Measurements of Magnetic Fields in the Early Phase of Star Formation

Martin Houde

1878

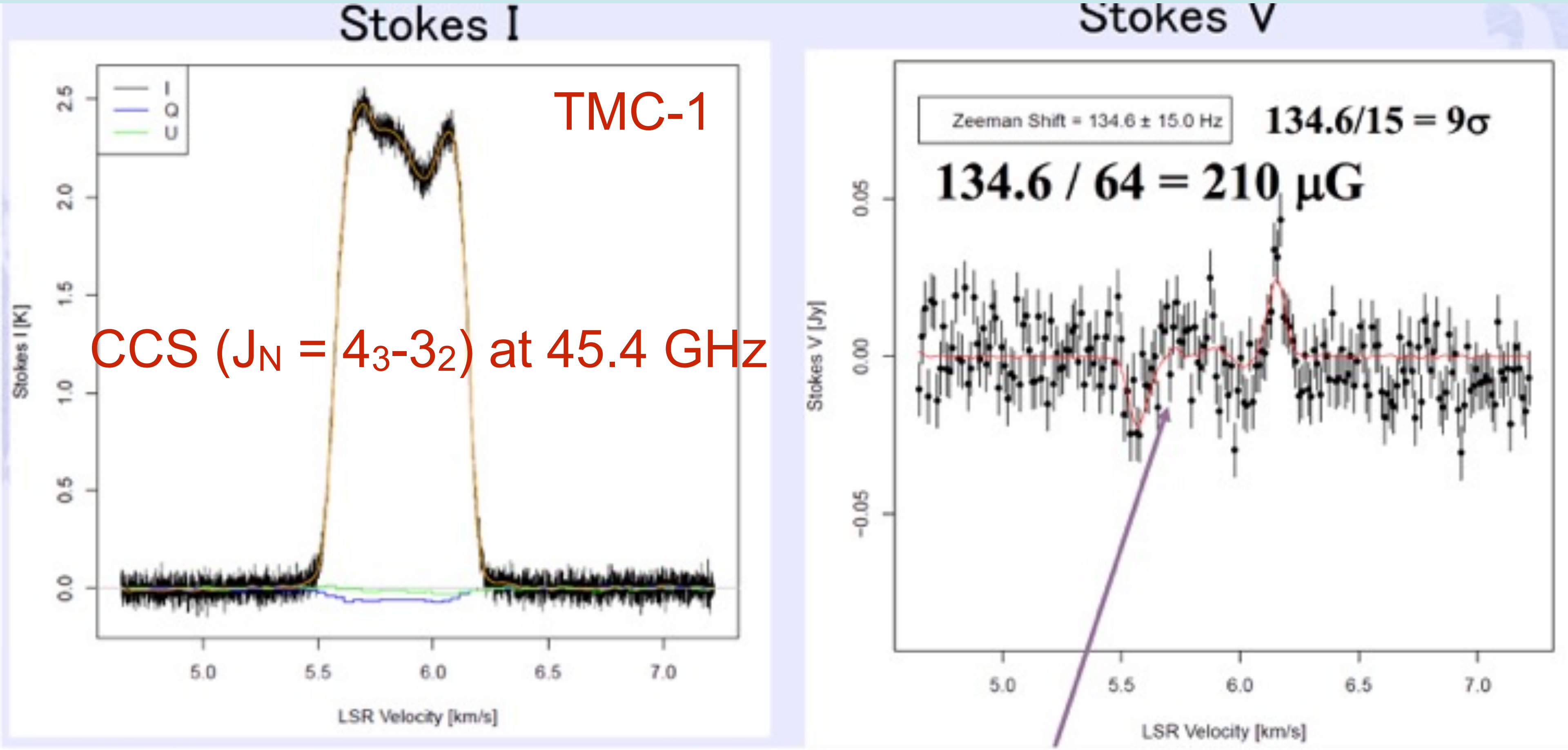
Western

UNIVERSITY · CANADA

Outline

- A few (brief) examples of recent progress…
  - The Zeeman world…
  - Planck (HRO)
  - BLASTPol (polarisation spectrum)
  - Interferometers (SMA and CARMA)
- Quantitative analysis of polarization maps
  - Single-dish and interferometer data
  - ALMA Era
    - where we stand, where should be or go…
- Spectral lines polarization
  - Goldreich-Kylafis Effect
  - Non-Zeeman circular polarisation (ARS Effect)

The Zeeman World…



TMC-1

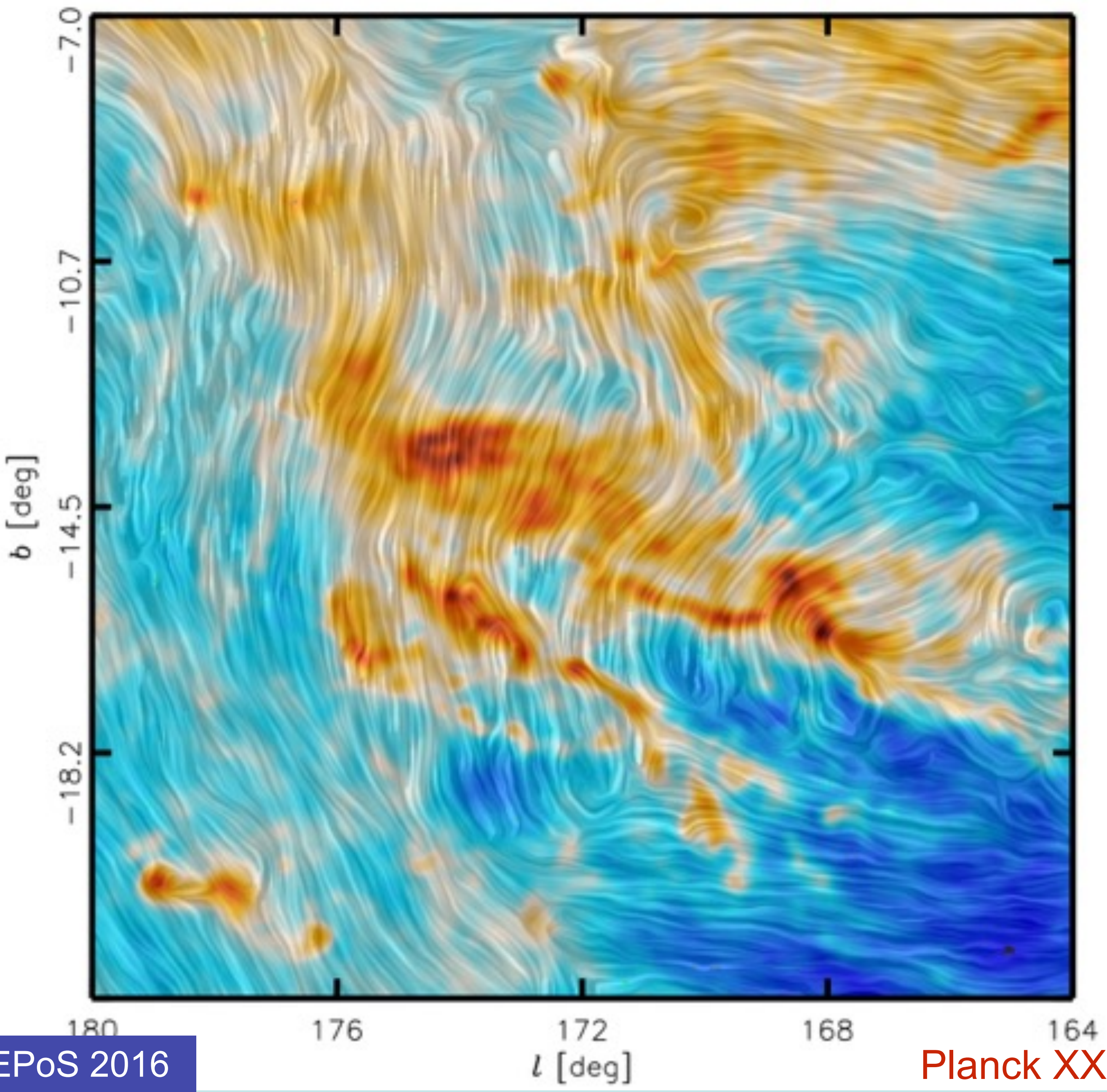
CCS ($J_N = 4_3$-3_2) at 45.4 GHz

$134.6/15 = 9\sigma$

$134.6 / 64 = 210\ \mu G$

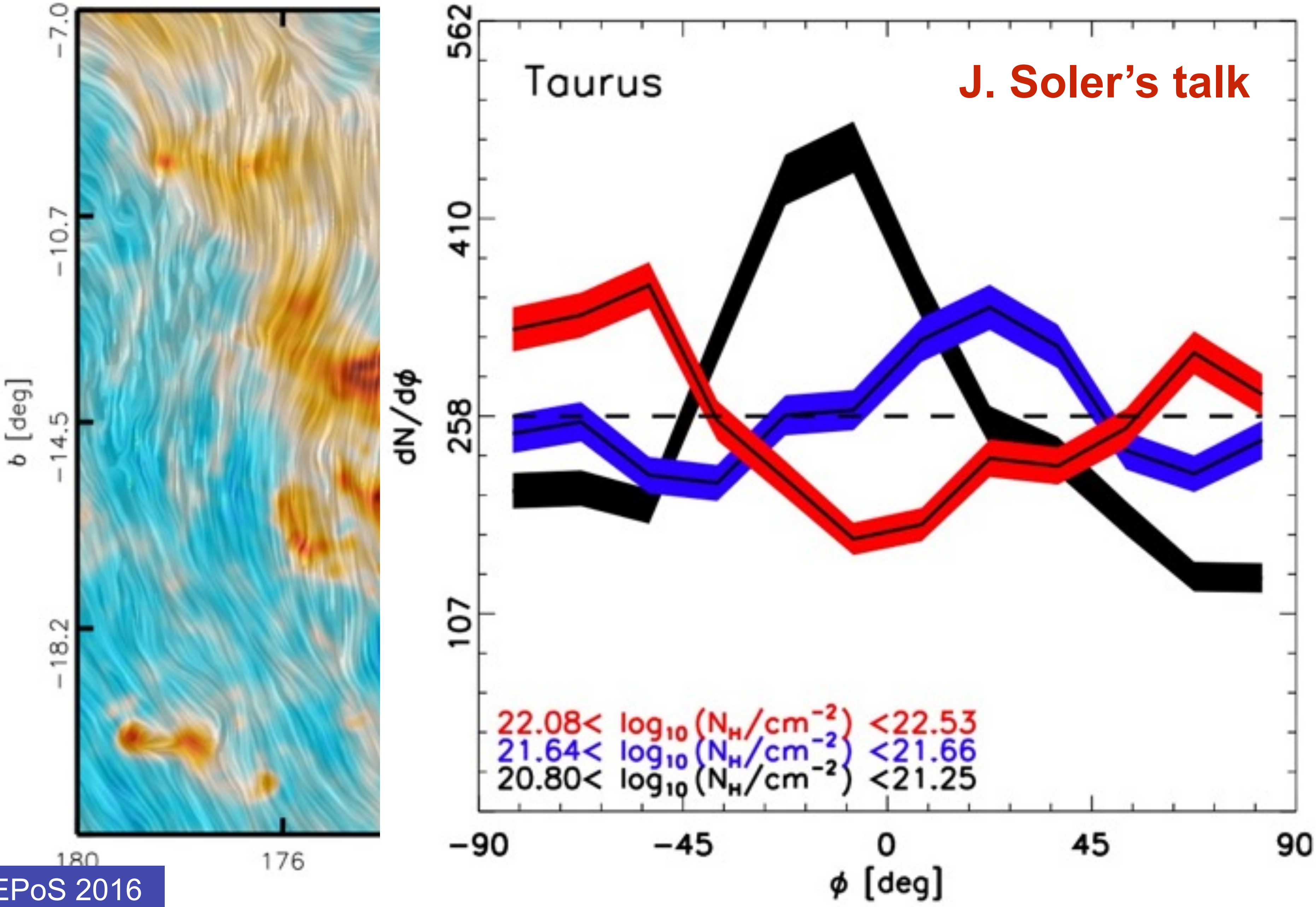
See:
P24 - F. Nakamura
R. Crutcher’s and
C. McKee’s talks

Planck - HRO



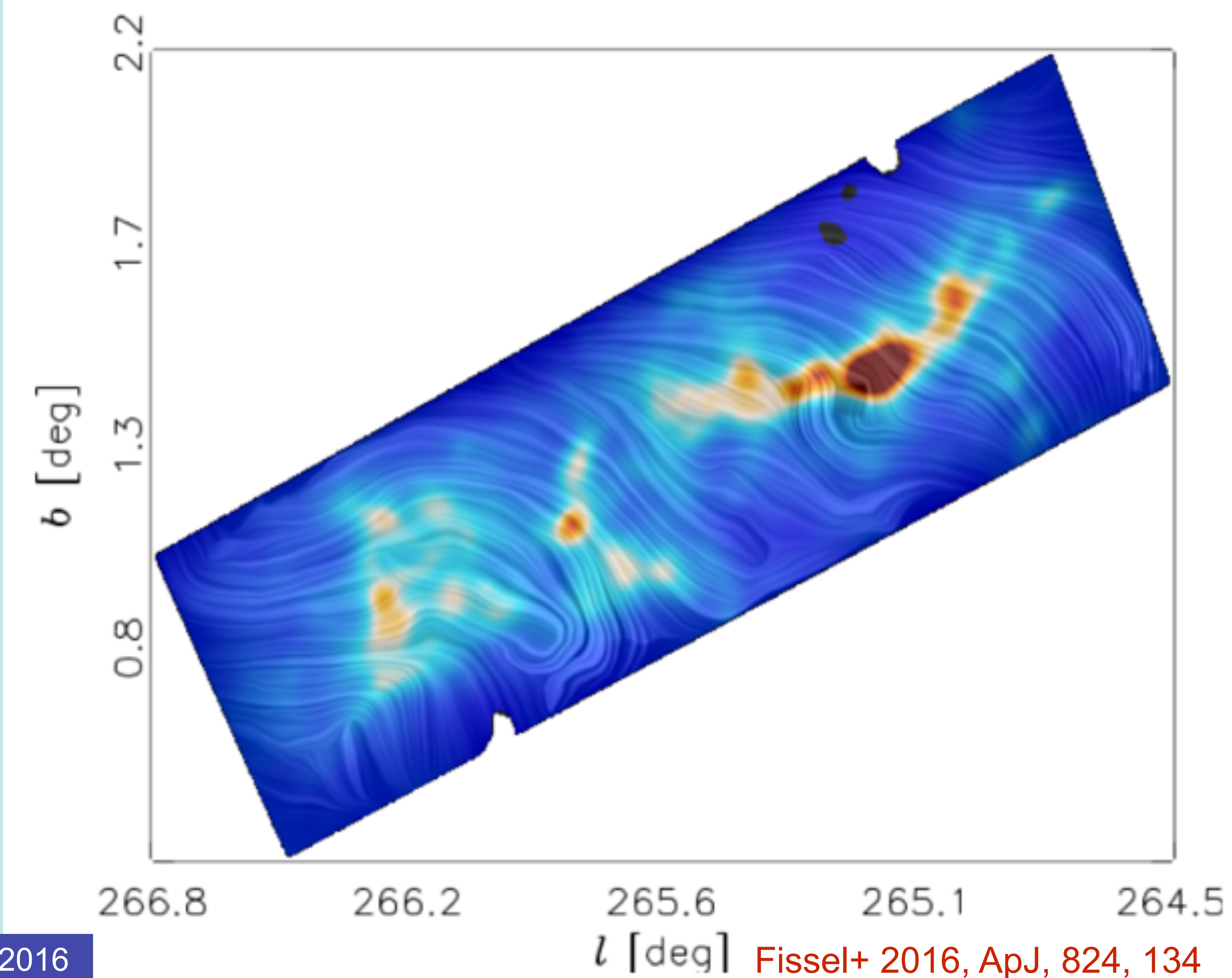
Planck XXXV 2016, A&A, 586, 138

Planck - HRO

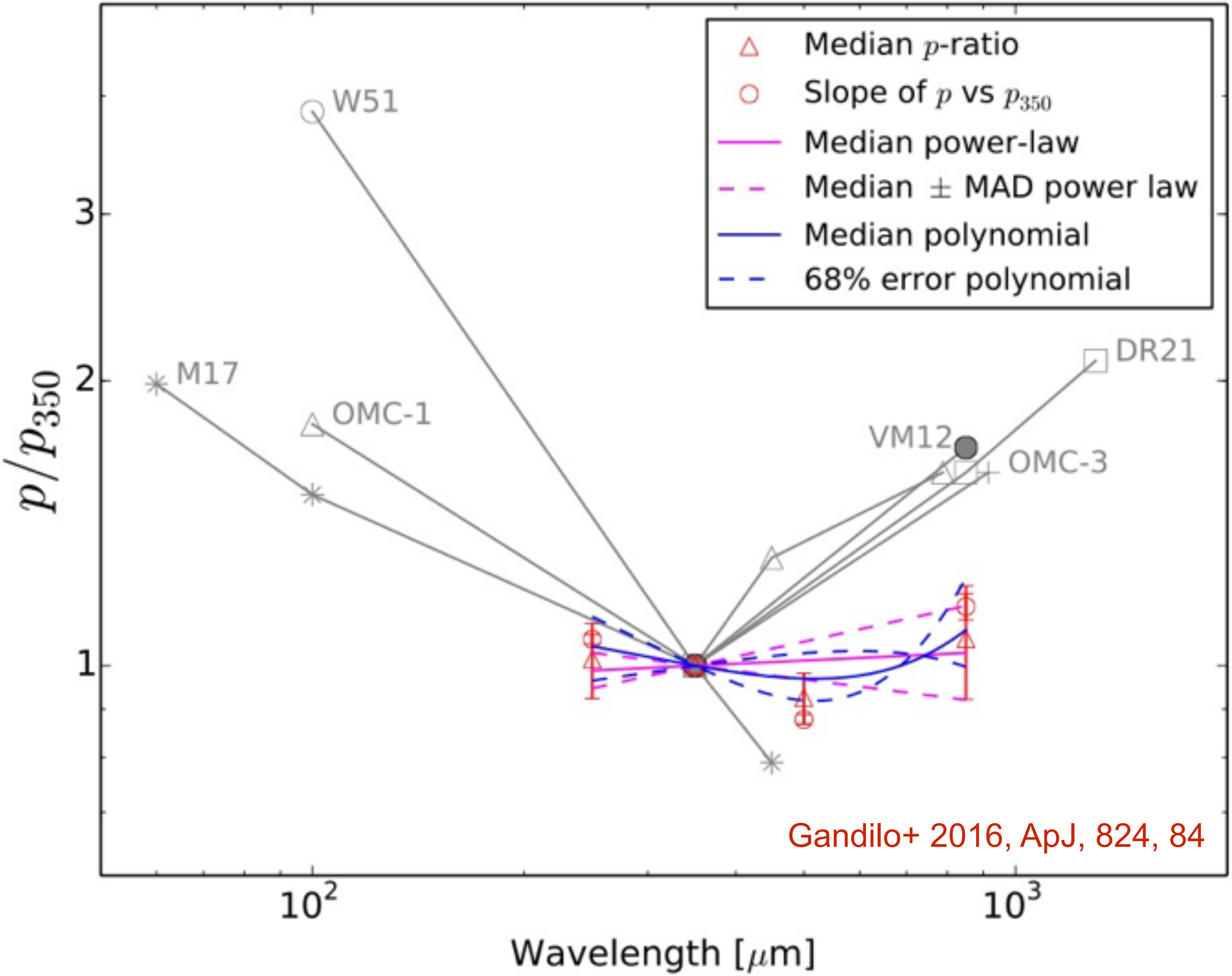


J. Soler's talk

BLASTPol - Vela C

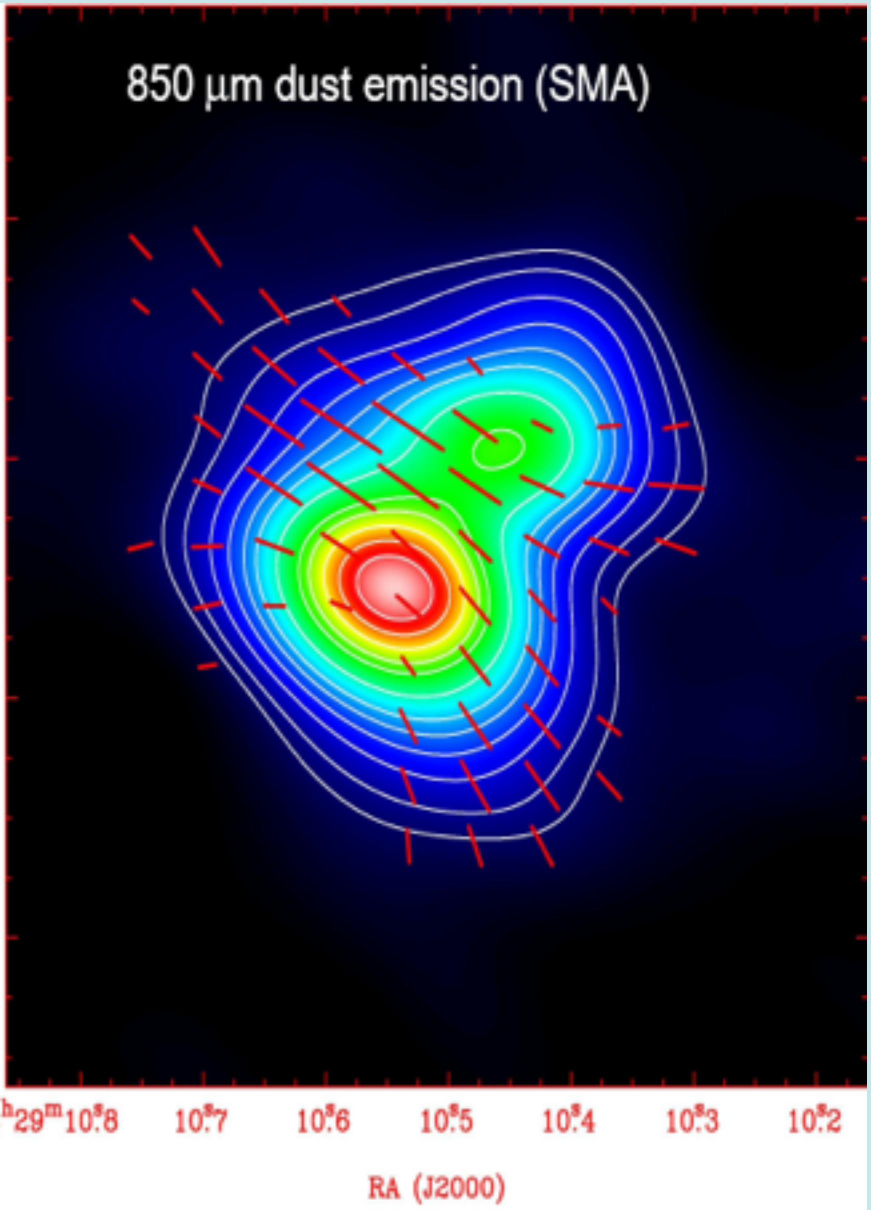


Fissel+ 2016, ApJ, 824, 134

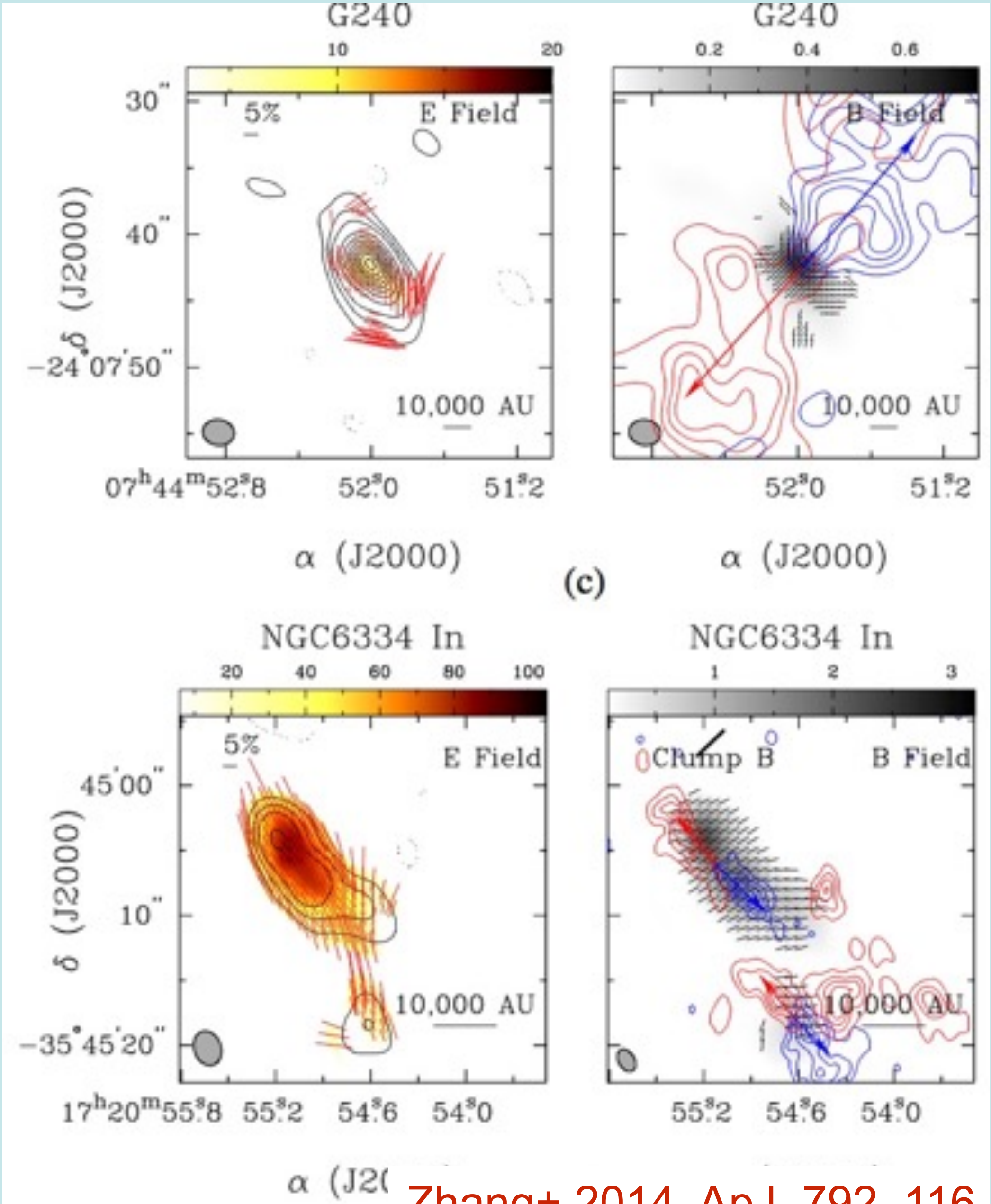


Gandilo+ 2016, ApJ, 824, 84

Interferometers - SMA

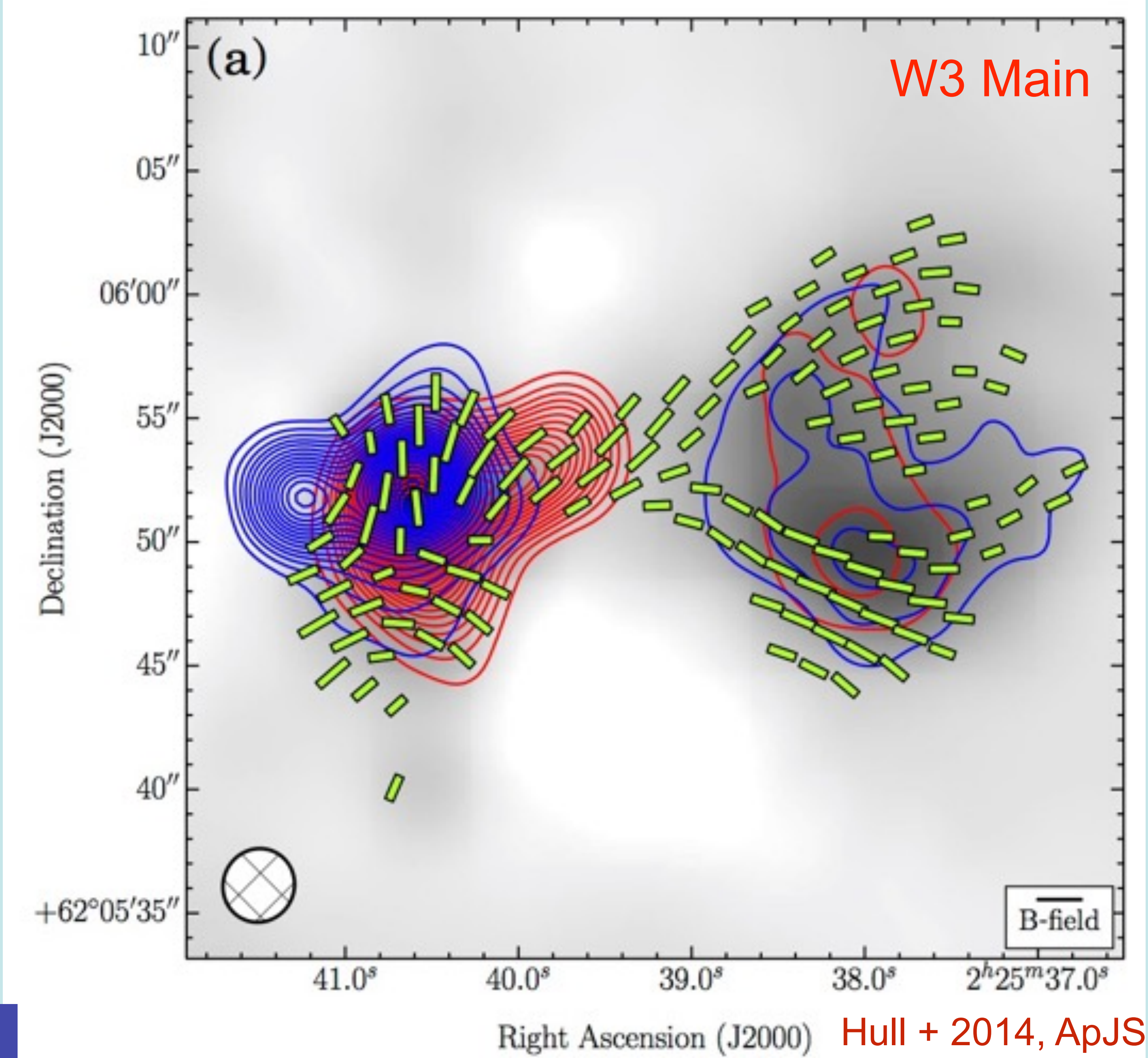


Girart+ 2006, Science, 313, 812



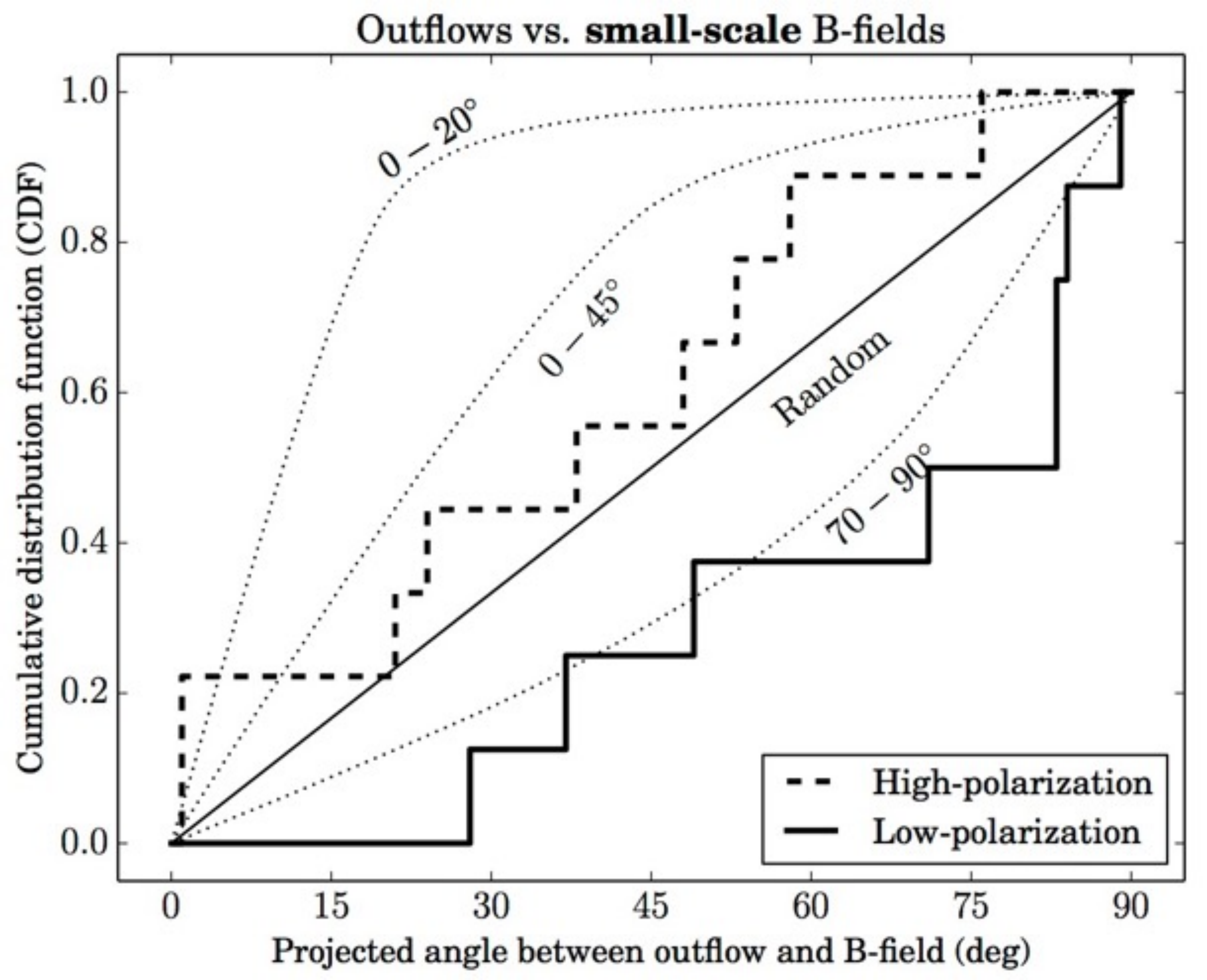
Zhang+ 2014, ApJ, 792, 116

Interferometers - CARMA/TADPOL



Hull + 2014, ApJS, 213, 13

Interferometers - CARMA/TADPOL



Methods of Analysis - Structure (and related) Functions

Given a polarization map

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

The Angular Structure Function

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

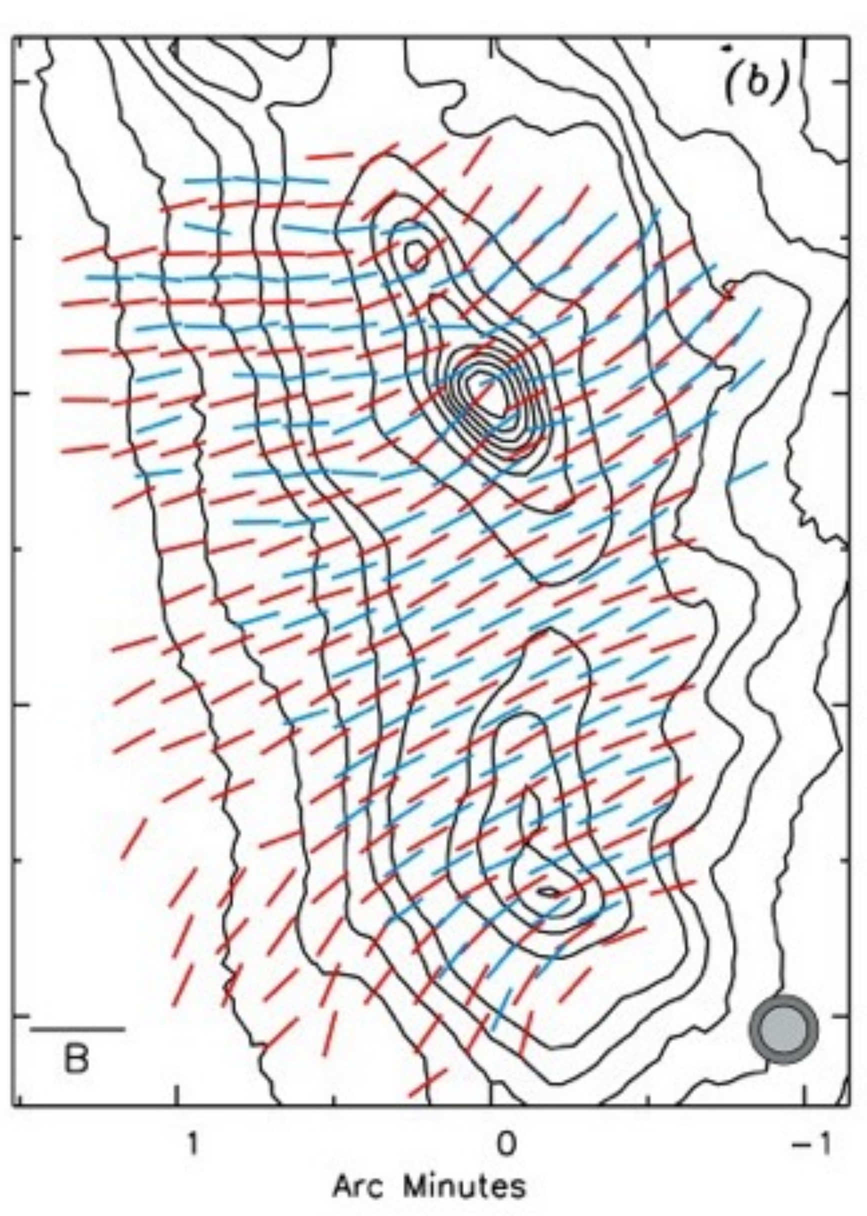
If $\mathbf{B} = \mathbf{B}_{\mathrm{t}} + \mathbf{B}_0$ (turbulent and ordered (large-scale) components)

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

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

OMC-1 with SHARP at 350 μm

OMC-1 - SHARP/CSO, 350 and 450 μm



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

OMC-1 with SHARP at 350 μm

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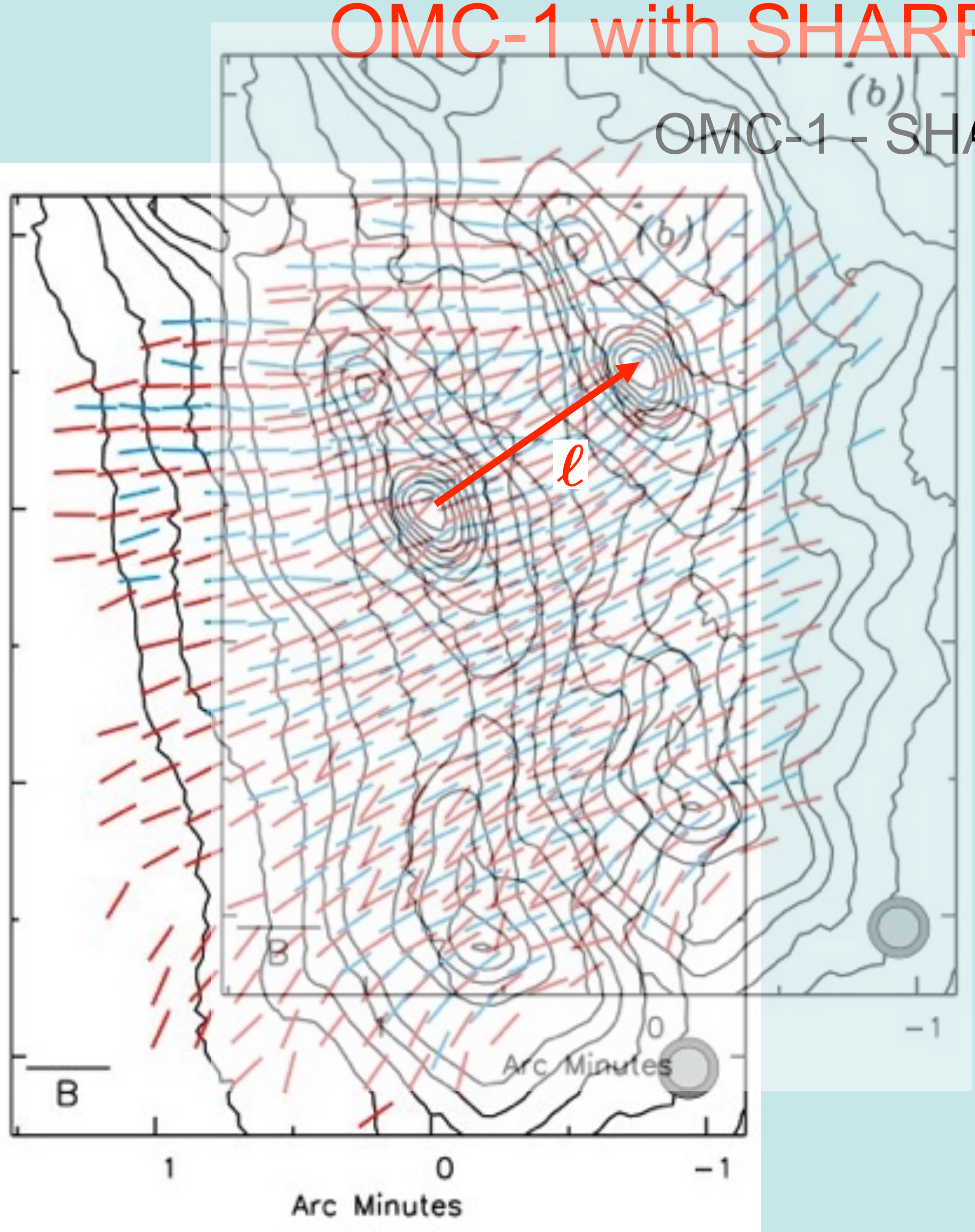

Vaillancourt et al., 2008, ApJ, 679, L25

OMC-1 with SHARP at 350 µm

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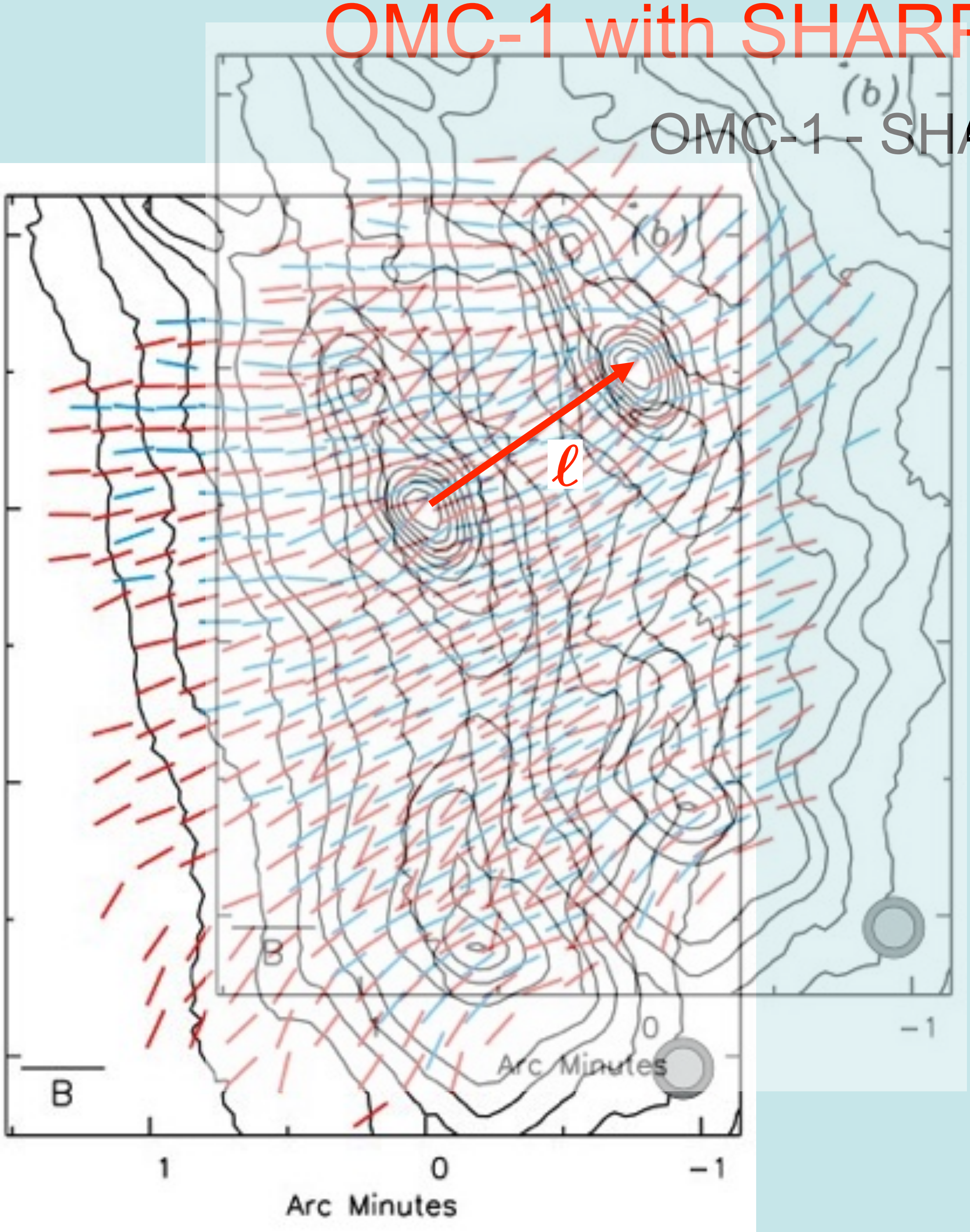
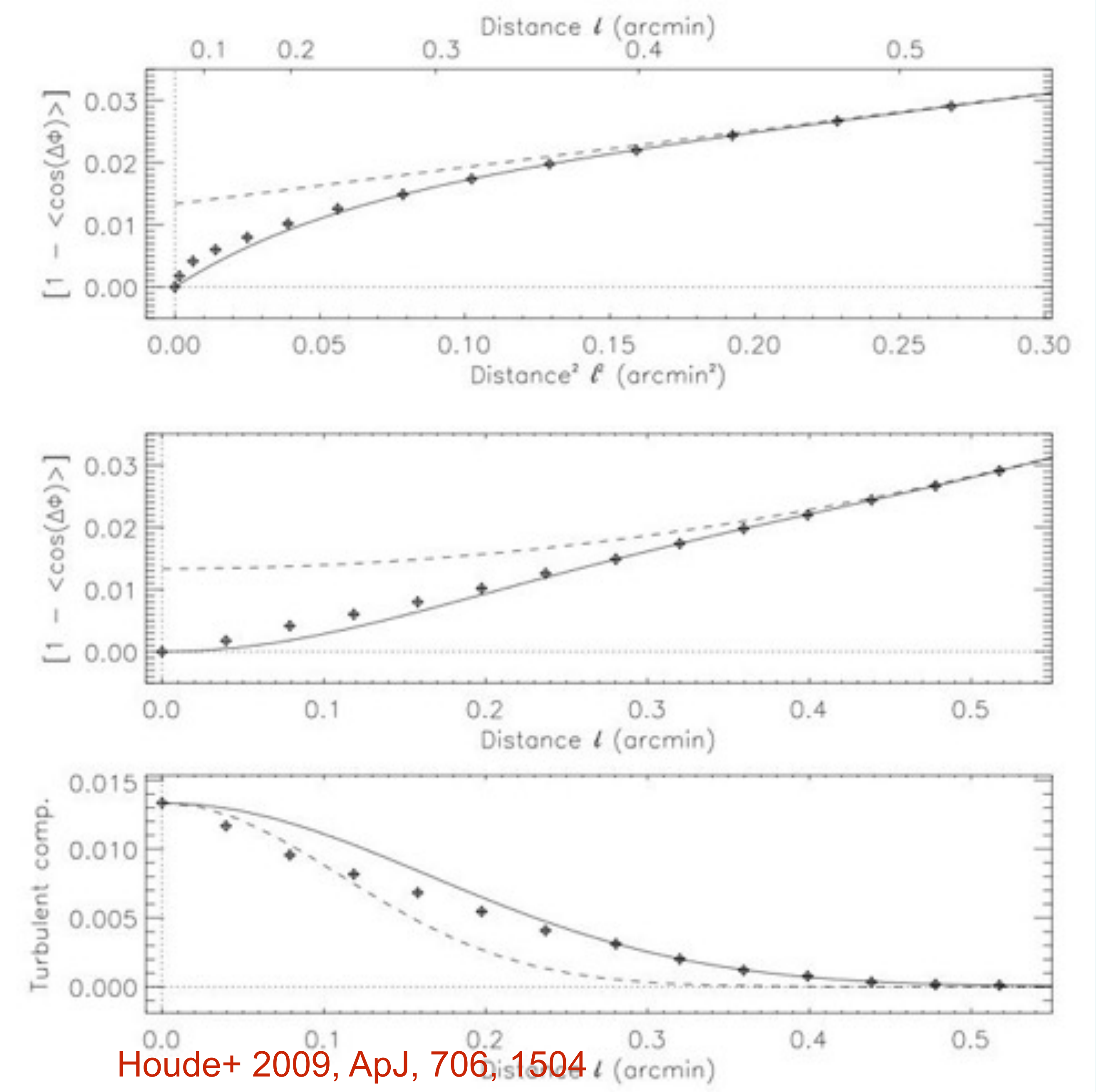


$$1-\left\langle \cos\left[\Delta\Phi(\ell)\right]\right\rangle \simeq \frac{\left\langle \Delta\Phi^{2}(\ell)\right\rangle}{2}$$

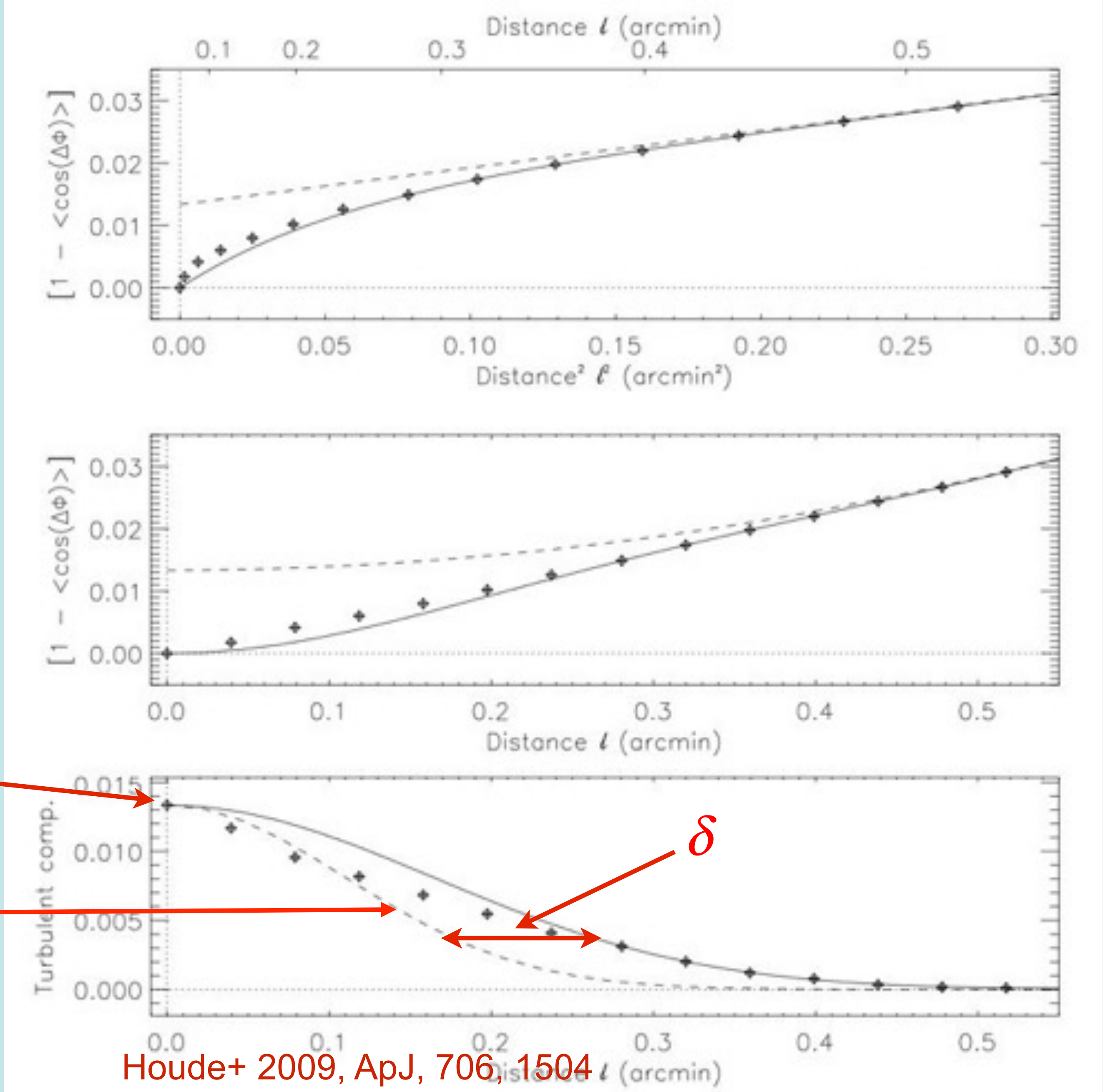
Vaillancourt et al., 2008, ApJ, 679, L25

OMC-1 with SHARP at 350 μm



Houde+ 2009, ApJ, 706, 1504

OMC-1 with SHARP at 350 μm



$$\frac{\left\langle \overline{B}_{\mathrm{t}}^{2} \right\rangle}{\left\langle \overline{B}_{0}^{2} \right\rangle}$$

beam

δ

Houde+ 2009, ApJ, 706, 1504

Dispersion Analysis… and the DCF Method

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

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

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

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

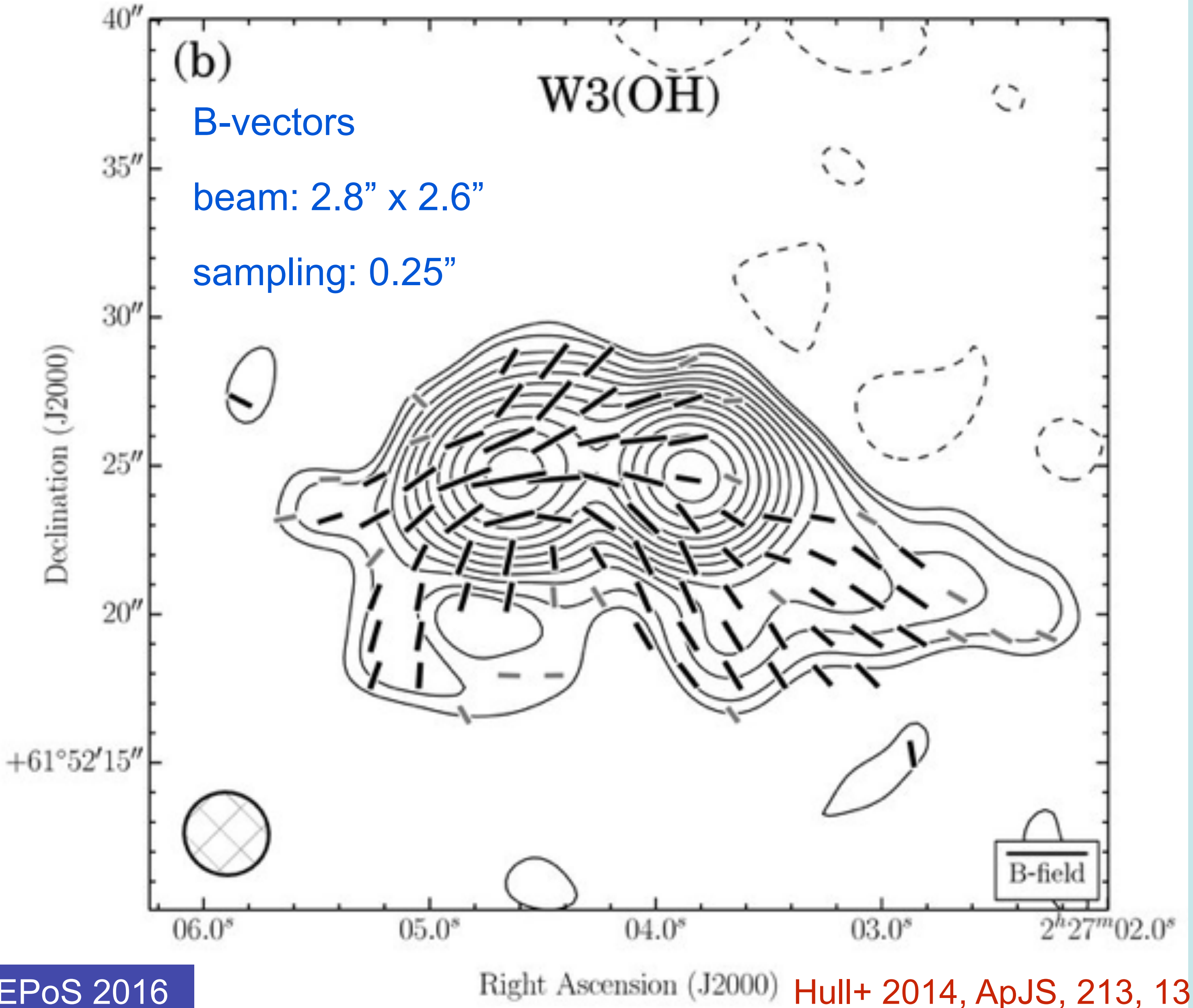
with the Davis-Chandrasekhar-Fermi equation

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

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

Houde+ 2009, ApJ, 706, 1504

CARMA / TADPOL - W3(OH)



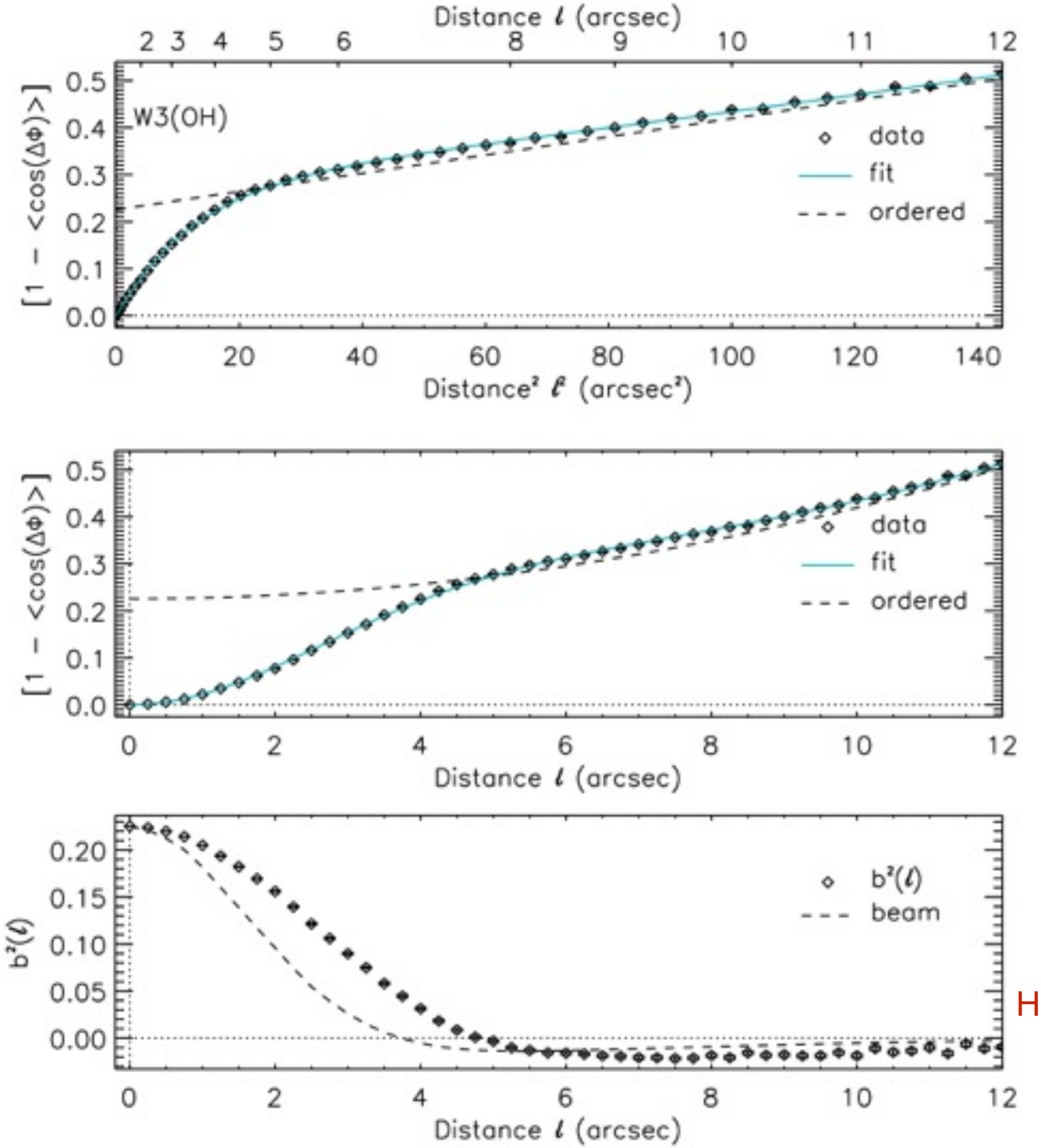
B-vectors

beam: 2.8” x 2.6”

sampling: 0.25”

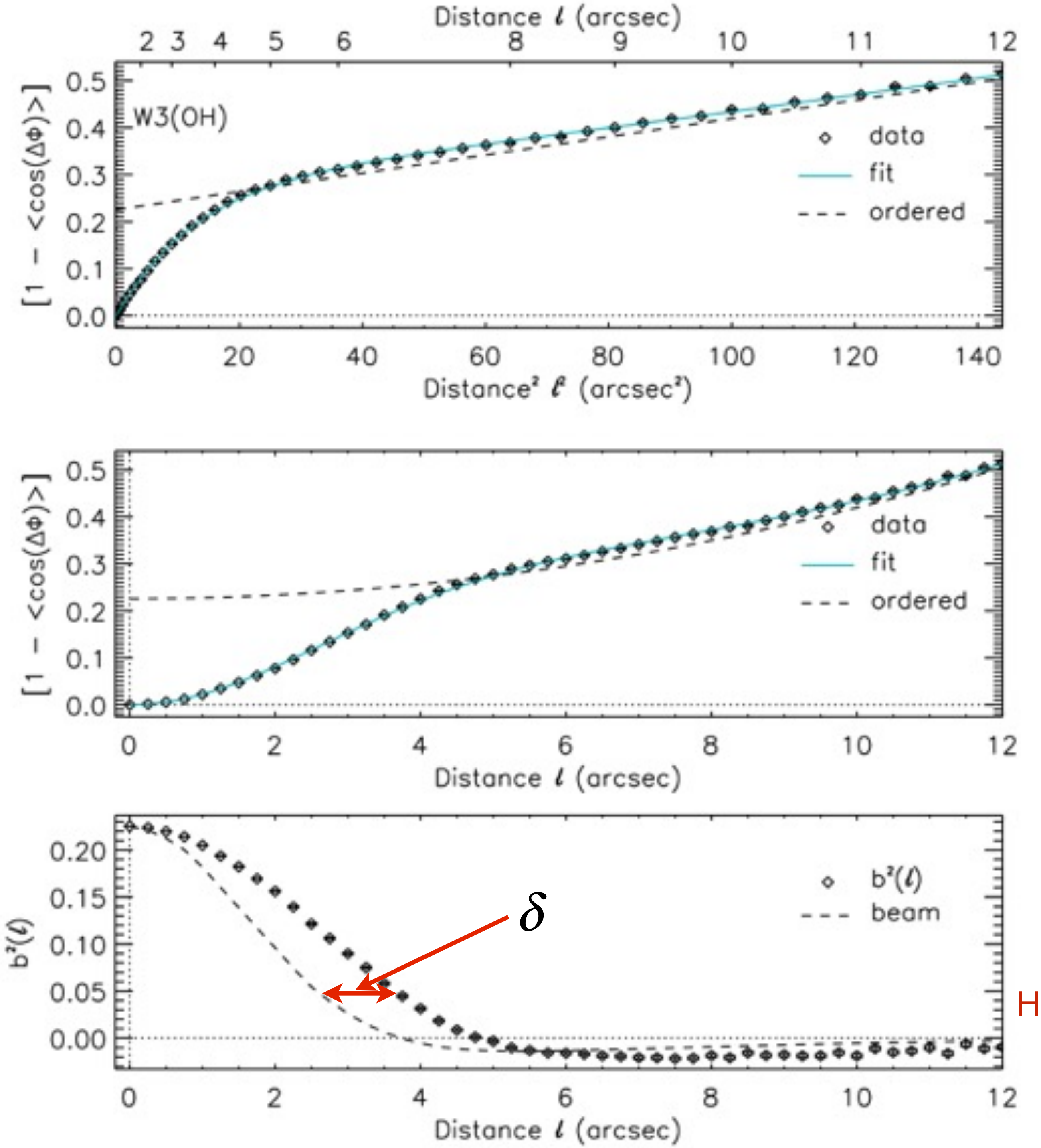
Hull+ 2014, ApJS, 213, 13

CARMA - W3(OH)



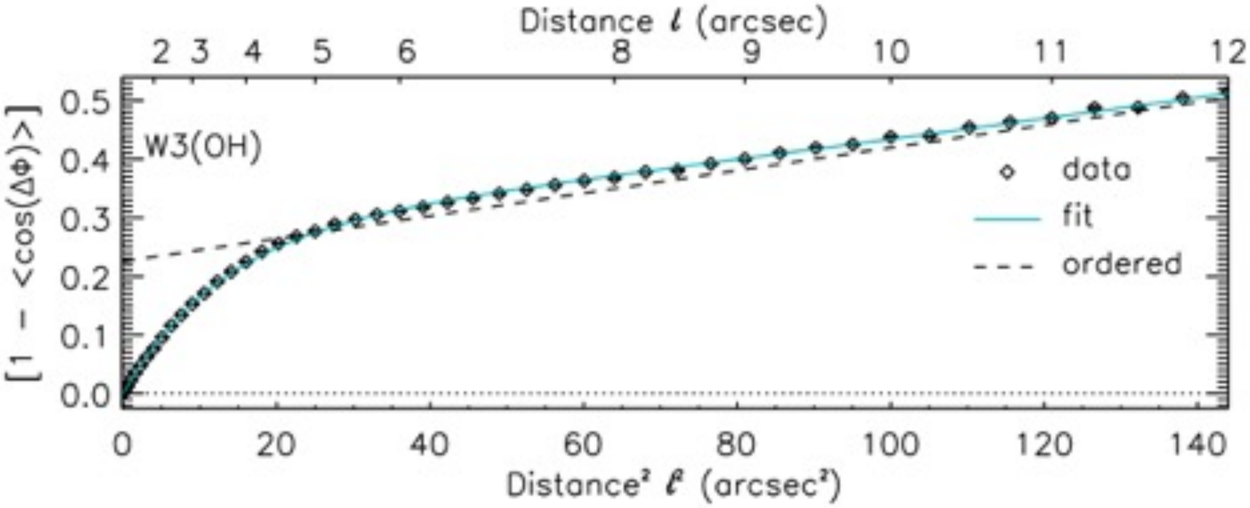
Houde+ 2016, ApJ, 820, 38

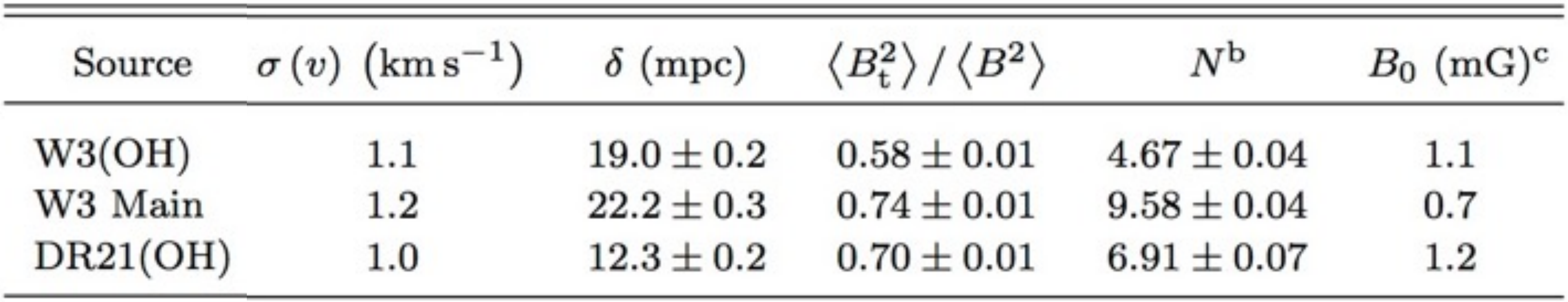
CARMA - W3(OH)



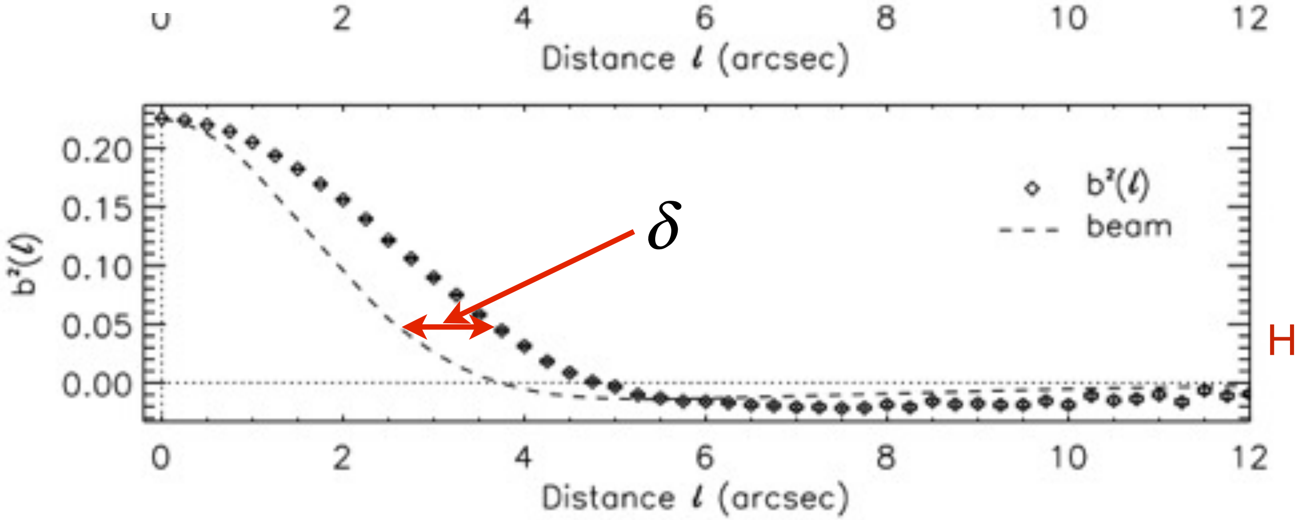
Houde+ 2016, ApJ, 820, 38

CARMA - W3(OH)





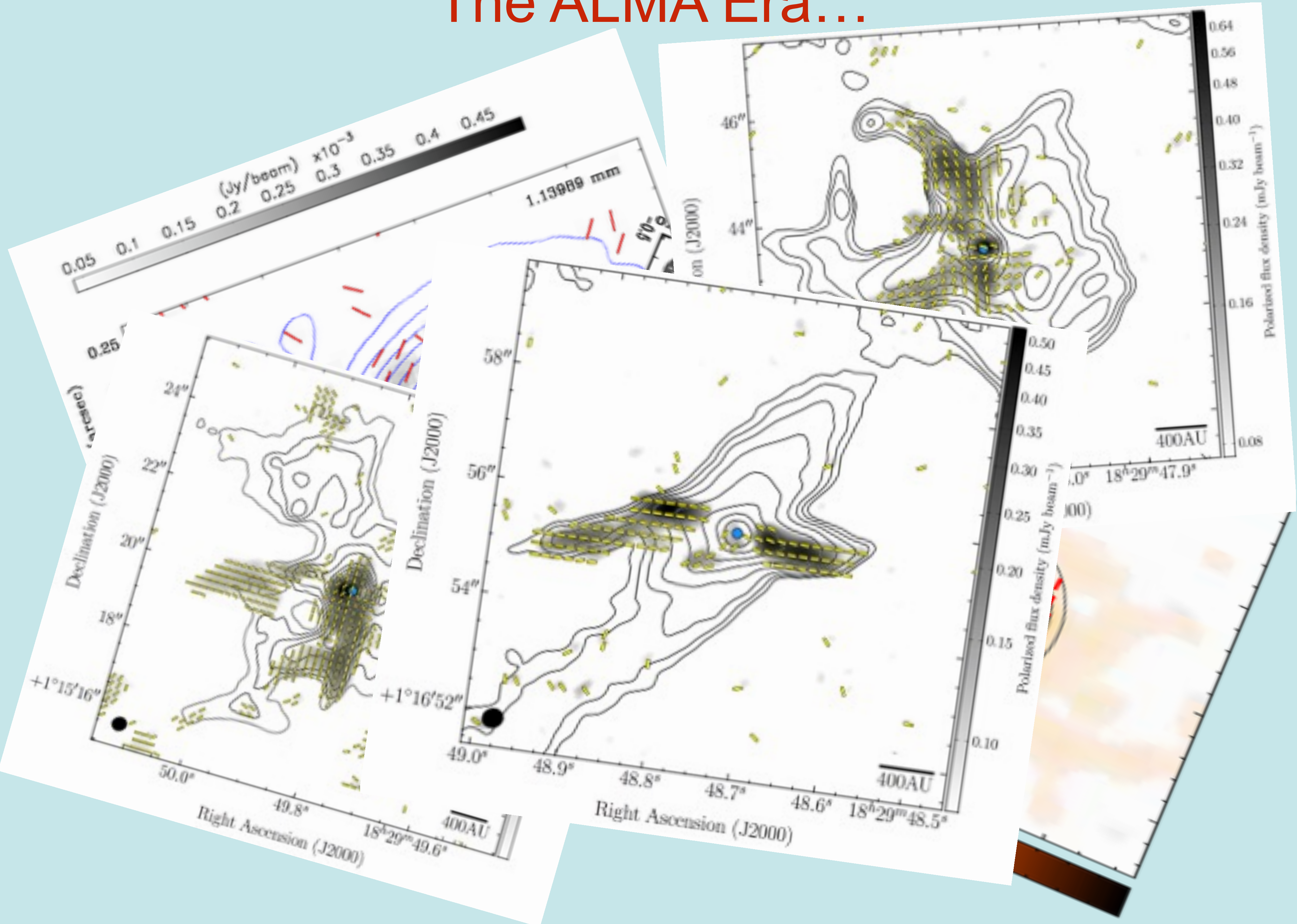
Source	$\sigma(v)$ $(\mathrm{km\,s^{-1}})$	δ (mpc)	$\langle B_t^2\rangle / \langle B^2\rangle$	N^{b}	B_0 (mG)$^{\mathrm{c}}$
W3(OH)	1.1	19.0 ± 0.2	0.58 ± 0.01	4.67 ± 0.04	1.1
W3 Main	1.2	22.2 ± 0.3	0.74 ± 0.01	9.58 ± 0.04	0.7
DR21(OH)	1.0	12.3 ± 0.2	0.70 ± 0.01	6.91 ± 0.07	1.2



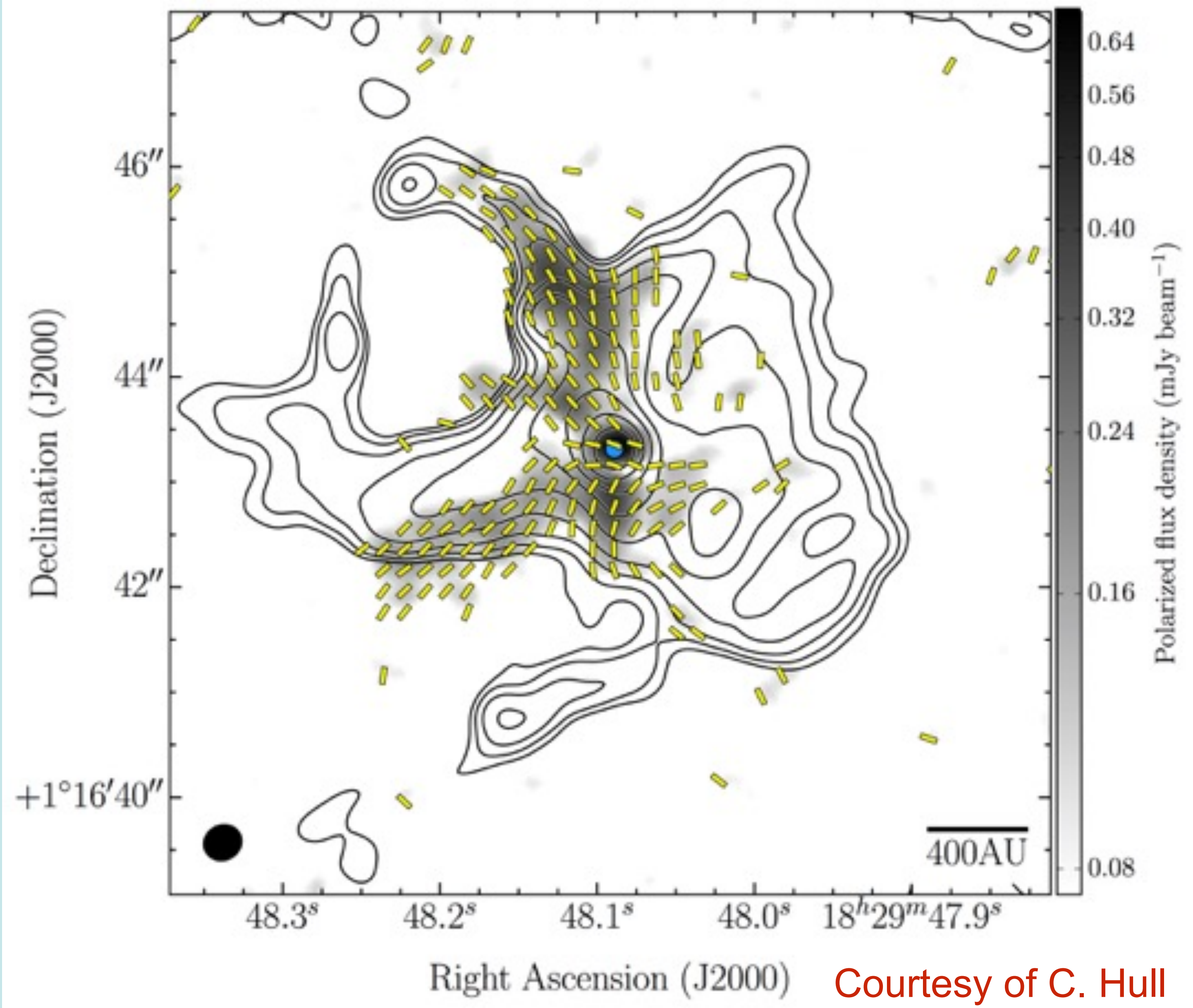
Houde+ 2016, ApJ, 820, 38

The ALMA Era…

The ALMA Era…


(Jy/beam) x10⁻³
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45
1.13989 mm
0.25
Declination (J2000)
24″
22″
20″
18″
+1°15′16″
50.0ˢ
49.8ˢ
18ʰ29ᵐ49.6ˢ
Right Ascension (J2000)
400AU
58″
56″
54″
+1°16′52″
49.0ˢ
48.9ˢ
48.8ˢ
48.7ˢ
48.6ˢ
18ʰ29ᵐ48.5ˢ
Polarized flux density (mJy beam⁻¹)
0.50 0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10
46″
44″
18ʰ29ᵐ47.9ˢ
0.64 0.56 0.48 0.40 0.32 0.24 0.16 0.08

The ALMA Era - Serpens 8

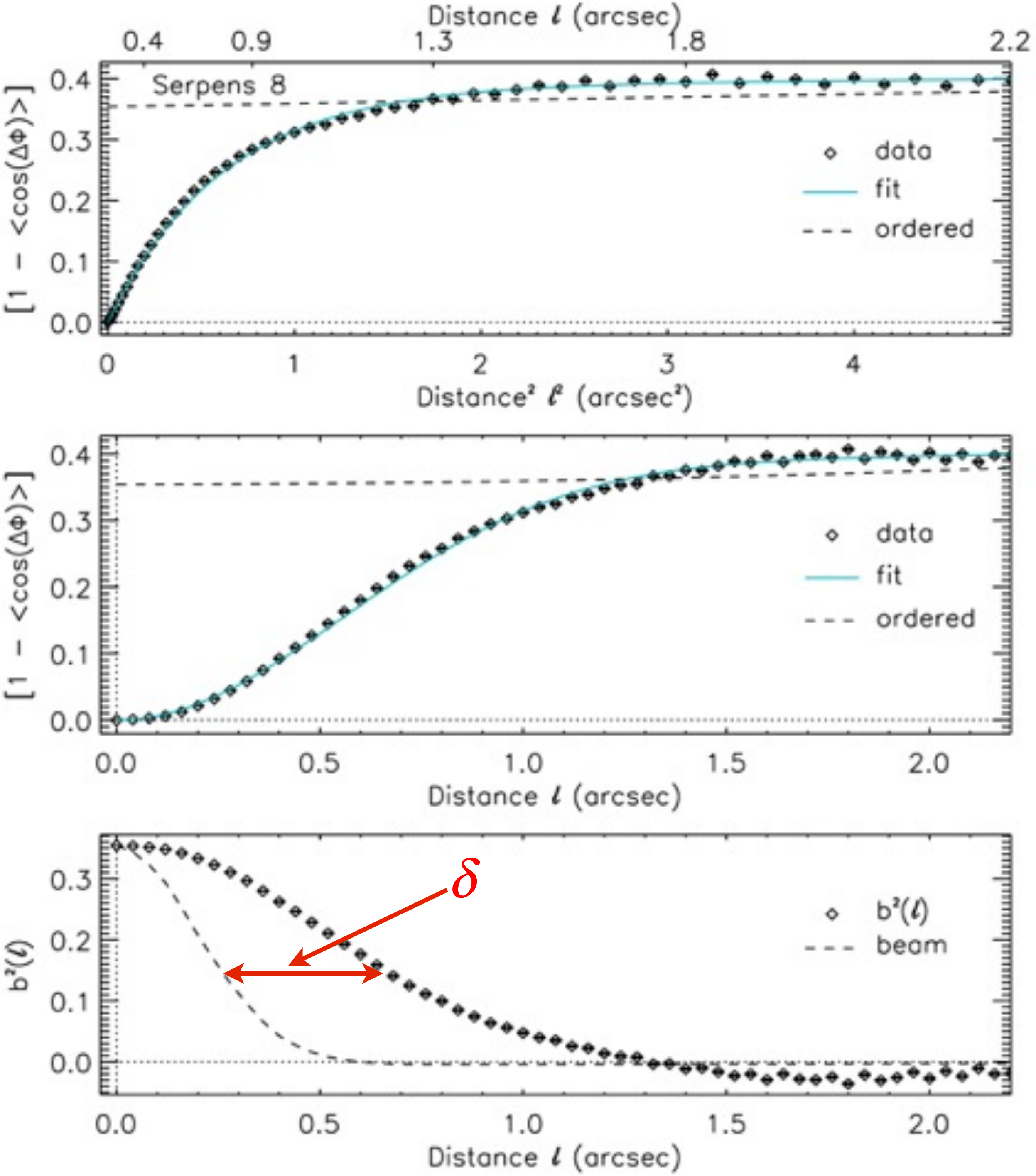


Courtesy of C. Hull

B-vectors

beam: 0.35” x 0.32”

sampling: 0.04”



8

B-vectors

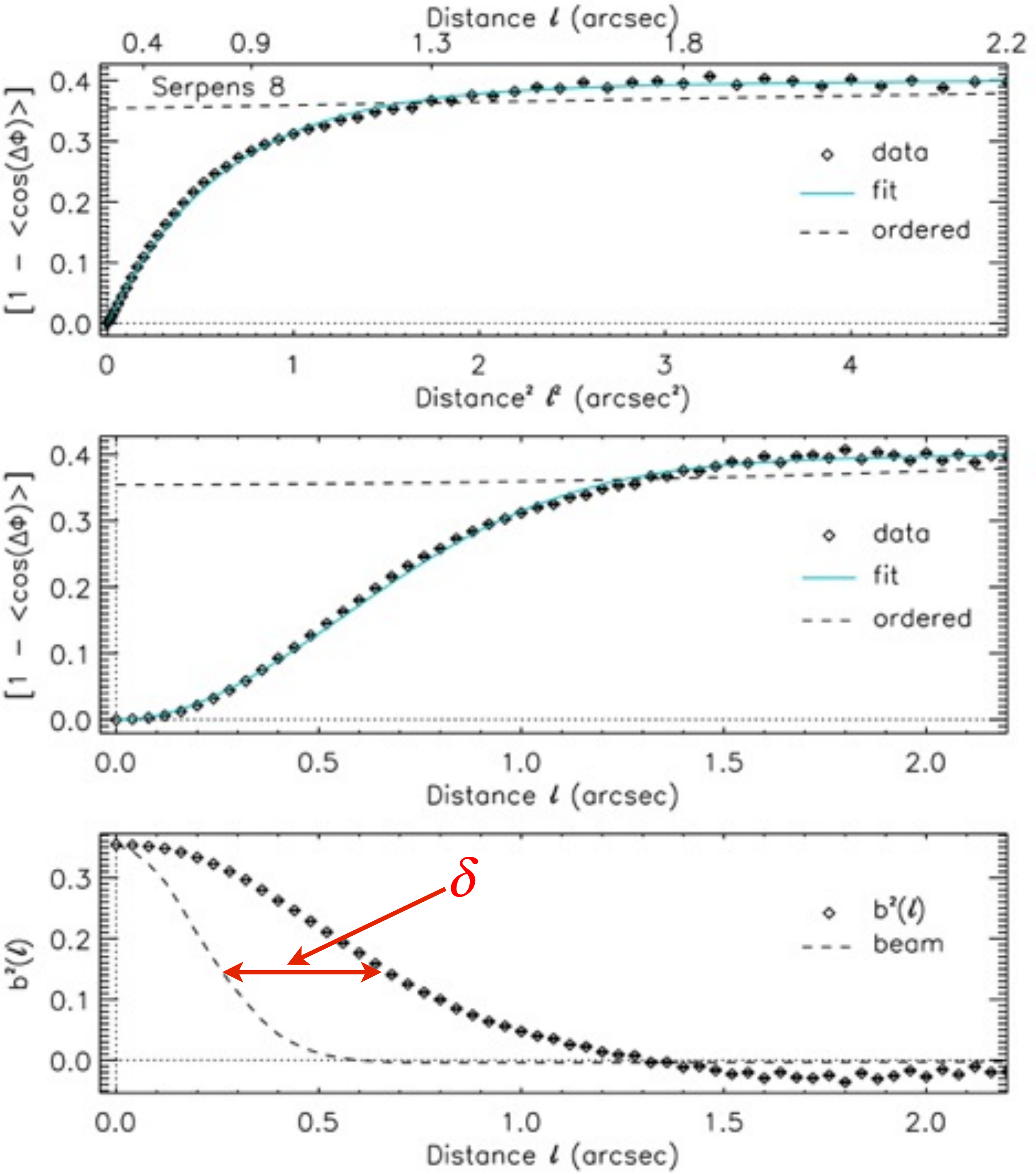
beam: 0.35” x 0.32”

sampling: 0.04”

$$\delta \simeq 1 \text{ mpc}$$

$$N \simeq 1.5$$

$$\frac{B_t^2}{B^2} \simeq 0.45$$



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B-vectors

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$$\frac{B_t^2}{B^2} \simeq 0.45$$

See:
P14 - C. Hull

ALMA - W3(OH)

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

but

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

Houde et al. 2011, ApJ, 733, 109

ALMA - W3(OH)

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

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 $H\left(k_v\right)$

Houde et al. 2011, ApJ, 733, 109

$1 -$

but

$\Rightarrow \langle$

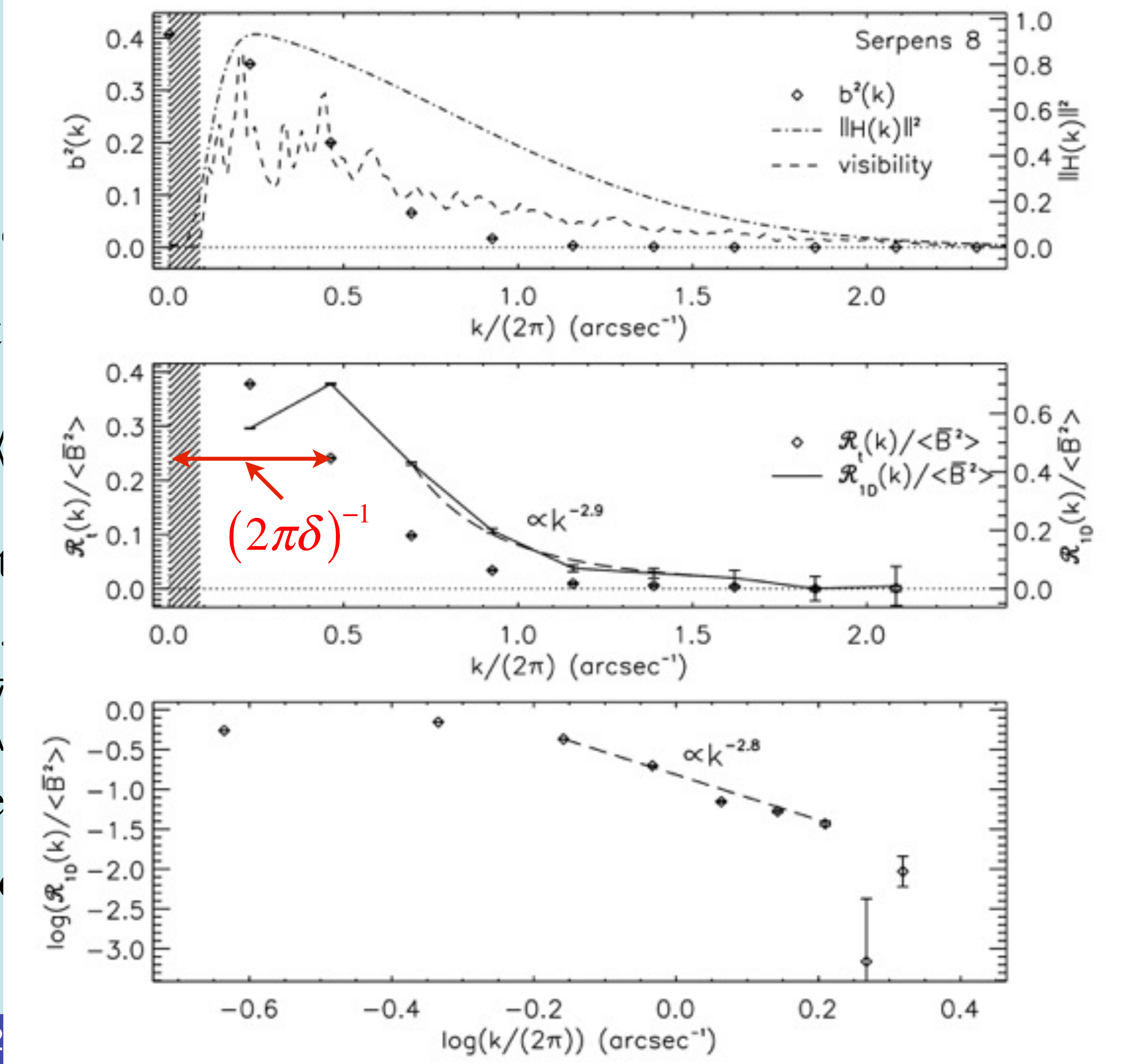
Wit

$\langle \bar{\mathbf{B}}$

$\langle$

We

by



$(2\pi\delta)^{-1}$

$1-$

but

$\Rightarrow \langle$

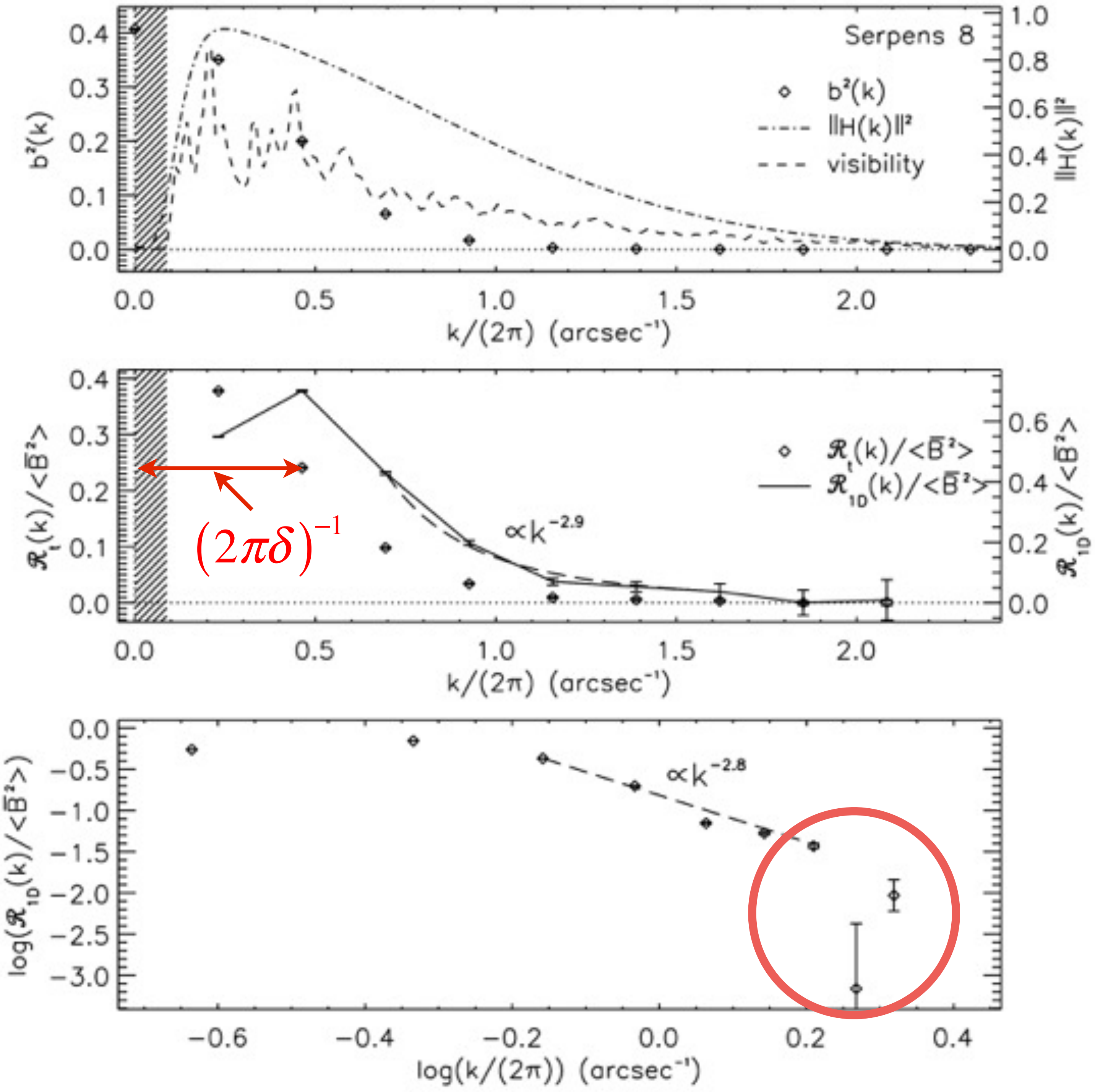
Wit

$\langle \bar{\mathbf{B}}$

$\langle$

We

by



$(2\pi\delta)^{-1}$

1 –

but

⇒ ⟨

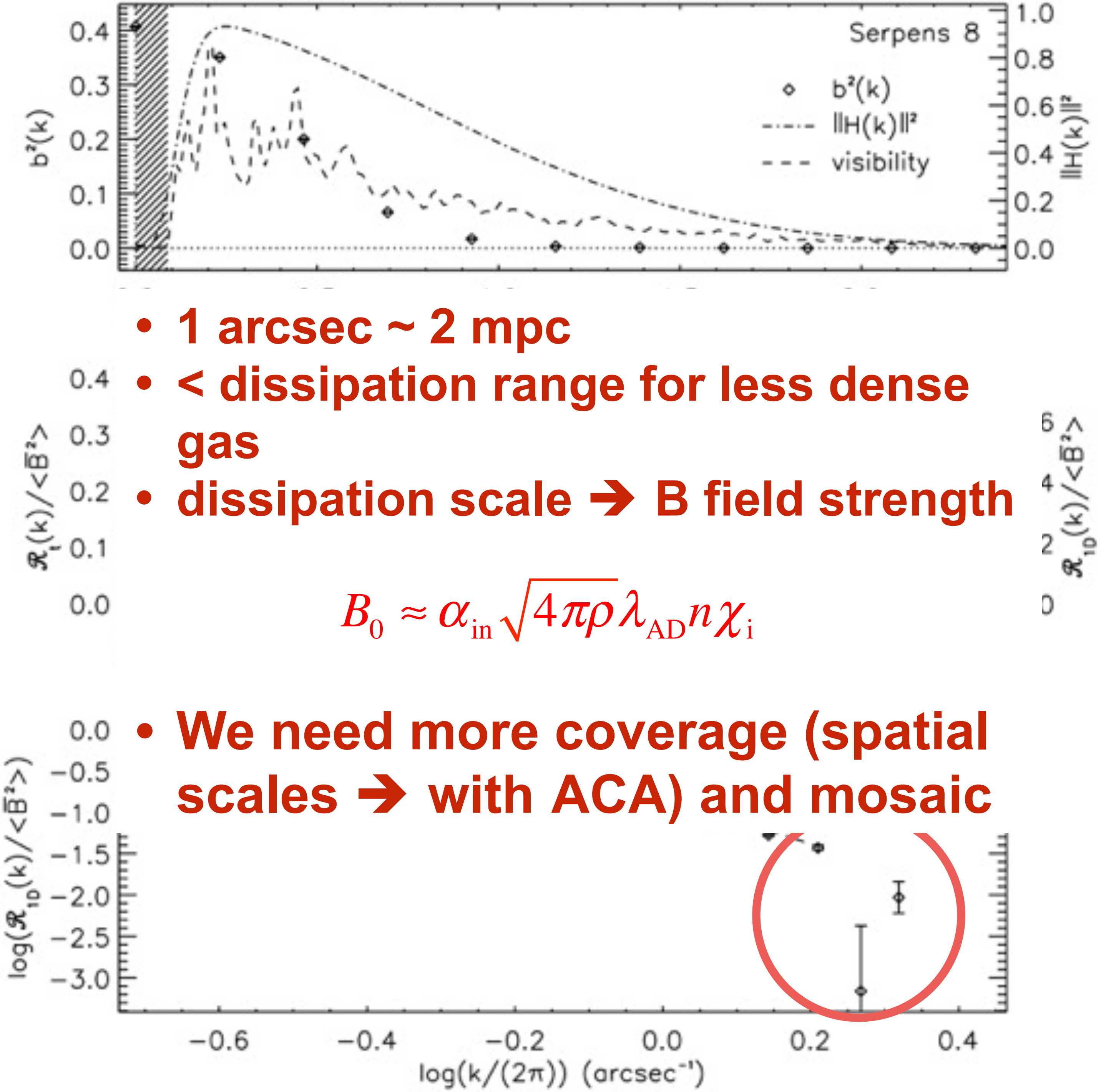
Wit

⟨**B̄**

⟨

We

by

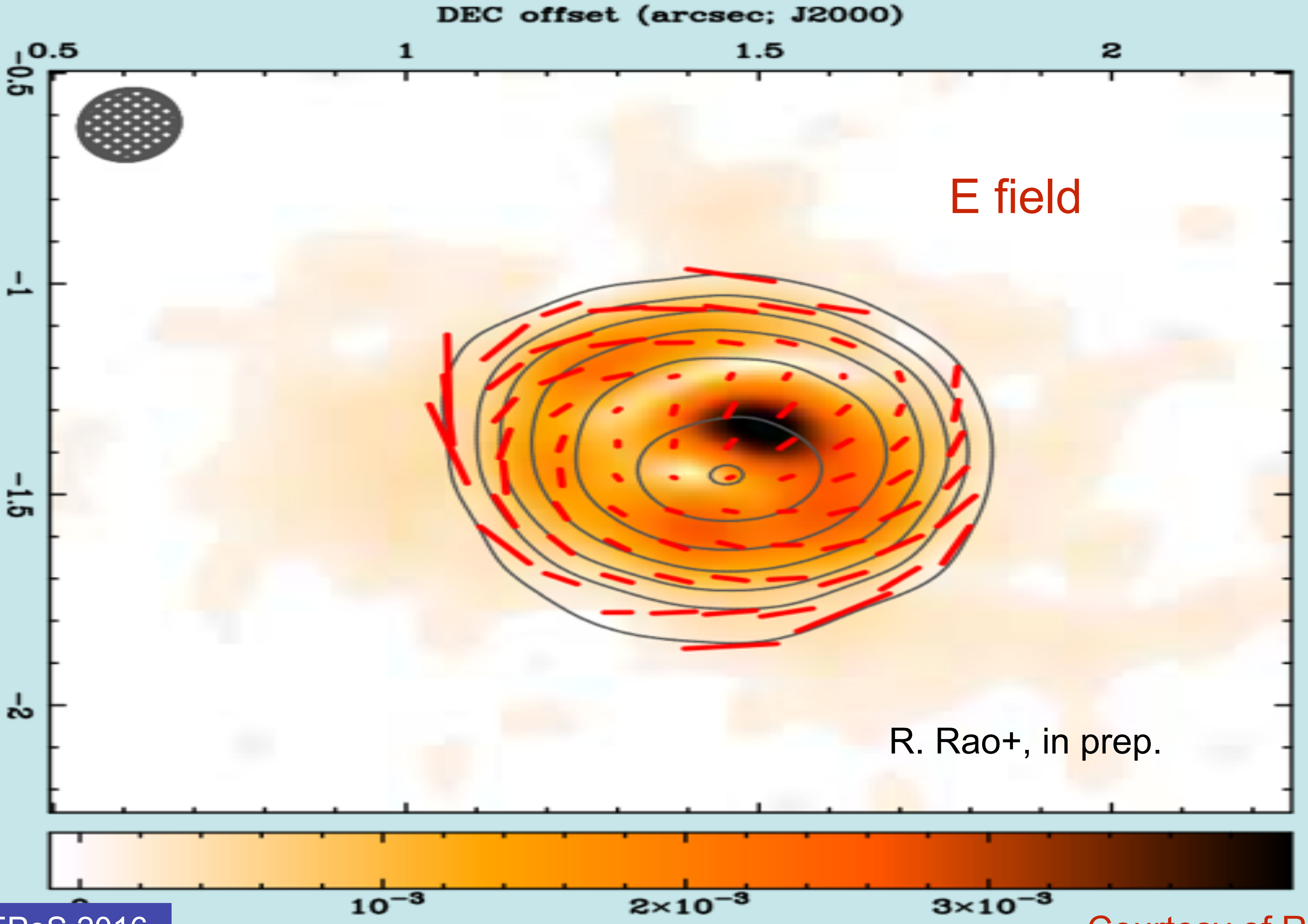


- **1 arcsec ~ 2 mpc**
- **< dissipation range for less dense gas**
- **dissipation scale ➔ B field strength**

$$B_0 \approx \alpha_{\mathrm{in}}\sqrt{4\pi\rho}\,\lambda_{\mathrm{AD}}\,n\chi_{\mathrm{i}}$$

- **We need more coverage (spatial scales ➔ with ACA) and mosaic**

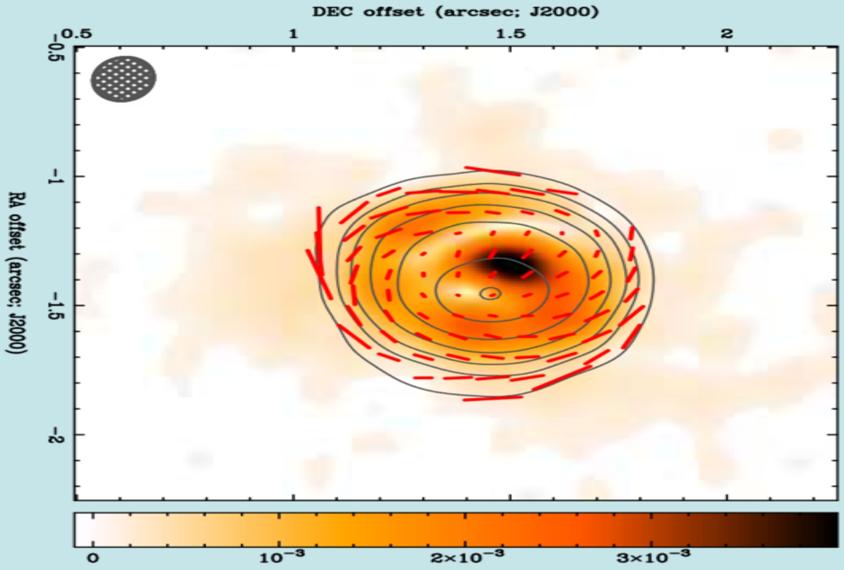
ALMA – IRAS16293B



R. Rao+, in prep.

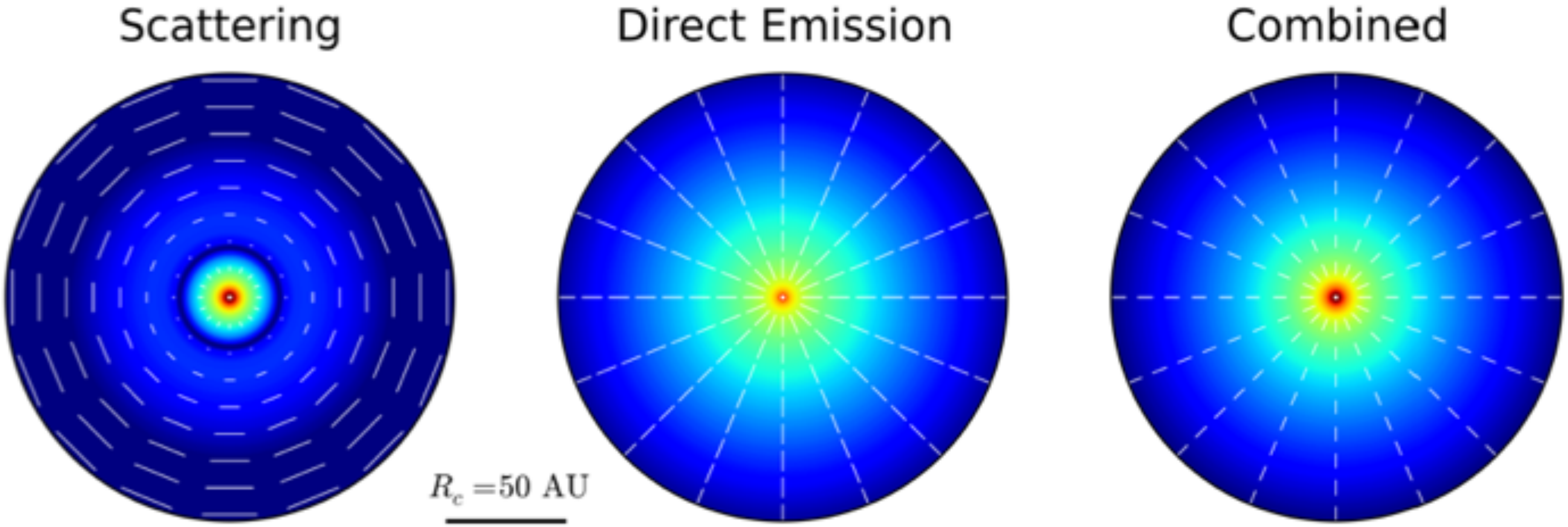
Courtesy of R. Rao

ALMA – IRAS16293B



R. Rao+, in prep.

Scattering Effects can be significant



Yang+ 2016, MNRAS, 456, 2794
Kataoka+ 2016, ApJ, 820, 54

Courtesy of R. Rao

The ALMA Era…

The ALMA Era…

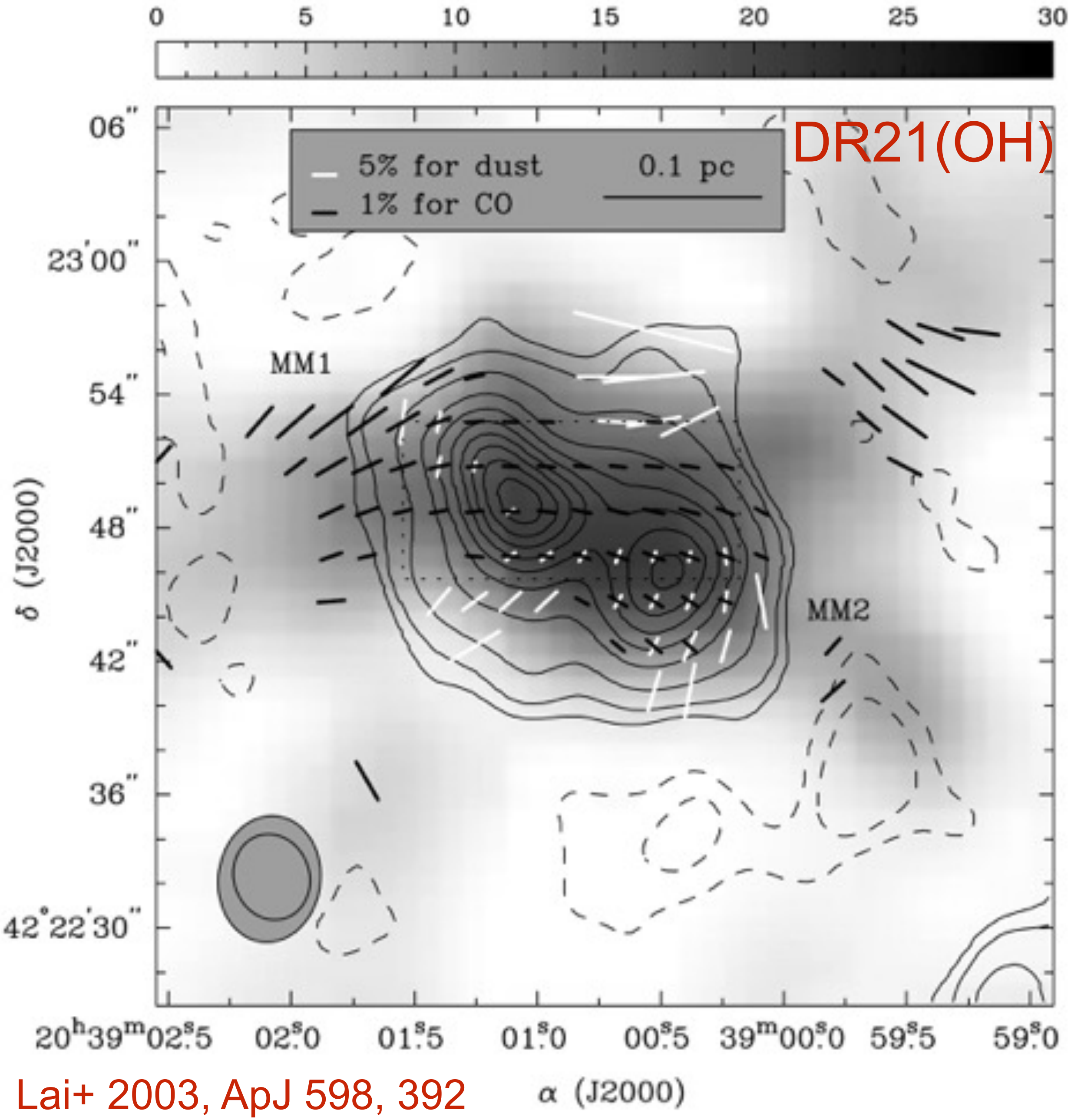
Don’t miss…

Focus Group 2 - Magnetic Fields and Polarization in Young Stellar Objects: Interpreting the Next Generation of Observations and Simulations (C. Hull and B. Liu).

Posters:
P03 - C.-Y. Chen
P10 - M. Gonzalez
P16 - R. Klein

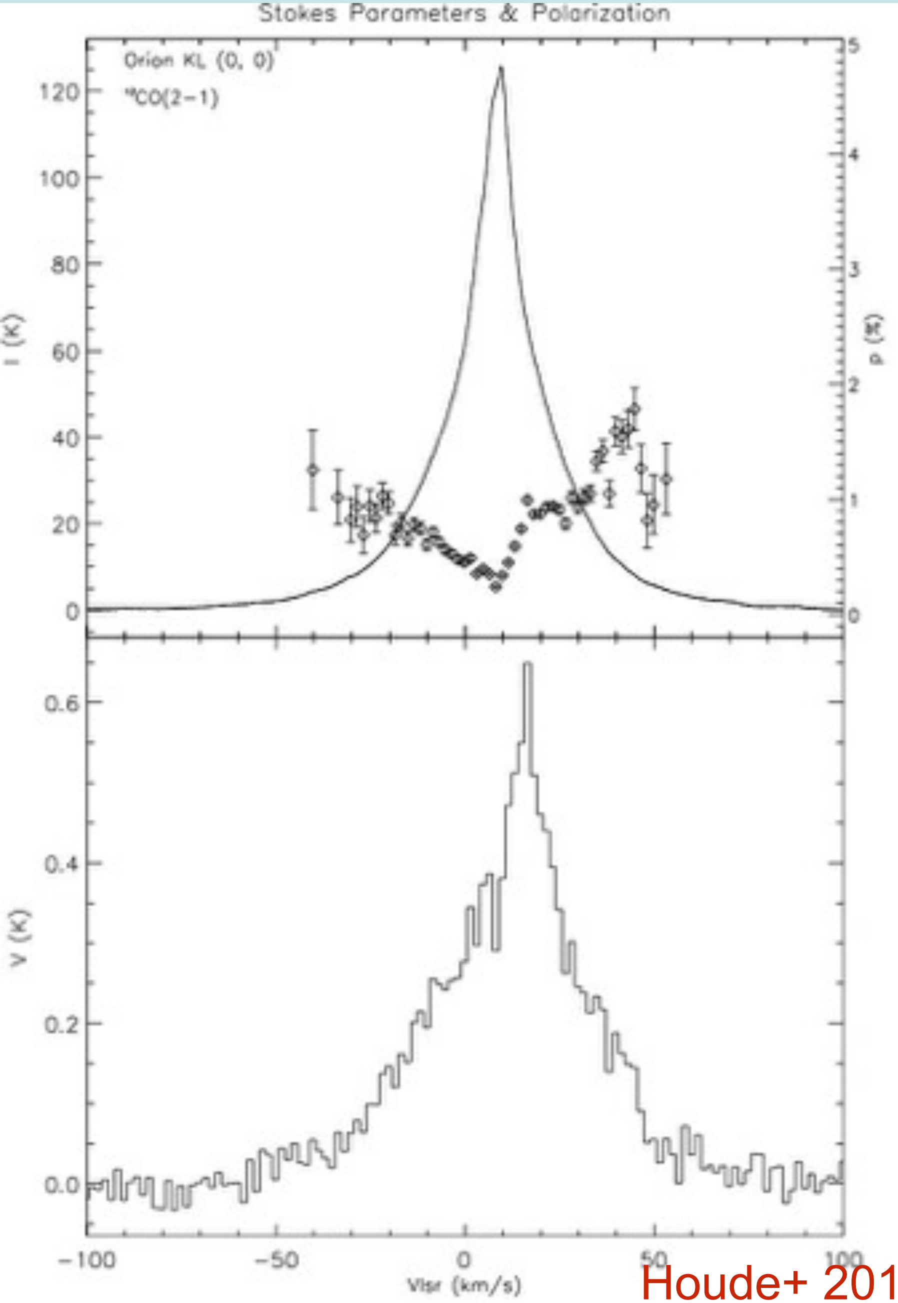
Goldreich-Kylafis (CO Linear Polarization)

- Complementary to dust polarization
- E.g., can be use to trace outflows
- GK effect has a 90 deg ambiguity…
- **We understand molecules better than dust**
- but there's a complication (opportunity)…



Lai+ 2003, ApJ 598, 392

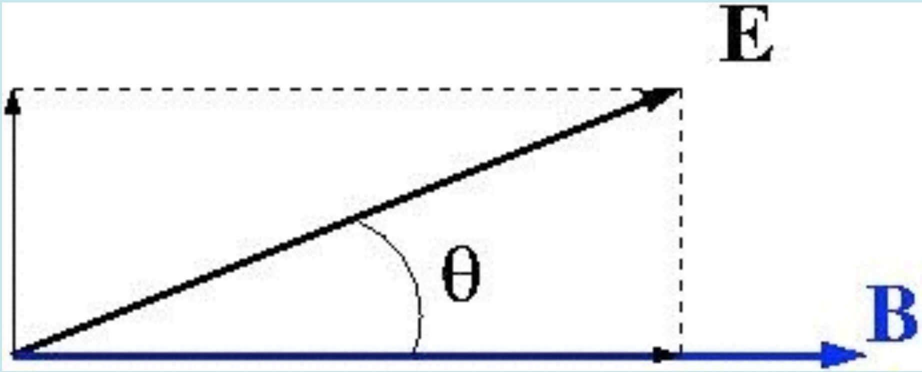
CSO / FSPPol - CP Measurements



- Circular polarization measurements in Orion KL of the $^{12}\mathrm{C}^{16}\mathrm{O}\left(J = 2 \rightarrow 1\right)$ rotational line at 230.5 GHz with FSPPol
- Zeeman splitting ~ 0.2 mHz/μG
  - ~4 orders of magnitude less than CN

Houde+ 2013, ApJ, 764, 24

Anisotropic Resonant Scattering



Radiation State of LP at angle θ

$$|\theta\rangle = \alpha|\parallel\rangle + \beta|\perp\rangle$$

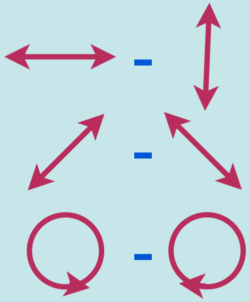
with $\alpha = \cos(\theta),\ \beta = \sin(\theta)$

$$|\theta'\rangle \simeq \alpha e^{-i\phi}|\parallel\rangle + \beta|\perp\rangle$$

$$Q = Q_0$$

$$U = U_0\cos(\phi)$$

$$V = U_0\sin(\phi)$$

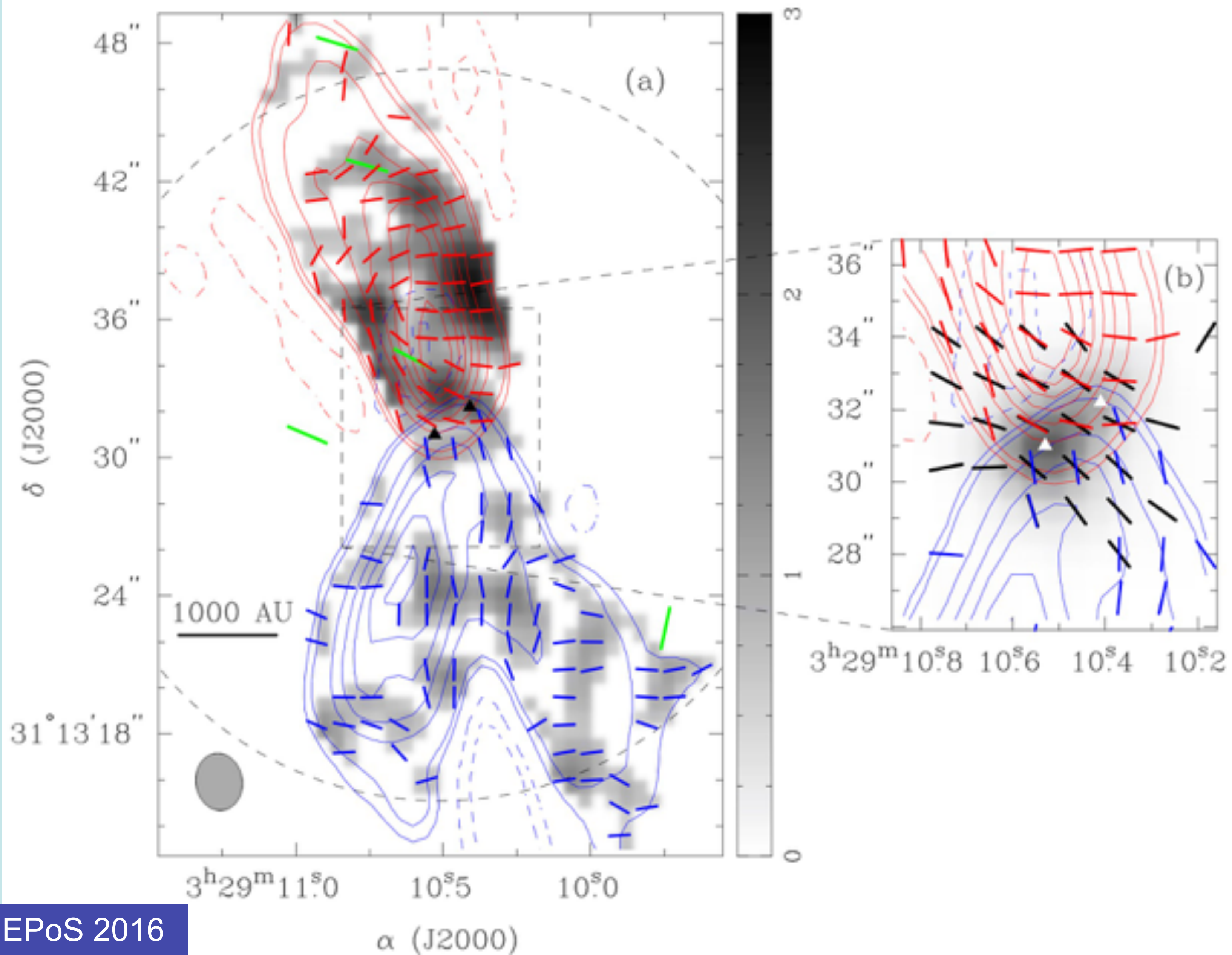


$$\tan(2\chi) = \cos(\phi)\tan(2\chi_0)$$

$$\boxed{\phi \propto B_{\mathrm{pos}}^2}$$

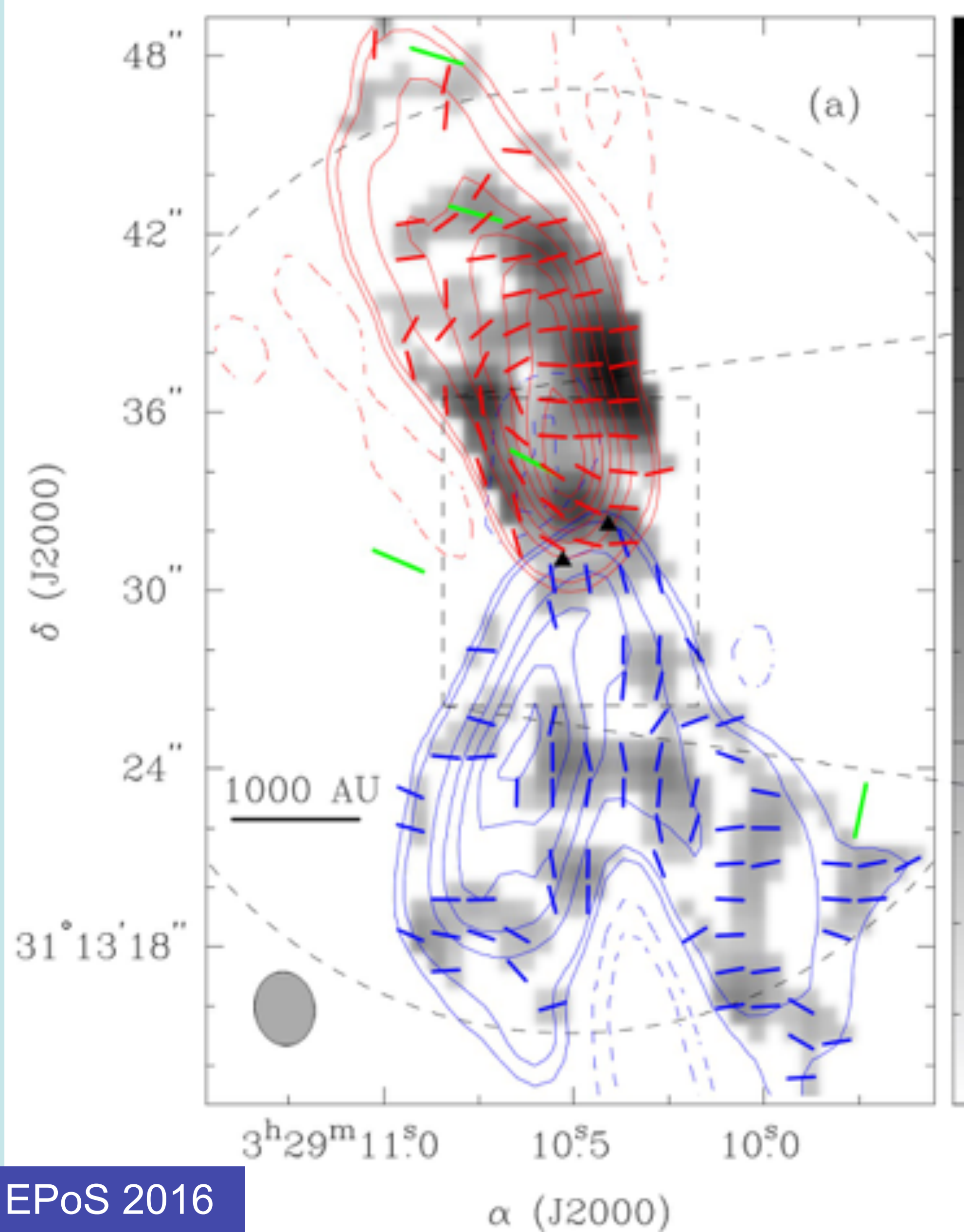
$$U_0 = U\cos(\phi) + V\sin(\phi)$$

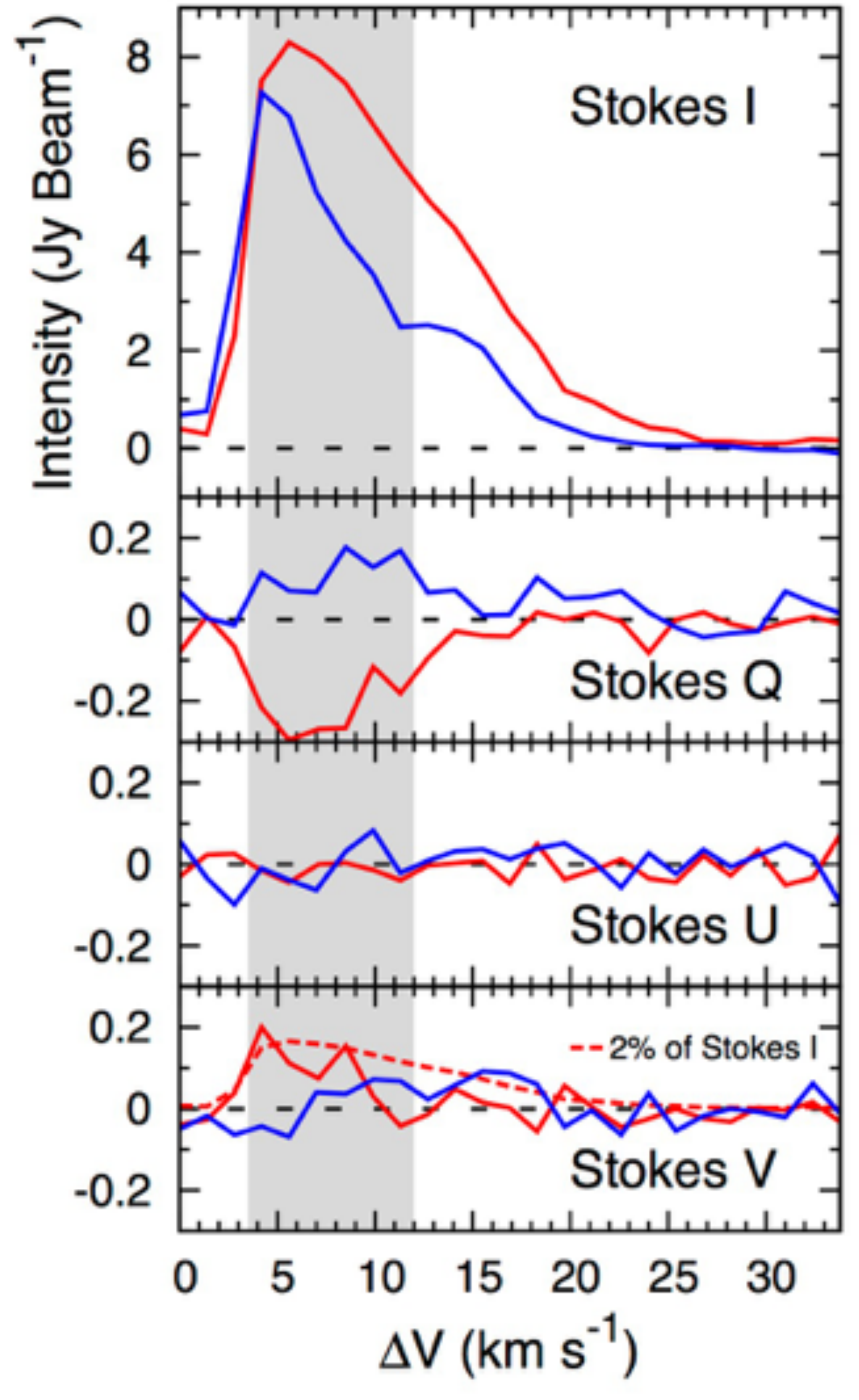
Goldreich-Kylafis (CO Linear Polarization)



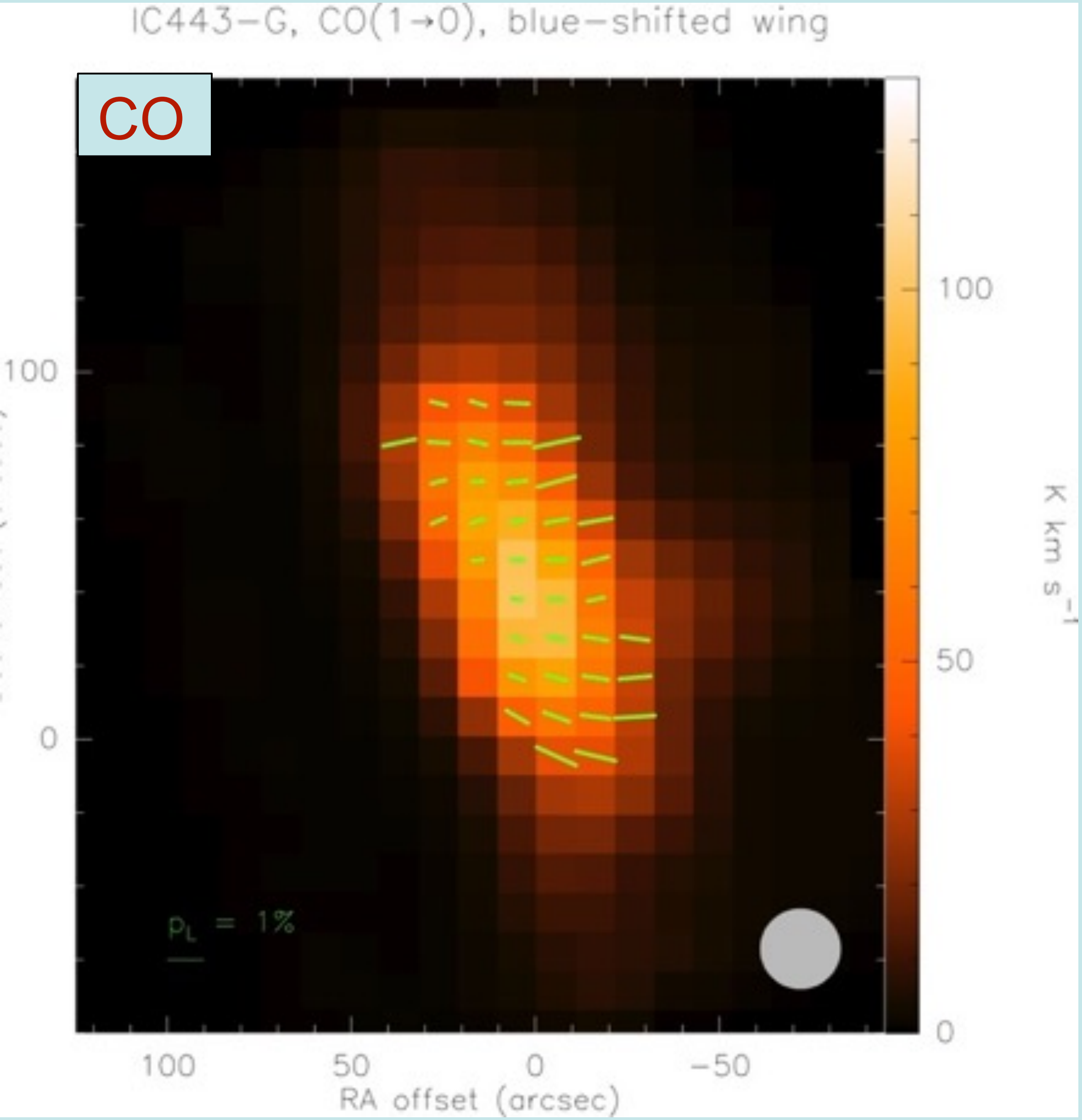
EPoS 2016

Goldreich-Kylafis (CO



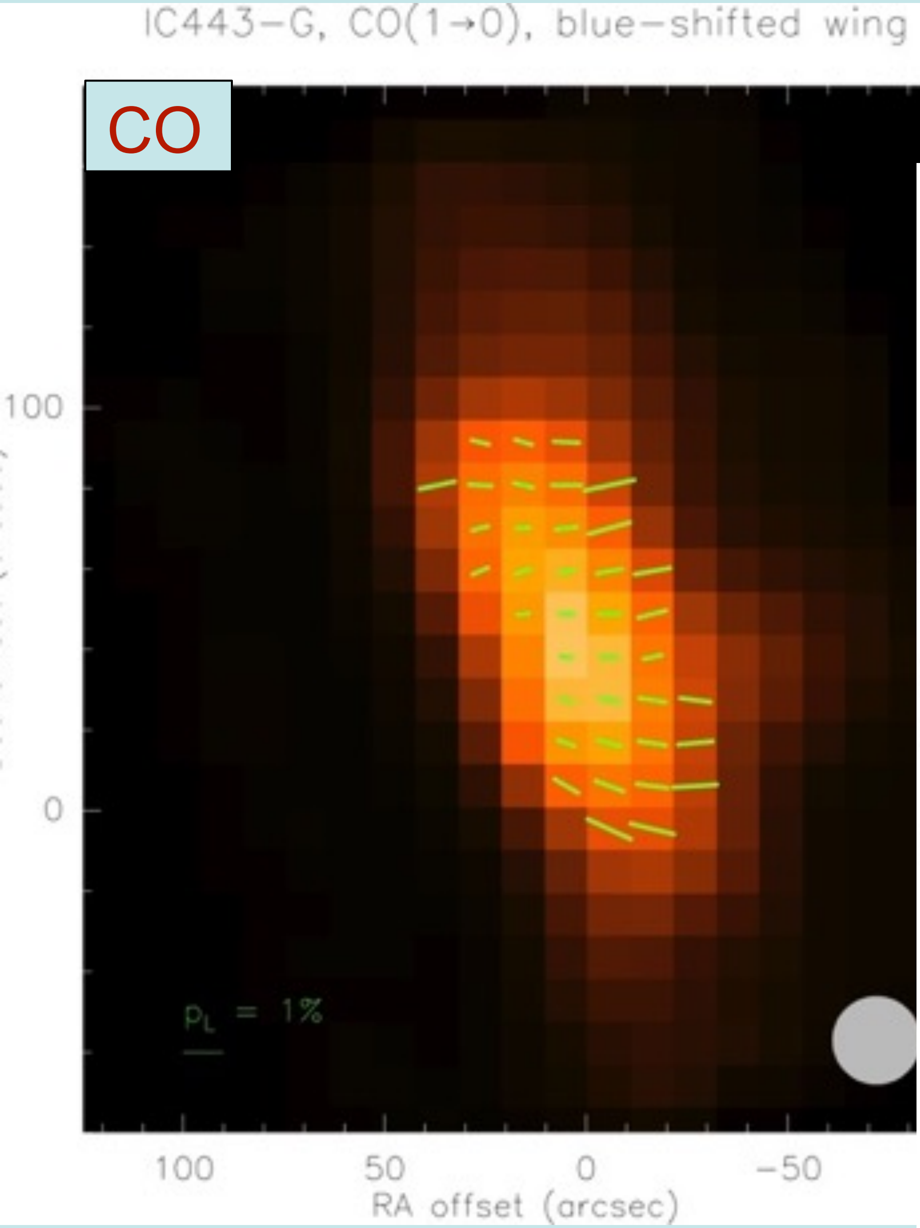


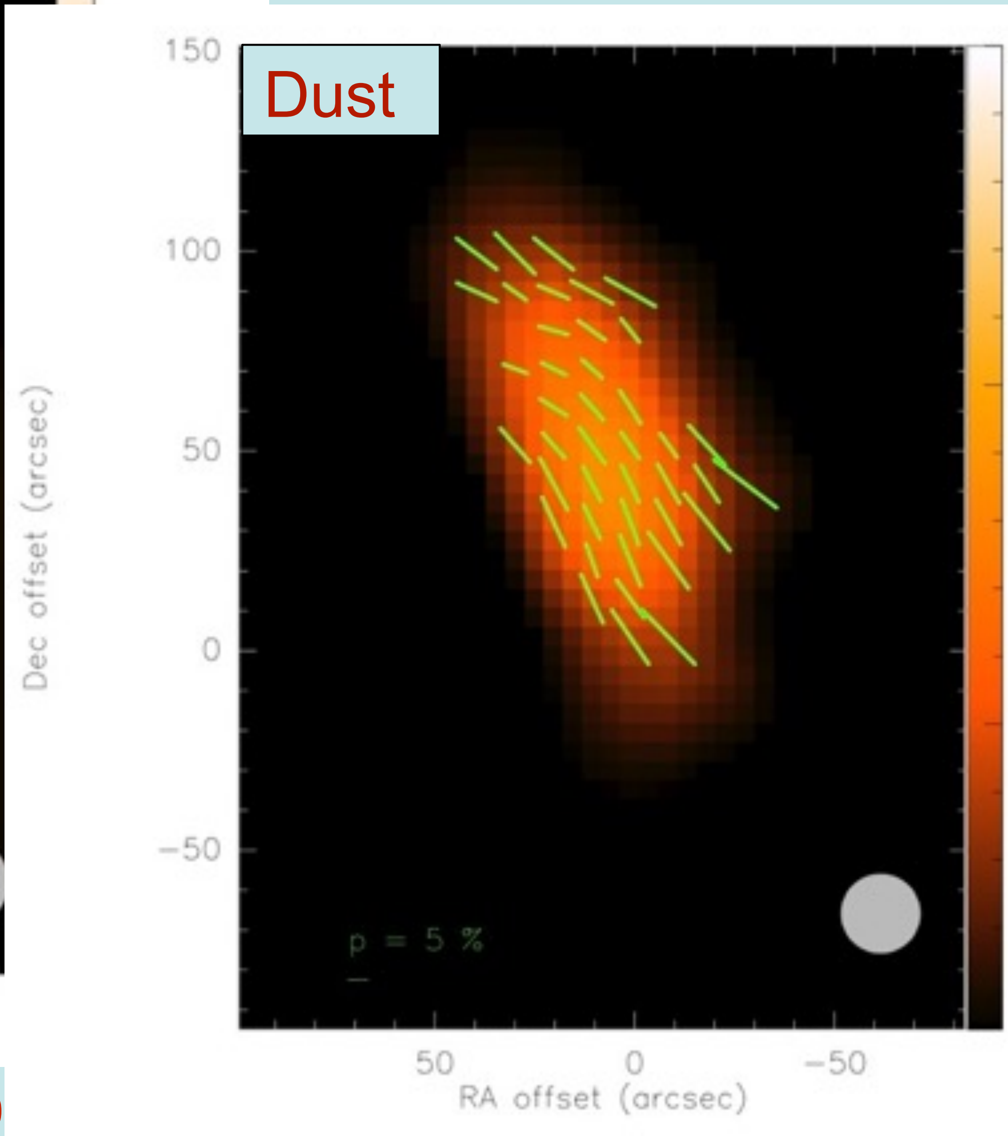
IRAM 30m/APEX - SNR IC 443 (G)



Hezareh+ 2013, A&A, 558, 45

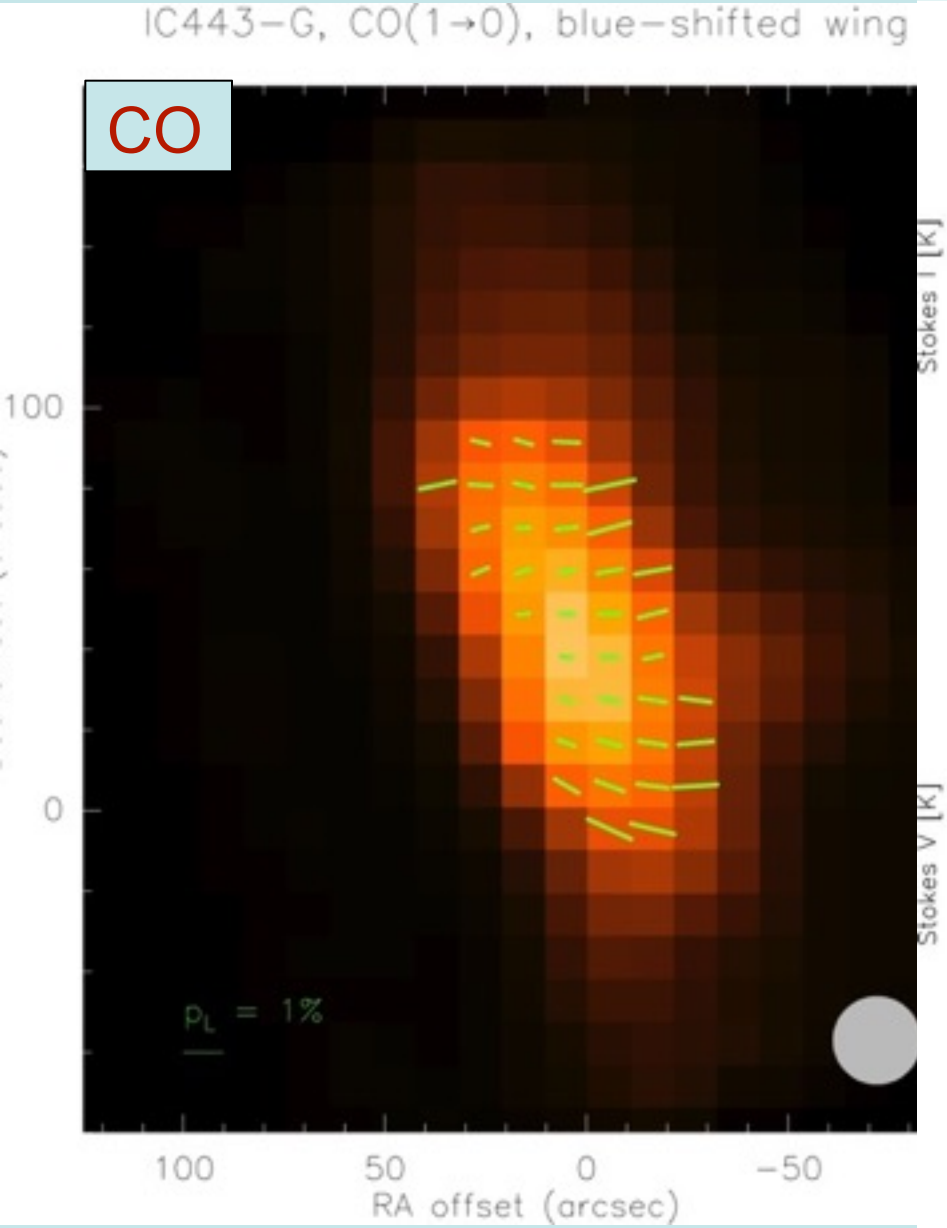
IRAM 30m/APEX - SNR IC 443 (G)

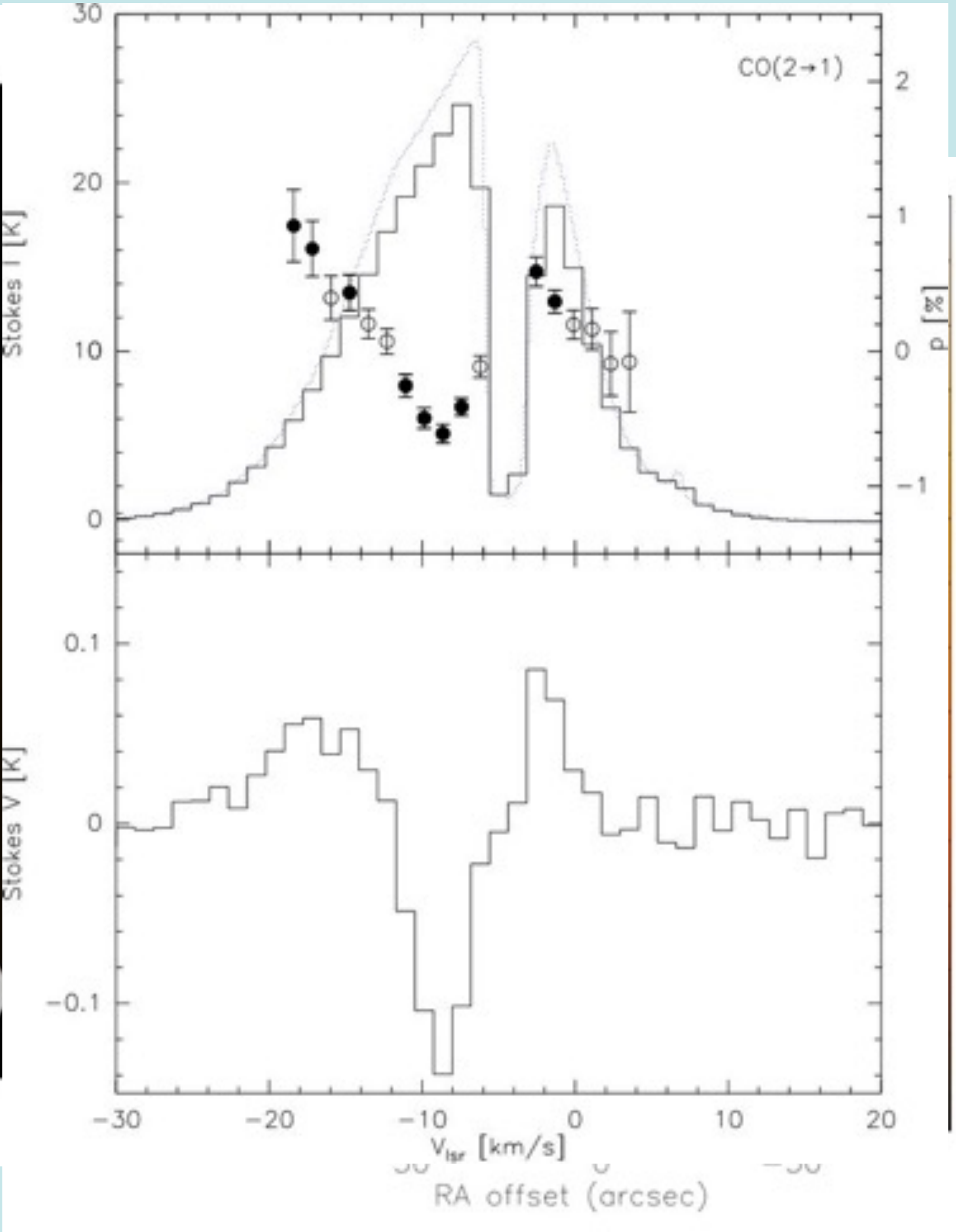




Hezareh+ 20

IRAM 30m/APEX - SNR IC 443 (G)





Hezareh+ 20

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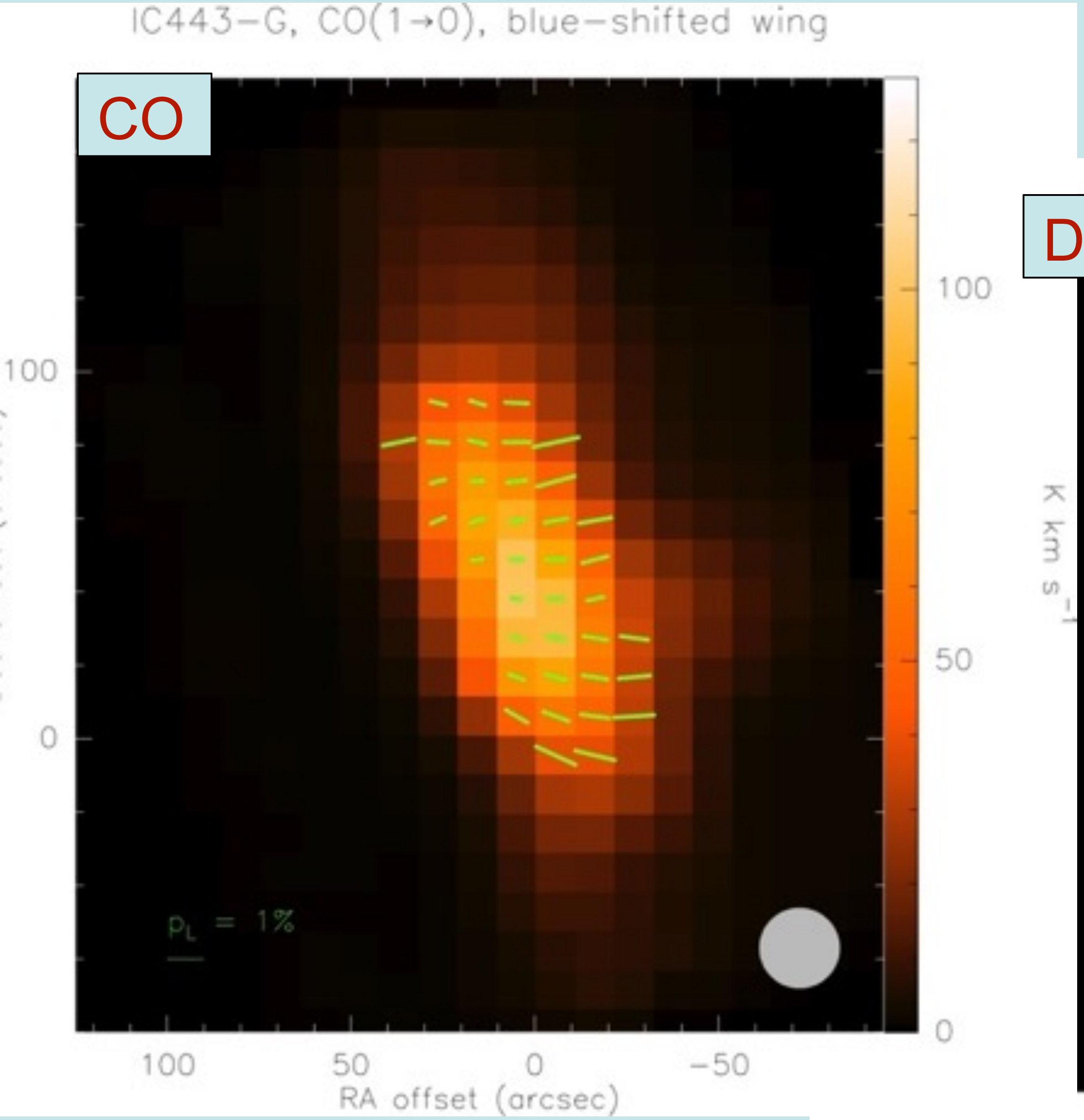
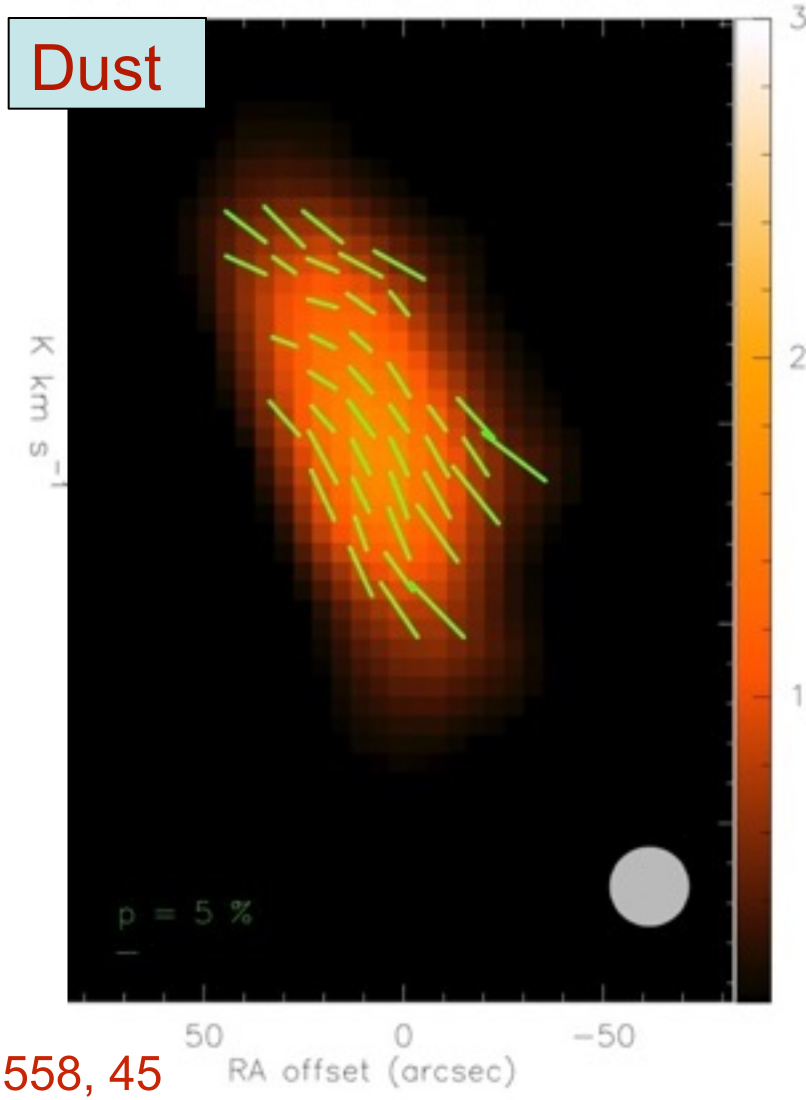
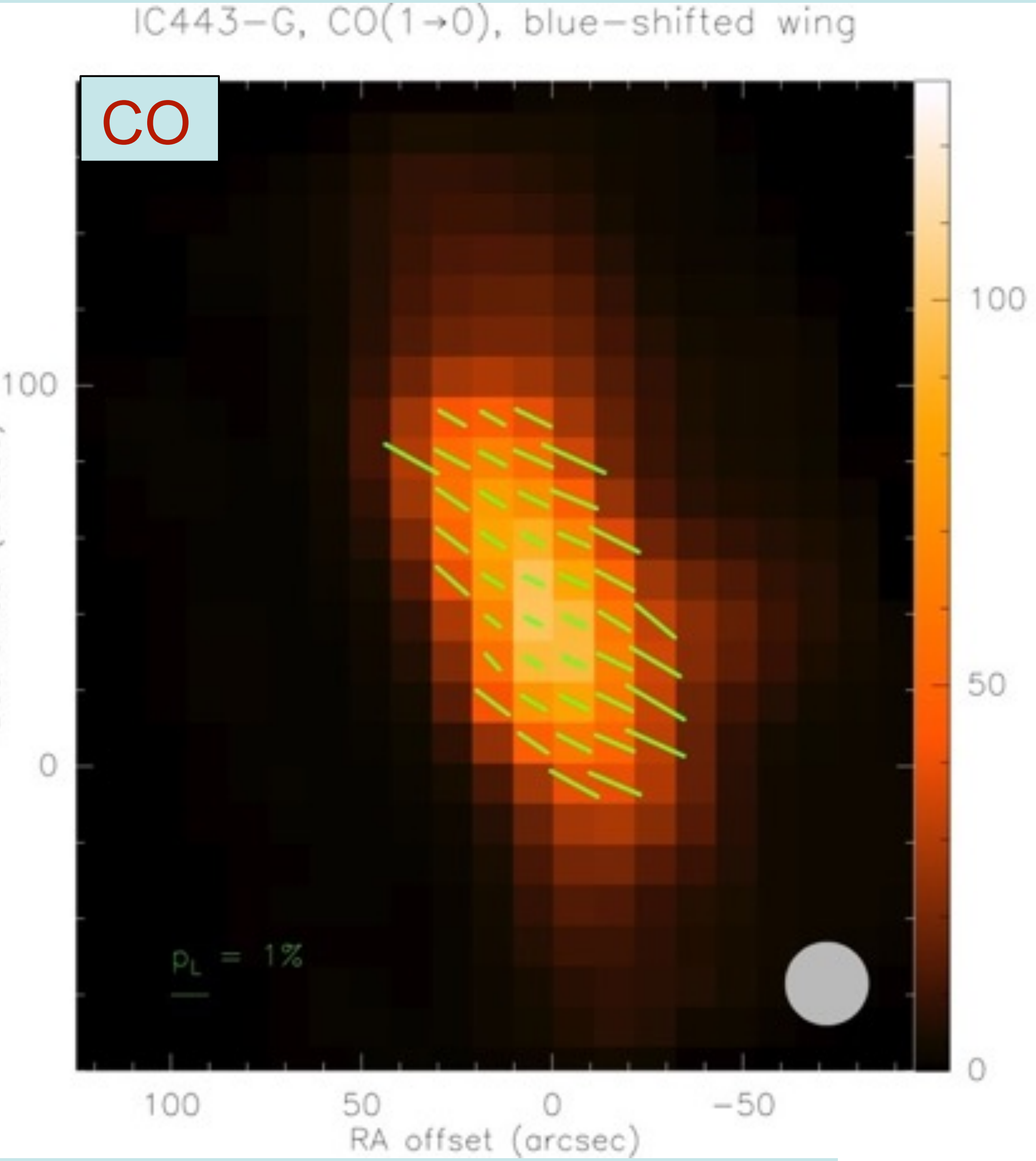
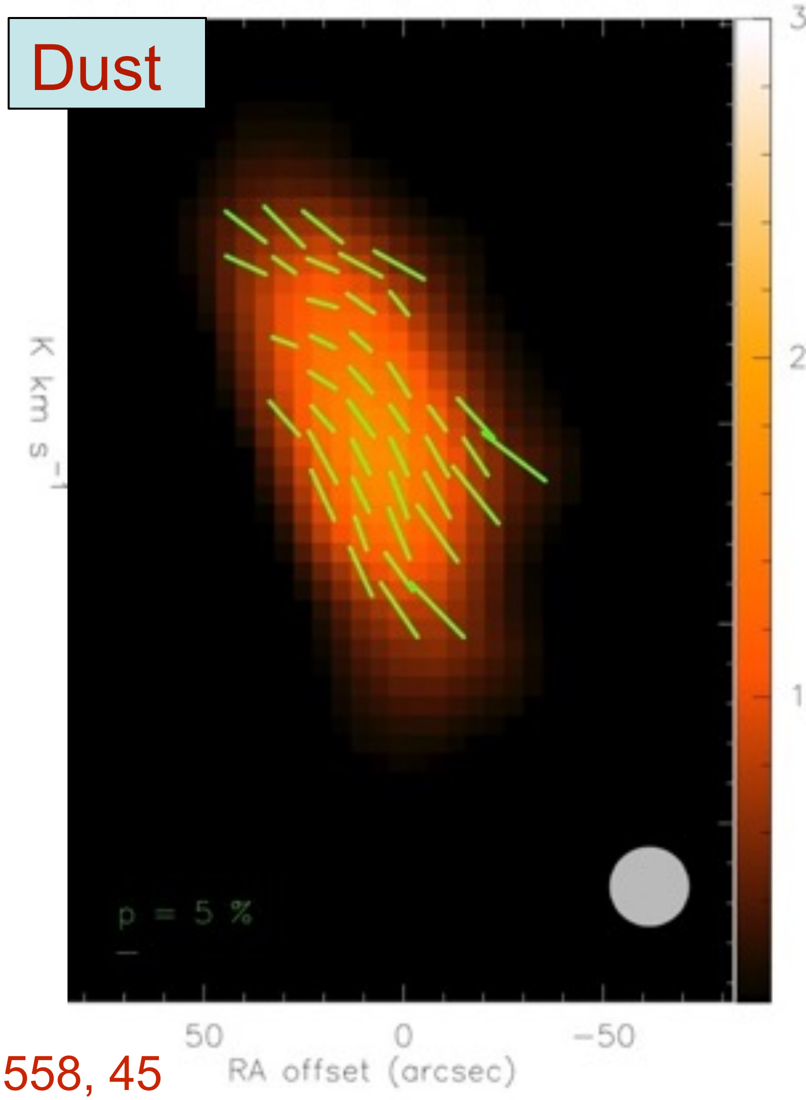




Hezareh+ 2013, A&A, 558, 45

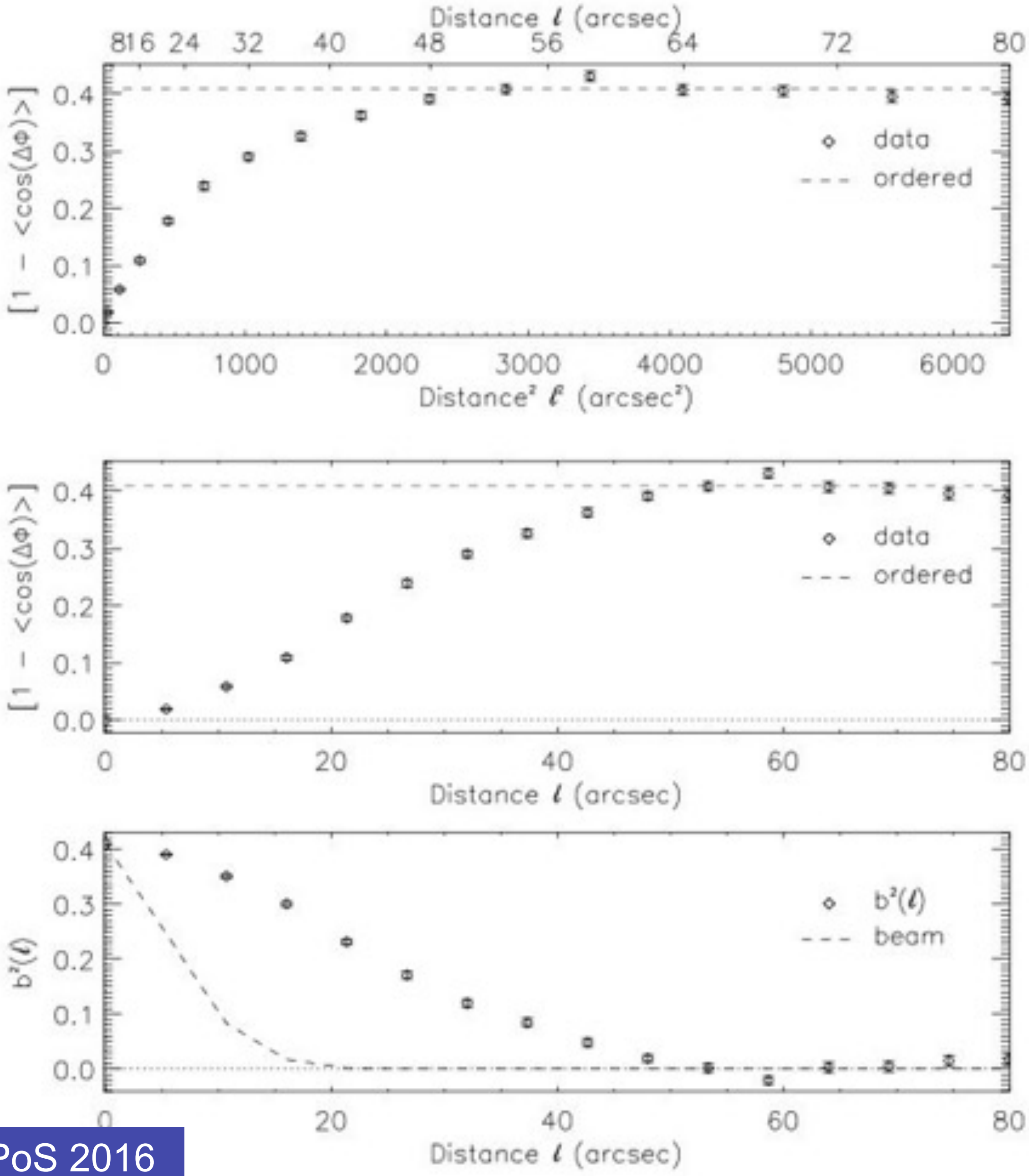
IRAM 30m/APEX - SR IC 443 (G)



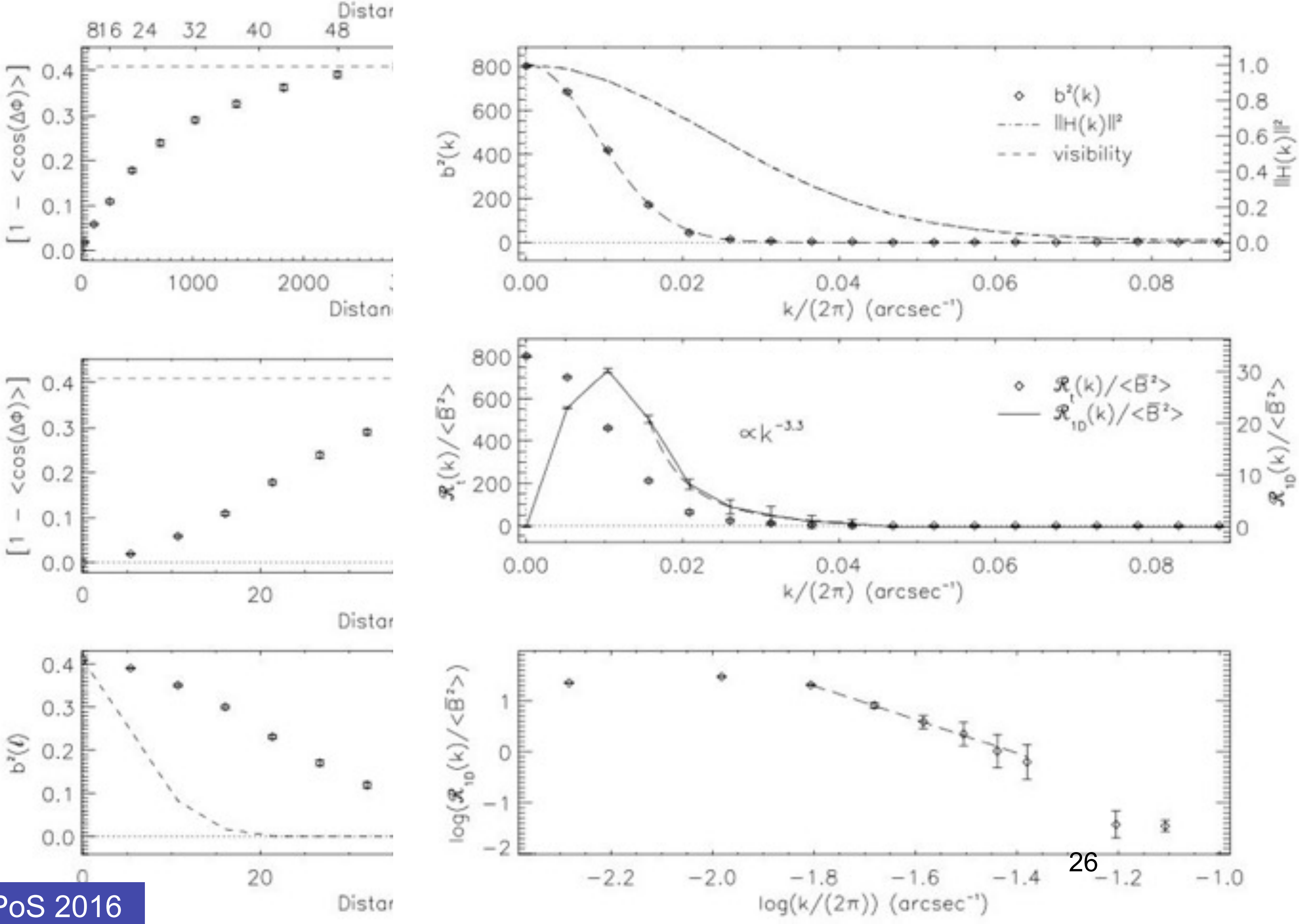


Hezareh+ 2013, A&A, 558, 45

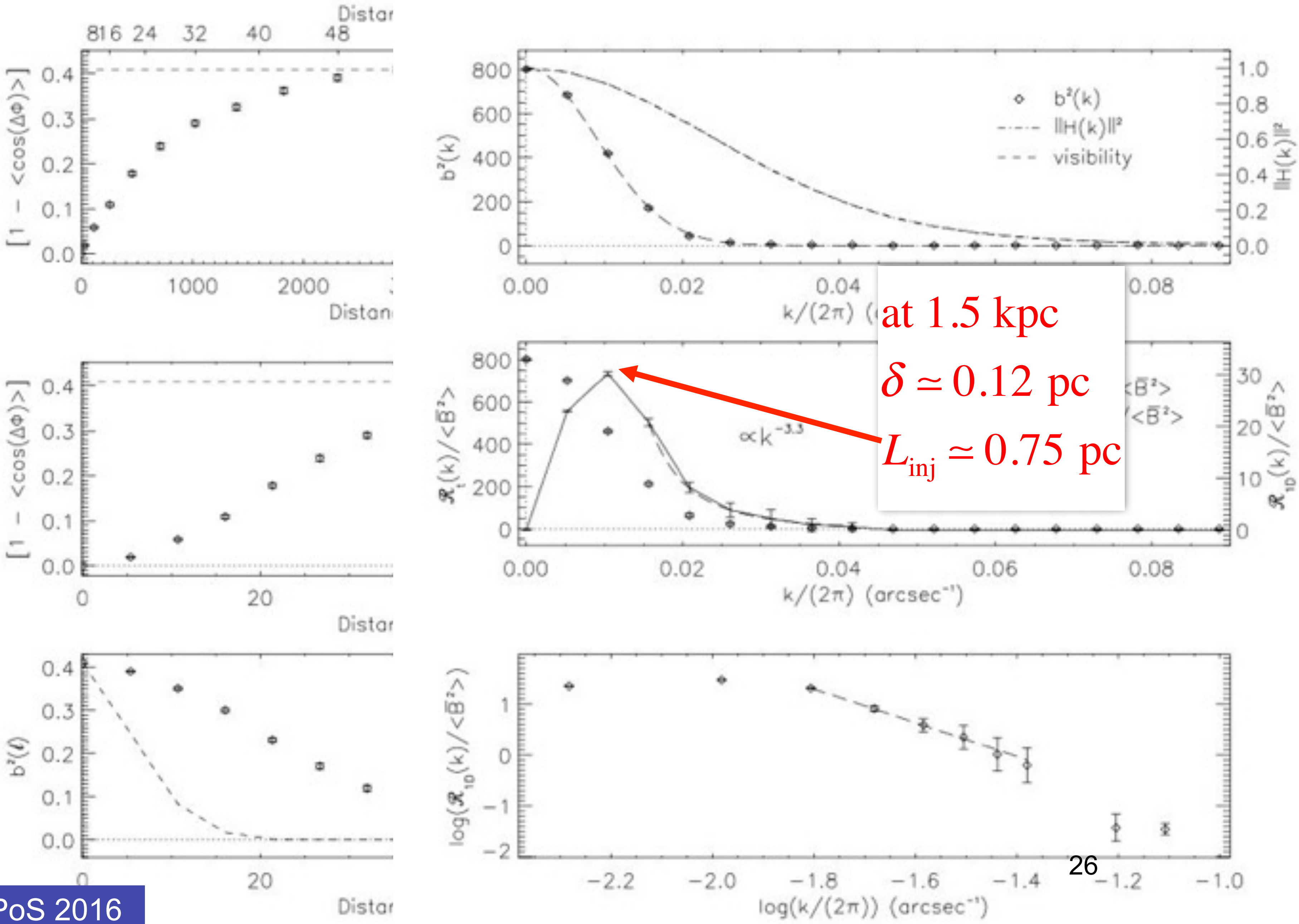
Line Polarization / Dispersion - SNR IC 443



Line Polarization / Dispersion - SNR IC 443



Line Polarization / Dispersion - SNR IC 443



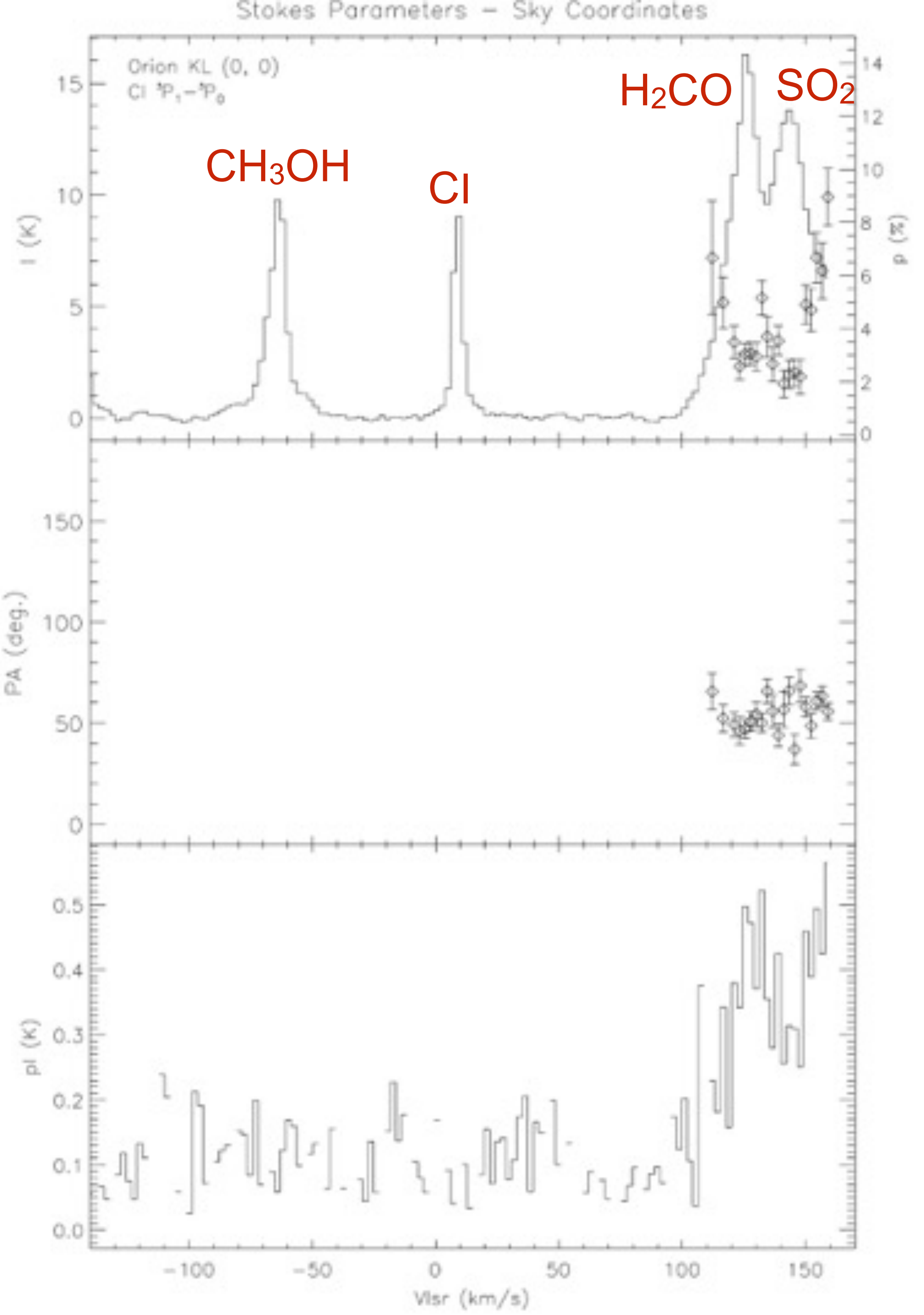
at 1.5 kpc

$\delta \simeq 0.12$ pc

$L_{\mathrm{inj}} \simeq 0.75$ pc

CSO / FSPPol - LP measurements

- CO is not the only species to exhibit polarization
- Different species/lines will trace different density regimes ➔ tomography
- Much better suited for the DCF technique



Summary

- Much progress in the observational characterization of magnetized turbulence.
- Still very difficult to obtain precise measurements of magnetic field strength ➔ Statistics!
- Improvements with ALMA and new instruments will help (e.g., SOFIA/HAWC+, IRAM/NIKA2…); we need more spatial coverage on small and large scales.
- Zeeman and dust linear polarization maps are still our main tools, but we should be focusing on spectral lines
  - We need Stokes I, Q, U, and V (for dust too!).
- And… Molecule ion-neutral spectral line comparisons… Good recent developments on theoretical/simulation fronts; provides a complementary path to magnetized turbulence without polarization measurements.

Merci !

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