Massive Star and Cluster Formation in Hierarchically Collapsing Molecular Clouds

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Introduction

- High-mass star-forming cores are systematically denser, more massive and have higher velocity dispersions than low-mass star-forming cores (e.g., Garay & Lizano 1999; Kurtz+00; Beuther+07; Tan+14).

- Recent work has proposed that GMCs may be in a generalized process of gravitational contraction (Burkert & Hartmann 2004; VS+07,+11; Heitsch+08; Schneider+10; Ballesteros-Paredes+11a,b).
  - A *hierarchical gravitational collapse* scenario (collapses within collapses) (Elmegreen 00; VS+09, ApJ, 707, 1023).

- This talk:
  - Outline the scenario and discuss massive star and cluster formation in this context.

- Why global collapse?

  - Because, if MCs form out of a transition from the ***warm/diffuse*** to the ***cold/dense*** atomic phase, they quickly become Jeans-unstable (Gómez & VS 14, ApJ 791, 124):

    $\rho \rightarrow 10^2 \rho, \quad T \rightarrow 10^{-2}\, T$

    → Jeans mass, $M_J \sim \rho^{-1/2}\, T^{3/2}$, decreases by ~ 10^4 upon warm-cold transition.

  - Flow collision produces turbulence (Vishniac 94; Walder & Folini 00; Koyama & Inutsuka 02; Heitsch+05; VS+06; Klessen & Hennebelle 10)

    - ... but not enough to support a GMC (VS+07, +10).

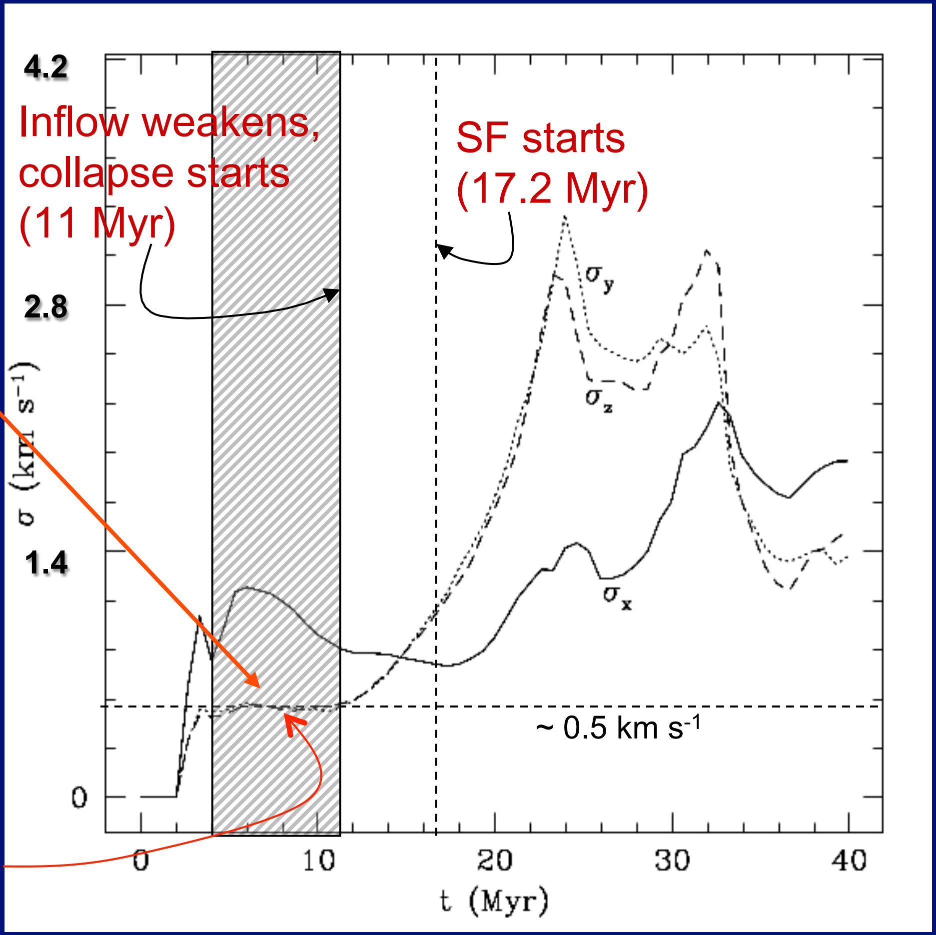
– Collision-driven turbulence is only *moderately* supersonic w.r.t. cold gas.

- **Strongly** supersonic velocities typical of GMCs appear *later*, and are dominated by gravitational contraction.

➔ Accretion-driven turbulence insufficient to support GMC-scale clouds.

(For clump-sized scales, it may be sufficient Klessen & Hennebelle [2010])

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



(Vázquez-Semadeni et al. 2007, ApJ, 657, 870.
See also Koyama & Inutsuka 2002; Heitsch+05)

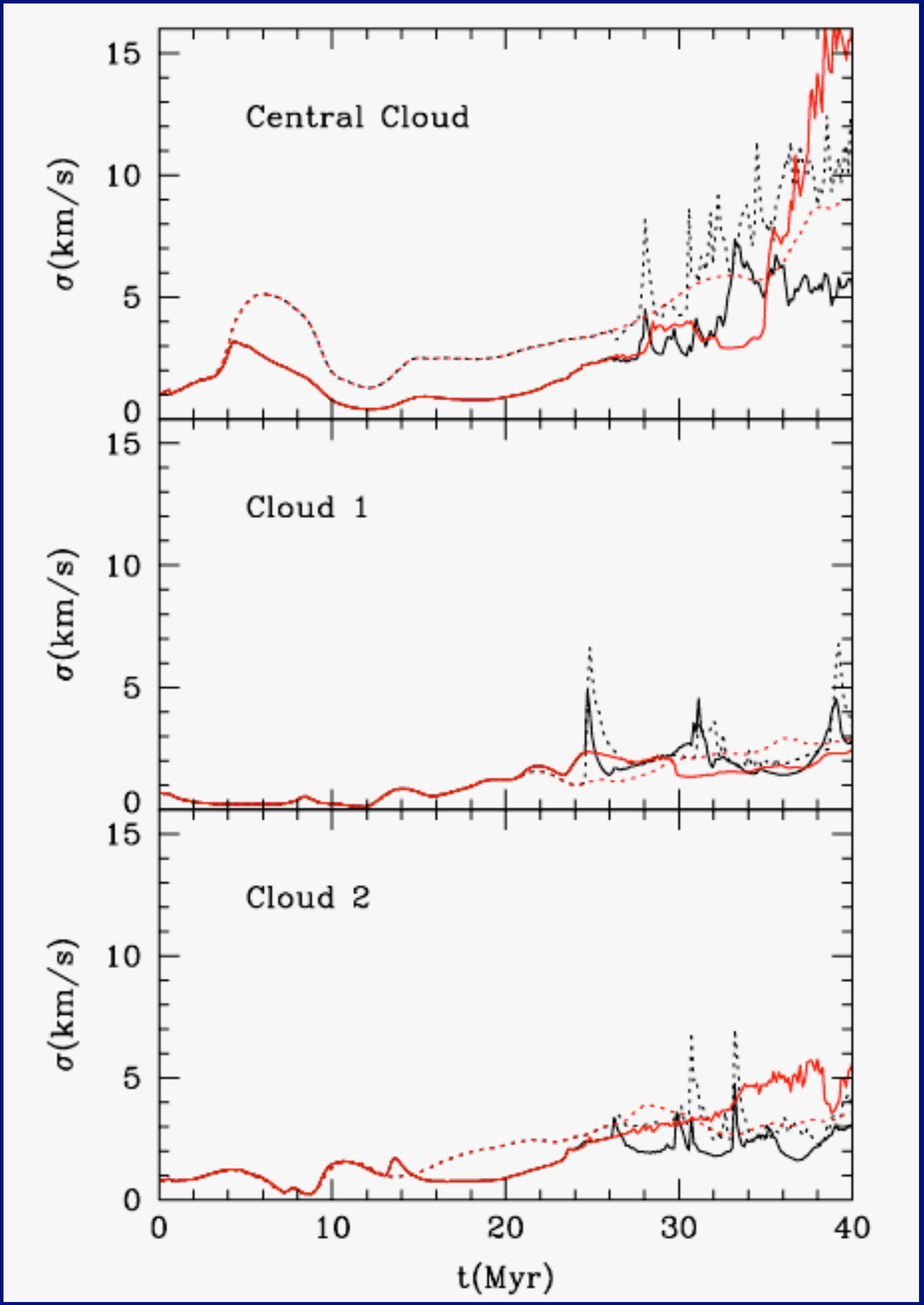
Same in AMR simulations.

Density-weighted

Volume-weighted

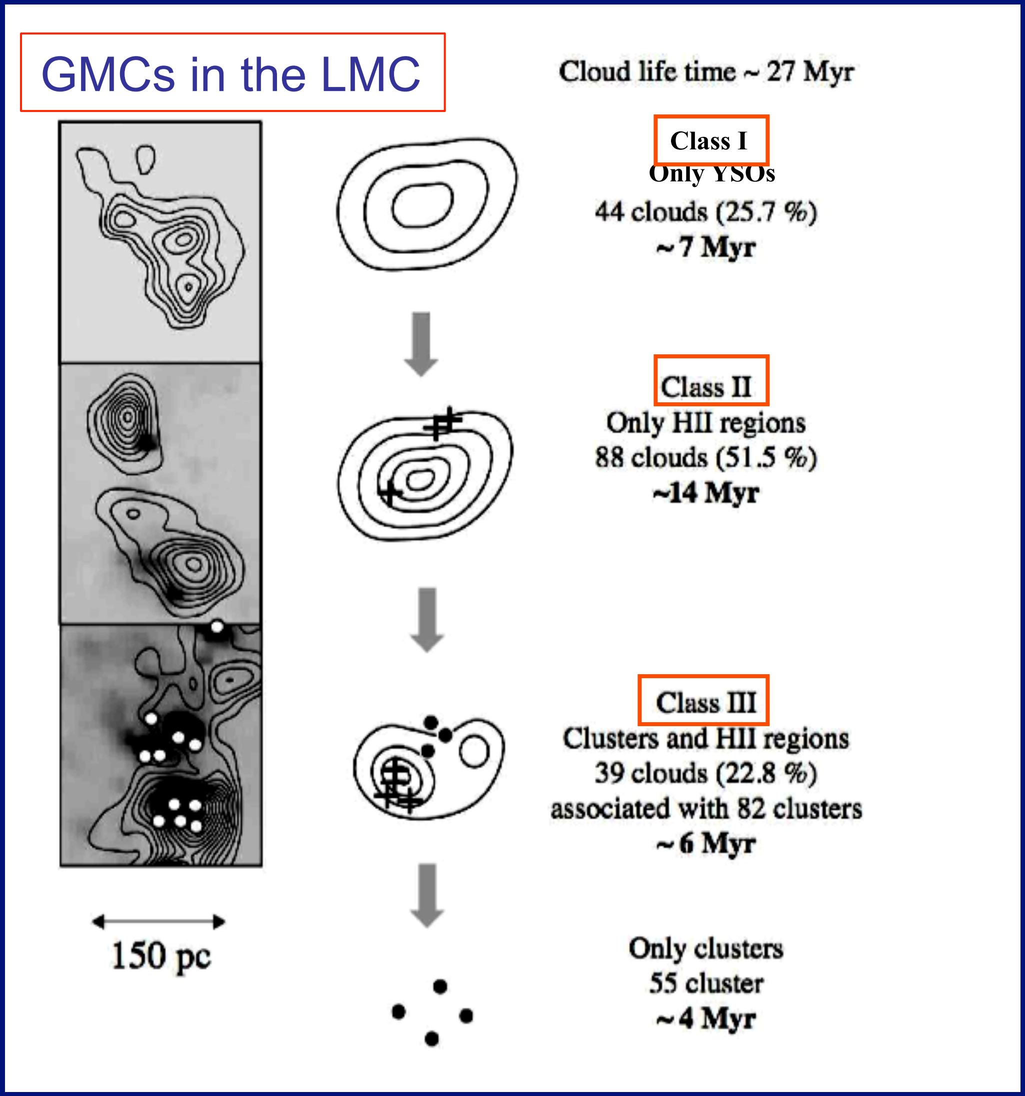
No feedback

Feedback

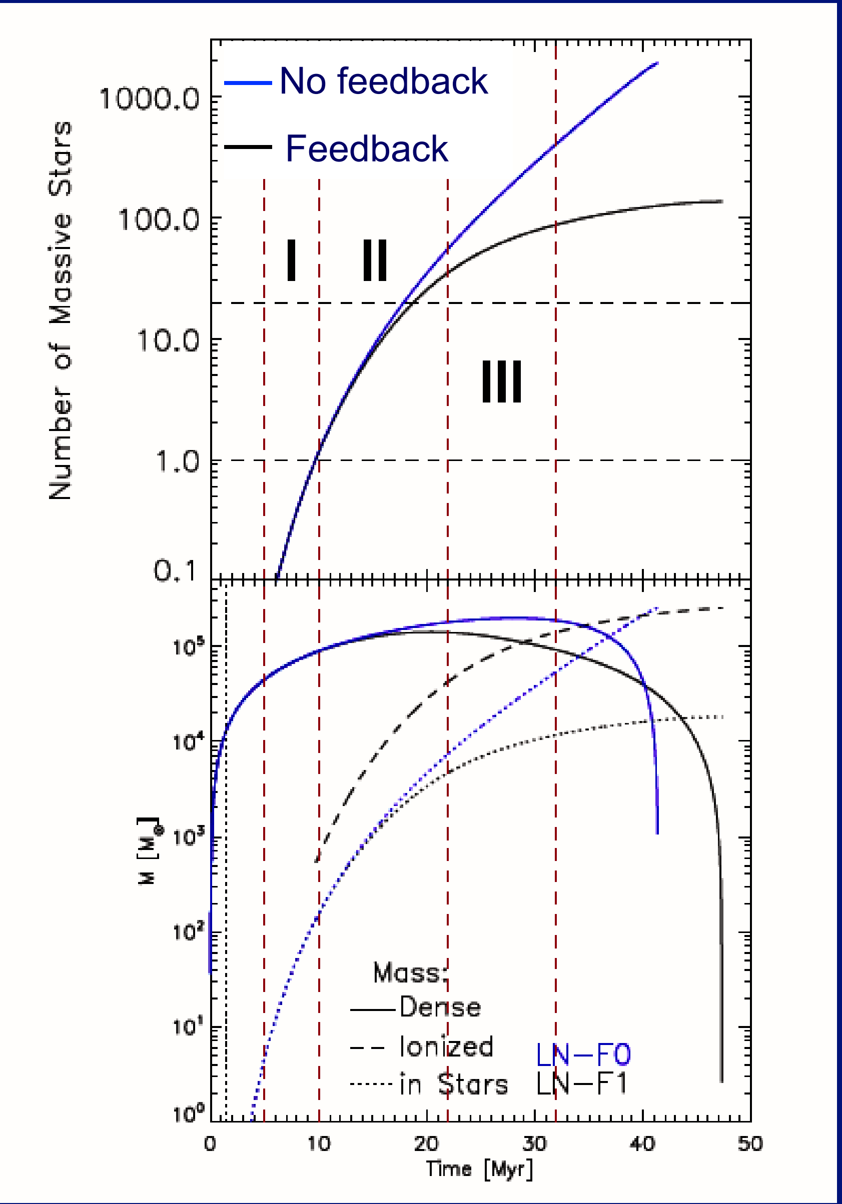


VS+10, ApJ, 715, 1302

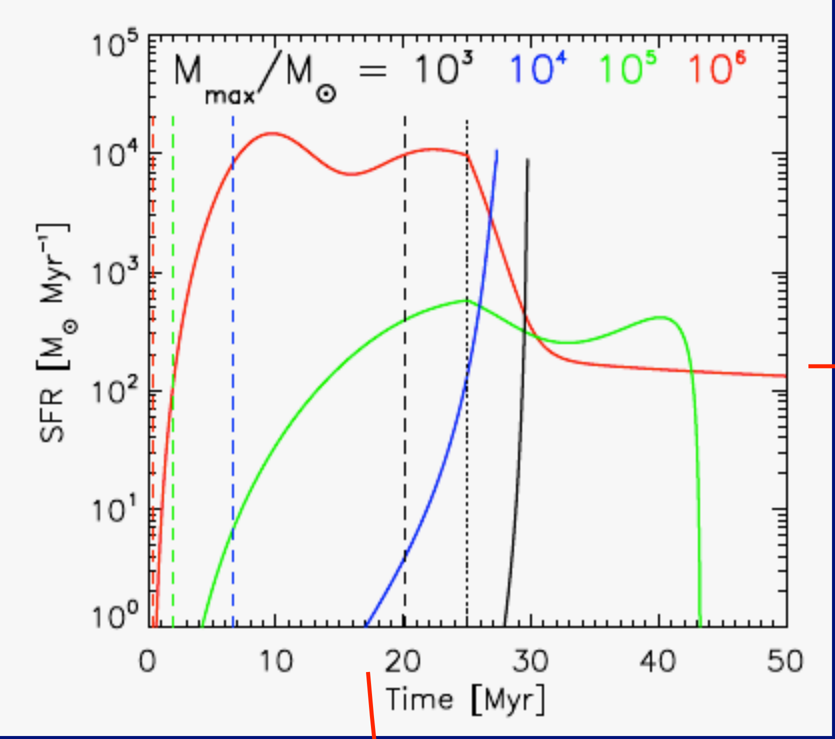
- Global collapse implies that *clouds evolve...*
  - ... and SFR *increases in time.*



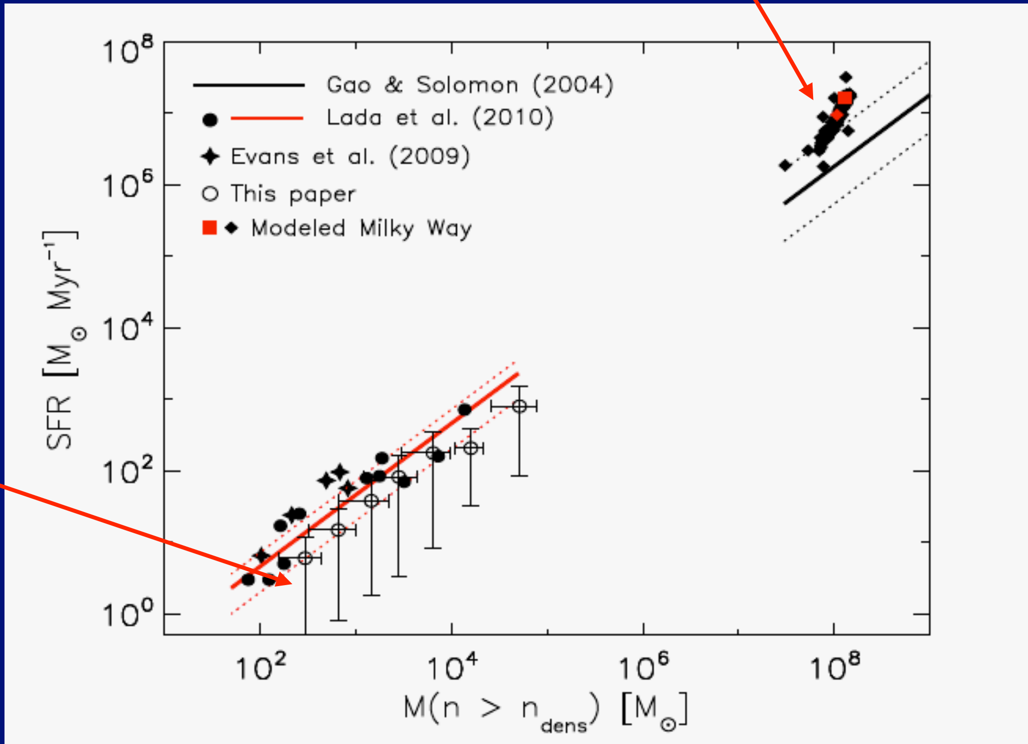
Kawamura+2009



Analytical model for SFR (Zamora-Avilés+12)



Integration over cloud mass spectrum



Time-averaging of individual clouds.

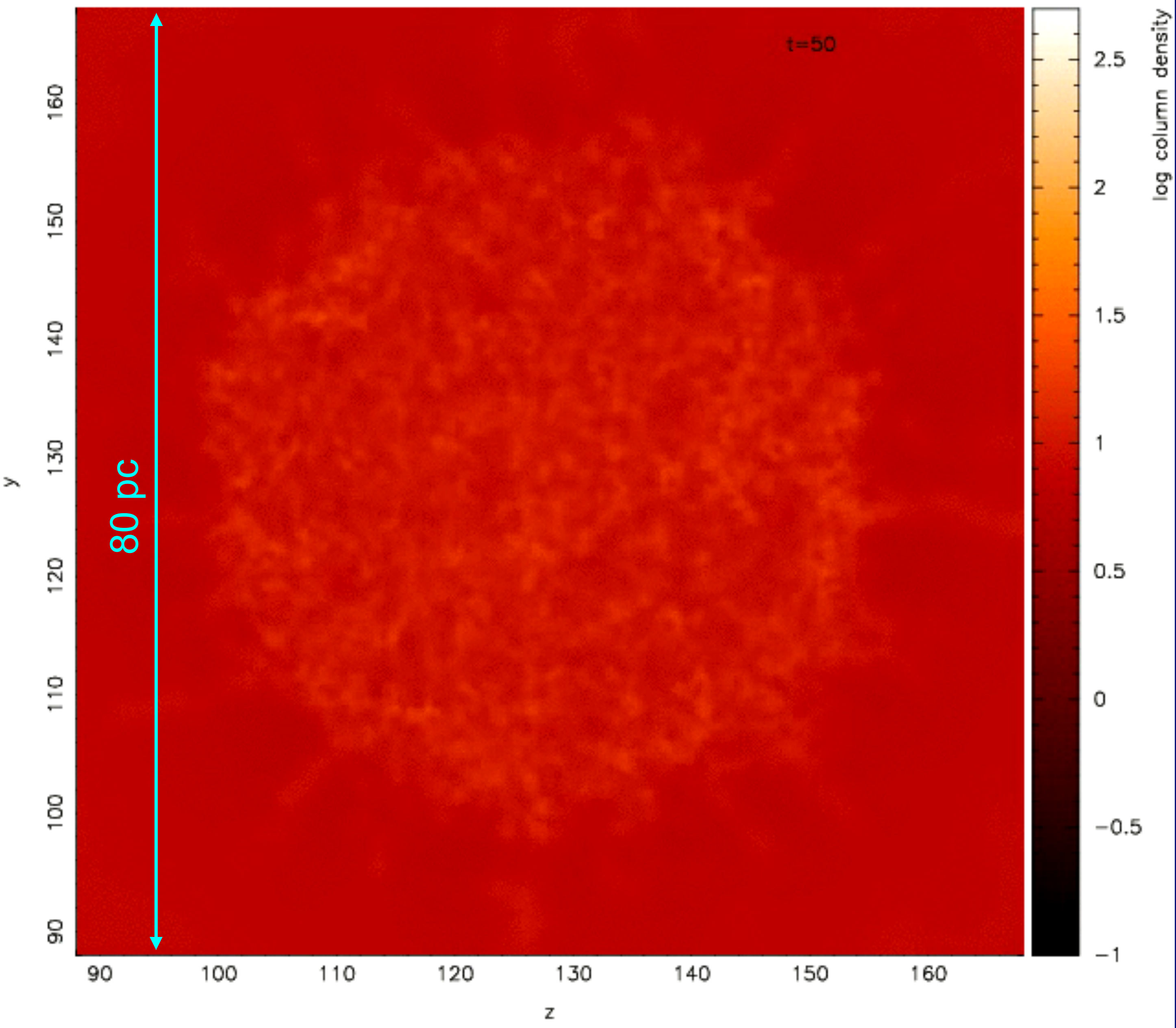
Zamora-Avilés & Vázquez-Semadeni 2014, ApJ, 793, 84

- Global collapse of turbulent, non-spherical medium is *hierarchical...* (Vázquez-Semadeni+09, ApJ, 707, 1023).
  - Turbulence produces small-scale, high-amplitude (nonlinear) density fluctuations.

    → shorter free-fall time than whole cloud.

    → terminate their collapse earlier than whole cloud.

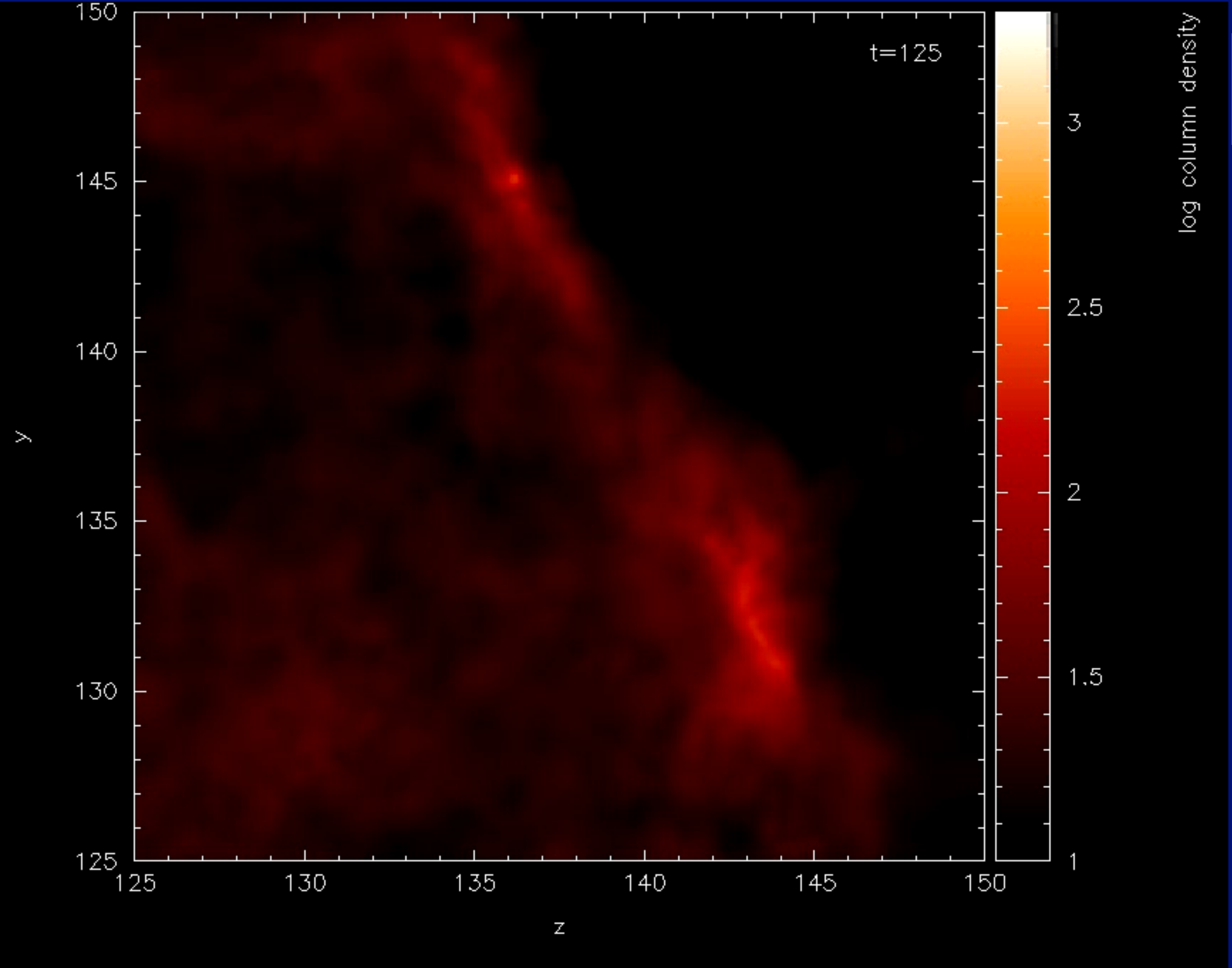
– Use simulations of MC formation by colliding flows in diffuse WNM.



SPH simulation includes cooling (leading to TI) and self-gravity (Vázquez-Semadeni+07).

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

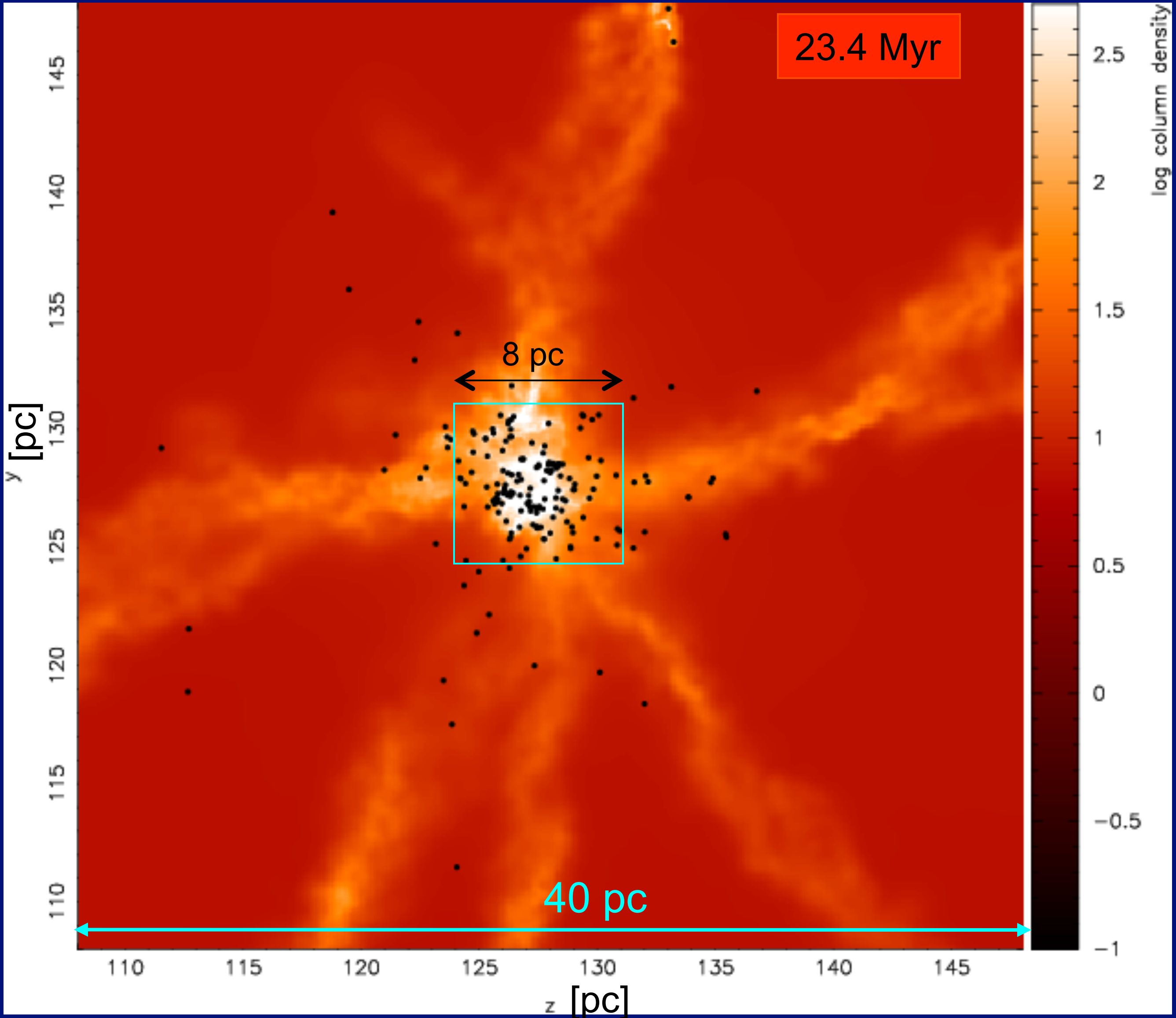
– Low-mass cloud: formed by local collapse of small-scale structure.



16.6 – 19.9 Myr
(Δt = 2.6 Myr)

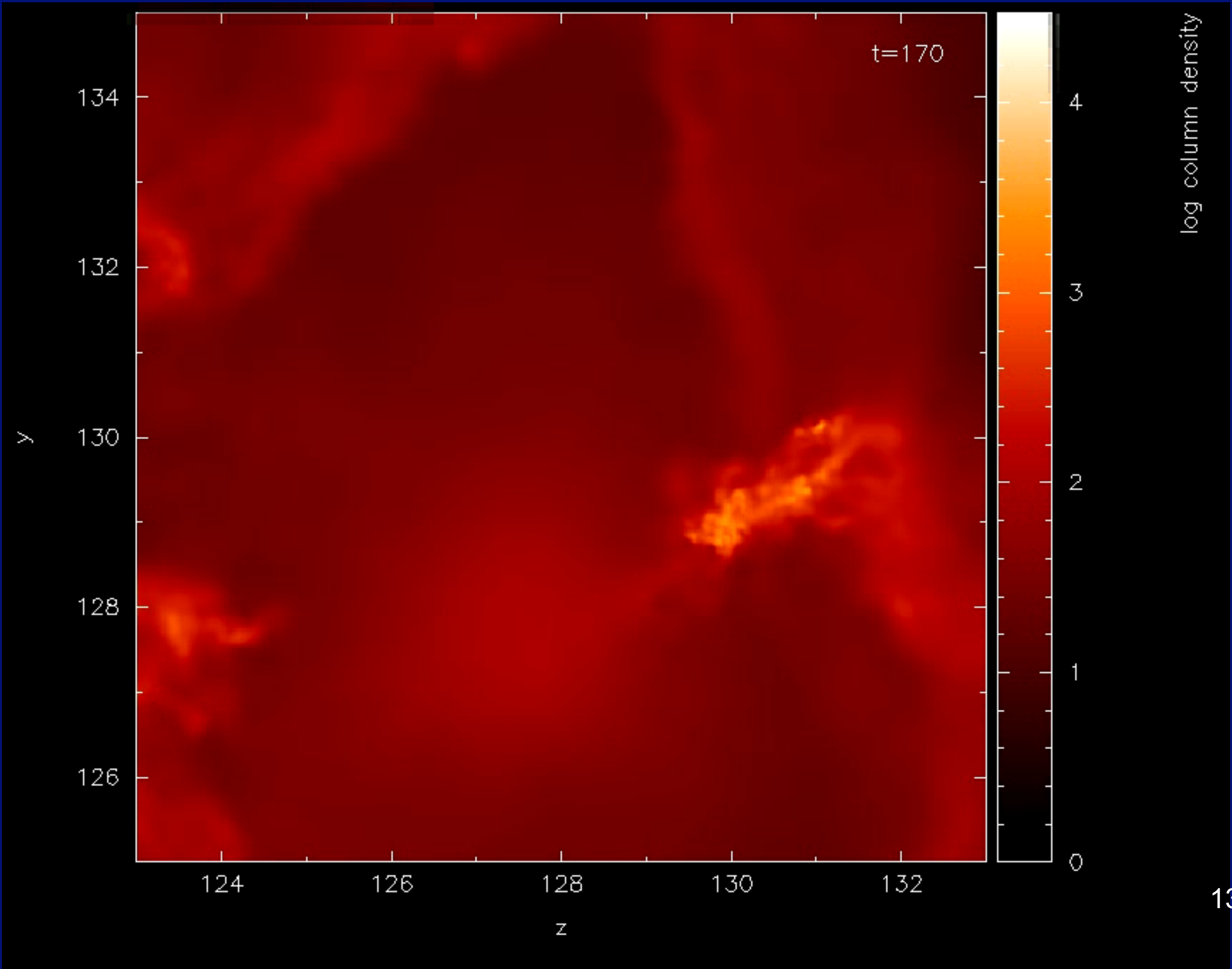
Low SFR

– High-mass cloud: formed by focused culmination of collapse of large-scale structure.

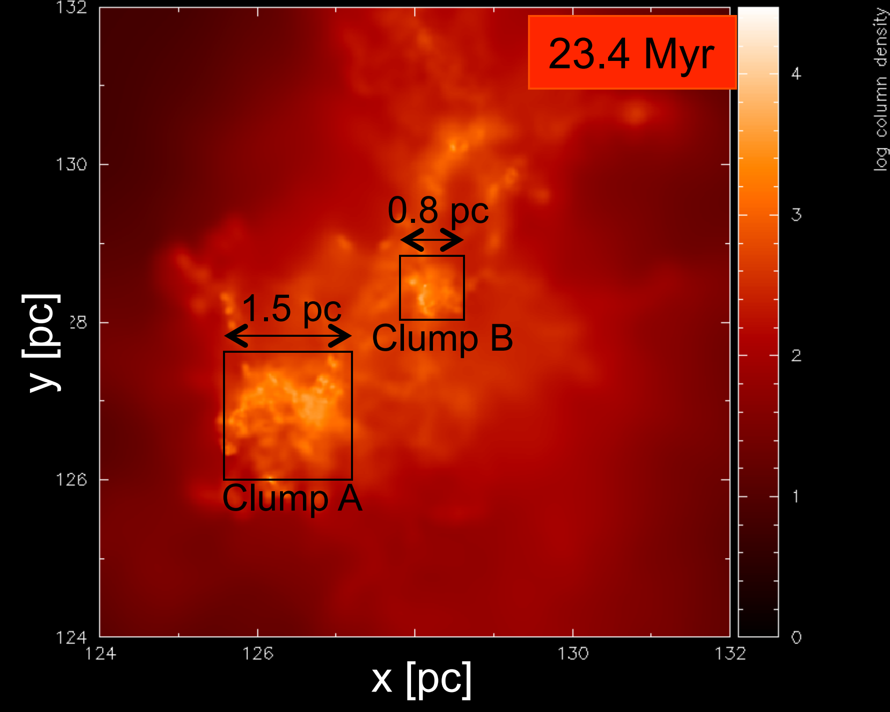


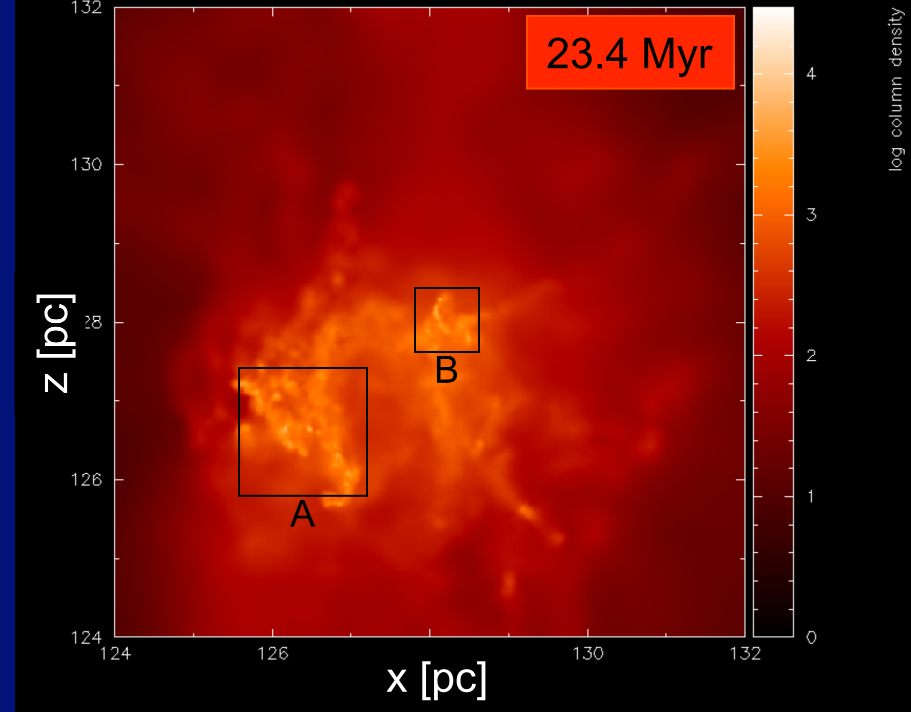
22.1 – 24.7 Myr (Δt = 2.6 Myr)

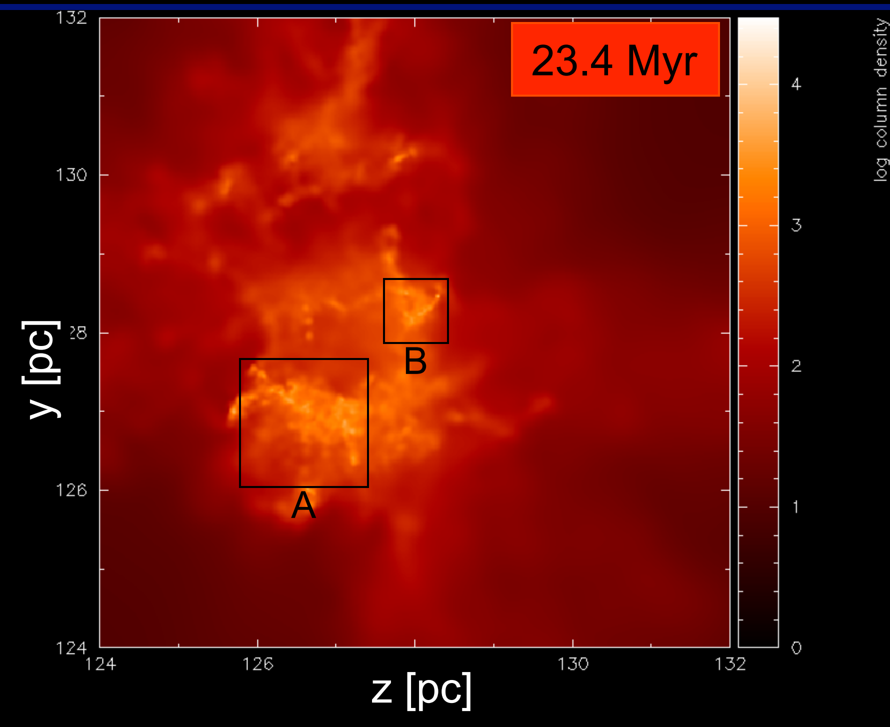
High SFR



Massive clumps







Central 8 pc resampled @ 0.03 pc resolution.

Vázquez-Semadeni+09

- # Physical properties:

Vázquez-Semadeni+09

- Whole 8-pc region:
  - <n> = 450 cm^{-3}
  - σ_{3D} = 5.0 km s^{-1}; σ_x = 2.3 km s^{-1}; σ_y, σ_z ~ 3.1 km s^{-1}
  - M ~ 7000 M_{sun}
  - Mass accretion rate ~ 3 x 10^{-3} M_{sun} yr^{-1}
- Clump A (L = 1.5 pc):
  - <n> = 1.27 x 10^{4} cm^{-3}
  - σ_{3D} = 3.6 km s^{-1}
  - M ~ 1400 M_{sun}
- Clump B (L = 0.8 pc):
  - <n> = 1.72 x 10^{4} cm^{-3}
  - σ_{3D} = 2.8 km s^{-1}
  - M = 300 M_{sun}

"Typical" massive clump
(Motte+07/Schneider+07):
M ~ 1000 M_{sun}
L ~ 0.7 pc
σ ~ 2 km s^{-1}
n ~ 1.4 x 10^{4} cm^{-3}

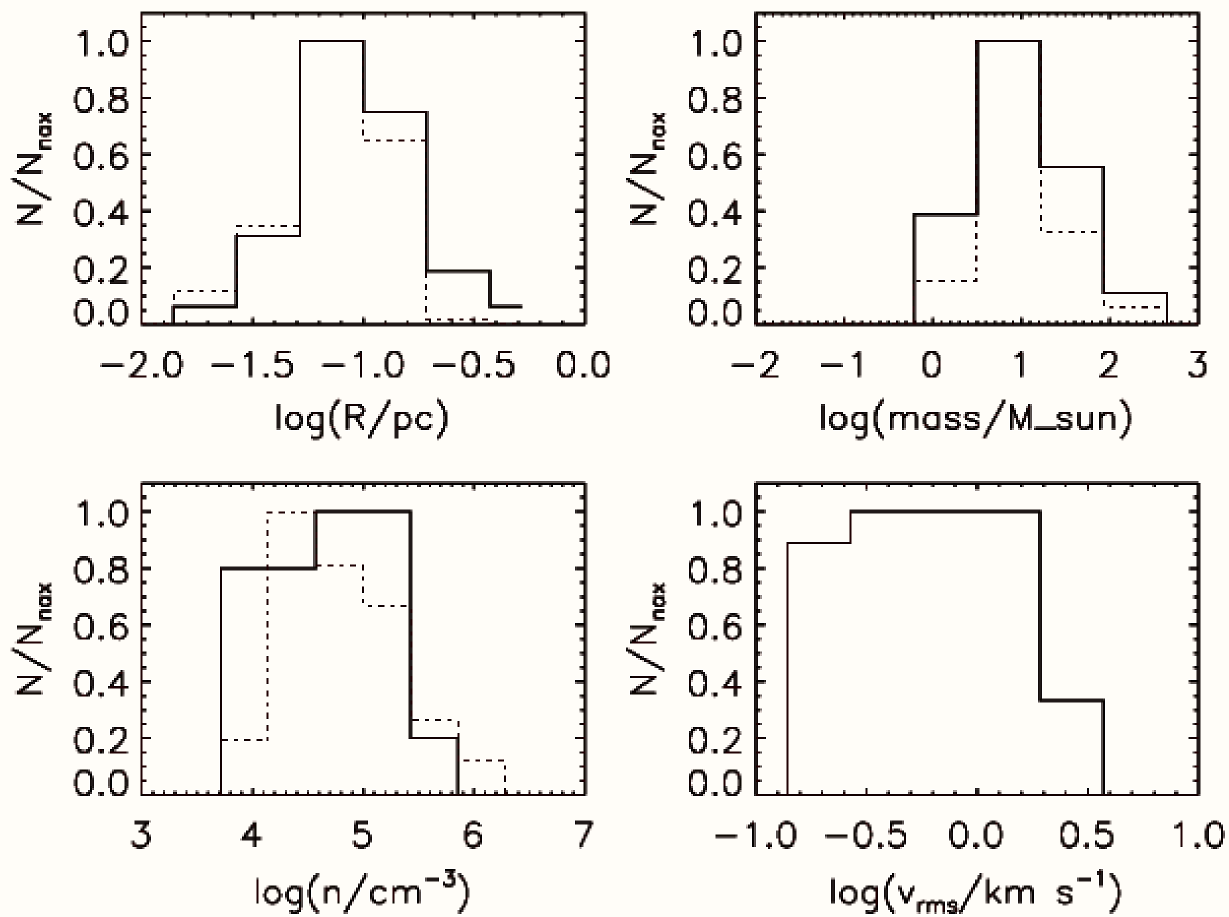
- High-density cores: (simple density threshold criterion, n > 5 x 10^{4} cm^{-3}, M > 4 M_{sun}).
  - Found 15 cores with
    - n_{max} ~ 10$^{5-6}$ cm^{-3}.
    - *Lifetimes << 1.3 x 10^{5} yr* (appear and disappear in << dt between frames). Compare to Motte's estimate: ~ 10^{3} yr.

Vázquez-Semadeni+09

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

Simulation (solid line)

Cygnus X-North (129 cores) (Motte et al. 2007). (dotted line)

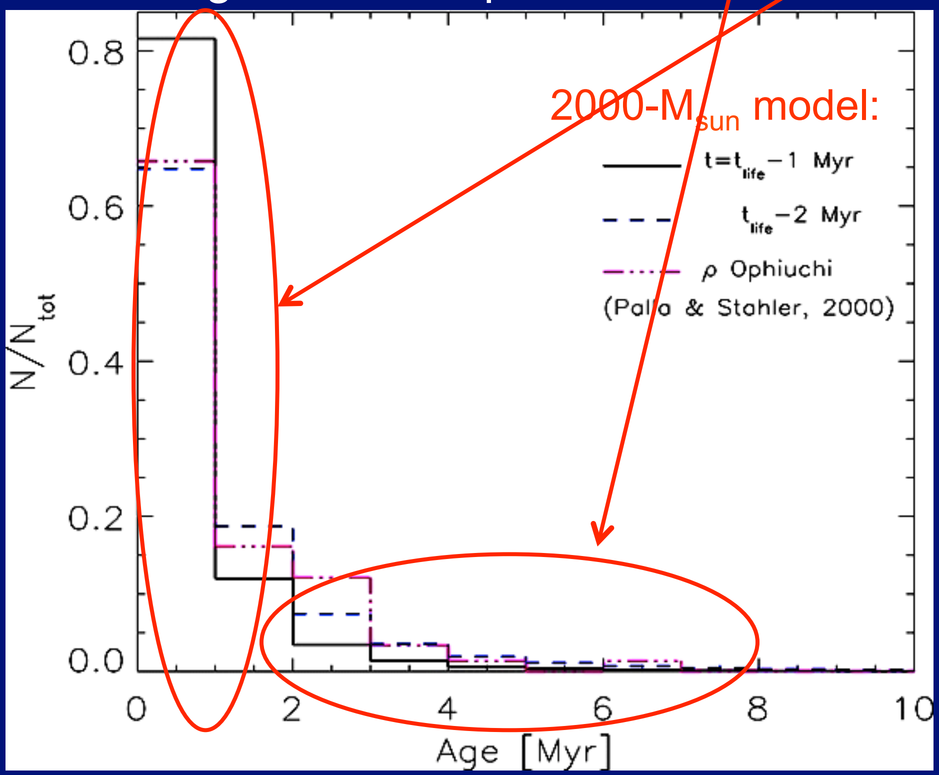


Conclude:
The central region of collapse exhibits similar statistical properties to regions of massive SF.

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

Implications for cluster formation

- Stellar population of an evolved star-forming region consists of:
  - Slightly older, scarce component formed by early, low-mass, low-SFR, and
  - Younger, more abundant component formed at later, massive, high-SFR collapse.



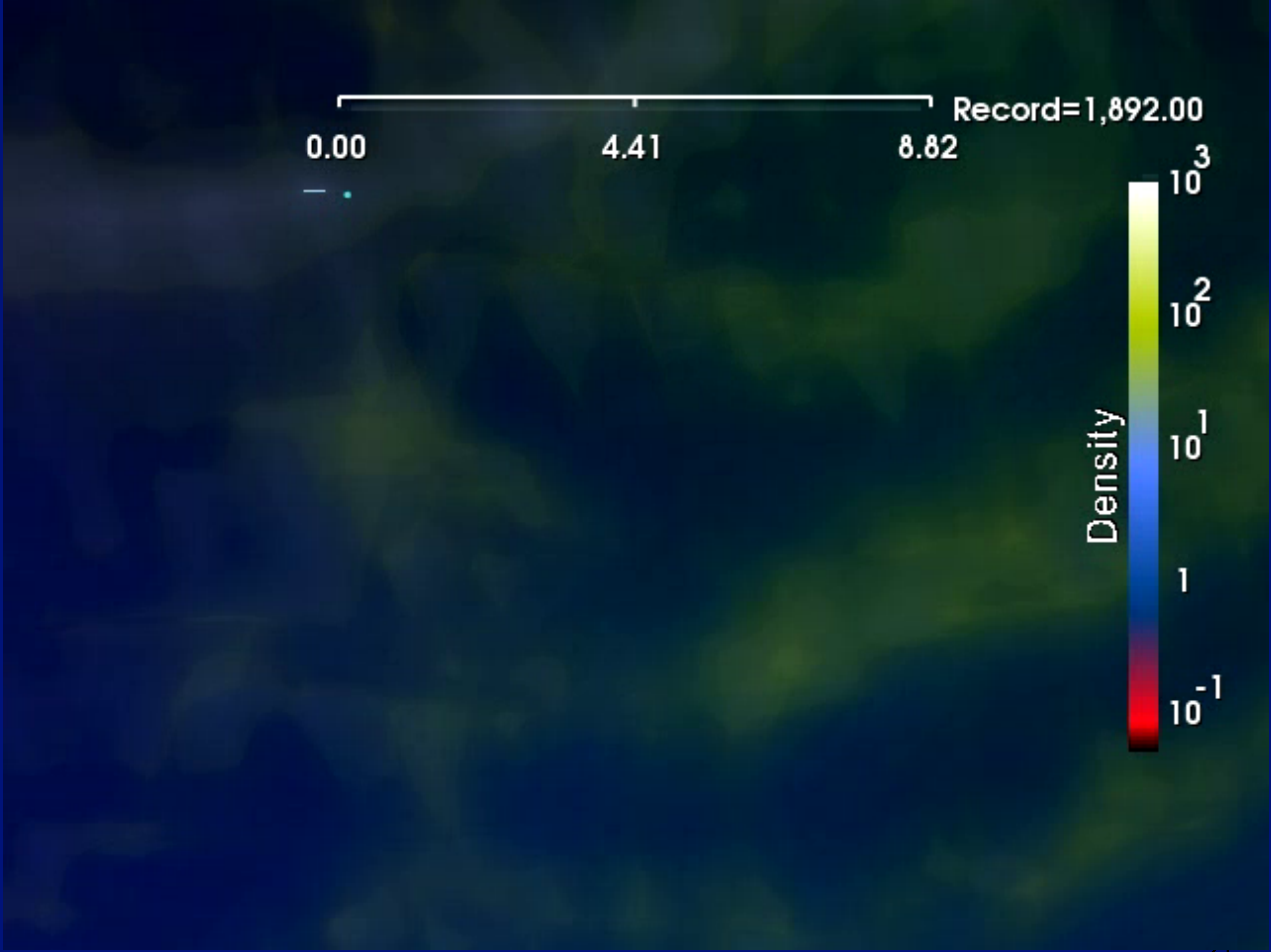
Consistent with age histograms in embedded clusters by Palla & Stahler 1999, 2000.

Analytical model by Zamora-Avilés+12, ApJ, 751, 77

- Age gradients (Vázquez-Semadeni et al, in prep.)
  - Small-scale SF sites are infalling onto large-scale potential well.
    - Have σ_v of large-scale collapse.
    - Stars formed there do not dissipate their E_k.

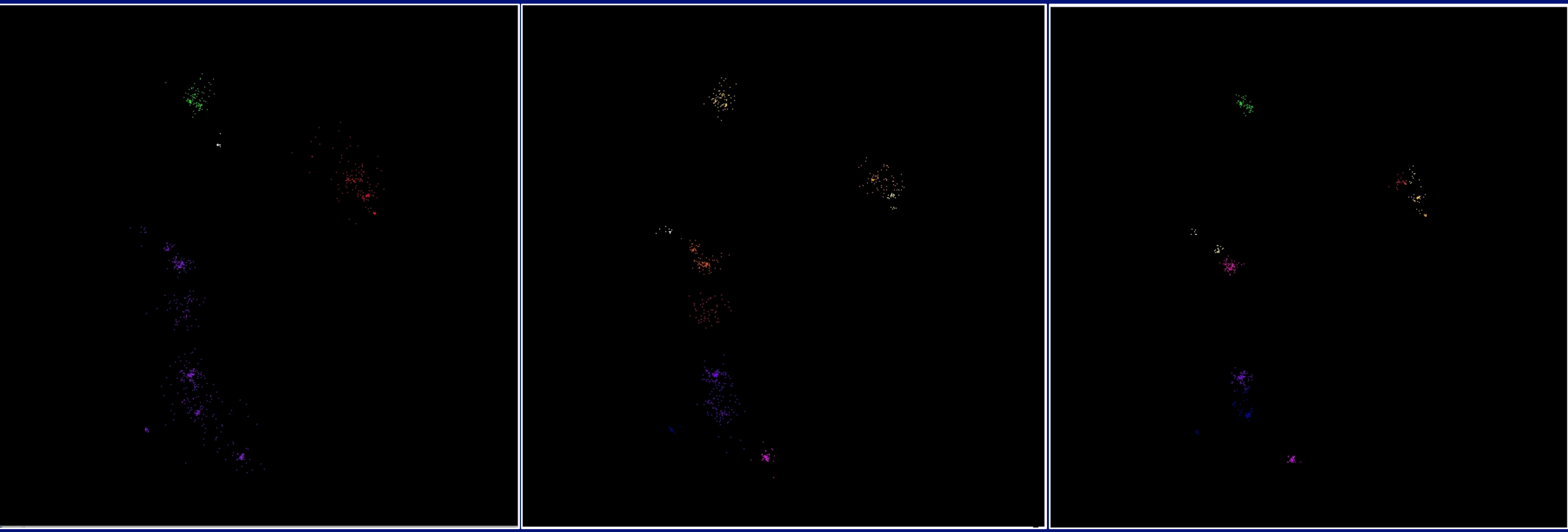
      ➔ "Puffed-up" component.
  - Large-scale SF sites shock at the potential trough and dissipate their E_k, so stars formed there have lower σ_v.
    - Qualitatively consistent with observed age gradients (Getman +14, ApJ, 787, 109).

- Clusters have a fractal structure (Vázquez-Semadeni et al, in prep.)
  - Large-scale structures consist of substructures (Larson 1995).
    - Due to *hierarchical collapse* of parent MC.



Vázquez-Semadeni et al. in prep.

- Applying a friends-of-friends algorithm:



Linking parameter = 2
4 groups

Linking parameter = 1
9 groups

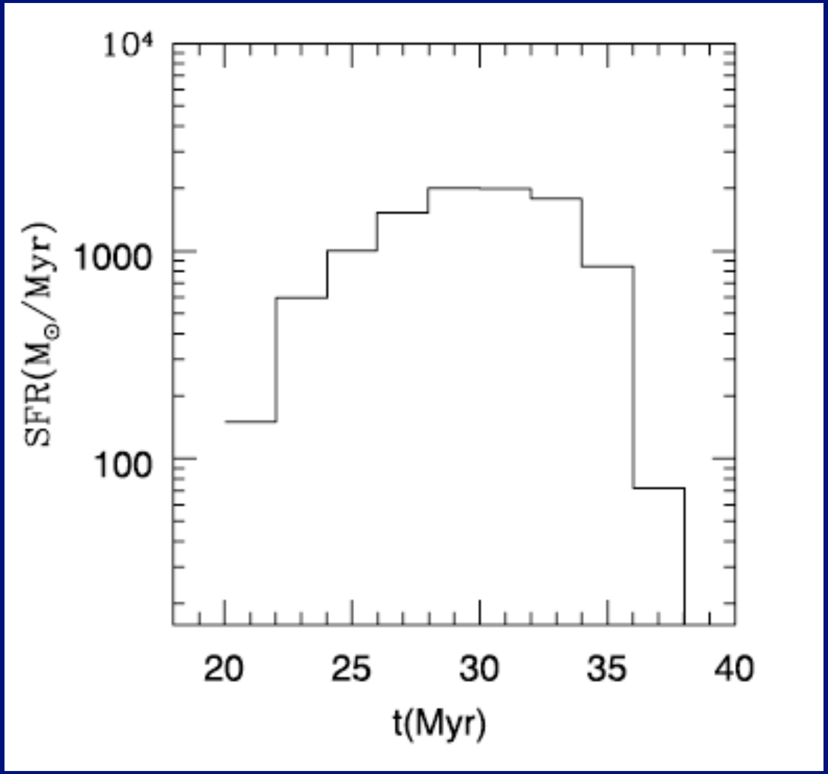
Linking parameter = 0.5
13 groups

- Conclusions:
  - MCs probably in *global*, *hierarchical* gravitational collapse.
    - SFR increases over time, until cloud disrupted/evaporated.
    - Hierarchical : collapses within collapses.
      - Local, small scale, early collapses → low-mass, low-SFR regions
      - Global, later collapse → high-mass, high-SFR regions.
    - Implications for clusters:
      - Age segregation.
      - Fractal structure.

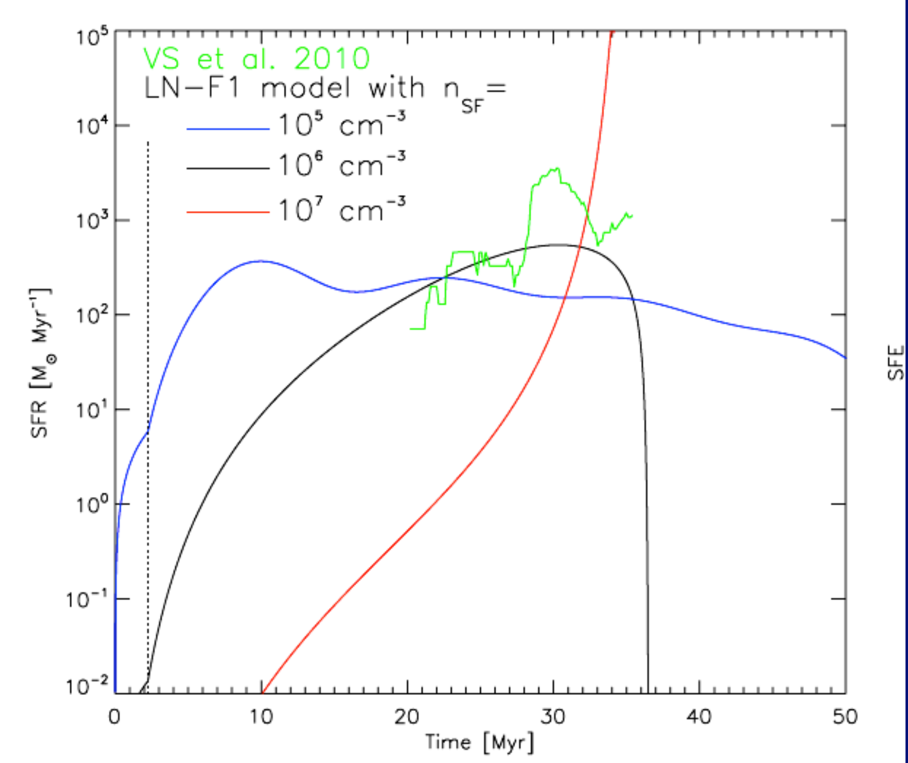

Diffuse ISM
SF-ing GMCs and their
HI envelopes
Stars

The End

- Global collapse implies that *clouds evolve...*
  - ... and SFR *increases in time* (before cloud is destroyed).



Colín+10, MNRAS 435, 1701
(simulation)



Zamora-Avilés+12, ApJ, 751, 77
(analytical model)

Comparison between low- and high-mass clouds

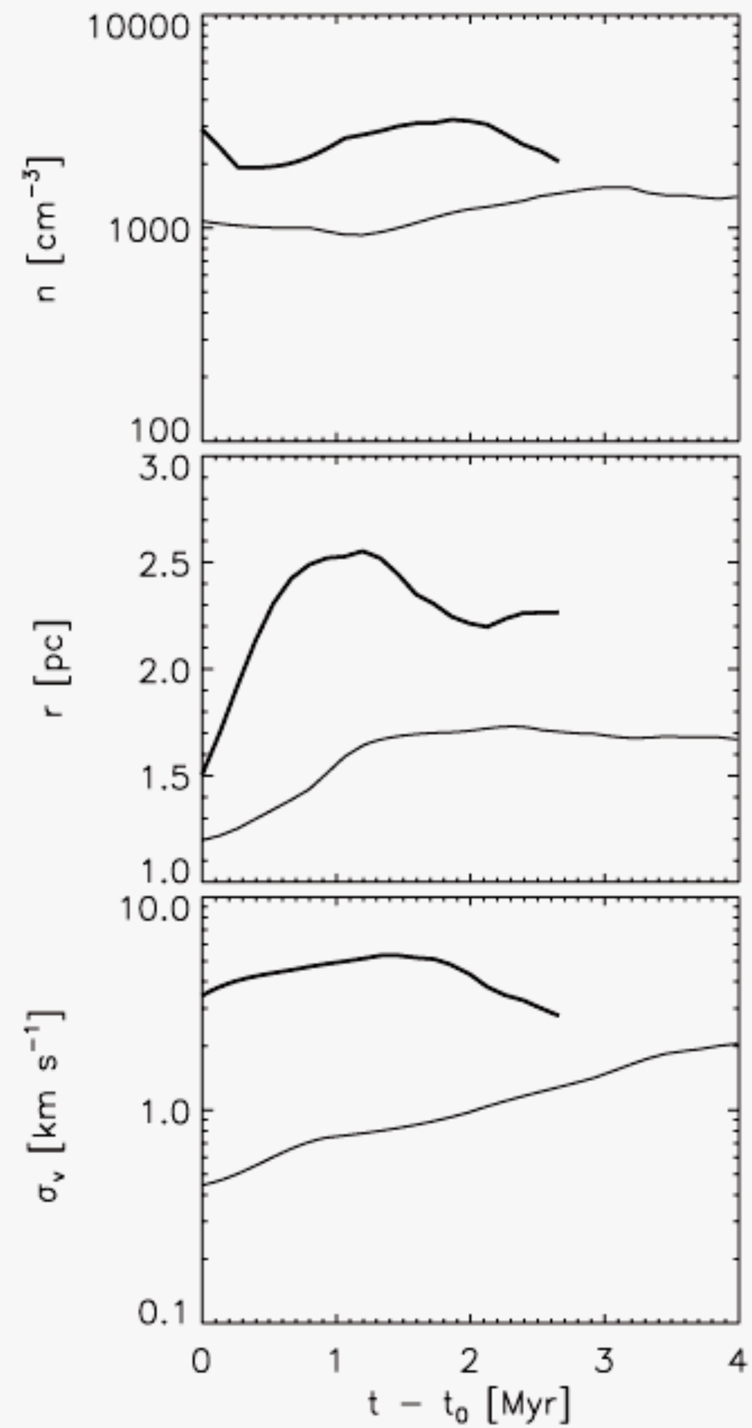
High-mass region

Low-mass region

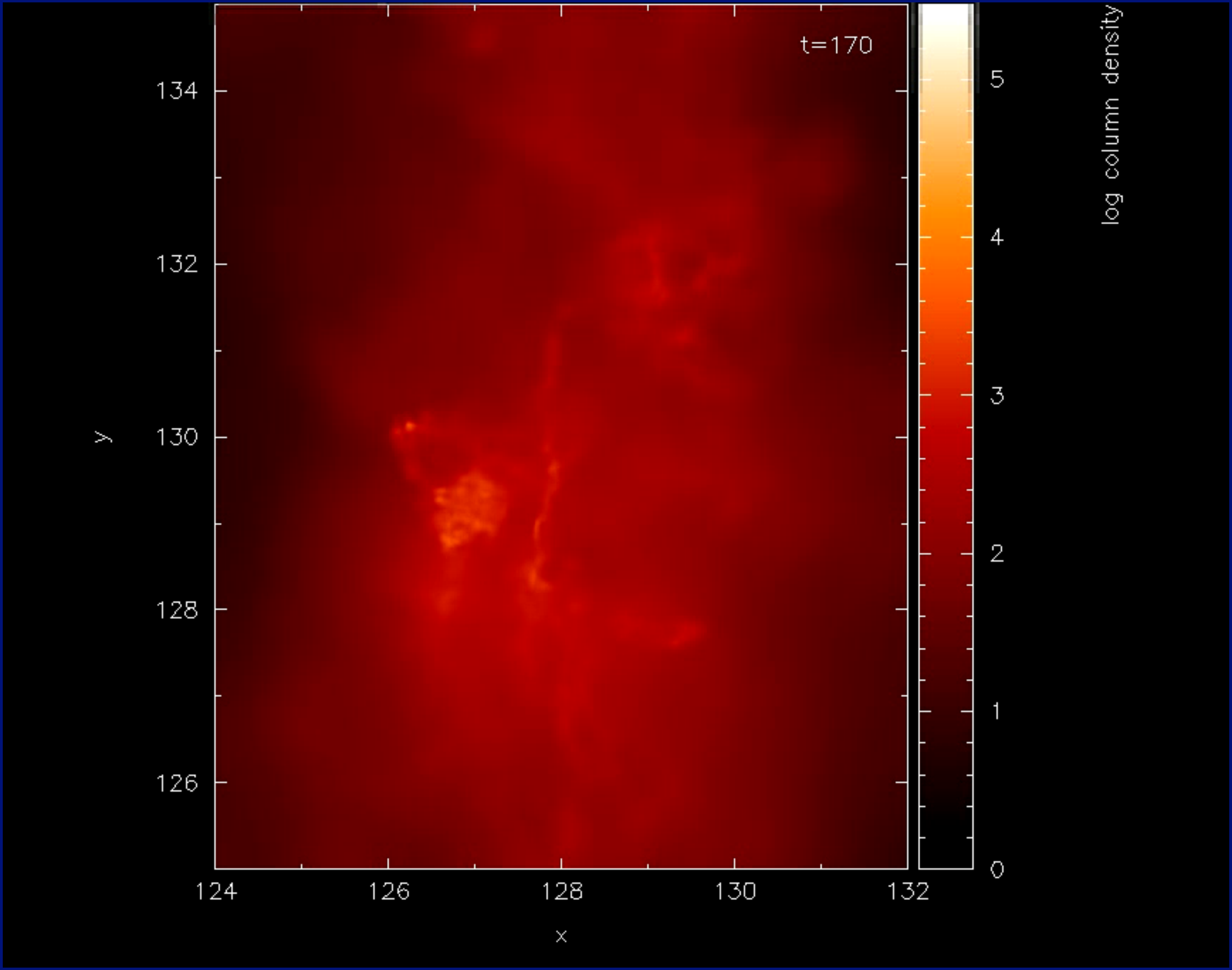
Both defined as the material above $n = 500\ cm^{-3}$ in the corresponding regions.

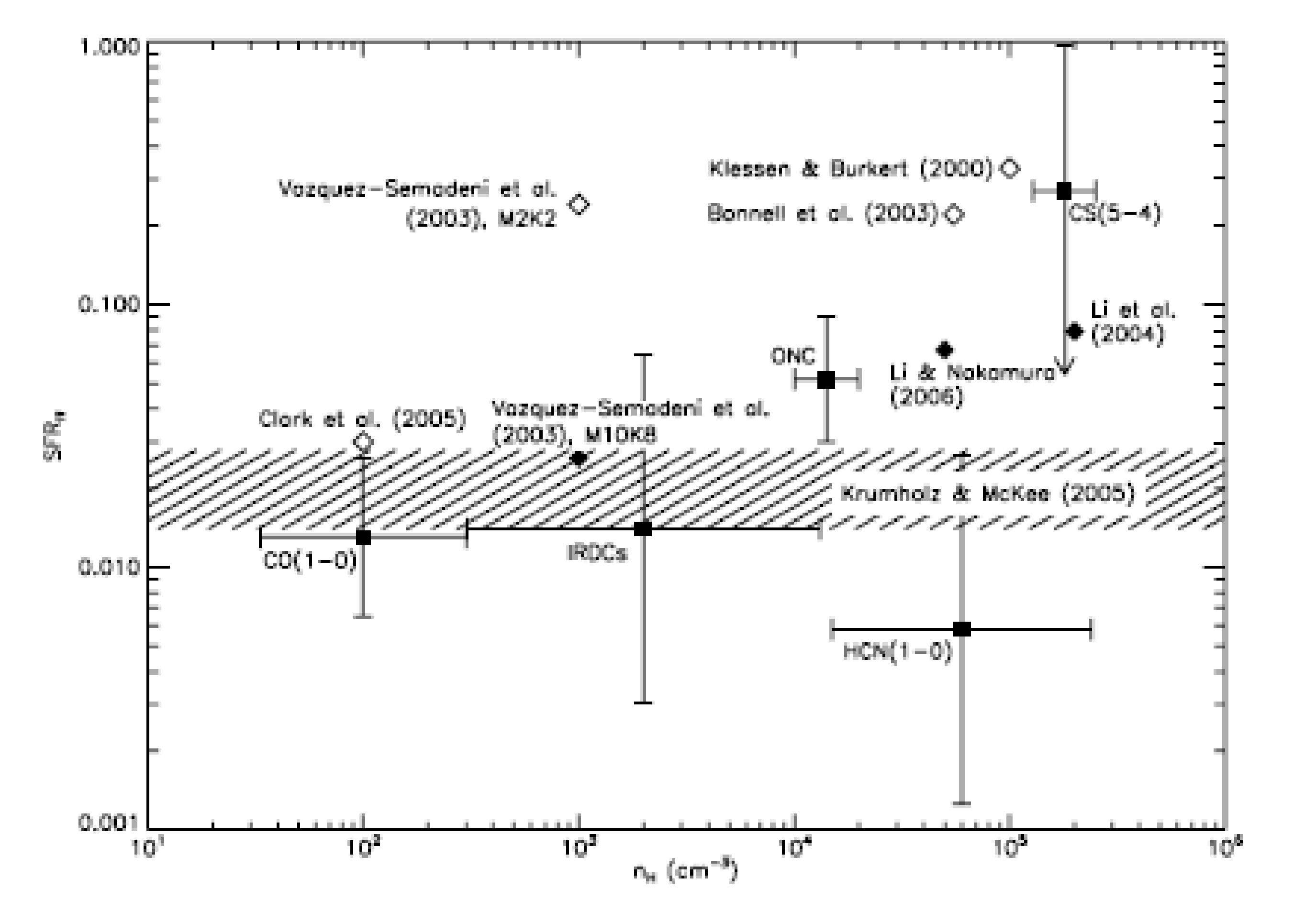
t_0 =
- 17.3 Myr for low-mass region.
- 22.6 Myr for high-mass region.

Vázquez-Semadeni+09, ApJ, 707, 1023

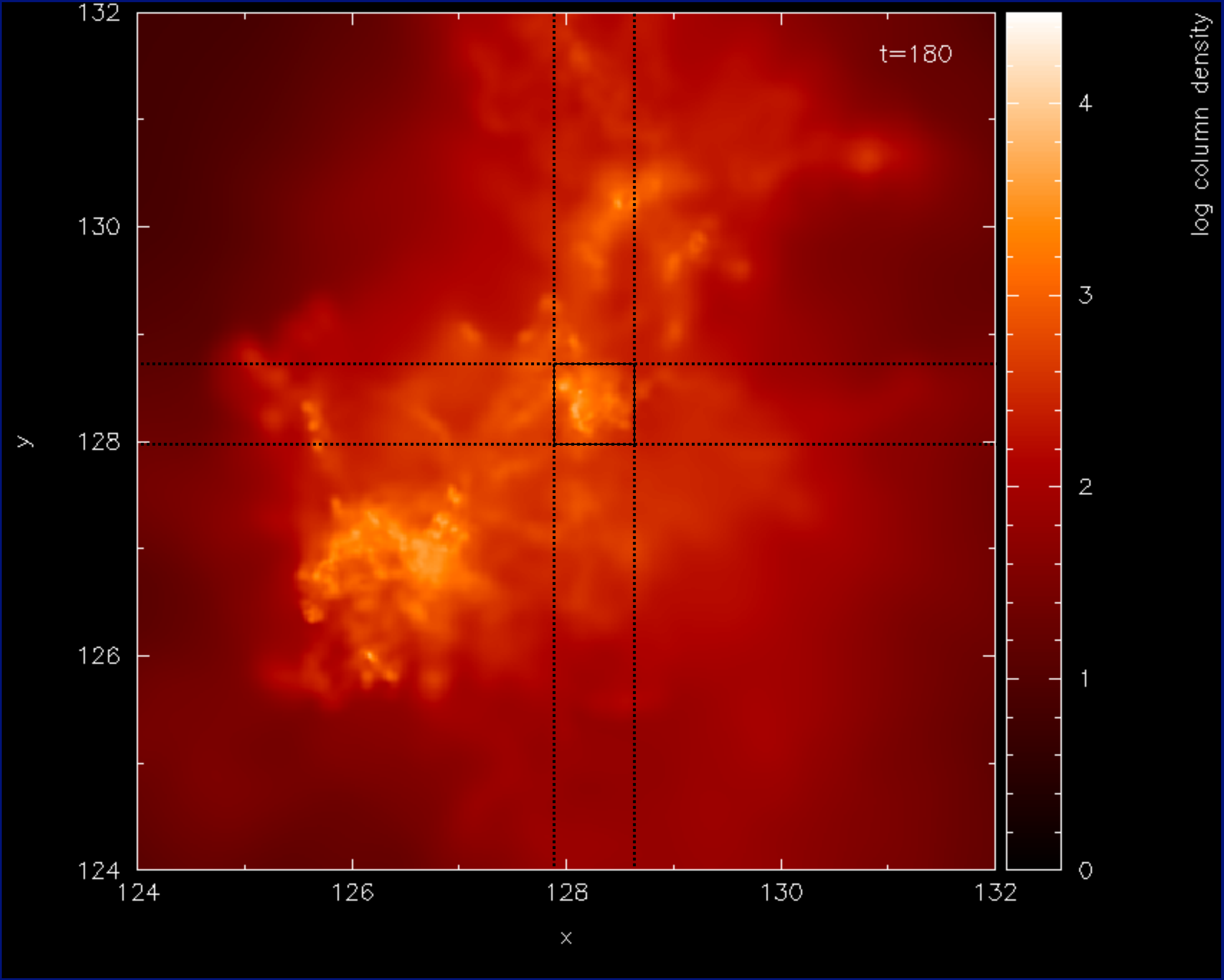


22.1 – 24.7 Myr (Δt = 2.6 Myr)

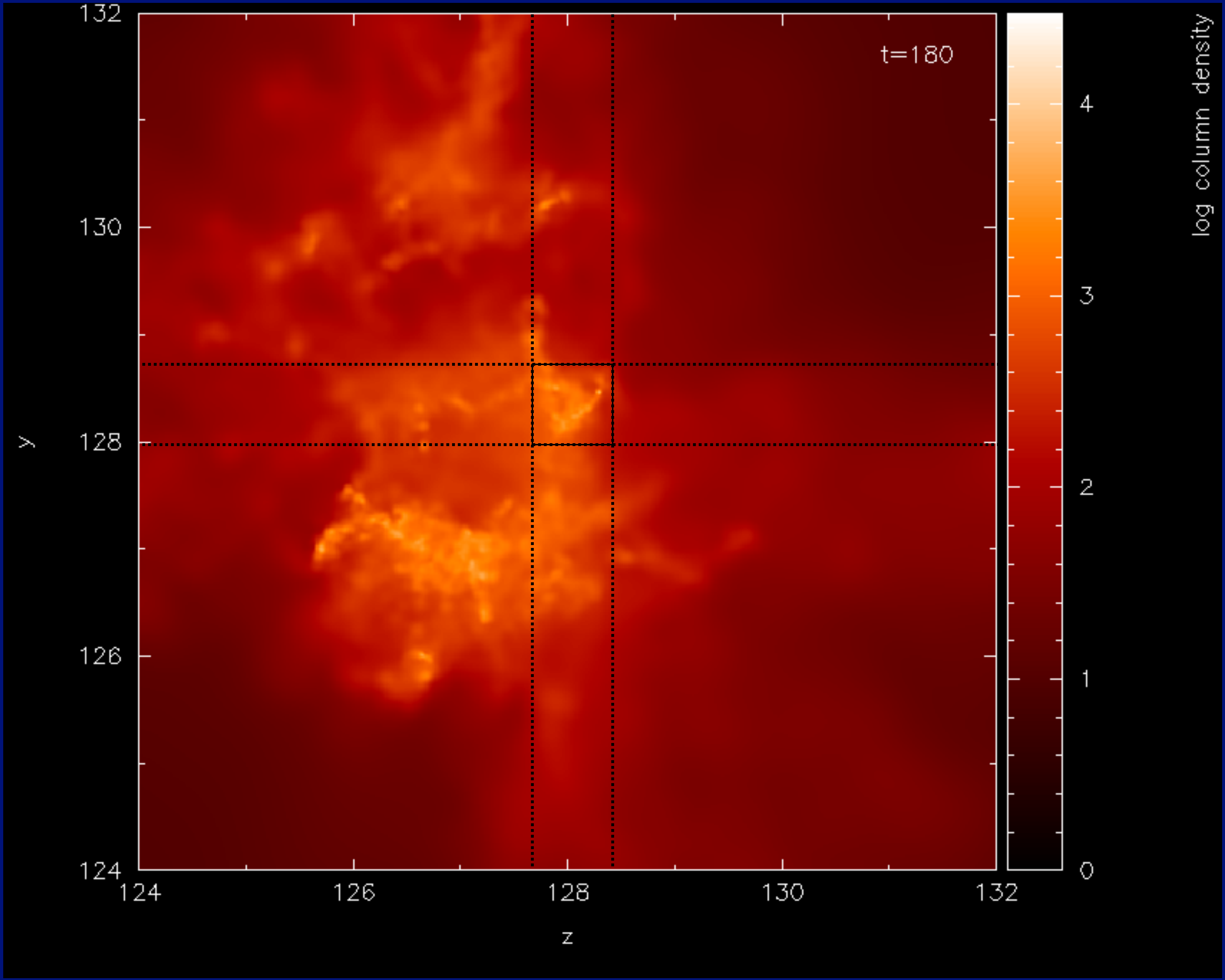




Krumholz & Tan 2007



t=180
y
x
log column density
132
130
128
126
124
124
126
128
130
132
4
3
2
1
0



t=180
132
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y
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z
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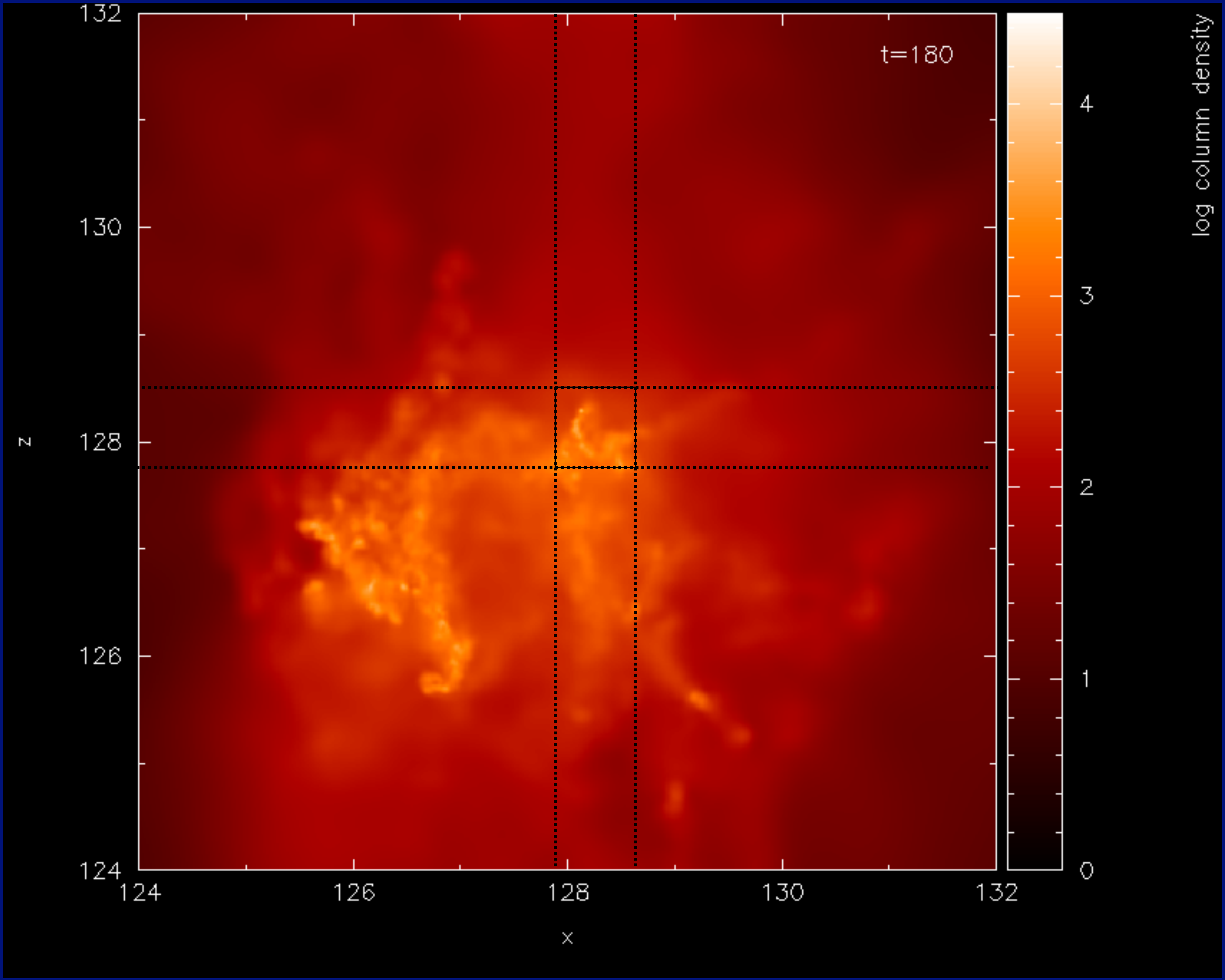
log column density


t=180
log column density
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