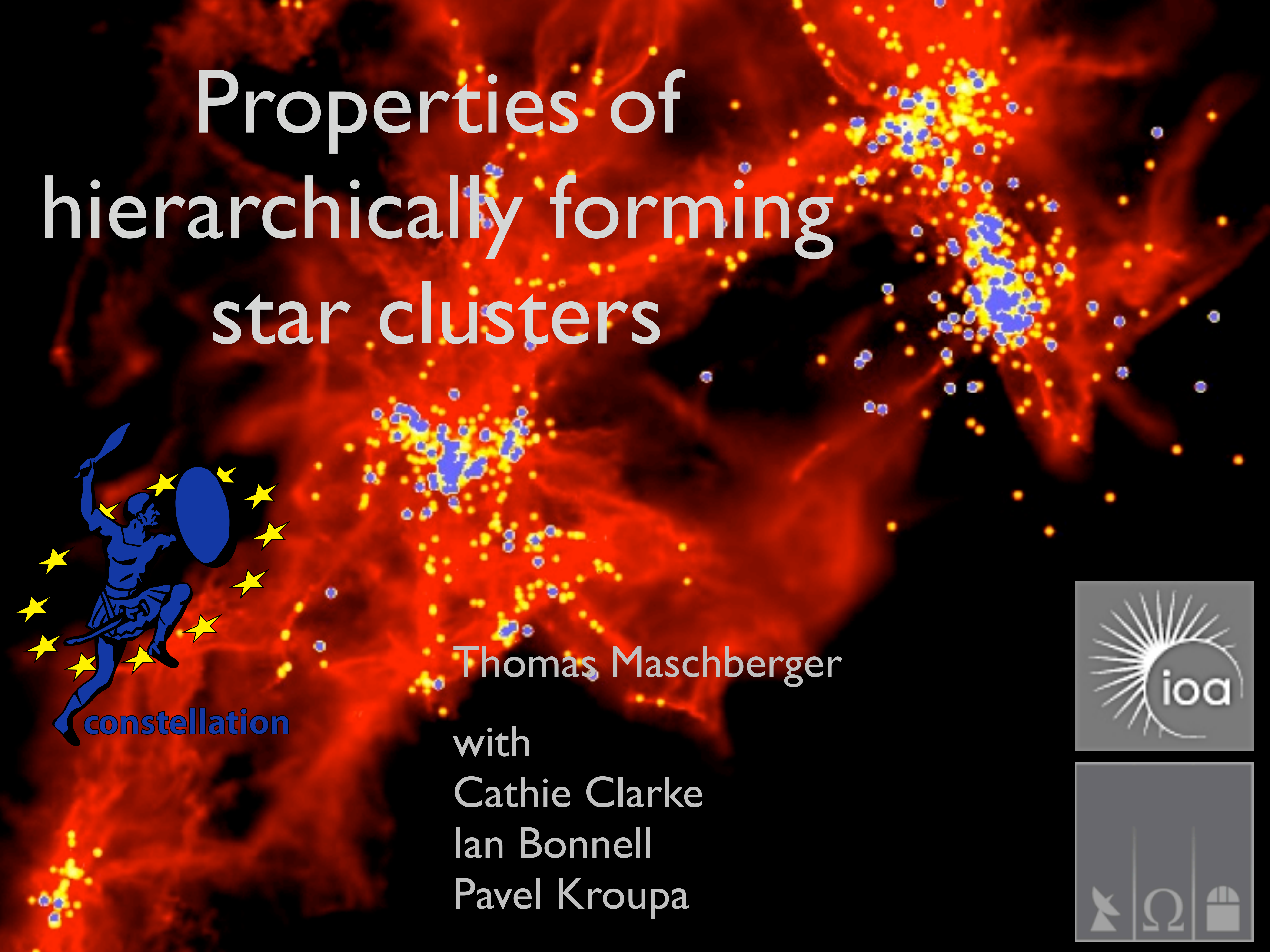


Properties of hierarchically forming star clusters

Thomas Maschberger

with
Cathie Clarke
Ian Bonnell
Pavel Kroupa

What is it about?

Analyse the properties of sink particles (stars) in the SPH calculations of Bonnell et al (2003, 2008)

1000 $\mathrm{M}_\odot$ gas, 550 stars, 1 final cluster
10000 $\mathrm{M}_\odot$ gas, 2300 stars, 3-5 clusters

Use the minimum spanning tree to find subclusters.

Determine observationally detectable properties:
Structure and appearance
Mass segregation
Mass functions

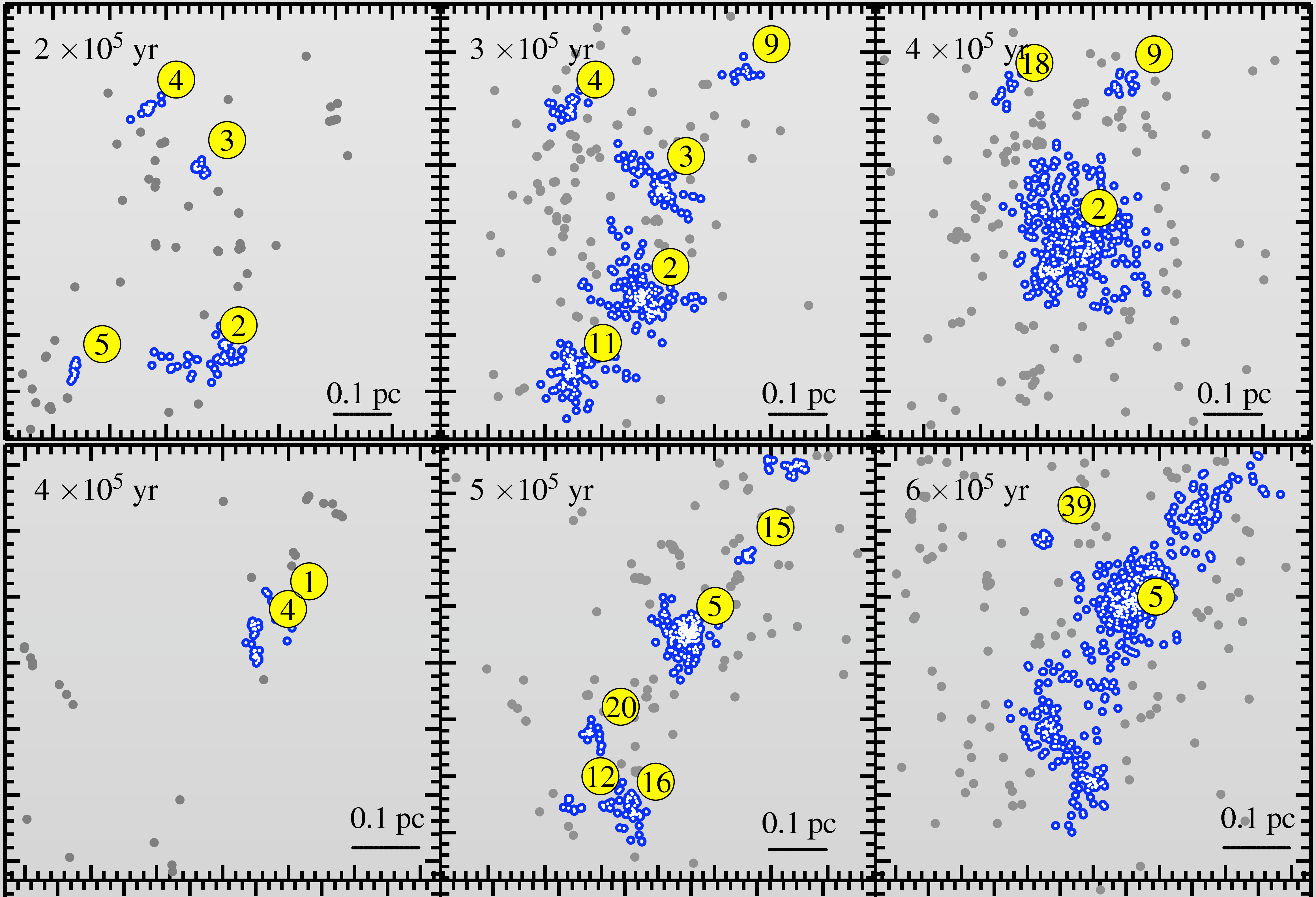
What is happening?

Subclusters for along filaments.

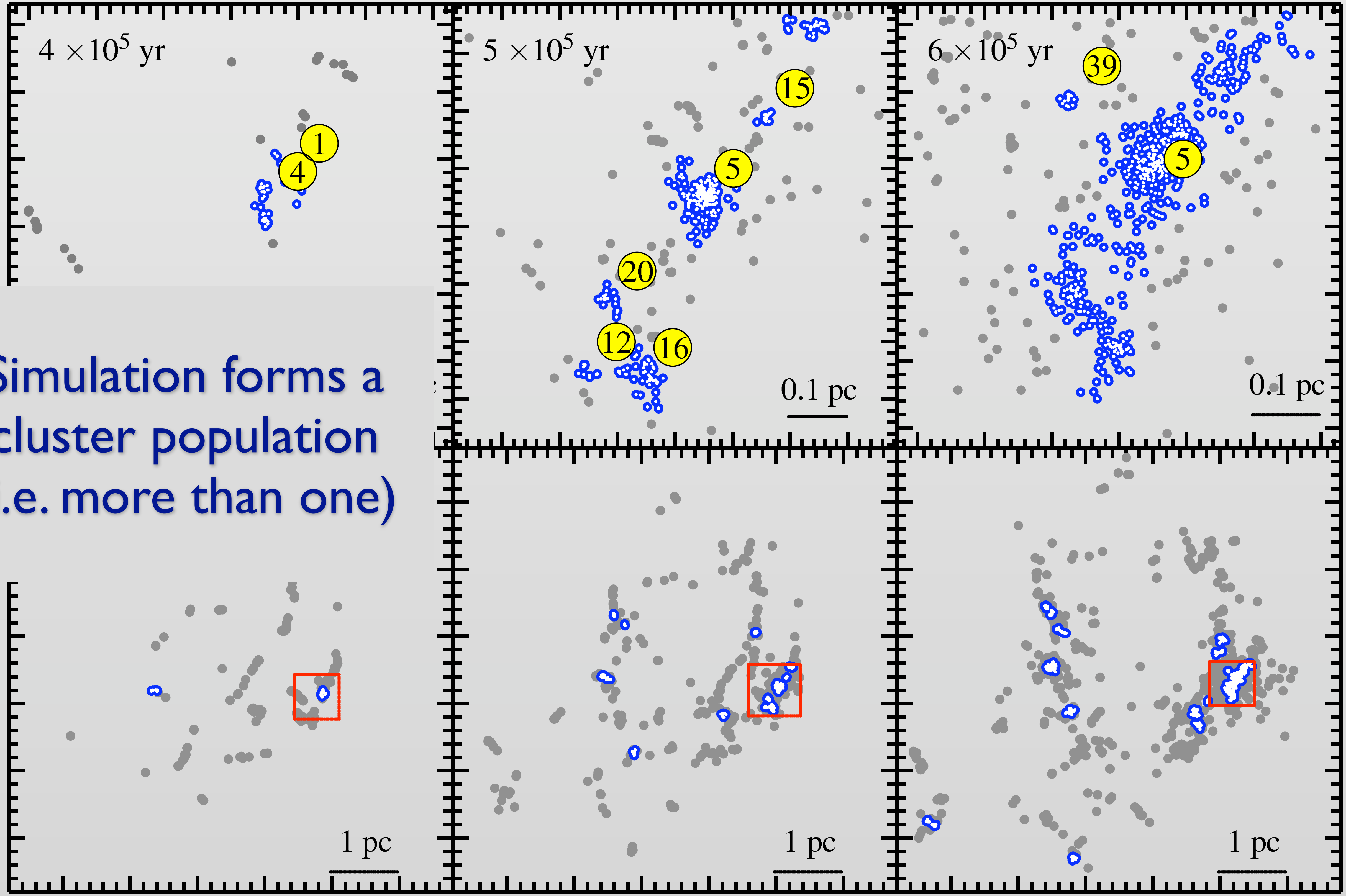
Simulations show similar structure

1000

10000



Time-evolution: Large Simulation



Simulation forms a cluster population (i.e. more than one)

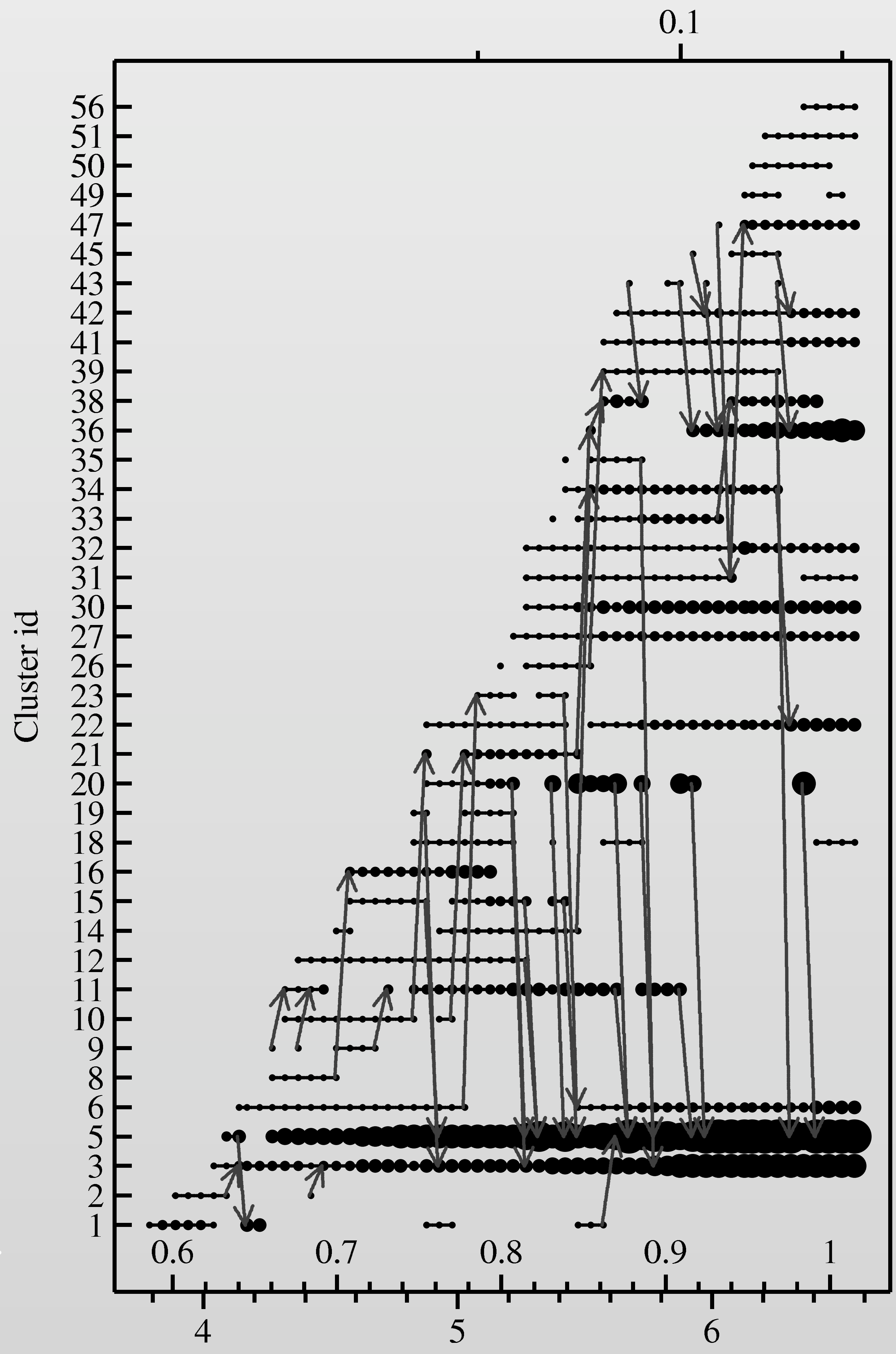
Merging history

Merging time scale

$\approx 5 \times 10^5$ yr

(until stable structure)

Sometimes the most massive star is overtaken!



Evolution of structure: Cartwright Q

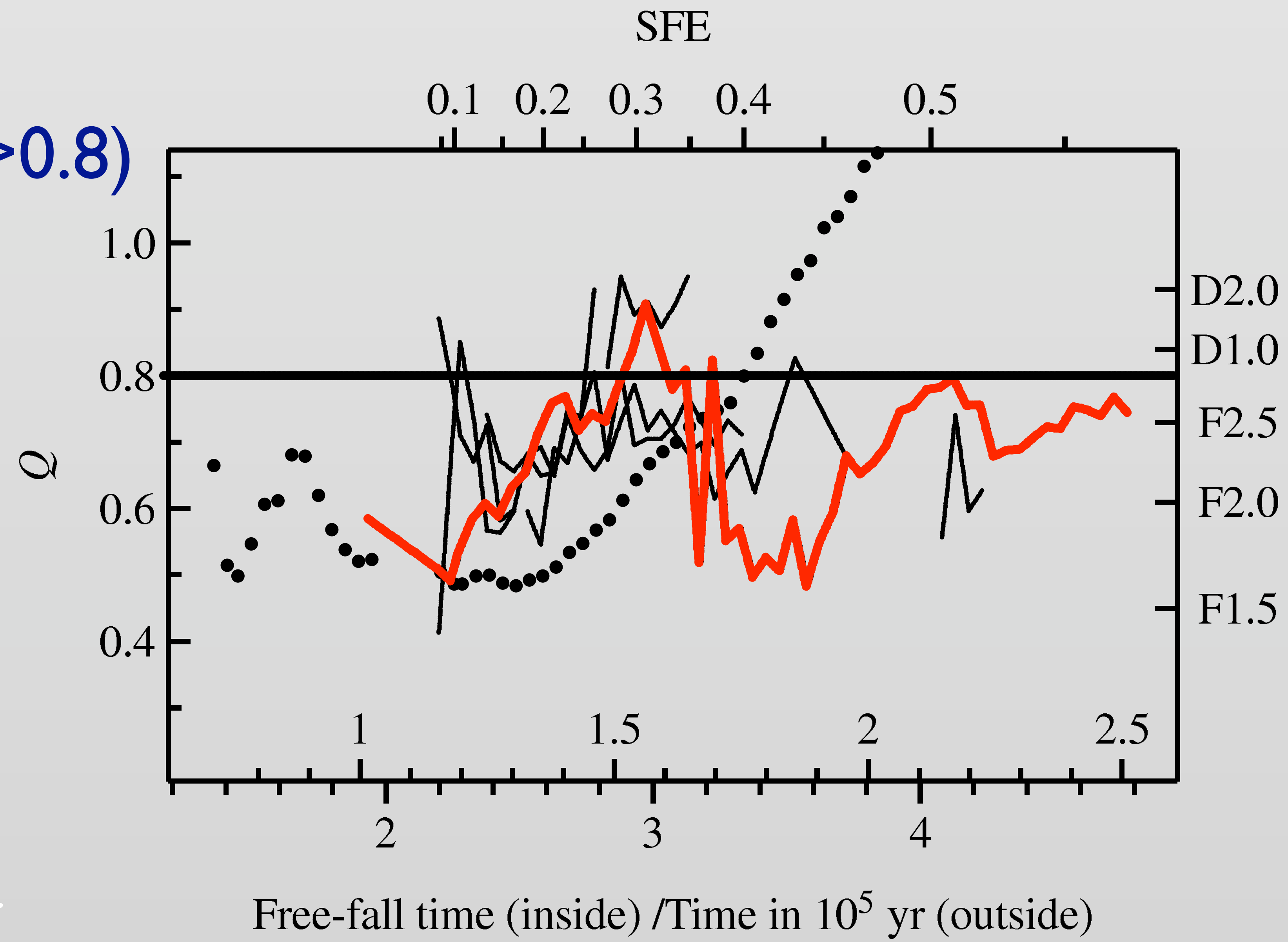
(The Cauliflowerometer)

Cartwright & Whitworth (2004)

$$Q = \frac{\text{mean MST edge length}}{\text{correlation length}}$$

distinguishes between substructured (<0.8) and centrally concentrated (>0.8)

Subclusters evolve to centrally concentrated systems.
Mergers introduce substructure again.

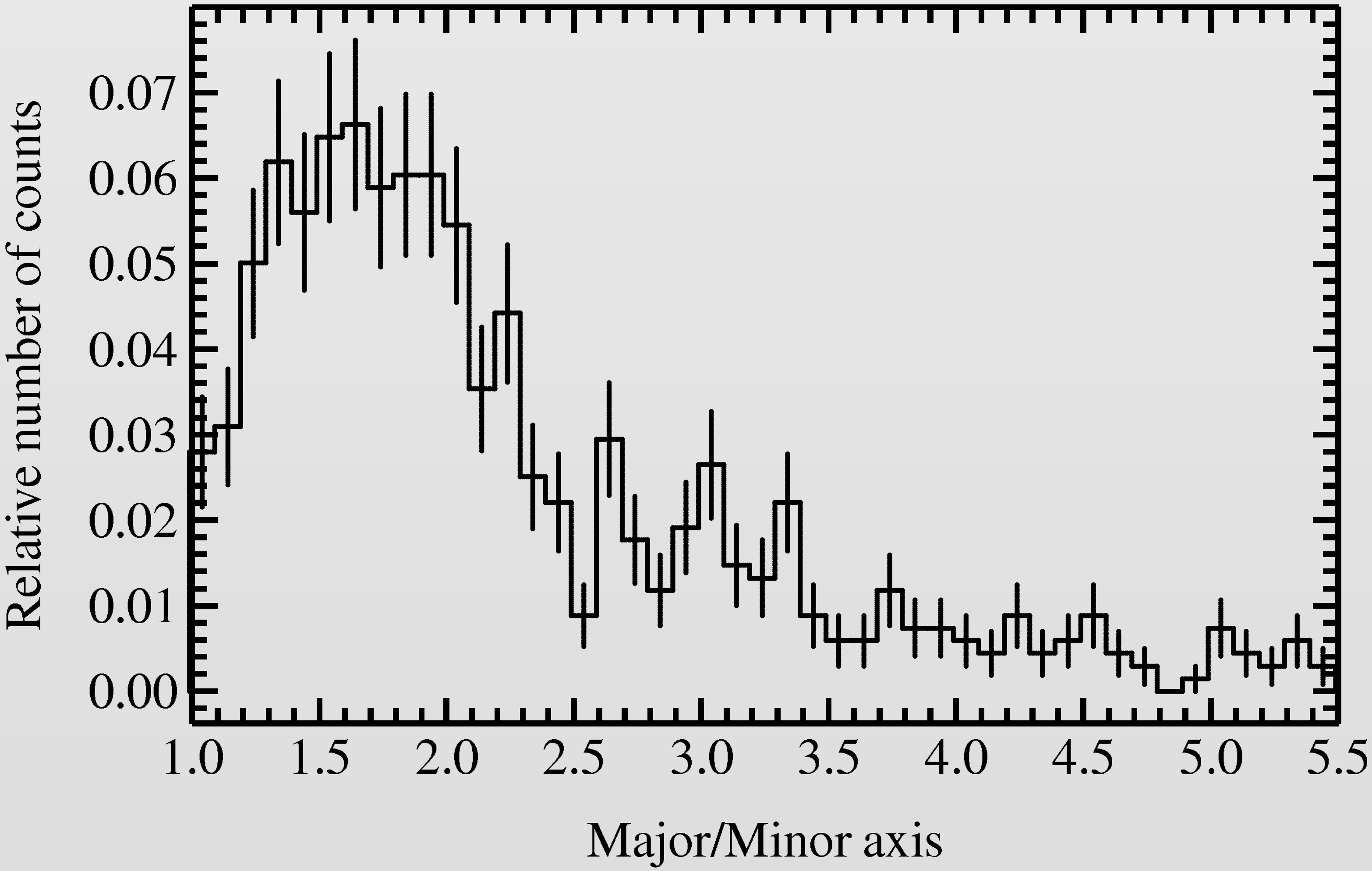


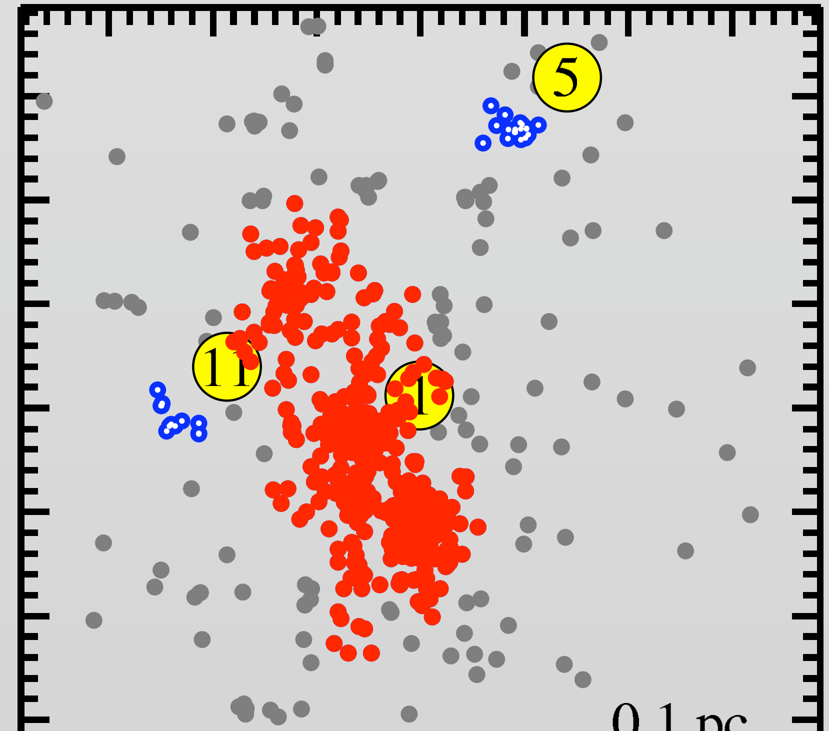
Cluster shapes

Derived from fitting a 2D Gaussian.

Most subclusters are most of the time roundish.

Elongated clusters appear during mergers.



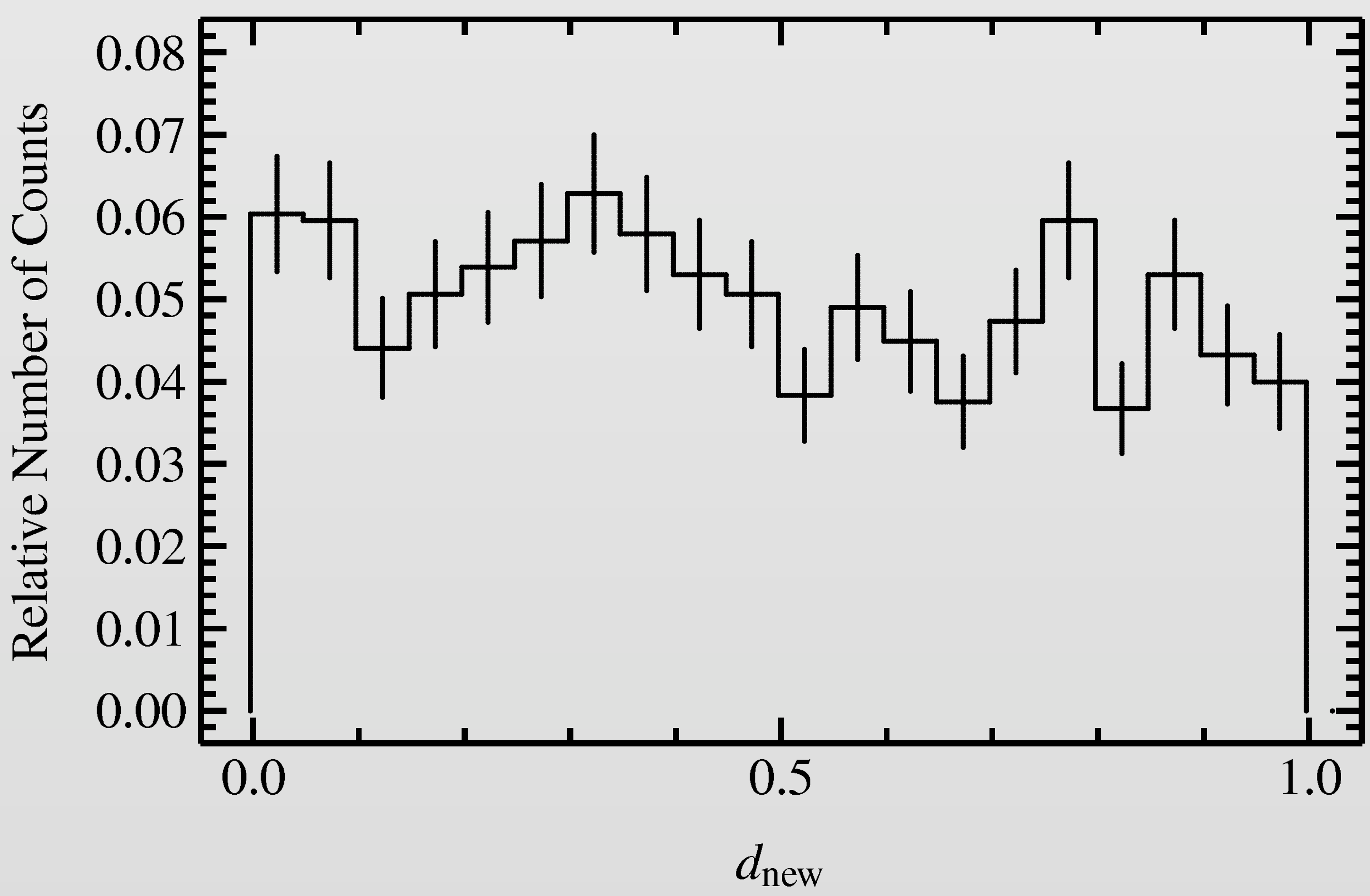


Where do stars form?

Only 50-60% of stars form within a subcluster.

No central concentration of new stars.

Subclusters form around massive stars!



Mass segregation: Allison's Λ

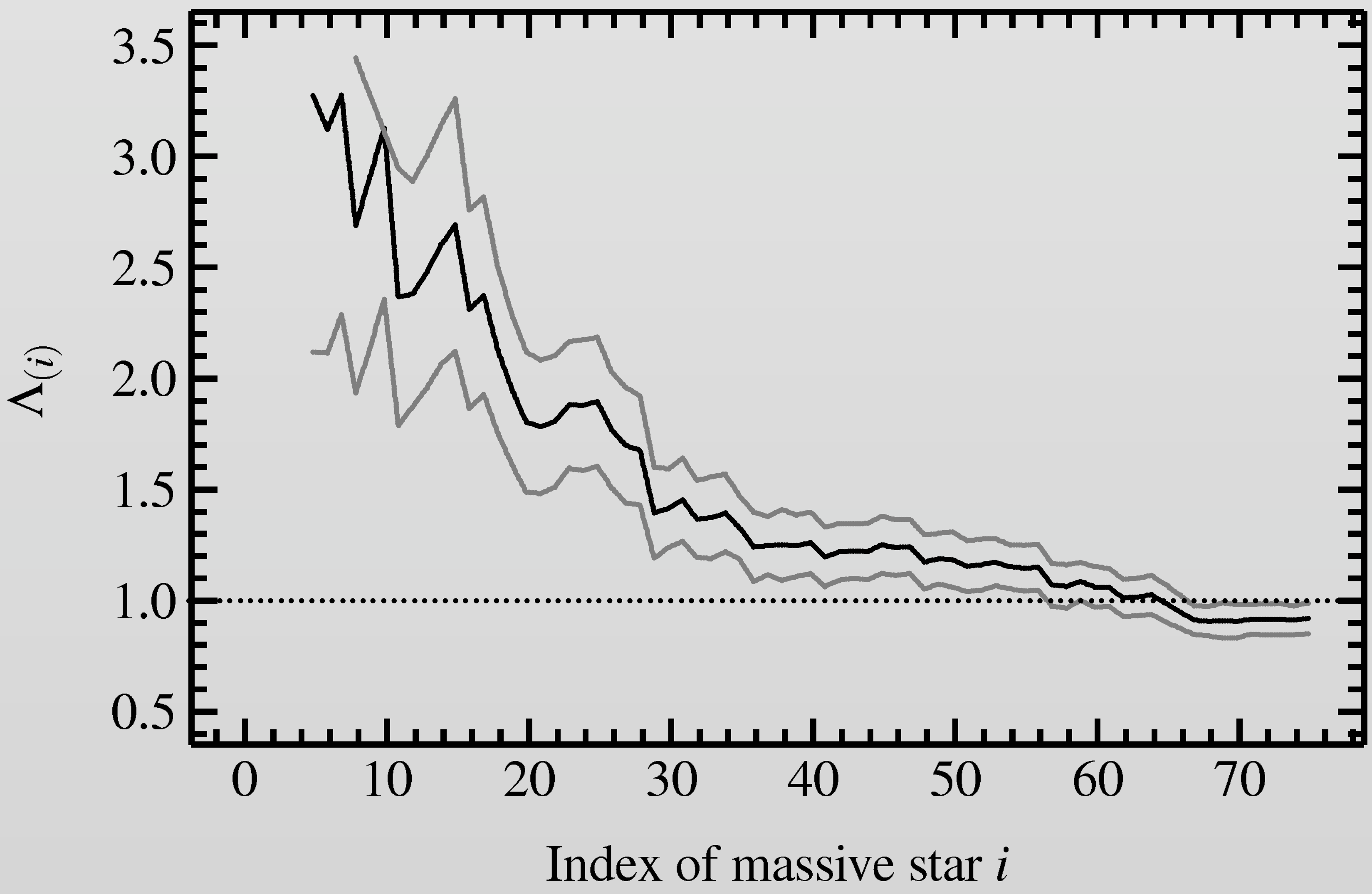
Allison et al. 2009

$$\Lambda = \frac{\text{Mean edge length of i random stars}}{\text{Edge length of the i most massive stars}}$$

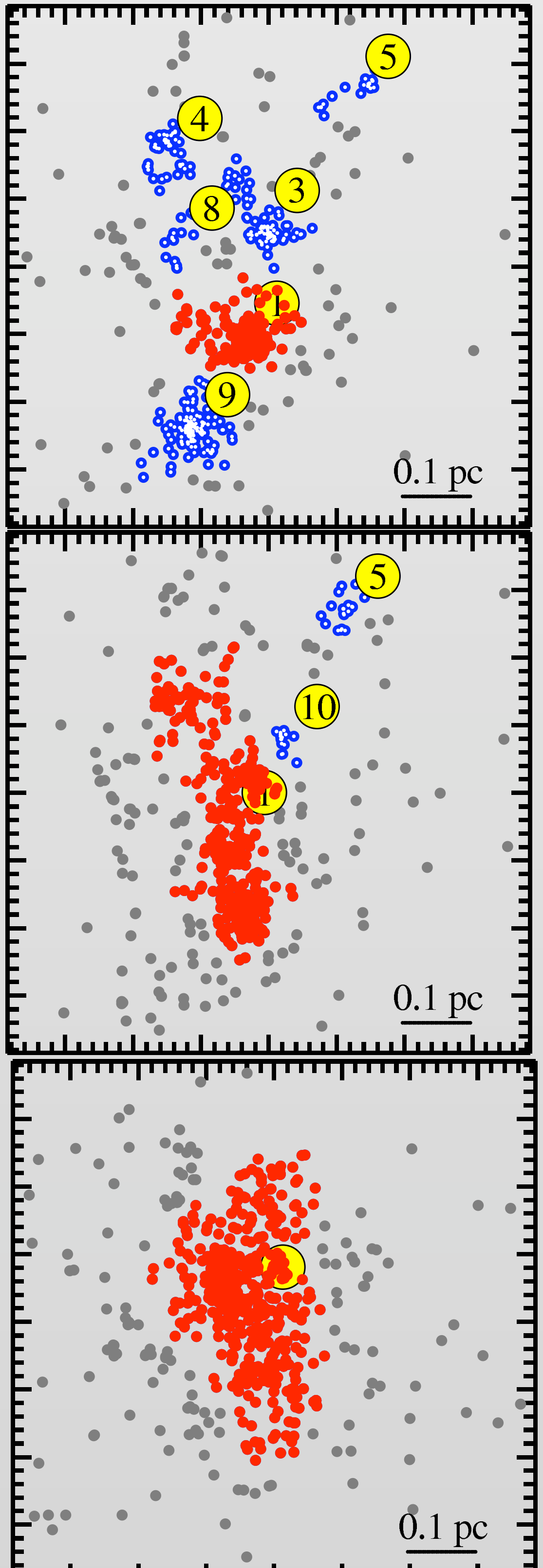
Massive stars more concentrated: $\Lambda > 1$

This cluster never merged!

Λ monotonously decreases



Mass segregation during a merger

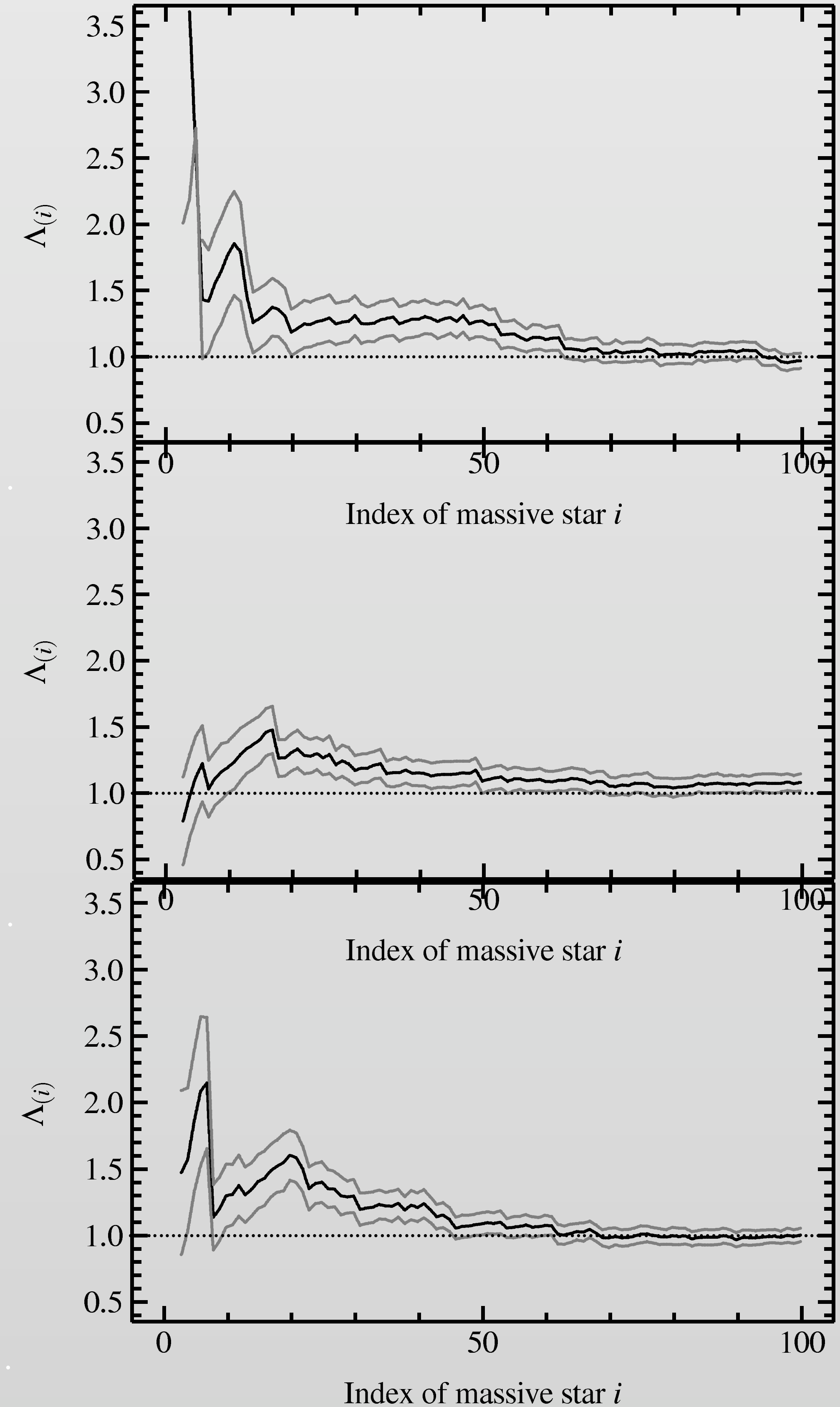


Before merger:
segregated

During merger:
weird
(massive stars still in previous centres)

After merger:
segregated

Subclusters are mass segregated
(unless they are not)



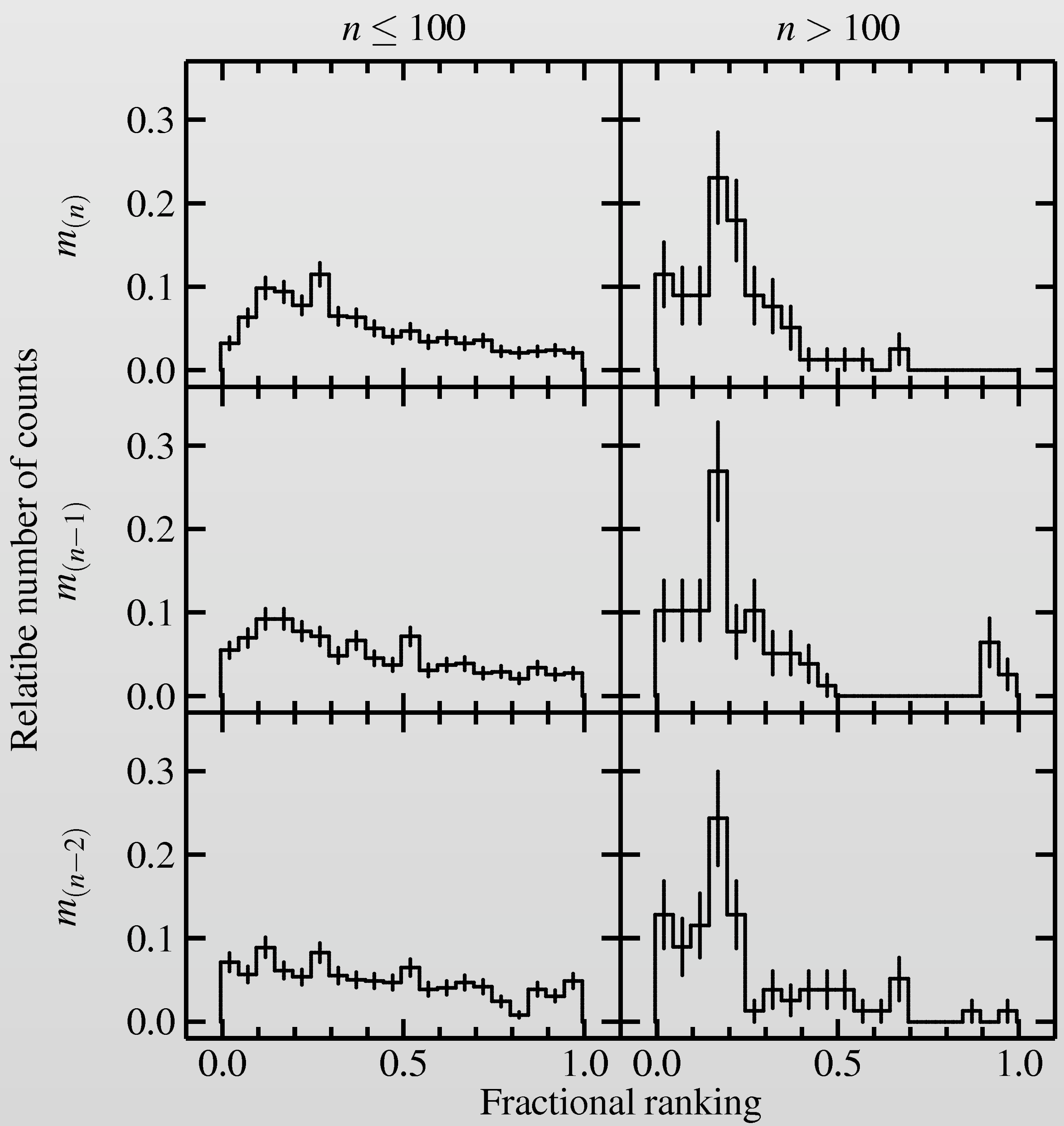
Mass segregation in low-n subclusters

Histogram of the fractional rankings of the most massive stars:

usually in the centre

for the second most massive another peak due to mergers

Also low-n clusters appear to be mass segregated



Upper stellar mass function

$$\xi(m) \propto m^{-\alpha} \qquad \alpha = 2.35 \quad m > 0.5\ \mathrm{M}_\odot$$

Canonical parameters

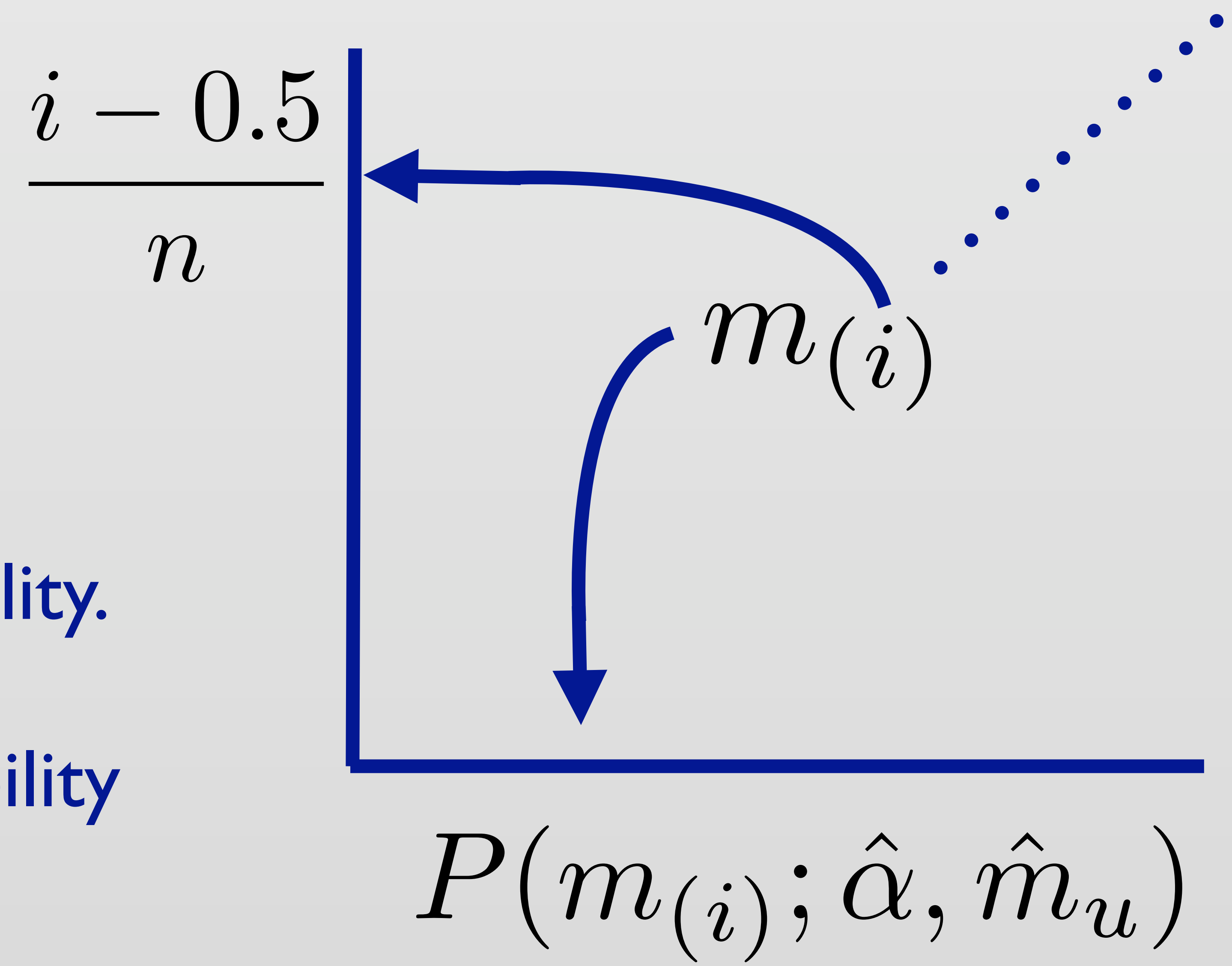
Starting with the end
- large sample (hopefully)
- direct statistical methods applicable
- estimate exponent (ML)
- estimate truncation mass
- verify visually and statistically the power law assumption (SPP plot and goodness of fit tests)

Ending with the inbetween
- use indirect means to analyse (mean mass, most massive star)
- easier to interpret when you know what to look for

Understanding the SPP plot

Visual test whether a power law fits.

In a sorted sample of stellar masses we know two things:
The rank:
Calculate the empirical cumulative probability.
The mass:
Put in the cumulative probability of the null hypothesis



SPP plot:
Compare these two cumulative probabilities.
Visualise the KS test (parallels to diagonal, 95% confidence)

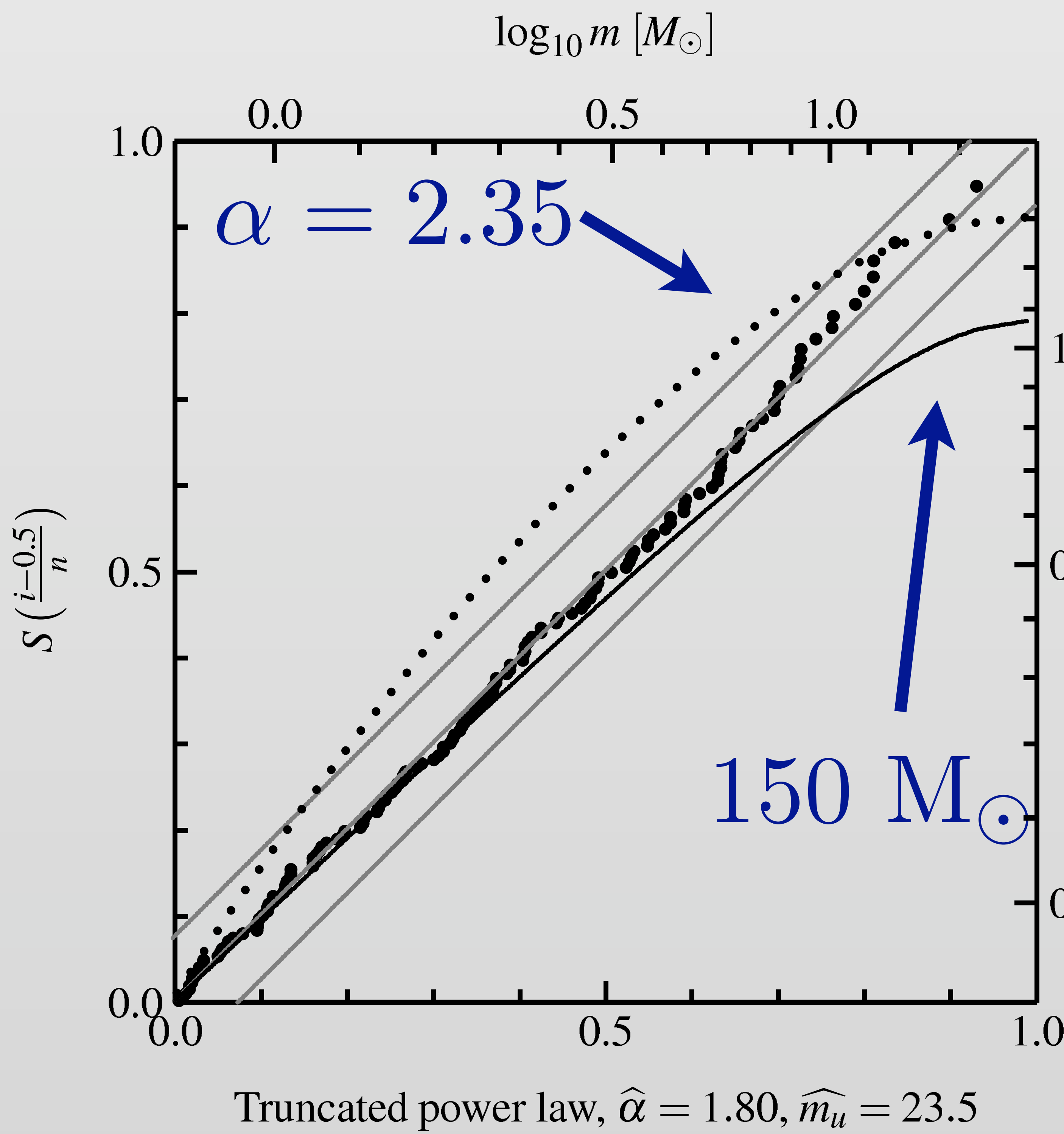
Mass function in a Cluster (1000$M_\odot$)

Mass function follows a truncated power law!

Exponent rather small (1.80)

Truncation mass only slightly above the most massive star ("strong truncation")

Exponent rather small: massive stars concentrated in centre

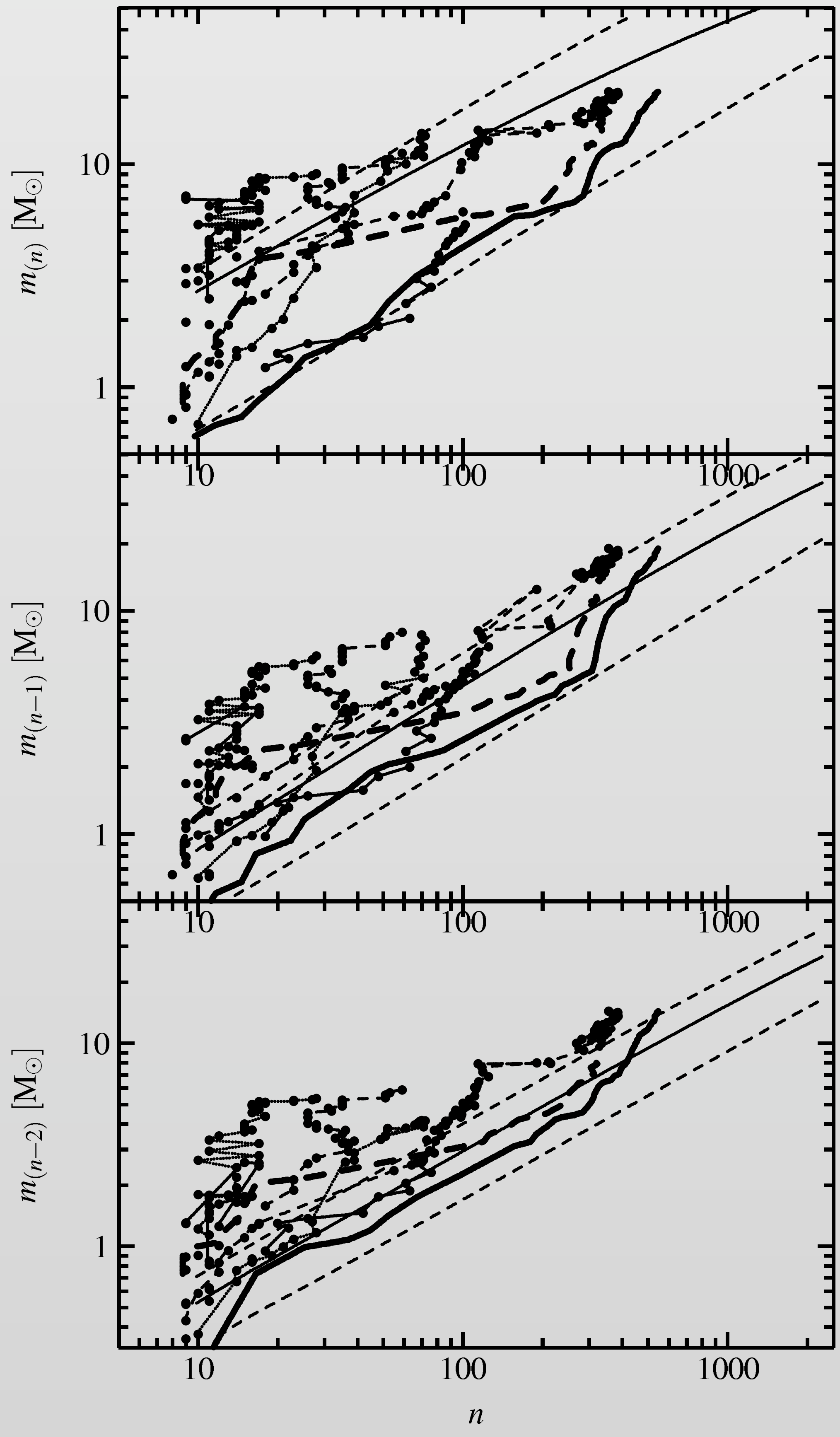


Mass function in small-n systems

Use the dependence of the most massive, second and third most massive star on n.

They lie very high.

Their spacing is smaller than expected.

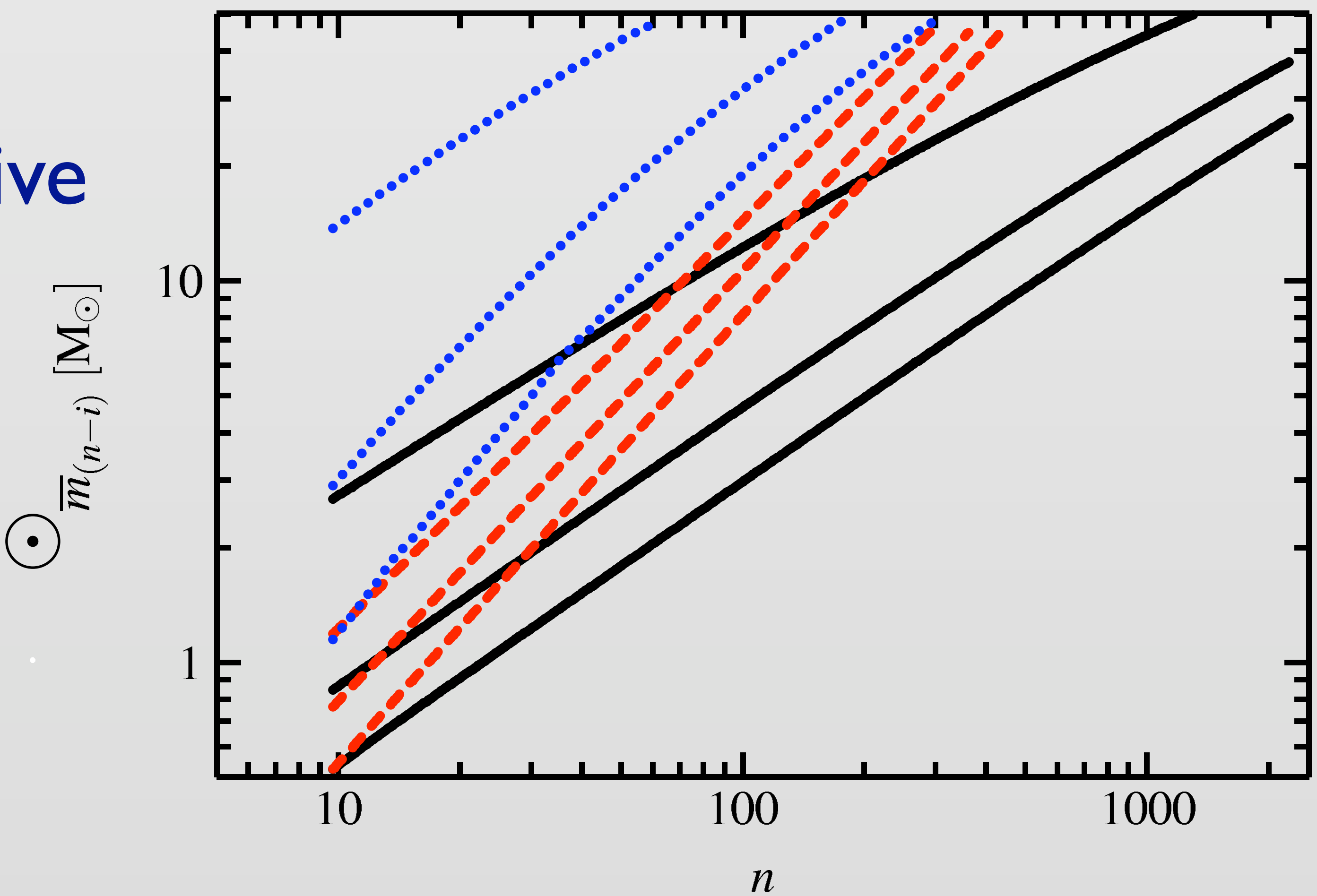


Mass function in small-n systems

Mean of the most massive, second and third most massive star.

Standard:

$\alpha = 2.35 \quad m_u = 150\ \mathrm{M}_\odot$



They lie very high:

Flatter mass function

$\alpha = 1.8 \quad m_u = 150\ \mathrm{M}_\odot$

Their spacing is smaller than expected:

Truncated mass function

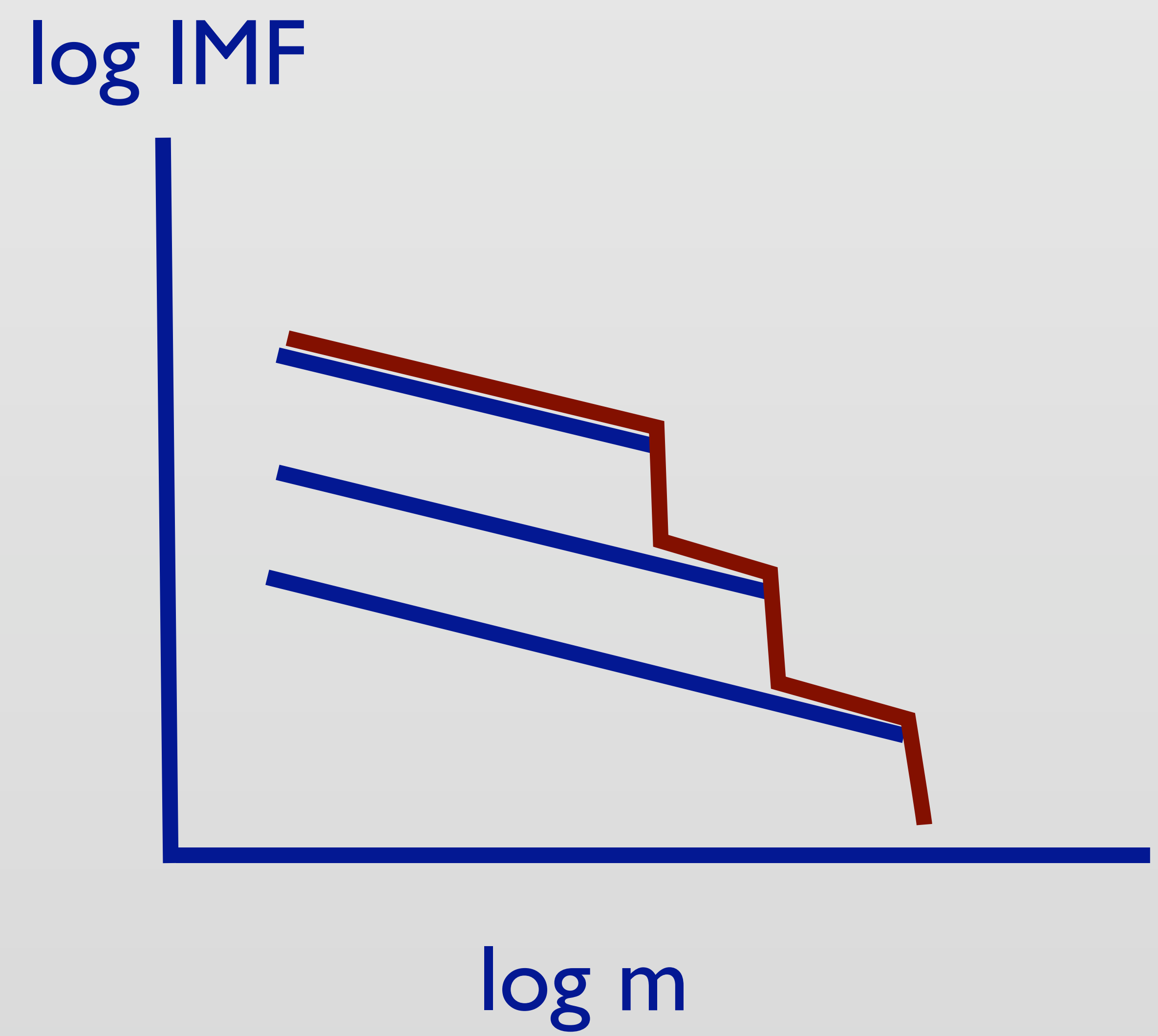
$\alpha = 1.8 \quad m_u = f(n)$

IGIMF effect?

Large simulation produces several clusters.

If you add up mass functions with different truncation masses, the resulting mass function will have a different shape.

Steepening of the high-mass slope
or
turn-down.



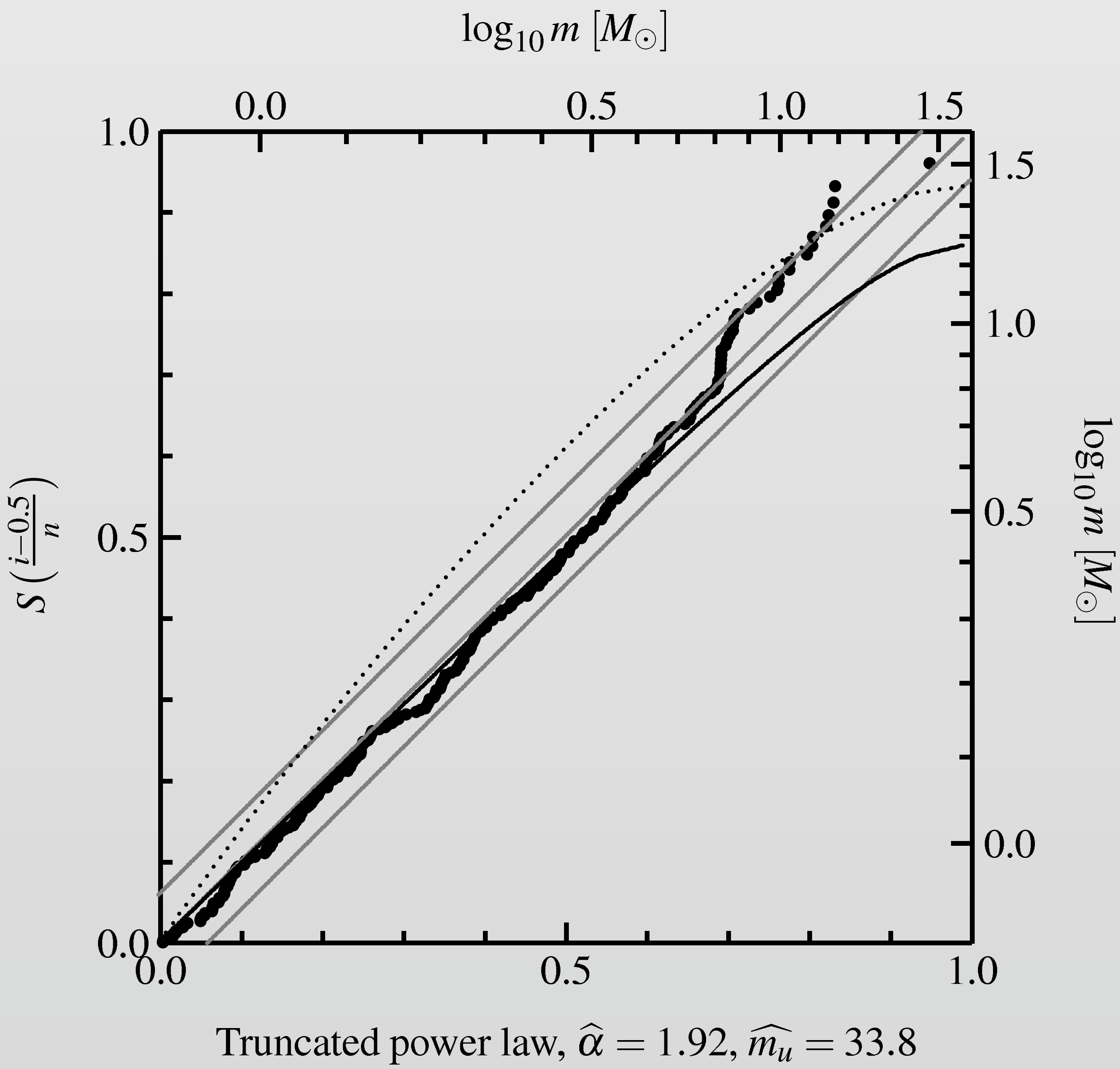
SPP plot of all stars in clusters

Adding up all stars in clusters to have a homogeneous sample.

Truncated power law not a good fit.

Data curve towards a turn-down at high masses.

A sign of the IGIMF effect?



Conclusions

Subclusters are usually round.
Mergers happen quickly.
Subclusters quickly reach a central concentration.

Subclusters form around massive stars.
Subclusters are primordially mass segregated.

The mass function is rather flat.
The mass function is strongly truncated.

There might be signs of the IGIMF effect.