Turbulent Control of the Star Formation Efficiency

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I. INTRODUCTION

- The Star Formation Efficiency (SFE) can be defined as

the fraction of a molecular cloud's mass that ends up in stars during its lifetime.

- It is the integral of the SFR over the cloud's lifetime Δt:

$$\mathrm{SFE} = \frac{1}{M_{\mathrm{cl}}} \int_{\Delta t} \mathrm{SFR}\, dt$$

- The SFE is known to be low:

    ~ a few % in global cloud complexes (e.g., Myers et al. 1986)
    ~ 10-30% in cluster-forming cores (e.g., Lada & Lada 2003)

- Why?
  - low SFR? (“Slow”) (e.g., Mouschovias 1976; Shu et al. 1977; Klessen et al. 2000; Palla & Stahler 2002; Mouschovias & Tassis 2004; Vázquez-Semadeni et al. 2003, 2005; Krumholz, Tan & McKee 2006),
  - or small Δt? (“Brief”) (e.g., Ballesteros-Paredes et al. 1999; Elmegreen 2000; Hartmann et al. 2001; Hartmann 2003; Bate et al. 2003; Vázquez-Semadeni et al. 2007; Ballesteros-Paredes & Hartmann 2007; Elmegreen 2007),
  - or something else? A combination of the above?

II. MECHANISMS FOR A SLOW SFR

1. Magnetic support (Mouschovias 1976, 1991; Shu, Adams & Lizano 1987).

- Low-mass SF occurs in magnetically subcritical molecular clouds (MCs) mediated by ambipolar diffusion (AD).
  - Low efficiency because
    - Low filling factor of supercritical gas.
    - Long AD timescale (τ_{AD}) in quiescent, strongly subcritical conditions.
- High+low-mass SF occurs in supercritical clouds
  - High efficiency.

- However,
  - GMCs are supersonically turbulent... (e.g., Zuckerman & Palmer 1974; Larson 1981; Heyer & Brunt 2004) :
    - Cores form in (short) crossing time (Ballesteros-Paredes et al. 1999; Elmegreen 2000).
    - τ_{AD} is comparable to dynamical time (Fatuzzo & Adams 2002 ; Heitsch et al. 2004).
  - ... and marginally magnetically critical (e.g., McKee 1989; Bourke et al. 2001; Hartmann et al. 2001)
    - τ_{AD} is comparable to dynamical time in moderately subcritical clouds (Ciolek & Basu 2001).
  - Most low-mass stars form in high-mass star forming regions (supercritical mode).
  - So, probably cannot appeal to low-mass mode of magnetic support model to account for low SFE.

2. 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).

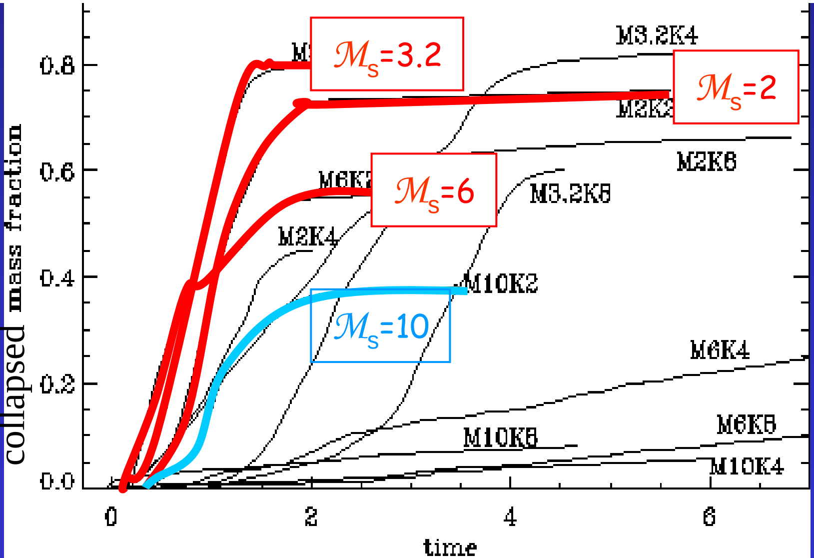
- Dual role of supersonic turbulence:
  - Prevent monolithic cloud collapse.
  - Promote *nonlinear* (large amplitude) small-scale density fluctuations that
    - Shorter formation and free-fall times than parent cloud’s.
    - Involve only a fraction of the total cloud mass (a different kind of filter 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).

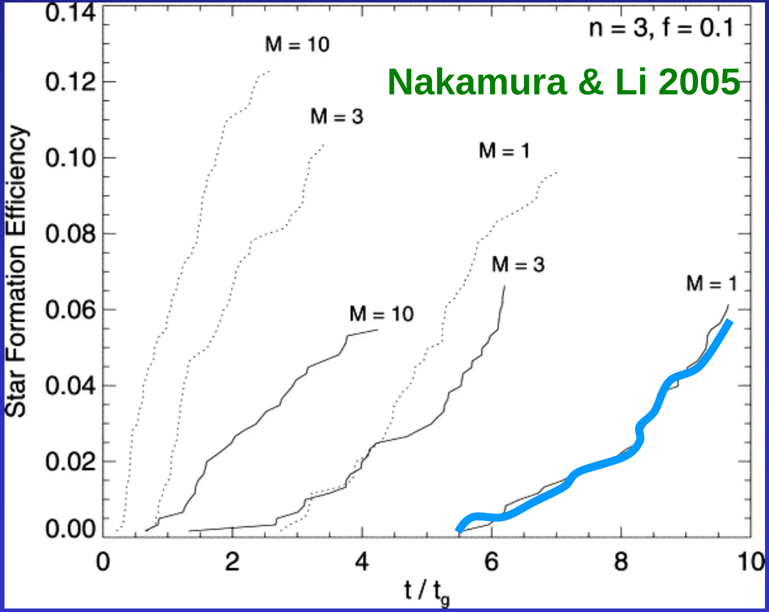
- Precise effect of turbulence strength depends on global cloud conditions:
  a) *Smaller SFE* requires:

Larger turbulent rms Mach # in continually driven regimes.

Smaller turbulent rms Mach # in decaying regimes.

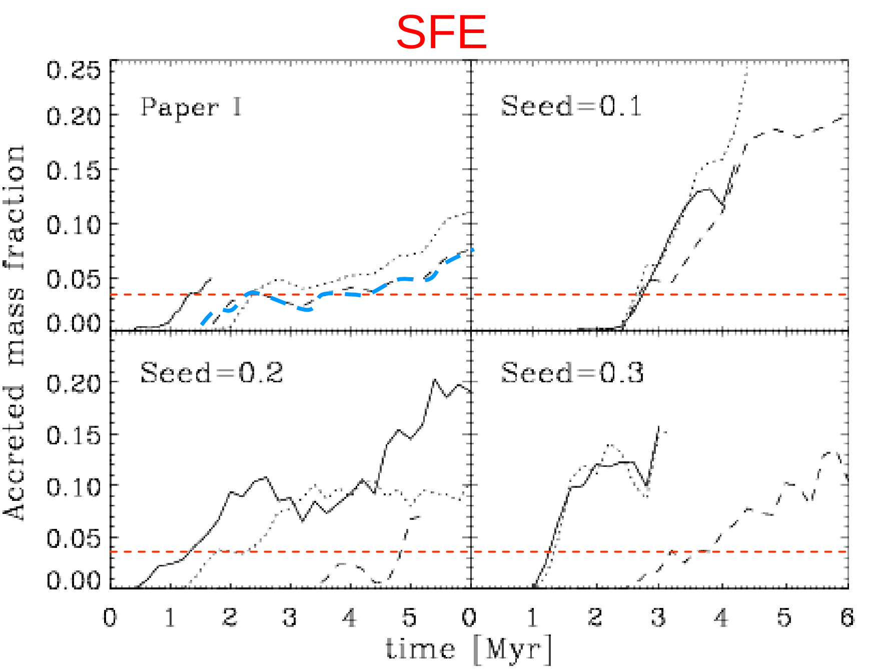
Klessen et al. 2000; Vázquez-Semadeni et al. 2003





Nakamura & Li 2005

b) Same (2-5%) values of SFE over “reasonable” cloud lifetimes require moderately supercritical B in driven regimes, moderately subcritical B in decaying regimes,



Vázquez-Semadeni, Kim & Ballesteros-Paredes (2005). 3D, supercritical, no AD.

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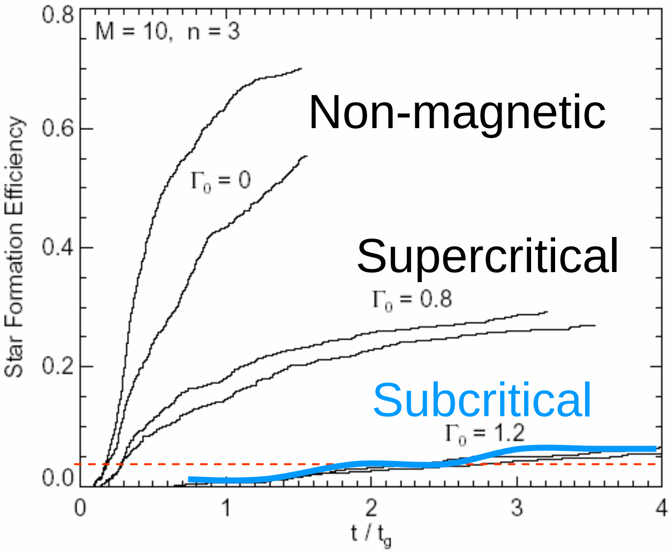


FIG. 6.— Efficiencies of star formation for clouds of the same initial turbulent velocity field but different degrees of magnetization, measured by the dimensionless flux-to-mass ratio $\Gamma_{\blacksquare}$ labeled beside the curves. The heavy (thin) solid lines are for strong (weak) outflow cases with $f = 0.1$ (0.01).

Nakamura & Li (2005), 2D, decaying, with AD.

——— Non-magnetic

B ⋯⋯⋯ Strongly supercritical

– – – – Moderately supercritical

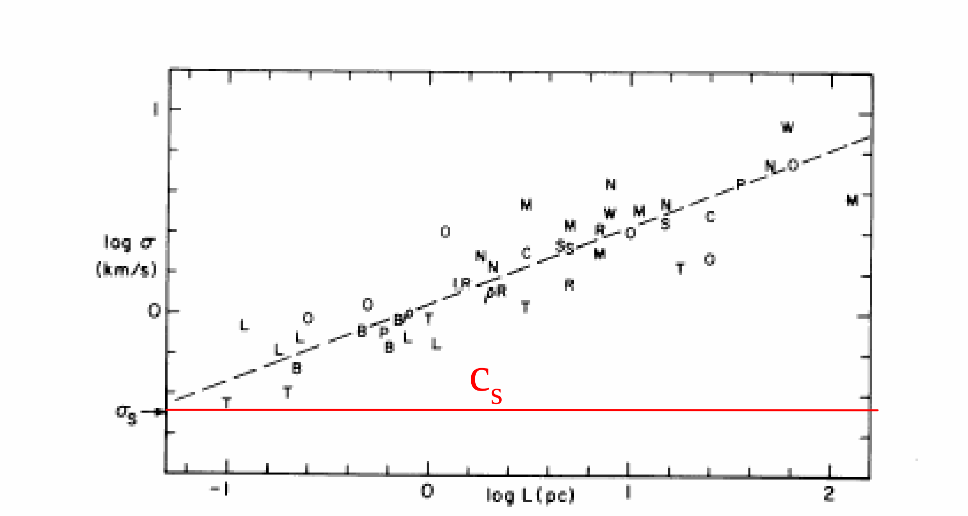
A model for the inhibitory effect of turbulence in stationary turbulent regimes (continuously driven), is based on the *sonic scale* λ_s (Padoan 1995; Vázquez-Semadeni et al. 2003; Krumholz & McKee 2005):

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

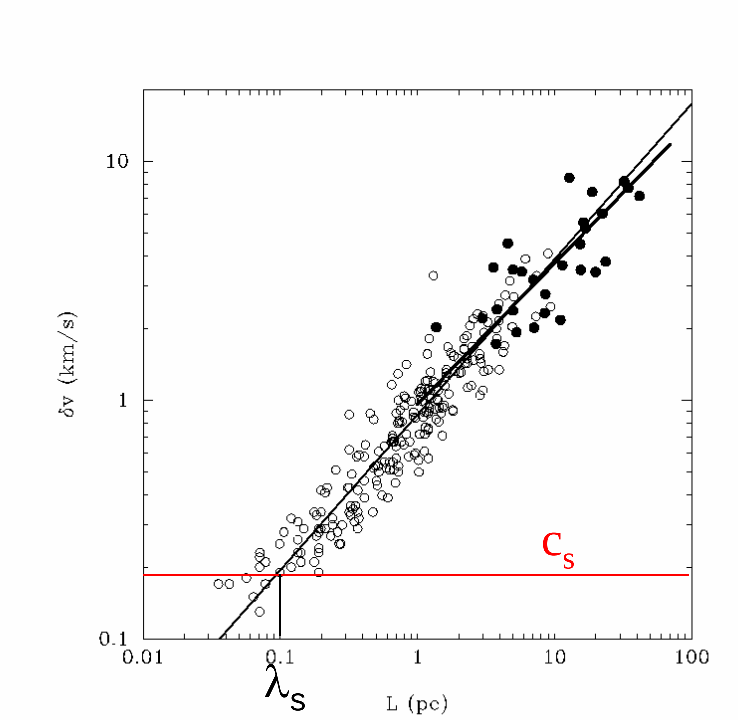
$$\Delta\upsilon \approx 0.8\,\mathrm{km\,s^{-1}} \left(\frac{L}{1\,\mathrm{pc}}\right)^{\alpha}$$

$$\alpha \approx 1/2$$

$\lambda_s \sim 0.07$ pc



Larson 1981

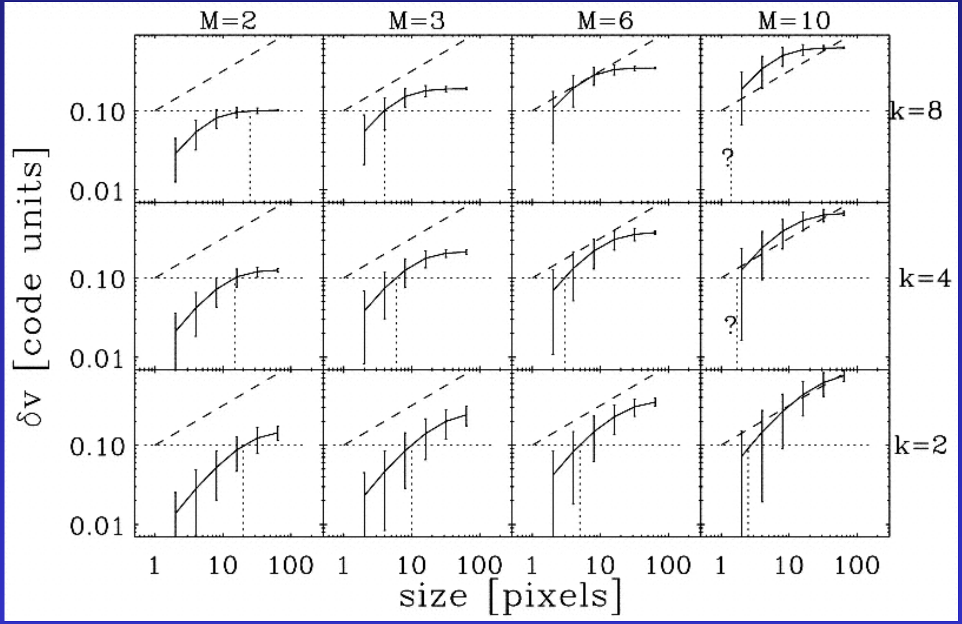


Heyer & Brunt 2004

- 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 ($\delta u_{turb} < c_s$).

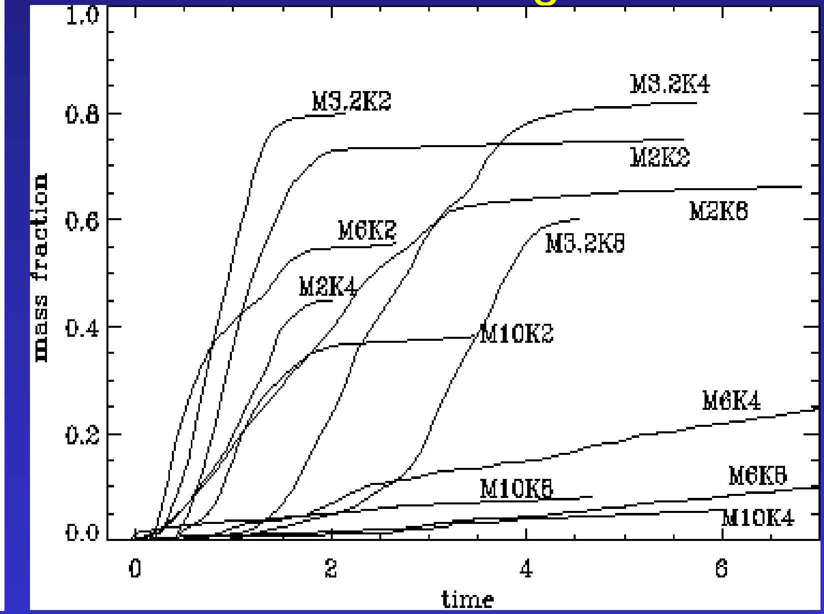
➔ Maybe SFE related to fraction of mass in Jeans-unstable cores of size < λ_s? (i.e., “super-Jeans”, subsonic cores).

- 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:



λ_s decreases with increasing levels of turbulence at given T.

SFE measured as collapsed mass fraction after 2 crossing times.

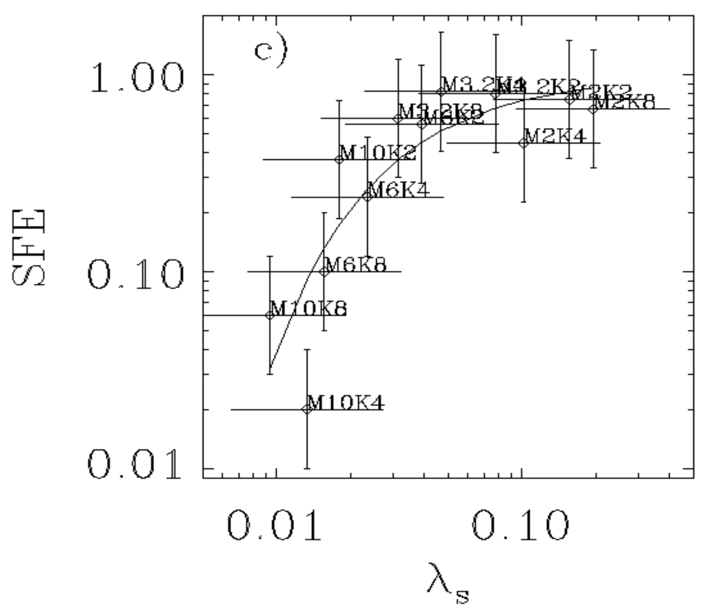


M_s	2	3.2	6	10
$2\tau_c/\tau_0$	12.5	10	6.7	2

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

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

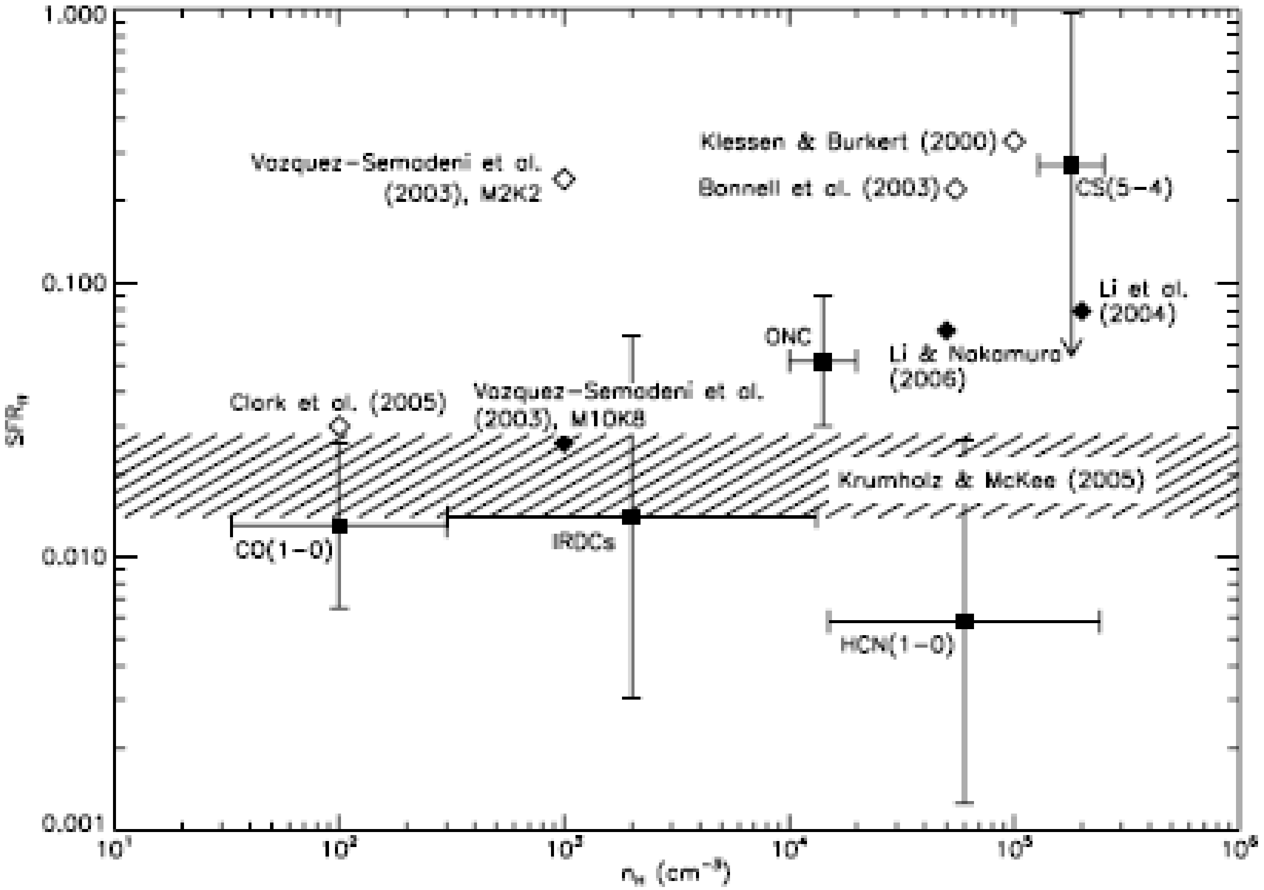
- The model has been extended by (Krumholz & McKee (2005) to use the ratio of λ_s to the Jeans length L_J as the condition for gravitational collapse,
  - Select the regions from lognormal density PDF (Vázquez-Semadeni 1994; Padoan et al 1997; Padoan & Nordlund 2002)
  - for obtaining the SFE after one free-fall time

$$\mathrm{SFR}_{\mathrm{ff}} \approx 0.014 \left(\frac{\alpha_{\mathrm{vir}}}{1.3}\right)^{-0.68} \left(\frac{\mathcal{M}}{100}\right)^{-0.32} .$$

where

$$\alpha = \frac{E_{\mathrm{kin}}}{|E_{\mathrm{grav}}|} \propto \left(\frac{\mathcal{M}}{J}\right)^2$$

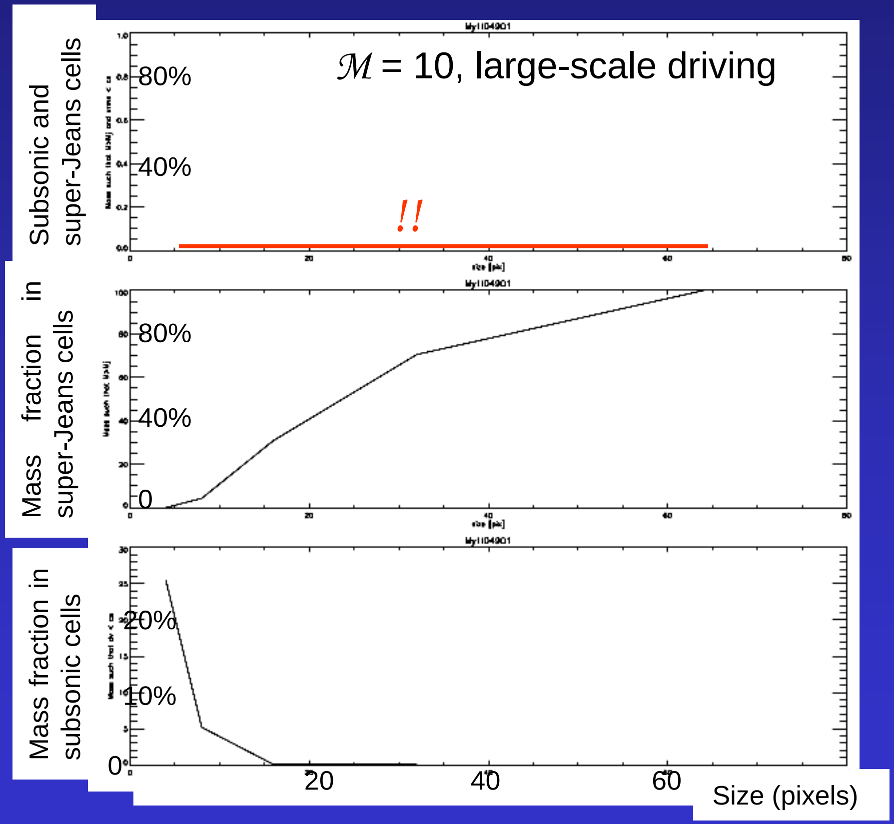
is the *virial parameter.* $\mathcal{M}$ is the rms Mach number and J the Jeans number (L/L_J).

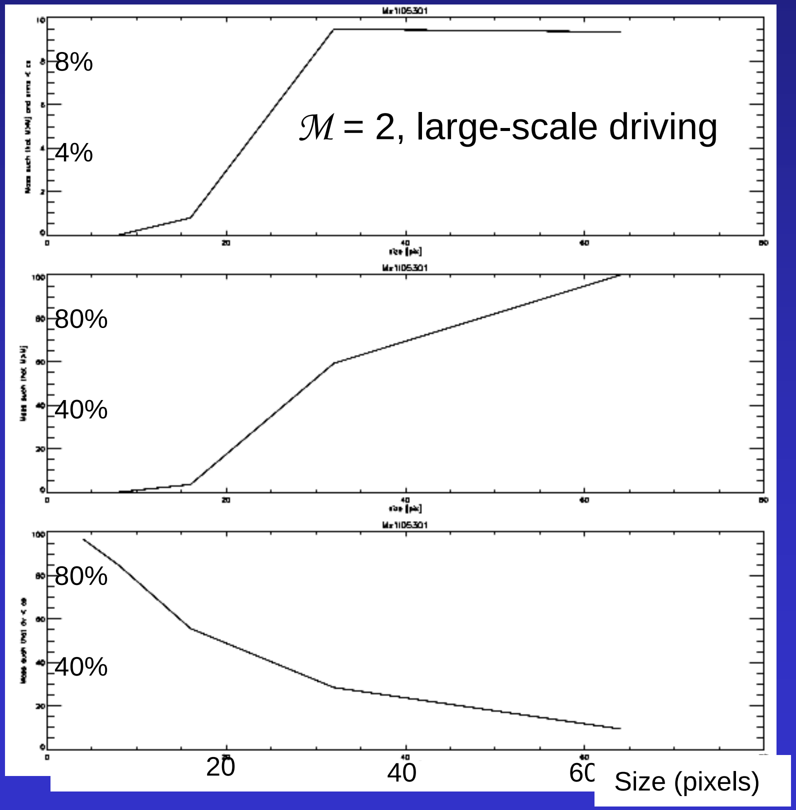


Krumholz & Tan 2007

However (#1)...

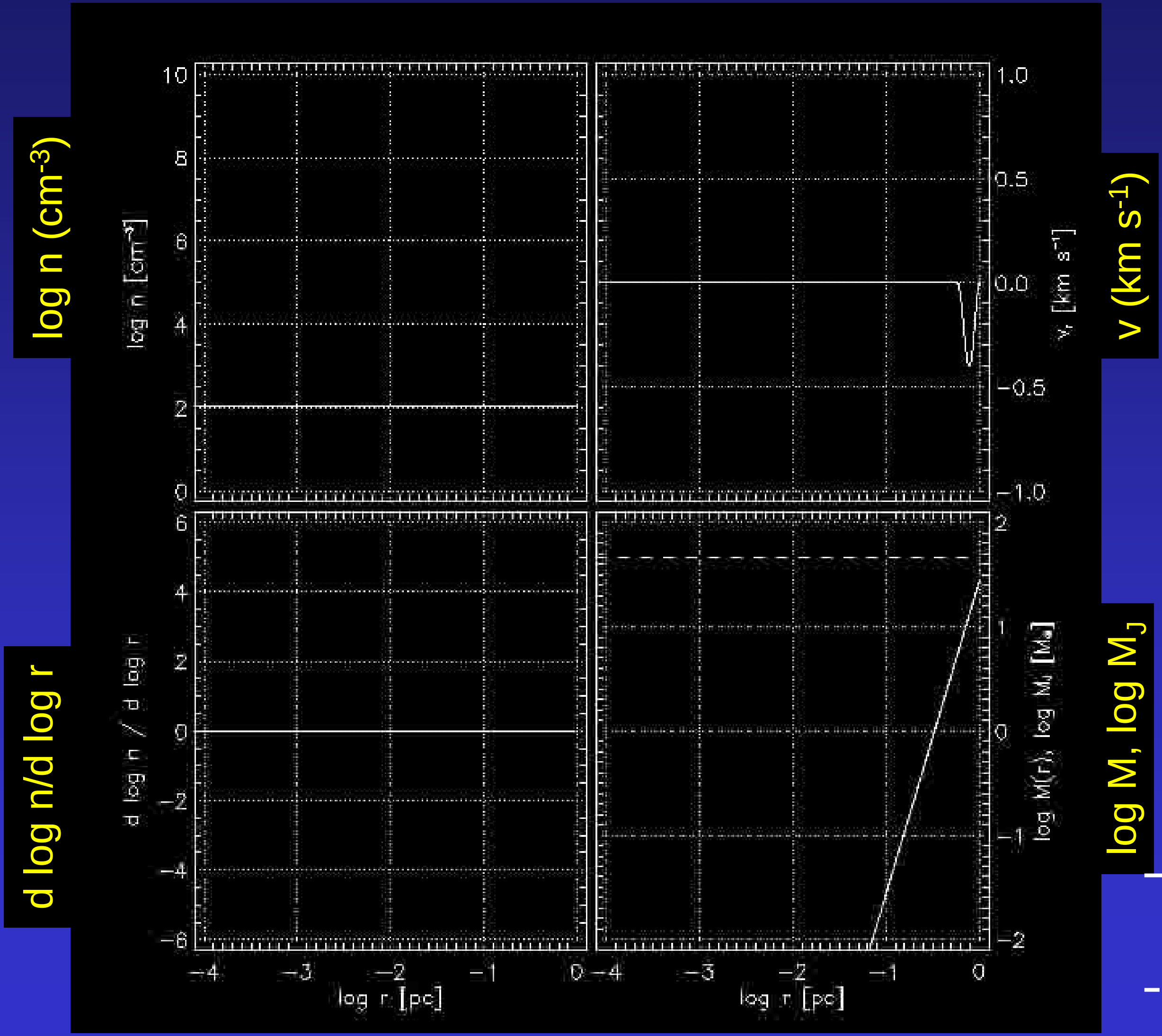
- Fraction of mass in subsonic, super-Jeans cells as function of cell size may be lower than mass in collapsed objects, even zero at large Mach numbers (Vázquez-Semadeni & Ballesteros-Paredes, in prep.)





Subcells in simulation, not clumps.

- There ***must*** be some subsonic, super-Jeans structures:
  - Quiescent starless cores.
  - Seen in idealized simulations...



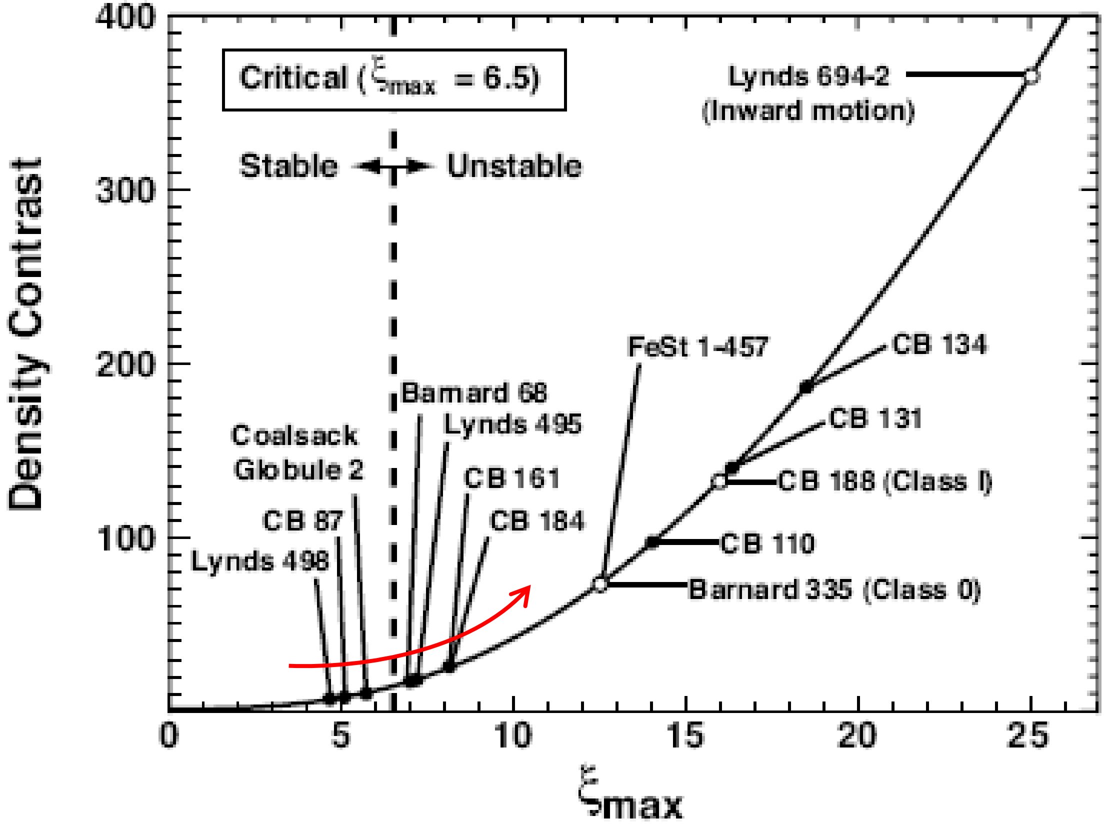
Growing, ram-pressure confined BE spheres.

—— M(r)

- - - - $M_J(r)$

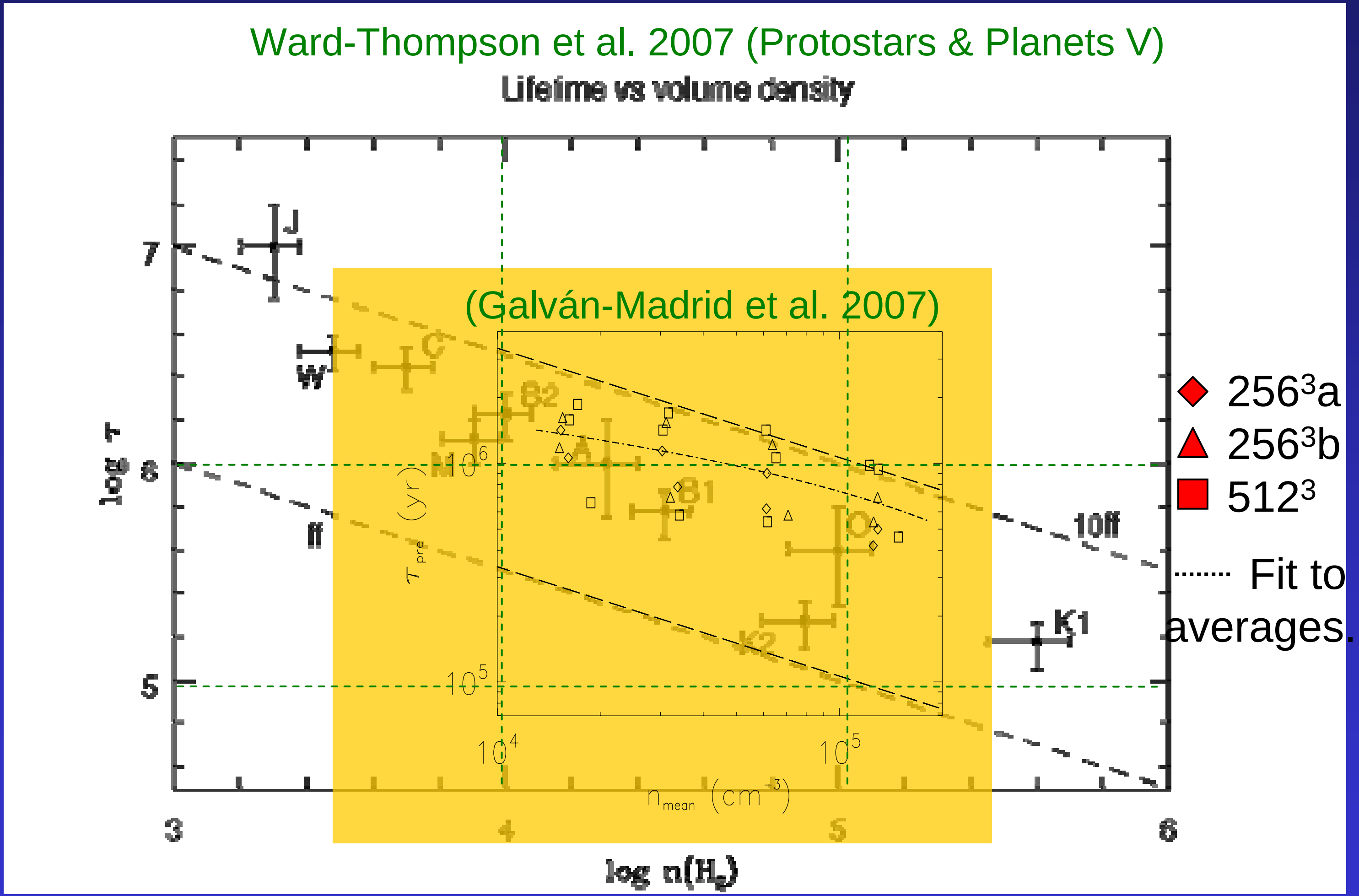
Gómez et al. 2007, ApJ in press, arXiv/0705.0559

– ... which evolve along the stability sequence:



Lada et al. 2007 (Protostars & Planets V)

- Collapse times in moderately supercritical MHD isothermal, driven simulations (“prestellar lifetimes”): 2—10 τ_{ff}.
  - Consistent with observations.

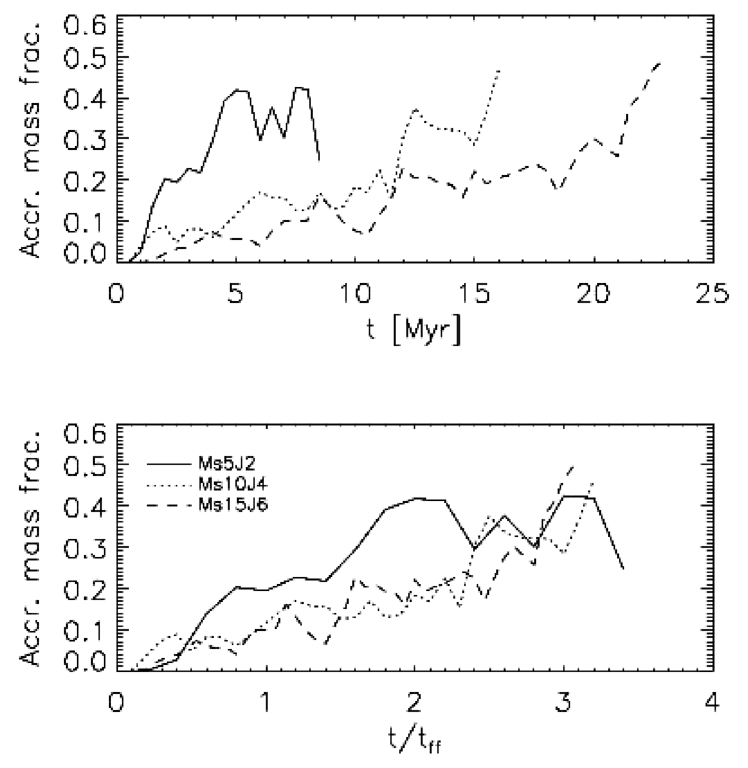


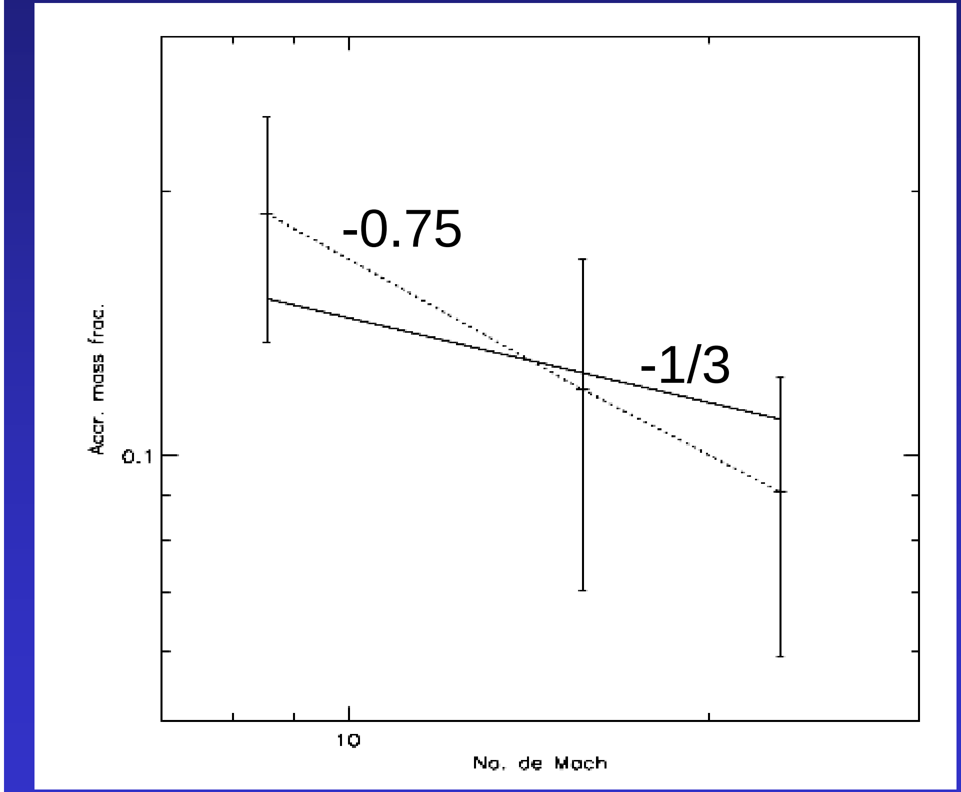
Ward-Thompson et al. 2007 (Protostars & Planets V)

(Galván-Madrid et al. 2007)

(Galván-Madrid et al. 2007, ApJ in press, arXiv/0704.3587)

- However #2: Numerical simulations of turbulent clouds with various Mach numbers, keeping α cst. are marginally consistent with the sonic-scale/L_J model.





Vázquez-Semadeni, González & Kim, 2007, in prep.

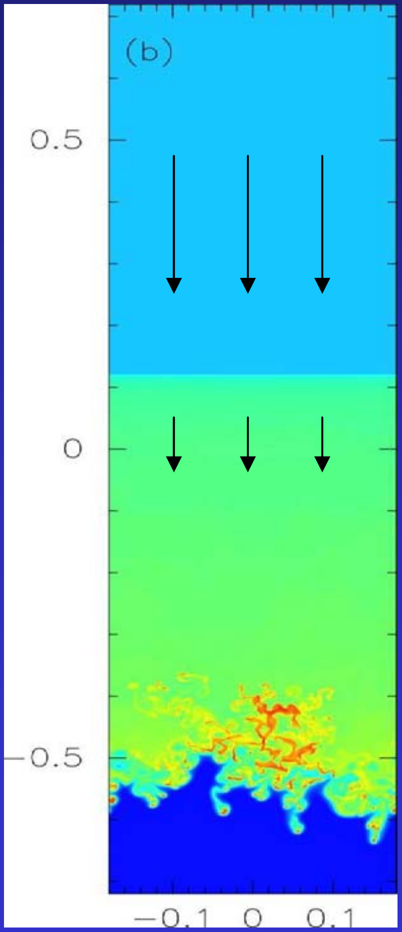
- Conclude:
  - Not all collapsing mass may come from subsonic, super-Jeans structures (Bate, Bonnell et al...)
    - Correlation between SFE and λ_s may be representative of disruptive effect of turbulence, but not exhaust mass reservoir for collapse.
    - Need full virial balance studies (e.g., Tilley & Pudritz 2004, 2005; Dib et al. 2007), but correlating with SFE.
  - Moreover, all these studies have been in closed boxes. A certain lifetime for the clouds has to be *assumed*.
    - Cloud lifetimes need to be assessed to understand SFE.

➔ Cloud evolution studies.

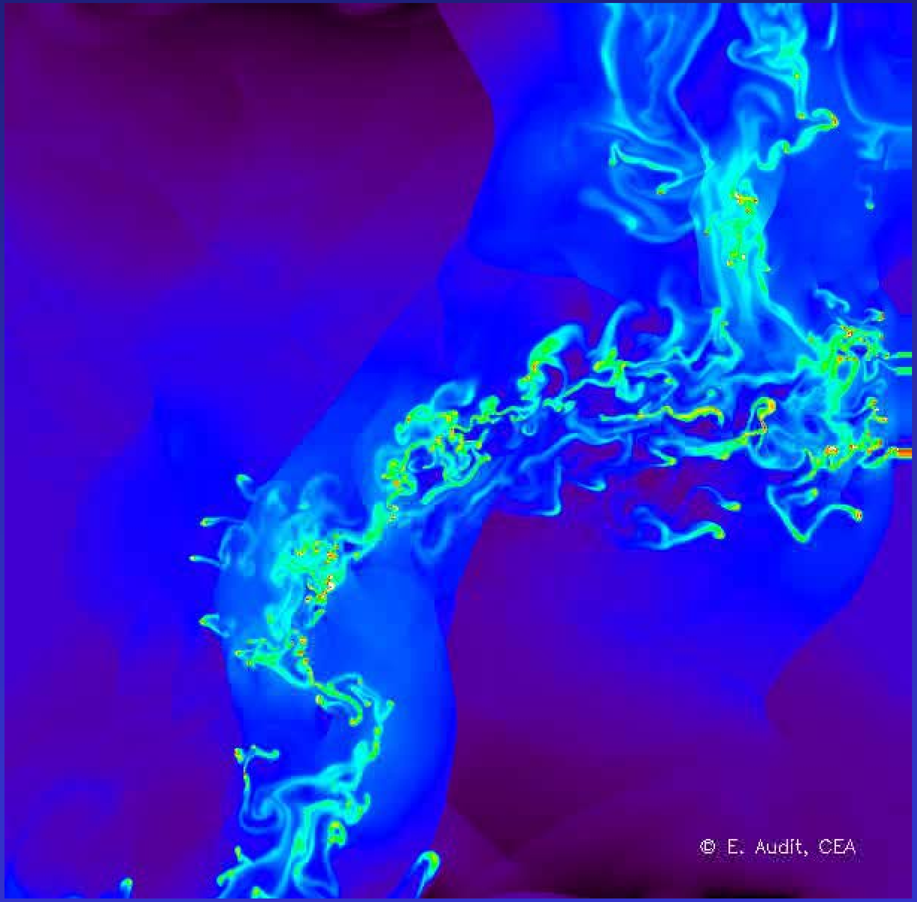
III. MC FORMATION AND EVOLUTION (“BRIEF” SF?)

- Some key questions in MC evolution:
  - How do they form?
    - Large-scale instabilities mainly? (Mac Low and Ostriker talks)
    - Cooling and thermal instability are essential (Hennebelle & Pérault 1999, 2000; Koyama & Inutsuka 2000, 2002; Heitsch et al. 2005, 2006; Audit & Hennebelle 2005, 2007; Vázquez-Semadeni 2006, 2007).
      - Can trigger turbulence with transonic compressions.
  - How do they get their turbulence and how long is it driven?
  - How long do they live?

- Two kinds of models for driving/lifetime of GMCs:
  1) Turbulence “built in” from formation mechanism from diffuse atomic ISM (Vishniac 1994; Walder & Folini 2000; Koyama & Inutsuka 2002, 2004; Audit & Hennebelle 2005; VS et al. 2003, 2006; Heitsch et al. 2005, 2006).
     -- ***Natural*** way of driving turbulence (including duration).



Koyama & Inutsuka 2002

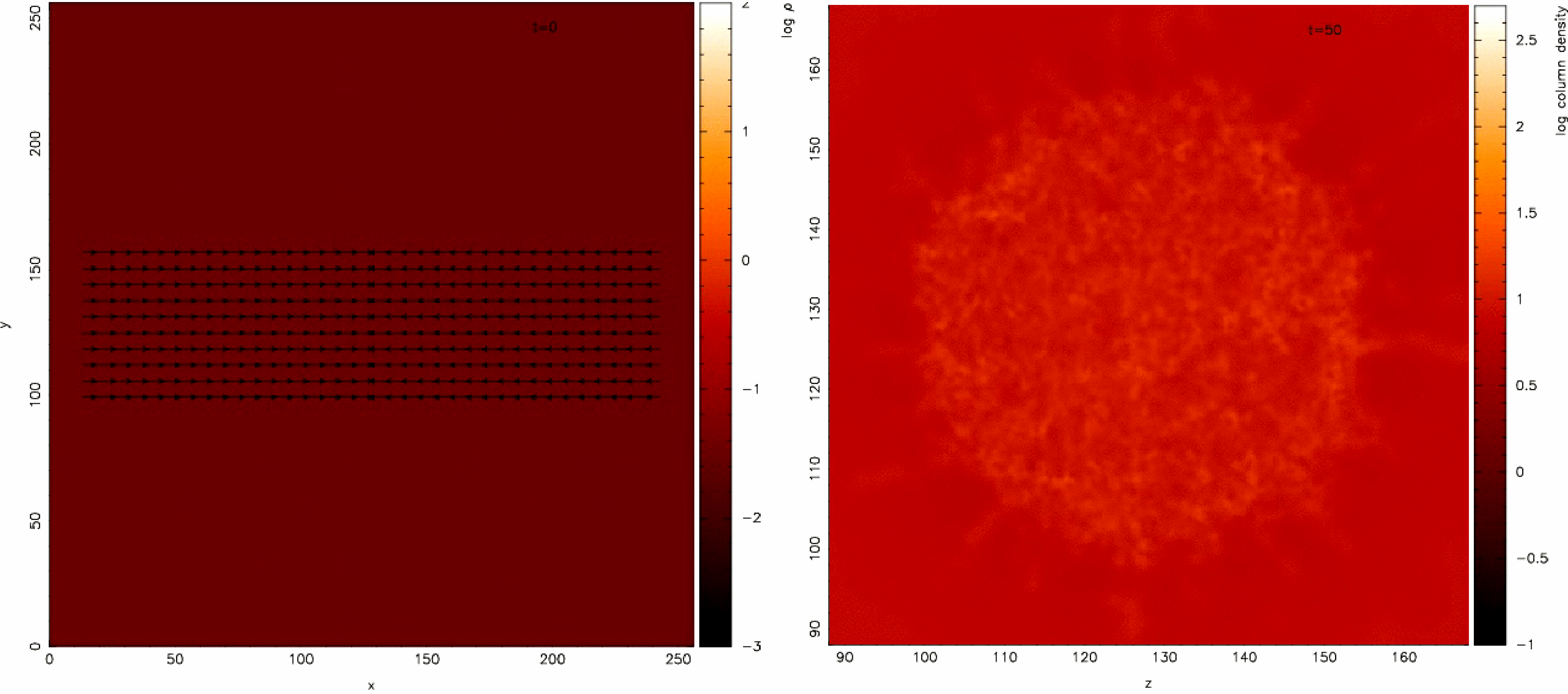


Audit & Hennebelle 2005

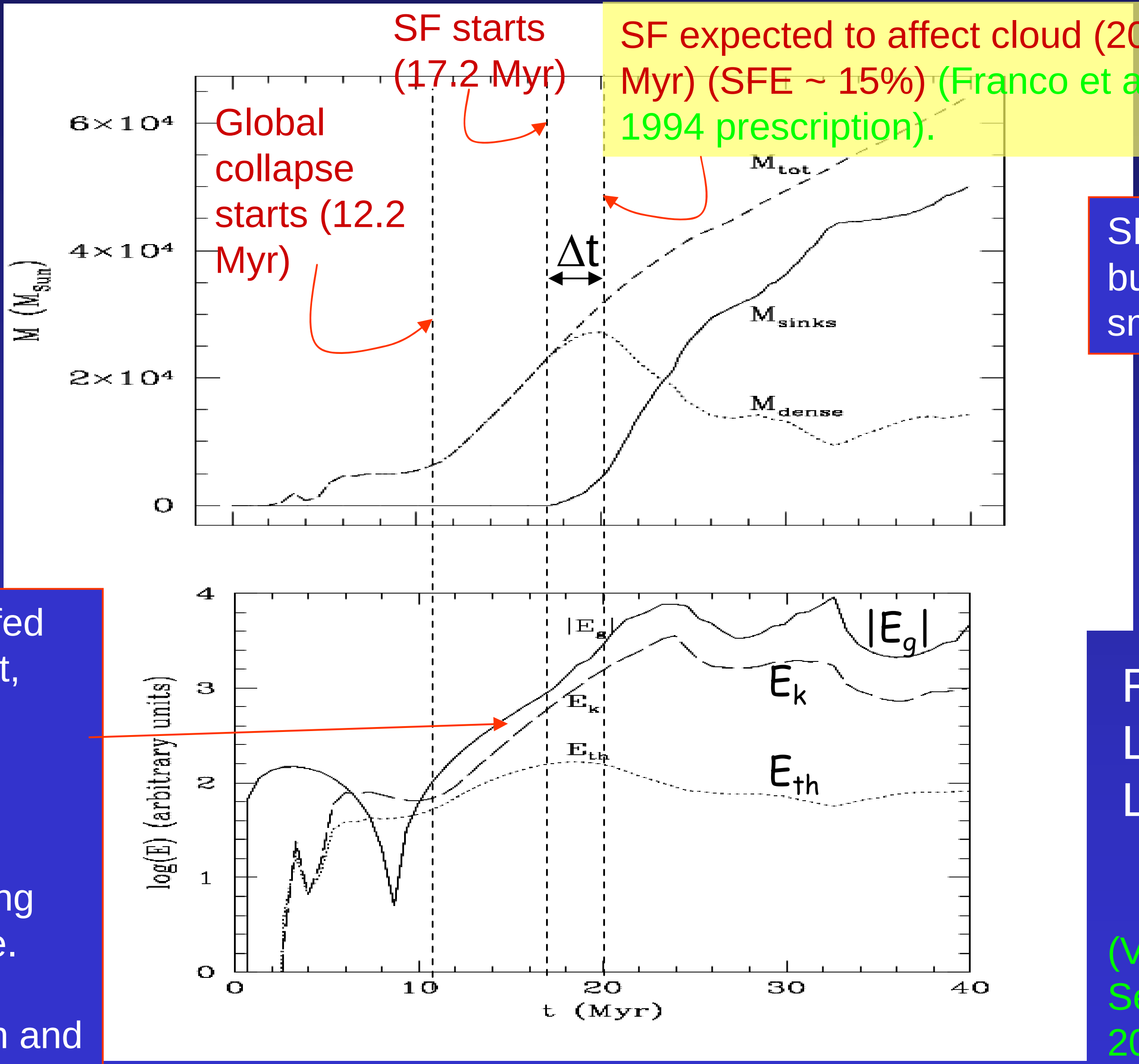
- SF proceeds rapidly and briefly (Ballesteros-Paredes et al. 1999;Elmegreen 2000; Hartmann et al. 2001).

- E_{kin} at later times driven by gravity (Hartmann & Burkert 2007; VS et al. 2007).

- Clouds probably dispersed shortly after SF episode (e.g., Whitworth 1979;Franco et al. 1994; Hartmann et al. 2001; VS et al. 2007; Elmegreen 2007).



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



Global collapse starts (12.2 Myr)

SF starts (17.2 Myr)

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

SFR not small, but Δt may be small.

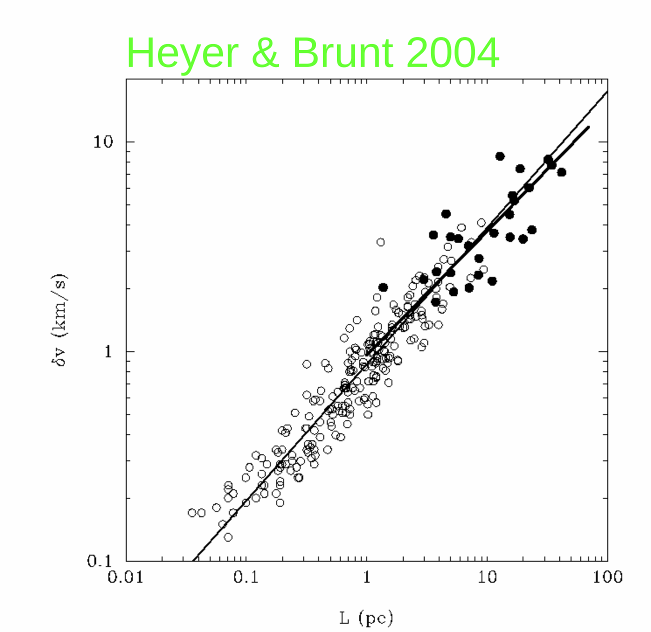
Turbulent E_{kin} fed by collision first, then by gravitational contraction.

Turbulent driving decays on time. Intermediate between driven and decaying.

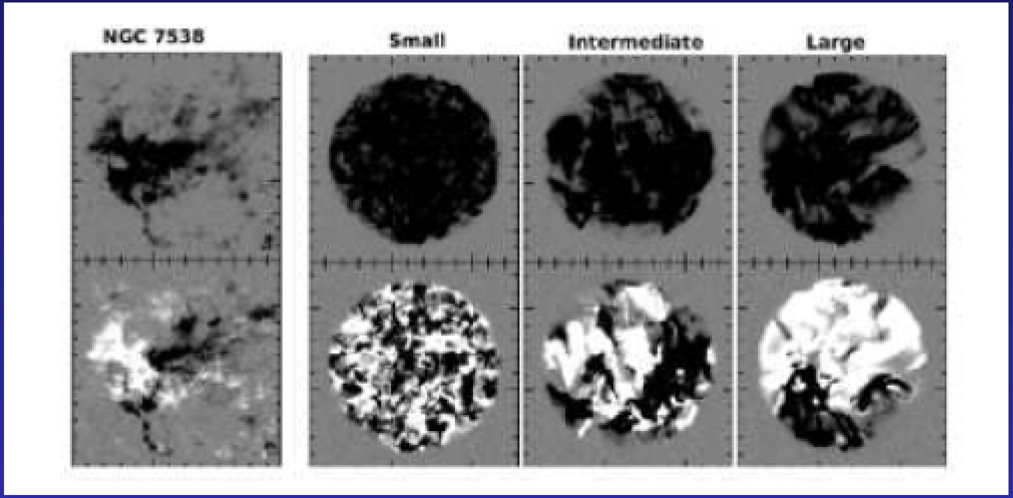
Run with:
L_{box} = 256 pc,
L_{inf} = 112 pc

(Vázquez-Semadeni et al. 2007)

– (Indirect) evidence in favor of externally-driven turbulence:


Heyer & Brunt 2004

a) A universal scaling law, independent of SF activity.

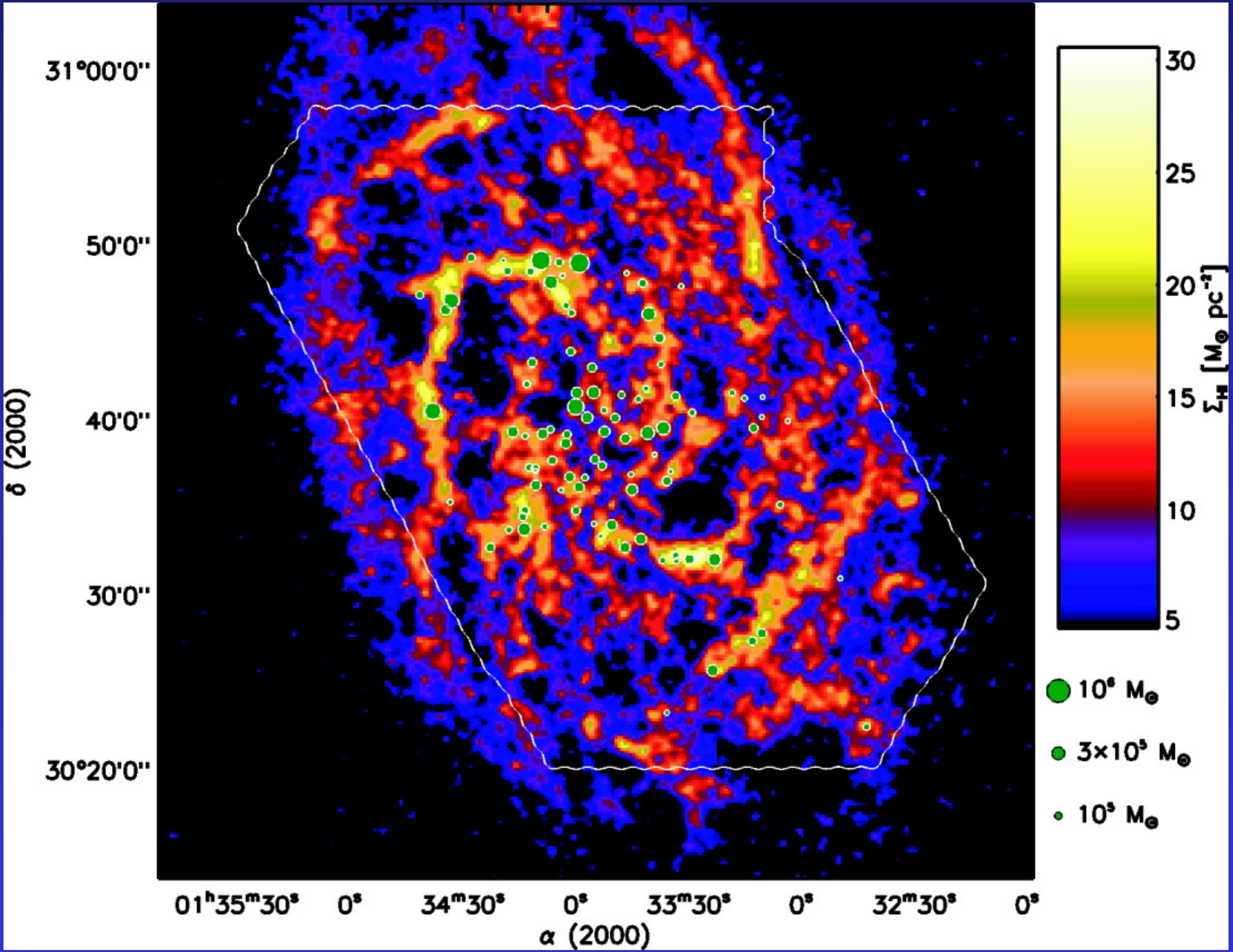


Heyer & Brunt 2007

b) A universal “dipole” large-scale mode. Consistent with “driving from the outside”.

- Suggest a (turbulent?) cascade from larger scales.
- No decay?

c) GMCs are not isolated, but rather the “tip of the iceberg” (or the “white caps”) of the galactic density distribution (e.g., Blitz et al. 2007, PPV).



Engargiola et al. 2003: Study of M33

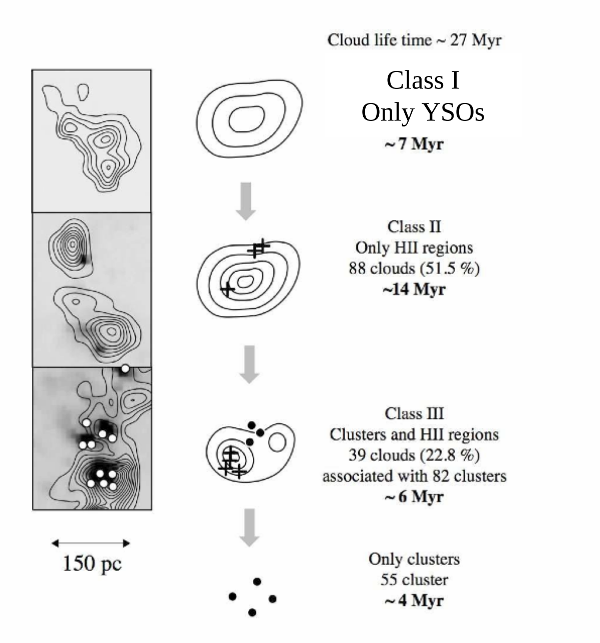
Color image: HI distribution

Circles: CO

They conclude that GMCs ***form*** out of the HI.

➔ GMC dynamics are part of global ISM dynamics.

- Two kinds of models for driving/lifetime of GMCs (cont'd):
  - 2) From stellar feedback (Whitworth 1979; McKee 1989; Matzner & McKee 1999; Matzner 2002; Krumholz et al. 2006; Nakamura & Li 2007; Nakamura's talk).
    - – SF may proceed slowly over relatively long times (Palla & Stahler 2000, 2002; Krumholz & Tan 2006).
  - (Indirect) evidence in favor of internally-driven turbulence:



Blitz, Fukui, et al 2007, PPV

Apparently long lifetimes (25-30 Myr) of GMCs in external galaxies.

BUT: "GMCs are probably ***not*** in virial equilibrium":

- highly filamentary
- not very centrally concentrated

- But are clouds supported or disrupted by stellar feedback?
    - Evidence in favor of quick cloud dispersal:
        - Clusters older than ~5-10 Myr are usually devoid of gas (Leisawitz et al. 1989; Fukui et al. 1999).

Observed in simulations with HII-region like driving:

J. BALLESTEROS-PAREDES 2004

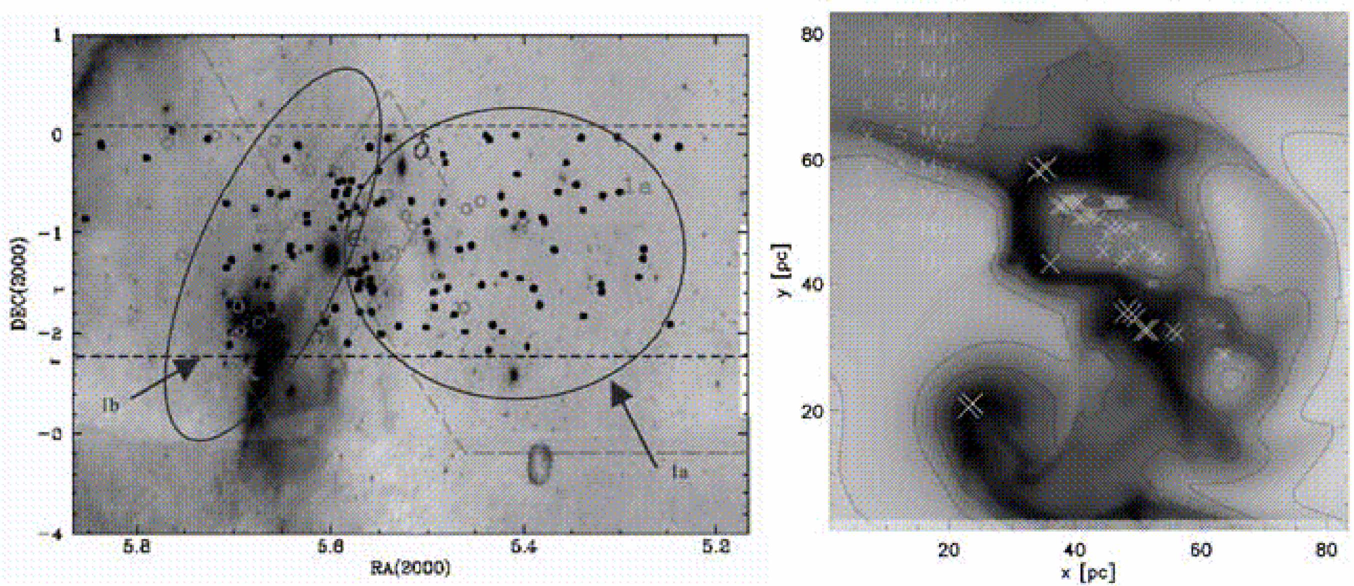
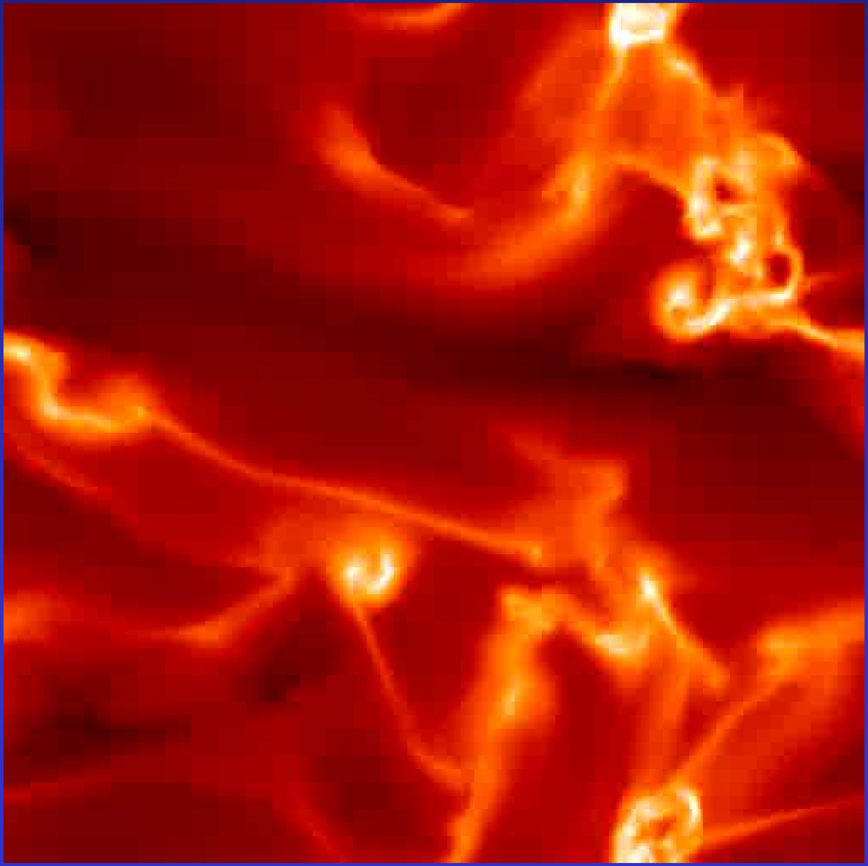


Figure 1. a. Orion OB1 association. b. Cloud in simulations from (Passot et al., 1995). Note that stars of more than 5 Myr old are 10 pc or more far from the dense gas. The simulation was not intended to reproduce the particular behavior of Orion.

Gas pushed sideways from SF regions.

- Stellar-driven “equilibrium GMC” concept may operate in an averaged sense over sufficiently large volumes.
    - Locally clouds can be dispersed, but globally GMCs may “persist”.



L= 1 kpc
Δt = 50 Myr
Including: self-gravity,
B, HII-like feedback.

A multi-timescale process
(Elmegreen 2000).

Passot, et al. 1995

- # CONCLUSIONS

  - Turbulence provides an effective filter for the mass that can collapse in a MC.

  - SFE levels below 10% over times ~ τ_{ff} (“slow SFR”) can be obtained *in closed boxes* with either

    - Stationary supersonic turbulence in magnetically supercritical clouds.
    - Decaying turbulence in moderately magnetically subcritical clouds.
    - Perhaps reality in intermediate, gradual decay regime?

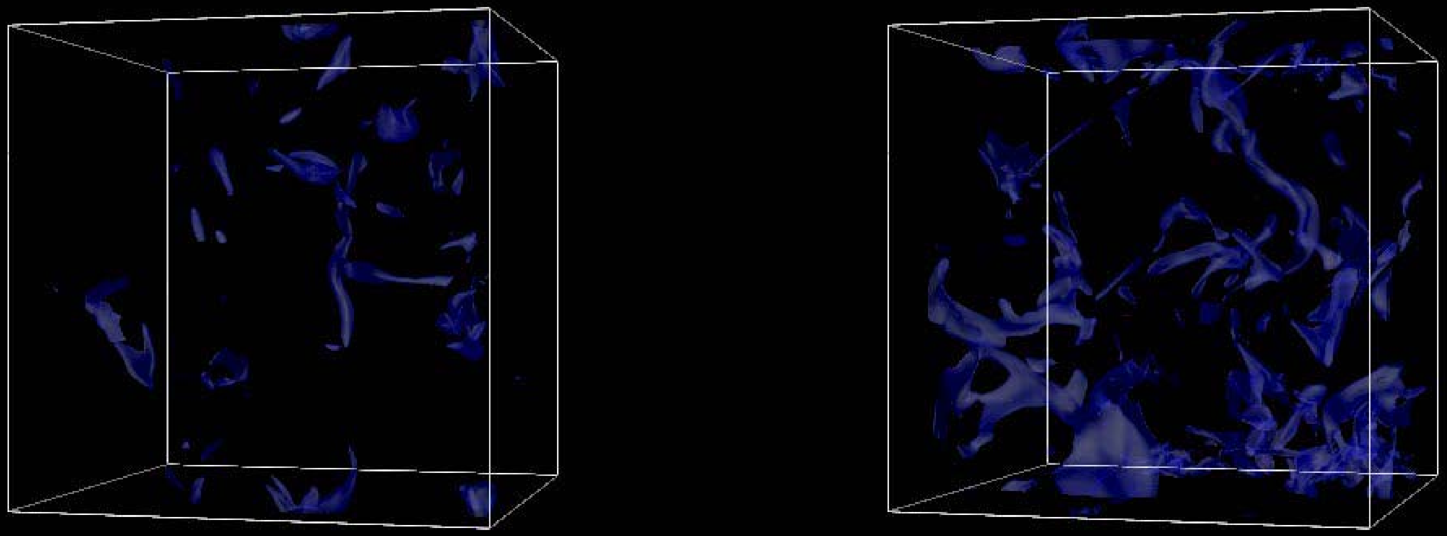
  - Super Jeans-, subsonic-fraction model of “mass filtering” for collapse explains low SFE.

- However:
  - Subsonic, super-Jeans model may possibly miss part of the total mass involved in collapse.
  - Effect of turbulent Mach number and magnetic field strength depend on nature of turbulence (driven or decaying).
  - Numerical models of cloud *and* star formation suggest
    - Turbulence from formation mechanism (at least initially).
    - *SFR may be not so small*,
      - but *then need brief Δt* (due to SF feedback?)
  - All models ***assume*** a cloud lifetime
    - Longish Δt for slow SFR.
  - Observations suggest turbulence driven from the outside of clouds.
    - Rather than from stellar feedback?
    - Does stellar feedback then disrupt parent clouds?

- Need:
  - Studies of cloud evolution+SFE including stellar feedback and magnetic fields in open boxes to determine:
    - Determination and evolution of clouds’ physical parameters.
    - Mechanism and duration of turbulence driving.
    - Duration of SF episodes as a function of scale size.
    - Role of magnetic fields.

The End

- Additional result: Magnetically supercritical case produces fewer but more massive collapsed objects than non-magnetic case.

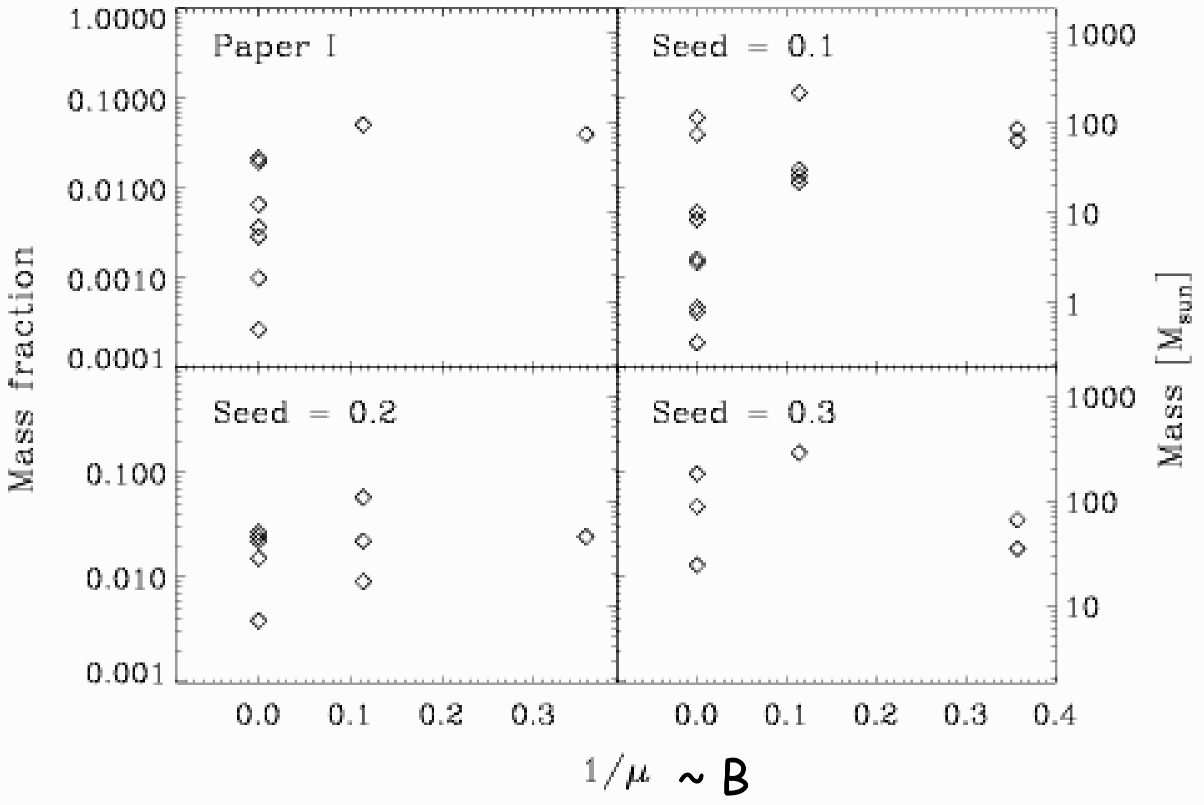


3D MHD, moderately supercritical, $\mu = 2.8$

3D non-magnetic

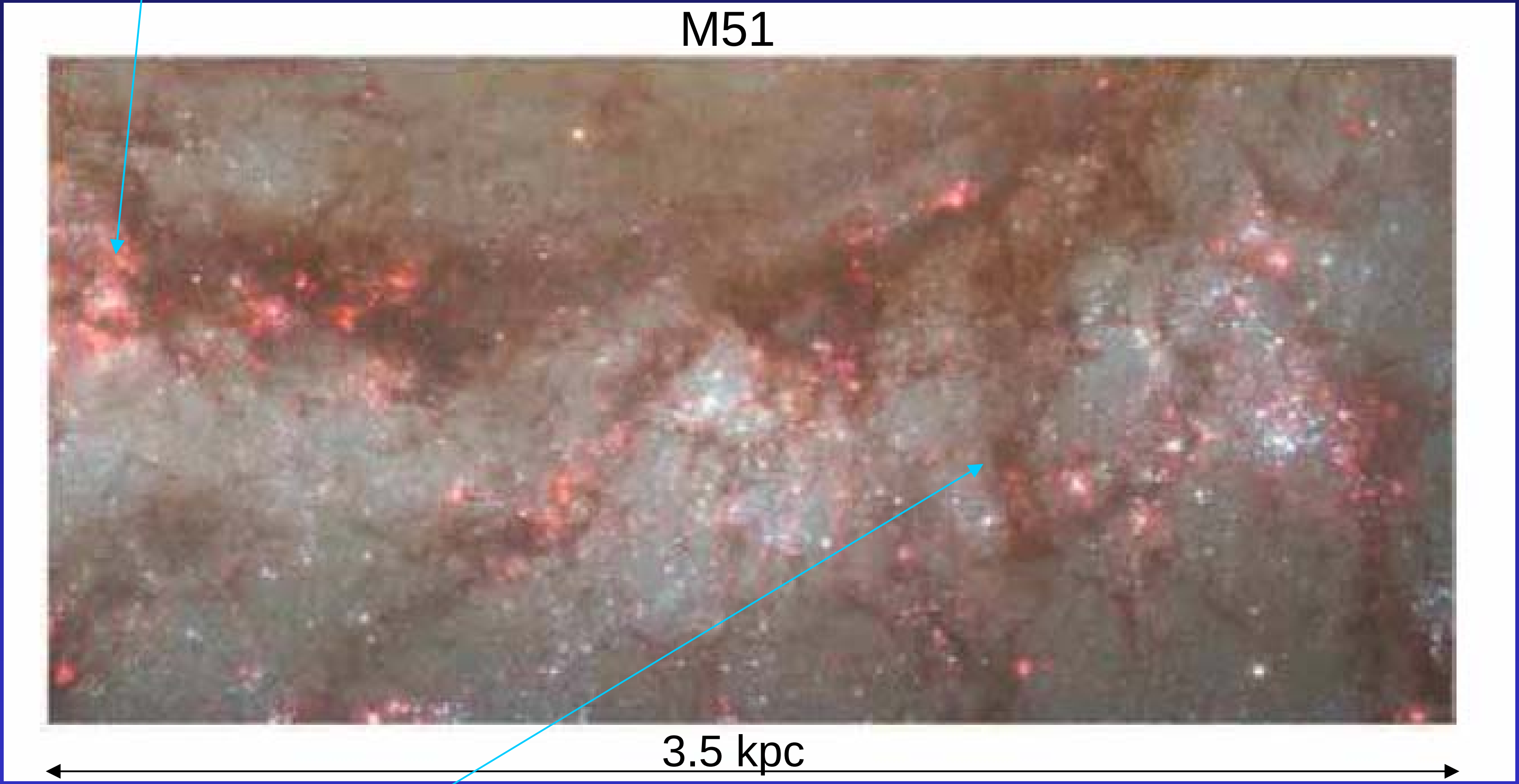
Vázquez-Semadeni, Kim, Shadmehri & Ballesteros-Paredes (2005)

Masses of collapsed objects vs. B ~ 1/μ



Vázquez-Semadeni, Kim & Ballesteros-Paredes (2005)

"Instantaneous" SF on the dust lane.



Shredded material and secondary SF behind arm.

Elmegreen 2007.

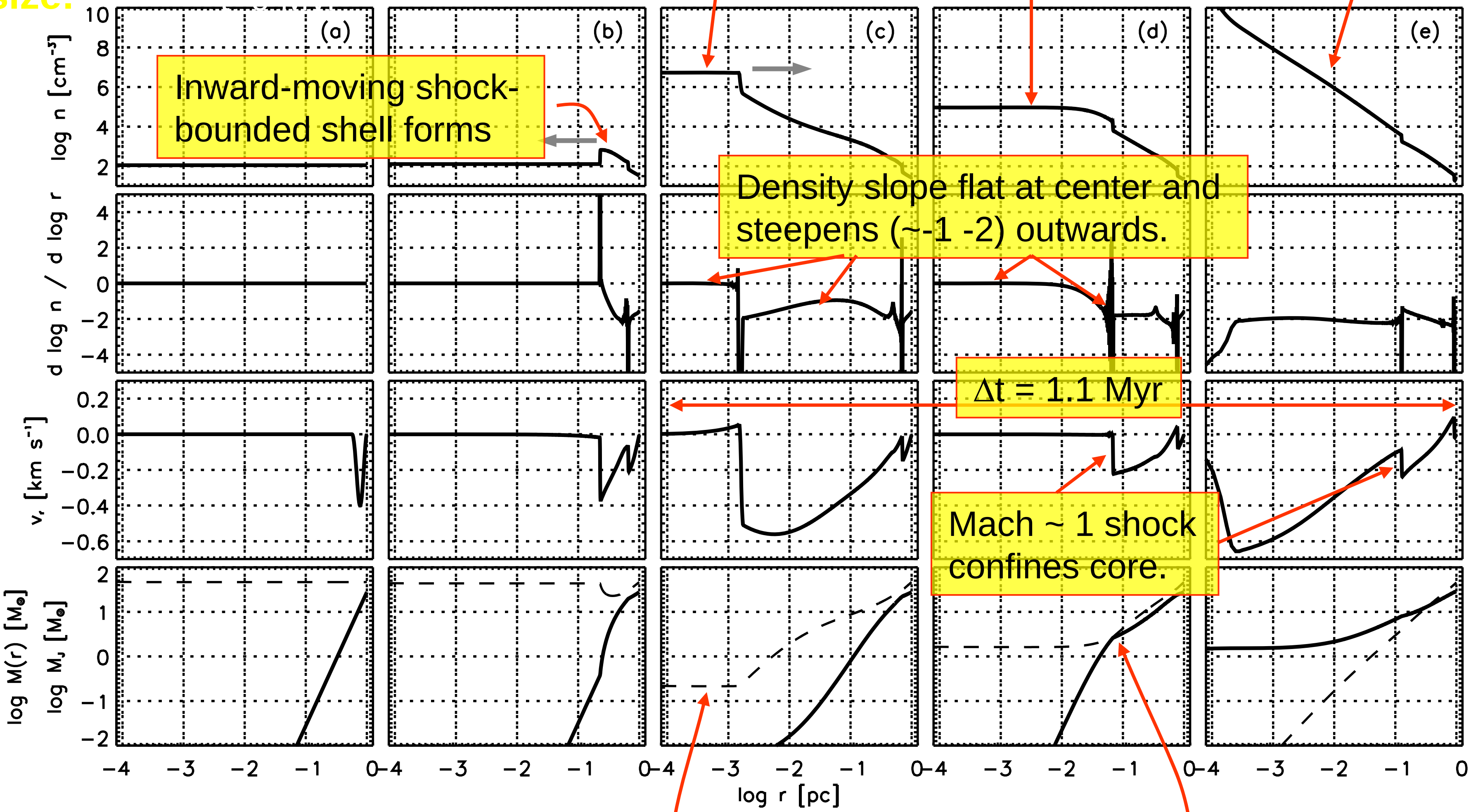
See also Ballesteros-Paredes & Hartmann 2007.

Compression forms central core that grows in mass and size:

Non-self-gravitating central core with high uniform density.

Self-gravitating central core with BE-like density profile.

Collapsed core, with SIS profile.



Inward-moving shock-bounded shell forms

Density slope flat at center and steepens (~-1 -2) outwards.

Δt = 1.1 Myr

Mach ~ 1 shock confines core.

t=0 Myr

t=1.125 Myr

t=1.525 Myr

t=2.0 Myr

t=2.625 Myr

Gómez et al. 2007, ApJ in press, arXiv/0705.0559

Jeans mass decreases in central dense core.

Core's mass catches up with Jeans mass.