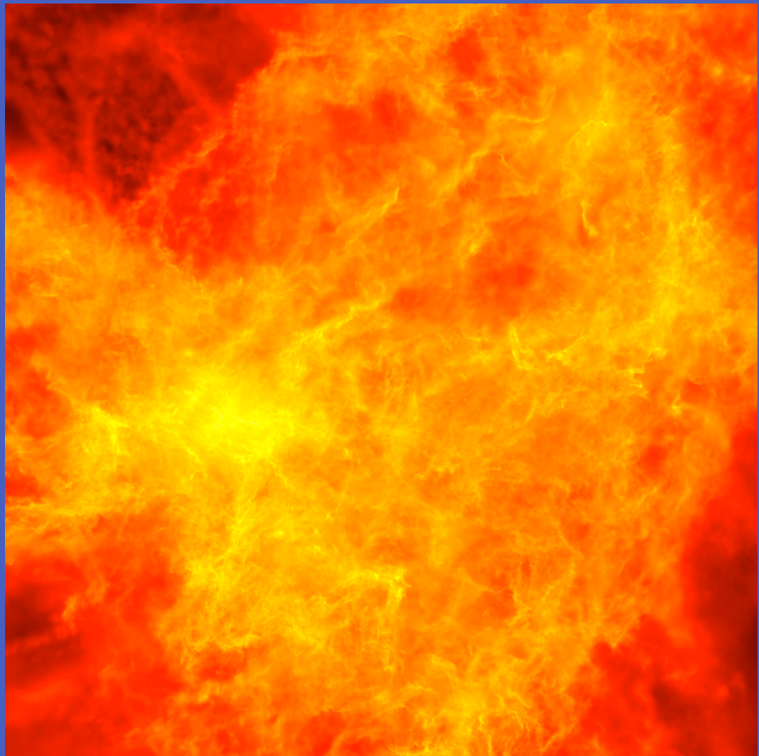
Star Formation in Molecular Clouds



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What we *think* we know…

From observations of the embedded phase:

- Nearly all star formation takes place in giant molecular clouds (GMCs)

  $M \sim 10^4\, M_\odot$ to $10^6\, M_\odot$; $T \sim 10$ to $40K$; $n \sim 100\ cm^{-3}$

  Clouds are highly structured and contain highly supersonic turbulent motions.

  Star formation efficiency is thought to be low, around a few percent.

- Stars tend to form in mass segregated clusters, rather than in isolation.
- At least locally, the whole process of star formation appears to be more rapid than the old SF models suggest (≤ 6 Myrs). Might not be true in general though!

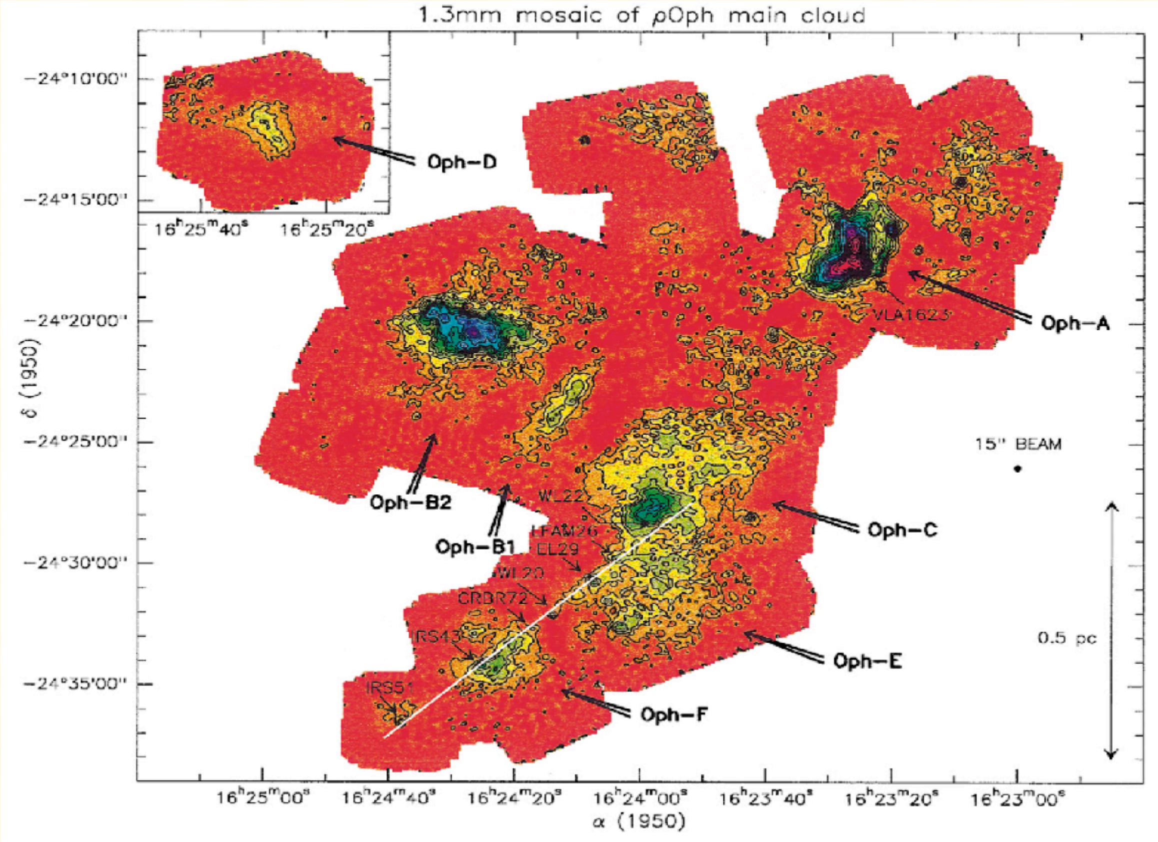
From the field star population:

- The mass function of stars, (initial mass function or IMF) appears to be constant, and has a reasonably well defined shape.
- Binary statistics

A new observational era

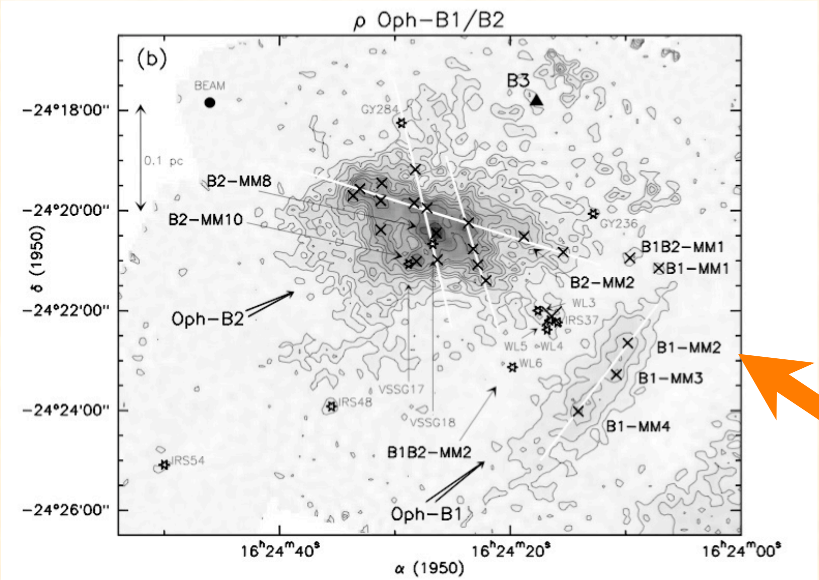
Sub-millimetre observations of dust emmission:

- Arrival of new instrumentation now permits the construction of column density maps of entire star forming regions.
- Has (arguably) less uncertainties in the interpretation than one finds in line-width studies.
- Provides perhaps some of the best mass measurements for molecular clouds.
- Probes a fairly large density regime.

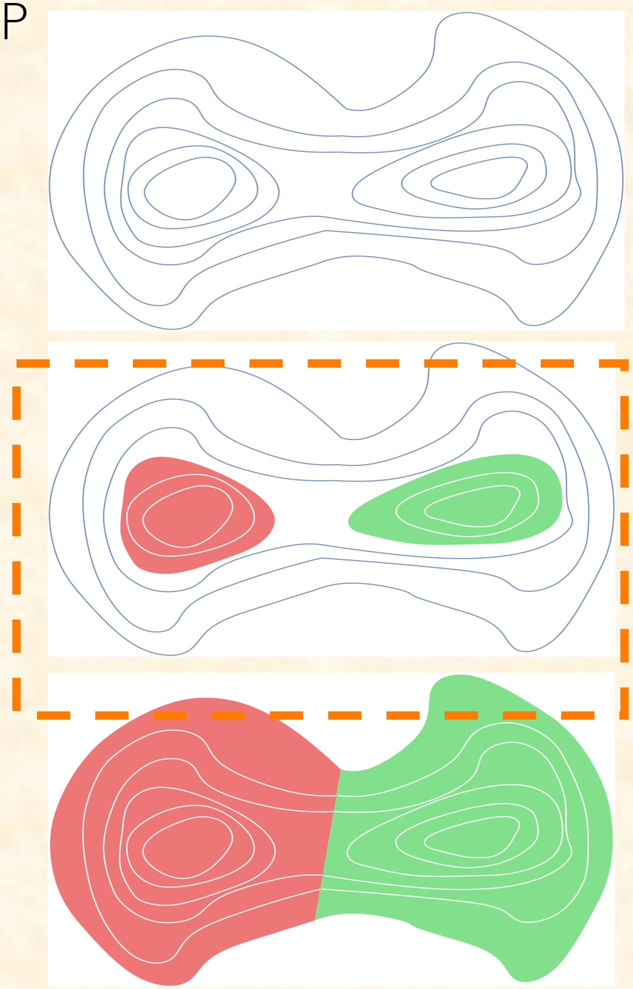


Motte, André & Neri 1998, A&A 336, 150

Clumps in the cores of ρ Oph



Use a 'wavelet' analysis approach to finding the clumps, rather than CLUMPFIND or GAUSSCLUMP

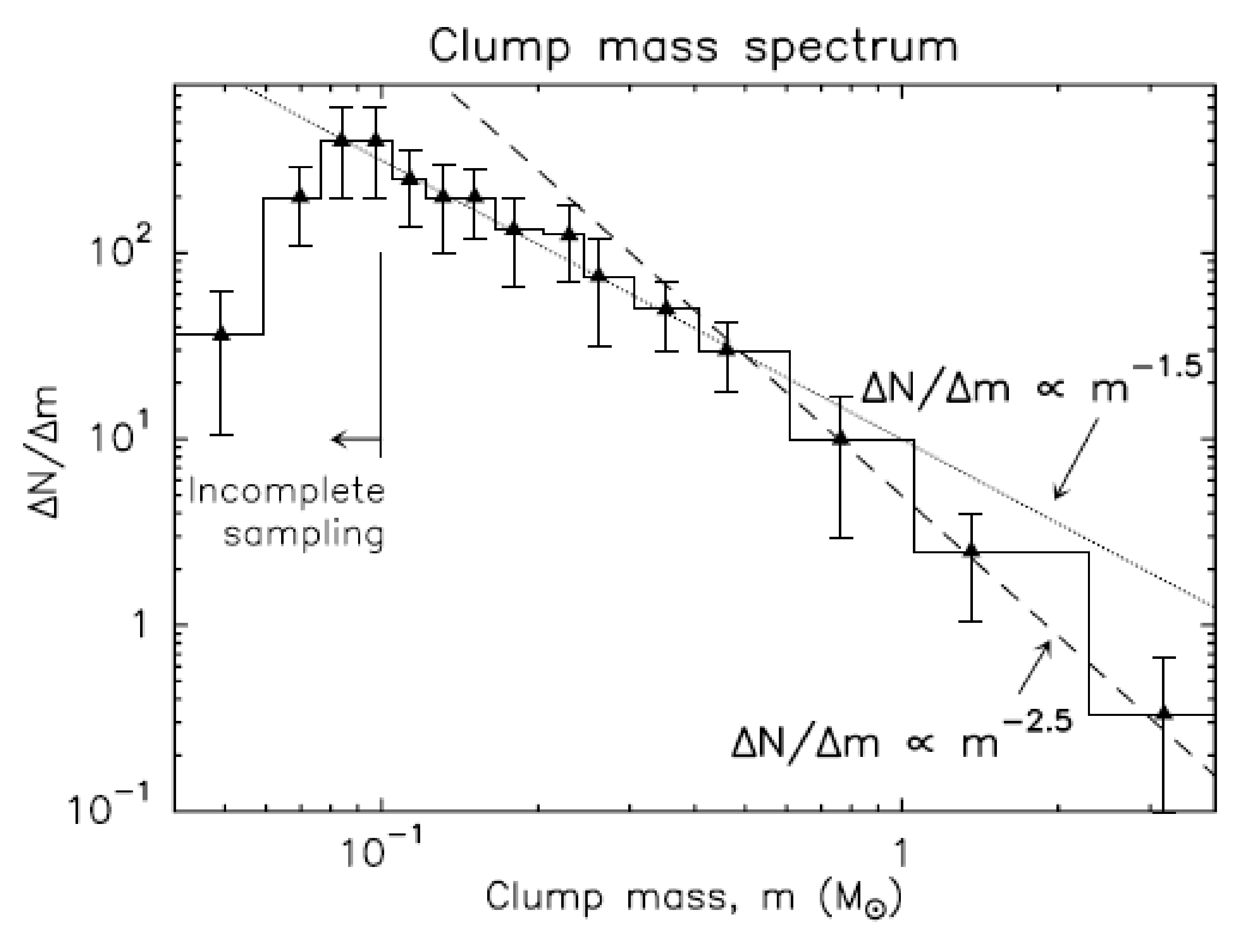


Motte et al (1998) studied the cores in ρ Oph:

- Throughout the 6 cores, find **59 starless 'clumps'**
- Clumps typically have a size of ~6000 AU but structure is seen down as far as the resolution limit will allow (~800AU)
- Typical clump densities are 10^5 to 10^9 cm^{-3}

Motte, André & Neri 1998, A&A 336, 150

Mass function of 'clumps'



$$\Delta N \propto m^{\alpha}\, \Delta m$$

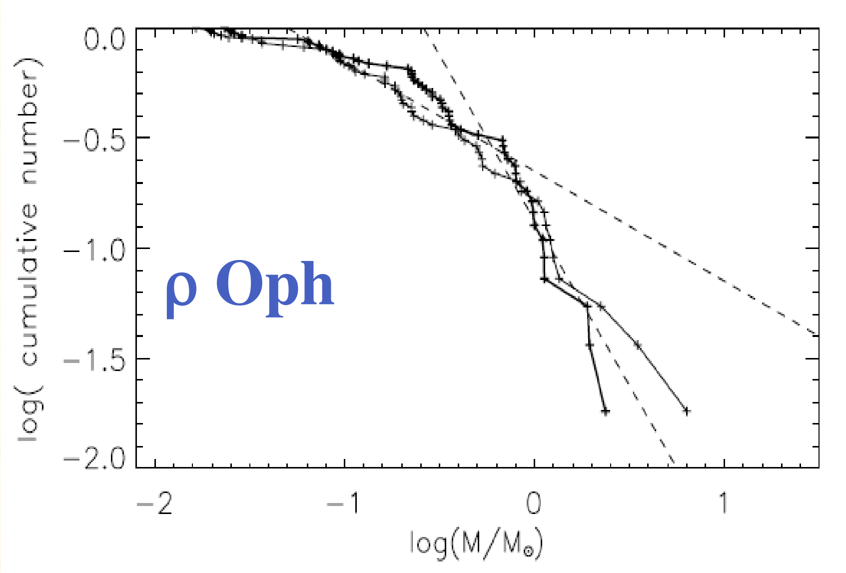
$\alpha = -1.5 \quad m < 0.5$

$\alpha = -2.5 \quad m > 0.5$

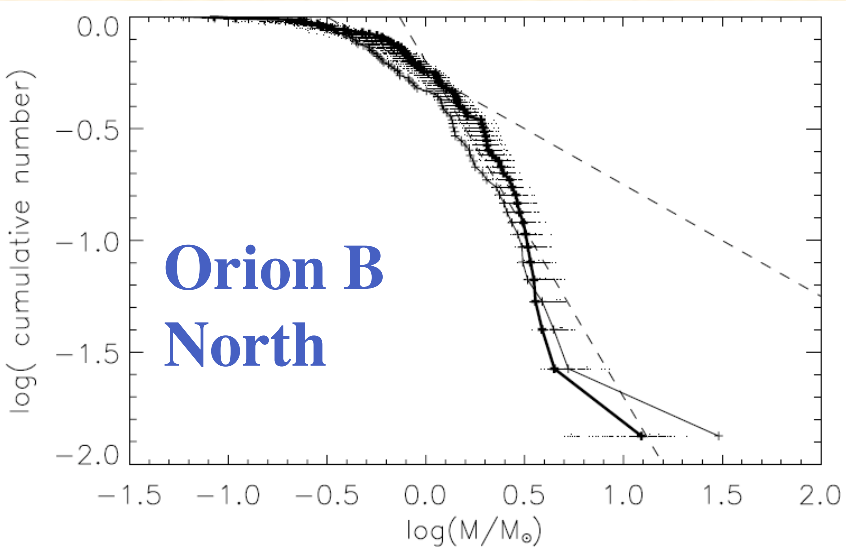
Motte, André & Neri 1998, A&A 336, 150

→ Looks fairly similar to the stellar IMF

Mass function of 'clumps'



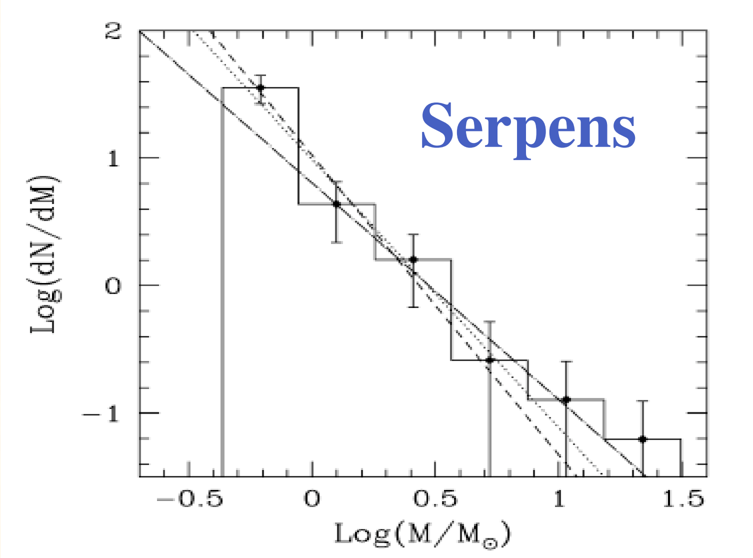
Johnstone et. al. 2000, ApJ, 545, 327



Johnstone et. al. 2001, ApJ, 559, 307

- Results of Motte et al (1998) have been confirmed by Johnstone et al 2000 for ρ Oph, using different methods

- Also seems to be true for other regions of SF



Testi & Sargent 1998, ApJ, 508L, 91

Turbulence and the creation of the IMF

- Scaling laws for turbulent motions (i.e. the 'Larson' laws) suggest that each scale in a cloud is characterised by a particular Mach number of shock. (isothermal gas).

$$\Delta v \propto L^{\alpha}$$

$$\rho \propto L^{\beta}$$

- Length of flows is also comparable to the size scale, ***L***.
- Identify post-shock (and thus denser) gas with 'clumps'

- Can create a scaling law which relates the mass of the clump to the length-scale:

$$m \approx \frac{\rho_0 L_0^3}{\mathcal{M}_{A,0}^2} \left[\frac{L}{L_0}\right]^{3-2\alpha}$$

(For a magnetically dominated gas)

Padoan & Nordlund 2002, ApJ, 576, 870

- Using some mass conservation arguments can show that the number of clumps of a given mass is:

$$N(m)\ d\log m \propto m^{-3/(3-2\alpha)}\ d\log m$$

- For MHD turbulence, with α = 0.37 (*Boldyrev et al 2002 ApJ, 569, 841*), gives a mass power of -1.33

Again, very similar to the stellar IMF

Primordial IMF ?

Clump observations are proving popular, since they suggest that IMF is a primordial property of star forming regions, that we can observe (relatively) easily.

They are also backed by the turbulent fragmentation theories, along with the more simple, hierarchical, fragmentation models.

Both these studies suggest that each 'clump' forms 1 star.

Is the IMF solved ?

Change Career ?

Time-scales for clump collapse

1) Assume each clump has ~1 Jeans mass

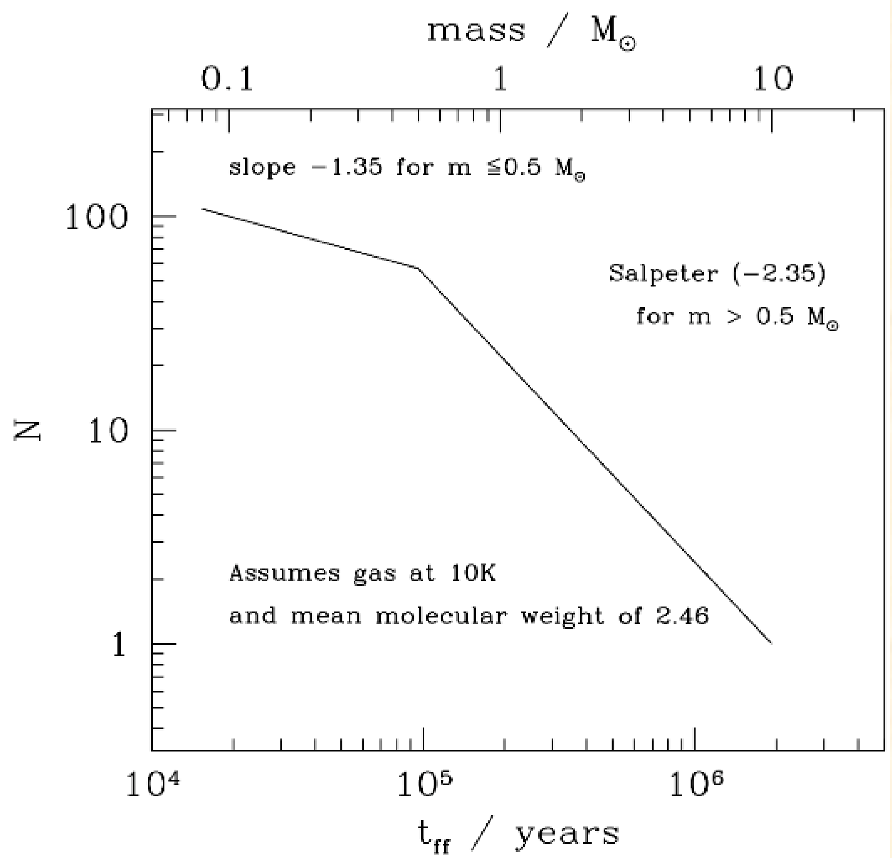
$$m_J = \left[\frac{4\pi\rho}{3}\right]^{-1/2} \left[\frac{5}{2}\frac{kT}{G\mu}\right]^{3/2}$$

2) Free-fall time is function of density too…

$$t_{ff} \propto \rho_J^{-1/2}$$

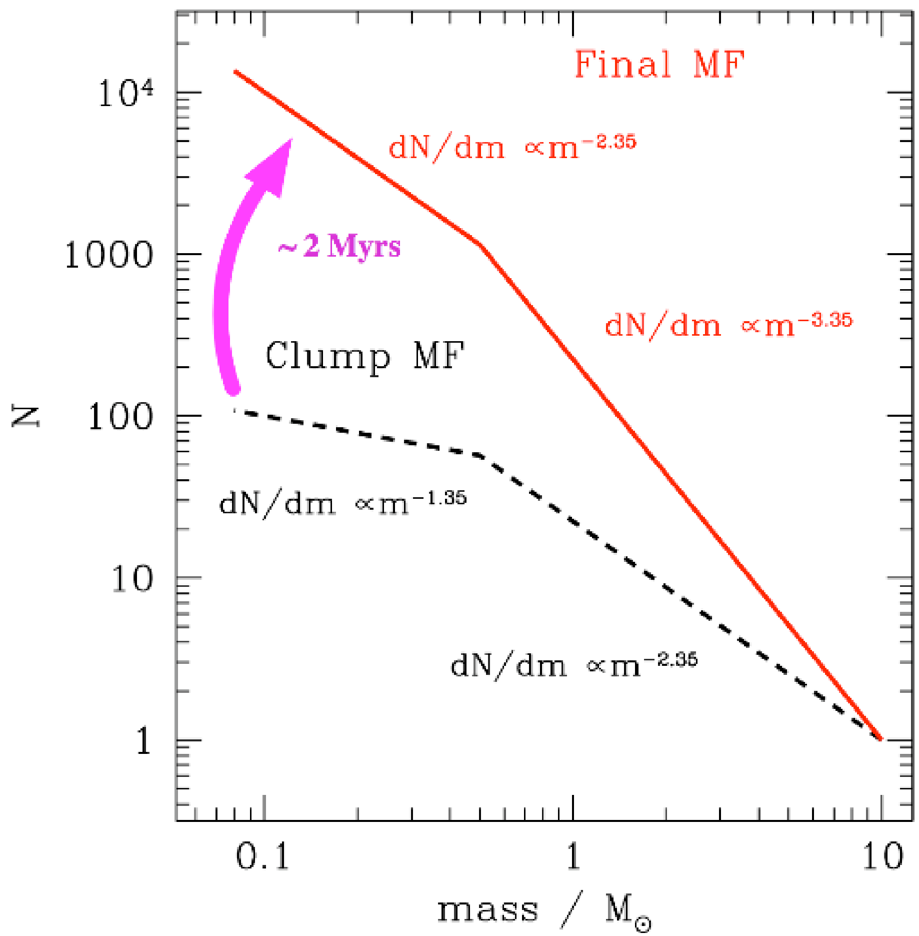
3) Which means the collapse time-scale is proportional to the **mass** of the clump:

$$t_{coll} \propto m_{clump}$$



Clumps collapse on different time-scales.

Clump mass distribution ⇒ stellar MF



Clark, Bonnell & Klessen, In prep.

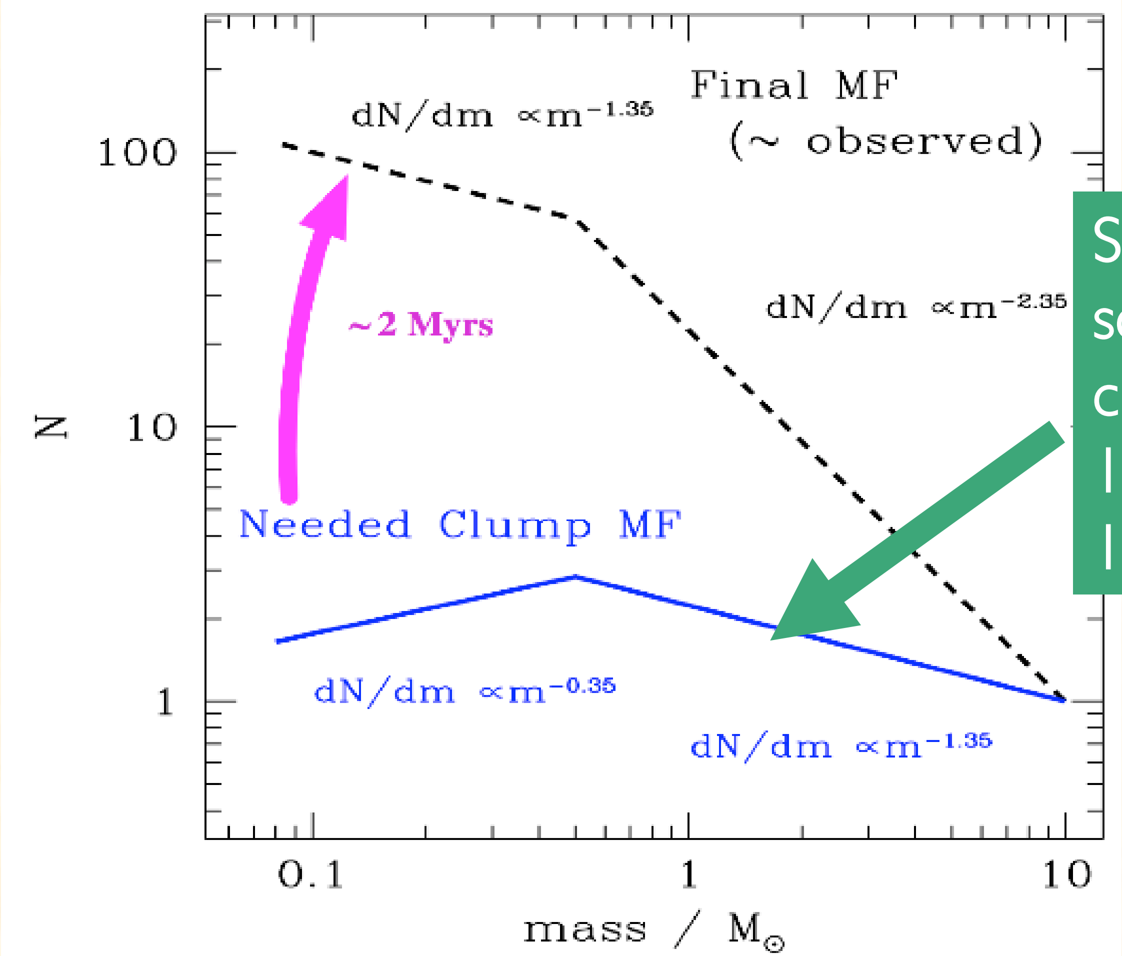
We can use these time-scales to predict how the clump mass spectrum would evolve into a population of stars.

Assume three main points:

1) Clump distribution is constant in time
2) Each clump has one Jeans mass
3) Each clump collapses on a free fall time

Evolve for the free-fall time of the most massive clump

Required clump mass distribution for stellar MF



Similar to scaling laws for clouds (Blitz 1993; Loren 1989)

The **required** clump mass function is much shallower than the observed clump mass functions for these regions.

Multiple systems: multiple problems

Cloud fragmentation has **always** had a problem forming binaries, since the Jeans length required to form (for example) a G - type star is 4 orders of magnitude larger than its typical separation when found in a binary system.

Can get around this problem (at least for low mass stars) if we assume that clumps fragment during the collapse, for example in some sort of rotationally supported core phase, into a small N group.

However this breaks the one-clump-one-star picture.

Clumps will likely need to have **several** Jeans masses to aid the fragmentation, and more if extra forms of support are present or acquired during collapse.

Multiple systems: observations

- Embedded objects have been shown to have a very high multiplicity fraction: essentially all the young stellar objects in rho Oph, Serpens and Taurus have been shown to exist as part of a multiple system.

e.g. Duchêne et. al., 2004, A&A, 427, 651;

Correia et. al. 2006, astro-ph/0608674

- The separations of these systems is typically smaller than, or at most comparable to, the observed clump sizes in these regions.

Suggests that clumps fragment into small N systems!

One-to-one mapping too simple.

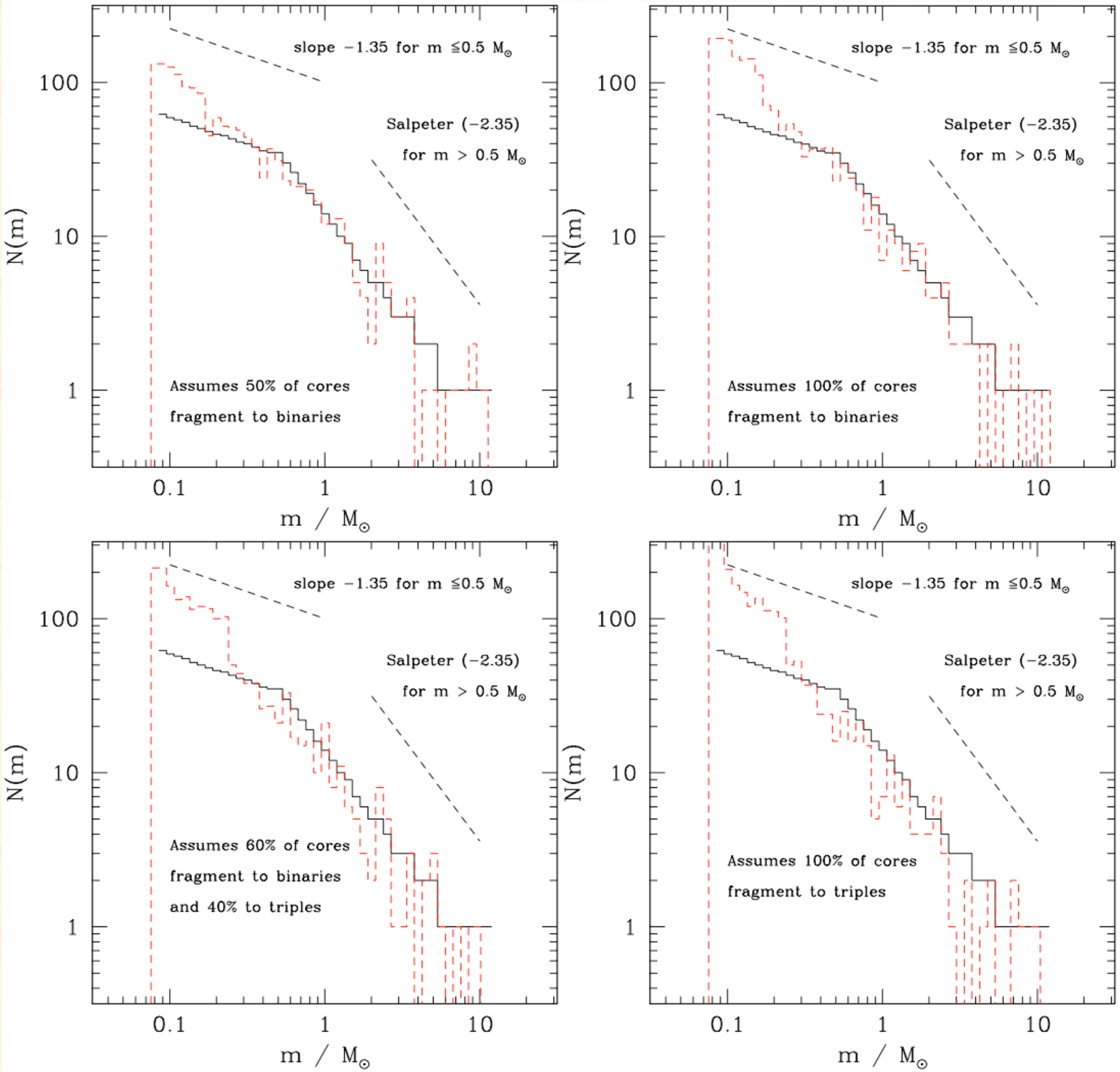
Multiple systems: clump fragmentation

Investigate fragmentation of the clump MF:

- Start with a simple IMF
- Use four different fragmentation prescriptions

Fragmentation results in the loss of the turn-over.

However, the Salpeter slope is maintained.



How likely is the one-clump-one-star picture?

Binary stars present a problem for the one-clump-one-star picture:

- **Either** stars need to form too far apart **or** fragmentation of the clumps destroys the turnover in the resulting IMF.
- However the Salpeter slope is preserved in our simple fragmentation schemes. Still cannot explain the observed properties of high mass stars!

Timescales are a problem:

- Assuming freely collapsing clumps that are both constantly replenished and have the required roughly 1"Jeans mass" of mass, requires a much shallower mass function than observed in order to yield the correct mass function of stars.

1 Jeans mass condition is unlikely:

- Why should a flow care about the size of the post shock region?

Turbulent flows are naturally hierarchical:

- So any clump theoretical clump distribution is also hierarchical.

So what is all this clumpy structure?

- Simulations of both driven and freely decaying turbulence AWAYS show a clump mass spectrum that is similar to the IMF.
- However, only the most massive of these clumps become bound, and collapse (and fragment) to form stellar groups.

  (e.g. Klessen 2001, ApJ, 556, 837; Clark & Bonnell 2005, MNRAS, 361, 2)

- Constant IMF clump distribution is never a problem, since the vast majority of it is unbound and thus transient.
- Further observations are required to establish whether the observed clumps are truly bound or not.

  Johnstone and collaborators suggest they are not even Jeans unstable!

Even ridiculous initial conditions….

Mach 10

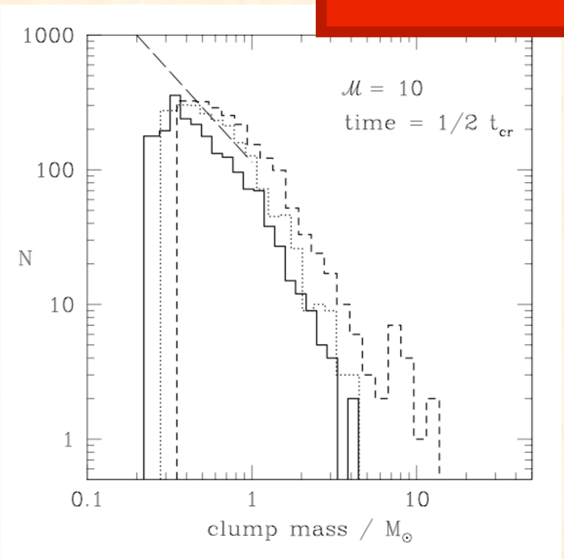
10% filling factor

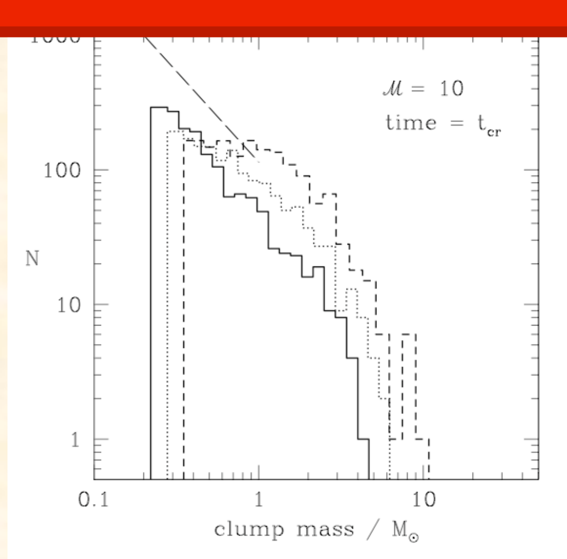
We ran flows of initially identical mass clumps through a shock.

(Baked Bean

Absolutely NO gravity was included in this simulation

= 1 tcr





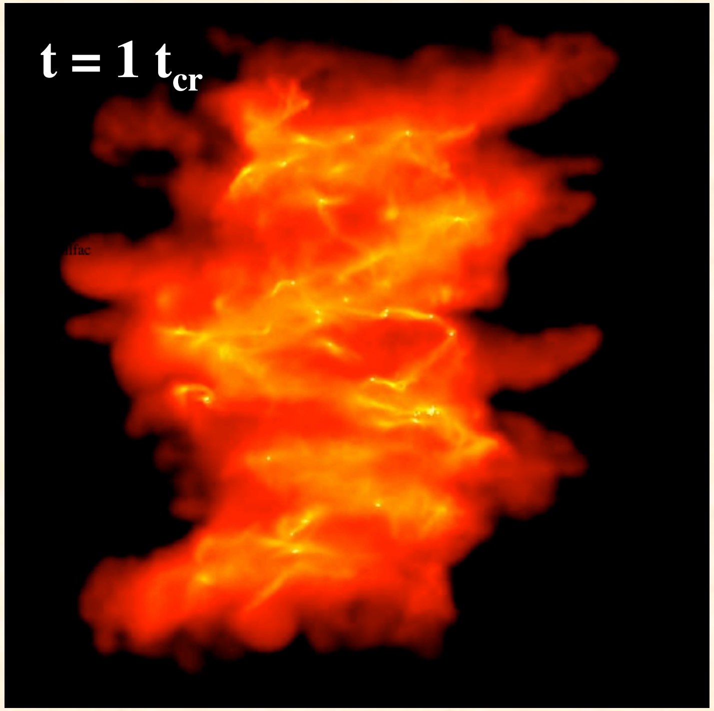
Resulting shredding/coagulation produces a clump mass function with ~ Salpeter slope.

Clark & Bonnell 2006, MNRAS, 368, 1787

…can give the right answer!

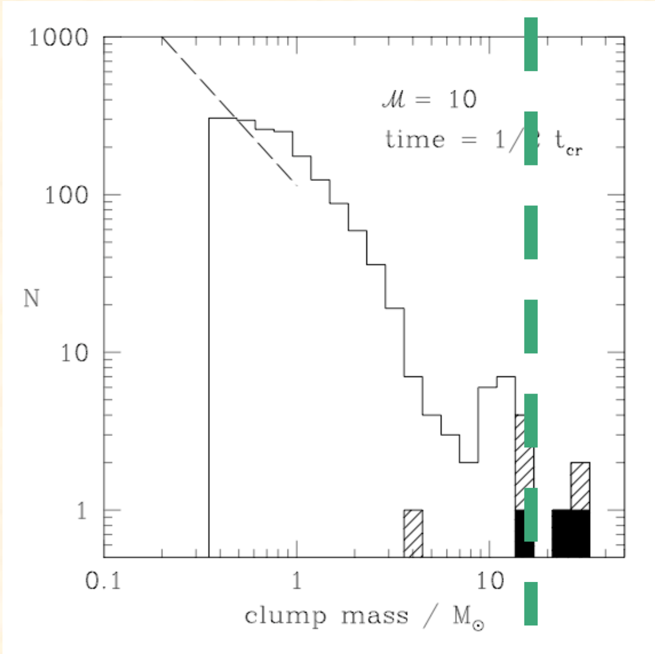
Similar results with gravity….

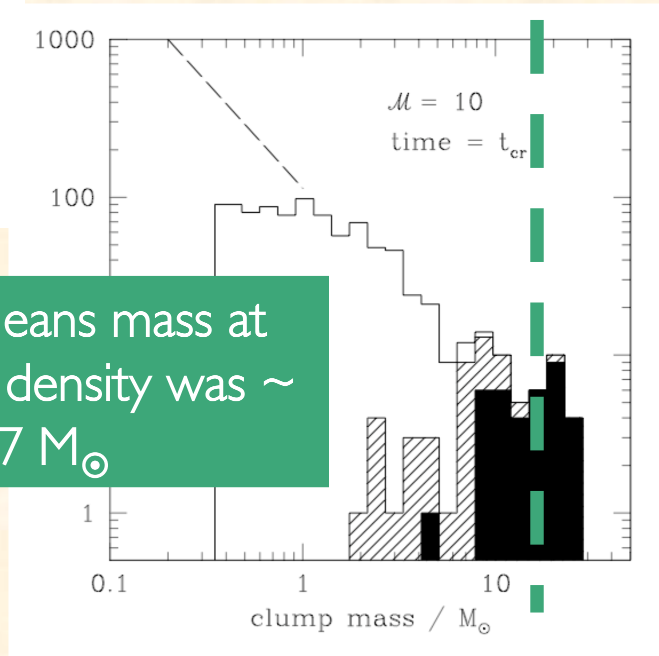
Self gravitating flow of Baked Beans this time!



Mach 10

40% filling factor





Original Jeans mass at pre-shock density was ~ 17 $M_\odot$

- Only the higher mass clumps are bound
- Fragment of these forms groups of stars

So how do you form the IMF?

Competitive accretion?

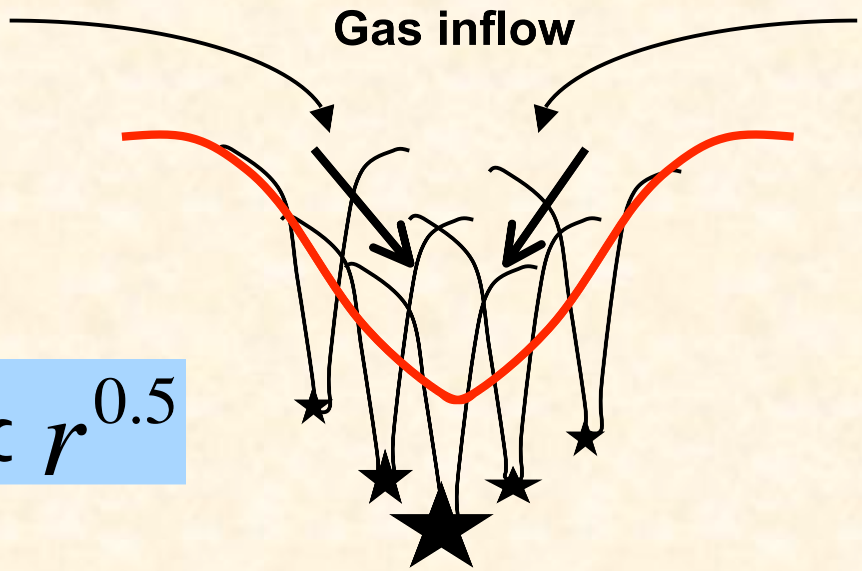
- Gas inflow due to cluster potential
  - to cluster centre
  - Higher gas density
- Initially low relative velocities
  - Turbulence locally small
  - Small-N clusters

$$v \propto r^{0.5}$$

- Stars in centre accrete more
  - Higher accretion rates

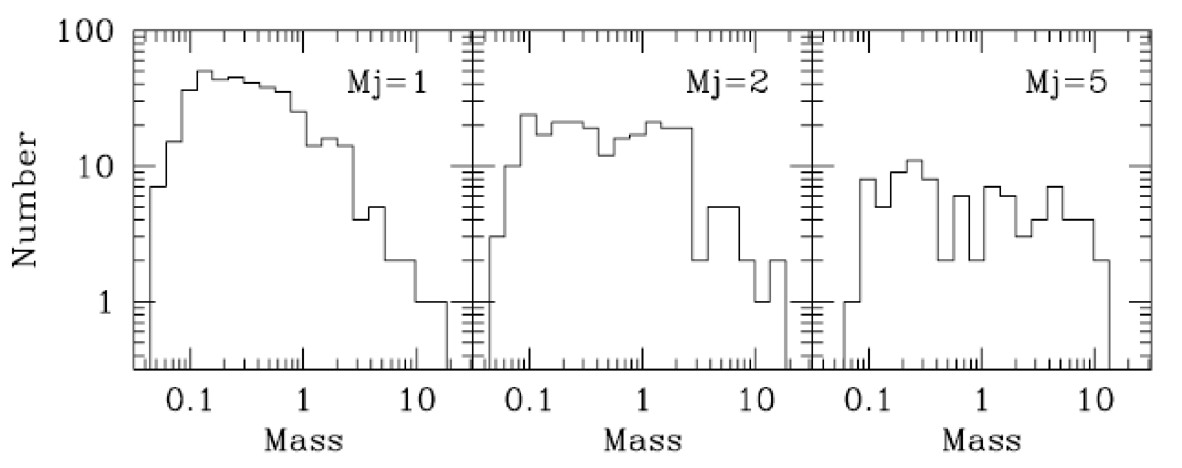
→ massive stars

Bonnell et. al. 2001, MNRAS, 324, 573



Gives a cluster with Salpeter type slope AND mass segregation

Knee of the IMF in competitive accretion



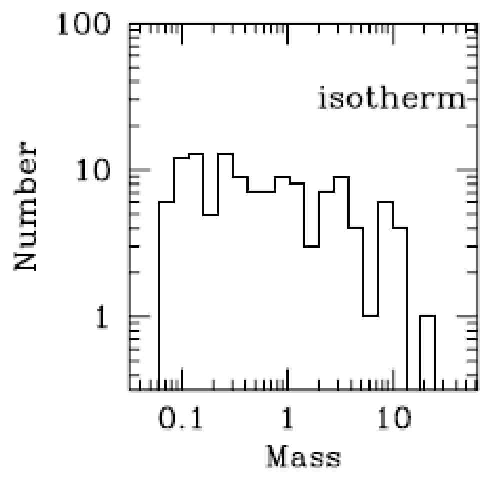
Bonnell, Clarke & Bate, 2006, MNRAS 138, 1296

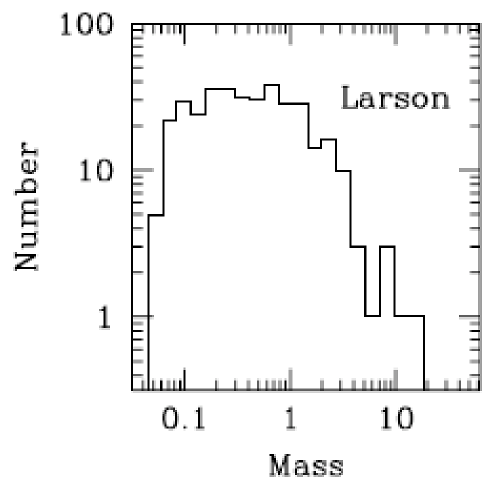
- Clouds of 1000 $M_\odot$ but different Jeans masses
- Knee is controlled by mean initial Jeans mass!

Initial Mj ~ 5 $M_\odot$

$$T = T_c \left(\frac{\rho}{\rho_c}\right)^{-0.25}, \qquad \rho < \rho_c$$

$$T = T_c \left(\frac{\rho}{\rho_c}\right)^{0.1}, \qquad \rho > \rho_c$$





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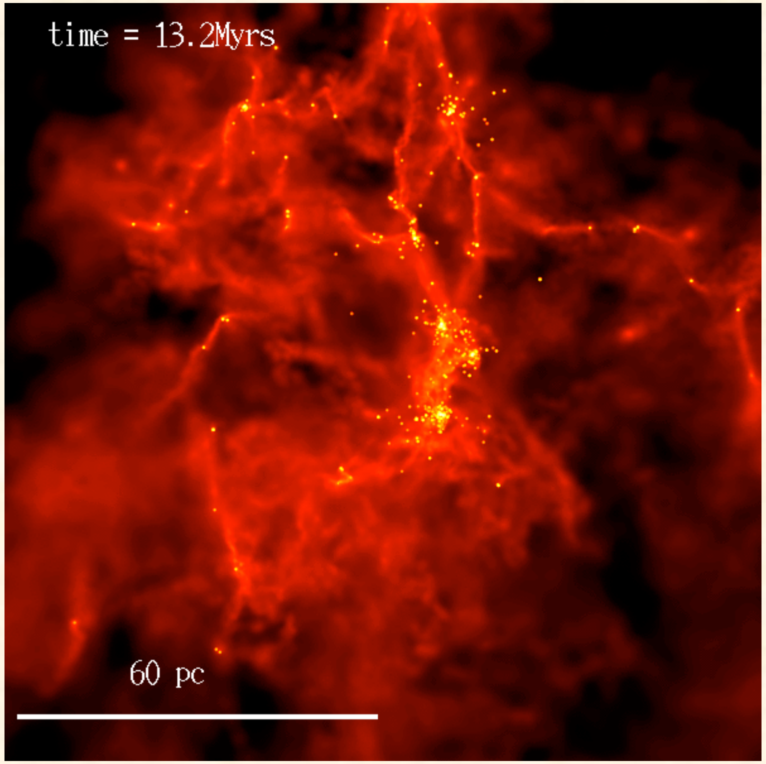
Unbound molecular clouds - naturally low SFE

- Clouds which are dynamically unbound (KE > PE) can still form stars while dispersing on ~2 crossing times, provided they have multiple Jeans masses. *Clark & Bonnell 2004, MNRAS, 347L, 36*

- Results in a naturally low star formation efficiency.

- Turbulence selects regions for star formation via the removal of kinetic energy.



Clark et. al. 2005, MNRAS, 359, 809

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GMC with KE = 2 PE

$M = 10^5 M_\odot$

R ~ 20 pc

SFE < 10% after 10Myrs

Forms a series of clusters which have similar properties to an OB association

Unbound clouds

- How low can the SFE get ?
- What happens to the IMF as clouds become progressively more unbound ?

Knee/normalisation of IMF depends on mean density in competitive accretion.

Changes with time!

Simulations

- Model clouds of 1000 $M_\odot$
- Use both isothermal and Larson style EOSs.
- 2,000,000 SPH particles (mass resolution of ~0.05 $M_\odot$)
- Initial density

Isothermal: $\rho_o \sim 2 \times 10^{-19}$ g cm^{-3}

Larson EOS: $\rho_o \sim 2 \times 10^{-20}$ g cm^{-3}

Larson style EOS:

$$T = T_c \left(\frac{\rho}{\rho_c}\right)^{-0.25}, \qquad \rho < \rho_c$$

$$T = T_c \left(\frac{\rho}{\rho_c}\right)^{0.1}, \qquad \rho > \rho_c$$

PE / EK = 0.5

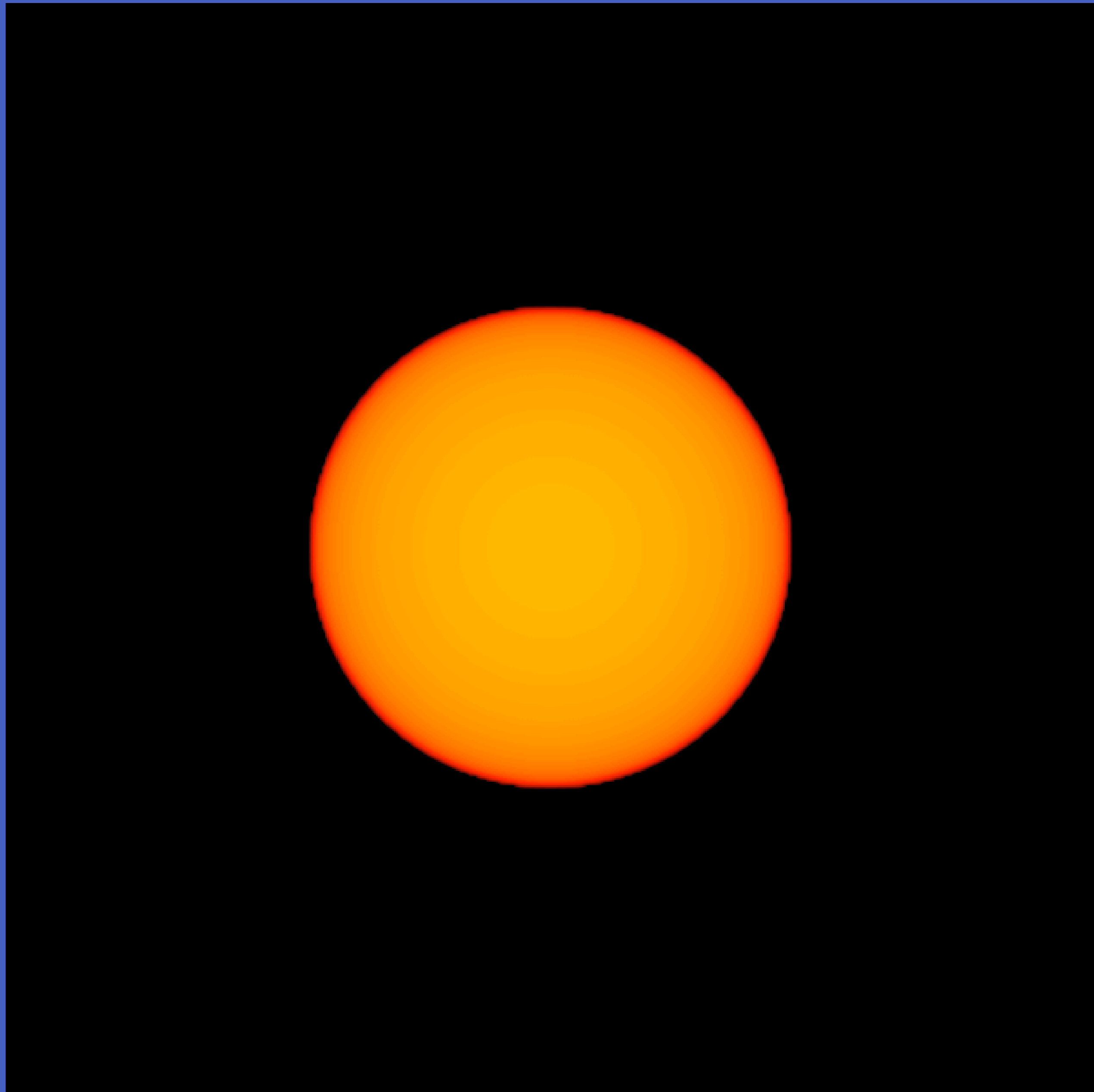
Isothermal EOS

T = 10K

$M = 1000 M_{\odot}$

$t_{ff} \sim 1.5 \times 10^{5}$ yr

$\rho_{o} \sim 2 \times 10^{-19}$ g cm^{-3}



~ 1 pc

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$PE / KE = 0.3$

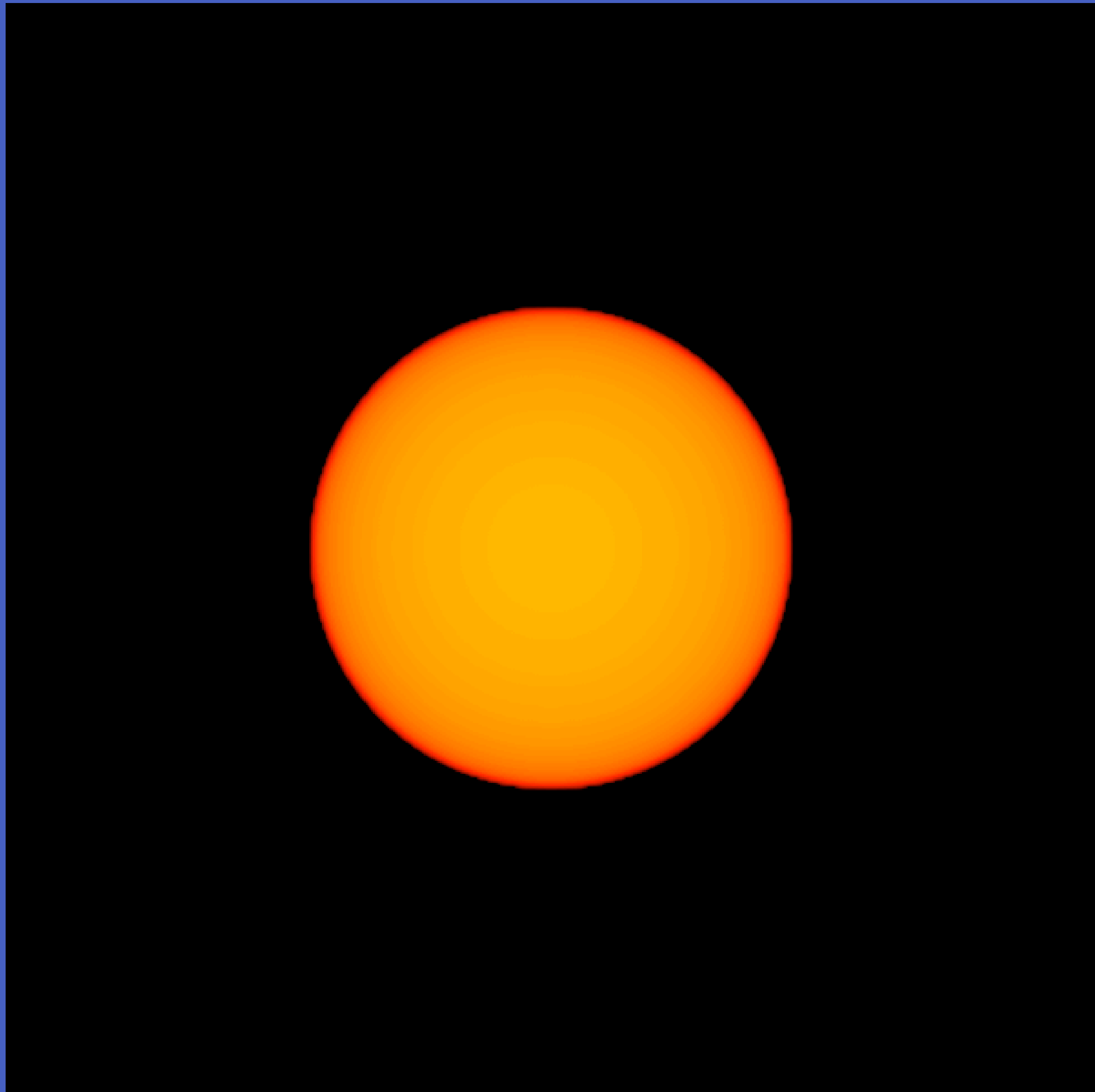
Isothermal EOS

$T = 10K$

$M = 1000 M_{\odot}$

$t_{ff} \sim 1.5 \times 10^5 yr$

$\rho_o \sim 2 \times 10^{-19}$ g cm^{-3}



~ 1 pc

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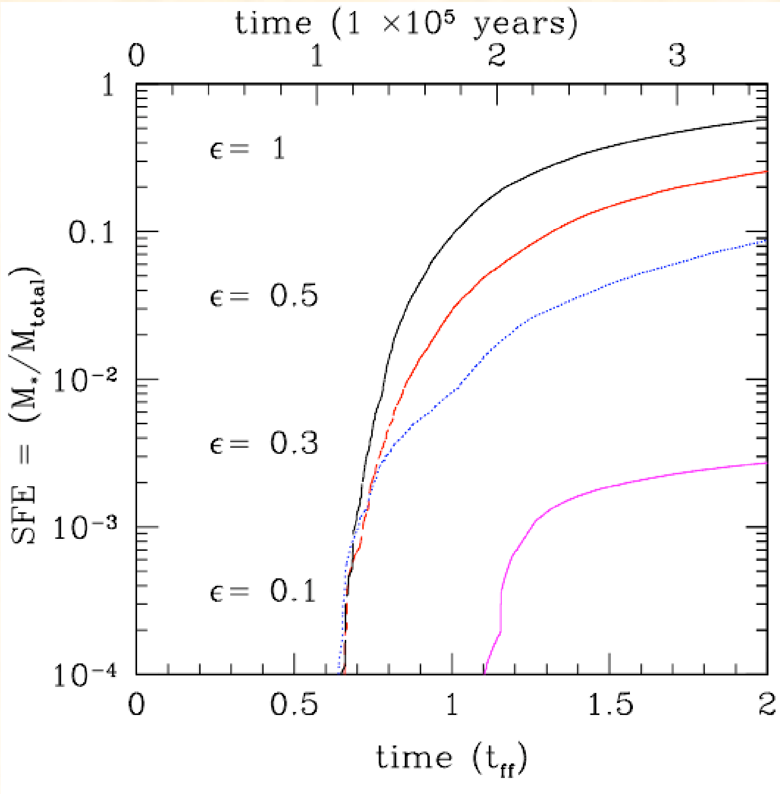
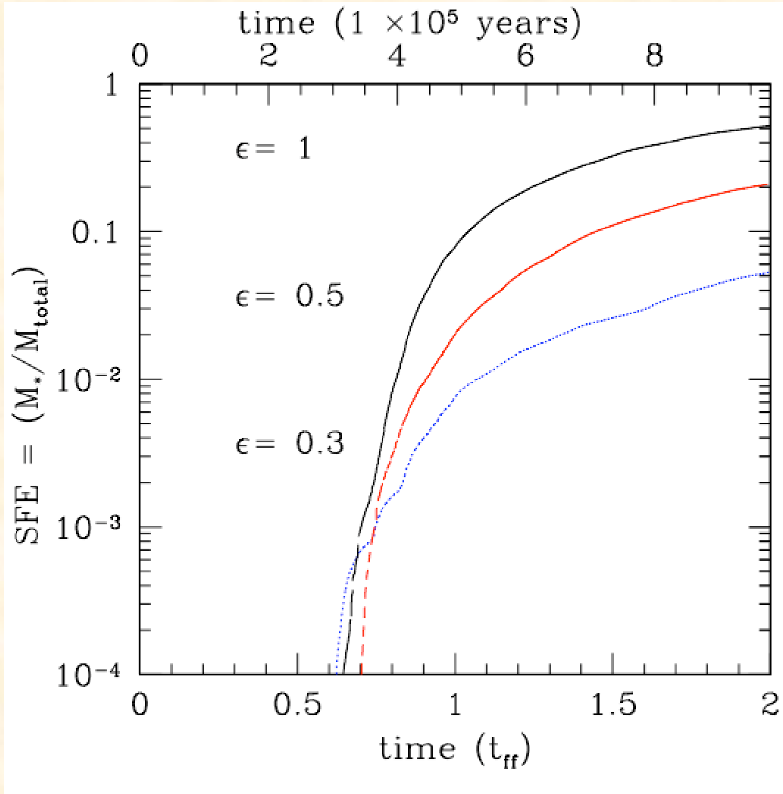
The star formation efficiency

Isothermal runs



Larson EOS runs



Arbitrarily low SFE is possible. However…

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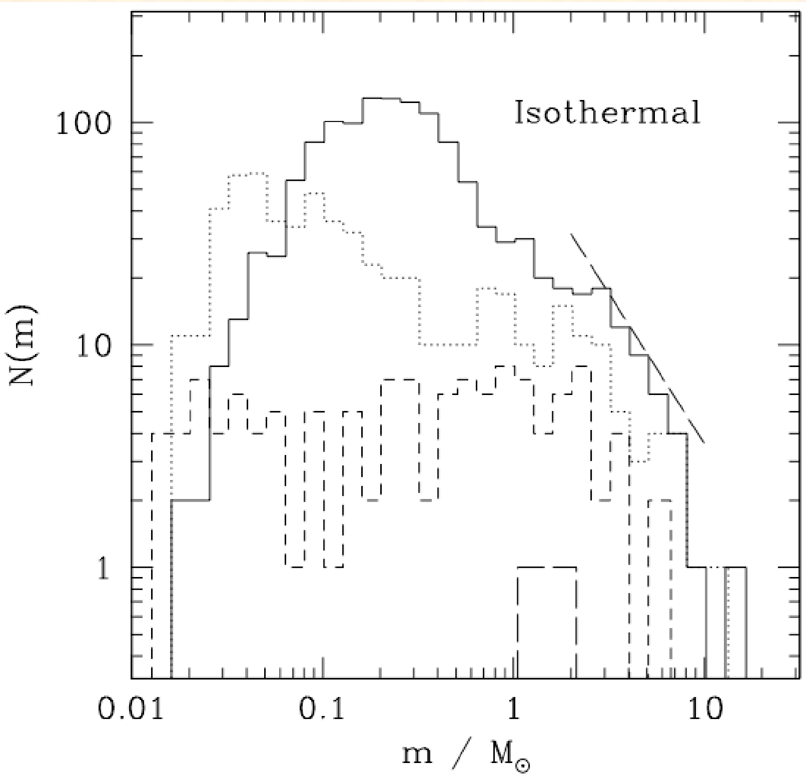
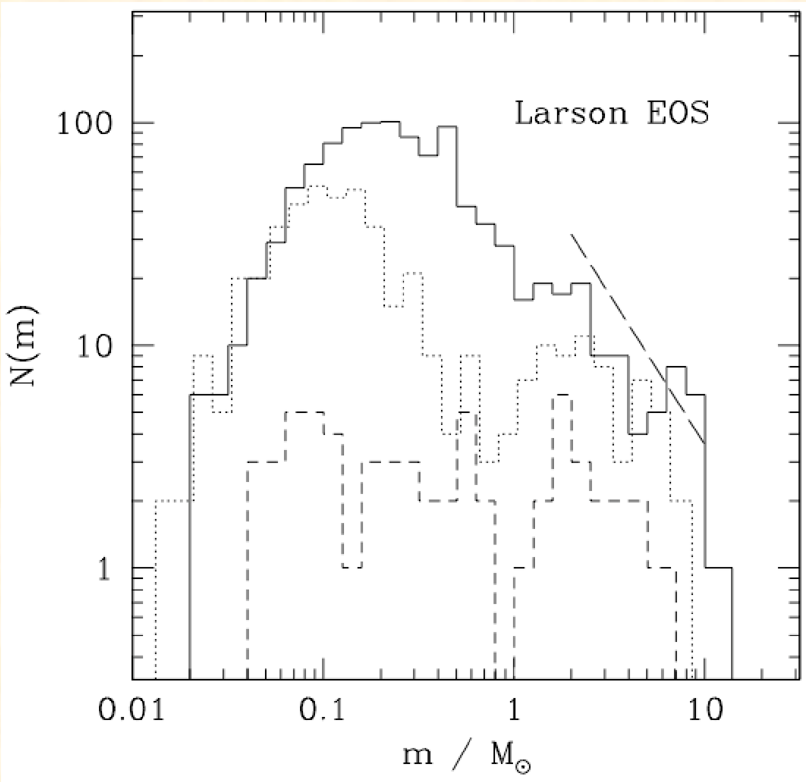
Clark, Bonnell & Zinnecker, In prep.

…the mass function may end up wrong!

Isothermal runs



Larson EOS runs



Perhaps only large bound can give stellar IMF.

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Clark, Bonnell & Zinnecker, In prep.

Unbound cloud IMFs

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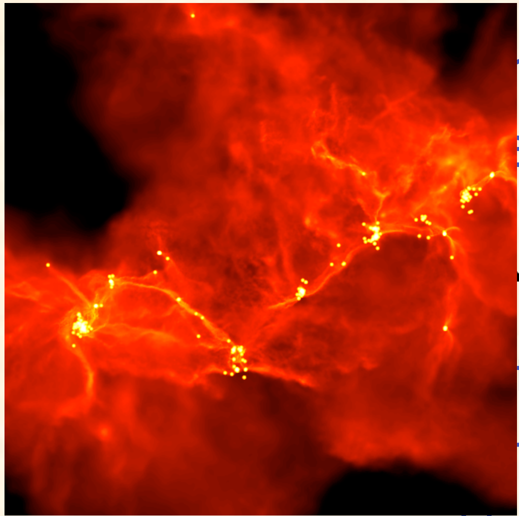
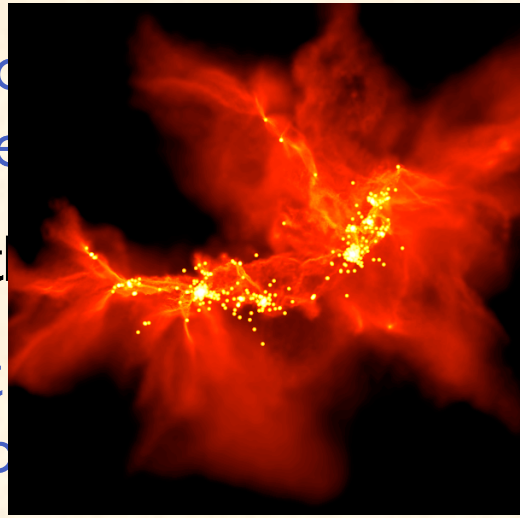
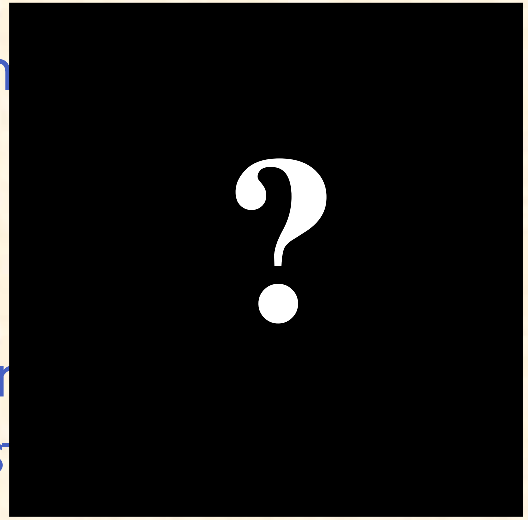
these simulations demonstrate that

s are possible:







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conditions.

$|E_P| - E_K < 0$ $\qquad$ $|E_P| - E_K = 0$ $\qquad$ $|E_P| - E_K > 0$

Flat IMF small N clusters	Stellar IMF	Steeper IMF ? Larger N clusters ?

A Cautionary Note

At the moment, no feed back is included in the simulations.

'Sink particles' are black holes, from which no mass escapes.

If mass-loss rates are some function of stellar mass, dm/dt = f(m), then our IMFs from the simulation may not be enough to capture the essence of the star formation process.

Problem for fragmentation theories of the IMF and the competitive accretion model.

Should we be seeking a different IMF from our simulations ?

Summary…

- It is unlikely that the clump mass function and the stellar IMF are related. The one-to-one mapping required contains too many problems.

- Competitive accretion is an attractive concept, since it can explain more than just the IMF.

- However it is very sensitive to the cloud conditions, and may not give the right answers everywhere.