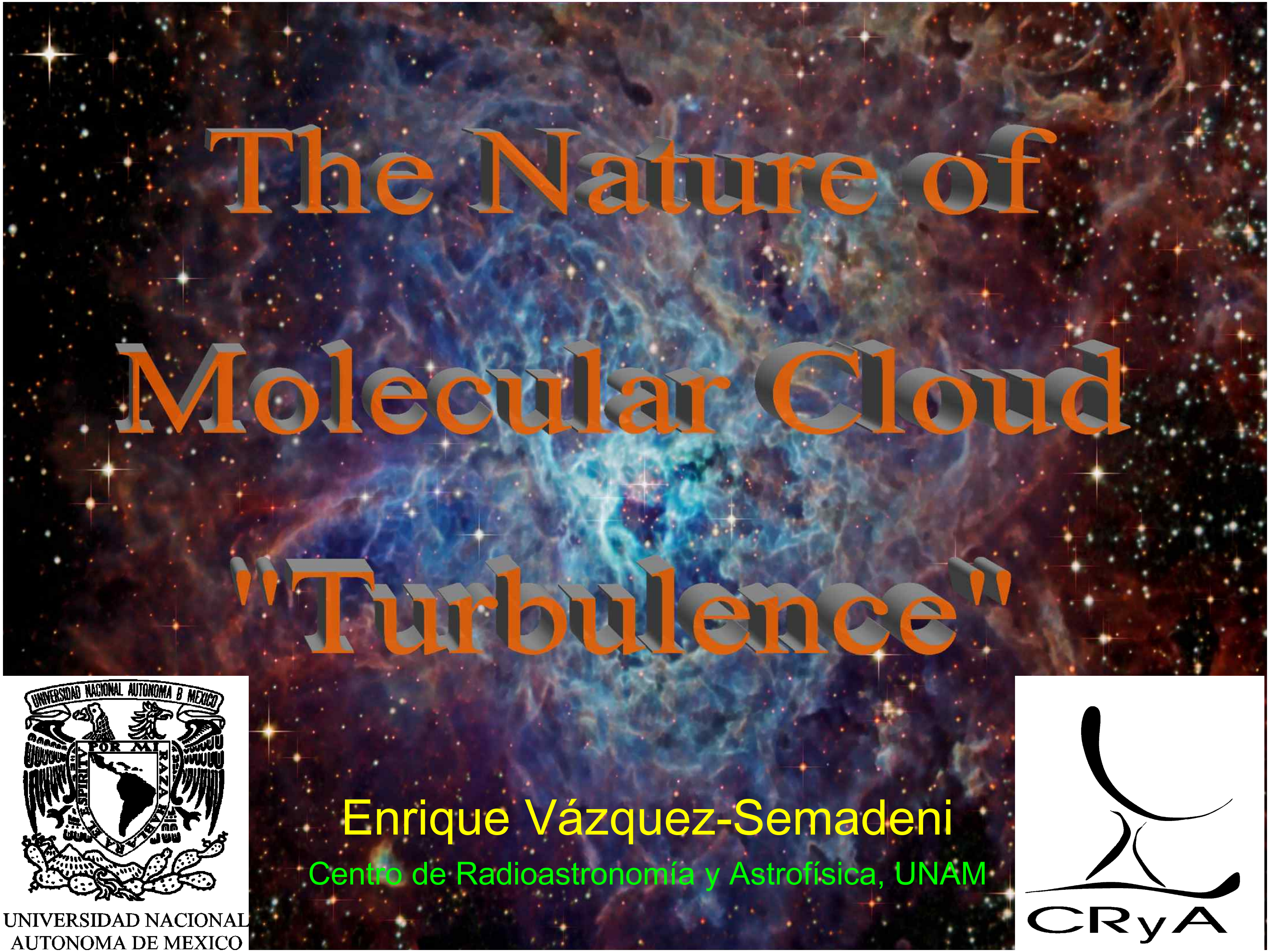

The Nature of Molecular Cloud "Turbulence"

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I. INTRODUCTION

- Giant Molecular Clouds (GMCs):
  - Are the densest regions in the ISM ($\langle n \rangle \gtrsim 100$ cm^{-3}).
  - Have supersonic linewidths (e.g., Zuckerman & Palmer 1974), generally interpreted as *turbulence*.
  - Are significantly self-gravitating:
    - Approximate equipartition between $|E_{grav}|$, E_{kin} (and E_{mag}?)
      - Generally interpreted as *virial equilibrium*...
      - ... powered by stellar energy injection.
    - Are the sites of all present-day star formation (SF) in the Galaxy.

A recently discovered property is that

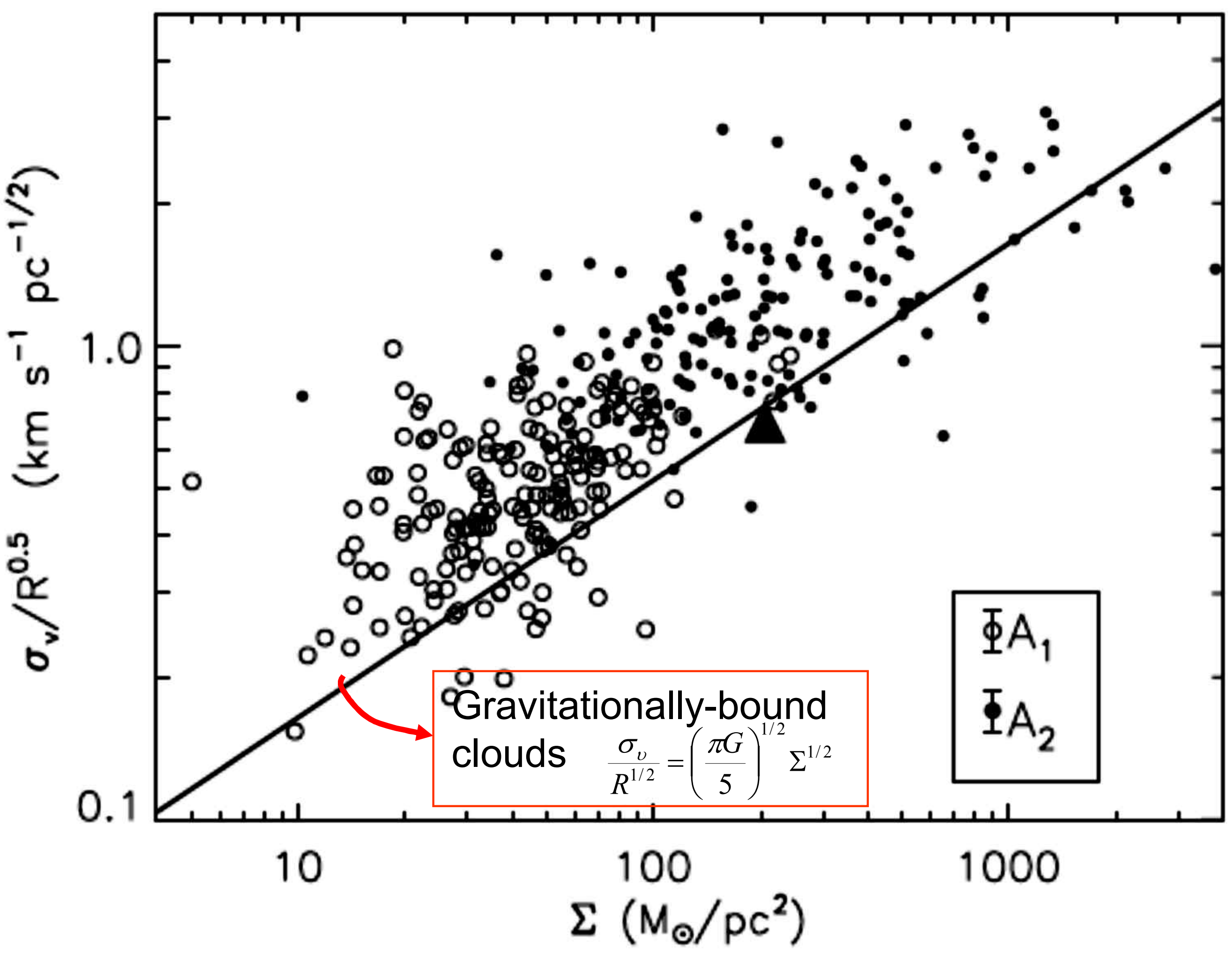
- Velocity dispersion seems to scale with column density *and* size (“radius”).

Heyer+(2009):
$\sigma_v / R^{1/2} \sim \Sigma^{1/2}$

Supersedes Larson´s relations (1981):

$\sigma_v \sim R^{1/2}$
$\langle\rho\rangle \sim R^{-1} \Rightarrow$
$\Sigma = \rho R = \text{cst.}$

Heyer+2009



Gravitationally-bound clouds $\frac{\sigma_v}{R^{1/2}} = \left(\frac{\pi G}{5}\right)^{1/2} \Sigma^{1/2}$

- This talk addresses the nature of “turbulence” in molecular clouds (MCs),
  - the density probability density function (PDF).
  - atomic cloud formation: MC precursors. How do they acquire
    - mass,
    - turbulence?
  - GMC formation:
    - need for self-gravity
  - stellar feedback:
    - How does it regulate the SF efficiency?
    - Does it maintain clouds in equilibrium?
  - the topology of bulk motions in molecular clouds.

I. The probability density function (PDF) of the density field

The probability density function (PDF) of the density field:

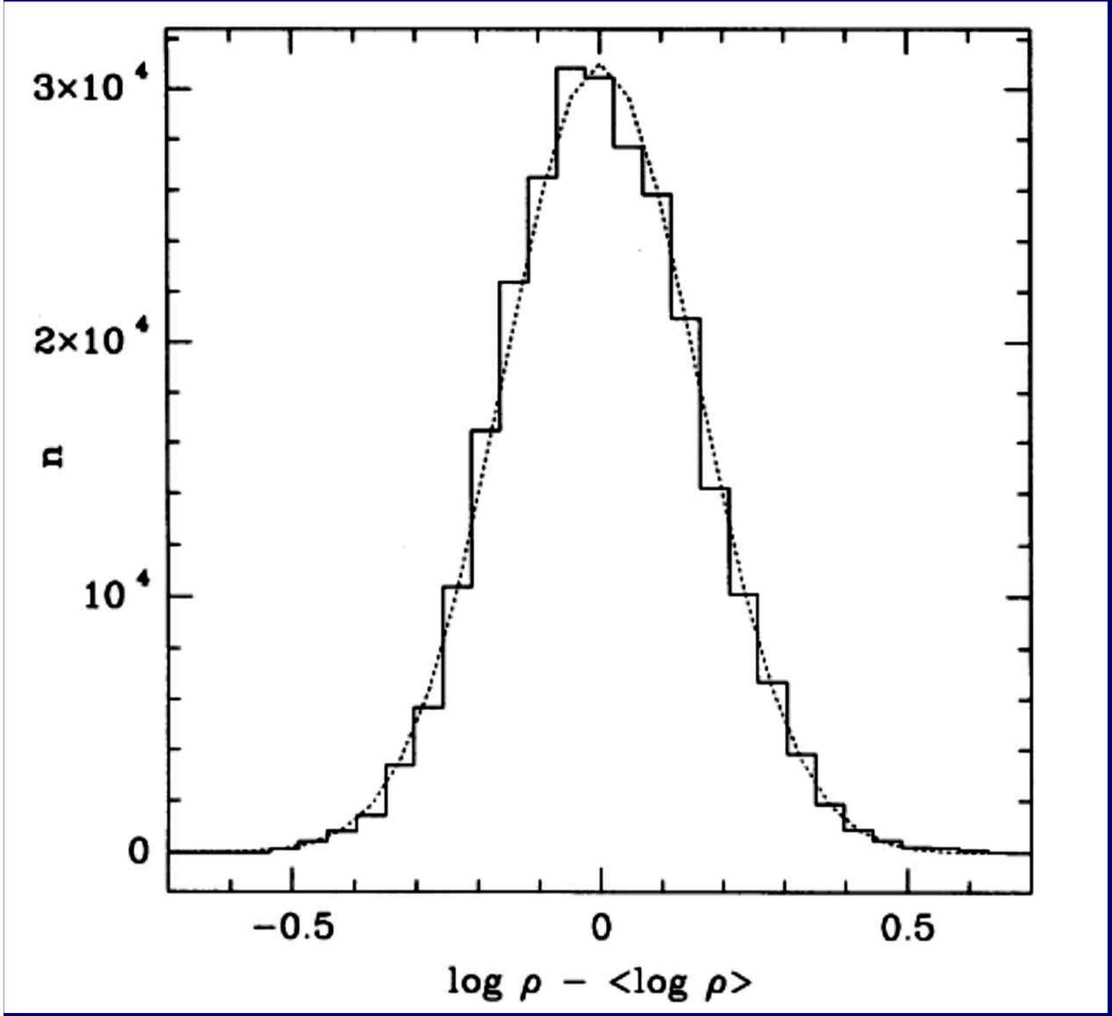
- The simplest (e.g., one-point) statistic for a compressible flow.
- Relevant for understanding the formation of density fluctuations.
- For isothermal flows, it develops a lognormal shape (Vázquez-Semadeni 1994).

- A consequence of (Passot & Vázquez-Semadeni 1998, Phys. Rev. E, 58, 4501):
  - Shock jumps are multiplicative in the density: $\rho_2/\rho_1 = \mathcal{M}^2$, where $\mathcal{M}$= Mach #.
    - Thus additive in $s = \ln \rho$.
  - ***In an isothermal flow, the sound speed c_s is constant, so the multiplicative factor depends only on the Mach number.***
  - The turbulent flow contains a distribution of velocity differences.
  - Thus, there is a distribution of additive increments in s, all belonging to the same distribution, and independent from each other.

➔ According to the Central Limit Theorem, s has a normal distribution.

➔ ρ has a lognormal distribution.

Density PDF in 512^2 simulation of isothermal, $\mathcal{M} = 0.6$ turbulence.



Vázquez-Semadeni 1994, ApJ 423, 681

$$P(s)ds = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(- \frac{(s - s_o)^2}{2\sigma_s^2} \right) ds,$$

with

$$\sigma_s \approx M \text{ and } s_o = -0.5\sigma_s^2 .$$

Passot & Vázquez-Semadeni 1998

- However, for general polytropic flows (Passot & Vázquez-Semadeni 1998)
  - The sound speed, and thus $\mathcal{M}$, become density-dependent:

$$P \propto n^{\gamma} \propto nT \Rightarrow T \propto n^{\gamma-1}$$

$$\Rightarrow c \propto n^{\frac{\gamma-1}{2}}$$

$$\Rightarrow \mathcal{M} \propto n^{\frac{1-\gamma}{2}}$$

  - Thus, it is convenient to rescale

$$\mathcal{M} \to \mathcal{M}_0 \left(\frac{n}{n_0}\right)^{\frac{1-\gamma}{2}} = \mathcal{M}_0 \exp\left[\frac{1-\gamma}{2} s\right]$$

where $\mathcal{M}_0$ is the Mach # of the isothermal case.

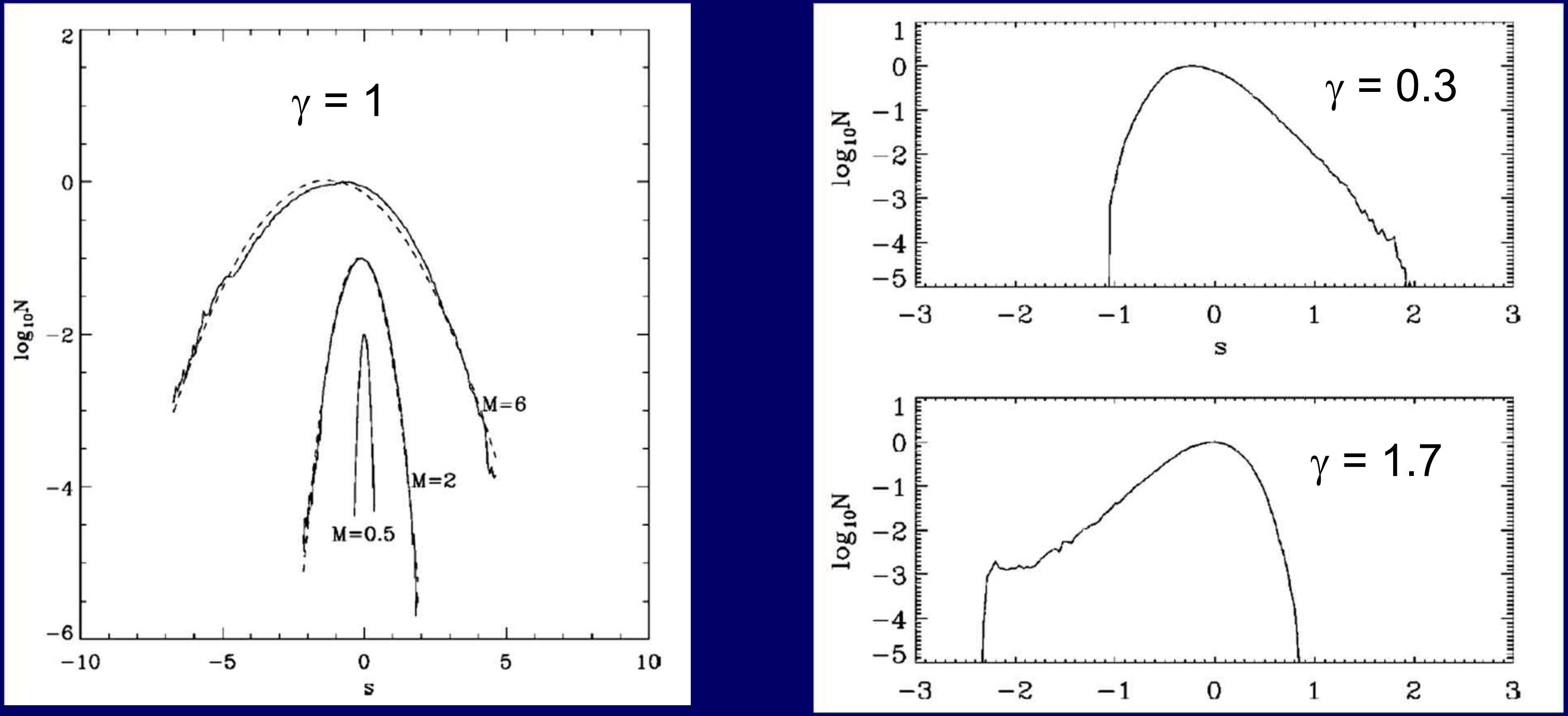
- So that the PDF reads

$$
\begin{aligned}
\mathrm{P}(\mathrm{s};\gamma) &= A\exp\left(-\frac{s^2 e^{(\gamma-1)s}}{2M_0{}^2}+\frac{s\sigma_s{}^2}{2\sigma_s{}^2}\right)\\
&= A\exp\left(-\frac{s^2 e^{(\gamma-1)s}}{2M_0{}^2}\right)\exp\left(\frac{1}{2}\ln\rho\right)\\
&= A\exp\left(-\frac{s^2 e^{(\gamma-1)s}}{2M_0{}^2}\right)\rho^{1/2}.
\end{aligned}
$$

- In the limit of large s and $\gamma<1$, this is dominated by the power-law part.

- PV98 conjectured that the power-law in r might differ from 1/2 due to the requirement of mass conservation.

- Besides, there is a symmetry $s \rightarrow - s$, $\gamma \rightarrow 2 - \gamma$:



1D simulations

Passot & Vázquez-Semadeni 1998

Other causes for departures from the lognormal PDF

- A driving based on force, rather than acceleration, because the applied acceleration depends on density again (Passot & VS 1998).

- Self-gravity causes the development of a power-law tail at high ρ (Klessen 2000; Dib & Burkert 2005; VS+ 2008; Kritsuk+ 2010; Ballesteros-Paredes+ 2011).

- In general, anything that breaks the property of density-independent jumps.

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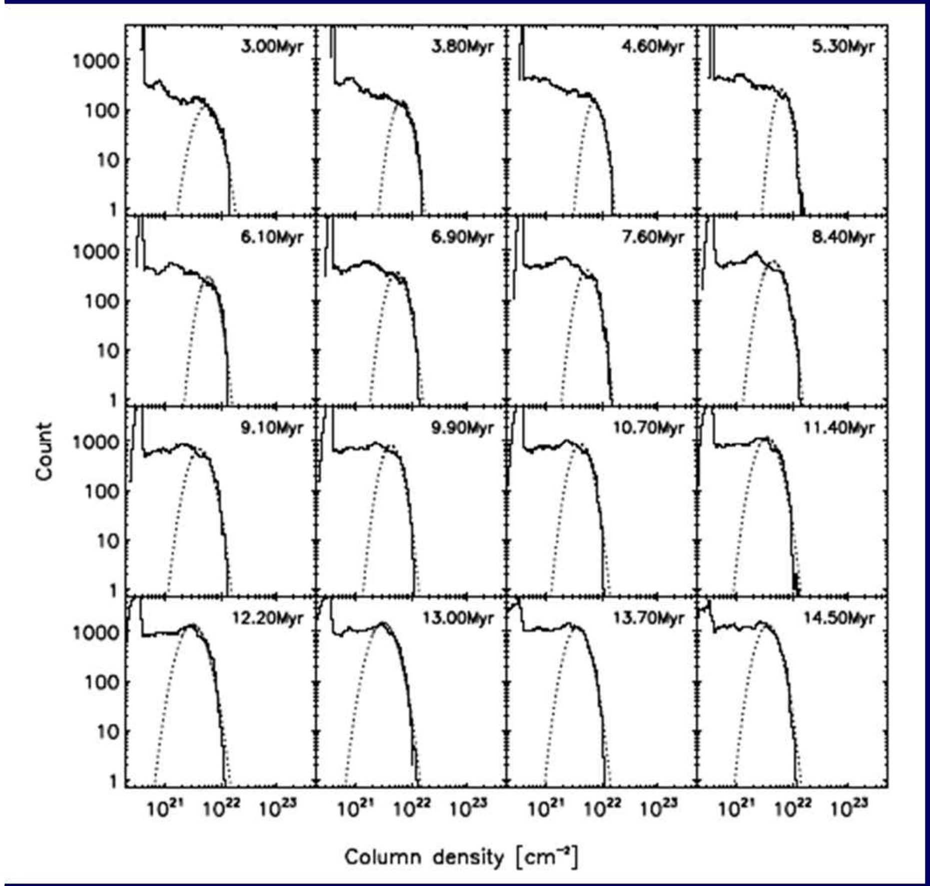
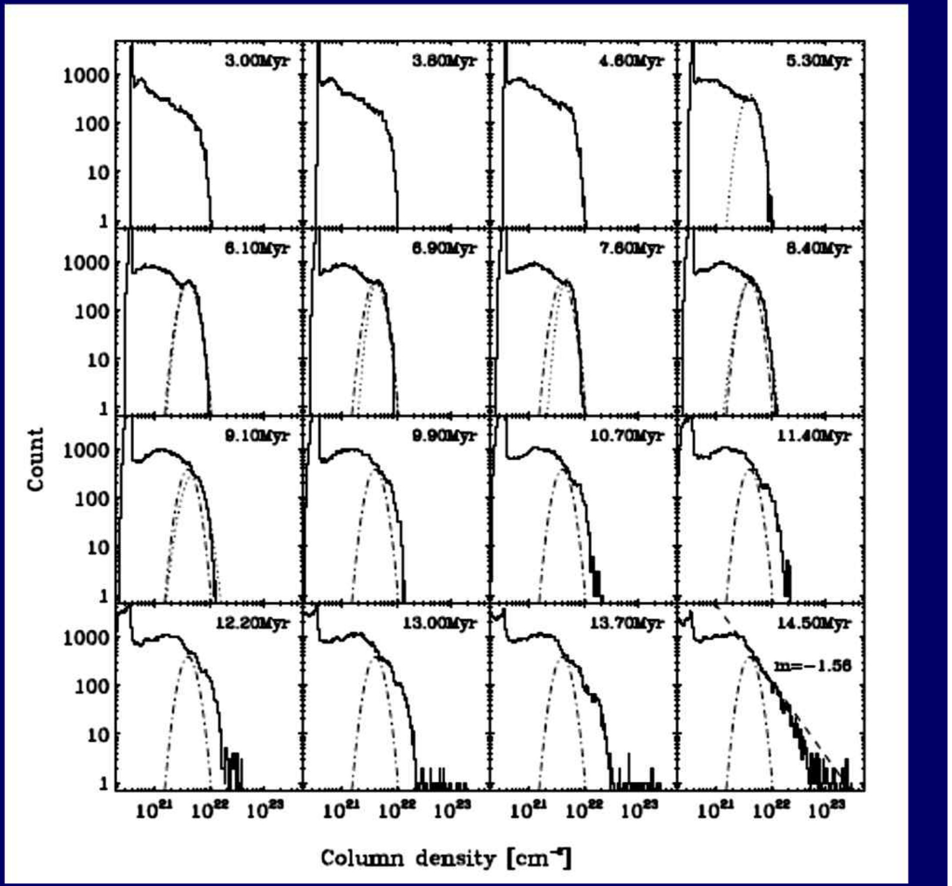
Without self-gravity



With self-gravity



Ballesteros-Paredes + 2011, MNRAS

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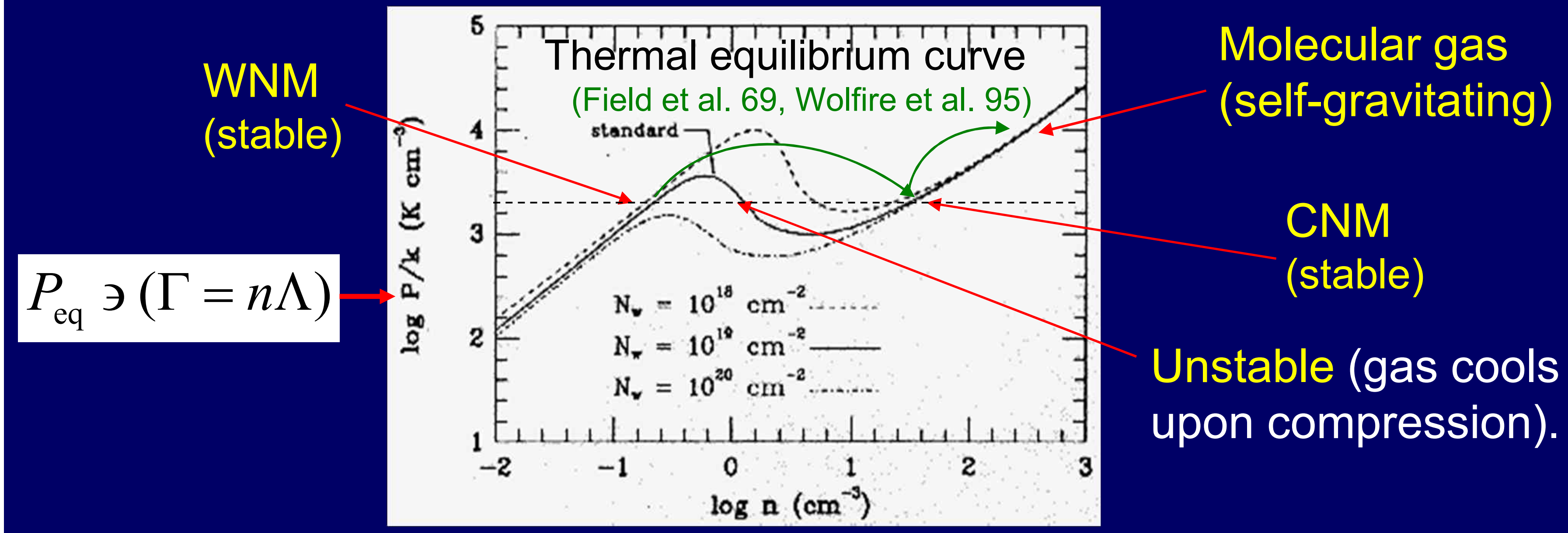
- In general, anything that breaks the property of density-independent jumps.

III. FORMATION OF ATOMIC CLOUDS

- The mechanism of cloud formation by generic compressions in the warm neutral medium (WNM) involves:
  - The ***atomic*** medium is thermally bistable.



Thermal equilibrium curve

(Field et al. 69, Wolfire et al. 95)

WNM (stable)

Molecular gas (self-gravitating)

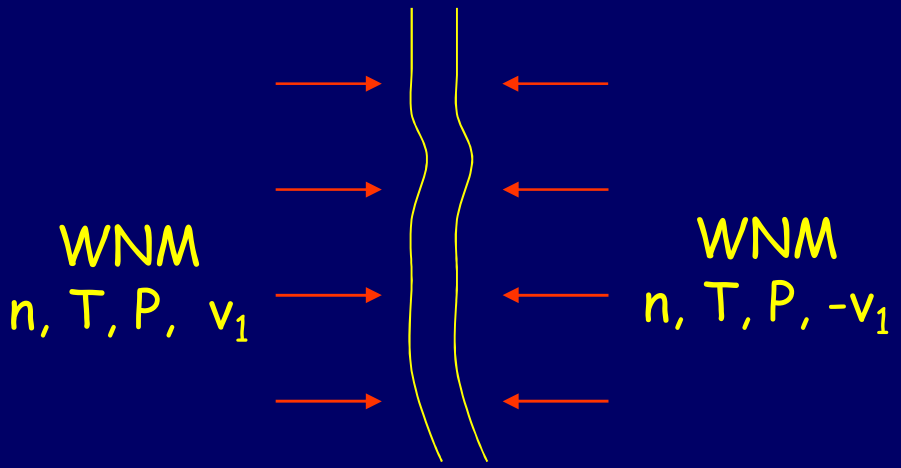
CNM (stable)

Unstable (gas cools upon compression).

$$P_{\mathrm{eq}} \ni (\Gamma = n\Lambda)$$

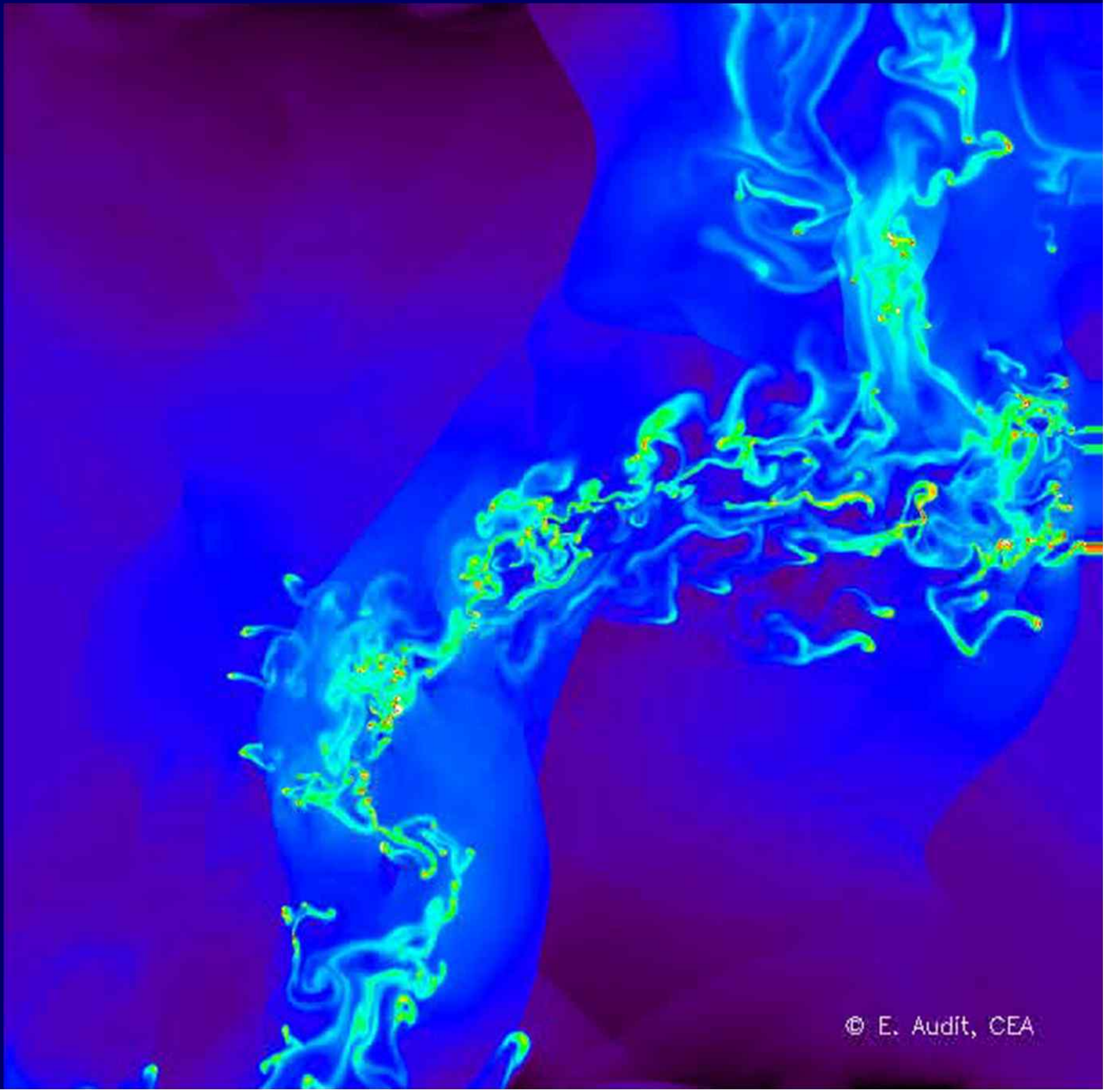
  - A moderate (transonic) compression in the WNM can induce a ***phase transition*** to the cold neutral medium (CNM) (Hennebelle & Pérault 1999).
  - As gas continues to transit from the diffuse to the dense phase, a dense cold cloud forms.
  - Due to ram pressure of inflow or self-gravity, dense gas can overshoot from CNM to GMC conditions and become significantly self-gravitating.

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



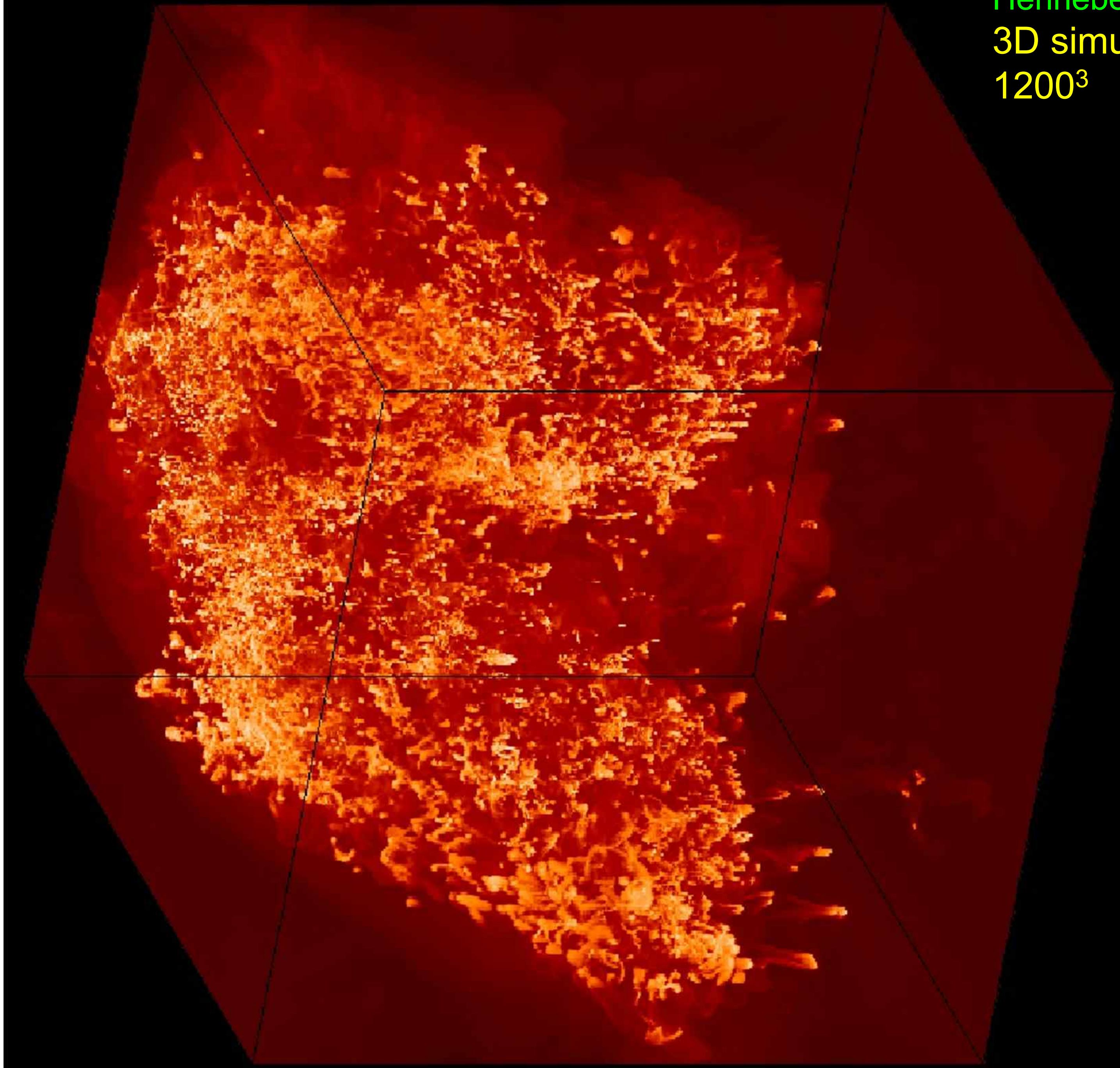
- The compression may be driven by global turbulence, large-scale instabilities, etc.

- For stronger compressions and later times, the compressed layer becomes denser, turbulent, and thick, *and continuously grows in mass*.



$\mathcal{M}_s \sim 2$

Audit & Hennebelle 2005

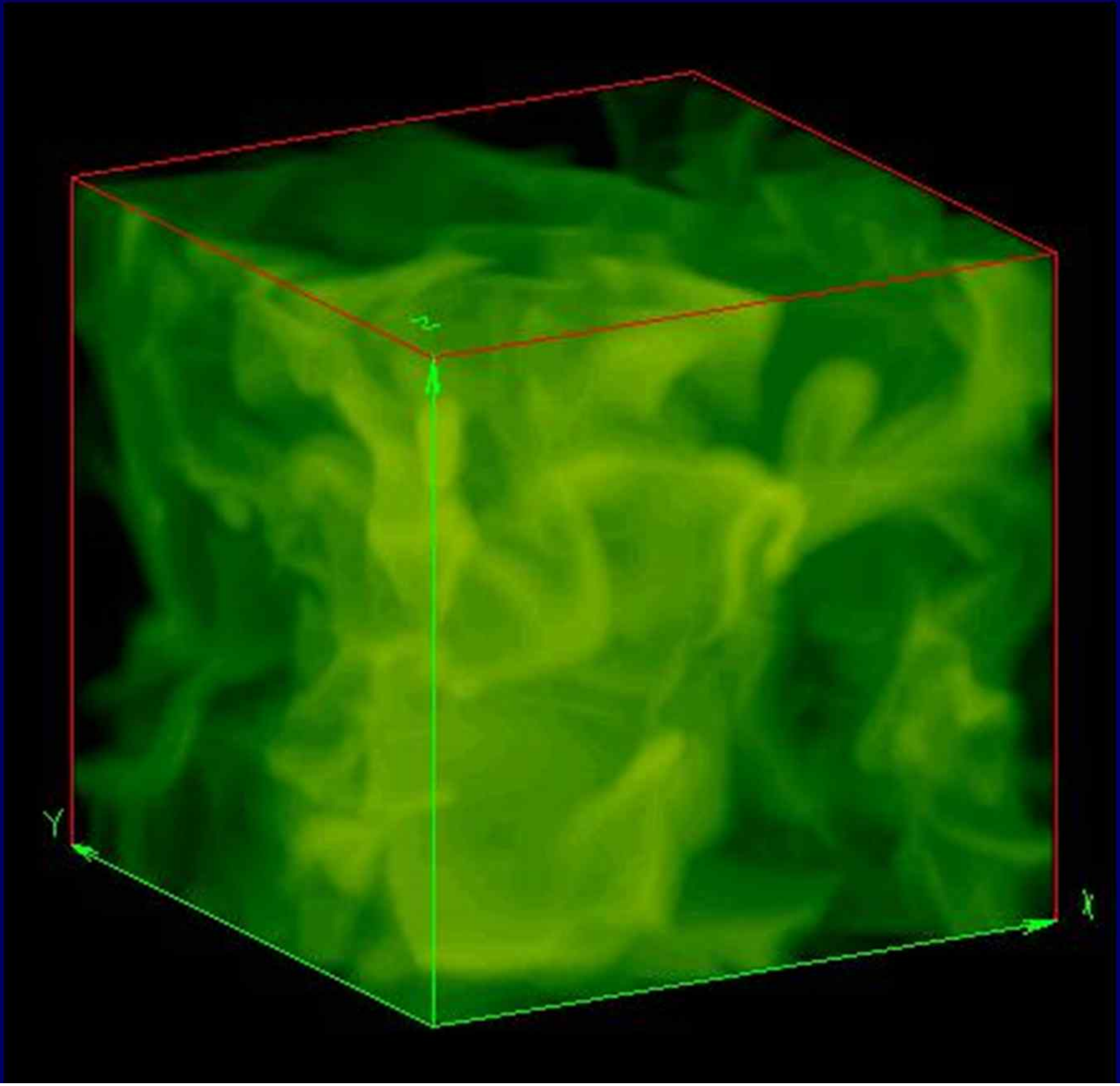


Hennebelle & Audit 2007

3D simulation

1200^3

Very different from $\mathcal{M}_{\rm rms} \sim 10$, Fourier-driven isothermal boxes!



Vázquez-Semadeni+ 2008

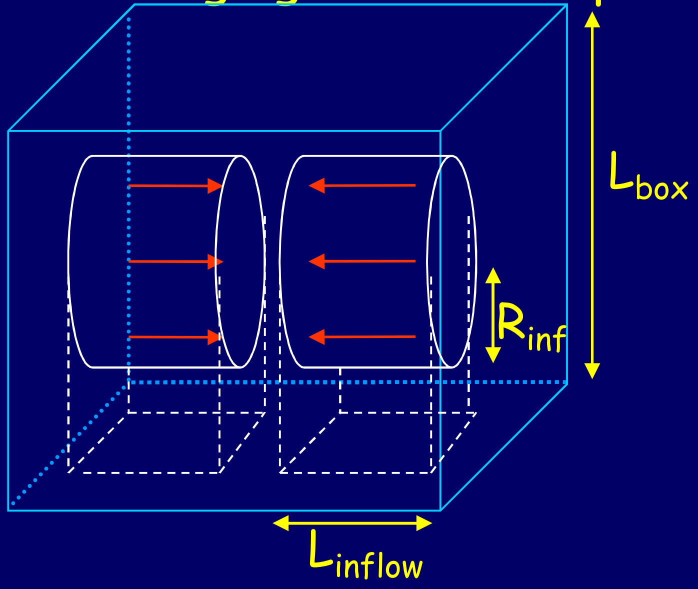
- Implications:
  - The mass of a cloud is in general *not constant,* because there is a continuing mass flux into it.
    - Cloud’s mass generally increasing...
    - ... except when consumed by SF.

IV. FORMATION OF MOLECULAR CLOUDS

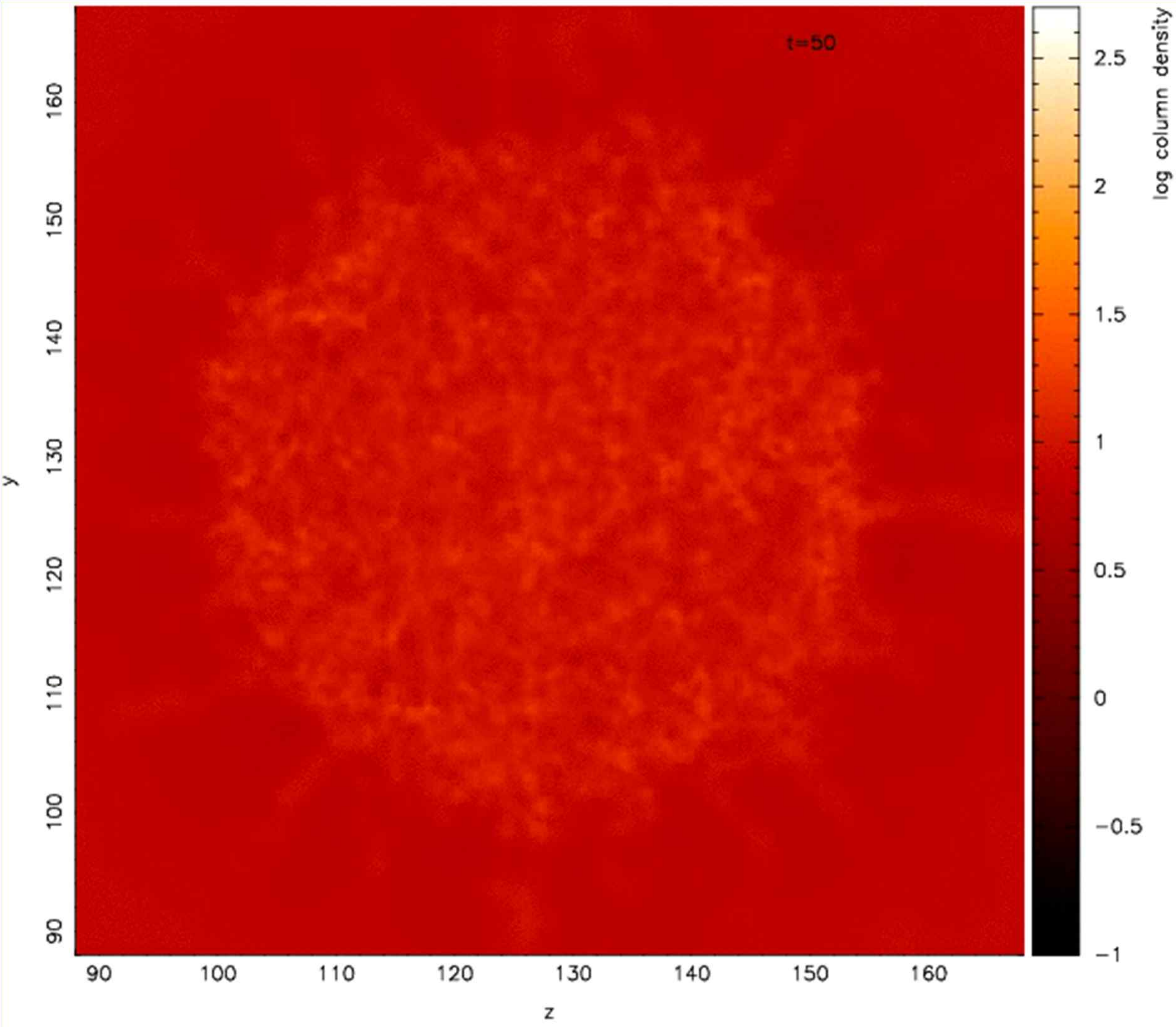
- As a CNM cloud grows, it may eventually involve enough mass to become ***strongly self-gravitating.***

- Simulations of MC formation and turbulence generation including thermal instability AND self-gravity (Vázquez-Semadeni et al 2007, ApJ 657, 870; see also Heitsch et al. 2008, 2009).
    - SPH (Gadget) code with sink particles and heating and cooling.
  - WNM inflow:
    - $n = 1\ \mathrm{cm}^{-3}$
    - $T = 5000\ \mathrm{K}$
    - Inflow Mach number in WNM: $\mathcal{M} = 1.25$ ($v_{\mathrm{inf}} = 9.2\ \mathrm{km\ s}^{-1}$)
    - 1% velocity fluctuations.

Converging inflow setup



	Run 1	[redacted]
L_{box}	128 pc	[redacted]
L_{inflow}	48 pc	[redacted]
$\Delta t_{\mathrm{inflow}}$	5.2 Myr	[redacted]
M_{inflow}	$1.1\times10^4\ M_{\mathrm{sun}}$	[redacted]
M_{box}	$6.6\times10^4\ M_{\mathrm{sun}}$	[redacted]



Face-on view.

Note: Local ***nonlinear*** fluctuations collapse earlier than whole cloud.

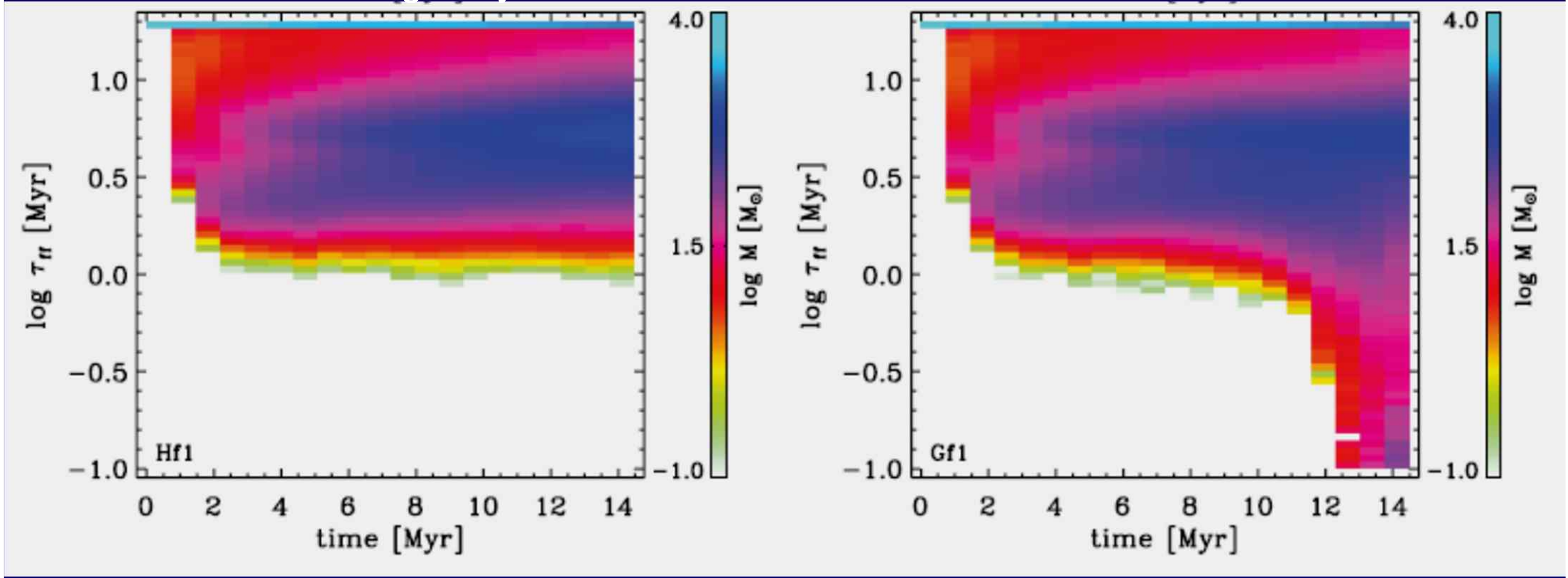
Because of shorter free-fall time (Heitsch & Hartmann 2008).

Evolution of mass fraction at a given free-fall time τ_{ff}

(Heitsch & Hartmann 2008)

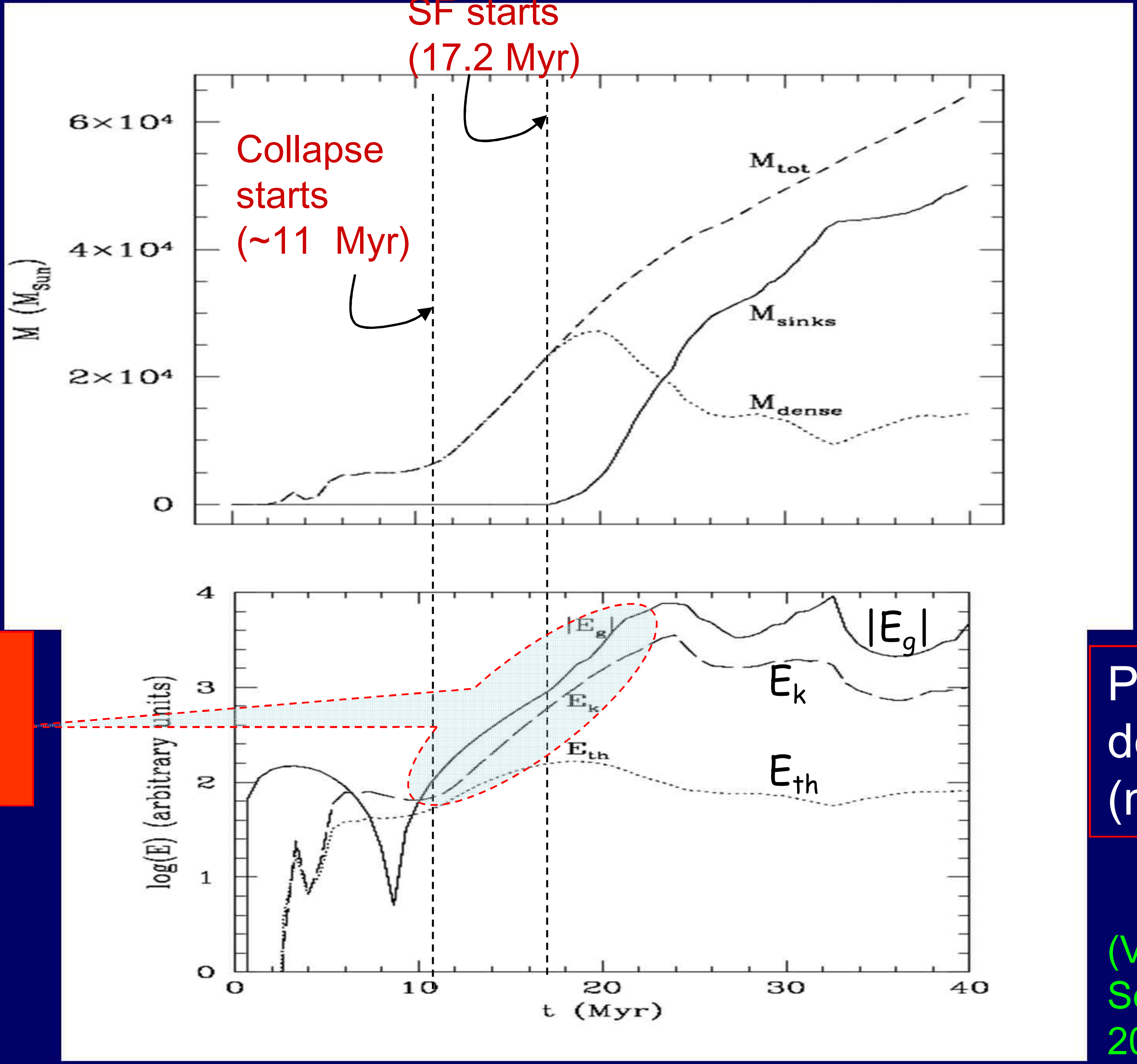
No self-gravity

With self-gravity



Most of the mass has long (CNM-like) free-fall time, but a small fraction reaches very short τ_{ff}.

These clouds are *never* in true virial equilibrium, but *appear* virialized because of gravitational contraction.



SF starts (17.2 Myr)

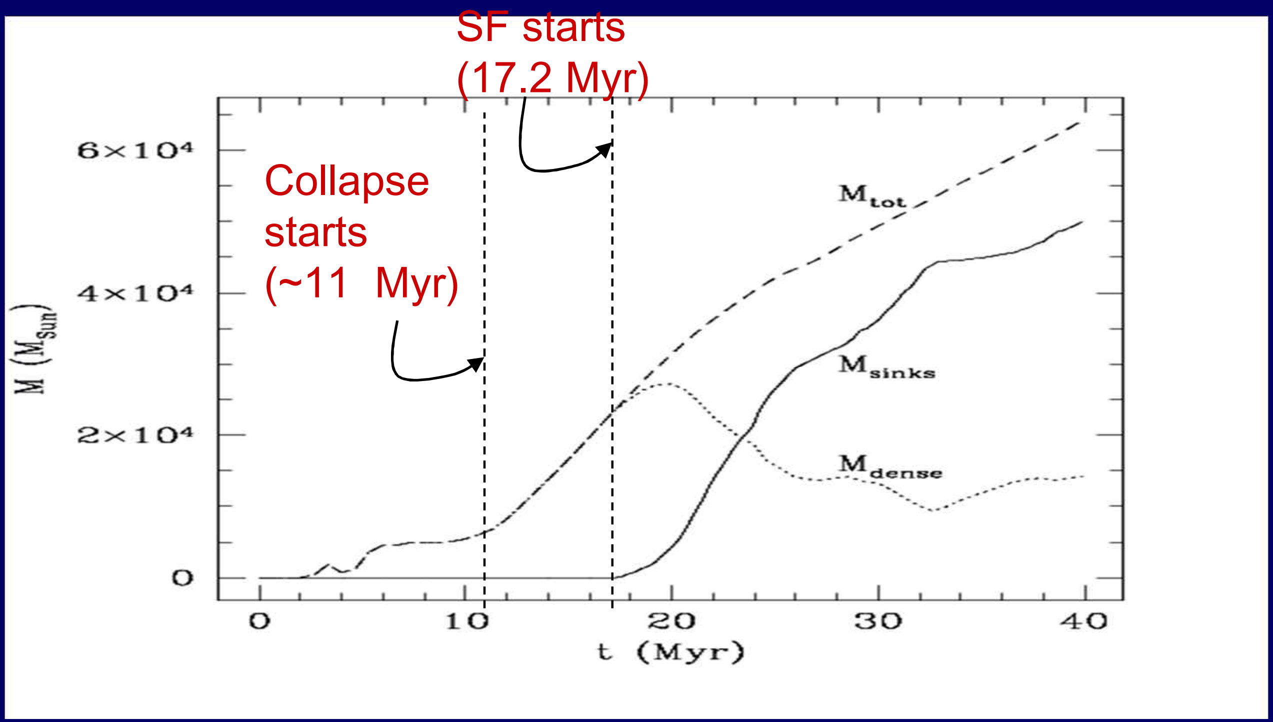
Collapse starts (~11 Myr)

Apparent virialization: $|E_g| \sim 2\ E_k$

Plots for the dense gas ($n > 50\ \text{cm}^{-3}$)

(Vázquez-Semadeni et al. 2007)

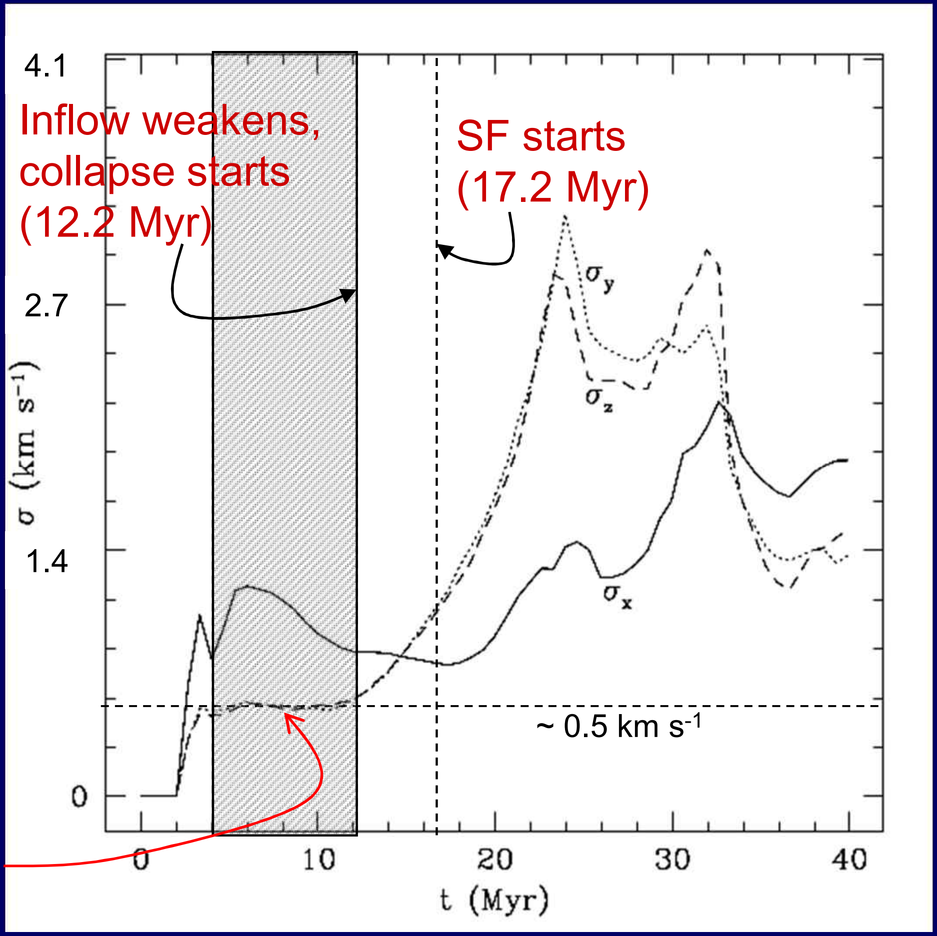
Star formation begins *long* after onset of gravitational contraction.



If SF is to balance gravity, it must *revert* the ongoing collapse.

(Vázquez-Semadeni et al. 2007)

- Initial turbulence is transonic.
  - Bulk velocities increase later because of gravitational contraction.



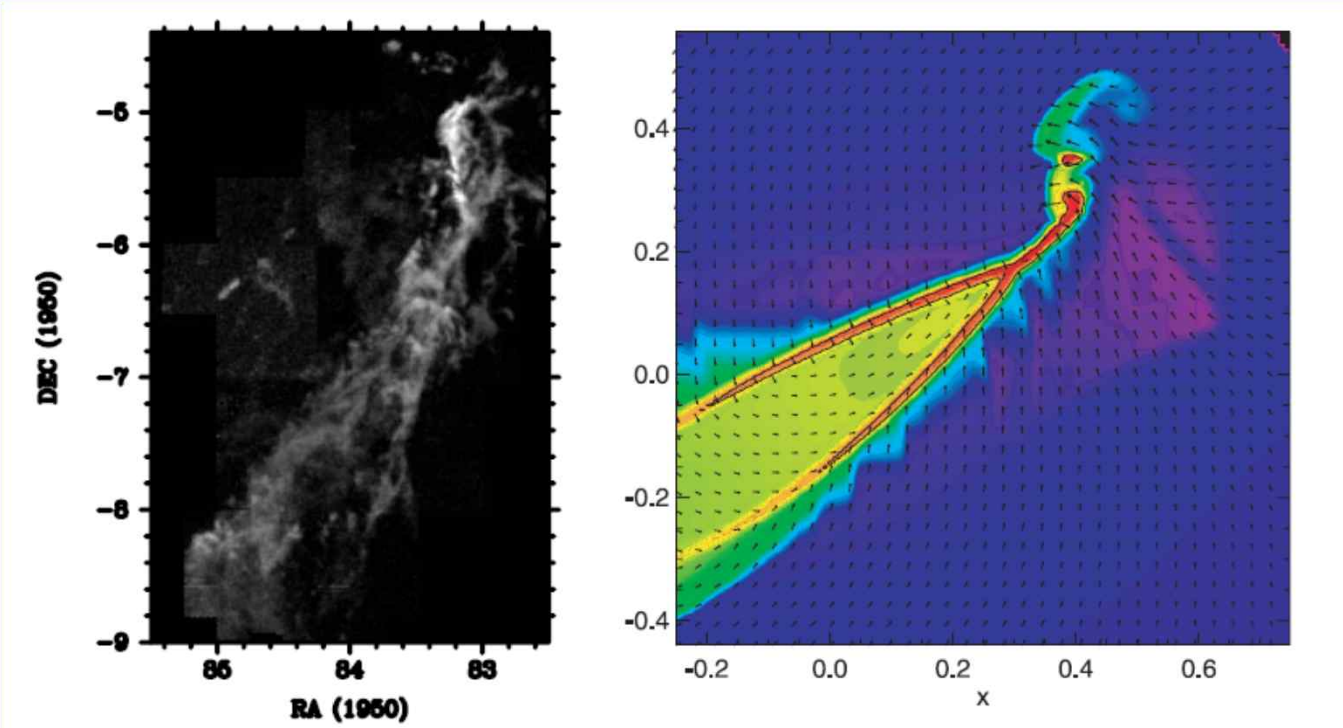
Inflow weakens, collapse starts (12.2 Myr)

SF starts (17.2 Myr)

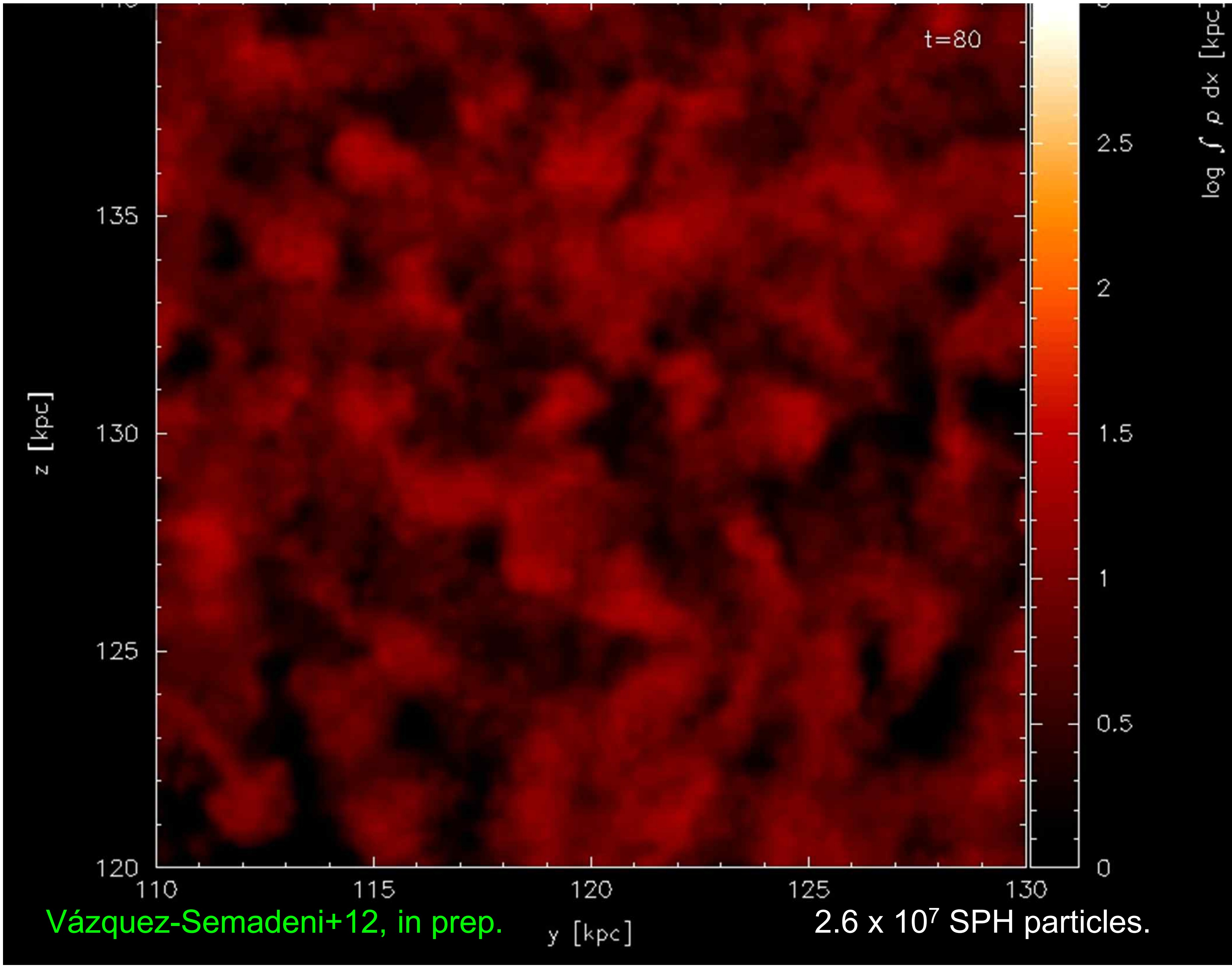
Turbulence driven by compression, through NTSI, TI and KHI (Walder & Folini1998; Koyama & Inutsuka 2002; Audit & Hennebelle 2005; Heitsch et al. 2005, 2006; Vázquez-Semadeni et al 2006)

(Vázquez-Semadeni et al. 2007)

- This scenario implies that
  - Molecular clouds should be undergoing gravitational contraction, not be in equilibrium.
    - Consistent with recent studies of the Orion A cloud (Hartmann & Burkert 2007), of clump NGC2264-C (Peretto et al. 2007), and of massive-star forming regions (Galván-Madrid et al. 2009; Schneider et al. 2010; Csengeri et al. 2011).



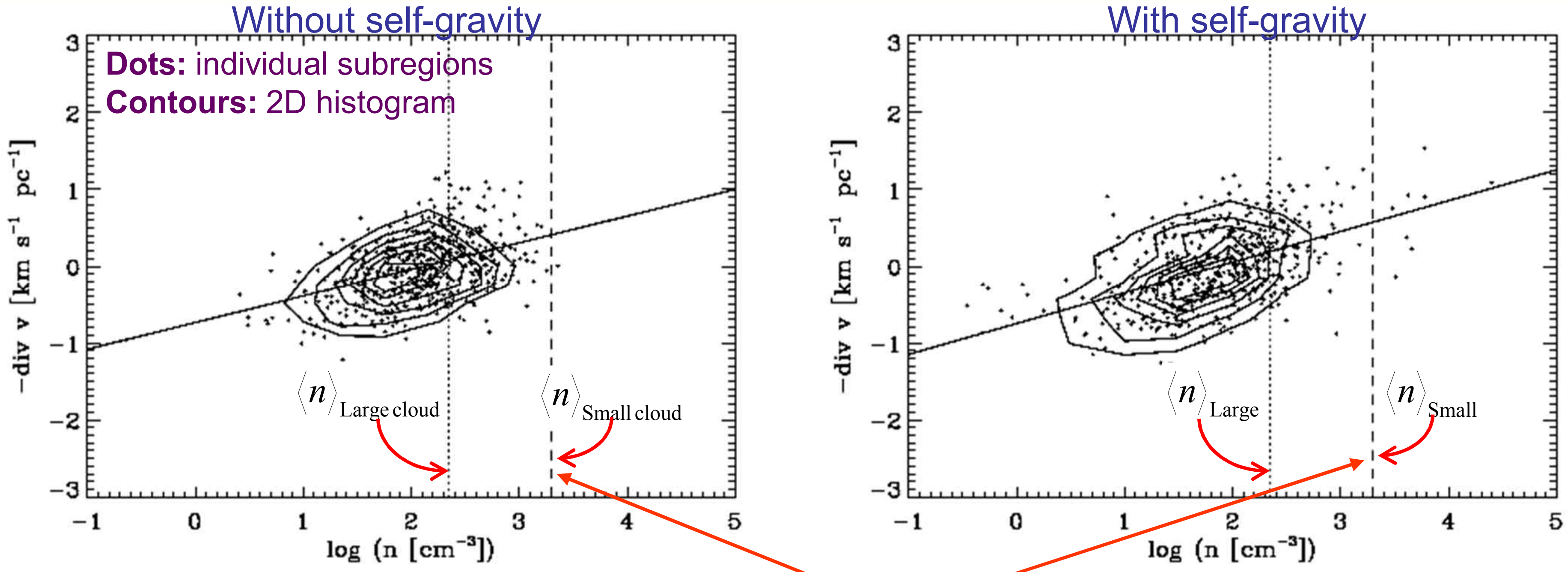
Hartmann & Burkert 2007



Vázquez-Semadeni+12, in prep.

2.6×10^7 SPH particles.

- And also that (Vázquez-Semadeni, Kim et al. 2008):
  - Density enhancements in turbulent media have in general a significant inward component of their velocity field.
  - Gravity is necessary not only to cause collapse of Jeans-unstable objects, *but even to form them.*


Without self-gravity

With self-gravity

Density of gravitationally-bound box of the same size as the sub-boxes represented by the dots.

IV. STELLAR FEEDBACK

- It is usually believed that stellar feedback can feed the turbulence...
- ... which in turn can maintain clouds in approximate equilibrium (Norman & Silk 1980; McKee 1989; McKee & Tan 2003; Krumholz & McKee 2005; Krumholz+06).
- Can it?

f) Large-scale numerical simulations of GMC formation and evolution, including feedback (Vázquez-Semadeni et al. 2010, ApJ, 715, 1302).

- The model:
  - Cloud formation by colliding flows in warm neutral medium (WNM).
  - Self-gravity; Heating and cooling; Star formation; Heating from stellar particles.

$\mathcal{M}_{s,\mathrm{inf}}$: Mach number of inflow speed w.r.t. warm gas.

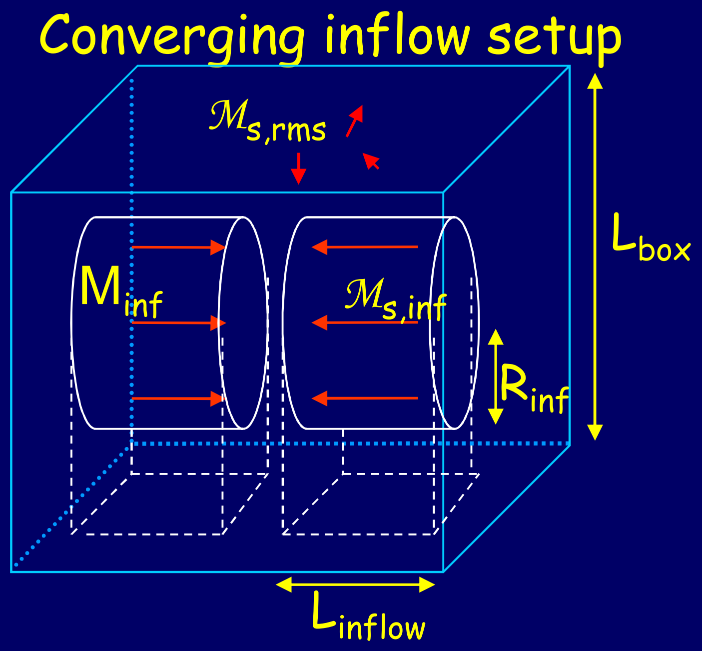
$\mathcal{M}_{s,\mathrm{rms}}$: Mach number of background turbulence in WNM.

M_{inf}: Mass in colliding cylinders $= 2\,\rho\,\pi\,R_{\mathrm{inf}}^2\,L_{\mathrm{inf}}$

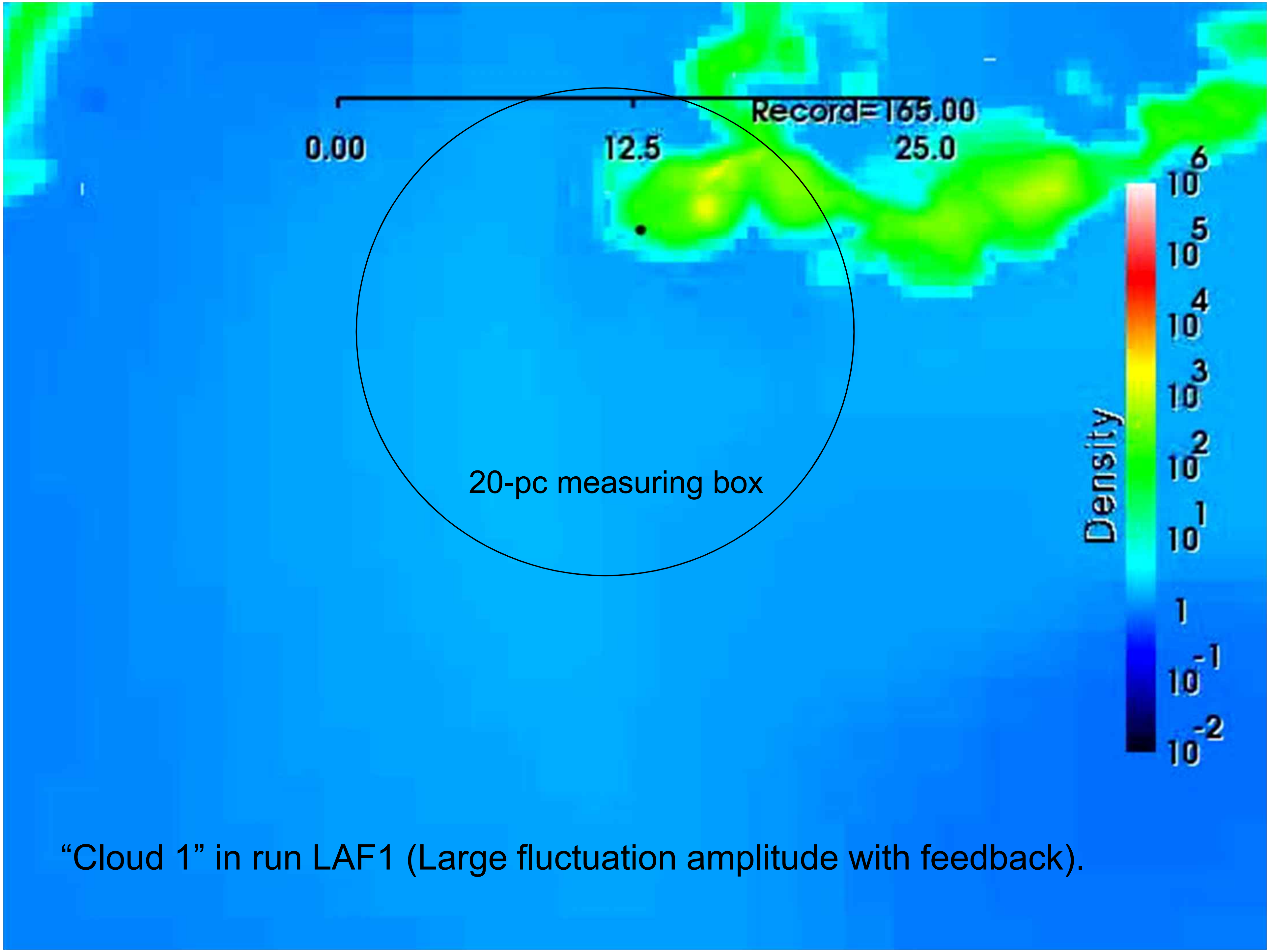
$n_{\mathrm{WNM}} = 1\ \mathrm{cm}^{-3}$

$T_{\mathrm{WNM}} = 5000\ \mathrm{K} \rightarrow c_s = 7.4\ \mathrm{km\ s}^{-1}$

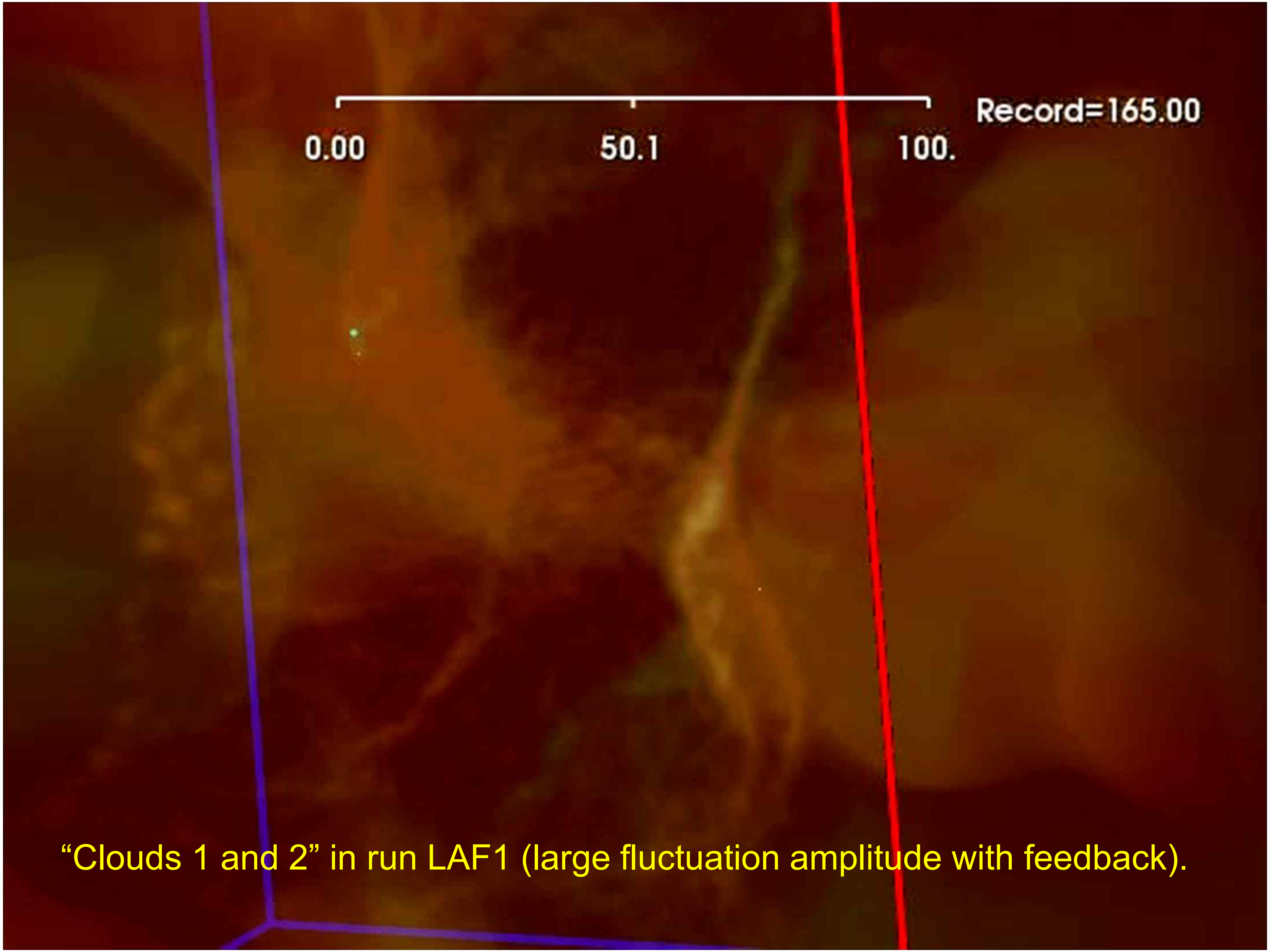
$L_{\mathrm{inflow}} = 112\ \mathrm{pc}$ $R_{\mathrm{inflow}} = 64\ \mathrm{pc}$



- Use code ART + AMR hydrodynamics (Kravtsov+1997, Kravtsov 2003).
- SF prescription:
  - Stellar particles formed in cells where $n > 4 \times 10^6$ cm^{-3}.
  - Stellar particles take ½ of cell's mass ➔ $M_{cell} \sim 120$ M_{sun}.
  - No accretion onto stellar particles.
  - Each particle is assumed to contain one 8-M_{sun} B star and form one HII region.



“Cloud 1” in run LAF1 (Large fluctuation amplitude with feedback).



“Clouds 1 and 2” in run LAF1 (large fluctuation amplitude with feedback).

- Results:

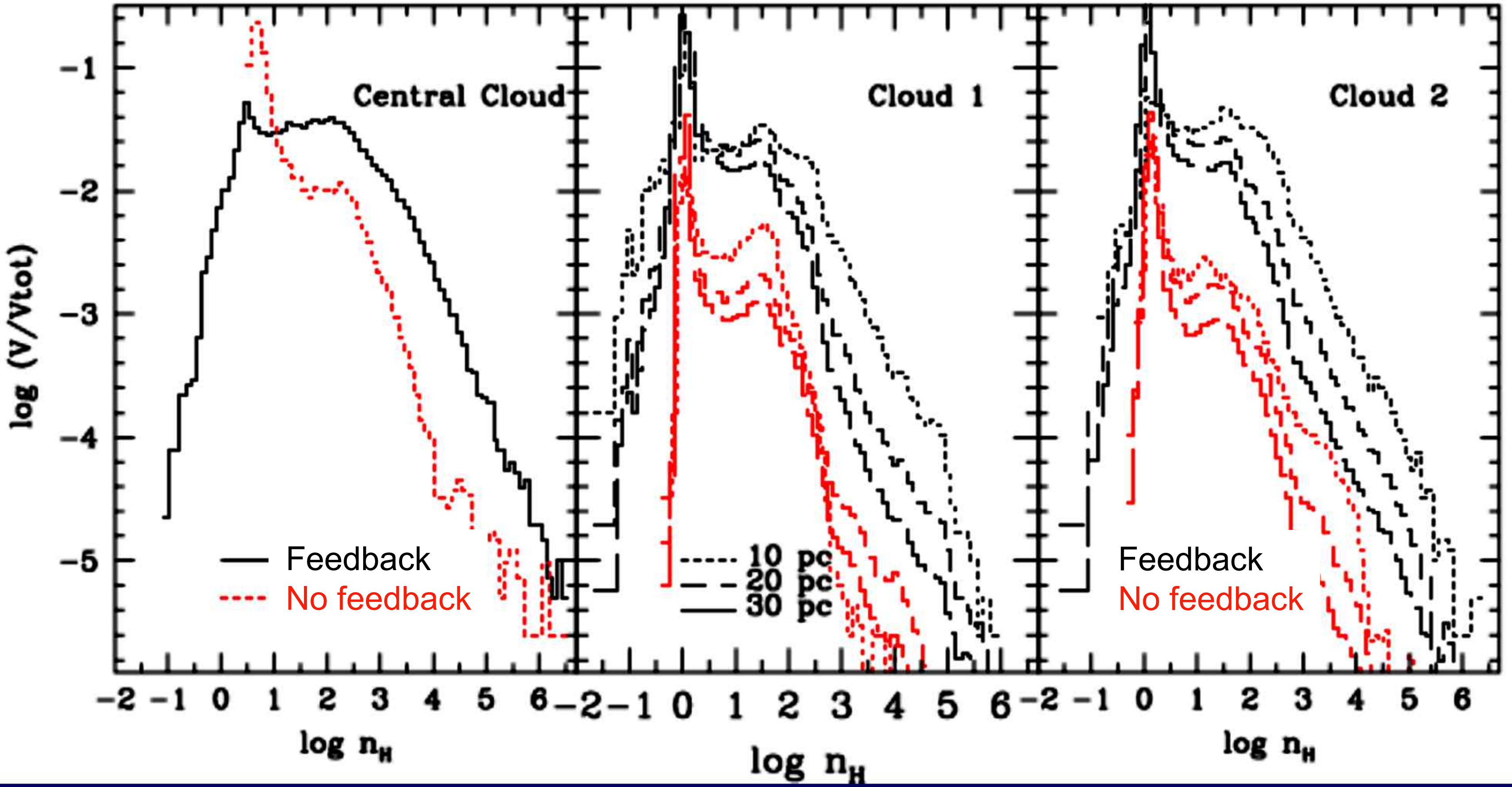
1. Massive clouds are not kept near virial equilibrium...

   ... nor dispersed!

   Instead, *accretion approximately balances gas consumption by SF and dispersal by feedback.*

   Large-scale accretion continues; SF shifts from one place to another.

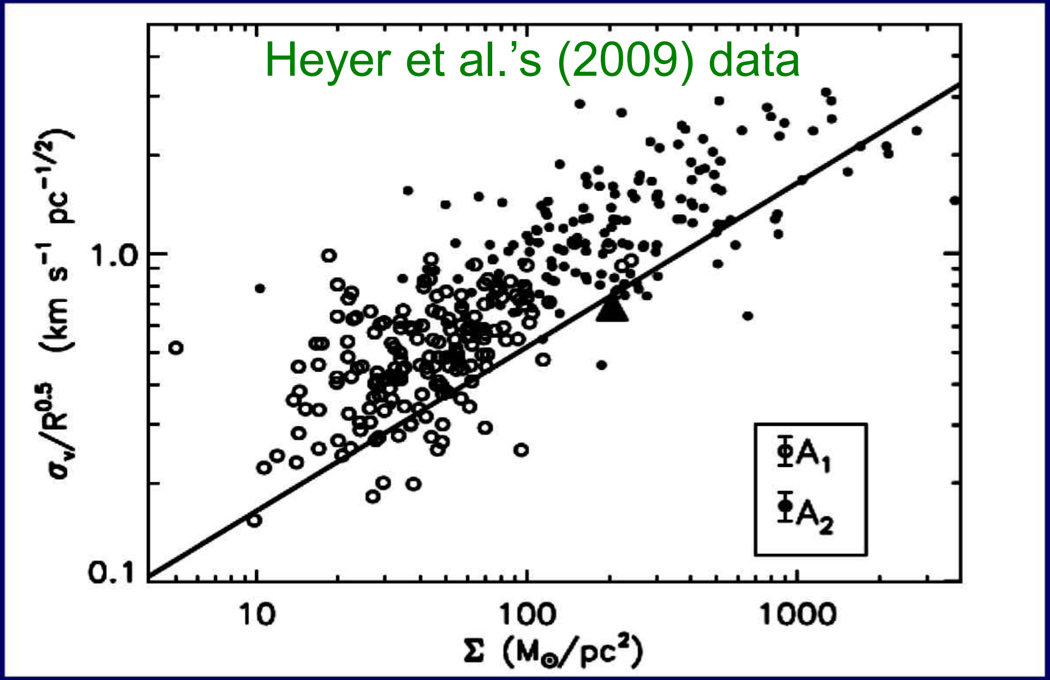
2. Again, density PDFs are *not* lognormal.



3. Feedback mainly inhibits the *local* conversion of gas to stars.
    - Feedback operates on smaller scales than the scale of the gravitational potential well.
        - Feedback cannot prevent accretion from large scales.
    - *Feedback reduces SFE by redirecting some of the infalling gas back to the diffuse medium.*

VI. GRAVITATIONALLY CONTRACTING MOLECULAR CLOUDS?

- All the numerical models above show that MCs should be gravitationally contracting.
- Consistent with recent observations:

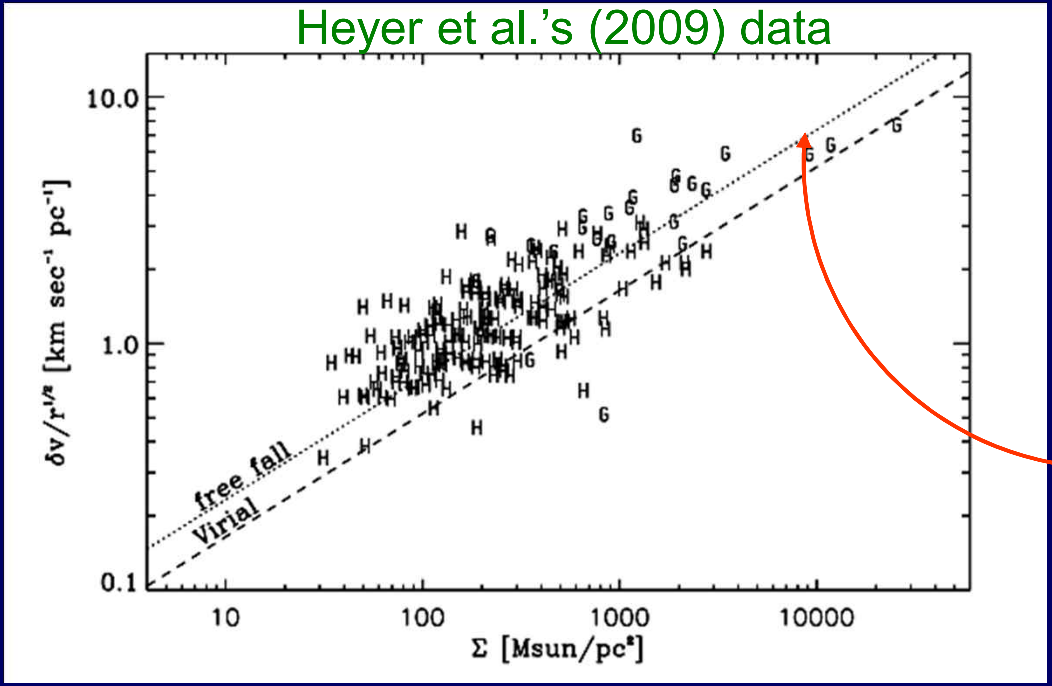


$$\frac{\delta v^2}{R} = G\Sigma$$

Virial equilibrium

- All the numerical models above show that MCs should be gravitationally contracting.

- Consistent with recent observations:



Heyer et al.'s (2009) data

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

Virial equilibrium

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

Free-fall

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

VII. CONCLUSIONS

Simulations of MC formation suggest that:

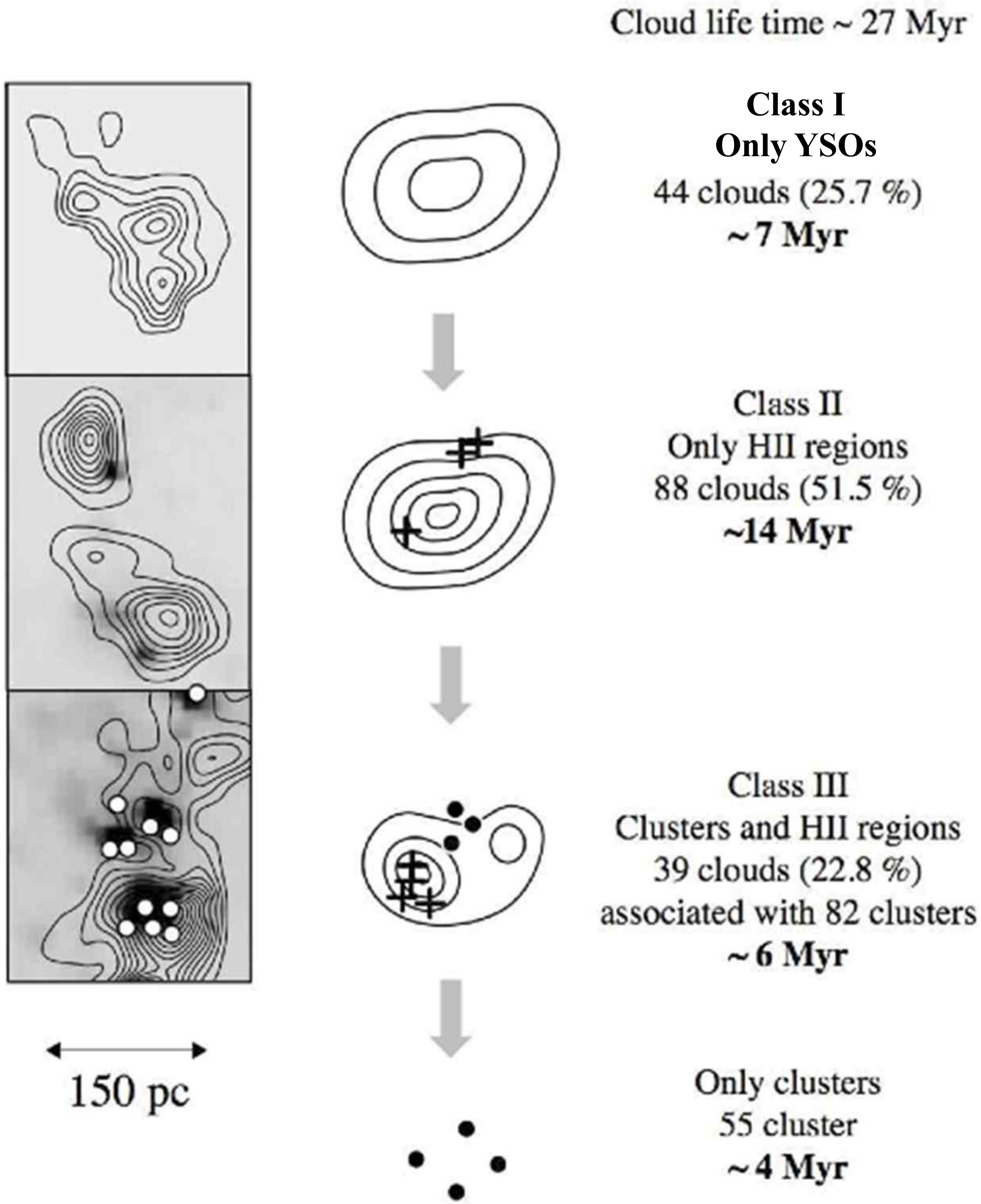
1. Converging WNM flows drive the formation of *transonically turbulent* CNM clouds and GMCs.
   - Not *strongly* supersonic.
   - Cloud's mass *not* constant, because of infall from envelope.
     - Accretion must be taken into energy and mass budget.

2. Supersonic "GMCs" appear *after* gravitational contraction has begun.
   - GMC *formation* may generally require self-gravity (but see Dobbs & Burkert 2011).
   - MCs may be porous, permeated by more diffuse atomic gas (Goldsmith).
   - SF starts last.
   - A *hierarchy* of collapsing motions.
3. *Dominant bulk motions in MCs may be gravitational contraction.*
   - Contraction starts *before* SF.
   - Feedback inhibits the conversion of gas to stars, but not the large-scale accretion onto the cloud.
   - Random motions superposed on dominant collapsing motion.
   - Produced by either
     - Conversion of infall to random motions, or
     - Stellar feedback.

- Open questions:
  - What is the efficiency of conversion of gravitational into random kinetic energy? (Vázquez-Semadeni+1998; Klessen & Hennebelle 2010)
  - What controls the star formation efficiency?
  - Observations to test the scenario (Galván-Madrid et al. 2009; Schneider et al. 2010; Csengeri et al. 2011).

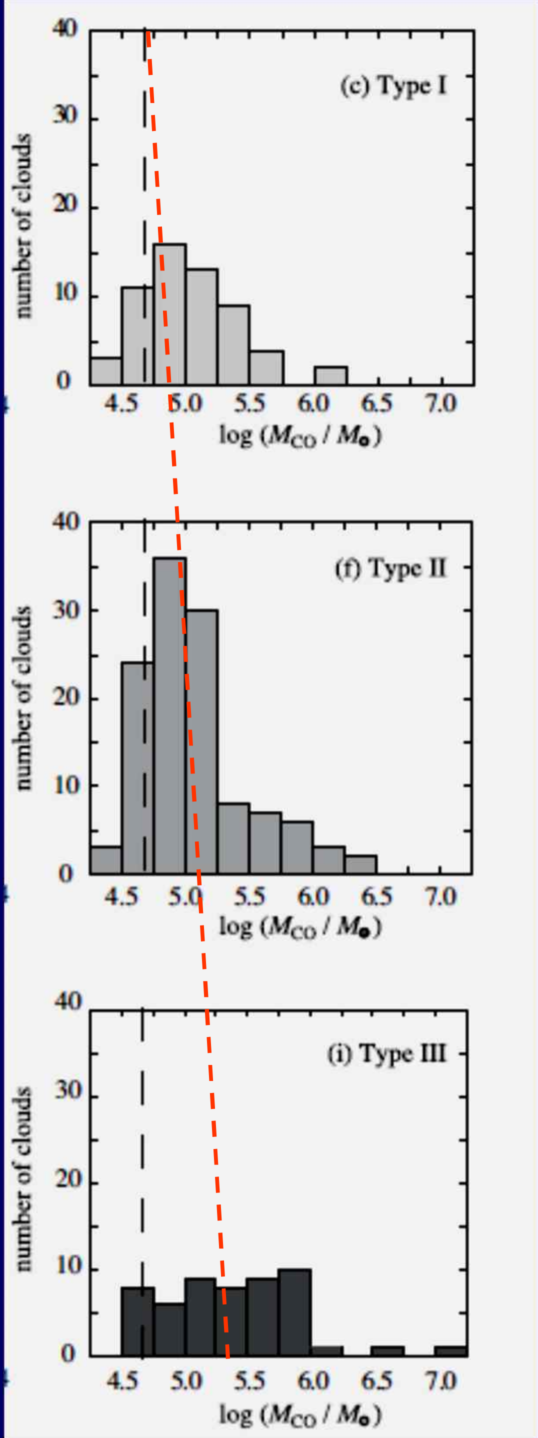
THE END

– Exhibit a possibly evolutionary sequence...



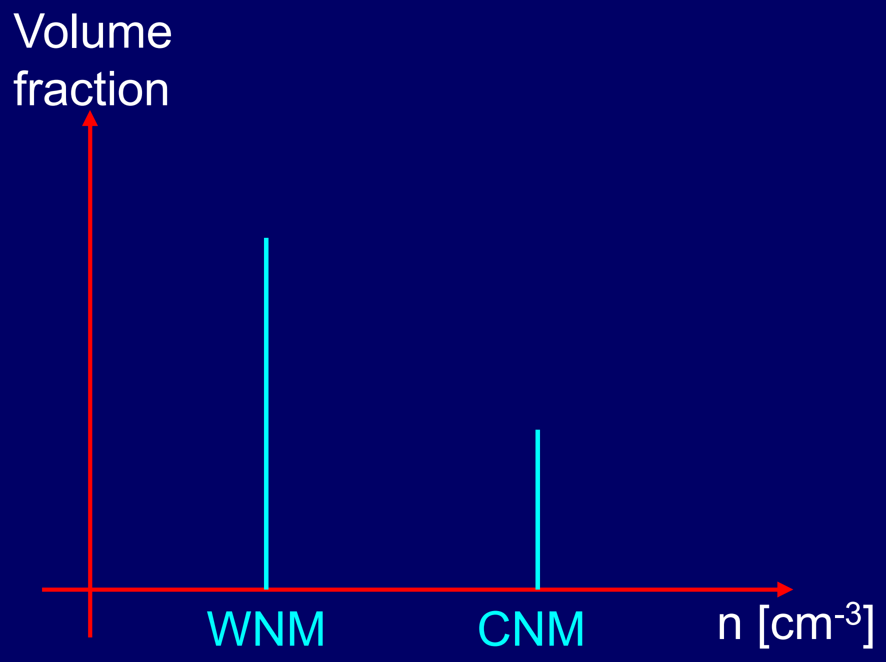
Kawamura et al. 2009

– ... which appears to also be a mass sequence.

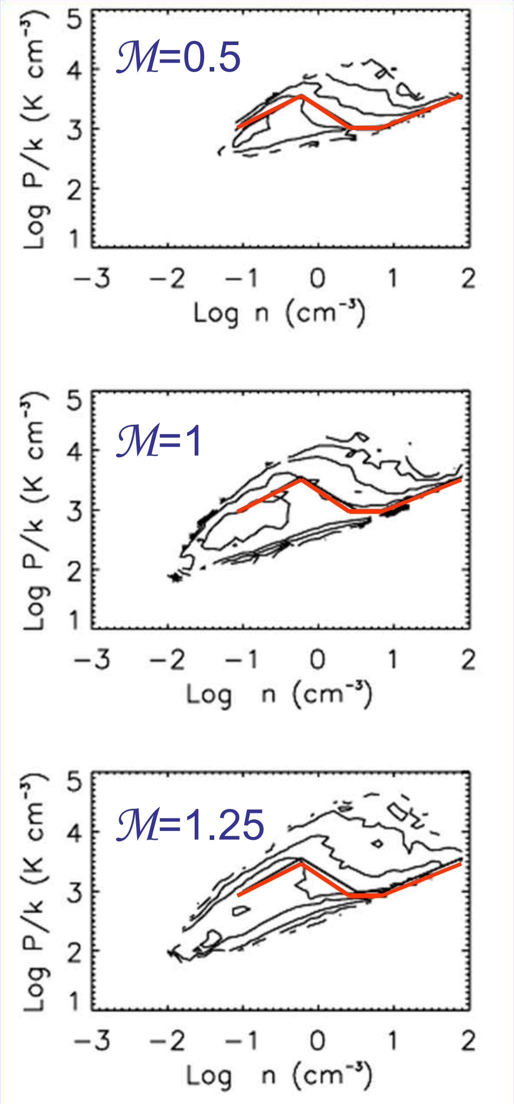


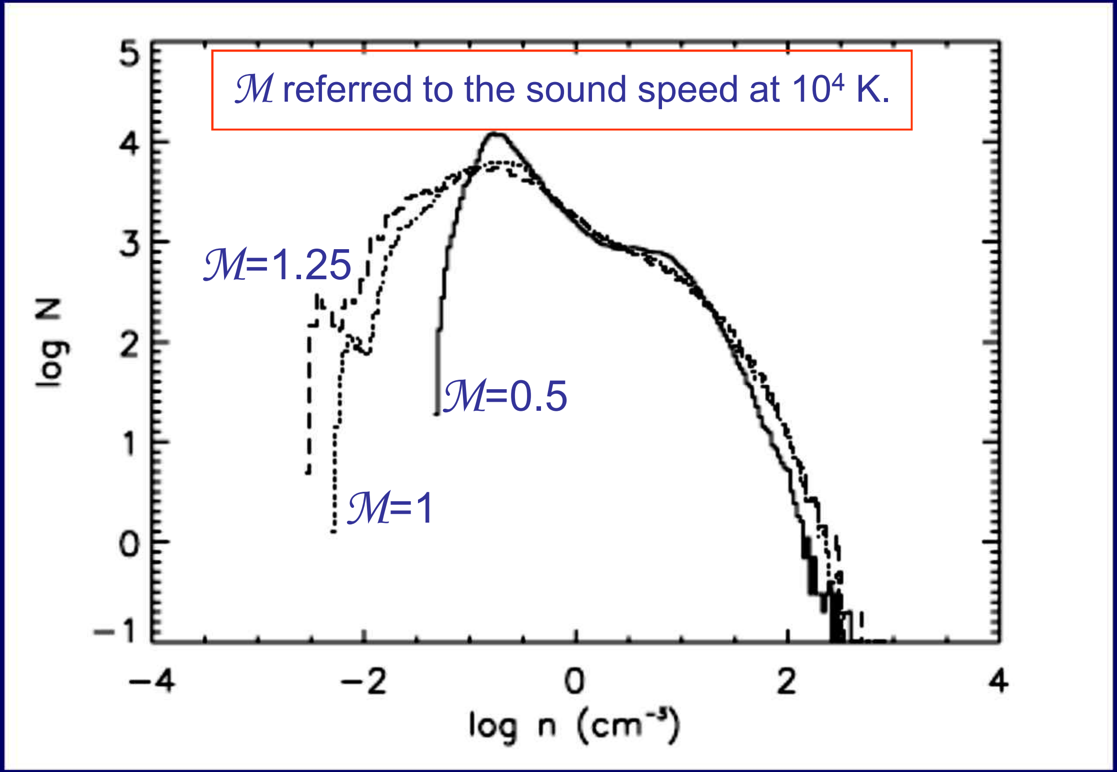
Kawamura et al. 2009

- In two-phase atomic medium, in perfect pressure equilibrium, expect a two-δ-function PDF.



- 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 $\tau_{cool} > \tau_{cross}$.




$\mathcal{M}$ referred to the sound speed at 10^4 K.

Bimodality increasingly erased by turbulence as $\mathcal{M}$ increases.

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

- Run with L_{box} = 256 pc:

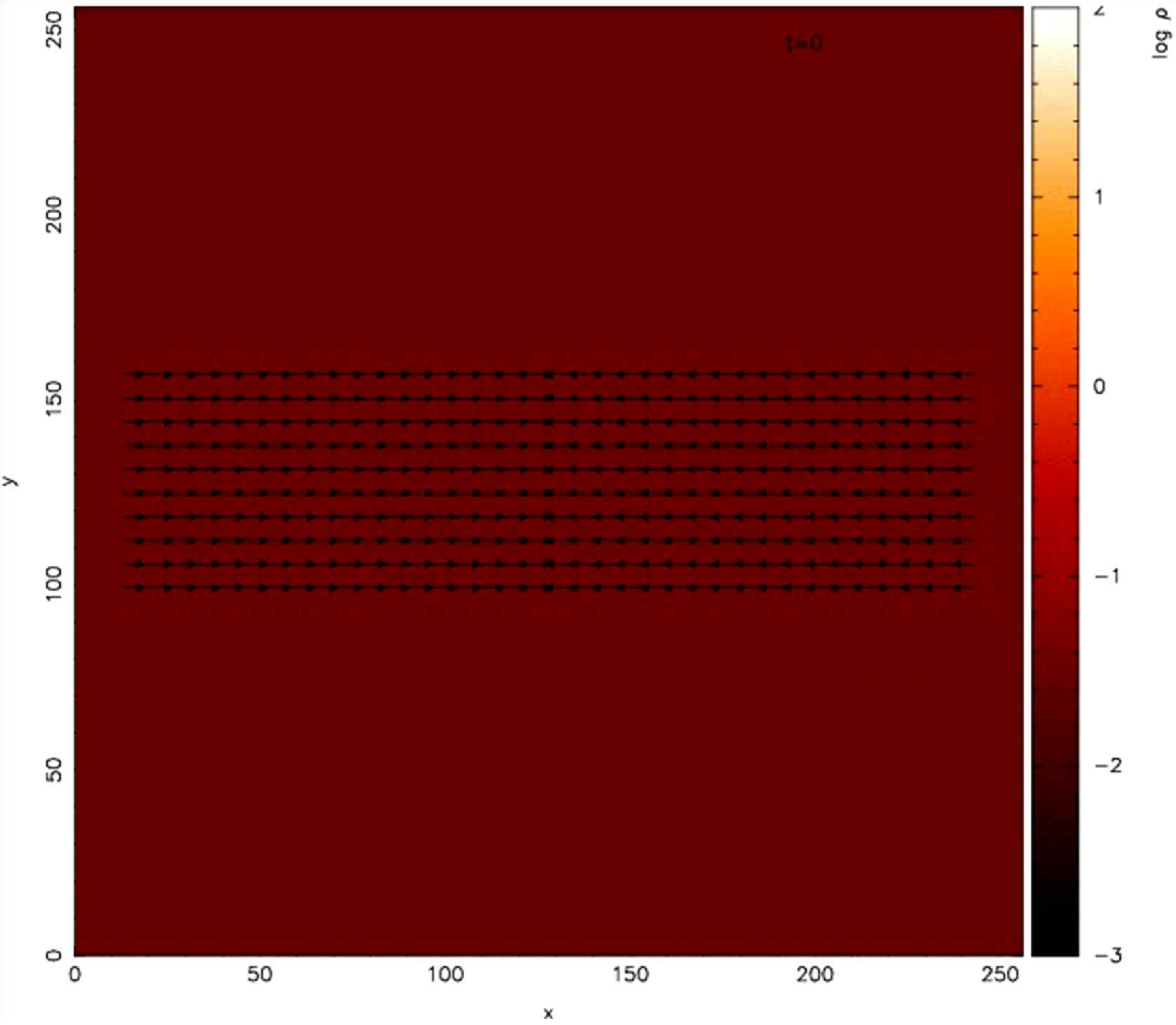
(Vázquez-Semadeni et al. 2007, ApJ 657, 870)

WNM in box is initially ***Jeans-stable***. (M_{box} ~ 0.01 M_J)

Compression cools and compresses the gas.

Dense, cold gas soon becomes turbulent and ***Jeans-unstable***

Edge-on view.



- Four simulations:

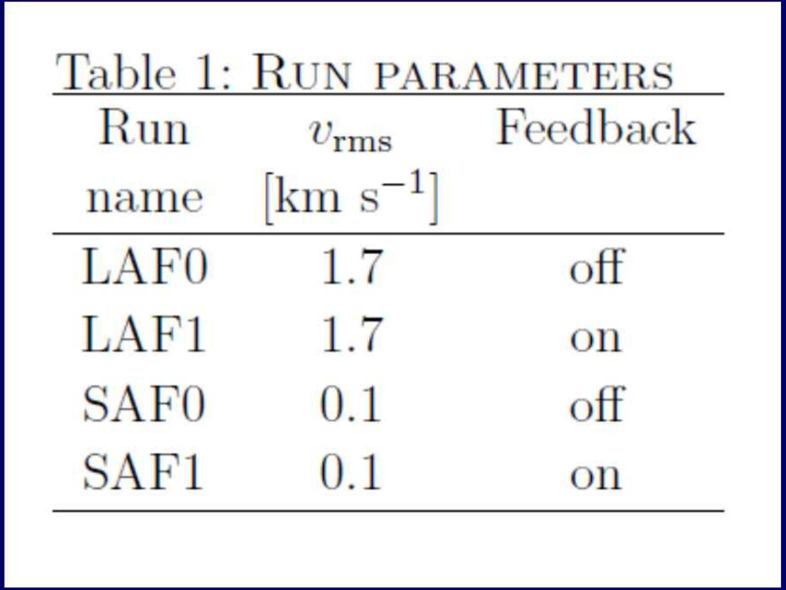
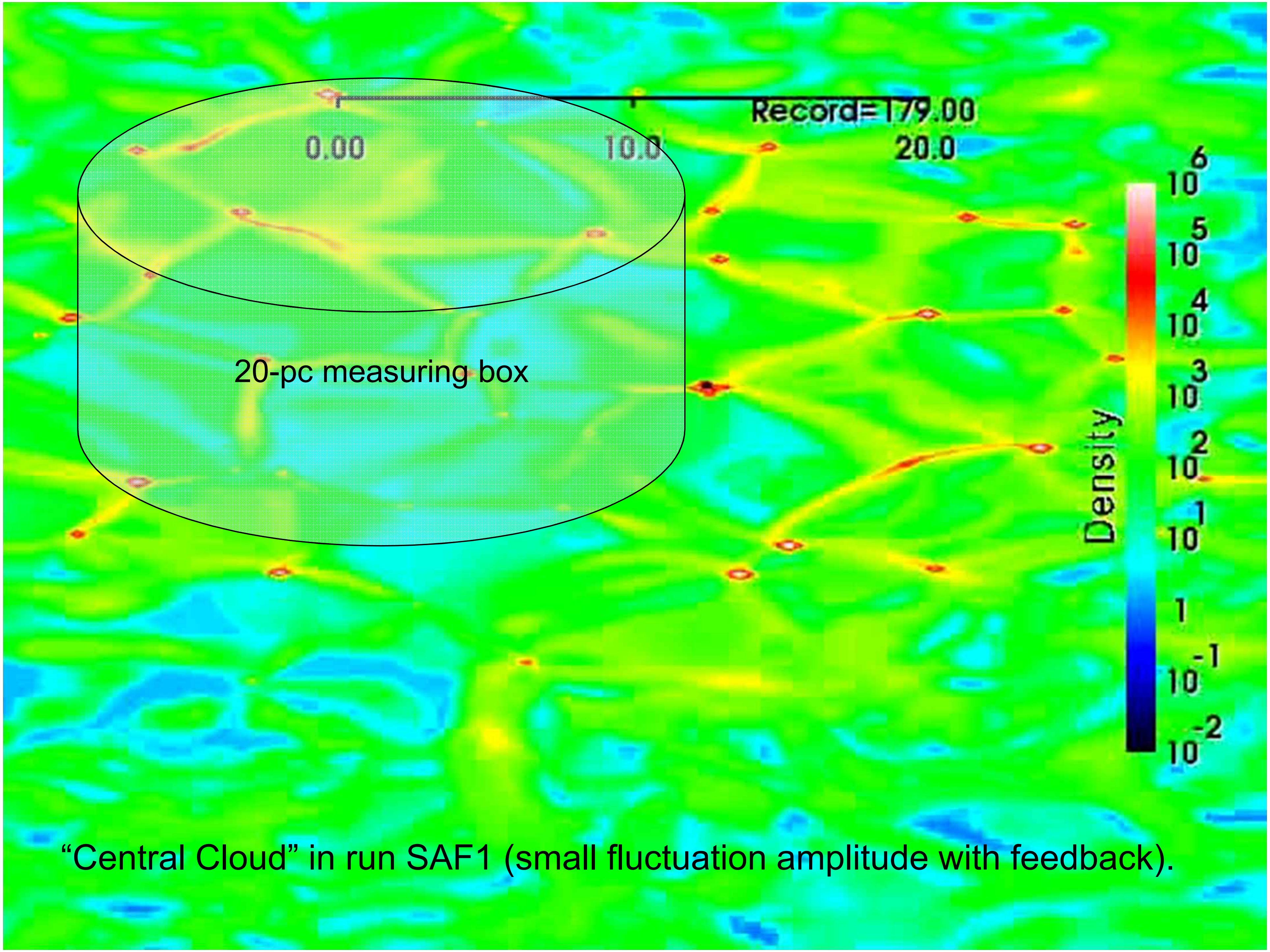


Table 1: Run parameters

Run name	$v_{\rm rms}$ [km s^{-1}]	Feedback
LAF0	1.7	off
LAF1	1.7	on
SAF0	0.1	off
SAF1	0.1	on

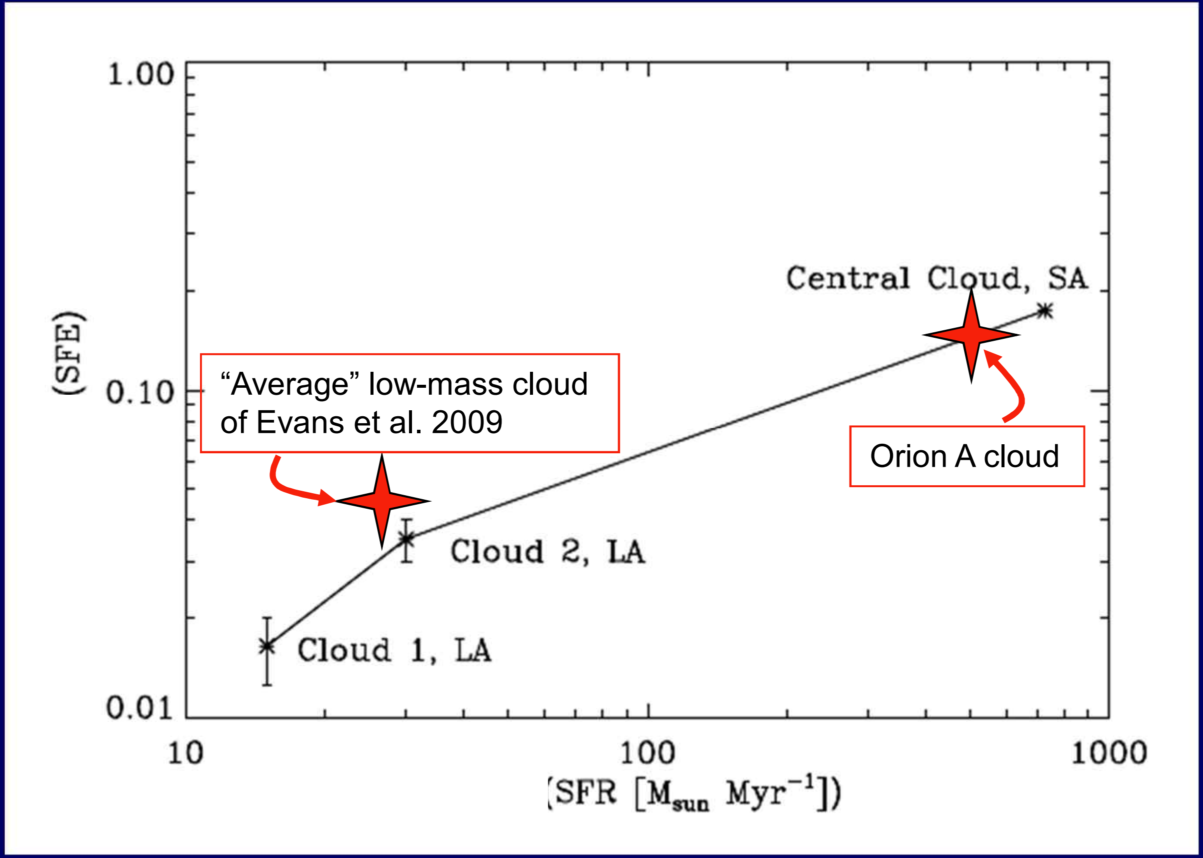
Large-amplitude initial fluctuations

Small-amplitude initial fluctuations



“Central Cloud” in run SAF1 (small fluctuation amplitude with feedback).

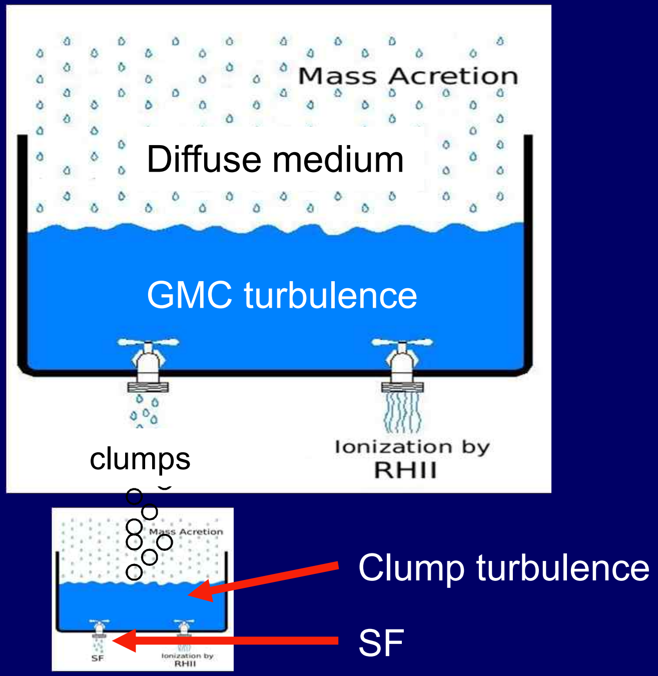
3. Coherence (smoothness) and scale of initial compression(s) determine type of star-forming region:
   - Measured SFRs and SFEs consistent with
     - Massive star-forming regions: Large-scale coherent collapse.
     - Low-to-intermediate-mass regions: Small-scale coherent collapse.



"Average" low-mass cloud of Evans et al. 2009

Orion A cloud

6. All self-gravitating simulations, including those with feedback, exhibit global, cloud-scale gravitational contraction.
   - Linewidth may correspond to infall, not virialized motions.
   - Consistent with observed SFE if feedback destroys clouds.
   - A simple model of cloud contraction + self-regulation yields realistic SFEs and evolutionary stage durations.



   - A hierarchical gravitational contraction process, perhaps driven from Galactic scales?