Magnetic Fields: Recent Past and Present

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A Fundamental Relation

EVIDENCE FOR MAGNETIC AND VIRIAL EQUILIBRIUM IN MOLECULAR CLOUDS

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ABSTRACT

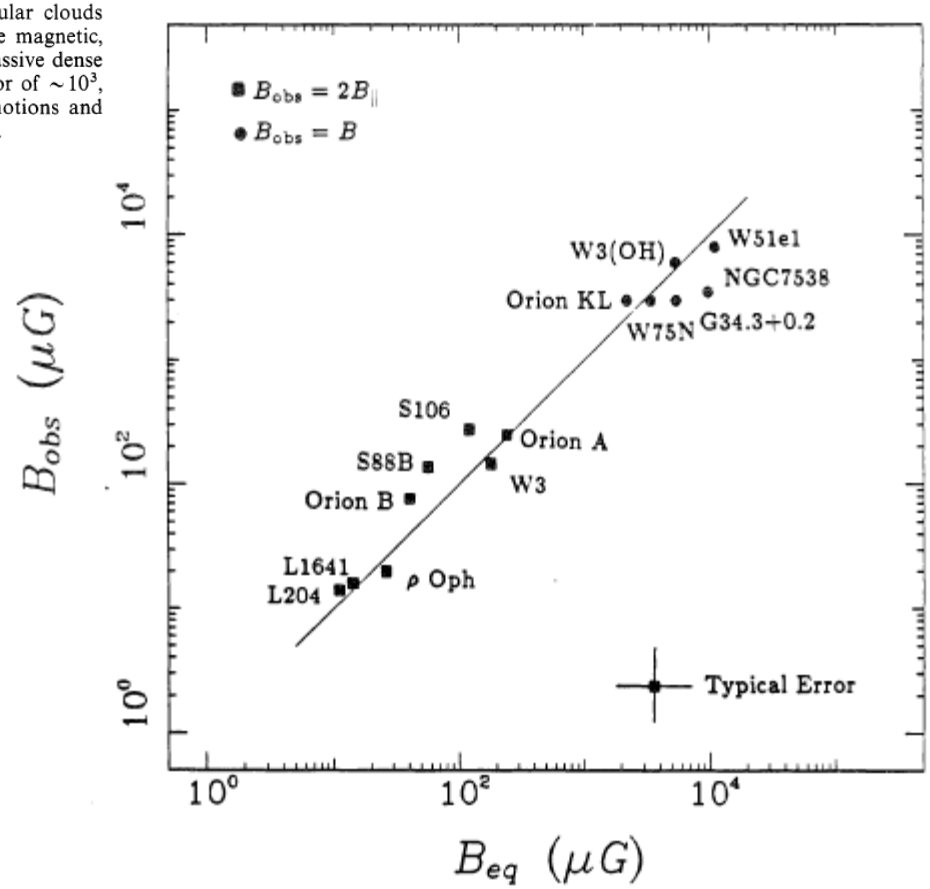
Recent measurements of the magnetic field strength, velocity dispersion, and size of 14 molecular clouds agree, within uncertainty of a factor of ~ 2, with the predictions of a simple model in which the magnetic, kinetic, and gravitational energies are all equal. The clouds range from extended dark clouds to massive dense cores associated with OH masers and compact H II regions. Their field strengths range over a factor of $\sim 10^3$, from $\sim 10\ \mu$G to ~ 10 mG. This result suggests that the magnetic contribution to the internal motions and energy of many molecular clouds is crucial for cloud dynamics, cloud evolution, and star formation.

Myers & Goodman (1988)

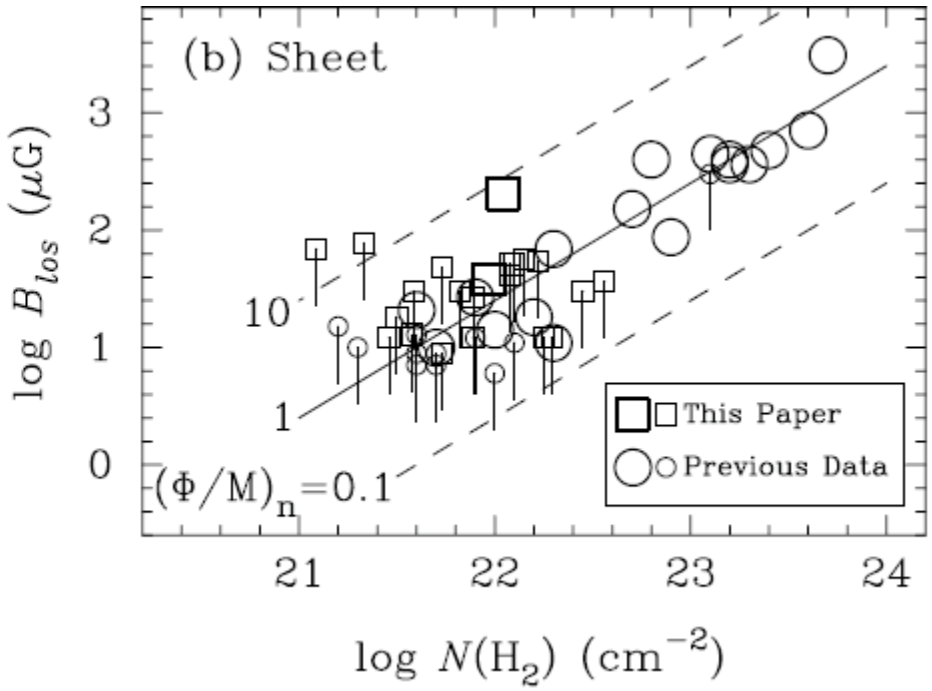
(2), (8), and (10), for the 14 clouds in Table 1. The field strength generally increases as $n^{1/2}$, in accord with the trends noted by Crutcher, Kazès, and Troland (1987) and Heiles (1987*b*). This trend is easily understood, since $\mathsf{M} \approx \mathsf{K}$ implies

$$B_{\rm eq} \approx \left(\frac{3\pi m}{2 \ln 2}\right)^{1/2} \Delta v\, n^{1/2}\,, \qquad (4)$$

according to MG equations (2) and (6), assuming negligible thermal motions. In Figure 2, $n^{1/2}$ varies by a factor $\sim 10^3$, while Δv varies by a factor of only ~ 10. Therefore, B should appear correlated with $n^{1/2}$, given the assumption that $\mathsf{K} \approx \mathsf{M} \approx \mathsf{G}$, which is corroborated by Figure 1, and the fact



Another Important Relation



NEW OH ZEEMAN MEASUREMENTS OF MAGNETIC FIELD STRENGTHS IN MOLECULAR CLOUDS

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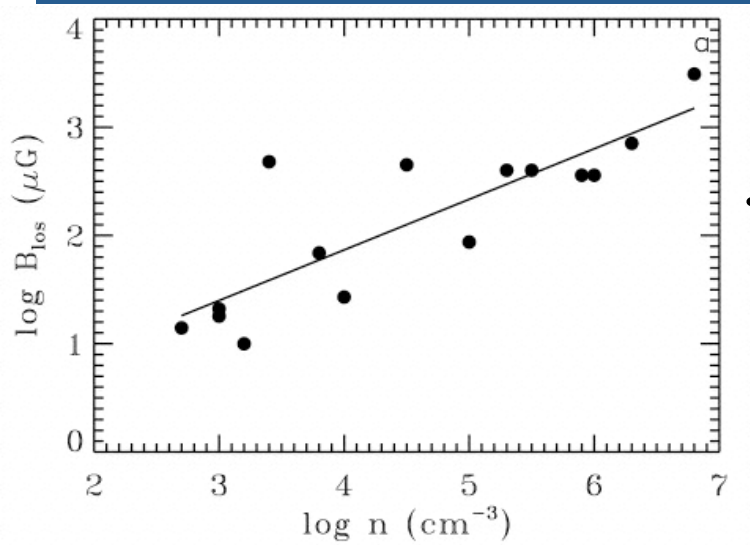
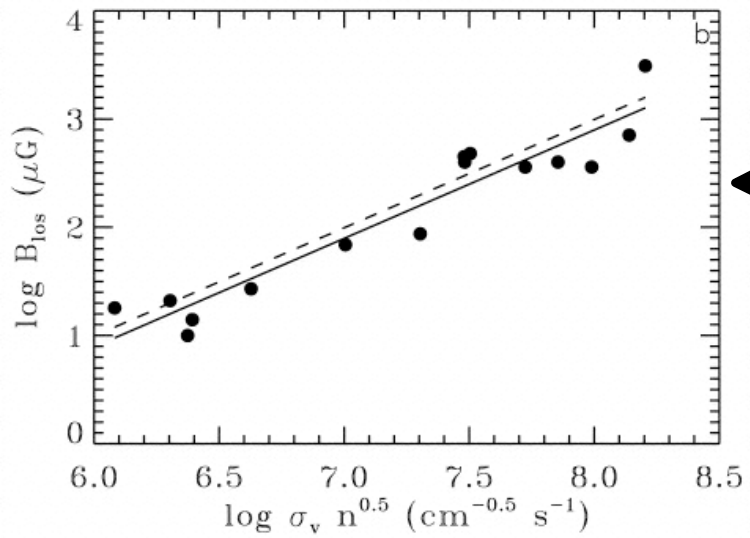
Bourke et al. (2001)

Magnetic field strength correlates with column density. Best fit corresponds to near-critical mass-to-flux ratio.

Don't Correlate B with n!



Poor correlation; ignores velocity dispersion σ_v.



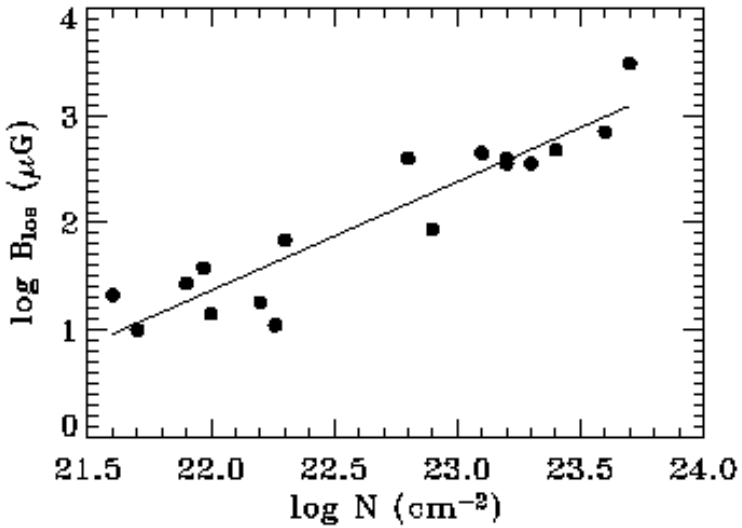
Dramatically improved correlation when including effect of velocity dispersion.

$$B \propto \sigma_v n^{1/2}$$

$$\Leftrightarrow \sigma_v \approx 0.5 v_A$$

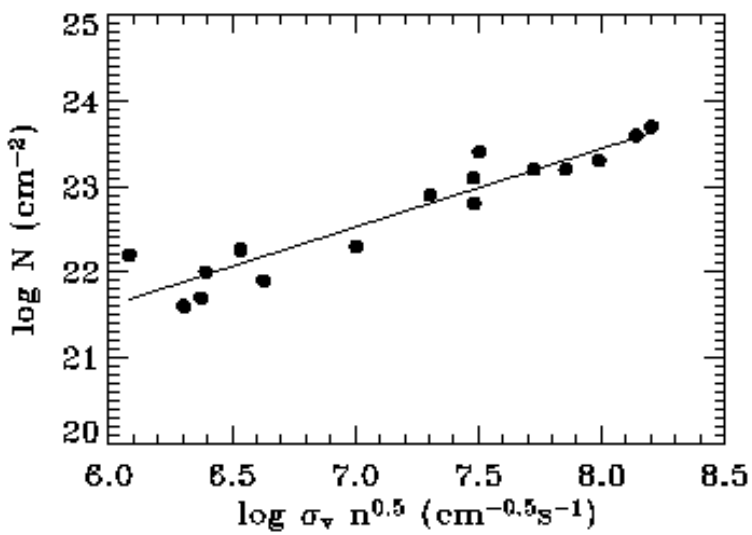
Basu (2000)

The Two Underlying Correlations



$$\mu = \frac{\Sigma}{B} 2\pi G^{1/2} \approx 1 \qquad (\Sigma = \bar{m}N)$$

Near-critical mass-to-flux ratio



A generalized linewidth-size relation, applied to dense regions with $N \approx \bar{N}$.

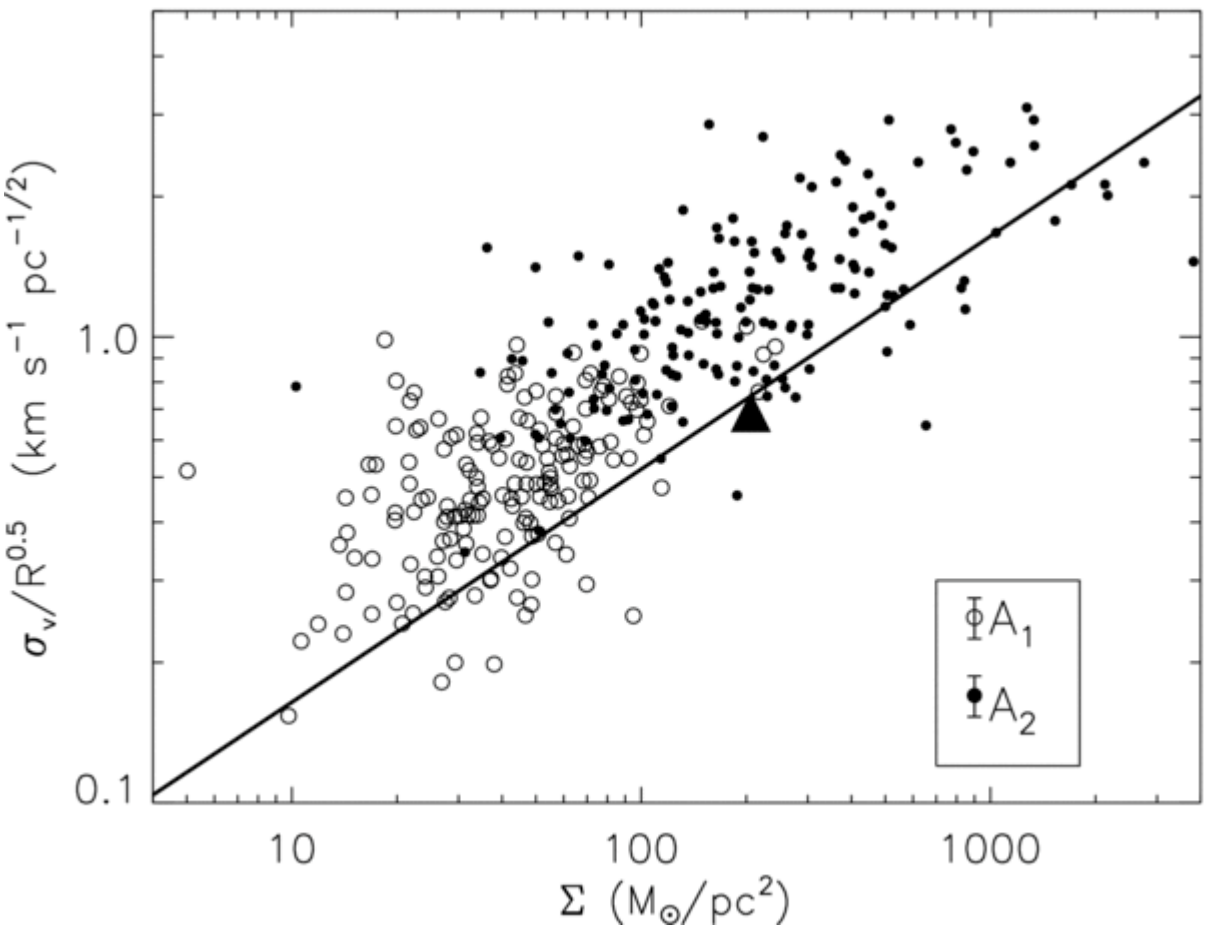
$$N \propto \sigma_v n^{1/2}.$$

$$\text{If } N(\propto nR) = \text{constant}$$

$$\Rightarrow \sigma_v n^{1/2} = \text{constant} \Rightarrow \sigma_v \propto R^{1/2}$$

from Basu (2005)

Generalized LWS relation



Heyer et al. (2009)

$$N \propto \sigma_v^2 / R$$

$$\Leftrightarrow N \propto \sigma_v n^{1/2}$$

$$\text{since } R \propto N/n$$

How do stars get their masses?

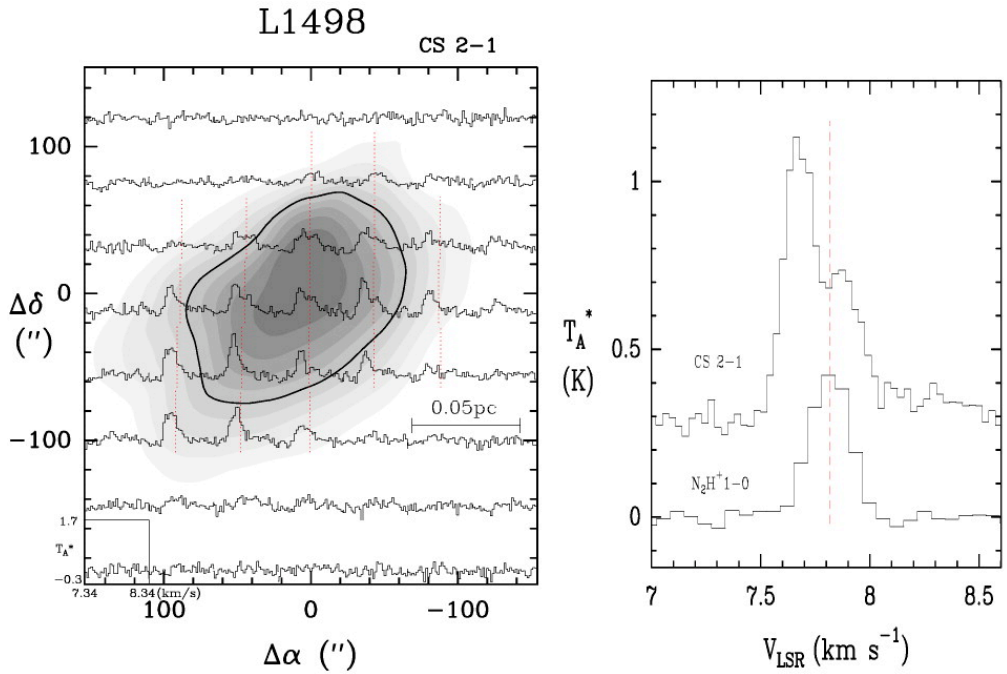
1970's: Mouschovias – magnetic field (tension) may set final mass

1980's-90's: Shu, Adams, Lizano; Adams & Fatuzzo - Outflow feedback may set masses

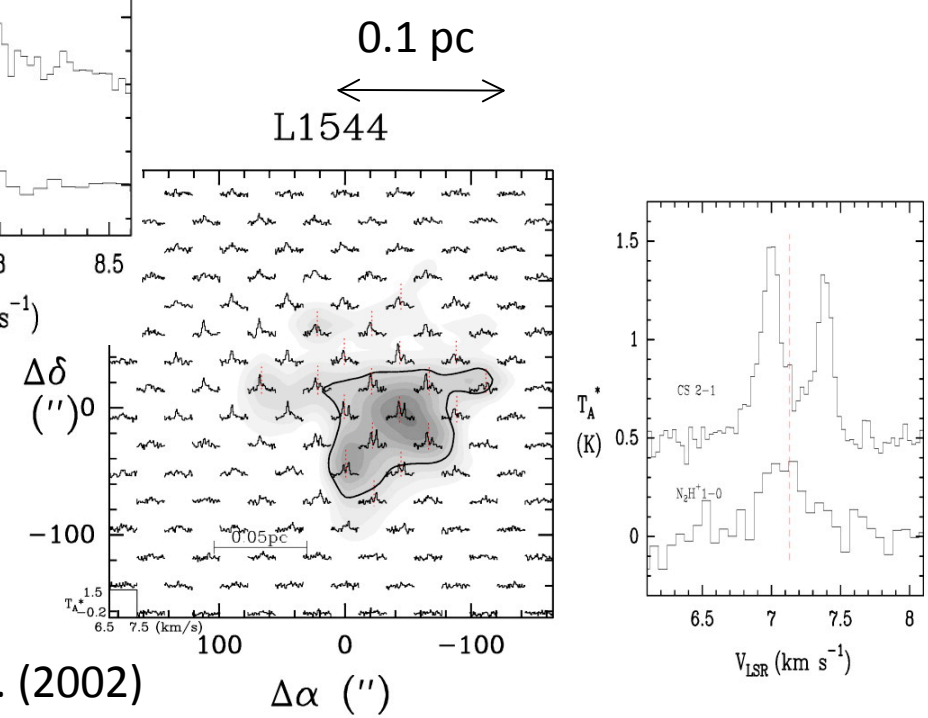
Late 1990's: Padoan & Nordlund – turbulent compression (ram pressure) may set masses

Infall Motions: Insight into B

Lee, Myers, & Tafalla (2001)



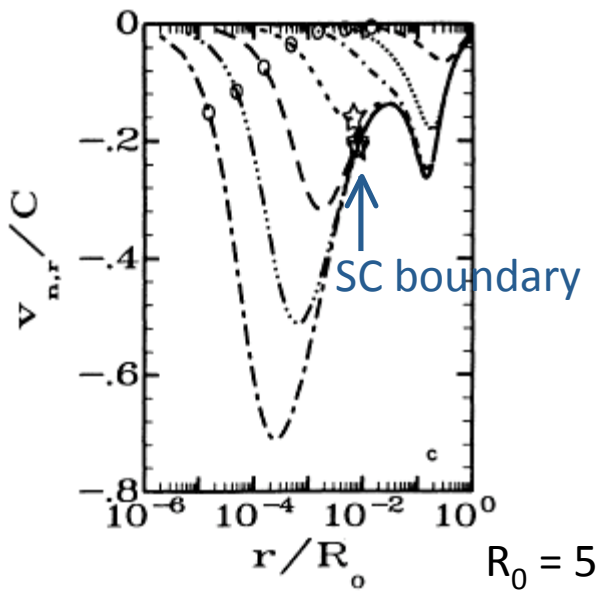
"infall speeds in starless cores are generally faster than expected from ambipolar diffusion in a strongly subcritical core."

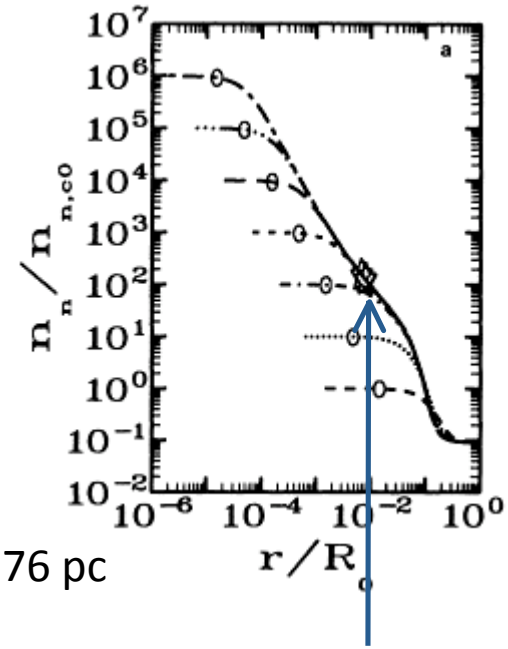


Extended (R ~0.1 pc) infall, ~ 0.5 c_s

Also, notably Tafalla et al. (1998), Caselli et al. (2002)

Highly subcritical cloud models problematic





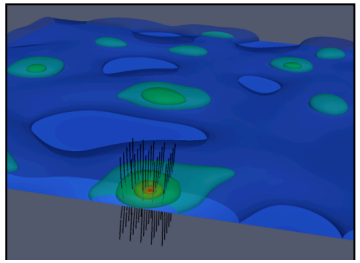
R_0 = 5.76 pc

Supercritical core boundary at ~ 0.05 pc.

Basu & Mouschovias (1995)

The more subcritical the initial state, the smaller the size of the eventual runaway collapse region.

Above model has $\mu_{c,0} = \frac{\Sigma_{c,0}}{B_{c,0}} 2\pi G^{1/2} = 0.1$ (initial magnetic domination, subcritical by factor 10)



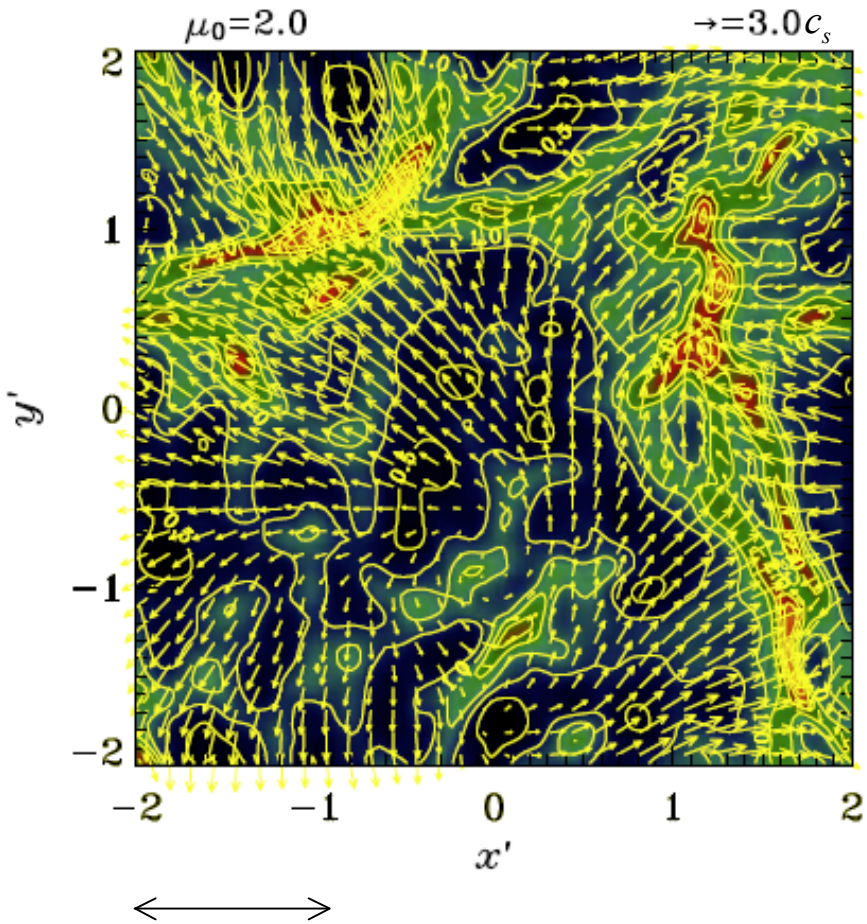
with an initial central density $n_{n,c0} = 3\times10^{3}\ \mathrm{cm}^{-3}$

Can turbulence induce small collapse scales?

$$v_k^2 \propto k^{-4}$$

initially, decaying turbulence

Thin-sheet model

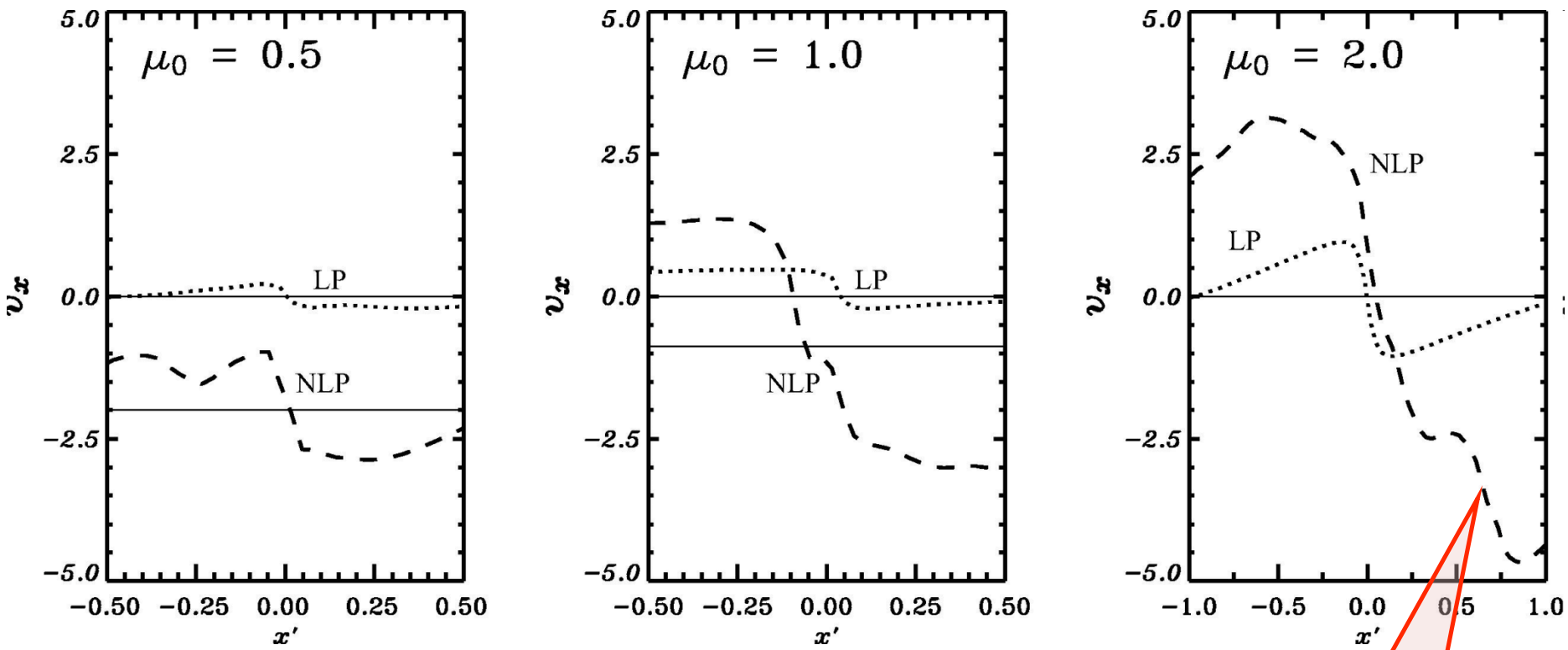


~ 0.5 pc

Ram pressure generated dense regions. Highly supersonic systematic motions.

Basu, Ciolek, Dapp, & Wurster (2009)

Highly turbulent models have problems in core vicinity



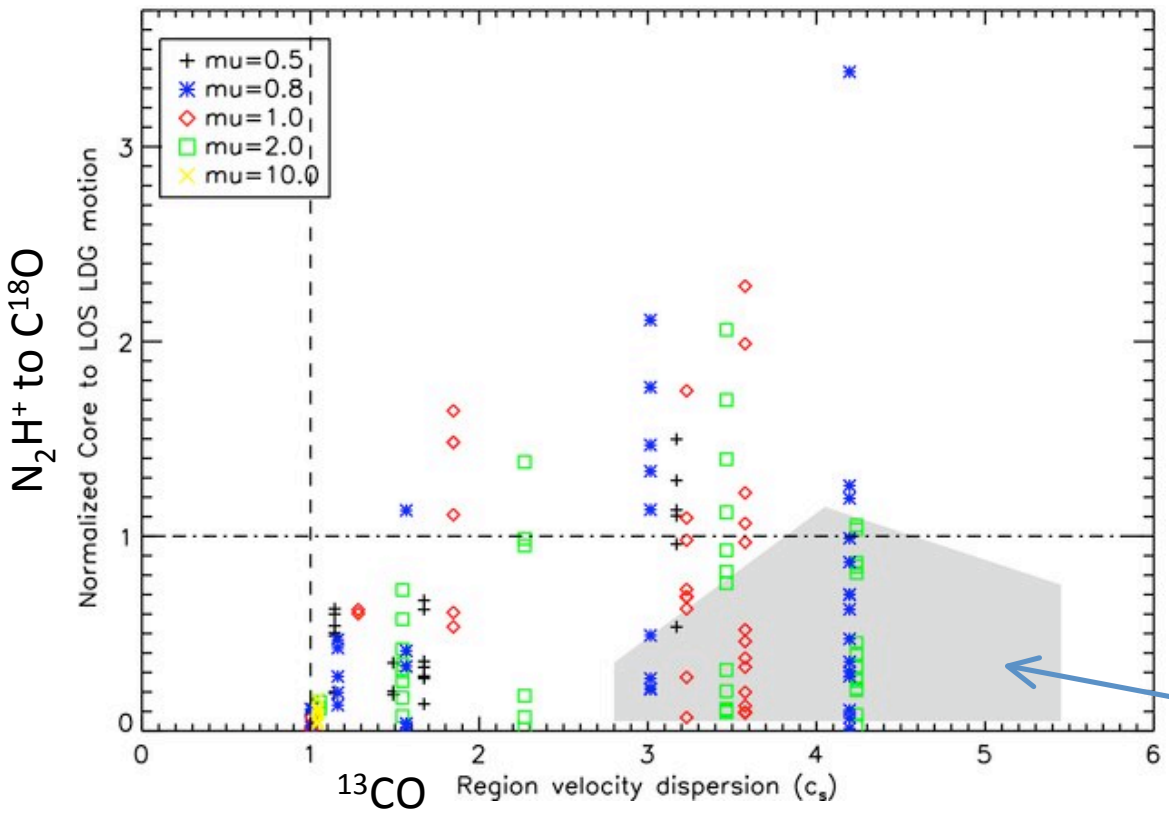
LP = initial linear pertutbations
NLP = initial nonlinear turbulent perturbations

turbulent and supercritical

v_x normalized to c_s
x' normalized to ~ 0.05 pc.

Basu, Ciolek, Dapp, & Wurster (2009)

Observed Simulations: More problems with highly turbulent models



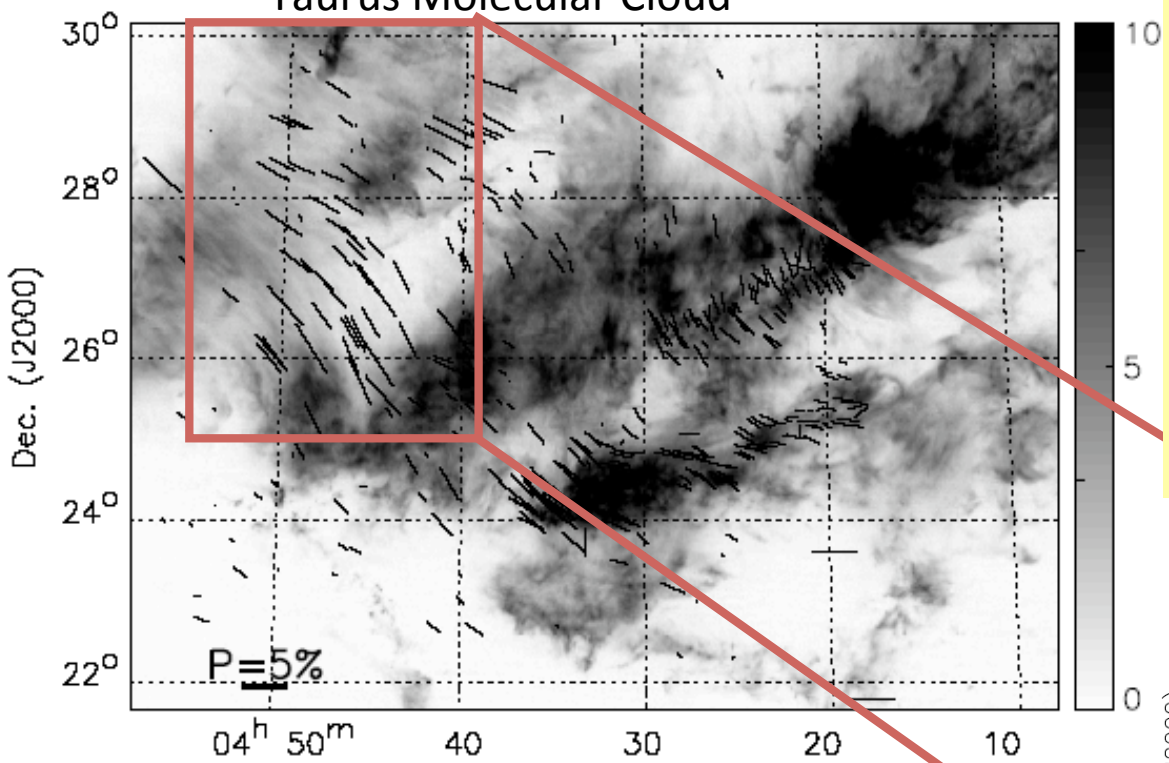
Model cores in turbulent simulation box can have large systematic motions relative to neighboring lower density gas. Observed cores do not.

Observed data points fall in shaded region

Kirk, Johnstone, & Basu (2009), using N_2H^+ , $C^{18}O$ and ^{13}CO observations and models of Basu, Ciolek, Dapp, & Wurster (2009)

B and σ_v can still dominate large scales

Taurus Molecular Cloud

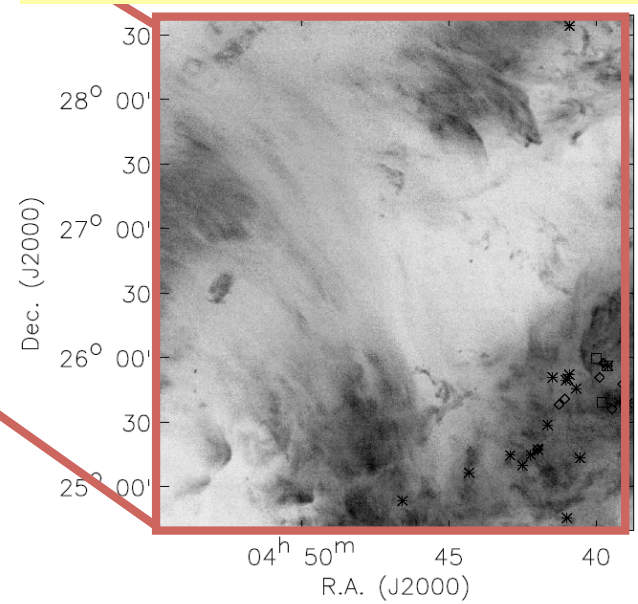


Goldsmith et al. (2008), ^{12}CO emission

Striations of gas emission consistent with magnetically-dominated envelope.

Goldsmith et al. (2008): Stellar mass only ~1% of total mass. Most of cloud is empty of cores. Mass is mostly in the low density envelope.

Heyer et al. (2008): Polarization of starlight plus velocity data → low density regions are magnetically dominated.



Some conclusions

• Core infall regions have extended (subsonic) motion. Mass reservoir is significant.

• Observed infall is too fast for highly subcritical models and too slow for highly turbulent models.

• Theoretical efforts to explain typical (low) stellar masses by large magnetic or turbulent pressure in the near-core environment have not been successful.

• The role of near-stellar processes, e.g., outflows, disk fragmentation, ??, may be crucial to determining stellar masses.

• Termination of mass accretion onto nascent stellar cores may be the key ingredient to setting stellar masses. One cannot ignore the TEMPORAL aspect of this process (e.g., Myers 2009).