Molecular Cloud Evolution Including Magnetic Fields and Ambipolar Diffusion

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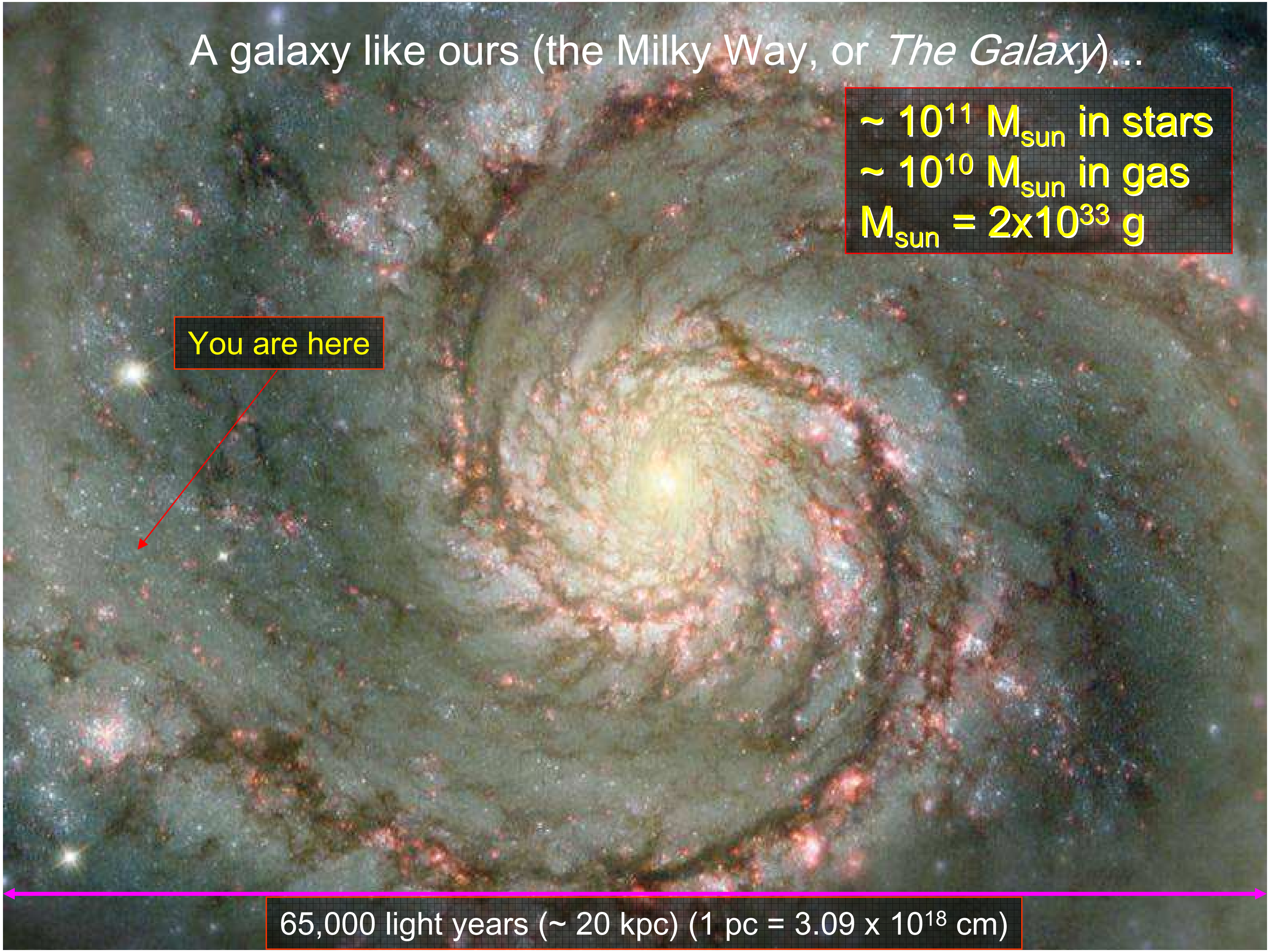
I. INTRODUCTION

- 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:
  - Outline of physical processes underlying cloud formation.
  - Results from cloud-formation simulations including MHD and ambipolar diffusion (AD).

A galaxy like ours (the Milky Way, or *The Galaxy*)...



~ 10^{11} M_{sun} in stars
~ 10^{10} M_{sun} in gas
$M_{sun} = 2 \times 10^{33}$ g

You are here

65,000 light years (~ 20 kpc) (1 pc = 3.09×10^{18} cm)

Brief summary of ISM structure:

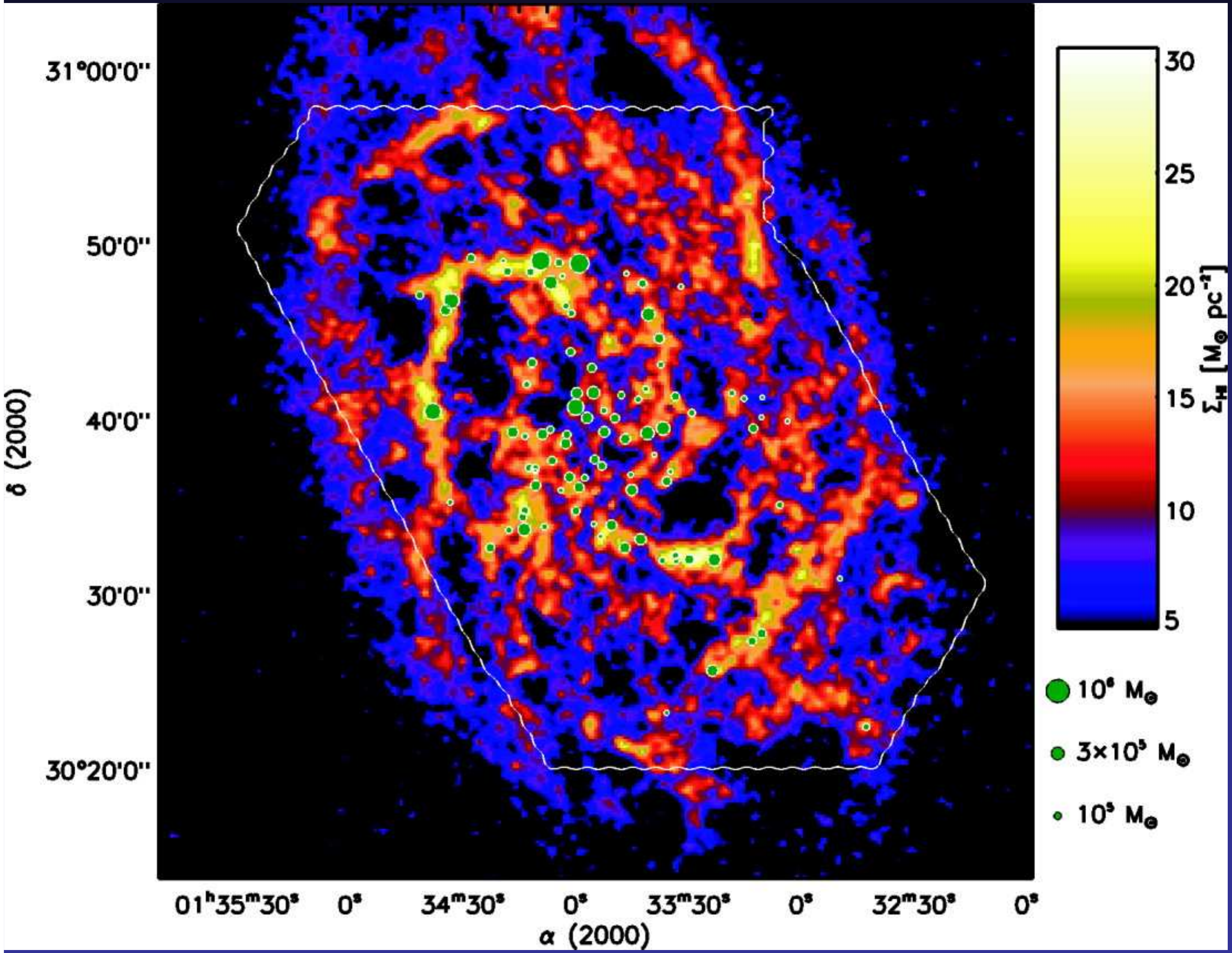
- The ISM contains gas in a wide range of conditions:

	Density	Temperature
Cold molecular (H_2) gas (clouds, clumps, cores)	10^2 – >10^6 cm^{-3}	10–30 K
Cold atomic (“HI”) gas (diffuse clouds)	~ $10^{1–2}$ cm^{-3}	100–500 K
Warm (atomic or ionized) gas (intercloud gas)	~ 10^{-1} – 10^0 cm^{-3}	$10^{3–4}$ K
Hot gas (supernova remnants)	~ 10^{-2} cm^{-3}	10^6 K

- Note these are ranges, not single values.
  - Possibly a density continuum.

A hierarchical (nested) structure:

Engargiola et al. 2003: Study of M33

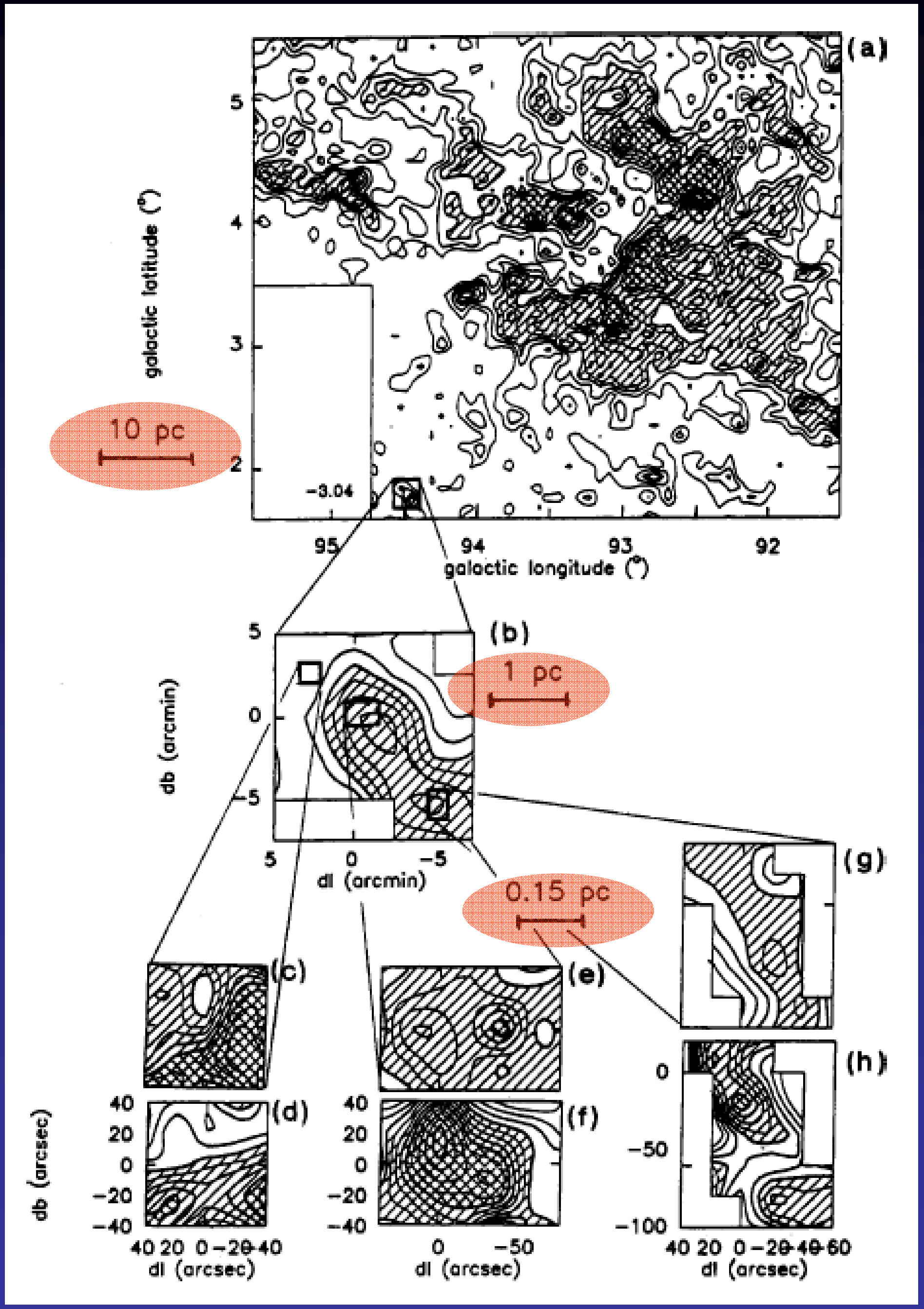


Color image: HI distribution

Circles: Giant Molecular Clouds (GMCs)

GMCs seem to be the “tip of the iceberg” of the density gas distribution.

They conclude that ***GMCs form out of the HI.***
(See also Blitz et al. 2007, PPV.)



GMCs are extremely hierarchical as well.

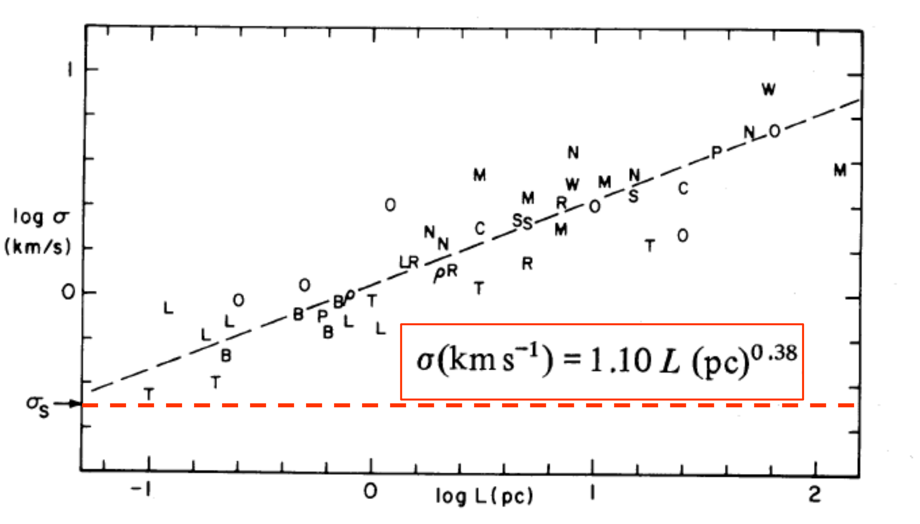
CO J(1→0) emission in Cygnus OB7 complex (Falgarone et al. 1992).

“Clumps”

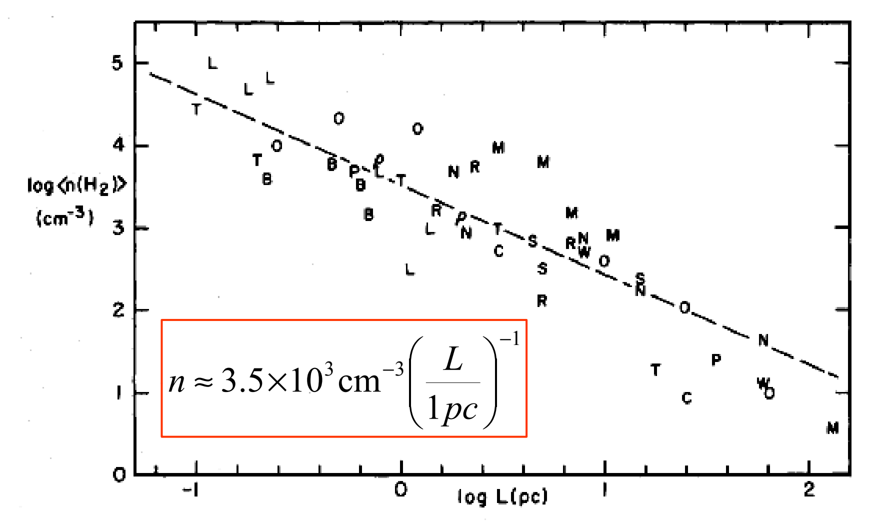
Really, a continuum.

“Cores”

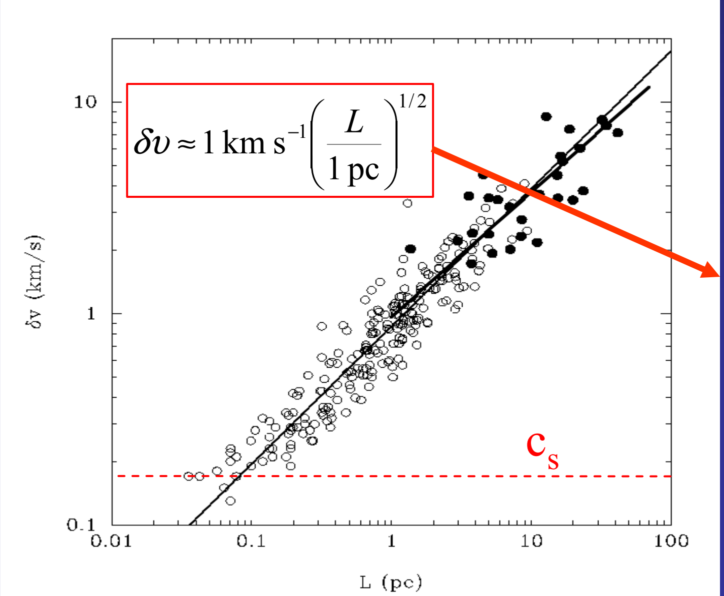
- Used to be thought that they followed Larson’s (1981, MNRAS, 194, 809) relations:



$\sigma(\mathrm{km\,s^{-1}}) = 1.10\,L\,(\mathrm{pc})^{0.38}$



$n \approx 3.5\times10^{3}\,\mathrm{cm}^{-3}\left(\frac{L}{1\,pc}\right)^{-1}$



$\delta\upsilon \approx 1\,\mathrm{km\,s^{-1}}\left(\frac{L}{1\,\mathrm{pc}}\right)^{1/2}$

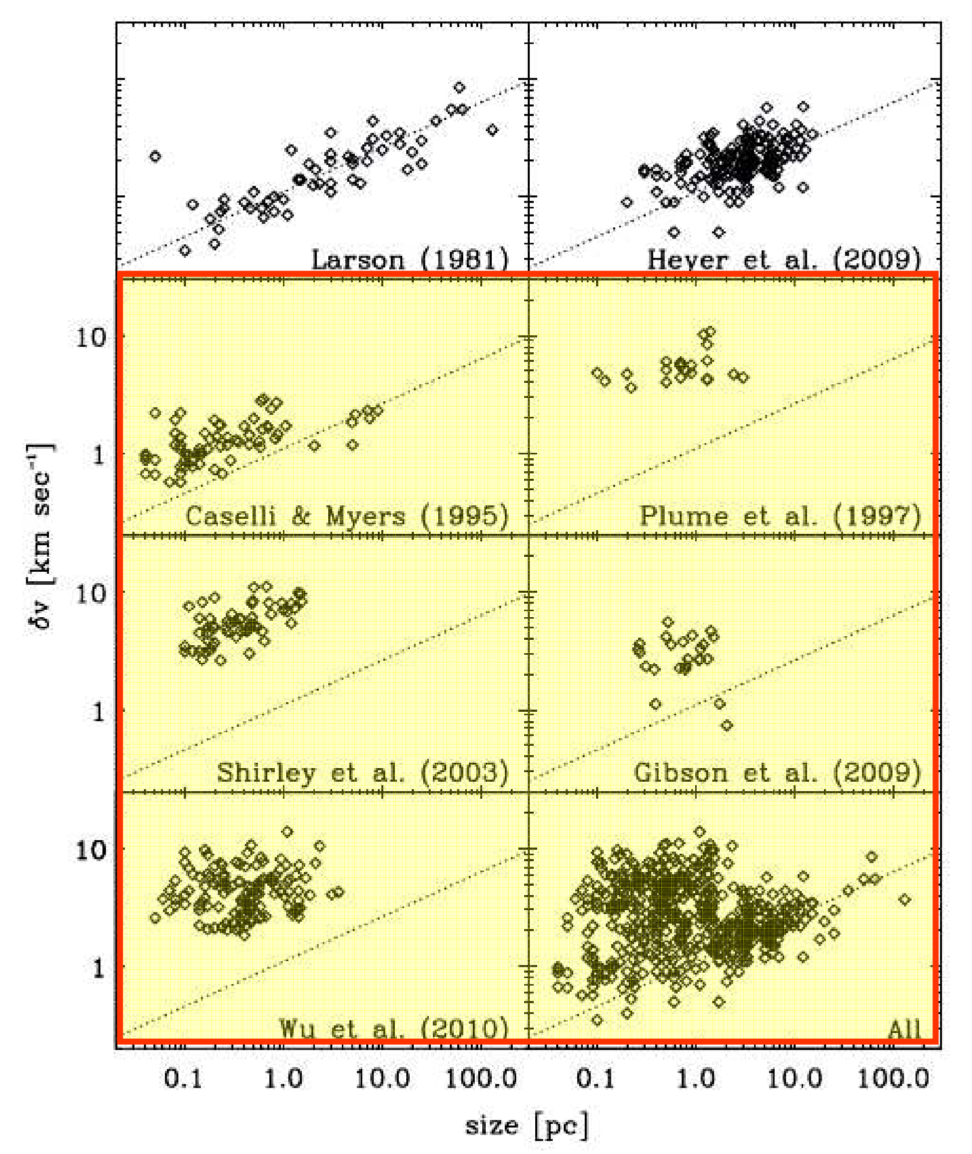
Modern take:

Often attributed to Burgers-like spectrum $E(k) \sim k^{-2}$.

Heyer & Brunt 2004

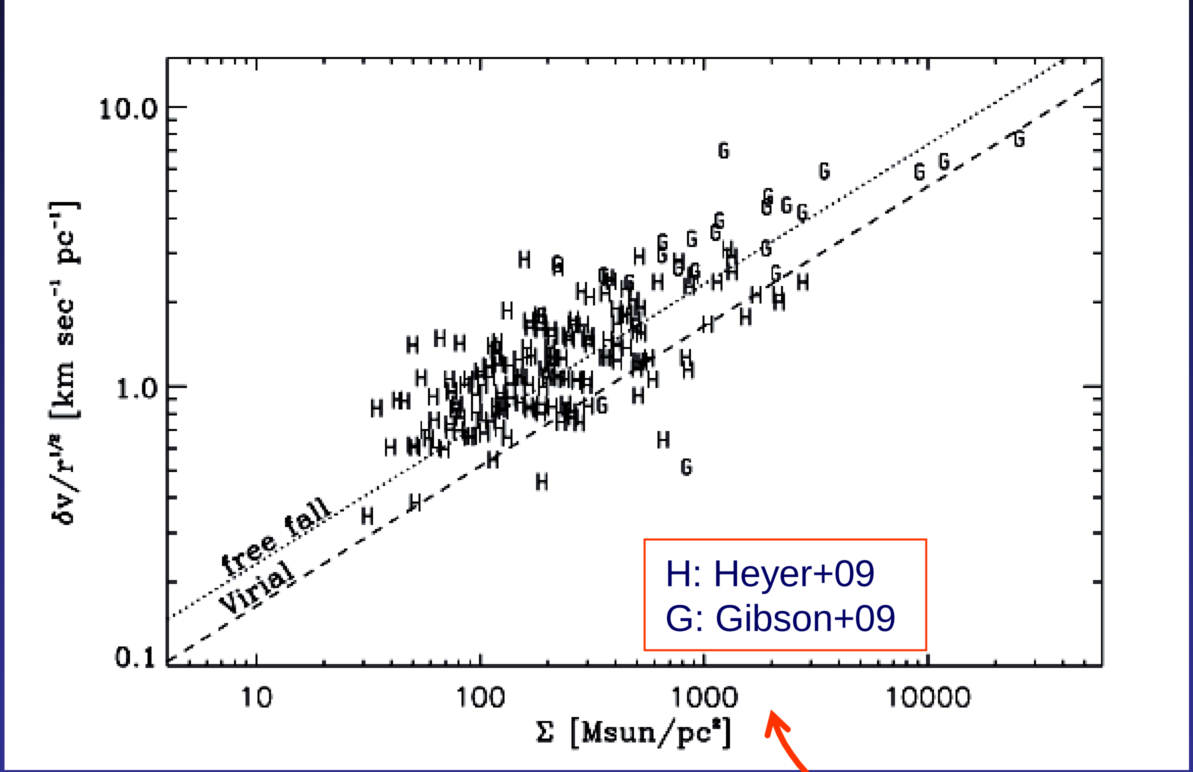
Implies a roughly constant column density Σ = ρL = cst.

- However, massive clumps do not follow this scaling.



Ballesteros-Paredes+11, MNRAS, 411, 65

- ... although they do seem to follow the generalized scaling (when Σ is not cst.) of Heyer+09:



Ballesteros-Paredes+11, MNRAS, 411, 65

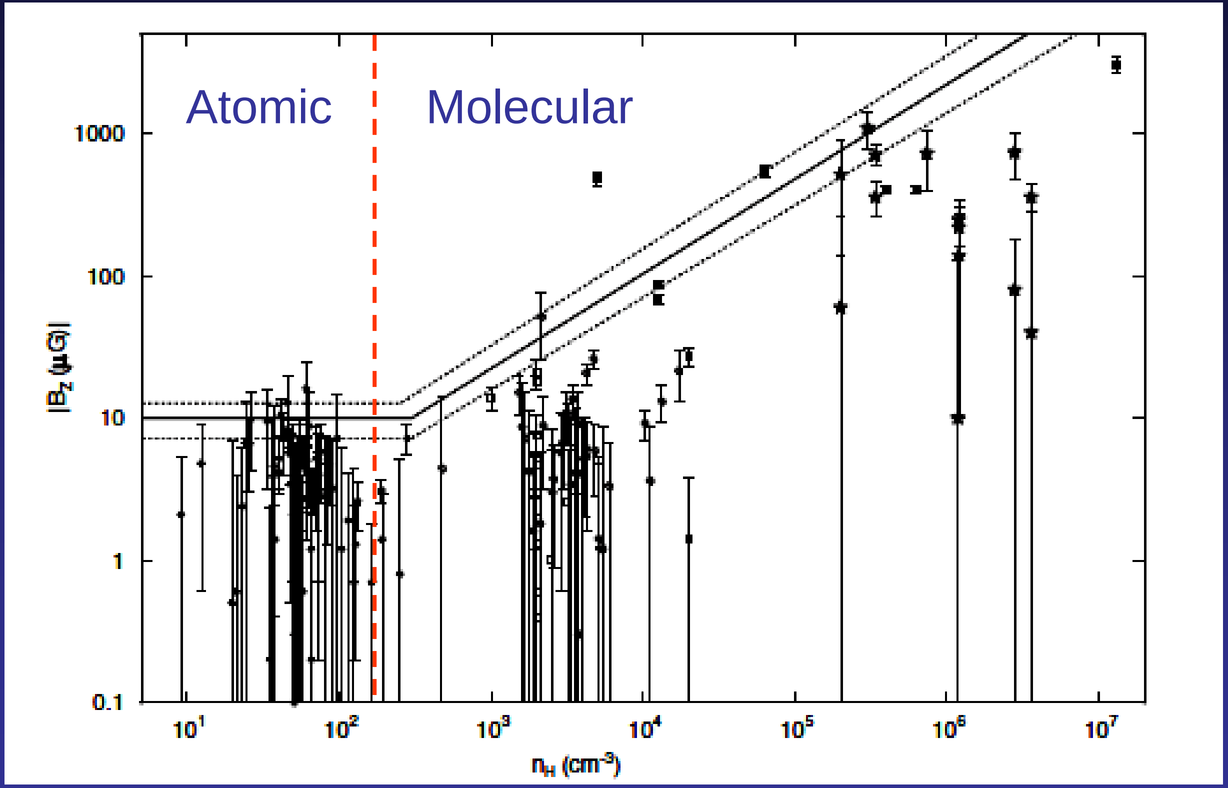
$$\boxed{\sigma_v / R^{1/2} \sim \Sigma^{1/2}}$$

Both Larson's relations and the Heyer relation imply near virial equilibrium

...or free-fall.

Column density is ***not*** constant.

– Atomic gas and MCs are magnetized.



Crutcher+10: Zeeman measurements

- Theoretical views of MCs and their star-formation activity have evolved:
  - Mid 1970s:
    - (Goldreich & Kwan 1974): Supersonic motions in MCs correspond to gravitational collapse.
    - Zuckerman & Palmer (1974): No, they don't:
      - » Free-fall estimate of SFR:

$$\mathrm{SFR}_{\mathrm{ff}} \sim \frac{M_{\mathrm{mol}}}{\tau_{\mathrm{ff}}} \sim \frac{10^9\ M_{\mathrm{sun}}}{3\ \mathrm{Myr}} = 300\ M_{\mathrm{sun}}\,\mathrm{yr}^{-1}$$

      - » Observed rate is $\mathrm{SFR}_{\mathrm{obs}}$ ~ 2—3 Msun yr^{-1}; i.e., ~100x lower.
    - Zuckerman & Evans (1974): Supersonic motions correspond to ***micro***-turbulence.
  - Early-1980s — late-1990s: (Shu+87, Mouschovias91):
    - Clouds are globally supported by magnetic fields.
    - Locally, collapse can occur because AD allows magnetic flux to slip from the neutral gas.

- 2000s:
  - Magnetic fields are not strong enough to support clouds (Bourke+01; Crutcher+10).
  - Support must then be provided by supersonic turbulence (VS+03; Mac Low & Klessen 04).

- Late 2000s — 2010s: (Burkert & Harmann 04; Heitsch+08, 09; VS+07, 09; VS12, 14):
  - Back to global collapse
    - » Turbulence is ***not*** microscopic.
    - » Turbulence only provides initial seeds for collapse.
    - » As global collapse proceeds, Jeans mass decreases, and fluctuations collapse
    - » Early collapses destroy cloud and keep SFR in check.

- Let’s take a look...

II. BASIC PHYSICAL PROCESSES

1. Fundamental fact:

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

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

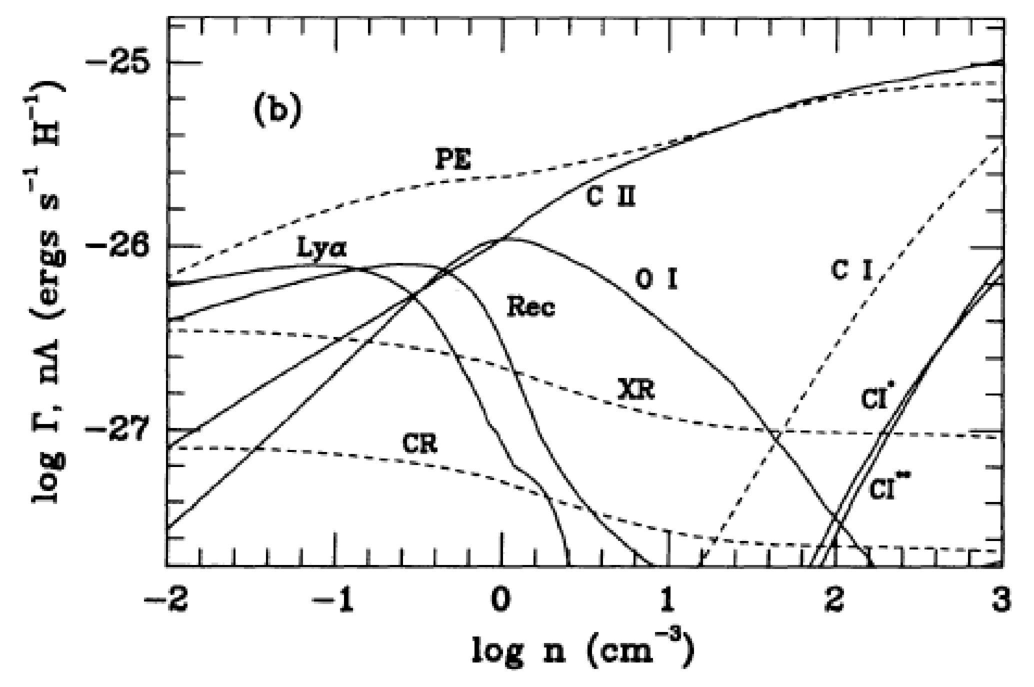
i.e., need to *move* the material from the surroundings into the region.

Trivial, but neglected every time we consider a stationary cloud.

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 atomic ISM…

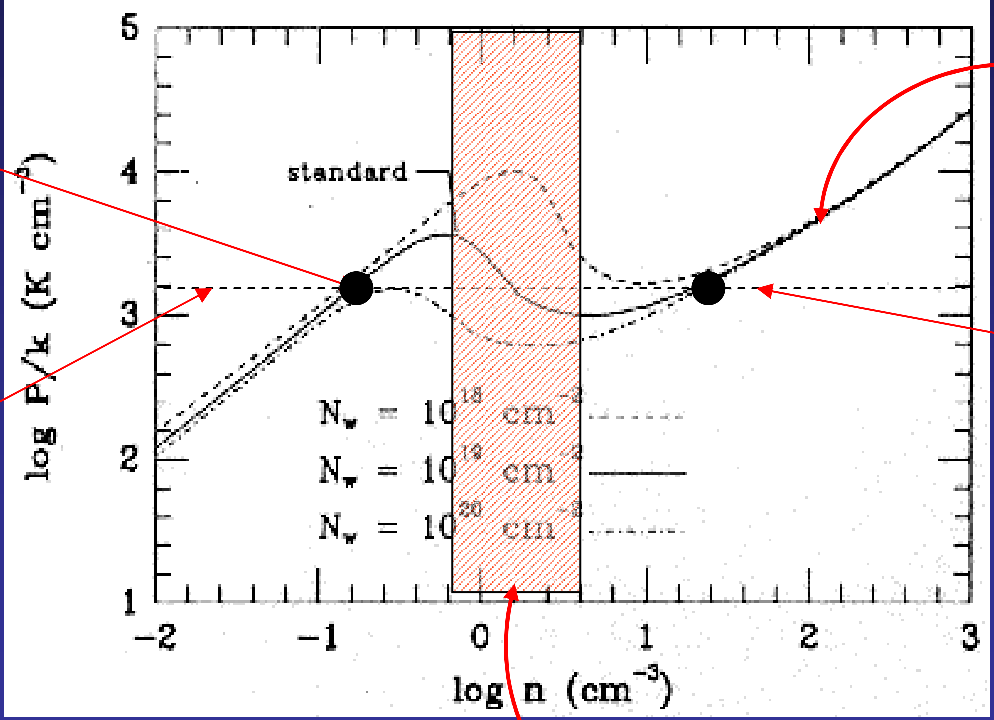


- - - - Heating
—— Cooling

Wolfire et al. 1995

… causes 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).



WNM
(stable)

Mean ISM thermal pressure

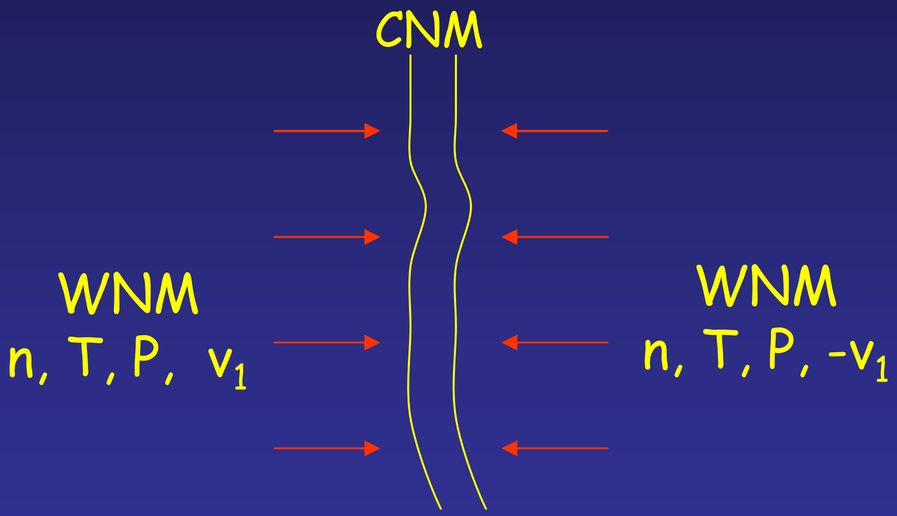
P_{eq}, at which heating Γ equals cooling $n\Lambda$.

CNM
(stable)

Wolfire et al. 1995

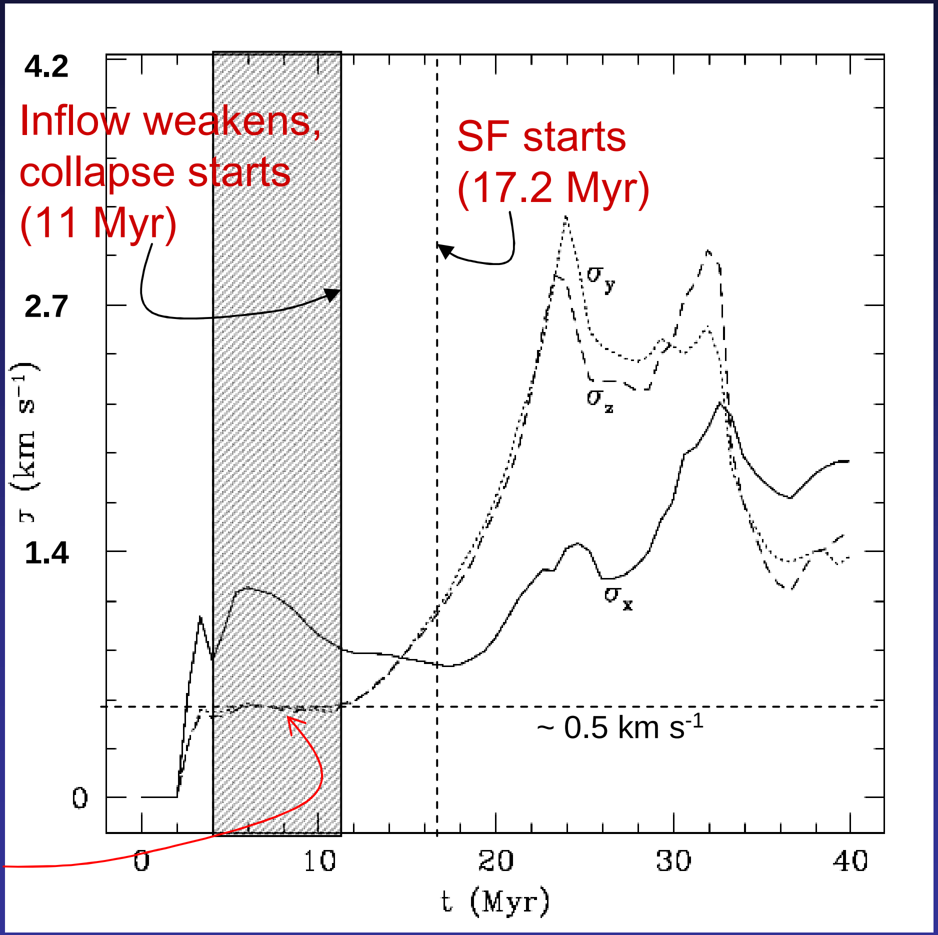
Thermally unstable range

- When a dense cloud forms out of a compression in the WNM, (Ballesteros-Paredes+99ab, Henebelle & Pérault 99) it “automatically”
  - acquires mass.
  - cools down (from WNM to CNM).
  - *acquires turbulence* (through TI, NTSI, KHI) (Hunter+86; Vishniac 1994; Walder & Folini 1998, 2000; Koyama & Inutsuka 2002, 2004; Audit & Hennebelle 2005; Heitsch+2005, 2006; Vázquez-Semadeni+2006).



- The compression may be driven by large-scale turbulence, large-scale instabilities (spiral arms), etc.

- However, the induced turbulence in the cloud is *transonic*.
  - In simulations, strongly supersonic velocities appear *later*, as a consequence of gravitational contraction.



Inflow weakens, collapse starts (11 Myr)

SF starts (17.2 Myr)

~ 0.5 km s^{-1}

Turbulence driven by compression, through NTSI, TI and KHI.

(Vázquez-Semadeni et al. 2007)

3. MHD turbulent fluctuations and B-ρ correlation:

- Passot & Vázquez-Semadeni (2003, A&A, 398, 845) investigated the correlation between magnetic pressure and density in isothermal, supersonic turbulence.

- Used “simple”, ideal MHD waves (Mann 1995, J. Plasma Phys., 53, 109) in 1+2/3D (slab geometry).
  - The nonlinear equivalent of the classical MHD waves.
  - Same Alfvén, fast and slow modes.

- Found dependence of *B* on ρ for each mode:

$$B^2 = \rho^2$$ Fast wave

$$B^2 = c_1 - c_2\rho$$ Slow wave

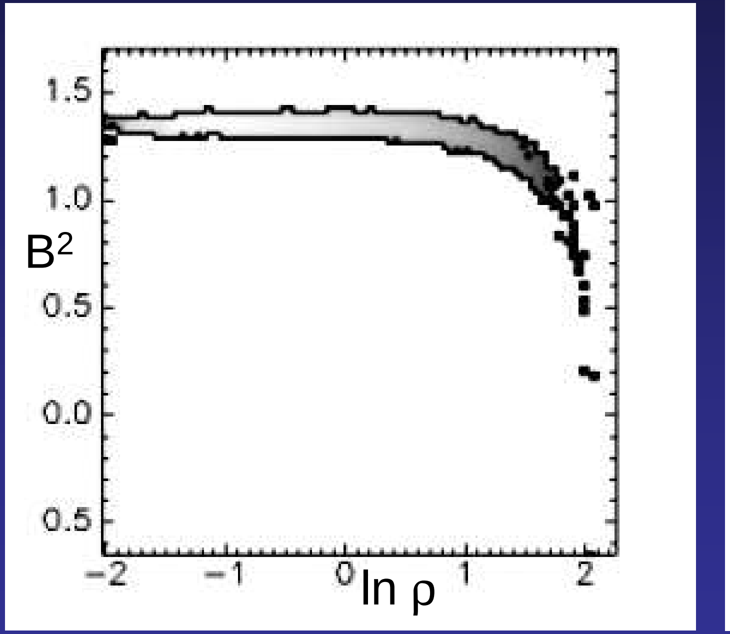
$$B^2 \propto \rho^\gamma; \qquad \gamma = 1/2 - 2$$ Circularly polarized Alfvén wave

(see also McKee & Zweibel 1995)

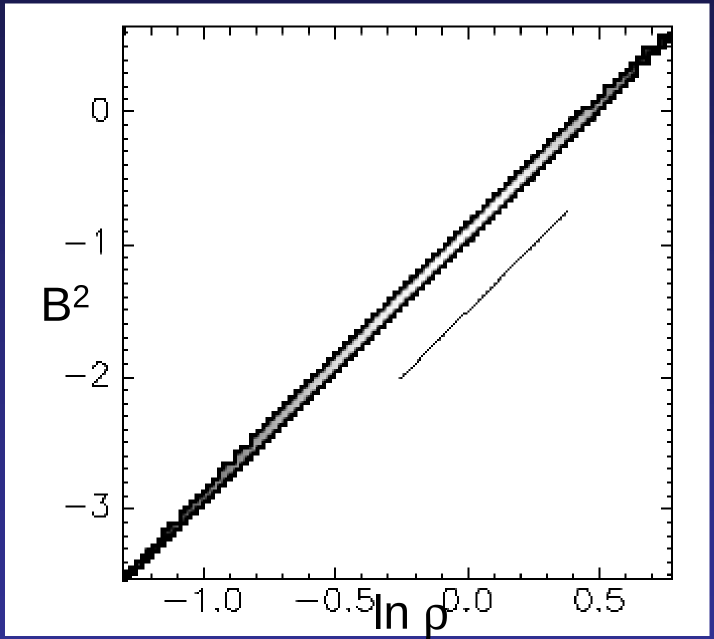
$$\gamma \approx \begin{cases} 1/2 & \text{for low } M_a \\ 3/2 & \text{for moderate } M_a \\ 2 & \text{for large } M_a \end{cases}$$

M_a: Alfvénic Mach #

- Slow mode tends to dominate at low ρ, and disappears at high enough ρ.
  - In a log-log plot, looks constant at low densities.
- Fast mode tends to dominate at high ρ.



Slow mode

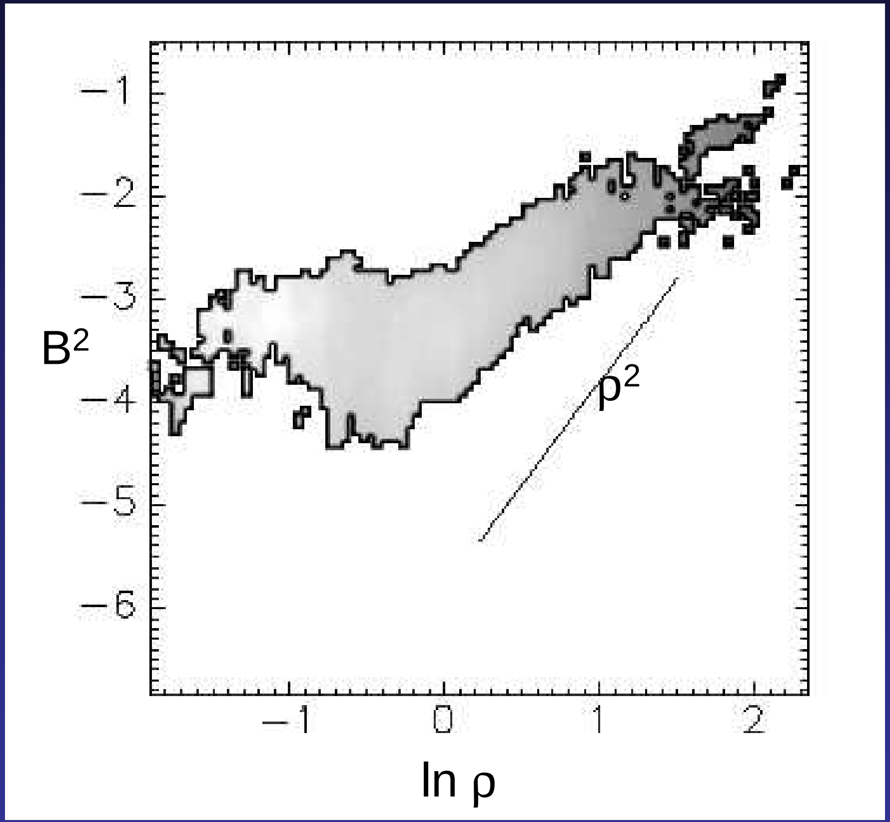


Fast mode

(Arbitrary units)

Passot & Vázquez-Semadeni 2003

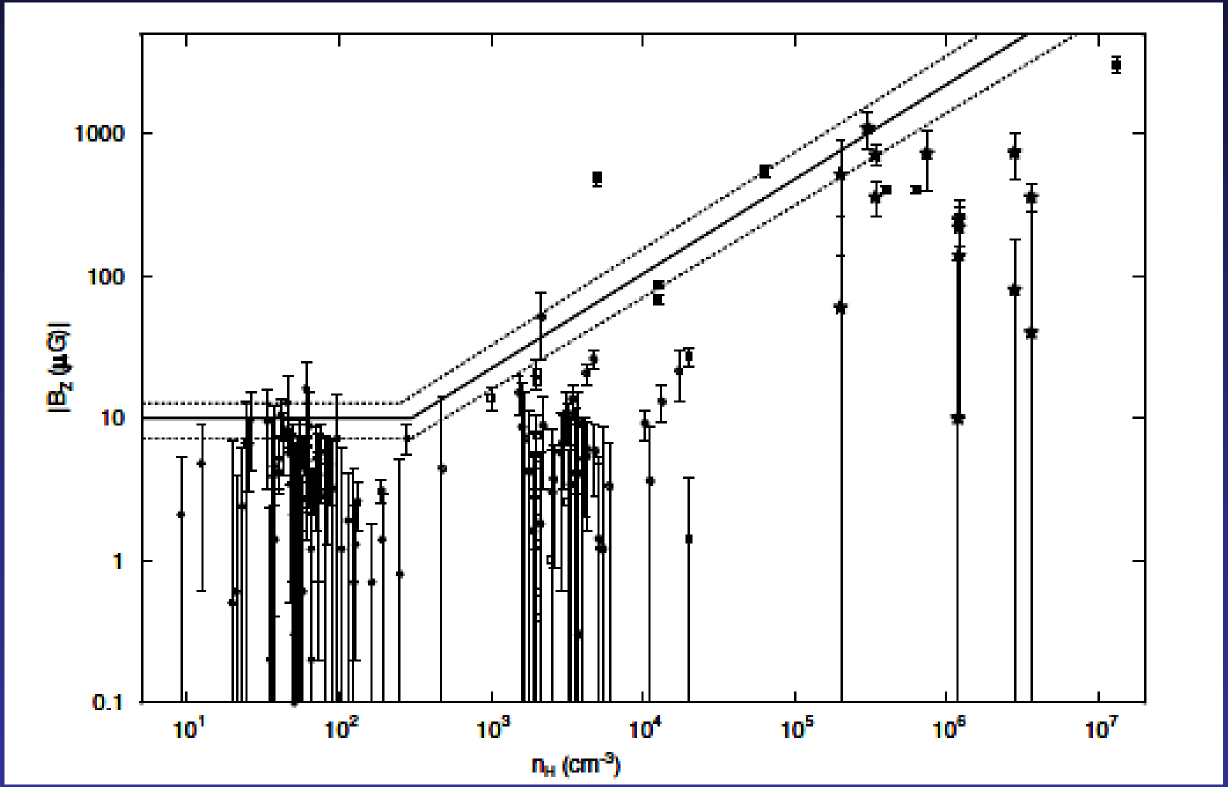
- When both modes are active:



(Arbitrary units)

Passot & Vázquez-Semadeni 2003

– Consistent with observed trend in HI and molecular clouds:



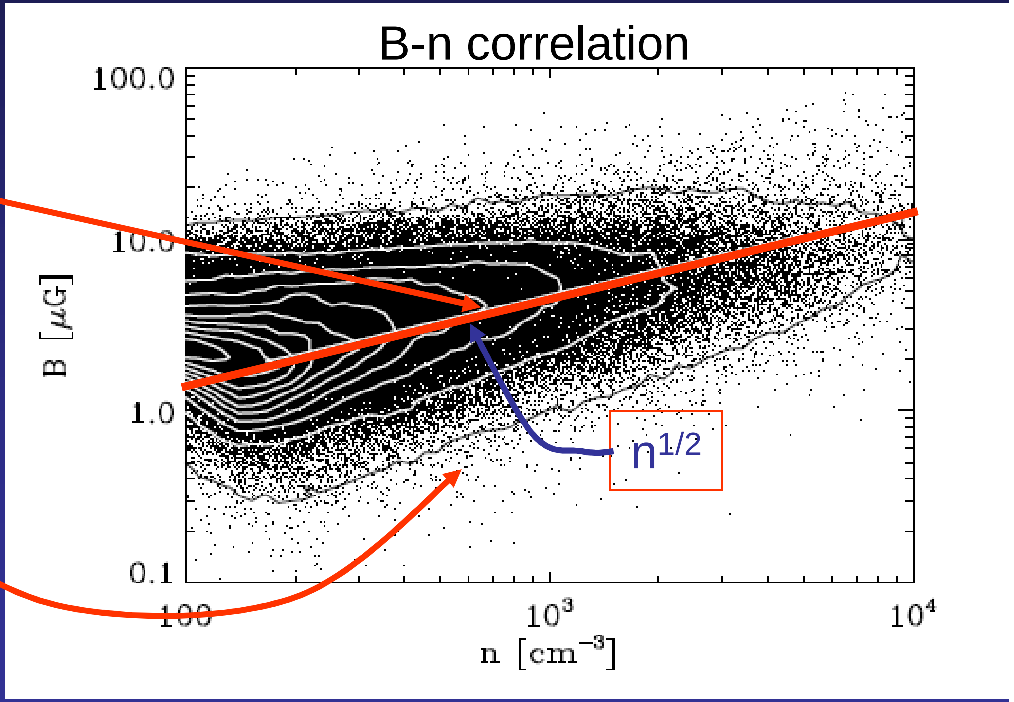
Crutcher+10

- Explanations of this phenomenon based on AD (Heitsch+04) and turbulent reconnection (Santos-Lima+10) have also been proposed.

- In a 3D turbulent regime, all modes coexist
  - Large fluctuations around mean trend, caused by the ***different B-ρ scalings*** of the different modes.
  - At large densities, combination of Alfvén and fast modes dominates.

At large B (low M_a), shallower slope

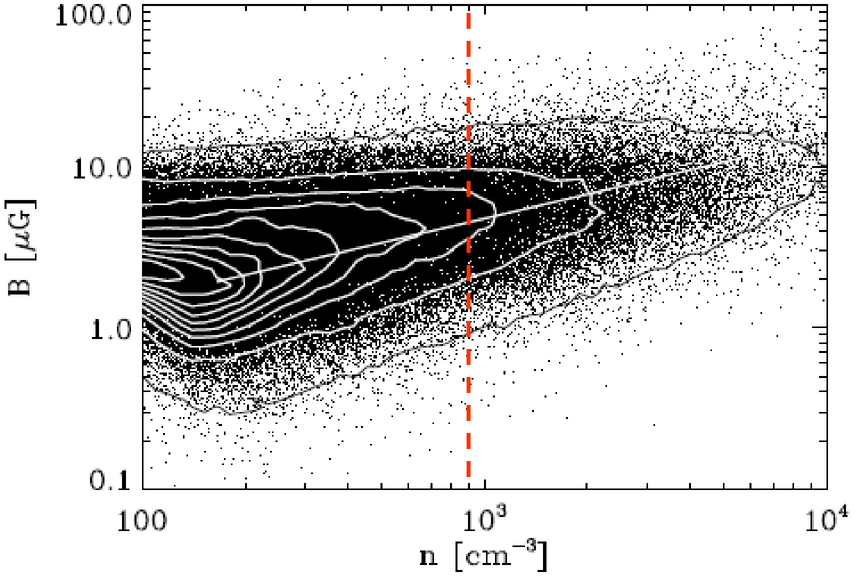
At low B (large M_a), steeper slope:



Dense cloud formation simulation with self-gravity, B=1 μG, FLASH code (Banerjee et al. 2009, MNRAS, 398, 1082)

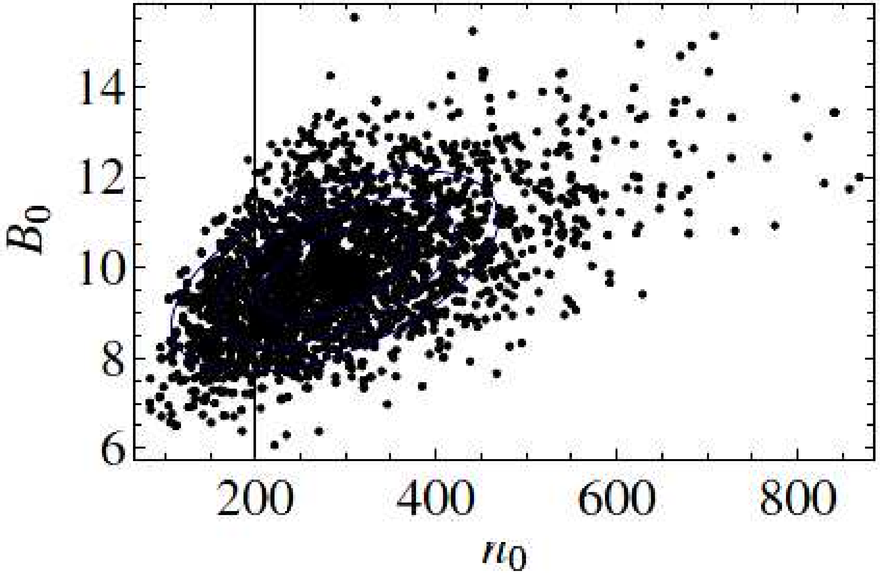
Numerical simulation

Banerjee, VS et al, 2009, MNRAS, 398, 1082



Zeeman observations

Crutcher et al, 2010, ApJ, 725, 466



- Implications:

  - According to above results, observed trend in molecular clouds (Crutcher+10),

$$B \sim \rho^{0.65} \quad (P_{\mathrm{mag}} \sim \rho^{1.3})$$

    is consistent with transalfvénic motions in molecular clouds
    - But gravity may be at play, too.

  - Density PDF is close to lognormal in MHD case because P_{mag} has no systematic scaling with ρ;
    - Systematic restoring force continues to be dominated by ∇P_{th}, except when B is very large.

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

- The ratio of gravitational to kinetic energy

$$\frac{|E_g|}{E_m} = \frac{18}{5}\frac{GM^2}{B^2R^4} = \frac{18\pi^2 G}{5}\left(\frac{M}{\Phi}\right)^2 \equiv \frac{18\pi^2 G}{5}\mu_{\rm crit}{}^2$$

implies the existence of a critical mass-to-flux ratio (M2FR) for a cloud to be supported against self-gravity by the magnetic field:

$$\mu_{\rm crit} \equiv \left(\frac{5}{18\pi^2 G}\right)^{1/2}$$

– A cloud with

- $M/\Phi > (M/\Phi)_{\rm crit}$ is magnetically supercritical: collapses.
- $M/\Phi < (M/\Phi)_{\rm crit}$ is magnetically subcritical: cannot collapse.

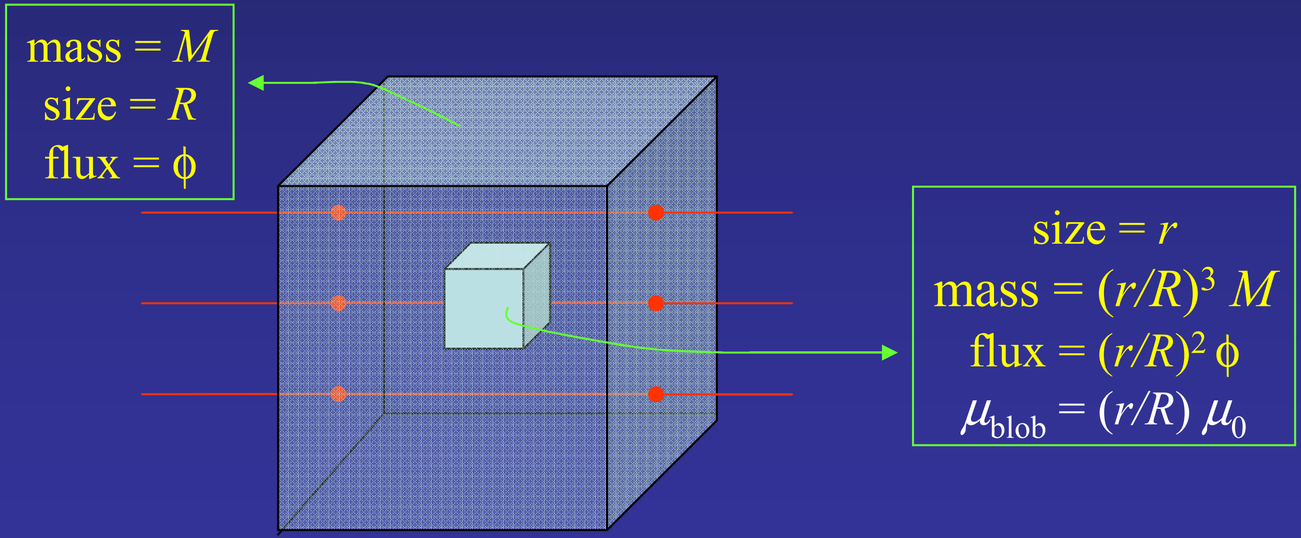
3.1. Under ***ideal*** MHD conditions, and for a ***fixed cloud mass***, the mass-to-flux ratio μ of a clump of size r within an initially uniform cloud of size R is expected to range within:

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

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

Consider two limiting cases under ideal MHD:

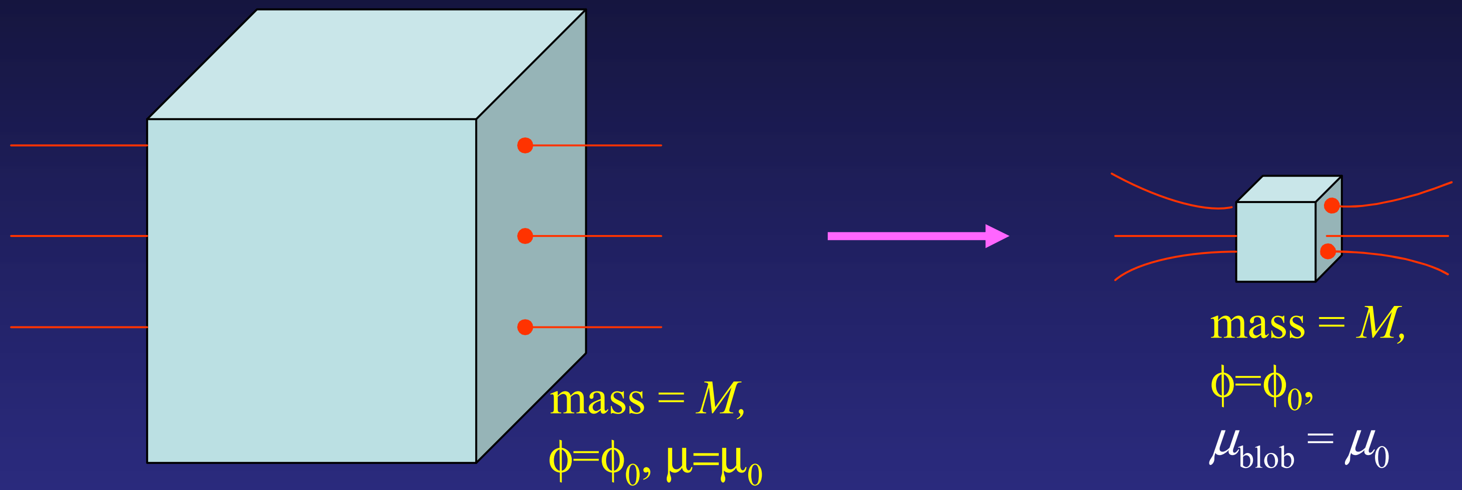
a) A subregion of a uniform cloud with a uniform field:



mass = M
size = R
flux = ϕ

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

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



mass $= M,$

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

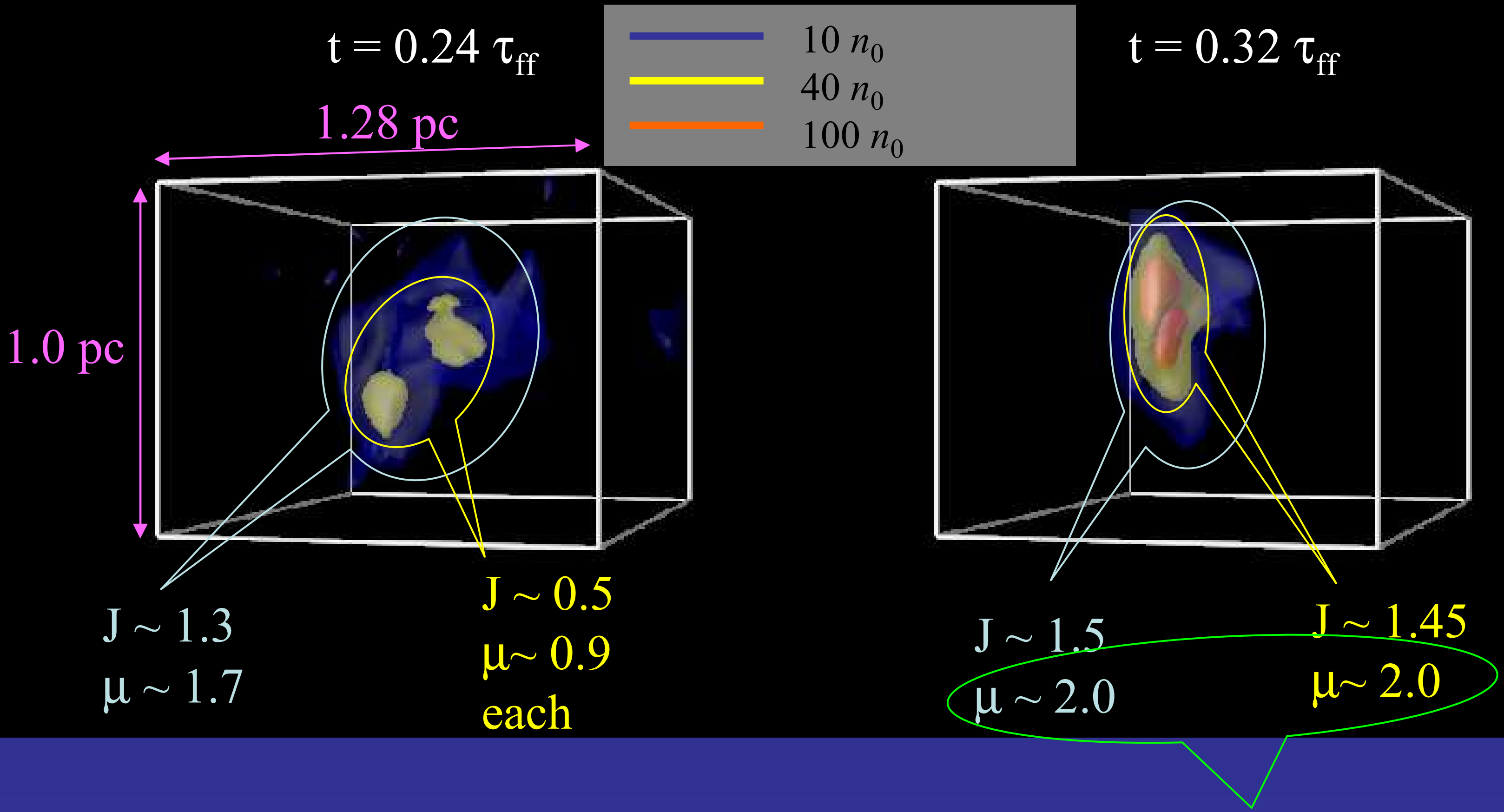
mass $= M,$

$\phi=\phi_0,$

$\mu_{\mathrm{blob}} = \mu_0$

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.

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, Kim 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

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

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

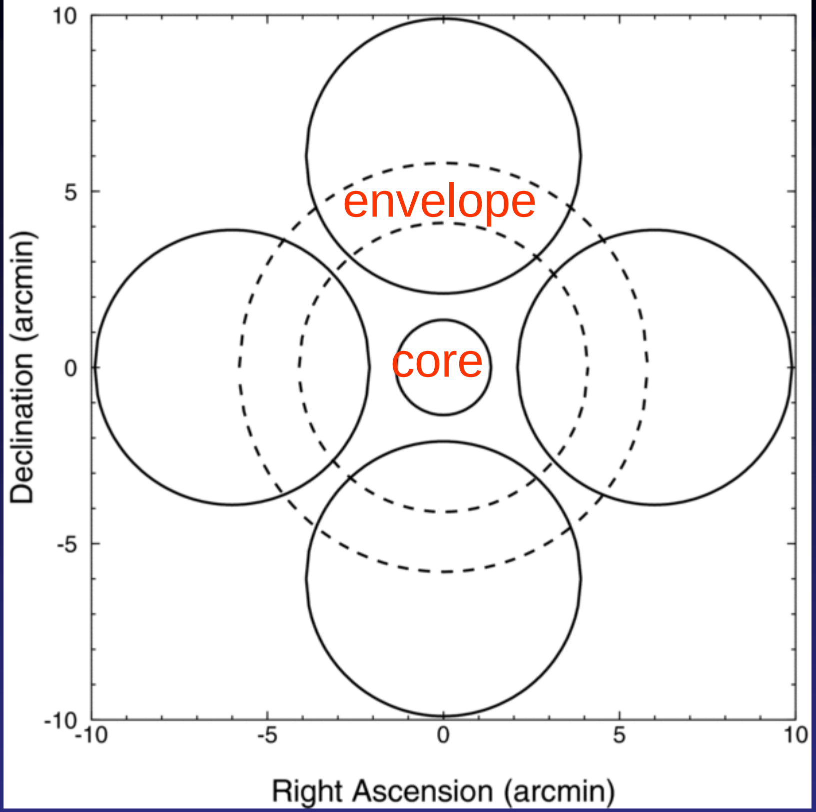


Table 2
Relative Mass/Flux

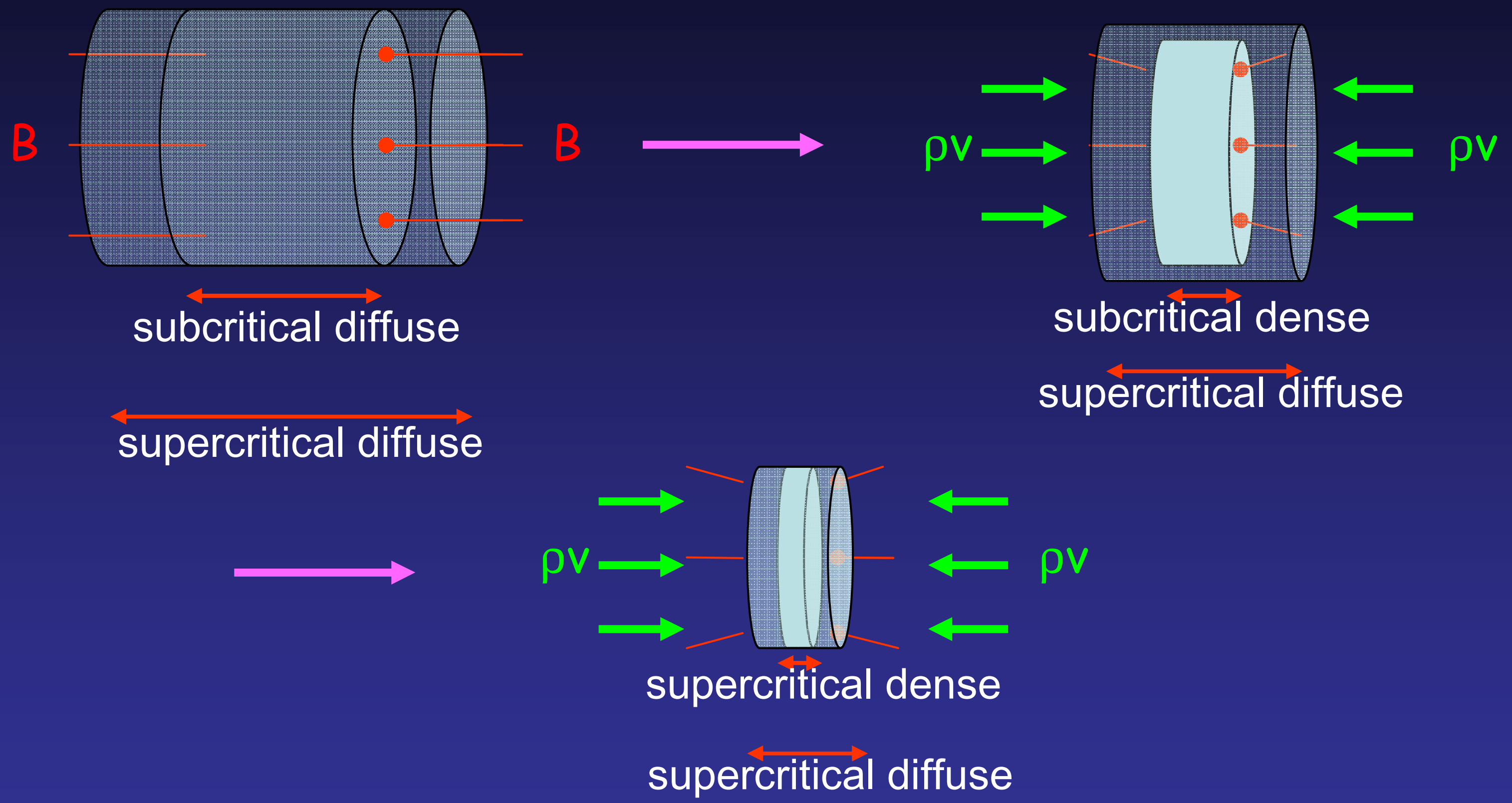
Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010

The core has lower μ than the envelope.

Collapse by AD would require the opposite.

- An explanation of this phenomenon based on turbulent reconnection (Santos-Lima+10; Lazarian12) has also been proposed.

3.2. If a cloud (i.e., a dense region) is formed by a compression with a component along the field lines, the *cold* cloud's 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 diffuse

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):

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

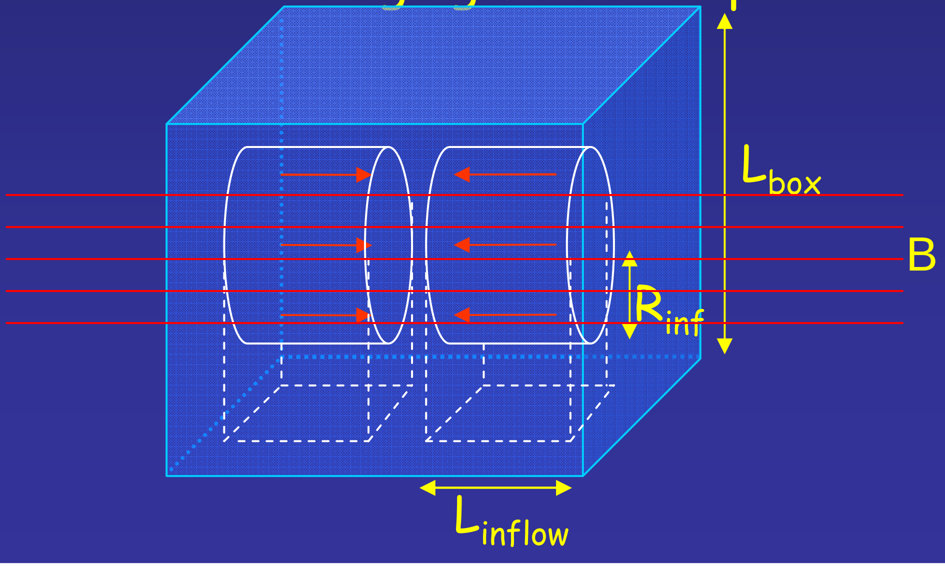
- Very similar to the column density threshold for transition from atomic to molecular gas, $N \sim 10^{21}$ cm^{-2} ~ 8 M_{sun} pc^{-2} (Franco & Cox 1986; van Dishoek & Black 1988; van Dishoek & Blake 1998; Hartmann et al. 2001; Bergin et al. 2004; Blitz 2007).

- 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 (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).
- Thus, most MCs appear *not* to be supported by B, and should collapse freely.
  - I.e., no turbulent nor magnetic support.

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, 414, 2511).
  - 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.

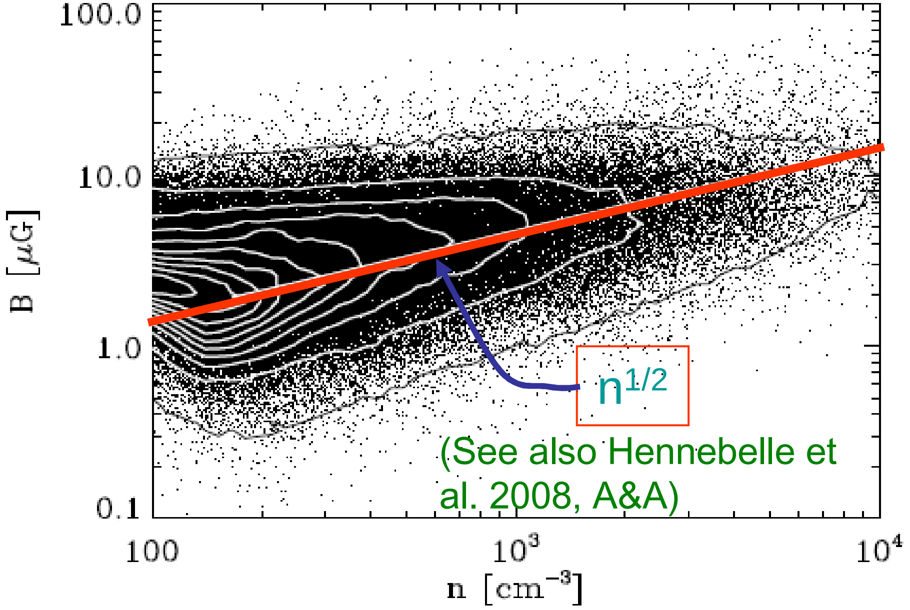
Converging flow setup



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

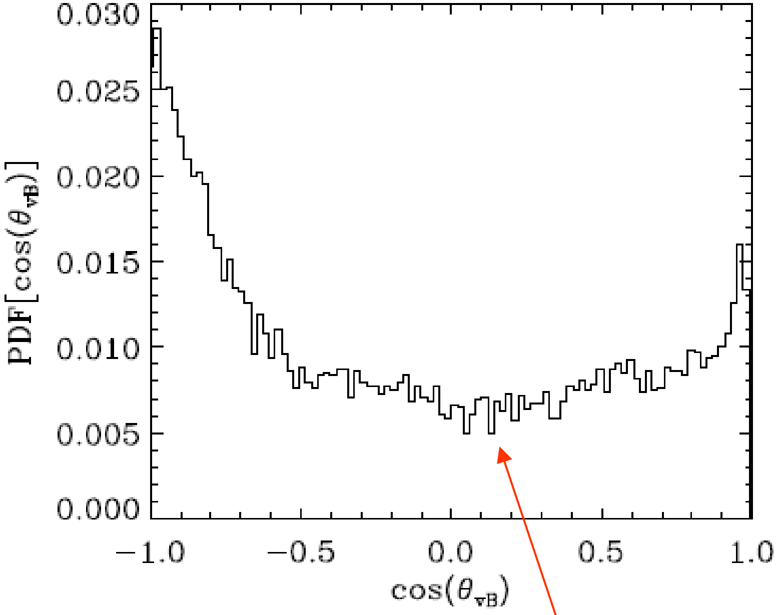
See also Inoue & Inutsuka (2008) for configuration with B perpendicular to compression.

B-n correlation

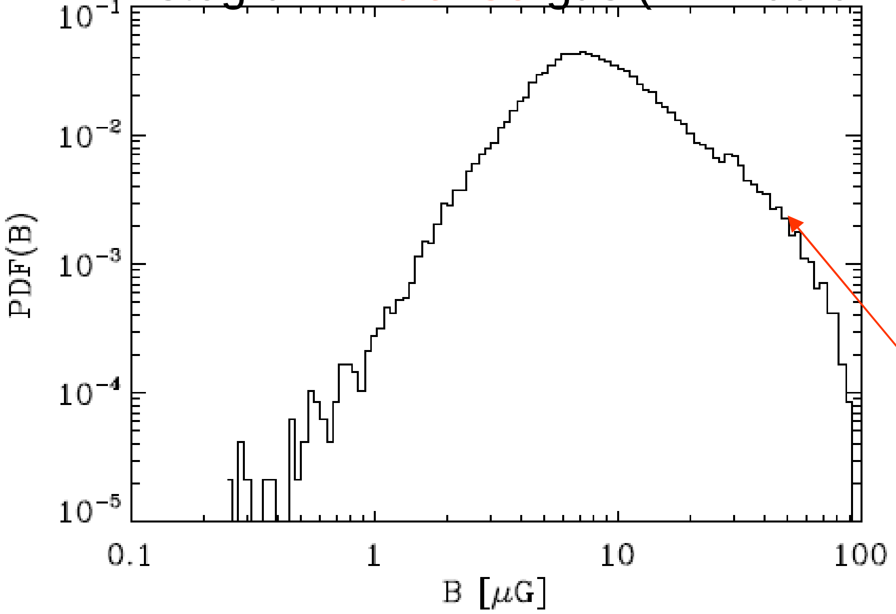


(See also Hennebelle et al. 2008, A&A)

B-v correlation



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)

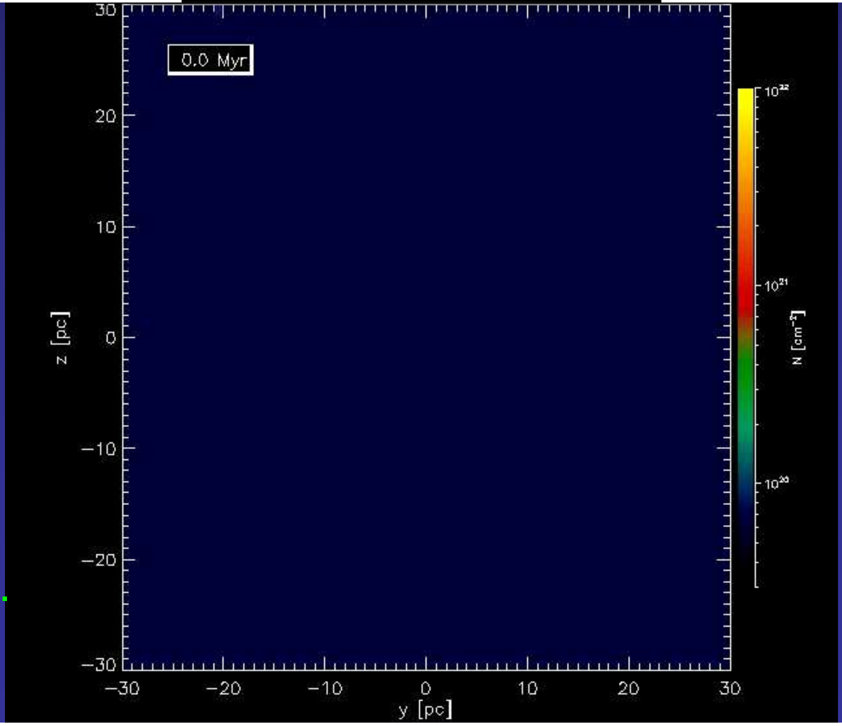
Three simulations with $\mu = 1.3$, 0.9, and 0.7, including AD.

Face-on view of column density.

Dots are sink particles.

$\mu = 0.9$

$\mu = 1.3$



$\mu = 0.7$

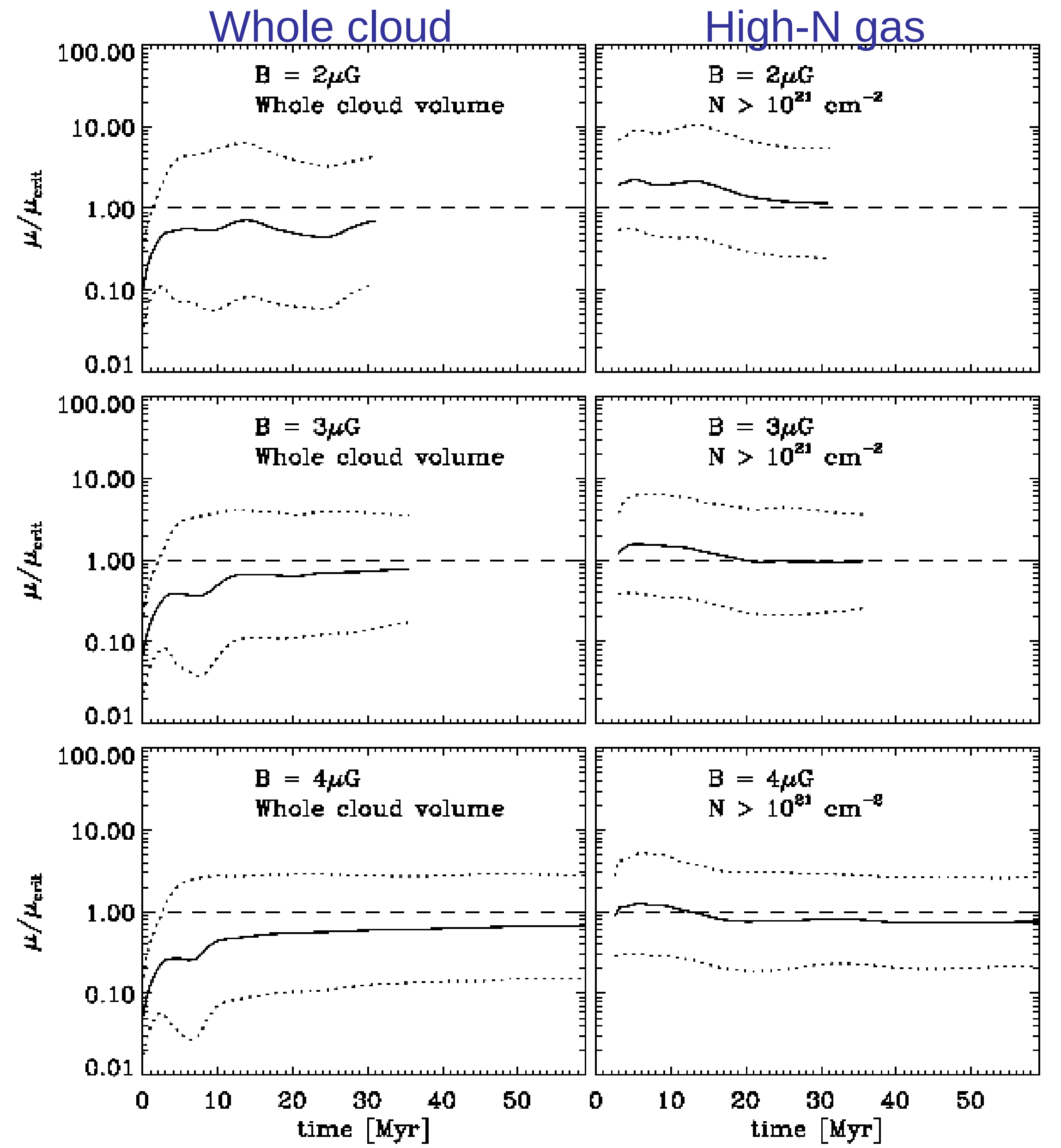
Vázquez-Semadeni et al. 2011, MNRAS, 414, 2511.

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

μ = 1.3

μ = 0.9

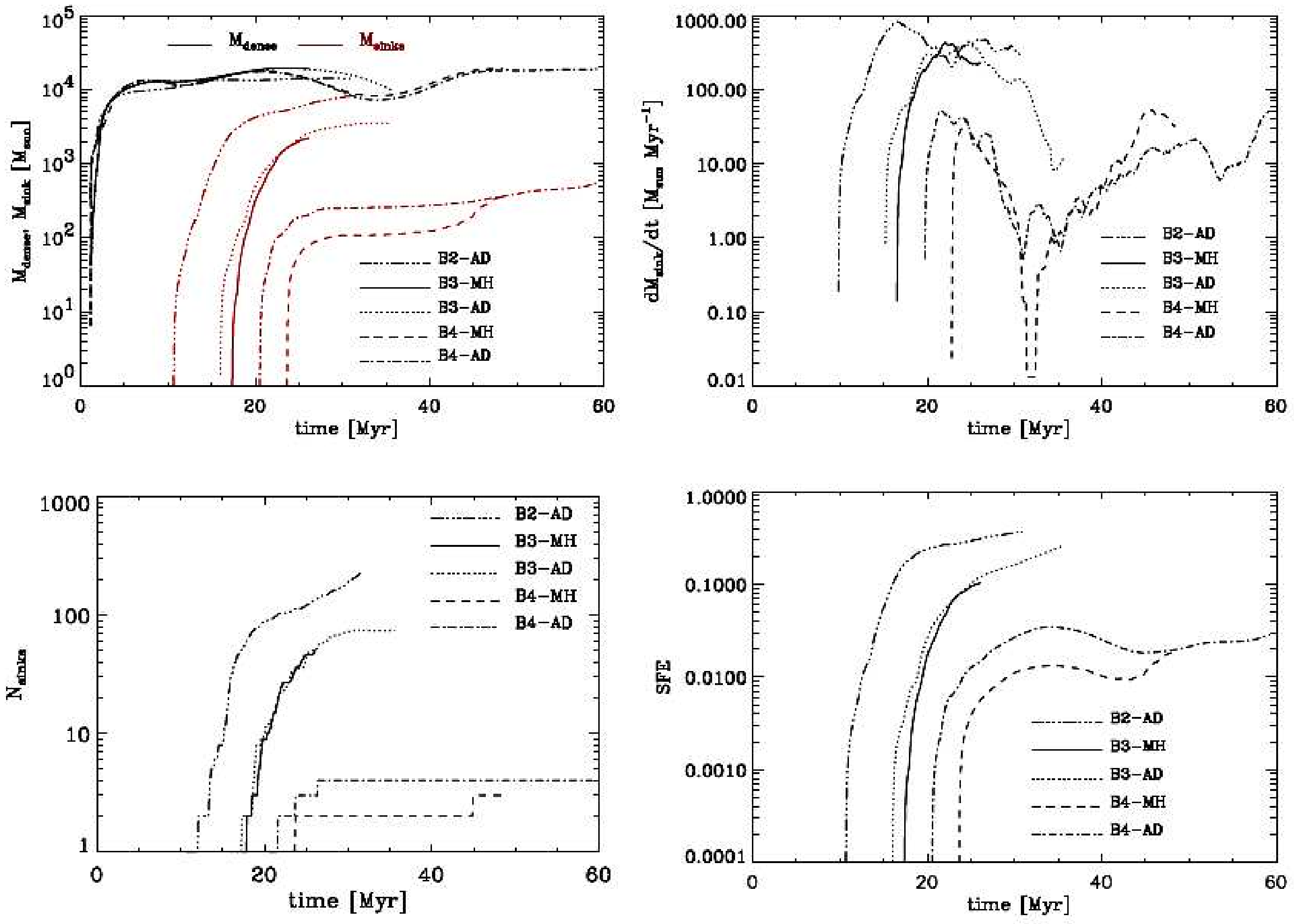
μ = 0.7



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

Vázquez-Semadeni et al. 2011, MNRAS, 414, 2511

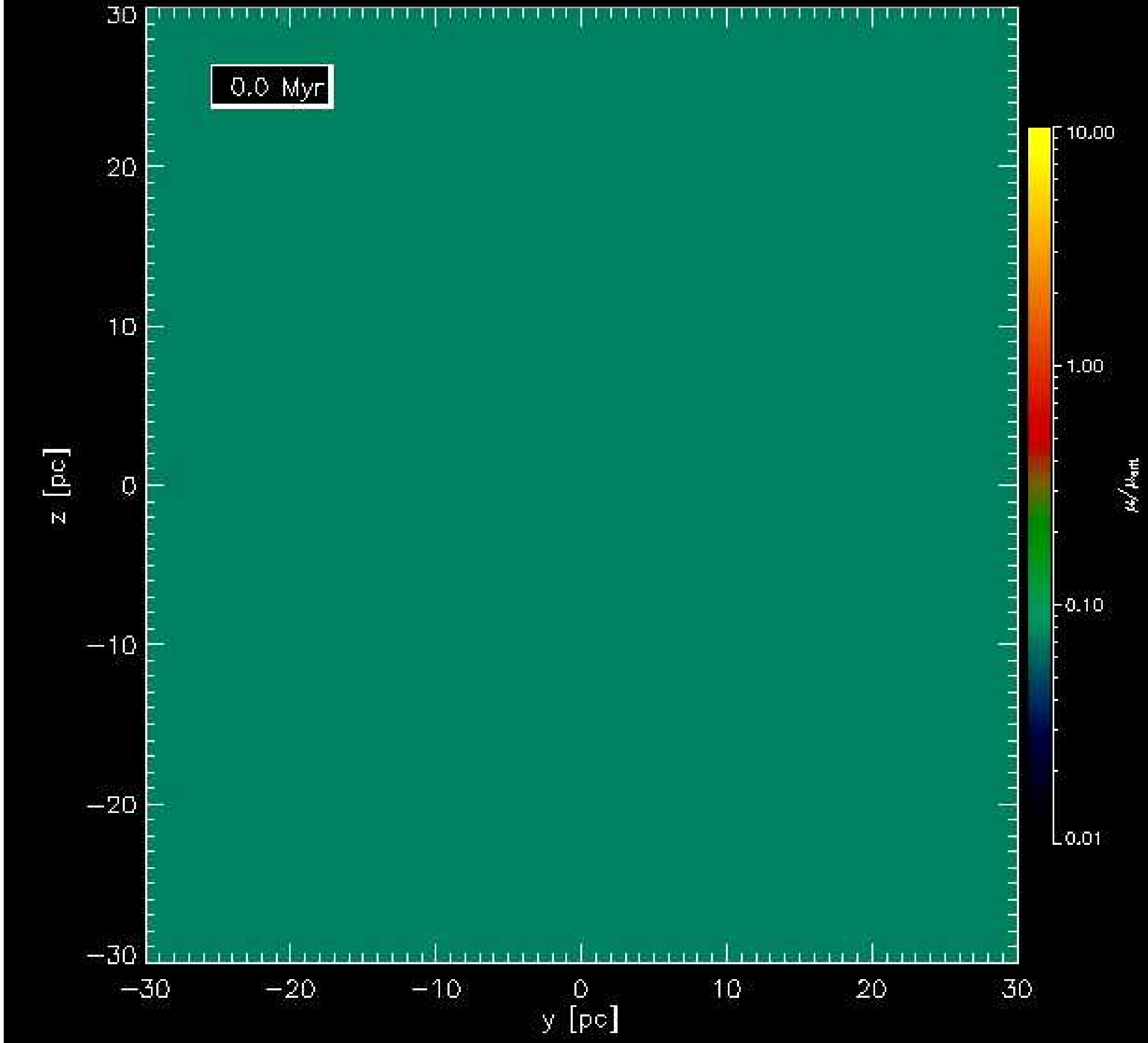
Evolution of gaseous and stellar masses, and of the SFR.



- Cloud mass nearly same in all cases.
- SFR of μ=0.7 case nearly shuts off.
- SFE of μ=0.9 and μ=1.3 cases not too different.
- Upon inclusion of stellar feedback, expect further SFE reduction, so favor higher-μ cases.

Vázquez-Semadeni et al. 2011, MNRAS, 414, 2511

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, 414, 2511

IV. REGULATION OF THE STAR FORMATION RATE

- If clouds are free-falling, one must confront the Zuckerman-Palmer (1974) conundrum:
  - Free-fall estimate of SFR:

$$\mathrm{SFR}_{\mathrm{ff}} \sim \frac{M_{\mathrm{mol}}}{\tau_{\mathrm{ff}}} \sim \frac{10^{9}\ M_{\mathrm{sun}}}{3\ \mathrm{Myr}} = 300\ M_{\mathrm{sun}}\,\mathrm{yr}^{-1}$$

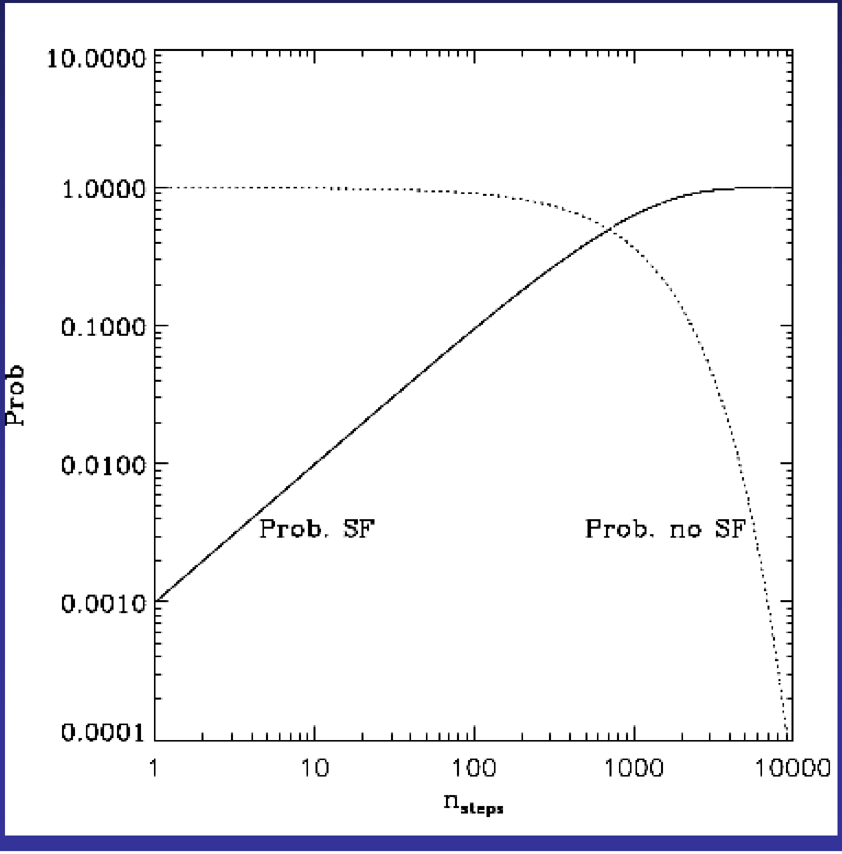
  - Observed rate is $\mathrm{SFR}_{\mathrm{obs}}$ ~ 2—3 $\mathrm{M}_{\mathrm{sun}}$ yr^{-1}; i.e., ~100x lower.

- I.e., need to reduce SFR from free-fall value to observed one (~1/100).

- Can stellar feedback do it?

- Simulations of cloud formation and evolution with OB star ionizing heating feedback and crude radiative transfer (Colín+2013, 435, 1701).
  - ART AMR+Hydro code (Kravtsov+2003)
  - A probabilistic SF algorithm:

    If n_{SF} is reached, create a stellar particle with probability p.
  - Repeat every coarse-grid timestep.
  - Probability of creating a stellar particle after n steps:



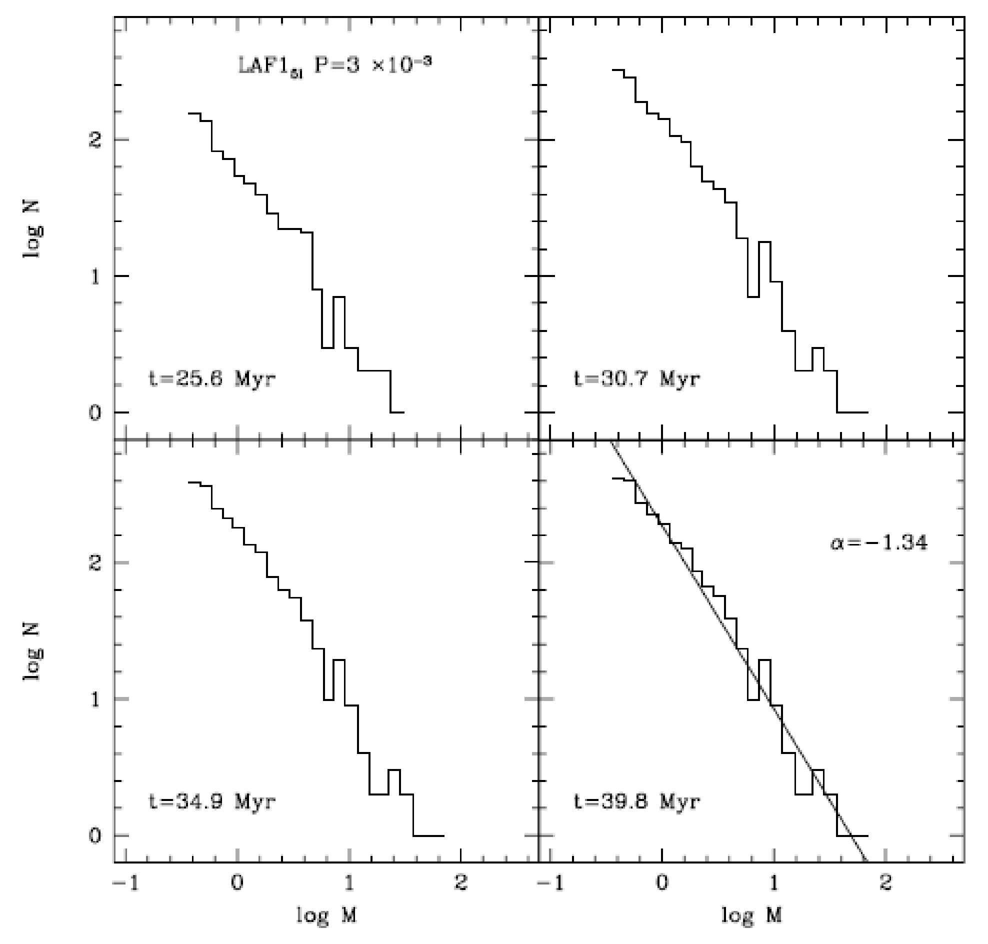
Stellar particles form with half the mass of the parent cell.

No refinement beyond n_{SF}

➔ The longer it takes to form a stellar particle in a collapsing site, the more massive the particle will be.

- Produces a power-law stellar-particle mass distribution.
- Value of p determines slope.

➔ Allows imposing a Salpeter-like IMF



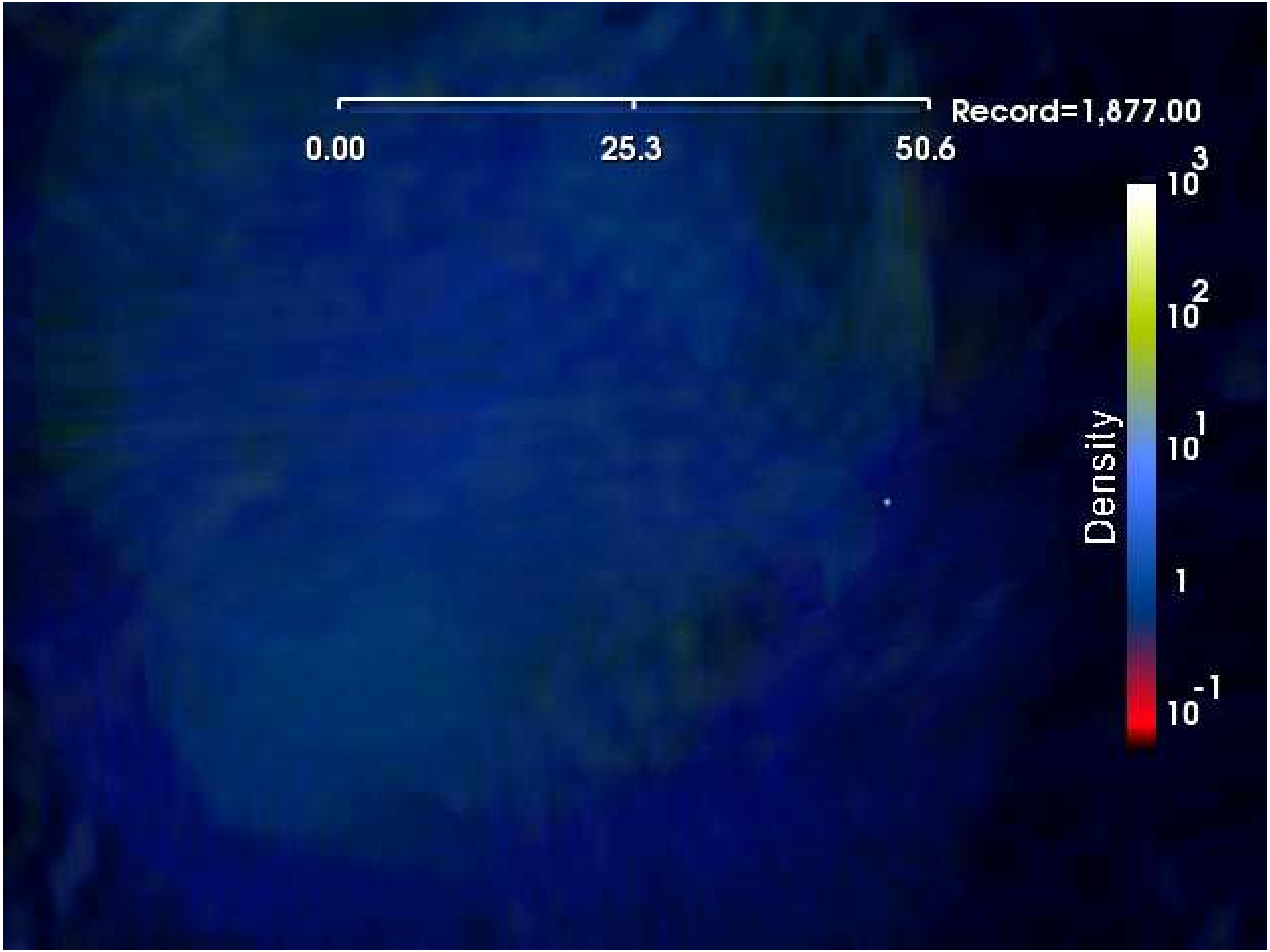
Stellar particles now represent individual stars, not small clusters.

- Feedback prescription: A “poor man’s radiative transfer” scheme:

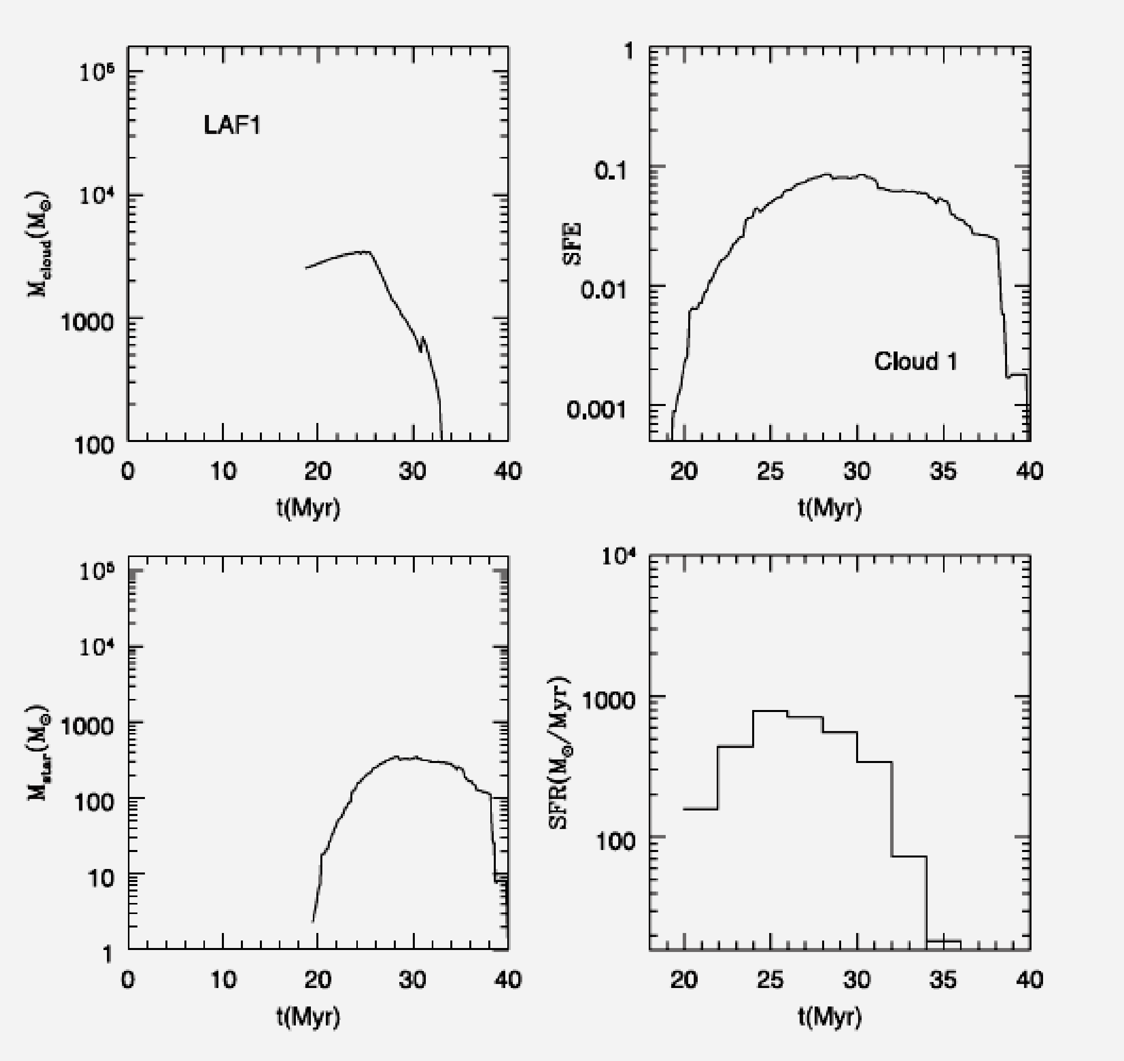
  - For each cell, compute distance *d* to each stellar particle.
  - Compute “characteristic density” as

$$n_{\mathrm{char}} = \sqrt{n_{\mathrm{star}} n_{\mathrm{cell}}}$$

  - Compute Strömgren radius R_s for star’s ionizing flux in medium of density n_{char}.
  - If $d < R_s$, set cell’s temperature to 10^4 K.
  - Scheme tested to produce correctly-growing HII regions.

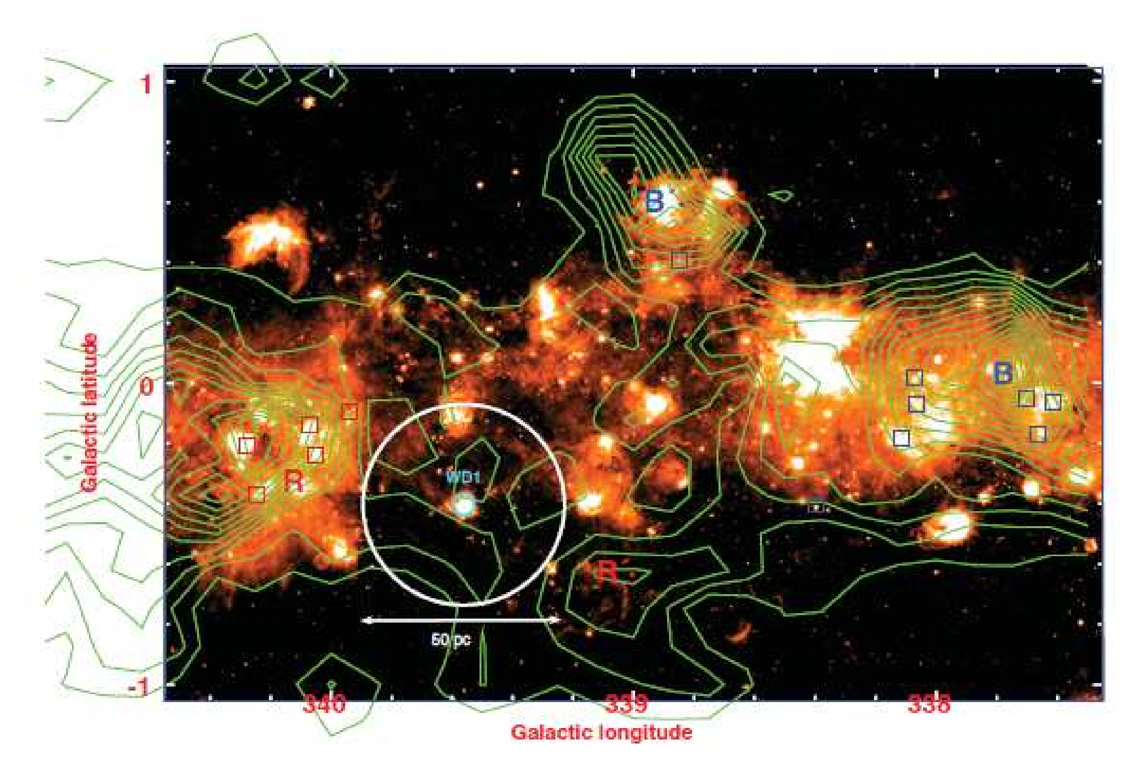

0.00
25.3
50.6
Record=1,877.00
Density
10^3
10^2
10^1
1
10^{-1}

- Effective termination of the SF episode (SFR goes to zero) in individual clouds.
- Maximum instantaneous SFE ~ 10%.



- Qualitatively consistent with observations of gas dispersal around clusters:

- Leisawitz+1989:
  - Clusters older than ~ 10 Myr do not have more than a few x10^3 M_{sun} within a 25-pc radius.
  - Surrounding molecular gas receding at ~ 10 km s^{-1}.



- Mayya+2012:

- CO, HI and Spitzer study of environment of Westerlund 1:

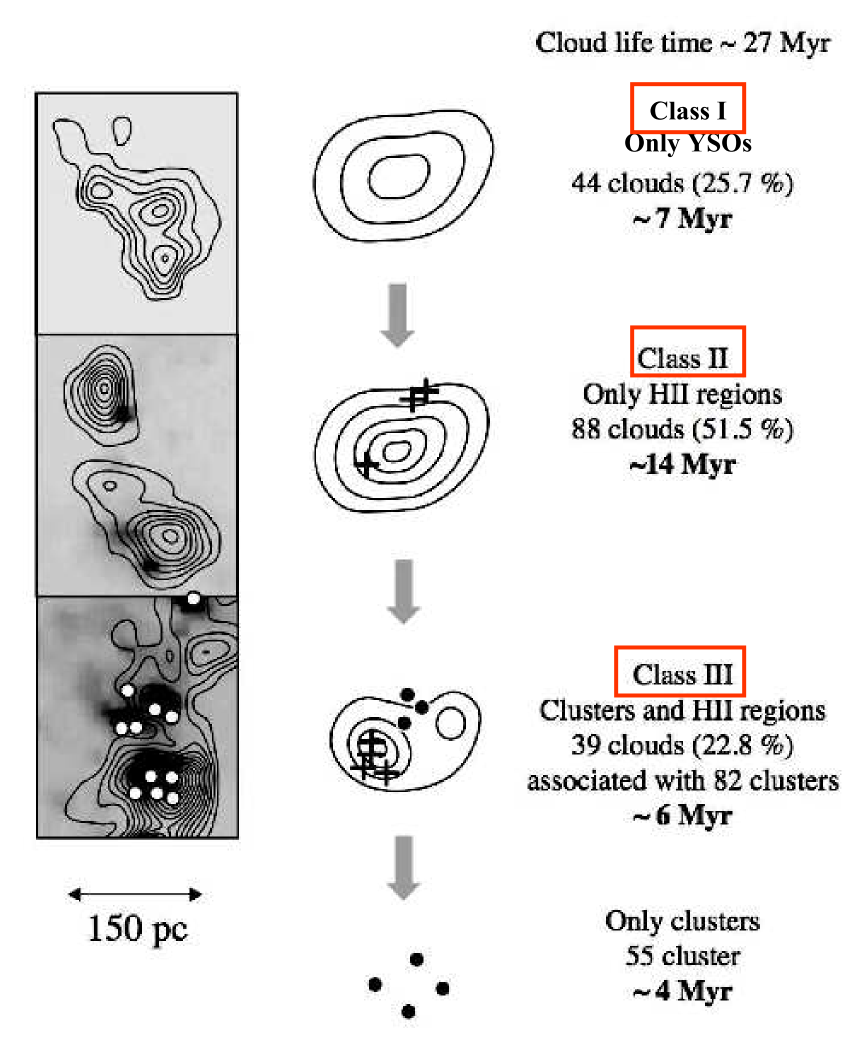
- Region of radius 25 pc contains only a few x10^3 M_{sun}. Much less than cluster.

- Surrounding molecular gas exhibits velocity difference ~ 15 km s^{-1}.

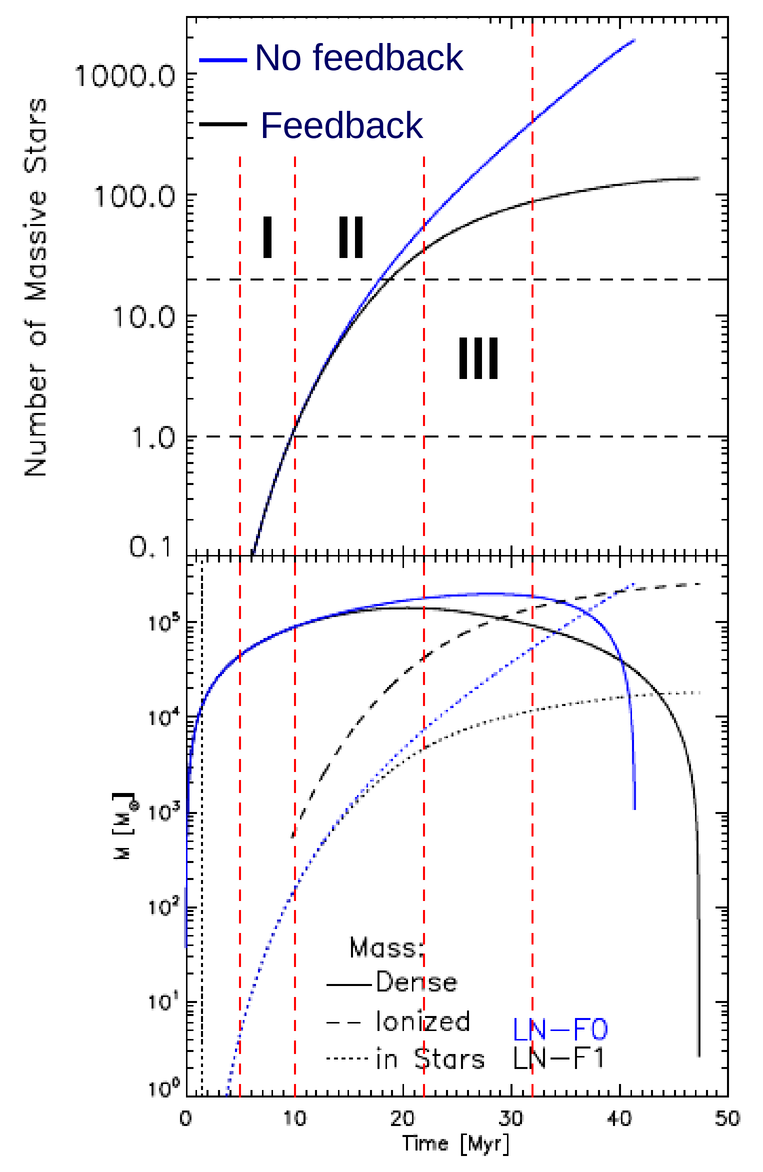
- In these simulations, feedback converts dense gas back into the warm phase, rather than sustaining the turbulence in the cold, dense gas.

- An analytical model (Zamora-Aviles+12) based on this scenario reproduces several observed evolutionary features of MCs.

– Evolution of stellar content for GMCs (R_{inf} = 100 pc → M ~ 10^5 M_{sun}):

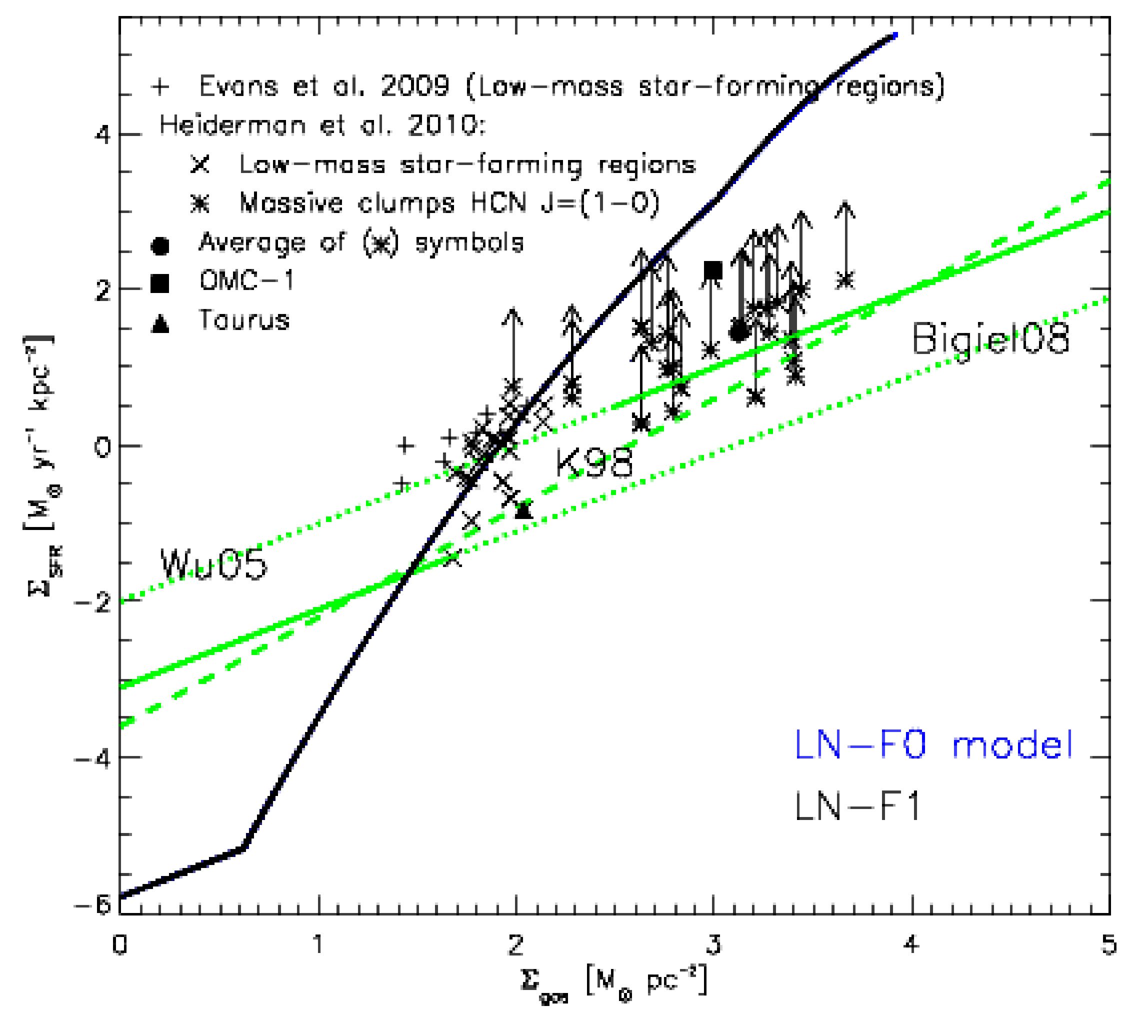


Kawamura+2009

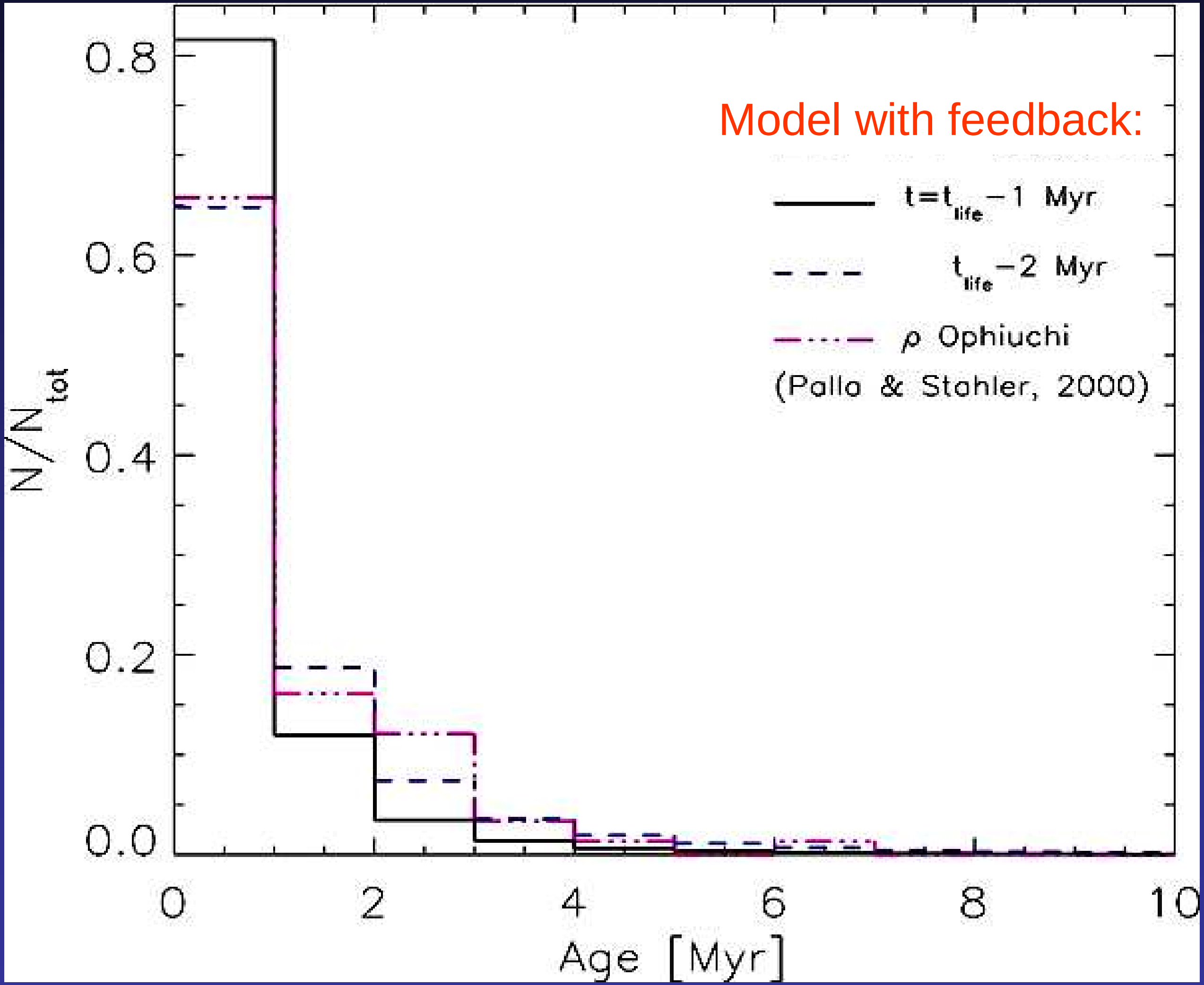


Zamora-Avilés+2012

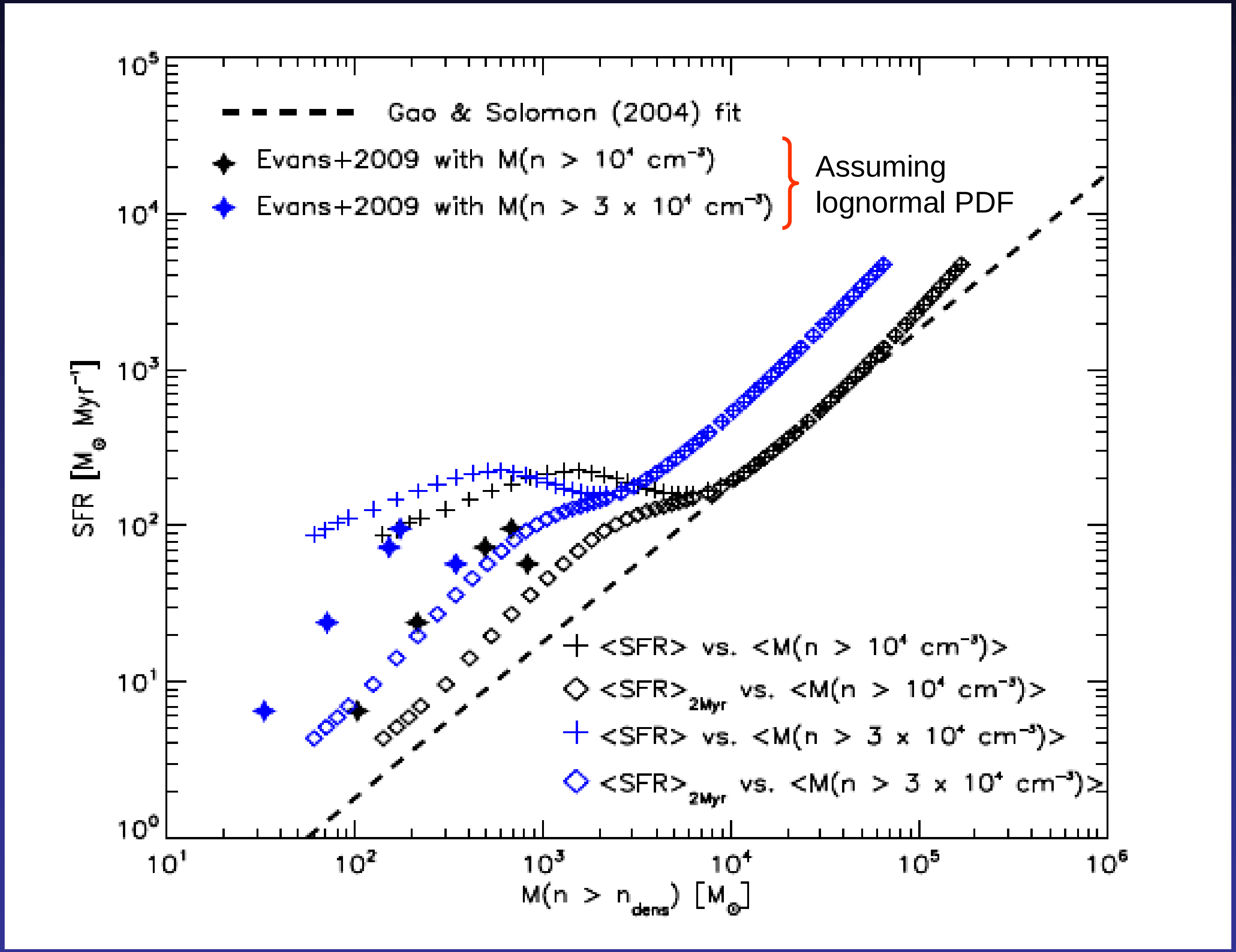
– Evolution of isolated clouds in the Kennicutt-Schmidt diagram (R_{inf} = 10 pc ➔ M ~ 2x10^3 M_{sun}):



- Stellar age histograms:

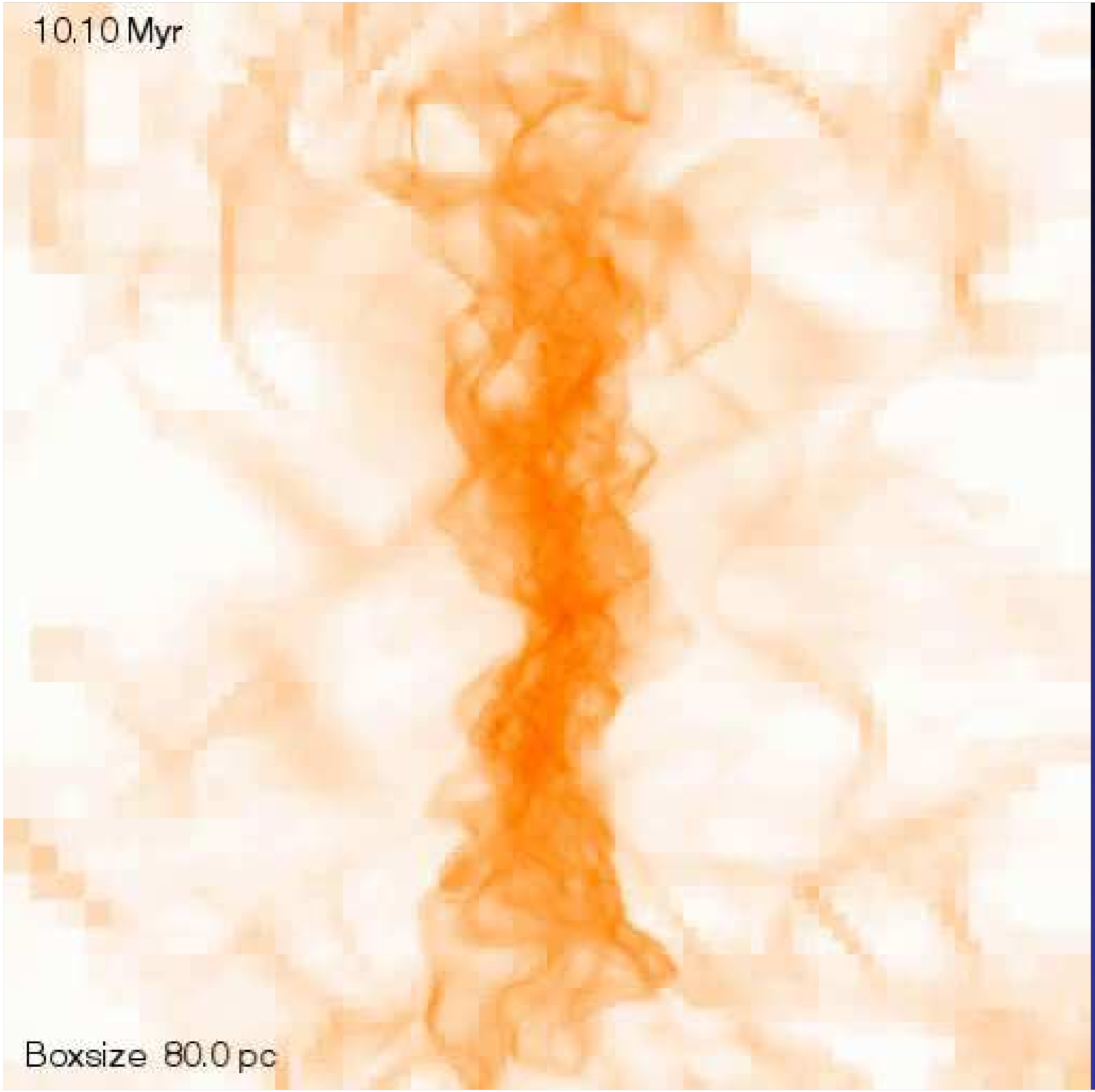


– SFR versus dense gas mass:



Zamora-Avilés & Vázquez-Semadeni, 2013, in prep.

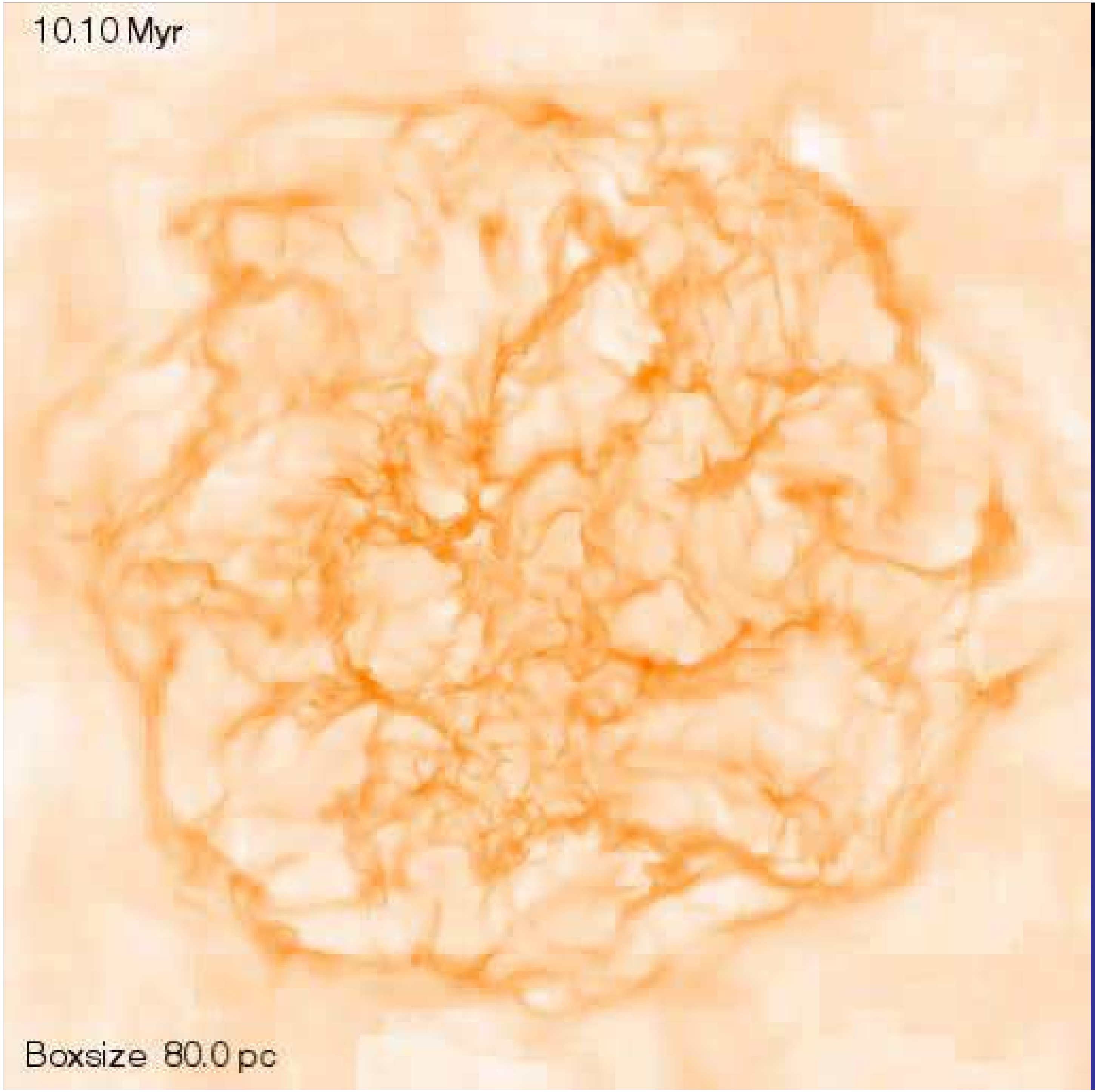
- Numerical simulations of molecular cloud formation with magnetic fields, self-gravity, sink particles and ionization heating (Zamora-Aviles et al., in prep).
  - Use FLASH code (AMR, MHD, self-gravity, sink particles, radiative transfer by Thomas Peters).
    - 10 refinement levels.
    - Refinement goal: resolution-independent sink-particle mass distribution:
      - Jeans criterion @ low ρ.
      - Constant-mass criterion @ high ρ.
    - No AD.



Edge-on view.

Sink particles colored by mass of most massive star:

- ● No massive stars
- ● 8 Msun < M < 12 Msun
- ● 12 Msun < M < 14 Msun



Edge-on view.

Sink particles colored by mass of most massive star:

- ● No massive stars
- 🟢 8 Msun < M < 12 Msun
- 🔵 12 Msun < M < 14 Msun

V. CONCLUSIONS

- Formation of 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 into clouds and cores.
  - Cloud and core boundaries are *phase transition fronts*.
  - Masses of clouds and cores evolve (generally increasing) with time.

- Under ideal MHD, core formation by compression within a larger cloud, implies

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

- Cold cloud assembly by WNM compression with a component along the magnetic field lines implies that

  the mass-to-flux ratio of the cold gas increases steadily.

- Dense clouds appear to become molecular, supercritical, and collapsing at roughly the same time.
  - Local collapse not mediated by AD.

- Magnetic decorrelation in cold atomic clouds and in clump cpres may be understood through diffusive processes or wave superposition.

- Properties of turbulent, magnetized clouds
  - Cores should initially have lower M2FRs than their envelopes.
  - $\vec{B}$ and $\vec{v}$ tend to be aligned, even for weak fields (B dragged by v).
  - At high densities ($n > 100$ cm^{-3}), $\langle B \rangle \sim n^{1/2}$, but with large scatter around mean trend.
    - Should expect large core-to-core fluctuations of B.
  - Stiff dependence of SFR on M2FR.
    - Magnetically subcritical clouds almost do not form stars, even with AD.
  - SFR probably regulated by destruction through stellar feedback, rather than by maintenance of equilibrium.

THE END