EPoS

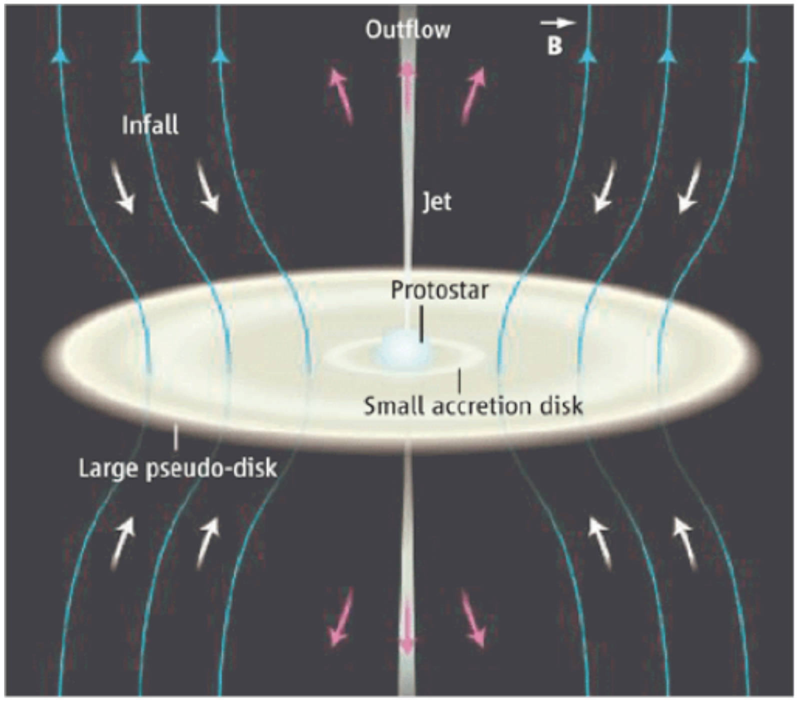
The Early Phase of Star Formation

MPIA Conference Series at Ringberg Castle

Role of Magnetic Fields in Star Formation: Observations

Dick Crutcher

University of Illinois



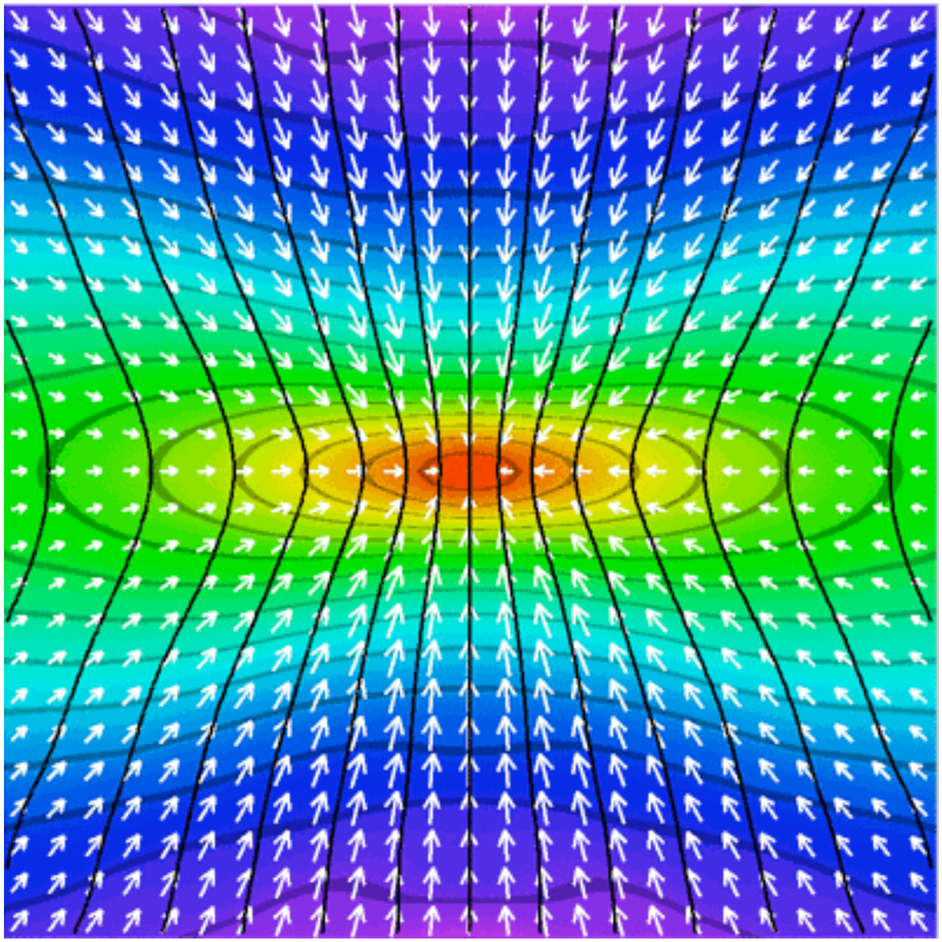
What Drives (Triggers) Star Formation?

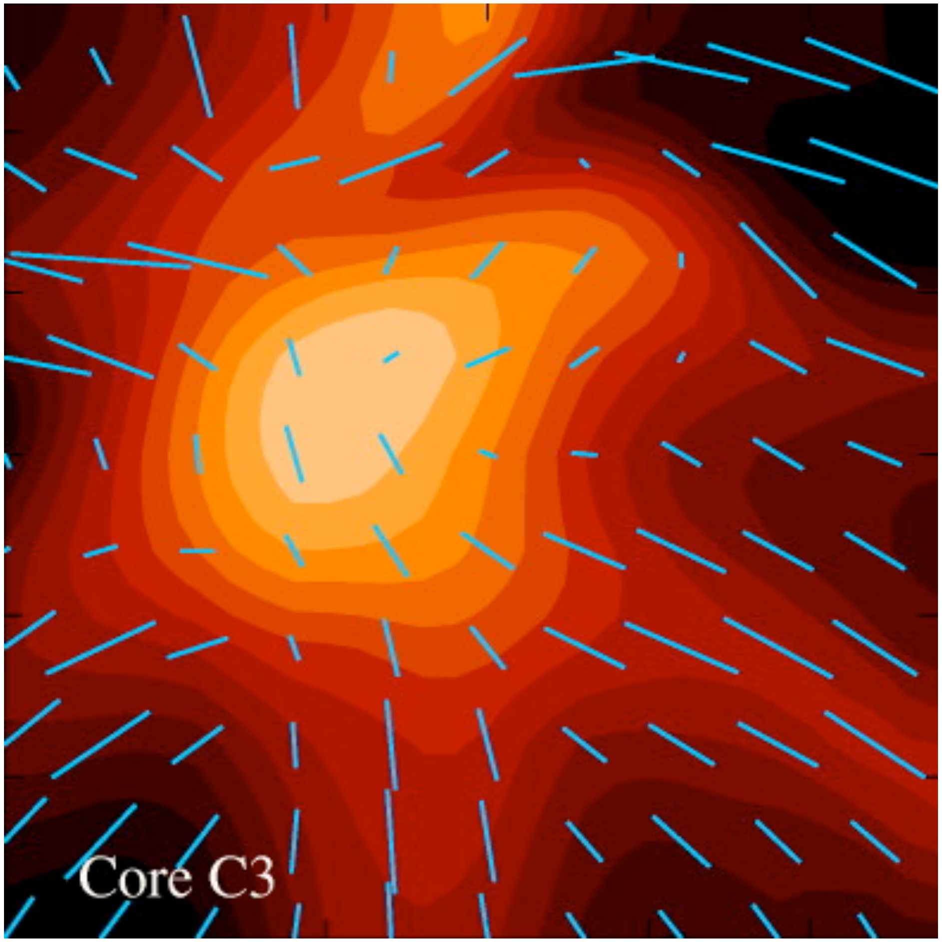
- Two (extreme case) paradigms:
  1. magnetic support (turbulence unimportant)
     - self-gravitating clouds are magnetically supported
     - magnetic field only frozen into ions, not neutrals
     - gravity leads to contraction of neutrals through ions and magnetic field: ambipolar diffusion
     - mass in core overwhelms core magnetic field, collapses
  2. compressible turbulence (magnetic fields unimportant)
     - turbulence forms structure in the interstellar medium
     - dense clumps form, and usually dissipate
     - some clumps are self-gravitating and collapse
- Observations of magnetic fields in molecular clouds can distinguish between these models
  1. magnetic field morphology
  2. ratio of gravity to magnetic support: M/Φ
  3. scaling of magnetic field strength with density

Magnetic Field Morphology

ambipolar diffusion

turbulence





Fiedler & Mouschovias 1993

Padoan et al. 2001

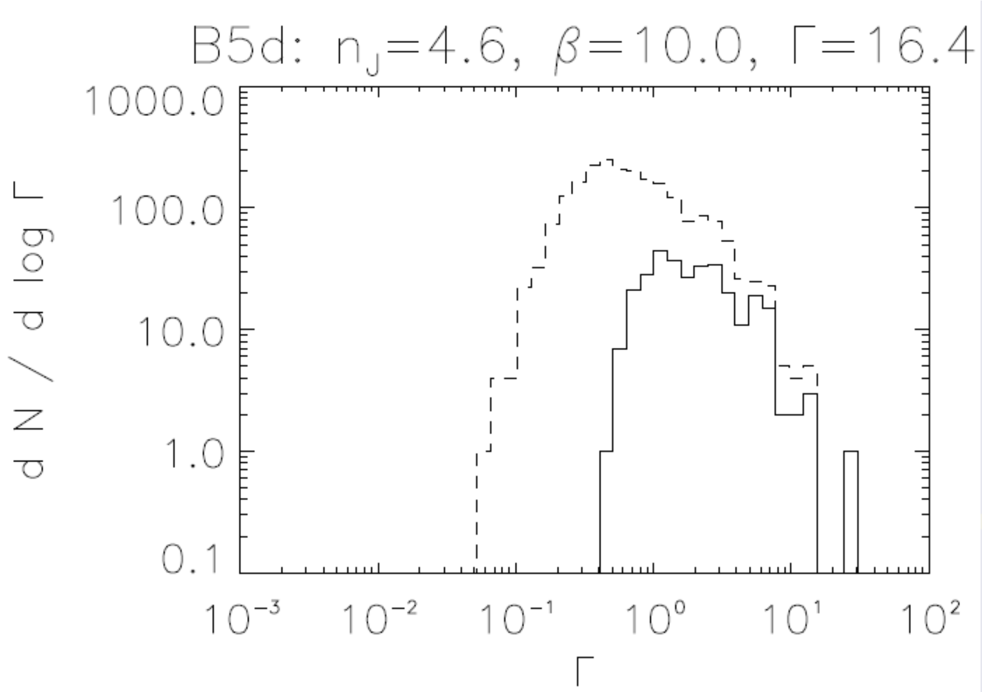
Mass/Flux = M/Φ, ratio of gravity to magnetic support

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

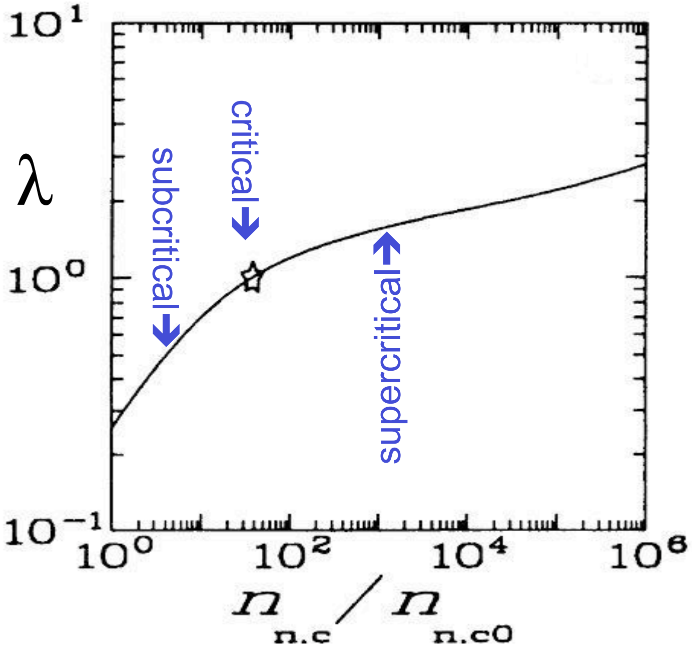
Nakano & Nakamura 1978

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

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

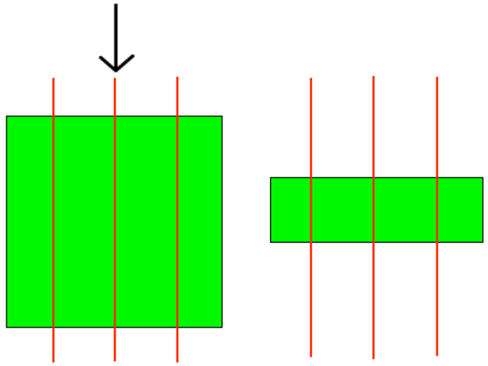


Tilley & Pudritz 2007

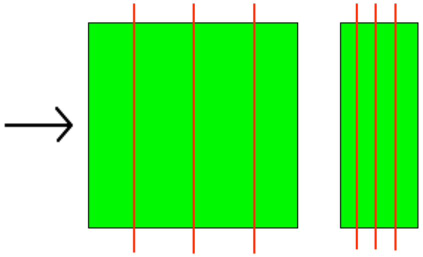


Ciolek & Mouschovias 1994

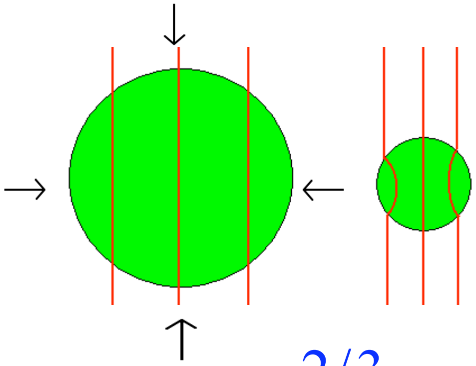
Scaling of B with ρ



$B \propto \rho^{0}$

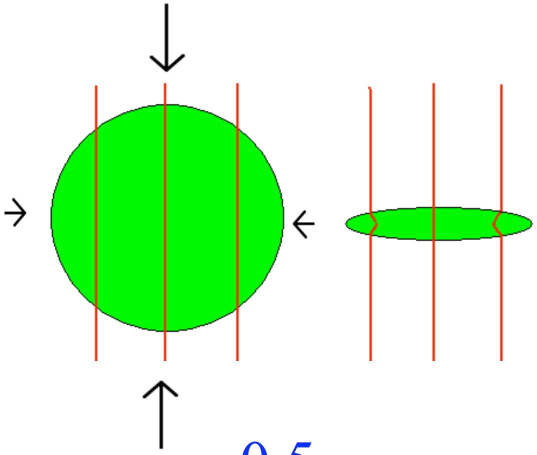


$B \propto \rho^{1}$

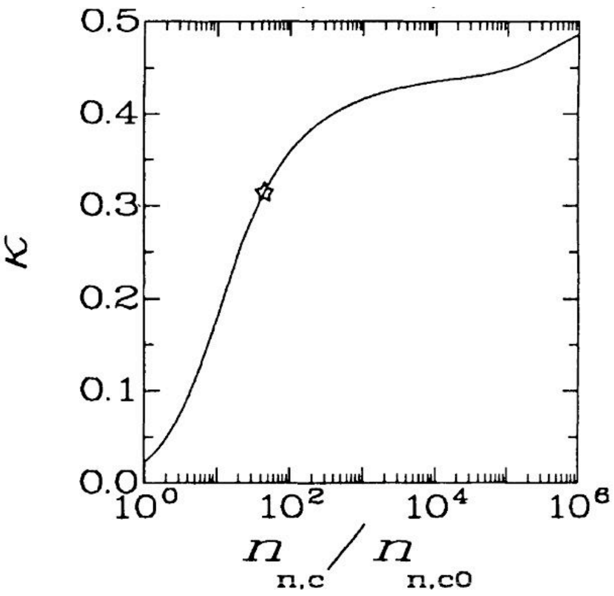


$B \propto \rho^{2/3}$

Mestel 1966

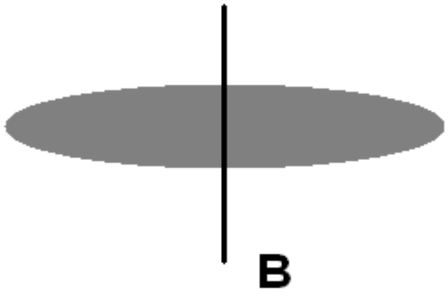


$B \propto \rho^{0.5}$



Ciolek & Mouschovias 1994

Polarized emission from paramagnetic grains

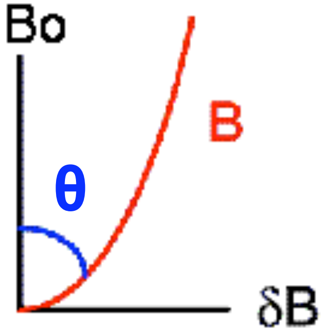


- grain alignment with minor axis ll to B
- linear polarization, hence morphology of B_{pos}
- polarization percentage independent of the strength of the magnetic field, so no direct measurement of field strength
- indirectly (Chandrasekhar & Fermi):

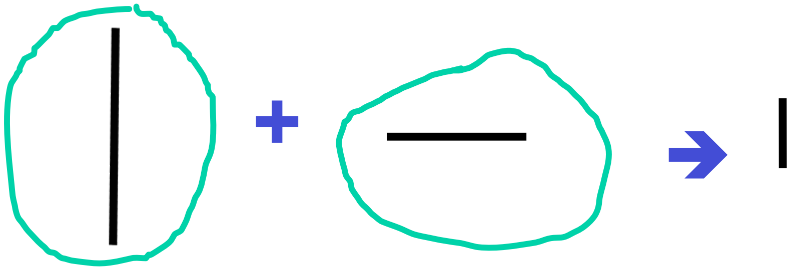
$$\delta V \approx \delta B / \sqrt{4\pi\rho}, \quad \delta\theta \approx \delta B / B_{pos}$$

$$\therefore B_{pos} \approx f \sqrt{4\pi\rho}\ \delta V_{los} / \delta\theta$$

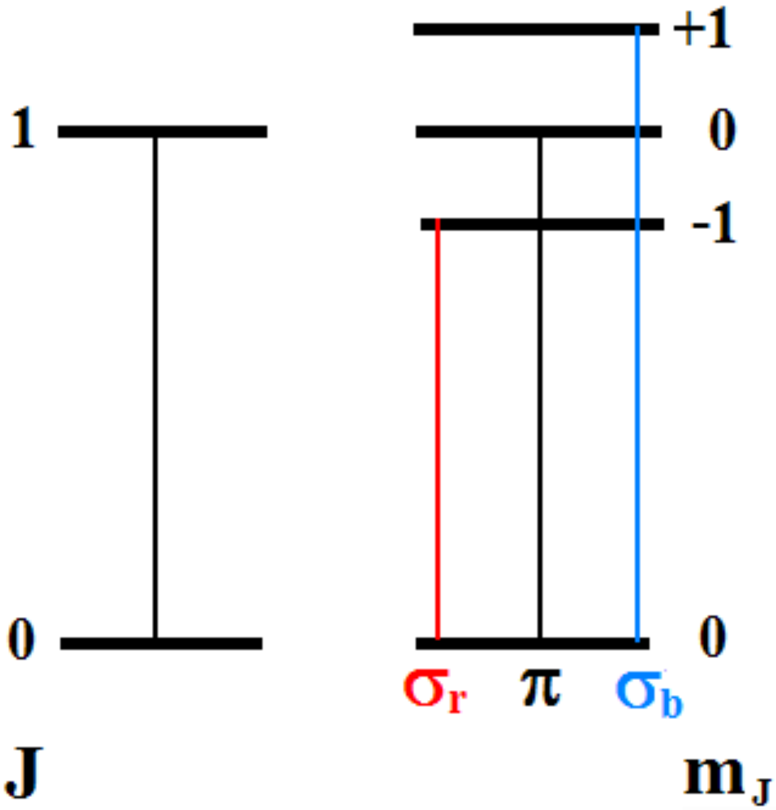
$$f \approx 0.5$$



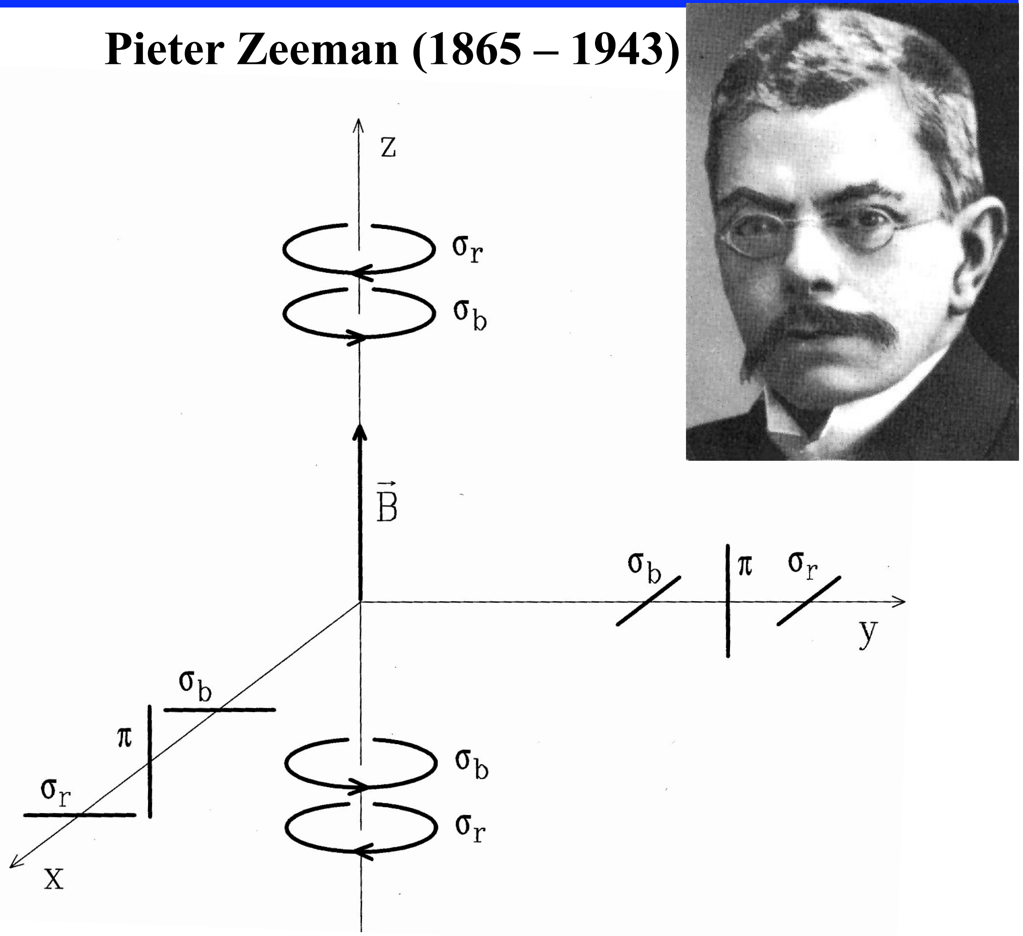
- gives field direction in strongest clump along line of sight



Zeeman Effect

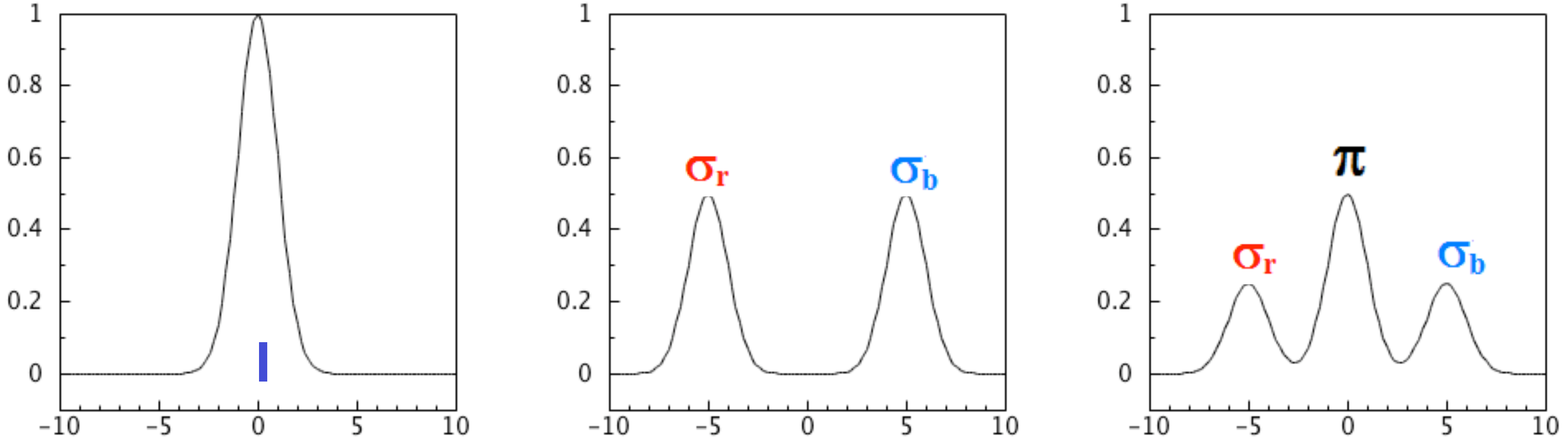


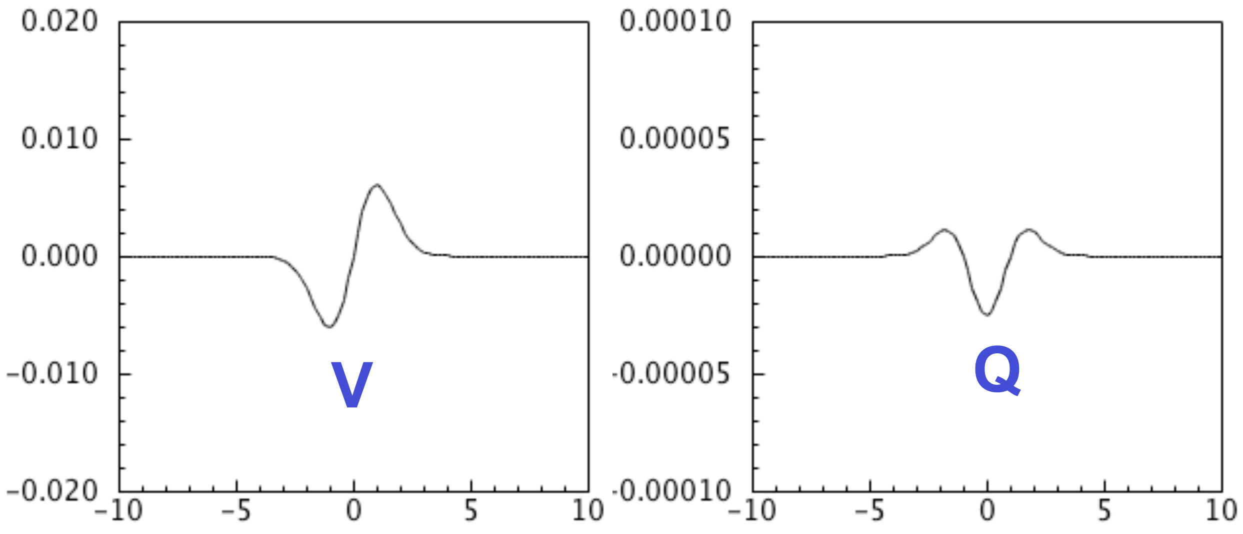
Pieter Zeeman (1865 – 1943)



Species	Wavelength	n(H) traced
H I	21-cm	$10^1 – 10^2$ cm^{-3}
OH	18-cm	$10^3 – 10^4$ cm^{-3}
CN	3 mm	$10^5 – 10^6$ cm^{-3}

Zeeman Effect





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

$$\Rightarrow \textit{plane of sky } B \quad (\textit{not really})$$

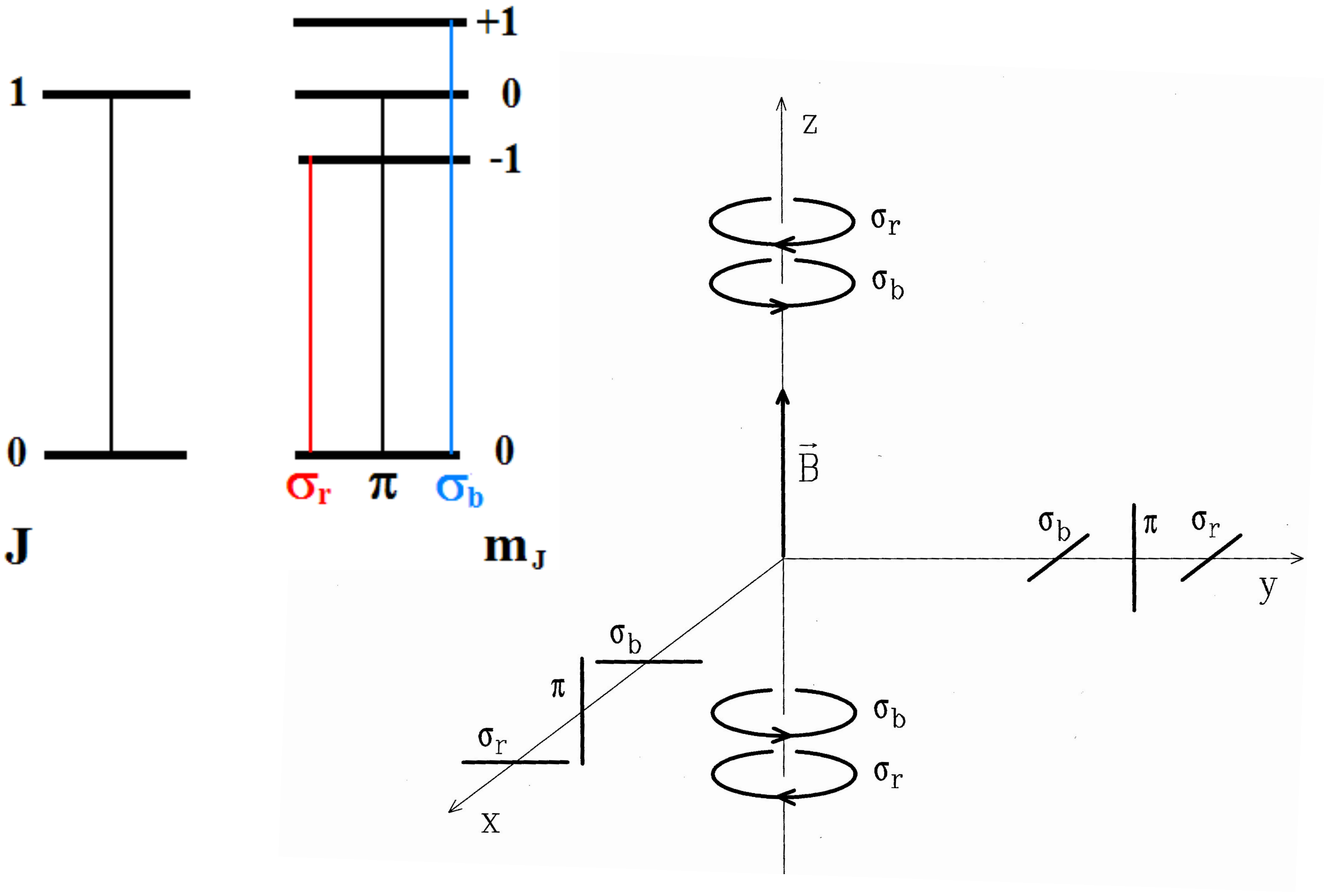
$$Q, U \propto (\Delta\nu_Z / \textit{linewidth})^2$$

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

$$\Rightarrow \textit{line of sight } B$$

$$\Delta\nu_Z \propto Z\, B$$

Goldreich-Kylafis Effect



Goldreich-Kalafis Effect

Requirements

1) local anisotropy in line optical depths

OR

2) anisotropy in radiation field

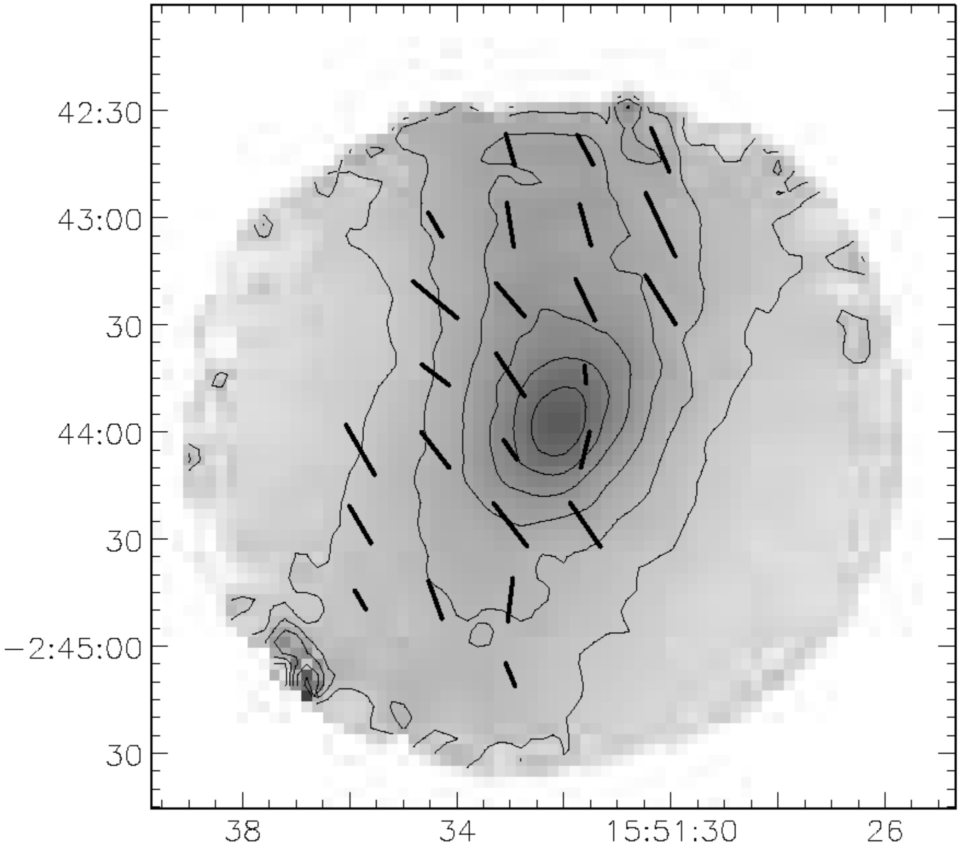
Result

1) non-LTE population of magnetic sublevels
2) linearly polarized spectral lines
3) linear polarization is parallel or perpendicular to B
4) gives only direction of B in plane of sky

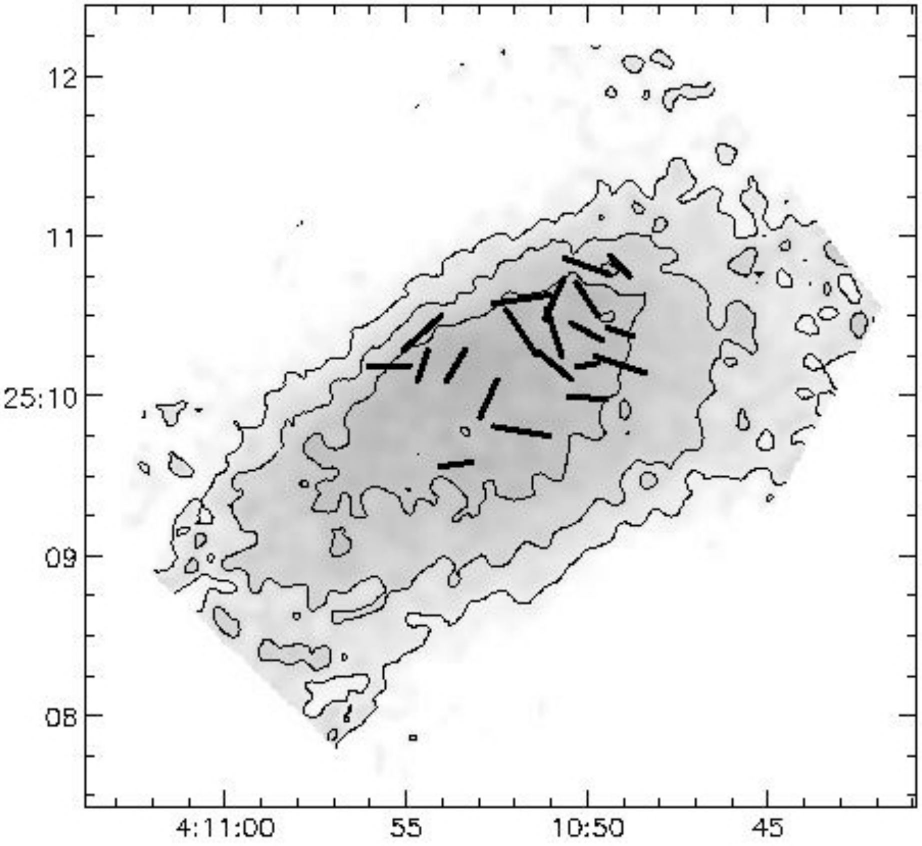
L183 & L1498 Starless Cores

L183

L1498



$n(H_2) \approx 3 \times 10^5$, $N(H_2) \approx 3 \times 10^{22}$,
$B_{pos} \approx 80\ \mu G$, $\lambda \approx 2.7$



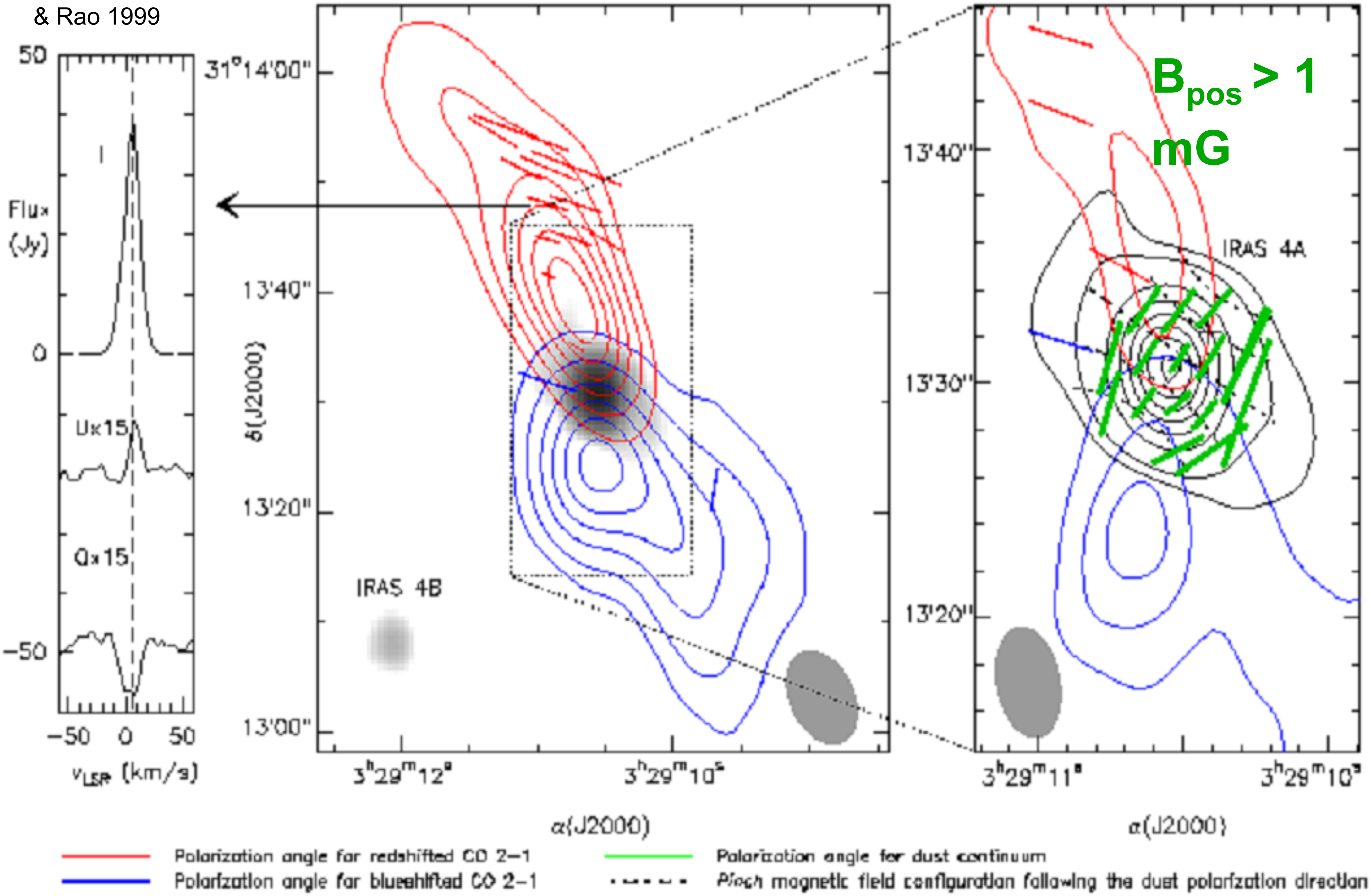
$\Delta\theta \approx 40°$

Crutcher et al. 2004

Kirk, Ward-Thompson & Crutcher 2006

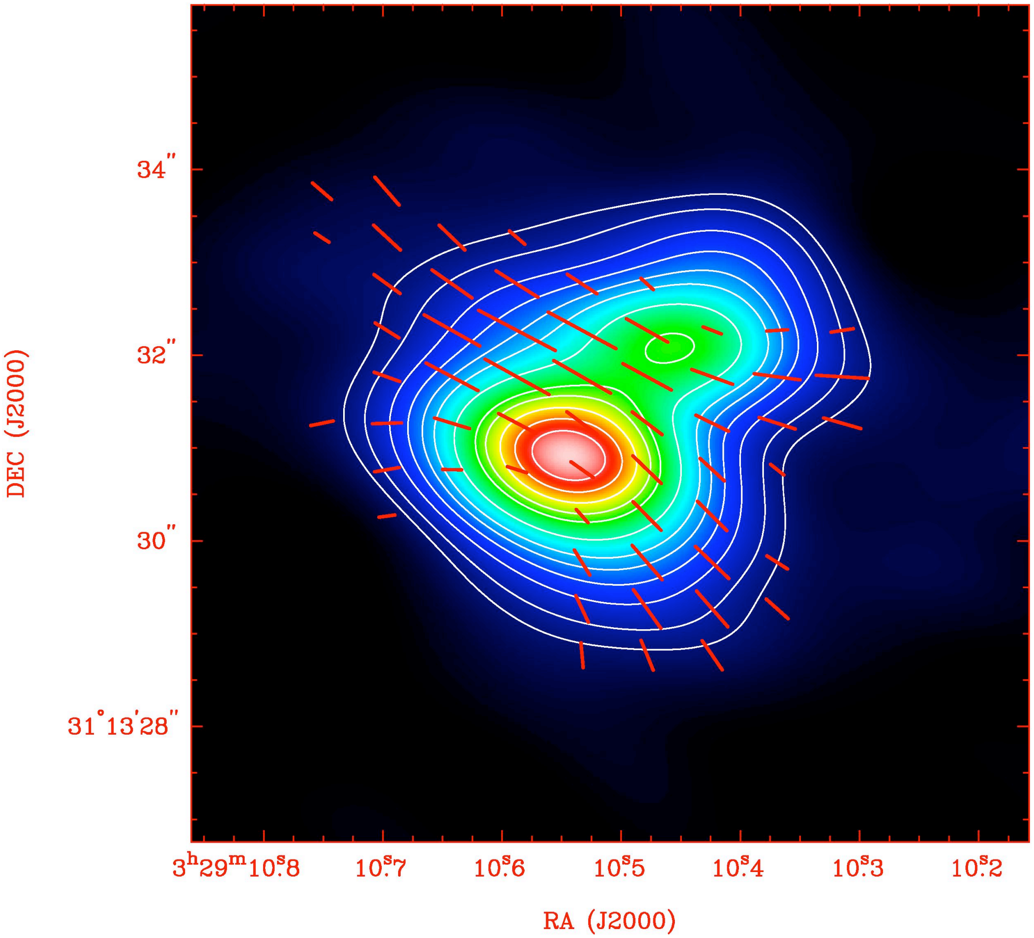
NGC1333 IRAS4 (BIMA 230 GHz)

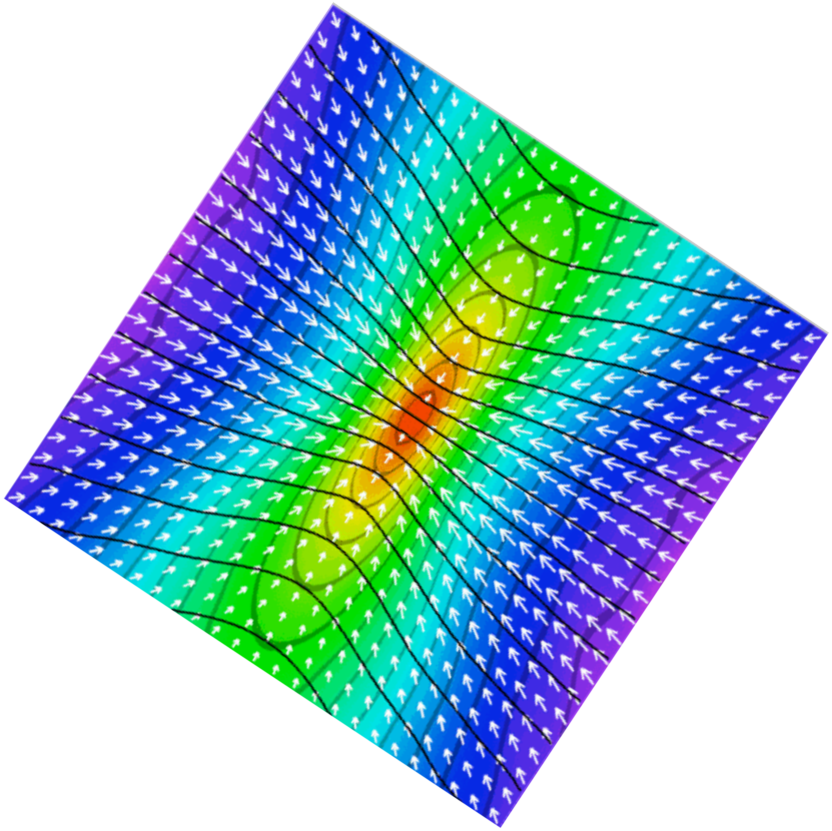
Girart, Crutcher & Rao 1999



B_{pos} > 1 mG

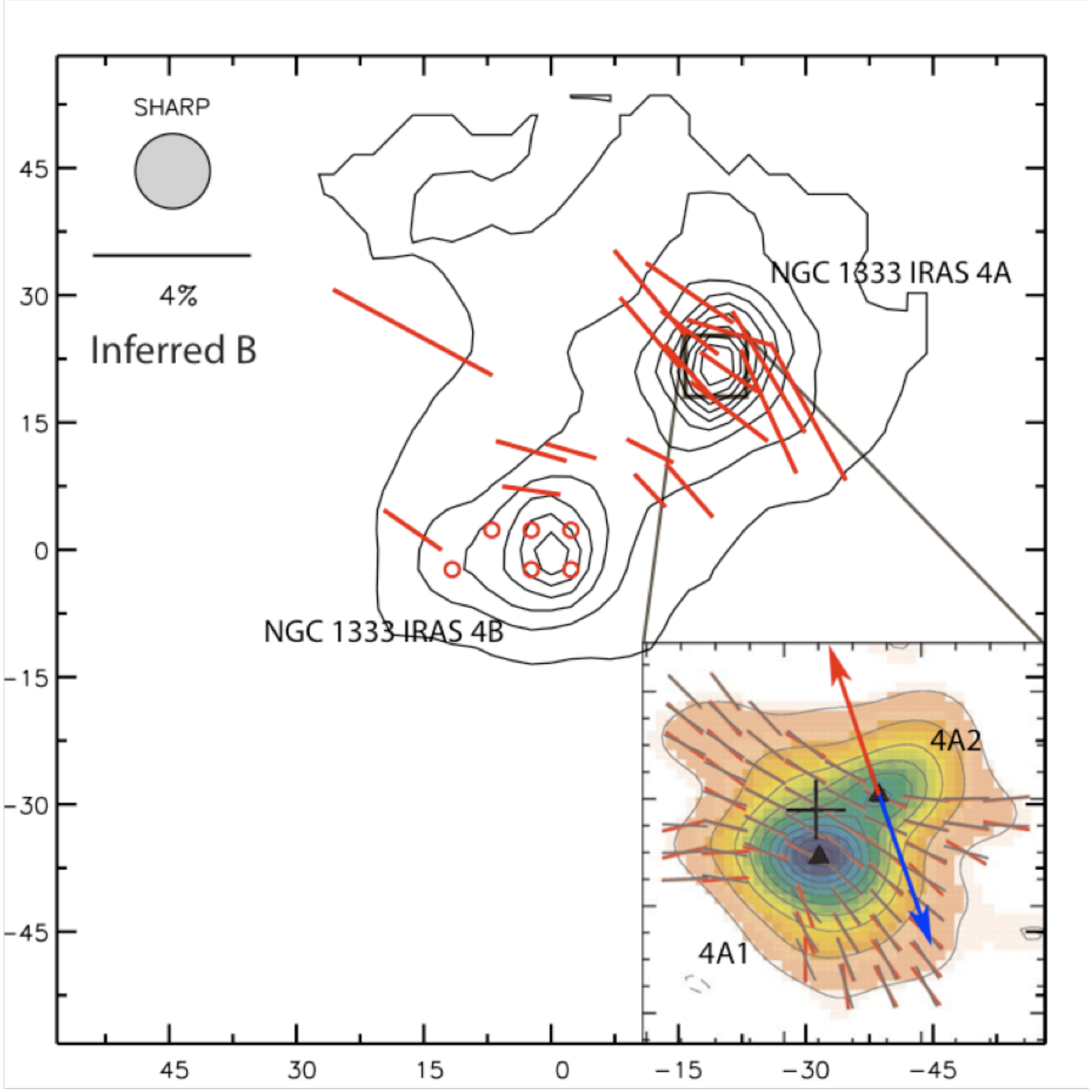
NGC1333 IRAS4 (SMA 345 GHz)





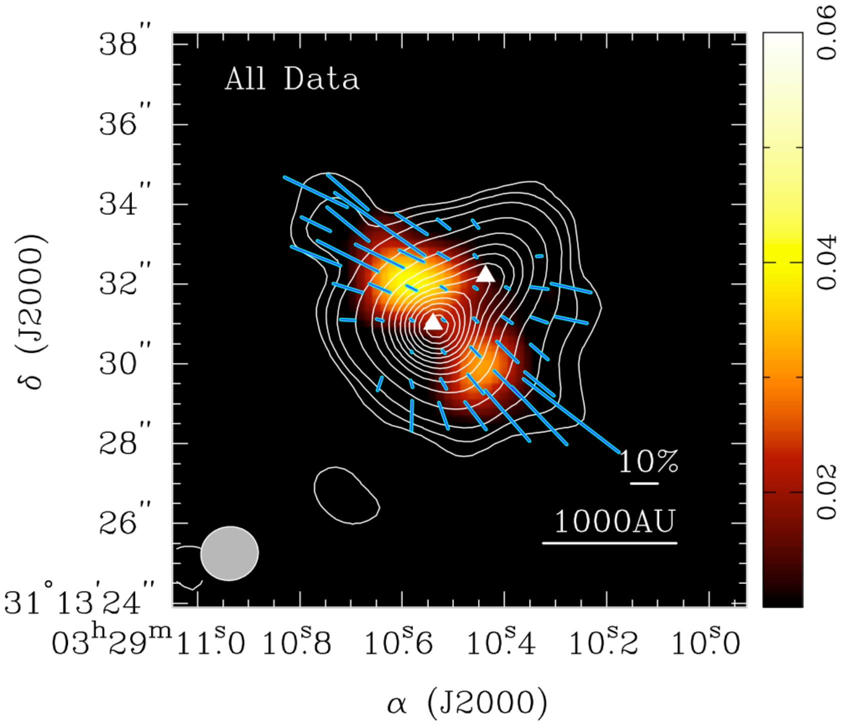
Girart, Rao & Marrone 2006

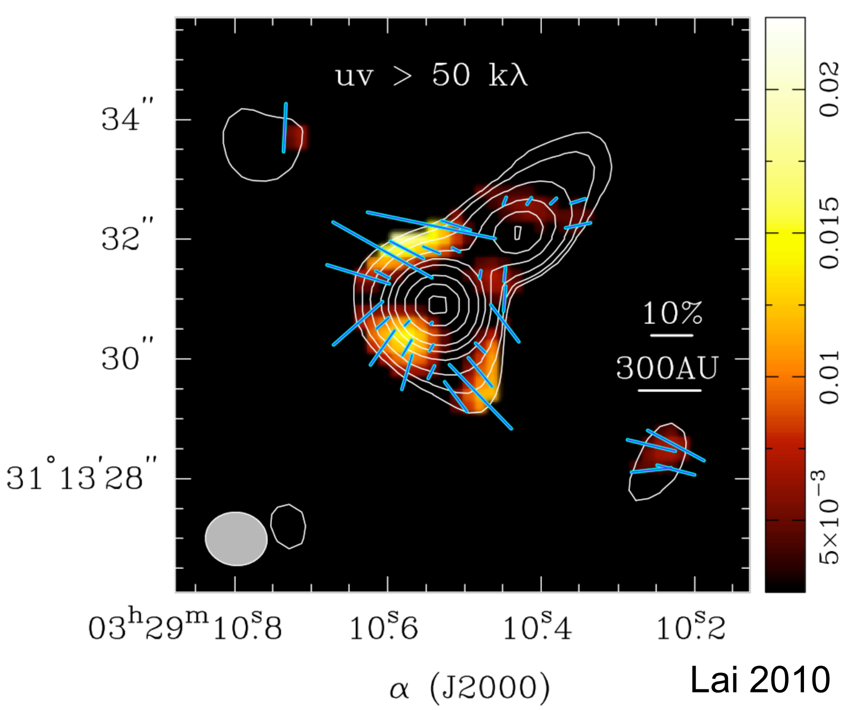
NGC1333 IRAS4 (SHARP CSO)



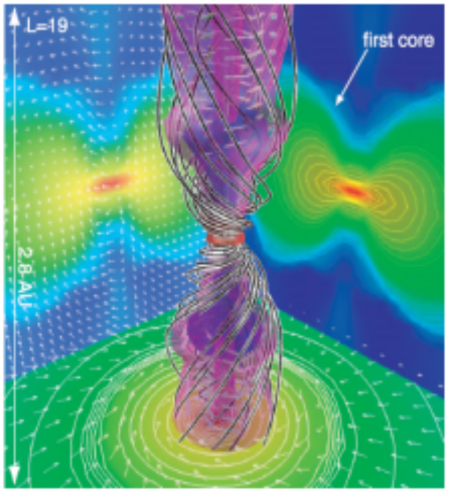
Novak 2010

NGC1333 IRAS4 (SMA 345 GHz)

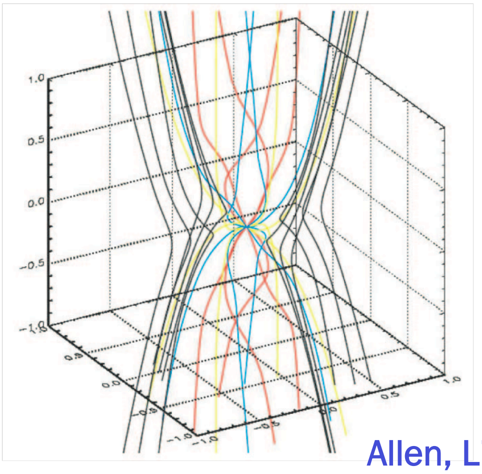




Lai 2010



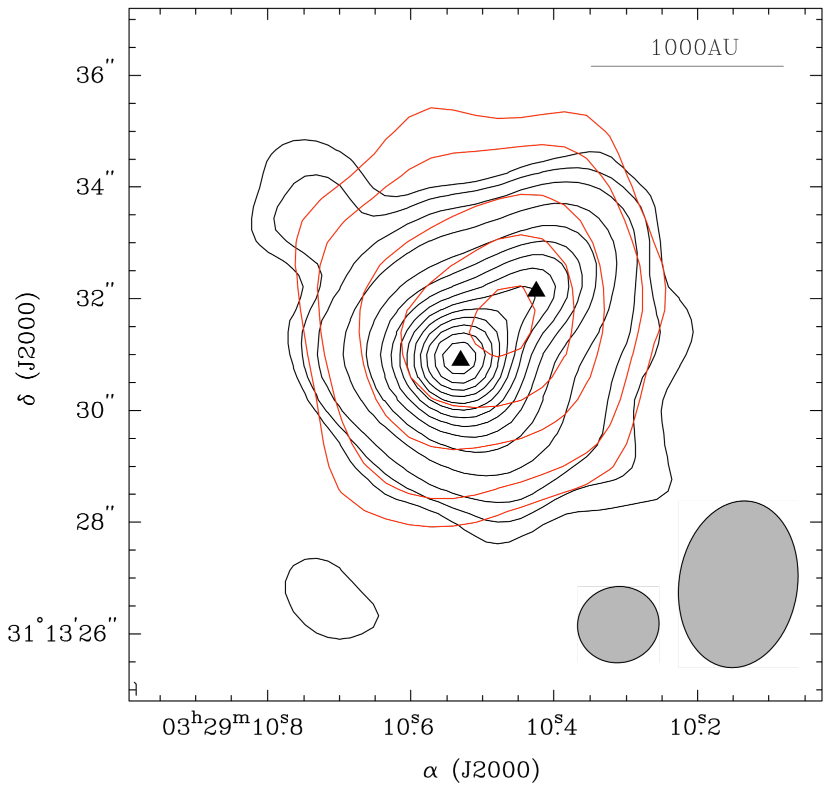
Machida et al. 2008

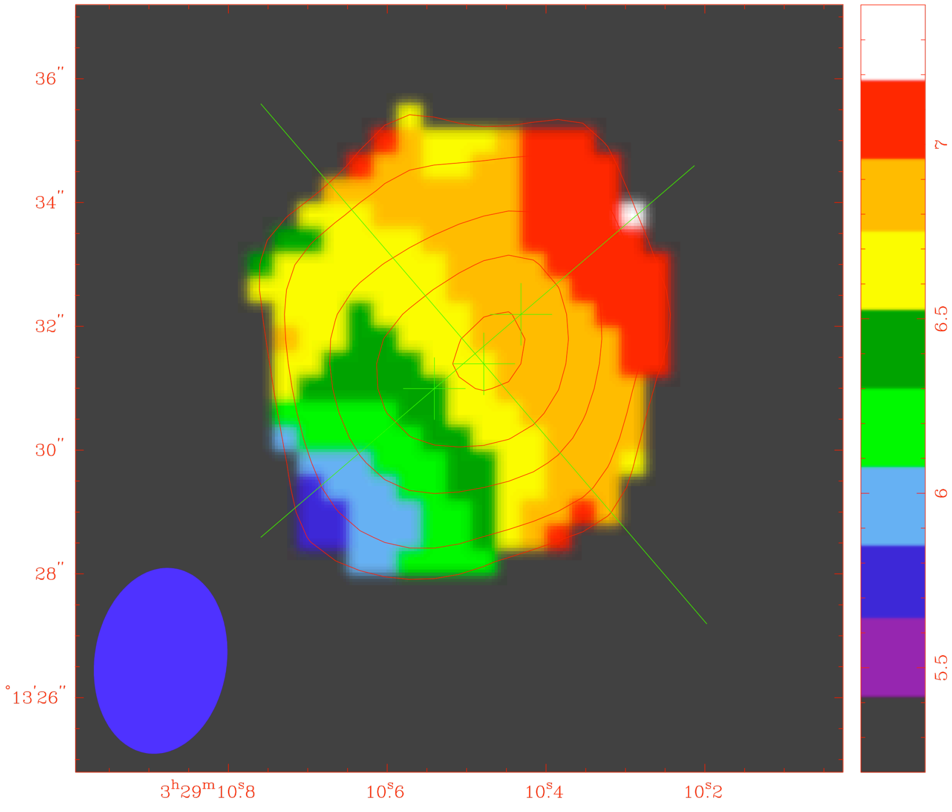


Allen, Li, Shu 2003

NGC1333 IRAS4 (SMA 345 GHz)

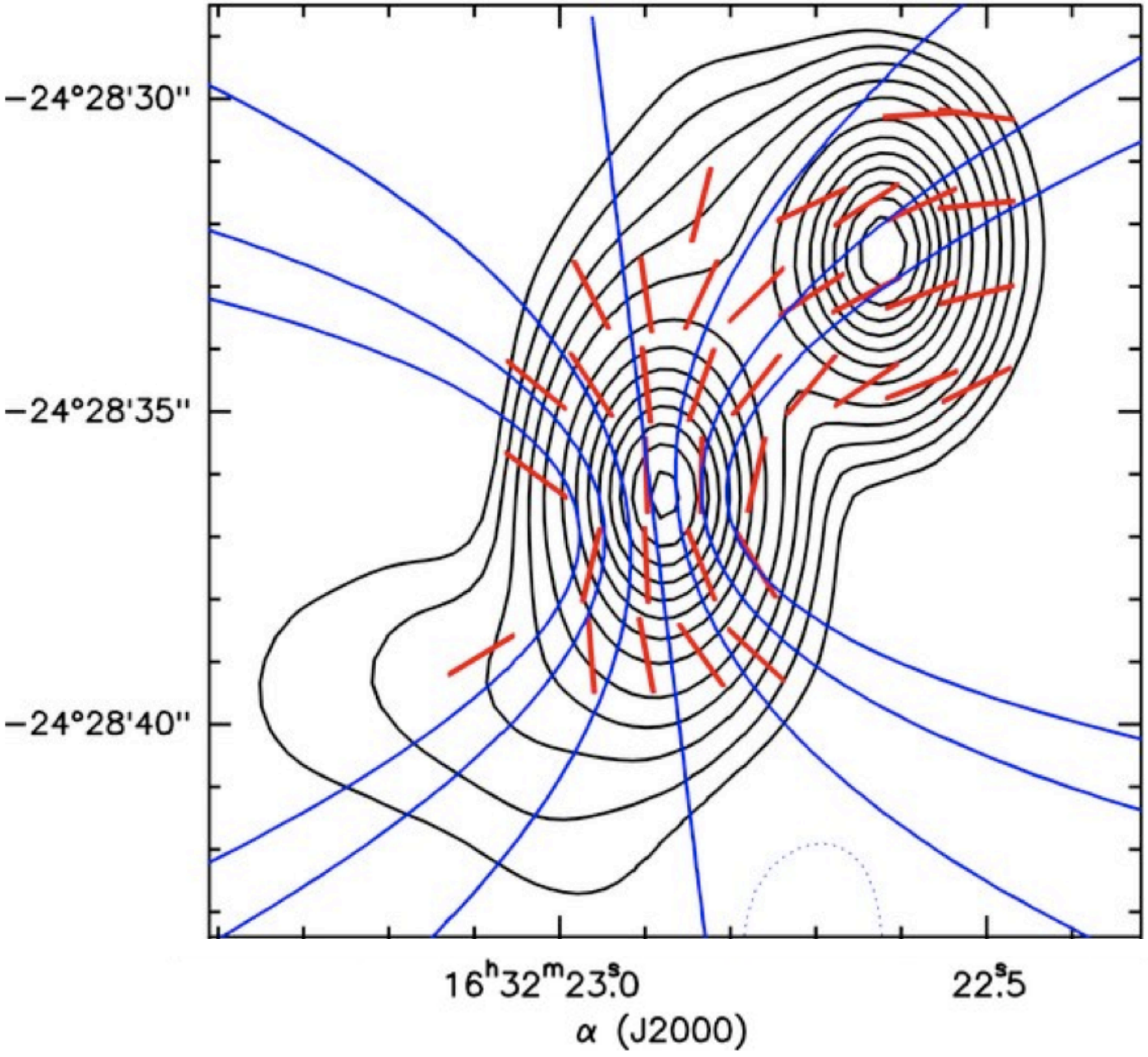
Dust $C^{17}O$





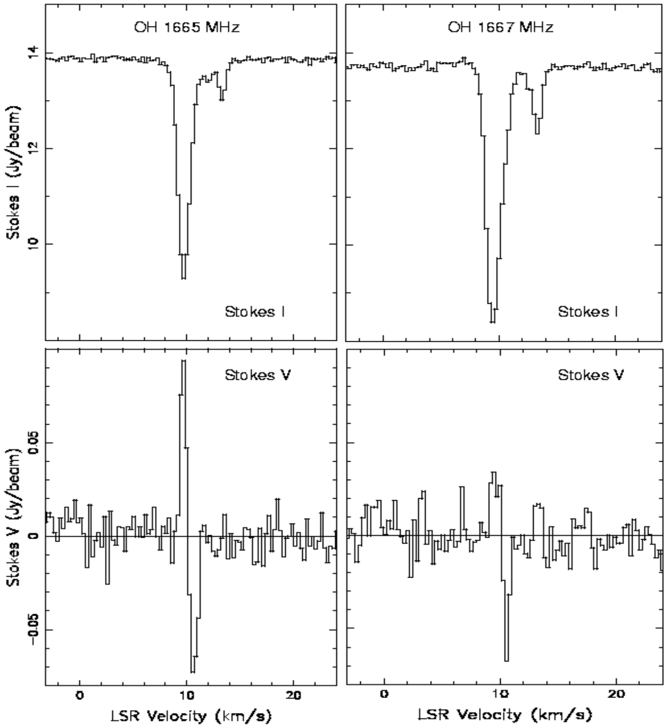
Lai 2010

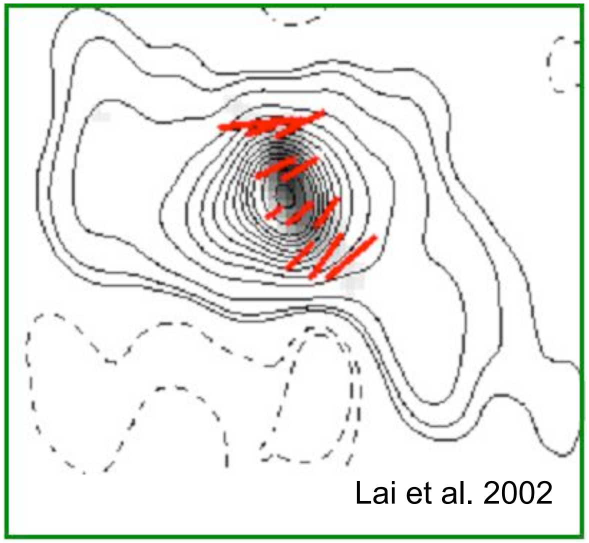
IRAS 16293 (SMA 345 GHz)



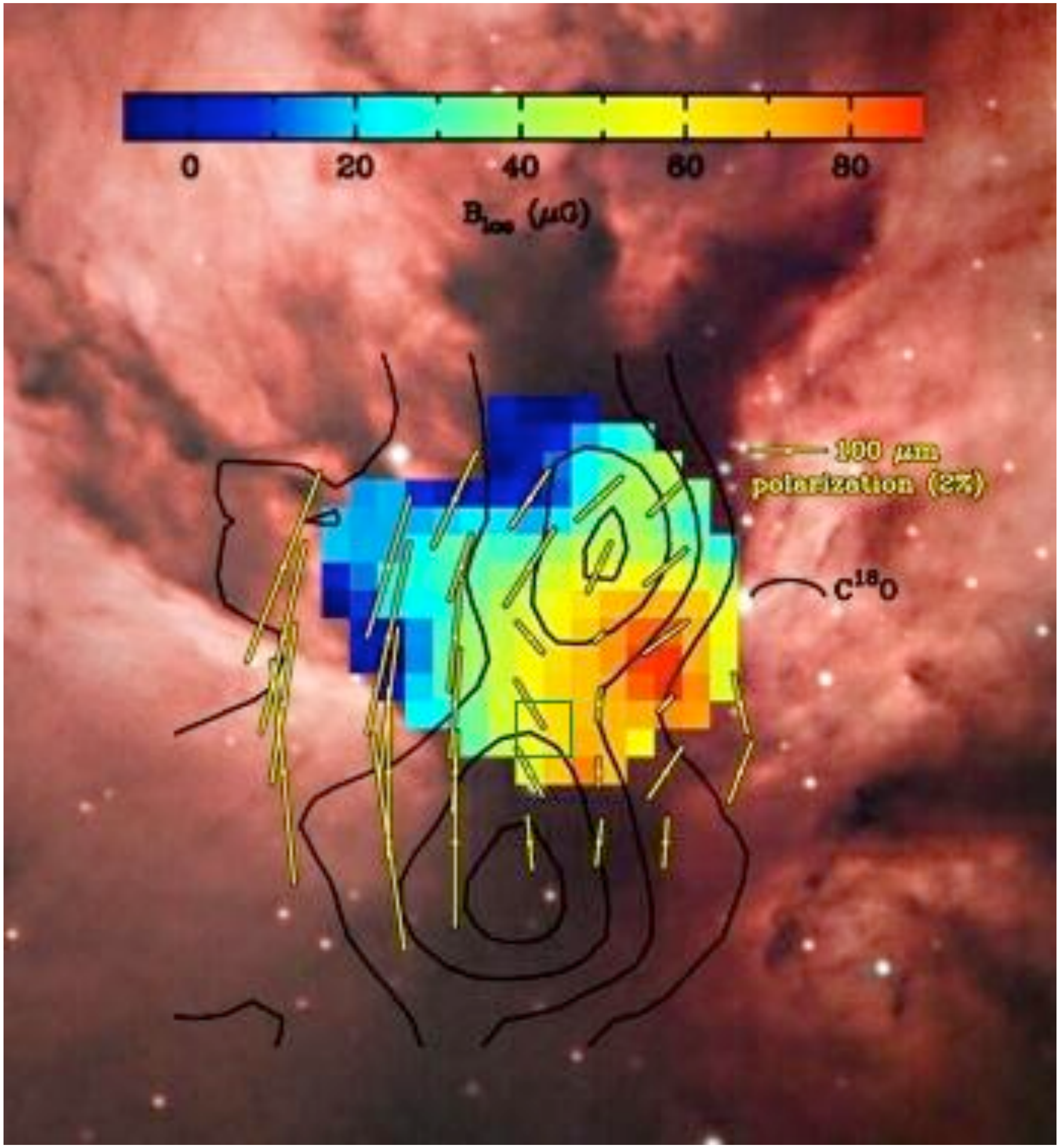
Rao et al. 2009

NGC 2024 (Orion B)

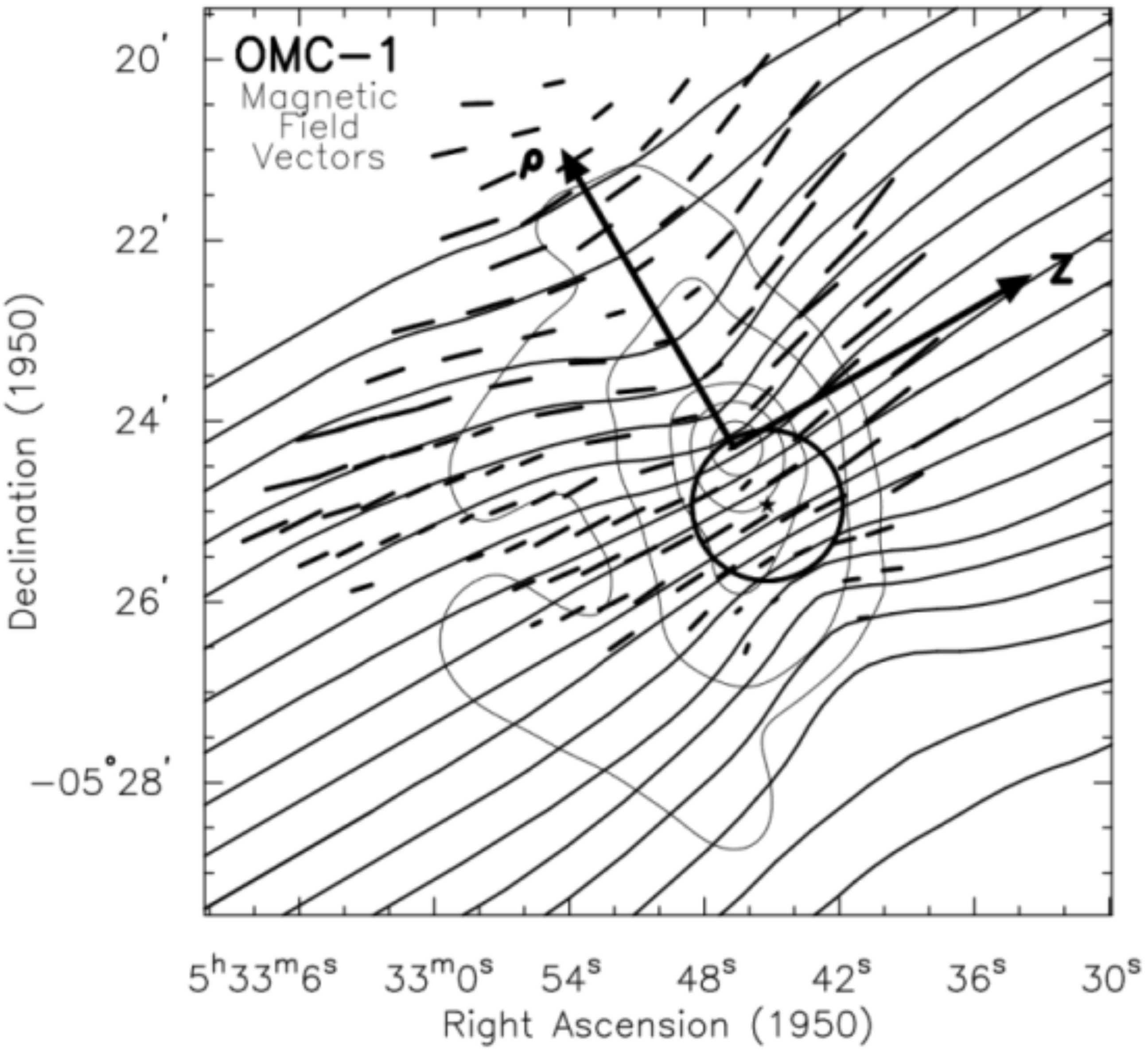




Lai et al. 2002

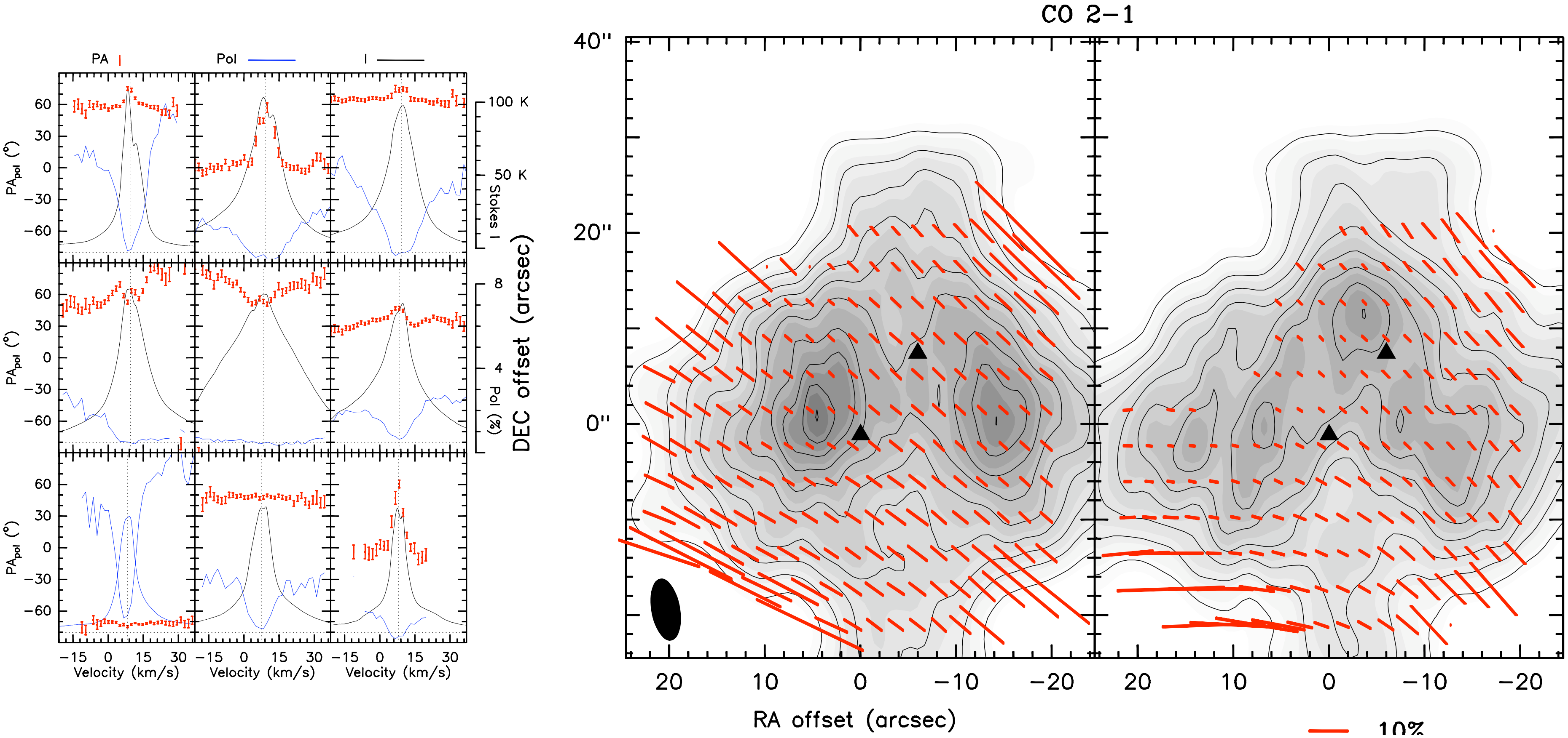


Orion Molecular Cloud 1



Schleuning 1998

Orion Molecular Cloud 1

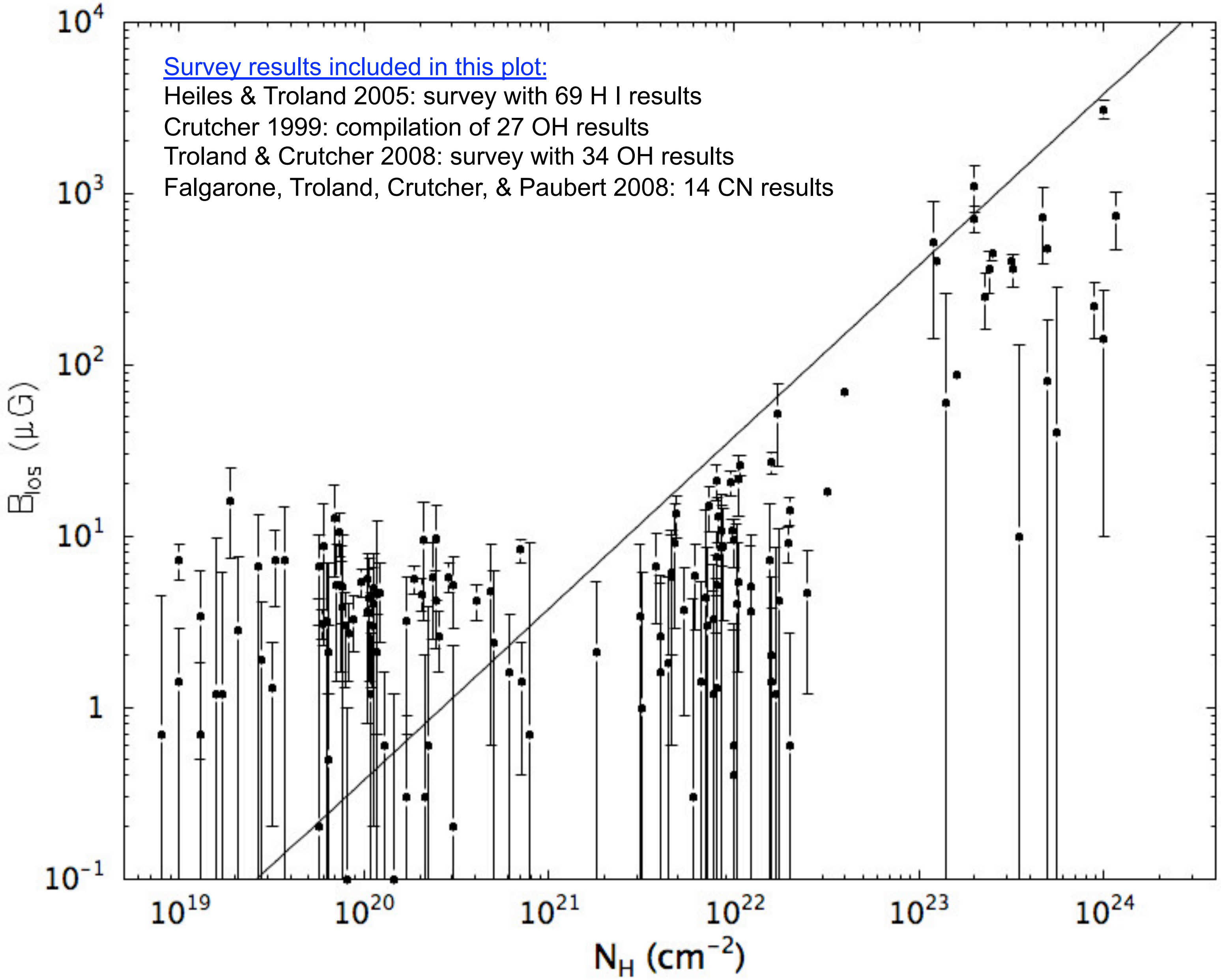


Girart et al.2004

Zeeman Surveys

Data Set	Measurements of B_{los}
1. Compilation Crutcher 1999, ApJ 520, 706	27
2. Arecibo H I Millinium survey Heiles & Troland 2005, ApJ 624, 773	69
3. Arecibo OH dark clouds Troland & Crutcher 2008, ApJ 680, 457	34
4. IRAM CN Falgarone,Troland, Crutcher & Paubert 2008, A&A 487, 247	11 (+3 incl. in #1)
TOTAL	**141**

Results for Field Strength


Survey results included in this plot:

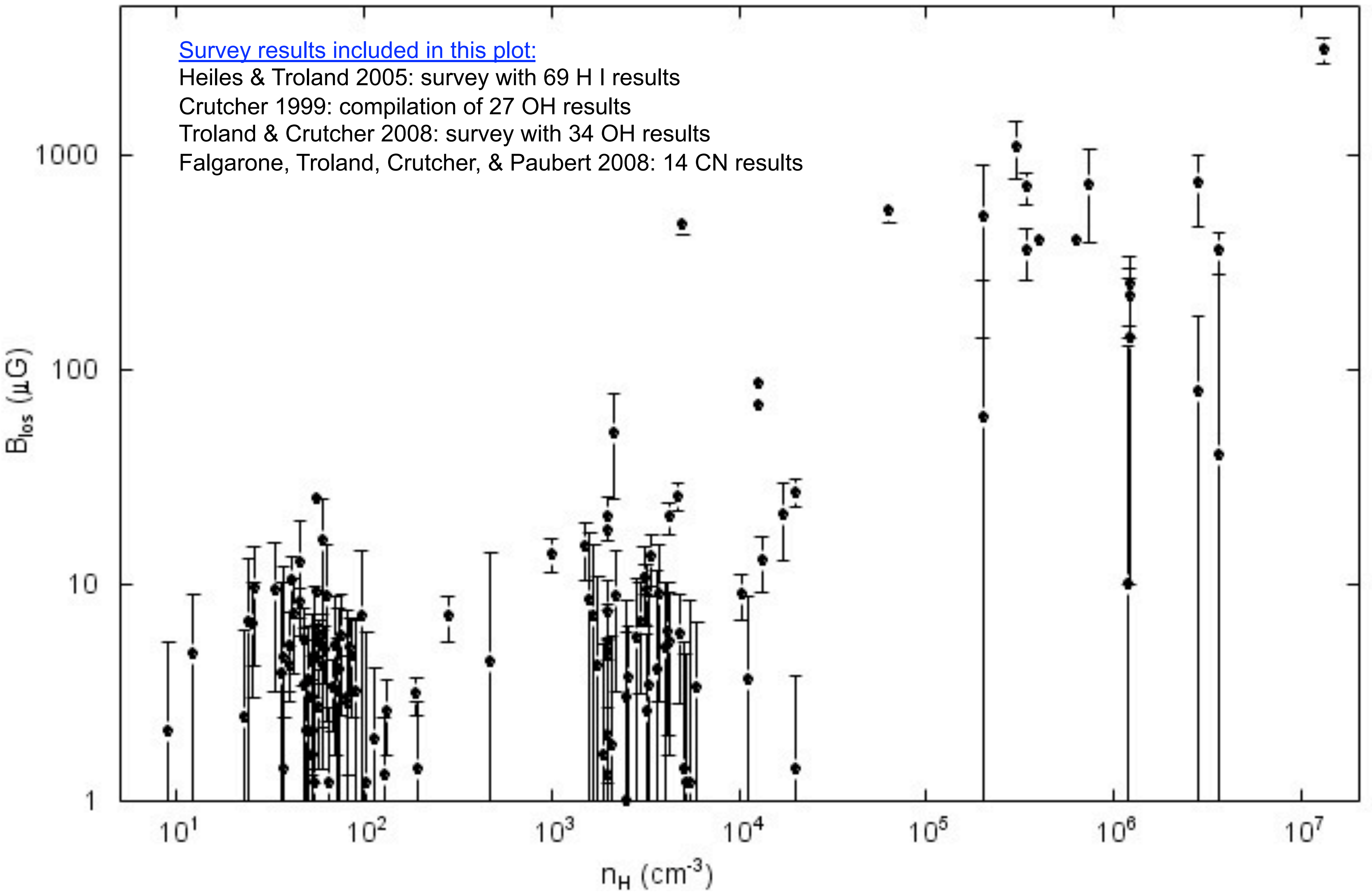
Heiles & Troland 2005: survey with 69 H I results

Crutcher 1999: compilation of 27 OH results

Troland & Crutcher 2008: survey with 34 OH results

Falgarone, Troland, Crutcher, & Paubert 2008: 14 CN results

Results for Field Strength



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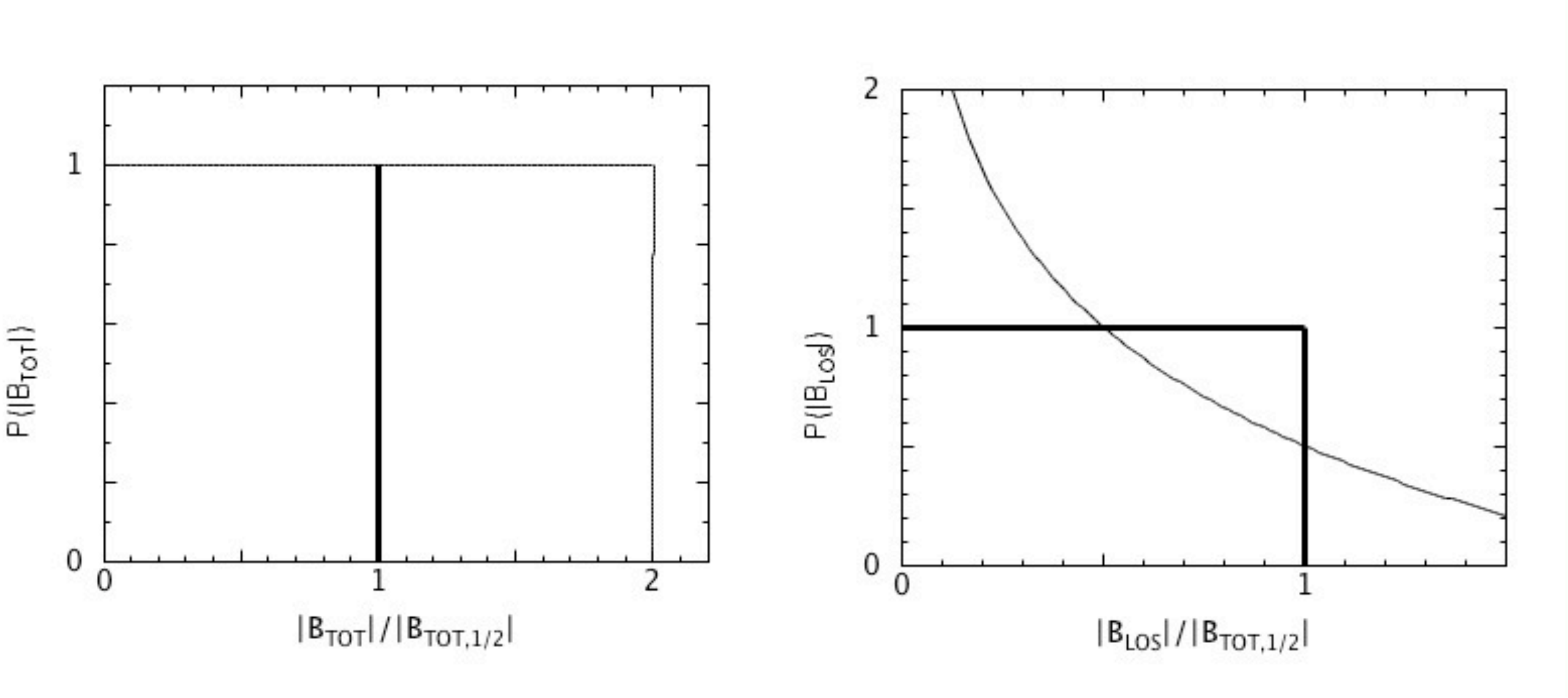
Falgarone, Troland, Crutcher, & Paubert 2008: 14 CN results

What to do about measuring B_{los}, not B_{tot}?

PDFs of total B and corresponding los B



For reasonable pdf, mean or median of $B_{los} \approx \frac{1}{2}$ mean or median of B_{total}

Heiles & Crutcher 2005

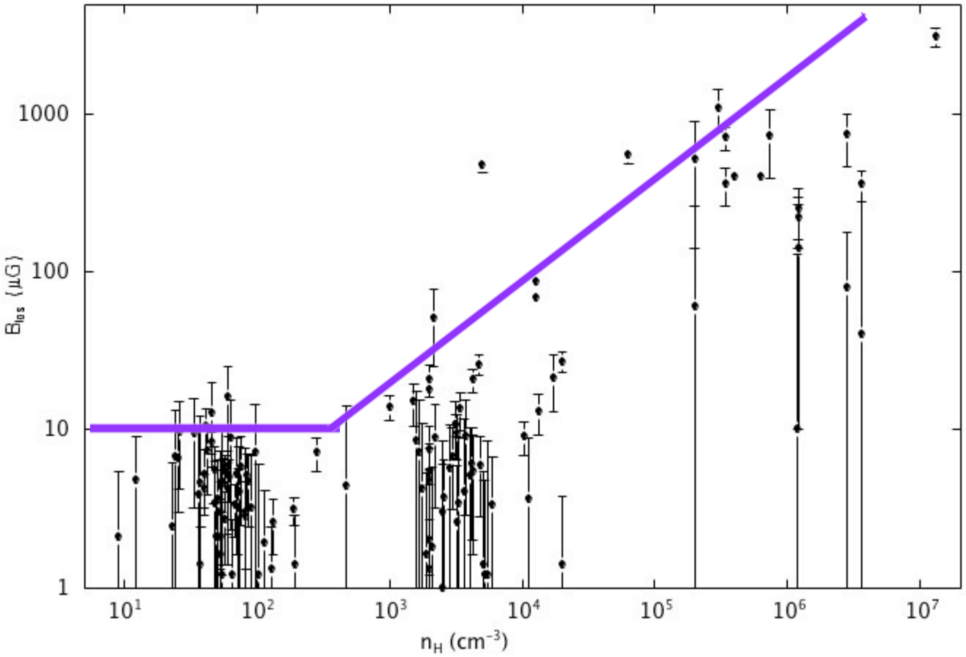
Bayesian Analysis

Priors (data): $B_{los} \pm \sigma_{B_{los}}$ & $(n_H)^{+2n_H}_{-0.5n_H}$

The model: $B_{\max} = B_0, \quad n < n_0$

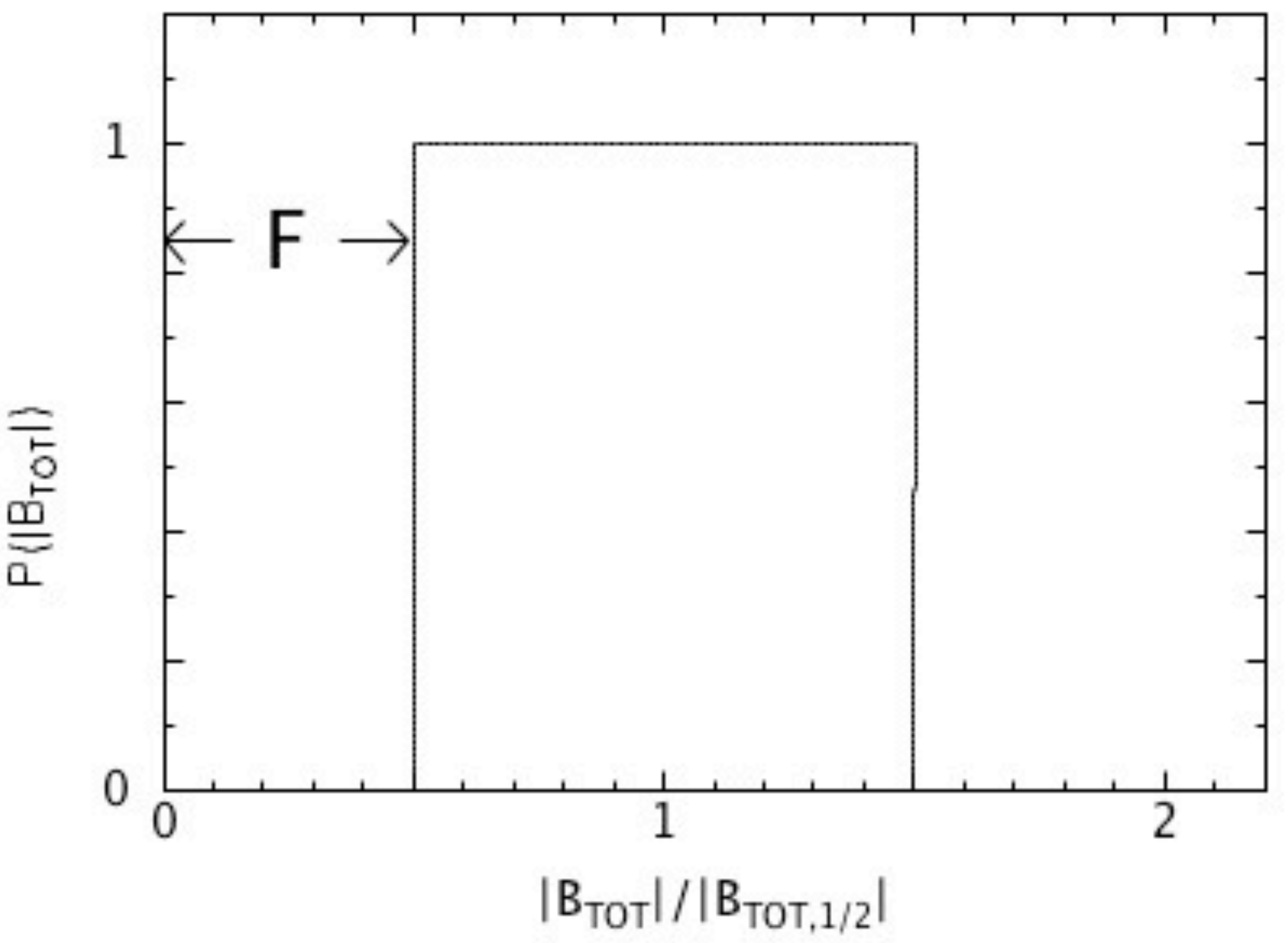
$$B_{\max} = B_0\, n^{\kappa}, \quad n > n_0$$

$$F\, B_{\max} < B_{tot} < B_{\max}$$



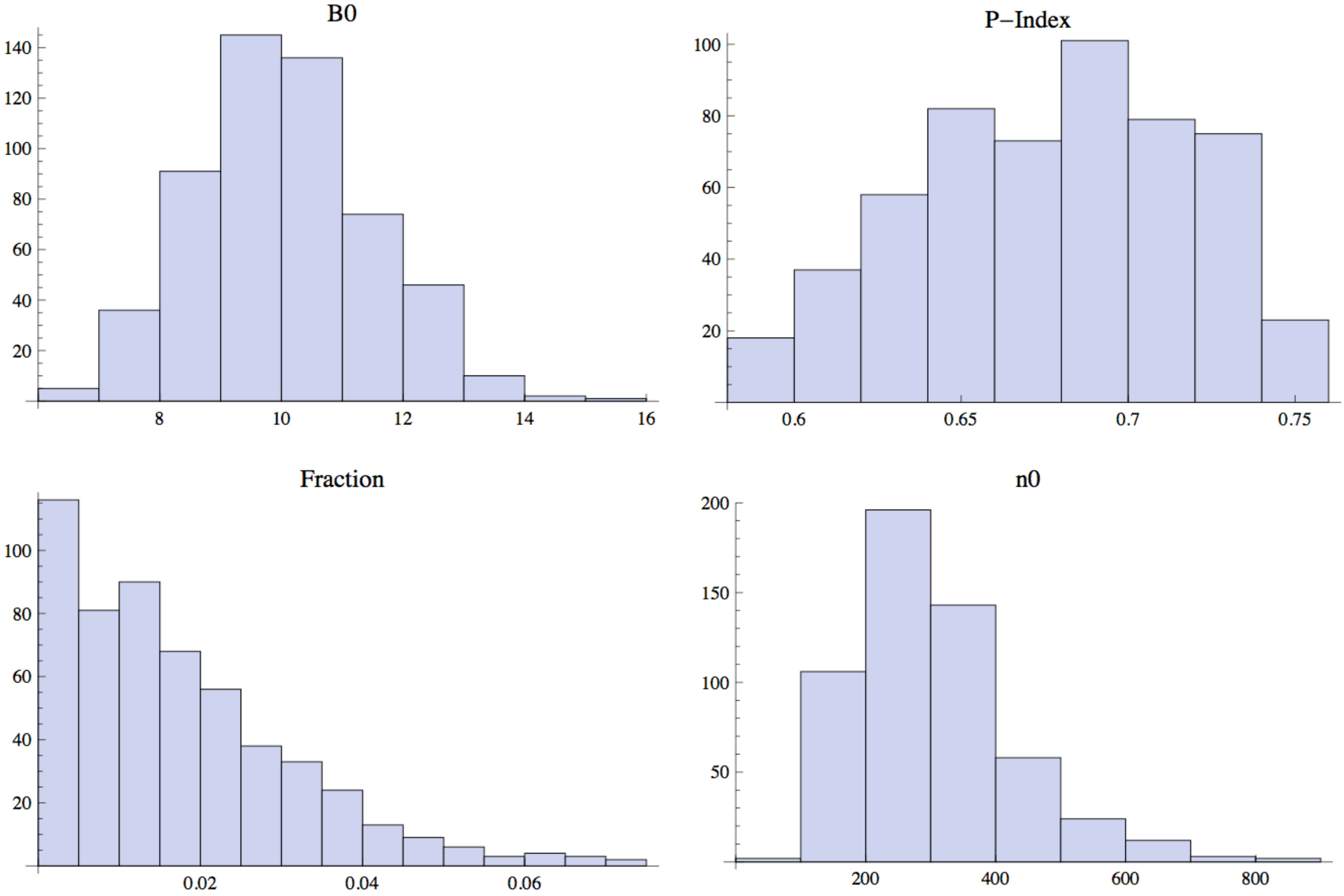
Crutcher et al. 2010

Assumed Parameterization of PDF



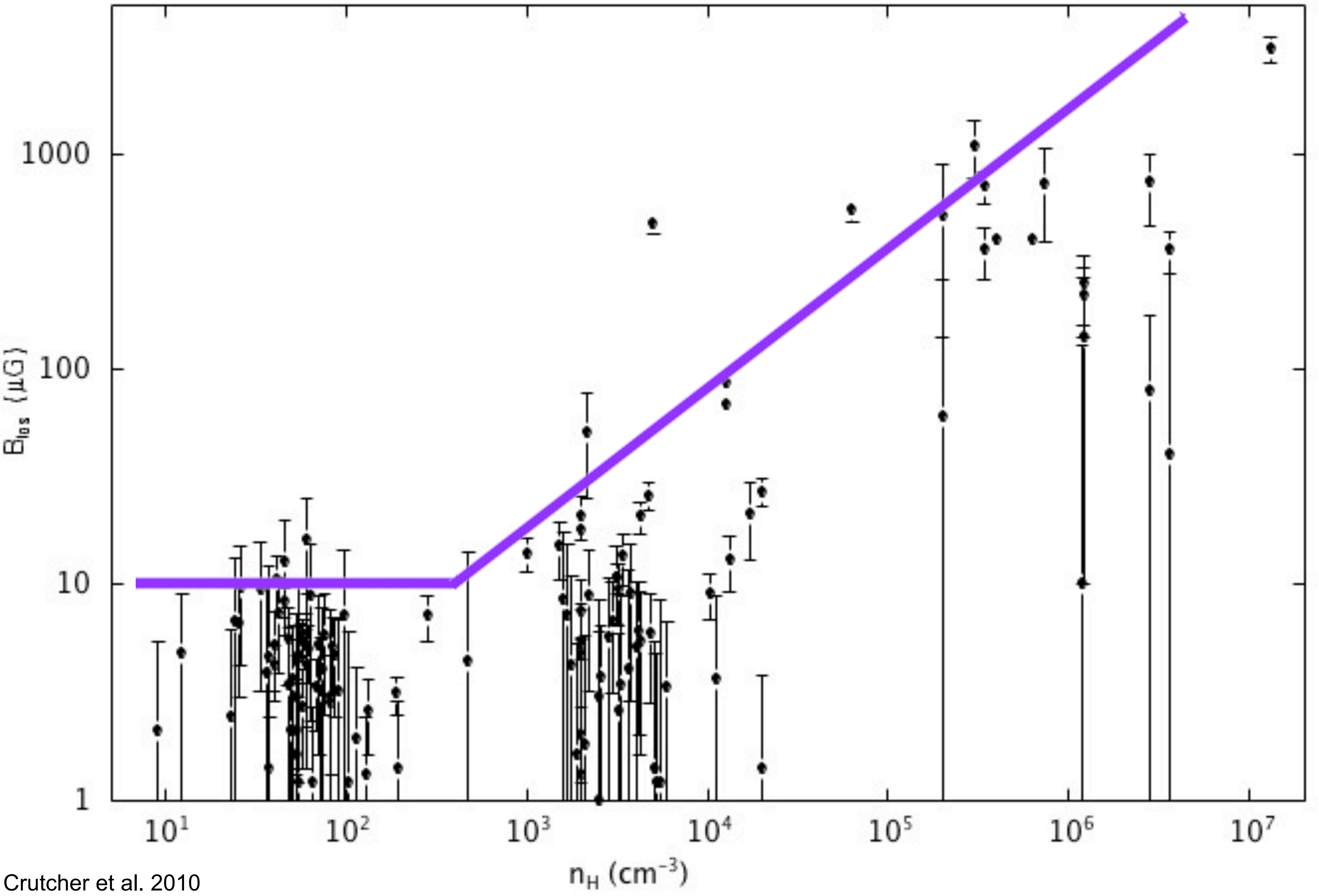
Crutcher et al. 2010

Results of Bayesian Analysis



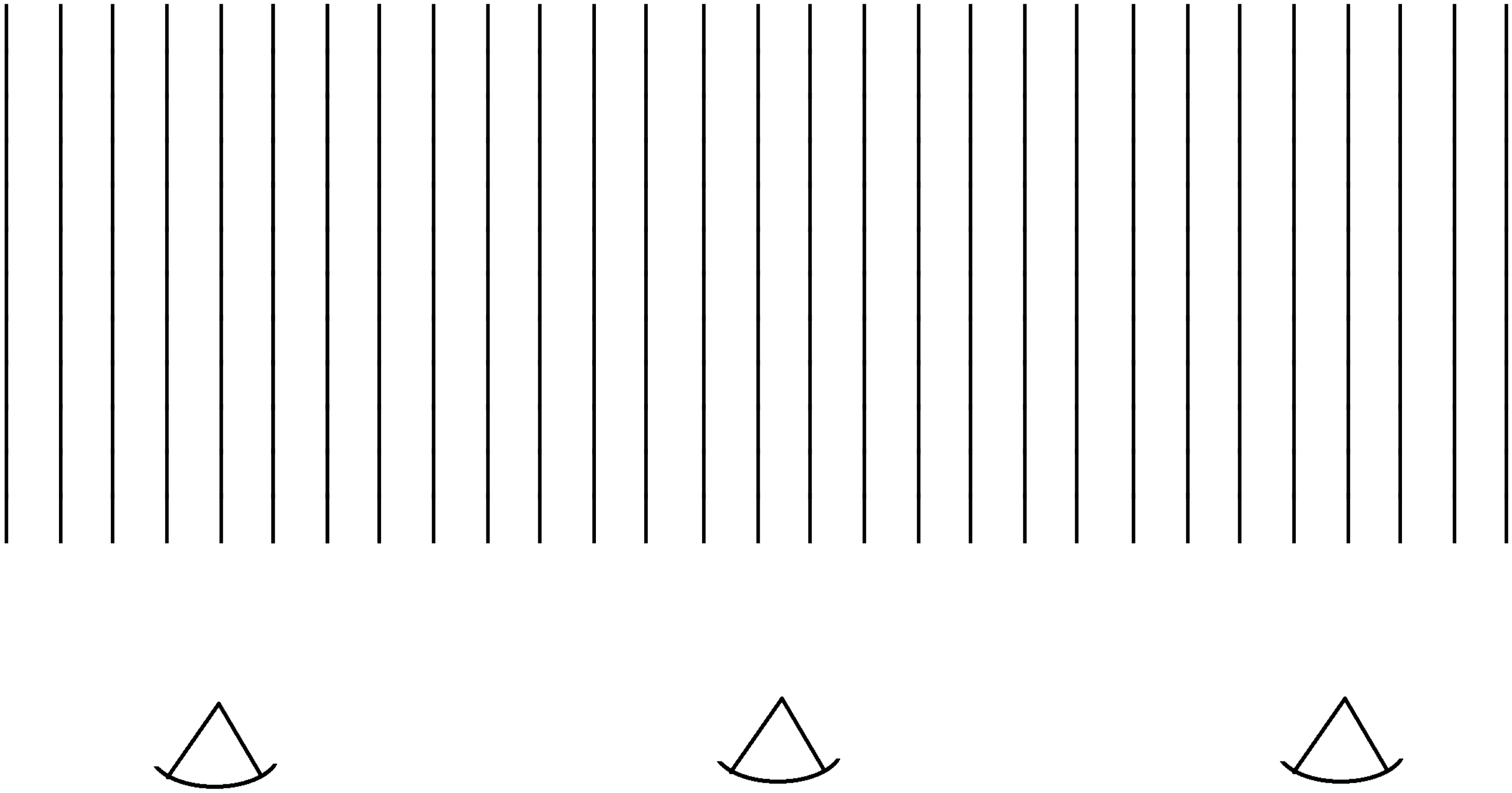
Crutcher et al. 2010

Results of Bayesian Analysis

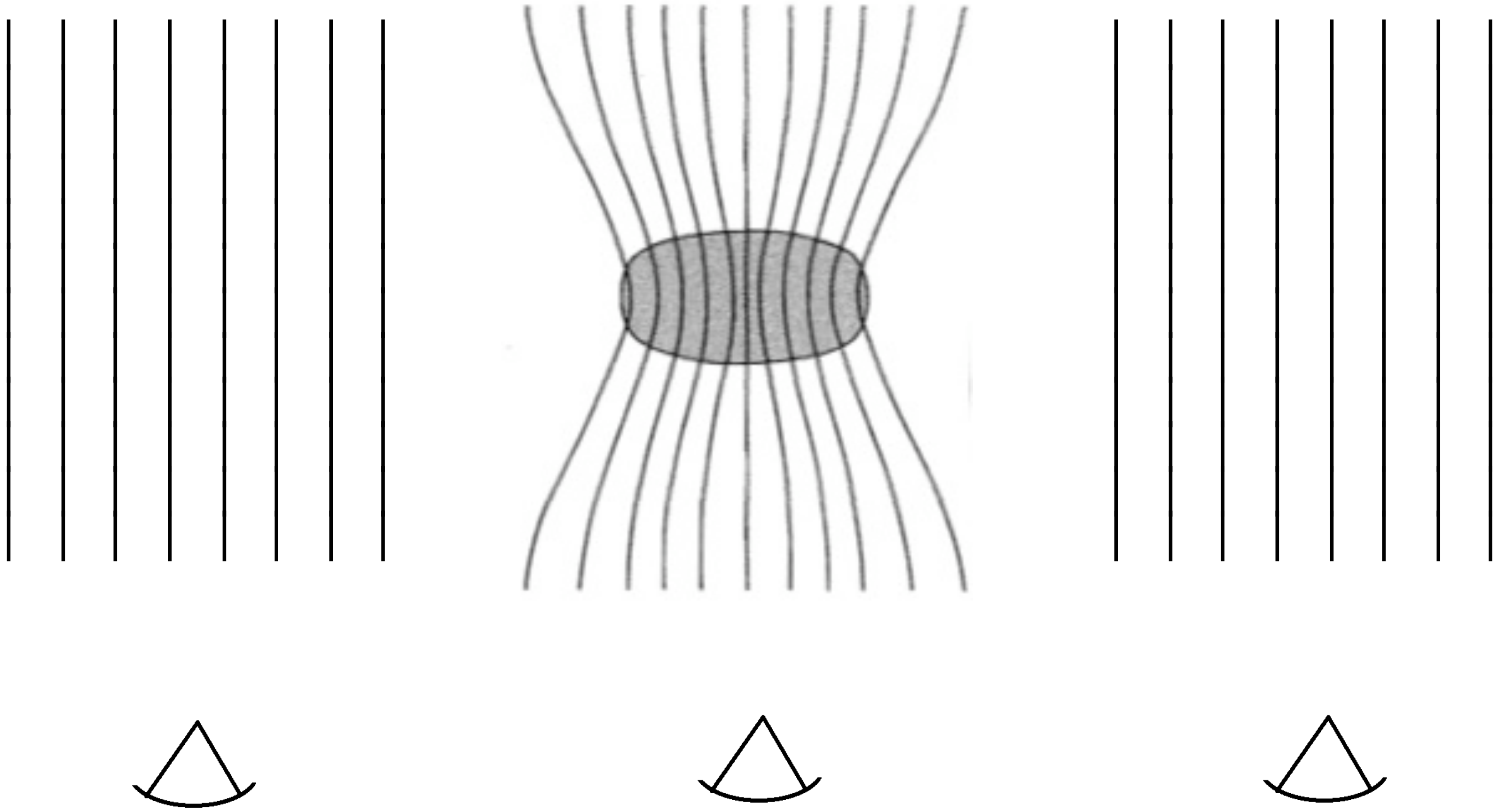


Crutcher et al. 2010

Testing M/Φ Change from Envelope to Core



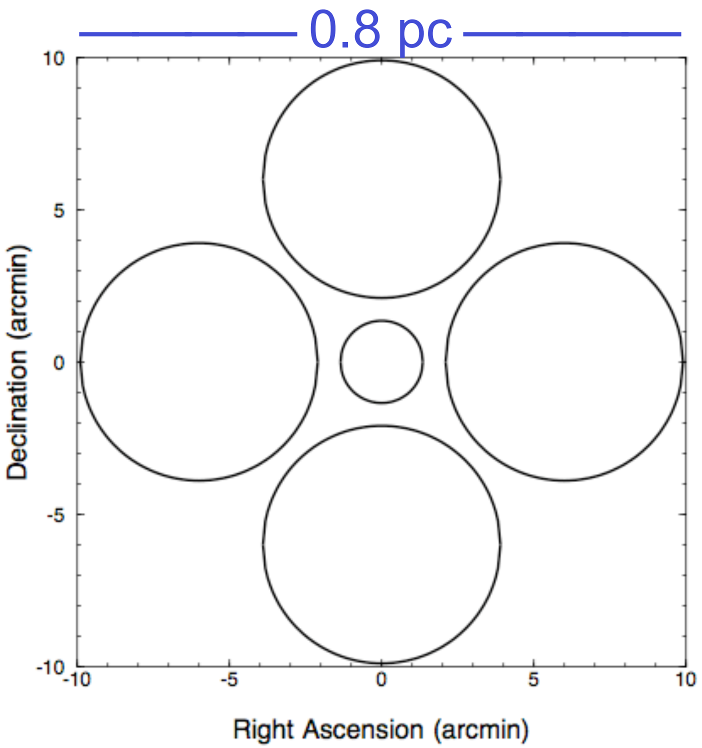
Testing M/Φ Change from Envelope to Core



Testing M/Φ Change from Envelope to Core

Measure differential M/Φ between core and envelope:

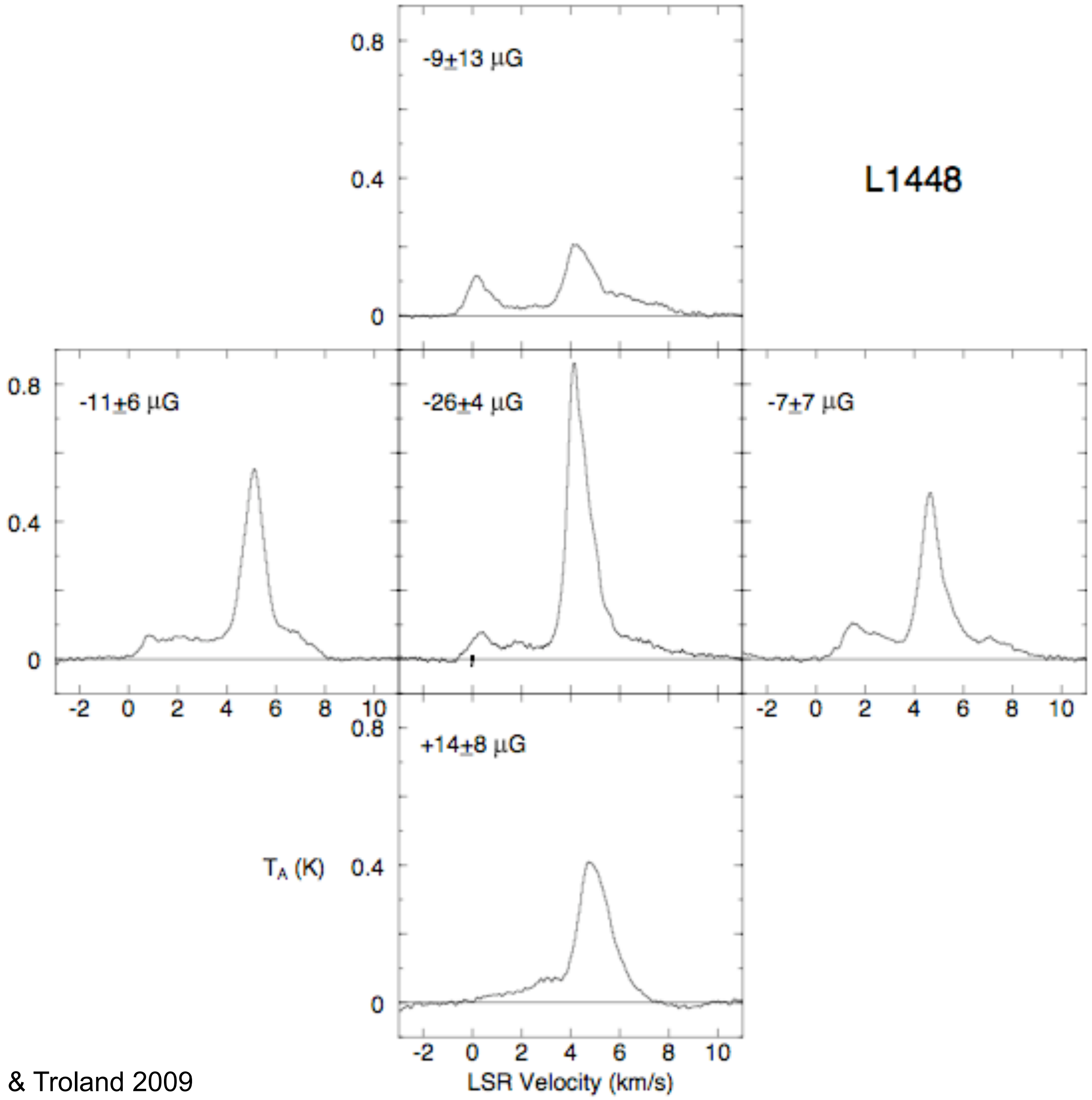
$$\frac{[M/\Phi]_{core}}{[M/\Phi]_{envelope}} = \frac{[T_{line}\,\Delta V / B_{los}]_{core}}{[T_{line}\,\Delta V / B_{los}]_{envelope}}$$



Telescope beam sizes were chosen to ideally sample core and envelope regions of published ambipolar diffusion models. Averaging the four large GBT beams “synthesizes” a toroidal beam, exactly what is needed to sample only the envelope region.

Crutcher, Hakobian & Troland 2009

Testing M/Φ Change from Envelope to Core



Crutcher, Hakobian & Troland 2009

Results

Cloud:	L1448	B217-2	L1544	B1
B(core):	-26 ± 4	+14 ± 4	+11 ± 2	-27 ± 4
B(envelope):	-3 ± 4	+2 ± 5	+5 ± 3	-7 ± 4
$T_{line}\,\Delta V$ (core):	1.21	0.60	1.17	2.20
$T_{line}\,\Delta V$(envelope):	0.73	0.47	0.64	1.60
$\frac{M/\Phi\,(\text{core})}{M/\Phi\,(\text{envelope})}$:	0.21 ± 0.30	0.19 ± 0.46	0.89 ± 0.59	0.37 ± 0.18
Probability of > 1:	0.005	0.07	0.37	0.003

Published ambipolar diffusion models require ratio ~ $1/\lambda_{initial}$, typically ~ 2

SuperAlfvénic simulation result: mean $\frac{M/\Phi\,(\text{core})}{M/\Phi\,(\text{envelope})}$ = 0.67, range is 0.08 to 1.6

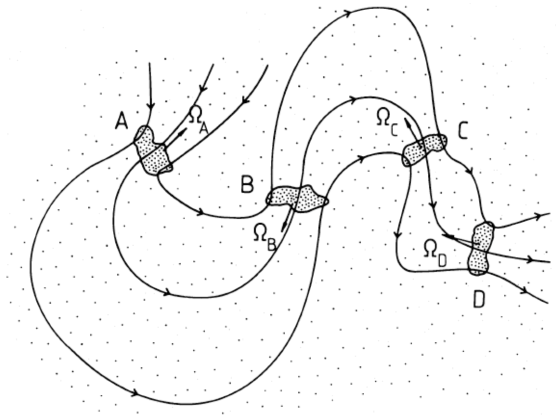
(Luntila, Padoan, Juvela, & Nordlund 2008)

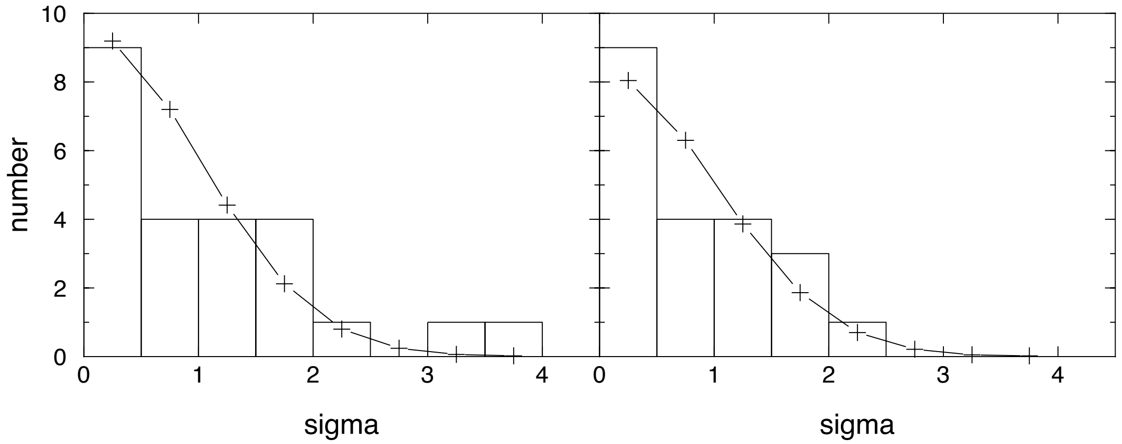
Crutcher, Hakobian & Troland 2009

What about Mouschovias-Tassis Criticism?

1) Beams are too large.

2) Data show that B_{los} varies from one envelope position to another around each core. Hence, our assumption that θ, the angle between the field and the line of sight, is approximately constant is inconsistent with our data.





3) Their analysis, which includes ***both*** the uncertainty introduced by the putative significant variation of B(los) from one envelope position to another around each core in order to argue that the uncertainty in R is consistent with R >1, ***double counts*** the measurement uncertainty.

4) Their analysis, which assumes that θ is the same between core and envelope, is inconsistent with their suggestion (above) that θ varies from envelope to core, producing the variation in B(los) among envelope positions.

Conclusions

1. Subcritical M/Φ is ***never*** seen unambiguously in molecular cores.
2. Total strength of **B** seems to range from near zero to a maximum value in molecular clouds; maximum values of B_{tot} imply ~ critical cores, smaller values of B_{tot} imply significantly supercritical cores.
3. Slope of B vs. n(H) is about 2/3, consistent with collapse with magnetic fields not dominate during a contraction/collapse phase.
4. Increase in M/Φ from envelope to core required by published ambipolar diffusion models is not seen.
5. Nonetheless, magnetic fields are highly significant and probably crucial to understanding the physics of star formation; for example, in resolving the angular momentum problem, in fragmentation, etc. In at least some cases, M/Φ is ~ critical in molecular clouds. However, observational evidence now favors the generally weak field, turbulent model over the model in which fields are strong in all cloud cores with ambipolar diffusion always governing core formation and evolution. But the picture is not simple – magnetic fields may not dominate core and hence star formation, but they ***cannot*** be ignored.