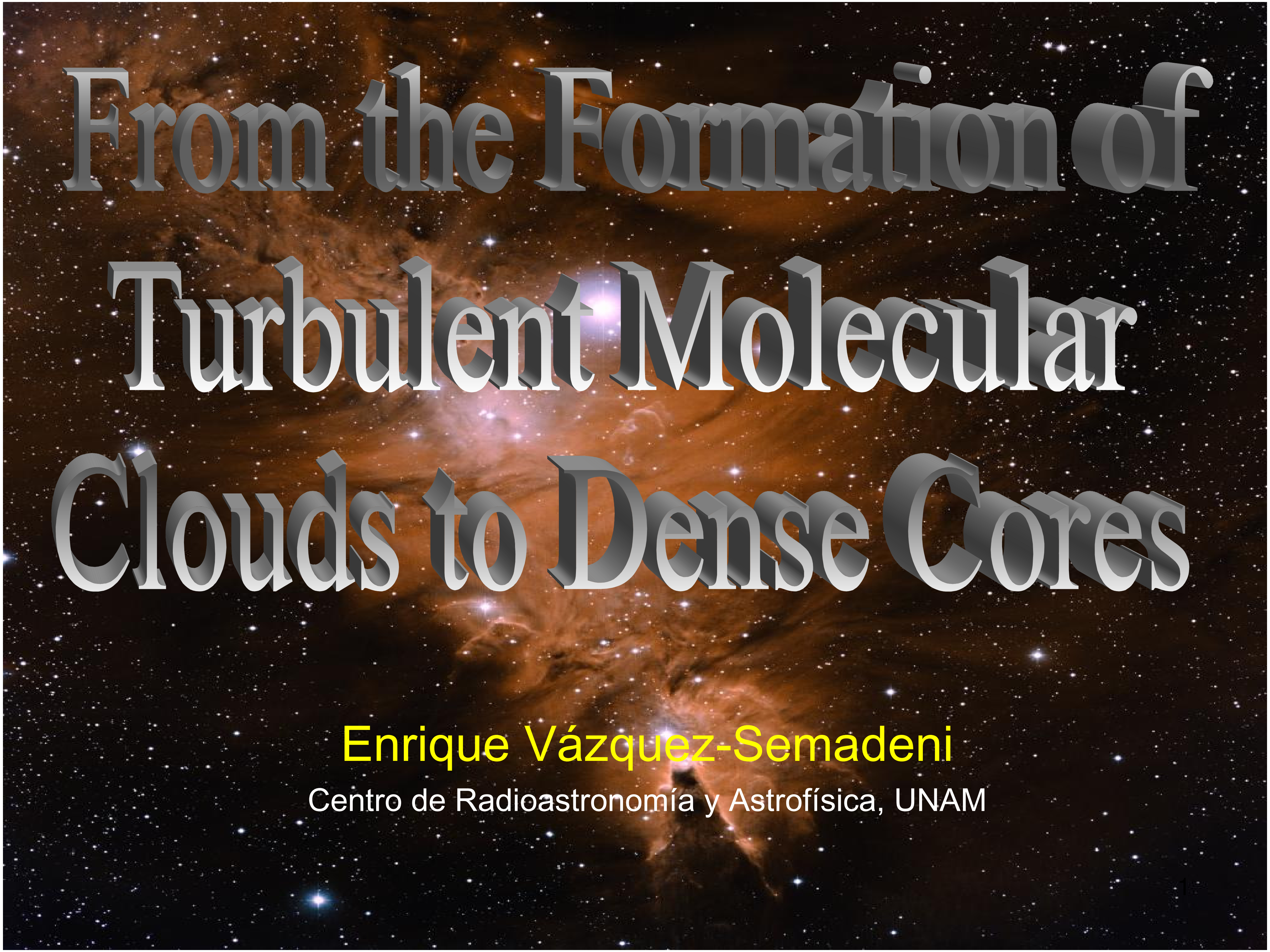


From the Formation of Turbulent Molecular Clouds to Dense Cores

Enrique Vázquez-Semadeni
Centro de Radioastronomía y Astrofísica, UNAM

Collaborators:

CRyA UNAM:

Roberto Galván-M.
Gilberto Gómez
Javier Ballesteros-P.
Ricardo González

ABROAD:

Mohsen Shadmehri (Dublin)
Jongsoo Kim (KASI, Korea)
Katharina Jappsen (CITA)
Ralf Klessen (Heidelberg)
Daniel Price (Exeter)

I. Introduction

- High-mass star-forming cores are systematically denser, more massive and more “turbulent” (have higher velocity dispersions) than low-mass star-forming cores (e.g., Garay & Lizano 1999; Kurtz et al. 2000; Beuther et al. 2007).

- Understanding the formation mechanisms of low- and high-mass cores is essential for understanding SF in general.

- This talk:
  - Recall ideas of core formation and control of SF efficiency (SFE) by turbulence in molecular clouds.
  - Revisit these ideas in light of preliminary results on properties of high-density regions in simulations of MC formation and collapse out of the diffuse WNM.

II. Turbulent regulation of the SFE in isolated clouds.

- Turbulence is a *multiscale* phenomenon, with largest velocities and timescales at largest spatial scales (Kolmogorov 1941; Larson 1981; Heyer & Brunt 2004).

- Dual role of supersonic turbulence:
  - Prevent monolithic cloud collapse.
  - Promote *nonlinear* (large amplitude) small-scale density fluctuations that
    - Shorter formation and free-fall times than parent cloud's.
    - Involve only a fraction of the total cloud mass (a different kind of filter than AD-mediated cores).
    - Only a fraction of which proceeds to collapse (Elmegreen 1993; Padoan 1995; Vázquez-Semadeni et al. 1996, 2003, 2005; Klessen, Heitsch & Mac Low 2000; Heitsch, Mac Low & Klessen 2001; Padoan & Nordlund 2002; Nakamura & Li 2005).

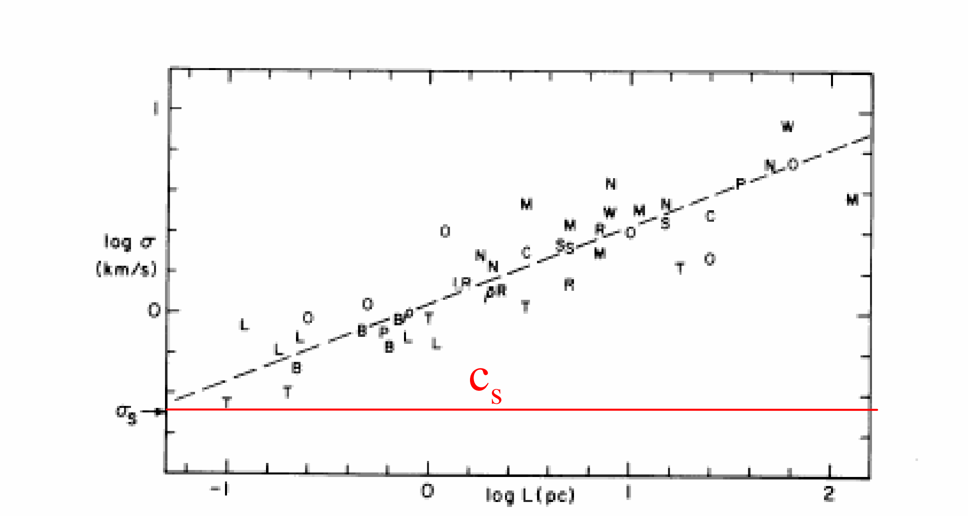
- A model for the inhibitory effect of turbulence in stationary turbulent regimes (continuously driven), is based on the *sonic scale* λ_s (Padoan 1995; Vázquez-Semadeni et al. 2003; Krumholz & McKee 2005):

  λ_s: The scale across which the typical turbulent velocity difference equals the sound speed:

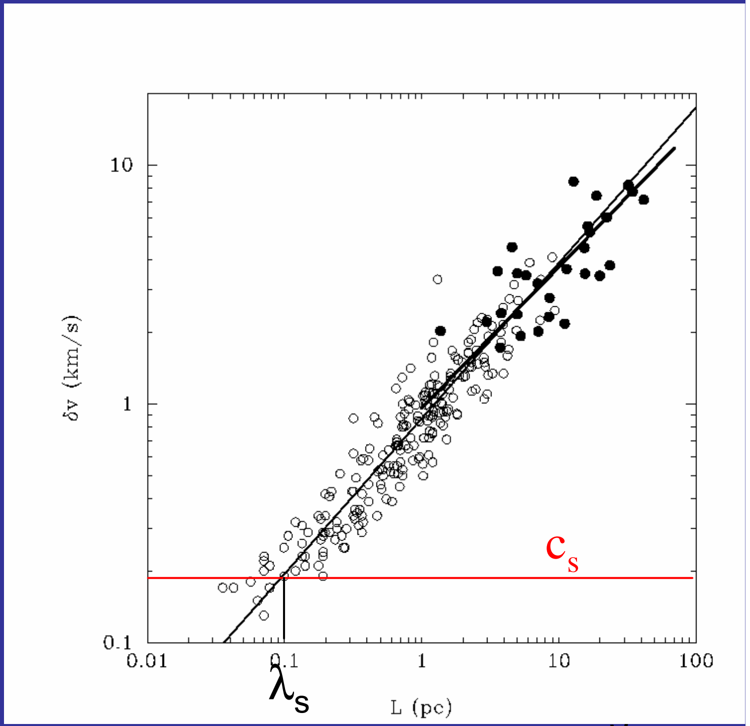
$$\Delta v \approx 0.8\,\mathrm{km\,s^{-1}}\left(\frac{L}{1\,\mathrm{pc}}\right)^{\alpha}$$

$$\alpha \approx 1/2$$

$\lambda_s \sim 0.07$ pc



Larson 1981

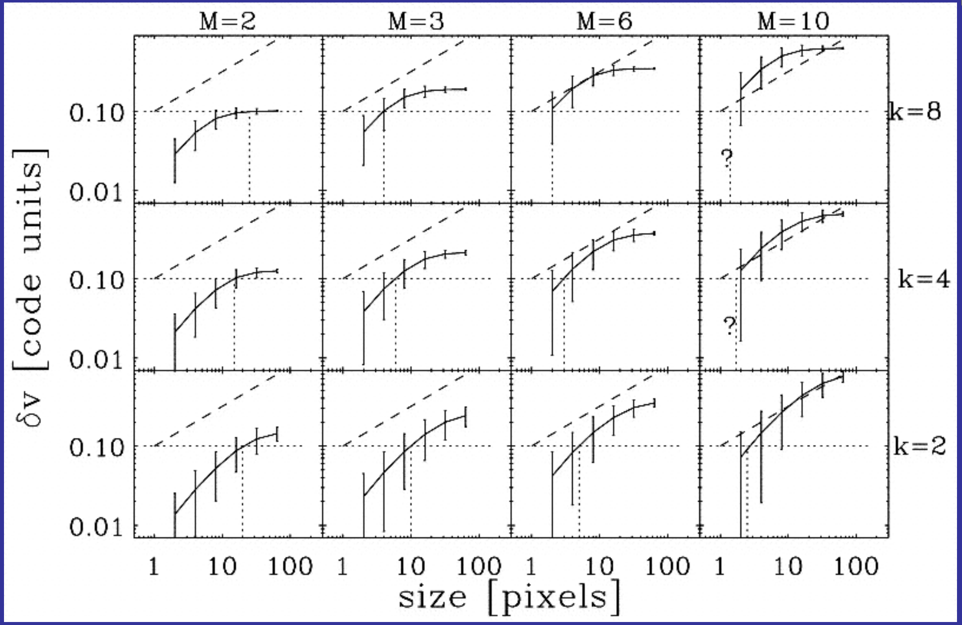


Heyer & Brunt 2004

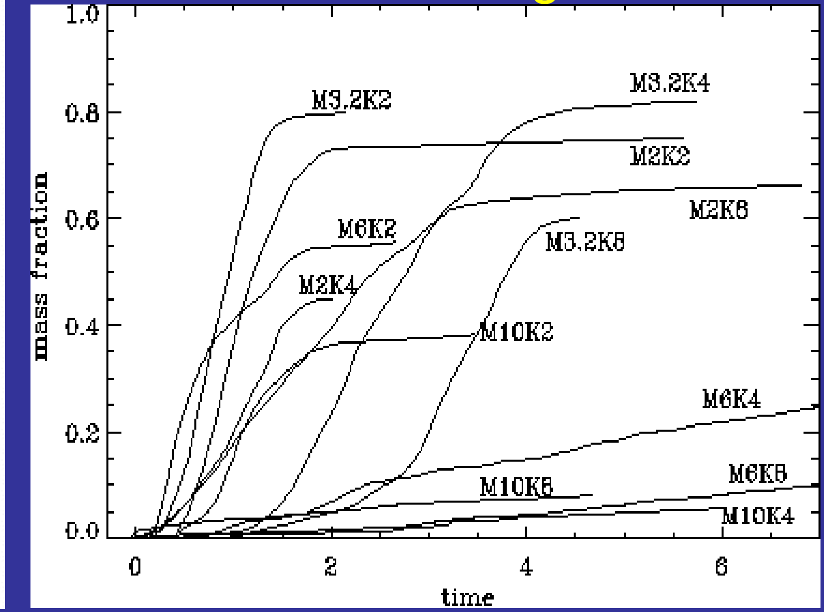
- Below λ_s:
  - Turbulent subfragmentation becomes weaker ($\delta\rho/\rho \sim M_s^2 < 1$) (or ~ M_a for MHD turbulence – Padoan & Nordlund 2002)
  - Turbulent support becomes subdominant ($\delta u_{turb} < c_s$).

➔ Maybe SFE related to fraction of mass deposited by turbulence in Jeans-unstable cores of size < λ_s? (i.e., “super-Jeans”, subsonic cores).

- Supported by simulations of varying M_s and driving scale at constant $J=L/L_J=4$ (Vázquez-Semadeni, Ballesteros-Paredes & Klessen 2003, ApJ 585, L131).
  - Sonic scale and SFE measured in the simulations:



SFE measured as collapsed mass fraction after 2 crossing times.



λ_s decreases with increasing levels of turbulence at given T.

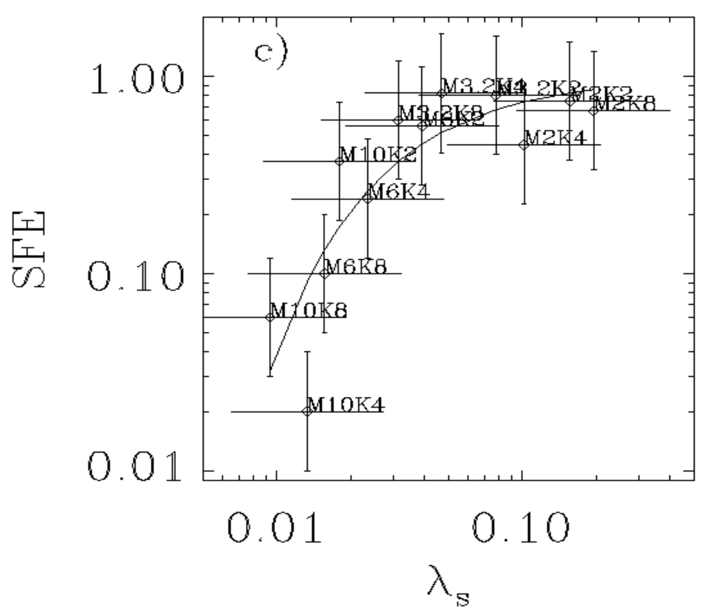
M_s	2	3.2	6	10
$2\tau_c/\tau_0$	12.5	10	6.7	2

$\tau_0 \sim 2/3\ \tau_{ff}$

SFE depends monotonically on λ_s

(regardless of driving length)

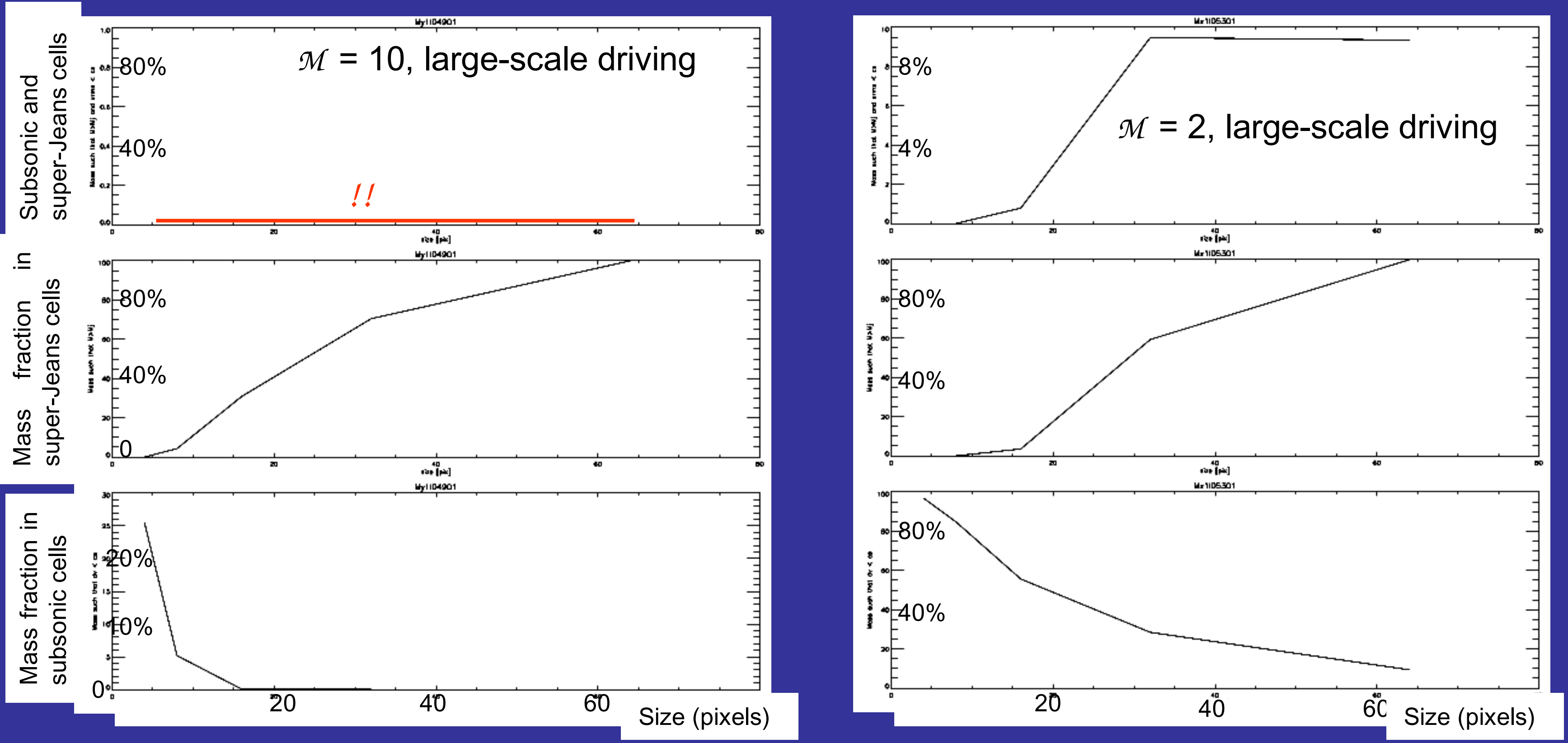
$$\mathrm{SFE}(\lambda_s) \propto \exp(-\lambda_0/\lambda_s)$$



Vázquez-Semadeni et al. 2003

- The model has been extended by Krumholz & McKee (2005) to use the ratio of λ_s to the Jeans length L_J as the criterion for gravitational collapse.

- Caveat : Fraction of mass in subsonic, super-Jeans cells as function of cell size may be lower than mass in collapsed objects, even zero at large Mach numbers (Vázquez-Semadeni & Ballesteros-Paredes, in prep.).



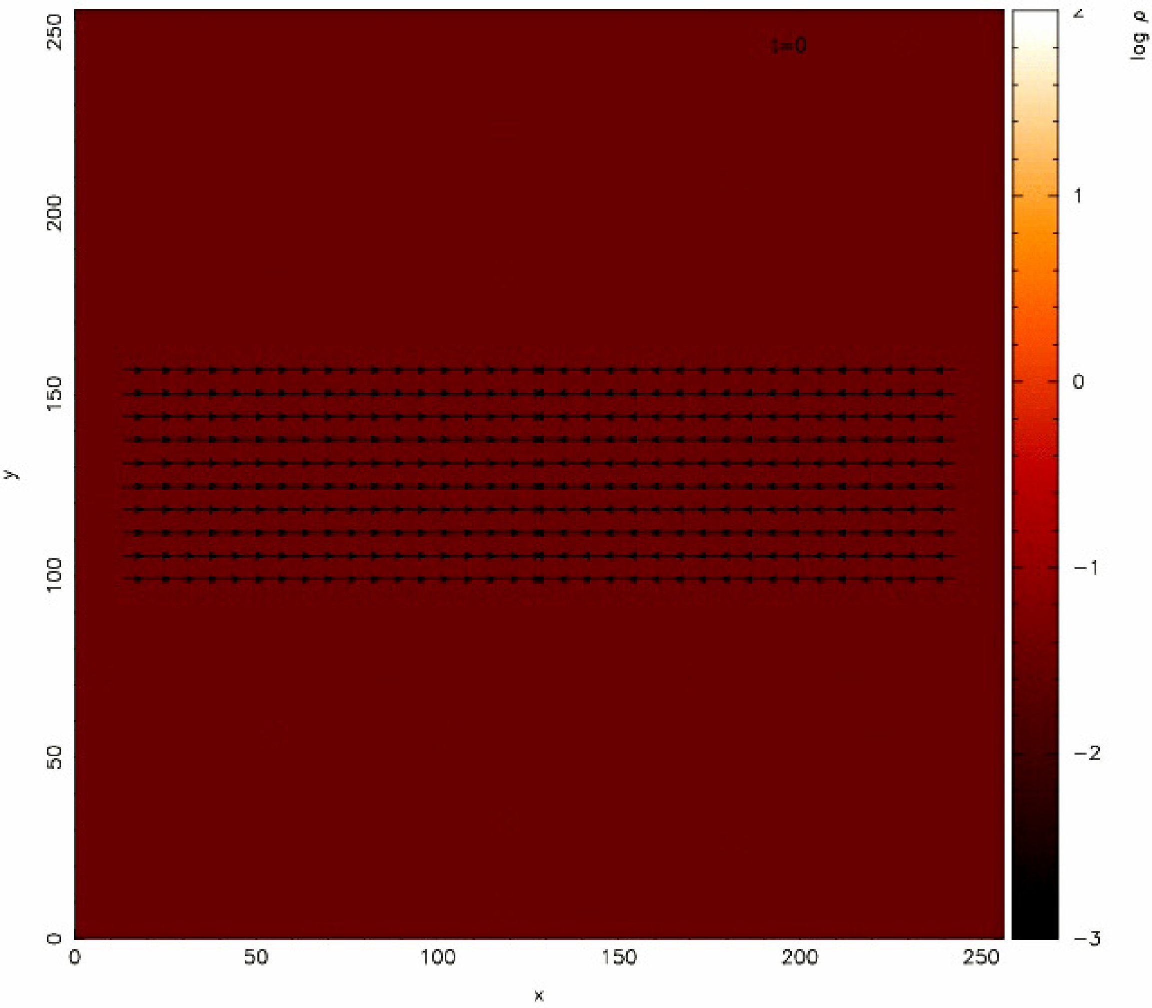
Subcells in simulation, not clumps.

- Conclude:
  - Not all collapsing mass may come from subsonic, super-Jeans structures (Bate, Bonnell et al…)
    - Supersonic regions may also be involved in collapse to form stars.
      - Must *flow* into the collapsed object.
    - What is the nature of the “turbulence” in these regions?
      - Support against collapse (e.g., Matzner, McKee, Krumholz, Tan, Li & Nakamura), or *driven* by gravity? (Goldreich & Kwan 1974; Burkert & Hartmann 2004; Hartmann & Burkert 2007; Peretto et al. 2007; Field et al. 2006) (“Chicken or egg”?).
  - Need to study the *formation* of the cores in clouds with “natural” turbulence (Heitsch’s talk).

→ Cloud formation and evolution studies

III. Search for massive-SF-like regions in numerical simulations of MC formation (Vázquez-Semadeni, Ballesteros-Paredes, Jappsen, Klessen & Price 2007, in prep.)

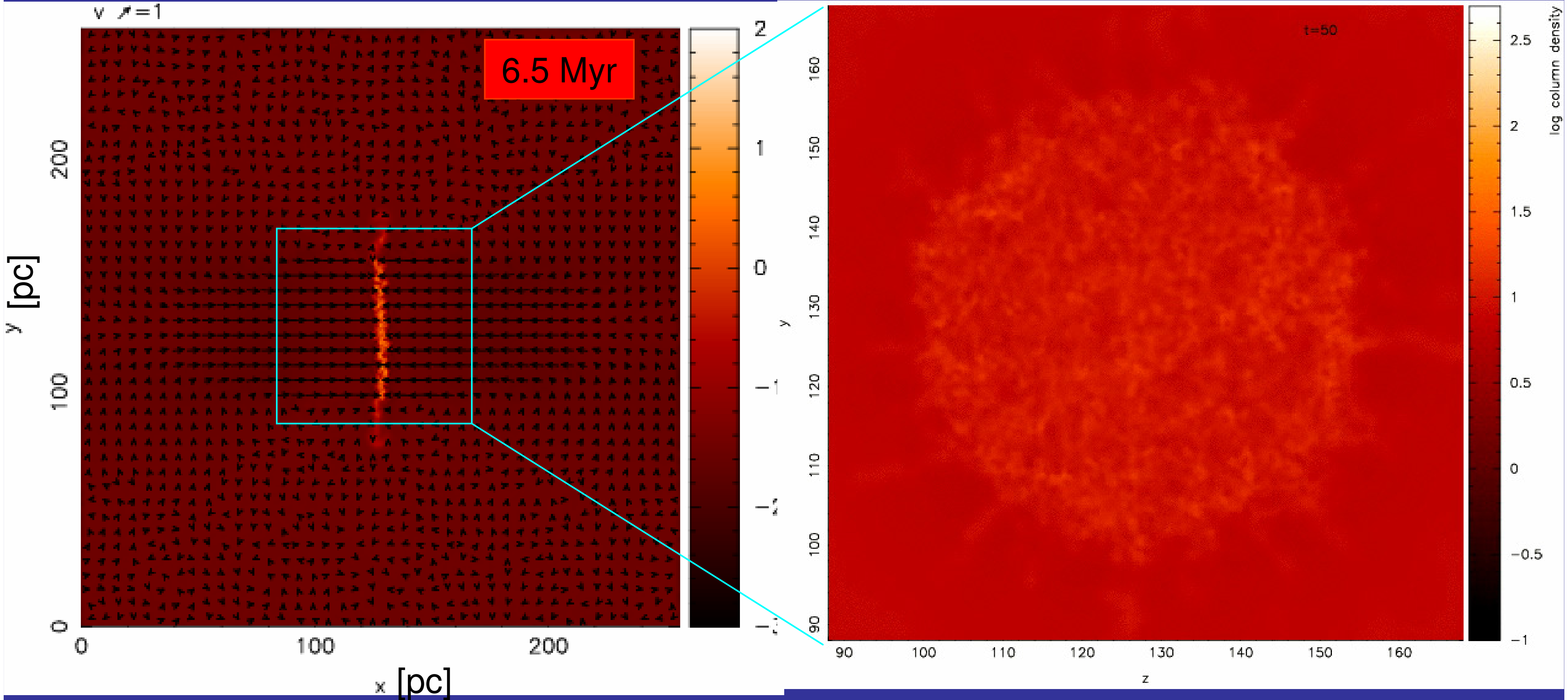
- *Preliminary and tentative results!*
- Use simulations of MC formation by transonic compressions in diffuse WNM (Vázquez-Semadeni et al. 2007, ApJ 657, 870).



SPH simulation includes cooling (leading to TI) and self-gravity.

L = 256 pc
Dt = 39 Myr
<n> = 1 cm^{-3}
v_{inf} = 9.2 km s^{-1}
T_{ini} = 5000 K

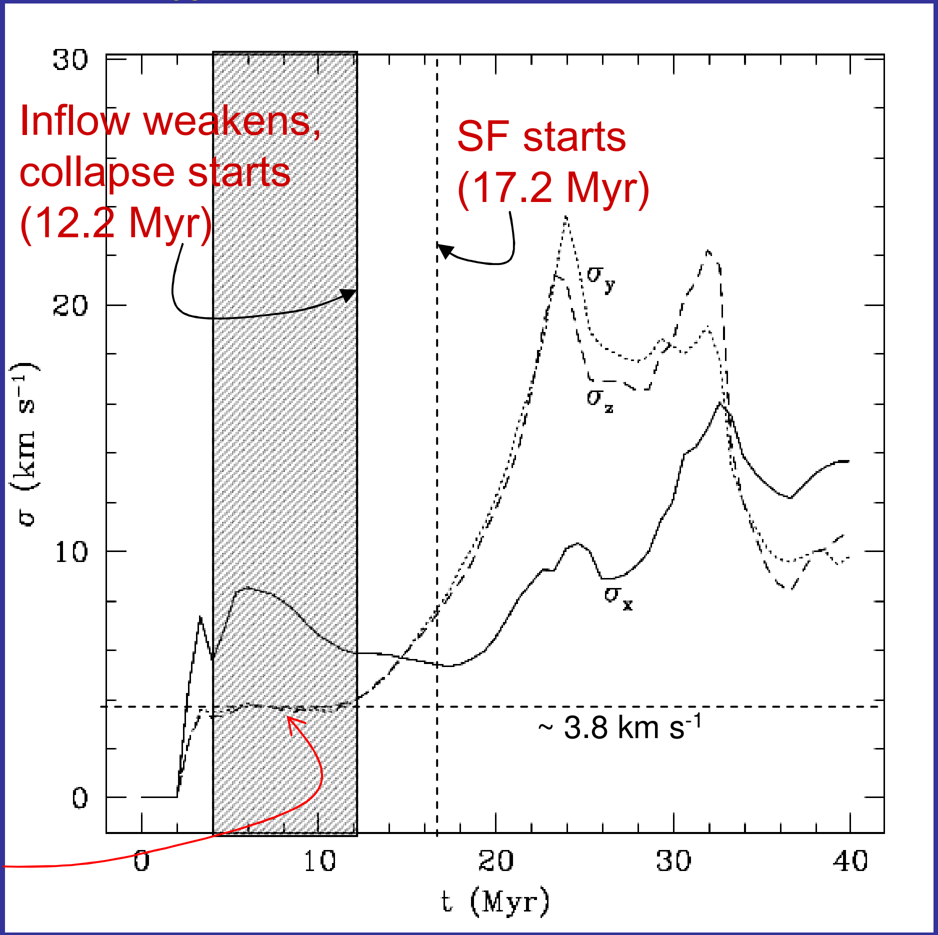
Cloud formation and turbulence generation proceed by TI, KHI, and NTSI as described by Fabian Heitsch.


v ↗=1
6.5 Myr
y [pc]
x [pc]
0
100
200
2
1
0
−1
t=50
y
z
90
100
110
120
130
140
150
160
log column density
2.5
2
1.5
1
0.5
0
−0.5
−1

6.5 – 39 Myr

- E_{kin} driven first by inflow, then by gravitational contraction.

L_{box} = 256 pc , L_{inf} = 112 pc



Inflow weakens, collapse starts (12.2 Myr)

SF starts (17.2 Myr)

~ 3.8 km s^{-1}

Turbulence driven by compression, through NTSI, TI and KHI

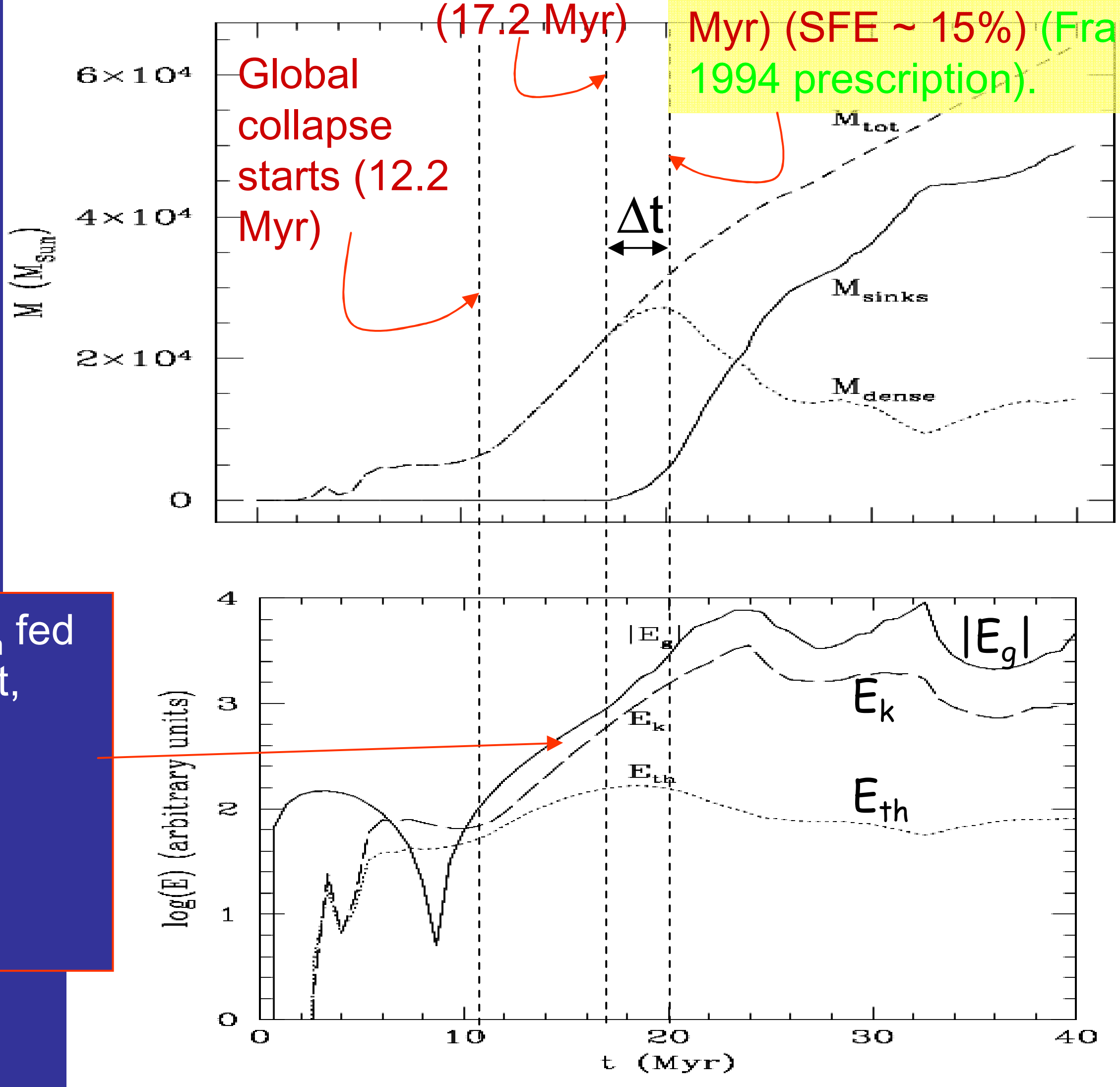
(Walder & Folini1998; Koyama & Inutsuka 2002; Audit & Hennebelle 2005; Heitsch et al. 2005, 2006; Vázquez-Semadeni et al 2006)

(Vázquez-Semadeni et al. 2007)

SF starts (17.2 Myr)

SF expected to affect cloud (20.3 Myr) (SFE ~ 15%) (Franco et al.'s 1994 prescription).

Global collapse starts (12.2 Myr)



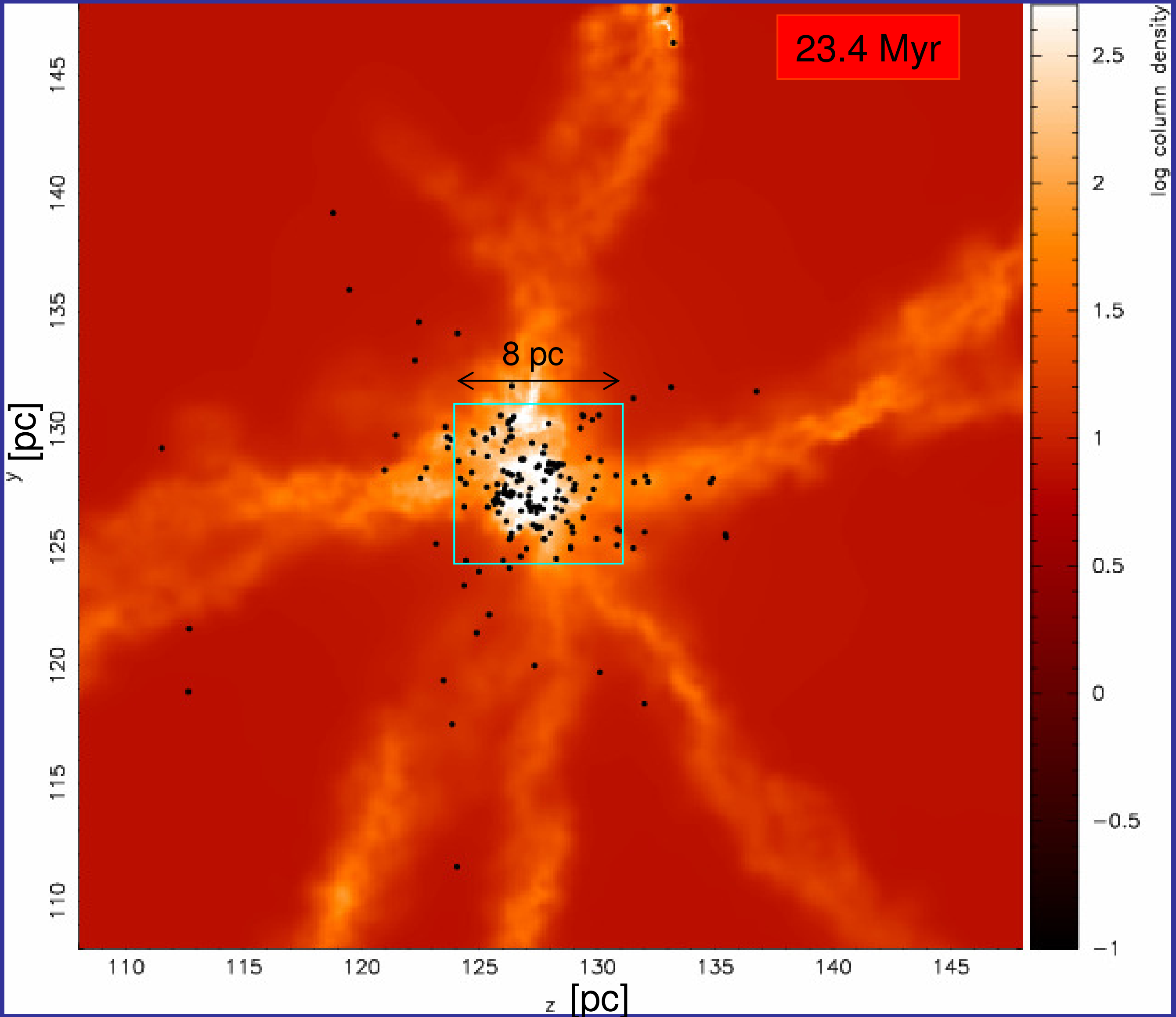
- Turbulent E_{kin} fed by collision first, then by gravitational contraction.

- $|E_g| \sim 2\ E_k$

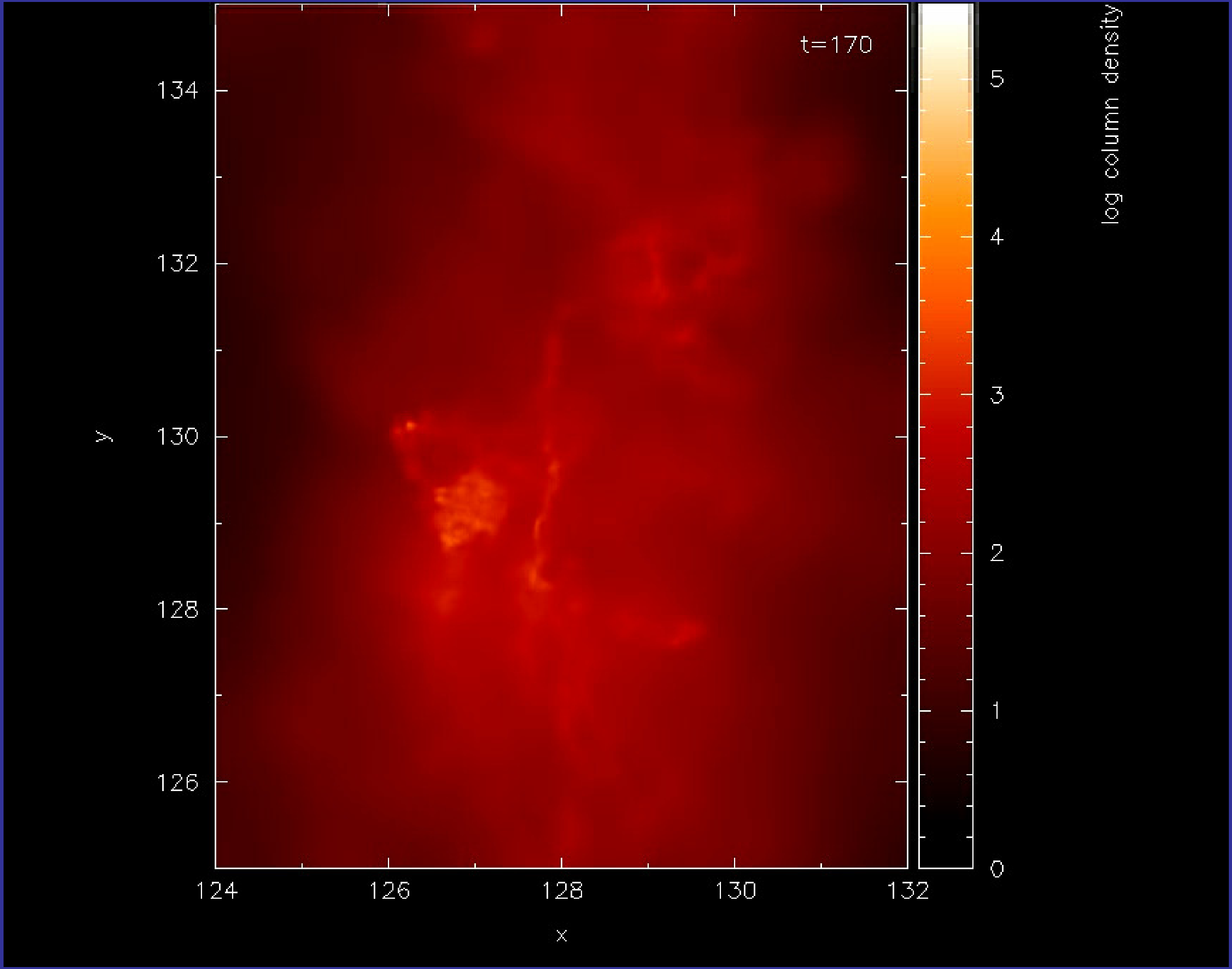
Run with:
L_{box} = 256 pc,
L_{inf} = 112 pc

(Vázquez-Semadeni et al. 2007)

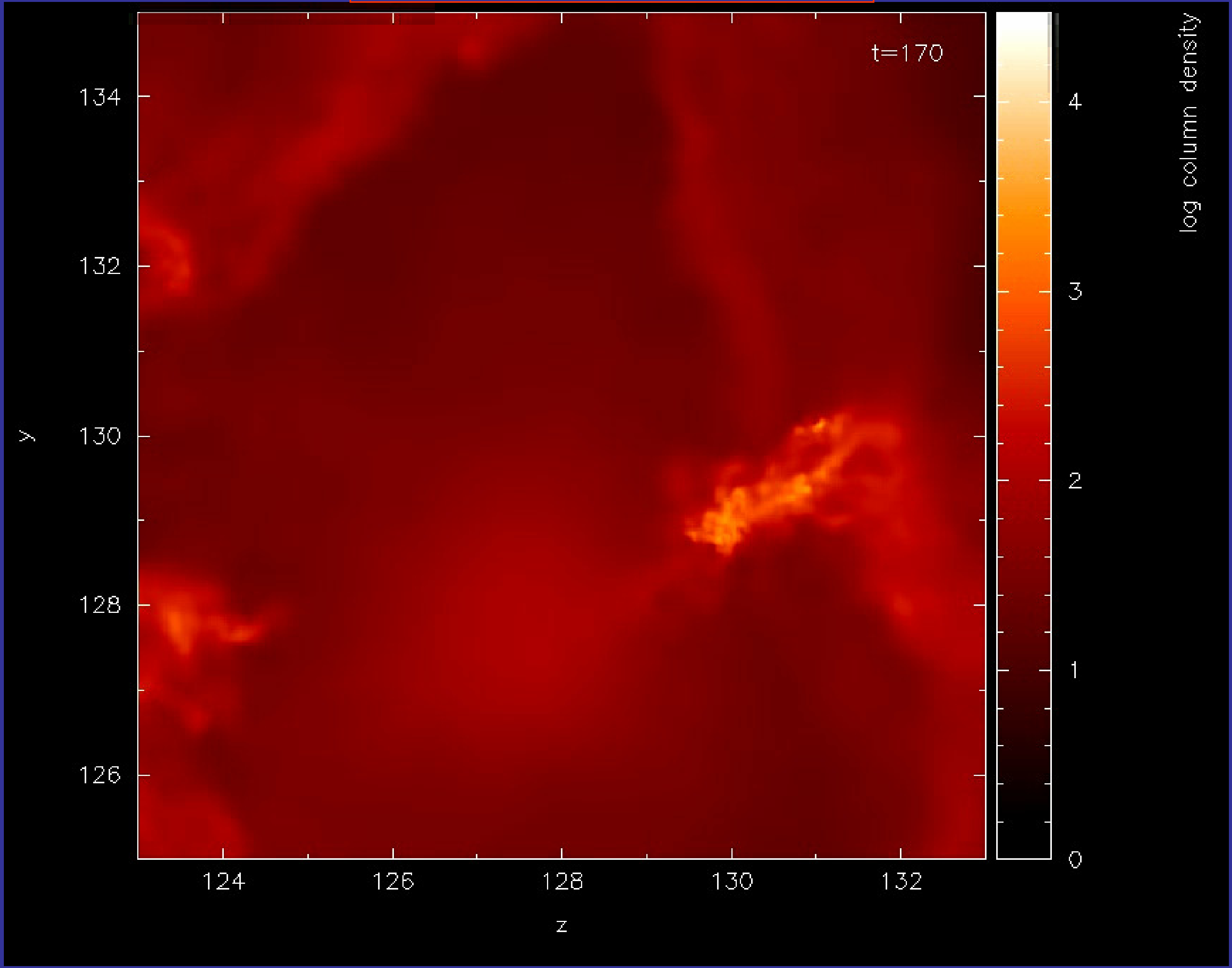
- Focus on time and place of central collision

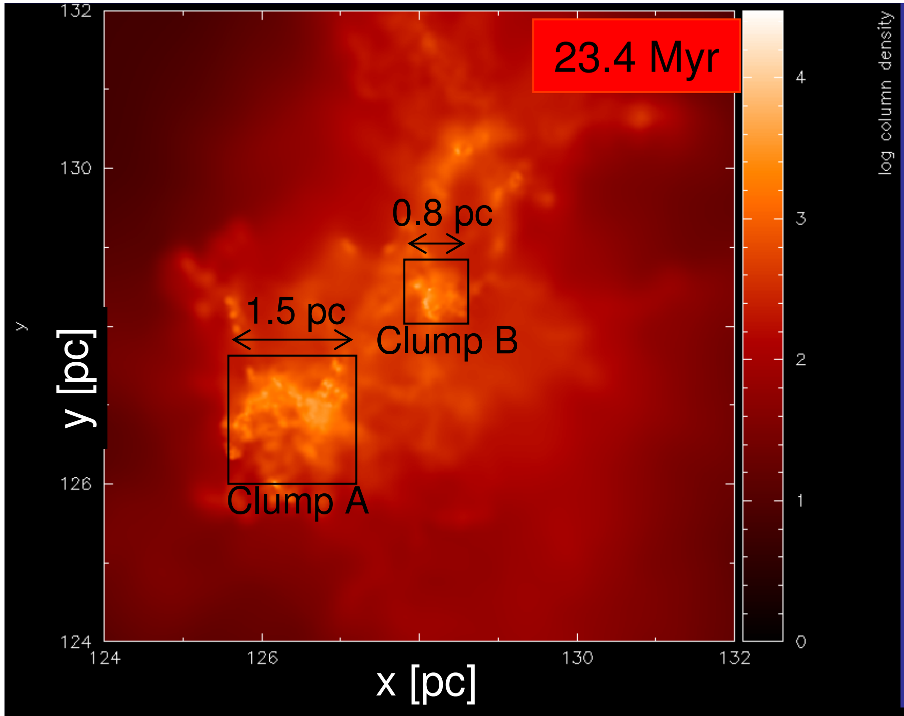


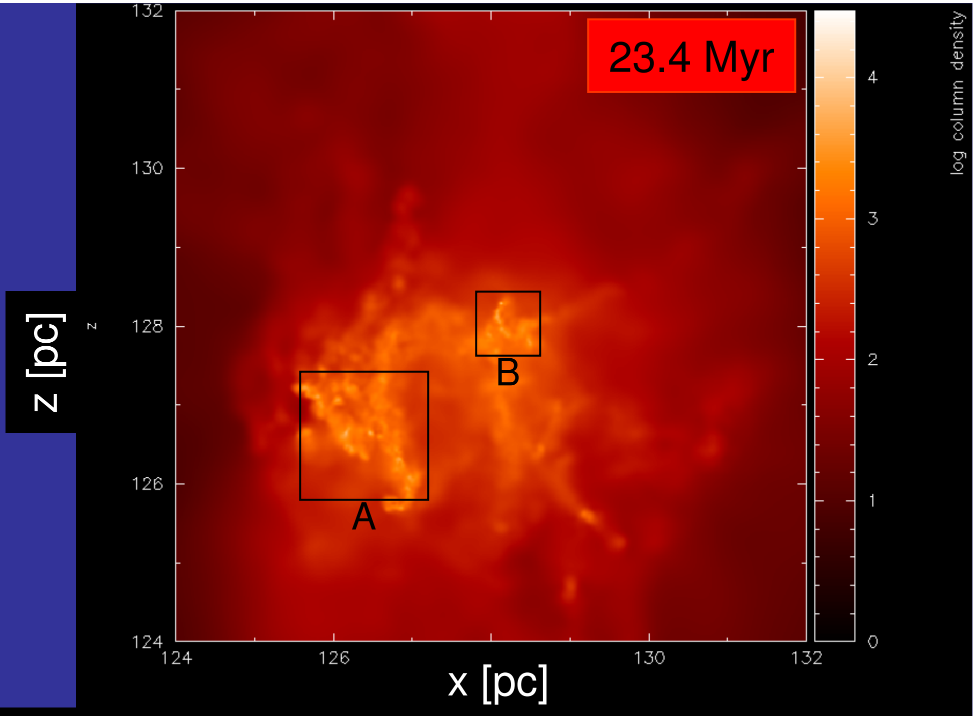
22.1 – 24.7 Myr (Δt = 2.6 Myr)

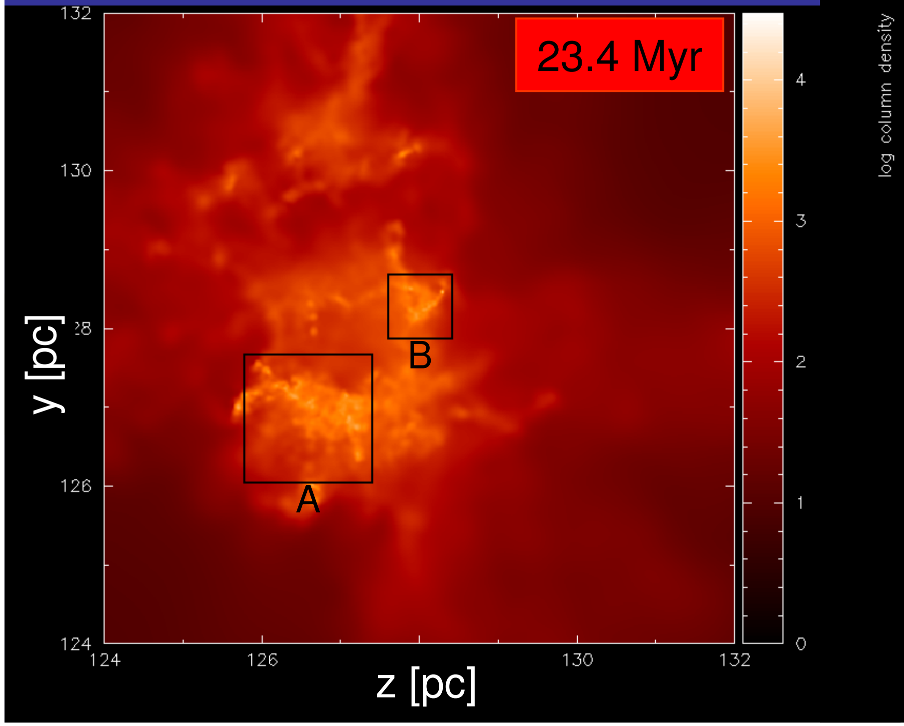


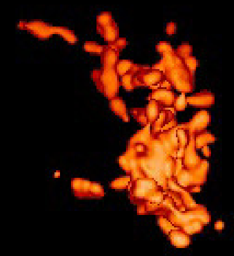
22.1 – 24.7 Myr (Δt = 2.6 Myr)











Central 8 pc resampled @ 256^3 (0.03 pc) resolution.

- Physical properties:
  - Whole 8-pc region:
    - $\langle n \rangle = 450\ \mathrm{cm}^{-3}$
    - $\sigma_{3D} = 5.0\ \mathrm{km\ s}^{-1}$; $\sigma_x = 2.3\ \mathrm{km\ s}^{-1}$; $\sigma_y, \sigma_z \sim 3.1\ \mathrm{km\ s}^{-1}$
    - $M \sim 7000\ M_{sun}$
  - Clump A (L = 1.5 pc):
    - $\langle n \rangle = 1.27 \times 10^4\ \mathrm{cm}^{-3}$
    - $\sigma_{3D} = 3.6\ \mathrm{km\ s}^{-1}$
    - $M \sim 1400\ M_{sun}$
  - Clump B (L = 0.8 pc):
    - $\langle n \rangle = 1.72 \times 10^4\ \mathrm{cm}^{-3}$
    - $\sigma_{3D} = 2.8\ \mathrm{km\ s}^{-1}$
    - $M = 300\ M_{sun}$
  - High-density cores: (simple density threshold criterion, $n > 5 \times 10^4\ \mathrm{cm}^{-3}$, $M > 4\ M_{sun}$).
    - Found 15 cores with
      - $n_{max} \sim 10^{5\text{-}6}\ \mathrm{cm}^{-3}$.
      - *Lifetimes << 1.3 x 10^5 yr* (appear and disappear in << dt between frames). Compare to Motte’s estimate: ~ 10^3 yr.

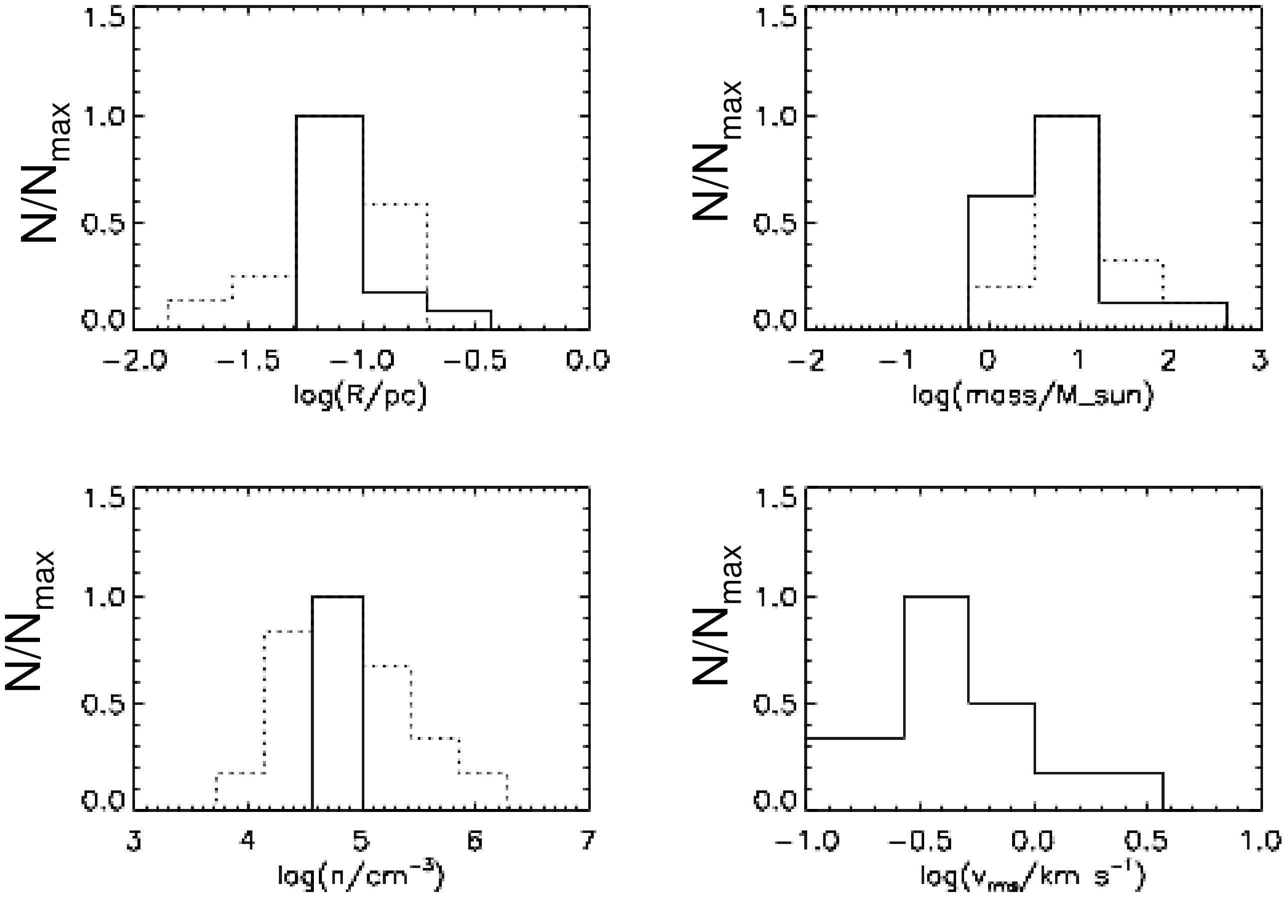
“Typical” Motte et al. (2007) clump:
$L \sim 0.8$ pc
$n \sim 7000\ \mathrm{cm}^{-3}$

- Core statistics:
  - (Zeroth order confrontation with observations.)

—— Simulation

.... Cygnus X-North (57 cores)

(Motte et al. 2007 [arXiv:0708.2774]).



Conclude:
The central region of collapse exhibits similar statistical properties to regions of massive SF.

Note: Velocity field has a large infall component, not just random turbulence.

- Conclusions:
  - Random turbulence provides an effective filter for the mass that can collapse in a MC.
    - Super Jeans-, subsonic-fraction model of “mass filtering” for collapse explains low SFE.
  - However:
    - Subsonic, super-Jeans model may possibly miss part of the total mass involved in collapse.
    - Numerical simulations of molecular cloud formation with self-gravity (Vázquez-Semadeni et al. 2007) with global cloud contraction (Goldreich & Kwan 1974; Hartmann & Burkert 2007 [Orion]; Andre et al 2007 [Oph]) suggest that
      - Clouds may follow a secular evolutionary path, without equilibrium.
        - » *Appear* virialized, though, due to gravitational contraction.
      - “Turbulence” *(at all scales)* may contain a significant *infall* component.
      - Cores in center of global collapse resemble high-mass SF regions.
      - SFE probably regulated by stellar feedback in this case.
        - » Equilibrate the cloud or disperse it??
      - Work in progress: magnetic fields (Banerjee); stellar feedback (Gómez).

The End