Magnetic Fields & Star Formation
(The “Twilight” Energy)

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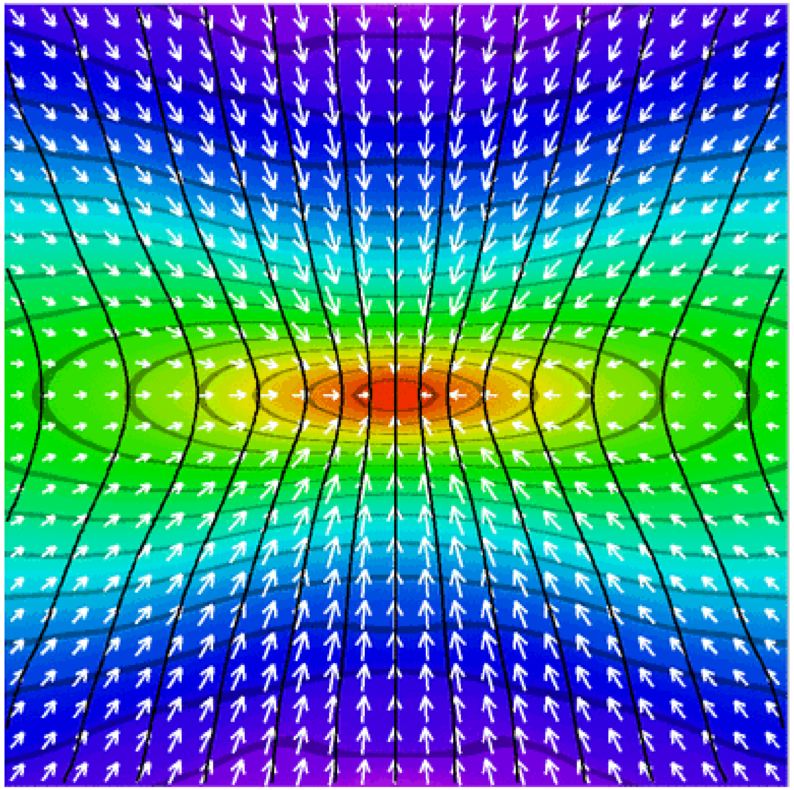
Testing Star Formation Theory

- Two (extreme case) models:
  1. compressible turbulence (with negligible magnetic fields)
     - turbulence forms dense clumps, some of which are self-gravitating and collapse
  2. magnetic support and ambipolar diffusion (with turbulence having only an insignificant role)
     - magnetic field only frozen into ions, not neutrals, which contract under gravity
- Observations of magnetic fields in molecular clouds can distinguish between these models

Magnetic Field Morphology

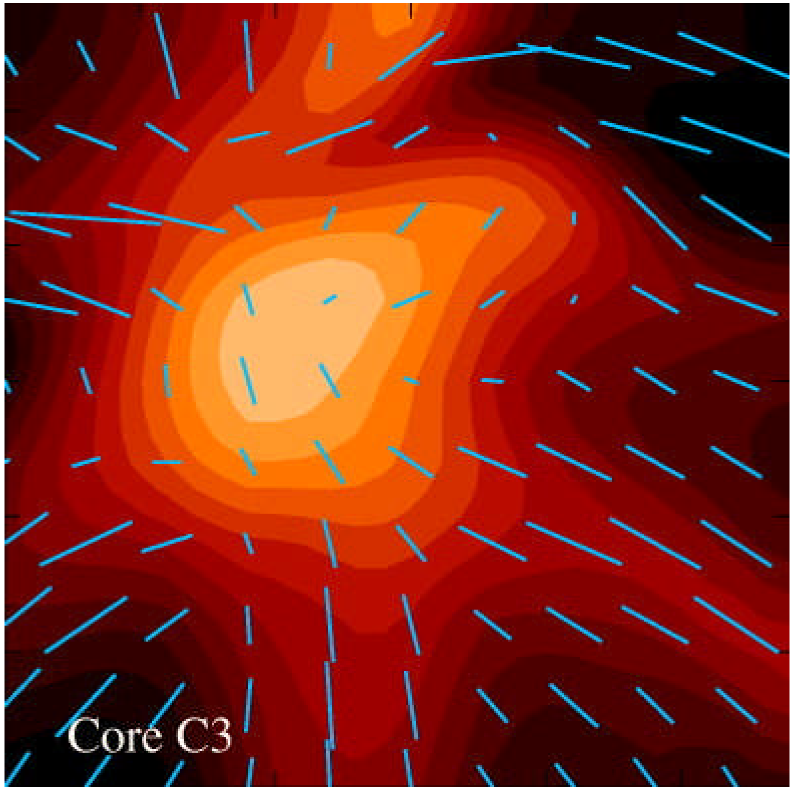
ambipolar diffusion



Fiedler and Mouschovias (1993)

- field lines smooth
- field lines || minor axis
- hourglass morphology

turbulence



Padoan et al. (2001)

- field lines more chaotic

Mass-to-Flux Ratio: M/Φ

mass/flux ratio ≡ gravitational collapse / magnetic support

- Uniform disk Nakano & Nakamura (1978)

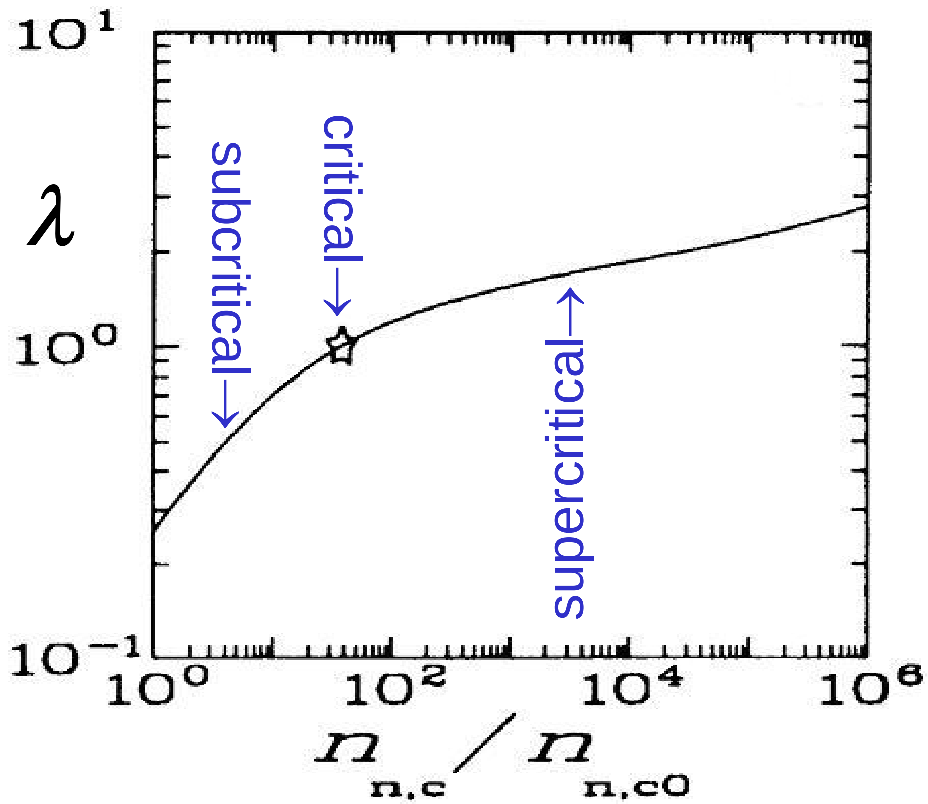
$$\left(\frac{M}{\Phi}\right)_{critical} = \frac{1}{2\pi\sqrt{G}}$$

- Observing M/Φ

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

- λ definition

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



Ciolek & Mouschovias (1994)

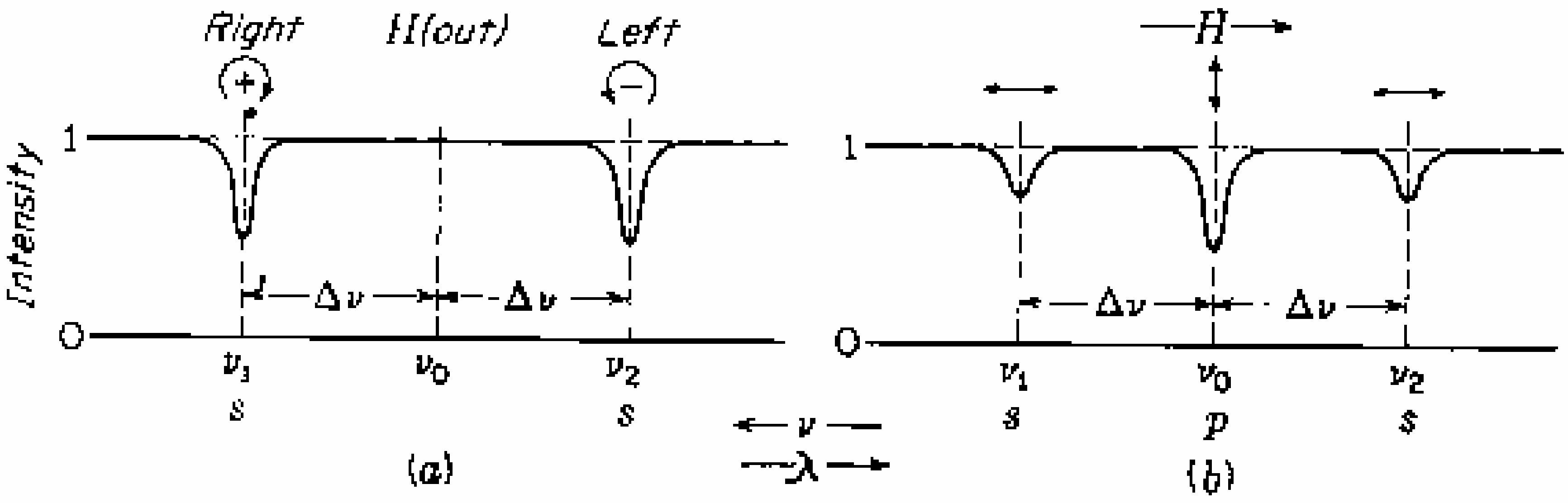
Observational Techniques

1. Zeeman effect

2. Polarization of emission from paramagnetic grains

3. Linear polarization of spectral lines (Goldreich-Kylafis effect)

Zeeman Effect



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

Requires species with unpaired electron: H I, OH, CN, …

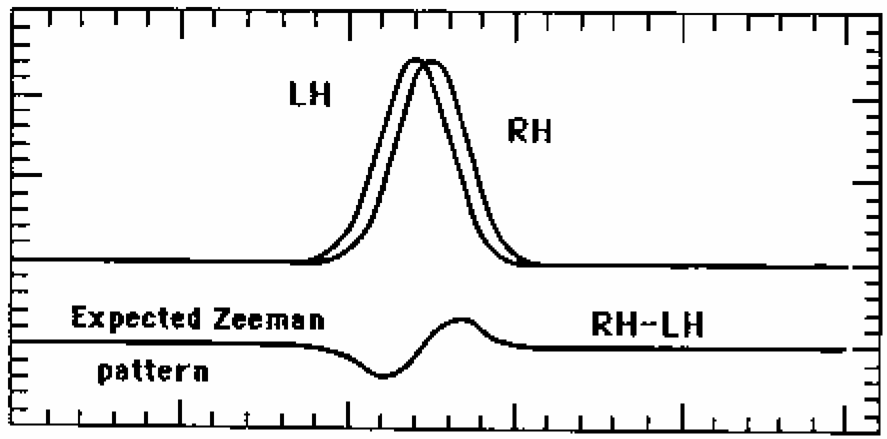
Q or U $\propto (d^2I/d\nu^2)(\Delta\nu_Z \sin\theta)^2 \Rightarrow$

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

Q or U $\propto (\Delta\nu_Z/\text{linewidth})^2$

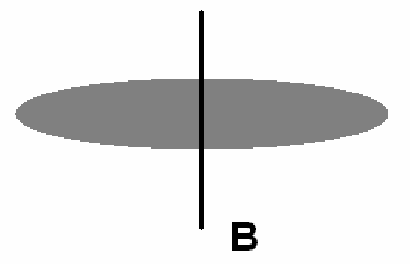
V = L–R $\propto (dI/d\nu)(\Delta\nu_Z \cos\theta) \Rightarrow$

line of sight **B**

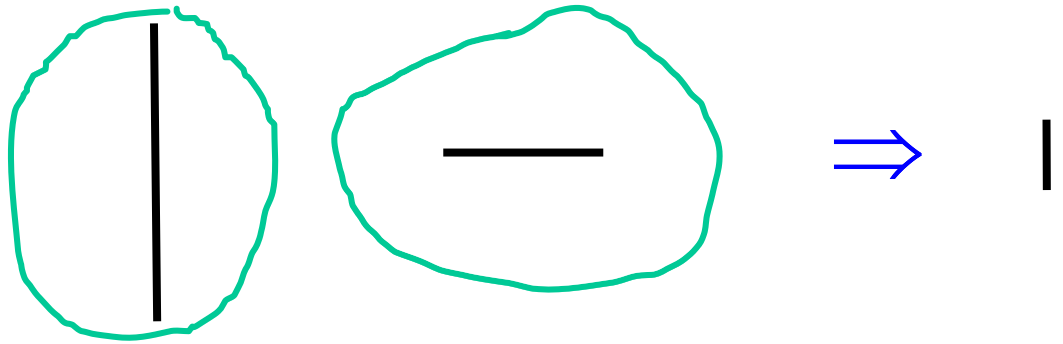


Dust Grain Polarization

- linear polarization $\perp$ **B**
  $\Rightarrow$ morphology of B_{pos}



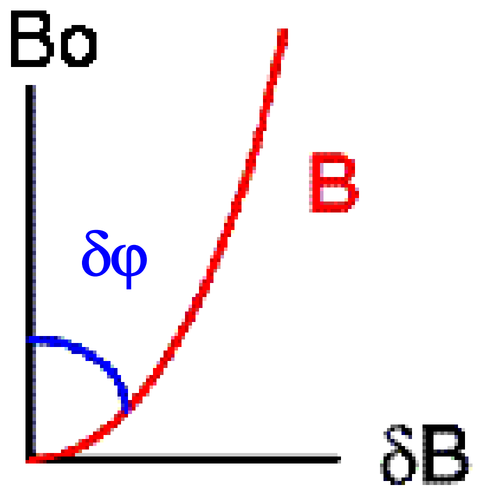
- gives field direction in strongest clump along line of sight



- indirect estimate of field strength
  (Chandrasekhar & Fermi 1953)

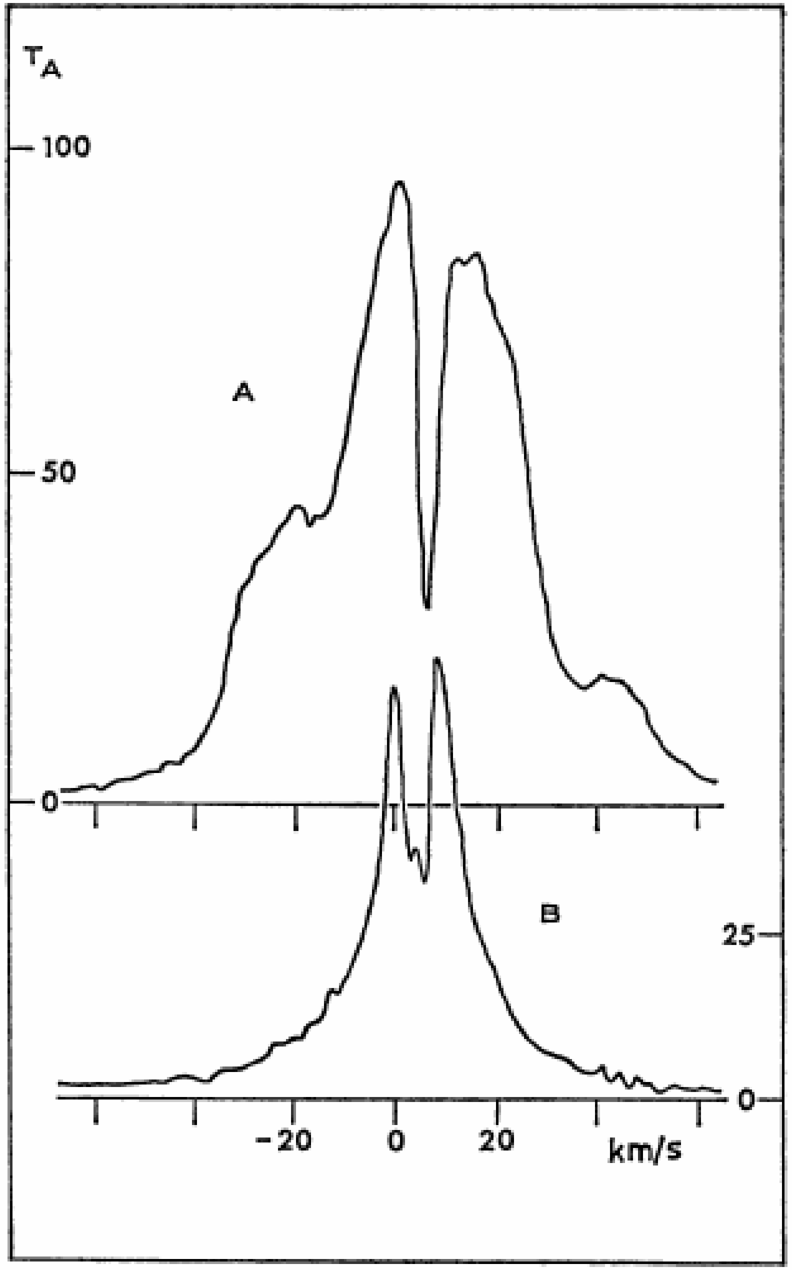
$$\delta V \approx \delta B/(4\pi\rho)^{1/2}, \ \delta\varphi \approx \delta B/B_o$$

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



Ostriker et al. (2001); Heitsch et al. (2001); Padoan et al. (2001)

"Riegel-Crutcher" H I Self-Absorption Cloud



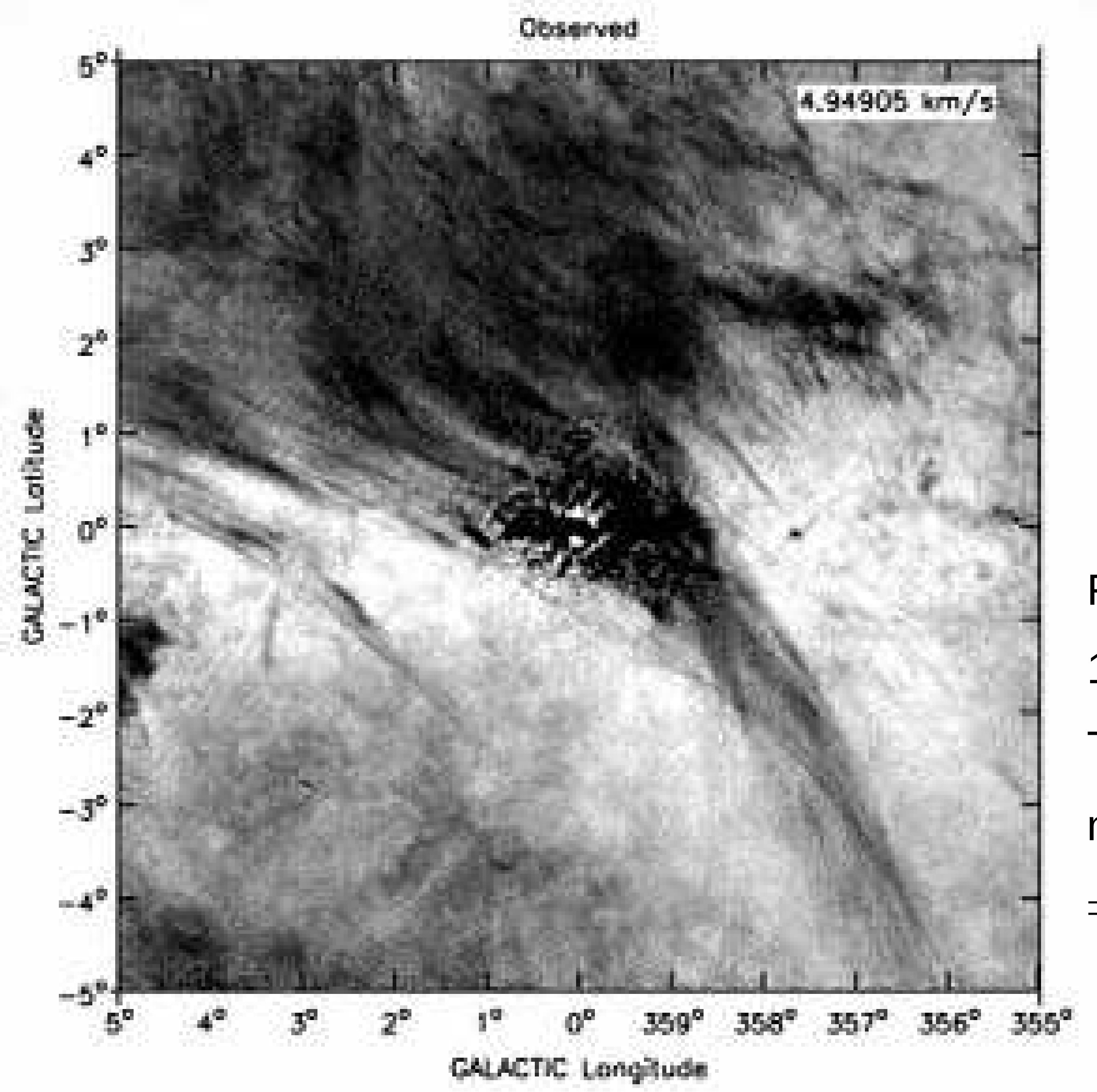
$345^\circ < \ell < 25^\circ$, $-10^\circ < b < +10^\circ$

$T_K \approx 20 - 40$ K

$d \approx 125 \pm 25$ pc

Riegel & Crutcher (1972)

"Riegel-Crutcher" Cloud Filaments



W 22

$\ell = 353^\circ$, $b = +1^\circ$

X

Filaments properties:

17 pc by < 0.1 pc

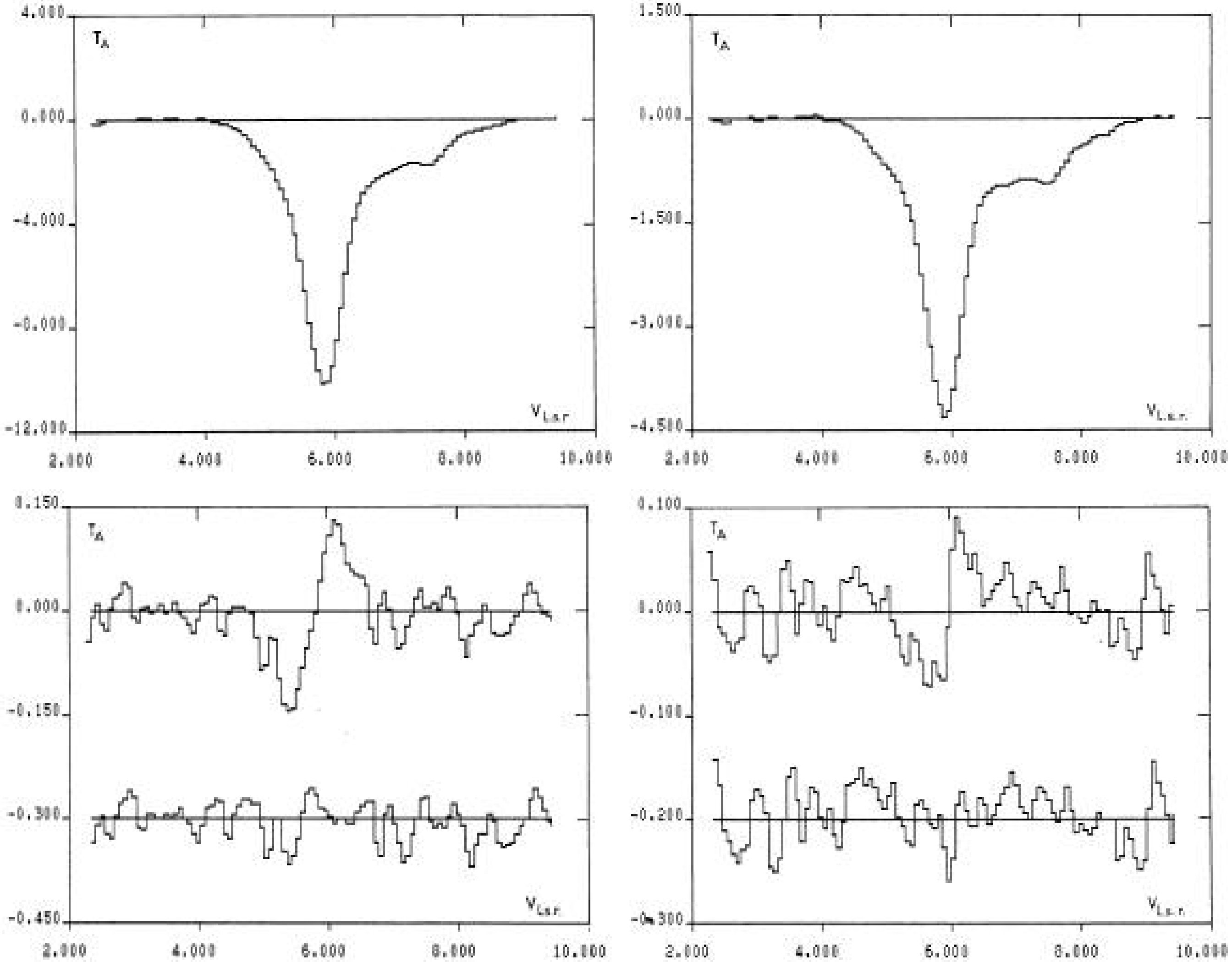
$T \approx 40$ K

magnetically dominated

$\Rightarrow B > 30\ \mu G$

McClure-Griffiths et al (2006)

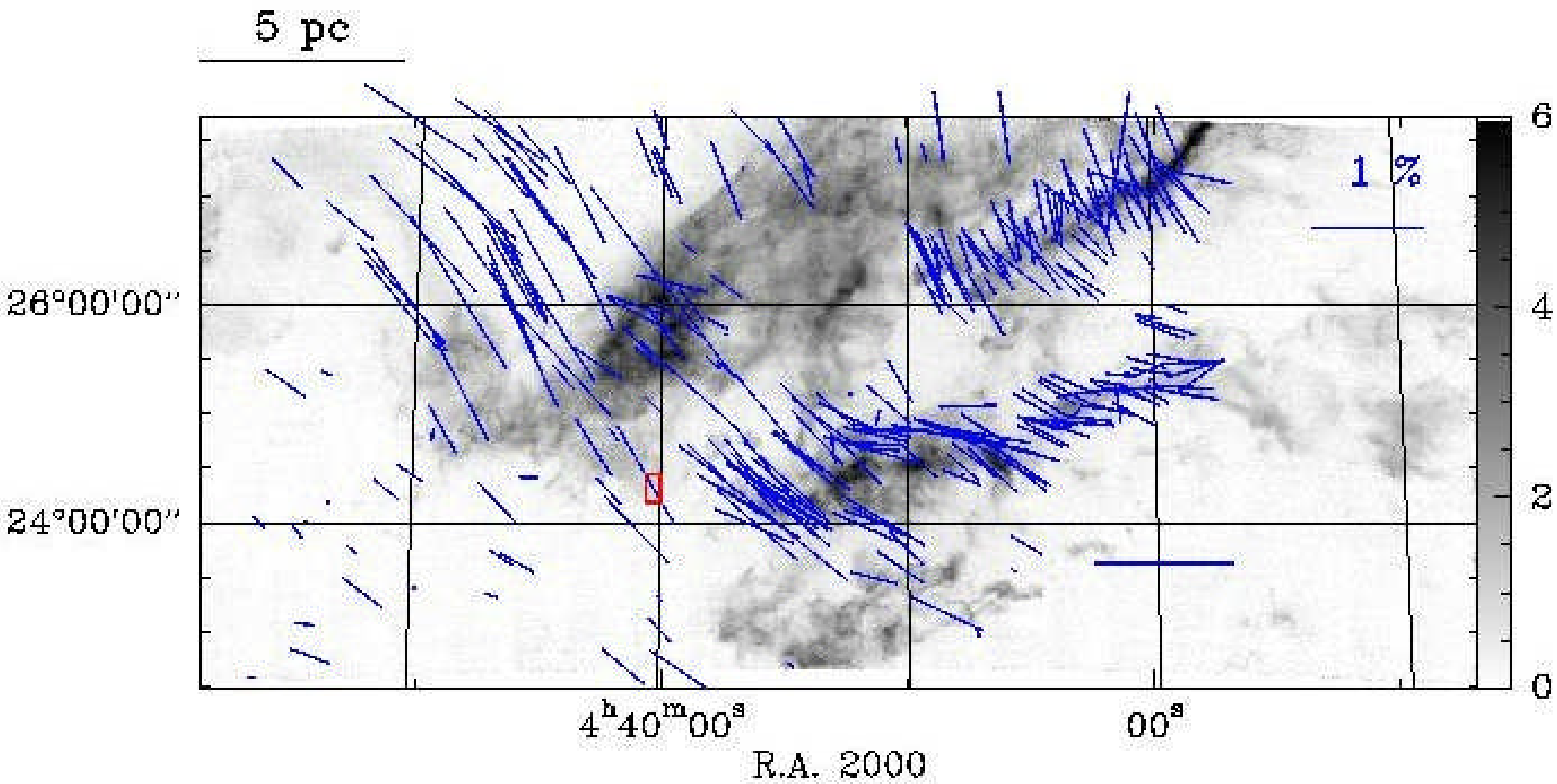
Zeeman Results toward W22



$B_{los} = -18 \pm 1\ \mu G$

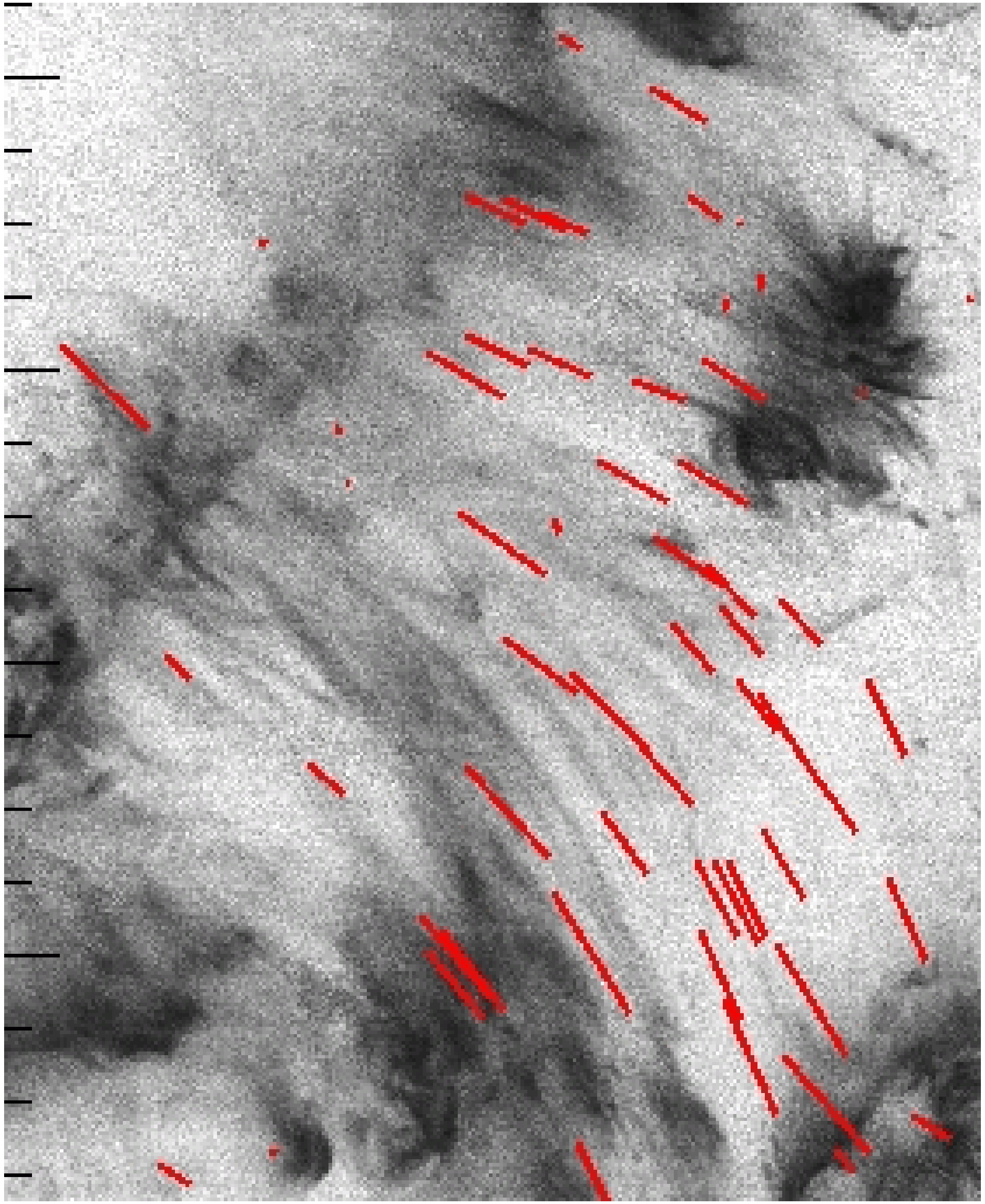
Kazes & Crutcher (1986)

Taurus CO & Magnetic Field



Goldsmith et al (2008)

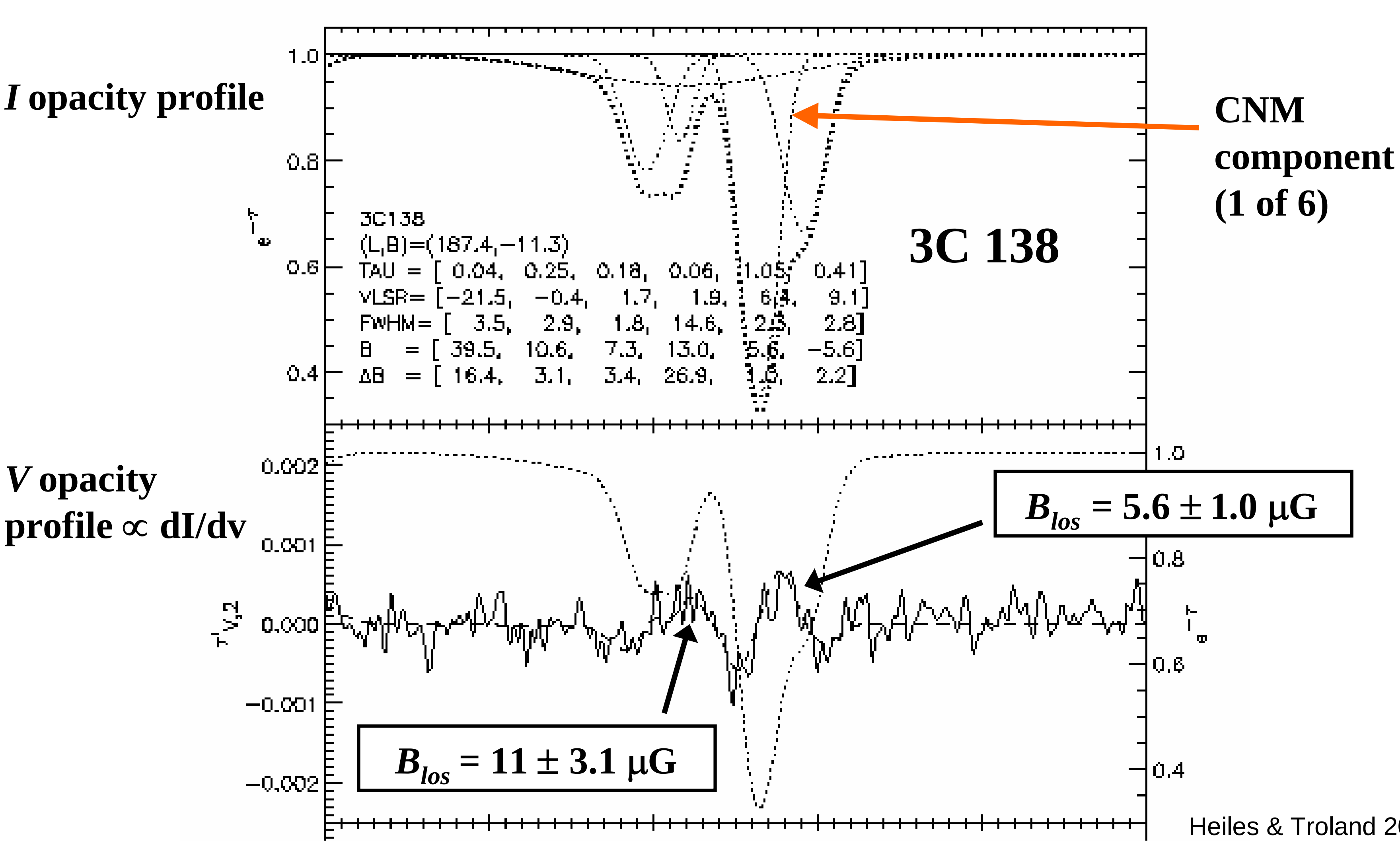
Taurus "Threads"



Goldsmith et al (2008)

Diffuse Cloud (H I Zeeman)

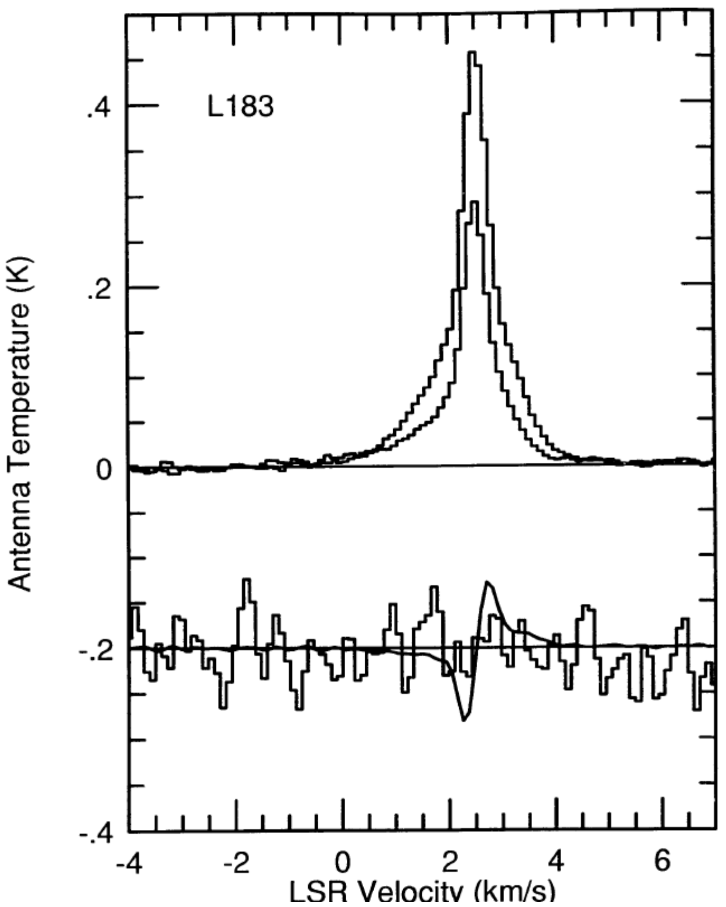
Arecibo "Millennium" Survey



Heiles & Troland 2005

L183 Starless Core

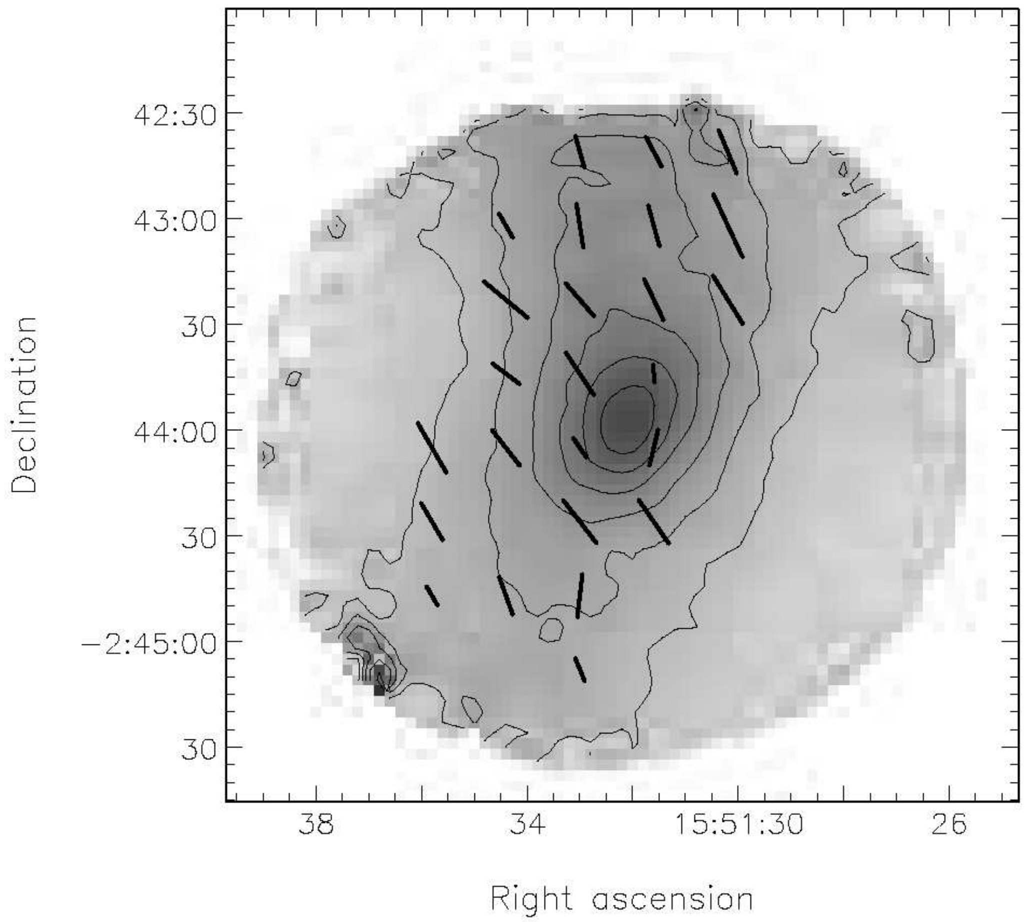
Crutcher et al. (1993)



$n(H_2) \approx 1 \times 10^3$, $N(H_2) \approx 3 \times 10^{21}$

$B_{los} < 16\ \mu G$

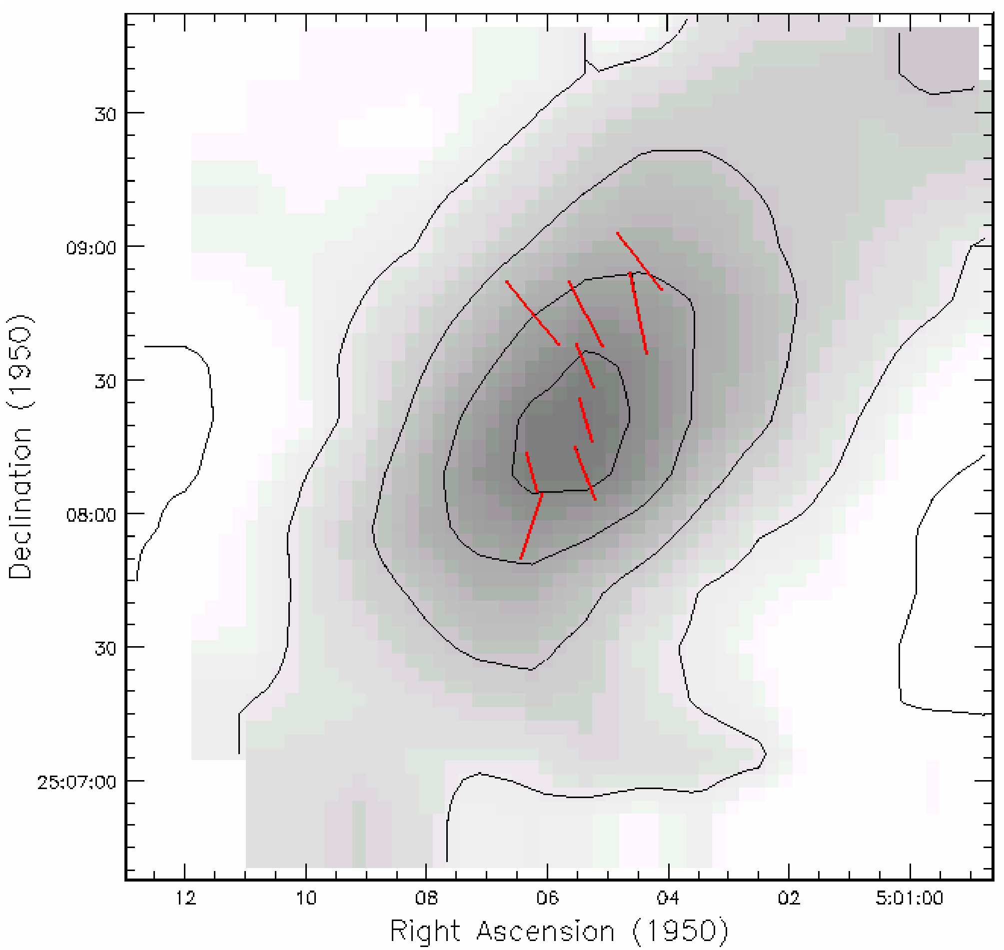
Crutcher et al. (2003)



$n(H_2) \approx 3 \times 10^5$, $N(H_2) \approx 3 \times 10^{22}$

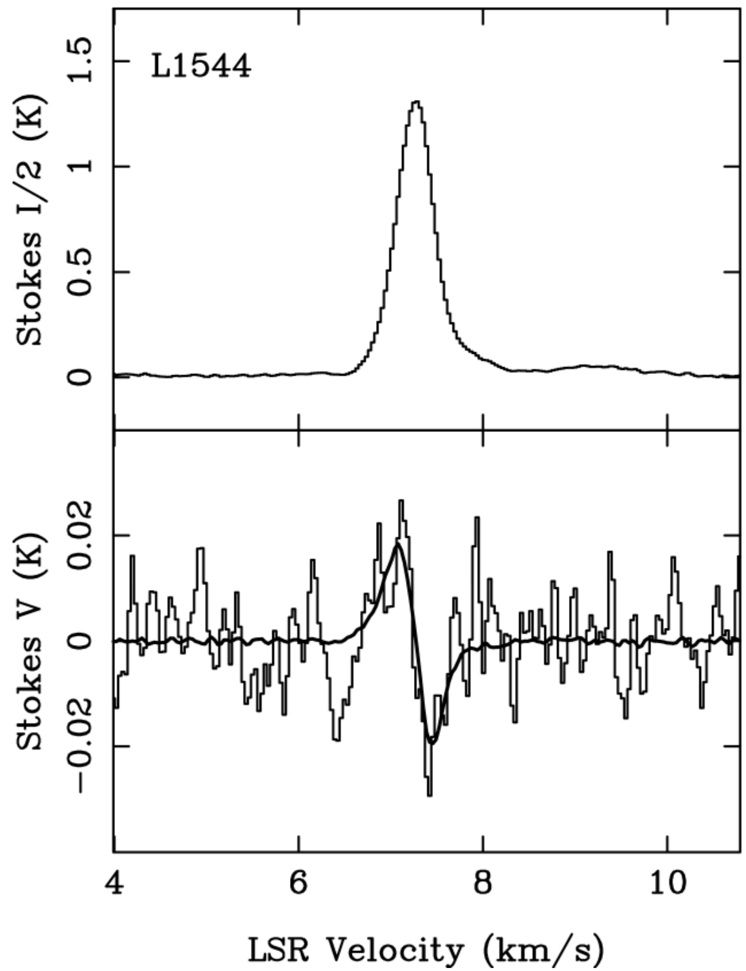
$B_{pos} \approx 80\ \mu G$

L1544 Starless Core



$n(H_2) \approx 5 \times 10^5$ cm^{-3}, $N(H_2) \approx 4 \times 10^{22}$,
$\delta\varphi = 13°$, $B_{pos} \approx 140\ \mu G$

Crutcher et al. (2004)



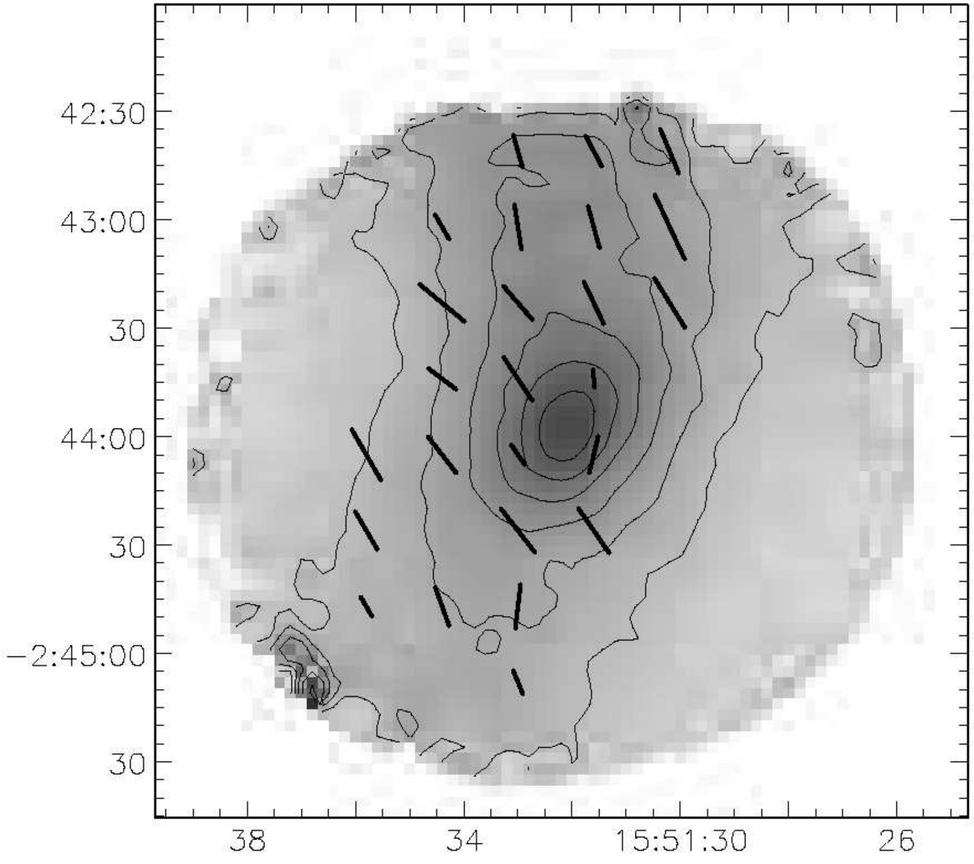
$n(H_2) \approx 1 \times 10^4$, $N(H_2) \approx 9 \times 10^{21}$,
$B_{los} = 11\ \mu G$

Crutcher & Troland (2000)

L183 & L1498 Starless Cores

L183

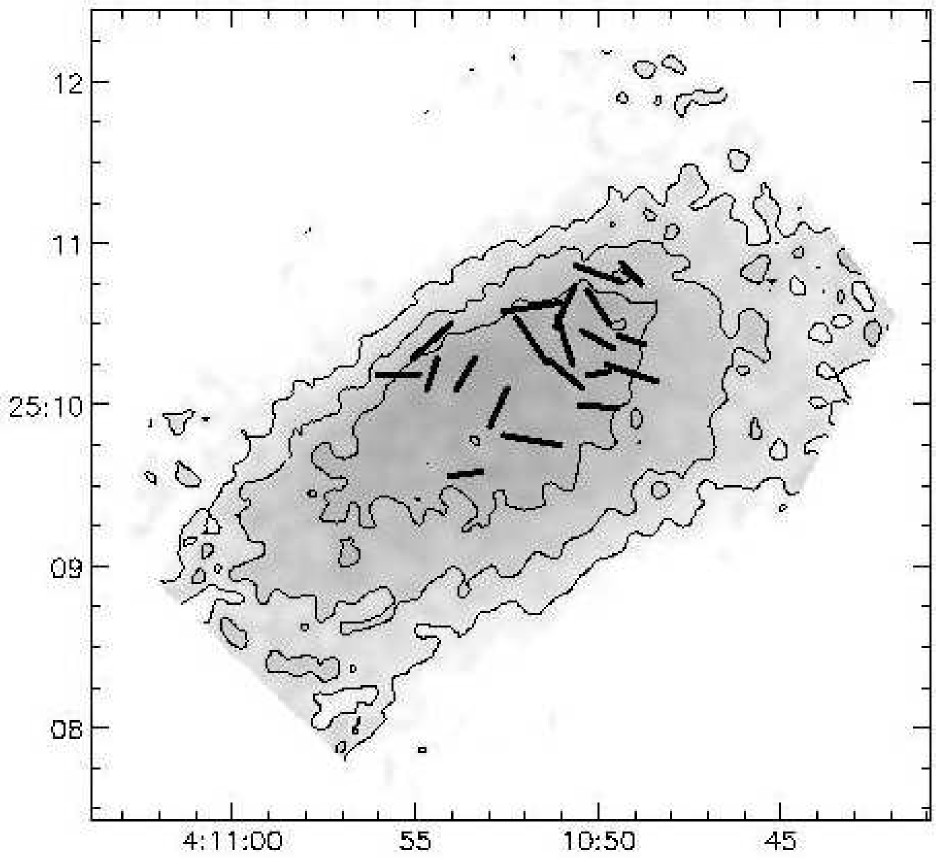
Crutcher et al. (2004)



$\delta\varphi = 13°$

L1498

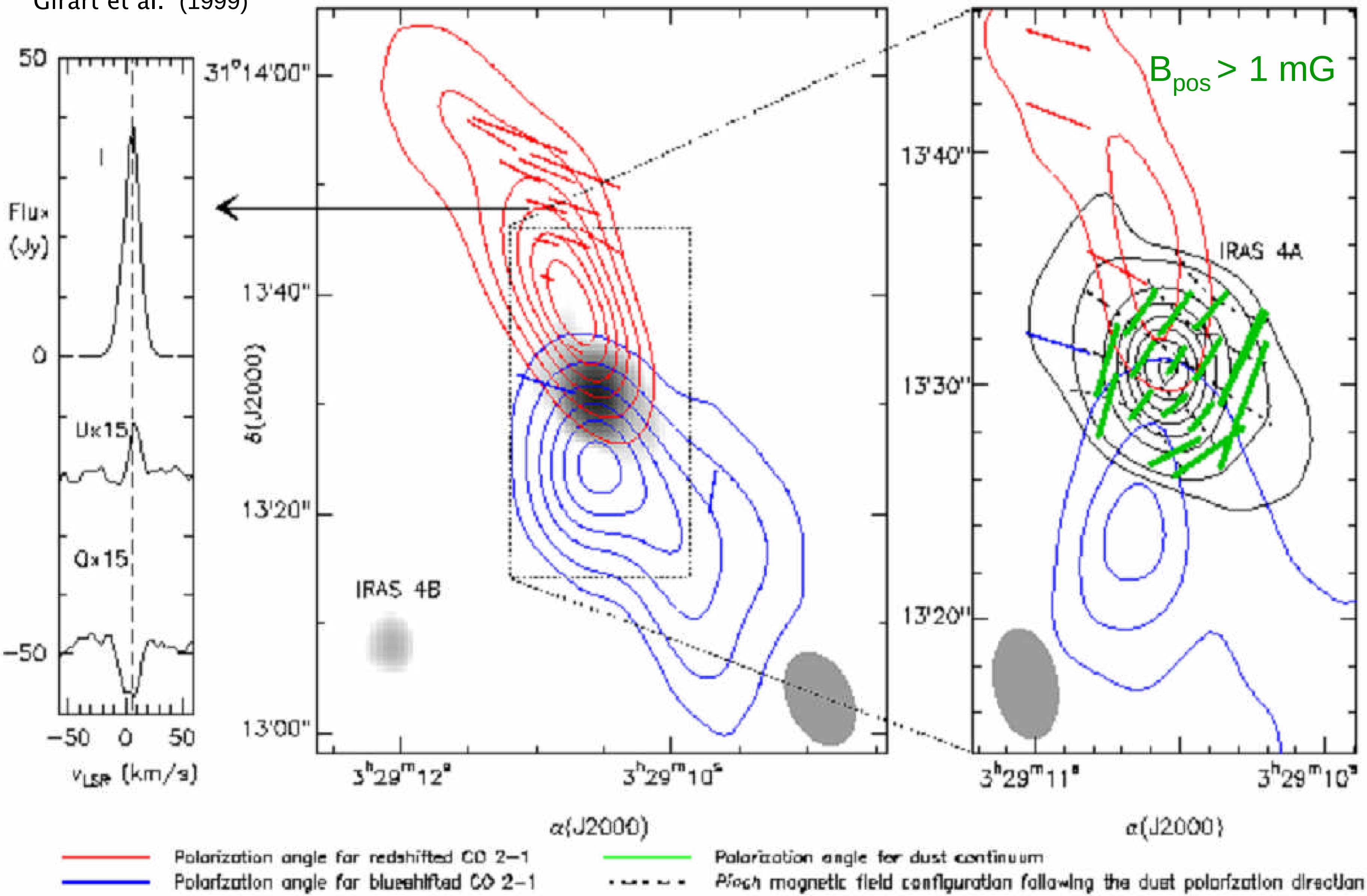
Kirk & Crutcher (2005)



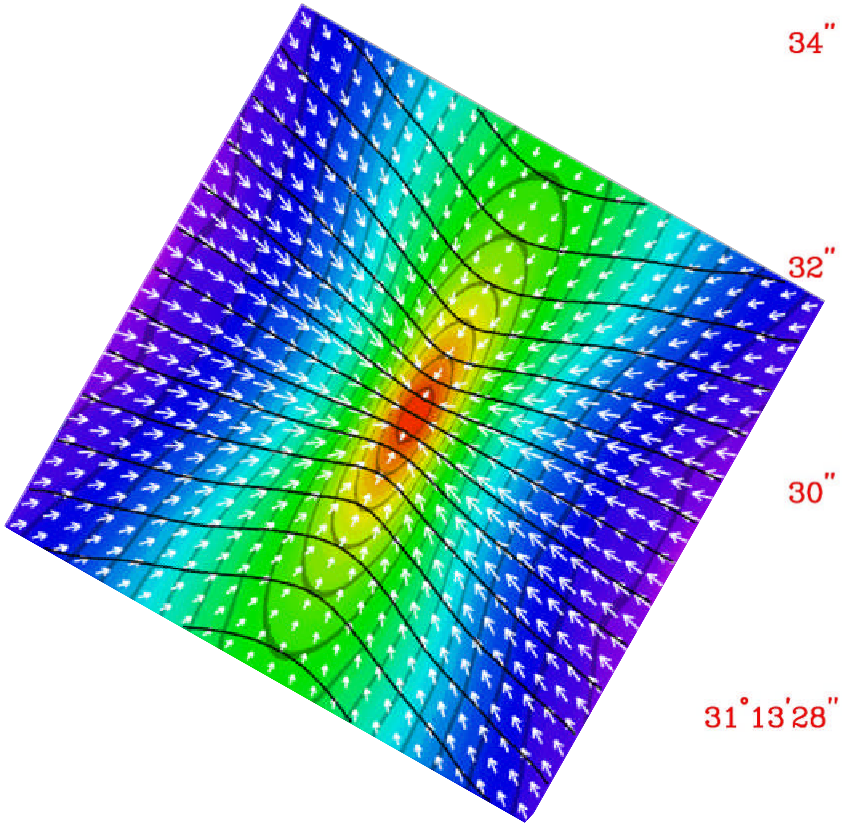
$\delta\varphi \approx 40°$

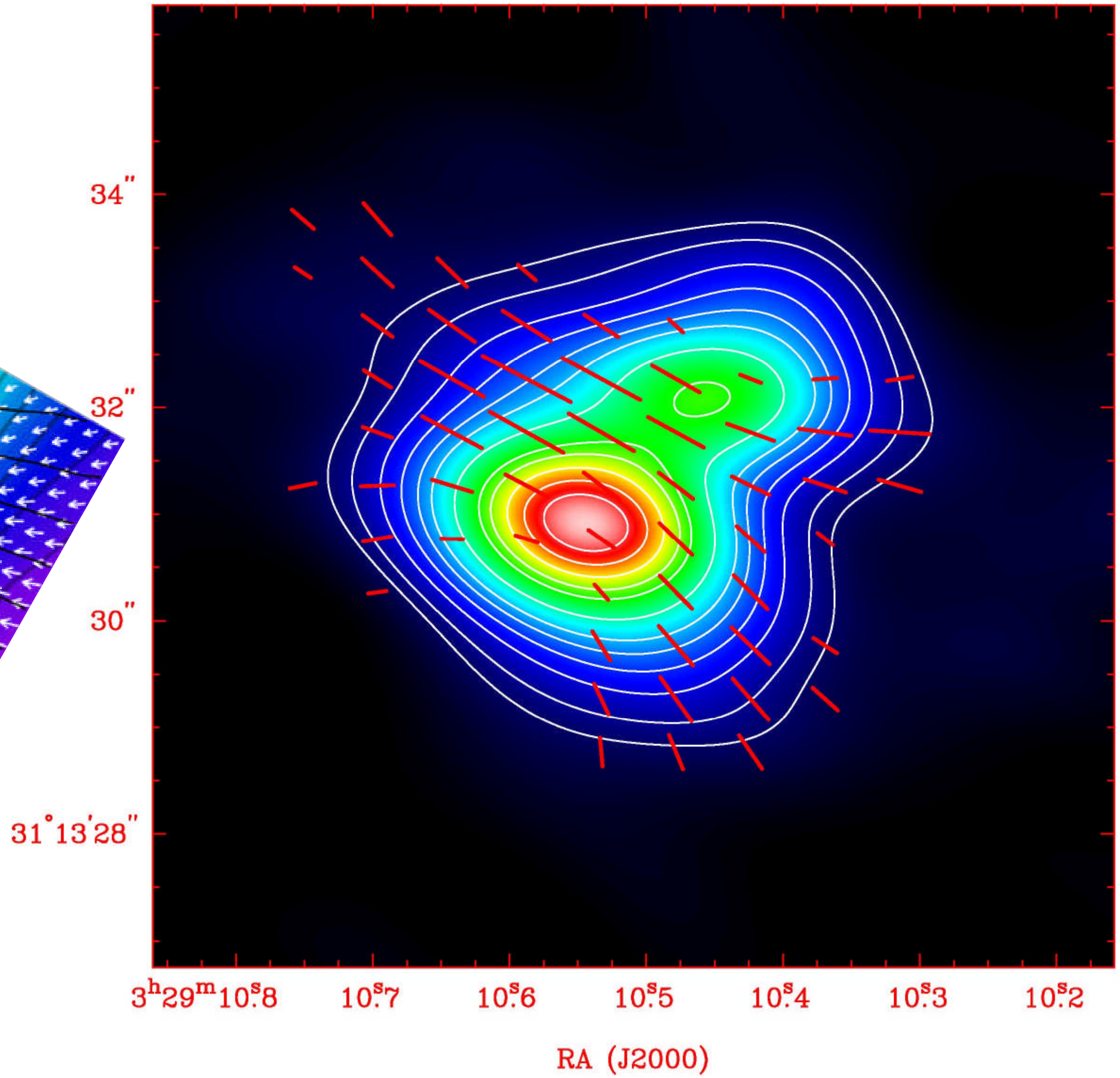
NGC1333 IRAS4 (BIMA 230 GHz)

Girart et al. (1999)



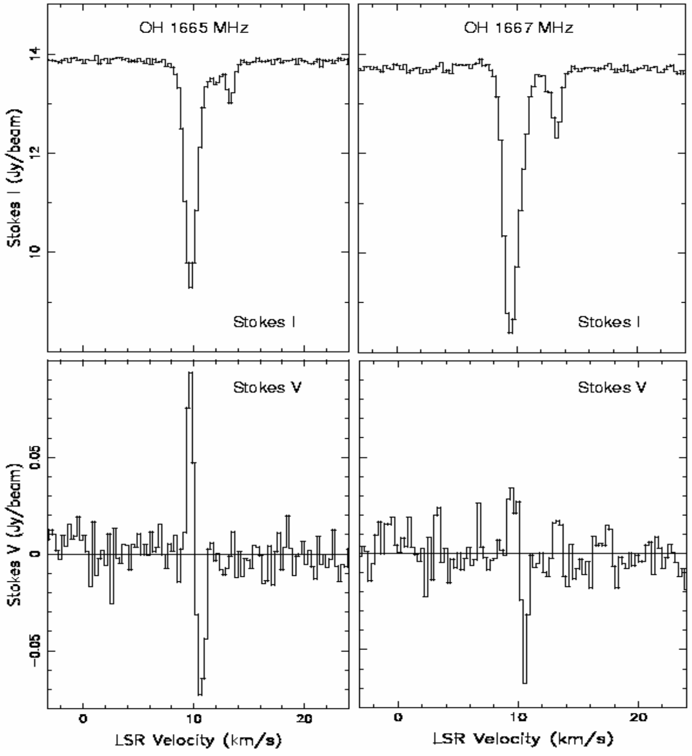
NGC1333 IRAS4 (SMA 345 GHz)

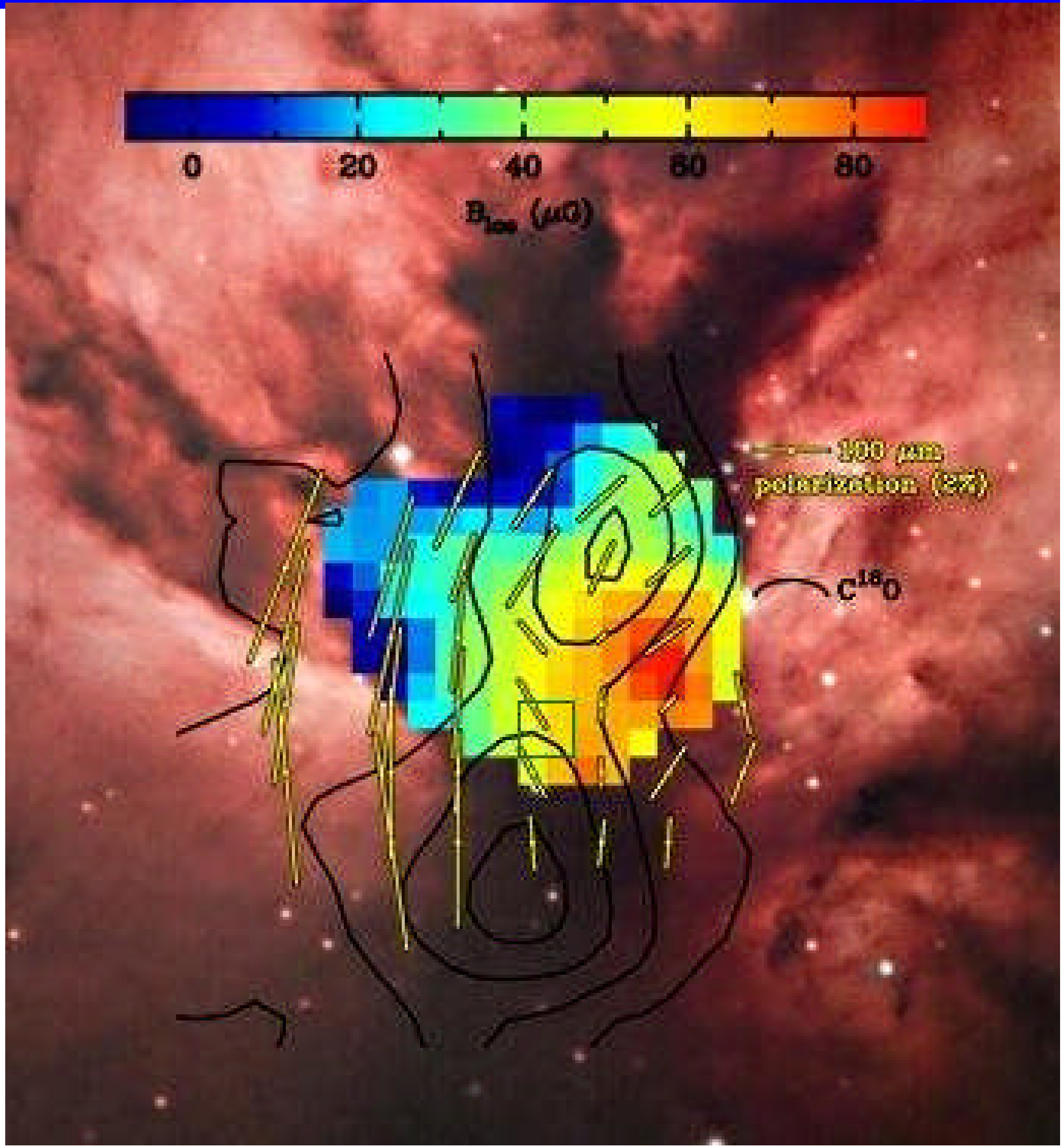




Girart, Rao, and Marrone (2006)

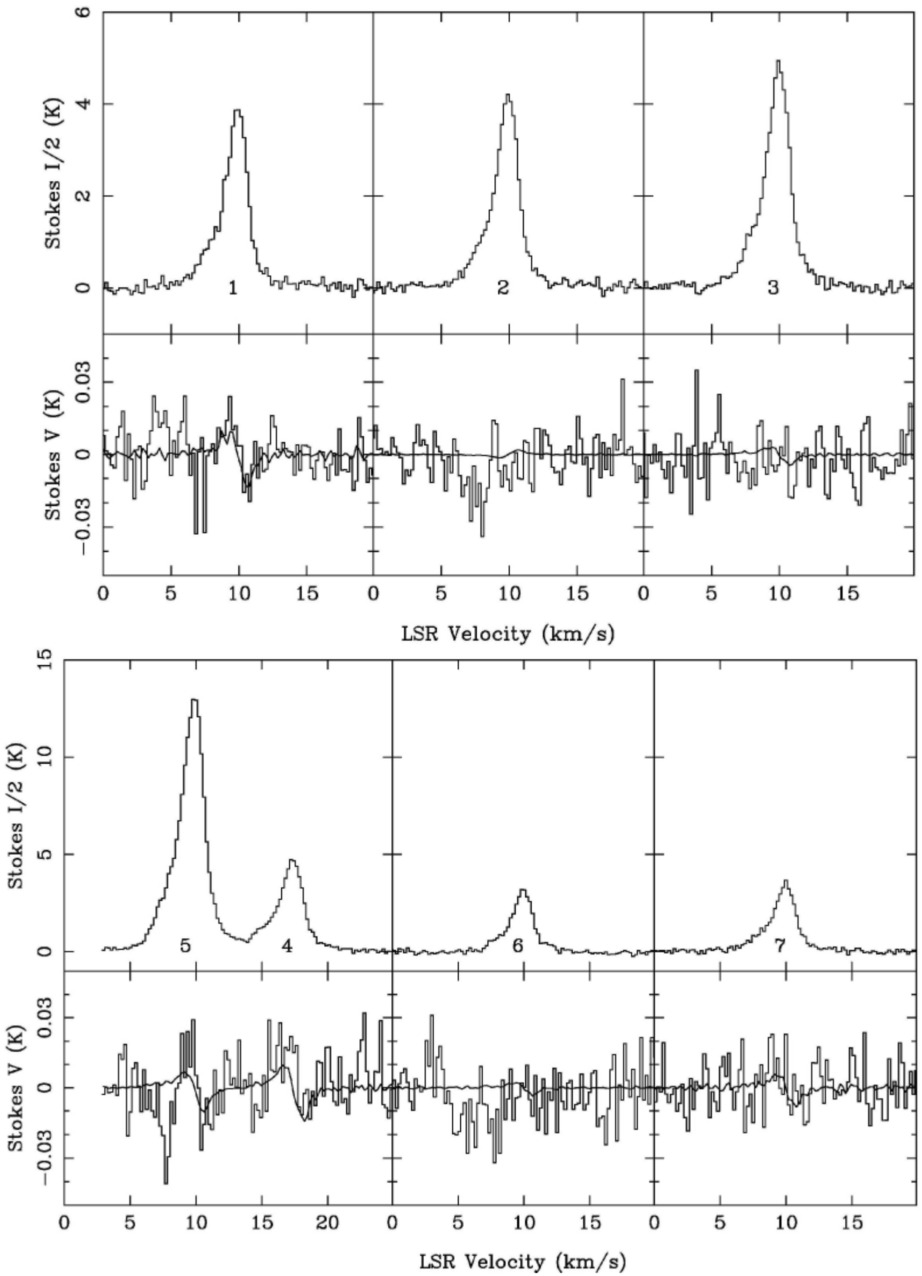
NGC 2024 (Orion B) Magnetic Field Maps

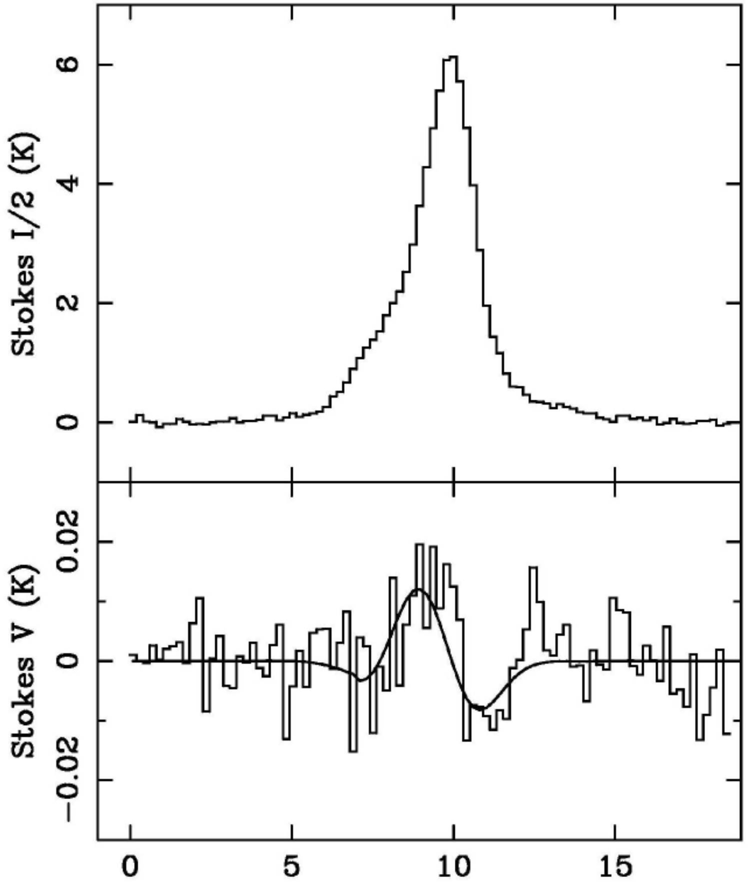




Crutcher et al. (1999)

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





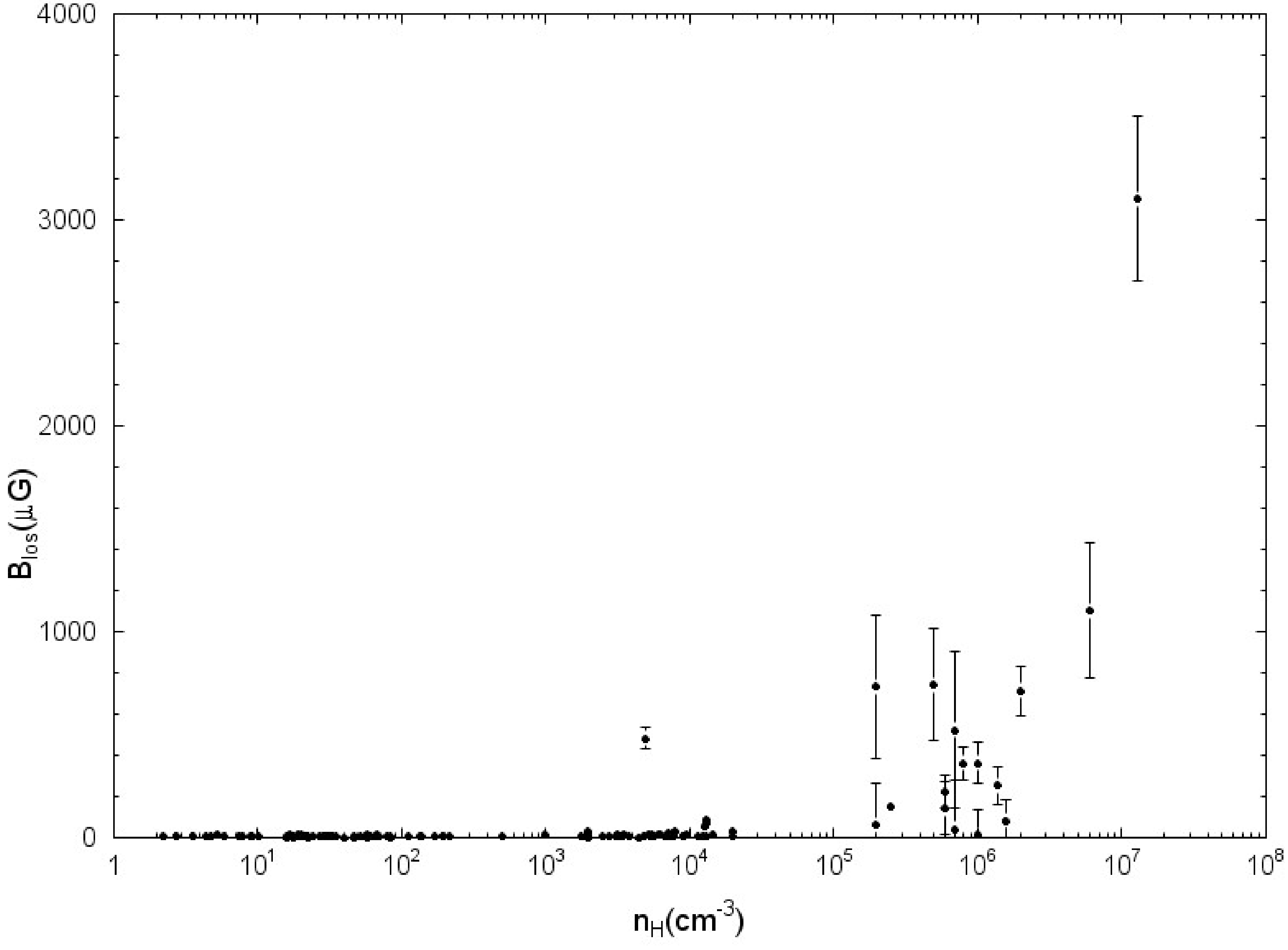
$B_{LOS} = -0.36 \pm 0.08$ mG

Crutcher et al. 1999

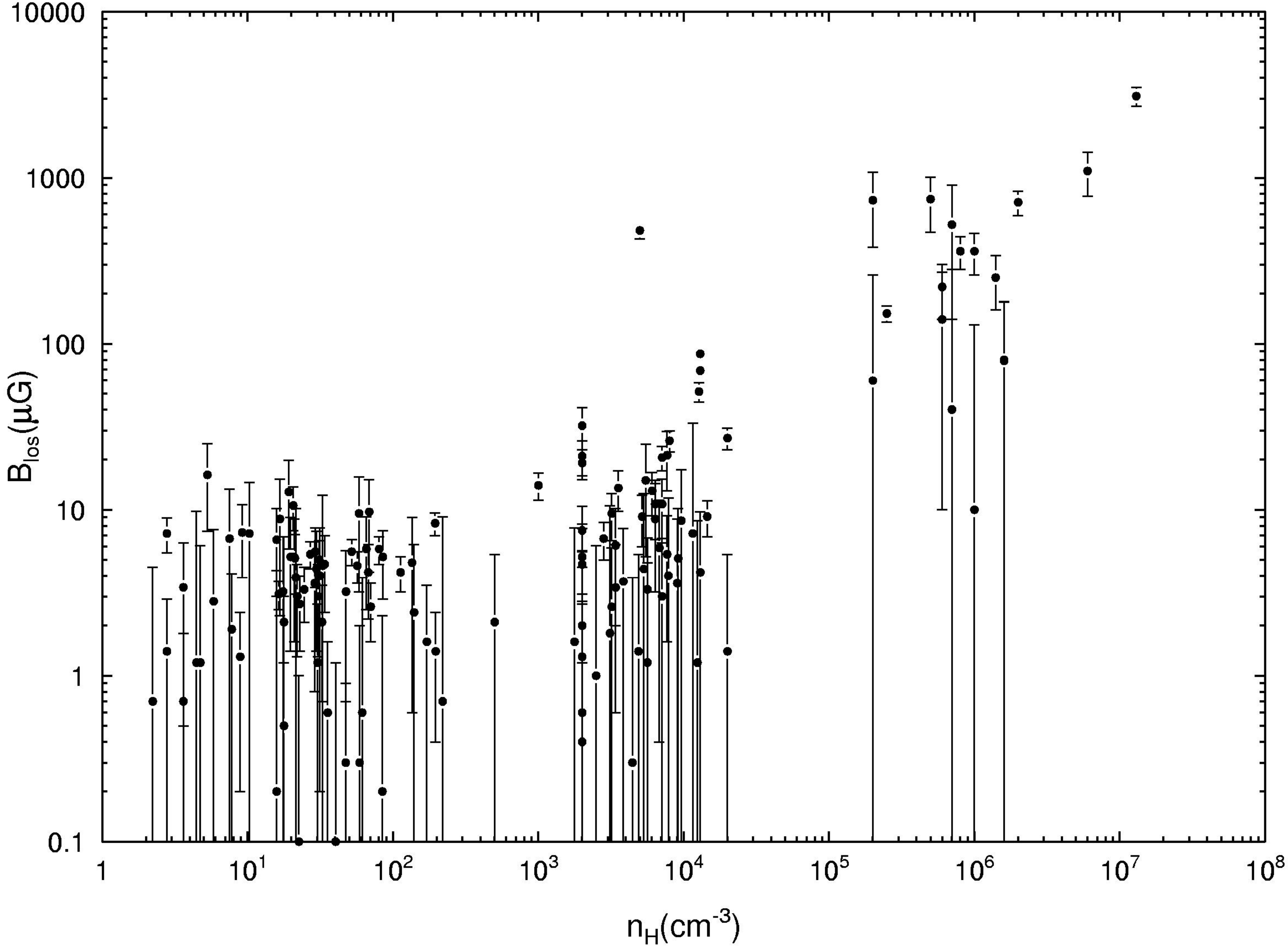
Major Zeeman Data Sets

	B_{los} detections/total
Arecibo H I quasar abs. Heiles & Troland 2005	20/67
GB OH dark clouds Crutcher et al. 1993	2/12
Arecibo OH dark clouds Troland & Crutcher 2008	17/48
VLA H I & OH mapping various; see Crutcher 1999	5/5
IRAM CN Crutcher et al 1996, 1999; Falgarone et al. 2008	9/15
Bonn excited OH Guesten et al. 1994	1/1

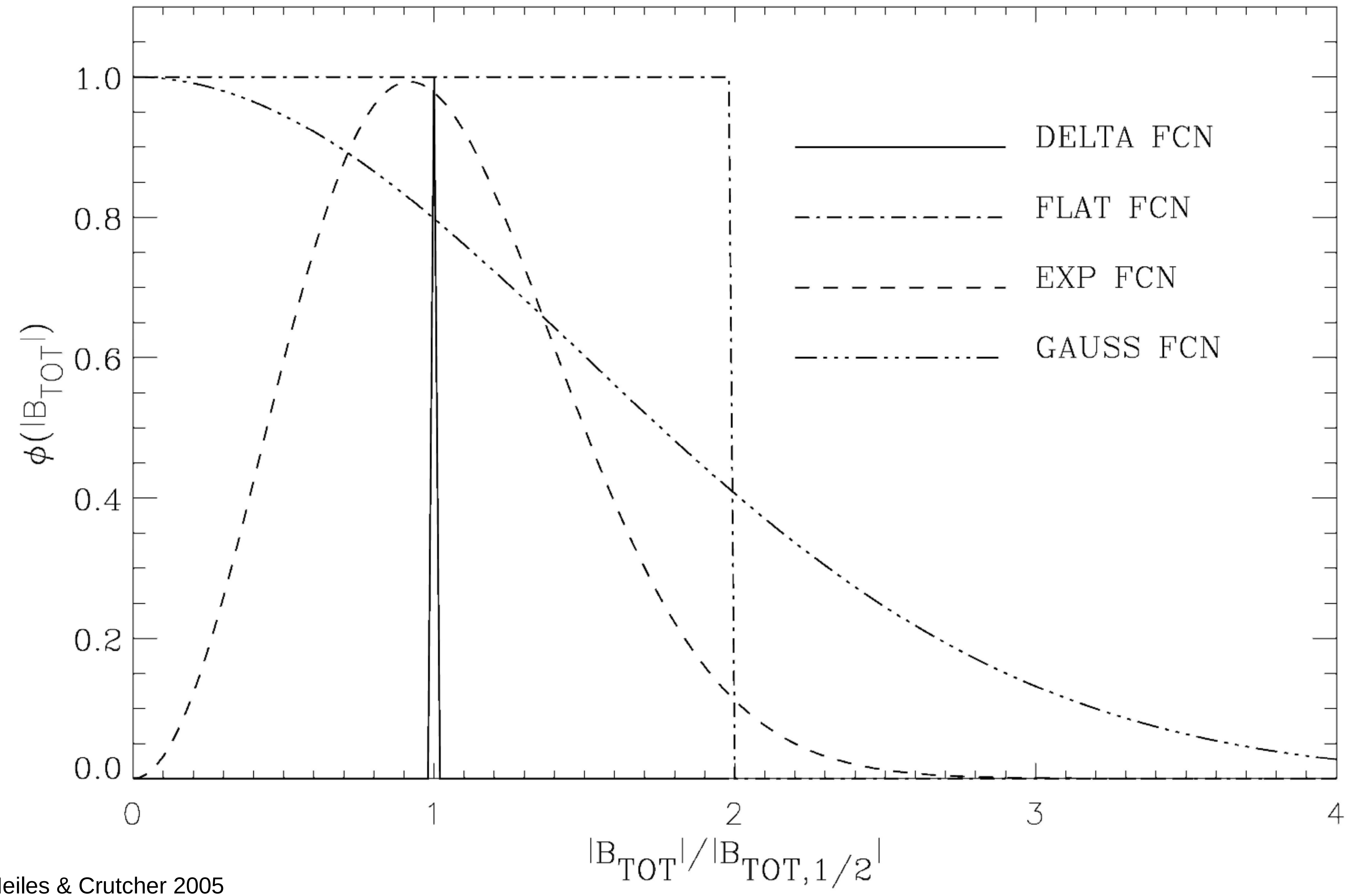
Results for Field Strength



Results for Field Strength

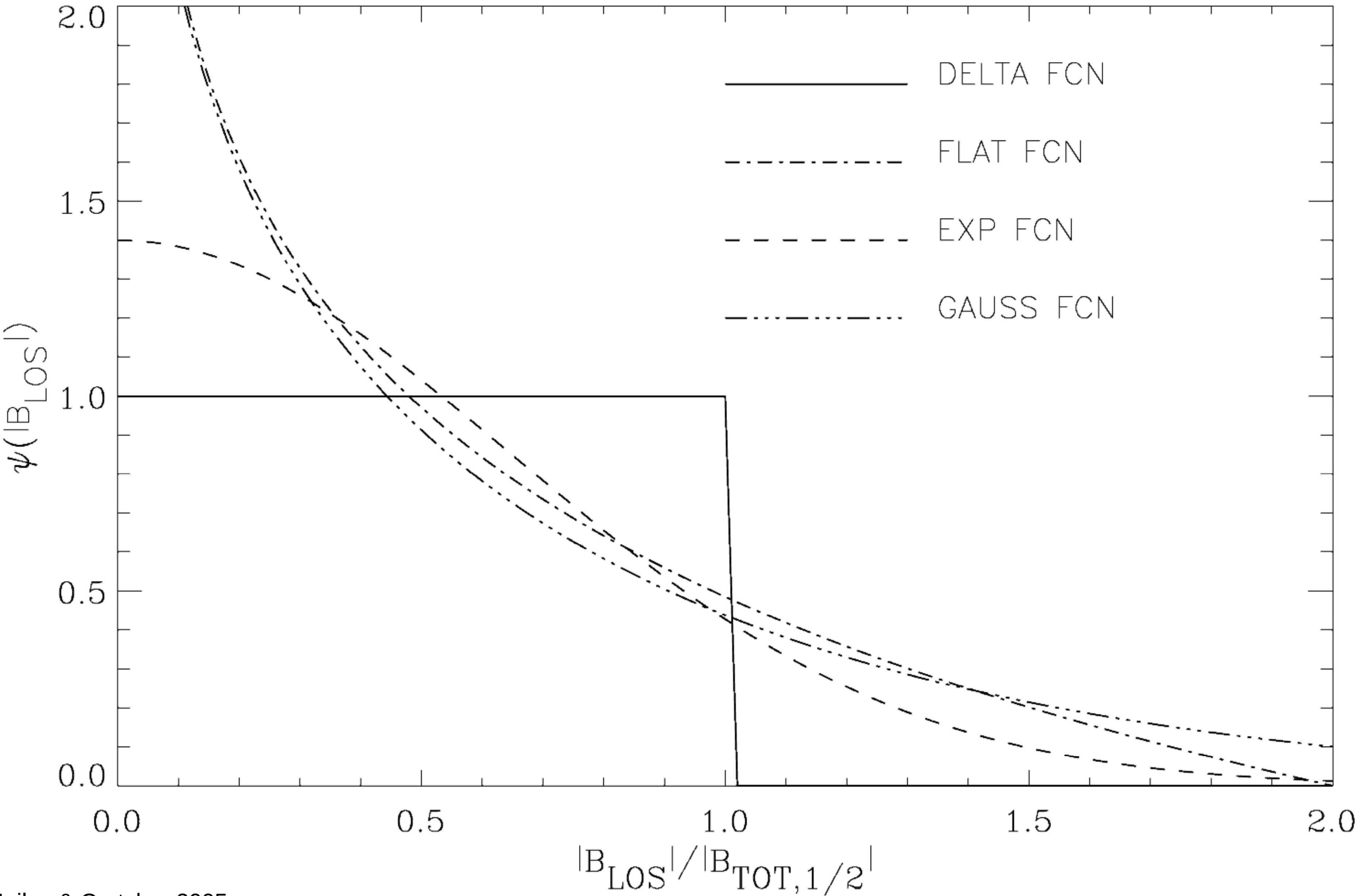


Probability Density Function of B_{total}



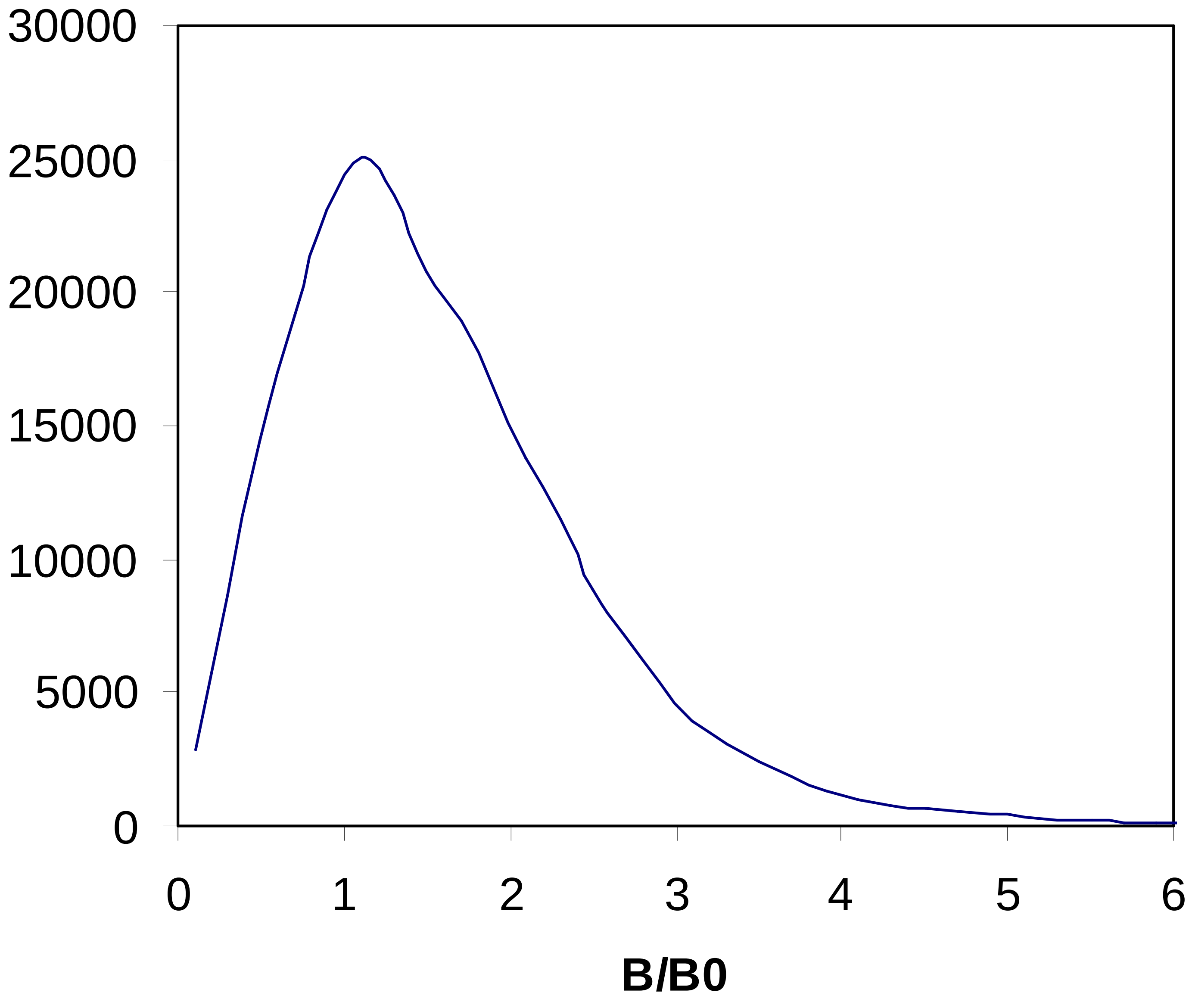
Heiles & Crutcher 2005

Probability Density Function of B_{LOS}



Heiles & Crutcher 2005

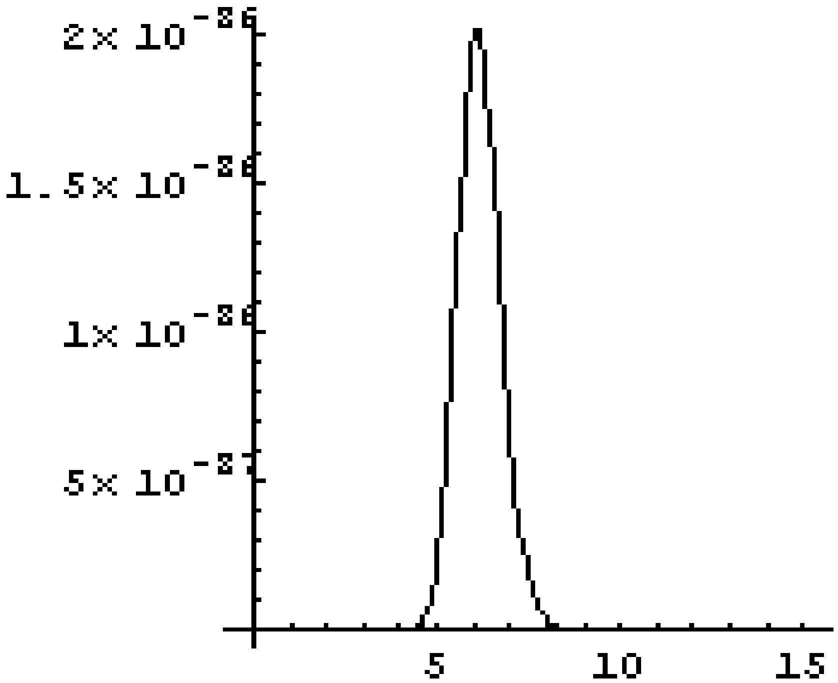
Super-Alfvenic Simulation



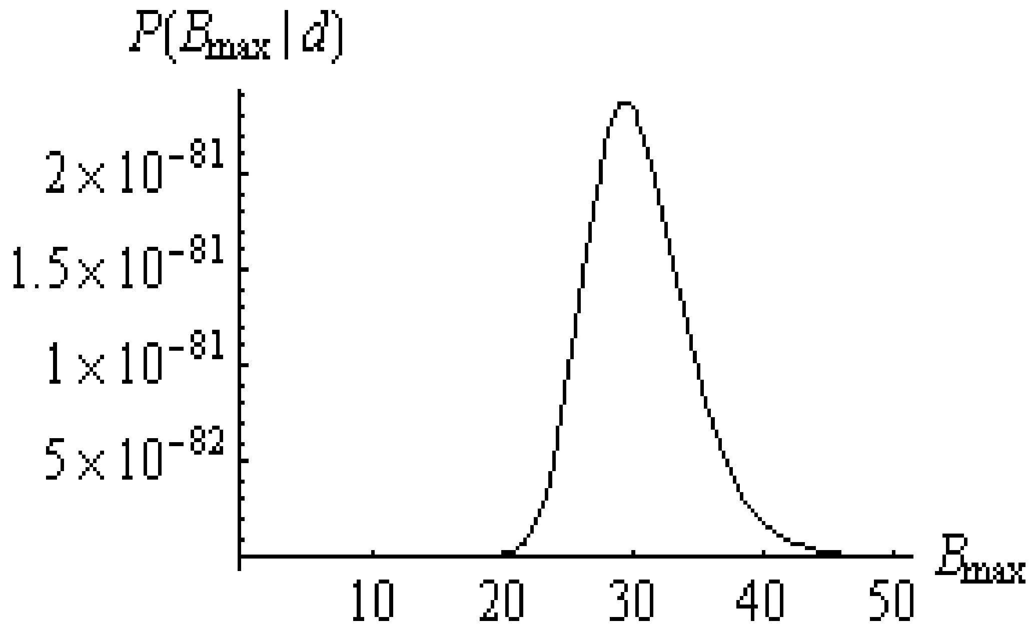
Lazarian & Goncalves 2007

Bayesian Analysis of H I & OH Zeeman

H I



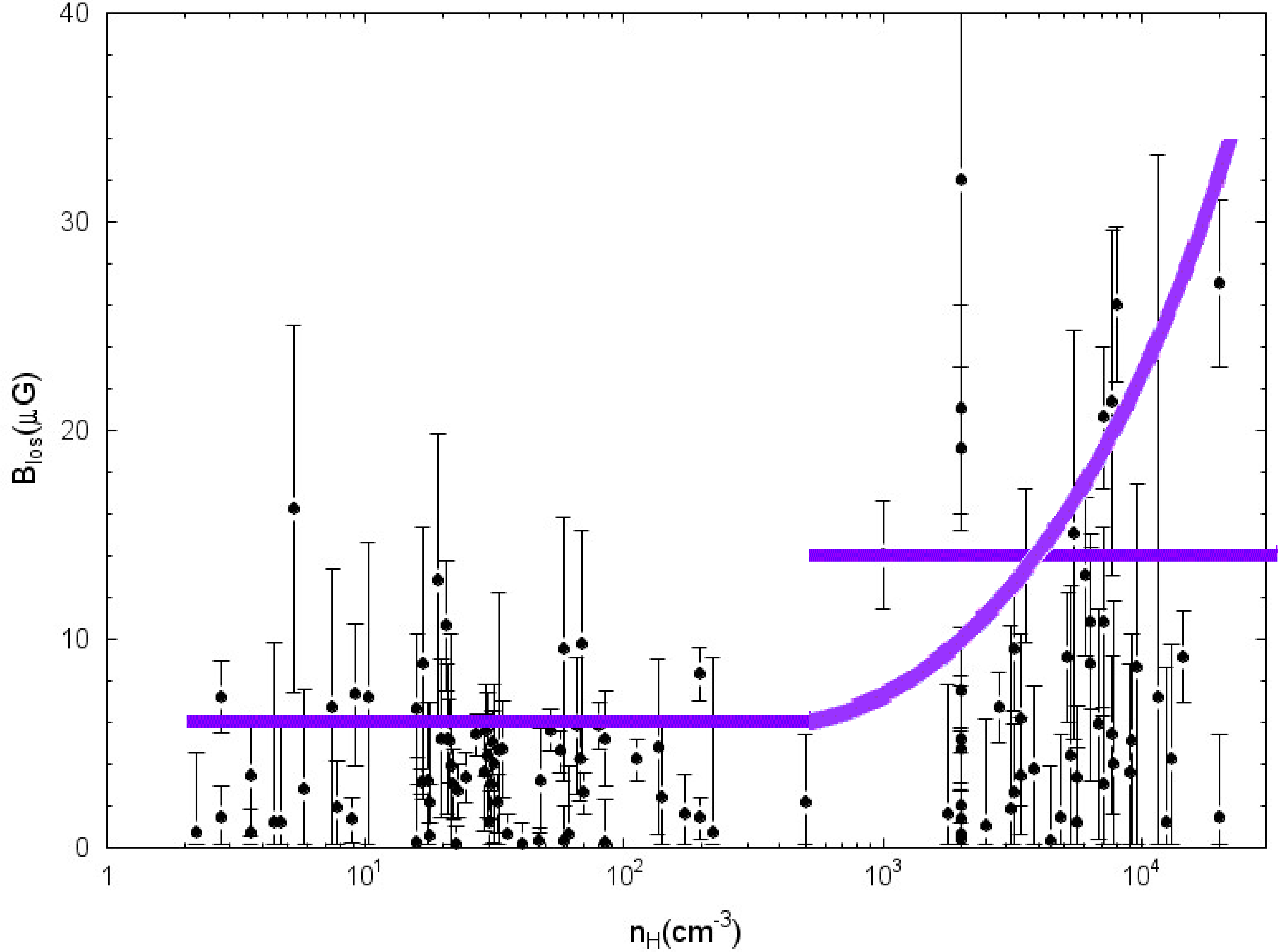
OH



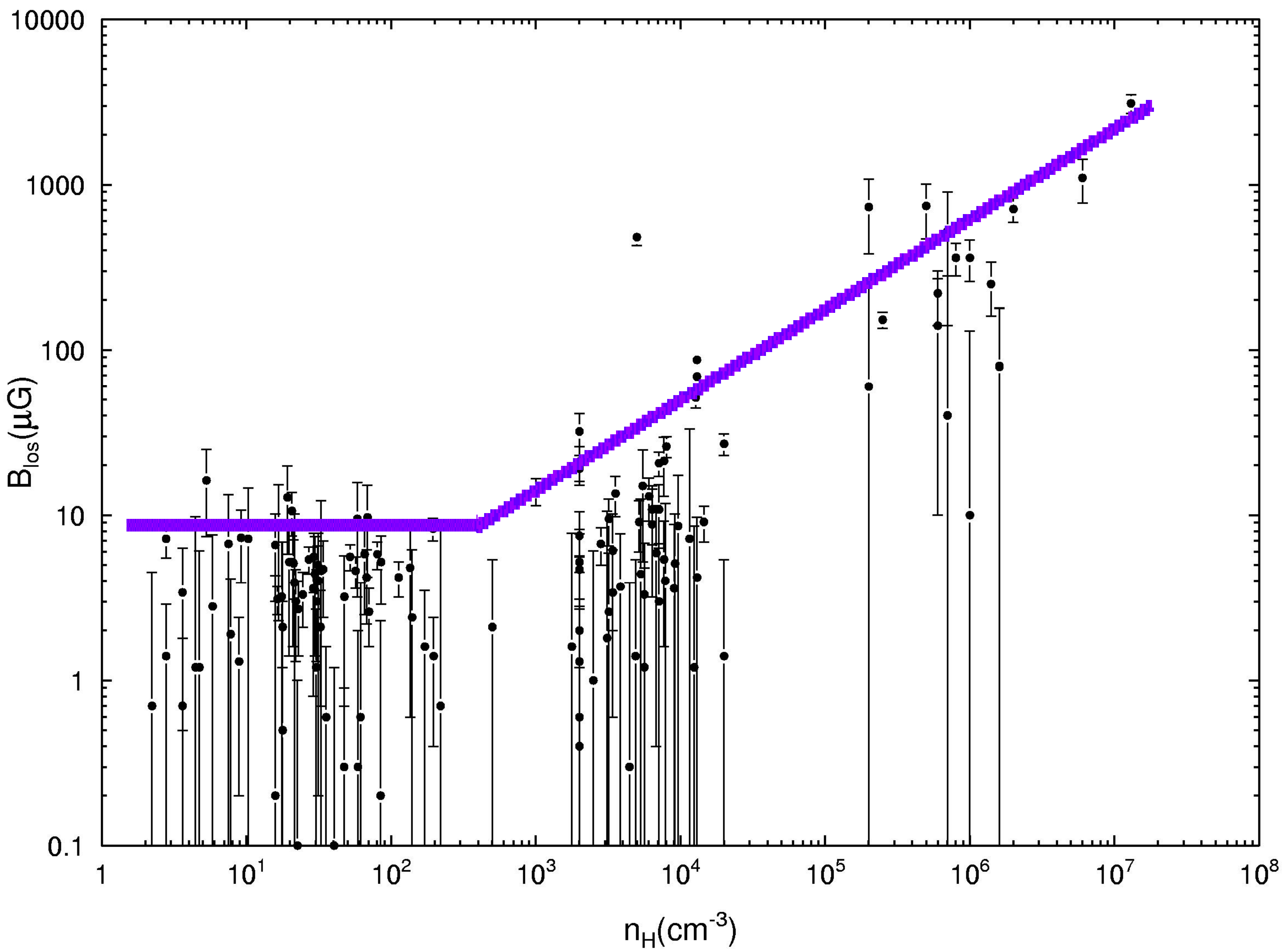
Unique : Uniform = 1 : 1.5

Unique : Simulation : Uniform = 1 : 1,000 : 10,000

Results for Field Strength



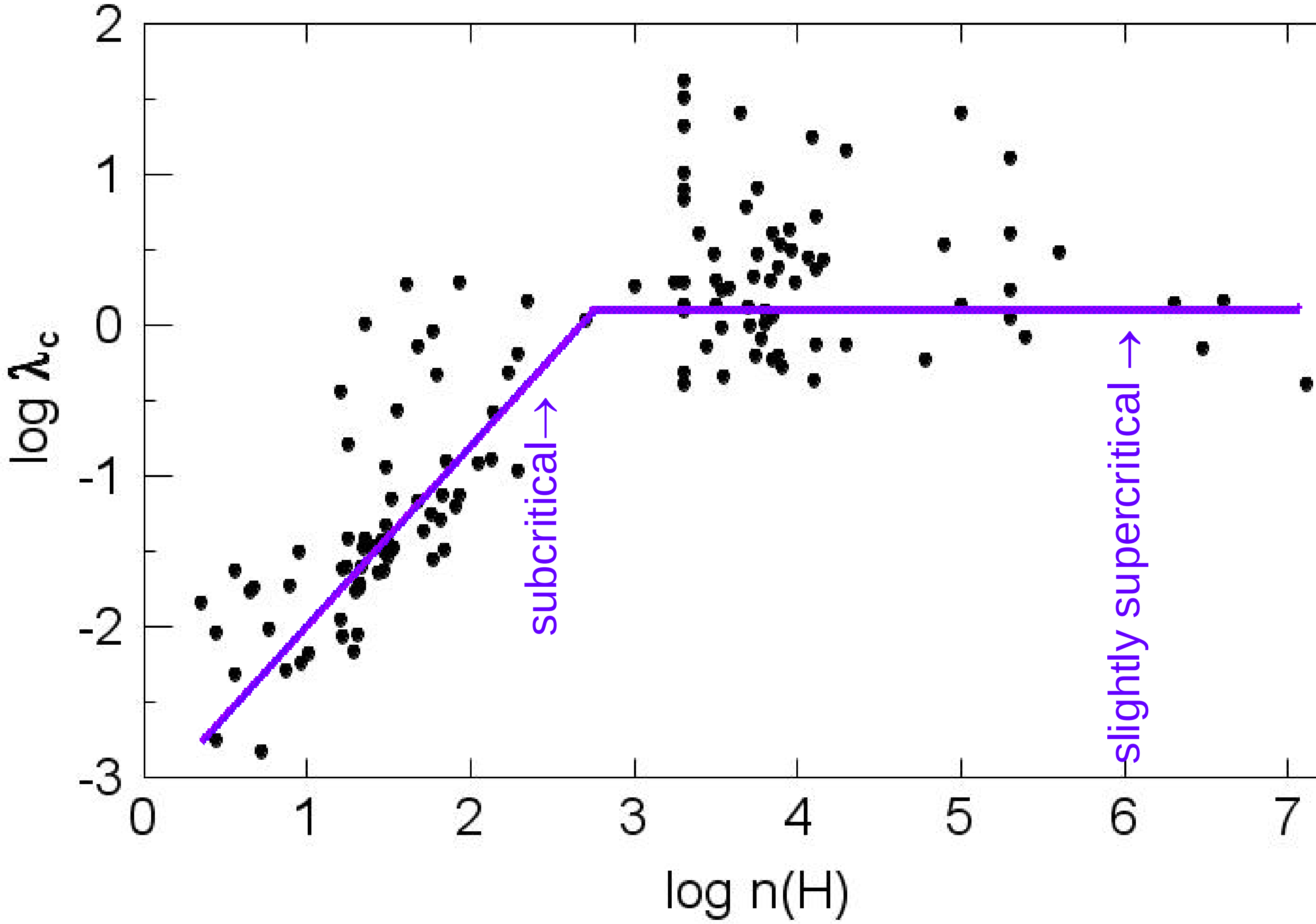
Results for Field Strength



Results for Diffuse and Molecular Clouds

	H I Clouds	OH Clouds	CN Clouds
T(K)	50	10	50
N_H (cm^{-3})	1×10^{20}	8×10^{21}	9×10^{22}
n_H (cm^{-3})	54	3.6×10^{3}	3×10^{5}
thickness (pc)	0.6	0.7	0.1
σ_{NT} (km/s)	1.2	0.37	1.2
$B_{total,1/2}$ (μG)	6.0	14	280
M_{sonic}	5.0	3.4	5.0
$M_{Alfvenic}$	1.4	1.5	2.2
M/Φ (wrt critical)	0.06	2.2	1.2

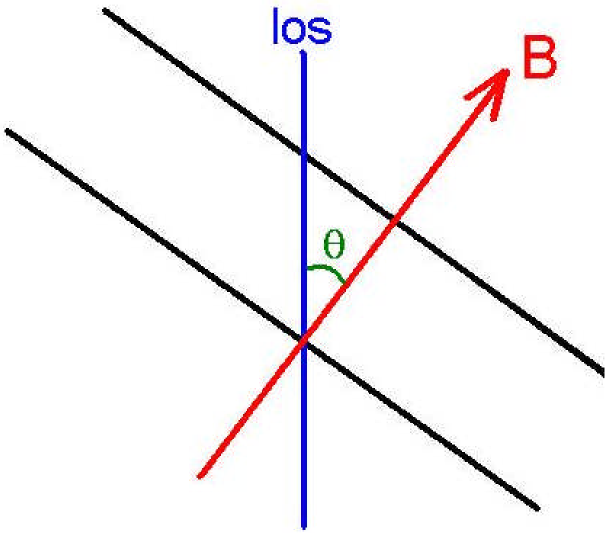
Results for Mass/Flux

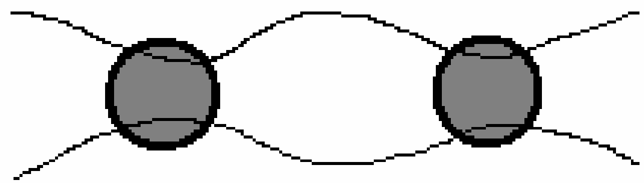


Mass-to-Flux Ratio: M/Φ

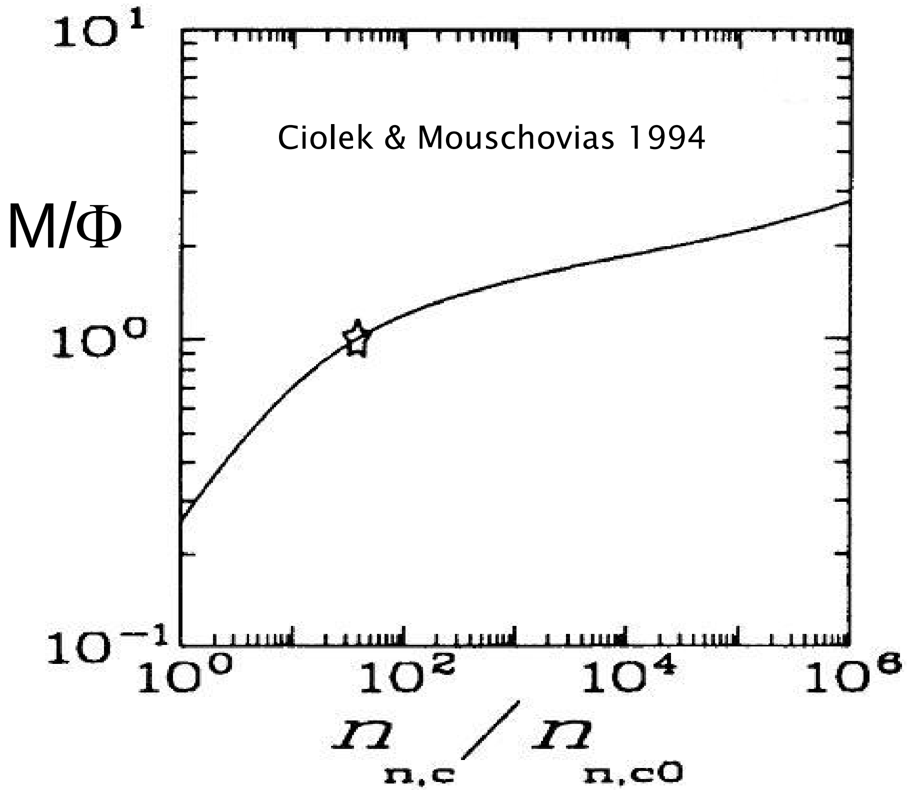
M/Φ has a correction ~2 for column density N if clouds are disks; this will decrease M/Φ

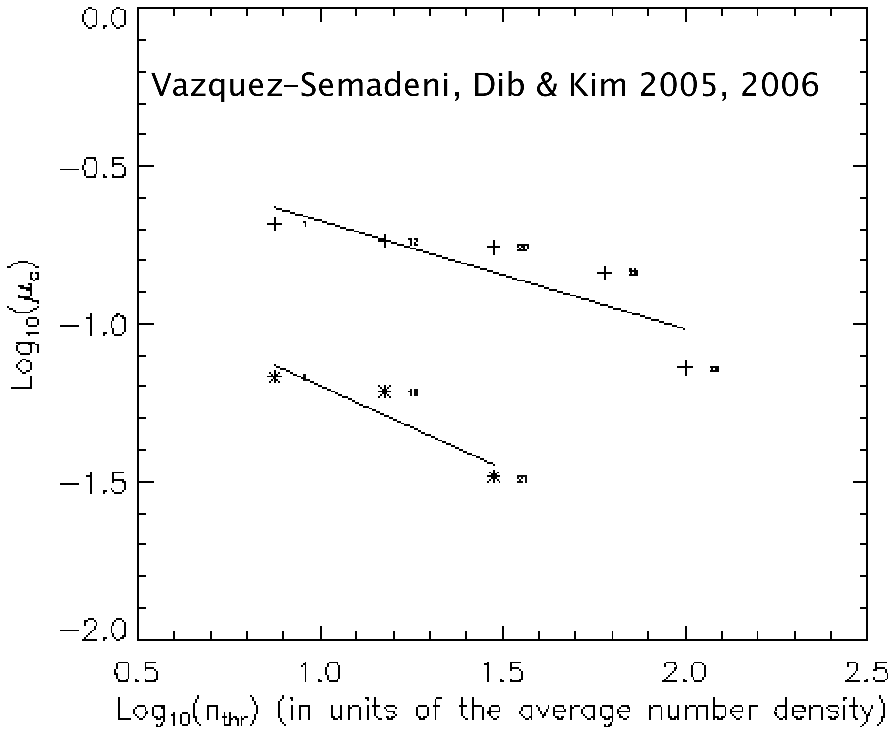
Multiple clumps will lead to larger measured M/Φ if they combine





A Definirive Test of Ambipolar Diffusion

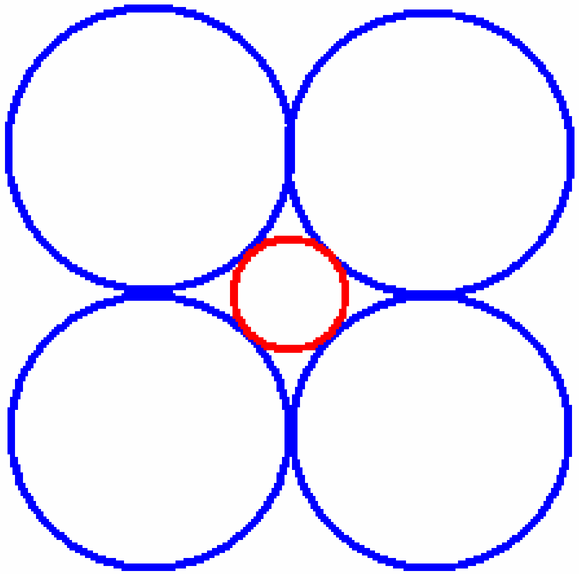




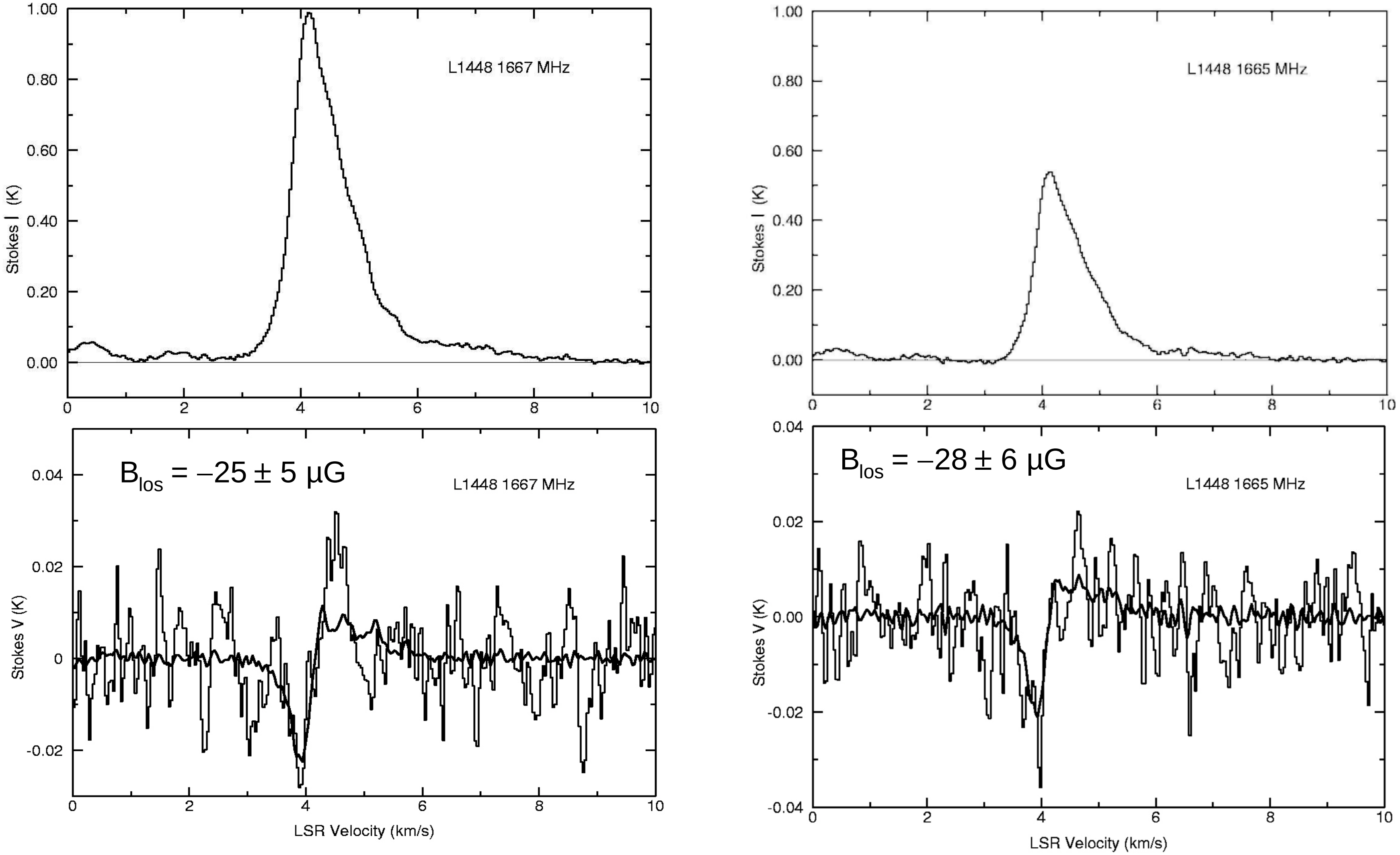
The Future

Measure differential M/Φ between core and envelope:

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

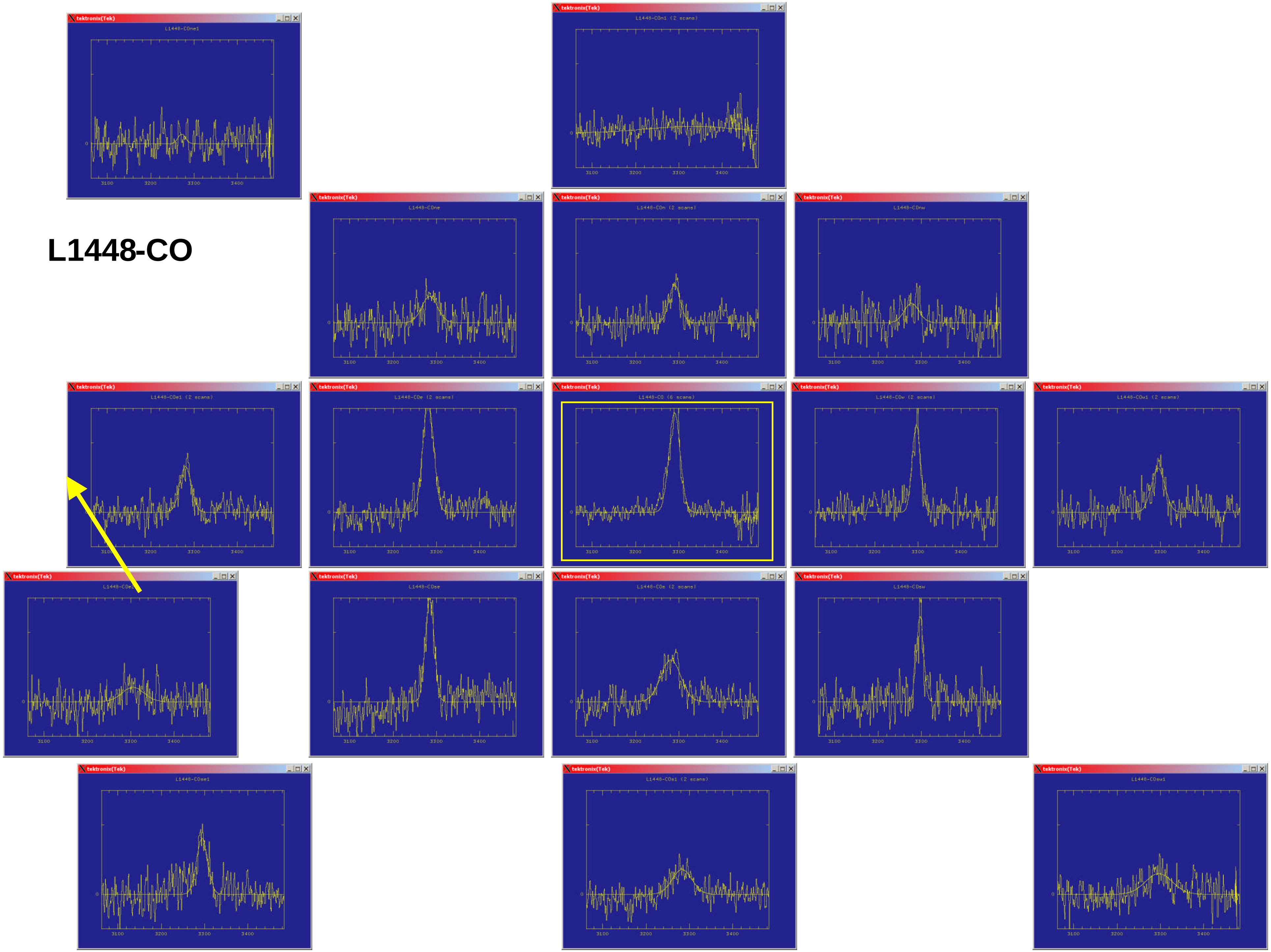


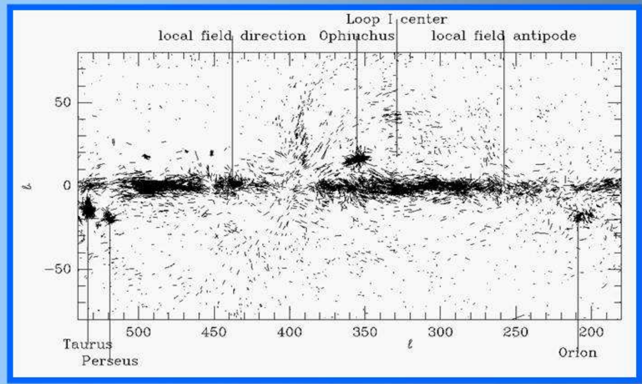
L1448 (OH Zeeman)



Troland & Crutcher 2007

L1448-CO





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- ▲Magnetic fields in the Galaxy at large
- ▲Magnetic fields in H II regions and PDRs
- ▲Magnetic fields in dense cores
- ▲New instrumentation & methods

Organizing Committee – C. Brogan, R. Crutcher, G. Ferland, C. Heiles, A. Sarma

http://thunder.pa.uky.edu/magnetic/

Speakers

Shantanu Basu, Crystal Brogan, You-Hua Chu, Richard Crutcher, Joanna Dunkley, Miller Goss, J. L. Han, Carl Heiles, Will Henney, Roger Hildebrand, Martin Houde, Athol Kemball, Alex Lazarian, Zhi-Yun Li, Mordecai Mac Low, Antonio Mario Magalhaes, Brenda Matthews, Telemachos Mouschovias, Giles Novak, Bob O'Dell, Eve Ostriker, Rick Perley, Richard Plambeck, Ramprasad Rao, Tim Robishaw, Anish Roshi, Anuj Sarma, Lew Snyder, Tom Troland, Bill Watson, Robin Williams, Al Wootten, Ellen Zweibel (as of July 2007)