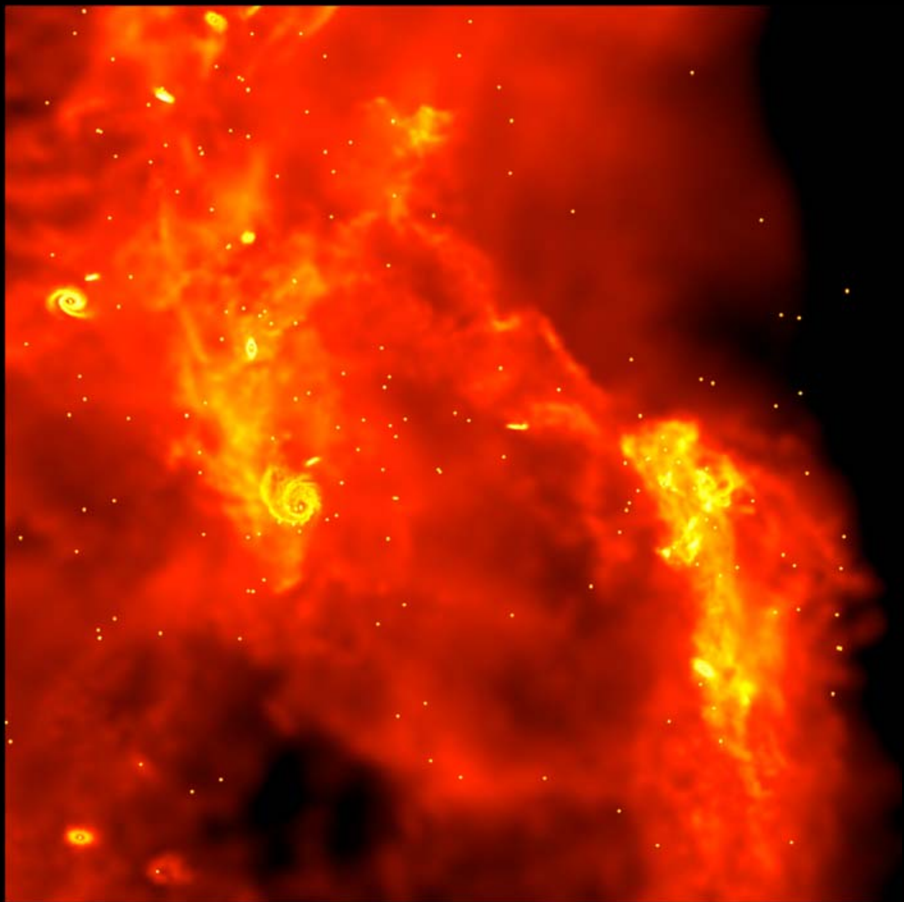
The Competitive Accretion Debate



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What is CA and how does it work?

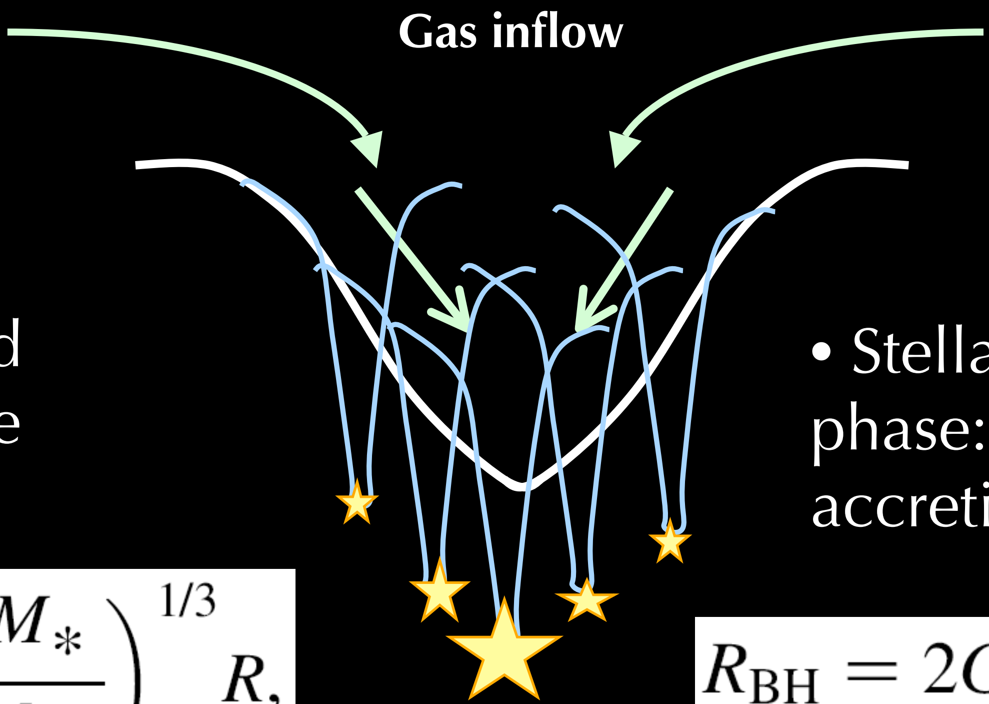
- Theory to help explain the form of the IMF, motivated by two properties of star formation:
  - Stars form in groups, (associations, clusters).
  - Clusters tend to be mass-segregated, perhaps from birth.

- Works by considering how much mass a newly formed star can accrete, over and above the mass which went into collapse to produce it.

Accretion and the IMF…

Accretion rate: $\dot{M}_* = \pi \rho V_{\rm rel} R^2_{\rm acc}$

Zinnecker (1982)
Bonnell et al (2001a,b)



• Gas dominated phase: tidal-lobe accretion,

$$R_{\rm tidal} \approx 0.5 \left(\frac{M_*}{M_{\rm enc}}\right)^{1/3} R,$$

• Stellar dominated phase: Bondi-Hoyle accretion,

$$R_{\rm BH} = 2GM_*/(V^2_{\rm rel} + c^2_{\rm s})$$

$dn/dm \propto m^{-1.5}$

$dn/dm \propto m^{-2.5}$

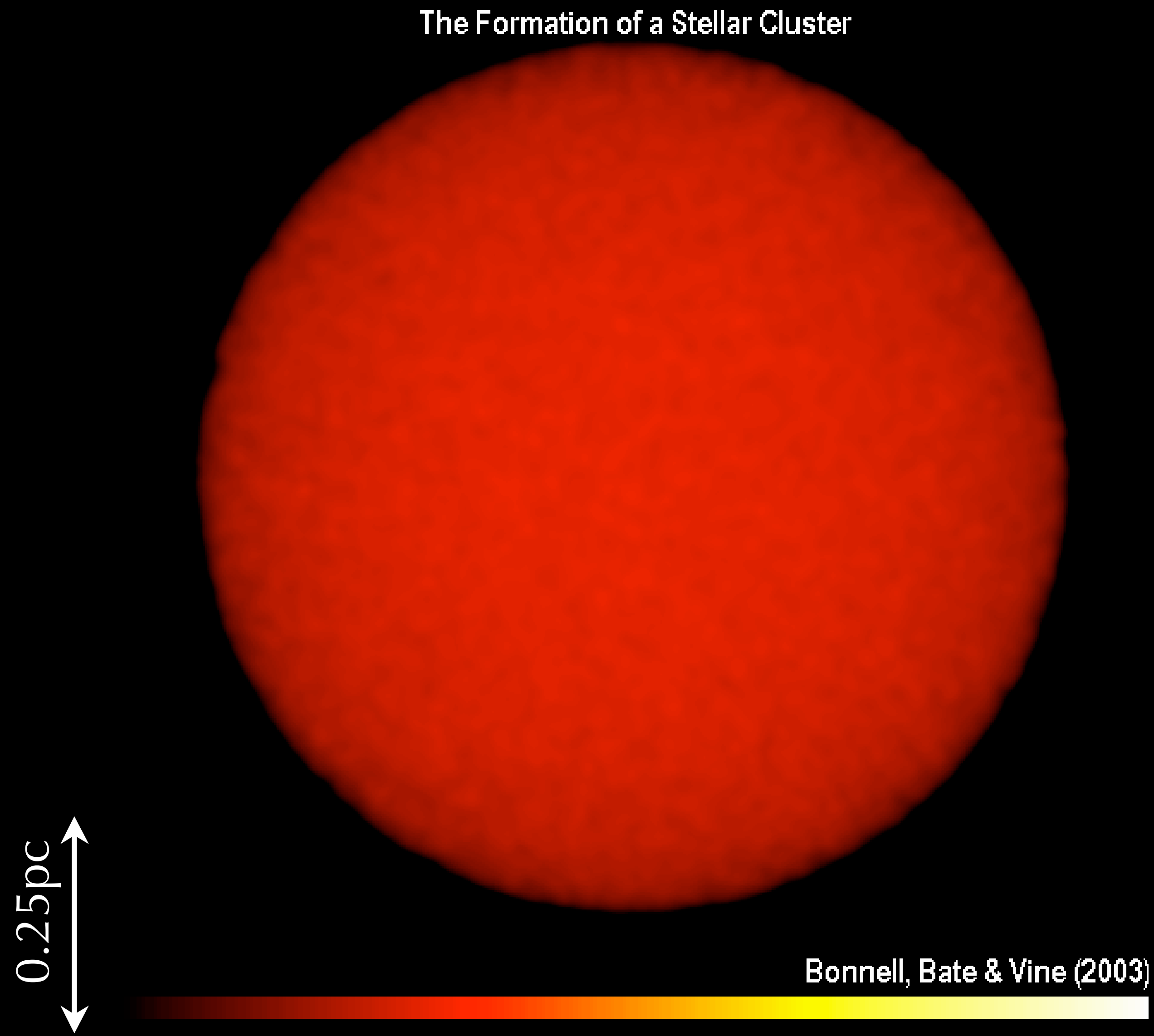
Hierarchical process…

- Hierarchical dissipation of turbulence
- Small scales loose support first:

$t_{disp} \sim t_{cross} \sim L/\sigma(L)$

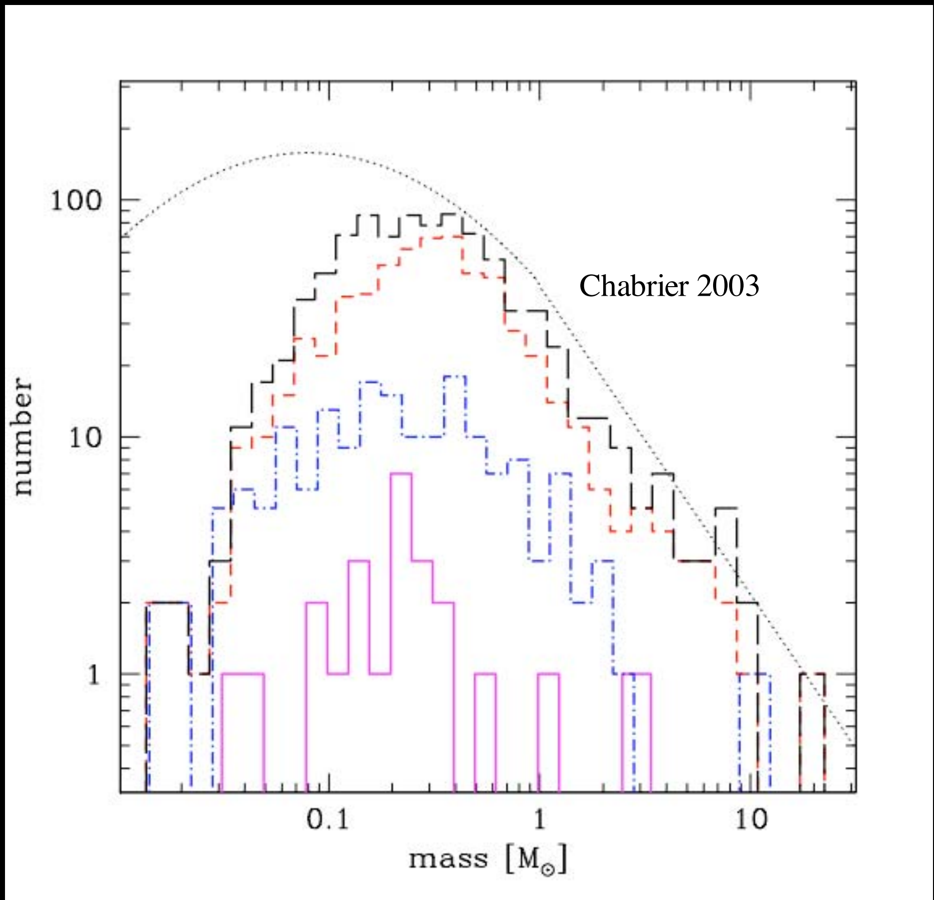
$t_{cross} \sim L^{0.5}$

- Followed by collapse of progressively larger regions

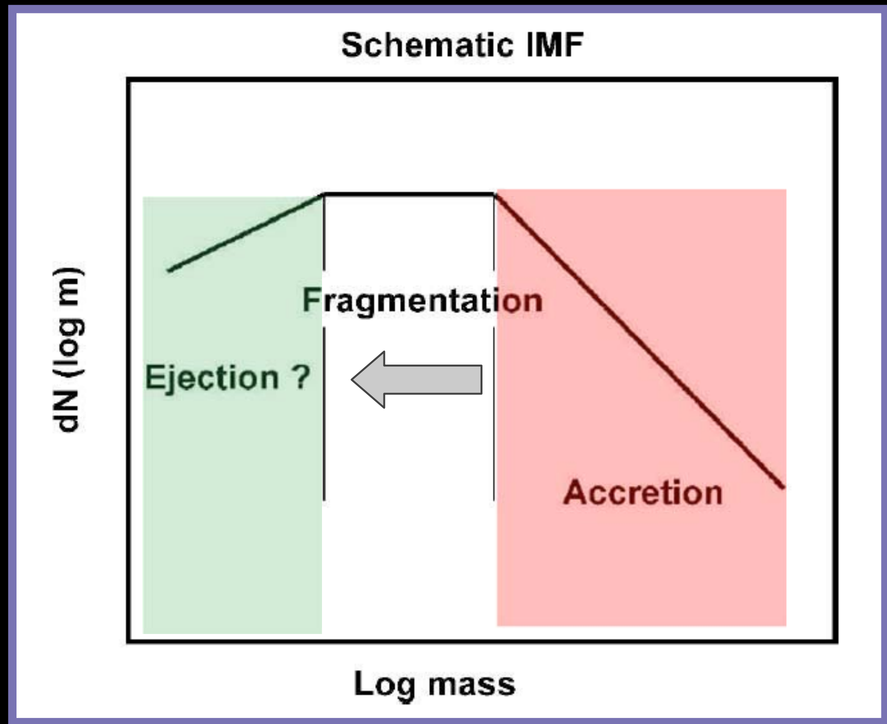


Features of the CA mass function

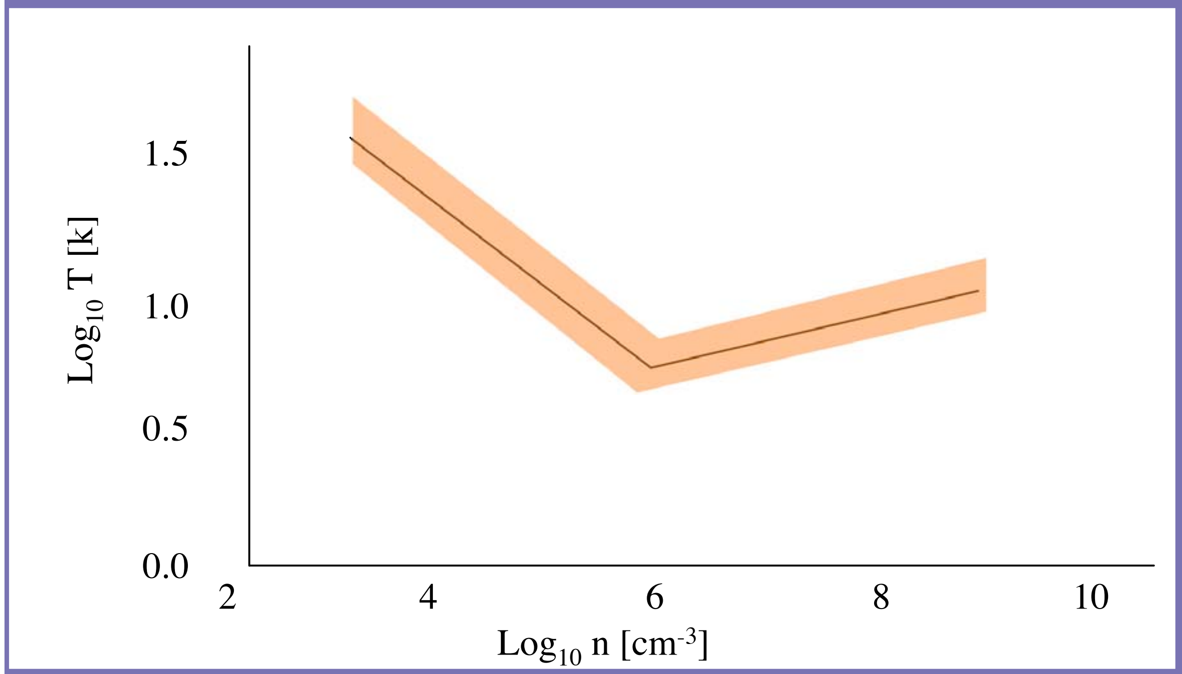
Grows in time



All mass bins are related



Sensitivity to cloud conditions….



Found that changing the initial Jeans mass in the set-up, alters the position of the 'knee' in the IMF.

Does competitive accretion really need such fine tuning?

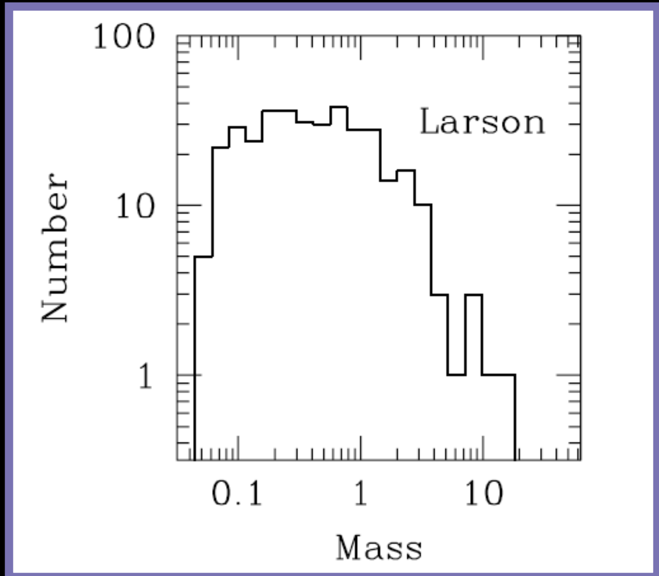
Larson (1985, 2005):

$T = 4.4\ (\rho\ /10^{-18})^{-0.27}$ K ,

$(\rho < 10^{-18}$ gcm$^{-3})$

$T = 4.4\ (\rho\ /10^{-18})^{+0.07}$ K ,

$(\rho > 10^{-18}$ gcm$^{-3})$

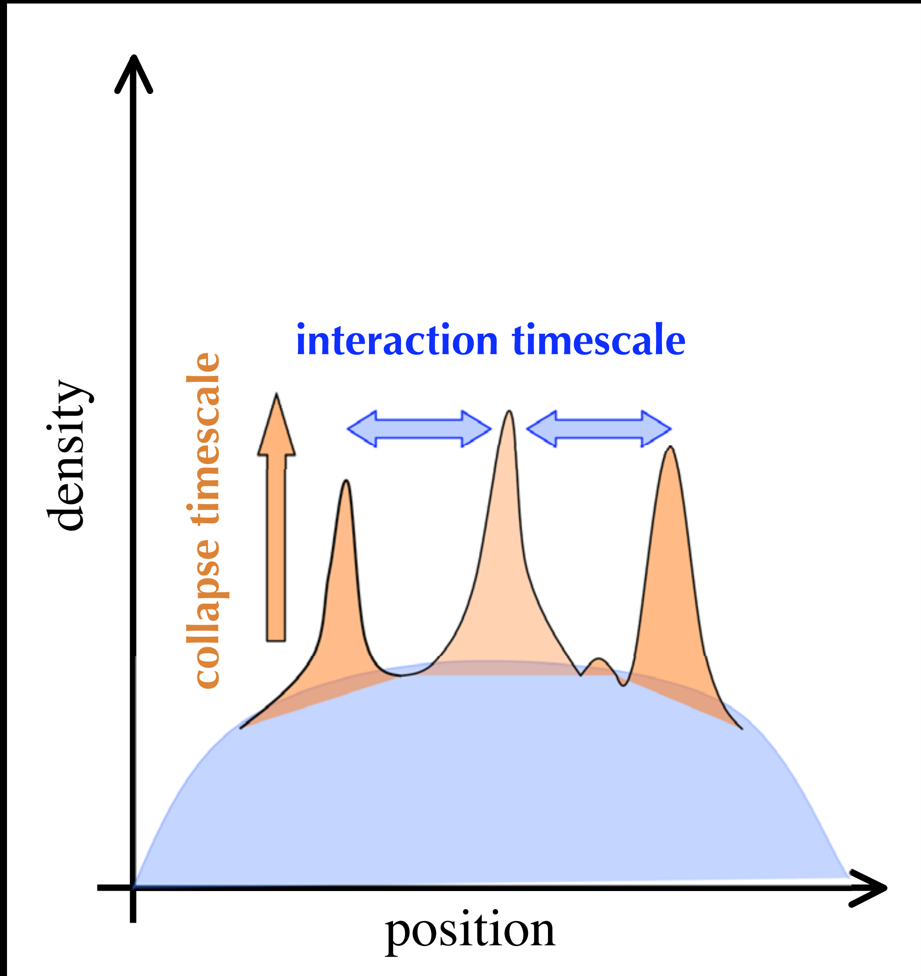


Conditions for CA (1)

- Competitive accretion requires a region in which the collapse timescale and interaction timescale are similar.
- If the clump densities and cloud density are roughly equal, then:

$$t_{inter} \sim t_{ff}$$

- Any region with multiple Jeans masses automatically satisfies this requirement.

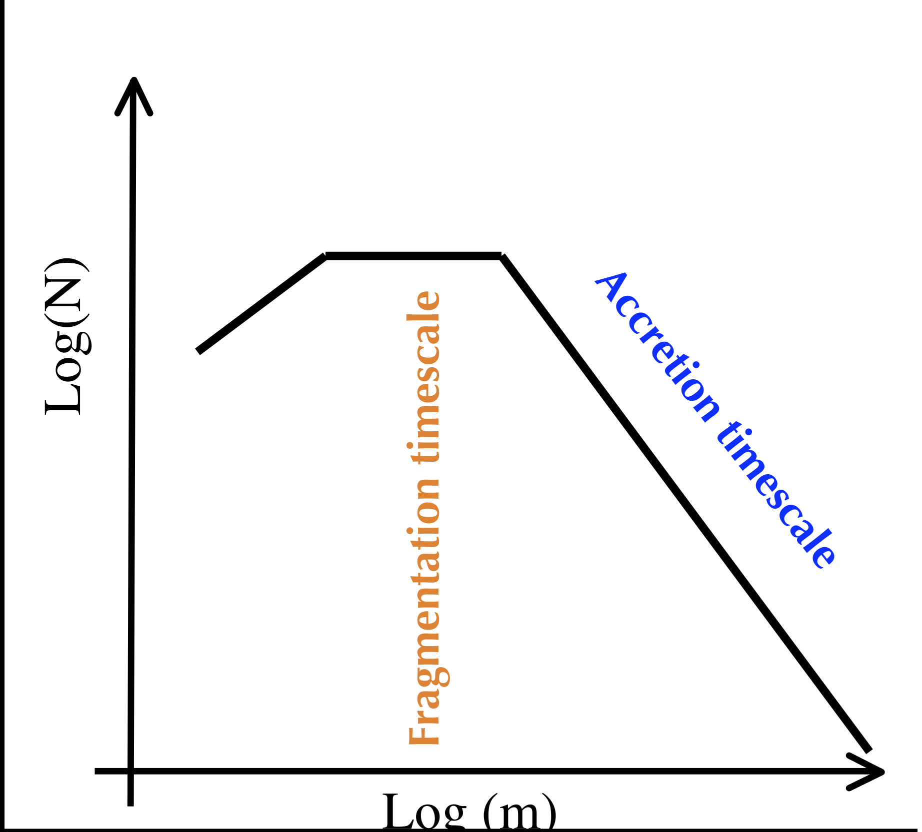


Conditions for CA (2)

- If the ratio of the mass above and below the Salpeter break is to remain the same, then:

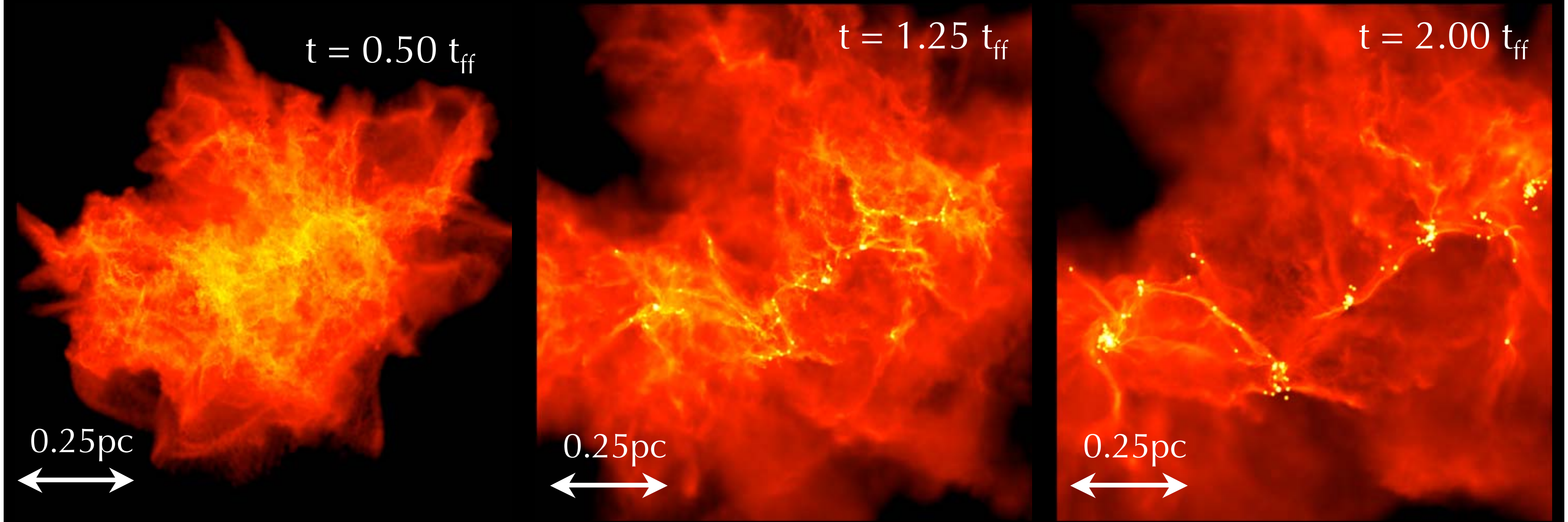
$$t_{frag} \sim t_{acc}$$

- Any region characterised by a common density, by which both fragmentation and accretion are dictated, satisfies this requirement.



Unbound clouds

KE = 2 × PE (initially), 1000 solar masses, 0.5pc



No global collapse:

local t_{ff} < global interaction time-scale

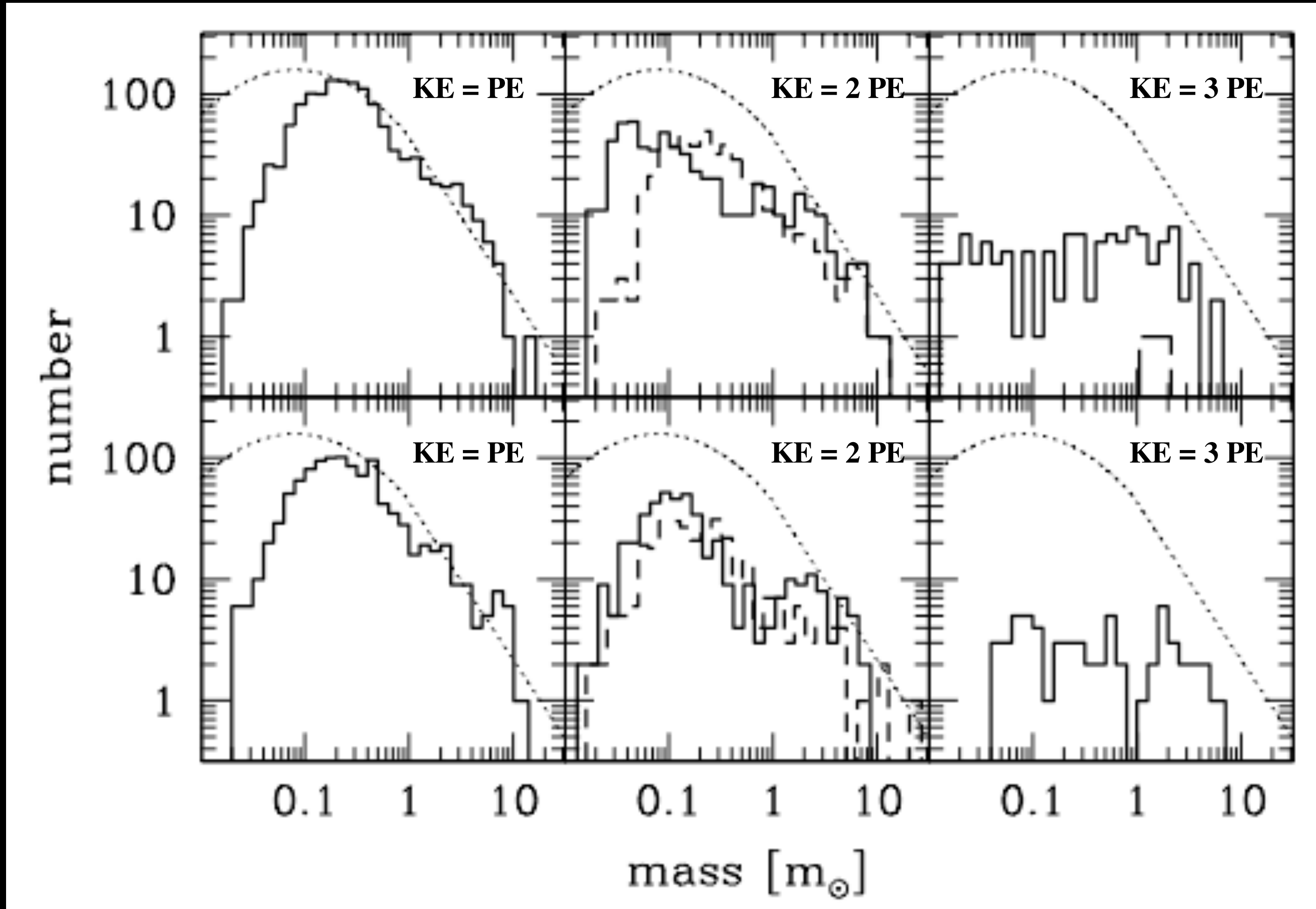
$t_{ff} \sim 2 \times 10^5$ years

Clark, Bonnell & Klessen (2007)

Mass functions?

Isothermal EOS

Barotropic, Larson (2005), Style EOS



RT! (without actually doing RT)

Fit (fudge) to MC models:

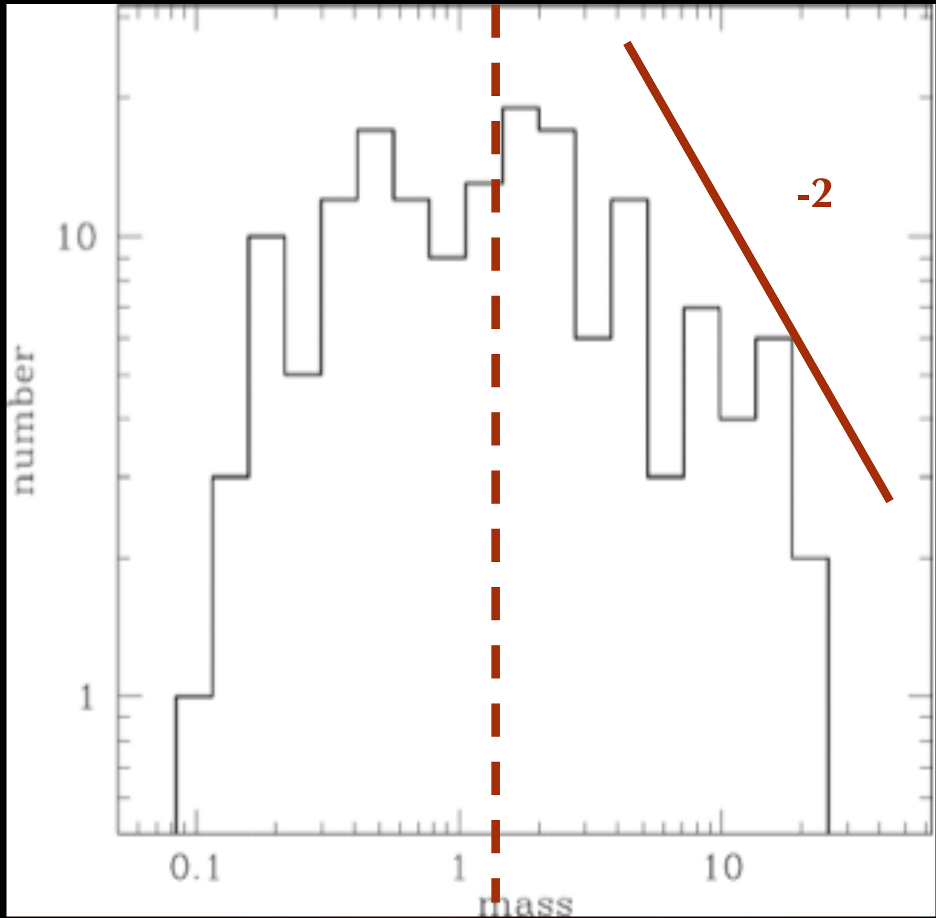
$$T = 100\text{K} \left(\frac{M}{10\ M_\odot}\right)^a \left(\frac{R}{1000\ \text{AU}}\right)^q$$

a: 0.33 $M_\odot < 10$

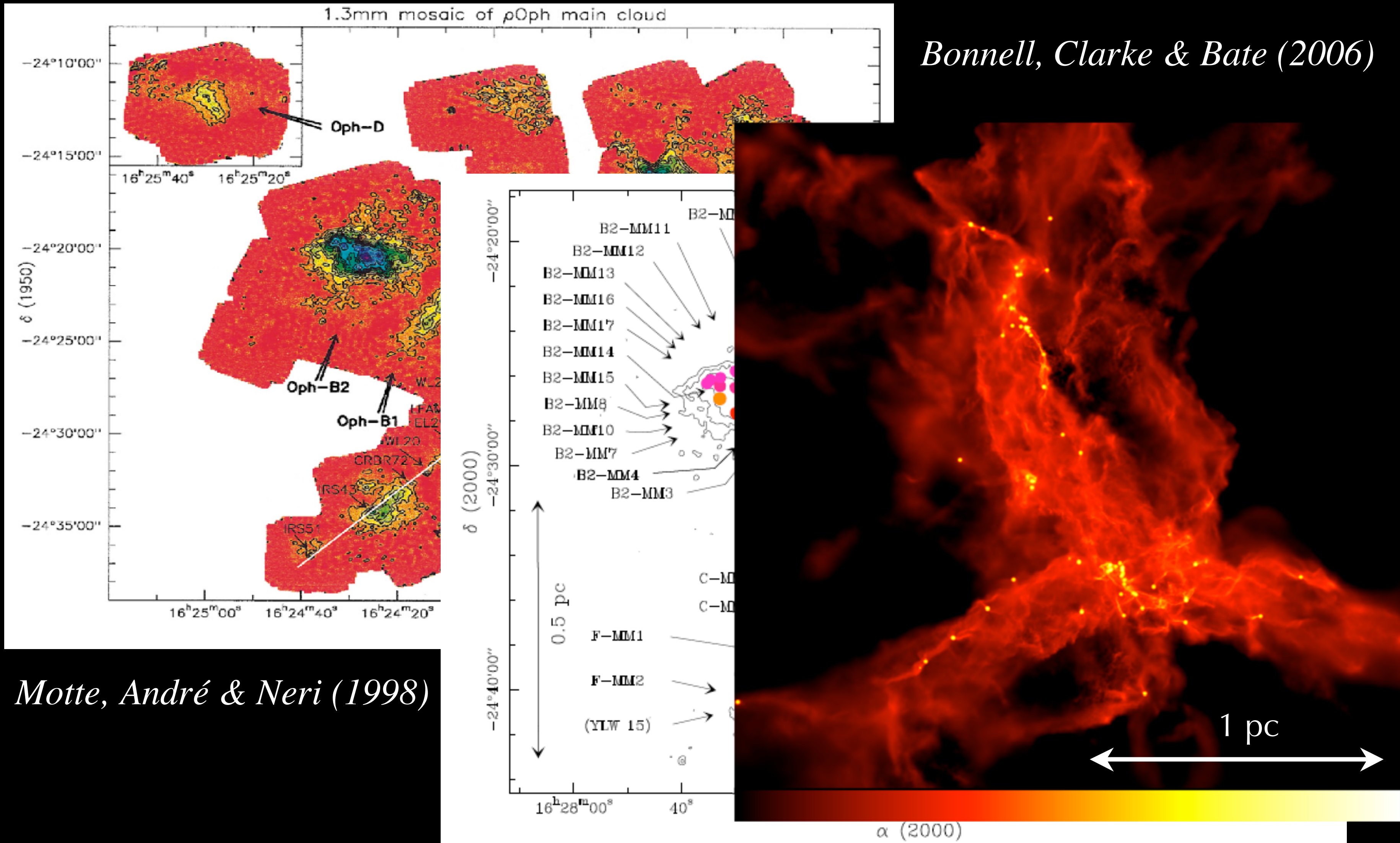
a: 1.1 $M_\odot > 10$

q: -0.4 to -0.5

Robitaille et. al. 2006



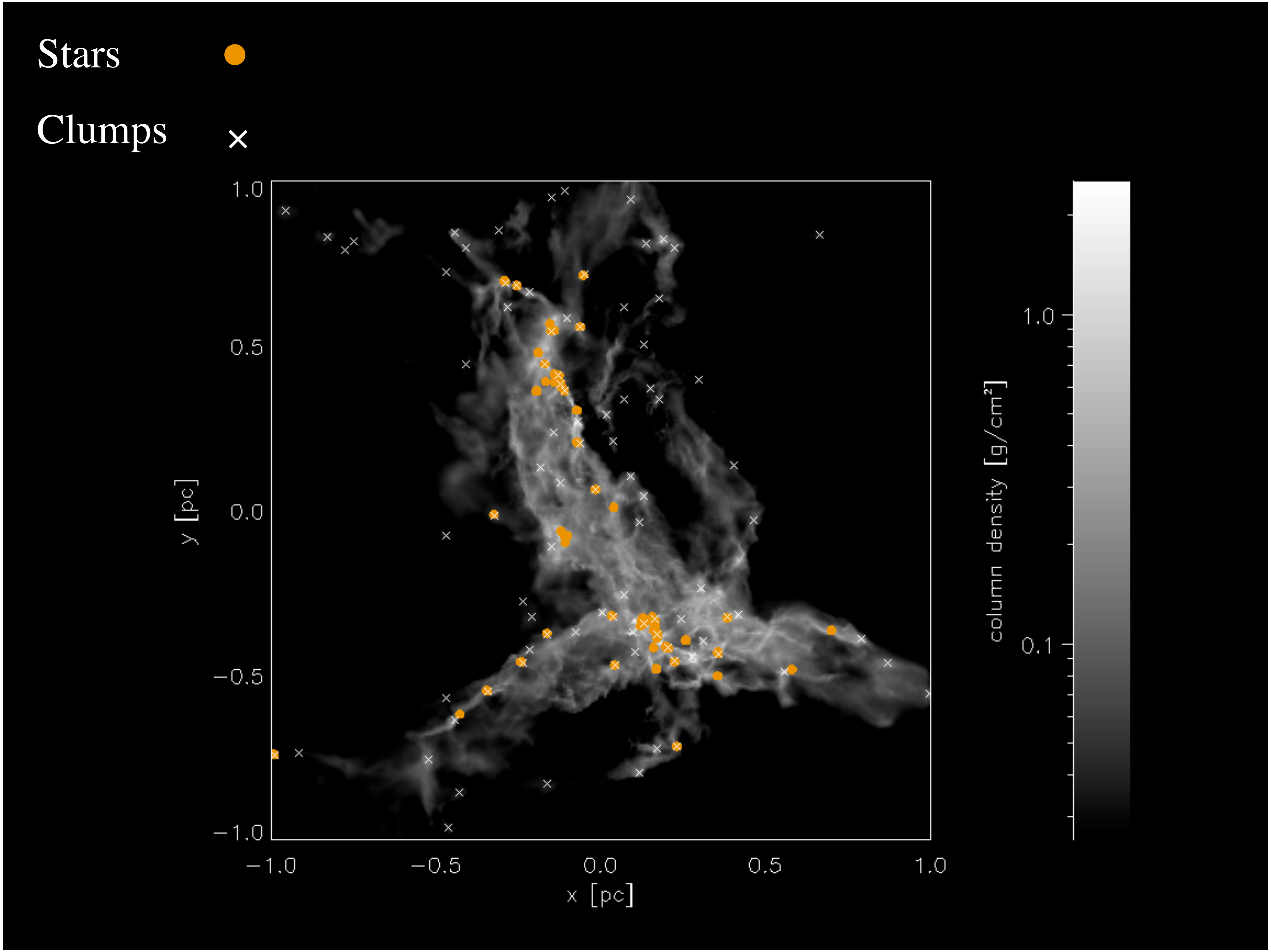
Observational tests?



Bonnell, Clarke & Bate (2006)

Motte, André & Neri (1998)

André et al. (2007)


Stars
Clumps
1.0
0.5
0.0
−0.5
−1.0
y [pc]
−1.0
−0.5
0.0
0.5
1.0
x [pc]
1.0
0.1
column density [g/cm²]

Clump mass functions

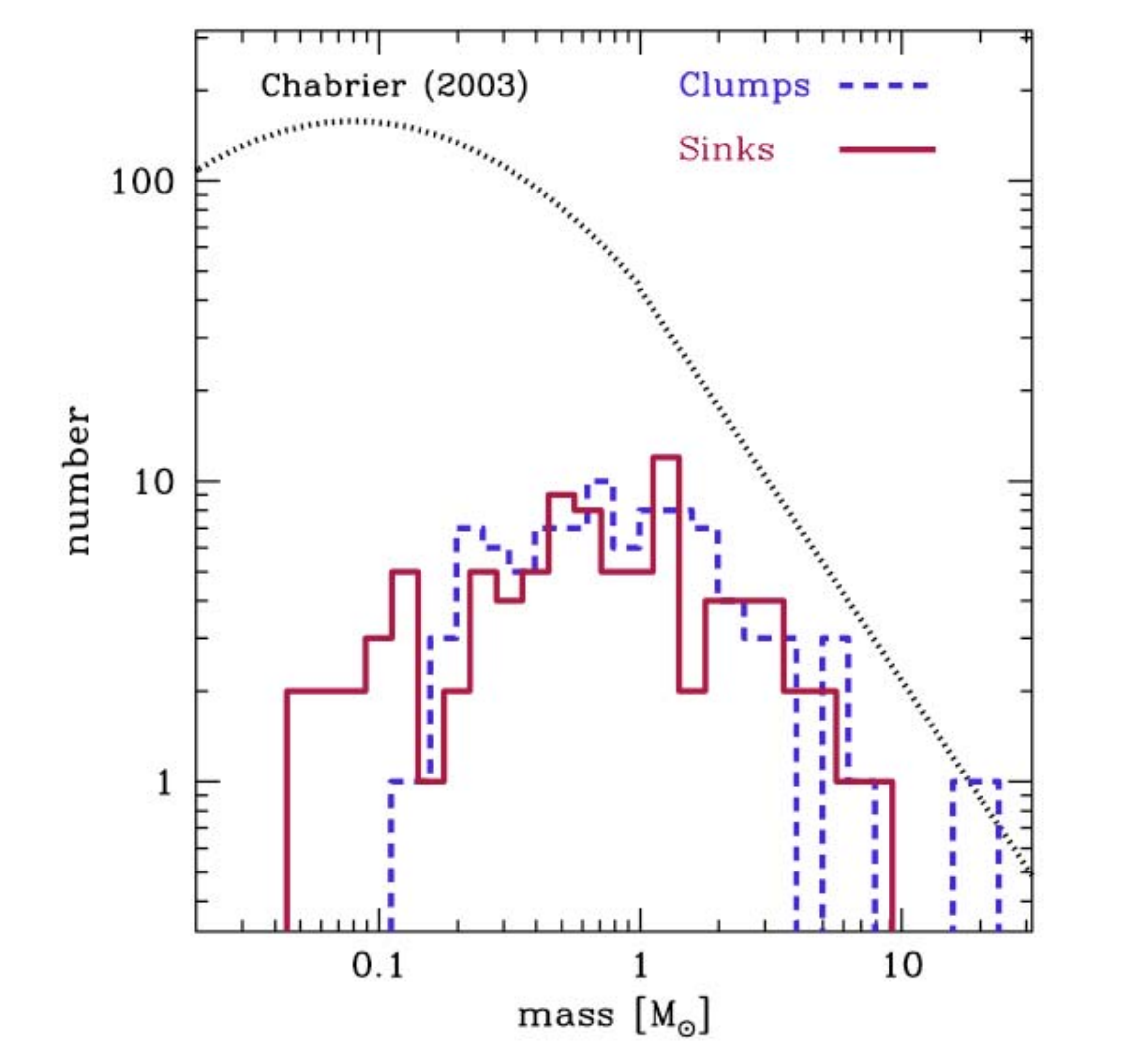
88 sink particles

SPH data mapped to a 2D grid with resolution ~1000 x 1000 au

Column densities limited to range 0.02- 2.00 cm^{-2}

Clumps required to have a density contrast of a factor 2 in column density

91 “sink-less” clumps



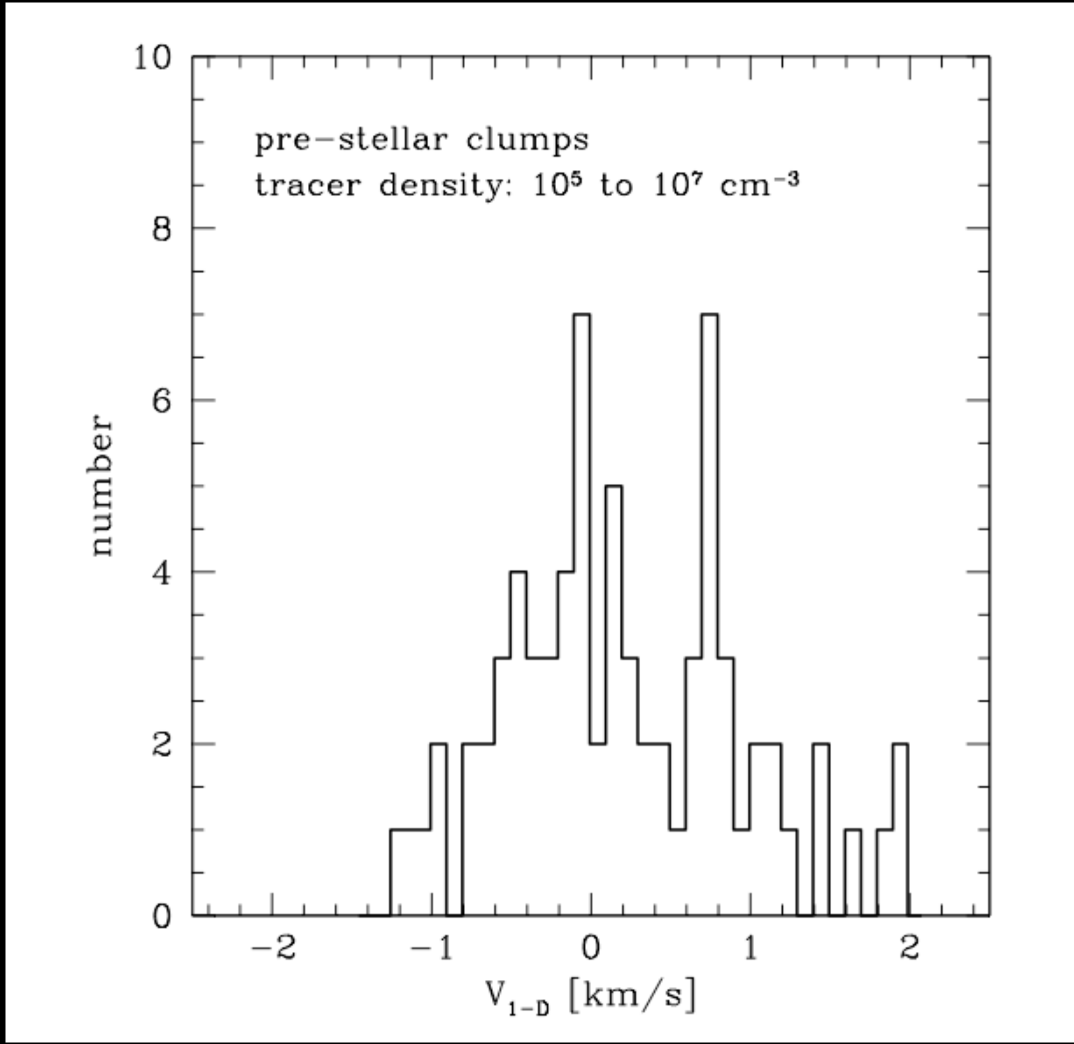
Clump velocity dispersions

Each cluster has it's own central velocity

Distribution around this velocity is ~ 0.25km/s, and the mean is only ~0.7 km/s for the whole region.

Typical of turbulent stagnation points (e.g Padoan et al 2001)

Similar velocities to *André et al (2007)*



Can you see competitive accretion?

André et al (2007):

• Used the

to estimate

interaction

• From Binn

(1987),

$$\frac{t_{coll}}{t_{cross}} = \frac{1}{2}\sqrt{\frac{\pi}{3}} \times \frac{R^2}{N_{cond}\, r_{cond}^2} \times \frac{1}{1+\Theta}$$

where,

$$1 + \Theta \equiv 1 + GM_{cond}/(\sigma_{1D}^2 r_{cond})$$

For the Bonnell et al (2006) cloud:

t_{cross} ~ 1.7Myr

t_{coll}/t_{cross} ~ 13.5

• Using (for L1688):

0.55pc

mps = 57

km/s

R_{cond} ~ 2500 AU

M_{cond} ~ $0.4 M_{\odot}$

t_{cross} ~ 1.78Myr

• Get time-scale ratio:

t_{coll}/t_{cross} ~ 9

Threshold for massive star formation?

- McKee and Tan (2003): $\Sigma_{crit} \sim 1 g/cm^2$

CHARACTERISTIC SURFACE DENSITIES OF REGIONS OF HIGH-MASS STAR FORMATION

Object	M ($M_\odot$)	$R_{1/2}$ (pc)	Σ ($\mathrm{g\ cm^{-2}}$)	$\bar{P}_{cl}/k$ ($\mathrm{K\ cm^{-3}}$)	References
Galactic star-forming clumps.......	3800[a,b]	0.5[b]	1.0	4×10^8	1
Orion Nebula Cluster..................	4600[a]	0.8	0.24	2×10^7	2
Arches cluster	2×10^4	0.4	4	7×10^9	3, 4
Galactic globular clusters............	2×10^5[a]	3.4	0.8	3×10^8	5, 6
NGC 1569 A1, A2.......................	4×10^5[a]	2.2	2.7	3×10^9	7, 8
NGC 5253..................................	$(0.6\text{–}1.5) \times 10^6$[c]	1.0	20–50	$(2\text{–}11) \times 10^{11}$	9

[a] Virial mass estimates.

[b] The half-mass radius is not well defined for the Plume et al. 1997 clouds, since the mass distribution on larger scales is not known. We therefore evaluate $\Sigma = M/\pi R^2$ using the typical radius and virial mass that they observe.

[c] Extrapolation from inferred Lyman continuum luminosity of H II region based on Salpeter IMF with a lower mass limit $m_\ell = 1, 0.1\ M_\odot$.

REFERENCES.—(1) Plume et al. 1997. (2) Hillenbrand & Hartmann 1998. (3) Figer et al. 1999. (4) Kim et al. 2000. (5) Binney & Merrifield 1998. (6) van den Bergh et al. 1991. (7) Gilbert & Graham 2001. (8) de Marchi et al. 1997. (9) Turner et al. 2000.

Conditions required by CA

- In CA calculations, roughly 500 $M_\odot$ gas accreted before massive star (8-10 $M_\odot$) is formed.

$$f_{sfe} = \frac{M_*}{M_* + M_{gas}} = \frac{M_*}{M_{clump}}$$

$$M_{clump} = M_* \,/\, f_{sfe}$$

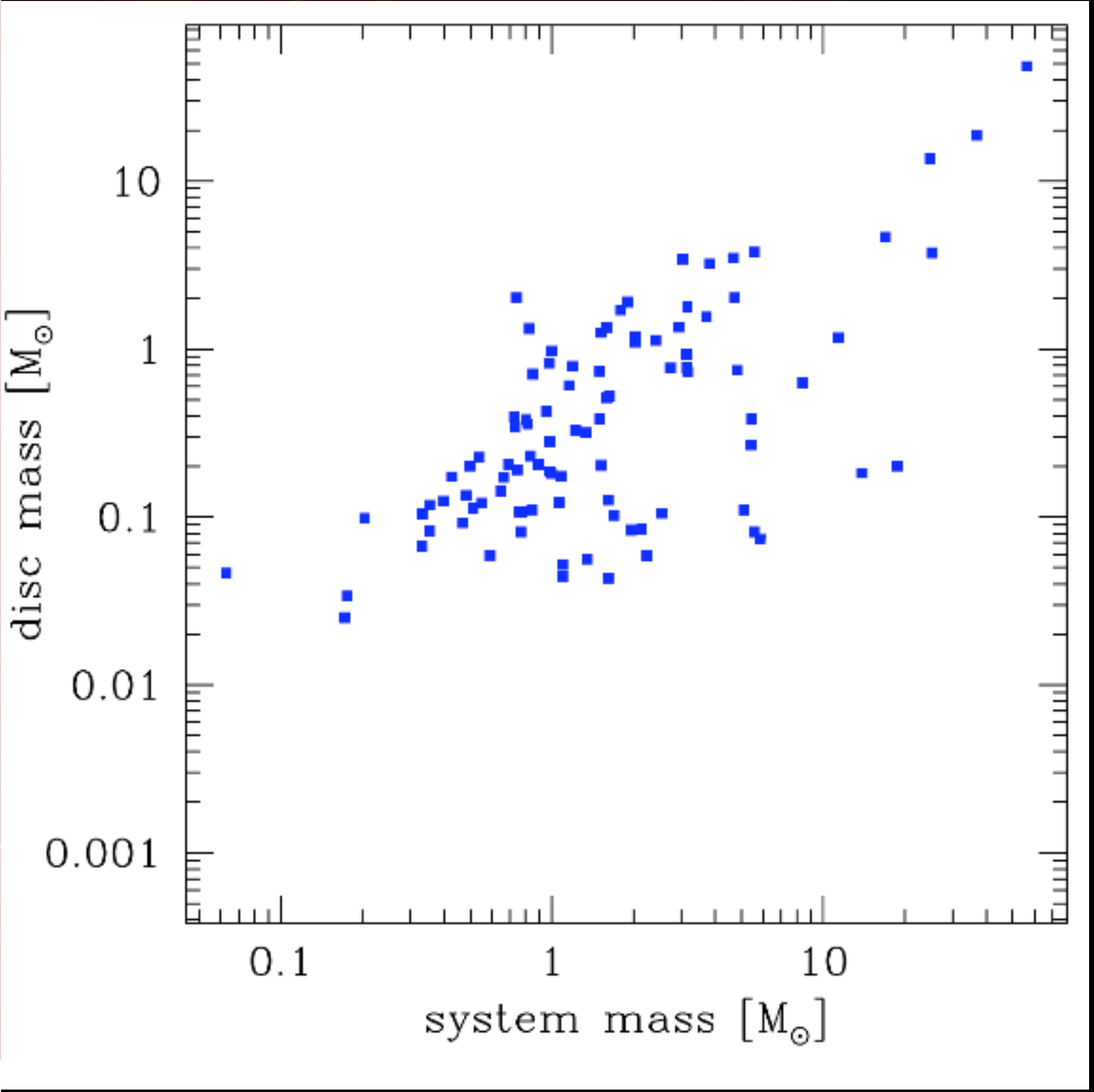
$$\Sigma_{crit} \sim M_{clump}^{1/3}\ \rho_{frag}^{2/3}\ \phi_{geom}^{2/3}$$

$$\phi_{geom} = (4\pi/3)$$

Larson (2005) suggests this is set by the transition from line to dust cooling: ρ_{frag} 10^{-20} - 10^{-17} g/cm^3

$$\Sigma_{crit} \sim 1\text{g cm}^{-2} \left[\frac{M_*}{500\ M_\odot}\right]^{1/3} \left[\frac{f_{sfe}}{0.5}\right]^{1/3} \left[\frac{\rho_{frag}}{2\times 10^{-19}\ \text{g cm}^{-3}}\right]^{2/3} \left[\frac{\phi_{geom}}{4.2}\right]^{2/3}$$

Discs?



- Relationship between disc mass and protostellar system mass:

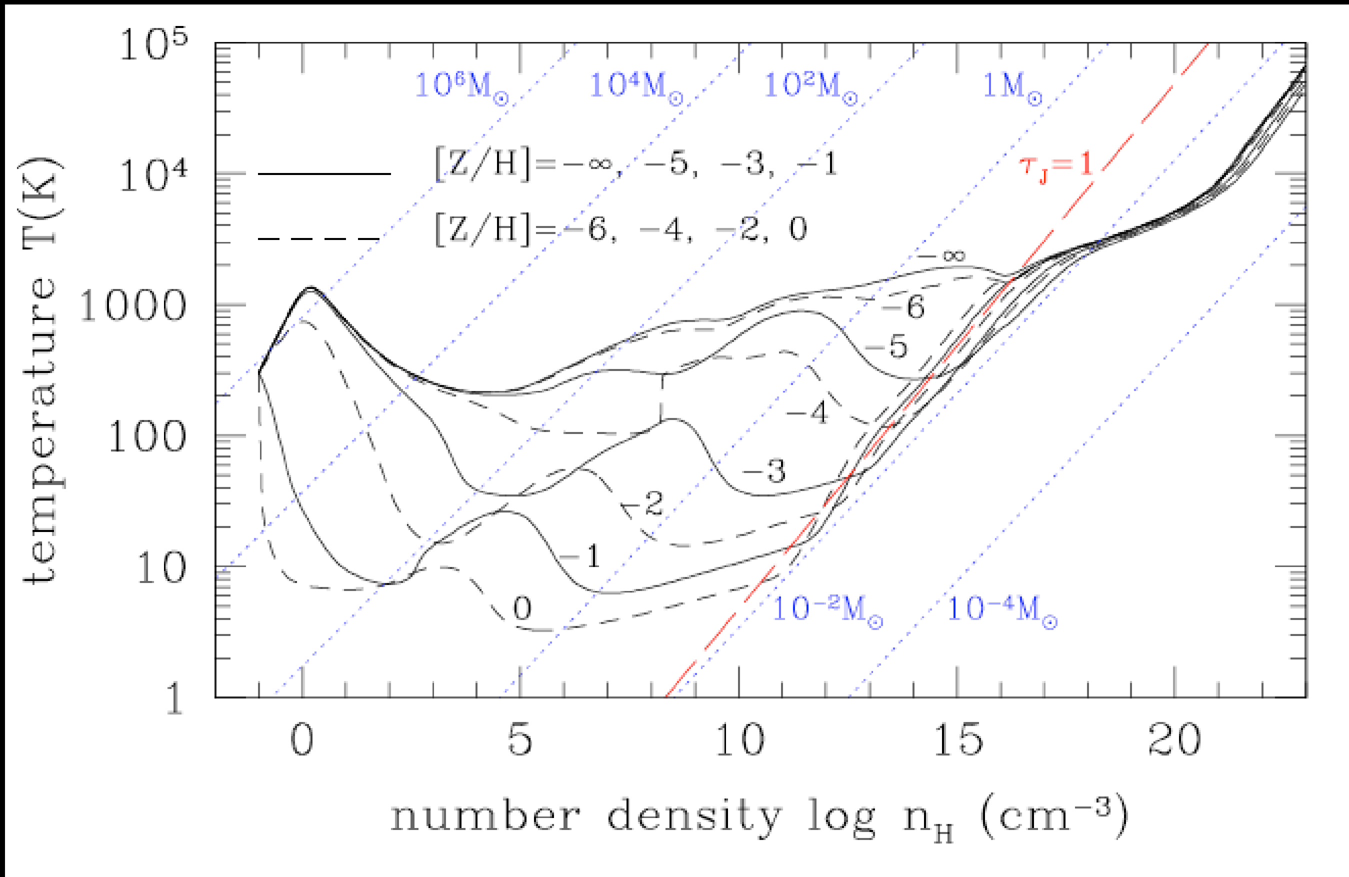
$$\mathbf{m_{disc} \propto m_{sys}^{1.5 - 2}}$$

- Note that discs come and go!
- Angular momentum vector can change!

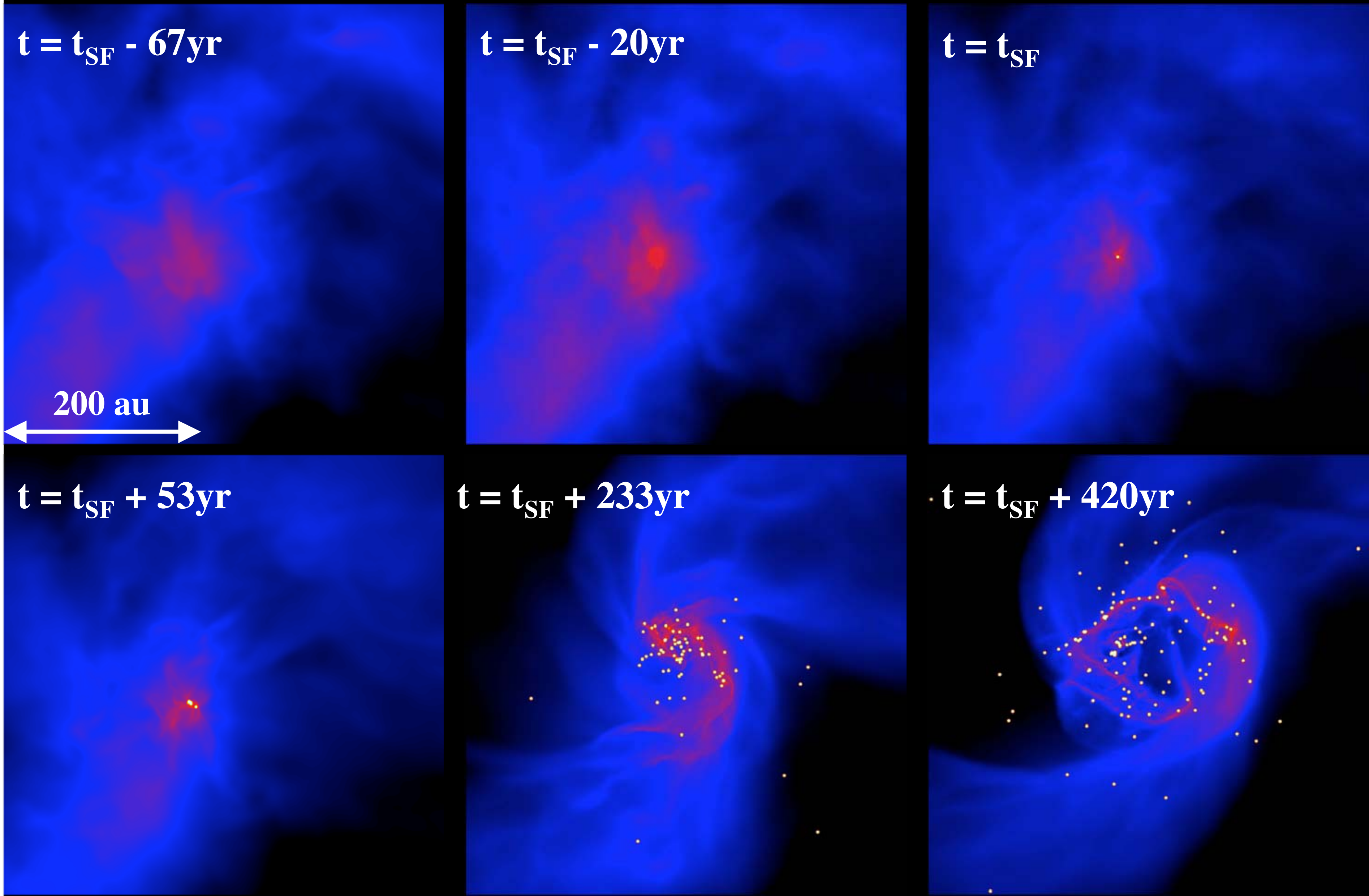
Bonnell, Clarke & Bate (2006) *Clark, Bonnell & Klessen, in prep*

CA at low metallicity?

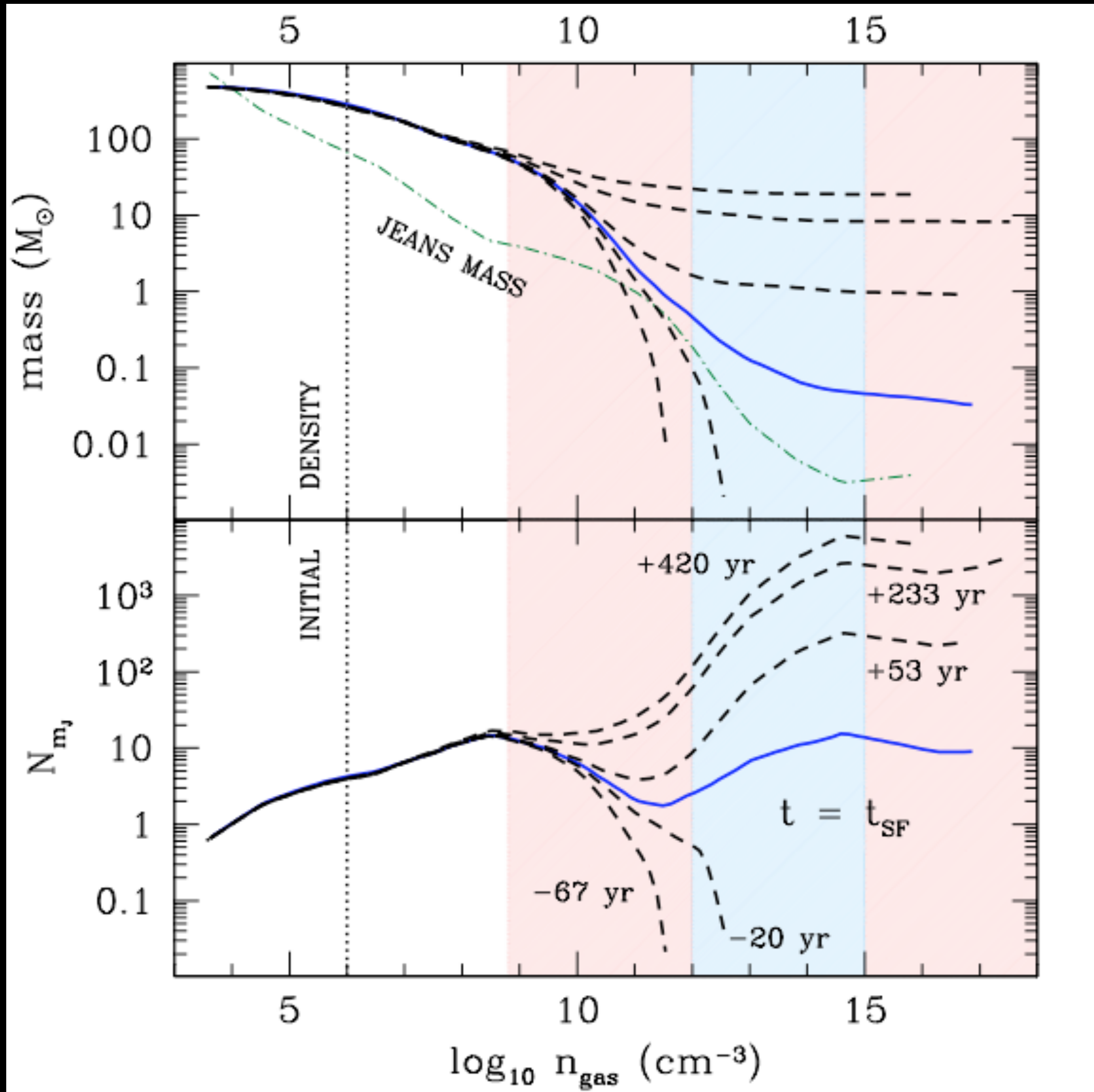
• Omukai et al (2005) suggest that cooling by dust can promote fragmentation, even at very low metallicities:



CA at low metallicity

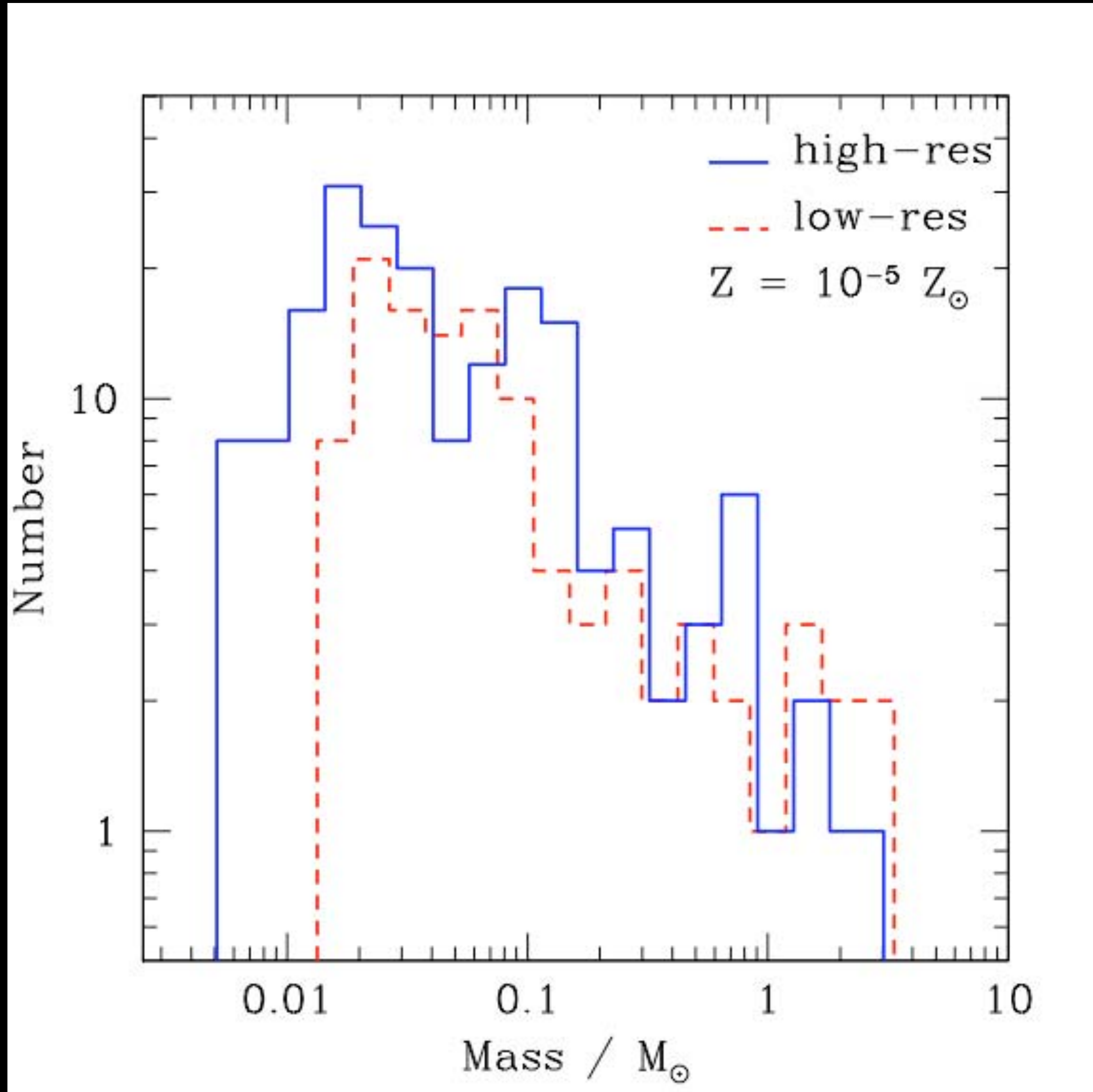


Violent fragmentation...



CA at low metallicity?

- Fragmentation at very low Jeans mass.
- Moves very rapidly into B-H accretion phase.
- Salpeter-type slope extends right down to the fragmentation mass.



Summary

• Competitive accretion requires bound, collapsing regions to produce the 'correct' IMF.

• Difficult to use observed interaction time-scales to estimate the competitive accretion rates: tend to neglect the changing potential which plays a crucial role.

• CA models so far require $\Sigma_{crit} \sim 1 g/cm^2$

• Disc observations may help to determine importance of interactions.