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UK Astrophysical Fluids Facility

Competitive Accretion in Stellar Clusters

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Origin of stellar masses

- Turbulently driven fragmentation
  - Structure in molecular clouds
  - Clump mass spectrum: IMF

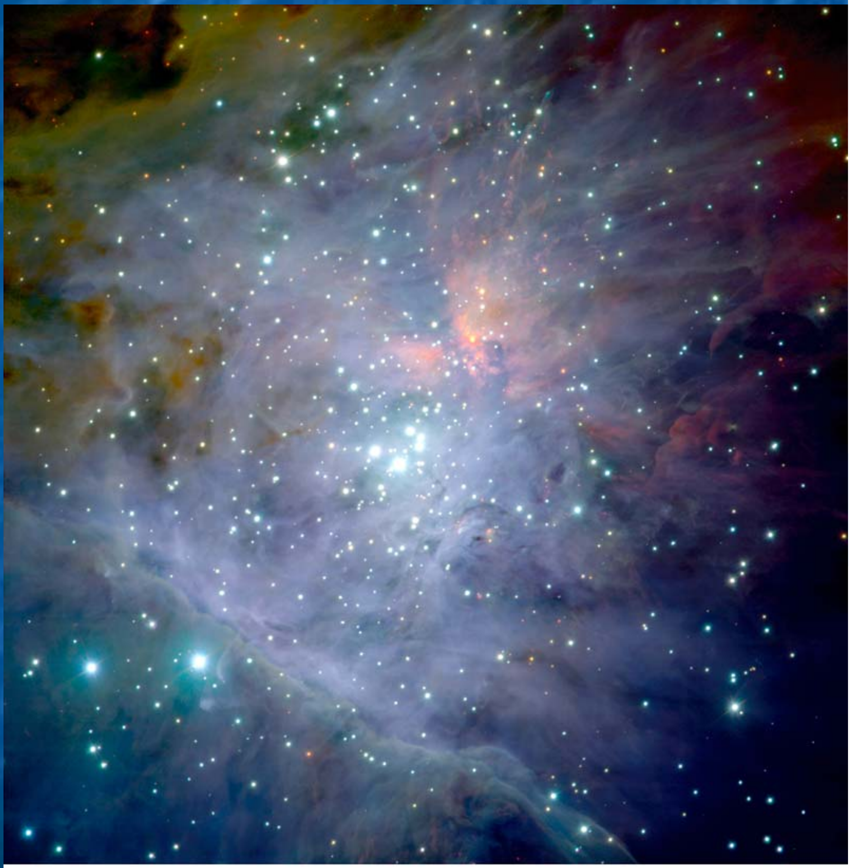
- Gravity driven fragmentation
  - ~ thermal Jeans masses
  - Accretion in clusters produces higher masses
  - Low masses from gravity-produced dense gas

- SPH Simulations: self-gravitating decaying turbulence
  - $E_{kin} \geq |E_{grav}|$
  - No Magnetic fields
  - Some feedback!

Origin of stellar masses: context

- Need to understand SF in context of forming full IMF

M. McCaughrean



The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)

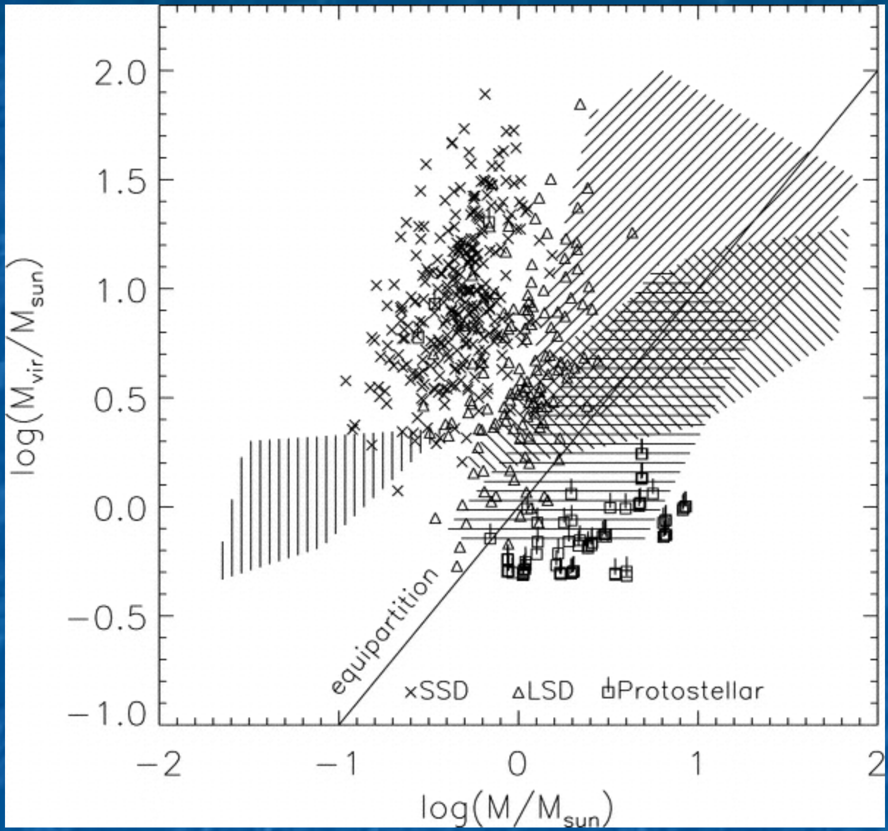
- many/most stars form in clusters
  - Full IMF
- ~ All higher mass stars

De Wit et al 2005

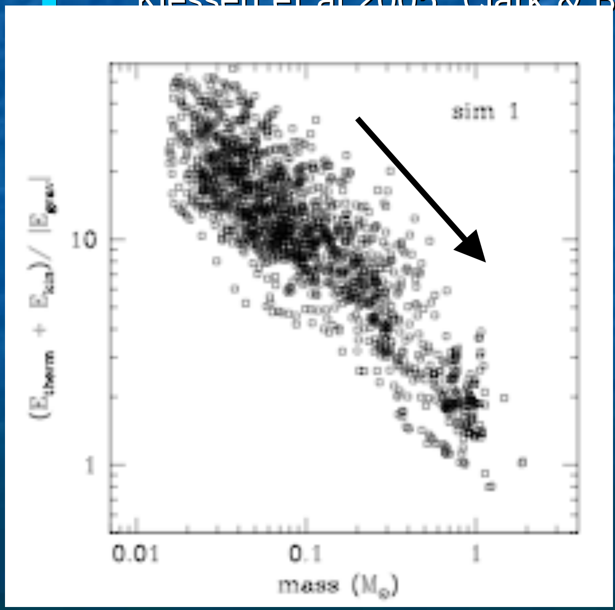
- Massive stars in centre
- Binaries
- Disks

Turbulent Fragmentation

- Produces full clump mass fn
- But low masses unbound
- High-mass clumps fragment
- Star formation occurs ~ Jeans Mass
  - Klessen et al 2005; Clark & Bonnell

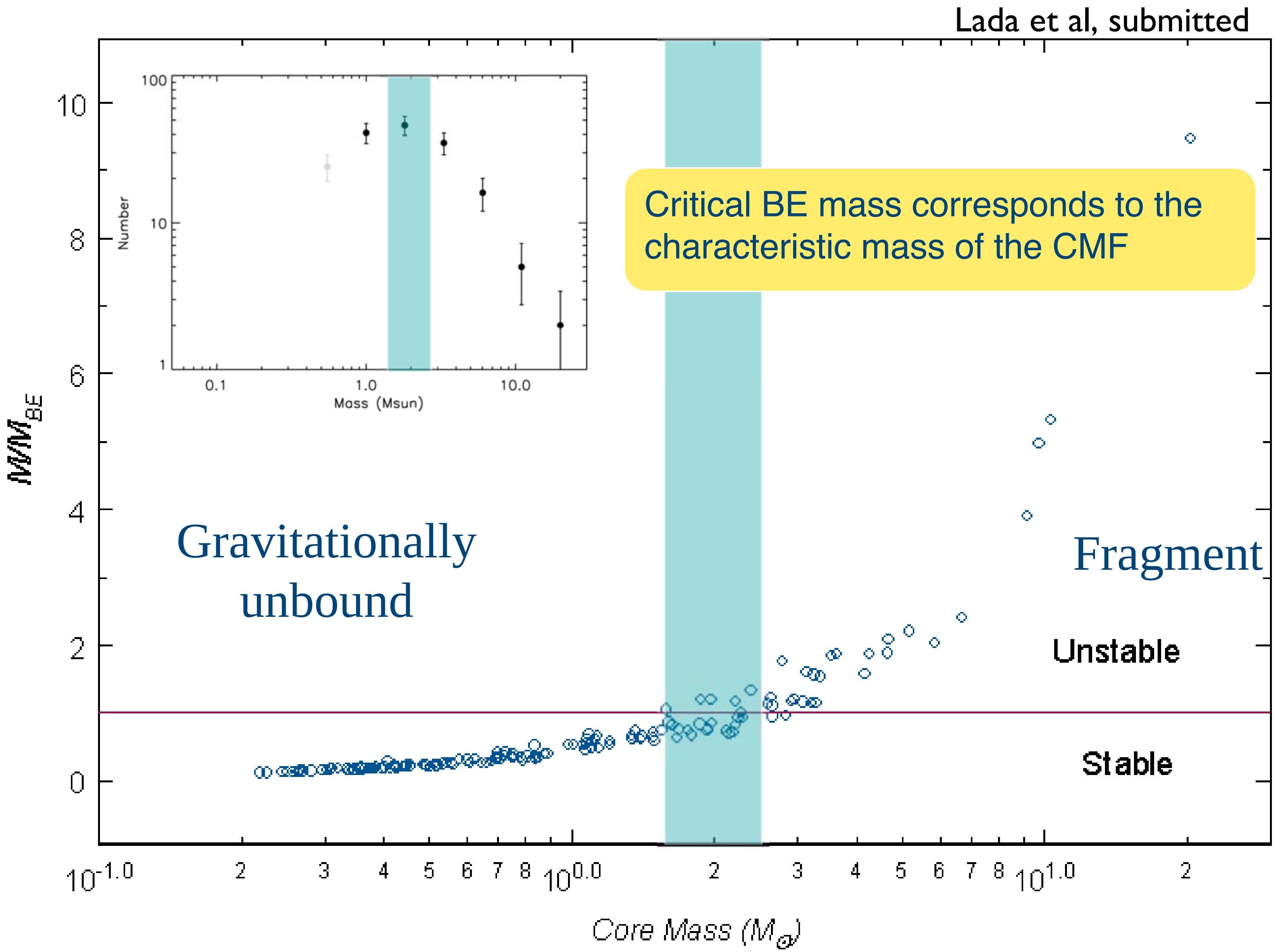


Klessen et al 2005



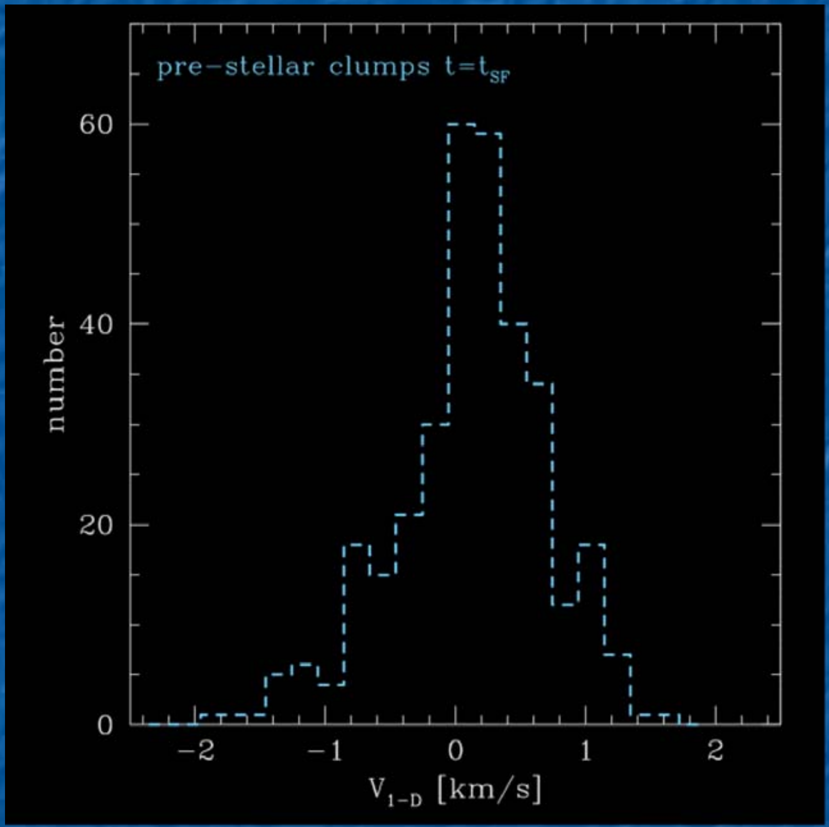
Evolution towards SF

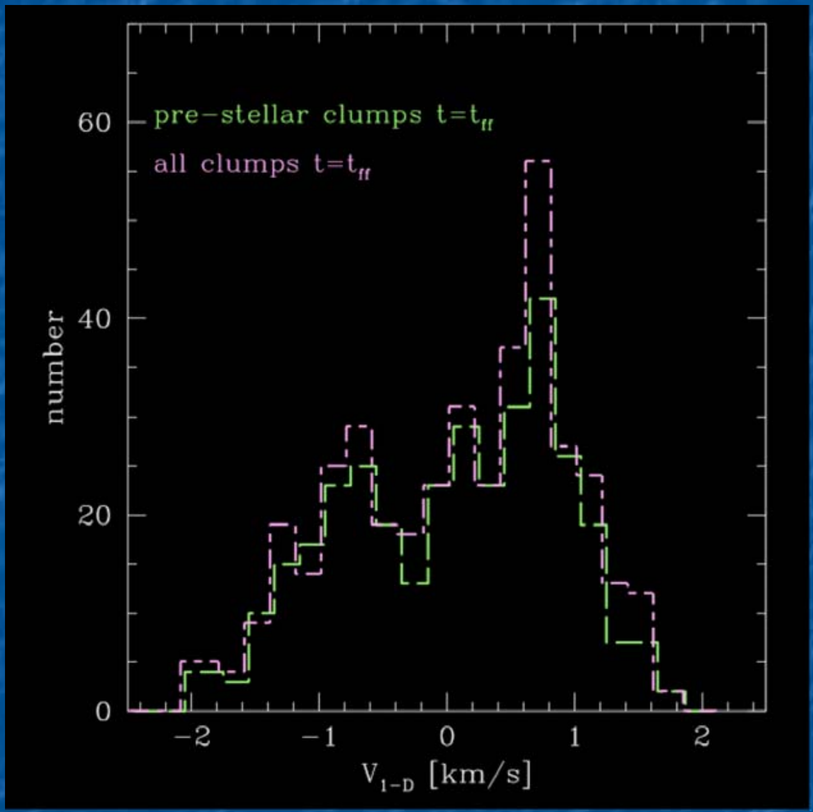
Clark & Bonnell 2005


Lada et al, submitted
Critical BE mass corresponds to the characteristic mass of the CMF
Gravitationally unbound
Fragment
Unstable
Stable
M/M_BE
Core Mass (M_☉)
Number
Mass (Msun)

Clump velocities

P. Clark





- At point of first SF
- Low clump-clump vels

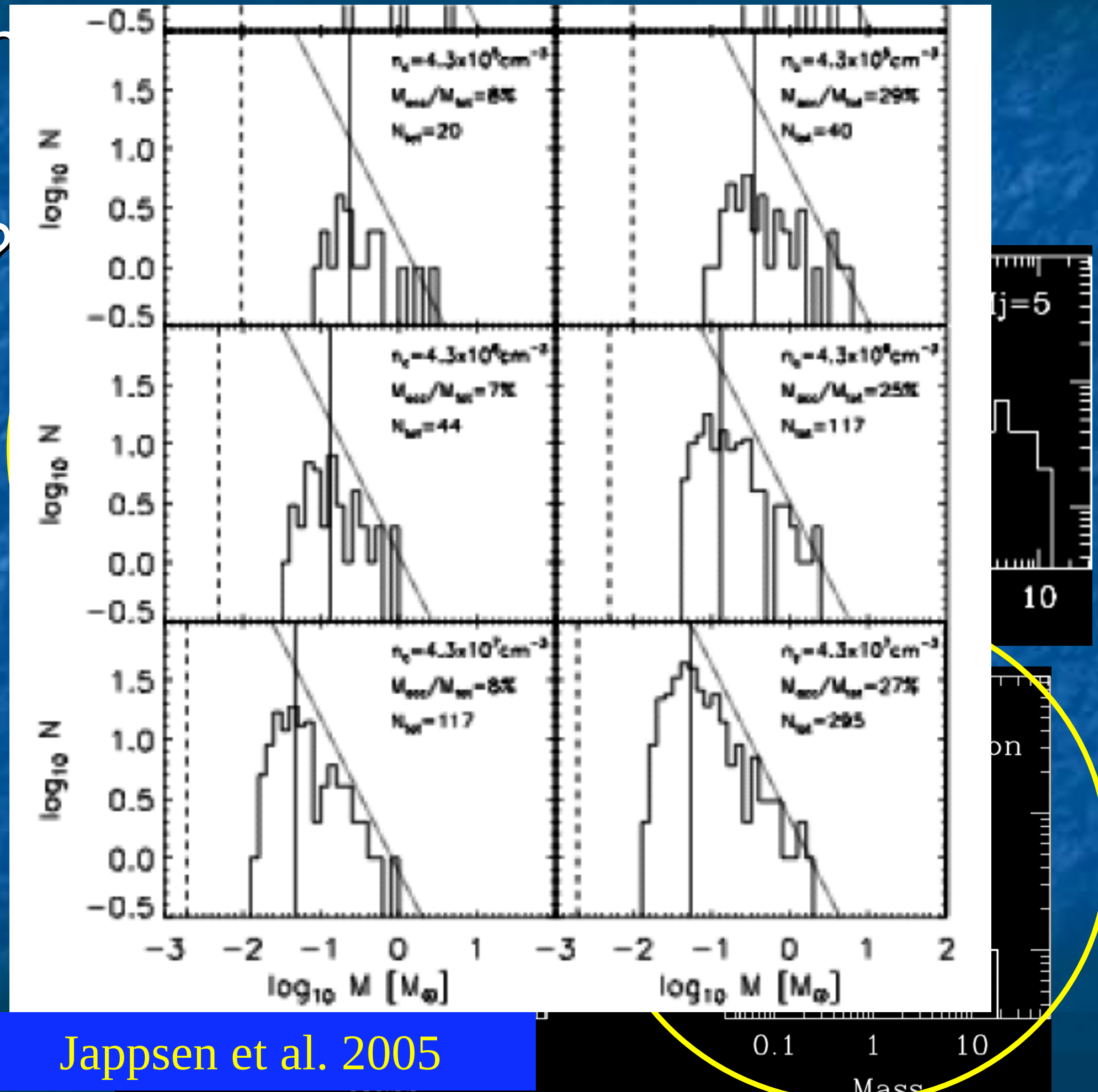
- After free-fall time
- ~ higher clump-clump vels

Characteristic stellar mass

- Simulations sh
- What sets M_J?

Thermal physics:

(Larson 2005, Spaans & Silk 2000)



Jappsen et al. 2005

Bonnell, Clarke & Bate 2006

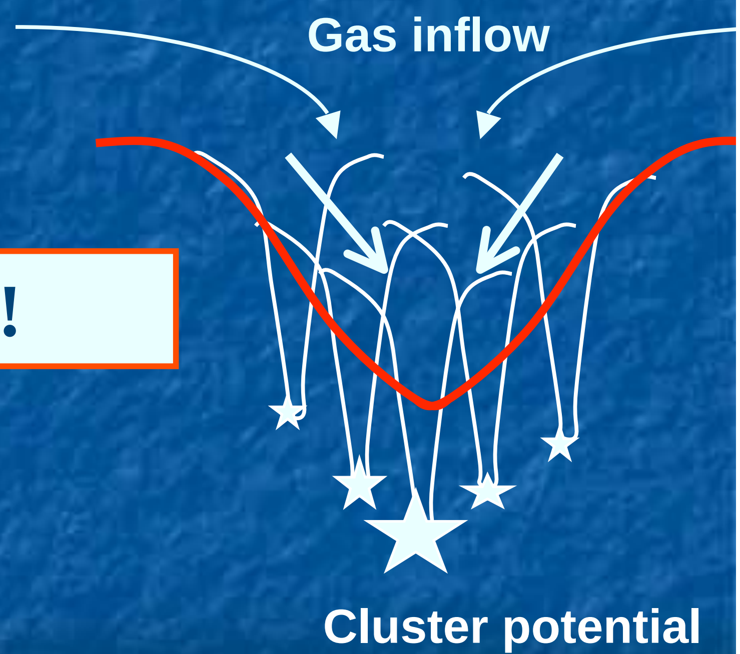
Competitive accretion

Bonnell et al 1997, 2001

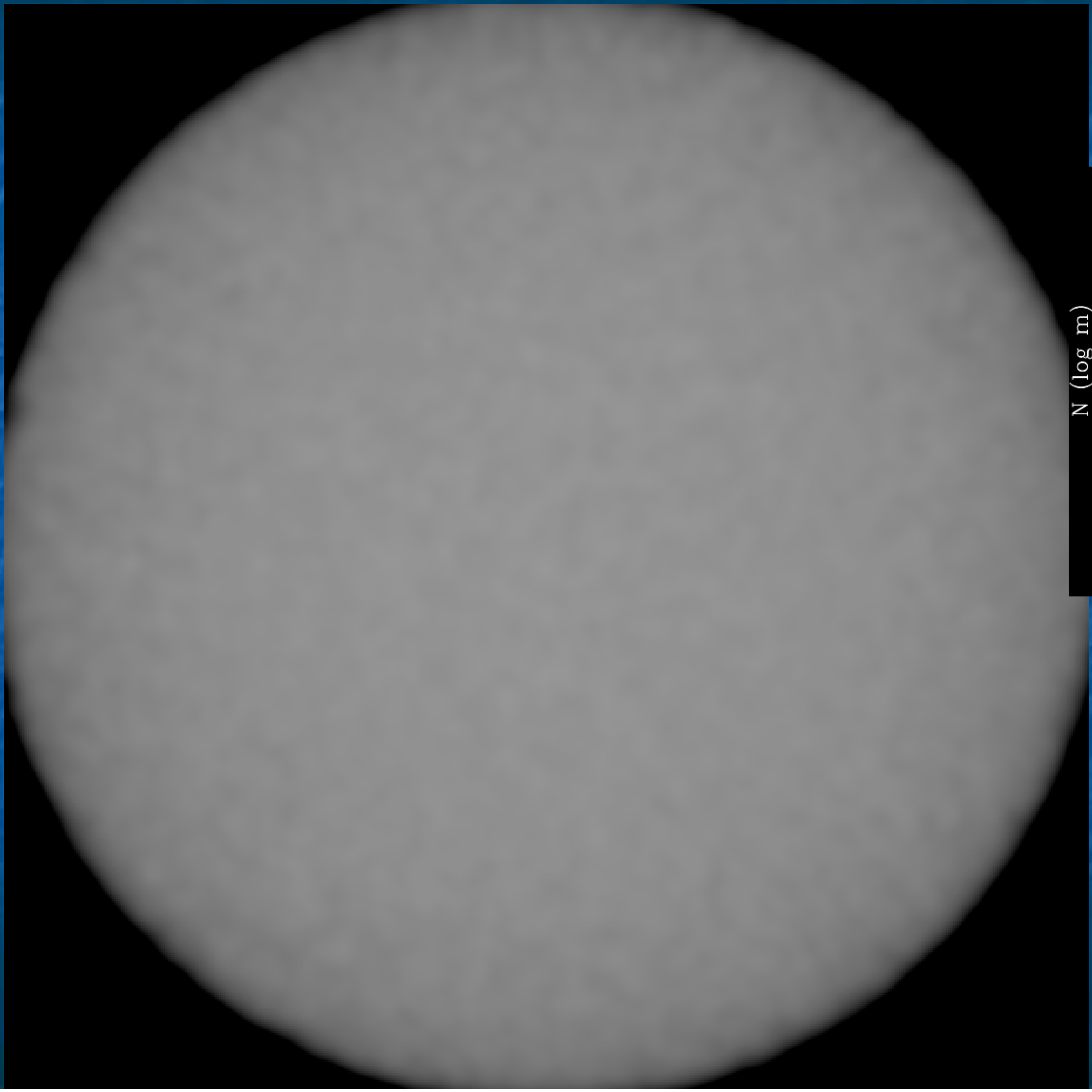
- Fragmentation down to (thermal) Jeans Mass
  - Form as lower mass stars (~ 0.5 M_{sun})
  - Subsequent accretion forms high-mass stars
- Accretion limited by
  - Tidal effects
  - Gas velocities: Bondi-Hoyle

Stars do not have to move!

- Gas inflow due to cluster potential
  - to cluster centre
  - Higher gas density:
    - Higher accretion rates
- Requirements:
    - N > 2 fragments
  - Common gas reservoir

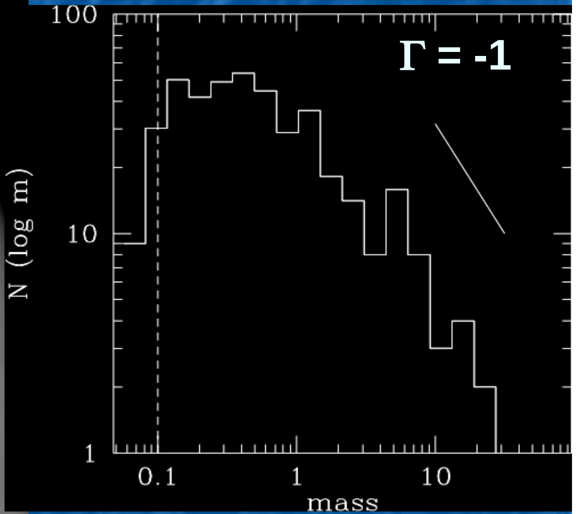


The Formation of a stellar cluster



10^3 M_{sun} in 1 pc

Stellar masses



Forms full IMF

Mass segregated clusters

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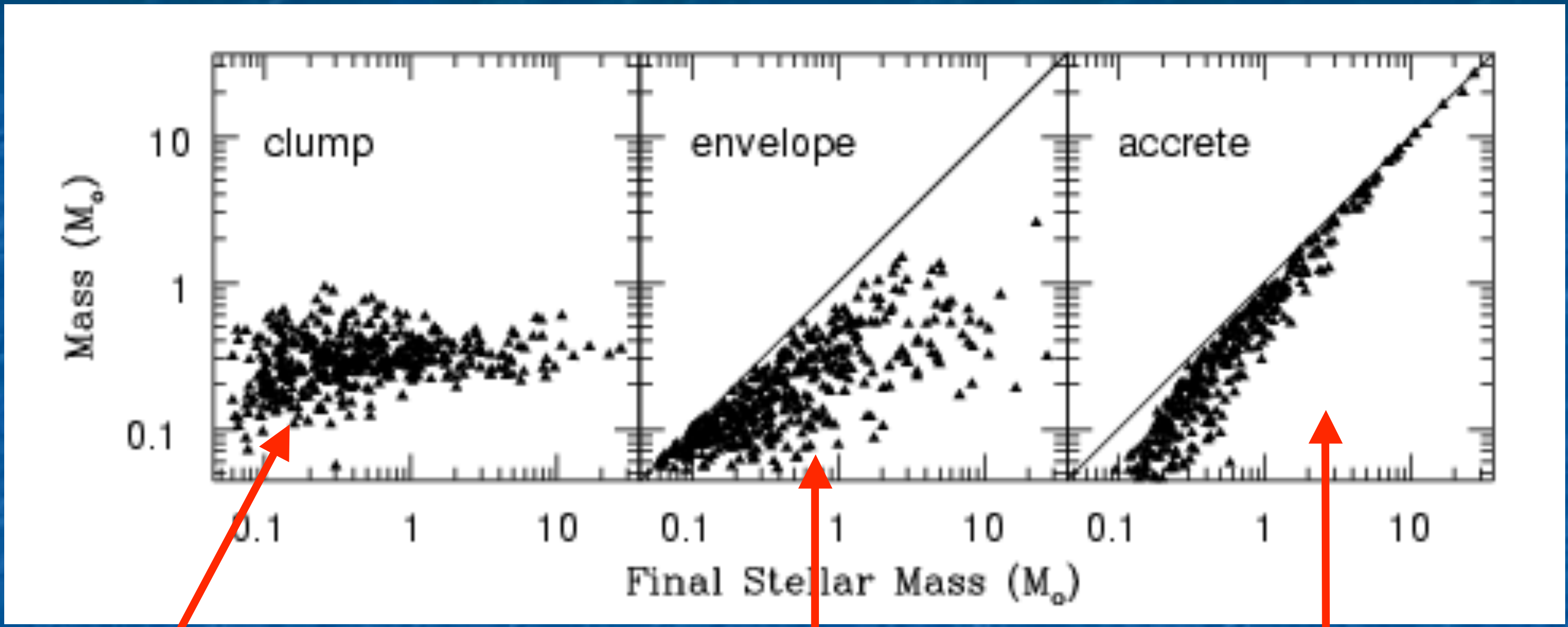
Bonnell, Bate & Vine 2003

Origin of stellar masses



Fragmentation mass
~ Jeans Mass

- **Envelope mass**

- **Accretion from outside stellar cluster**

•Massive stars form due to accretion from large-scale reservoir

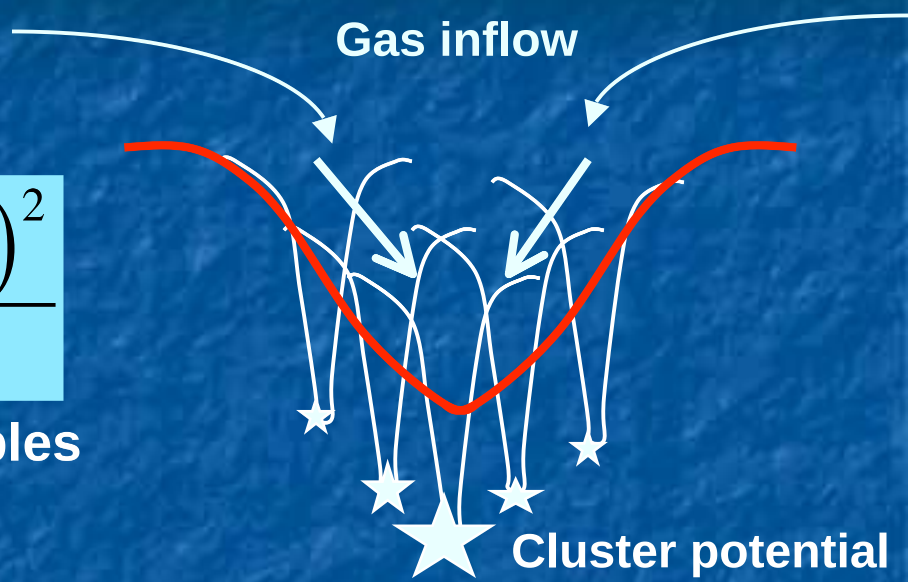
Bonnell, Vine & Bate (2004)

Competitive accretion

- Accretion rates

$$\dot{M}_{acc} = \pi\rho v R_{acc}^{\ 2} \approx \pi\rho \frac{(GM_*)^2}{v^3}$$

All local variables



	Global Cloud
ρ	$2\ 10^{-19}$ g/cm^3
v	2 km/s
M_*	0.1 M_{sun}
$\dot{M}_{acc}$	$10^{-9}\ M_{sun}$/yr

→ Competitve accretion doesn't work ?

Krumholz et al 2005

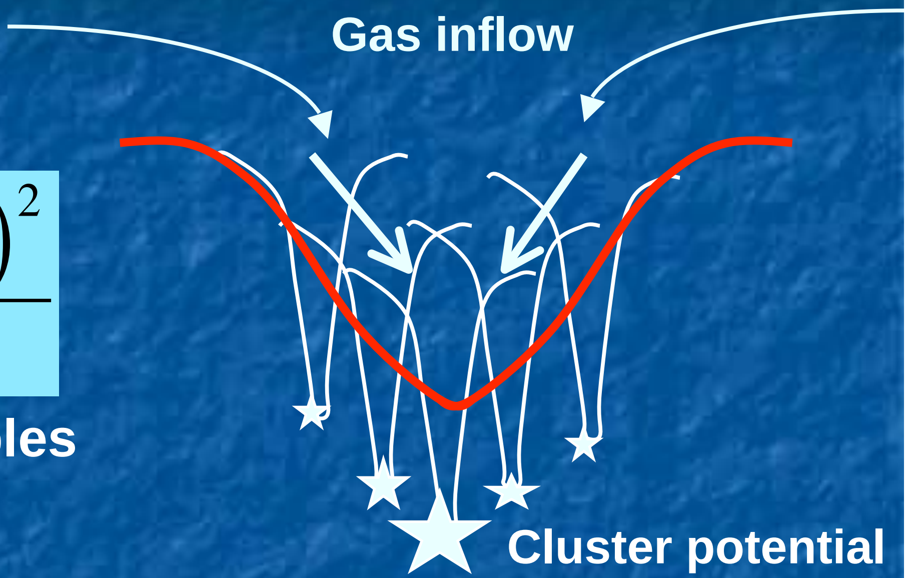
Bonnell & Bate 2006

Competitive accretion

- Accretion rates

$$\dot{M}_{acc} = \pi \rho v R_{acc}{}^{2} \approx \pi \rho \frac{(GM_*)^2}{v^3}$$

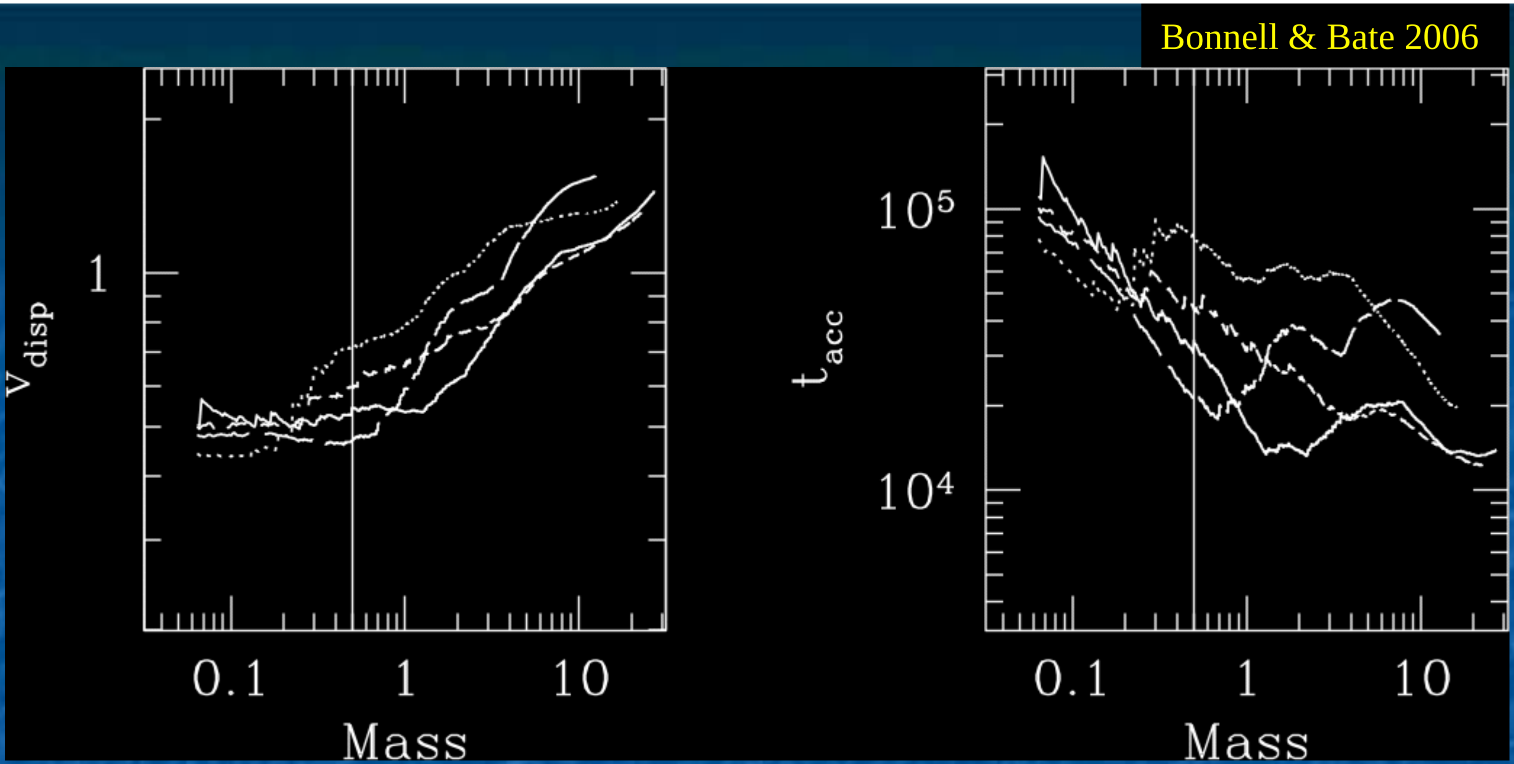
All local variables



	Global Cloud	Local Cluster Core
ρ	$2\ 10^{-19}$ g/cm^3	10^{-17} g/cm^3
v	2 km/s	0.5 km/s
M_*	0.1 M_{sun}	0.5 M_{sun}
$\dot{M}_{acc}$	10^{-9} M_{sun}/yr	10^{-4} M_{sun}/yr

Large range in possible $\dot{M}_{acc}$

➡ full IMF



- Accretion starts in small-N clusters
- Low velocity dispersion
  - Short accretion timescale

$$t_{acc} = M_* / \dot{M}_{acc}$$

- Attain ~higher masses before v_{disp} high
- Form massive stars in few 10^5 years

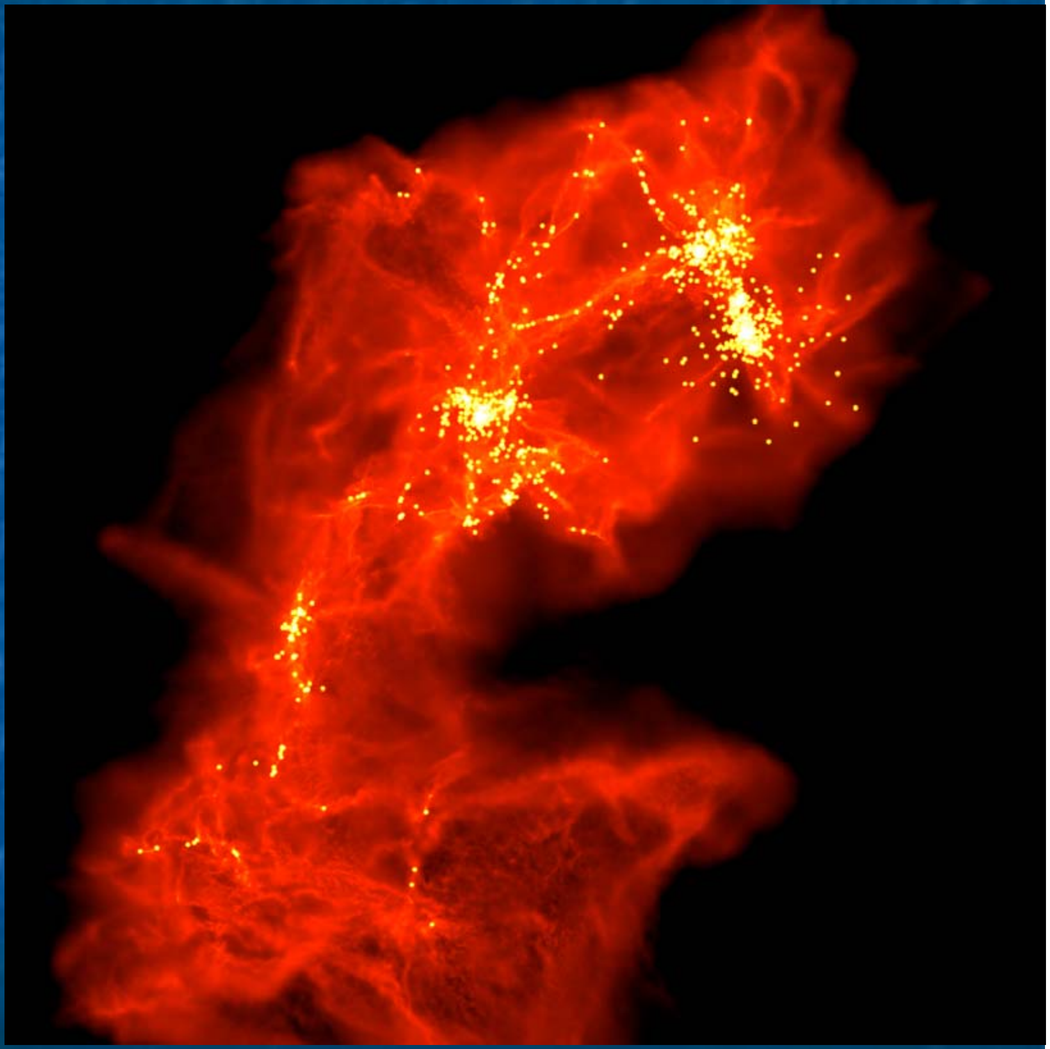
GMC scale star formation

- 10^4 M_{sun} in 10 pc
- Forms > 2500 stars
  - Over 6 x 10^5 years
- Full IMF
- 1.5 x10^7 SPH particles
  - On two levels

Mass resolution ~0.02 M_{sun}

- Sink radii 200 AU

Bound (top) and unbound (bottom) initial conditions



Bonnell, Clark & Bate 2007

Full GMC

Bound (top) and unbound (bottom) initial conditions

10^4 M_{sun} in 10 pc

Clustered and distributed SF

Efficiency varies from < 1% to 20%

Universal IMF

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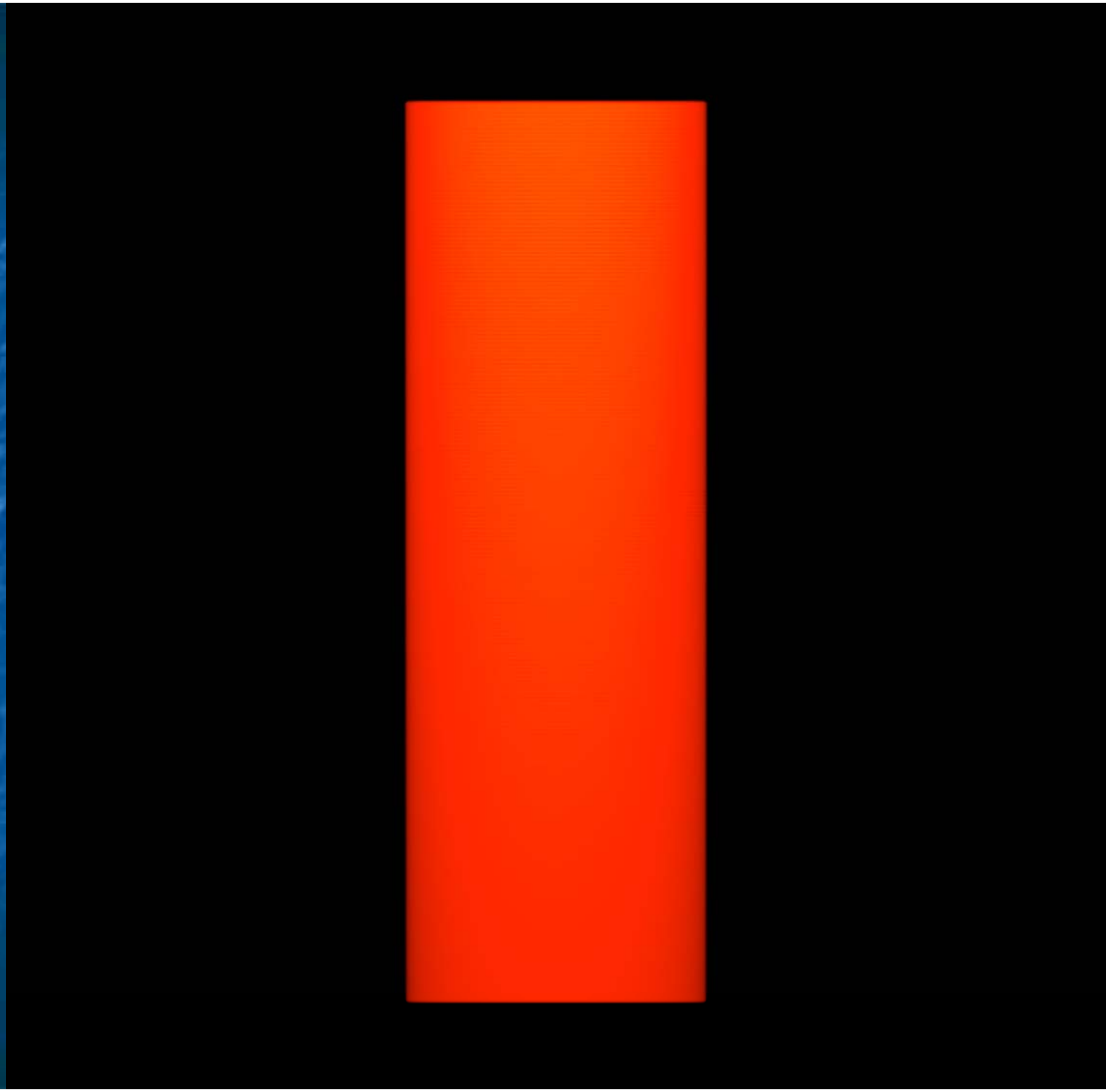
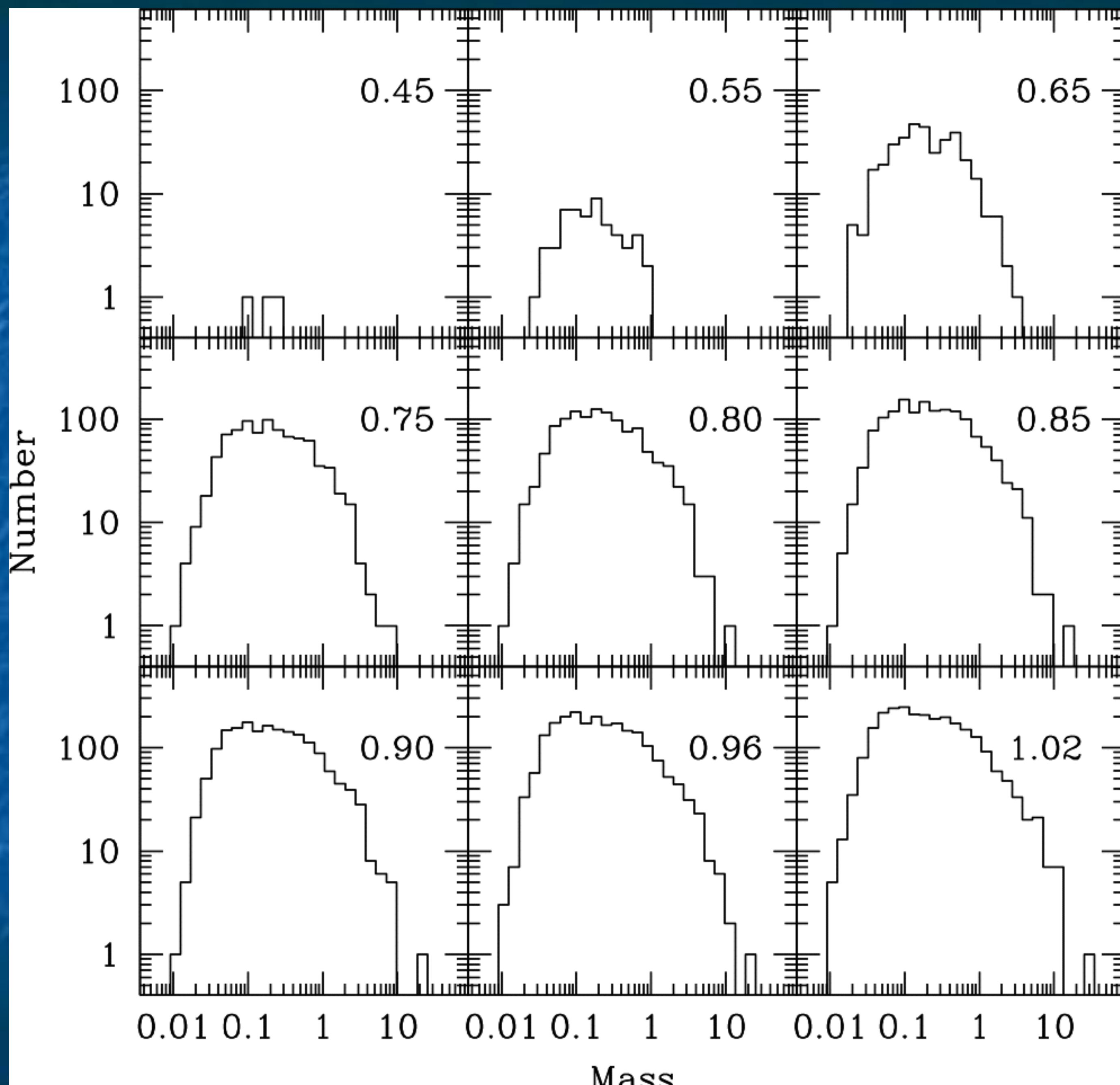




Number
Mass
0.45
0.55
0.65
0.75
0.80
0.85
0.90
0.96
1.02
100
10
1
0.01
0.1
1
10

Fragmentation environment

Gas density

in 0.1 pc

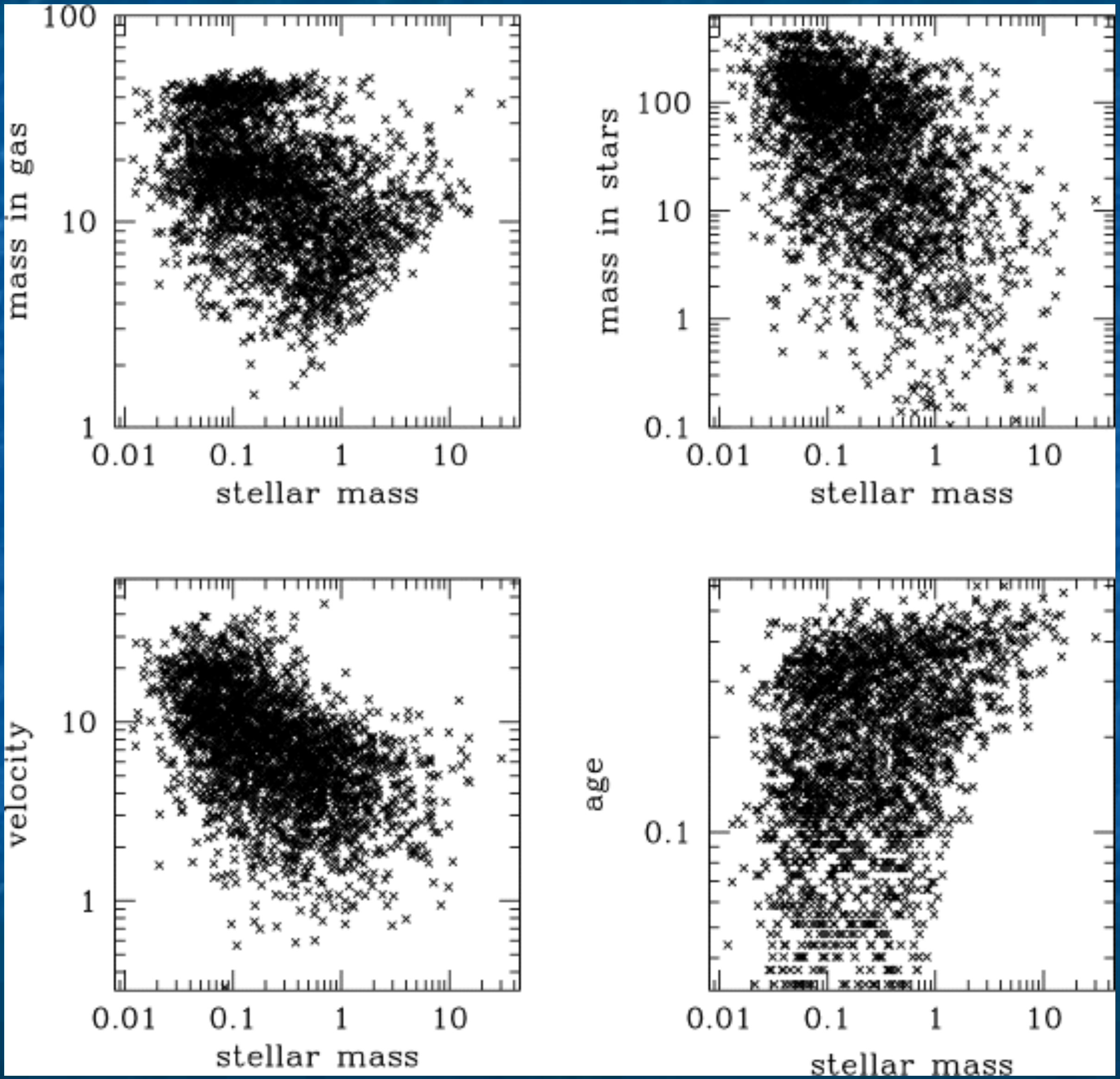
$M_J \sim \rho^{-1/2}$

Velocity

in (0.2 km/s)

relative to CoM

in 0.5 pc



Clusters

Stars in 0.5pc at point of fragmentation

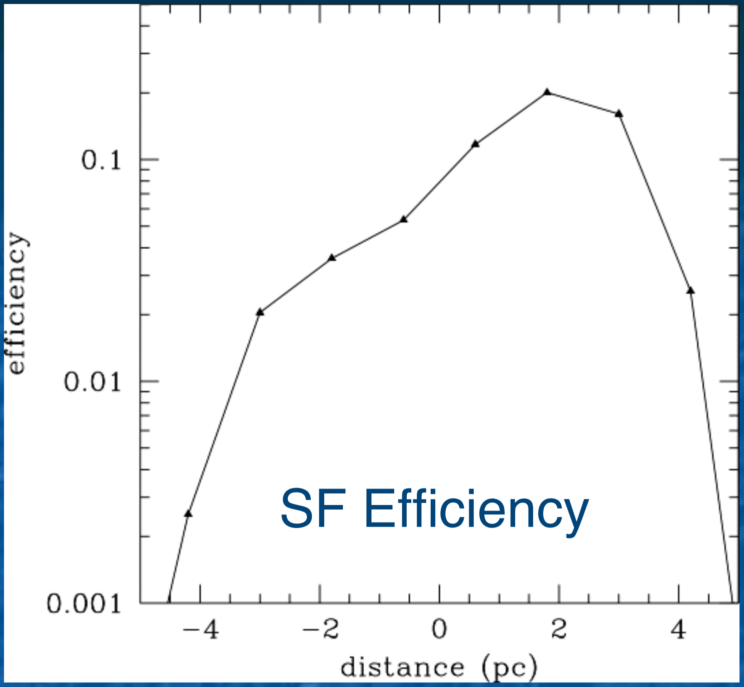
When fragment formed

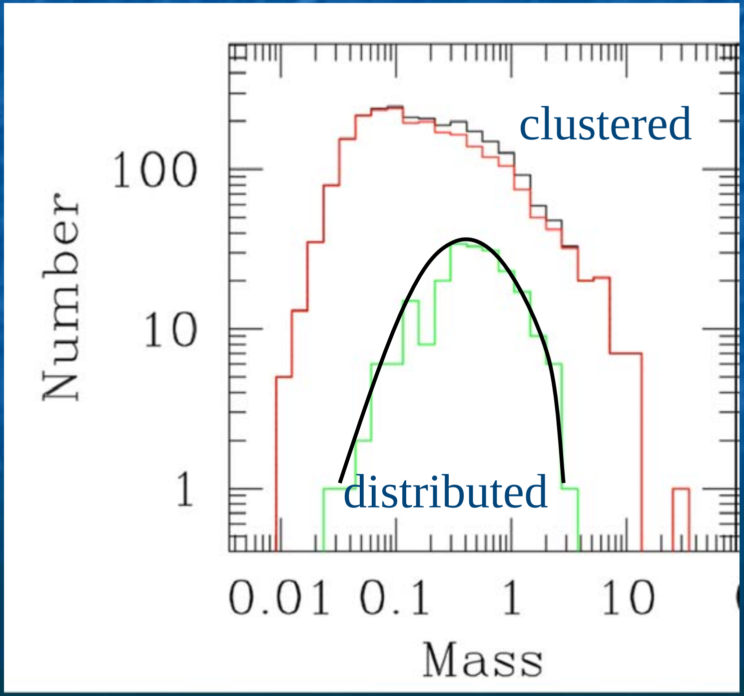
Origin of stellar masses

- Massive stars
  - Form early at ~M_J, sit in centre of cluster
  - High accretion rates
- Low-mass stars
  - Form later as gas falling into cluster potential
  - High relative velocity
  - Little subsequent accretion

SF efficiencies and clustered SF

- Bound conditions produce stellar clusters
  - Relatively high efficiencies
  - 20-50 %
  - Full IMF
- Unbound regions produce distributed SF
  - Low SF efficiencies
  - Few %
  - Flat/Peaked IMF
  - No high-mass, few low mass stars

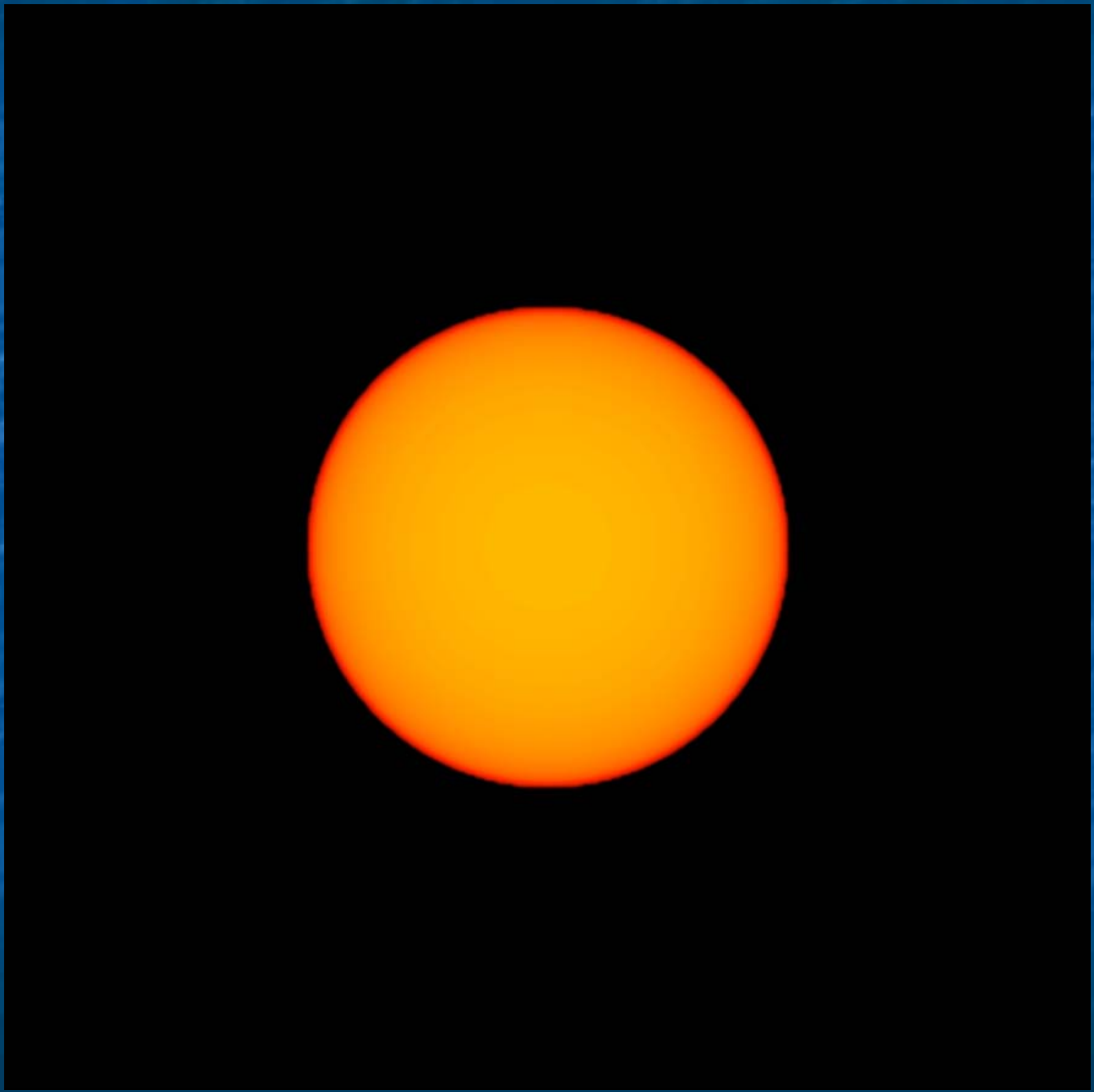




An unbound example…

KE = 2 × PE
(initially)

Isothermal
EOS



0.25pc

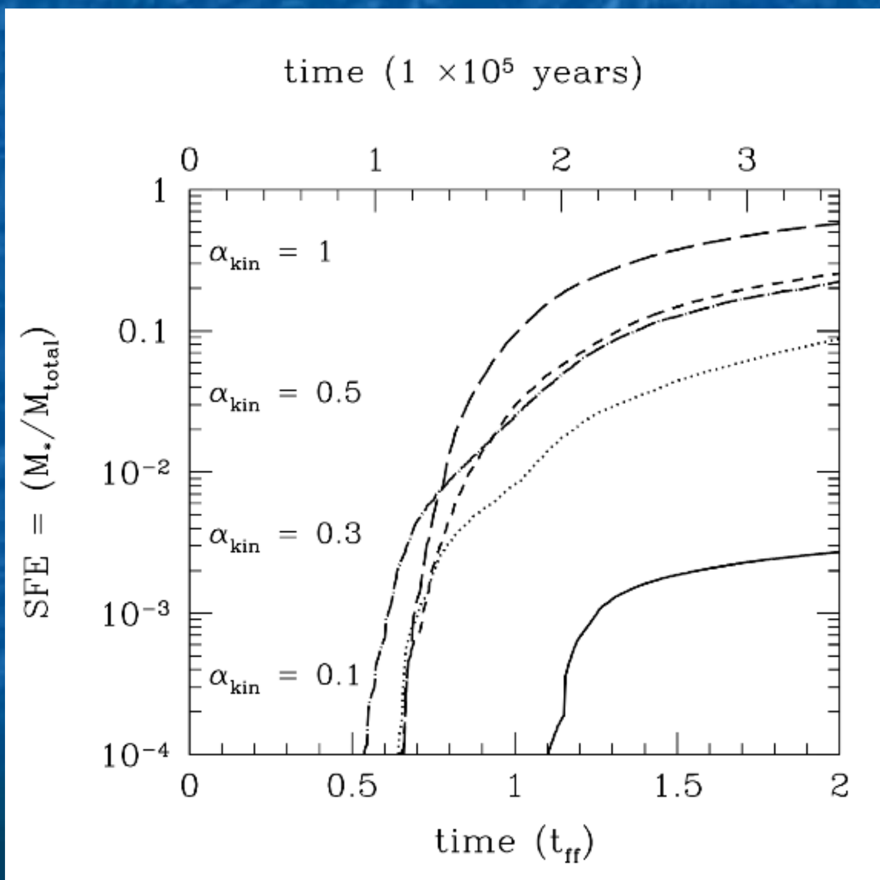
Clark, Bonnell & Klessen (2007)

Star formation efficiencies?

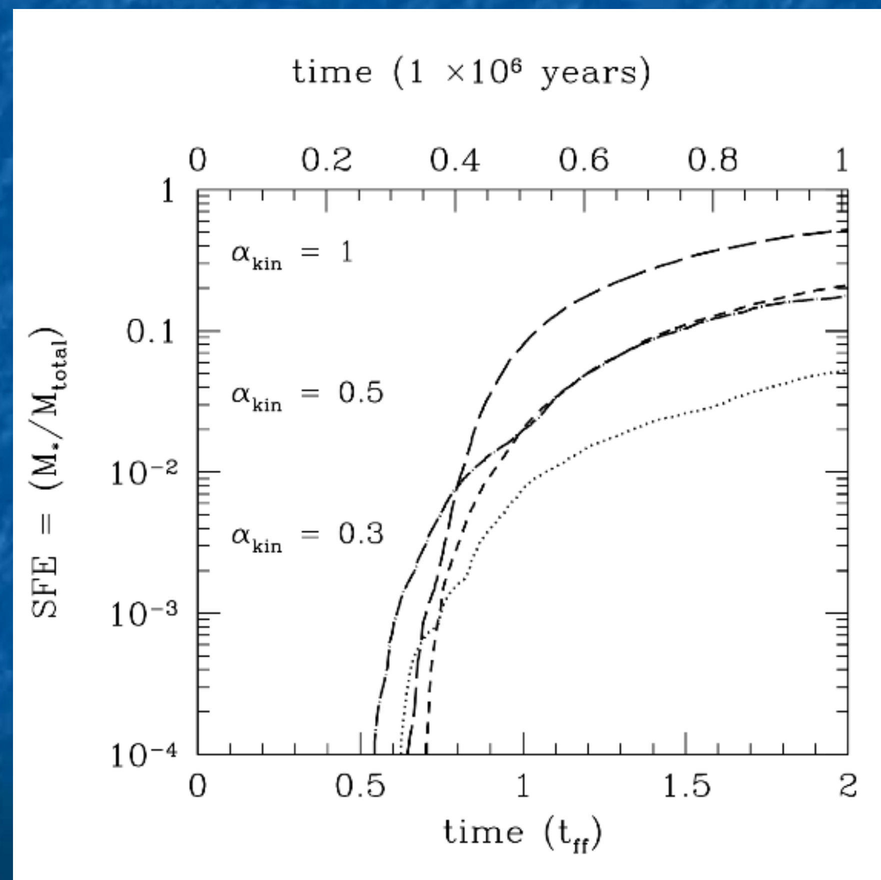
Naturally, more unbound clouds/regions have lower efficiencies…

$\alpha_{kin} = |PE|/KE$

Clark et al 2007



Isothermal EOS

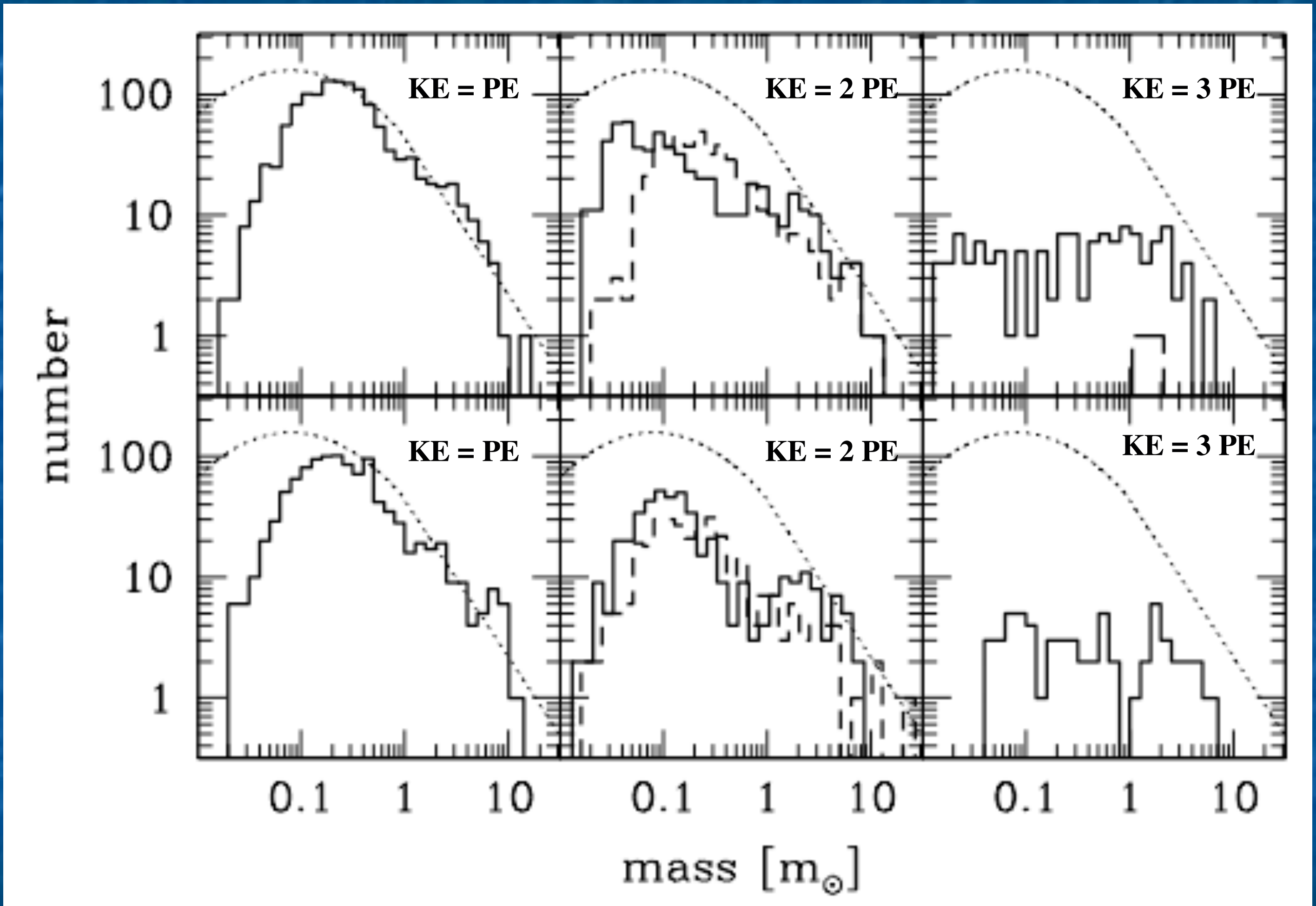


Barotropic EOS

IMFs of unbound clouds

Isothermal EOS

Barotropic (Larson Style) EOS



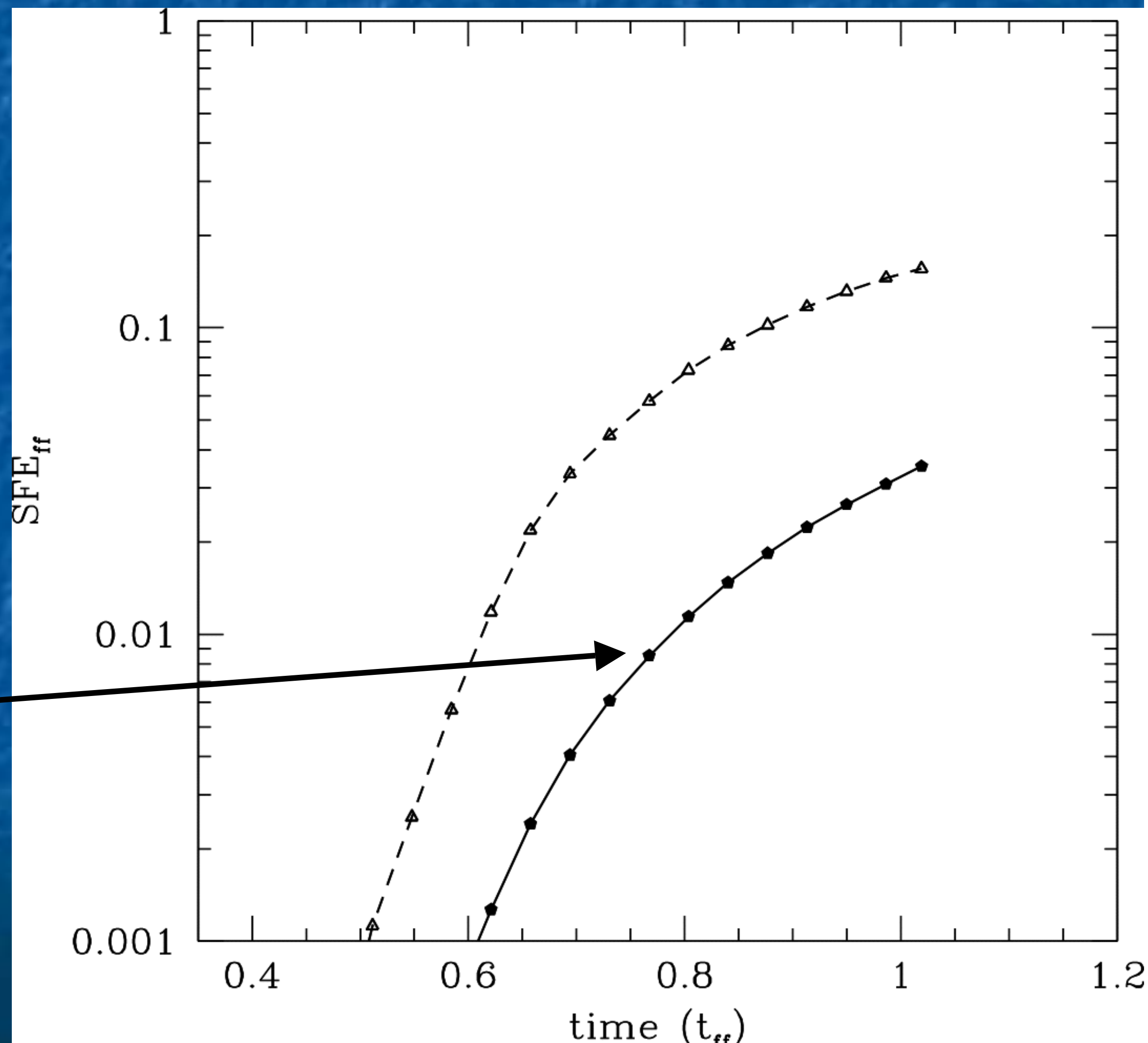
As clouds become more unbound → Competitive accretion is unable to create the 'correct' IMF

Star formation efficiency per t_{ff}

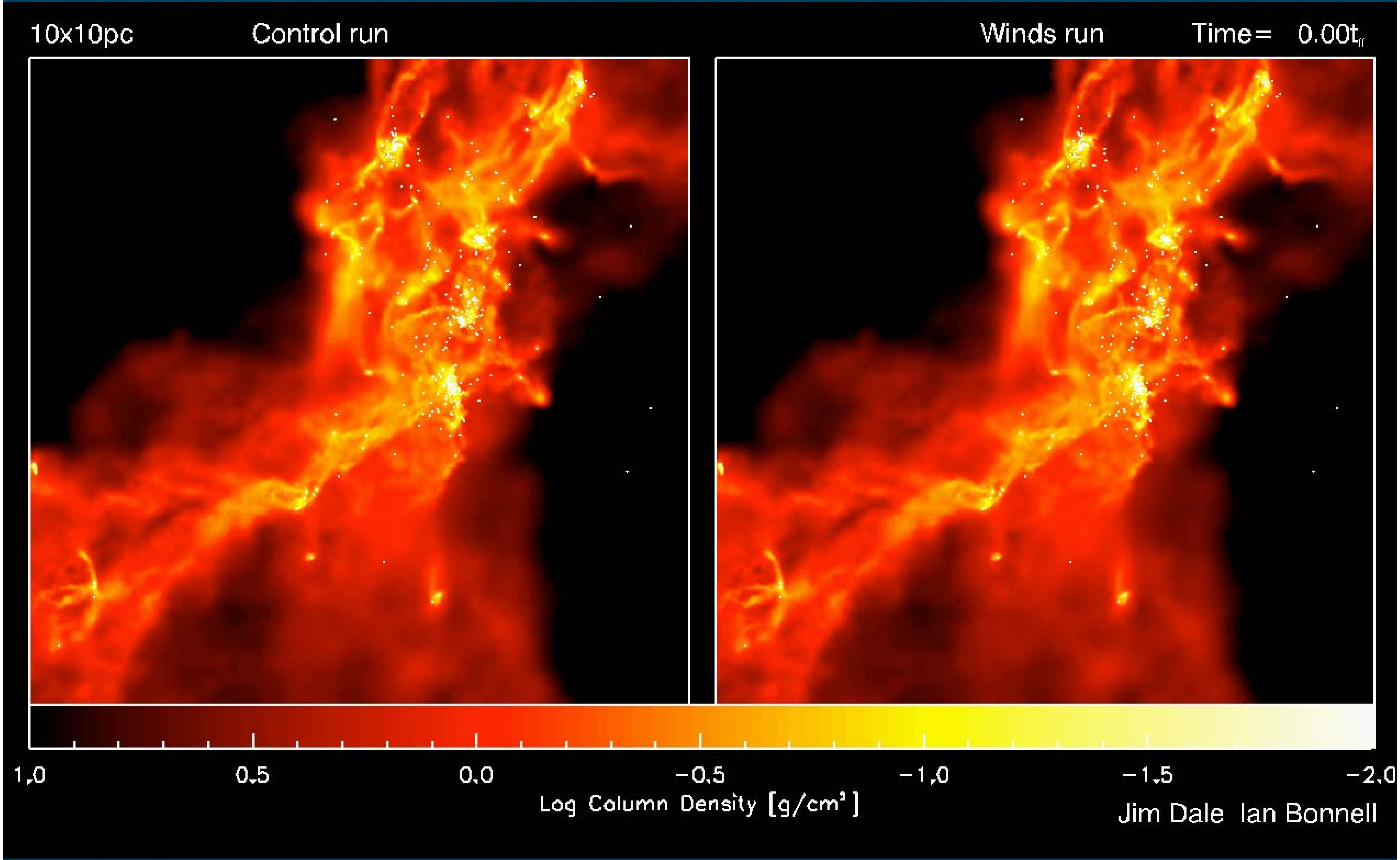
- GMC simulation
- Final SFE ~15 %

- BUT
- Equal probability of observing at all stages of evolution

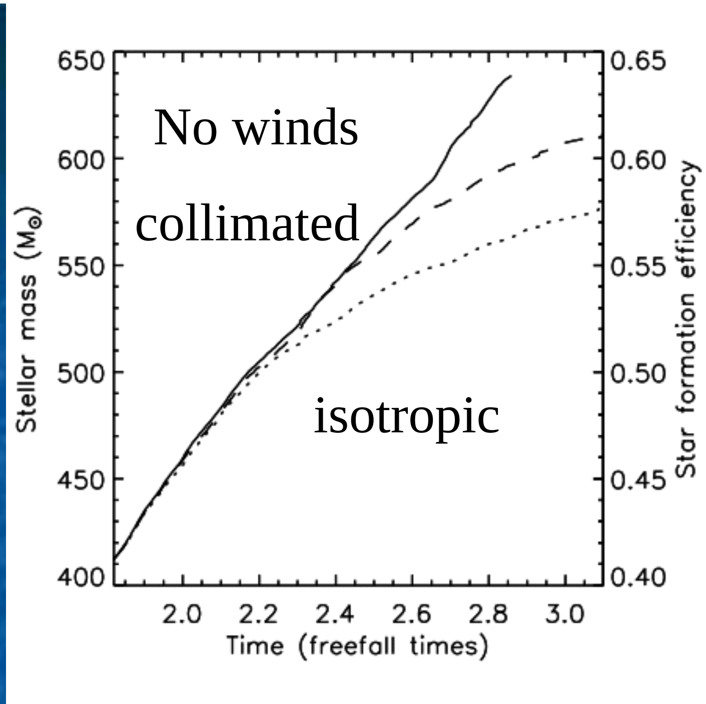
- Average value of SFE is then much lower
- ~ 3 % SFE/t_{ff}
  - Even for short cloud lifetimes

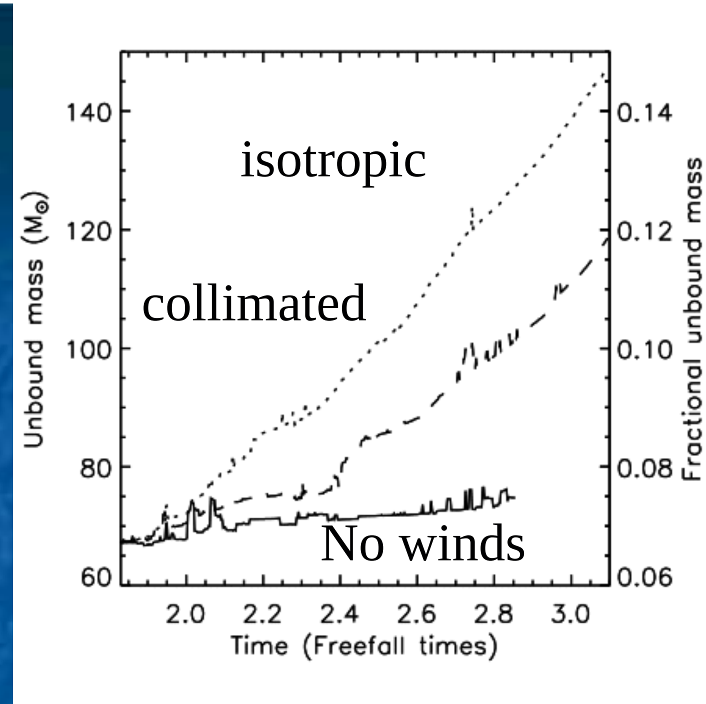


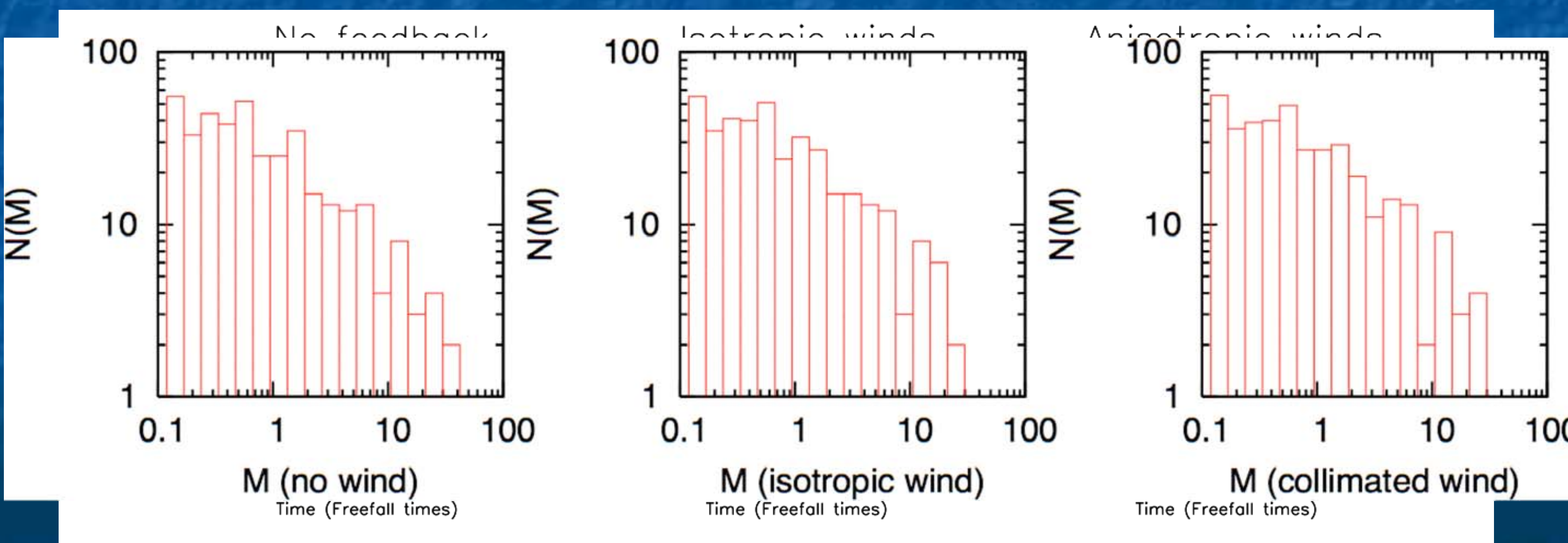
Feedback from stellar winds



Winds have moderate effect on accretion rates


No winds
collimated
isotropic
Stellar mass ($M_\odot$)
Star formation efficiency
Time (freefall times)
650
600
550
500
450
400
0.65
0.60
0.55
0.50
0.45
0.40
2.0 2.2 2.4 2.6 2.8 3.0


isotropic
collimated
No winds
Unbound mass ($M_\odot$)
Fractional unbound mass
Time (Freefall times)
140
120
100
80
60
0.14
0.12
0.10
0.08
0.06
2.0 2.2 2.4 2.6 2.8 3.0


N(M)
100
10
1
0.1 1 10 100
M (no wind)
Time (Freefall times)
M (isotropic wind)
Time (Freefall times)
M (collimated wind)
Time (Freefall times)

Conclusions

- Gravity driven SF can explain IMF
  - Competitive accretion in cluster potential:
    - Higher mass stars due to high accretion rates in cluster centres
    - Low mass stars/BDs from infalling gas into cluster
  - Unbound clouds produce low SFEs
    - Distributed SF
    - Abnormal IMFs
  - Most stars must form in bound groups
  - Need to include all feedback processes