Reflections on Modern Work

Simulated Zeeman Measurements and Magnetic Equilibrium in Molecular Clouds

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→ *ICREA - University of Barcelona (Spring 2010)*

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Phil's inf uence on my work, 15 years ago

Phil is the most cited author in my f rst paper, *Padoan 1995*:

Myers 1983, ApJ, 270, 185 (core subsonic turb. -- turb. dissipation heat + SF)

Myers, Linke, Benson 1983, ApJ, 264, 517 (equilibrium of dense cores)

Myers et al. 1986, ApJ, 301, 398 (SFE ≈ 2% -- SFE ~ $M_{\rm cl}^{-0.5}$)

Fuller and Myers 1992, ApJ, 384, 523 (Δv-R independent of stars I.C. for SF)

Crutcher et al. 1993, ApJ, 407, 175 (Green Bank OH Zeeman)

THE ASTROPHYSICAL JOURNAL, **326**: L27–L30, 1988 March 1

EVIDENCE FOR MAGNETIC AND VIRIAL EQUILIBRIUM IN MOLECULAR CLOUDS

P. C. MYERS
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AND

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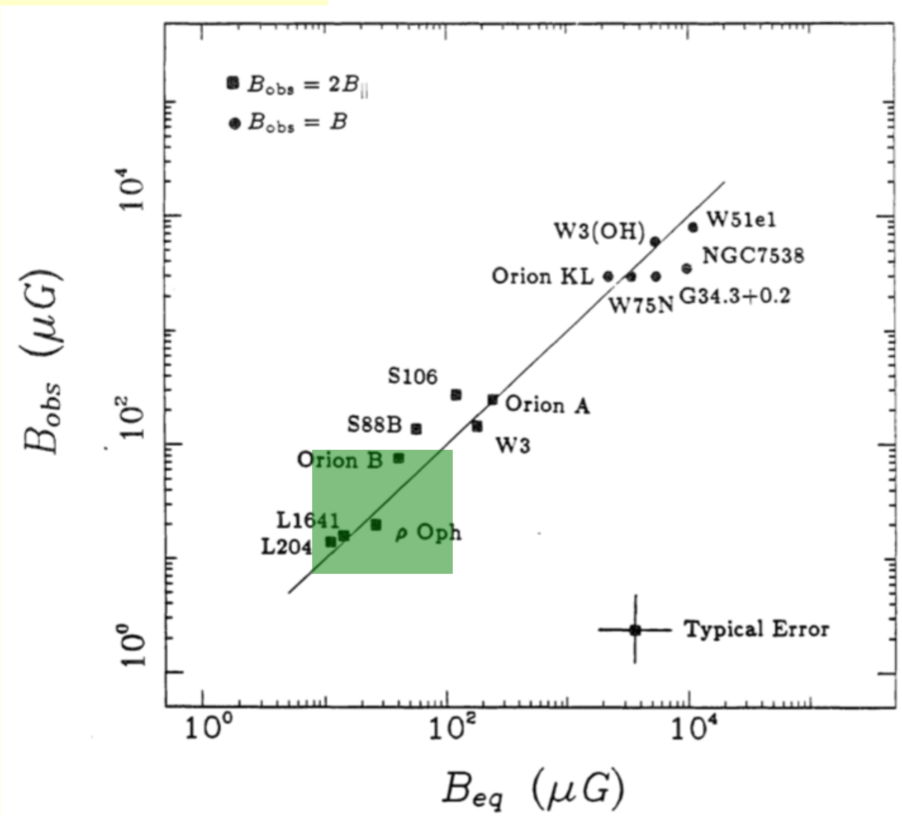
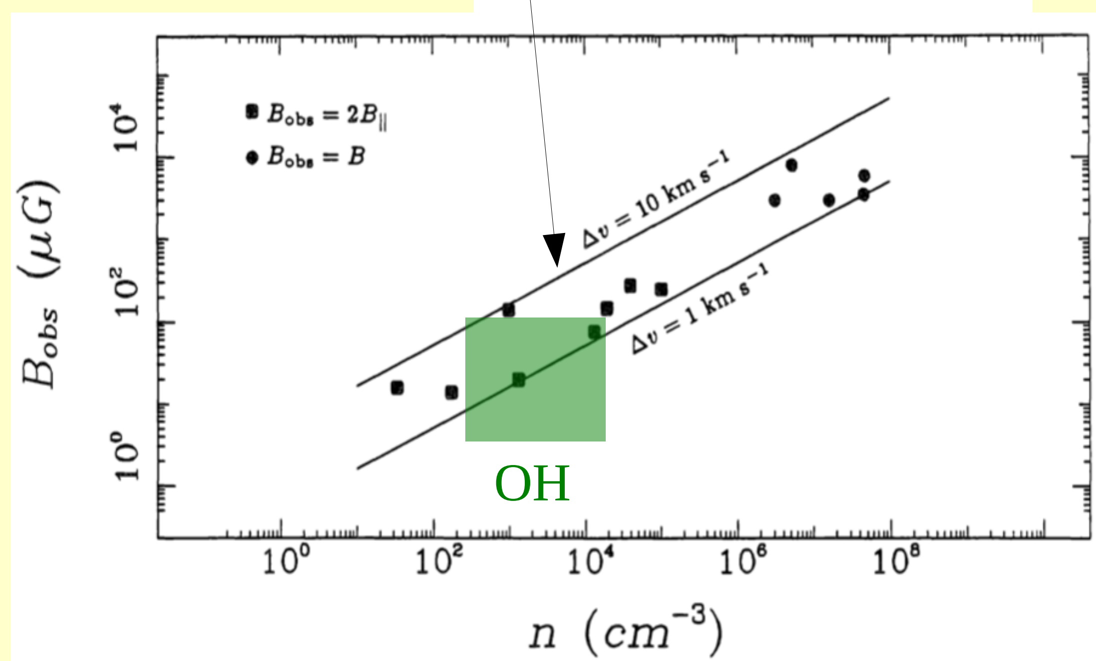
Received 1987 October 8; accepted 1987 December 7

$$M=K=G \rightarrow \quad B_{\rm eq} \approx \frac{3}{8 \ln 2}\left(\frac{5}{G}\right)^{1/2}\frac{\Delta v^2}{R}$$

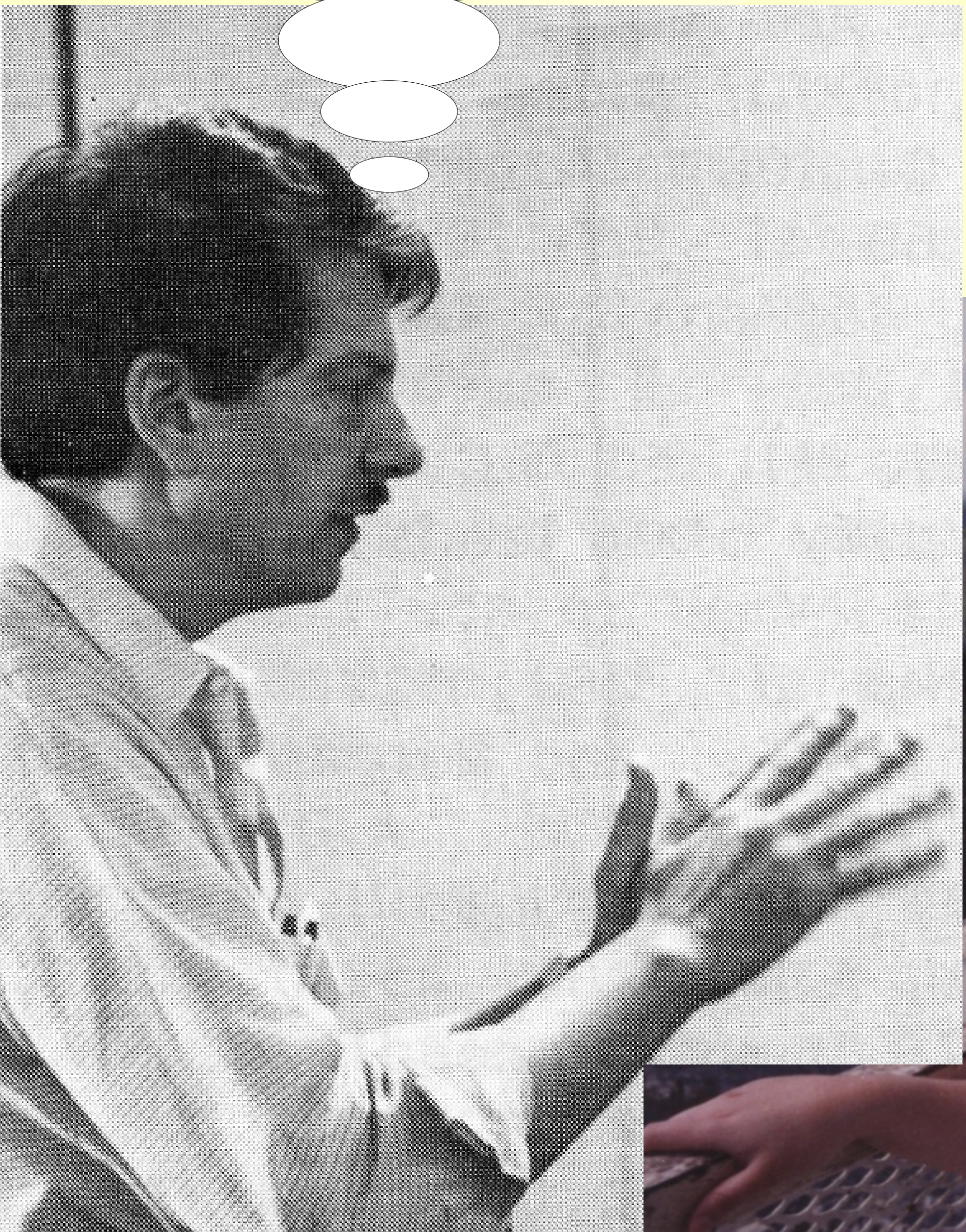


$$M=K \rightarrow \quad B_{\rm eq} \approx \left(\frac{3\pi m}{2 \ln 2}\right)^{1/2}\Delta v\, n^{1/2}$$



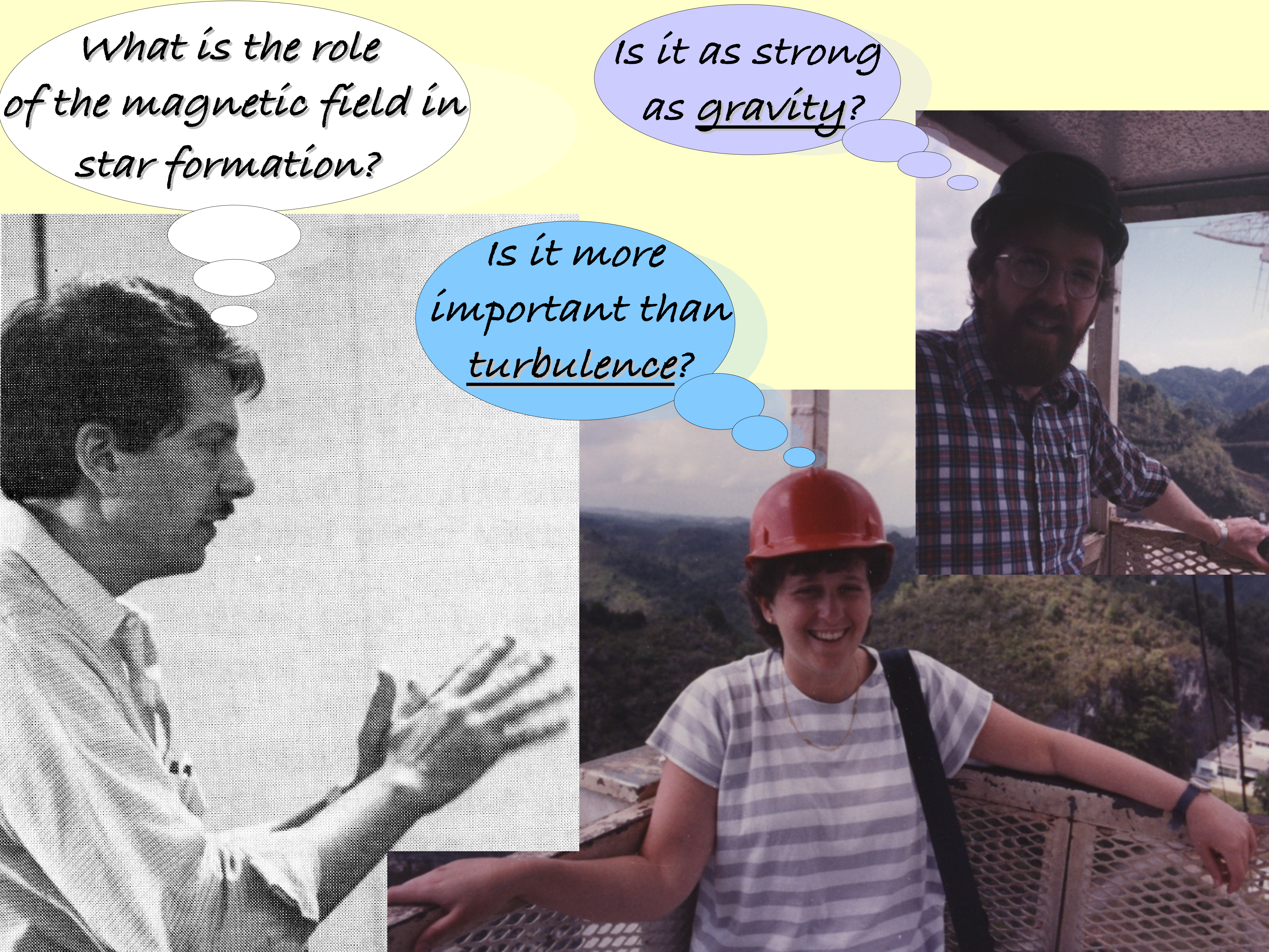
Radioastronomers in 1988.....

What is the role
of the magnetic field in
star formation?



What is the role of the magnetic field in star formation?

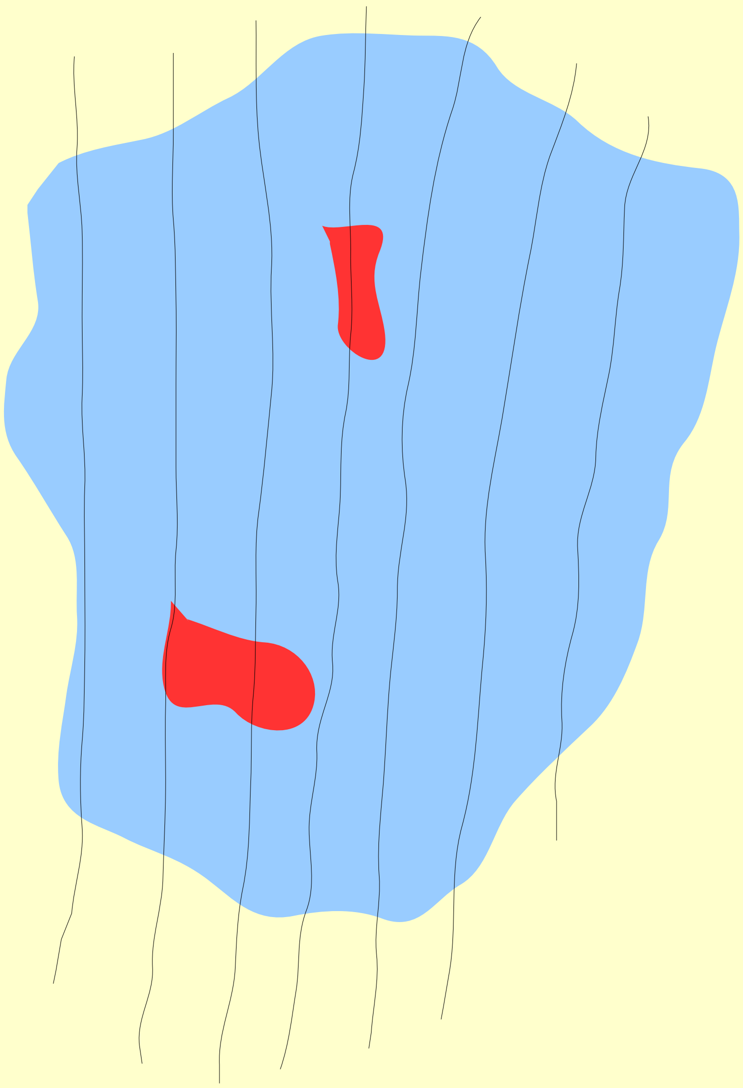
Is it more important than <u>turbulence</u>?


What is the role of the magnetic field in star formation?
Is it as strong as gravity?
Is it more important than turbulence?

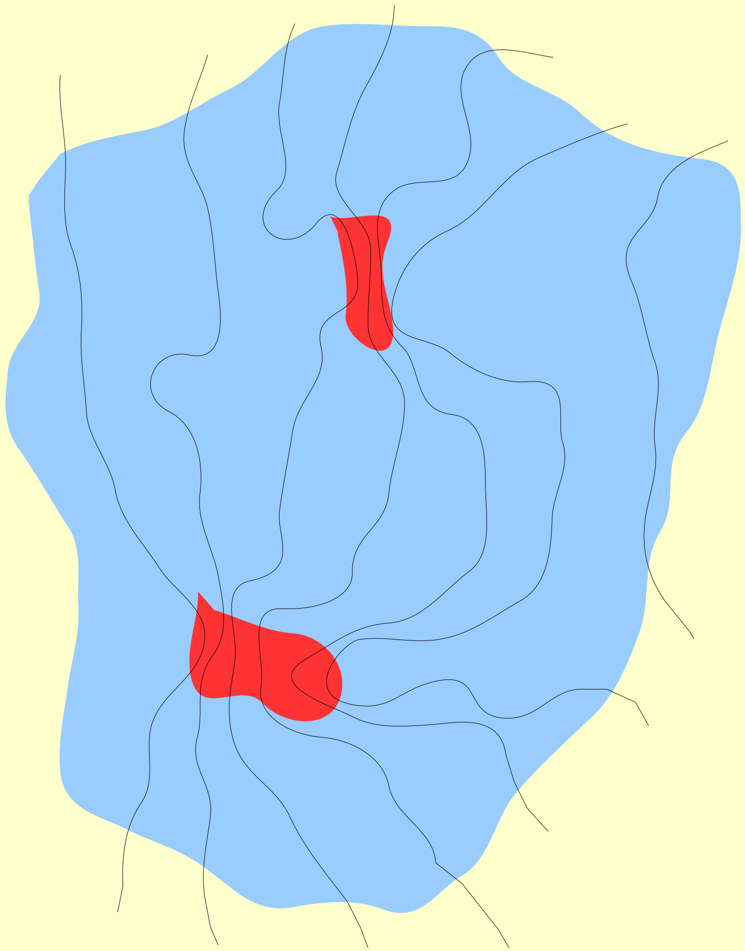
Cores (0.1-1 pc) versus large-scale fragmentation (10-50 pc)

Is the large-scale mean magnetic field as strong as in dense cores?

Strong Field: $E_G \sim E_K \sim E_M$



Weak Field: $E_G \sim E_K > E_M$



(Padoan & Nordlund 1999)

This talk:

Synthetic Zeeman measurements versus observations:

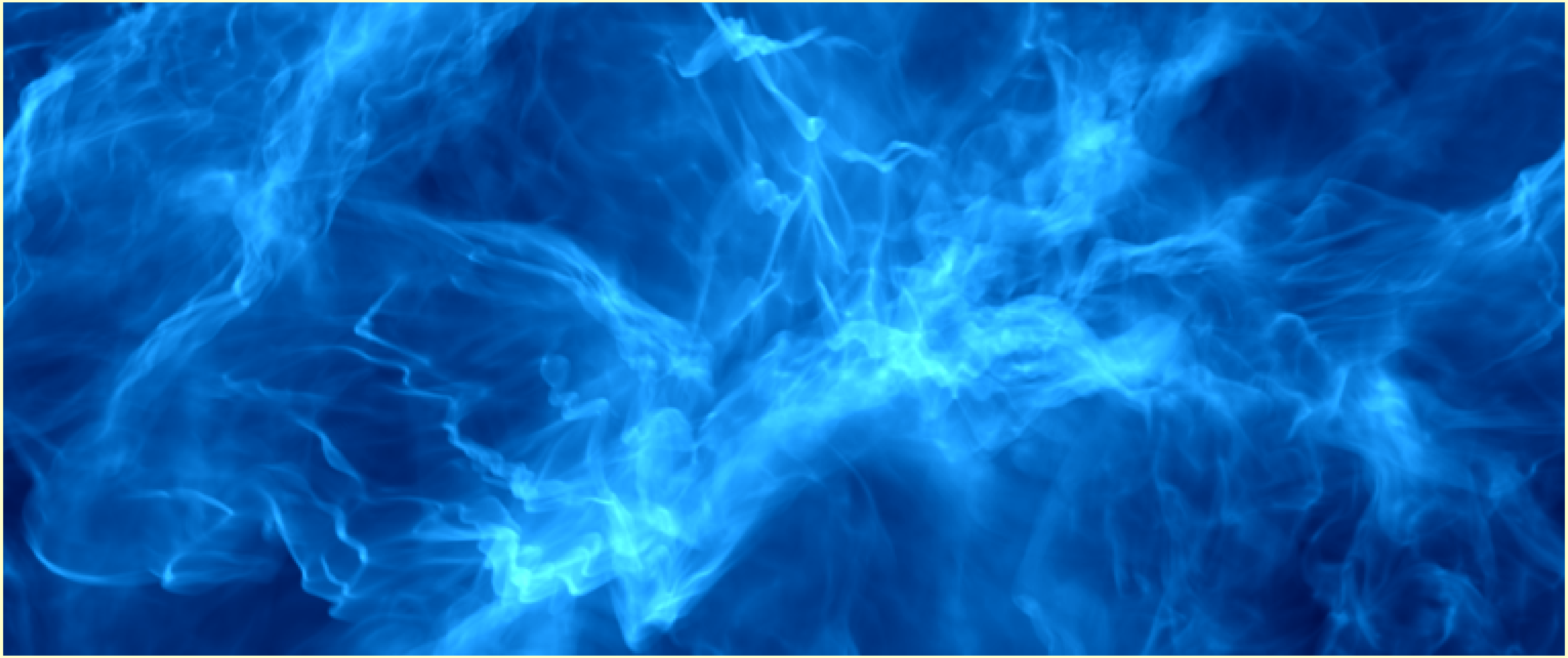
Lunttila, Padoan, Juvela, and Nordlund (2009, ApJL, 702, L37)

Troland & Crutcher (2008, ApJ, 680, 457)

No time for:

Falgarone et al. 2008: New CN Zeeman measurements, $G \geq M = K$
Lunttila et al. 2008: Relative mass-to-flux < 1 in super-Alfvenic turbulence
Crutcher et al. 2009: Relative mass-to-flux < 1

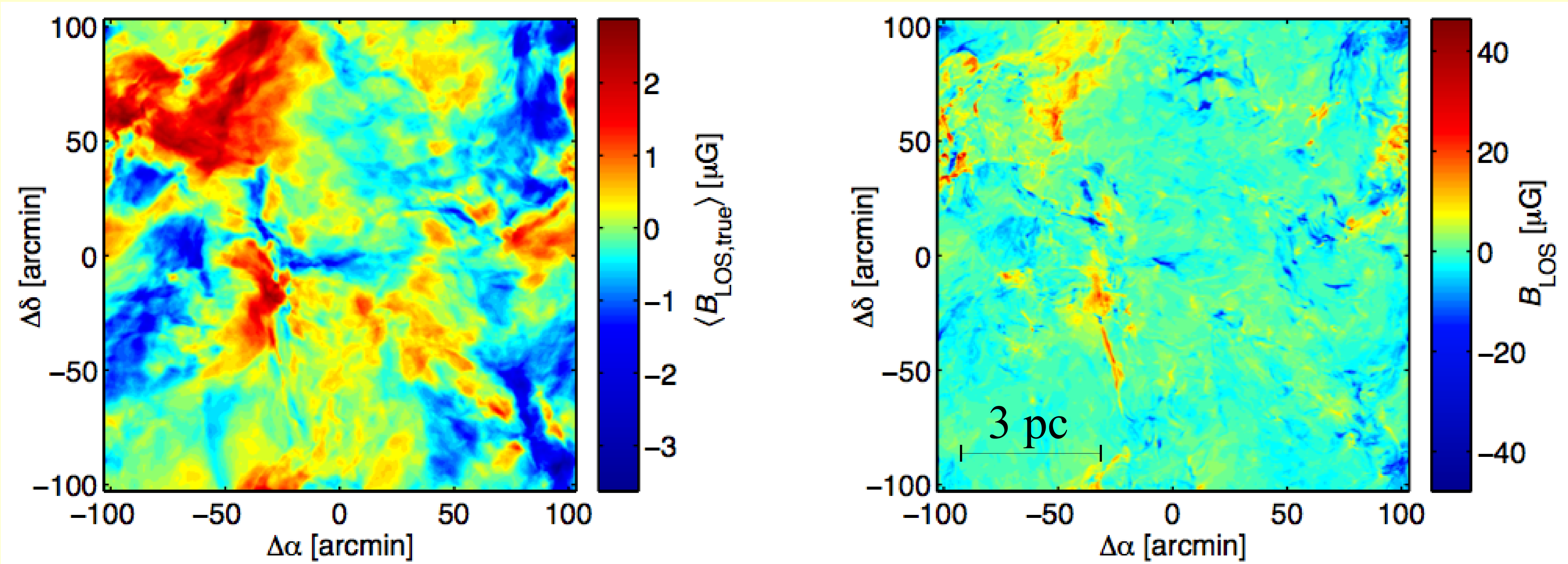
Numerical Simulations of Supersonic Turbulence



- **1000^3** zones with periodic boundary conditions
- Uniform initial magnetic and density fields
- Large scale ($1<k<2$), random, solenoidal initial velocity and forcing
- Forcing for several crossing times → steady state
- **No gravity, no ambipolar drift, isothermal equation of state**

Synthetic Zeeman Measurements *(1665 and 1667 MHz OH lines)* *(Lunttila et al. 2009)*

True mean l.o.s. B field | B from Zeeman measurement



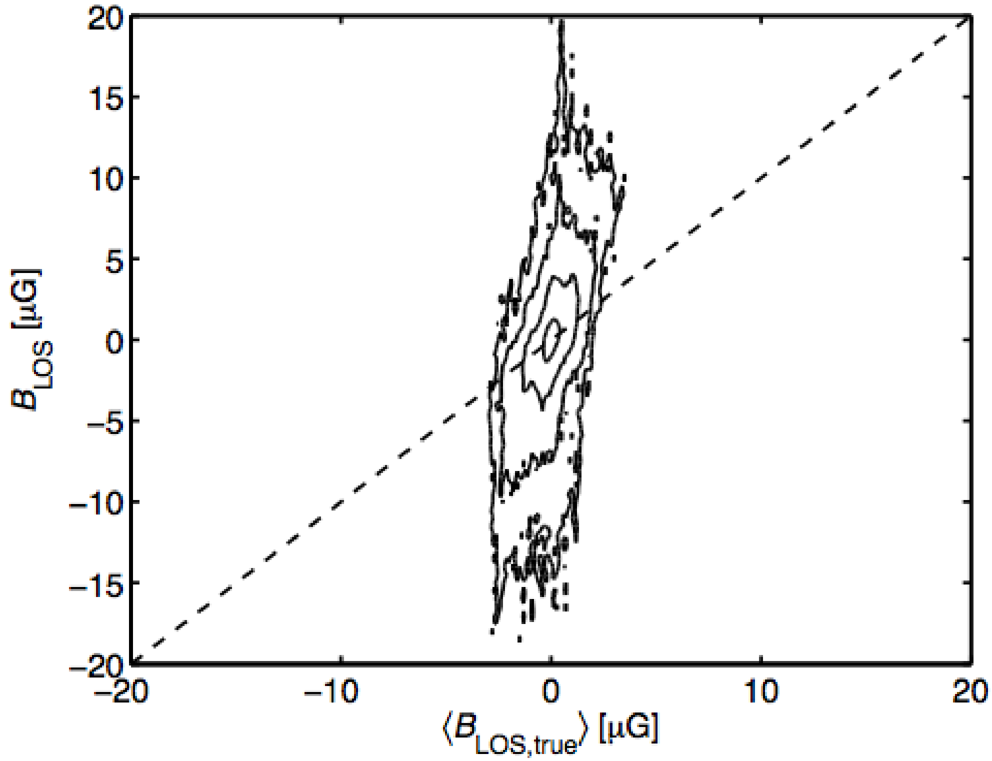
<u>Very low mean field, $\langle B \rangle = 0.34\ \mu$G</u> (but $\langle B^2 \rangle^{1/2} = 3.05\ \mu$G)

$B_{\rm los}$ also quite low, and more diffuse than the density structure.

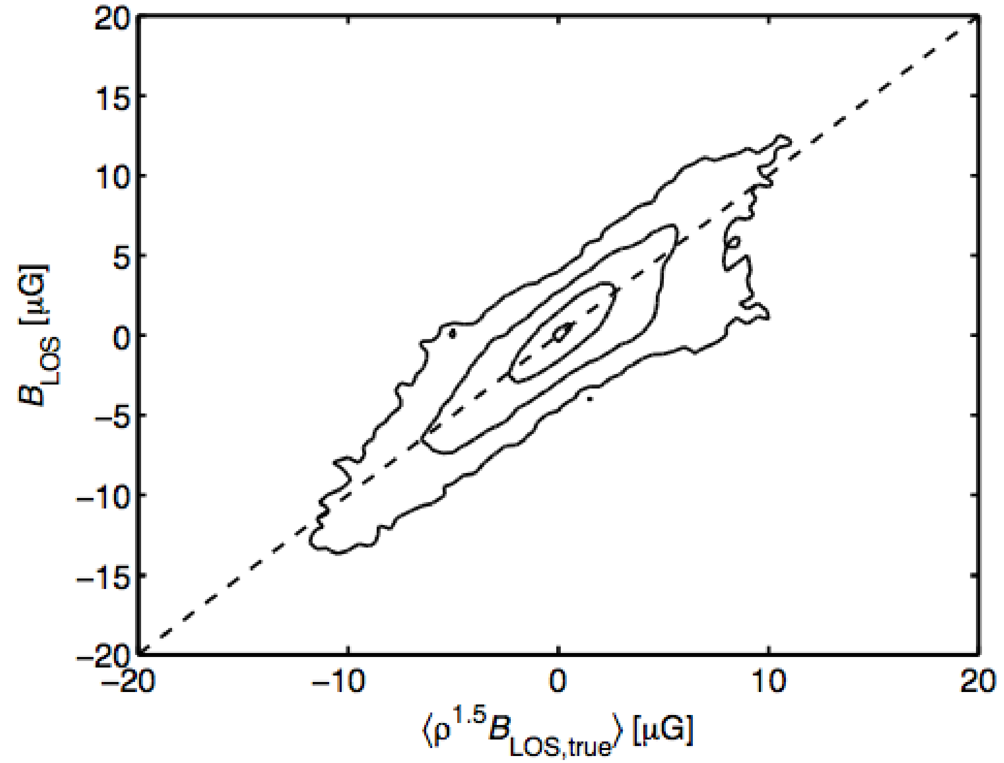
The mean field cannot be probed by Zeeman measurements!

B_{LOS} estimated from Zeeman measurements versus:

True mean B_{LOS}



Density-weighted true mean B_{LOS}



OH emission lines Zeeman measurements yield estimates of B_{LOS} strongly weighted by density. The result is biased towards the field strength in the densest regions, and very far from the true mean B along the line of sight.

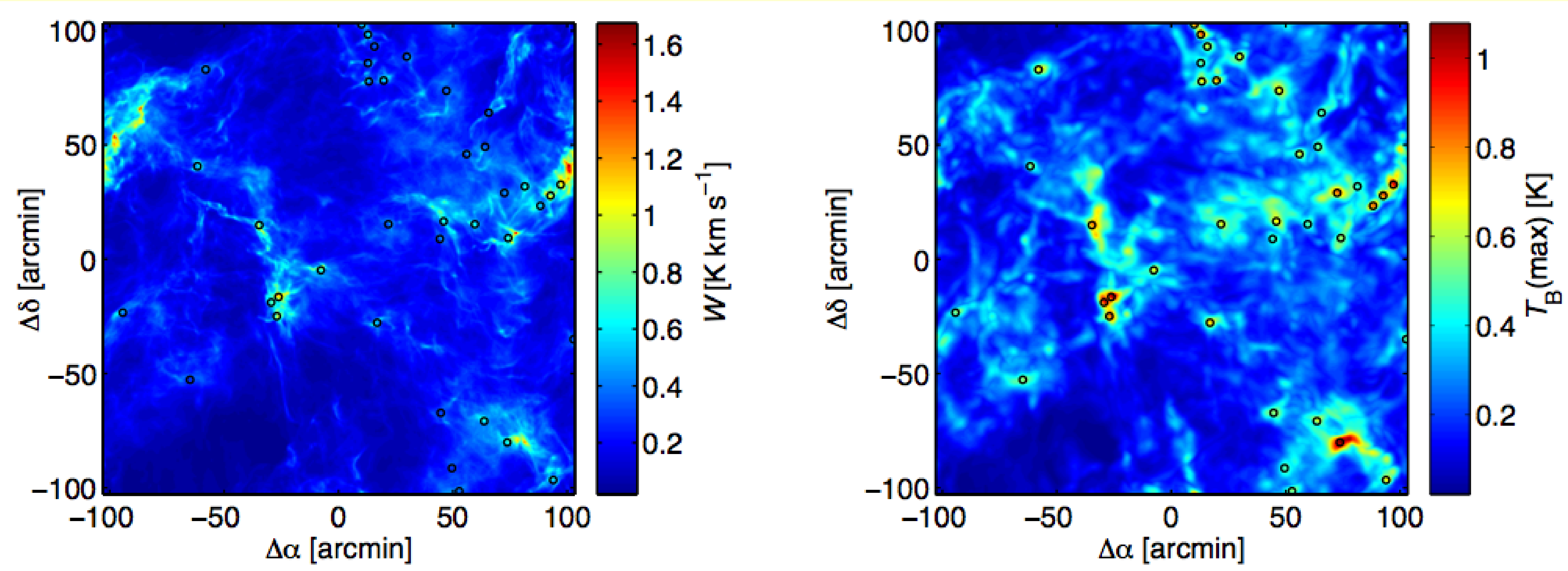
Core selection in the 1665 MHz OH maps (3' beam):

Position-Position-Velocity clumpfind algorithm *(Williams et al. 1995)*

Three distances: 130 pc (105 cores), 300 pc (40 cores), 1,000 pc (4 cores)

1665 MHz OH Integrated Intensity

Peak Brightness Temperature



Cores correspond to brightness temperature peaks (not so much to projected density structures).

Comparison with Observations *(Troland & Crutcher 2008)*

Mass-to-flux over critical value

$$\lambda = \frac{(M/\Phi)_{\mathrm{obs}}}{(M/\Phi)_{\mathrm{crit}}} = 7.6 \times 10^{-21} \frac{N(\mathrm{H}_2)}{|B_{\mathrm{LOS}}|}$$

Turbulent to magnetic energy

$$\beta_{\mathrm{turb}} = \frac{E_{\mathrm{turb}}}{E_{\mathrm{mag}}} = 0.32 \frac{n(\mathrm{H}_2)\,\Delta V_{\mathrm{NT}}^2}{3\,B_{\mathrm{LOS}}^2}$$

where $(M/\Phi)_{\mathrm{crit}} = 1/(2\pi G^{1/2})$ *(Nakano & Nakamura 1978)*

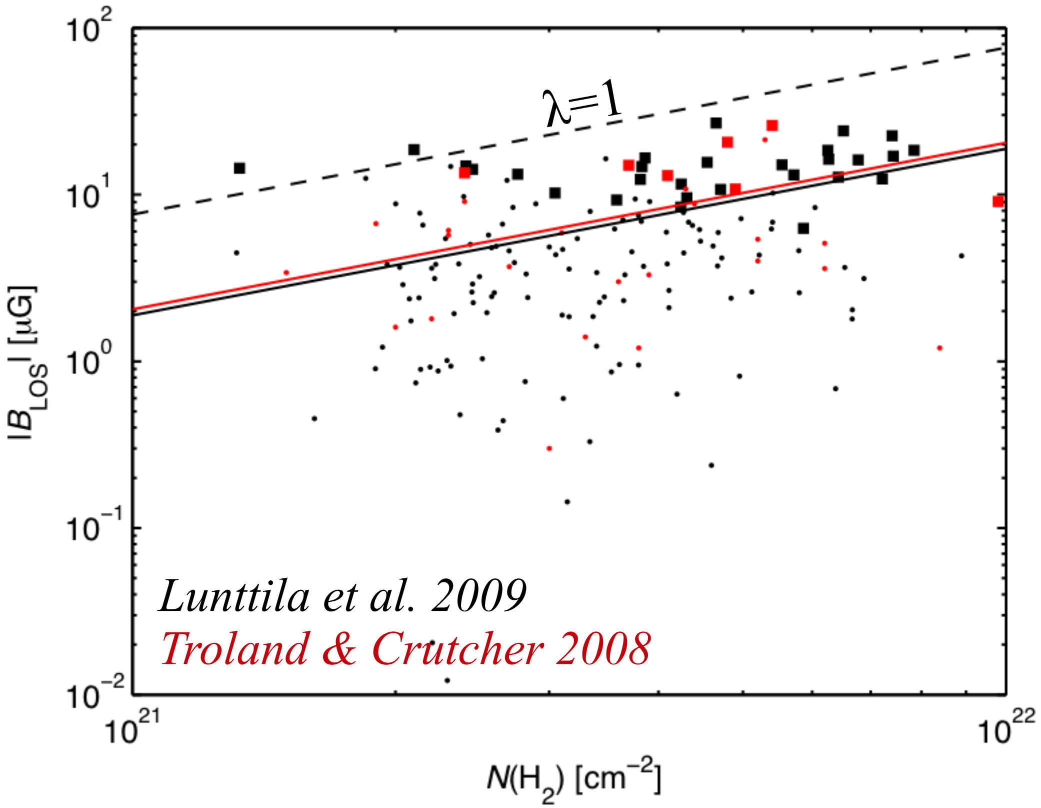
Average values for cores with D < 400 pc:

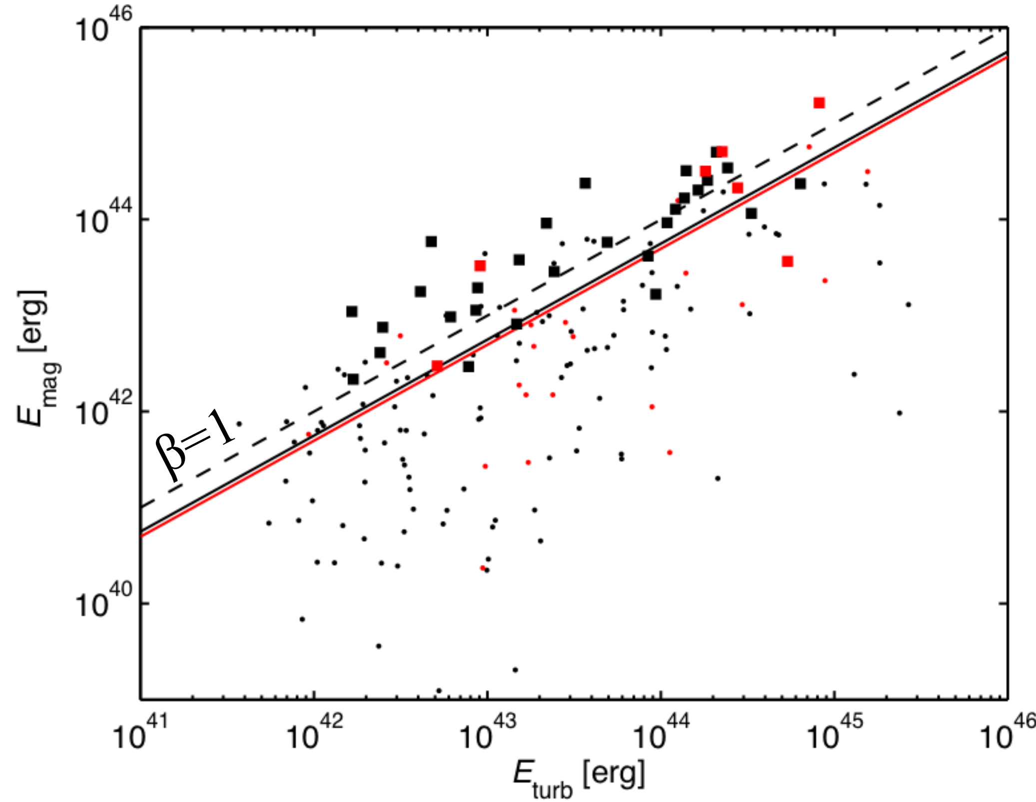
Simulations	Observations	Simulations	Observations
$\langle \lambda \rangle_{\mathrm{sim}} \approx 3.9$	$\langle \lambda \rangle_{\mathrm{obs}} \approx 3.8$	$\langle \beta_{\mathrm{turb}} \rangle_{\mathrm{sim}} \approx 1.8$	$\langle \beta_{\mathrm{turb}} \rangle_{\mathrm{obs}} \approx 1.9$

The energy ratios of the simulated molecular cores are consistent with those of the observed cores, despite the very weak mean magnetic field ($\langle B \rangle = 0.34$ μG).

Comparison with Observations

$\langle\lambda\rangle_{sim} \approx 3.9 \quad \langle\lambda\rangle_{obs} \approx 3.8$ $\quad\quad \langle\beta_{turb}\rangle_{sim} \approx 1.8 \quad \langle\beta_{turb}\rangle_{obs} \approx 1.9$





Using only detections, the magnetic energy would be very close to the turbulent energy (β≈1), but still below the critical value for support against gravity (λ>1):

$\langle\lambda\rangle_{sim} \approx 2.5 \pm 0.4, \quad \langle\lambda\rangle_{obs} \approx 2.5 \pm 0.6$ $\quad\quad \langle\beta_{turb}\rangle_{sim} \approx 0.6 \pm 0.4, \quad \langle\beta_{turb}\rangle_{obs} \approx 0.9 \pm 0.6$

Conclusions

1. Cores are pretty close to magnetic balance (especially when B is detected), as in *Myers and Goodman 1988*, but with a lot of scatter (part intrinsic, part orientation effect, part uncertainties)

2. OH Zeeman measurements in dense cores (and many other properties!) can be reproduced with a very weak large-scale mean magnetic field.

What is the origin of the scatter? Only orientation + uncertainties, or also large intrinsic magnetic field variations?

How strong can the large-scale mean magnetic field be?

Future work:
Observations versus synthetic Zeeman measurements from simulations with different magnetic field strength.