

Modeling Cloud and Core Formation in the Turbulent, Magnetized ISM

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I. INTRODUCTION

- The interstellar medium (ISM) is both turbulent and magnetized (e.g., Heiles & Troland 2003, 2005).
- Turbulence in the magnetized interstellar medium (ISM) produces density enhancements that constitute clouds, and clumps within them (Sasao 1973; Elmegreen 1993; Ballesteros-Paredes et al. 1999).
- Further density enhancements (turbulence- or gravity-driven?) constitute star-forming cores.
- This talk:
 - Outline of underlying physical processes.
 - Results from cloud-formation simulations including MHD and ambipolar diffusion (AD).

II. BASIC PHYSICAL PROCESSES

1. Fundamental fact:

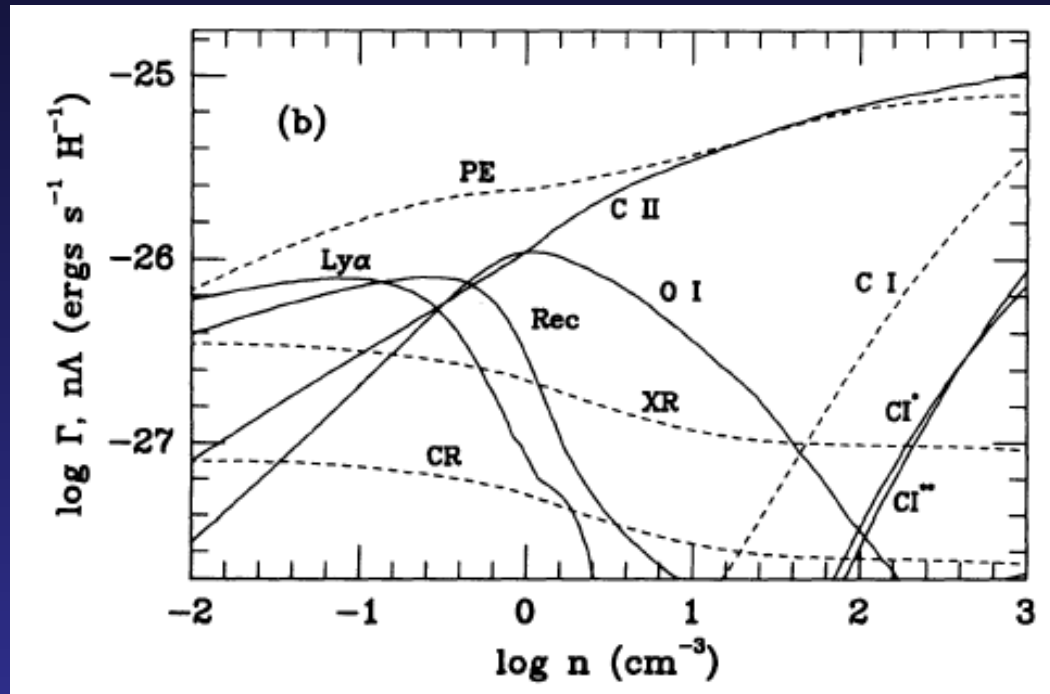
A density enhancement requires an accumulation of initially distant material into a more compact region.

$$\frac{d\rho}{dt} = -\rho \nabla \cdot u$$

2. ISM thermodynamics.

2.1. A key property of the ISM is that it is thermally bistable.

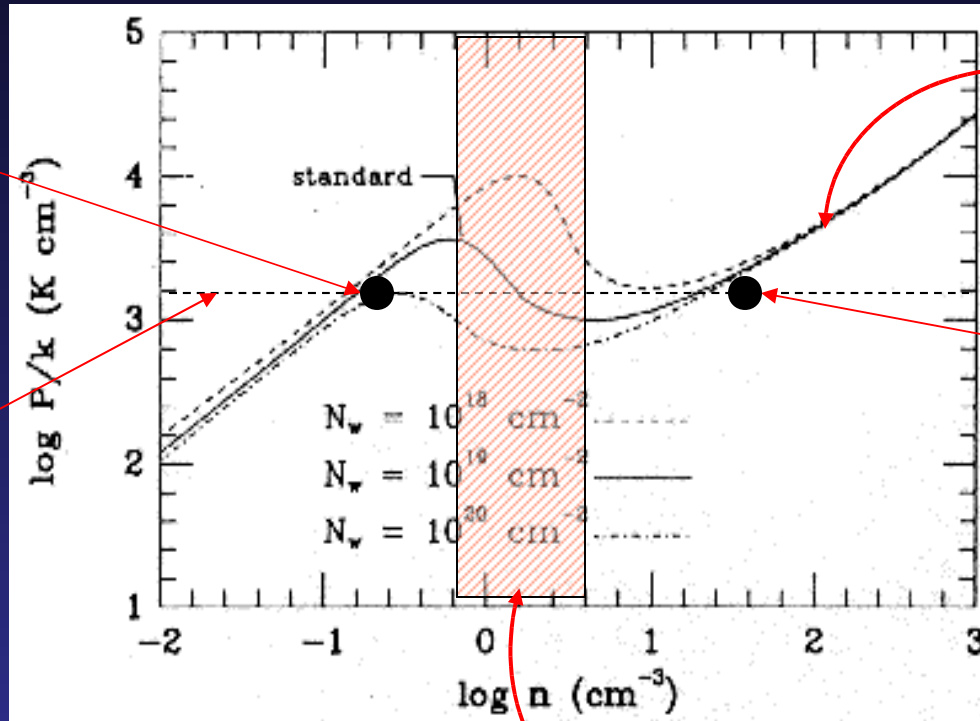
- The balance between the various heating and cooling processes affecting the ISM...



Wolfire et al. 1995

... cause its atomic component to be *thermally bistable*.

- A warm, diffuse phase (WNM, $T \sim 8000$ K, $n \sim 0.4$ cm⁻³) can be in a *stable* pressure equilibrium with a cold, dense (CNM, $T \sim 80$ K, $n \sim 40$ cm⁻³) phase (Field et al 1969; Wolfire et al 1995, 2003).



P_{eq} , at which heating Γ equals cooling $n\Lambda$.

CNM (stable)

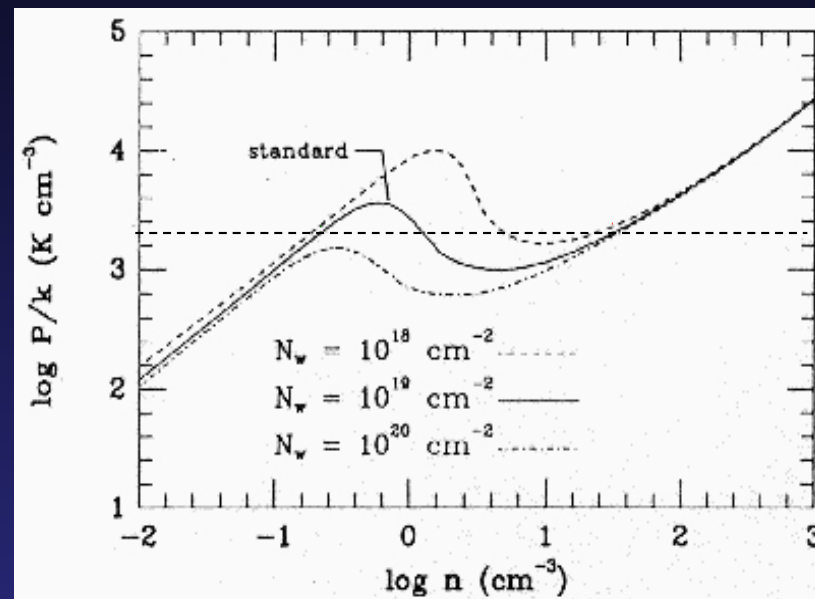
Wolfire et al. 1995

WNM (stable)

Mean ISM thermal pressure

Thermally unstable range

- This is the famous *two-phase model* of the ISM (Field et al 1969).
- The presence of turbulence and magnetic fields complicates the problem.
 - Transonic compressions in the linearly stable WNM can nonlinearly trigger a transition to the CNM... (Hennebelle & Pérault 1999).



- ... and, aided by gravity, an overshoot to molecular cloud conditions (Vázquez-Semadeni et al 2007; Heitsch & Hartmann 2008).
- This constitutes a fundamental process for *molecular cloud formation* out of the WNM.

Edge-on view of a
molecular cloud
formation
simulation
using GADGET.

Start: colliding
streams of WNM.

End: turbulent,
colliding dense
cloud.



(Vázquez-Semadeni et
al. 2007, ApJ 657, 870)

II. BASIC PHYSICAL PROCESSES (cont'd)

3. Compressions and the mass-to-flux ratio in ideal MHD.

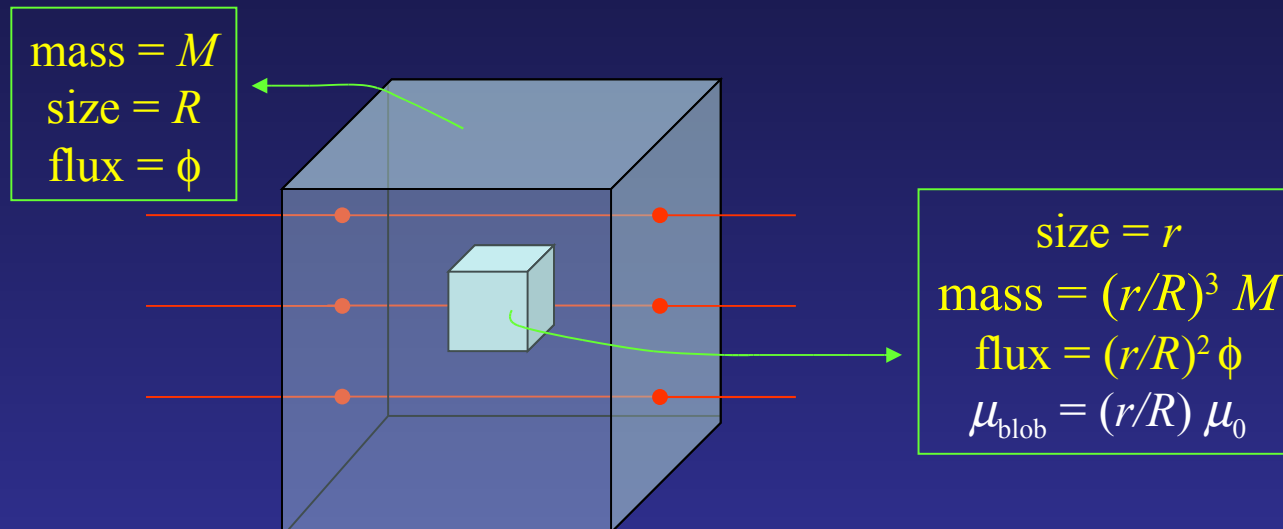
3.1. Under **ideal** MHD conditions, and for a **fixed cloud mass**, the mass-to-flux ratio μ of a cloud's fragment of size r is expected to range within:

$$\mu_0 \frac{r}{R} \leq \mu \leq \mu_0$$

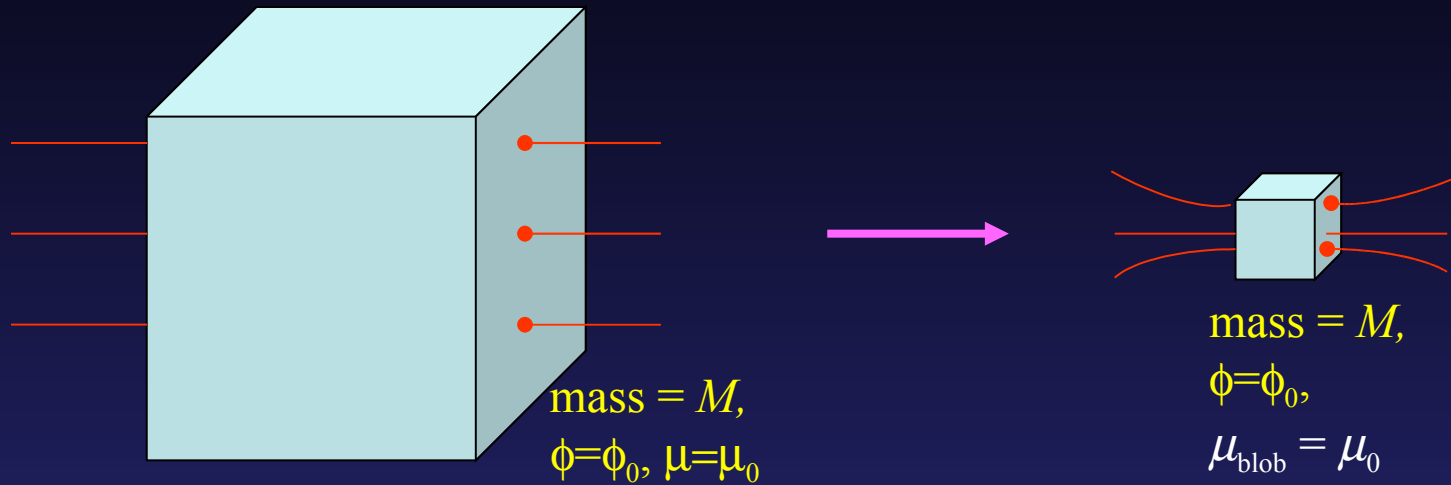
where R and μ_0 are the size and mass-to-flux ratio of the parent cloud (Vázquez-Semadeni et al. 2005, ApJ 618, 344).

Consider two limiting cases under ideal MHD:

a) A subregion of a cloud with the same density and field strength.

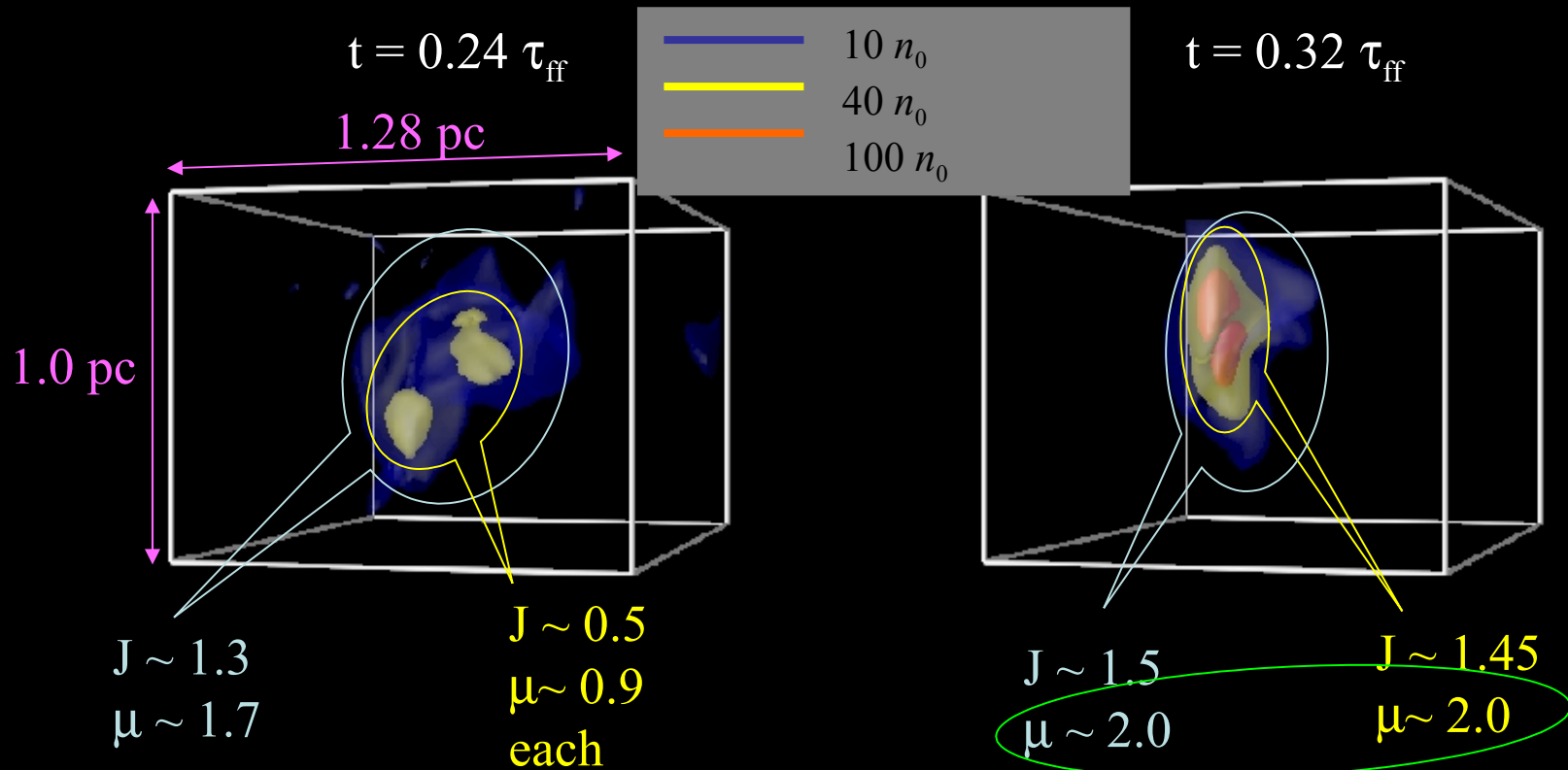


b) A full compression of the region into a smaller volume:



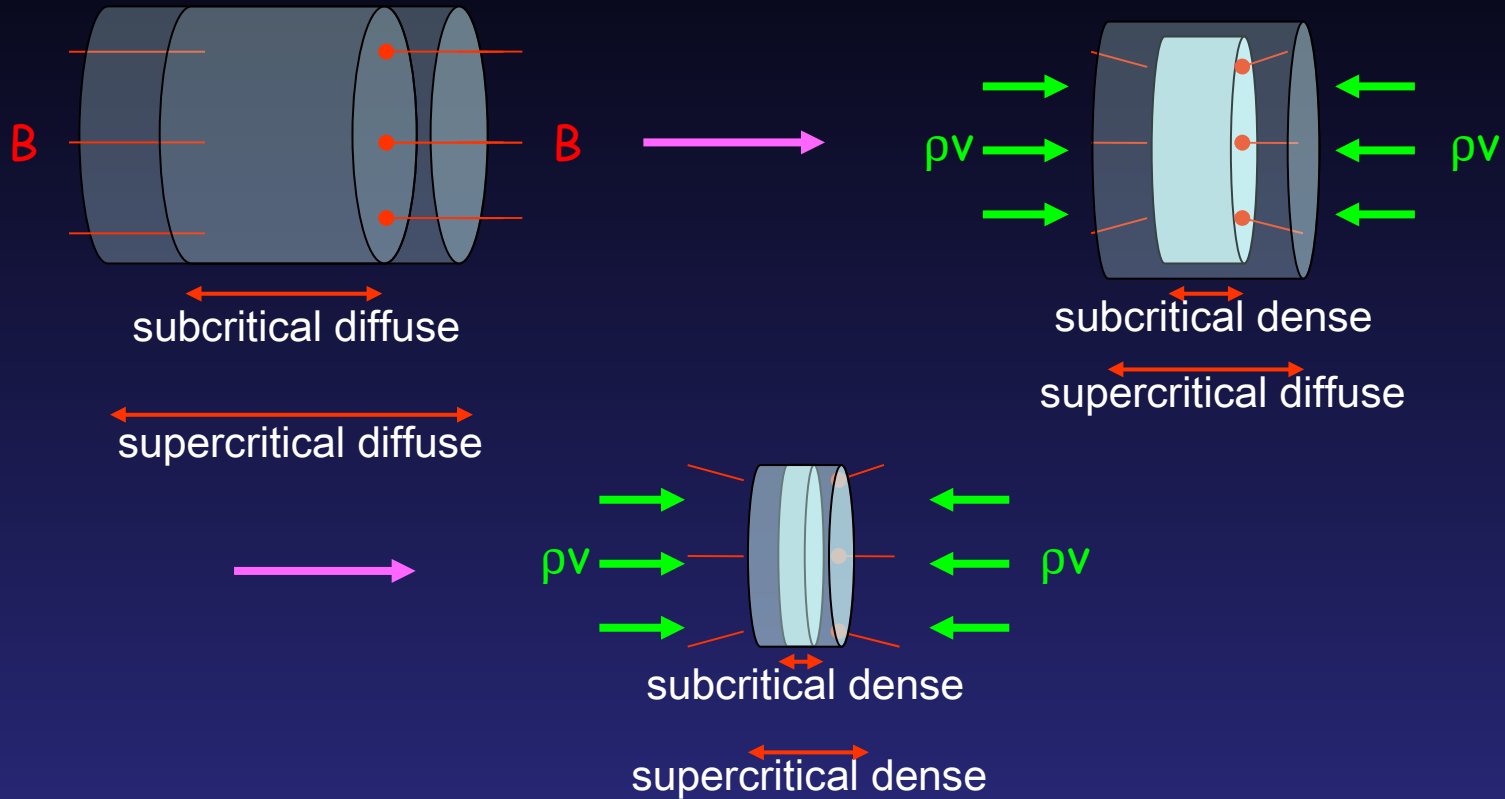
Thus, under ideal MHD conditions, the mass-to flux ratio of a fragment of a cloud must be smaller or equal than that of the whole cloud (recently observed by Crutcher et al. 2009).

Clumps in a subregion of an ideal-MHD simulation of a 4-pc box with global mass-to-flux ratio $\mu=2.8$ by Vázquez-Semadeni et al. 2005, ApJ, 618, 344 (see also Luttmila et al. 2009).



Numerical dissipation has started to act, increasing μ in the densest regions.

3.2. If a cloud (i.e., a dense region) is formed by a compression with a component along the field lines, the cloud's observed mass and mass-to-flux ratio *increase together* (Mestel 1985; Hennebelle & Pérault 2000; Hartmann et al. 2001; see also Shu et al. 2007).



Assumption: the background medium extends out to a sufficiently long distances to be supercritical.

Example: for $B=3 \mu\text{G}$ and $n=1 \text{ cm}^{-3}$, a length $L > 230 \text{ pc}$ is supercritical. 13

4. Combining compressions, MHD and thermodynamics:

- **Magnetic criticality condition** (Nakano & Nakamura 1978):

$$GN^2 = \frac{B^2}{4\pi^2} \quad \Rightarrow \quad N_{\text{crit}} \approx 1.5 \times 10^{21} \left[\frac{B}{5 \mu\text{G}} \right] \text{cm}^{-2}$$

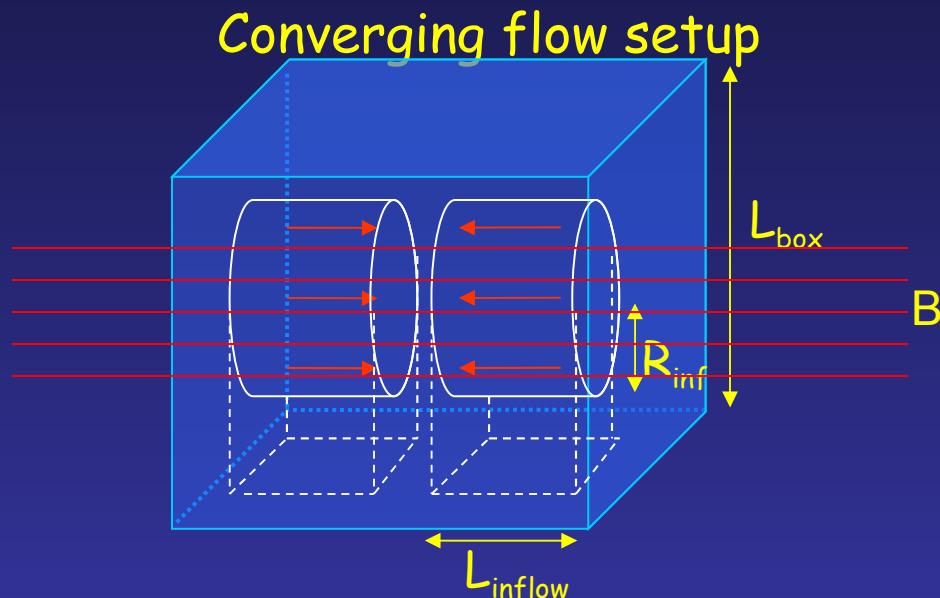
- This is **very similar** to the column density threshold for transition from atomic to molecular gas, $N \sim 10^{21} \text{ cm}^{-2} \sim 8 M_{\text{sun}} \text{ pc}^{-2}$ (Franco & Cox 1986; van Dishoek & Black 1988; van Dishoek & Blake 1998; Hartmann et al. 2001; Bergin et al. 2004; Blitz 2007).
- When taking into account the magnetic criticality *of the dense gas only*, expect the clouds to be:
 - **subcritical while they are atomic** (consistent with observations of atomic gas, e.g., Heiles & Troland 2005)
 - **supercritical when they become molecular** (not inconsistent with observations of molecular gas; Bourke et al. 2001; Crutcher, Heiles & Troland 2003).
- A consequence of mass accretion and a phase transition from WNM to CNM and H₂, not AD.

III. STATISTICS OF P_{th} AND P_{mag} IN ISM SIMULATIONS

- See Adriana Gazol's poster (# 20, JD15).

IV. MAGNETIC MOLECULAR CLOUD FORMATION

- Numerical simulations of molecular cloud formation with magnetic fields, self-gravity and sink particles (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS; VS, Banerjee, Hennebelle & Klessen 2009, in prep.).
 - Use FLASH code (AMR, MHD, self-gravity, sink particles, AD by Duffin & Pudritz 2008).
 - 11 refinement levels.
 - Same initial conditions as non-magnetic simulations with GADGET.
 - Low-amplitude initial fluctuations → allow global cloud collapse.
 - Add uniform field in the x-direction.
 - Optionally add fluctuating field.



$$\begin{aligned}L_{\text{box}} &= 256 \text{ pc} \\L_{\text{inflow}} &= 112 \text{ pc} \\ \Delta x_{\text{min}} &= 0.03 \text{ pc} \\ M_{\text{s,inf}} &= 1.2\end{aligned}$$

See also Inoue & Inutsuka (2008) for configuration with B perpendicular to compression.

- Cloud evolution and SFE (VS, Banerjee, Hennebelle & Klessen, in prep.).

Supercritical box ($B=3 \mu\text{G}$, $\mu = 1.1$), no AD



Supercritical box ($B=3 \mu\text{G}$, $\mu = 1.1$), with AD



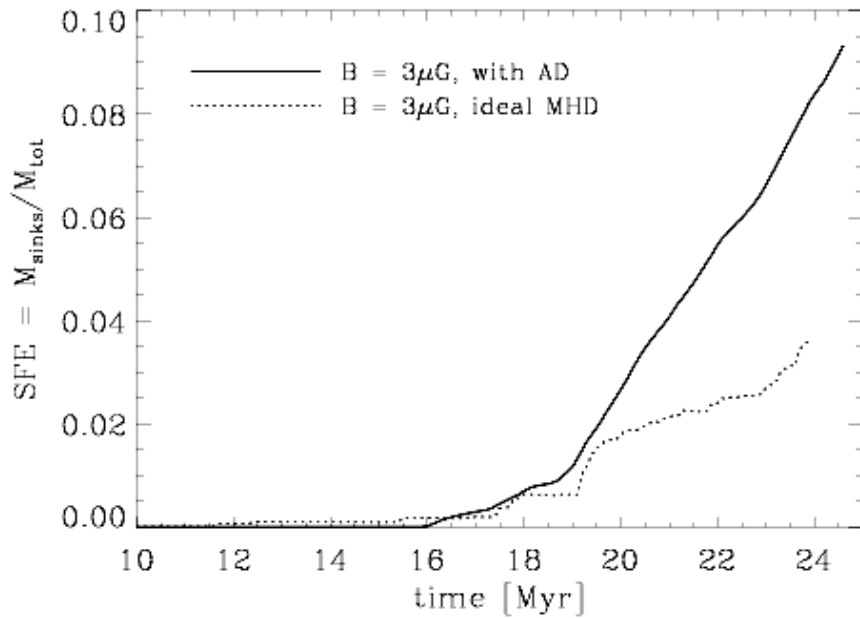
Subcritical box ($B=4 \mu\text{G}$, $\mu = 0.83$), no AD

Subcritical box ($B=4 \mu\text{G}$, $\mu = 0.83$), with AD

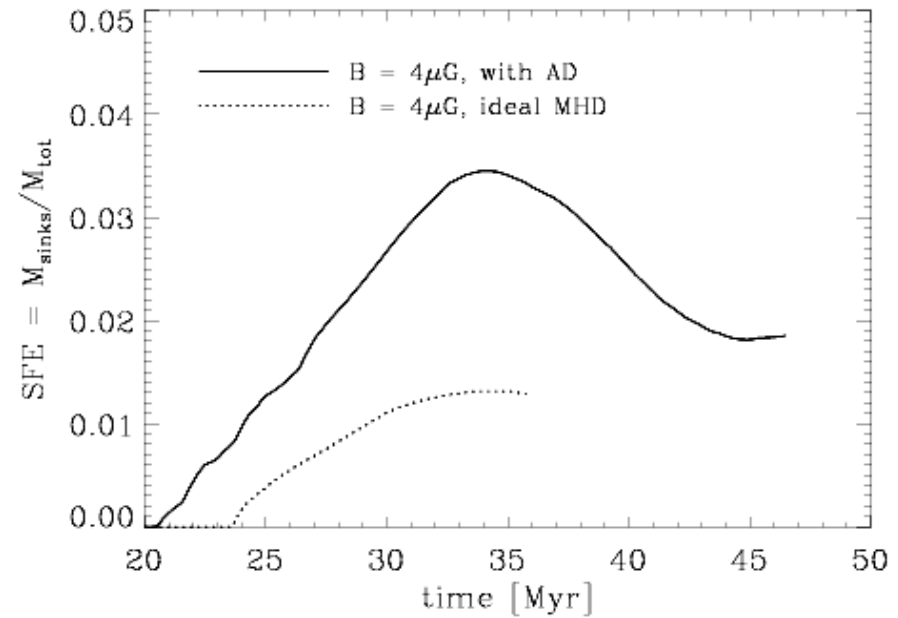


Note: “Star” formation in the non-AD case is due to numerical diffusion.

Supercritical box ($B=3 \mu\text{G}$, $\mu = 1.1$) runs



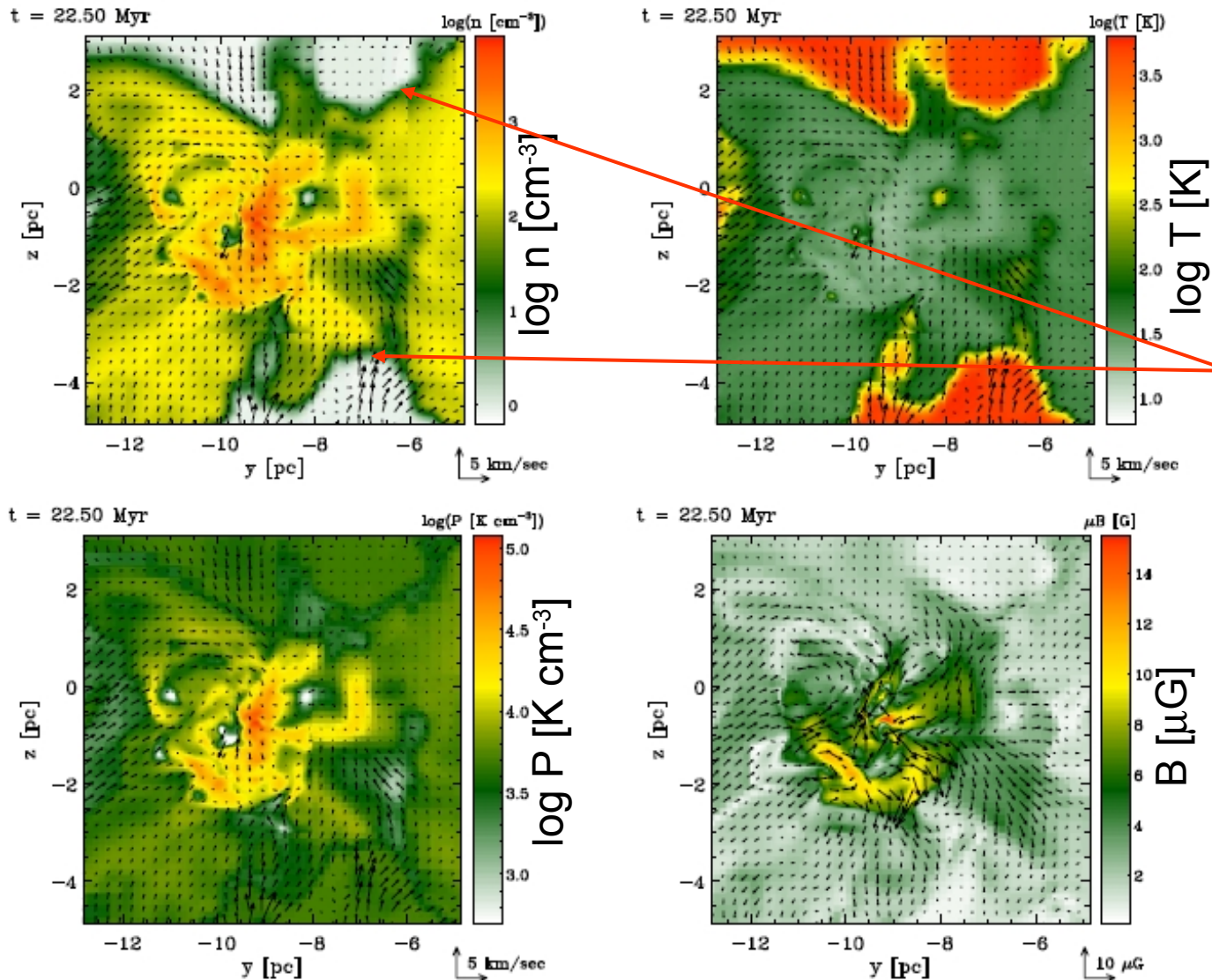
Subcritical box ($B=4 \mu\text{G}$, $\mu = 0.83$) runs



“Star” formation shuts off after ~ 15 Myr in both subcritical runs (cloud rebounds).

Note that
$$\text{SFE} = \frac{M_*}{M_{\text{dense}} + M_*}$$
, so the SFE **can** decrease with time.

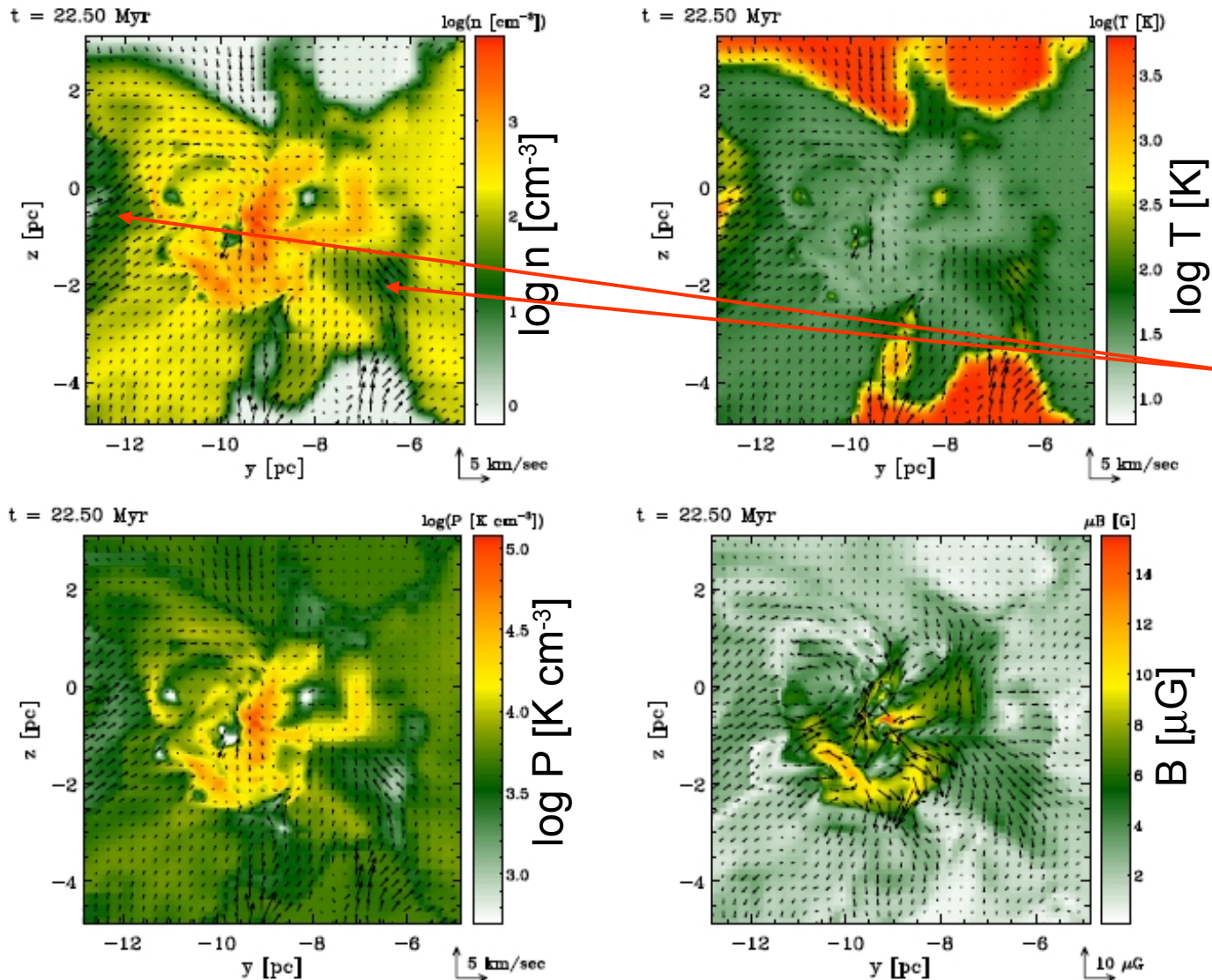
- Dense clump structure (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS, in press).
 - In a $B_0 = 1 \mu\text{G}$ supercritical simulation, with no AD:



Cuts through densest point in clump.

Sharp boundaries between WNM and CNM...

- Dense clump structure (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS, in press).
 - In a $B_0 = 1 \mu\text{G}$ supercritical simulation, with no AD:

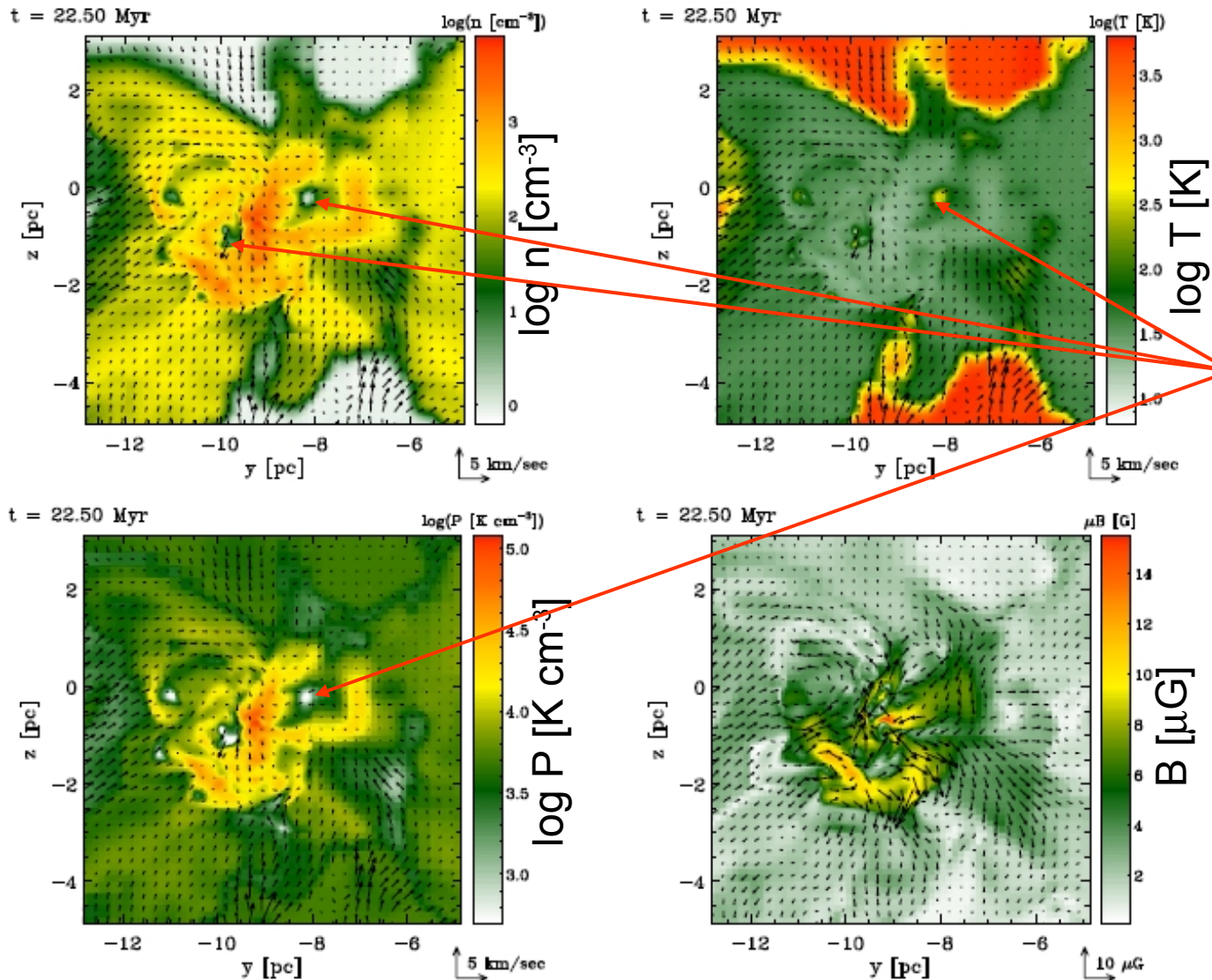


Cuts through densest point in clump.

... but also there are intermediate-n, T unstable regions.

More abundant towards periphery of cloud.

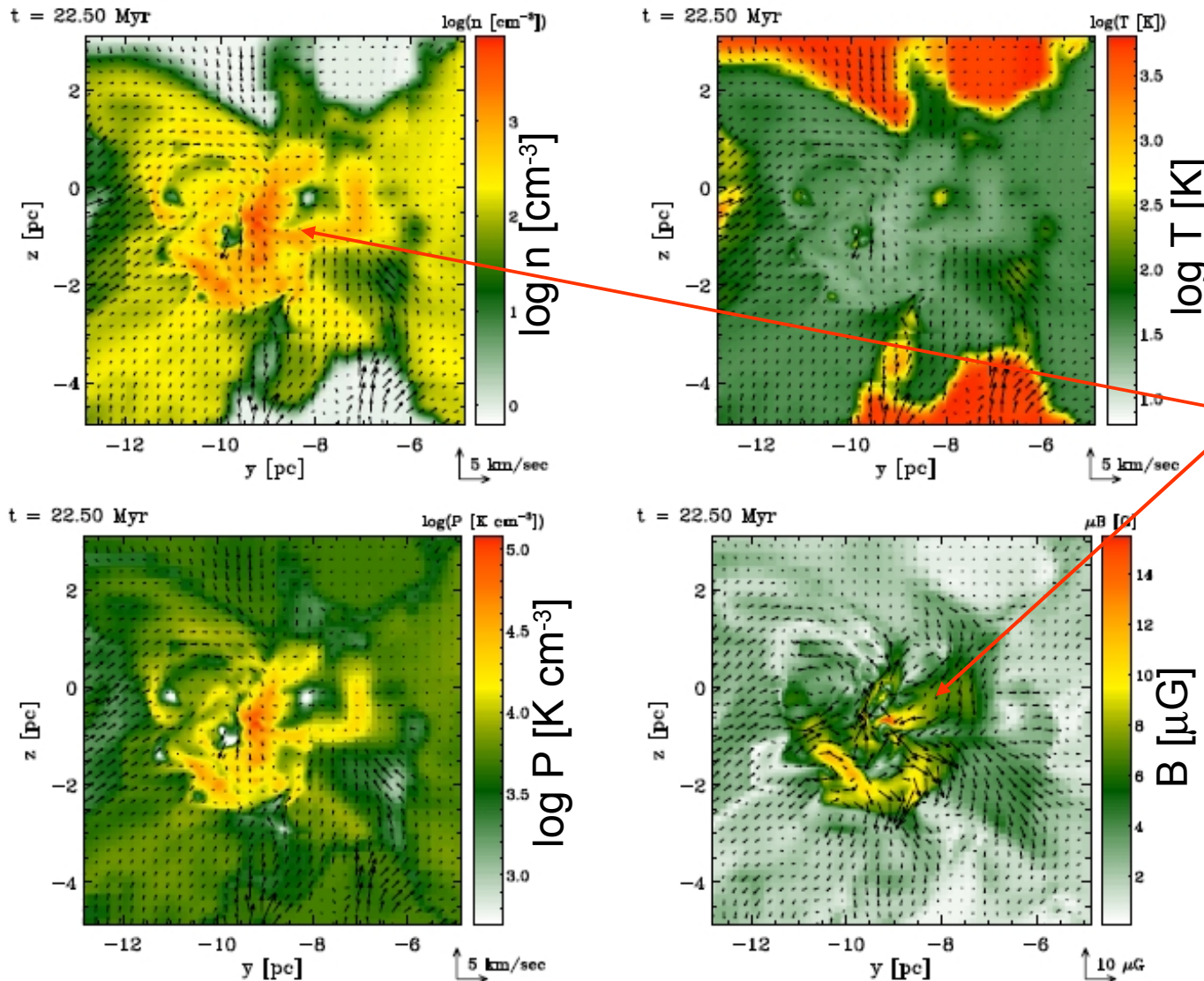
- Dense clump structure (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS, in press).
 - In a $B_0 = 1 \mu\text{G}$ supercritical simulation, with no AD:



Cuts through densest point in clump.

There exist warm, low-pressure, diffuse “holes” in the dense gas.

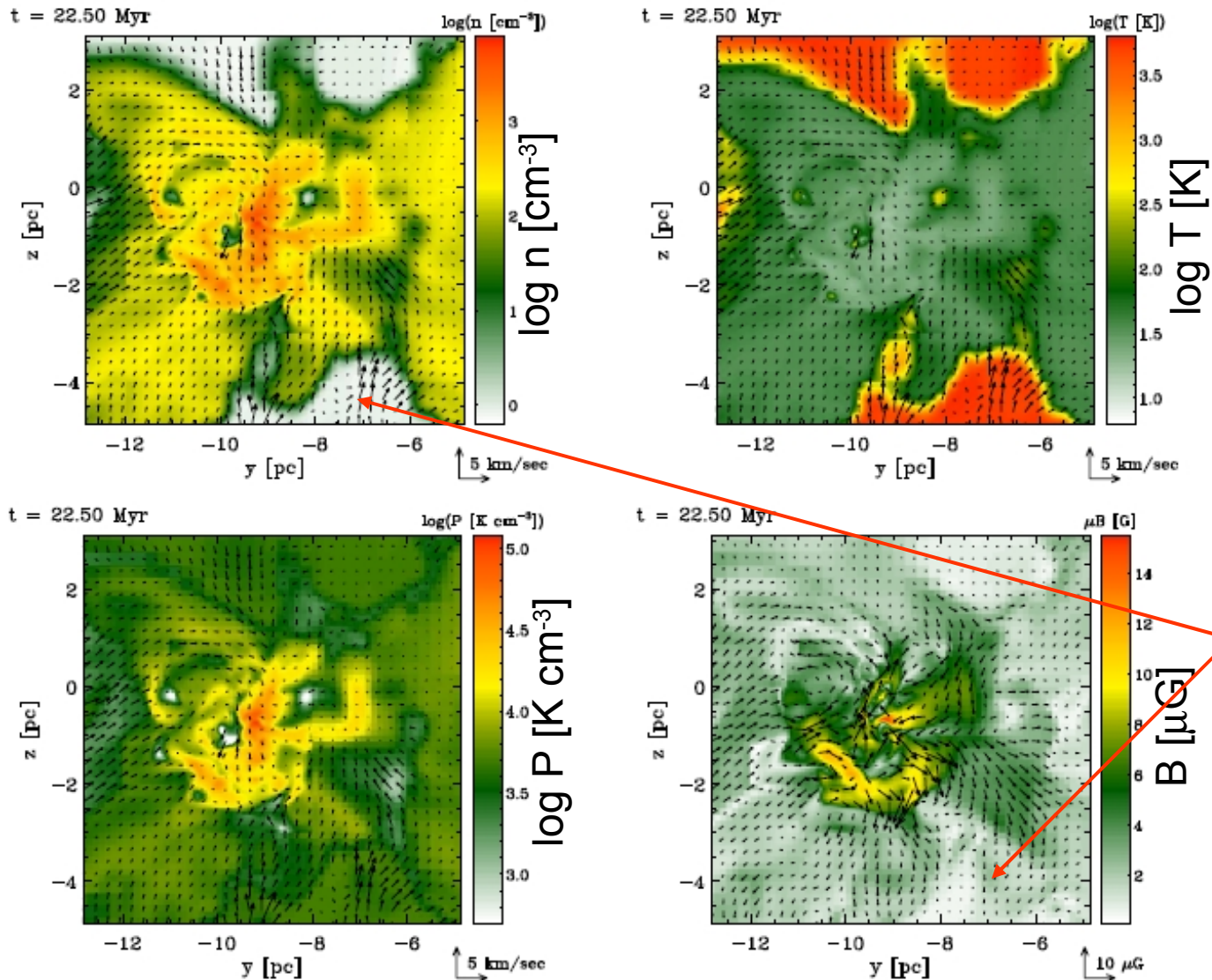
- Dense clump structure (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS, in press).
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Cuts through densest point in clump.

Magnetic field strength exhibits correlation with high-density gas...

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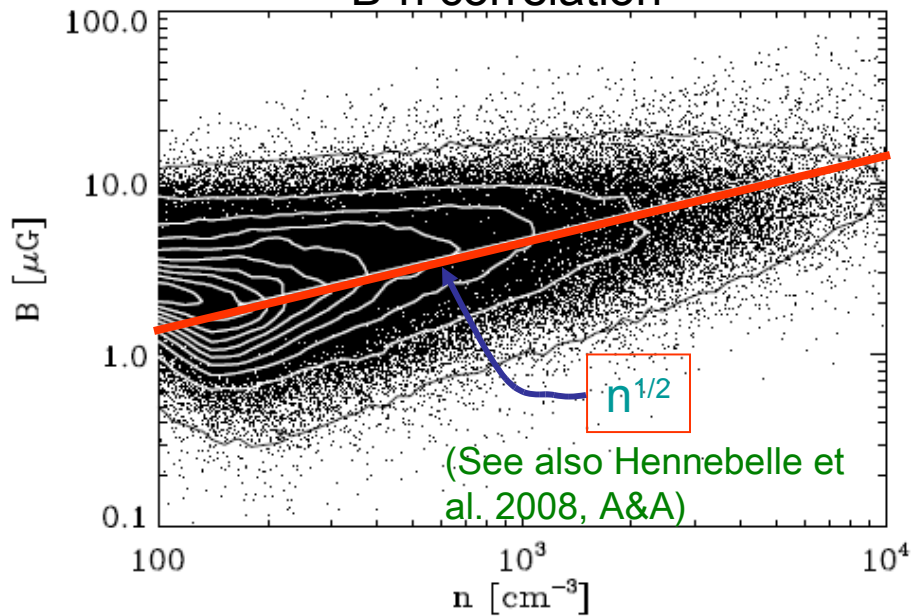


Cuts through densest point in clump.

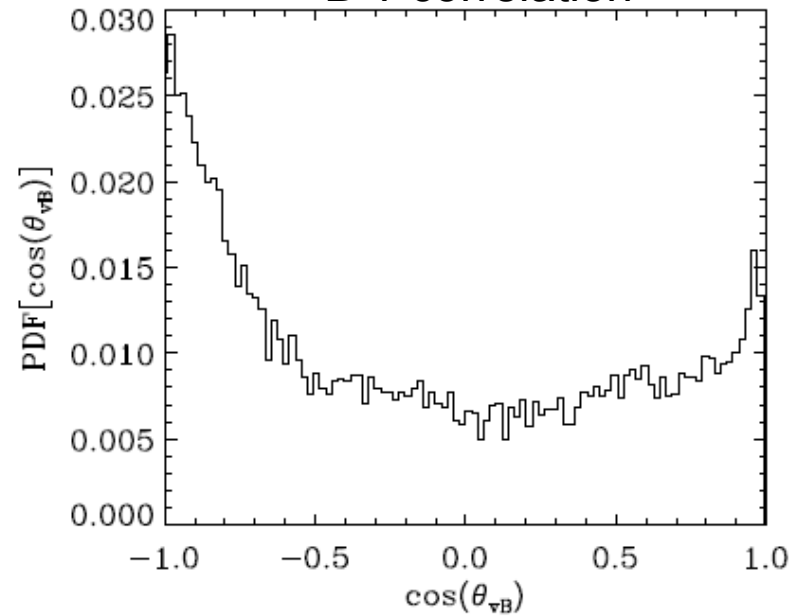
Magnetic field strength exhibits correlation with high-density gas...

... but almost none with low-density gas.

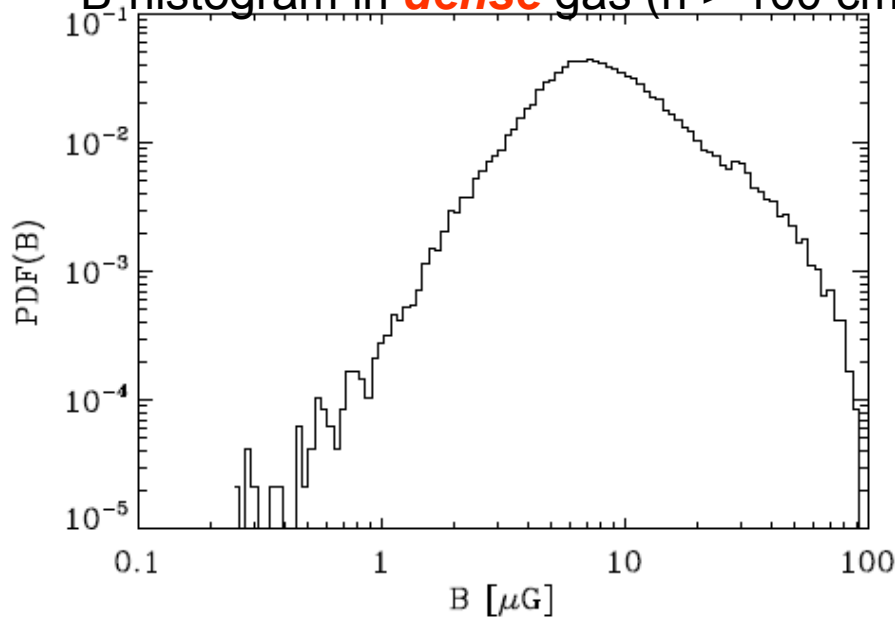
B-n correlation



B-v correlation



B-histogram in *dense* gas ($n > 100 \text{ cm}^{-3}$)



→ Large B scatter in dense clumps.

(Banerjee et al. 2009, MNRAS, in press)

V. CONCLUSIONS

- Forming clouds and cores involves moving material from surroundings into a small region

$$\frac{d\rho}{dt} = -\rho \nabla \cdot u$$

Implies:

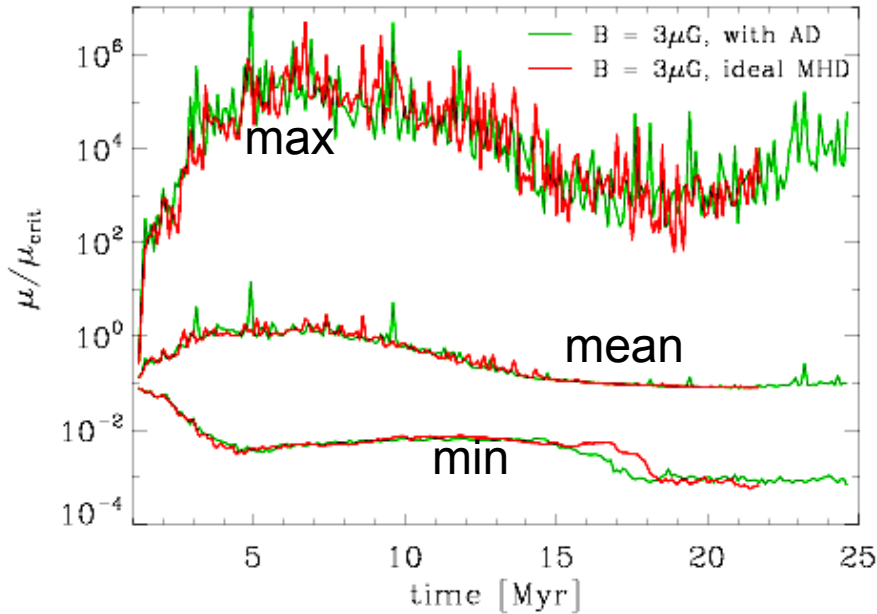
- Significant component of inward motions in clouds and cores.
 - Masses of clouds and cores evolve (generally increasing) with time.
- Under ideal MHD, core formation by compression within a larger cloud, implies

$$\mu_{\text{core}} \leq \mu_{\text{cloud}}$$

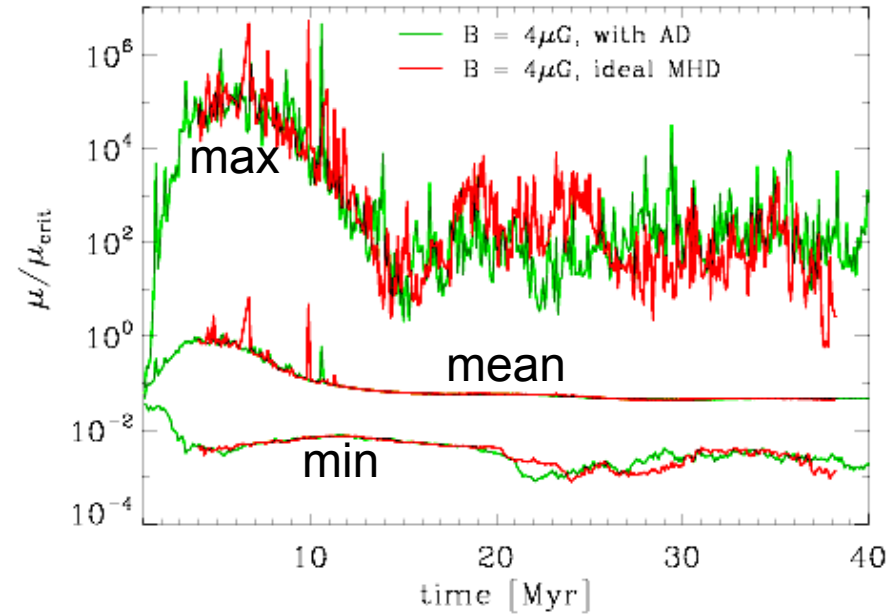
- Cold cloud assembly by WNM compression with a component along the magnetic field lines implies that
*the **observed** mass-to-flux ratio of the **cold** gas increases steadily*

- Thus, the mass, mass-to-flux ratio, and SFE of a cloud are *time-dependent quantities*.
- Numerical simulations of molecular cloud formation with AMR, MHD and AD show that:
 - Moderately supercritical simulations of global cloud collapse with AD produce
 - SFEs slightly larger than canonical observed value for average clouds,
 - but consistent with SFE of massive-SF regions.
 - Moderately subcritical simulations
 - Produce initially realistic SFEs for average clouds, but
 - SF shuts off after ~ 15 Myr, even with AD, due to cloud rebound.
 - AD is at the level of numerical diffusion.
 - Strongly supercritical simulations show
 - $B \sim n^{1/2}$ in dense gas, but with 2 dex scatter.
 - B and v tend to be aligned with each other anyway.

Supercritical box ($B=3 \mu\text{G}$, $\mu = 1.1$) runs



Subcritical box ($B=4 \mu\text{G}$, $\mu = 0.83$) runs



Mass-to-flux ratio calculated integrating the

“Star” formation shuts off after ~ 15 Myr in both runs (cloud rebounds).