Interstellar Flow: A Mélange of Physical Processes

Enrique Vázquez-Semadeni
Centro de Radioastronomía y Astrofísica, UNAM, México

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

CRyA

Collaborators:

CRyA UNAM:

Javier Ballesteros-Paredes
Pedro Colín
Adriana Gazol
Gilberto Gómez
Jonathan Heiner

ABROAD:

Lee Hartmann (Michigan)
Fabian Heitsch (North Carolina)
Katharina Jappsen
Jongsoo Kim (KASI, Korea)
Ralf Klessen (Heidelberg)
Thierry Passot (OCA, France)
Dongsu Ryu (Chungnam U., Korea)

INTRODUCTION

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

- These processes 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 underlying physical processes.
  - Discuss their interaction in shaping the ISM phases.

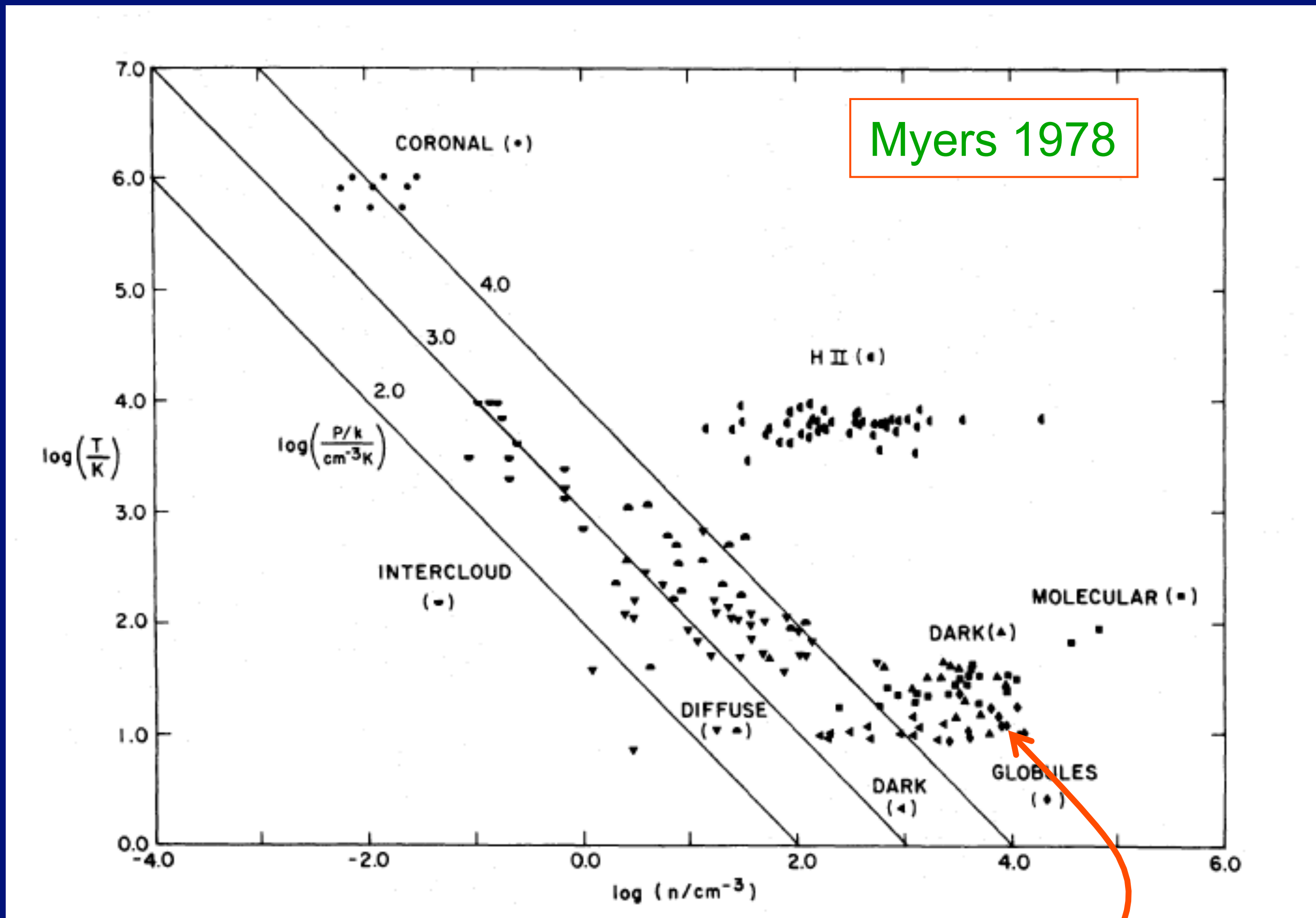
Brief summary of ISM structure:

- 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 continuum.

- Yet many kinds of structures are approximately at the same pressure:



- but not all... in particular, the molecular gas.

BASIC PHYSICAL PROCESSES

1. Velocity convergence:

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 have a ***convergence*** of the velocity field into the region.

However, most models of clouds have relied on the notion of static equilibrium.

2. ISM thermodynamics.

(See discussion in Vázquez-Semadeni+2003, LNP, 614, 213.)

A key property of the atomic ISM is that it is *thermally unstable* in some regimes (Field 1965).

The internal energy equation (per unit mass) is

$$\frac{de}{dt} = -(\gamma - 1)e\nabla \cdot u + \Gamma - n\Lambda,$$

where *n* = number density, in units of cm^{-3}, ($\rho = \mu\, m_H\, n$)

Γ is the (radiative) heating function, and

Λ is the (radiative) cooling function.

Define *thermal equilibrium* by the condition $\Gamma = n\Lambda.$

In the absence of local energetic events, the heating function to zeroth order satisfies $\Gamma \approx \text{cst.}$

The interstellar cooling function

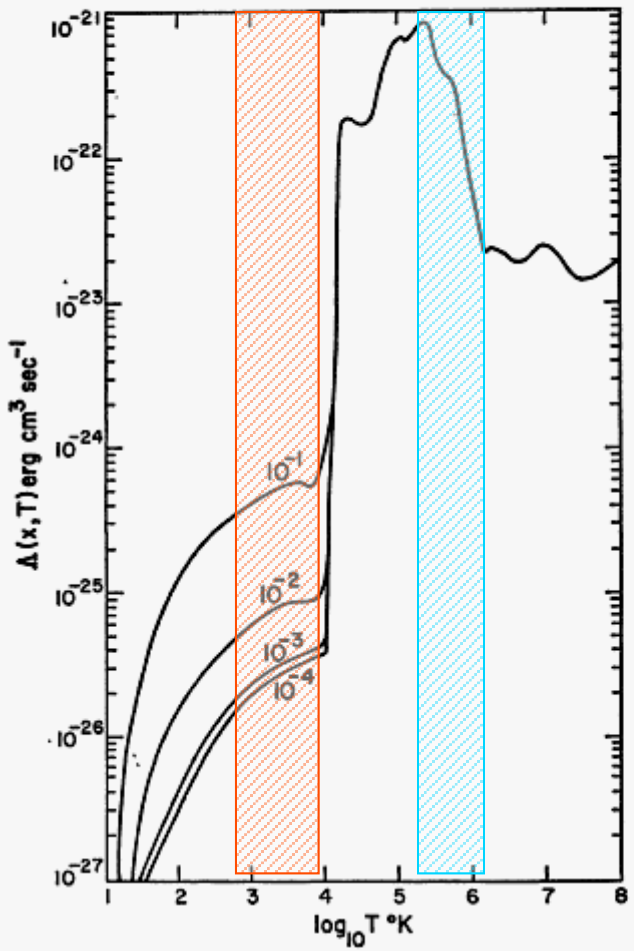


FIGURE 2. The interstellar cooling function $\Lambda(x, T)$ for various values of the fractional ionization x. The labels refer to the values of x.

TI under the isobaric criterion.

TI under the isochoric and the isobaric criteria.

Dalgarno & McCray 1972

- The isochoric mode.

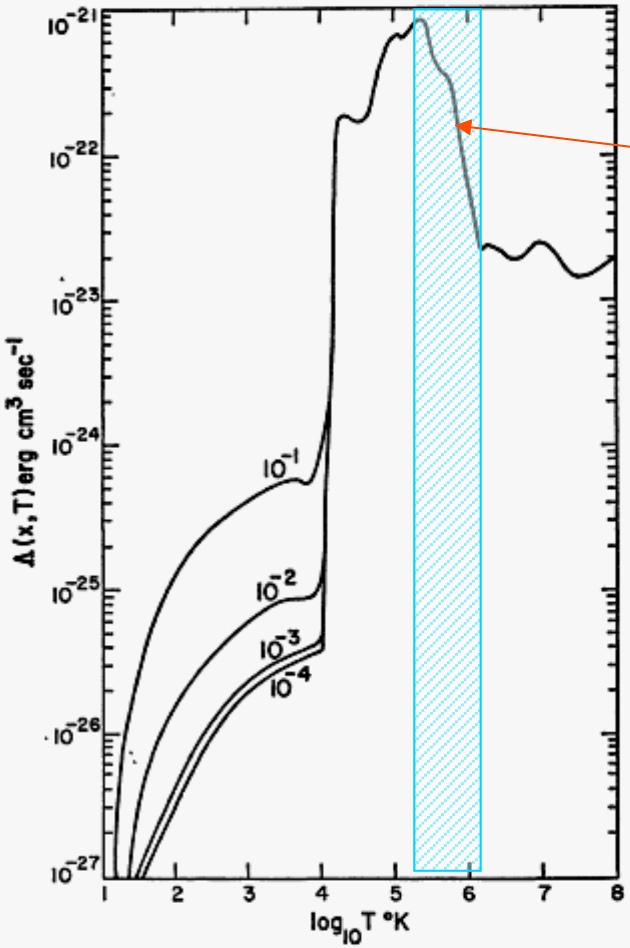


FIGURE 2. The interstellar cooling function $\Lambda(x, T)$ for various values of the fractional ionization x. The labels refer to the values of x.

(Note that the cooling rate per unit volume is $L = n^2 \Lambda$.)

The condition for instability is (Field 1965):

$$\left(\frac{\partial \Lambda}{\partial T}\right)_\rho < 0.$$

At cst. ρ, if T ↑, Λ ↓, so T ↑ even more. ➔ Runaway increase.

This mode is relevant at large scales, so that

$$\tau_{\mathrm{cool}} < \tau_{\mathrm{cross}},$$

where τ_{cool} = cooling time

τ_{cross} = crossing time

and the flow can maintain ρ = cst.

- The isobaric mode.

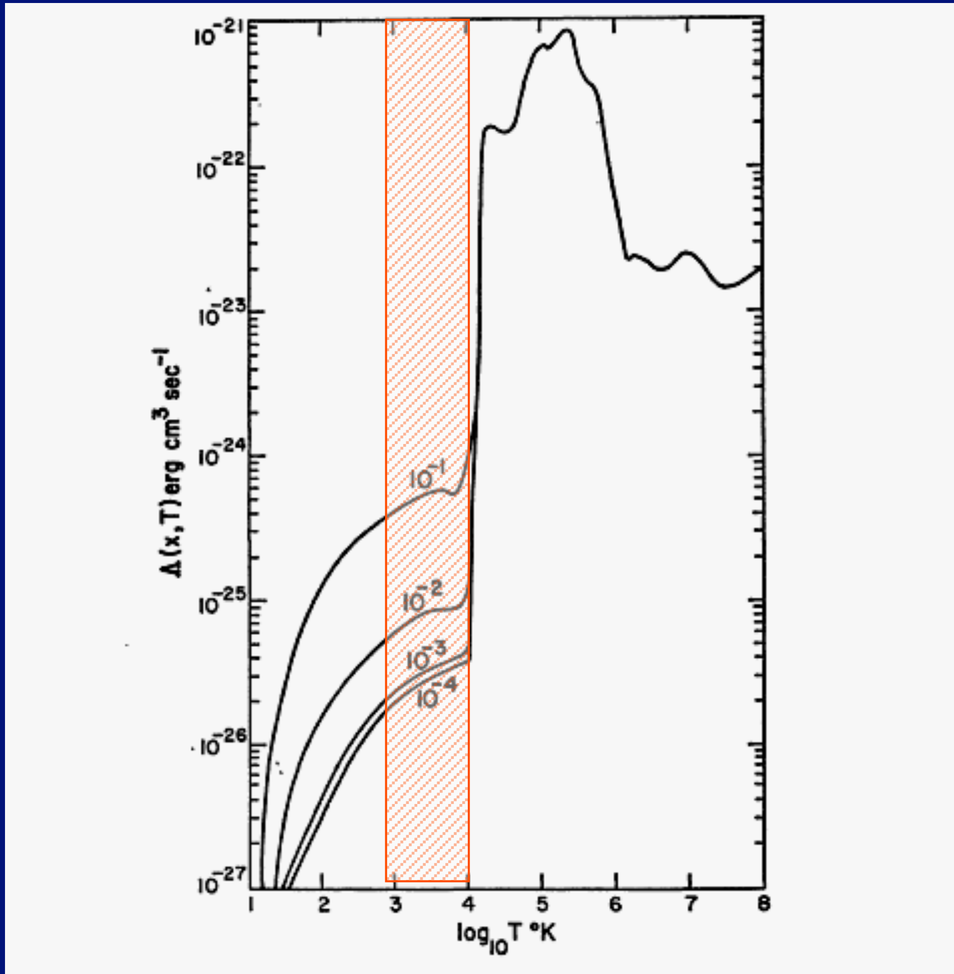


FIGURE 2. The interstellar cooling function $\Lambda(x, T)$ for various values of the fractional ionization x. The labels refer to the values of x.

The condition for instability is (Field 1965):

$$\left(\frac{\partial \Lambda}{\partial T}\right)_P < 0.$$

At cst. P, if T↑ , Λ↓, so T↑ even more. ➔ Runaway increase.

The growth of this mode can really operate isobarically if

$$\tau_{\rm cool} > \tau_{\rm cross},$$

so that the flow can maintain

P ~ cst

by moving the gas to change ρ and equalize P.

This mode is easiest to understand using the thermal equilibrium condition

$$\Gamma(\rho, T) = \frac{\rho}{\mu}\Lambda(\rho, T),$$

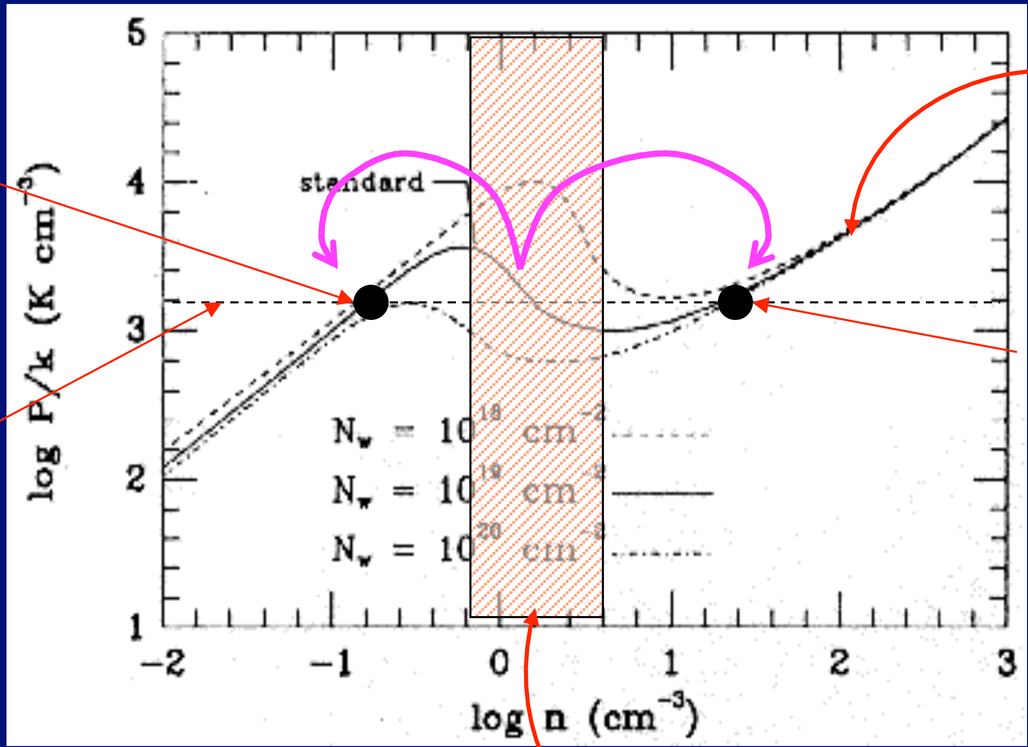
to eliminate the temperature from the ideal gas equation of state, to write

$$P = P(\rho) \equiv P_{\mathrm{eq}}(\rho).$$

– Due to the forms of the cooling and heating, the behavior of P_{eq} is:

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

– Where $dP/d\rho < 0$, the gas is unstable under the isobaric criterion:

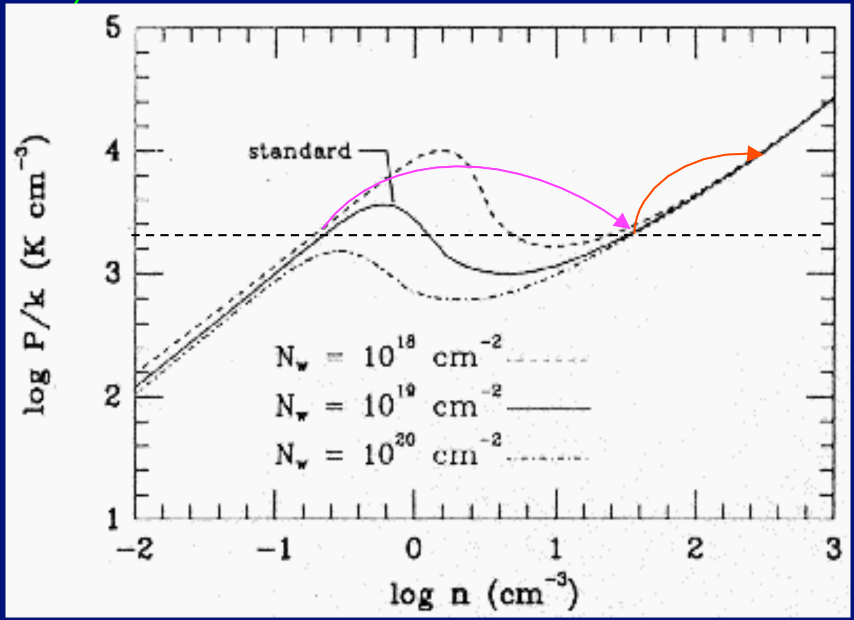
If ρ ↑ , P ↓ , and the fluid parcel is even further compressed.

Runaway compression until $dP/d\rho > 0$ again.

The flow segregates into a cold (~100 K) dense and a warm (~10^4 K) diffuse phase.

– The presence of turbulence adds complexity to the process.

- Transonic compressions in the linearly stable WNM can ***nonlinearly*** trigger a transition to the CNM… (Hennebelle & Pérault 1999; Koyama & Inutsuka 2000).

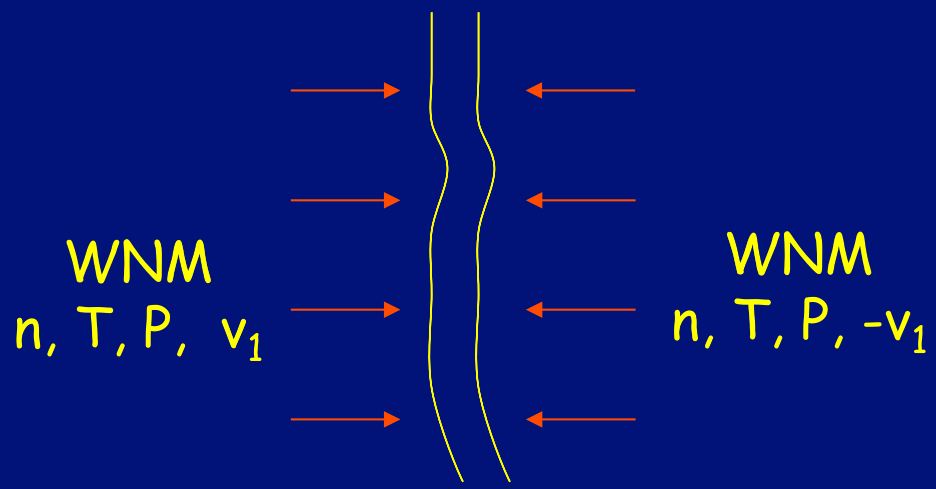


- … and, aided by gravity, an overshoot to molecular cloud conditions (Hartmann+2001; Vázquez-Semadeni+2007; Heitsch & Hartmann 2008).
  – The relevant scale of condensation in this case is that of the compressive wave, not the most unstable (small) scale of the linear case.

- When a dense cloud forms out of a compression in the WNM, it "automatically"

  - acquires mass;

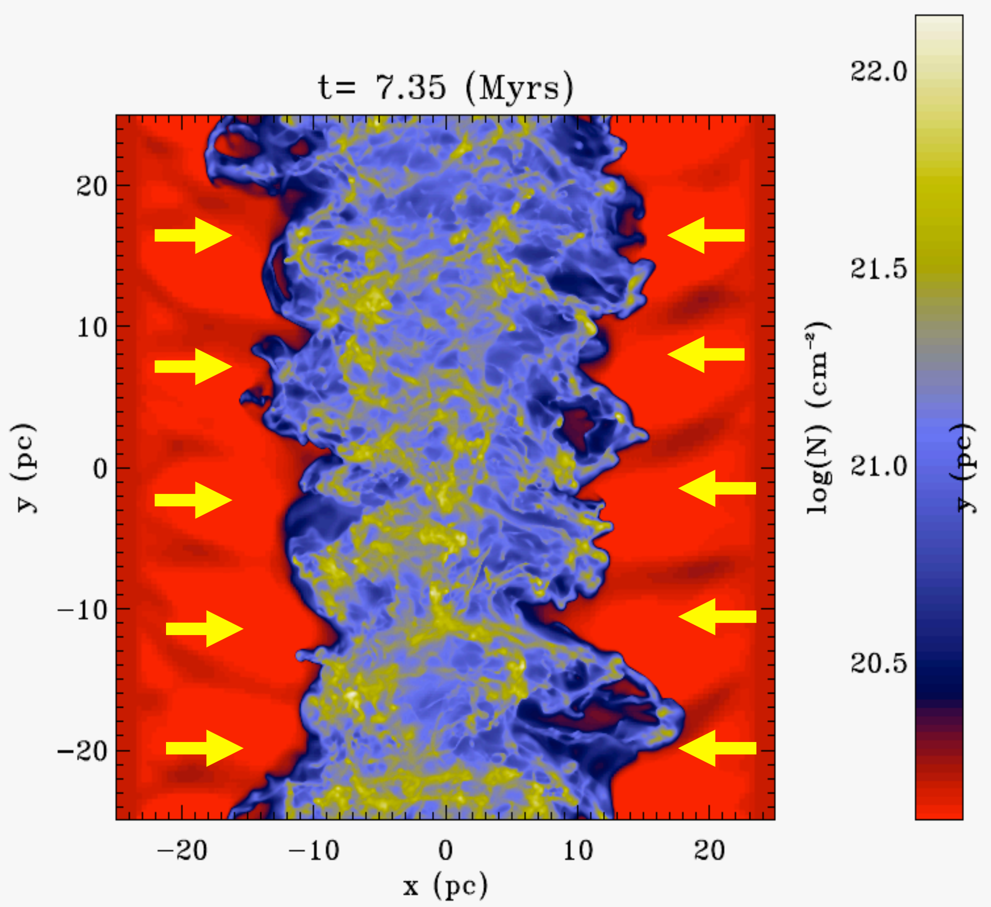
  - acquires turbulence (through TI, NTSI, KHI? – Vishniac 1994; Walder & Folini 1998, 2000; Koyama & Inutsuka 2002, 2004; Audit & Hennebelle 2005; Heitsch et al. 2005, 2006; Vázquez-Semadeni et al. 2006).

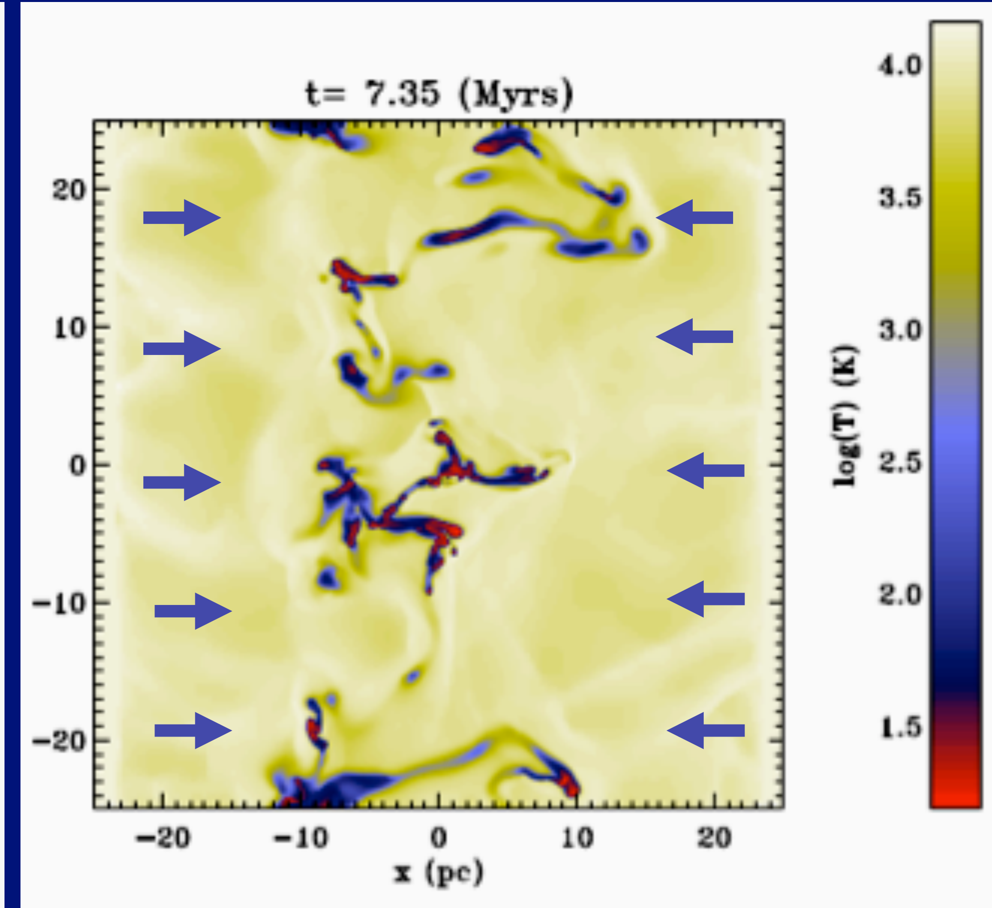


- The compression may be driven by global turbulence, large-scale instabilities, etc.

  - Not restricted to small scales in the ISM!

Cold, dense cloud formation simulation, 5 μG field, no gravity; RAMSES code (Hennebelle+08, A&A, 486, L43)





Edge-on view

3. Turbulence:

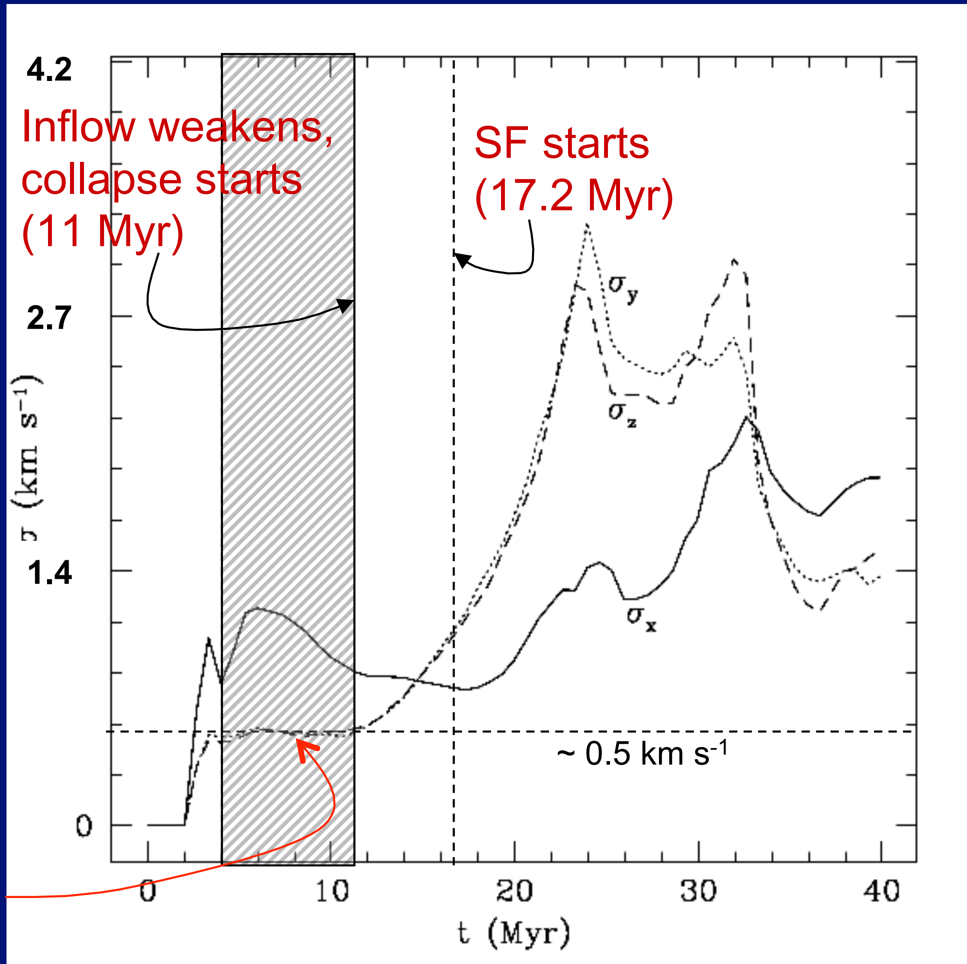
- The Reynolds number in the ISM is typically > 10^6 (e.g., Elmegreen & Scalo 2004);
  ➔ Turbulent flow.

- The flow in the WNM has a velocity dispersion $\sigma \sim 10$ km s^{-1} (e.g., Heiles & Troland 2003) and $T \sim 10^4$ K ➔ $c_s \sim \sigma$;
  ➔ Transonic flow: $M_s \sim 1$.

- In the CNM, $\mathcal{M} \sim$ a few (Heiles & Troland 2003);
  ➔ *Moderately* supersonic flow.

– Initial accretion-driven turbulence is *transonic*.

- Strongly supersonic velocities appear *later*, and because of gravitational contraction.



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

(Vázquez-Semadeni et al. 2007)

3. Turbulence:

- The Reynolds number in the ISM is typically > 10^6 (e.g., Elmegreen & Scalo 2004);

  ➔ Turbulent flow.

- The flow in the WNM has a velocity dispersion $\sigma \sim 10$ km s^{-1} (e.g., Heiles & Troland 2003) and $T \sim 10^4$ K ➔ $c_s \sim \sigma$;

  ➔ Transonic flow: $M_s \sim 1$.

- In the CNM, $\mathcal{M} \sim$ a few (Heiles & Troland 2003);

  ➔ Moderately supersonic flow.

- In molecular clouds, $\sigma \sim$ a few km s^{-1}, $c_s \sim 0.2$ km s^{-1};

  ➔ Strongly supersonic flow.

  (or is it, really?)

- In a supersonically turbulent flow, turbulence produces density fluctuations, which may constitute clouds and their substructure (von Weizsacker 1951, Sasao 1973, Elmegreen 1993, Ballesteros-Paredes+1999).

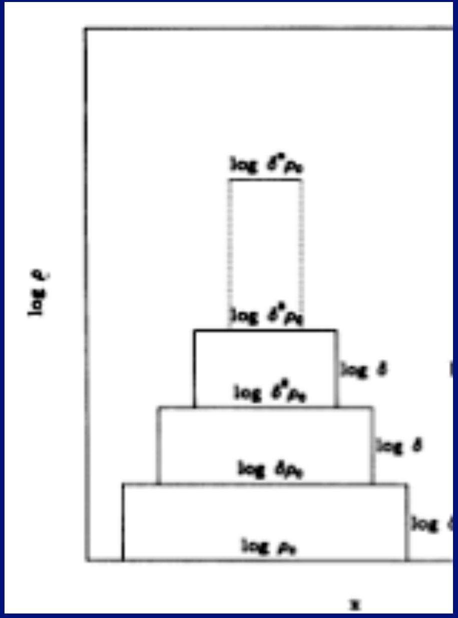
- The probability density function (PDF) of these fluctuations
  - Is the simplest (e.g., one-point) statistic for a compressible flow.
  - Is relevant for understanding the formation of density fluctuations.
  - For isothermal flows, it develops a lognormal shape (Vázquez-Semadeni 1994).

– Produced by a field of supersonic compressions:

- E.g., for isothermal, hydro shocks, the density jump: $\rho_2/\rho_1 = \mathcal{M}_s^2$, where $\mathcal{M}$ = Mach # in upstream gas.

- A turbulent flow contains a distribution of velocity differences.

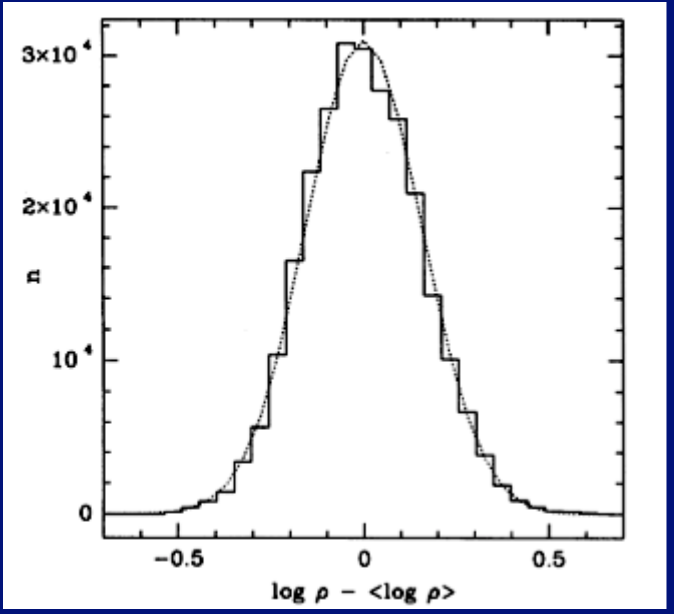
- At a given location, a succession of compressive waves produces the instantaneous density value.



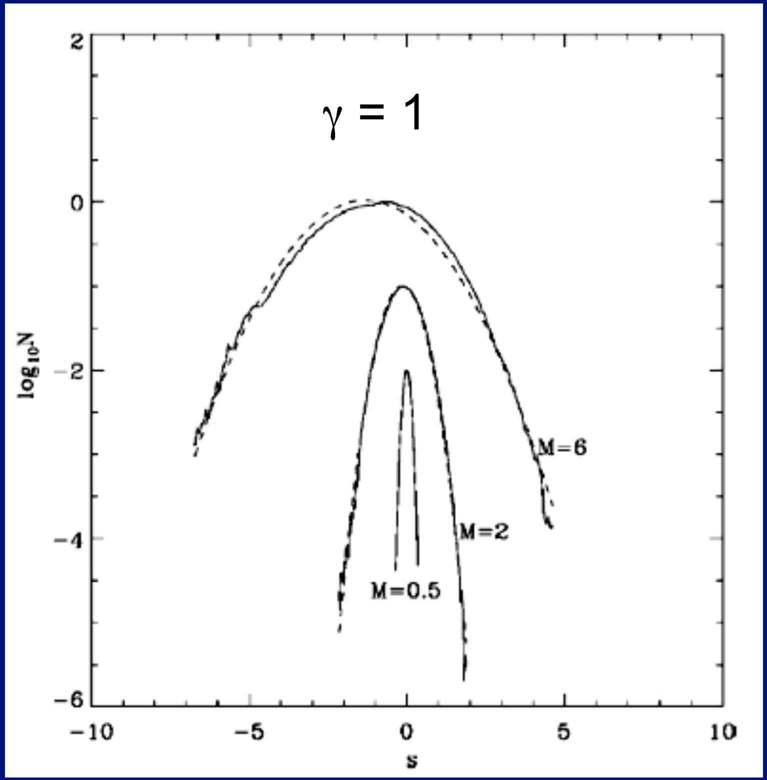
In isothermal flows:

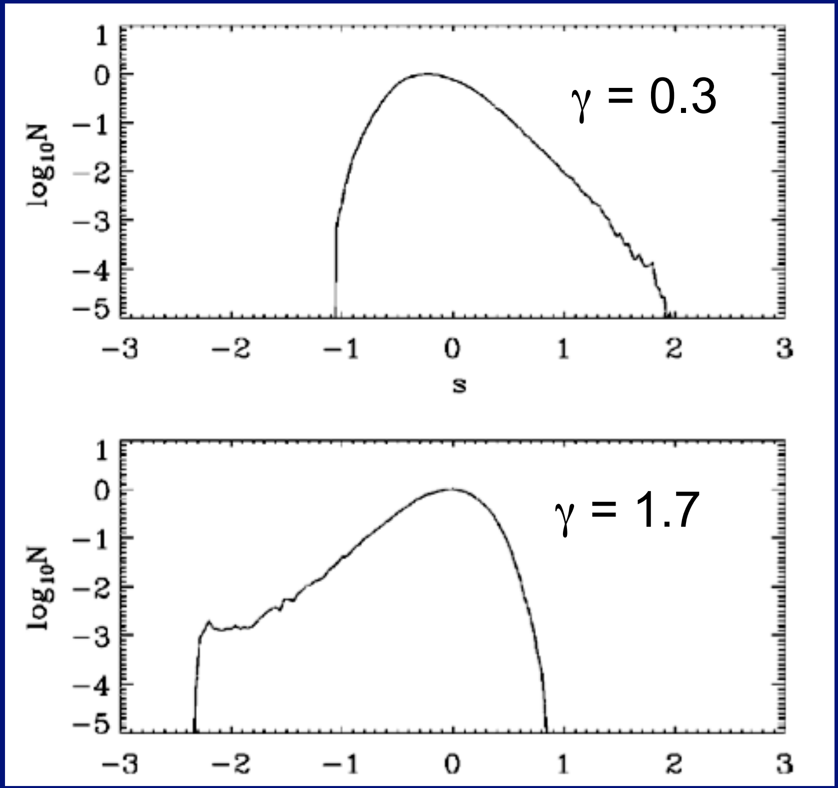
lognormal distribution

(Vázquez-Semadeni 1994)



– For general polytropic ($P \sim \rho^{\gamma}$) flows:



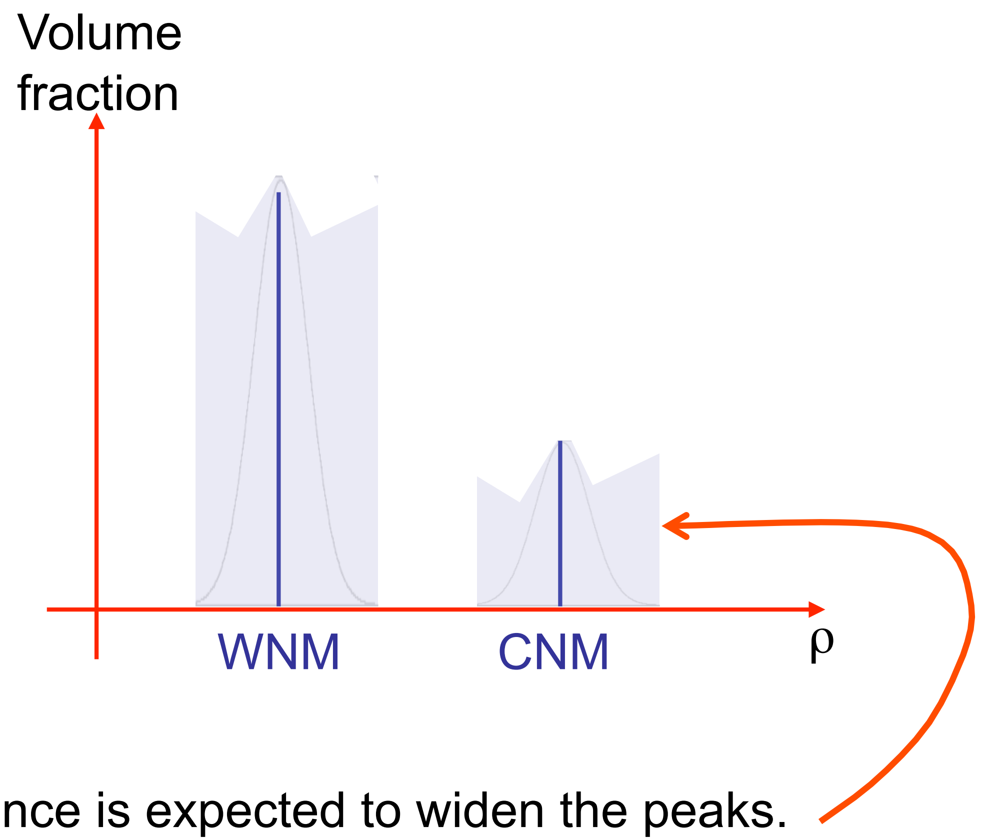


- There is a near symmetry $s \rightarrow -s$, $\gamma \rightarrow 2-\gamma$:

1D simulations

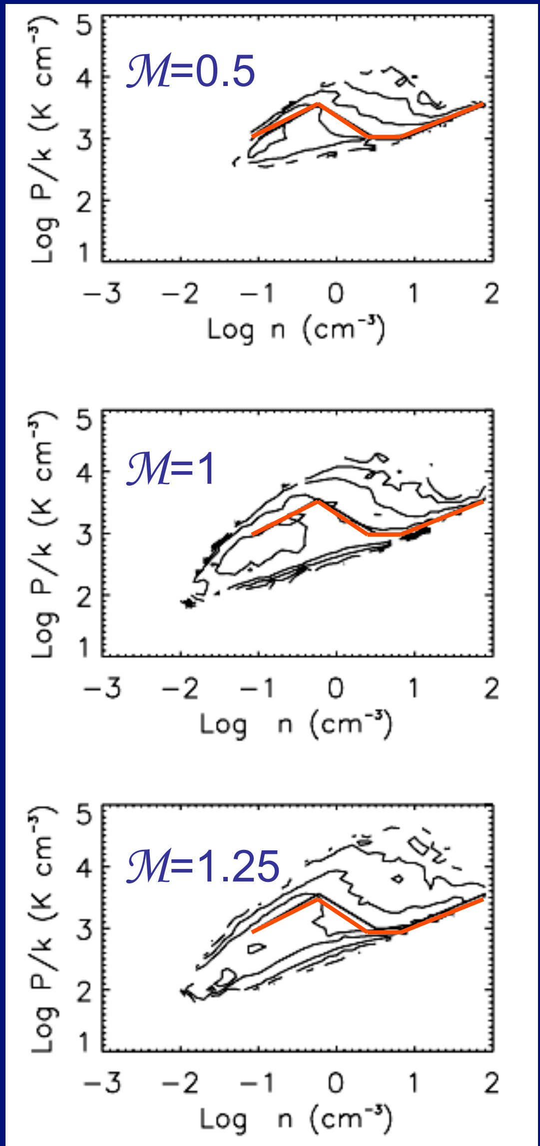
Passot & Vázquez-Semadeni 1998

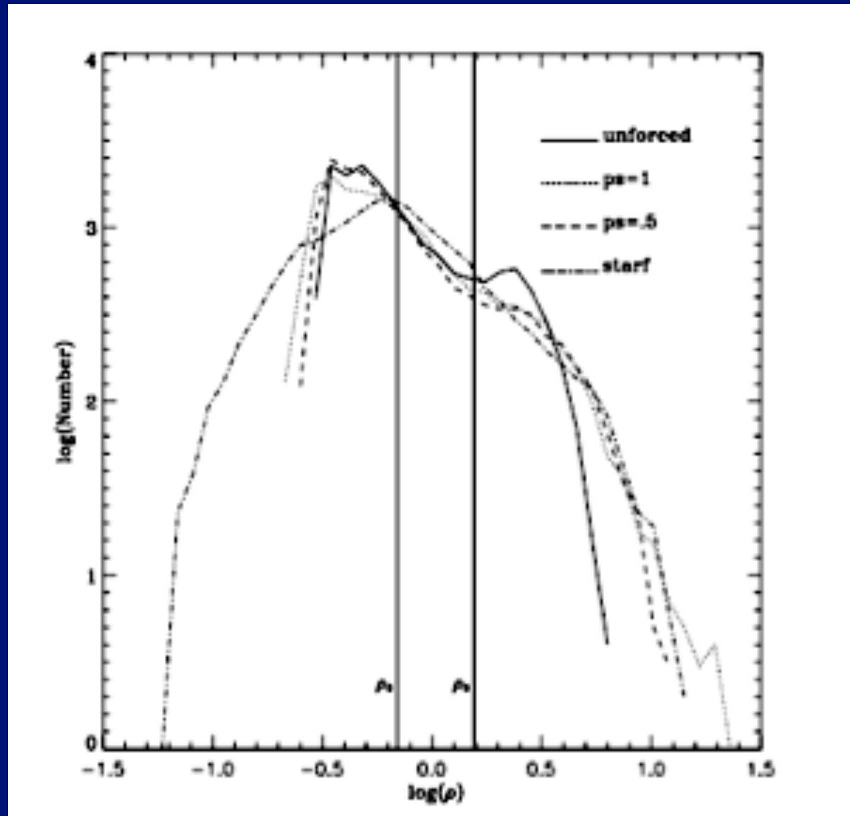
- In the thermally bistable WNM, in perfect pressure equilibrium, expect a two-δ-function PDF.



- Turbulence is expected to widen the peaks.
  - Because of its mixing nature

- In 2D simulations of Fourier-driven turbulence that forgo the polytropic assumption (i.e., solve the energy equation):
  - P strays away from P_{eq} where $\tau_{cool} > \tau_{cross}$.

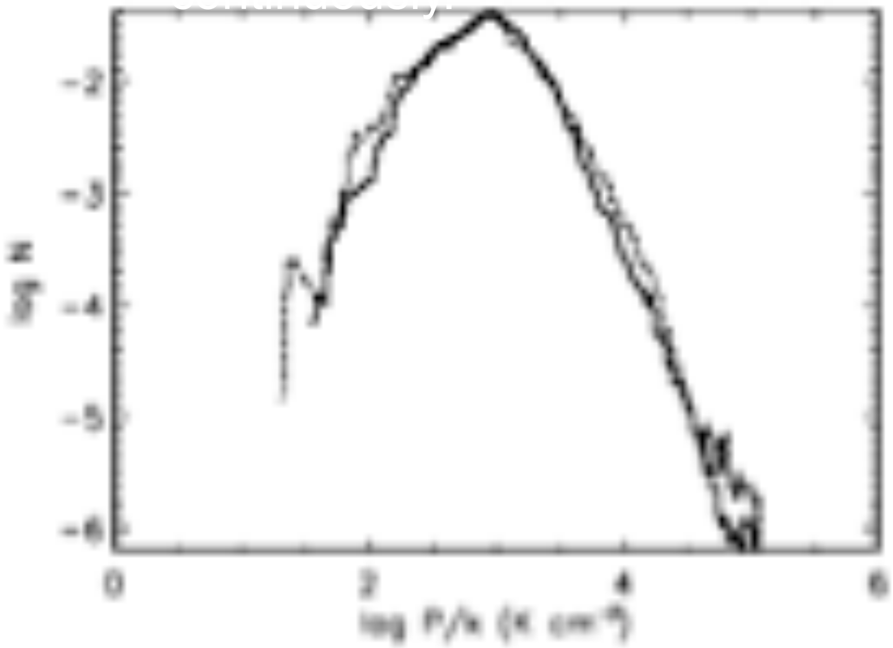




Bimodality erased to various levels by turbulence (Vázquez-Semadeni+2000)

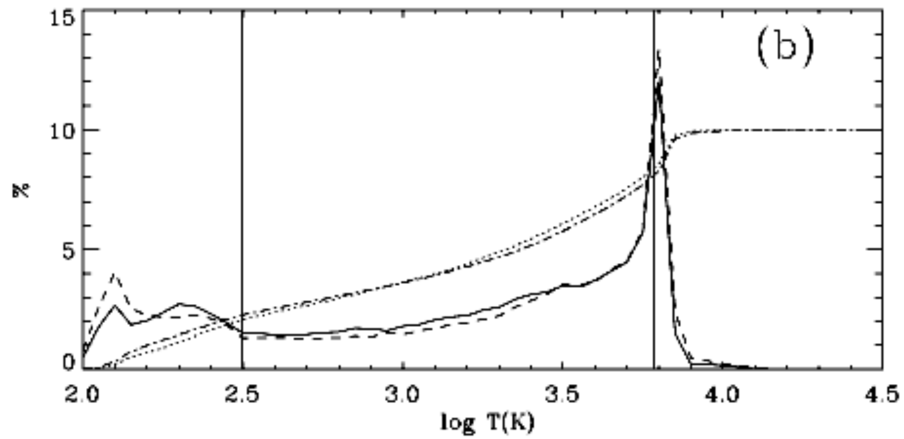
Gazol, VS & Kim, 2005, ApJ, 630, 911

- P PDF does not show bimodality because P varies continuously.



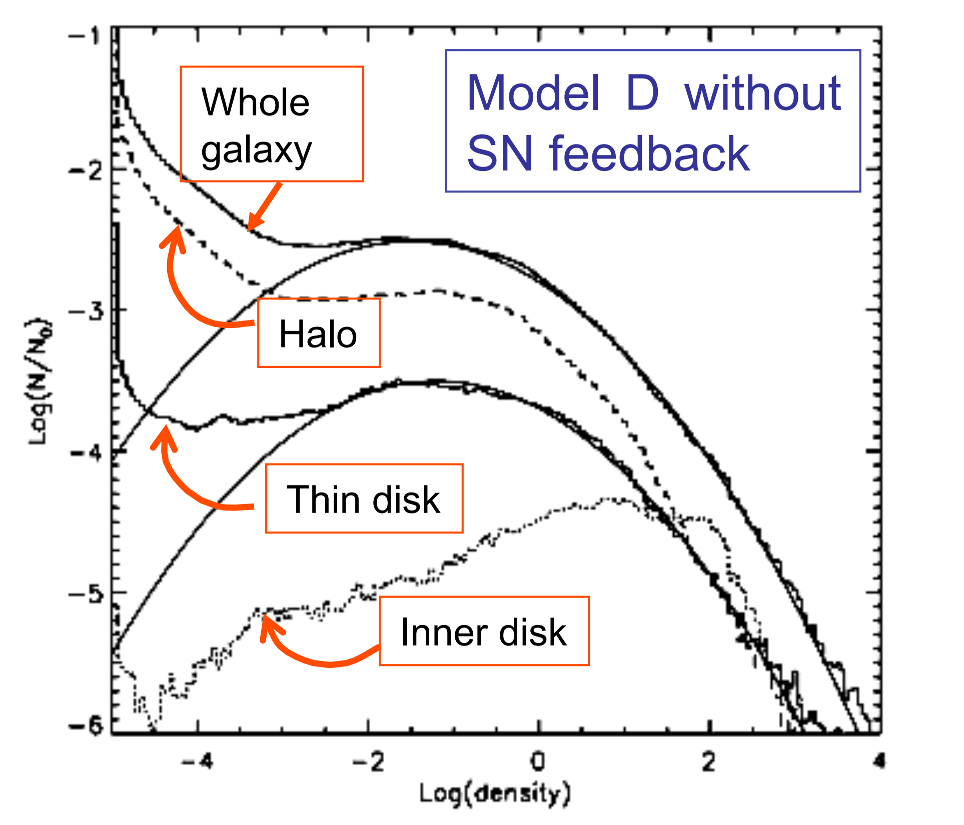
Gazol, VS & Kim, 2005, ApJ, 630, 911

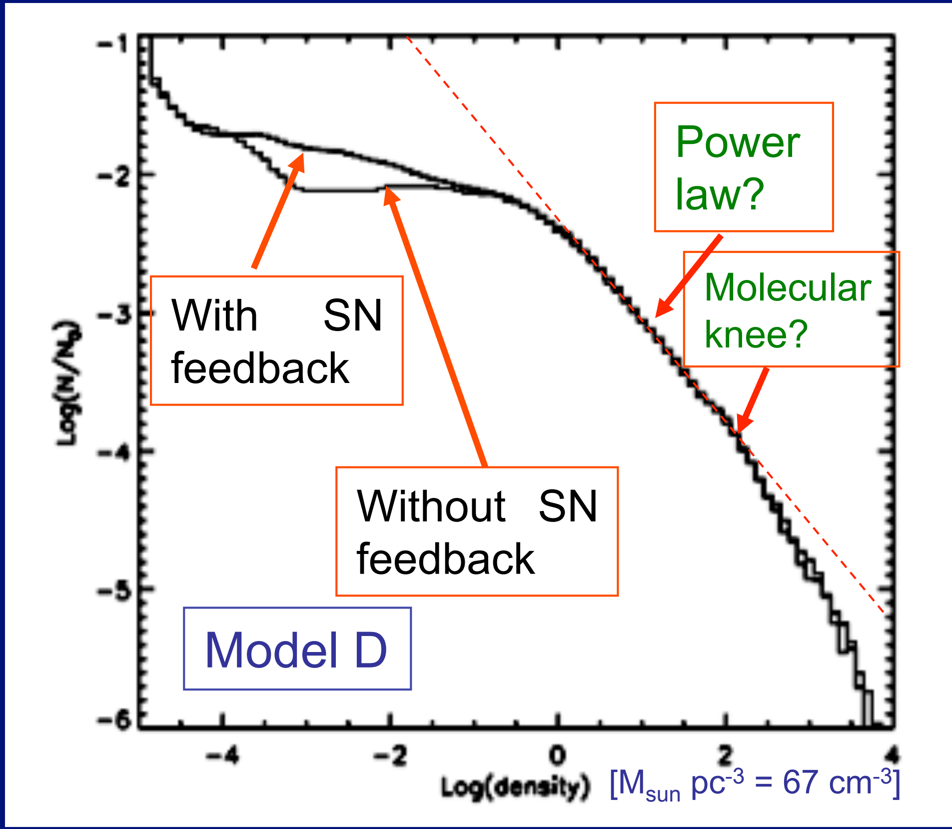
- T PDF and cumulative (x.0.1) distributions



Gazol, VS et al. 2001, ApJ, 557, L121

- Numerical simulations of the multi-phase ISM at large, including hot, warm, and cold phases (e.g., Wada & Norman 2007, ApJ, 660, 276).



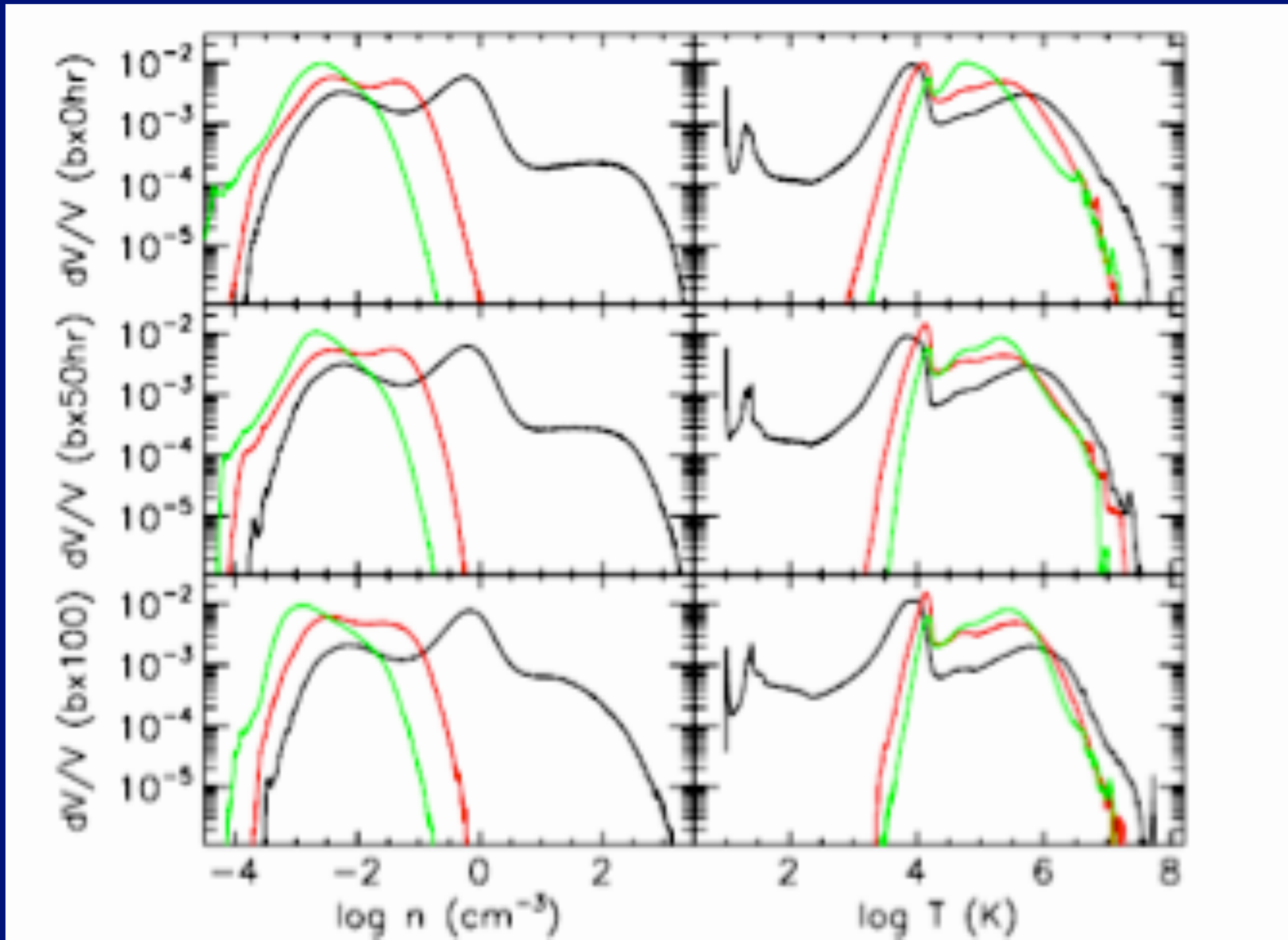


—— : Midplane

—— : |z| ~ 500 pc

—— : |z| ~ 1000 pc

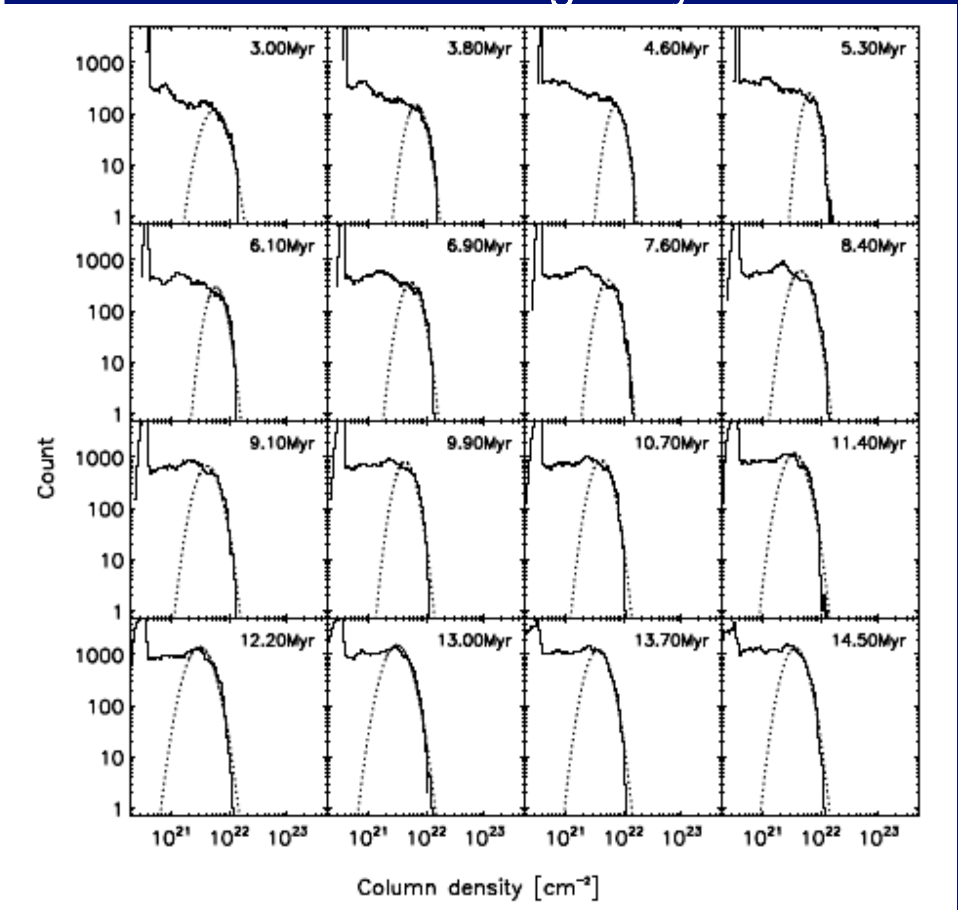
- Vertical dependence



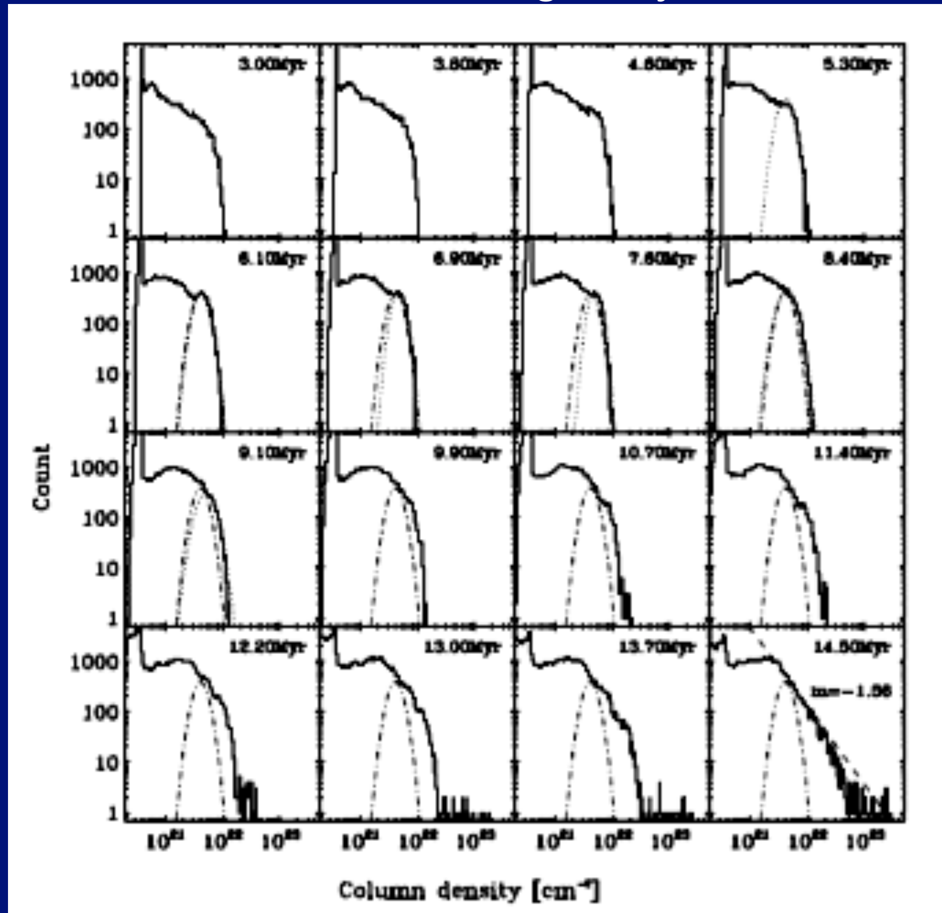
Hill+2012, ApJ, 750, 104

- Gravitational collapse causes the development of a power-law tail at high ρ (Klessen 2000; Dib & Burkert 2005; VS+ 2008; Kritsuk+ 2011; Ballesteros-Paredes+2011).
  - Because higher densities develop.

Without self-gravity

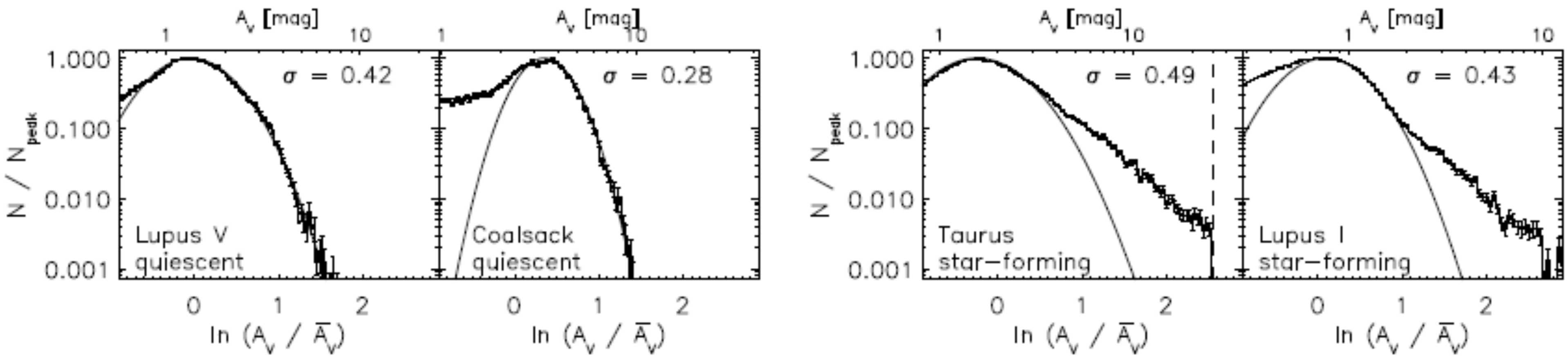


With self-gravity



Ballesteros-Paredes + 2011, MNRAS,416, 1436

- Observationally verified:



Kainulainen+2009, A&A, 508, L35

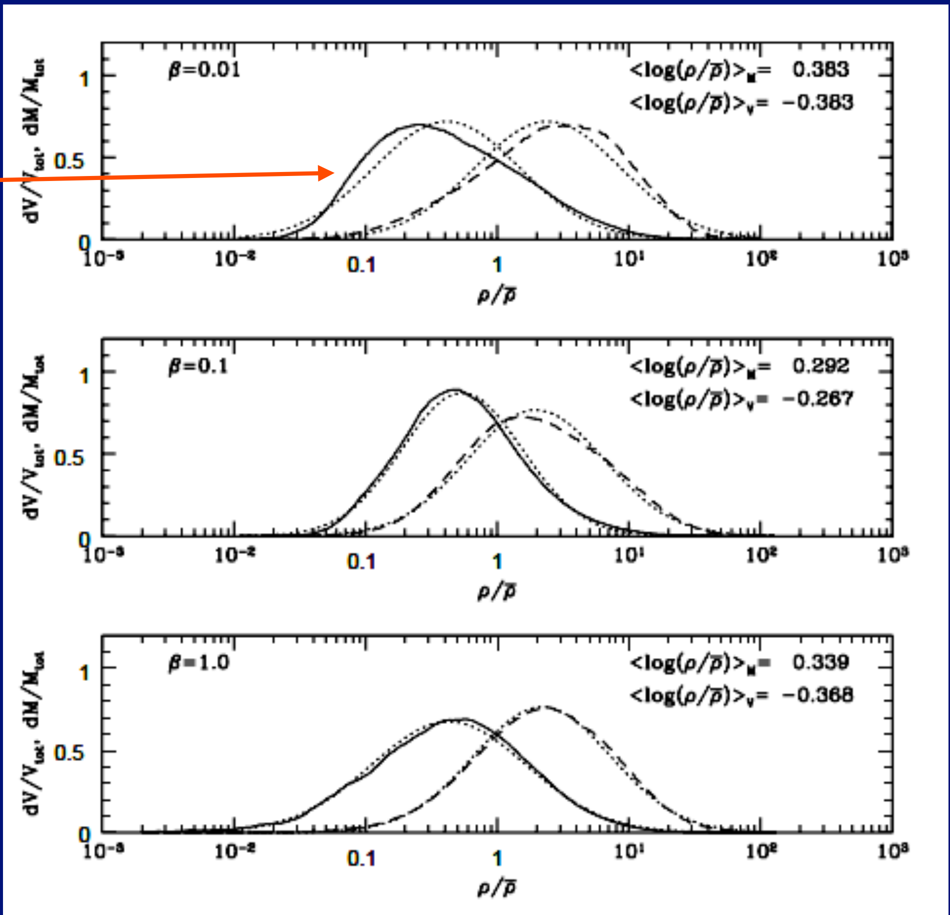
4. The magnetic field

– What happens in the magnetic case?

- Magnetic pressure generally behaves as $P \sim \rho^{\gamma}$, with $\gamma \sim 1/2$—2 (McKee & Zweibel 1995).

- Does this imply a change in the shape of the density PDF?

- Only for very strong fields:



Ostriker+01

– Why?

- 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

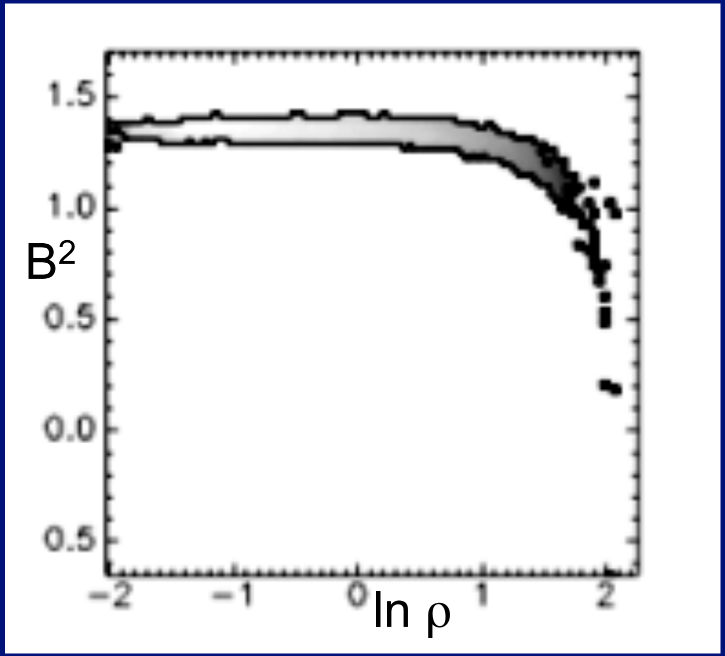
$$B^2 \propto \rho^\gamma; \qquad \gamma = 1/2 - 2$$ Circularly polarized Alfvén wave

(see also McKee & Zweibel 1995)

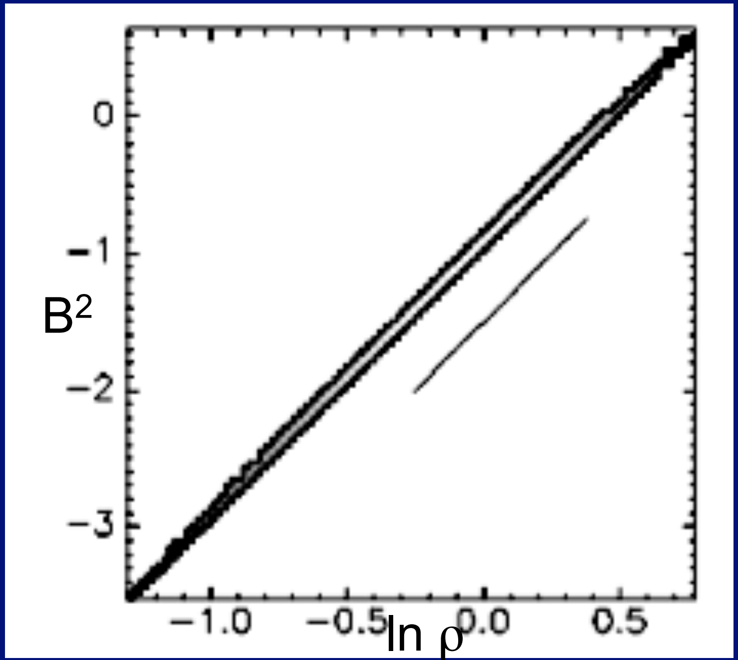
$$\gamma \approx \begin{cases} 1/2 & \text{for low } M_a \\ 3/2 & \text{for moderate } M_a \\ 2 & \text{for large } M_a \end{cases}$$

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

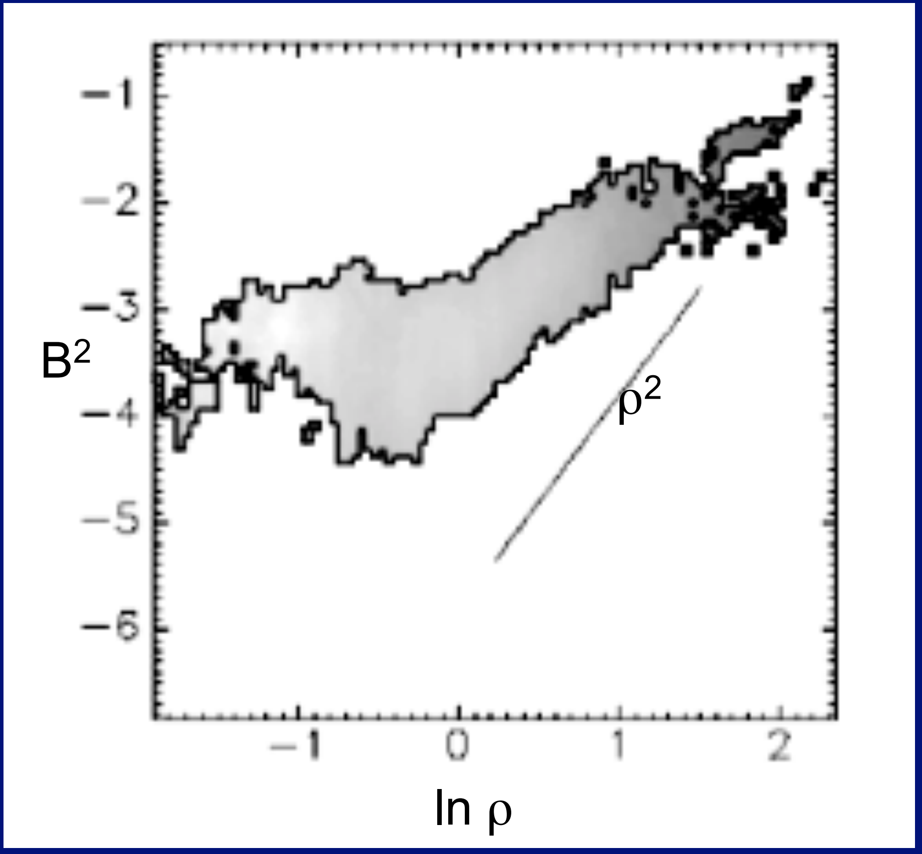


(Arbitrary units)

Fast mode

Passot & Vázquez-Semadeni 2003

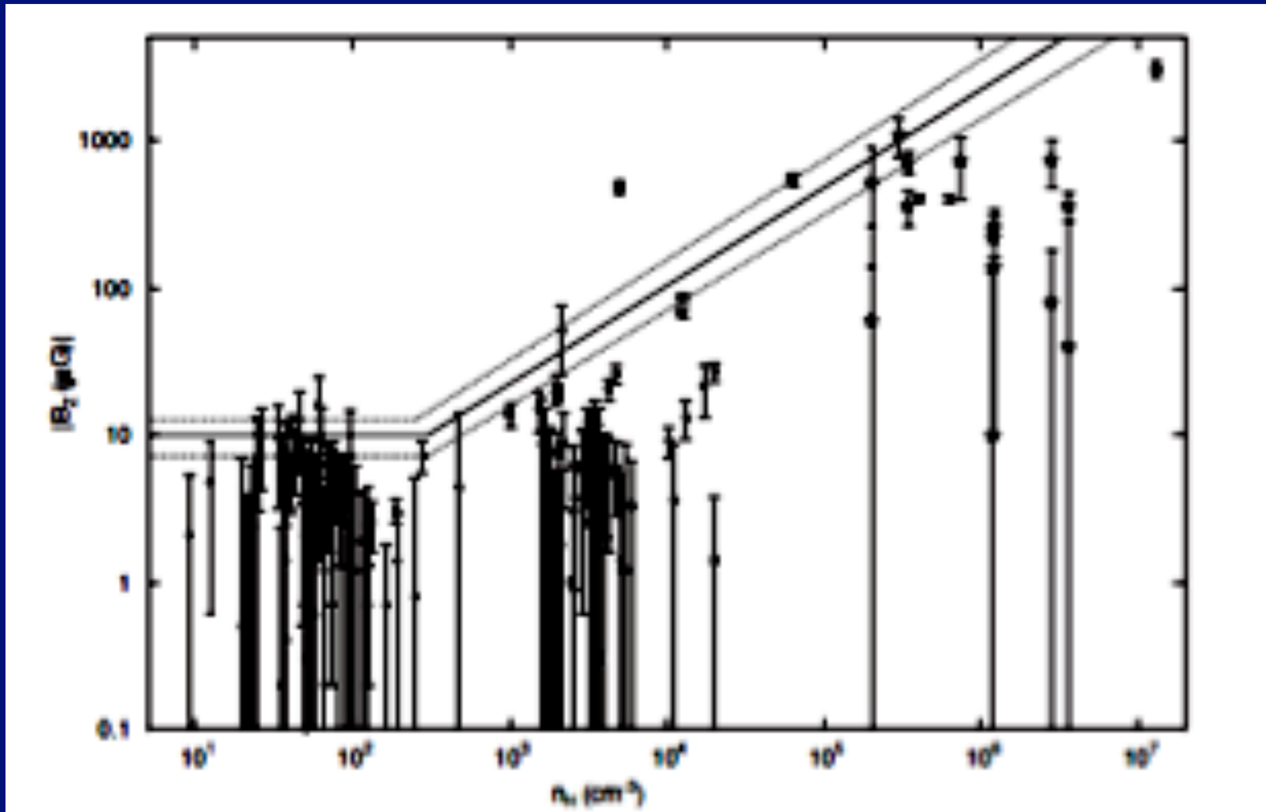
– When both modes are active:



(Arbitrary units)

Passot & Vázquez-Semadeni 2003

– Consistent with observed trend in HI and molecular clouds:



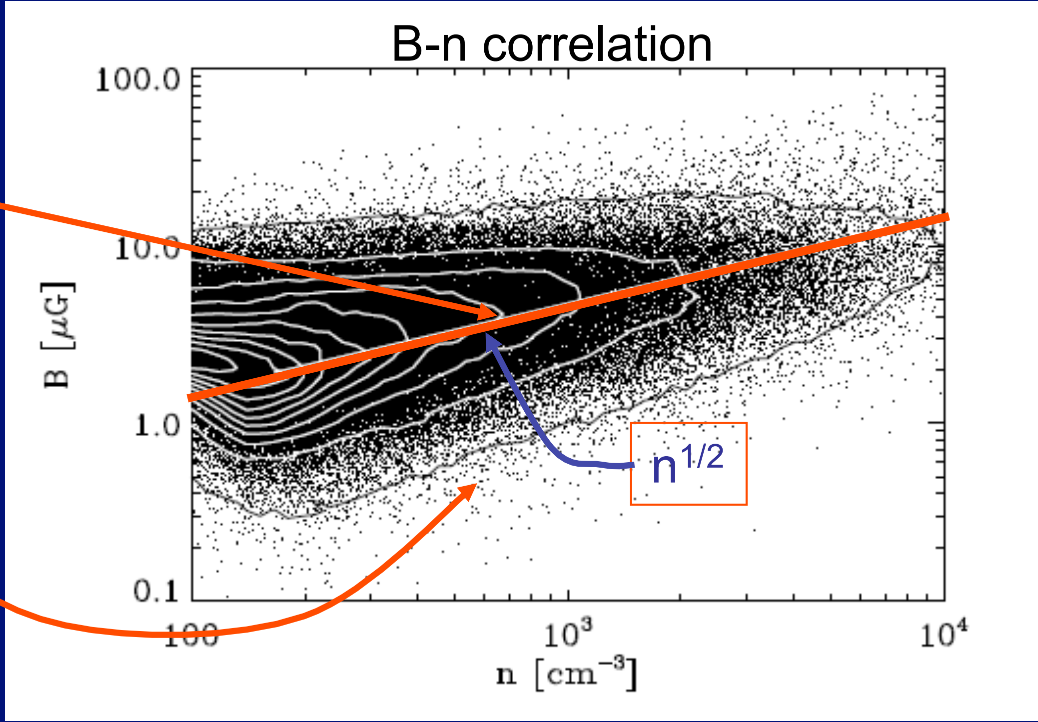
Crutcher+10

– In a 3D turbulent regime, all modes coexist

- Large fluctuations around mean trend, caused by different scalings of 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)

– Implications:

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

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

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 $\nabla P_{\rm th}$, except when B is very large.

5. Self-gravity

- Are cold clouds collapsing rather than in equilibrium?

  - Because they form out of a transition to the cold, dense phase, they quickly become gravitationally unstable.

    $\rho \rightarrow 10^2\,\rho$, $T \rightarrow 10^{-2}\,T$ ➔ Jeans mass decreases by ~ 10^4.

Edge-on view of an MHD colliding flow simulation
using FLASH.

M/ϕ = 1.3 x critical

Start: colliding streams of WNM.

End: turbulent, ***collapsing*** dense cloud.

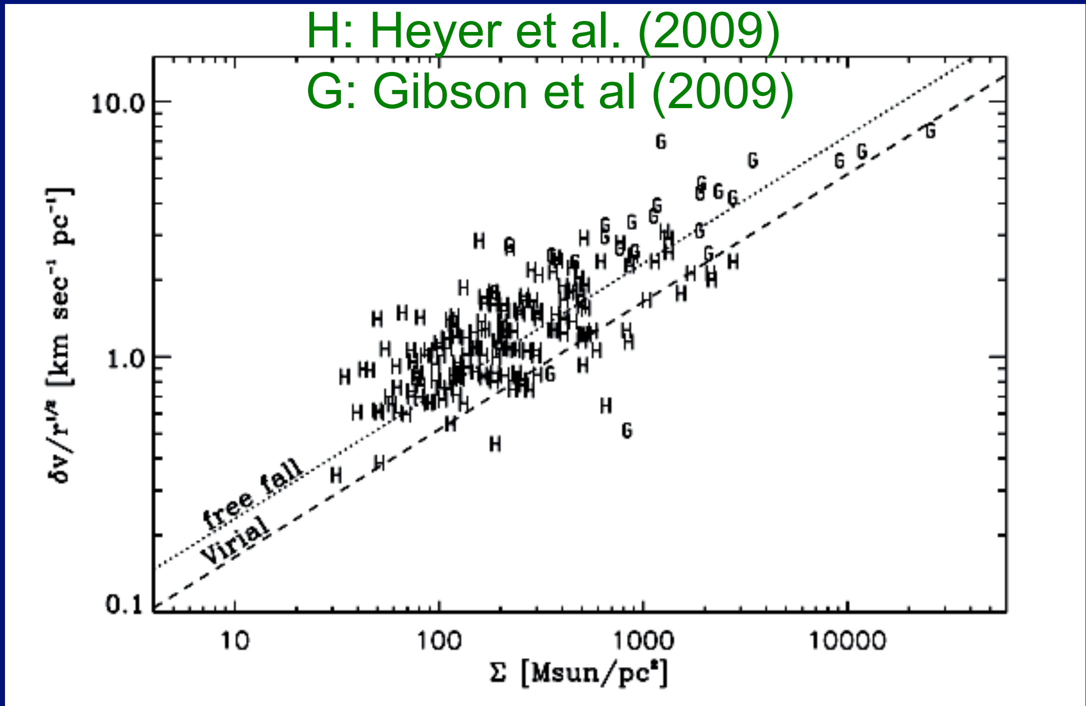
What collapses is the ***ensemble*** of cloudlets.

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

0.00 Myr

Boxsize 80.0 pc

- Can it then be that MCs are in general collapsing?
  - ***Then the observed motions are not plain turbulence, but mostly gravitational contraction.***
  - ***Explains their high pressures.***



$$\frac{\delta v^2}{R} = G\Sigma - \frac{4\pi}{\Sigma} P_{ext}.$$

Virial equilibrium

$$\frac{\delta v^2}{R} = 2G\Sigma.$$

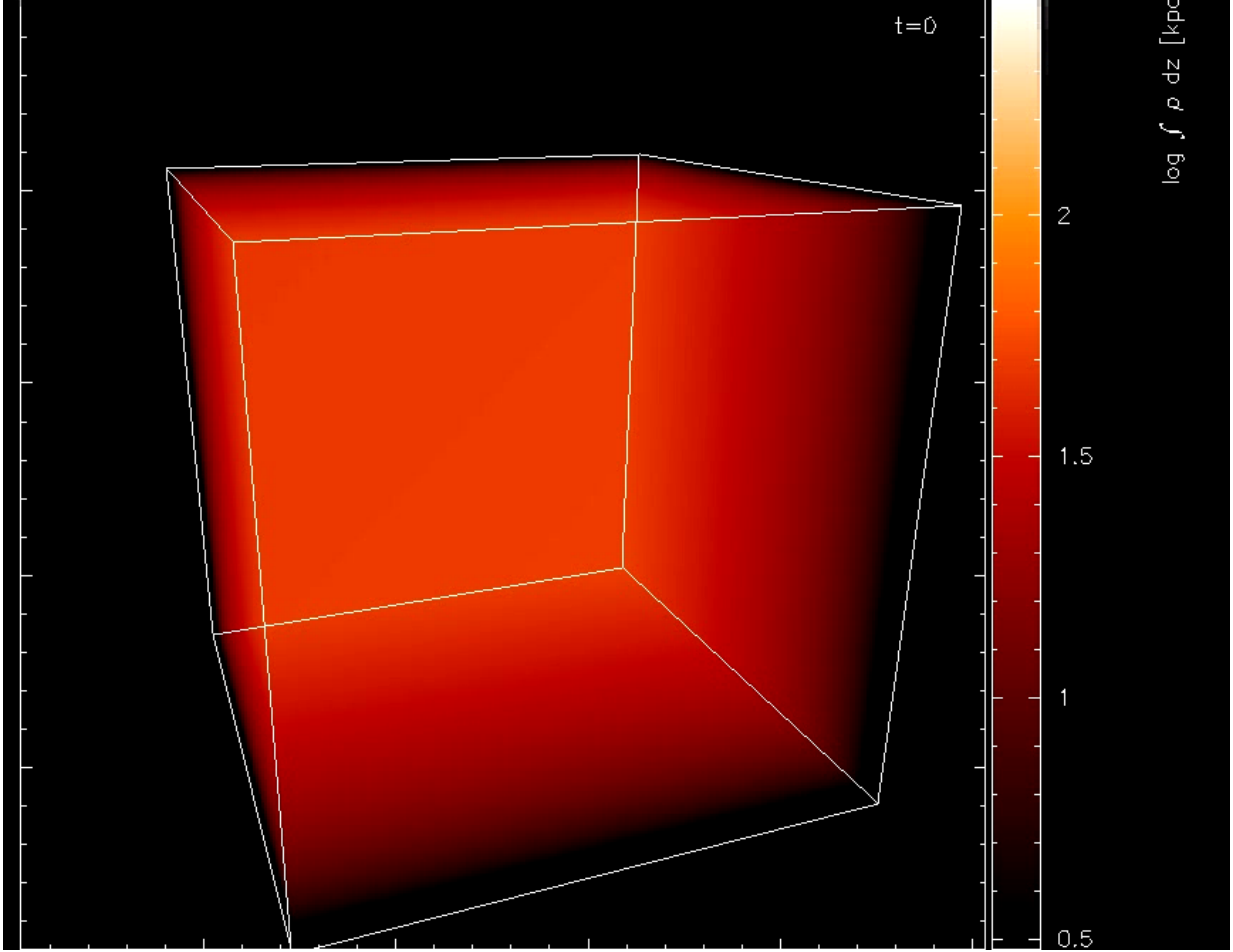
Free-fall

Ballesteros-Paredes et al. 2011, MNRAS, 411, 65

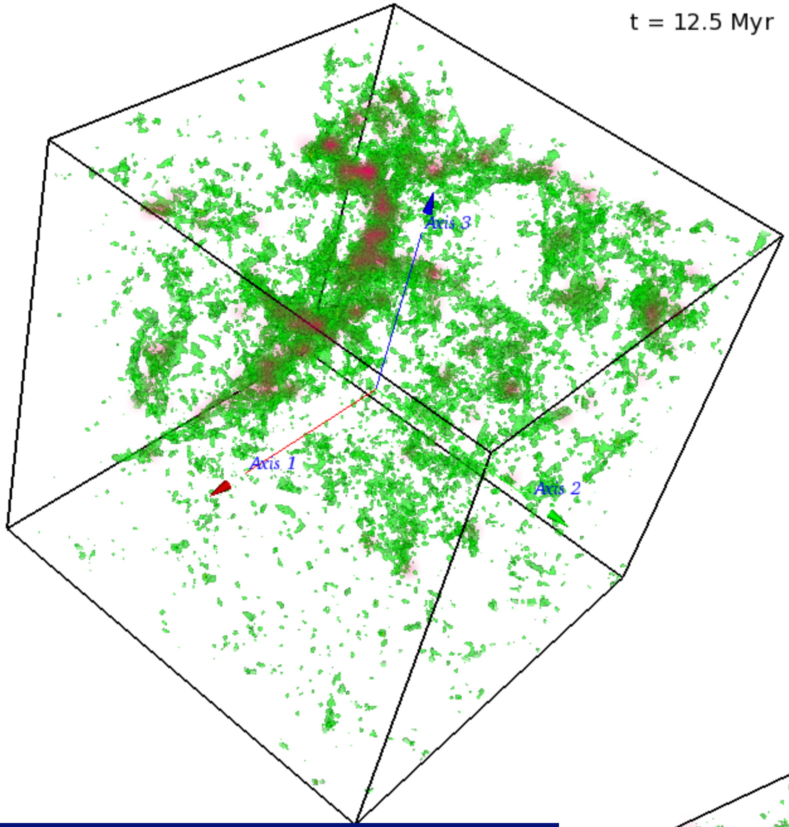
The atomic-molecular connection

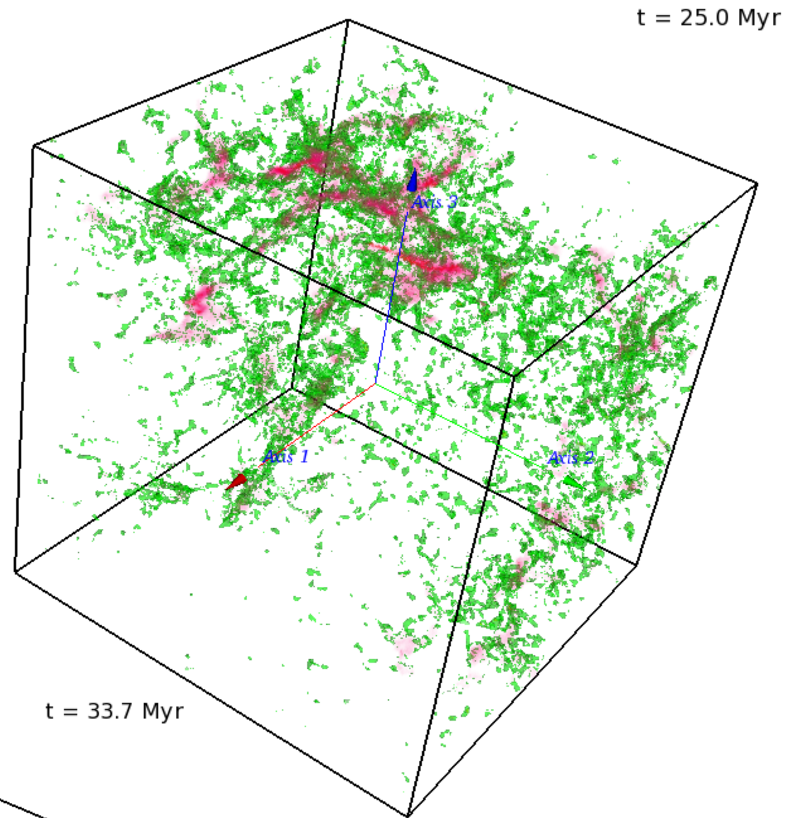
– If cold HI clouds and GMCs form from compressions in WNM, there should exist a flow from WNM → CNM → GMC.

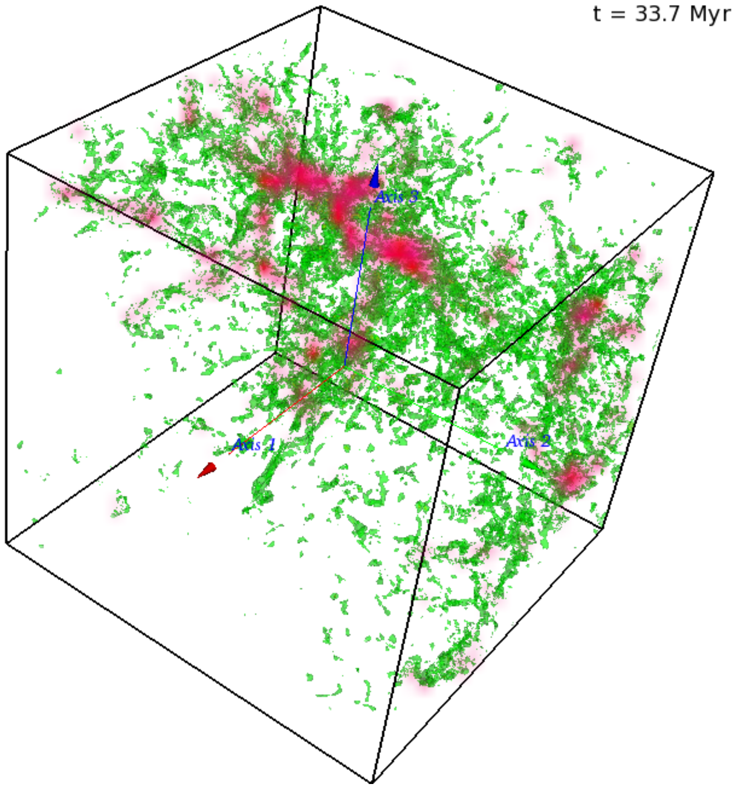
- Can we observe it?
- Synthetic observations of a decaying-turbulence simulation of the ISM (Heiner & Vázquez-Semadeni, in prep.):
  - Box size = 256 pc
  - <n> = 3 cm^{-3}
  - Gadget-2 code, 26 x 10^6 SPH particles.
  - Initial turbulent kick, then decaying.
  - Sink particles.
  - Assume anything above A_V = 1 is molecular (Heitsch & Hartmann 2008).



t=0
log ∫ ρ dz [kpc
2
1.5
1
0.5



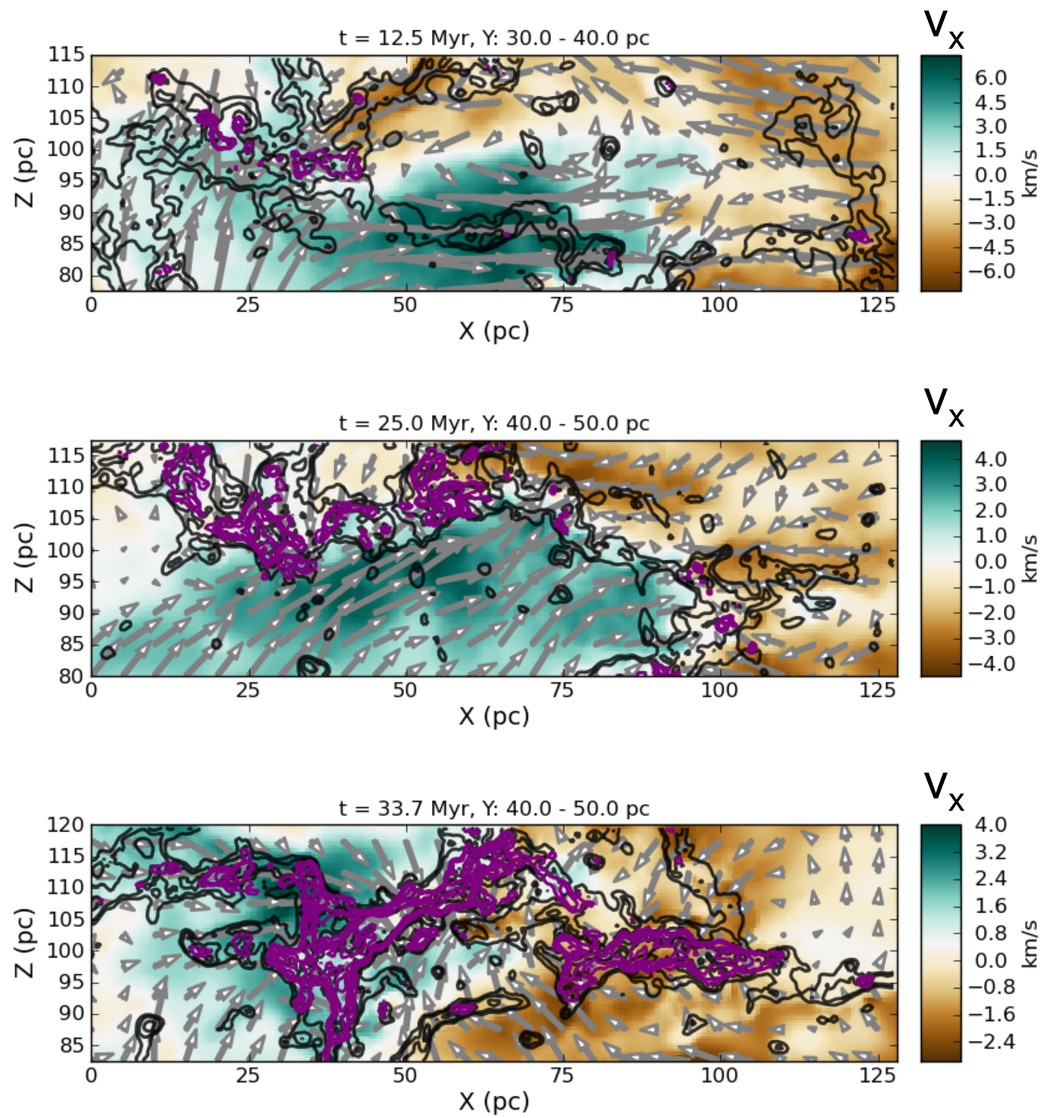


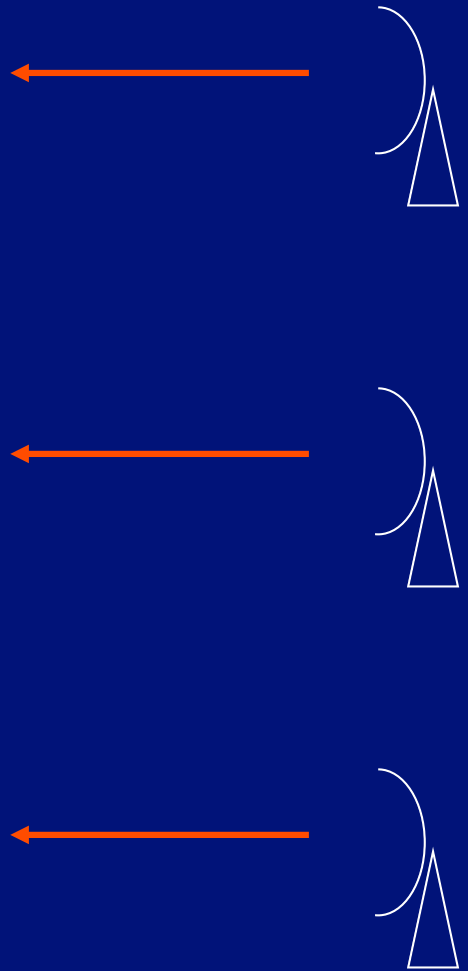


atomic, n>30 cm^{-3}

molecular

128-pc sub-boxes of simulation, containing the most massive cloud complex.



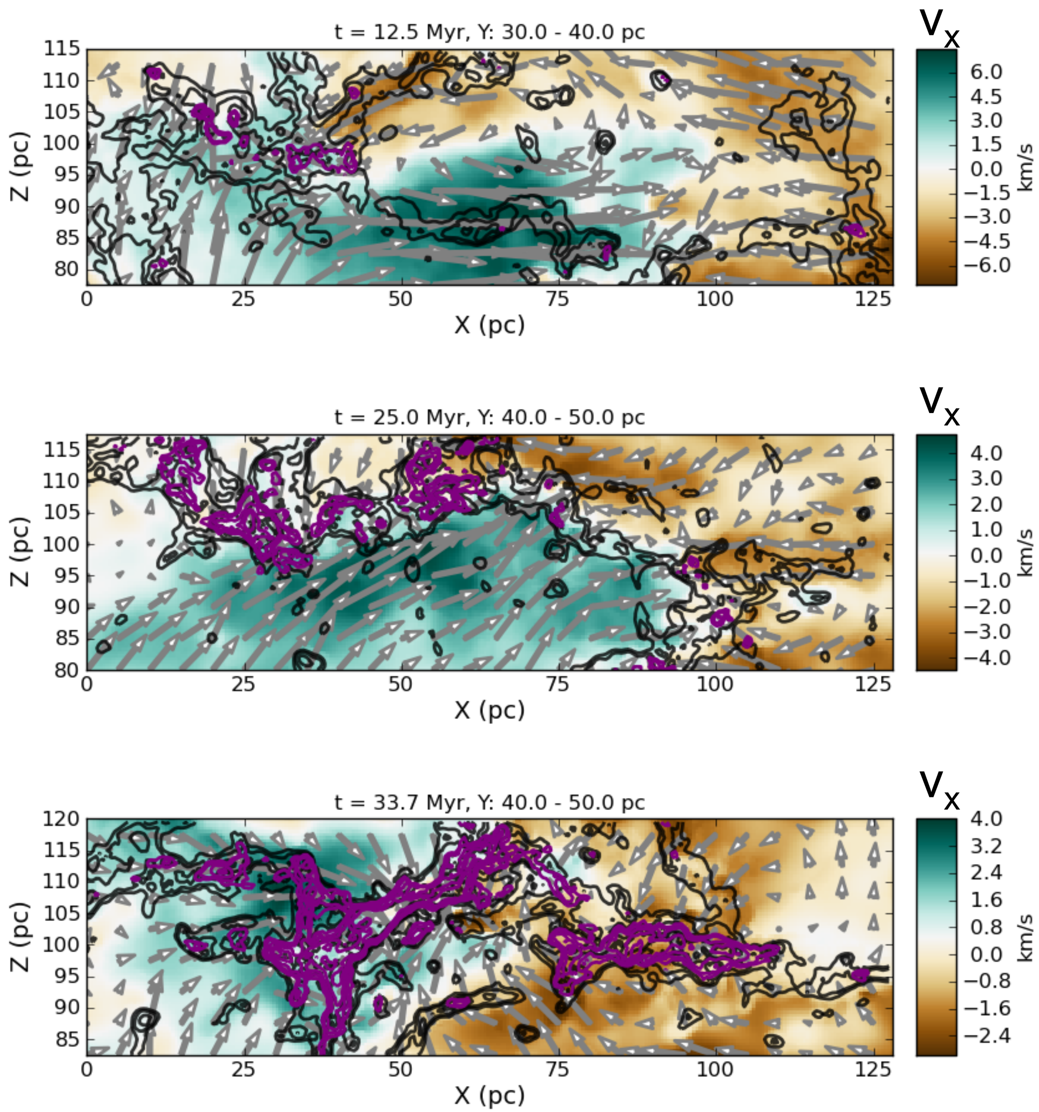


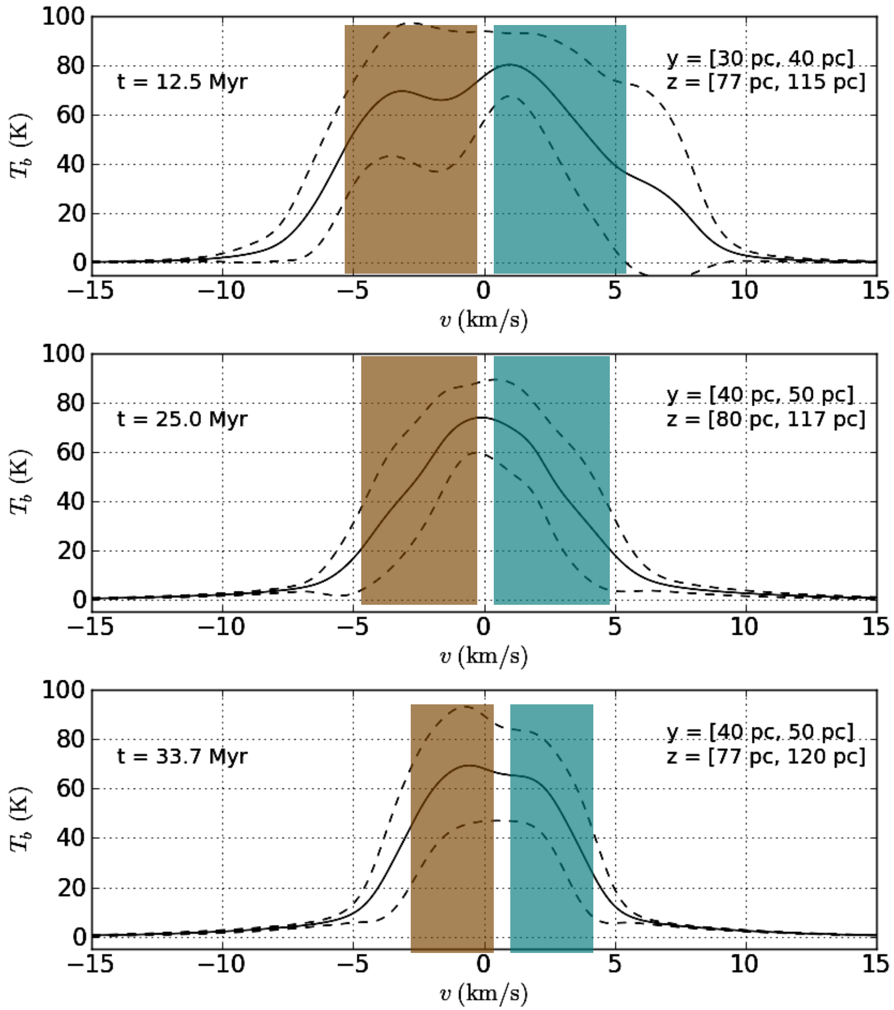
Colors: v_x

Black contours: N_{HI}

Purple contours: N_{mol} (including H_2)

Are we seeing the converging flows in the HI profiles?



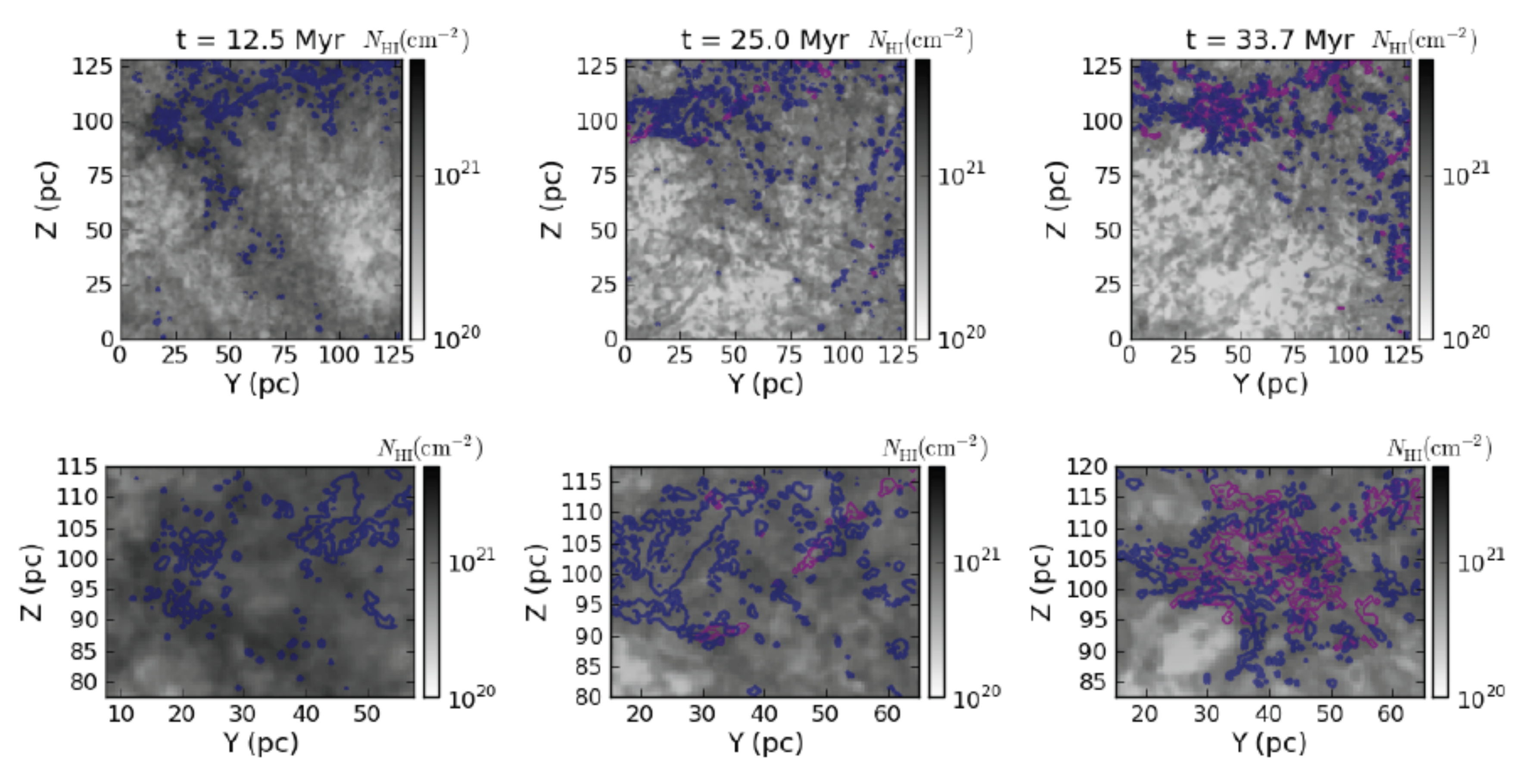


: molecular gas

———: Average HI profile

- - - - - -: 1-σ deviation

– Compared HI self-absorption (HISA) with CO emission.
  - Tested accuracy of Krco+2008 prescription for detecting HISA.



- Good but not perfect correlation.

Greyscale: HI
Blue contours: HISA
Purple contours: CO

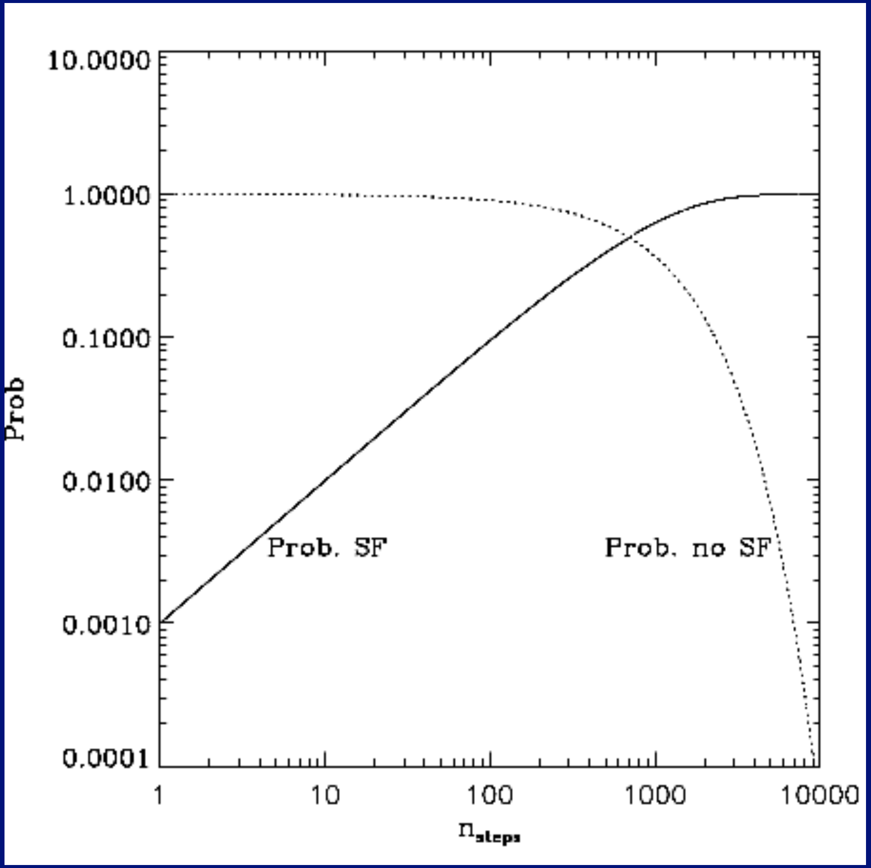
6. Stellar feedback

– Simulations of cloud formation and evolution with OB star ionizing heating feedback and crude radiative transfer (Colín +2013, accepted).

  – 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:



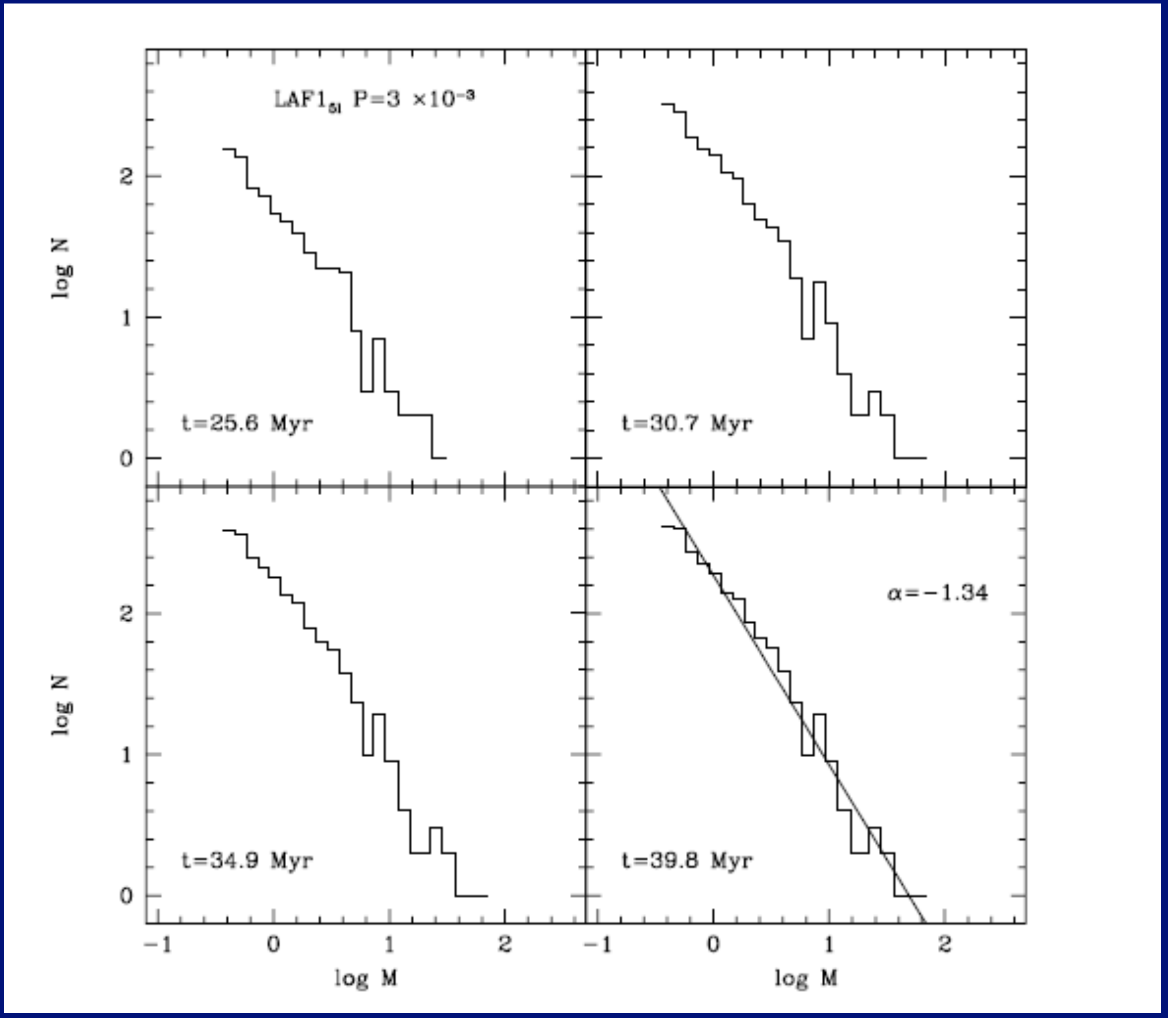
Stellar particles form with half the mass of the parent cell.

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.

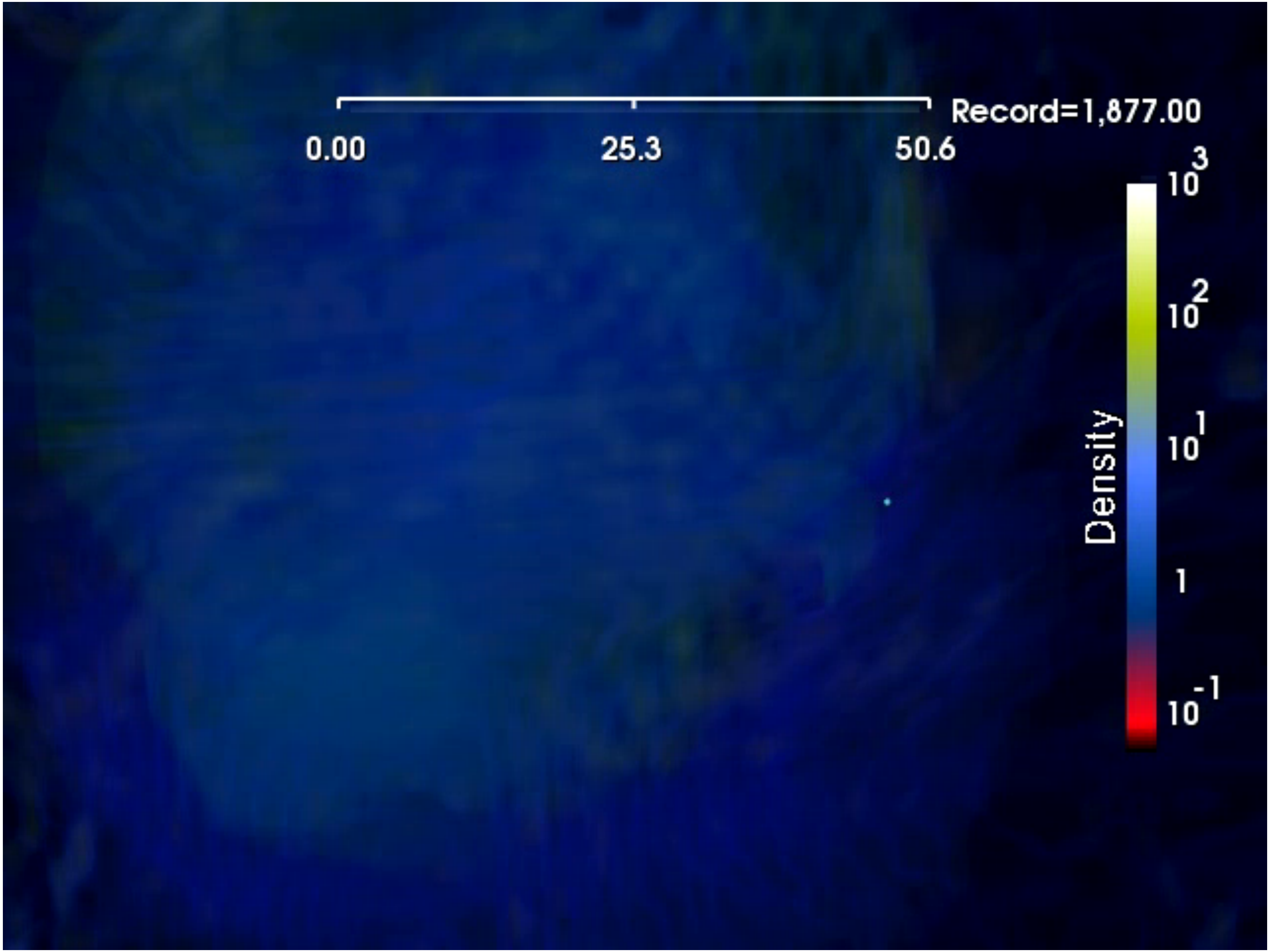
  - Compute "characteristic density" as

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

  - 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.

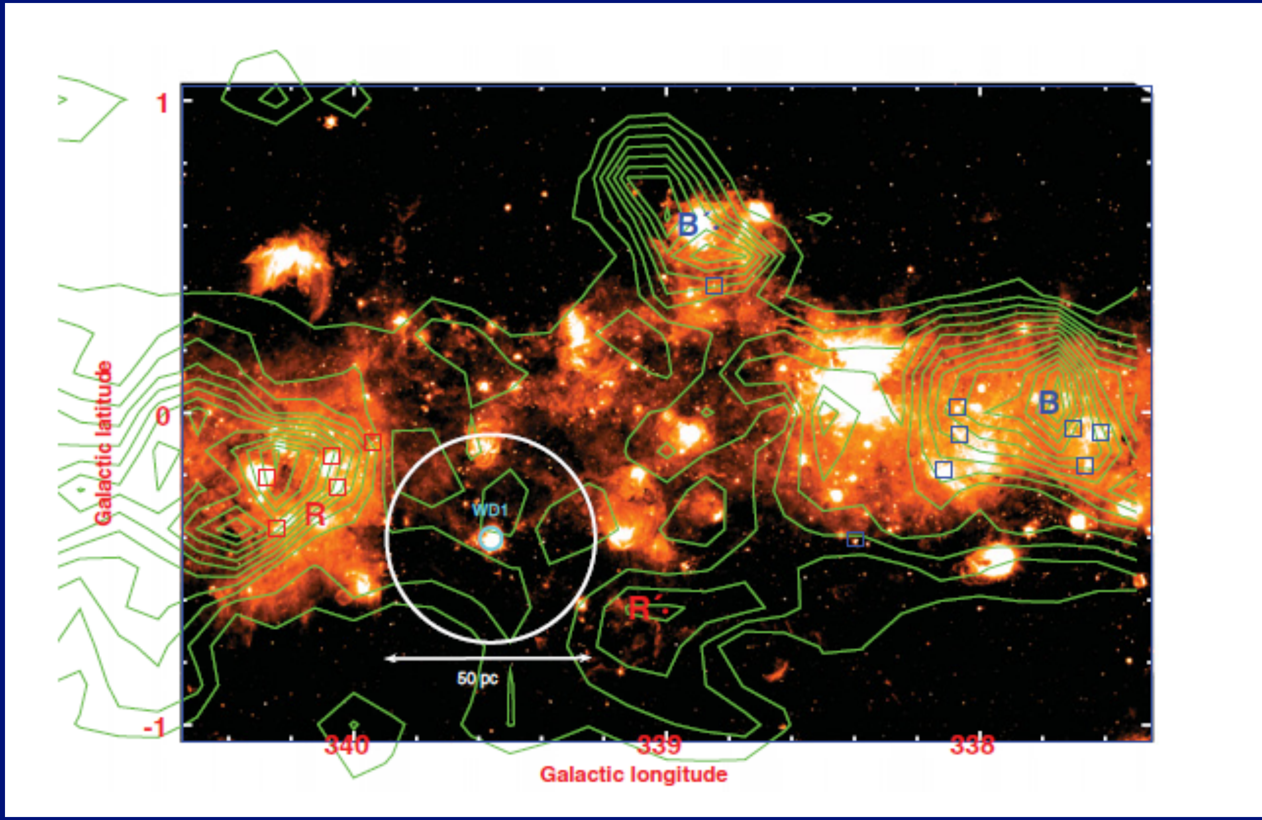

Record=1,877.00
0.00
25.3
50.6
Density
10^3
10^2
10^1
1
10^{-1}

– Clouds effectively (semi-locally) destroyed.

– 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.

CONCLUSIONS

Considered 6 processes:

1. Need for convergence of the velocity onto dense regions
   ➔ Clouds accrete from their surroundings.
2. ISM thermodynamics
   ➔ Moderate compressions in WNM can cause large density enhancements and cooling.
3. Turbulence
   1. A thermodynamics-dependent PDF of density fluctuations.
   2. P PDF shows no bimodality because P has no discontinuity.
   3. Accretion driven cloud turbulence transonic, *not* strongly supersonic.
4. Superposition of nonlinear MHD waves:
   1. No strong modification of density PDF.
   2. B-ρ uncorrelated at low densities (signature of slow mode).
5. Self-gravity:
   1. Combined with cooling ➔ cold clouds may be in general state of collapse.
   2. Causes power-law tail of density PDF of molecular gas.
   3. Collapse may produce the highly supersonic speeds and high pressure in molecular clouds .
6. Stellar feedback
   1. Regulates SFR and SFE by destroying dense gas.
   2. Returns dense gas to warm phase
   3. Does *not* maintain turbulence in the cold phase.

THE END