Characterizing Magnetized Turbulence with Polarization Maps

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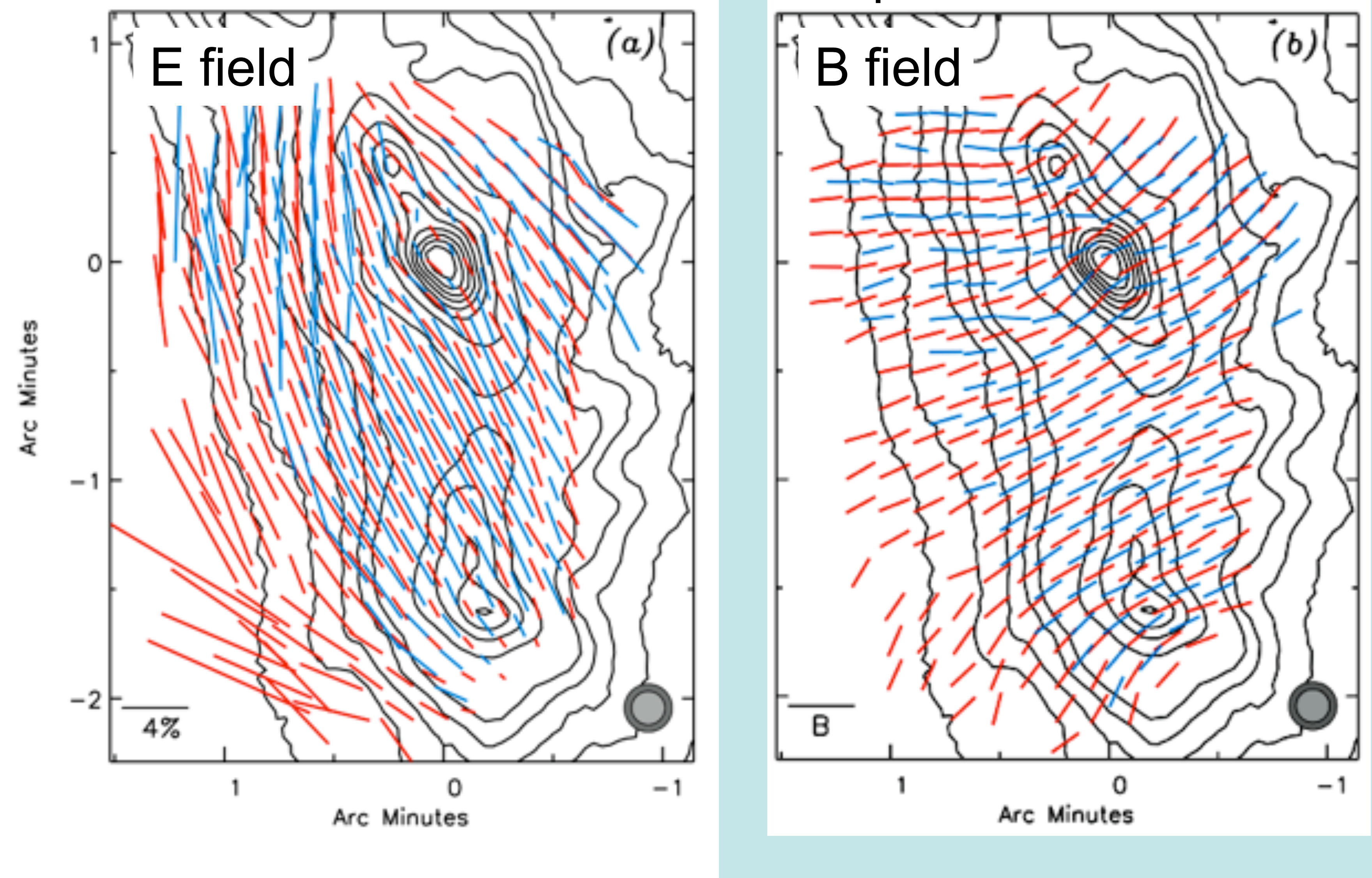
Outline

- 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 - CARMA
    - Magnetized turbulent power spectrum
    - Ambipolar diffusion scale
  - Single-dish + Interferometry
    - 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

Structure Functions

- Common for studying turbulence

ectra with

some time

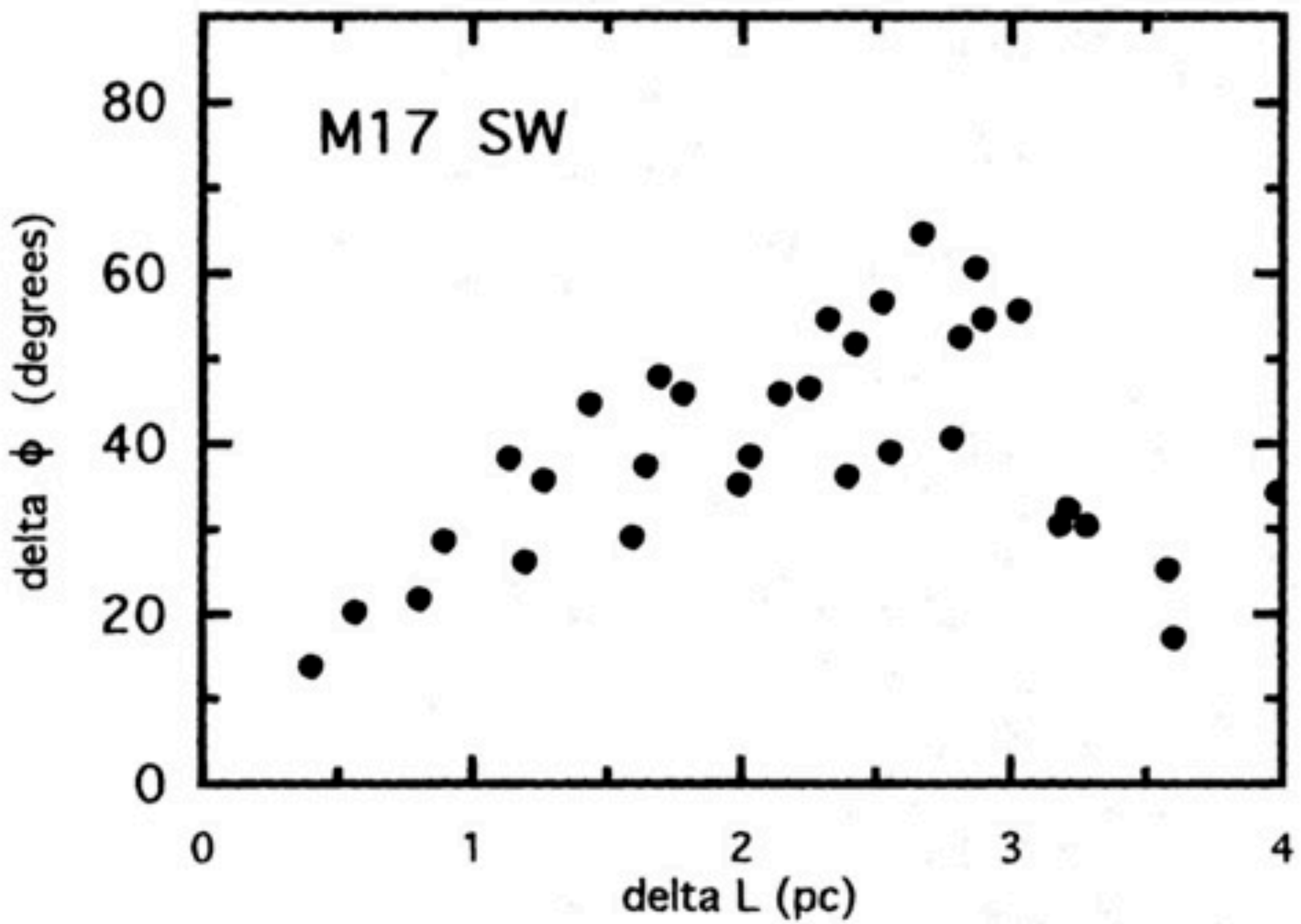


FIG. 9.—Average change in polarization direction between pairs of measurements plotted against the distance between the pairs of measurements. Measurements are taken only from the southwest portion of the cloud.

Dotson (1996, ApJ, 470, 566)

Structure Functions

- Common for studying

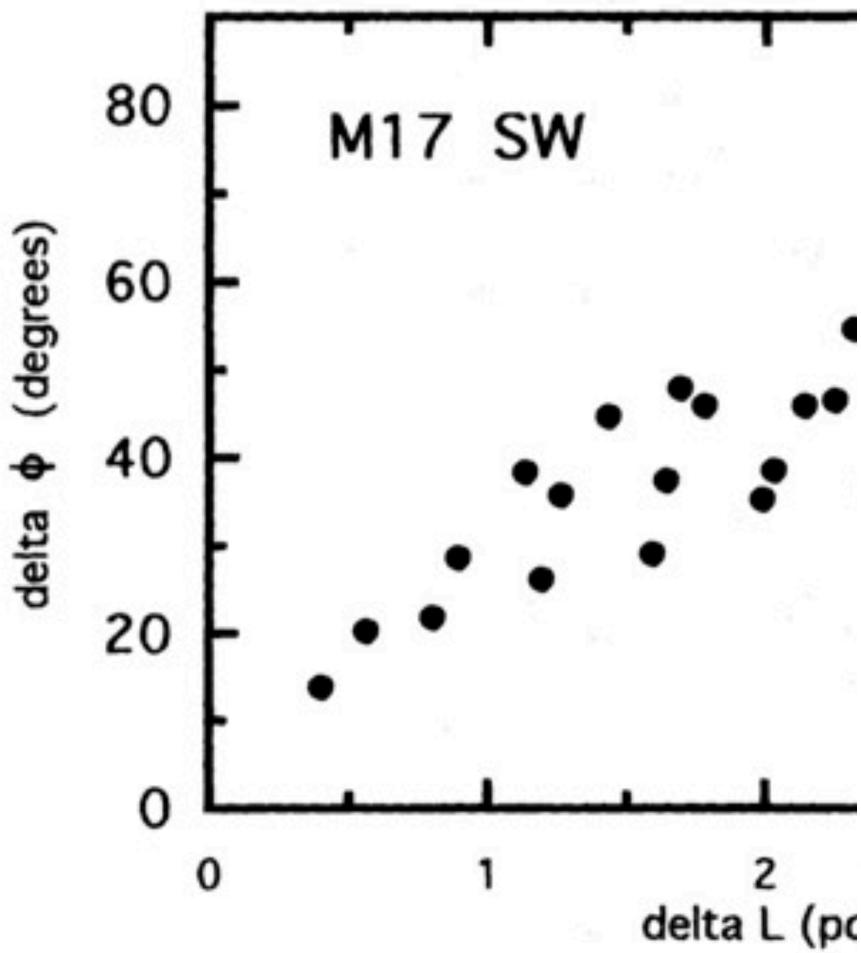


FIG. 9.—Average change in polarization
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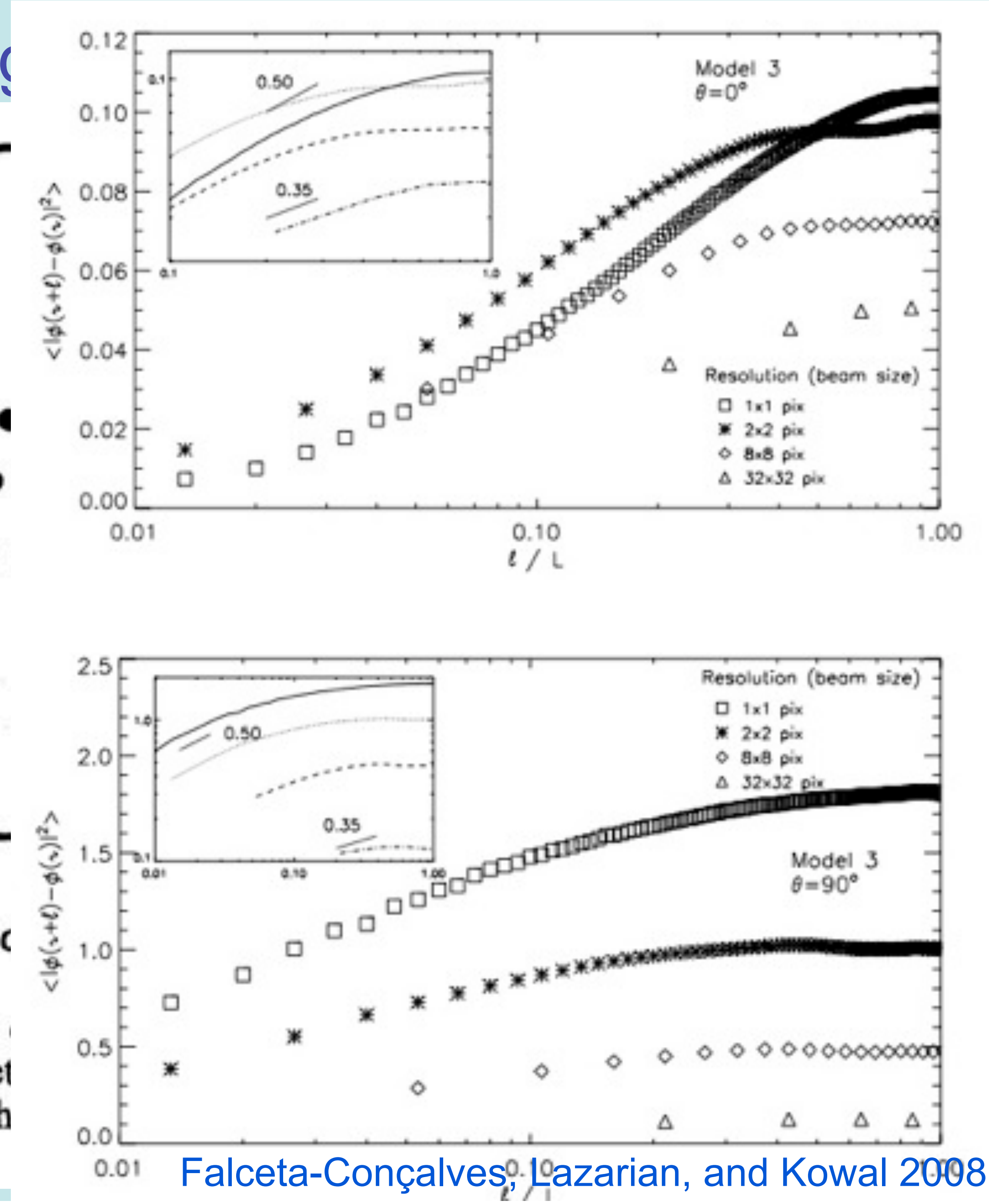
cloud.

Dotson (1996, ApJ, 470, 566)



Falceta-Gonçalves, Lazarian, and Kowal 2008

Structure Functions

Given a polarization map

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

The Angular Structure Function (stationarity and isotropy)

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

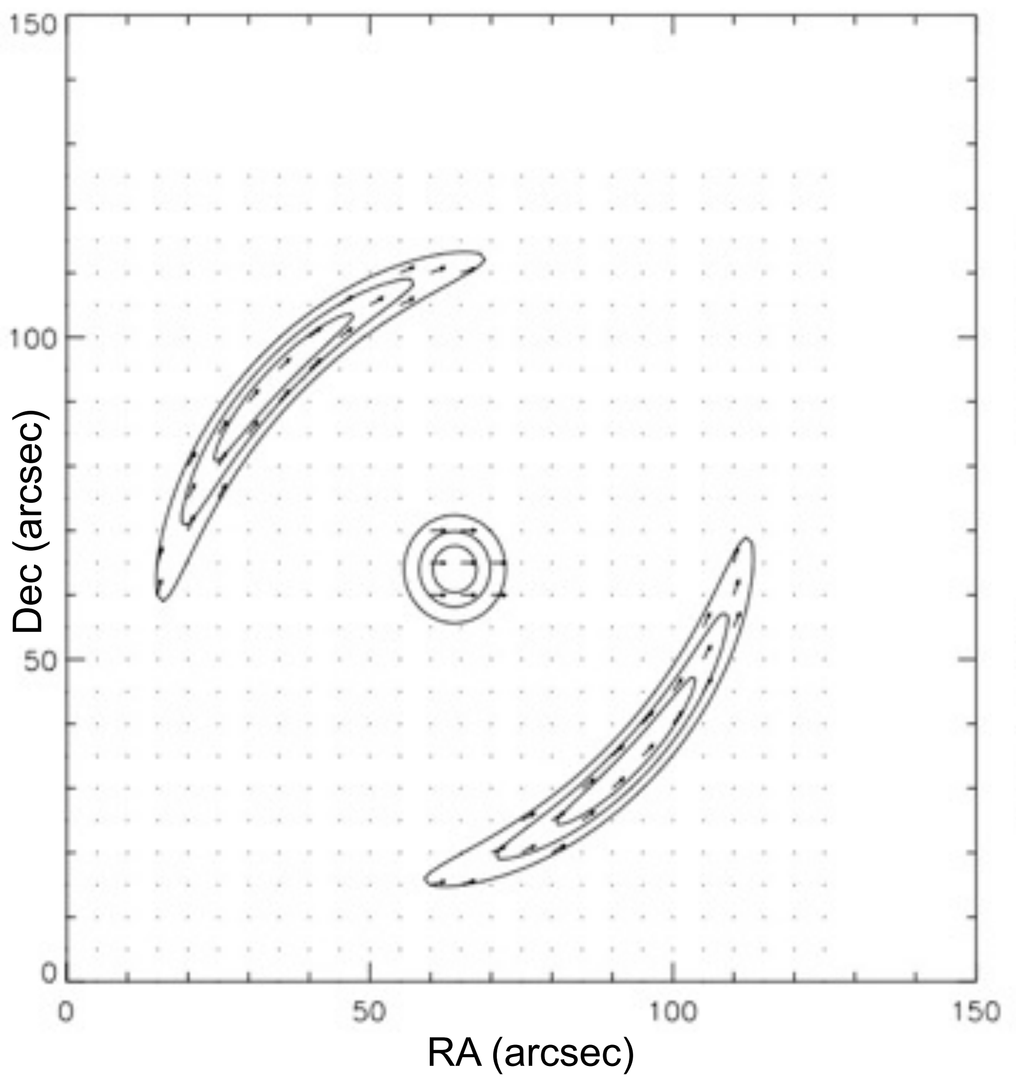
If $\mathbf{B} = \mathbf{B}_{\mathrm{t}} + \mathbf{B}_0$ (turbulent and ordered (large-scale) components)

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

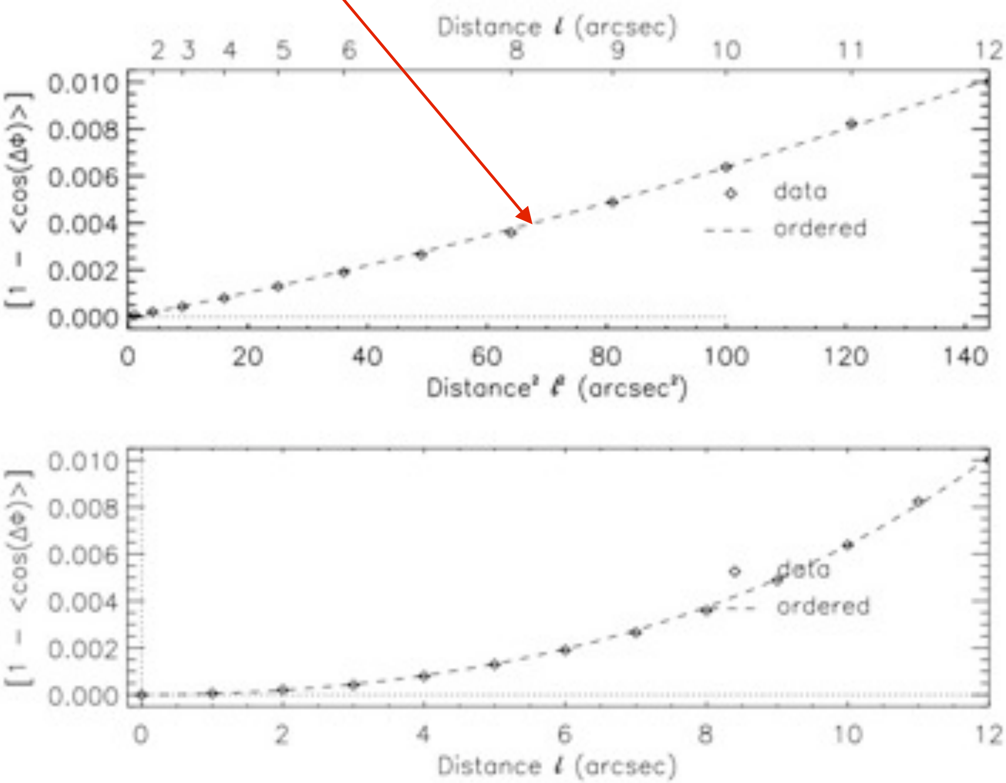
with statistical independence.

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

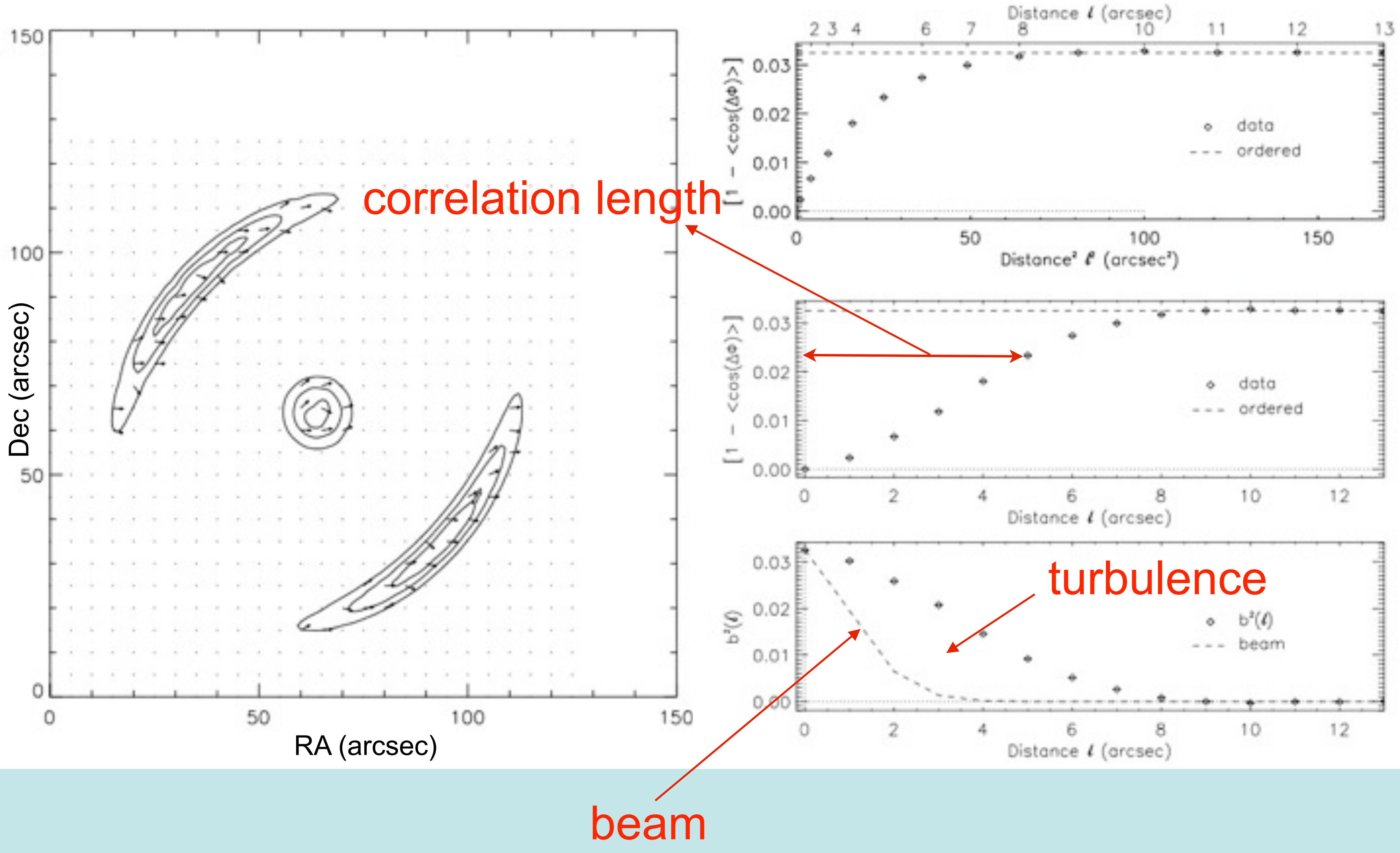
Structure Functions - Large-scale



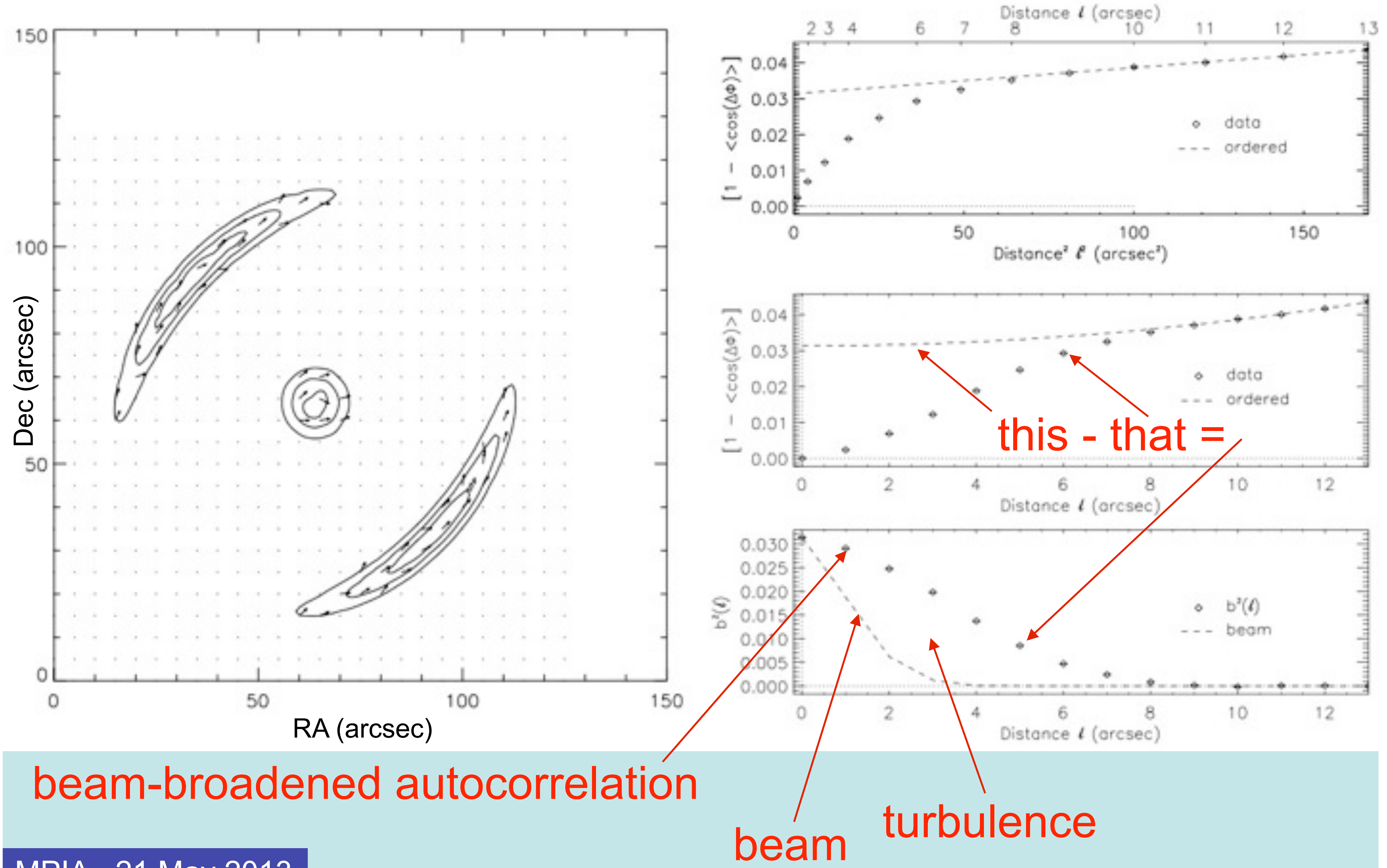
polynomial fit



Structure Functions - Turbulence



Structure Functions - Turb.+large-scale



Example - Chandra-Fermi Equation

turbulent

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

ordered field

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

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

Example - Chandra-Fermi Equation

Problems with the CF method

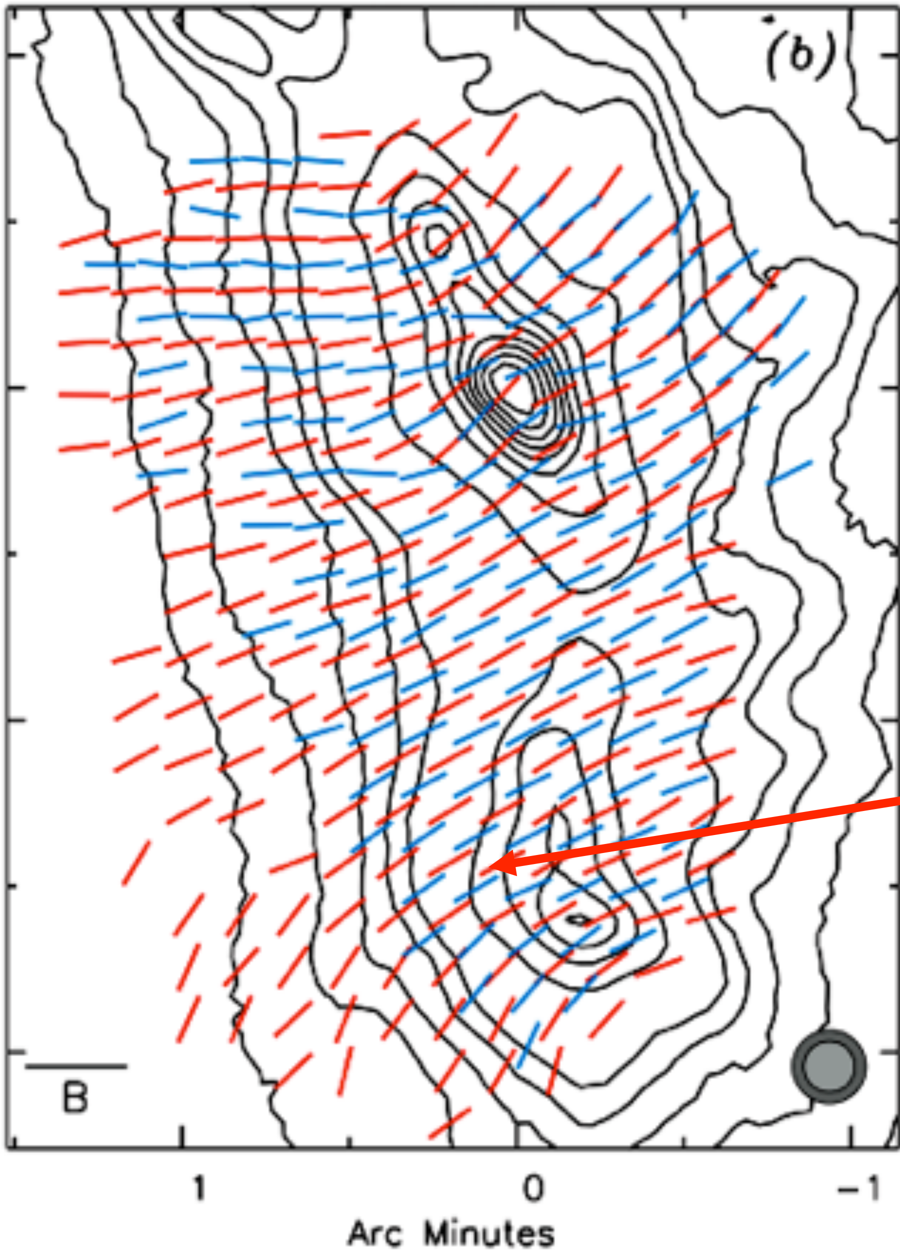
1. The models for $\mathbf{B}_0$ are imperfect and introduce more errors in the determination of $\delta\Phi$. This is solved with the structure function.

Moreover

2. Signal integration along the line of sight and across the telescope beam
   - $\left\langle \mathbf{B}_t^2 \right\rangle$ 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



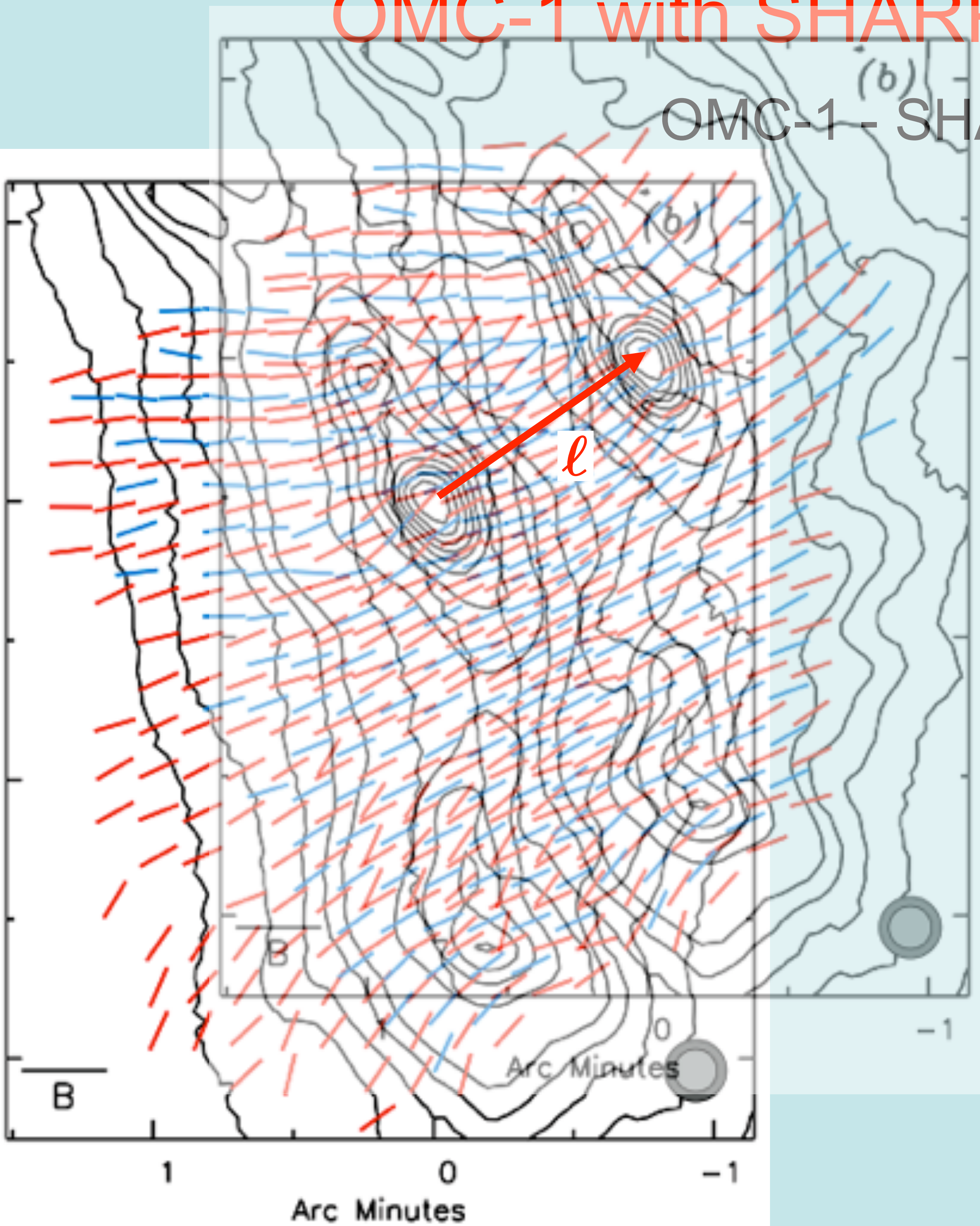
ordered + turbulent fields

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

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

OMC-1 with SHARP at 350 μm

OMC-1 - SHARP/CSO, 350 and 450 μm



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

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

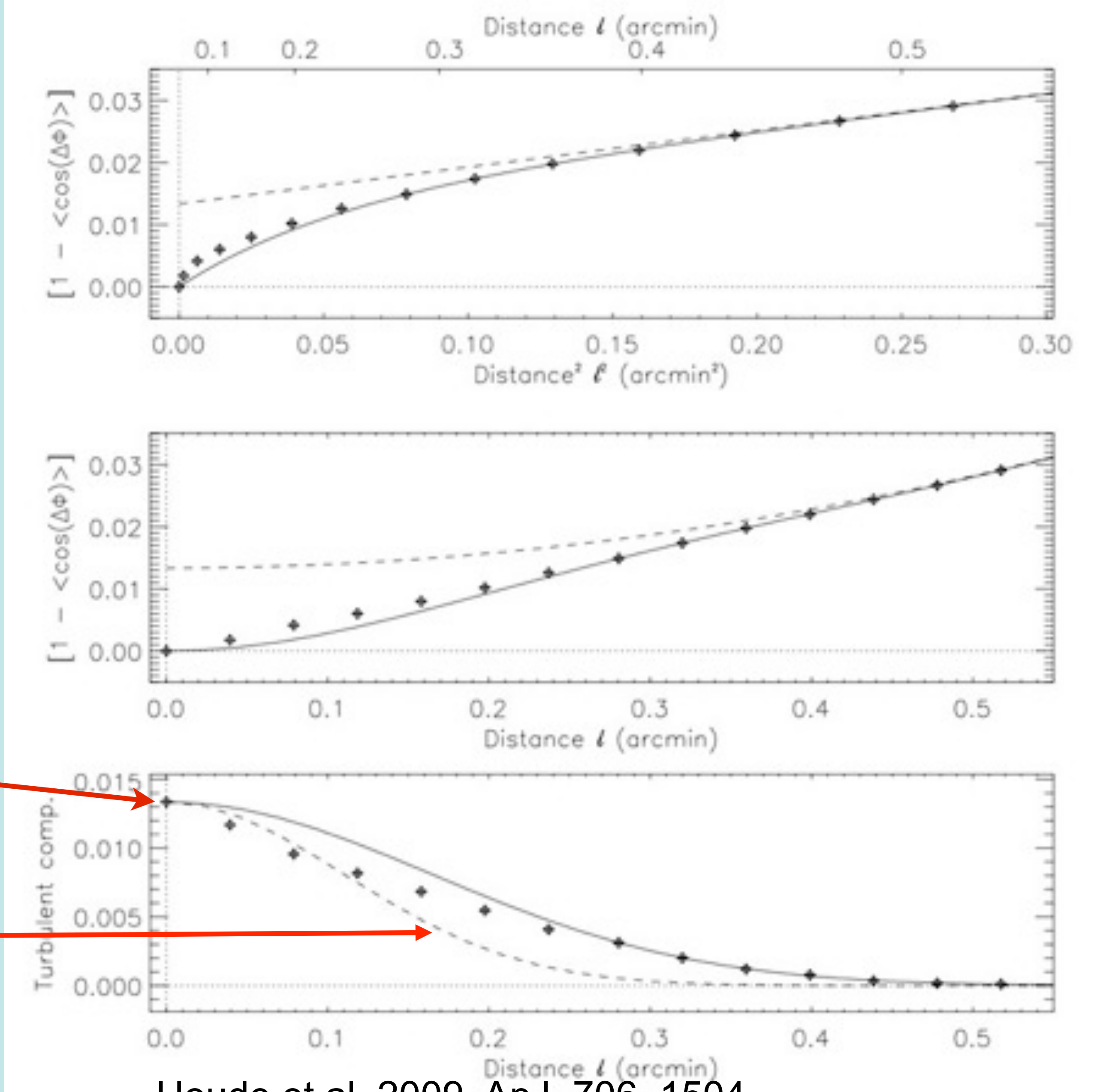
OMC-1 with SHARP at 350 μm

χ^2 fit - Gaussian model:

$\delta, \langle B_t^2 \rangle / \langle B_0^2 \rangle$.

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

beam



Houde et al. 2009, ApJ, 706, 1504

OMC-1 / SHARP - Results

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

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

$$\frac{\left\langle \bar{B}_t^2 \right\rangle}{\left\langle \bar{B}_0^2 \right\rangle} \simeq \frac{1}{N} \frac{\left\langle B_t^2 \right\rangle}{\left\langle B_0^2 \right\rangle} \simeq 0.013$$

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

with Chandrasekhar-Fermi equation

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

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

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

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

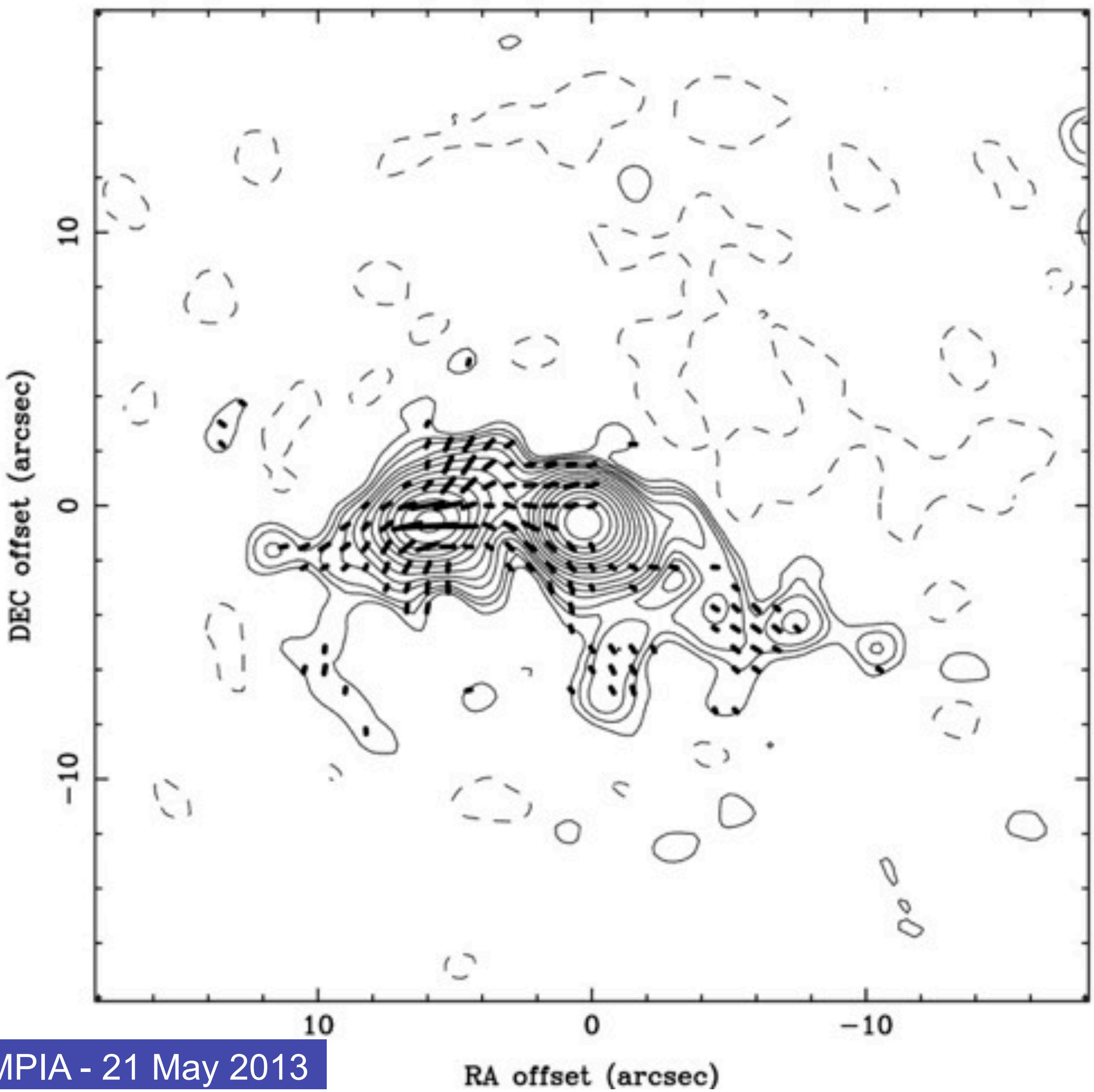
With a Fourier transform on the turbulent component

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

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

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

CARMA / TADPOL



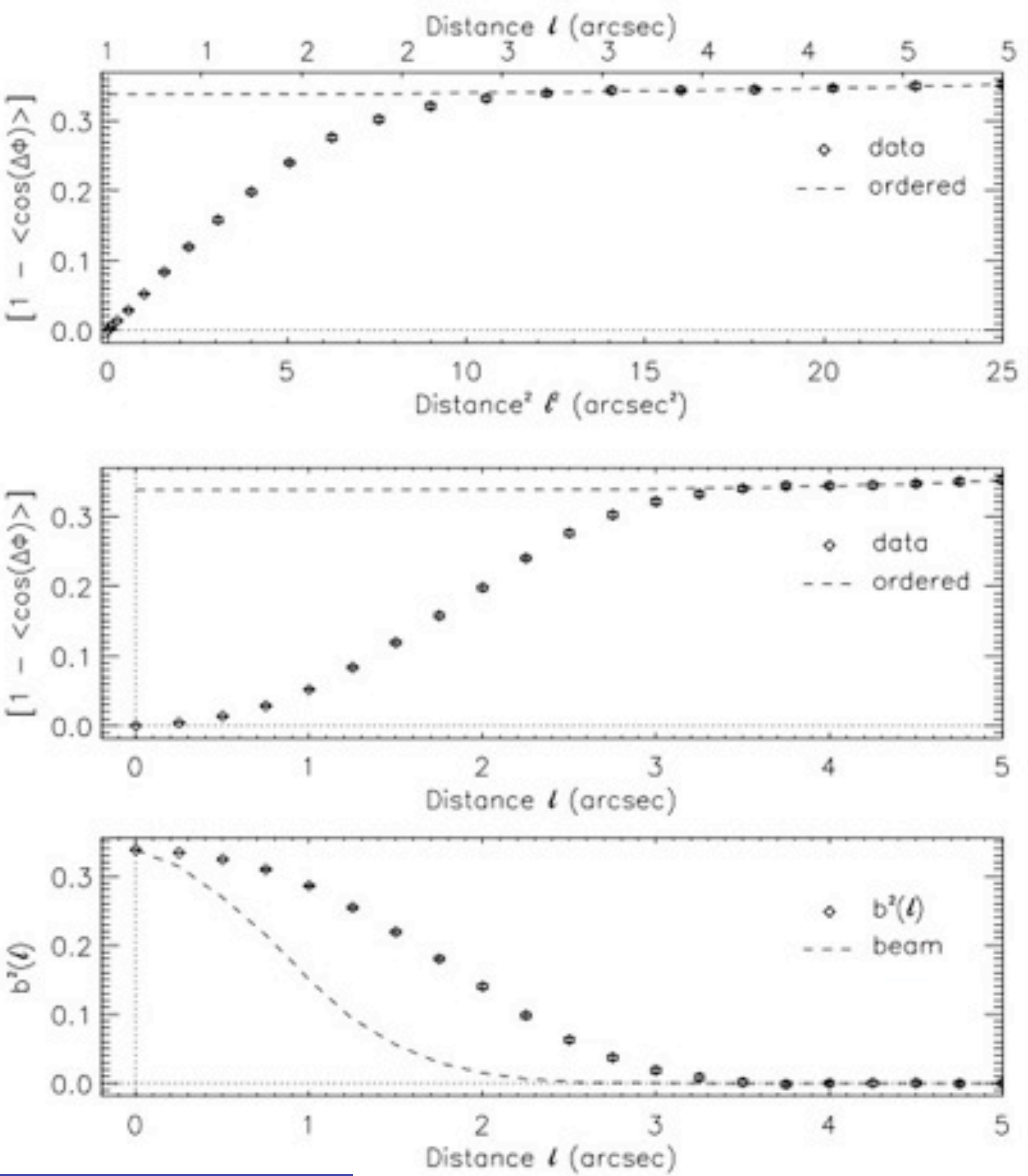
Chat Hull - UC, Berkeley

B-vectors

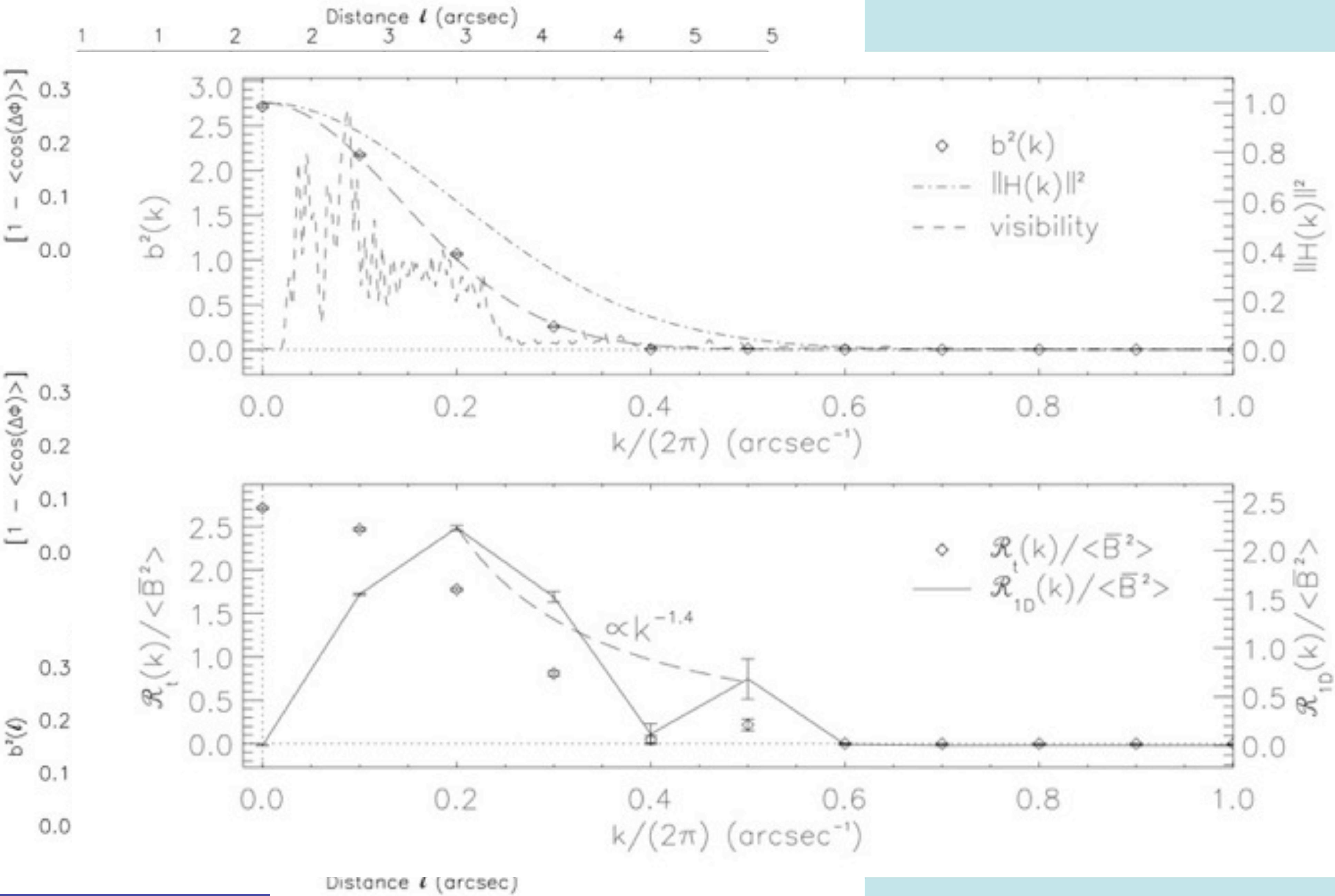
beam: 1.4” x 1.3”

sampling: 0.25”

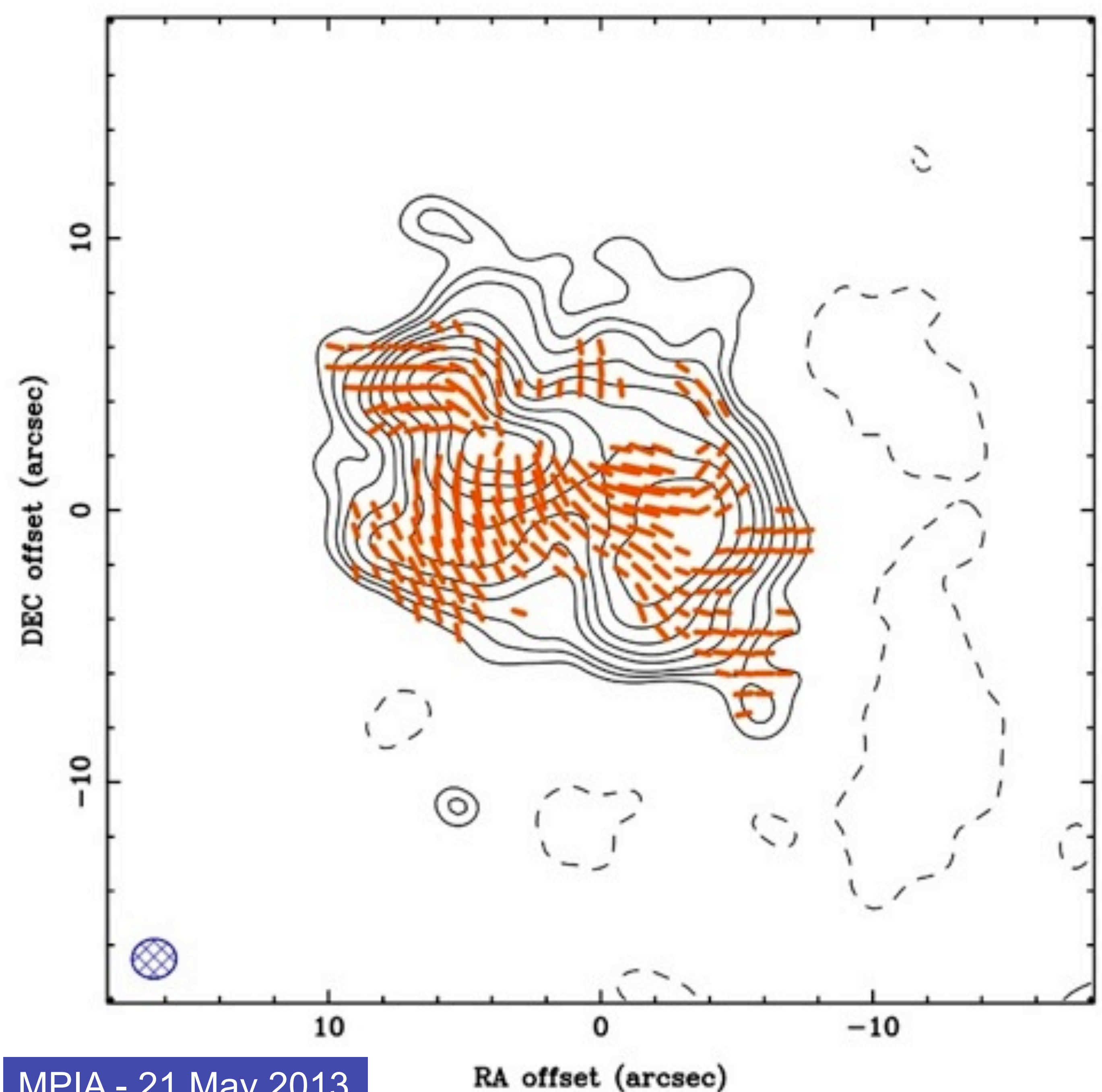
Turbulent Power Spectrum - W3(OH)



Turbulent Power Spectrum - W3(OH)



CARMA / TADPOL - DR21(OH)

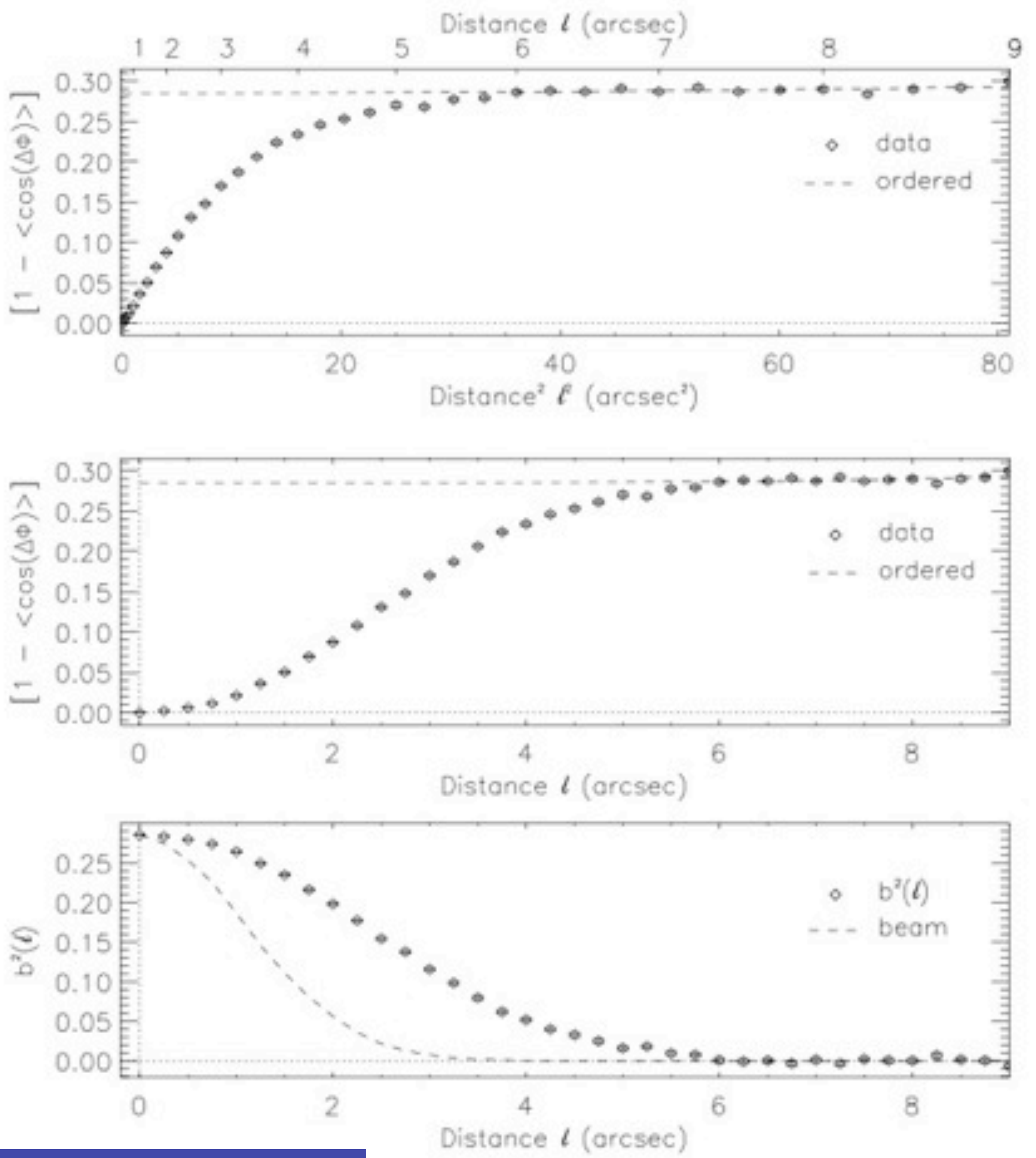


B-vectors

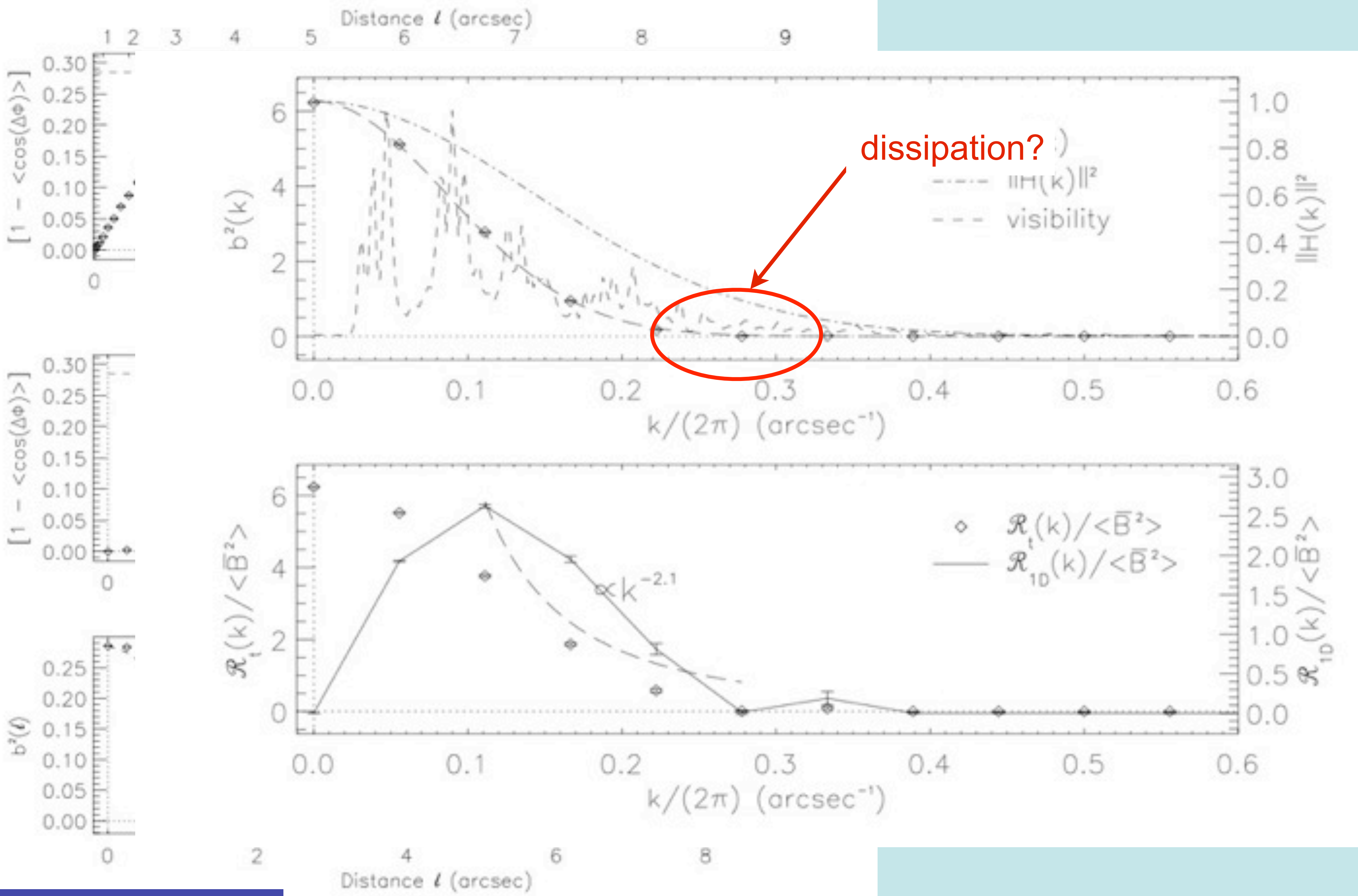
beam: 1.6” x 1.5”

sampling: 0.25”

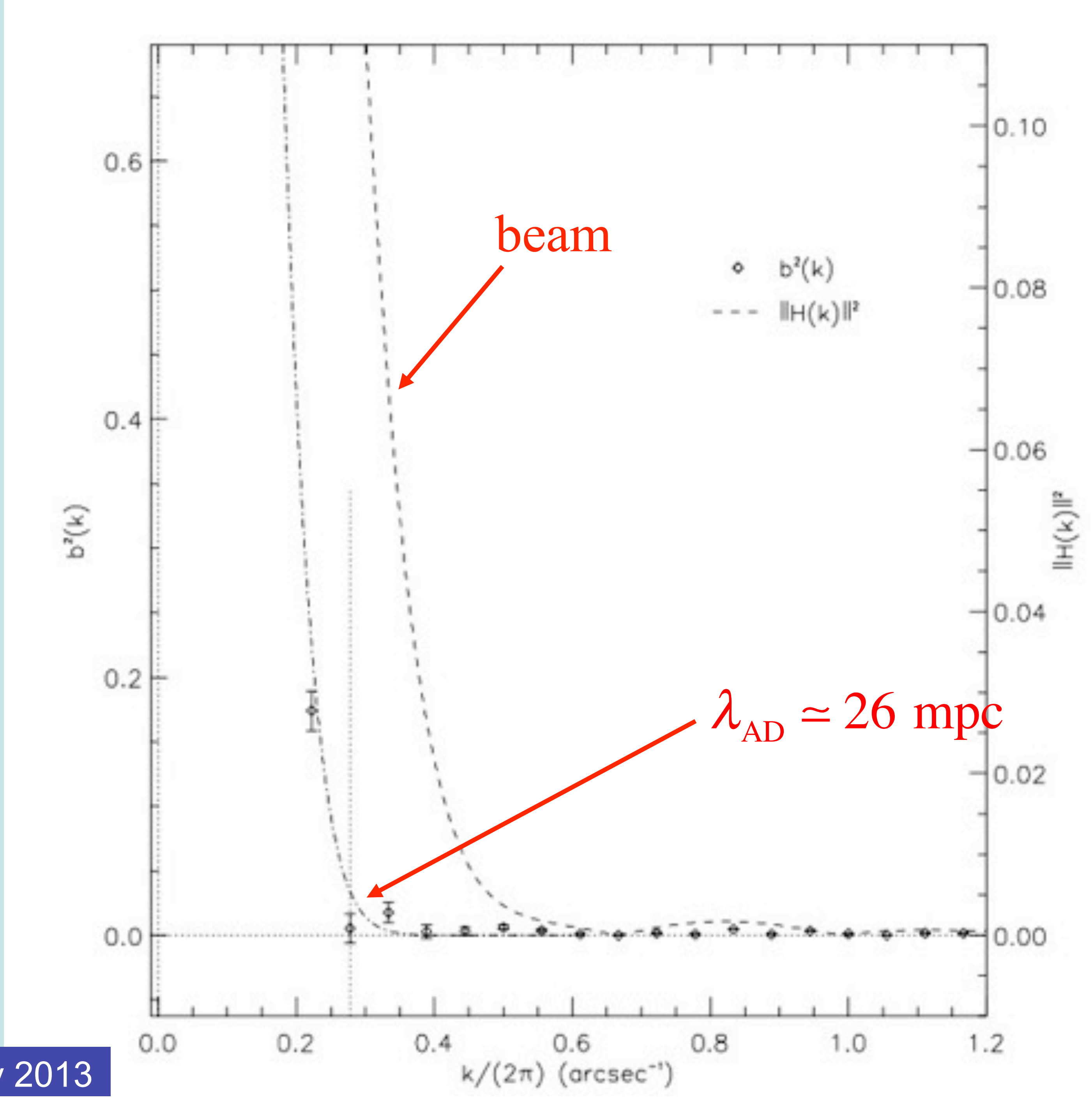
Turbulent Power Spectrum - DR21(OH)



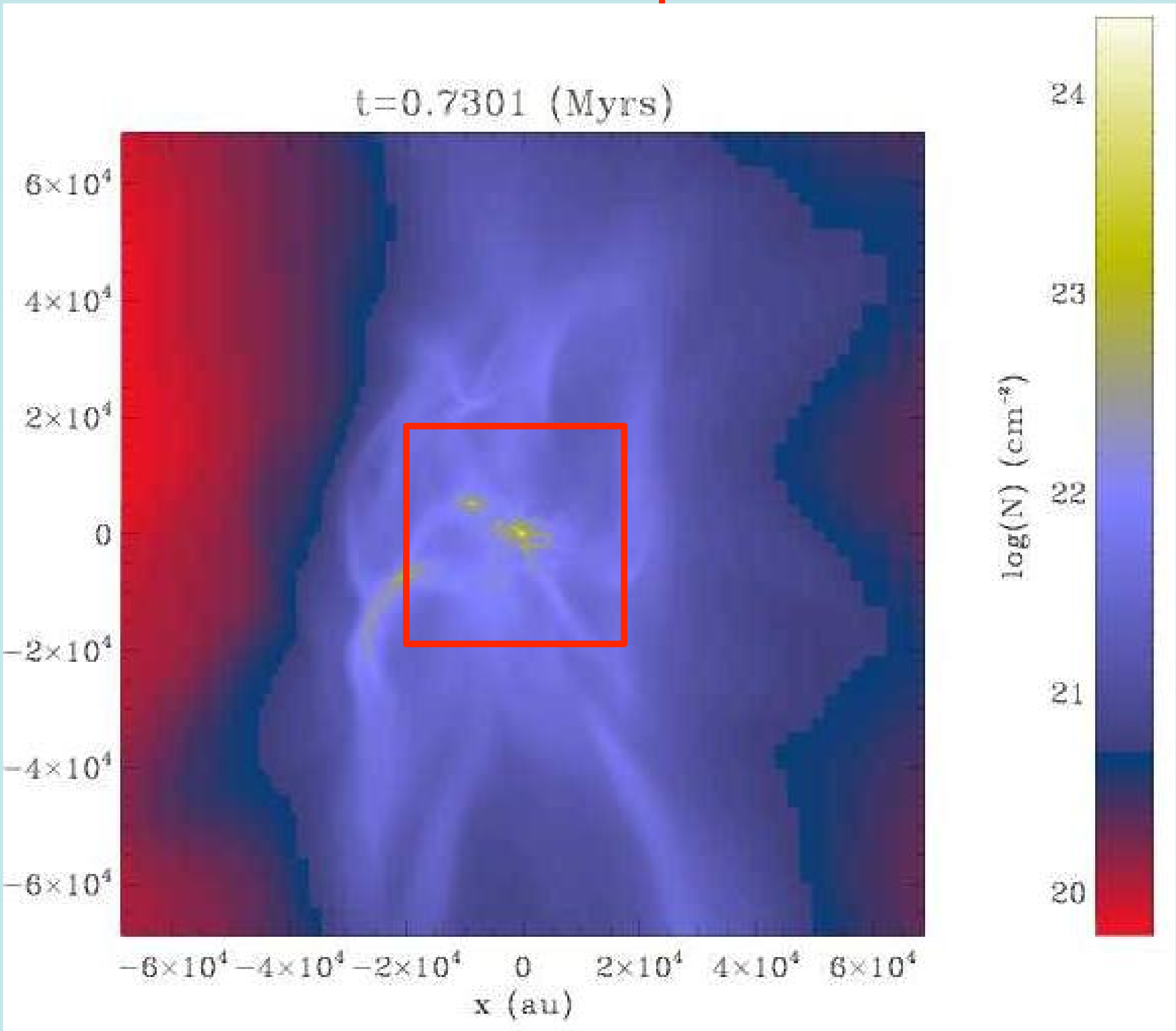
Turbulent Power Spectrum - DR21(OH)



Ambipolar Diffusion - DR21(OH)



Turbulent Power Spectrum - simulations

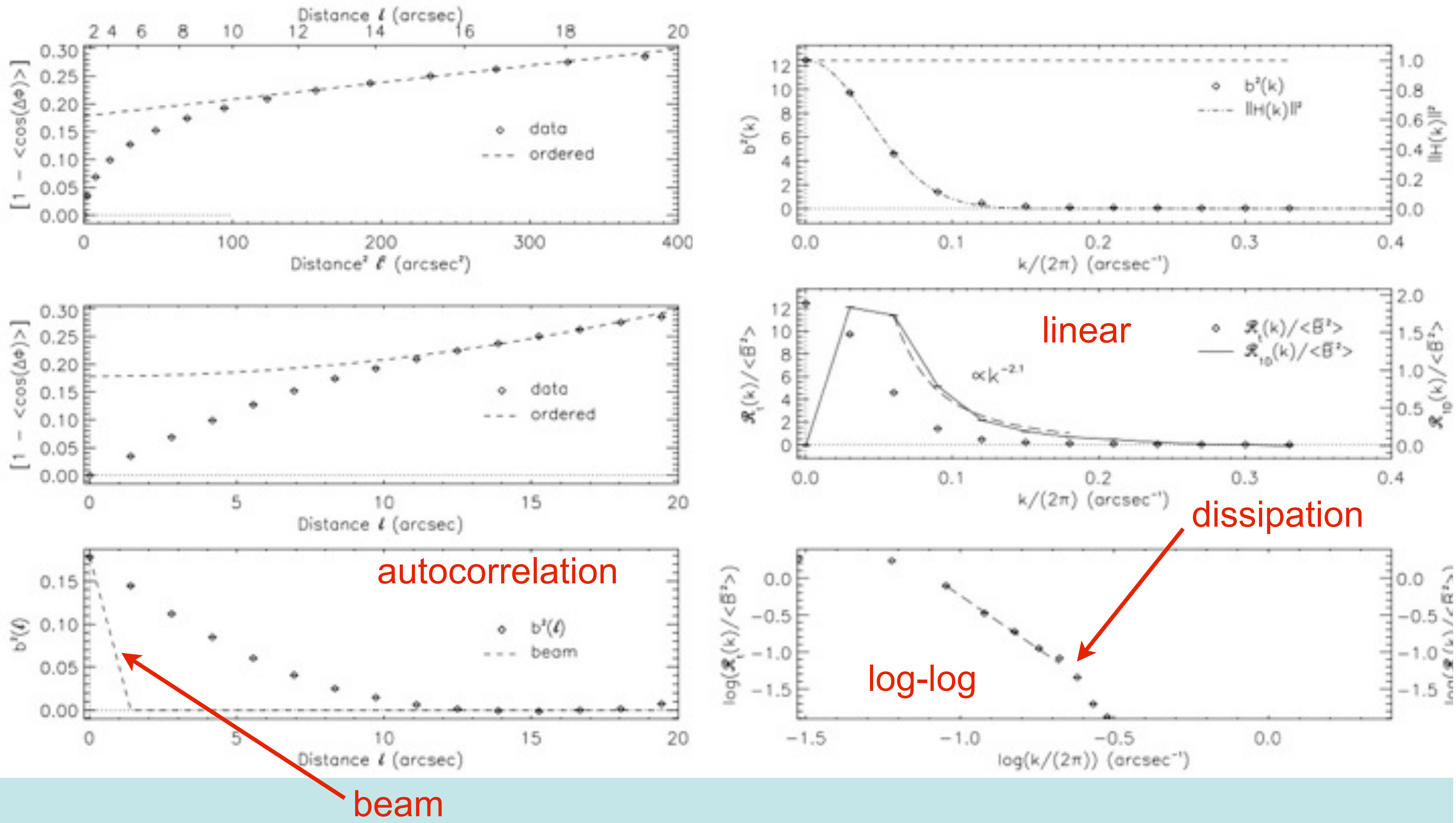


Hennebelle et al. 2011, A&A, 528, 72

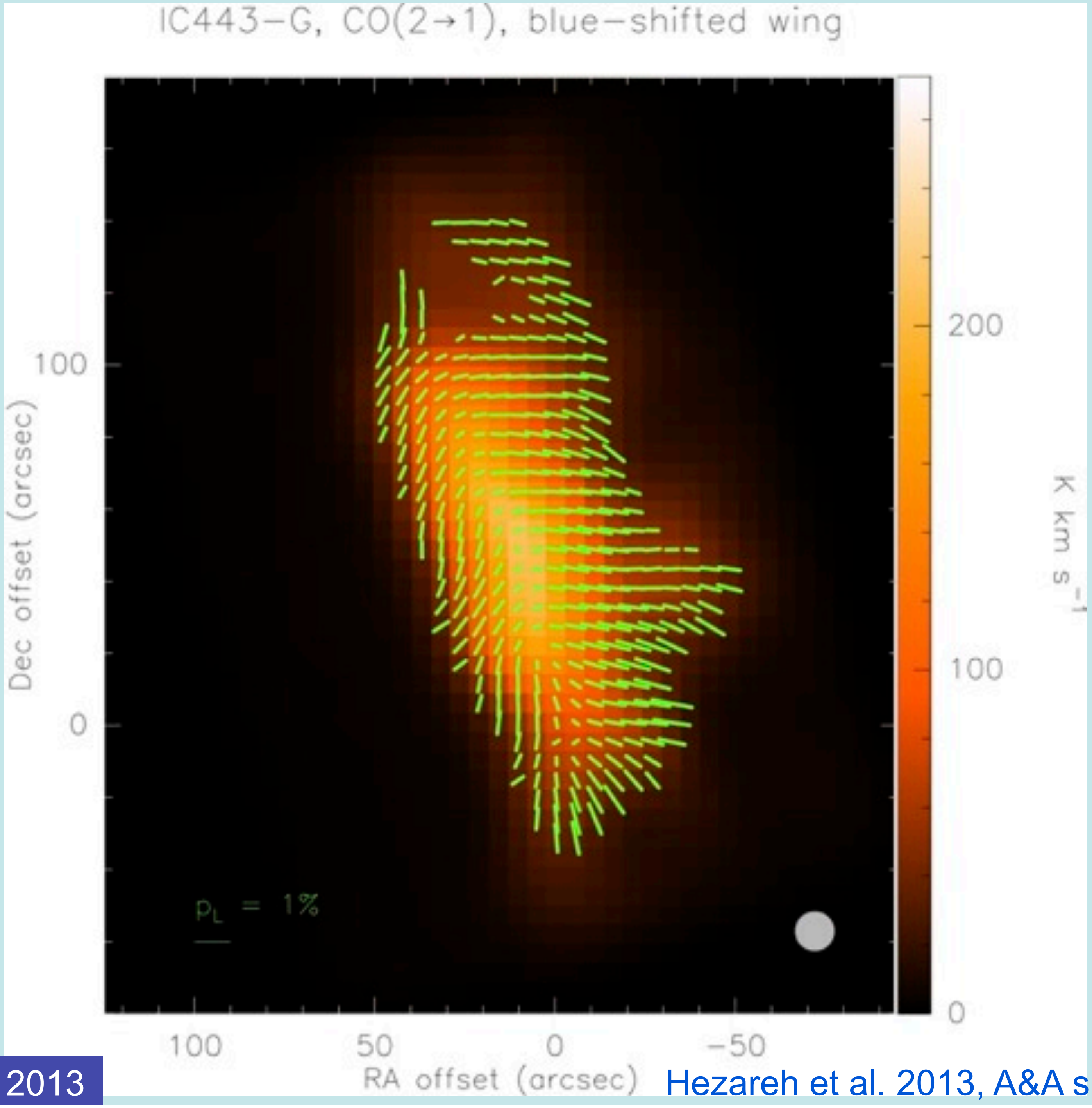
Turbulent Power Spectrum - simulations

Structure Function

Power Spectrum

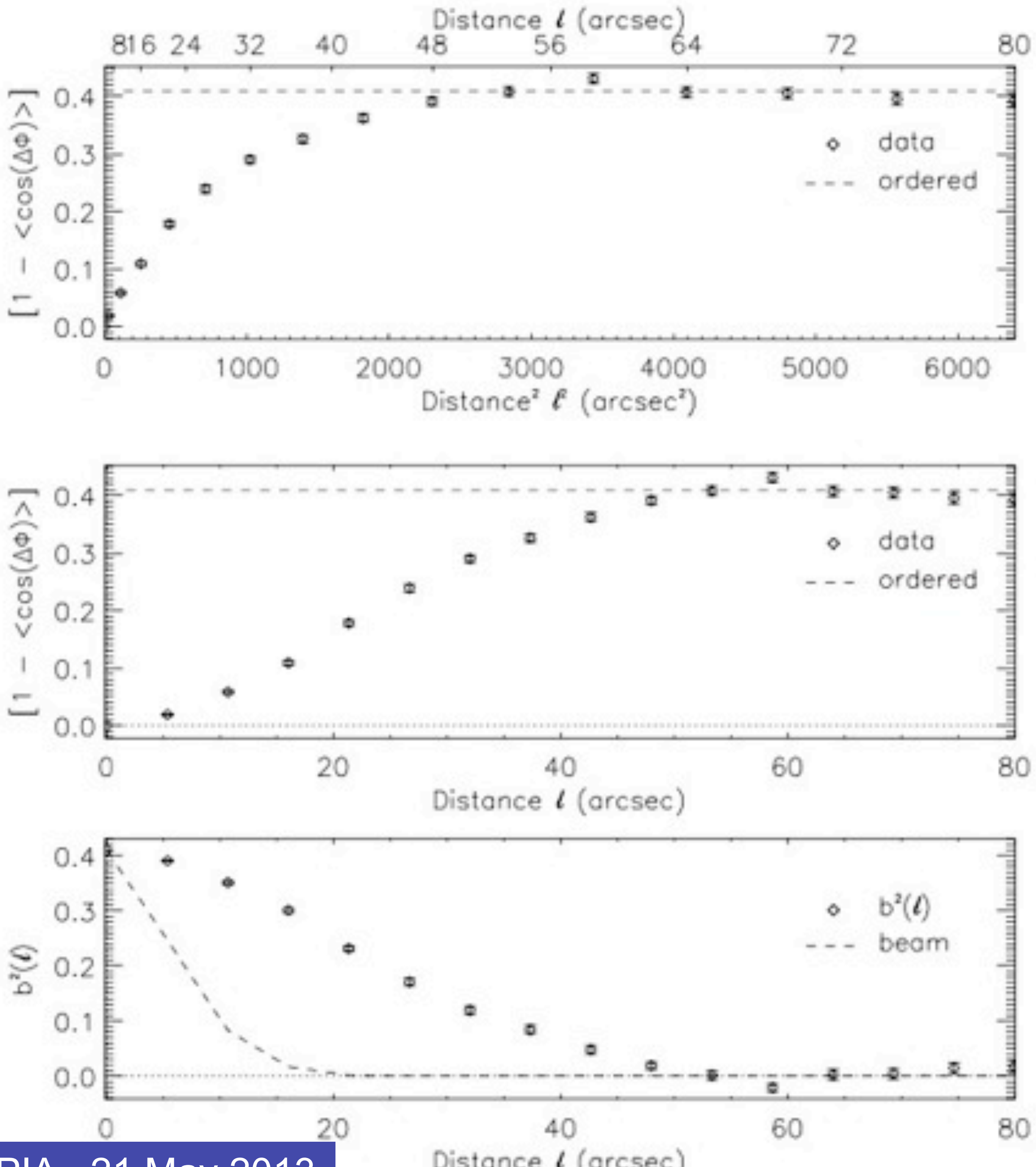


Line Polarization / GK effect - IC 443

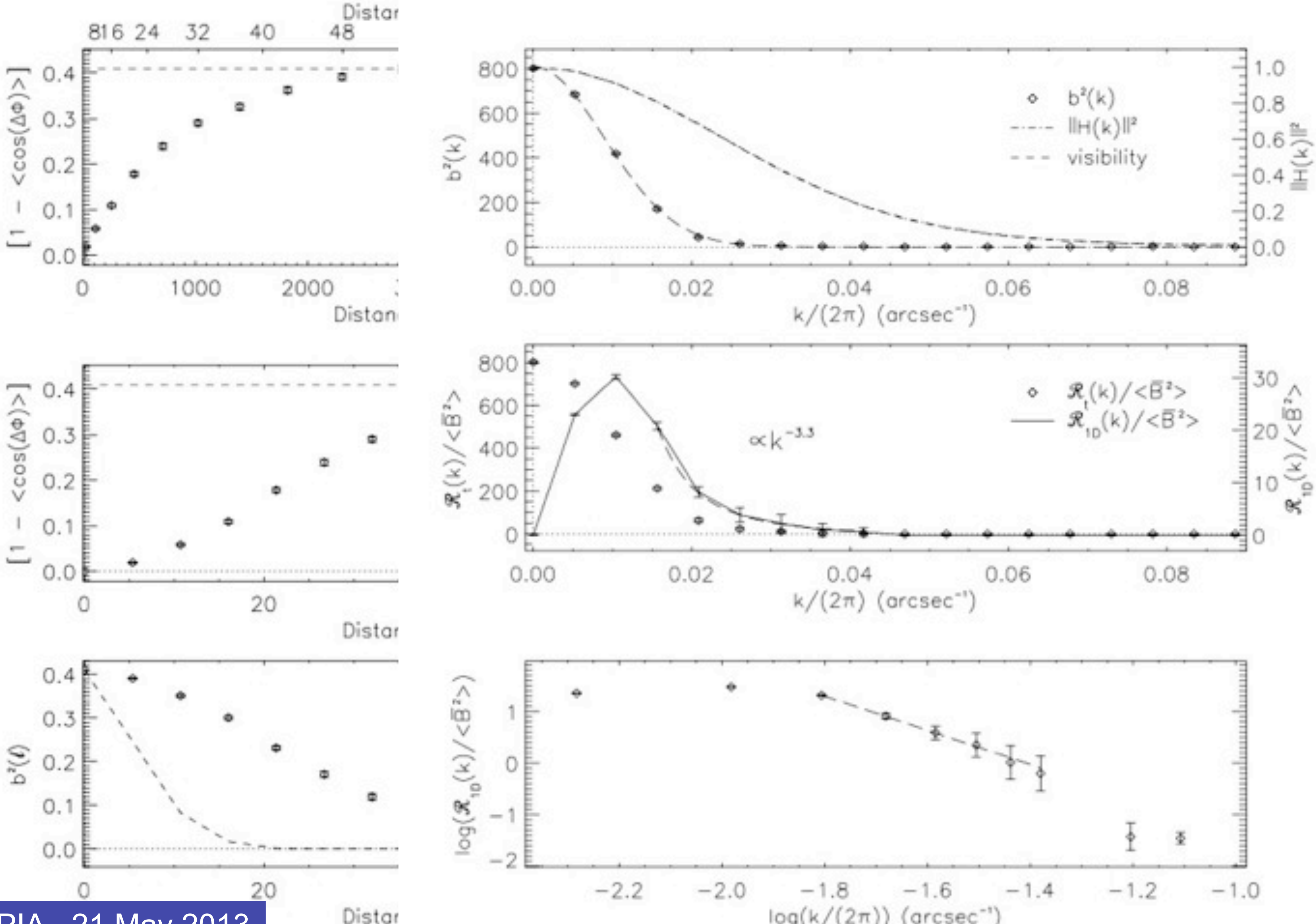


Hezareh et al. 2013, A&A submitted

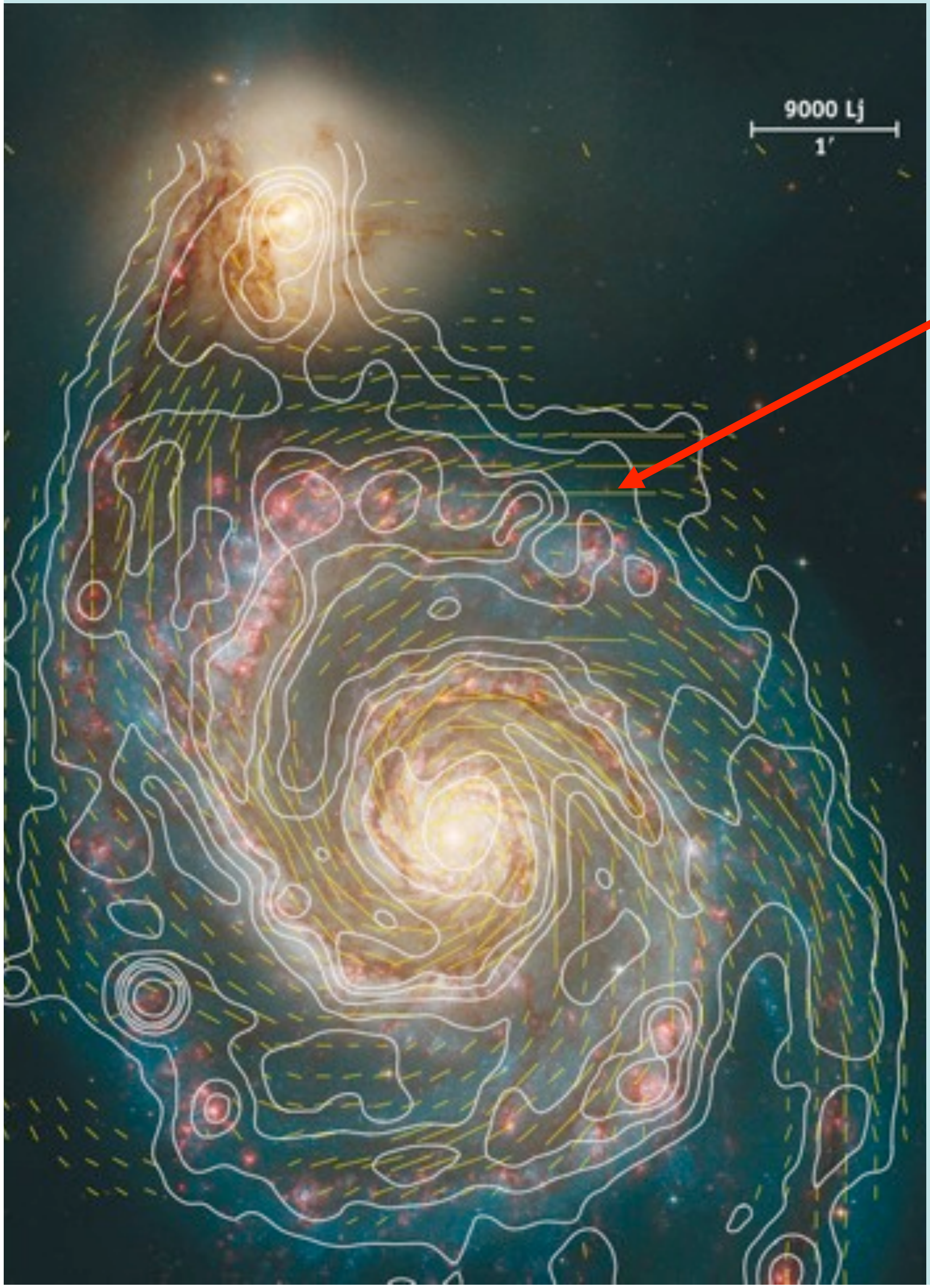
Line Polarization / GK effect - IC 443



Line Polarization / GK effect - IC 443



Magnetized Turbulence in Disks ...



M51 with Effelsberg (100m) + VLA

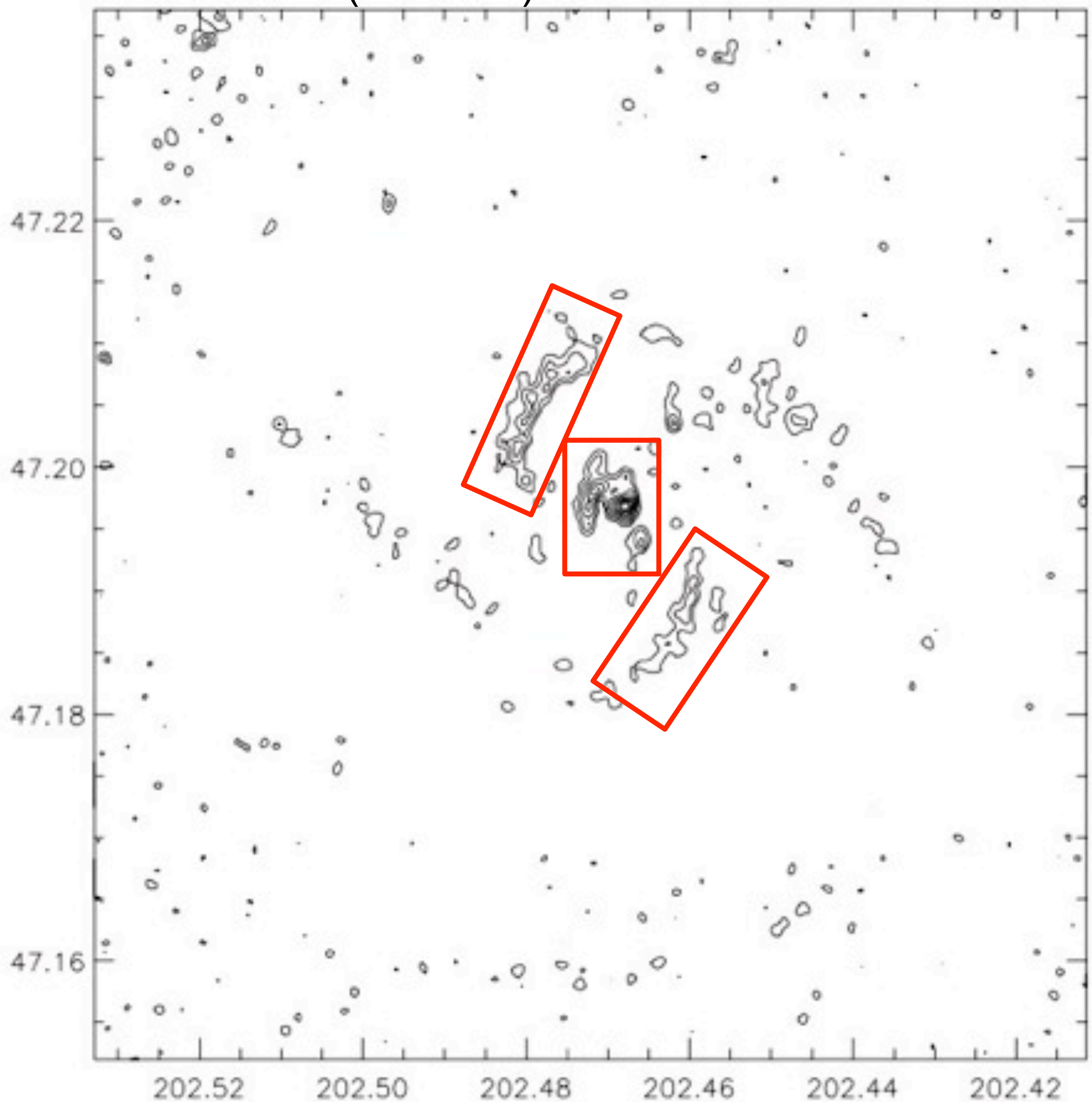
ordered + turbulent fields

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

Fletcher et al. 2011 (MNRAS)

M51 - Polarized Flux

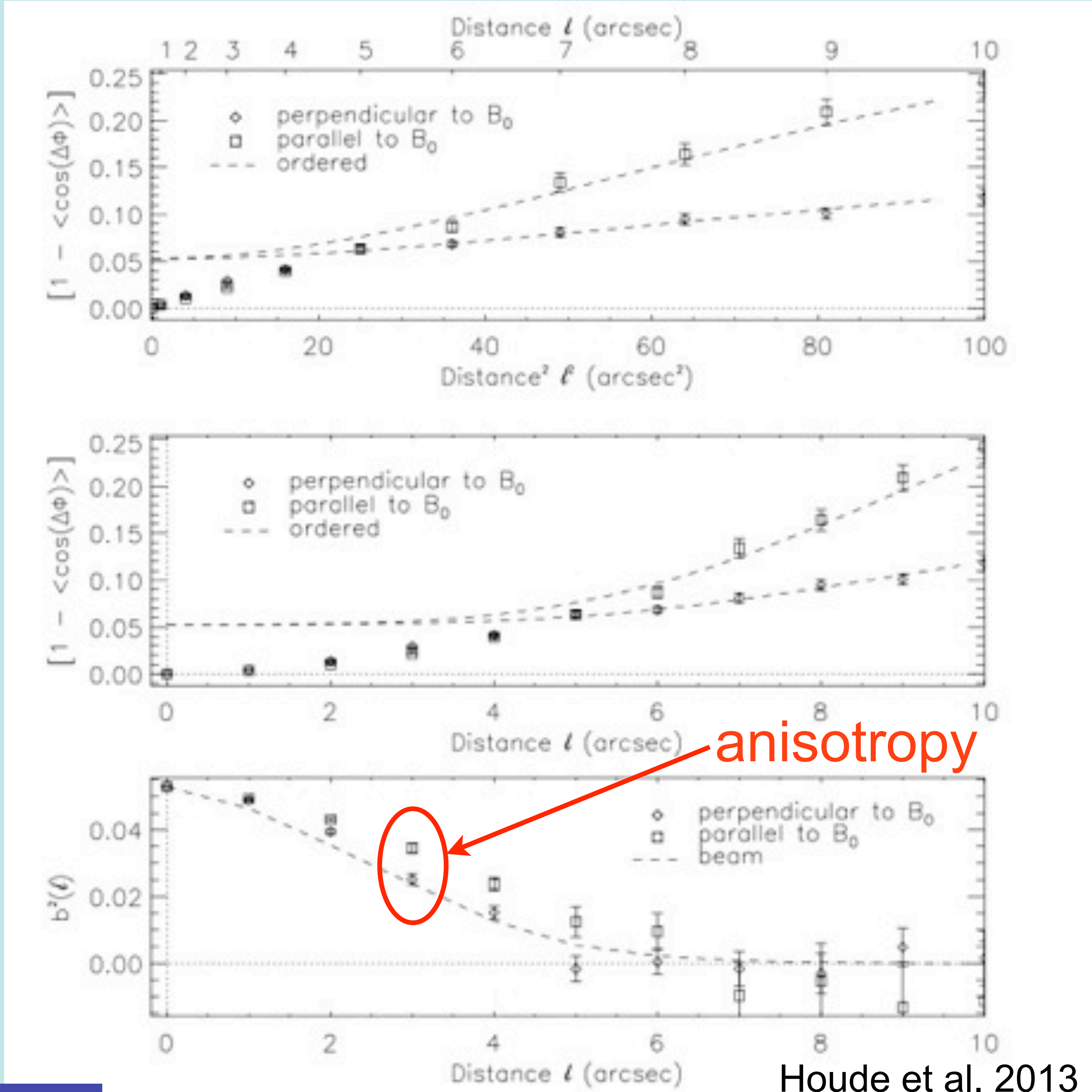
Fletcher et al. 2011 (MNRAS)



Houde et al. 2013

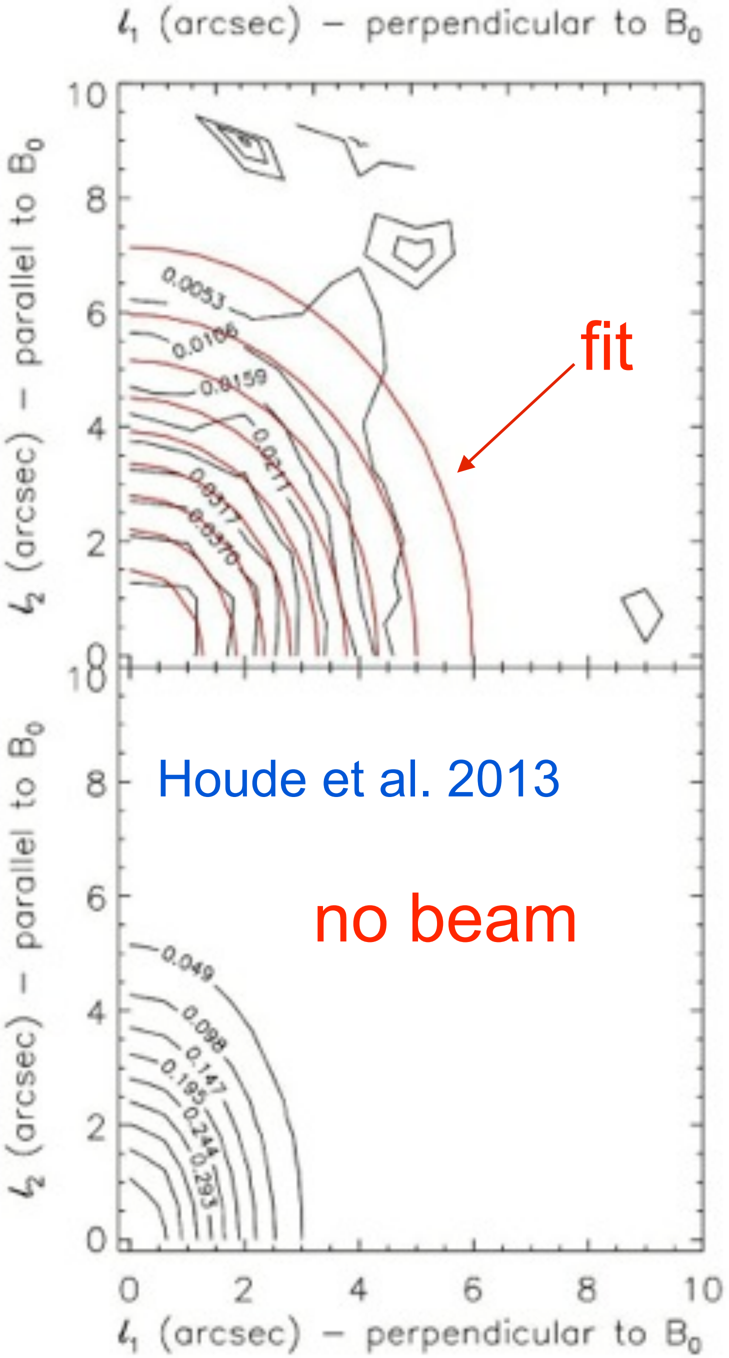
d = 7.6 Mpc
1” = 37 pc
λ = 6.2 cm
4” beam
1” sampling

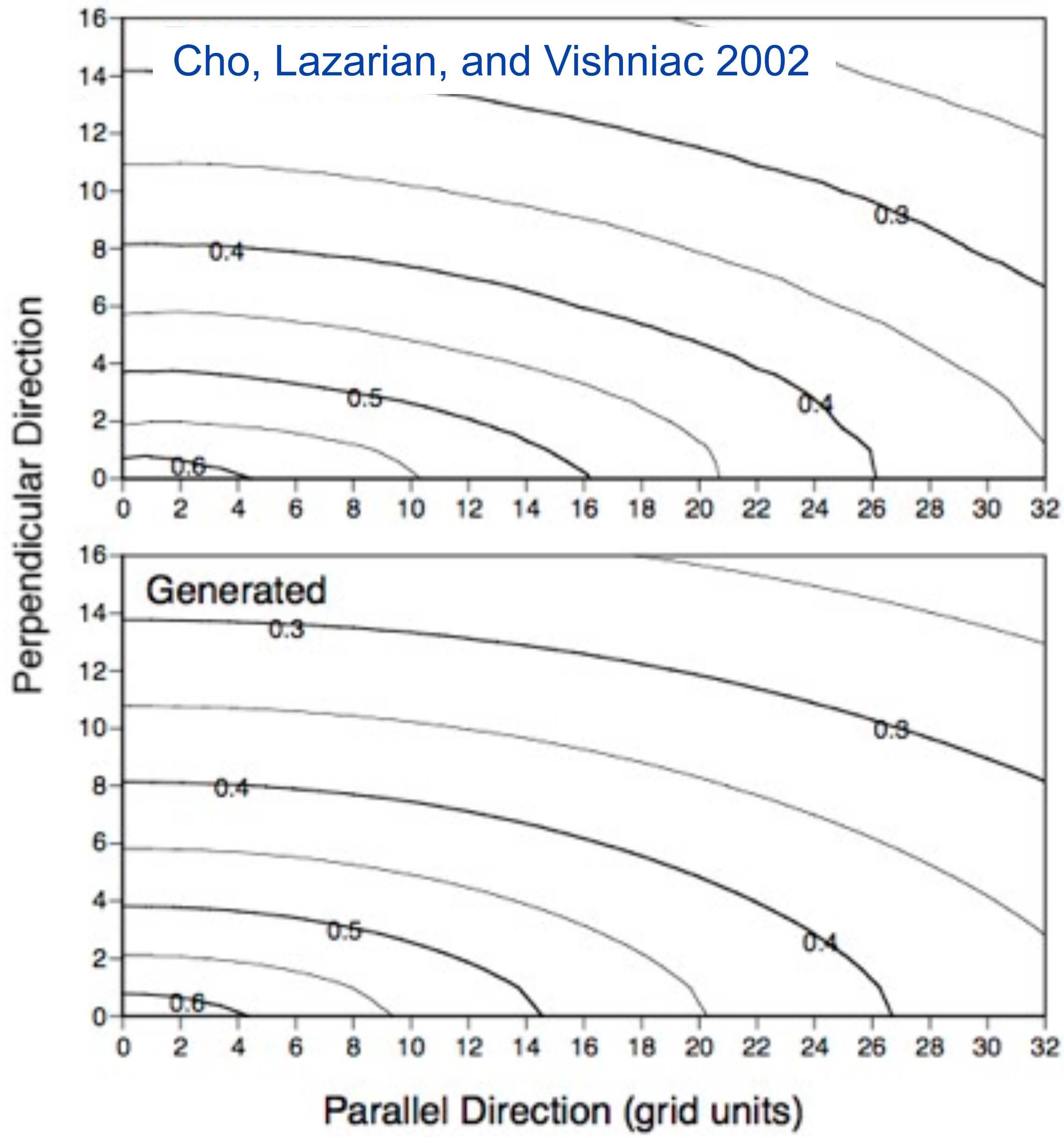
M51- Anisotropic Turbulence



Houde et al. 2013

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. 2013

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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