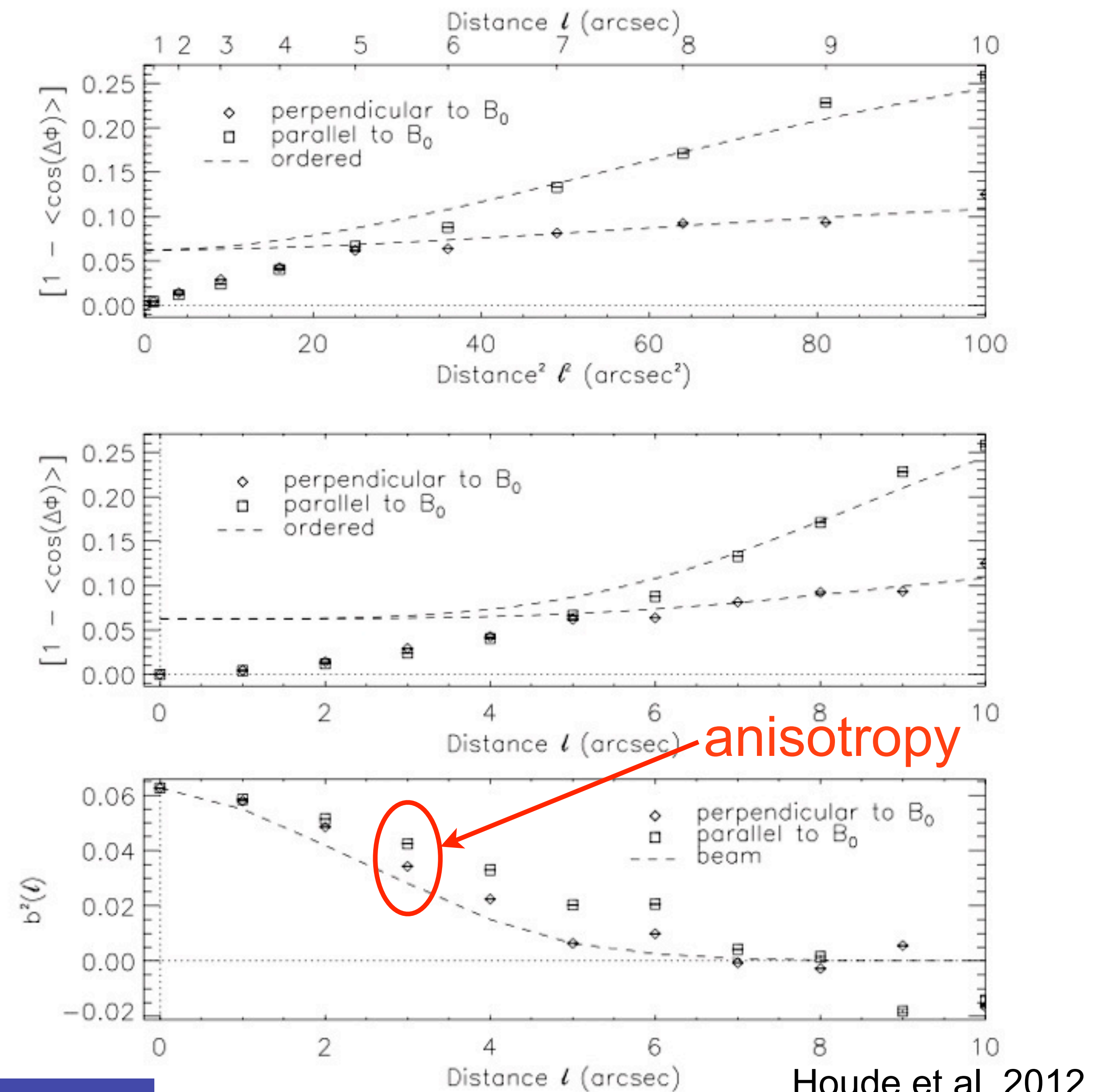
M51- Anisotropic Turbulence

Fletcher et al. 2011 (MNRAS)



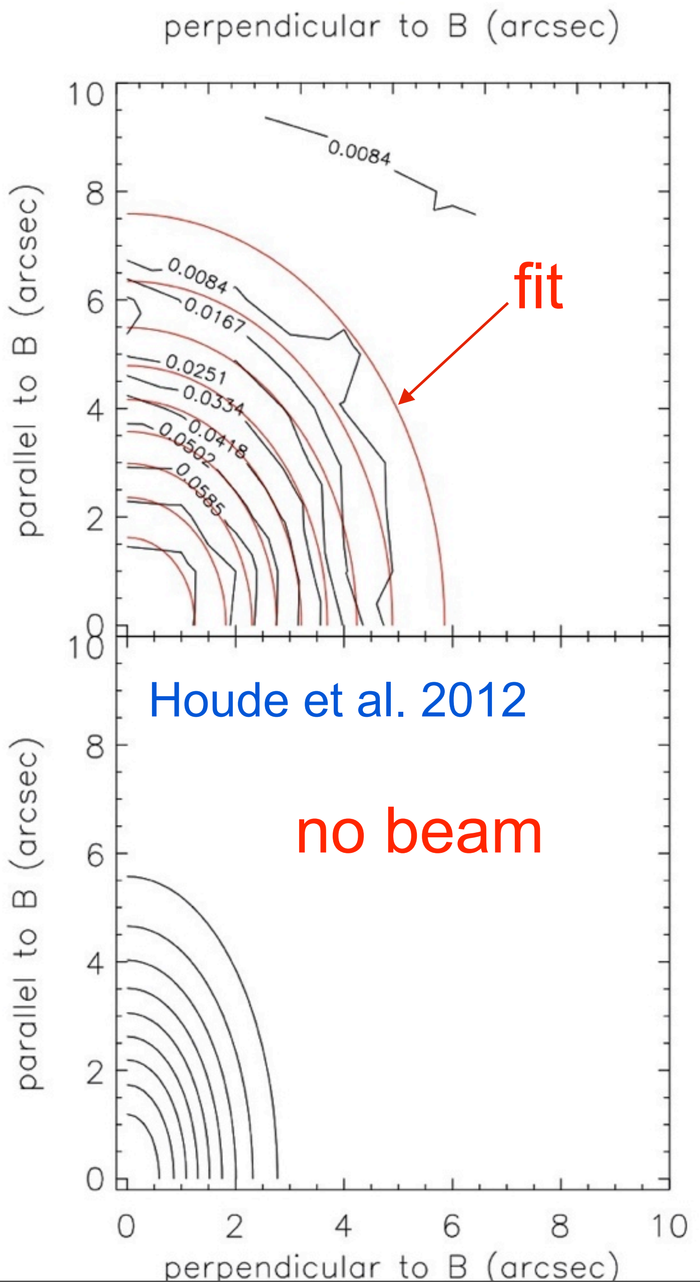
Consider all three regions at once
➔ more vectors

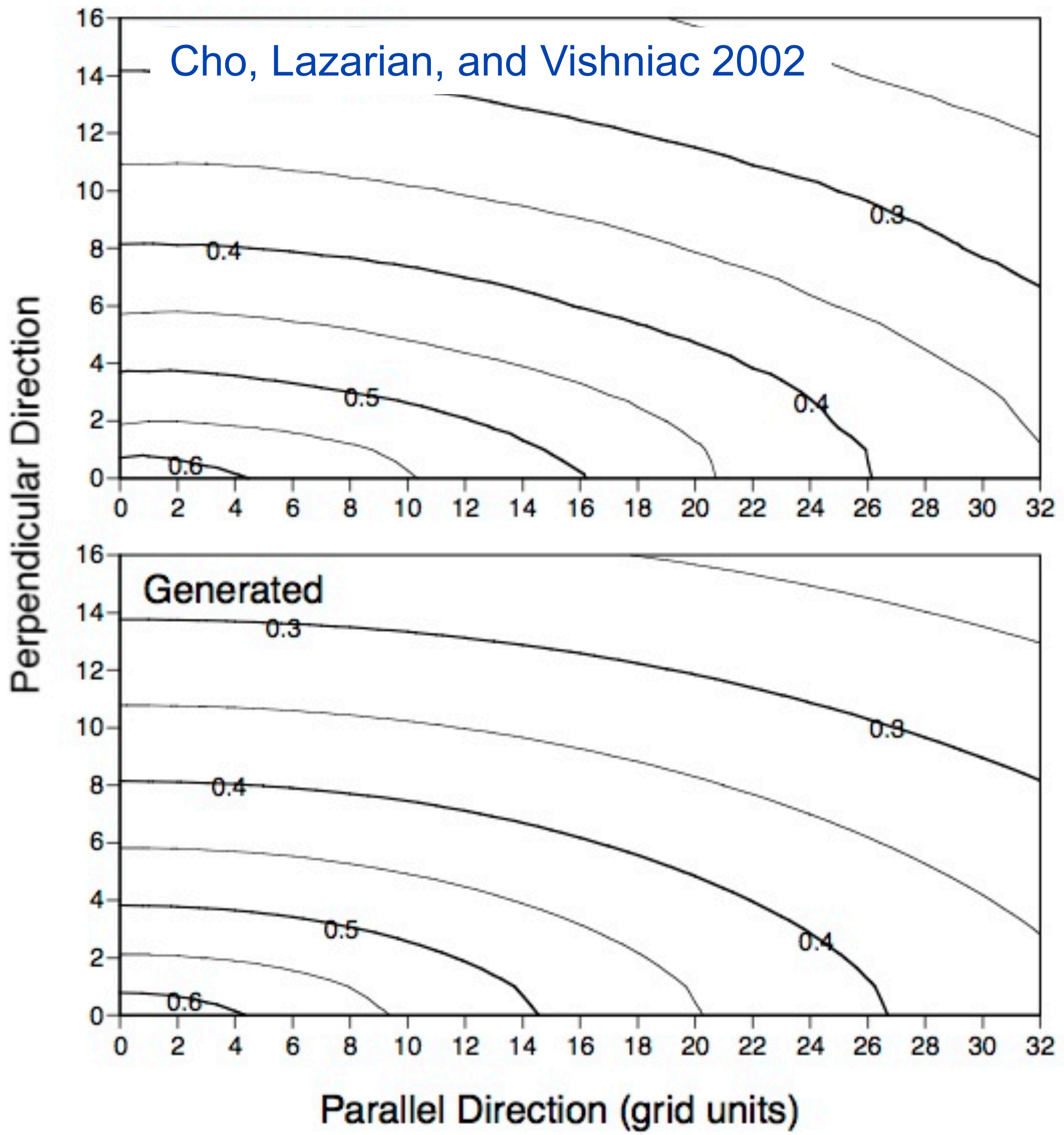
M51- Anisotropic Turbulence



Houde et al. 2012

M51- Anisotropic Turbulence





M51- Anisotropic Turbulence

$$\delta_{\parallel} \simeq 98 \pm 5 \text{ pc}$$

$$\delta_{\perp} \simeq 54 \pm 3 \text{ pc}$$

$$\delta_{\parallel} / \delta_{\perp} \simeq 1.87 \pm 0.14$$

$$N \simeq 15 \pm 2$$

$$\overline{B}_{\mathrm{t}}^2 / \overline{B}_0^2 \simeq 0.06 \pm 0.01$$

$$B_{\mathrm{t}}^2 / B_0^2 \simeq 1.02 \pm 0.08$$

$$B_{\mathrm{t}} / B_0 \simeq 1.01 \pm 0.04$$

Houde et al. 2012

Summary

- Angular dispersion function allows the separation of the turbulent and ordered components of the magnetic field without assuming any model for the latter.
- We can also account for the signal integration process along the line of sight and across the telescope beam.
- With high-enough resolution data → determination of the magnetized turbulent power spectrum (e.g., correlation length, inertial range index, dissipation scale).
- But we need even higher resolution (ALMA) and "larger" single-dish observatories, as well as an increase in the number of "vectors" (SOFIA and CCAT) for anisotropy measurements.

Merci!

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