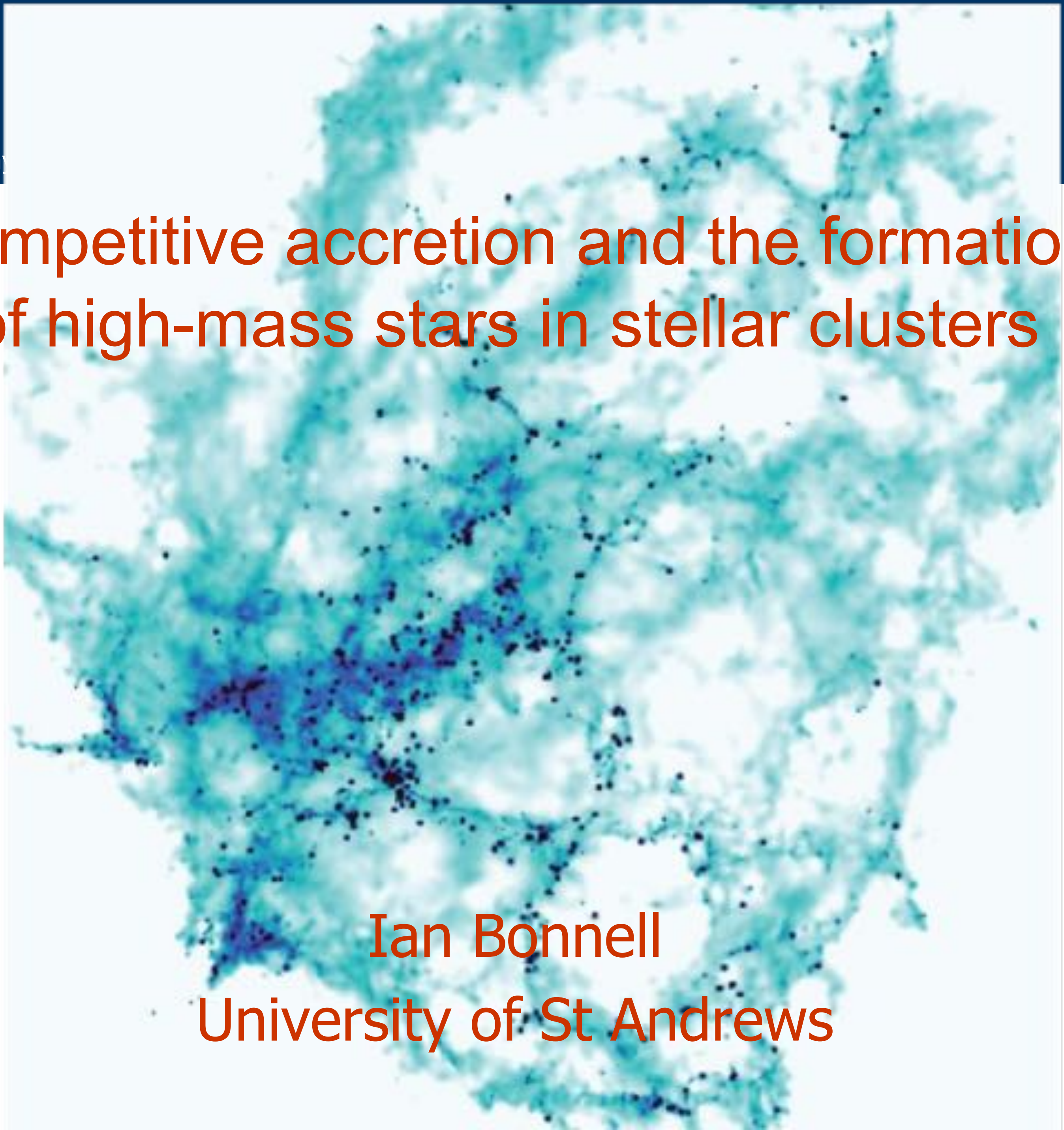
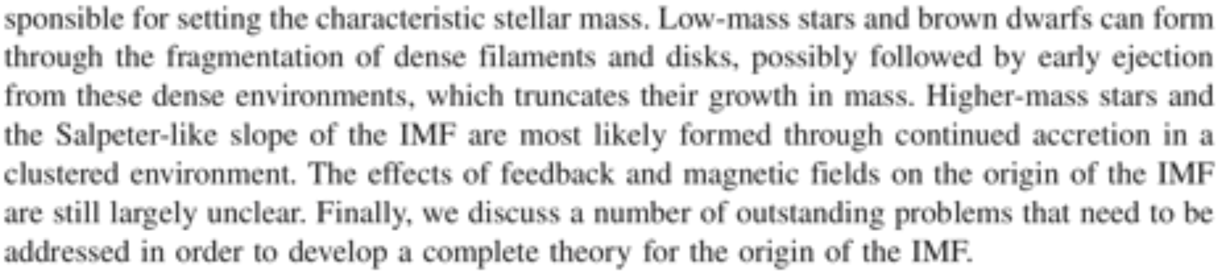
Competitive accretion and the formation of high-mass stars in stellar clusters



Zinnecker &
Yorke 2007,
ARA&A

Ian Bonnell
University of St Andrews

High-mass star formation :
Observations confront Theory, 2007



sponsible for setting the characteristic stellar mass. Low-mass stars and brown dwarfs can form through the fragmentation of dense filaments and disks, possibly followed by early ejection from these dense environments, which truncates their growth in mass. Higher-mass stars and the Salpeter-like slope of the IMF are most likely formed through continued accretion in a clustered environment. The effects of feedback and magnetic fields on the origin of the IMF are still largely unclear. Finally, we discuss a number of outstanding problems that need to be addressed in order to develop a complete theory for the origin of the IMF.

Protostars and Planets V, 2007

1989ESOC...33.

PRE-MAIN SEQUENCE BINARIES

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ABSTRACT

The astrophysics of pre-Main Sequence (PMS) binaries is discussed. Recent observational results on visual, speckle, lunar occultation and spectroscopic PMS binaries are summarized. An outlook into the near future is given. Several suggestions for new observations are made: to image the known visual PMS binaries with NIR arrays (to separate the NIR excess of the components); to measure the 10 μm excess of each component (to probe for separate circumstellar disks); to detect UV boundary layer emission from the individual components (as a tracer of the mass accretion rates); to search for aligned double jets from the components (to probe for coplanar disks). The latter observation might be a means to discriminate between a fragmentation and a capture origin of wide binaries. On the theory side, numerical calculations of the collapse of an elongated filament, rotating end over end, are proposed as a promising mechanism for the formation of wide binaries. The origin of close binaries remains a more daunting challenge. Any formation process must be capable of creating pairs of roughly equal mass and high orbital eccentricity.

1 Introduction

If we look at stars from a sociological point of view, pre-Main Sequence binaries would be the analogs of couples that just got married. Of course, there is a certain percentage of stars and people that remain single. That percentage may depend on (and vary with) the detailed conditions in the respective birthplaces and communities. Normally the percentage of singles is small (10-30%); obviously life is more interesting in pairs. It is also obvious that studying *young* pairs (when the constituents are settling) is more rewarding than *mature* pairs (when both have settled on the Main Sequence). Young pairs allow us to gain insight into the dating process, i.e. how the two bodies initially got physically attracted to each other.

At this point I will quit the comparative sociology of stars and people in the hope that it will have done the trick to remind the reader of the fundamental fact that most young stellar objects must be expected to be physical pairs – a fact well known, yet still too often ignored.

Zinnecker, 1989

HansFest: Wonders of Star Formation

Rotating filaments as binary formation

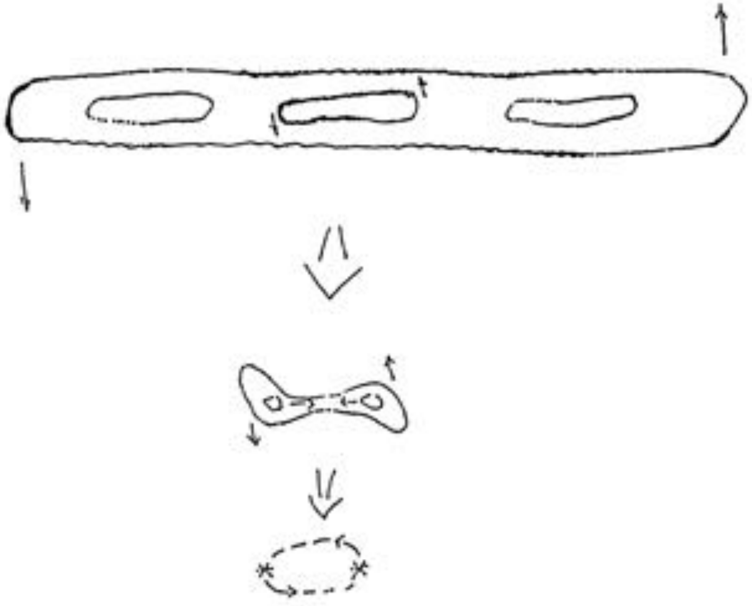

Fig. 1. Schematic evolution of a prolate subcondensation in a filament into a protobinary system. Here the angular momentum vector is perpendicular to the plane of the sky. The velocity gradient along the filament is ~ 1 km s^{-1} pc^{-1}. Arrows indicate the direction of motion. The initial length of the subcondensations is ~ 0.2 pc, the final major axis of the binary system is between 100 and 1000 AU.

Rotating filaments as binary formation

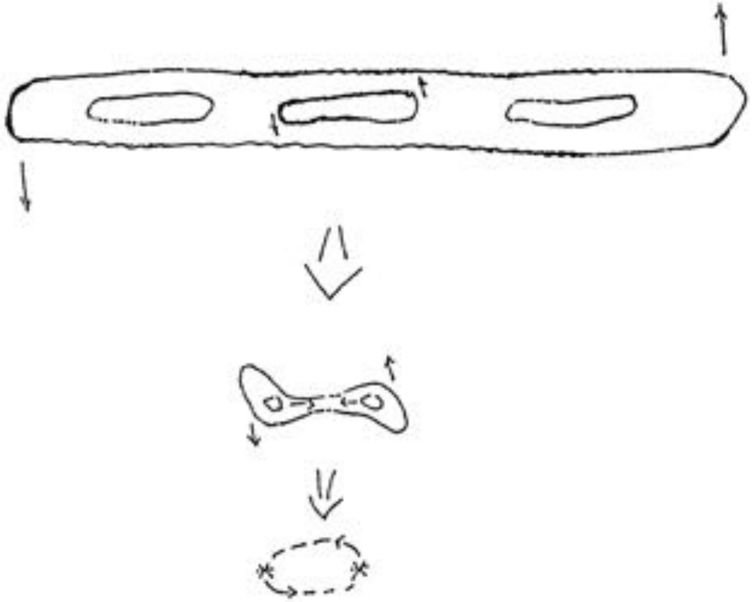

Fig. 1. Schematic evolution of a prolate subcondensation in a filament into a protobin
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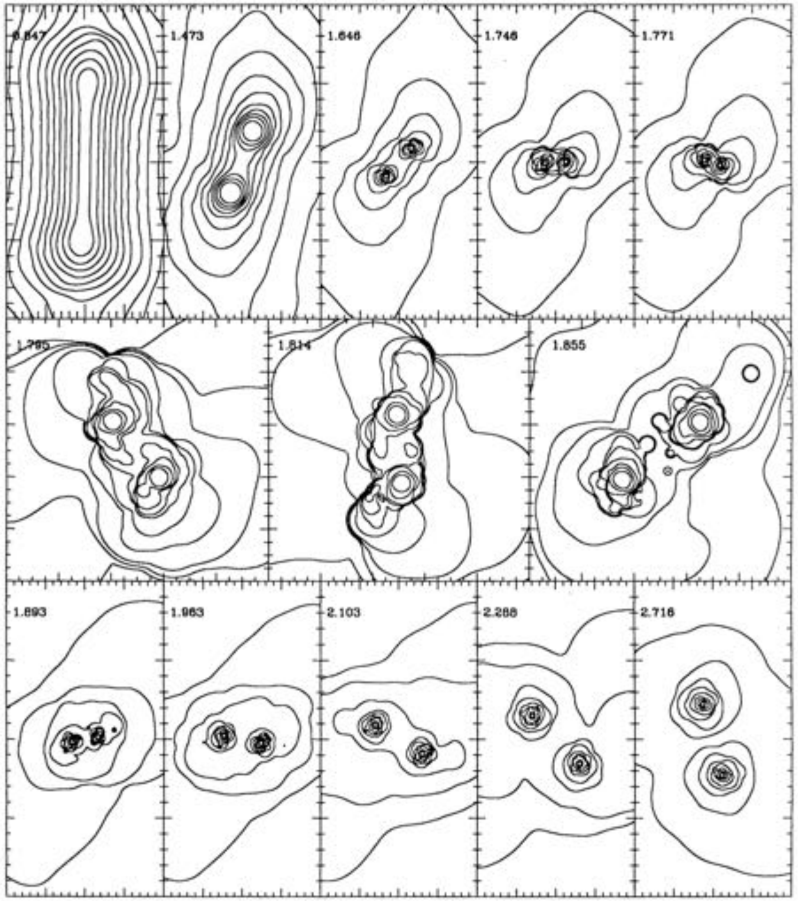
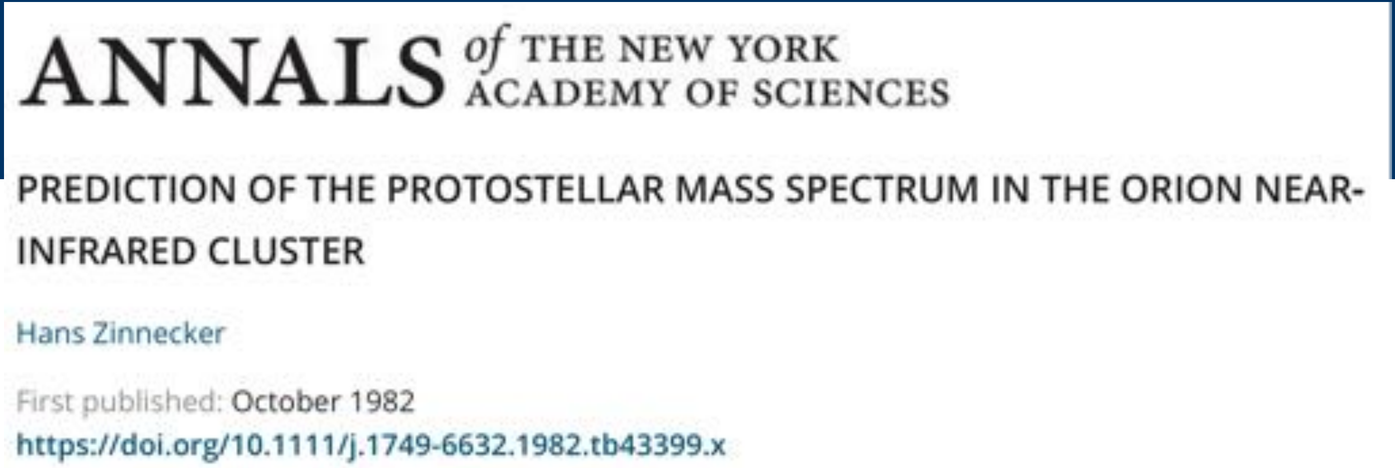




ANNALS of THE NEW YORK ACADEMY OF SCIENCES

PREDICTION OF THE PROTOSTELLAR MASS SPECTRUM IN THE ORION NEAR-INFRARED CLUSTER

Hans Zinnecker

First published: October 1982
https://doi.org/10.1111/j.1749-6632.1982.tb43399.x

Abstract

A simple analytical accretion model is developed for the protostellar mass spectrum in the infrared cluster in Orion (OMC1/KL region) in which protostellar cores compete for the accretion of the gas of their parent cloud. Unlike coagulation models, this model is a linear model which includes the conservation of the number of accretion nuclei, with no collisional mergers occurring. Gas exhaustion effects are not included, since less than 50 percent of the cloud gas will be accreted before the most massive star powers the formation of a hot H II region or the formation of an energetic stellar wind, thereby freezing the mass spectrum. A mass spectrum is predicted to be of the form dN/d log M approximately equal to 1/M for M greater than or approximately equal to 1 solar mass, independent of the form of the mass spectrum at the beginning of the accretion process. In particular, a runaway growth of the most massive star, with a big gap in mass to the next massive star, is predicted.

Competitive accretion

- Fragmentation down to (thermal) Jeans Mass
  - Form as lower mass stars (~ 0.5 M_{sun})
  - Subsequent accretion forms high-mass stars

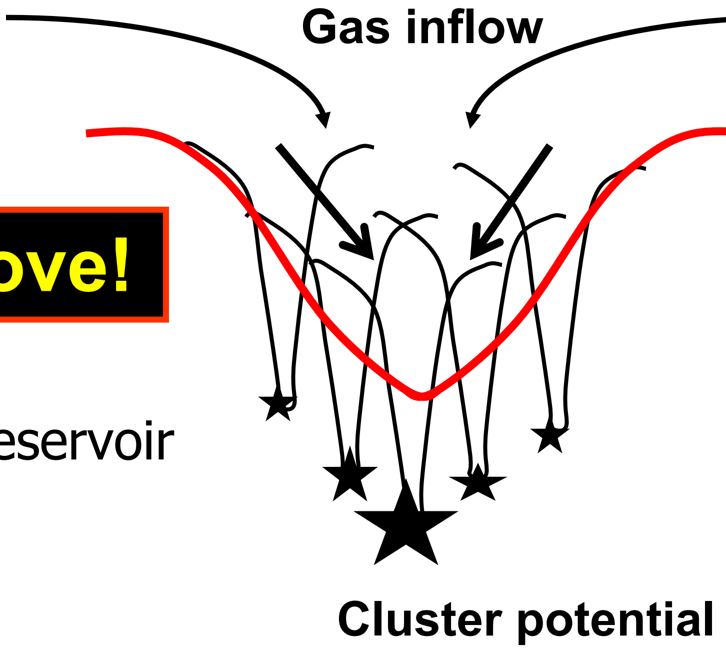
Bonnell et al 1997, 2001, 2004

Bonnell & Bate 2006

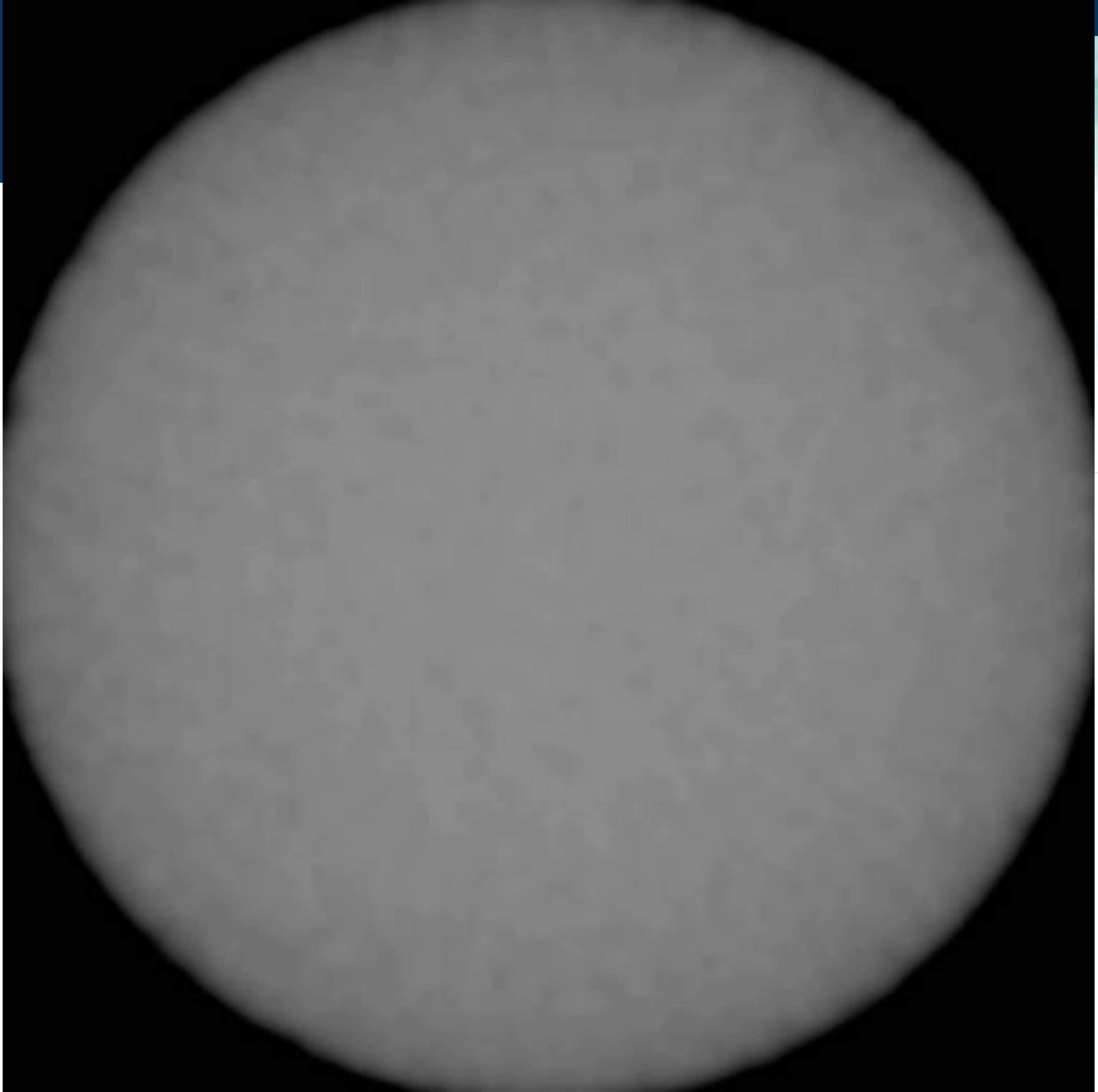
- Accretion limited by
  - Tidal effects
  - Gas velocities: Bondi-Hoyle

Stars do not have to move!

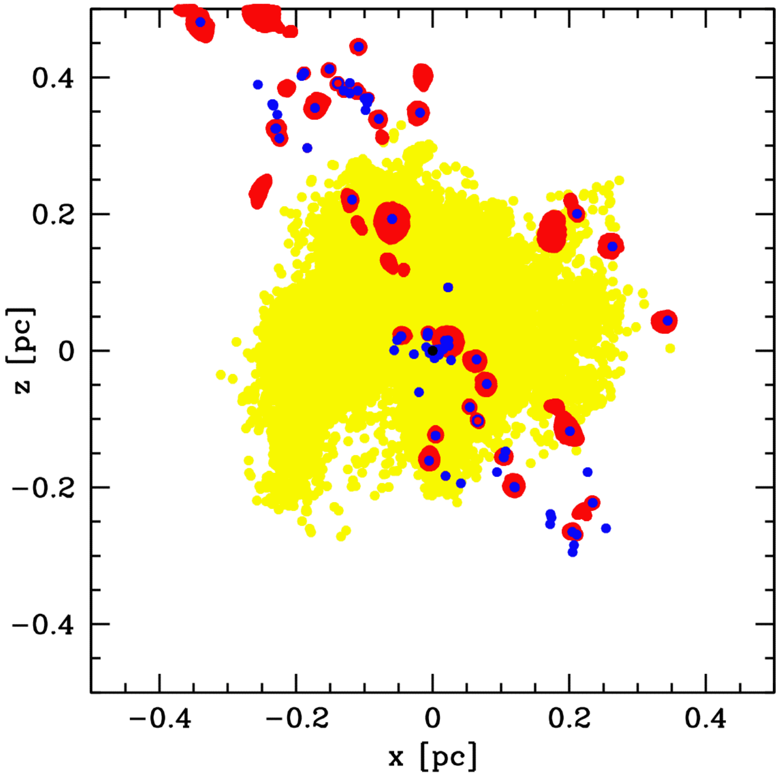
- Gas inflow due to cluster potential
  - Fragmentation inefficient : common gas reservoir
  - Higher gas densities and accretion rates:
- Requirements:
    - N > 2 fragments, gravitationally bound
  - Common gas reservoir



Bonnell, Larson & Zinnecker 2007

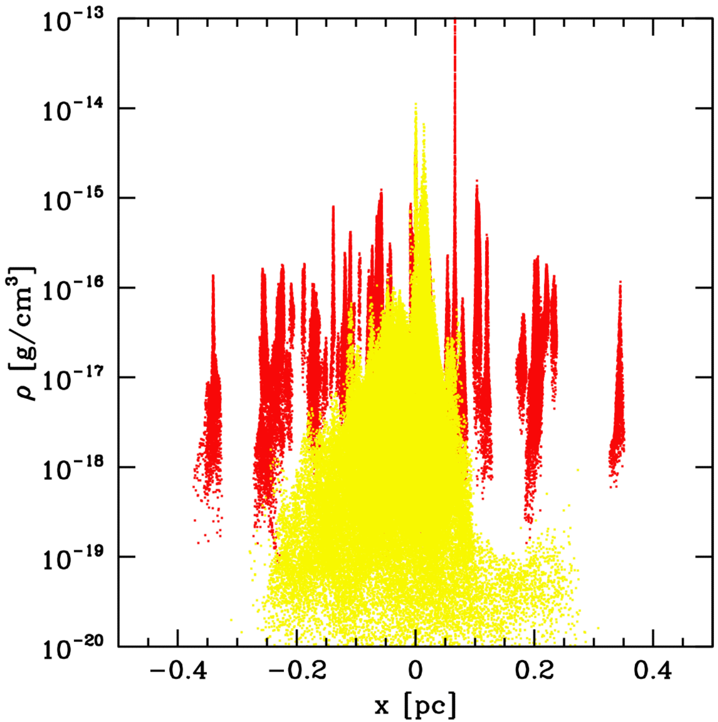


Accretion reservoirs



Accretion onto high-mass stars comes from cluster scale, lower density gas

Yellow = mass which will be accreted by the most massive sink within 0.25 t_{dyn}

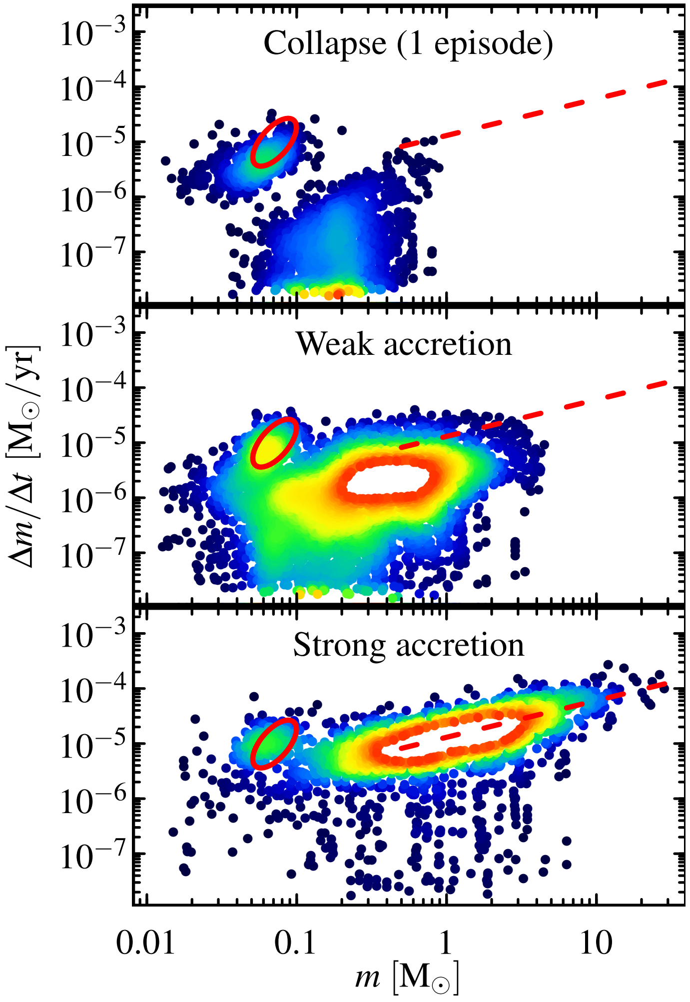


Infalling fragments (cores) need to be dense, tidally bound

form low-mass stars

Smith et al 2009

Accretion in clusters and the IMF

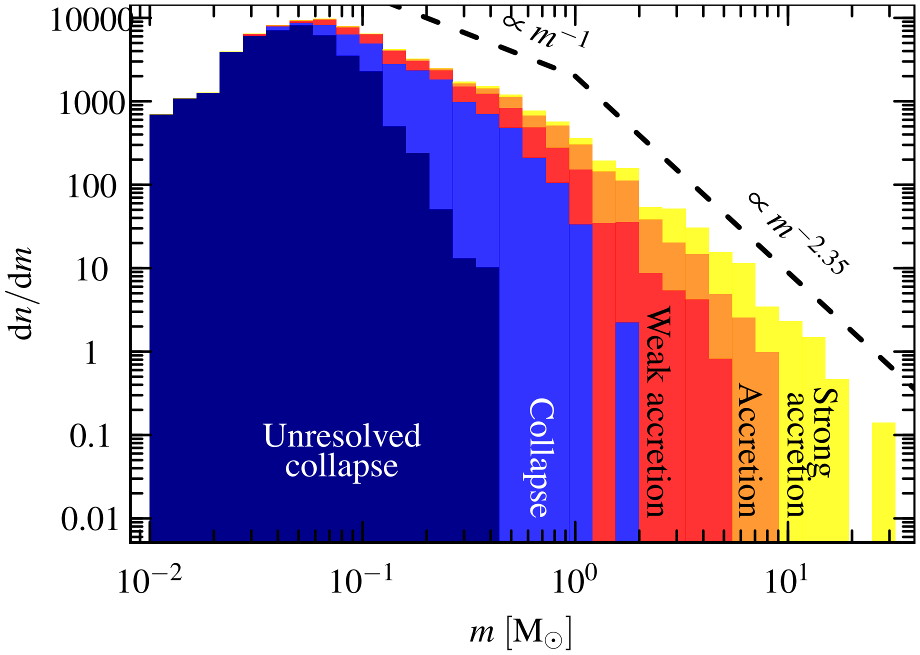


Maschberger et al 2014

- Higher mass stars formed through accretion

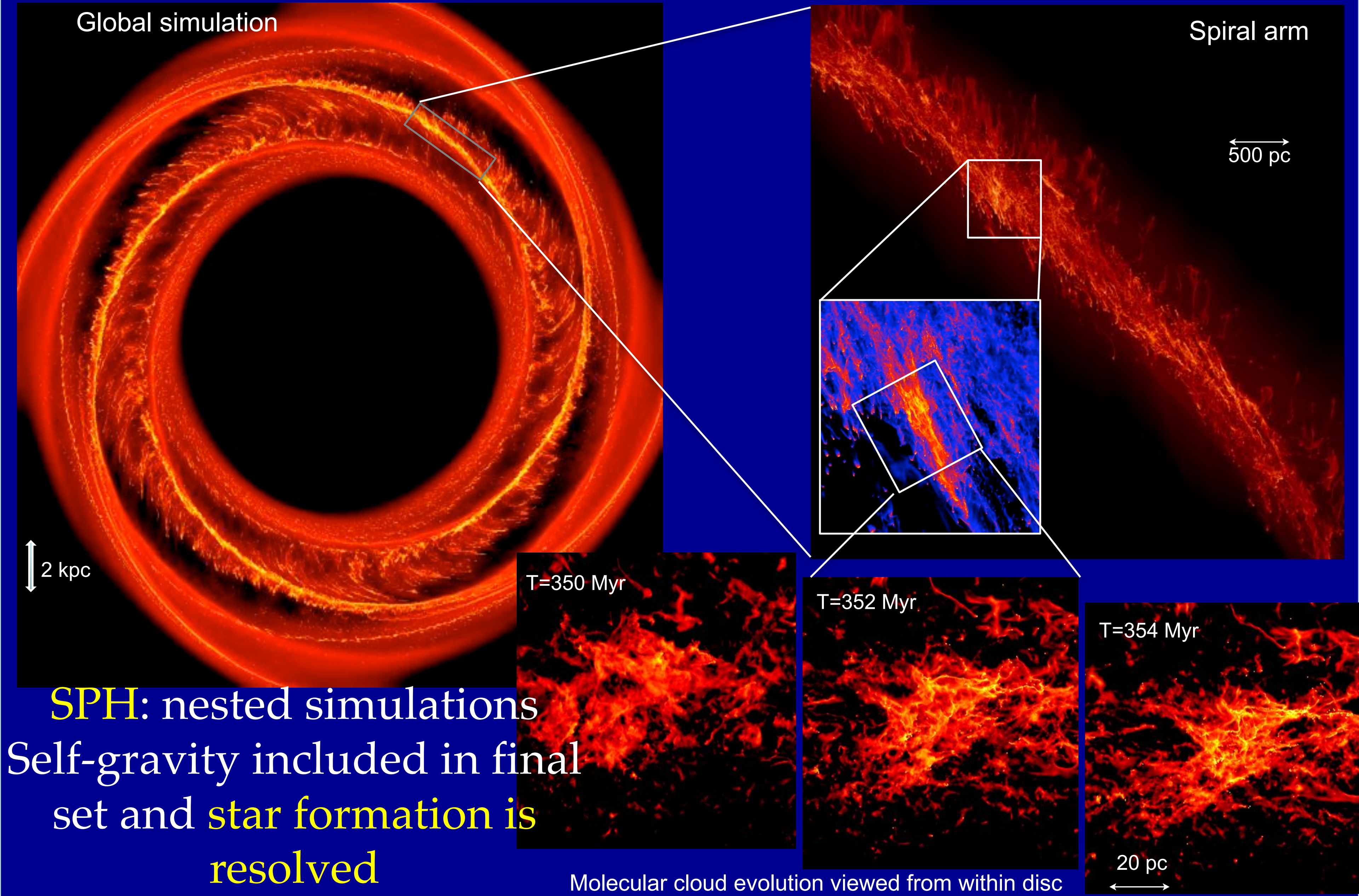
$$\dot{M} \propto M^{2/3}$$

- » Tidal radius accretion



Resolving star formation from Galactic-scale flows

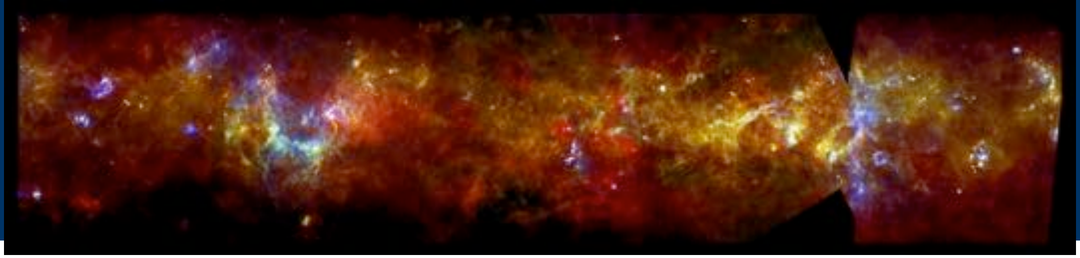
Ian Bonnell, Clare Dobbs & Rowan Smith 2013, MNRAS, 430,1790

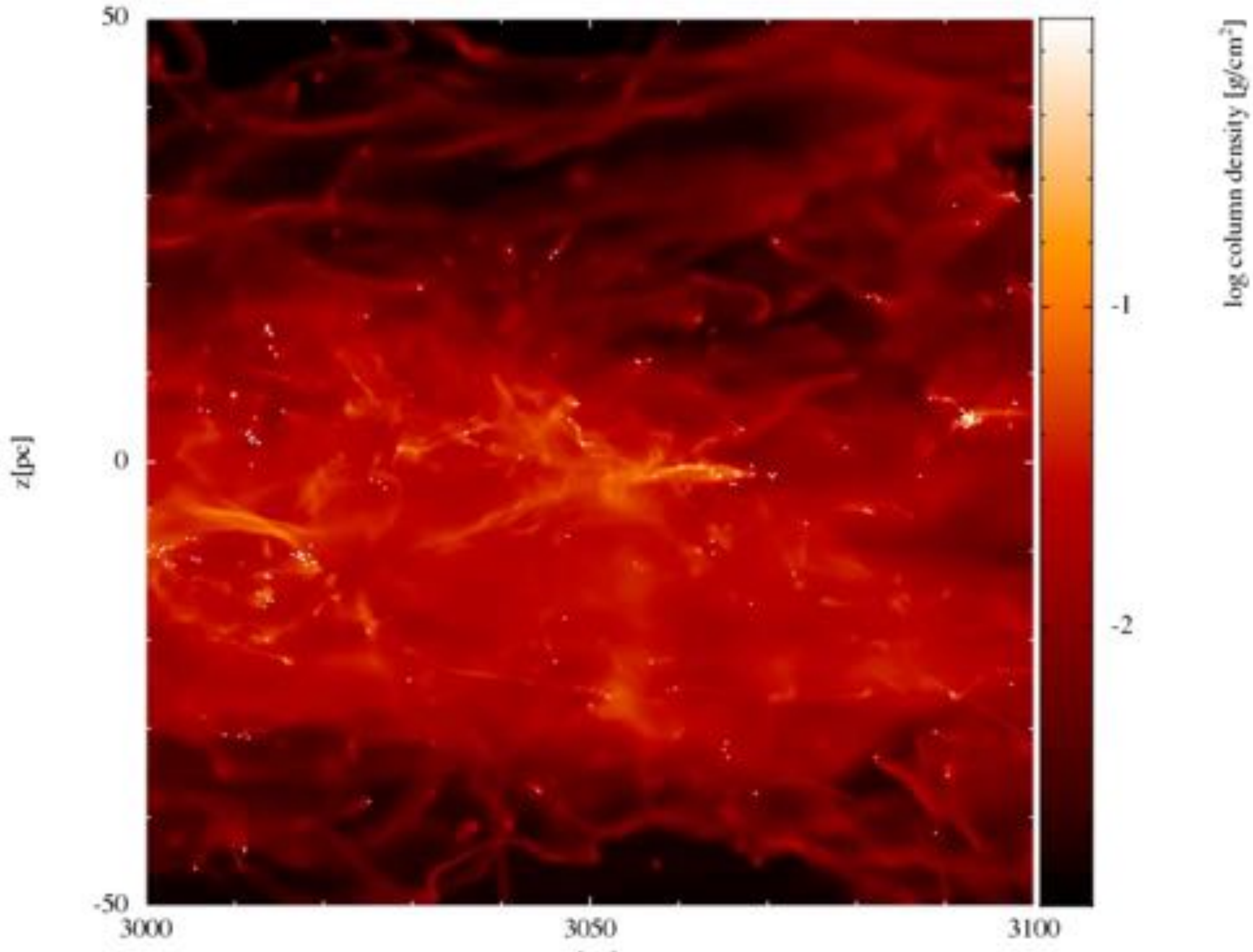


Molecular cloud evolution viewed from within disc

SPH: nested simulations
Self-gravity included in final set and star formation is resolved

The Galactic plane





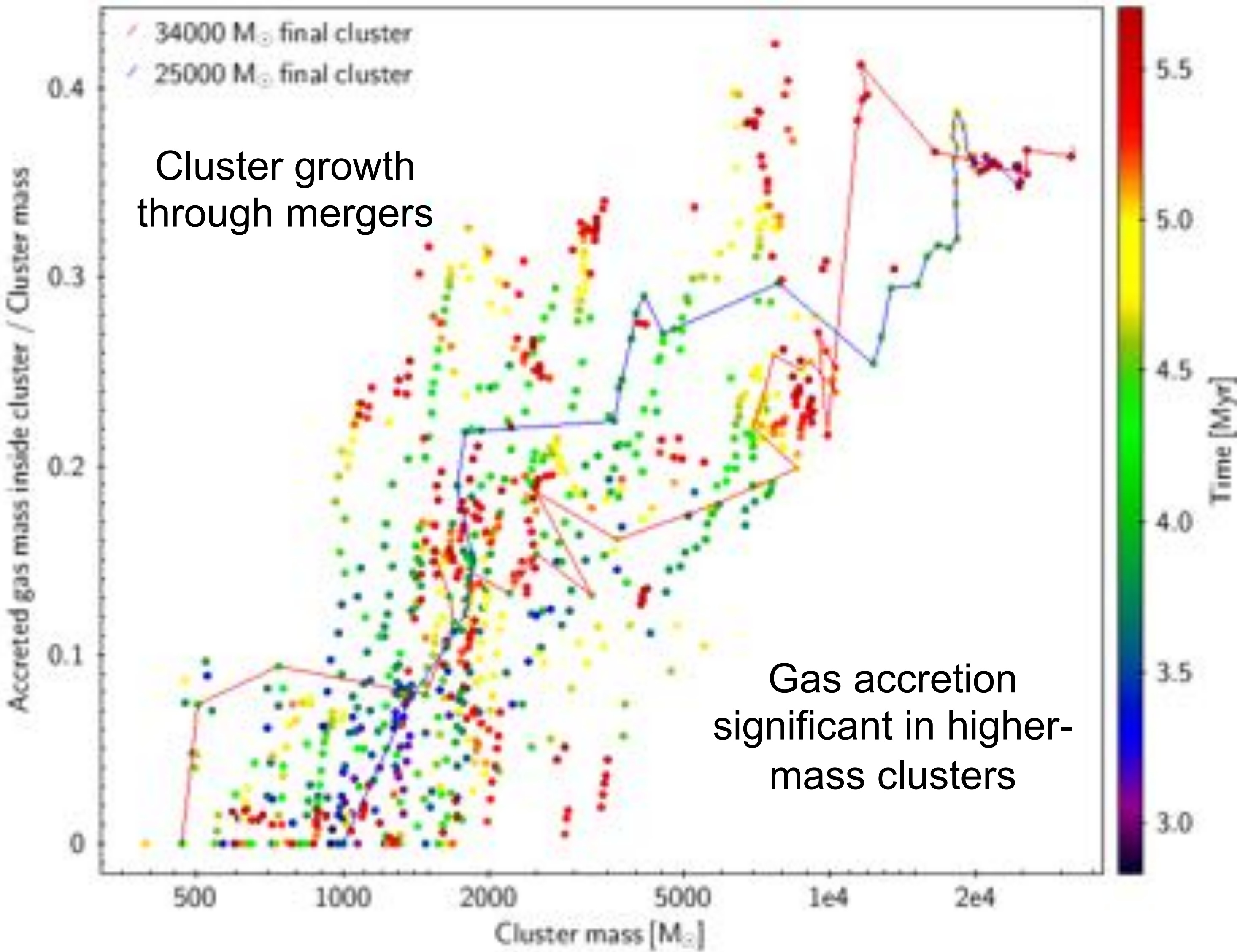
Cluster Formation

Smilgys & Bonnell 2017

Mass growth by accretion and mergers

Smilgys & Bonnell 2017

Mass fraction entering the cluster as gas

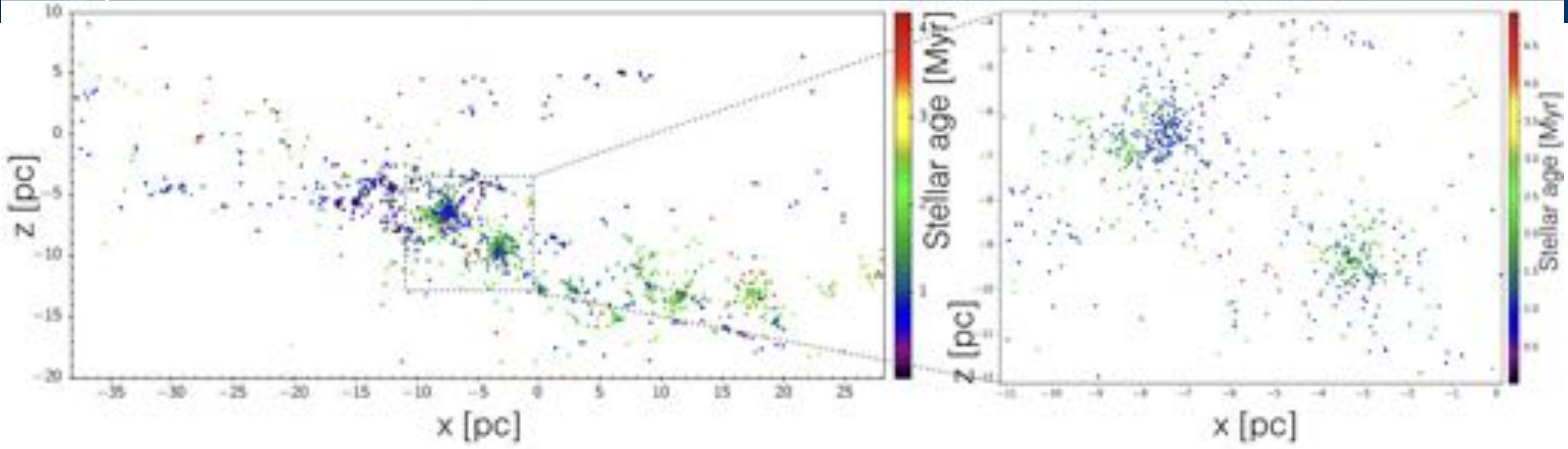


Cluster growth through mergers

Gas accretion significant in higher-mass clusters

Cluster properties

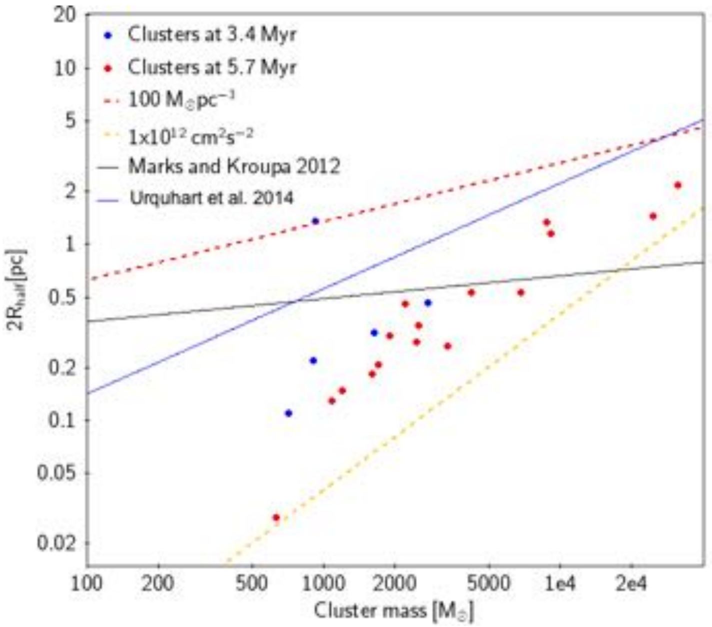
Smilgys & Bonnell 2017

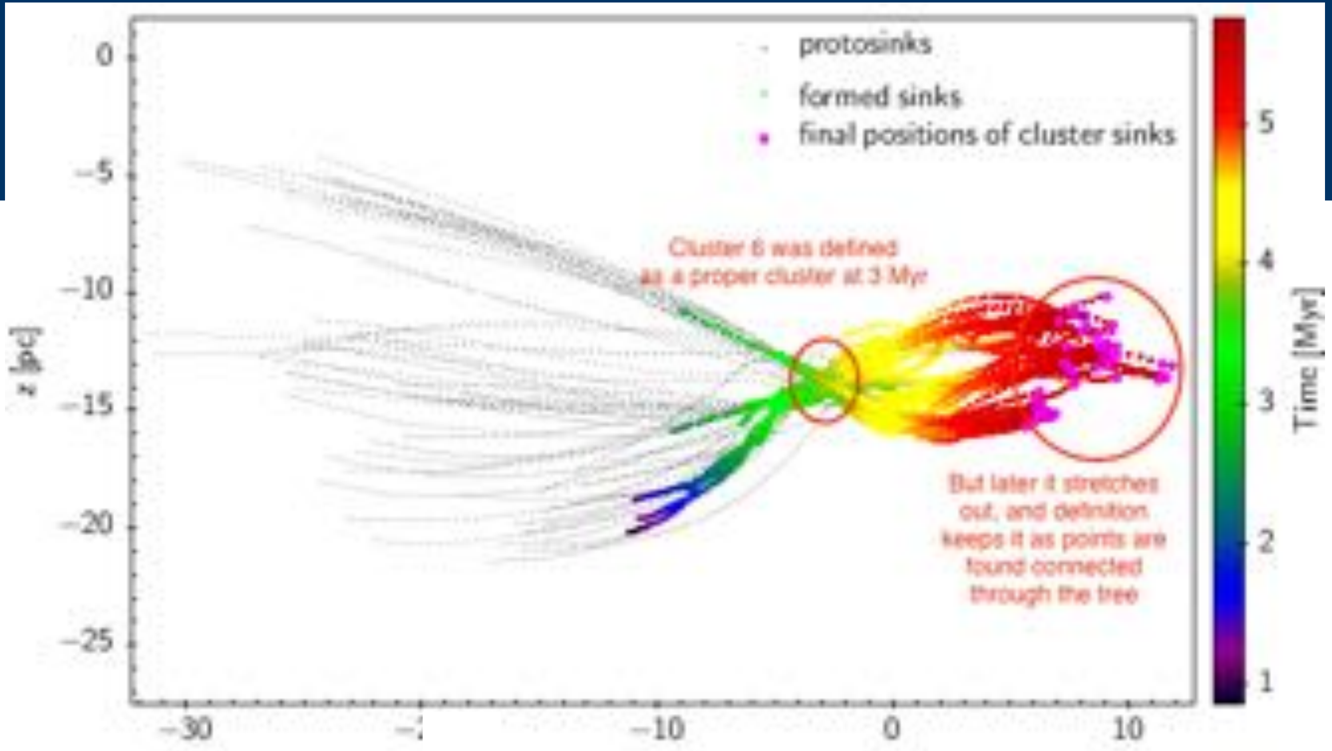


Clusters have significant age spreads

Cluster sizes R ~ M

Similar, smaller scaling to pre-cluster clumps



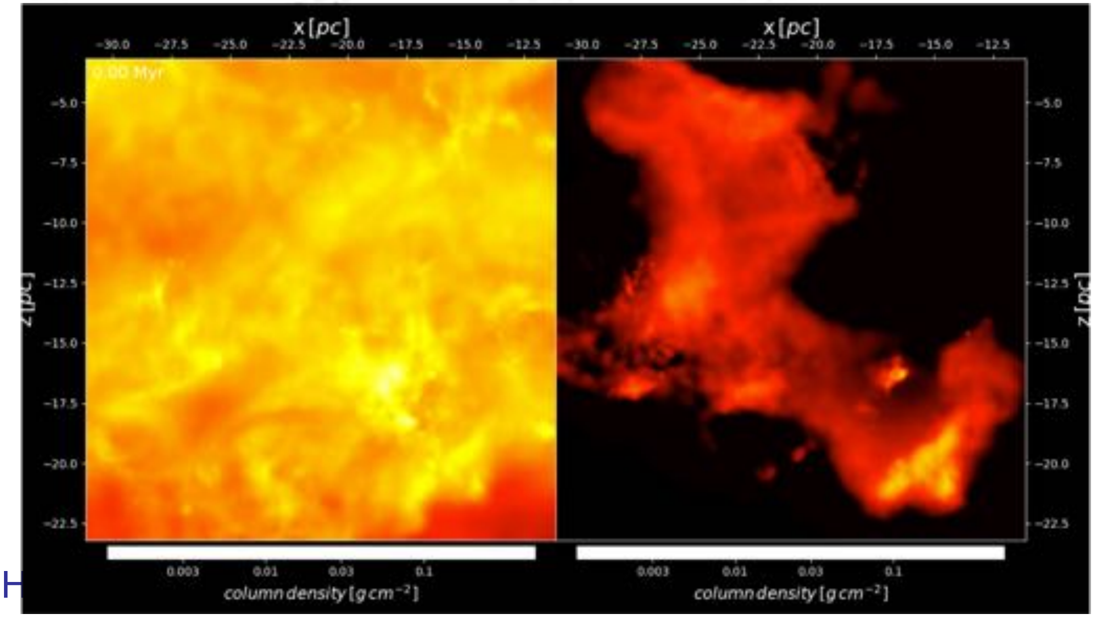


Failed cluster formation

Tidal forces impede merger,
Formation of OB association?

Smilgys & Bonnell 2018

H

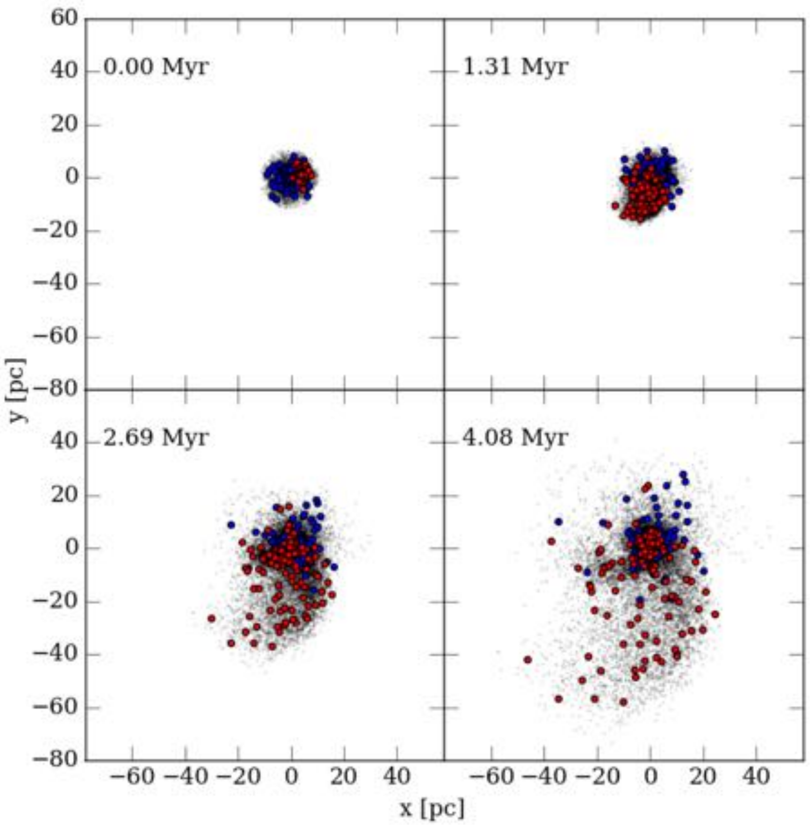


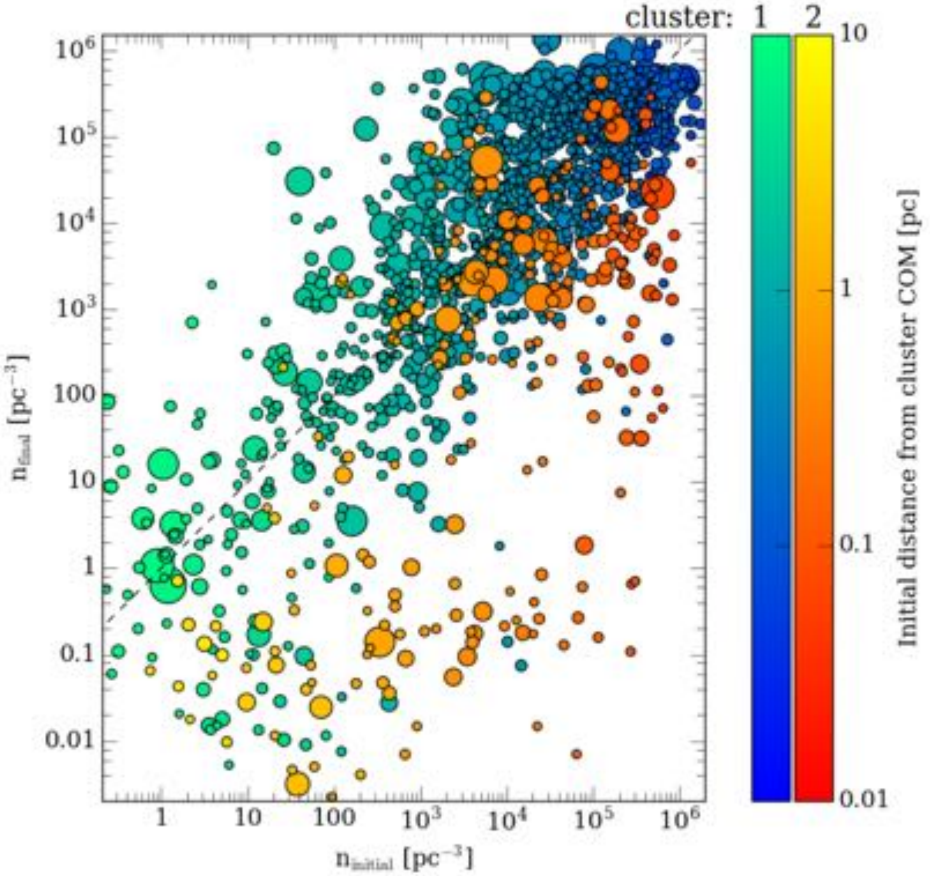
Merging clusters and isolated high-mass stars

Lucas et al 2018

Later, dry mergers in cluster formation

High-mass stars dispersed due to tidal fields of secondary cluster





Mon. Not. R. Astron. Soc. **298**, 93–102 (1998)

On the formation of massive stars

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ABSTRACT

We present a model for the formation of massive ($M \gtrsim 10\,\mathrm{M}_\odot$) stars through accretion-induced collisions in the cores of embedded dense stellar clusters. This model circumvents the problem of accreting on to a star whose luminosity is sufficient to reverse the infall of gas. Instead, the central core of the cluster accretes from the surrounding gas, thereby decreasing its radius until collisions between individual components become sufficient. These components are, in general, intermediate-mass stars that have formed through accretion on to low-mass protostars. Once a sufficiently massive star has formed to expel the remaining gas, the cluster expands in accordance with this loss of mass, halting further collisions. This process implies a critical stellar density for the formation of massive stars, and a high rate of binaries formed by tidal capture.

$$E_{\mathrm{tot}} = \frac{p^2}{2M_{\mathrm{stars}}} - \frac{GM_{\mathrm{core}}M_{\mathrm{stars}}}{R_{\mathrm{core}}}.$$

Accretion driven contraction : limits

Accretion can force core to contract

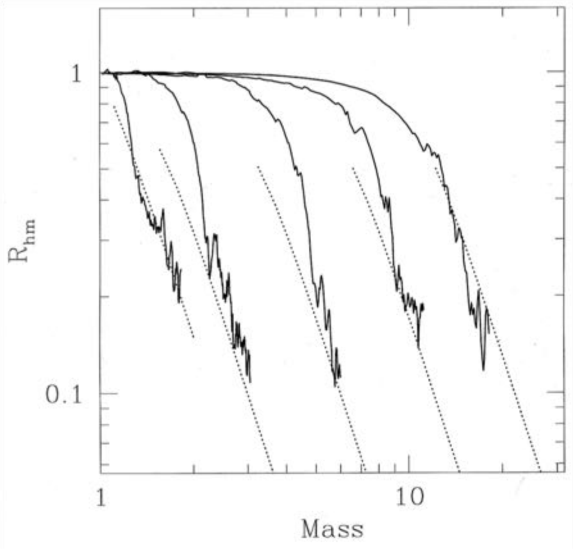
$$R_{\rm core} \propto M_{\rm stars}^{-3} .$$

But if core is decoupled from cluster, it will dissolve

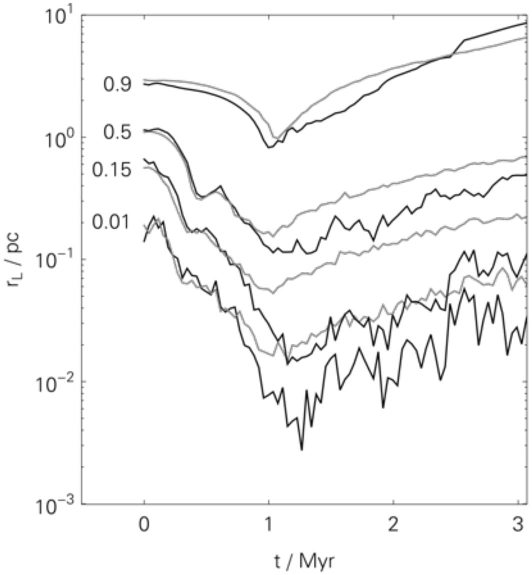
Requires large N clusters (> 30,000)

Collisional formation of very high-mass stars in rich stellar clusters possible

Clarke & Bonnell 2008
Moeckel & Clarke 2011



Bonnell, Bate & Zinnecker 1998



Cluster dynamics cannot explain high-mass close binaries

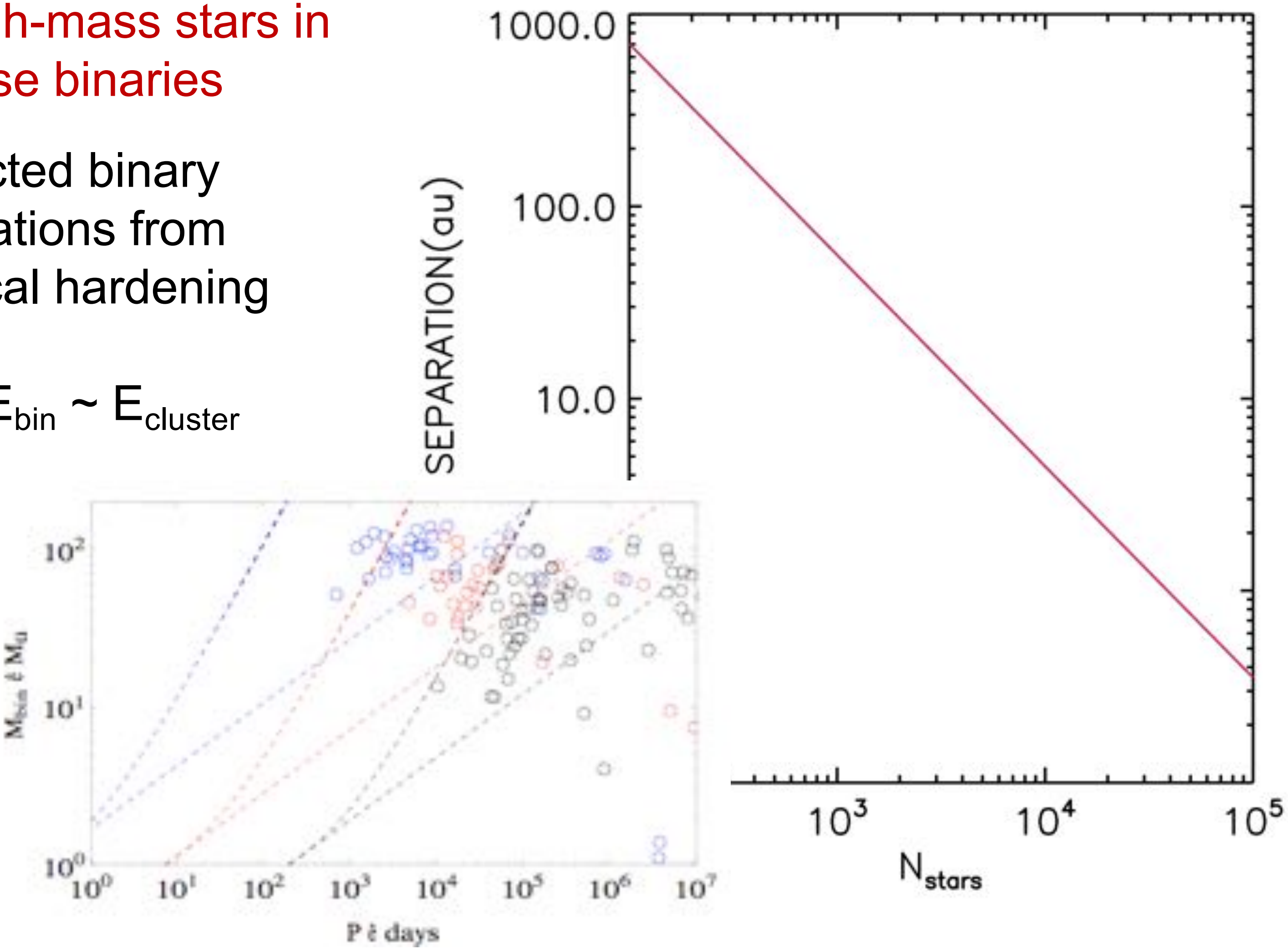
Lund & Bonnell 2018

Most high-mass stars in close binaries

Expected binary separations from dynamical hardening

Limit: $E_{bin} \sim E_{cluster}$

Requires
>

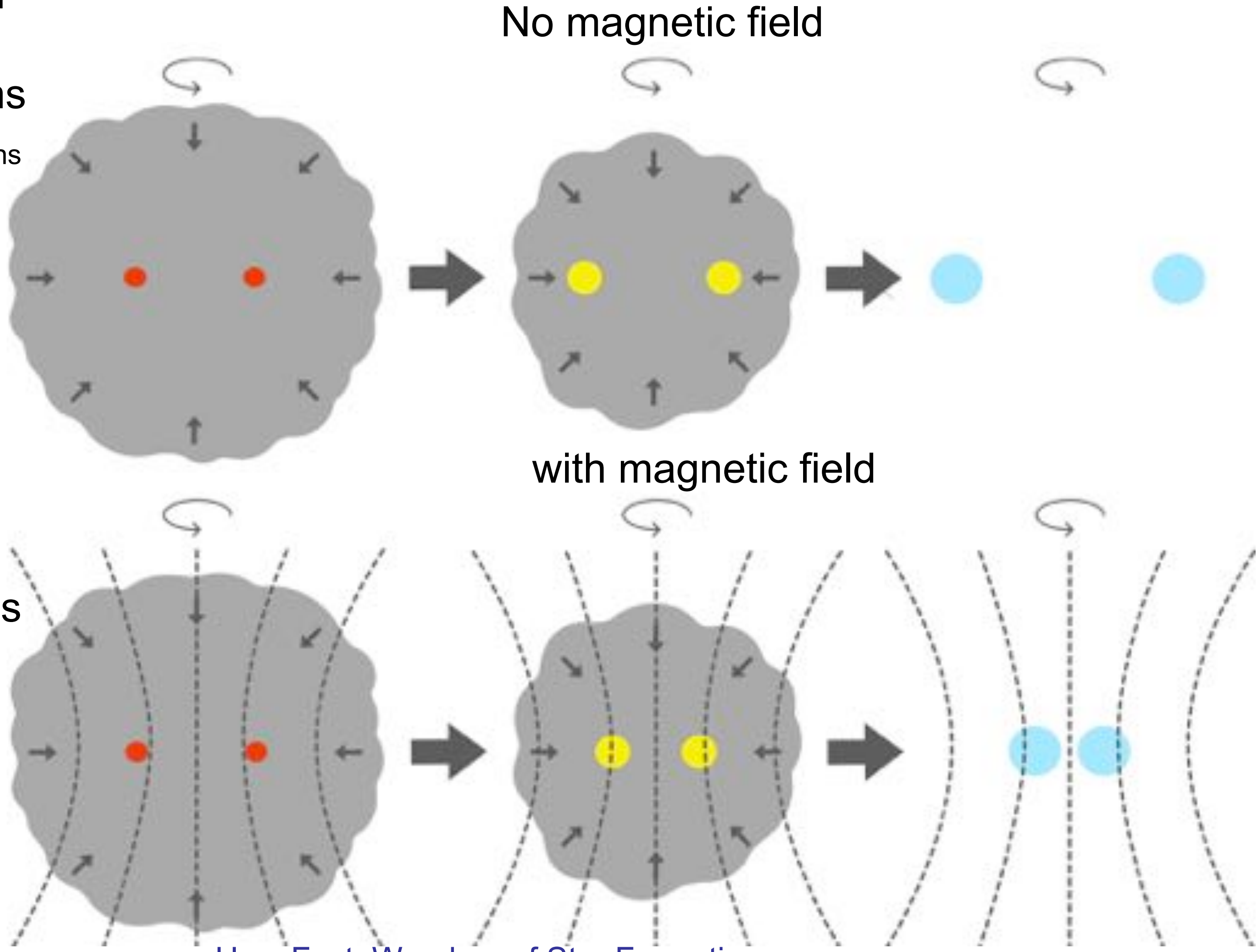


Nick Moeckel

High-mass close binaries

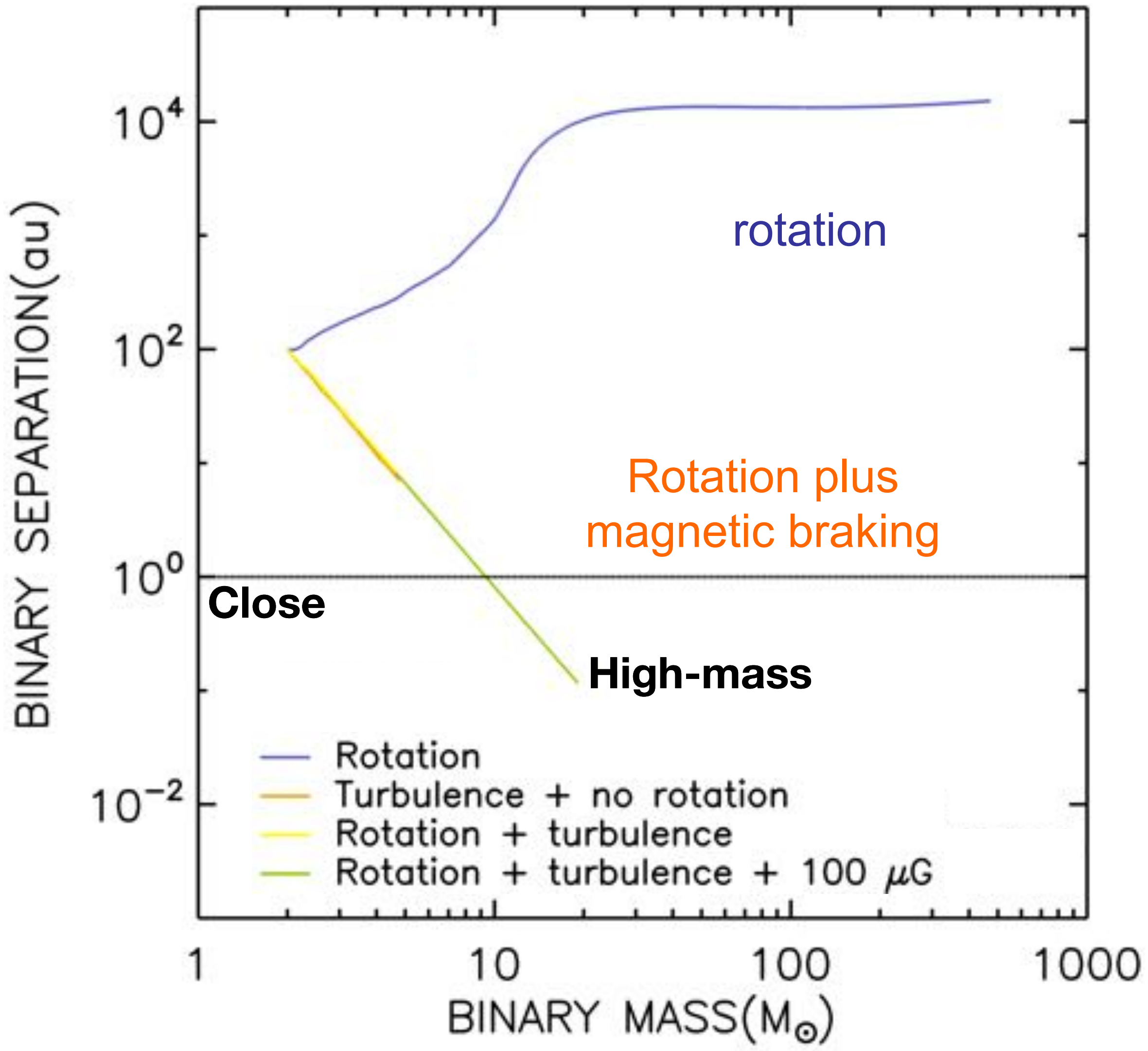
Lund & Bonnell 2018

Problem: most high-mass stars are in close binary systems
Separation << R_{Jeans}



Need to accrete mass without angular momentum
Solution: magnetic braking during accretion phase

Formation of close binaries by magnetic braking

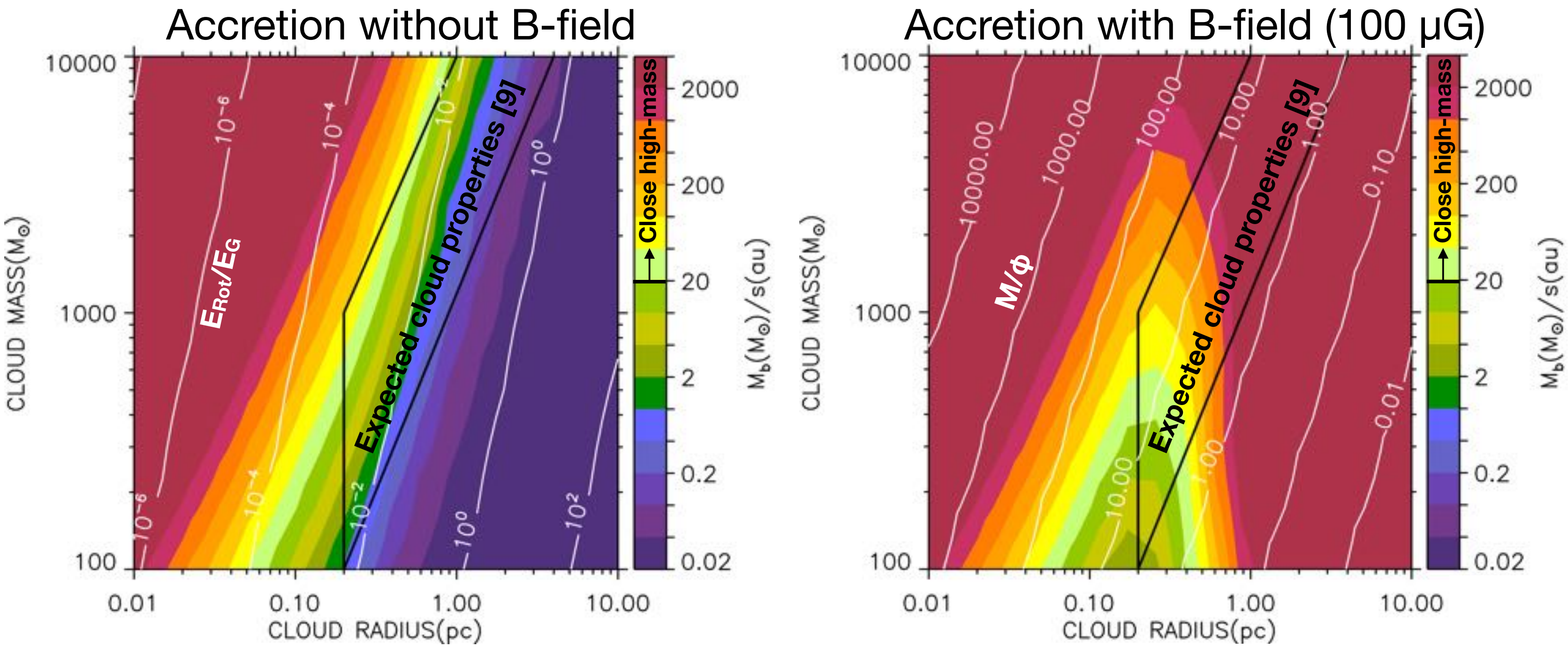


M = 500 Mo
R = 0.5 pc
$\Omega = 3\ 10^{-14}$ rad/s

Lund & Bonnell 2018

Close binaries from core properties

Lund & Bonnell 2018


Accretion without B-field

Accretion with B-field (100 μG)

Example:

Cloud mass ($M_\odot$)	Cloud radius (pc)	Binary mass ($M_\odot$)	Binary separation (au)	Magnetic field (μG)
1145	0.58	5.9	3.842	0
1145	0.58	**26.5**	**0.046**	100

[9] Urquhart J. S., et al., 2014, mnra

Accretion-induced binary mergers to form highest mass stars?

Ionisation and stellar winds

Dale, Ercolano & Bonnell 2012, 2014

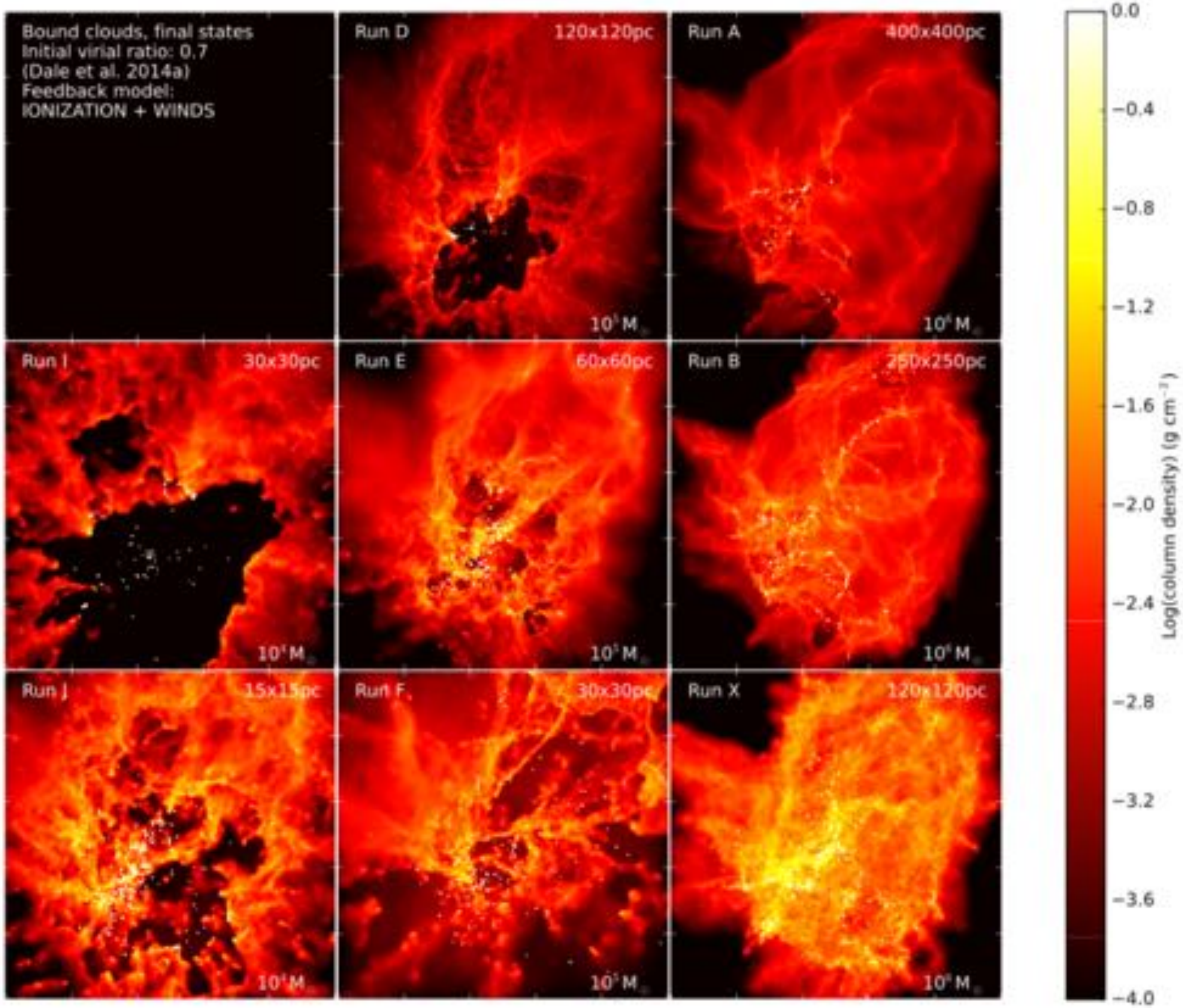
Lower density clouds affected

But none are destroyed outright

Radiation leaks out through cloud

Can unbind gas in clouds with

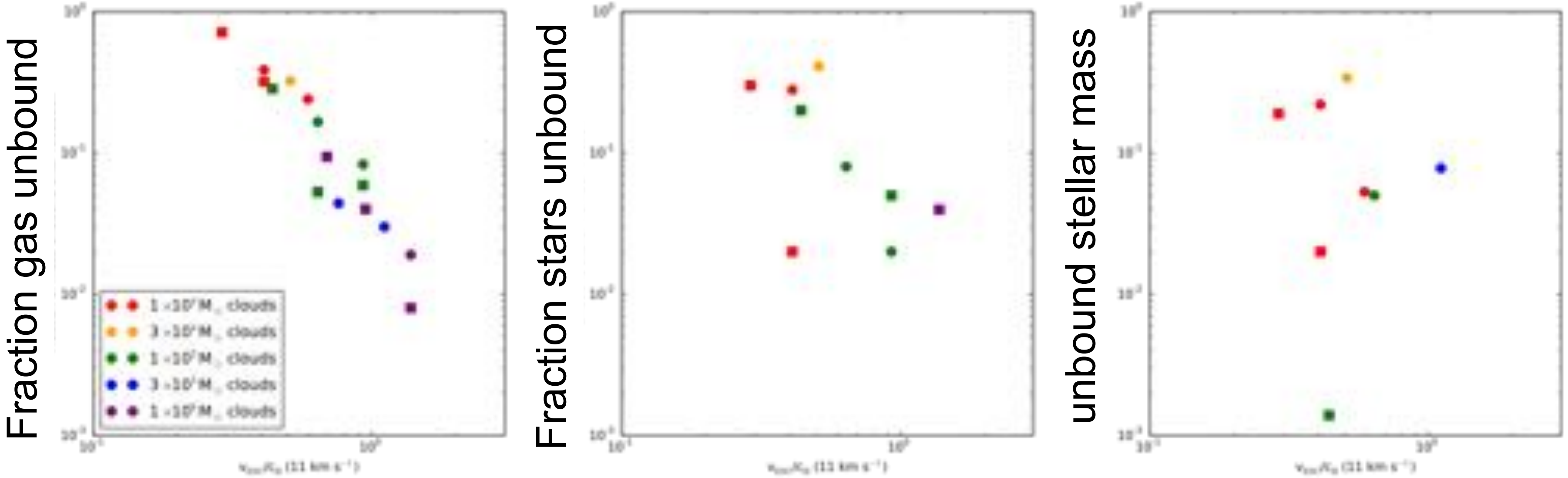
$v_{esc} << c_s$ (HII)



Ionisation and stellar winds

Dale, Ercolano & Bonnell 2012, 2014

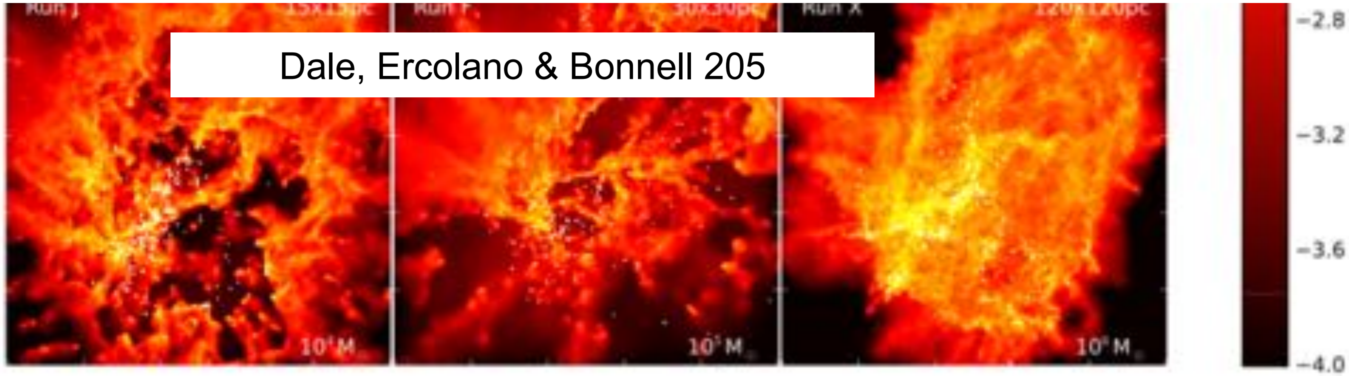
Lower density



(a) Gas

(b) Stars (by number)

(c) Stars (by mass)



Dale, Ercolano & Bonnell 205

$v_{esc} << c_s$ (HII)

Summary

- Star clusters form due to large-scale compressive flows
  - Self gravity dominates locally,
  - hierarchical fragmentation, gas accretion and mergers
- Accretion in clusters can explain (most) high-mass star formation
  - Simultaneous to cluster formation
- Close high-mass binaries from accretion and magnetic braking
  - Stellar mergers?
- Feedback predominately affects lower density gas
  - has moderate ~2 reduction on ongoing star formation
- If Hans has an idea: it is worthwhile listening!