Molecular Cloud Evolution IV: Magnetic Fields and Ambipolar Diffusion

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I. INTRODUCTION

- The interstellar medium (ISM) is turbulent, magnetized (e.g., Heiles & Troland 2003, 2005), and self-gravitating.

- Turbulence and gravity in the ISM lead to the formation of density enhancements that constitute clouds, and clumps and cores within them (Sasao 1973; Elmegreen 1993; Ballesteros-Paredes et al. 1999).

- This talk (Vázquez-Semadeni et al. 2011, MNRAS):
  - Outline of underlying physical processes.
  - Results from cloud-formation simulations including MHD and ambipolar diffusion (AD).

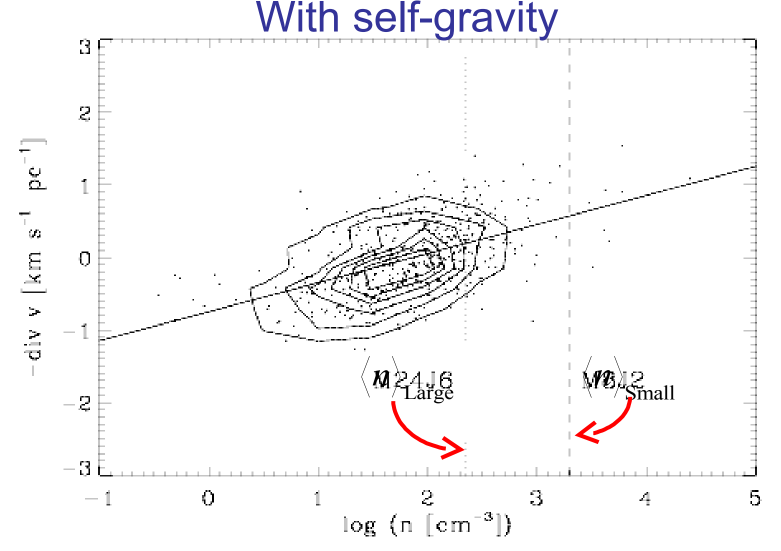
II. BASIC PHYSICAL PROCESSES

1. Fundamental fact:

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

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

i.e., need to ***move*** the material from the surroundings into the region.



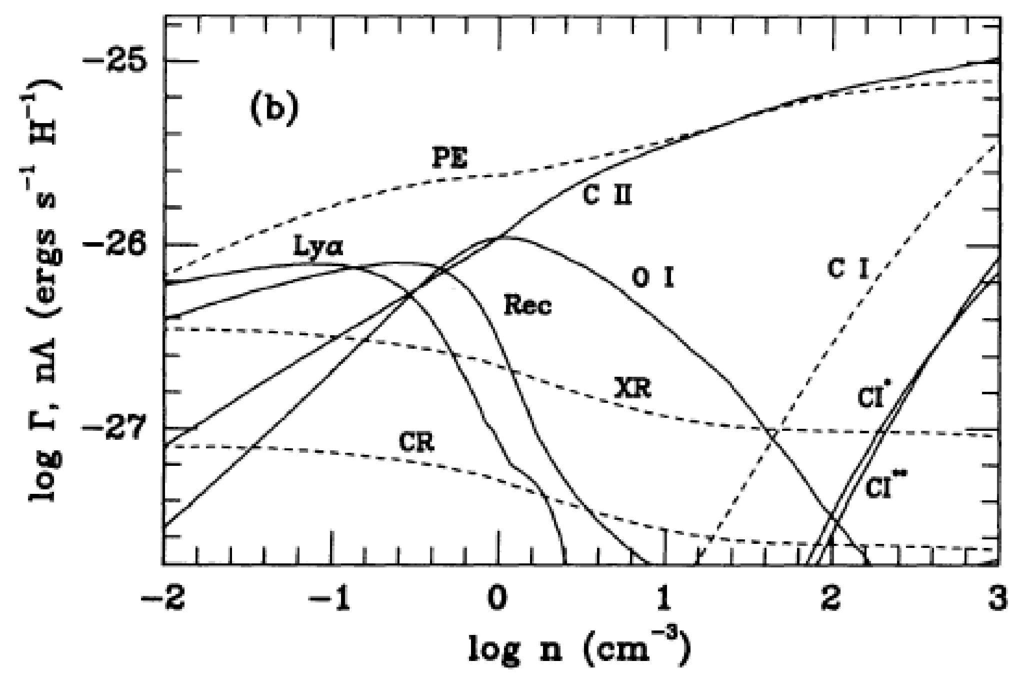
With self-gravity

Vázquez-Semadeni et al. 2008, MNRAS

2. ISM thermodynamics.

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

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

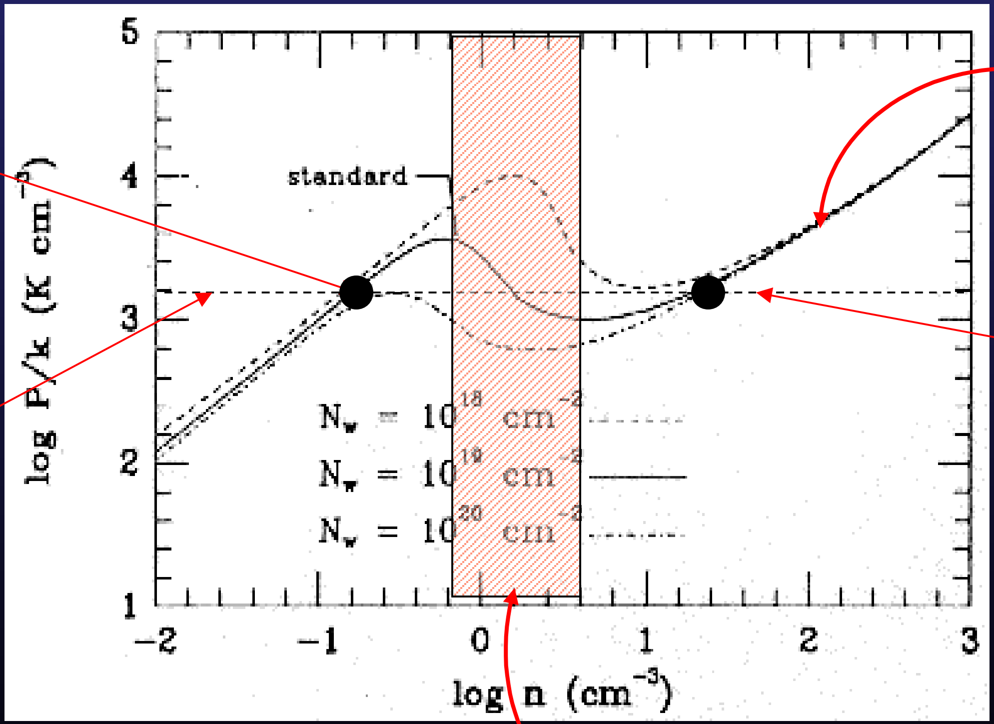


- - - - Heating
—— Cooling

Wolfire et al. 1995

… causes its atomic component to be ***thermally bistable***.

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



WNM
(stable)

Mean ISM
thermal
pressure

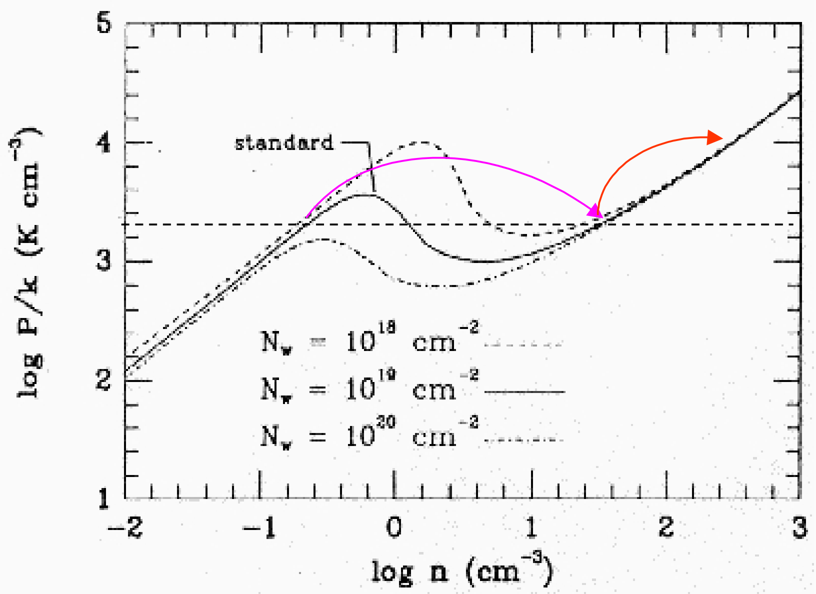
P$_{eq}$, at which
heating Γ equals
cooling nΛ.

CNM
(stable)

Wolfire et al. 1995

Thermally
unstable range

- This is the famous ***two-phase model*** of the ISM (Field et al 1969).
- The presence of turbulence and magnetic fields makes the problem more complex.
  - 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.

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

- An object can only collapse gravitationally if it is magnetically supercritical ($\mu = [M/\phi]/[M/\phi]_{\mathrm{crit}} > 1$) ***and*** Jeans unstable.

- The usual notion is that, if a (Lagrangian) object is subcritical, it can only collapse if it sheds enough magnetic flux ϕ to become supercritical.

- However, μ is actually not an absolute quantity, but rather ***depends on the boundary conditions***.

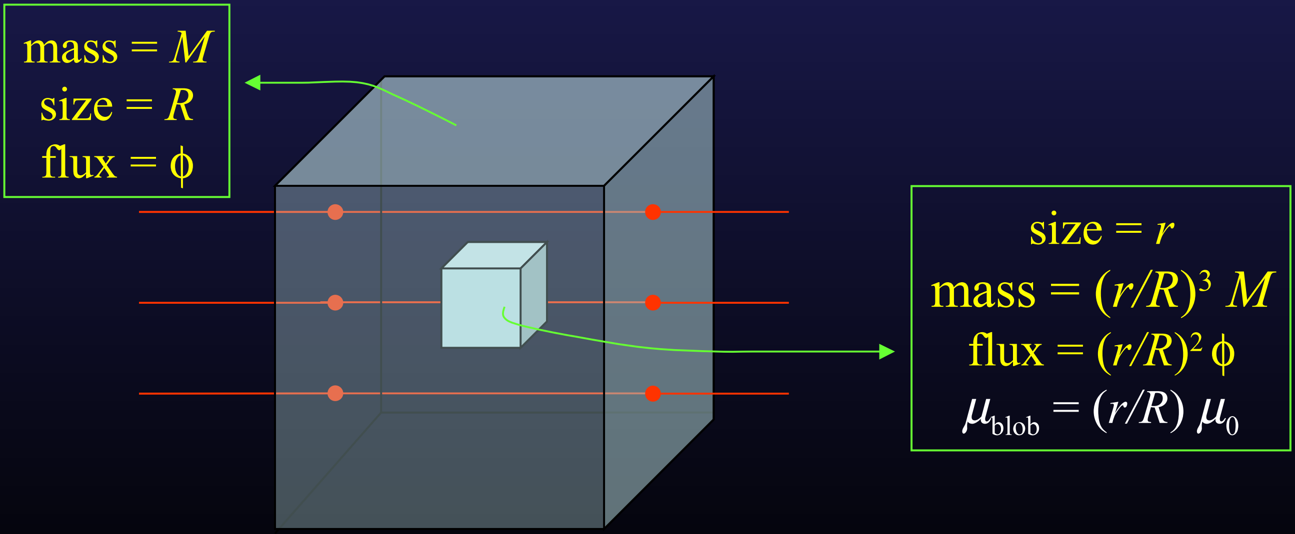
3.1. Under ***ideal*** MHD conditions, and for a ***fixed cloud mass***, the mass-to-flux ratio μ of a clump of size r within an initially uniform cloud of size R is expected to range within:

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

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

Consider two ***limiting*** cases under ideal MHD:

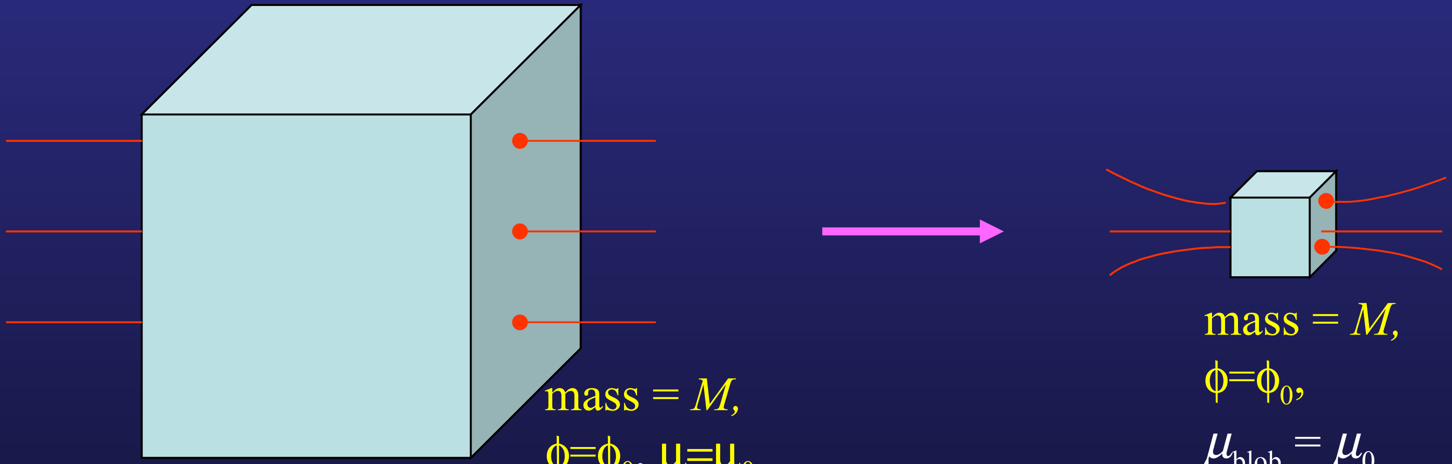
a) A subregion of a uniform cloud with a uniform field:



mass = M
size = R
flux = ϕ

size = r
mass = $(r/R)^3\ M$
flux = $(r/R)^2\ \phi$
$\mu_{\rm blob} = (r/R)\ \mu_0$

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

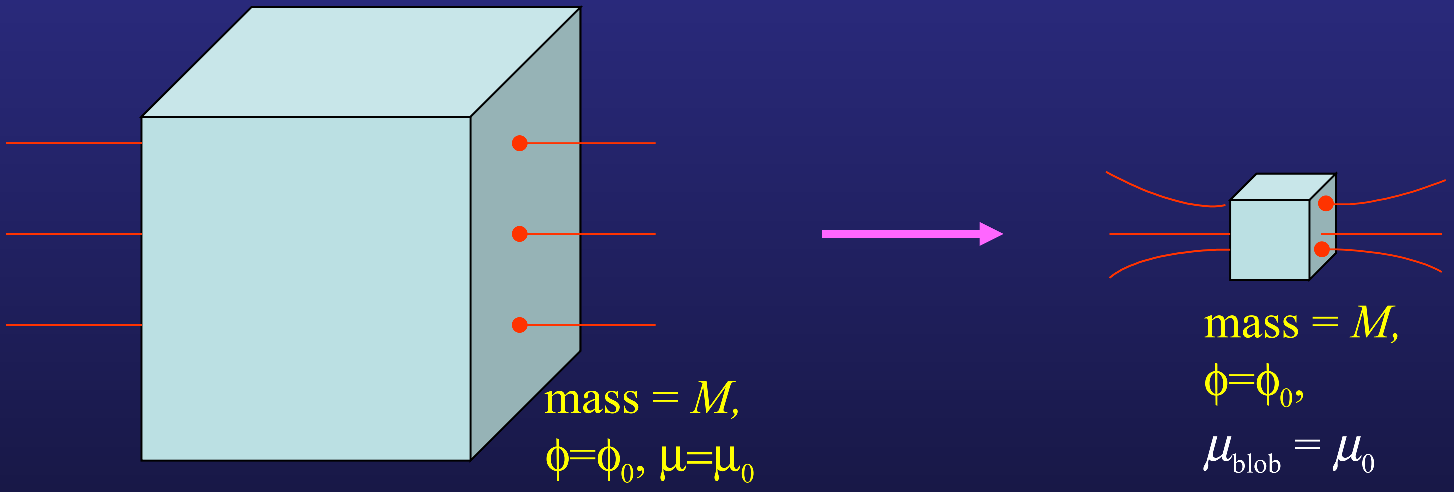


mass = M,
$\phi=\phi_0$, $\mu=\mu_0$

mass = M,
$\phi=\phi_0$,
$\mu_{\text{blob}} = \mu_0$

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.

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



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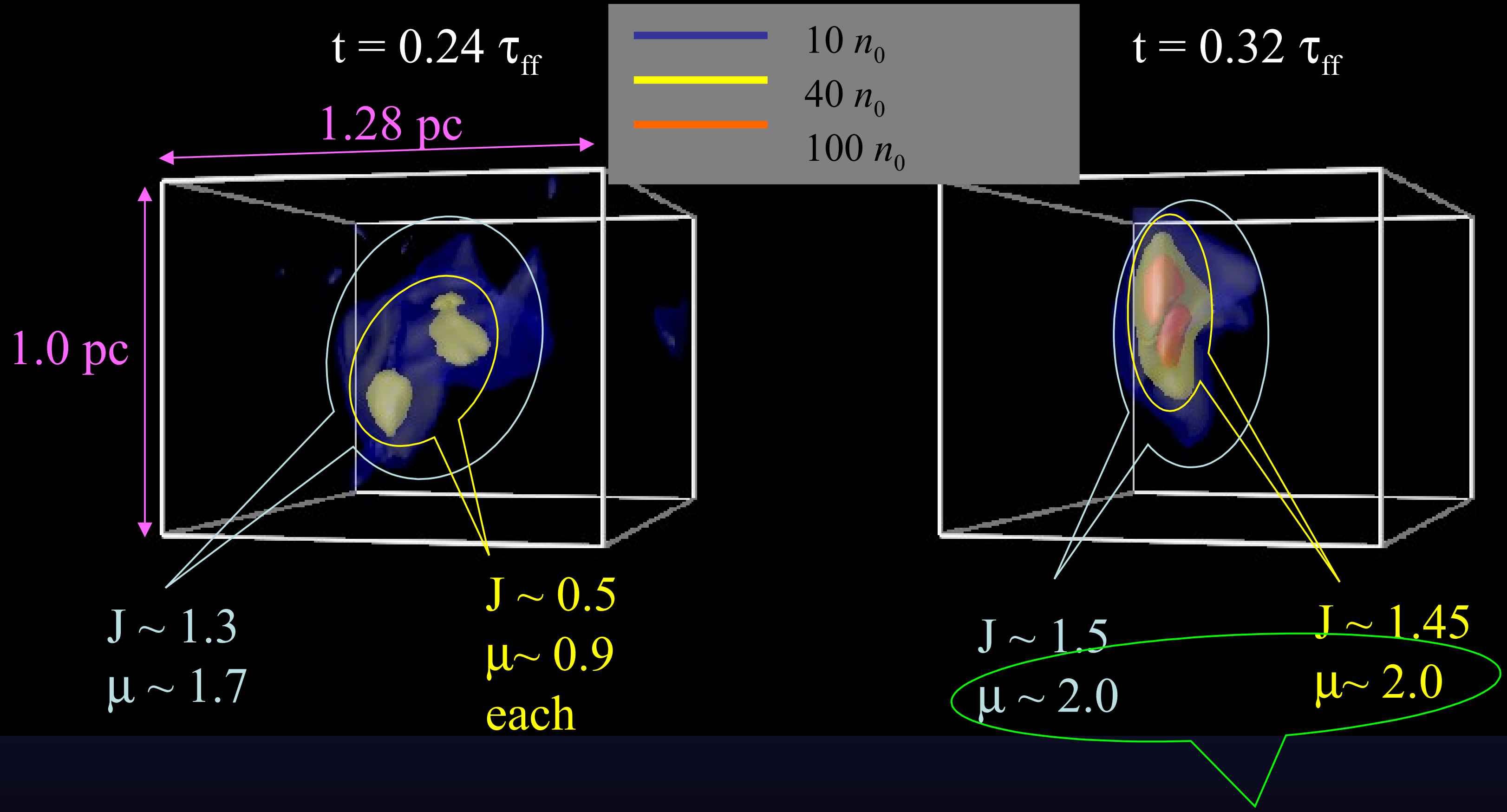
Thus, under ideal MHD conditions, the mass-to flux ratio of a ***fragment*** of a cloud must be smaller or equal than that of the whole cloud.

But note: if the magnetic field lines continue, so does the density field.

- Where is the boundary???
- ***μ is a boundary condition, not a physical property of the "cloud"!***

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

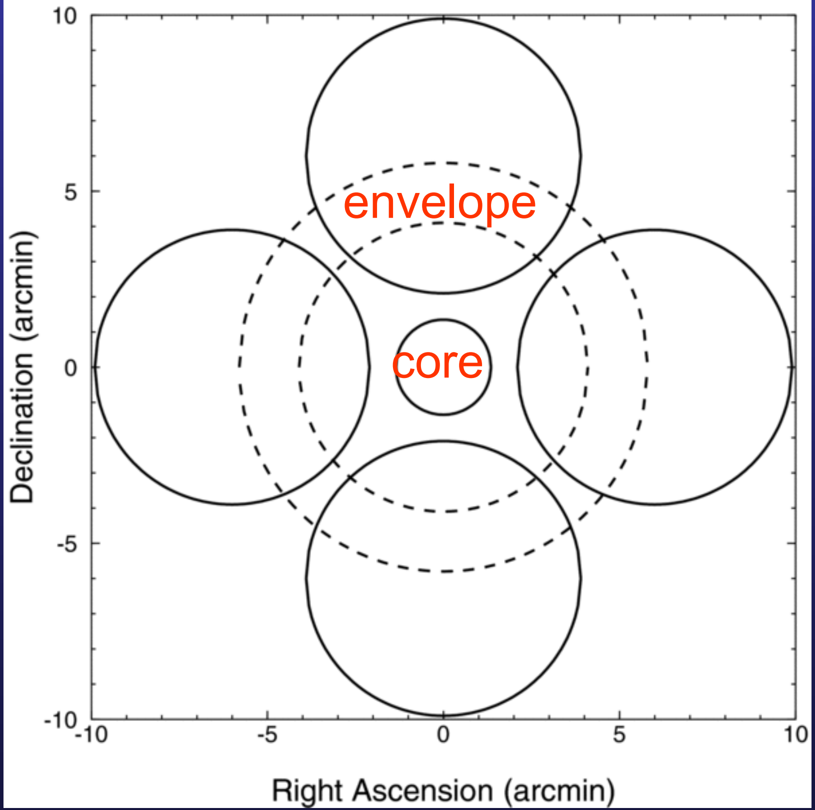


Numerical dissipation has started to act, increasing μ in the densest regions.

- Crutcher et al. 2009

$$\mathcal{R} \equiv \frac{M_{\mathrm{core}}/\Phi_{\mathrm{core}}}{M_{\mathrm{envelope}}/\Phi_{\mathrm{envelope}}}.$$

$$\mathcal{R}' \equiv \frac{M_{\mathrm{core}}/\Phi_{\mathrm{core}}}{M_{\mathrm{core+envelope}}/\Phi_{\mathrm{core+envelope}}}.$$



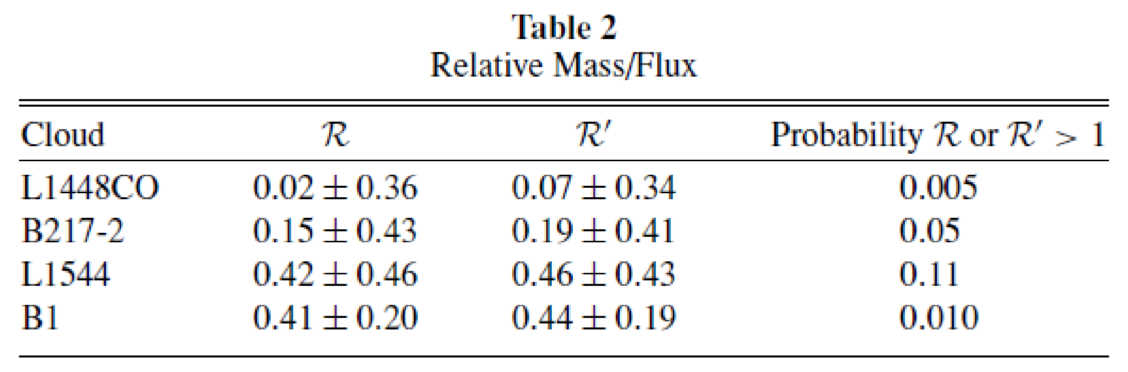


Table 2
Relative Mass/Flux

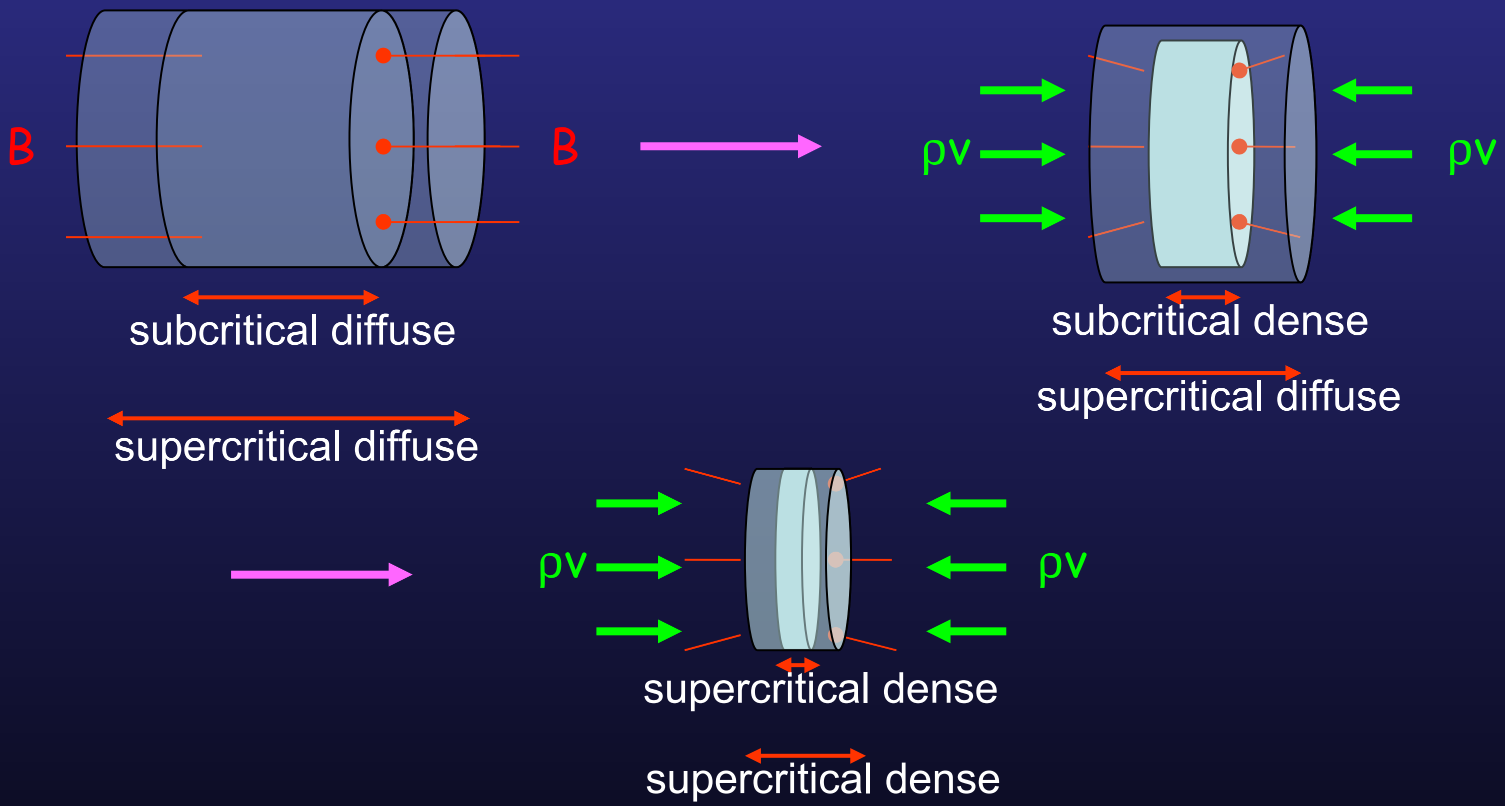
Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010

The core has lower μ than the envelope.

- Thus, for uniform ρ and B, the farther away the boundary is along the field, the larger μ is.

- The usual solution is to appeal to a warm, diffuse confining medium, but...

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; Shu et al. 2007; VS et al. 2011).



subcritical diffuse

supercritical diffuse

subcritical dense

supercritical diffuse

supercritical dense

supercritical dense

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

Example: for B=3 μG and n=1 cm^{-3}, a length L > 230 pc is supercritical.

4. Combining compressions, MHD and thermodynamics:

- Magnetic criticality condition (Nakano & Nakamura 1978):

$$GN^2 = \frac{B^2}{4\pi^2} \rightarrow \begin{cases} N_{\rm crit} \approx 1.5 \times 10^{21} \left[\frac{B}{5 \mu \rm G} \right] \rm cm^{-2} \\ L_{\rm c} \approx 470 \left(\frac{B_0}{5\ \mu \rm G} \right) \left(\frac{n}{1\ \rm cm^{-3}} \right)^{-1} \rm pc, \end{cases}$$

- This is very similar to the column density threshold for transition from atomic to molecular gas, N ~ 10^{21} cm^{-2} ~ 8 $M_{\rm sun}$ pc^{-2} (Franco & Cox 1986; van Dishoek & Black 1988; van Dishoek & Blake 1998; Hartmann et al. 2001; Bergin et al. 2004; Blitz et al. 2007).

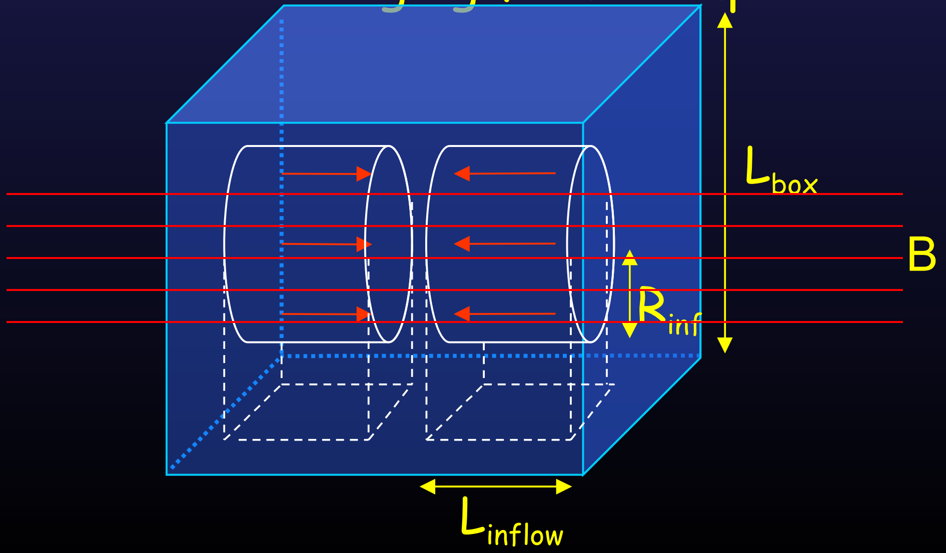
- When taking into account the magnetic criticality *of the dense gas only* (the one that produces the weight), expect the clouds to be:
  - subcritical while they are atomic (consistent with observations of atomic gas, e.g., Heiles & Troland 2005)
  - supercritical when they become molecular (consistent 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 (Vázquez-Semadeni et al. 2011).

III. MAGNETIC MOLECULAR CLOUD FORMATION

- Numerical simulations of molecular cloud formation with magnetic fields, self-gravity and sink particles (Banerjee et al. 2009, MNRAS, 398, 1082; Vázquez-Semadeni et al. 2011, MNRAS, in press).
  - Use FLASH code (AMR, MHD, self-gravity, sink particles, AD by Duffin & Pudritz 2008).
    - 11 refinement levels.
  - Similar initial conditions as non-magnetic simulations with GADGET.
    - Low-amplitude initial fluctuations ➔ allow global cloud collapse.
  - Add uniform field in the x-direction.

Converging flow setup

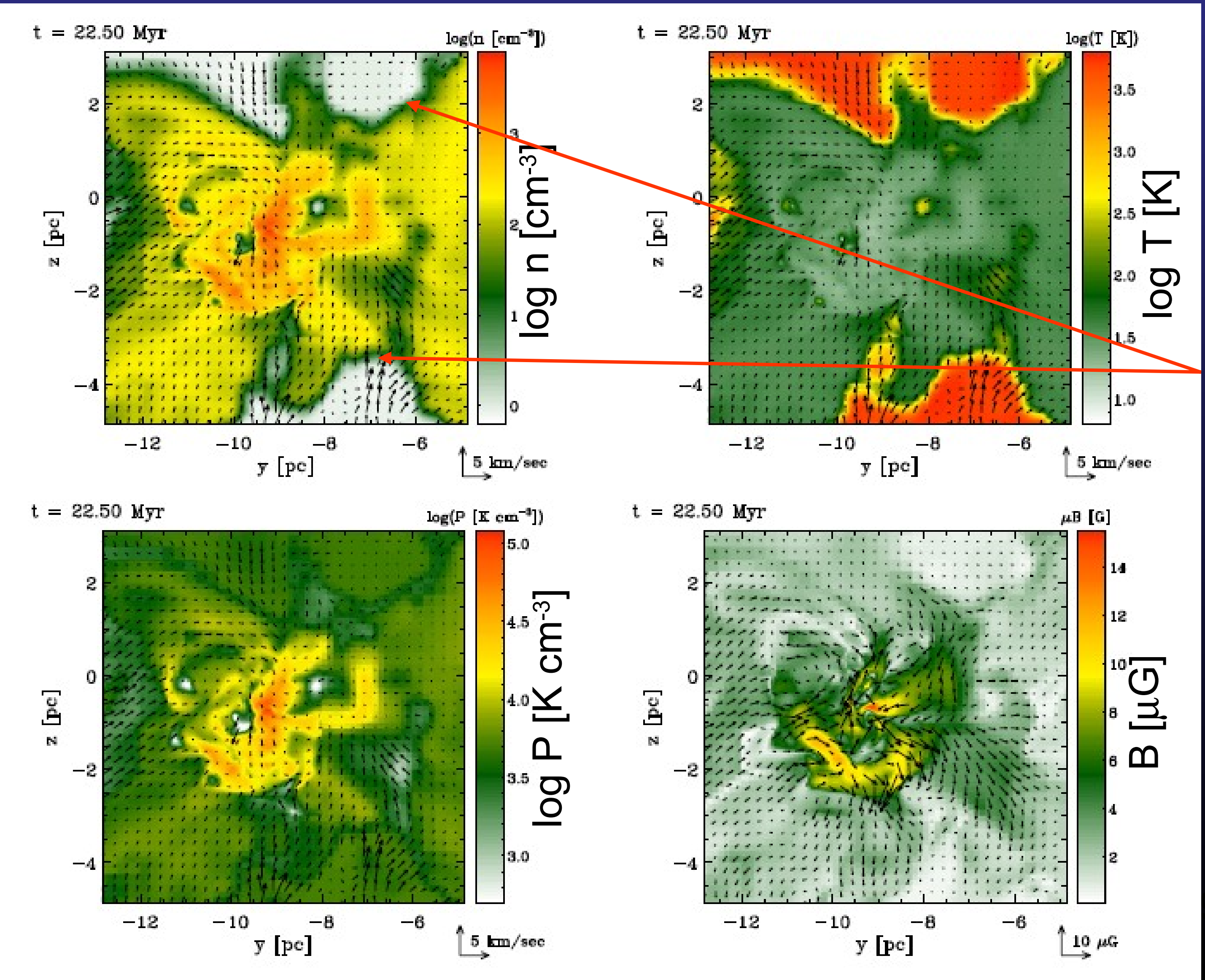


L_{box} = 256 pc
L_{inflow} = 112 pc
Δx_{min} = 0.03 pc
max res = 8192^3
$M_{s,inf}$ = 1.2, 2.4

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

Structure

- Dense clump structure (Banerjee, VS, Hennebelle & Klessen, 2009, MNRAS, 398, 1082).
  - In a B_0 = 1 μG supercritical simulation, with no AD:



Cuts through densest point in clump.

Sharp boundaries between WNM and CNM…

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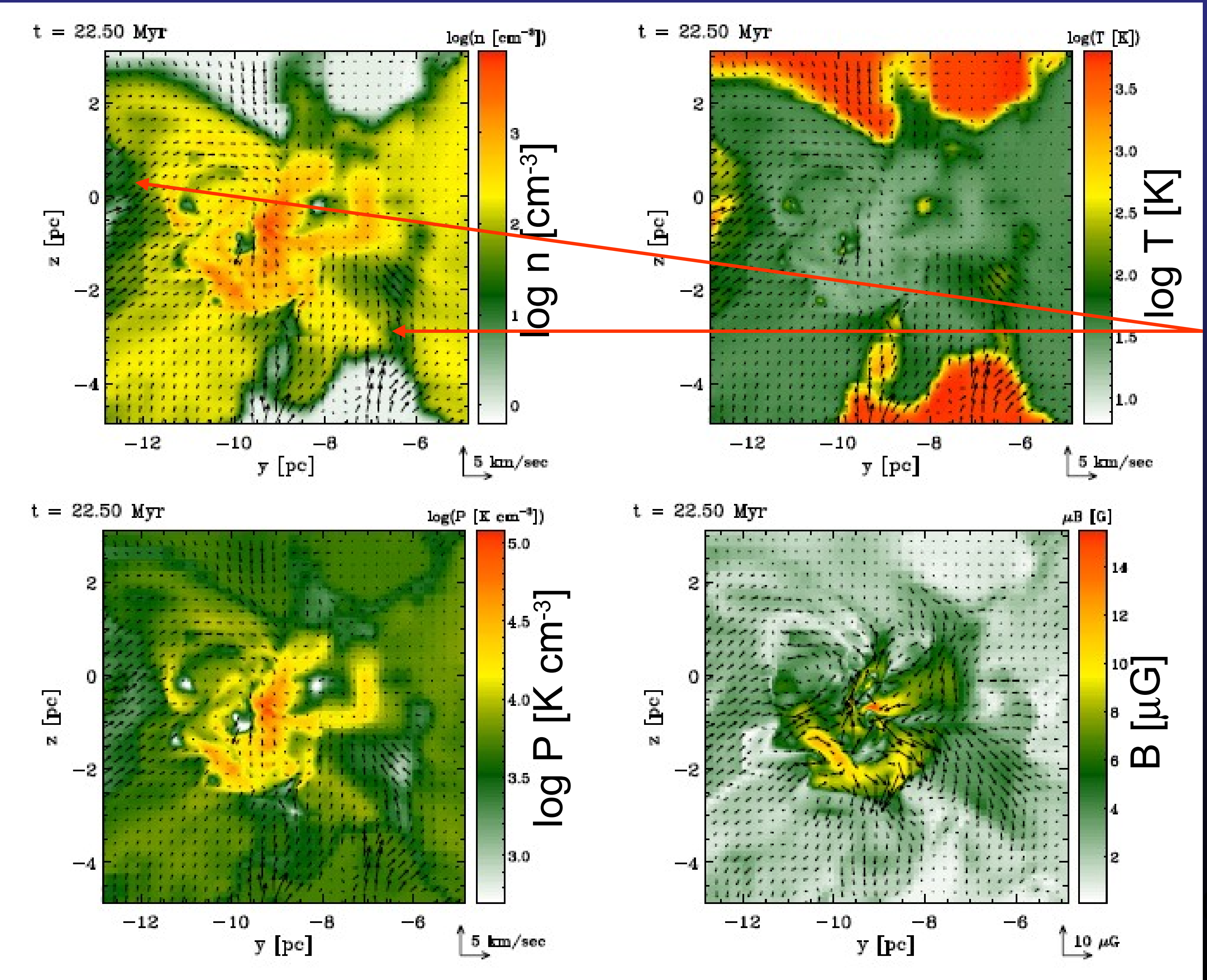


Cuts through densest point in clump.

But... gas flows from diffuse medium into dense clumps.

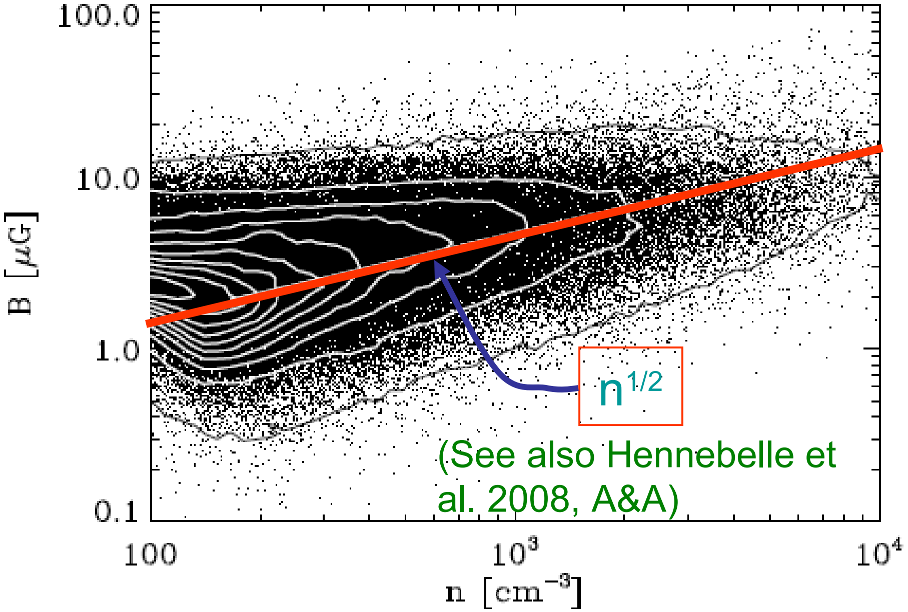
There is a net mass flux through clump boundaries.

The boundaries are ***"phase transition fronts"***, not rigid walls.

- Note:
  - Turbulence is produced self-consistently by various instabilities while cloud is being assembled (Vishniac 1994; Heitsch et al. 2005; Vázquez-Semadeni et al. 2006).

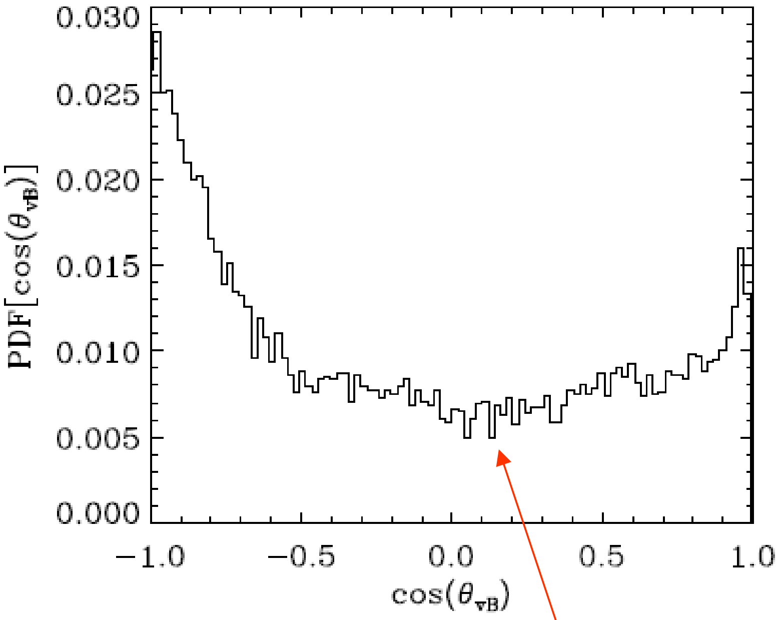
Correlations between variables

B-n correlation

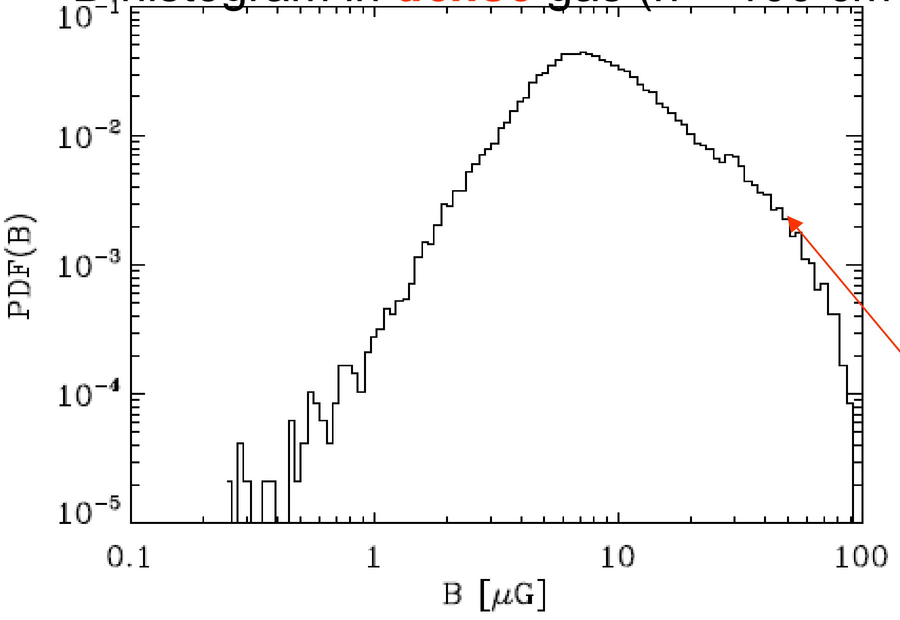


$n^{1/2}$

(See also Hennebelle et al. 2008, A&A)



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



$\vec{B}$ and $\vec{v}$ tend to be aligned, even though *B* is weak (~ 1 μG).

Large B scatter in dense clumps.

(Banerjee et al. 2009, MNRAS, 398, 1082)

Global evolution and the SFR

Three simulations with $\mu = 1.3$, 0.9, and 0.7, including AD.

Face-on view of column density.

Dots are sink particles.

$\mu = 0.9$
B=3 μG

$\mu = 1.3$
B=2 μG

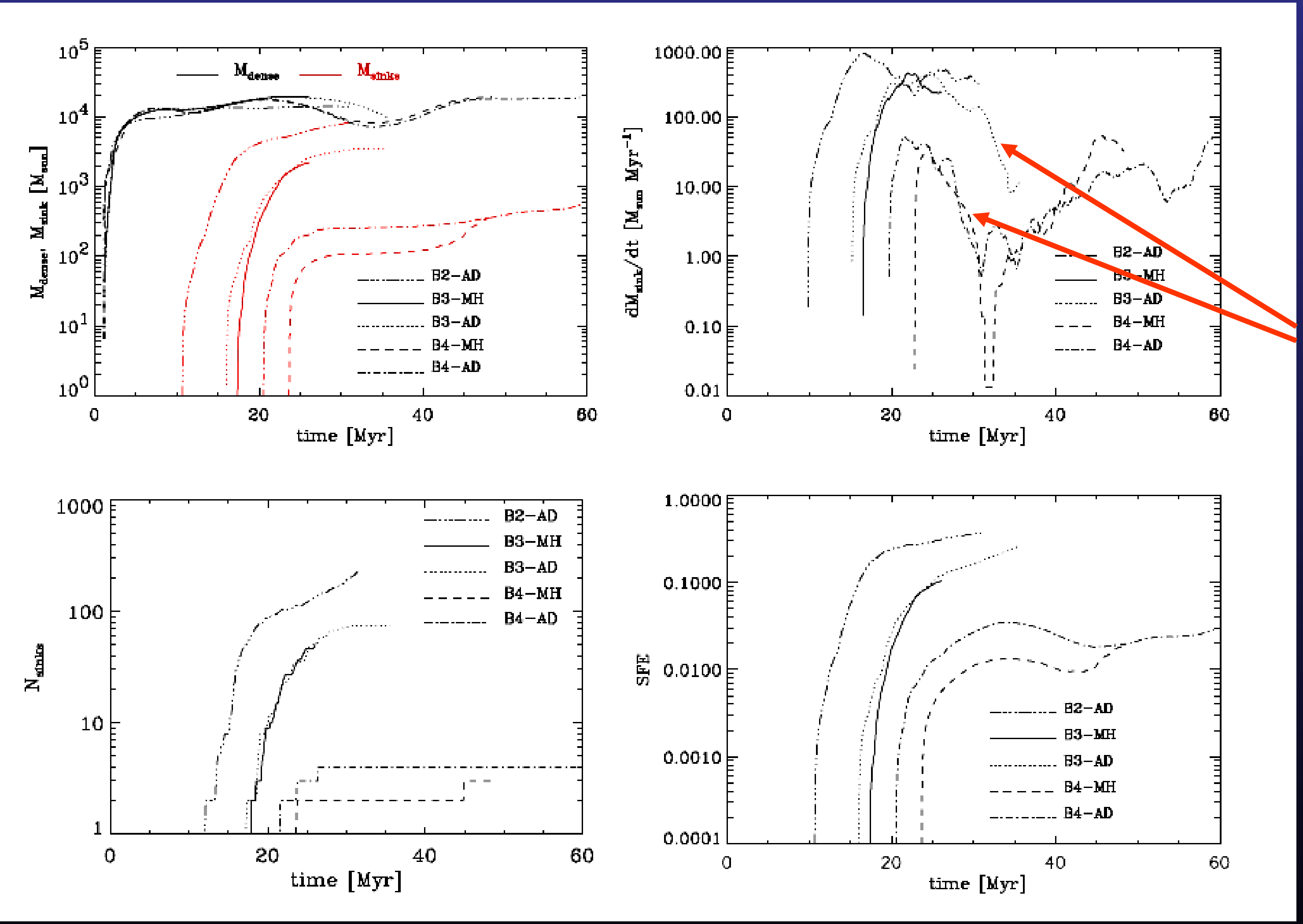
$\mu = 0.7$
B=4 μG

Simulations are globally subcritical (note bounce), but locally they produce collapsing sites, due to AD + numerical diffusion.

Vázquez-Semadeni et al. 2011, MNRAS

- In all cases, sub- or supercritical, cloud begins contracting after accumulating enough mass.
  - In subcritical cases, cloud bounces after a while, on timescales of 10s of Myr.
    - SF shuts off when cloud bounces.
  - In supercritical cases, collapse continues unimpeded.
  - No turbulent support other than at very beginning !

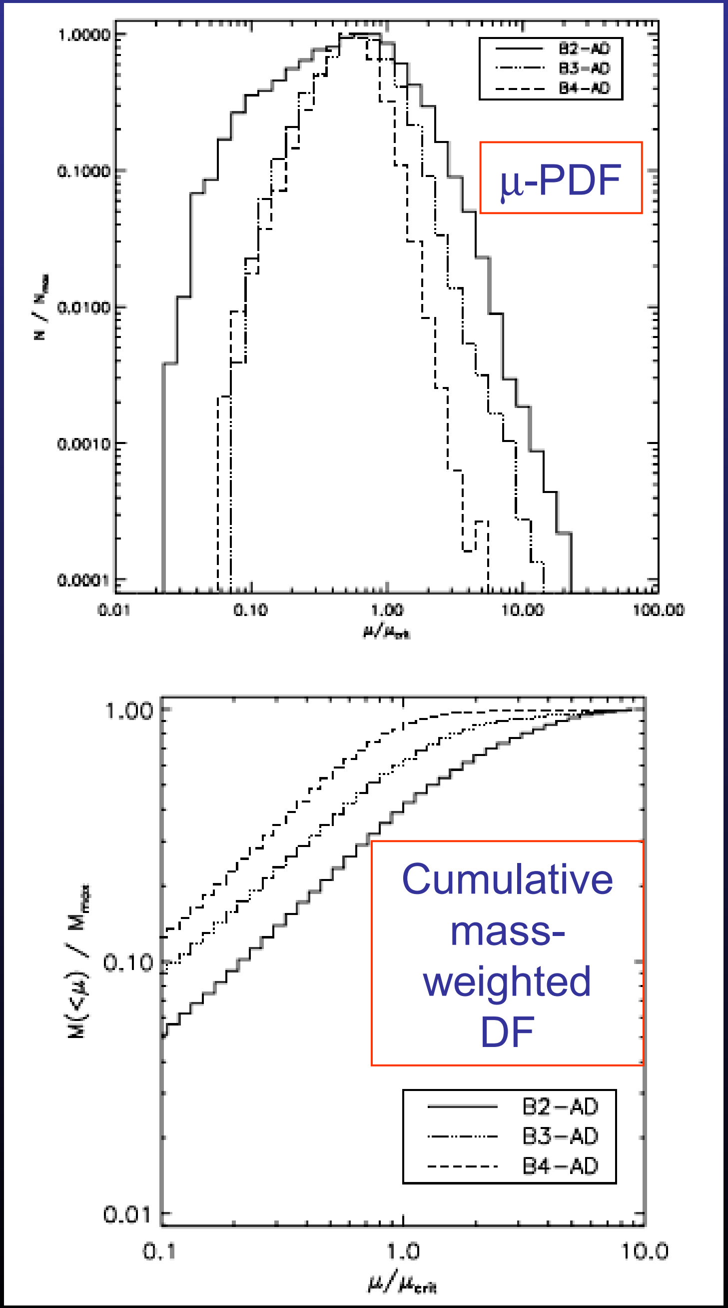
Evolution of gaseous and stellar masses, and of the SFR.



When global contraction ceases, so does the SF.

Vázquez-Semadeni et al. 2011, MNRAS

Evolution and distribution of the mass-to-flux ratio



μ-PDF

Cumulative mass-weighted DF

Wider μ-PDFs for weaker field.

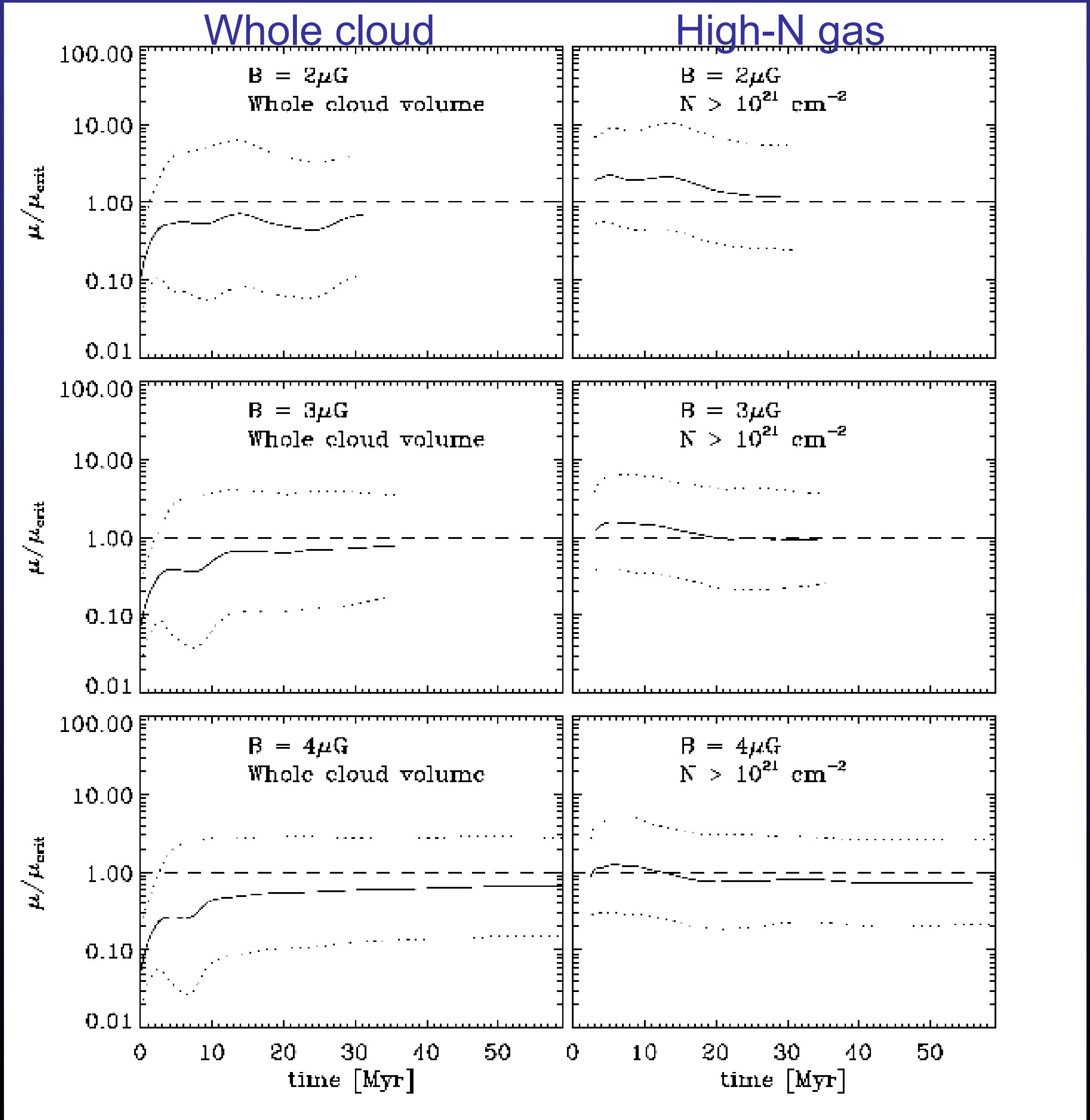
Cumulative mass distribution exhibits power-law behavior at low μ.

Evolution of the mean and 3σ values of $\mu = M/\phi$.

μ = 1.3

μ = 0.9

μ = 0.7



Mass-to-flux ratio is highly variable through the cloud, and evolving.

SF occurs where $\mu > 1$.

Vázquez-Semadeni et al. 2011, MNRAS

A bonus result

Low-μ gas develops buoyancy

Run with B=3 μG (μ = 0.9).

Like a macroscopic analogue of AD.

Vázquez-Semadeni et al. 2011, MNRAS

V. CONCLUSIONS

– Dynamically assembling clouds and cores involves moving material from surroundings into a small region

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

Implies:

- Cloud/clump boundaries are ***not*** rigid walls
  - Rather, they are ***arbitrary***, or, at most, ***phase transition fronts:*** There exists a continuous mass flux through them.
- Masses of clouds and cores are ***not*** fixed, but rather evolve (initially increasing) in time.
- While a cold cloud is assembled by a compression in the WNM with a component along the magnetic field lines, ***the mass-to-flux ratio of the cold gas increases.***
- Before diffusion becomes important, core formation by compression within a larger cloud, implies

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

- ***When*** diffusion begins to dominate, then should recover standard result,

$$\mu_{\mathrm{core}} > \mu_{\mathrm{cloud}}$$

- In simulations of cloud formation with B and AD, μ is a time-dependent, and highly fluctuating quantity.

- Although in simulations the box’s μ is bounded globally, in the actual ISM there is no such restriction (no boundaries).

- SFRs should be further reduced by inclusion of stellar feedback (Vázquez-Semadeni et al. 2010, ApJ).

THE END