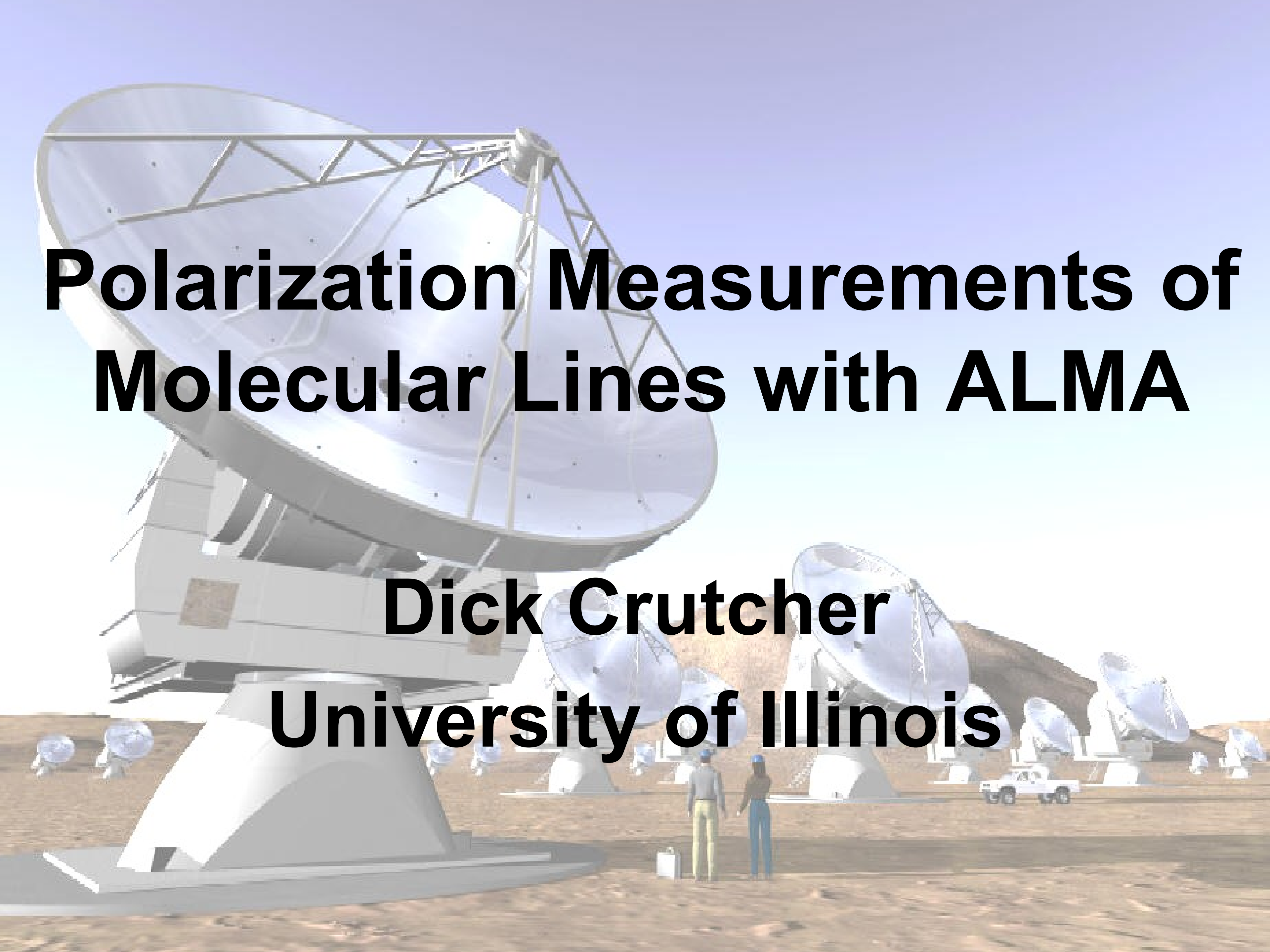


Polarization Measurements of Molecular Lines with ALMA

Dick Crutcher

University of Illinois

Why bother with polarization?

Magnetic fields!

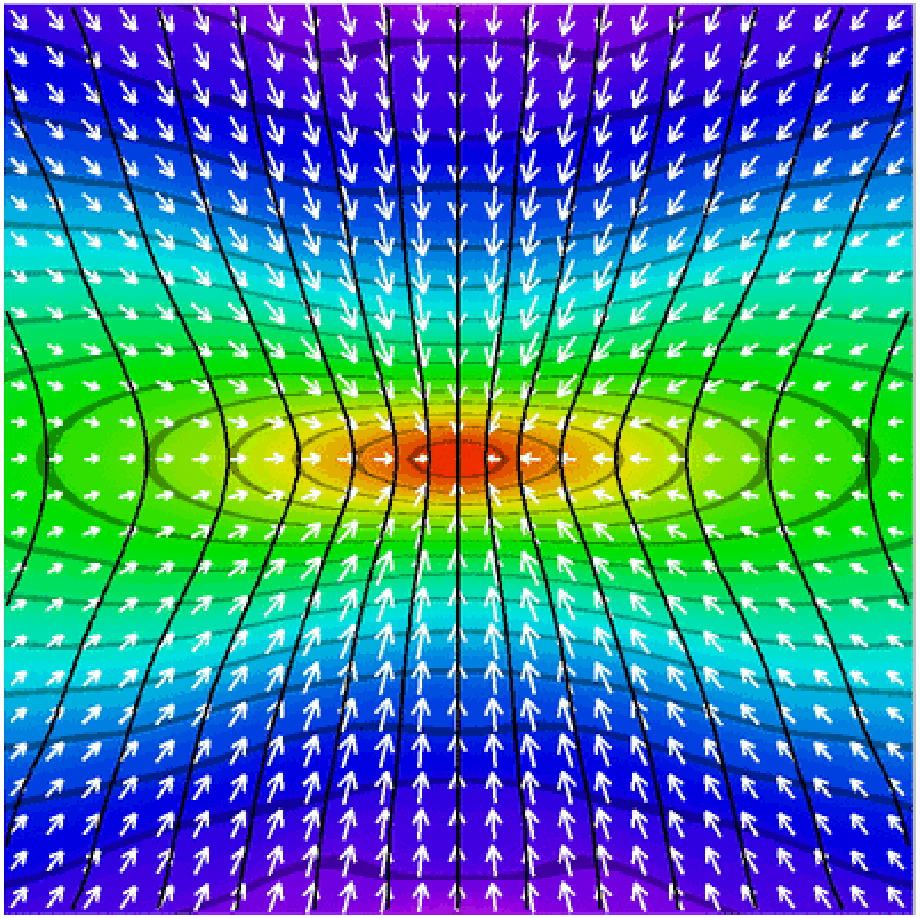
Why magnetic fields?

“Magnetic fields are to astrophysicists what sex is to psychoanalysts.”

- H. C. van de Hulst

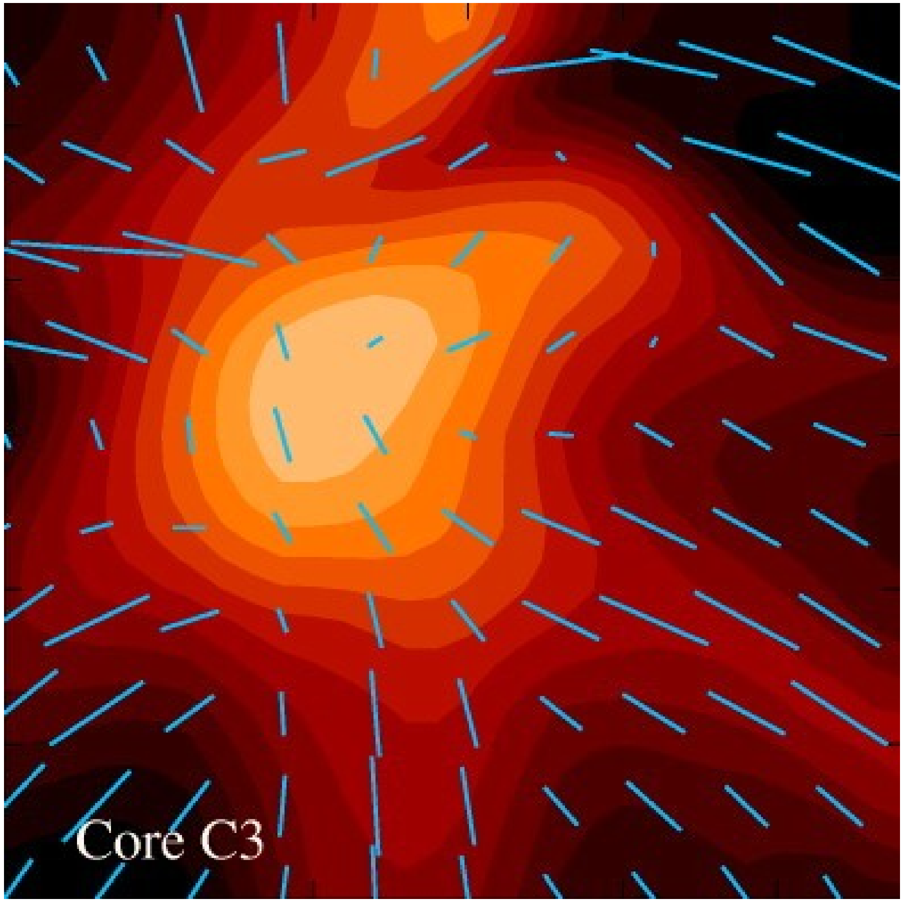
Magnetic Field Morphology

strong field case



Fiedler and Mouschovias (1993)

weak field case



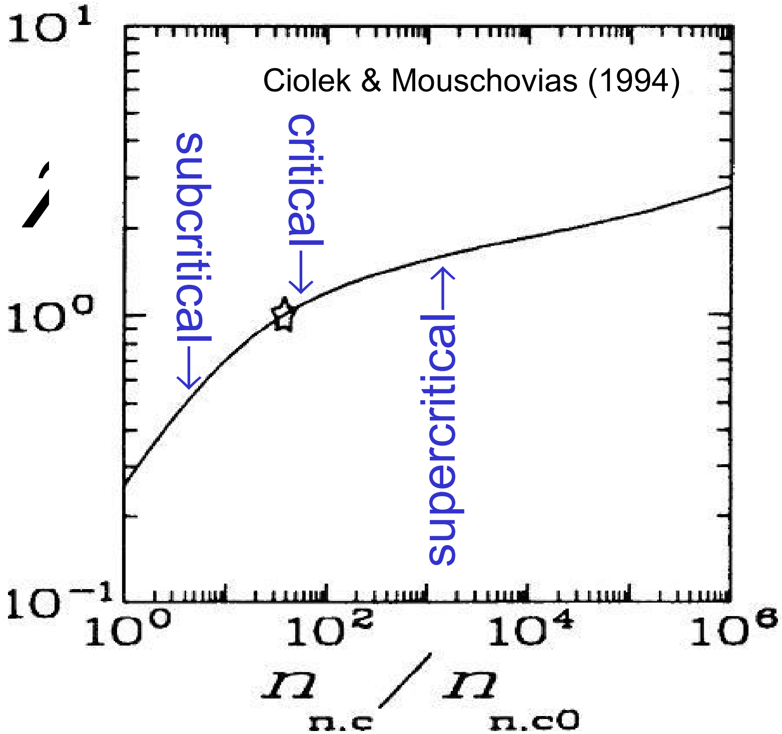
Padoan et al (2001)

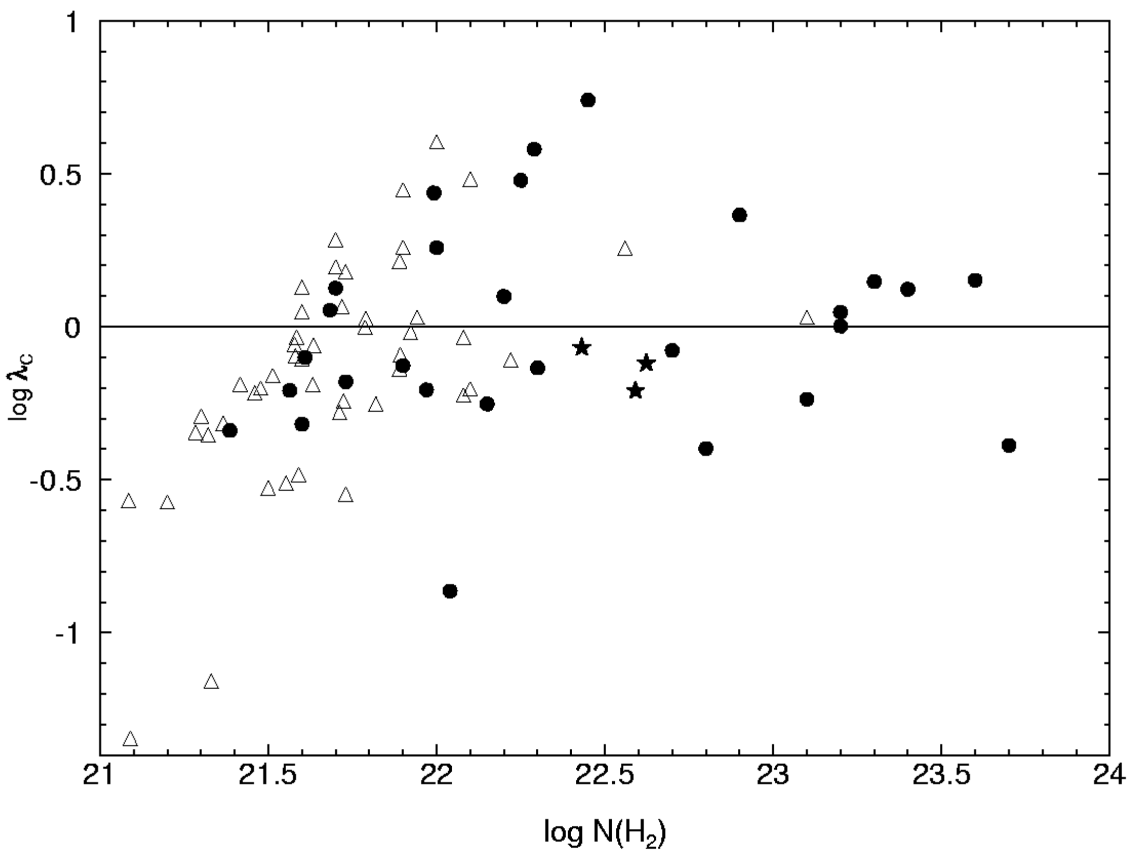
Mass-to-Flux Ratio: M/Φ

mass/flux ratio ≡ gravitational collapse / magnetic support

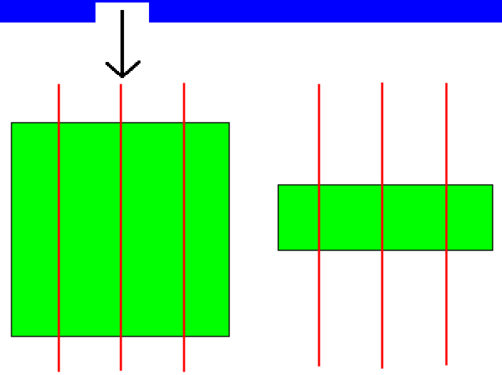
$$\frac{M_{observed}}{\Phi_{observed}} \propto \frac{N(H_2)}{B}$$

$$\lambda \equiv \frac{(M/\Phi)_{observed}}{(M/\Phi)_{critical}}$$

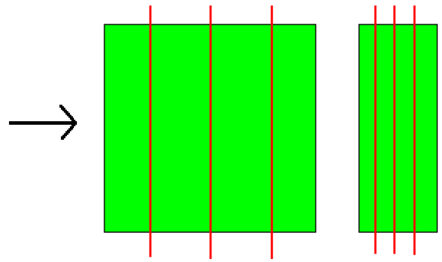




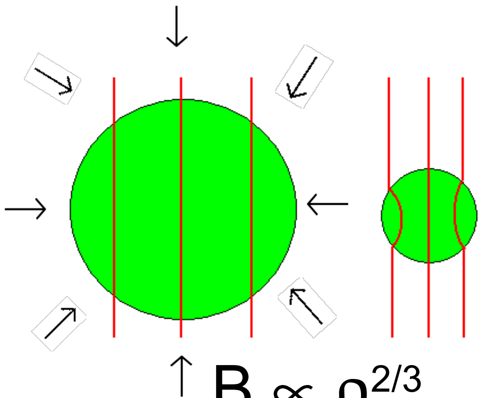
Scaling of B with ρ: $B \propto \rho^{\kappa}$



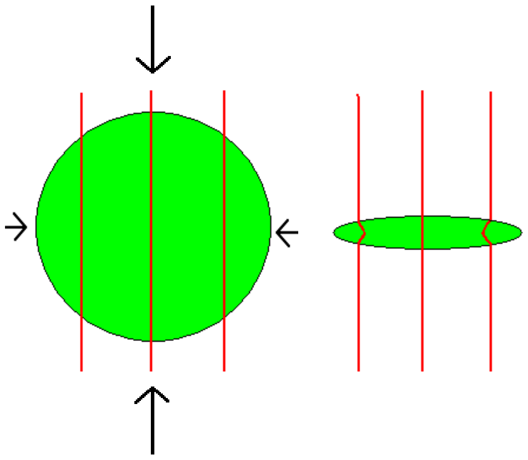
$B \propto \rho^0$



$B \propto \rho^1$

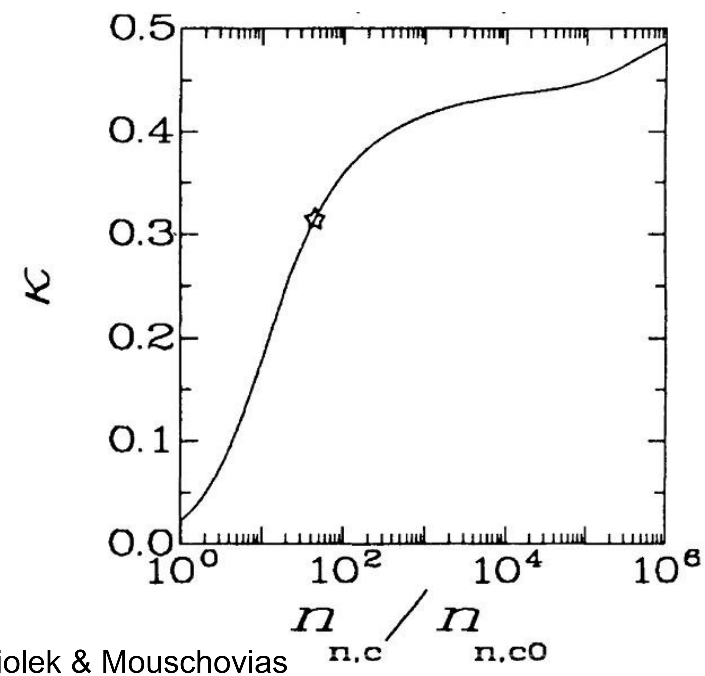


$B \propto \rho^{2/3}$

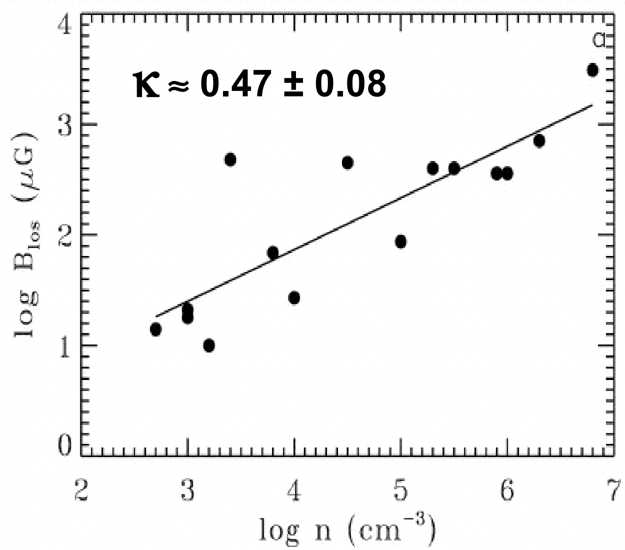


$B \propto \rho^{1/2}$

Magnetic support, ambipolar diffusion

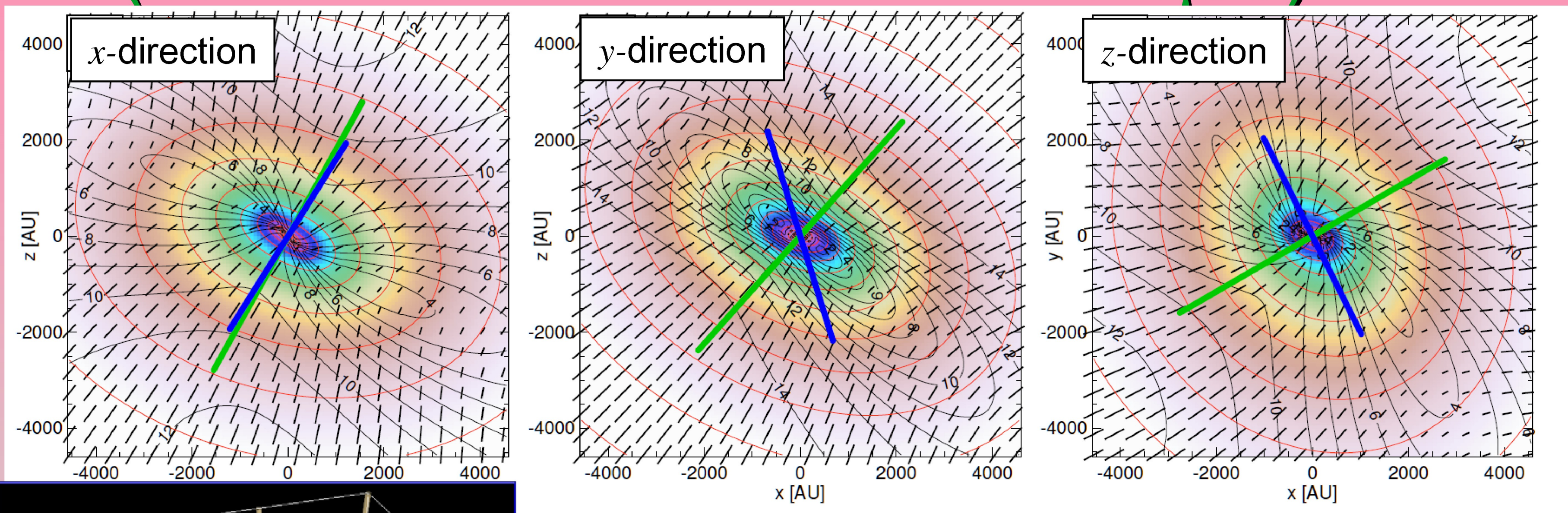


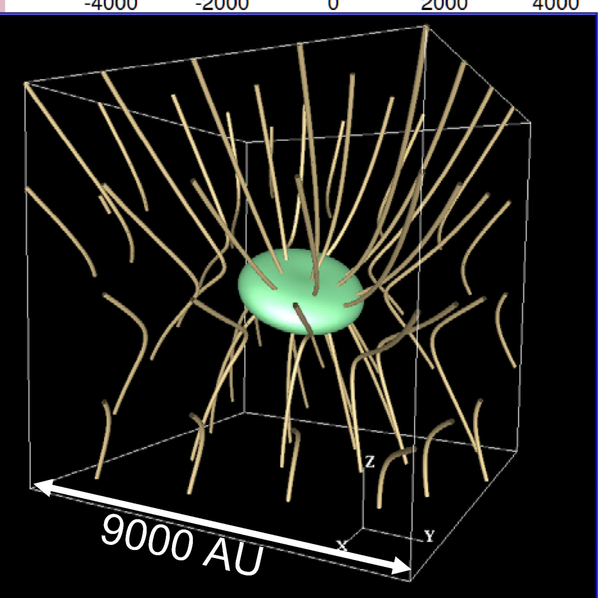
Ciolek & Mouschovias



Crutcher

Polarization vectors at 5000 AU scale (Weak field model: <B> = 50.1μG)



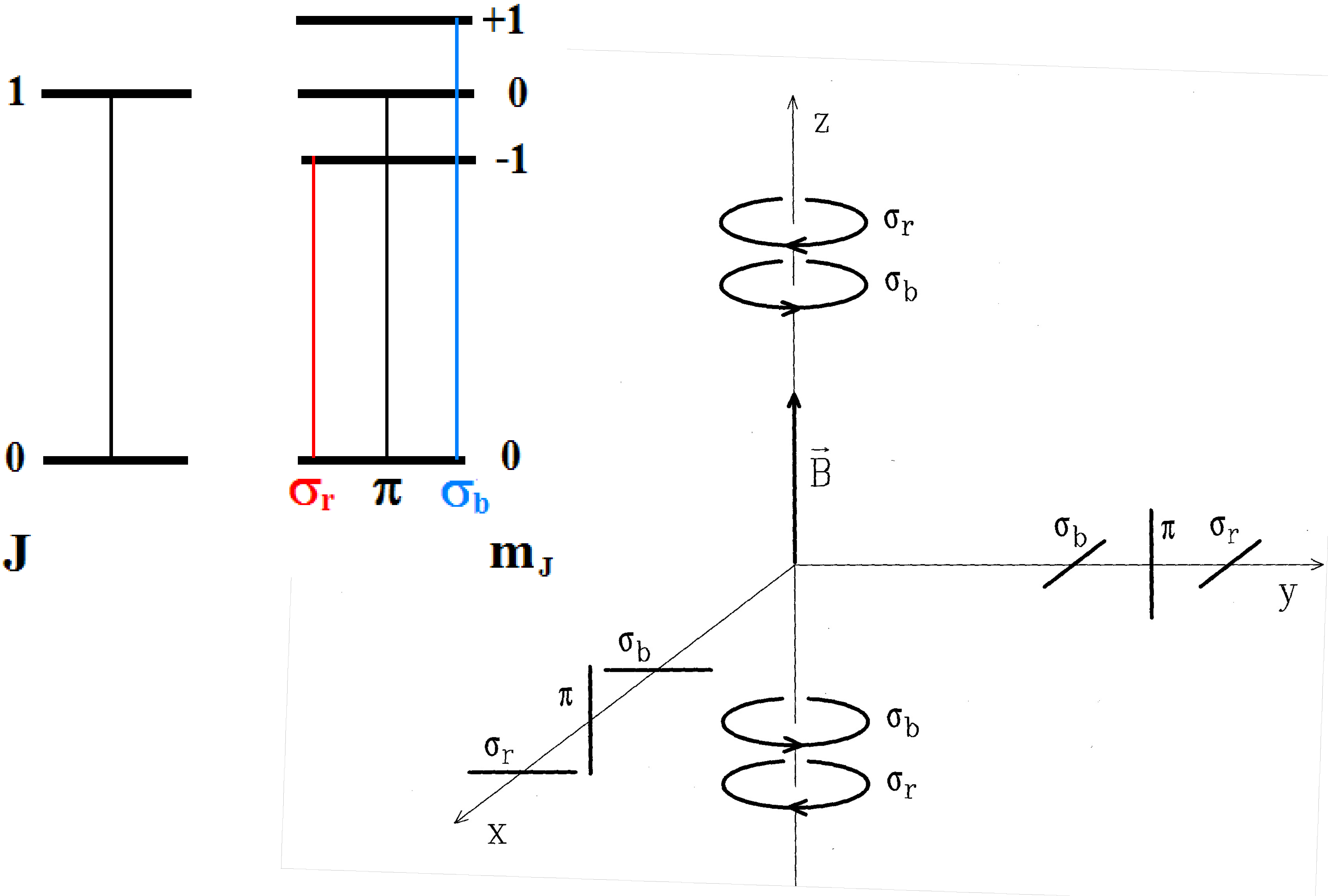


Tree-dimensional angle between the magnetic field and the outflow is 53.5 deg.

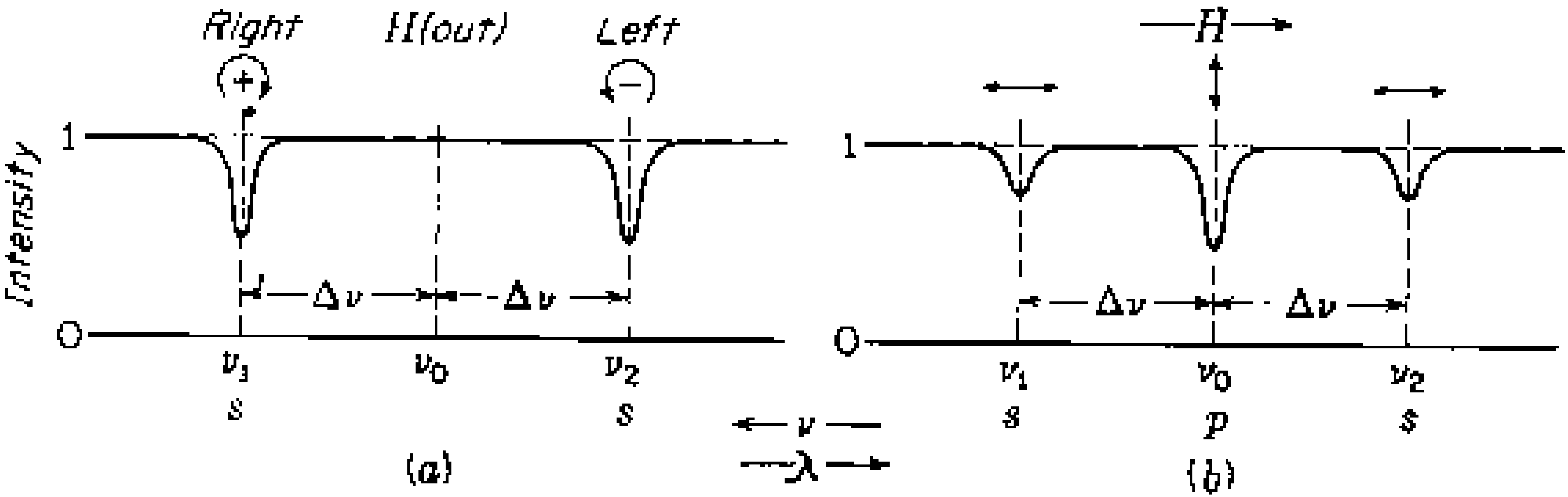
- The alignment depends on the line of sight.
- The direction of the central *B* cannot be inferred form a polarization map of the cloud core scale directly.
- The direction of the central *B* can be probed by the outflow.

Matsumoto, Nakazato, & Tomisaka (2006)

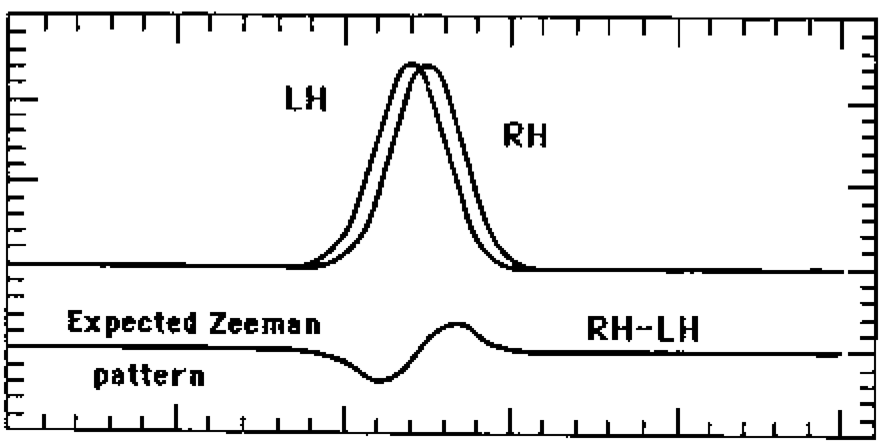
Zeeman Effect (1)



Zeeman Effect (2)



$$\Delta\nu_Z = |\mathbf{B}|Z,\ Z \approx 1 - 2\ \mathrm{Hz}/\mu\mathrm{G},\ \ (Z_{H\,I} = 1.4\ \mathrm{Hz}/\mu\mathrm{G})$$



$V = L - R \propto (dI/d\nu)(\Delta\nu_Z \cos\theta) \Rightarrow$

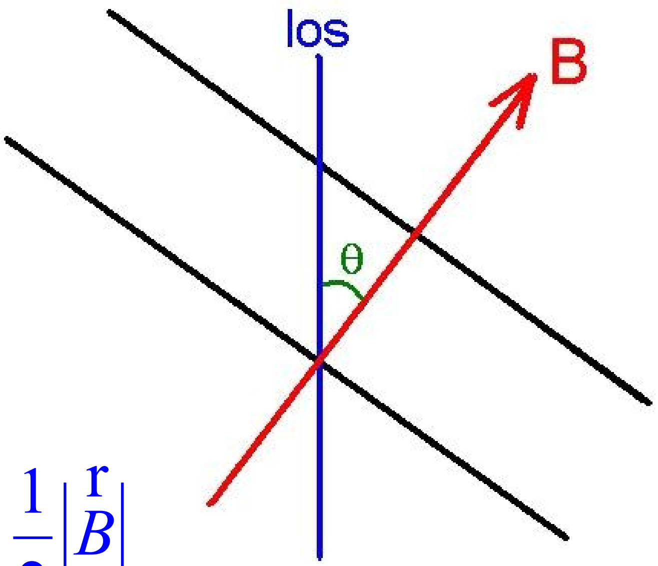
line of sight **B**

Q or $U \propto (d^2I/d\nu^2)(\Delta\nu_Z \sin\theta)^2 \Rightarrow$

plane of sky **B** (not really)

$(dI/d\nu)\Delta\nu_Z \propto I\,(\Delta\nu_Z / \Delta\nu_{FWHM})$

Zeeman Effect (3)



$$V \propto \frac{dI}{d\nu} \Delta\nu_z \cos\theta, \;\; \Delta\nu_z \propto \left|\vec{B}\right|$$

$$\Rightarrow B_{los} = \left|\vec{B}\right| \cos\theta$$

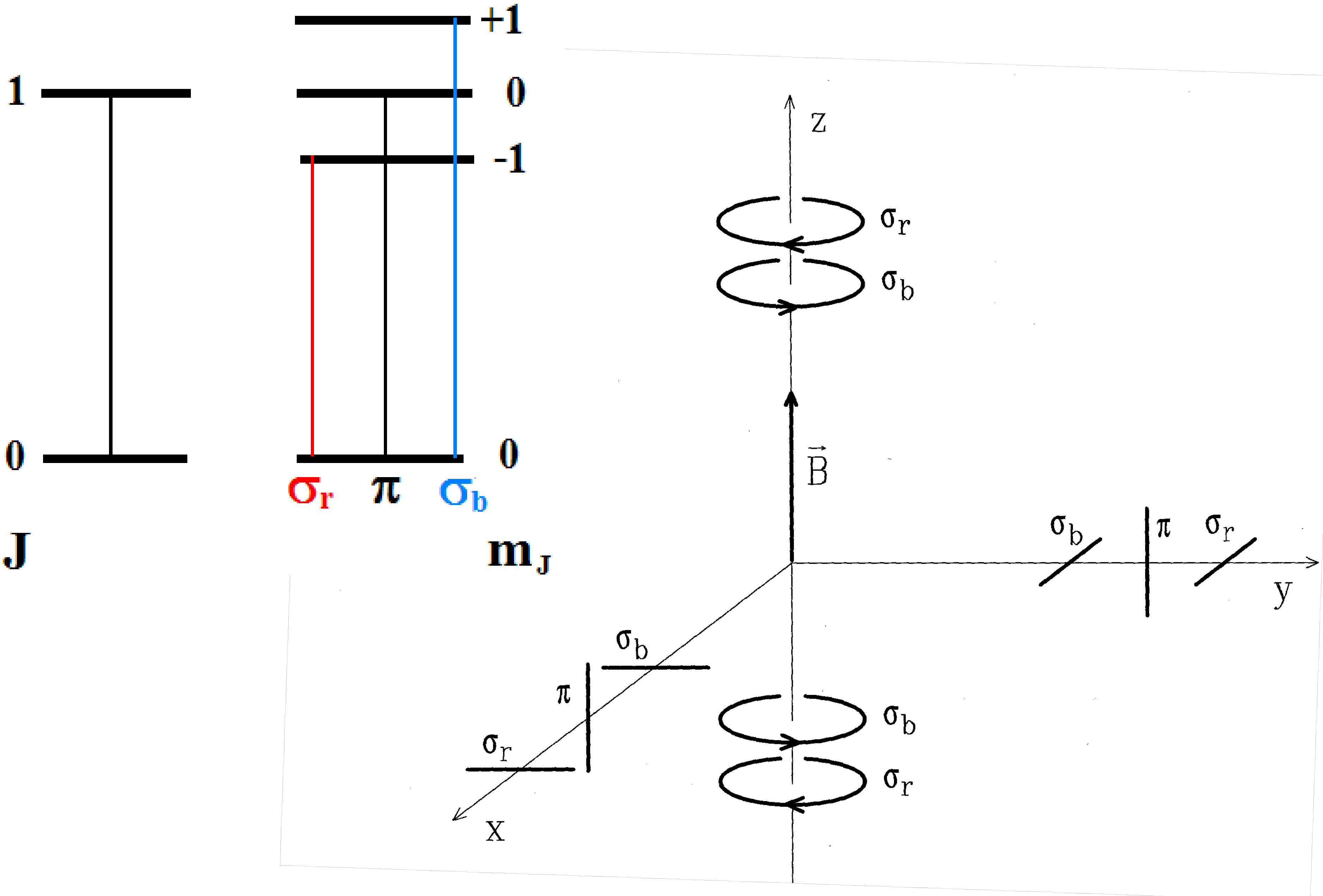
$$\left\langle B_{los} \right\rangle = \int_0^{\pi/2} \left|\vec{B}\right| \cos\theta \sin\theta d\theta \Big/ \int_0^{\pi/2} \sin\theta d\theta = \frac{1}{2}\left|\vec{B}\right|$$

$$\frac{M}{\Phi} \propto \frac{N_B}{B} = \frac{N_{los}\cos\theta}{B_{los}/\cos\theta} = \frac{N_{los}}{B_{los}}\cos^2\theta$$

$$\left\langle \frac{M}{\Phi} \right\rangle = \int_0^{\pi/2} \left(\frac{M_{obs}}{\Phi_{obs}}\right) \cos^2\theta \sin\theta d\theta \Big/ \int_0^{\pi/2} \sin\theta d\theta = \frac{1}{3}\left(\frac{M_{obs}}{\Phi_{obs}}\right)$$

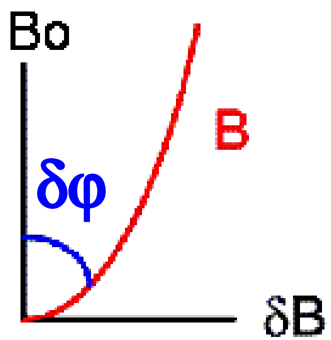
$$\lambda_C = \frac{1}{3}\lambda_{obs}$$

Goldreich-Kylafis Effect (1)



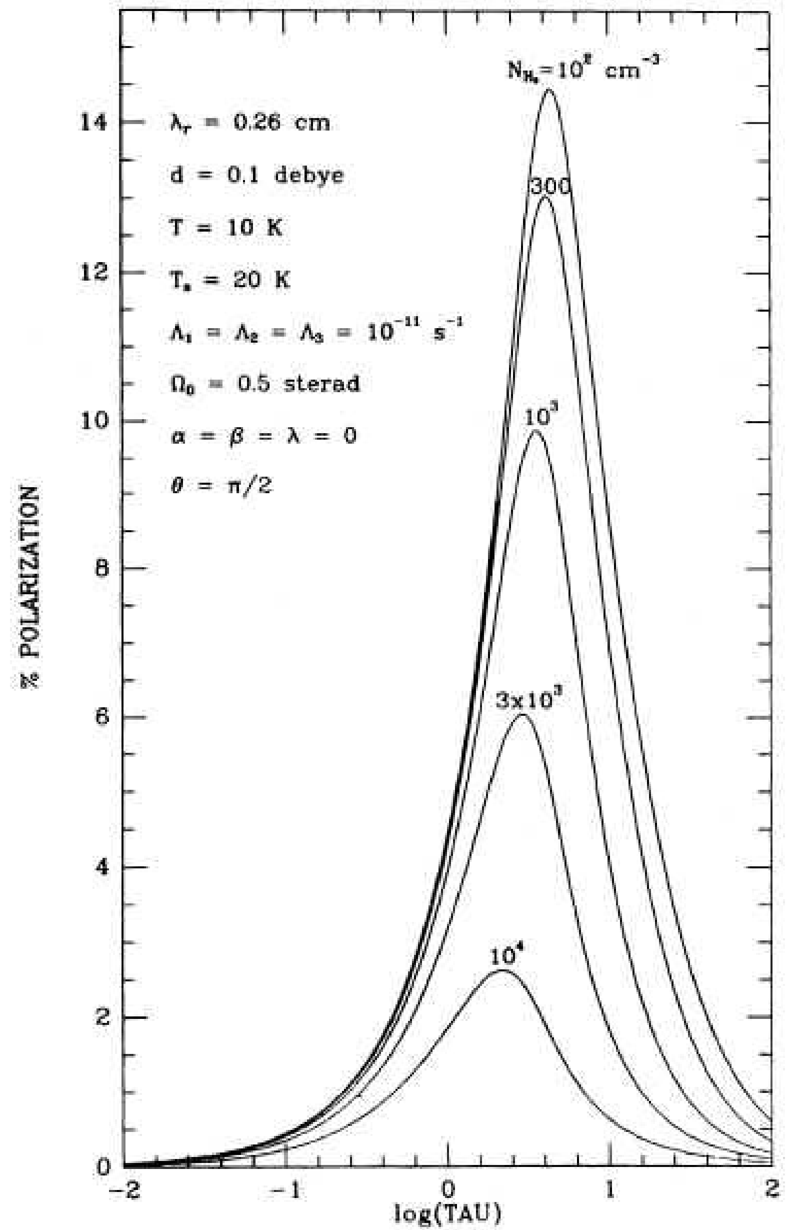
Goldreich-Kalafis Effect (2)

- Local anisotropy in line optical depth ⇒
- anisotropy in radiation field ⇒
- non-LTE population of magnetic sublevels ⇒
- linear polarization ⊥ or || **B**
- Chandrasekhar & Fermi:

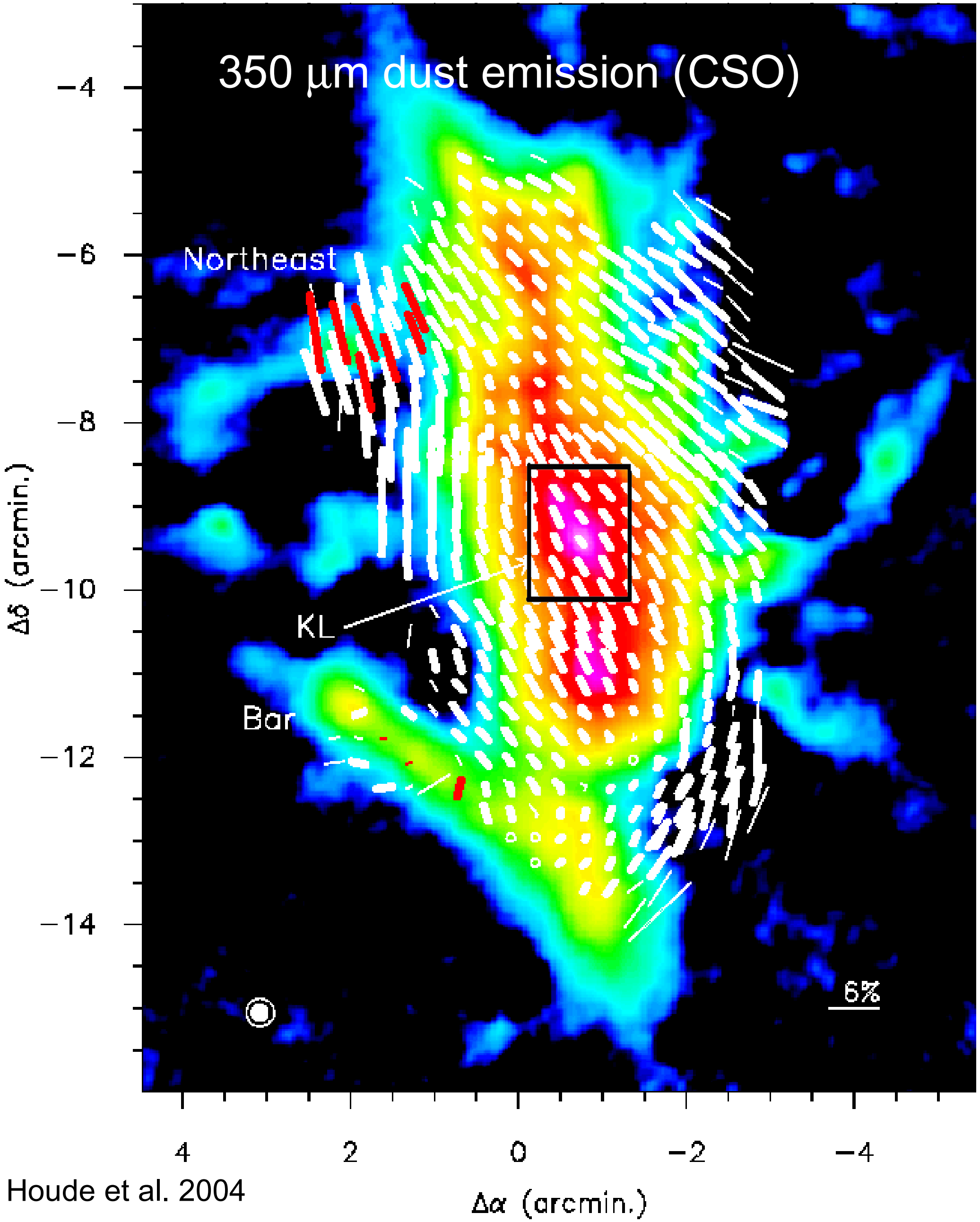


$$\delta V \approx \delta B/(4\pi\rho)^{1/2},\ \delta\varphi \approx \delta B/B_{pos}$$

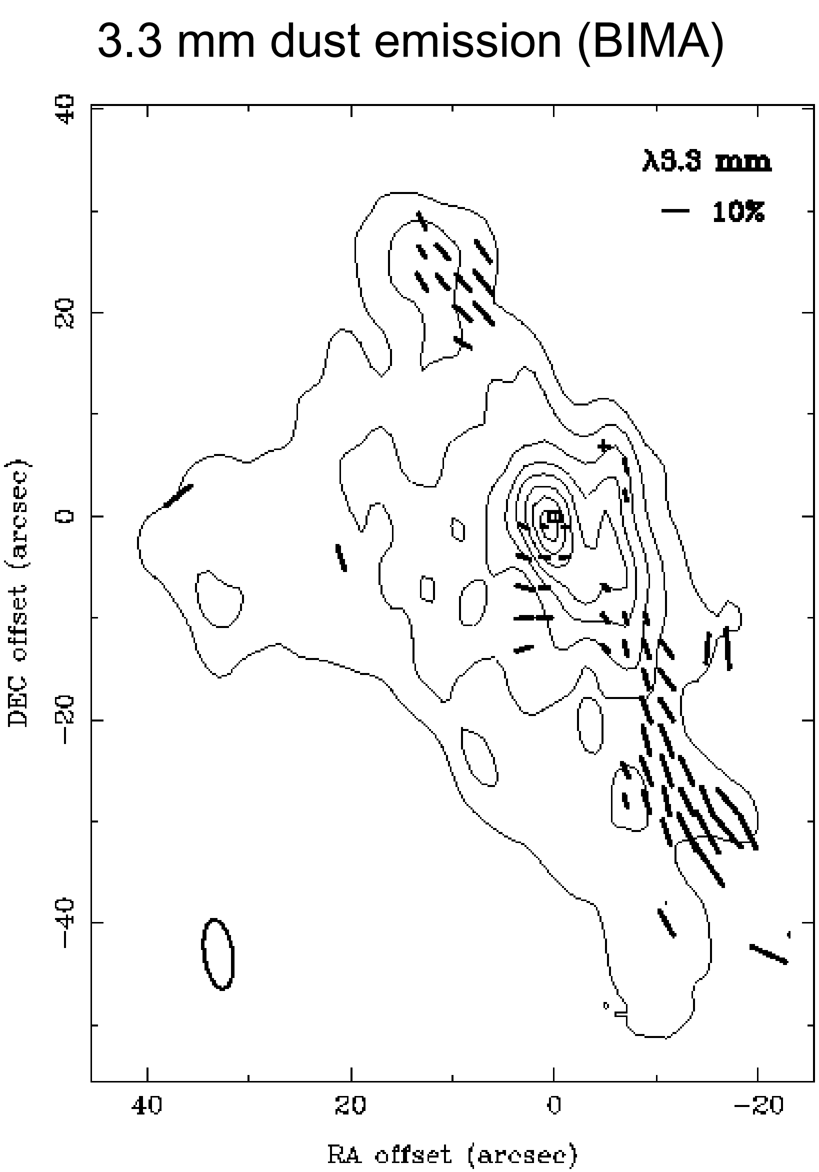
$$\therefore\ B_{pos} \approx 0.5(4\pi\rho)^{1/2}\,\delta V_{los}/\delta\varphi$$



OMC1 (1)

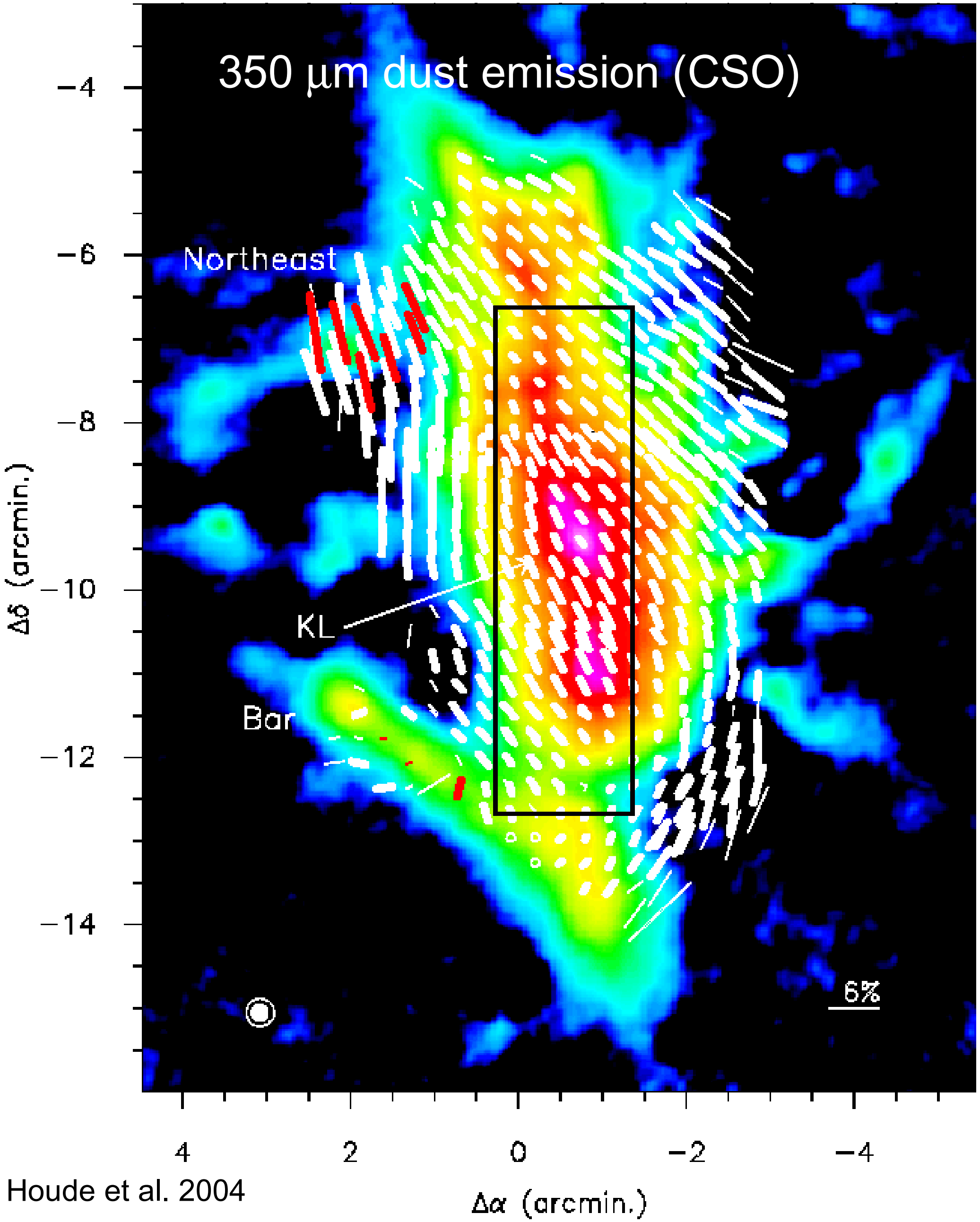


Houde et al. 2004



Rao et al. 1998

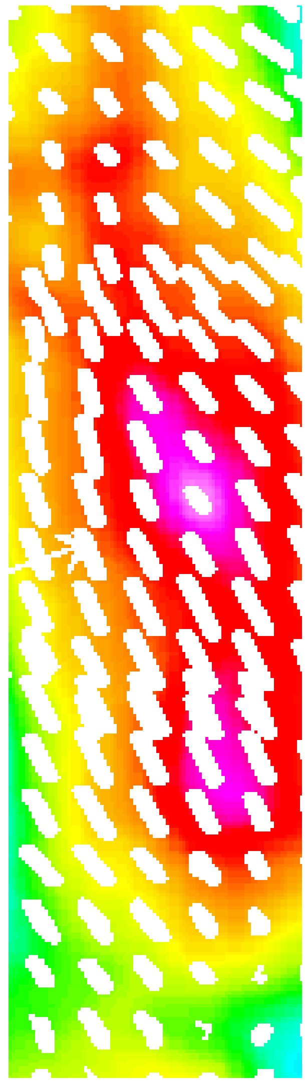
OMC1 (2)



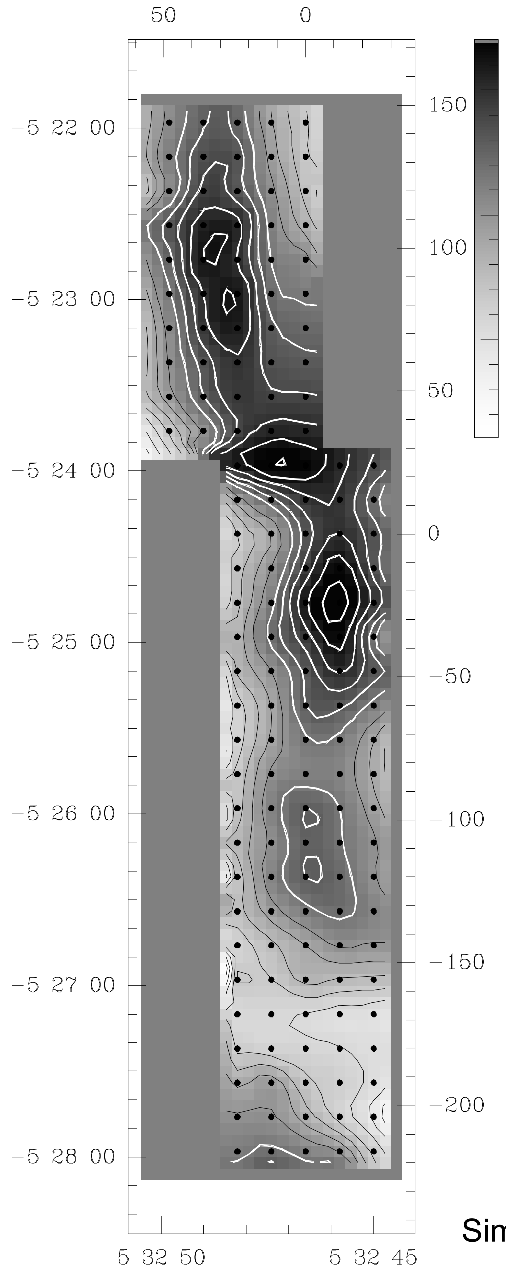
Houde et al. 2004

OMC1 (3)

350 µm dust emission (CSO)



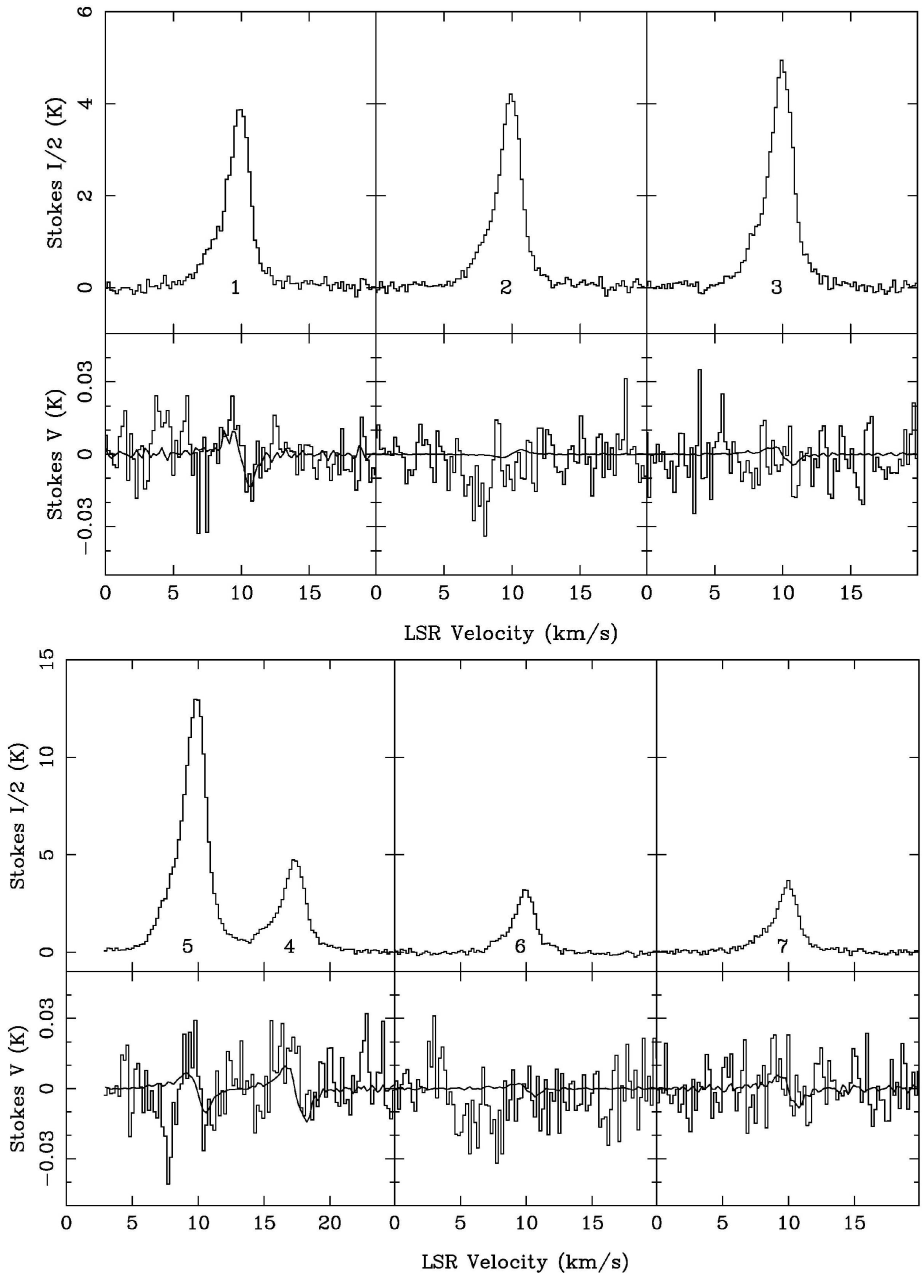
Houde et al. 2004



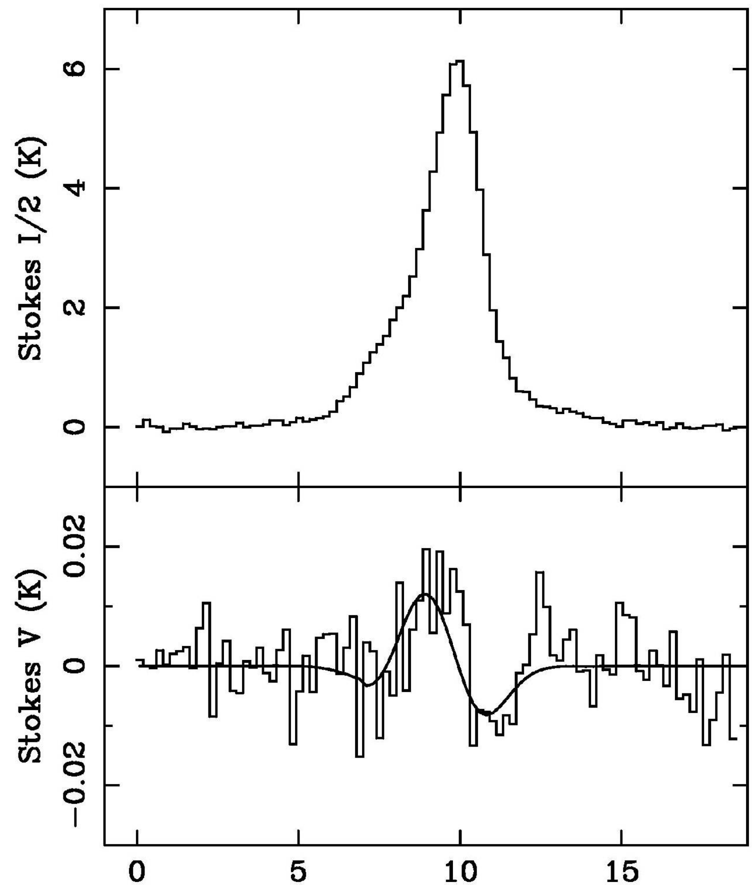
CN 1-0 (113 GHz) CN emission (IRAM 30-m)

Simon (1999)

OMC1 (4)



CN 1-0 (113 GHz) CN Zeeman (IRAM 30-m)

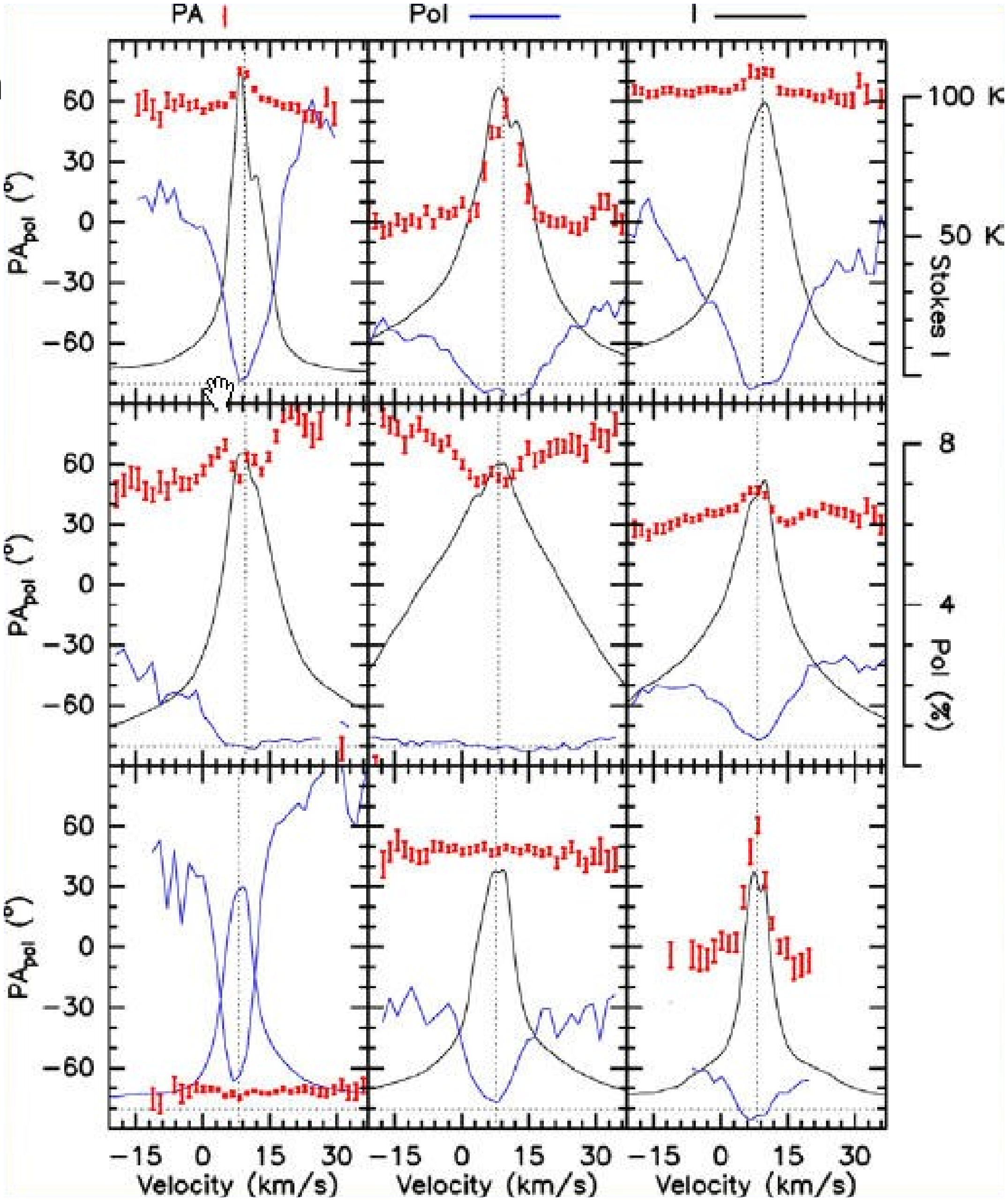


$B_{LOS} = -0.36 \pm 0.08$ mG

Crutcher et al. 1999

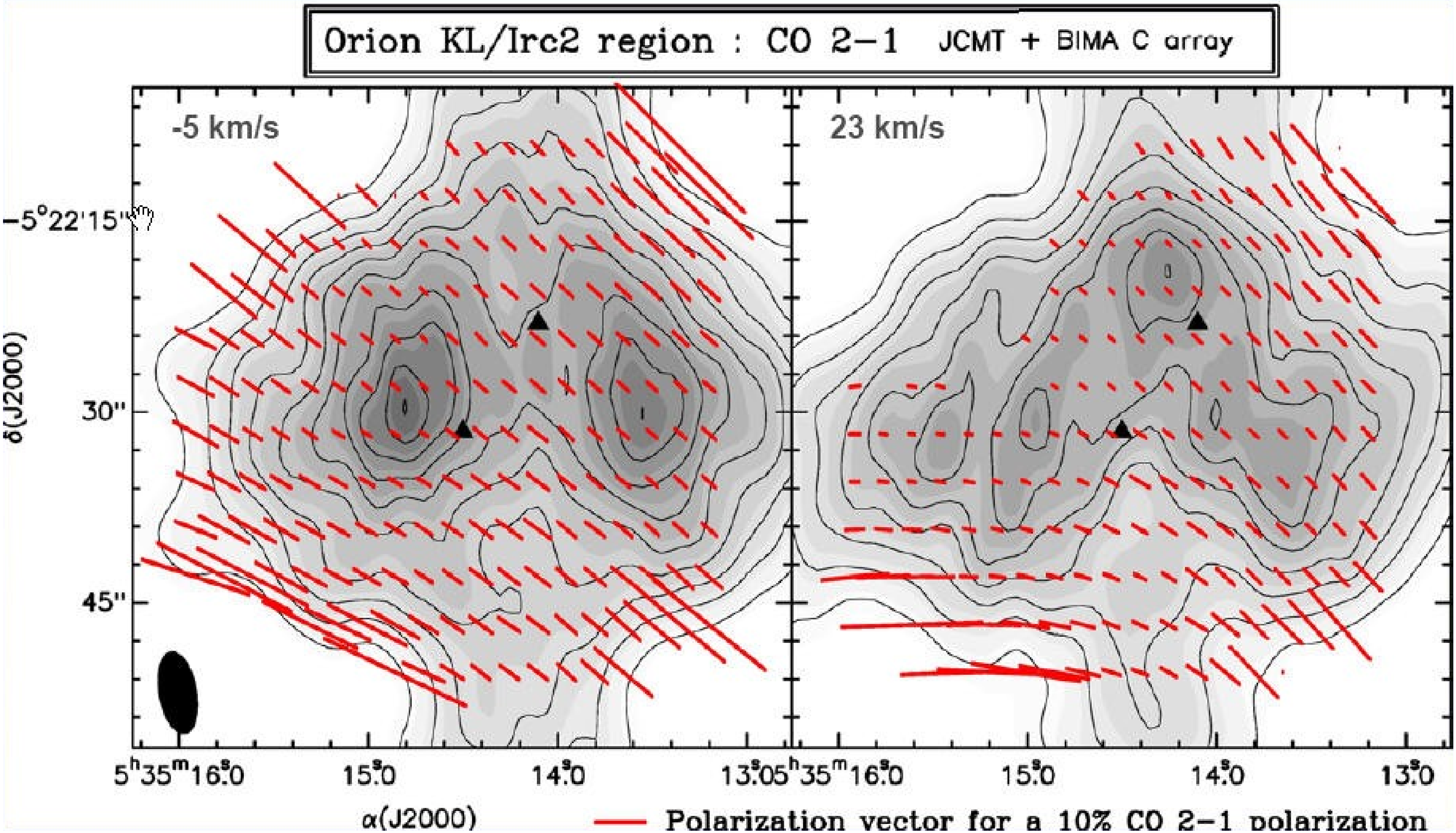
OMC1 (5)

CO 2-1 linear polarization
(BIMA + JCMT)



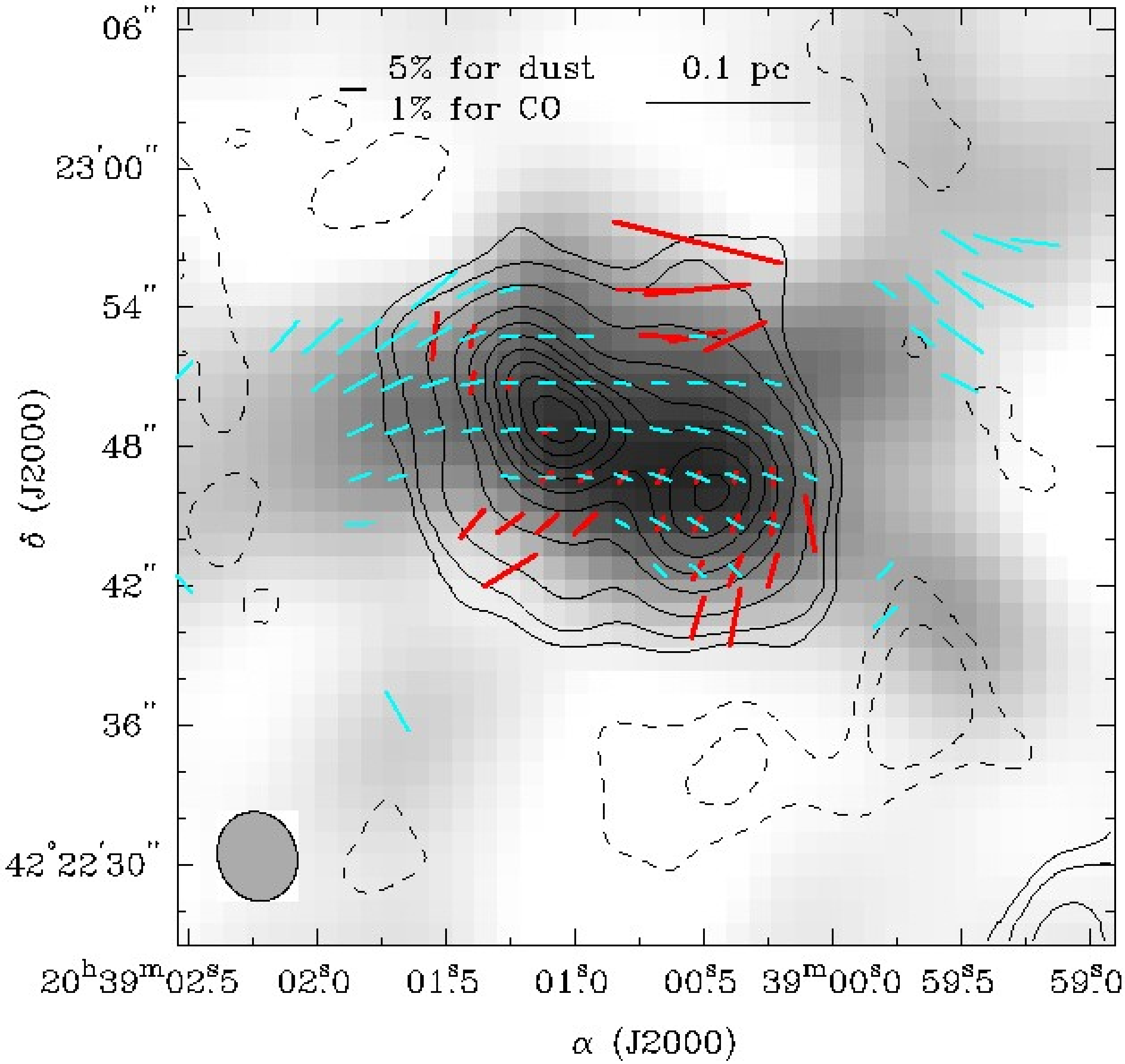
Girart et al. 2004

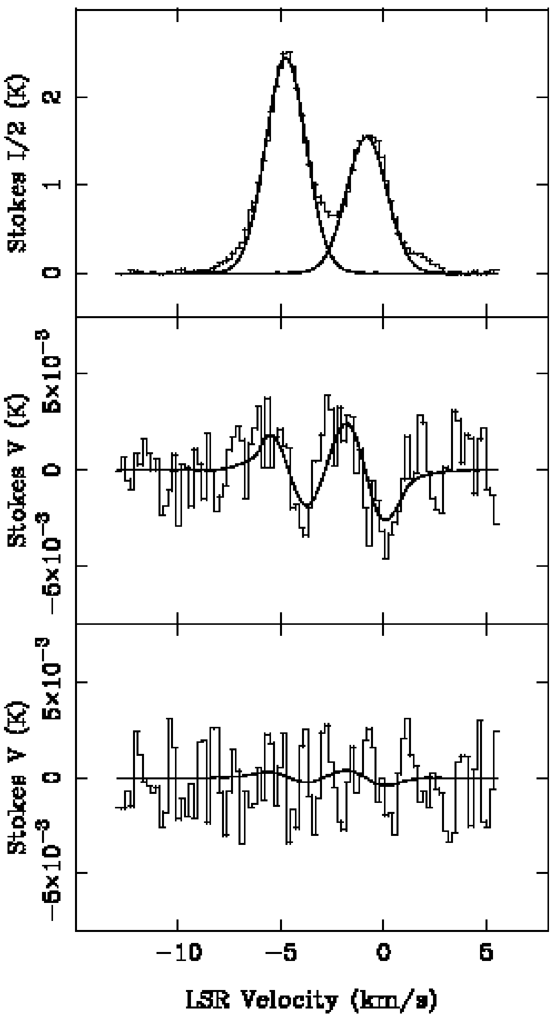
OMC1 (6)



Girart et al. 2004

DR21OH (1)





B_{los} = 0.4, 0.7 mG

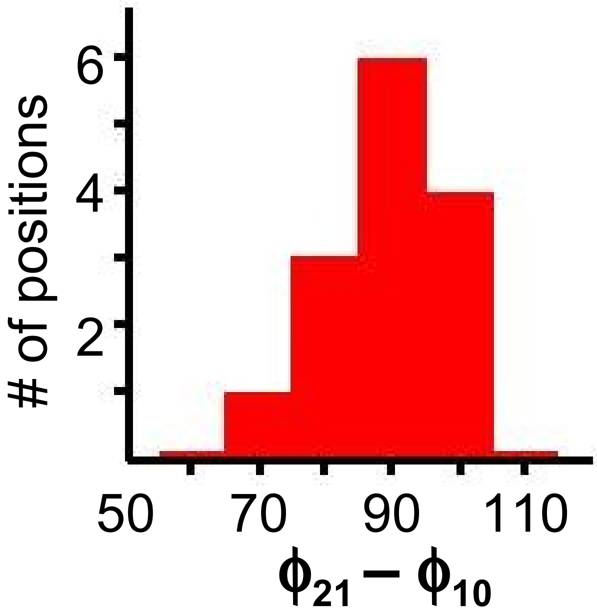
Lai et al. (2003)

Crutcher et al. (1999)

DR21OH (2)

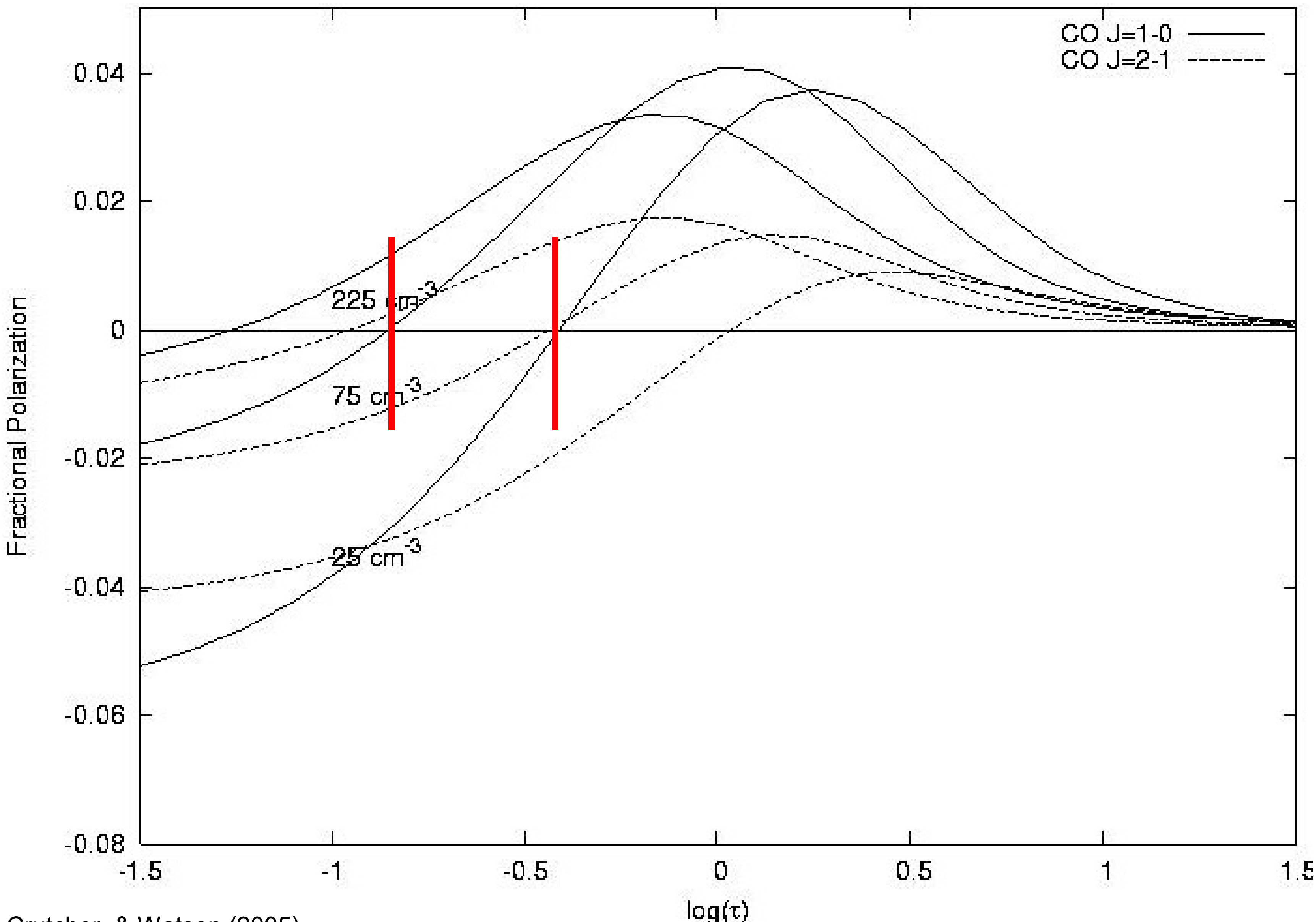
Linearly Polarized J=2-1 and J=1-0 Lines

- J=2-1 polarization is perpendicular to dust polarization and therefore parallel to the magnetic field
- J=1-0 polarization is orthogonal to J=2-1 polarization!



- requires two sources of anisotropic CO excitation
  - anisotropic velocity gradient (and τ), and photon trapping
  - IR from compact dust cores

DR21OH (3)



Cortes, Crutcher, & Watson (2005)

DR21OH (4)

1. CO polarization:

   $n(H_2) \sim 10^2$, $B_{pos} \approx 0.01$ mG

2. Dust polarization & CN Zeeman:

   $n(H_2) \sim 10^6$, $N(H_2) \approx 3 \times 10^{23}$

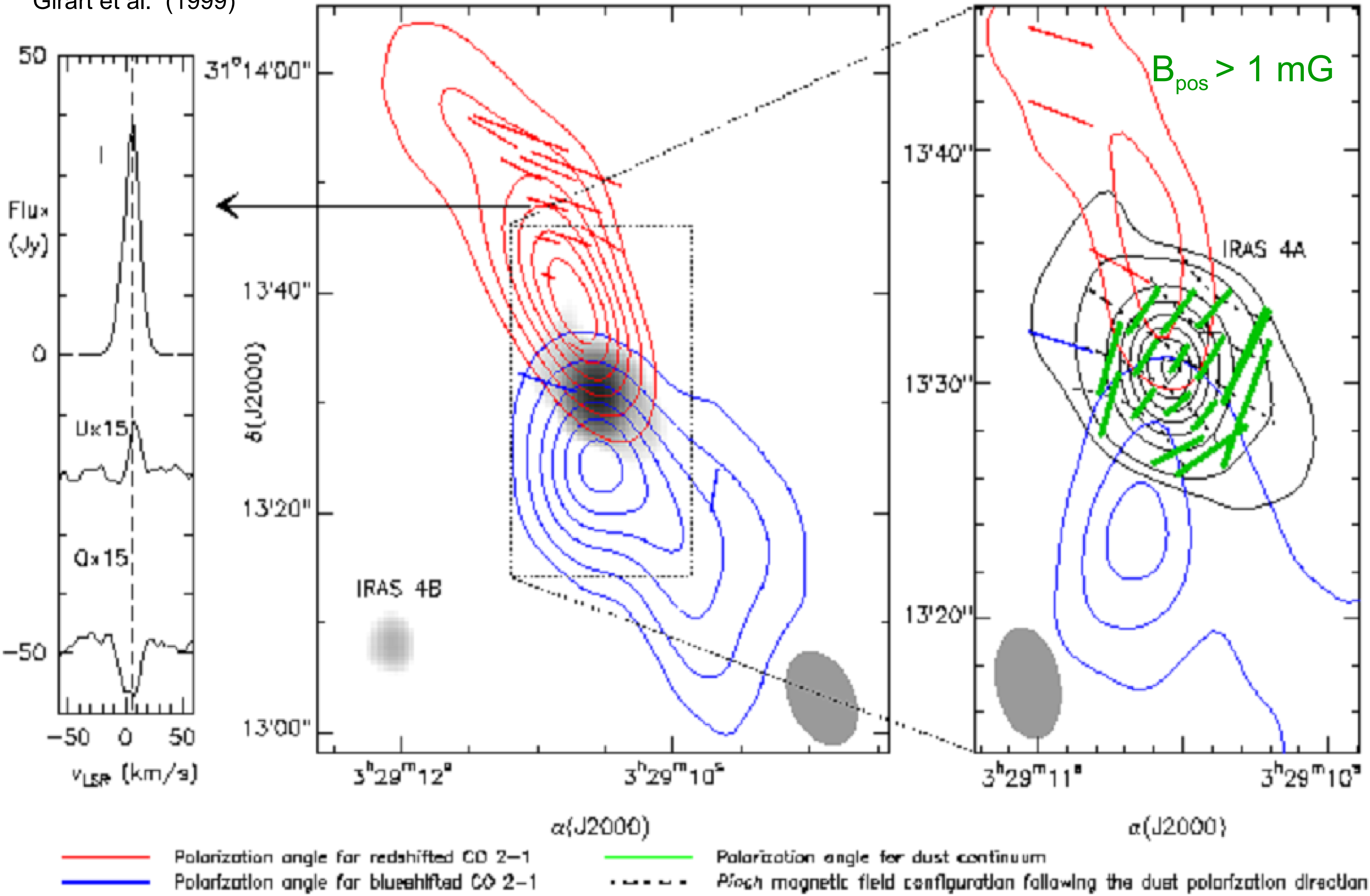
   $B_{pos} \approx B_{los} \approx 0.7$ mG, $M/\Phi \approx 3.3$

Combining 1 and 2, $B \propto \rho^{0.45}$

NGC1333 IRAS4 (1)

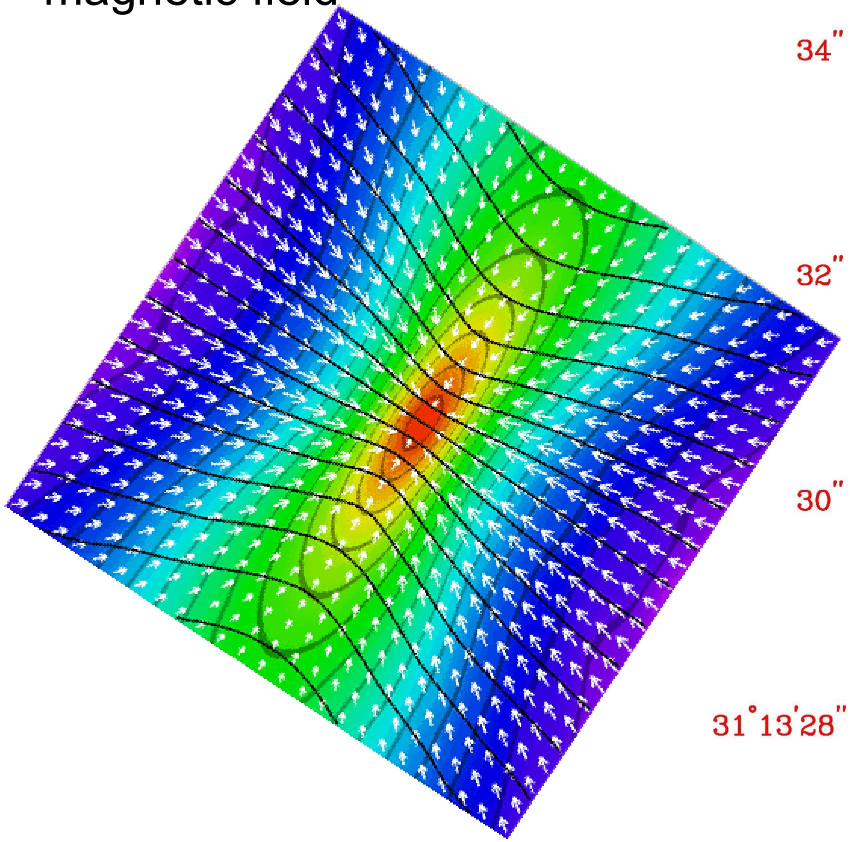
Dust emission (230 GHz) and CO 2-1 emission (BIMA)

Girart et al. (1999)

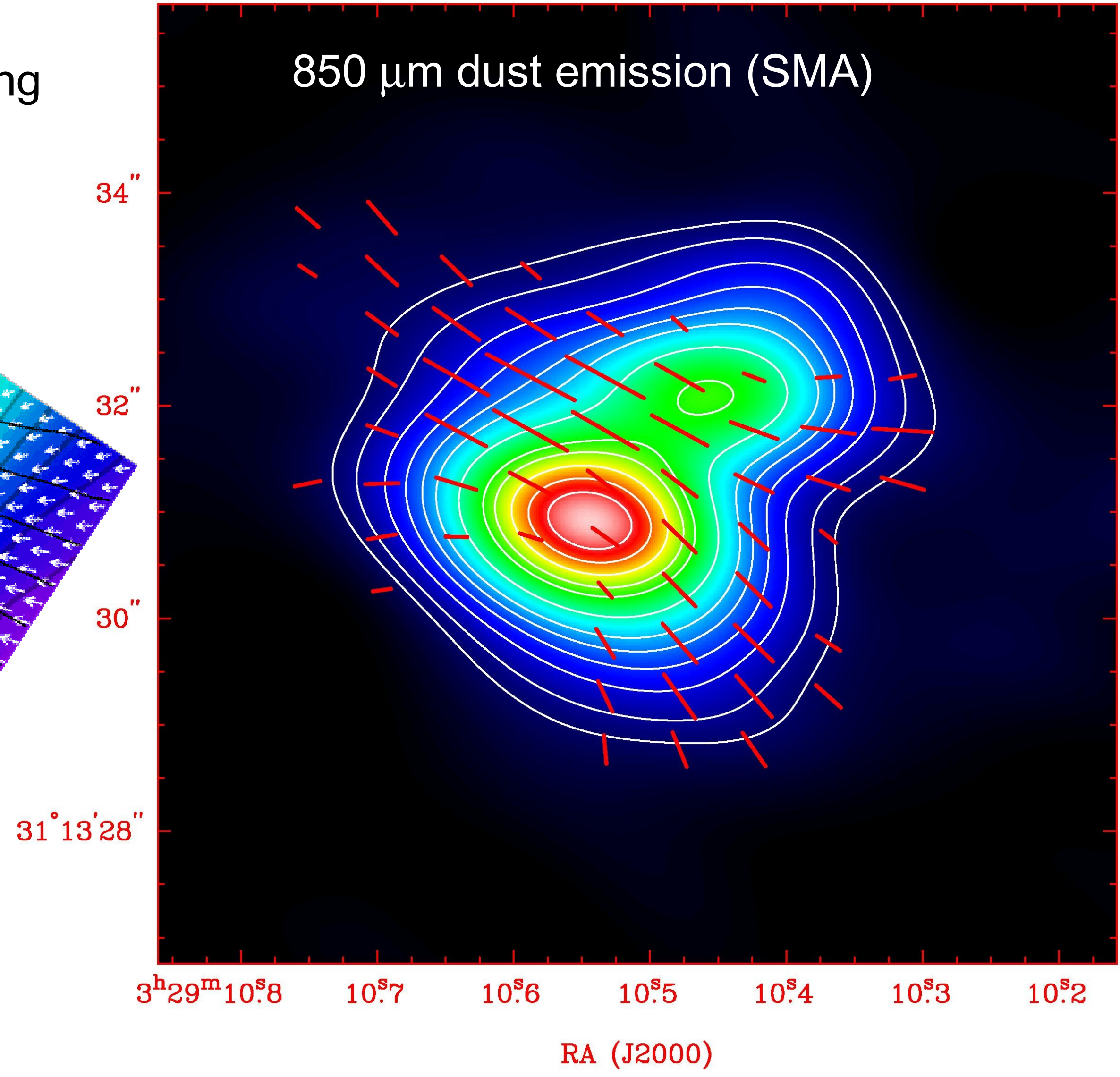


NGC1333 IRAS4 (2)

core formation simulation, strong magnetic field



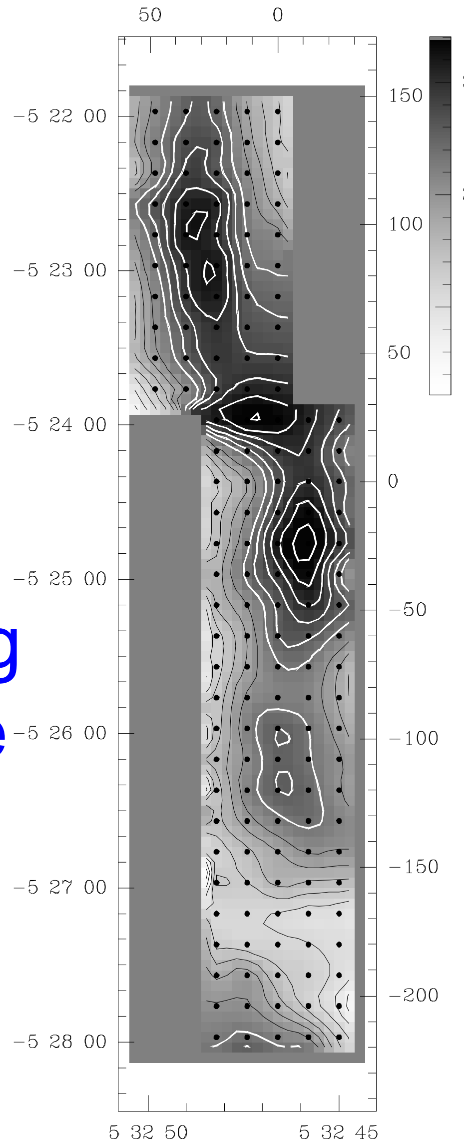
Fiedler and Mouschovias (1993)



Girart, Rao, and Marrone (2006)

ALMA Polarization Science

- Simultaneous CN (113 GHz) Zeeman, CO (115 GHz) linear polarization, & 3 mm dust emission polarization mapping
- Simultaneous CO (345 GHz) linear polarization and 0.85 mm dust polarization mapping
- Spectral-line linear polarization mapping of other lines (HCN, N_2H^+, etc.) to probe field morphologies at higher densities than CO
- 3-D tomography of magnetic fields in star formation regions




"That's all Folks!"