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Dynamical evolution of clusters and the influence of binaries

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Open questions:

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   - What is a cluster?
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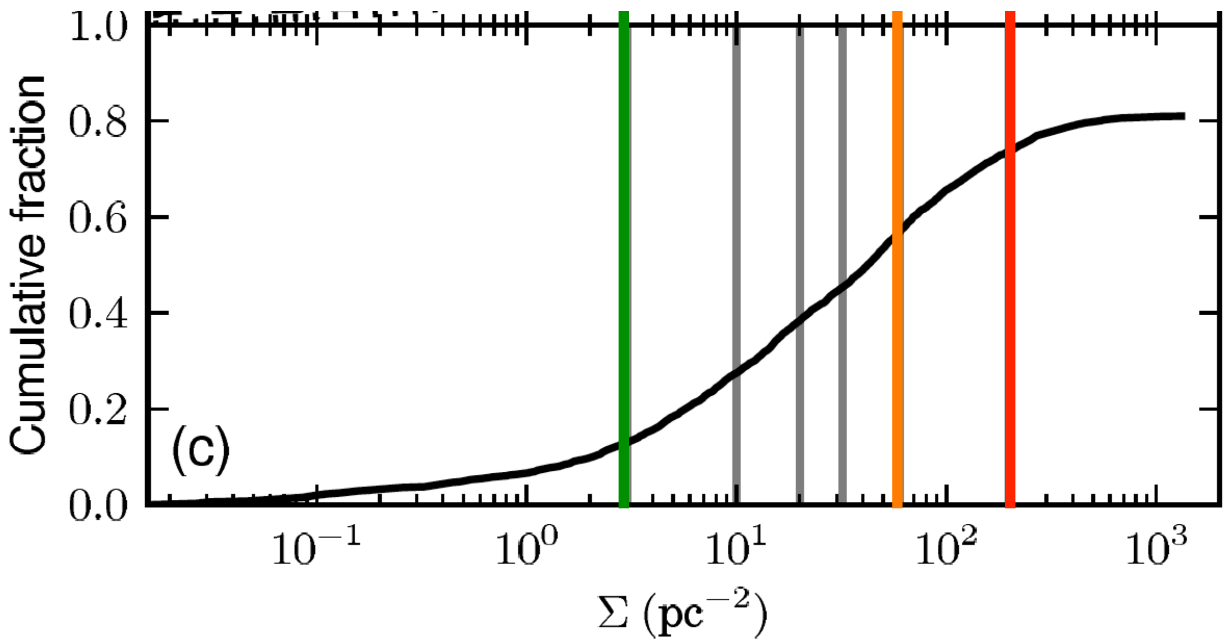
3. Do star clusters contribute to the Galactic field?
4. Can we determine the initial conditions of star formation?
5. Can *Gaia* (and surveys) help?

What is a star cluster?

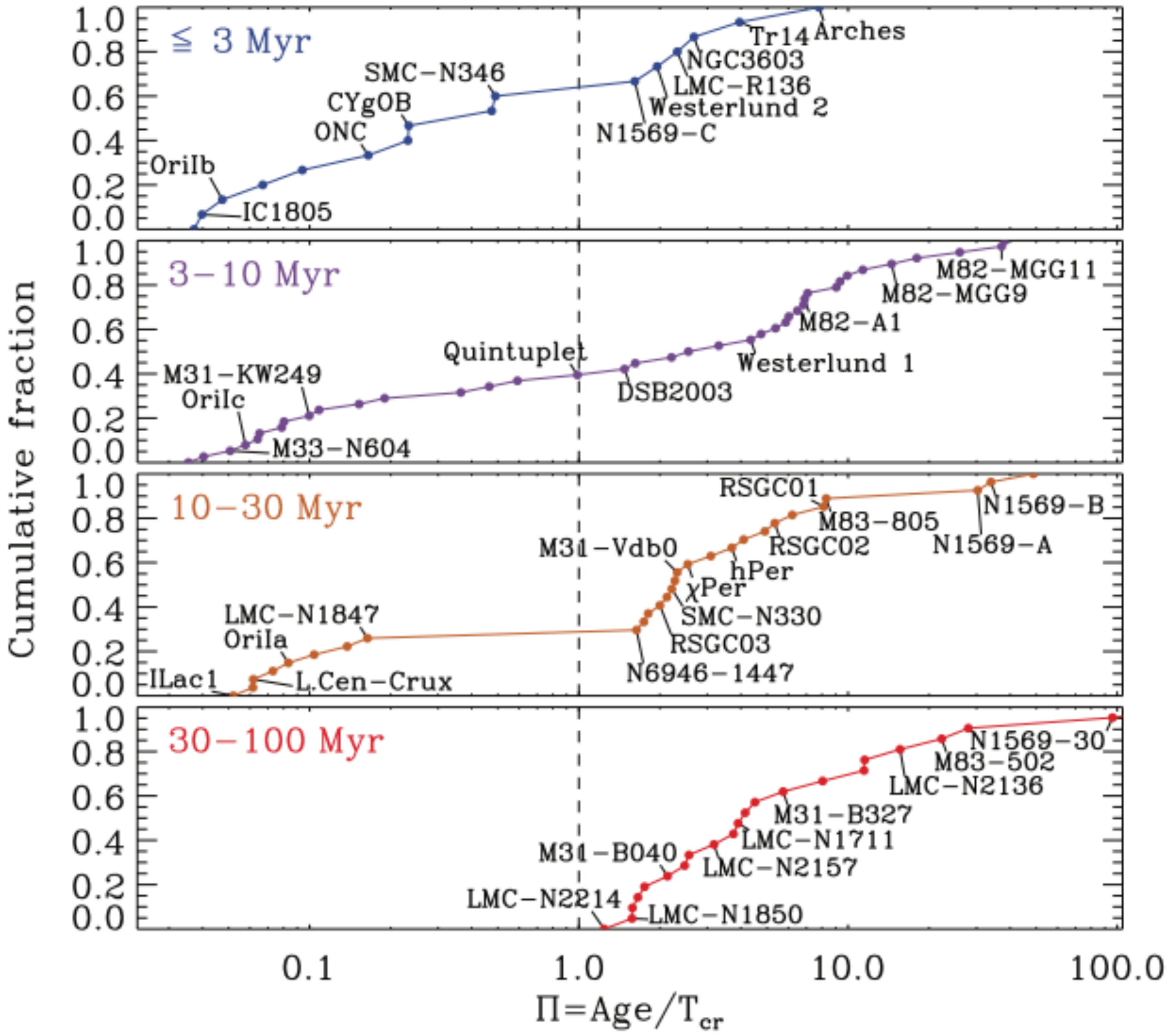
- Define based on a surface density threshold:
  - Lada & Lada (2003): 3 stars pc^{-2}
  - Gutermuth et al. (2009): 60 stars pc^{-2}
  - Bressert et al. (2010): “dense clusters” – 200 stars pc^{-2}



What is a star cluster?

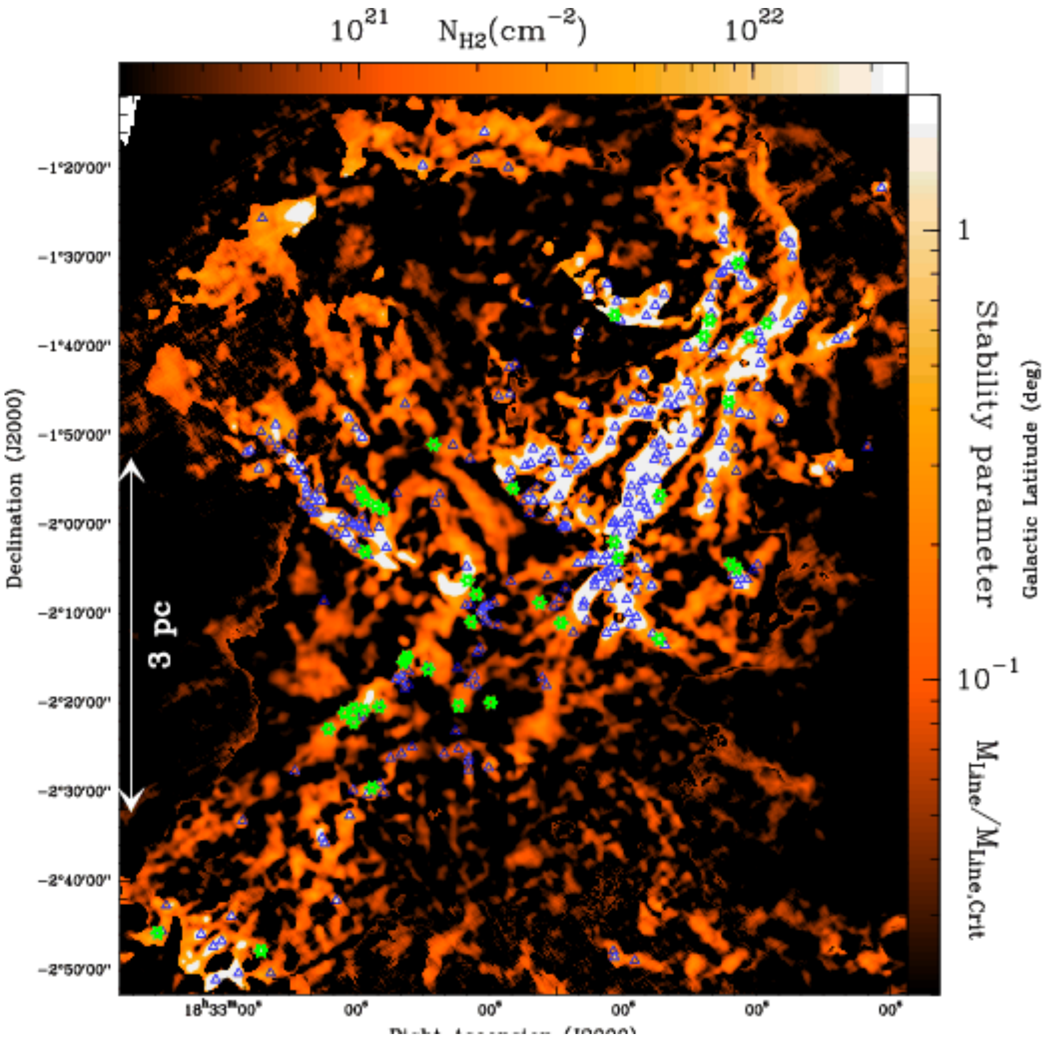
- "Bound" versus "unbound" (e.g. Gieles & Portegies Zwart 2011)
- Define based on crossing time:

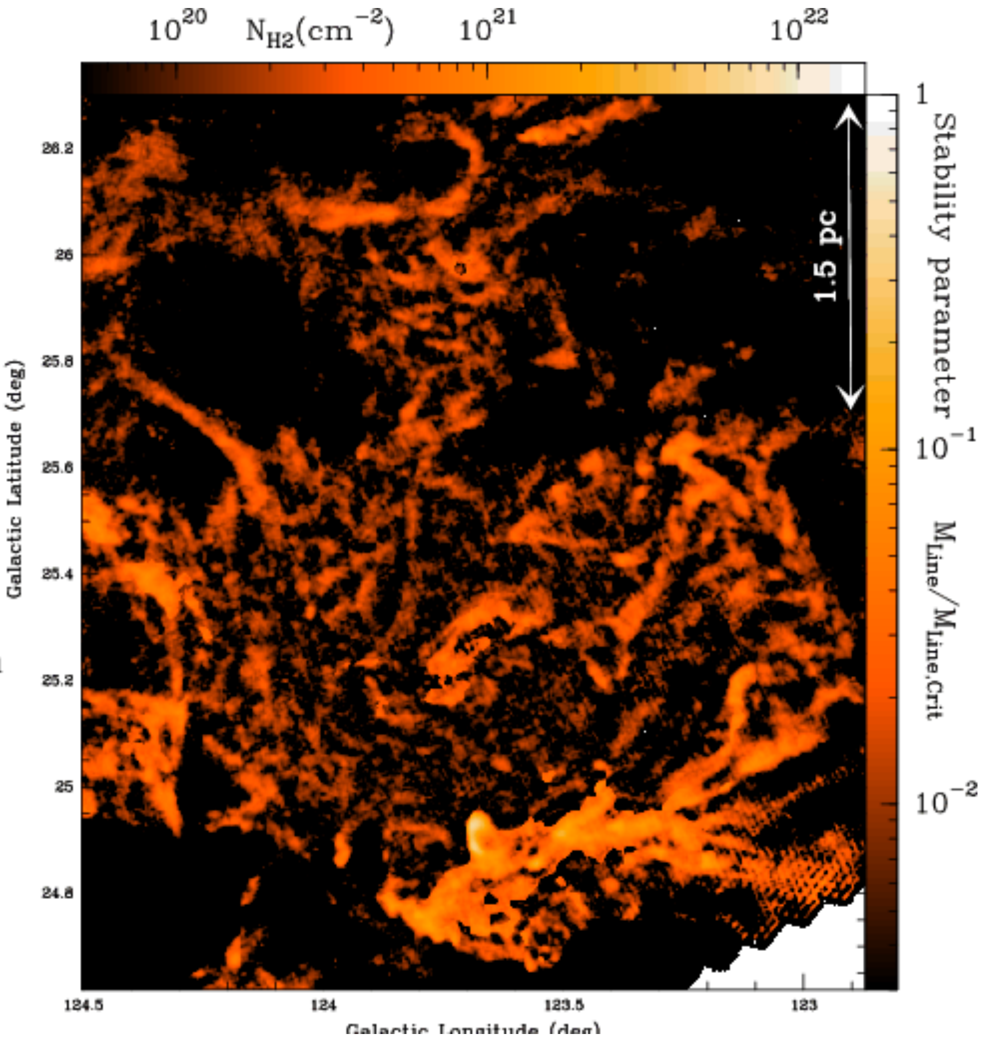
$$T_{cr} \equiv 10 \left(\frac{R_{eff}^3}{GM} \right)^{1/2}$$



The birthplace of clusters?

- Star-forming cores observed in filaments (e.g. Andre et al 2010, Herschel) – low velocity dispersion
- Filaments intersect at “hubs” (Myers 2012)





Clustered star formation

Trapezium/ONC

(M. McCaughrean/ESO 2001)

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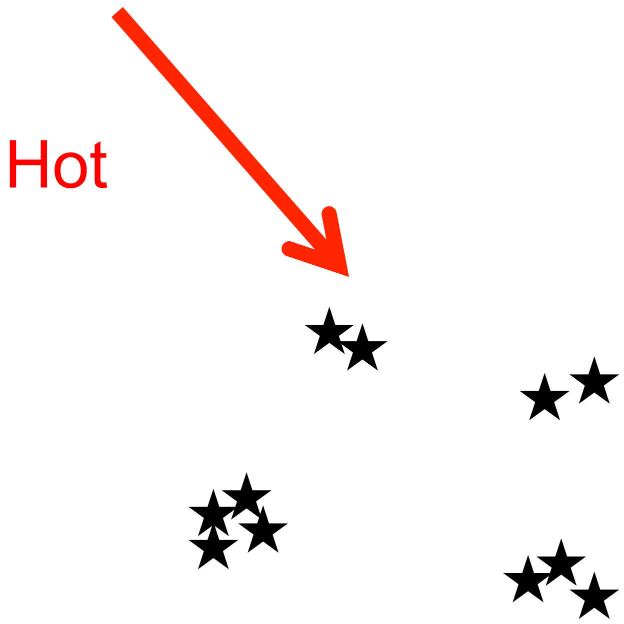
Clusters versus associations?



Universal initial conditions?

What can we measure?

- Initial mass function
- Binary properties (overall fraction, mass ratio, separation)

- Cluster structure/morphology
- Mass segregation
- Local surface density
- Velocity dispersions

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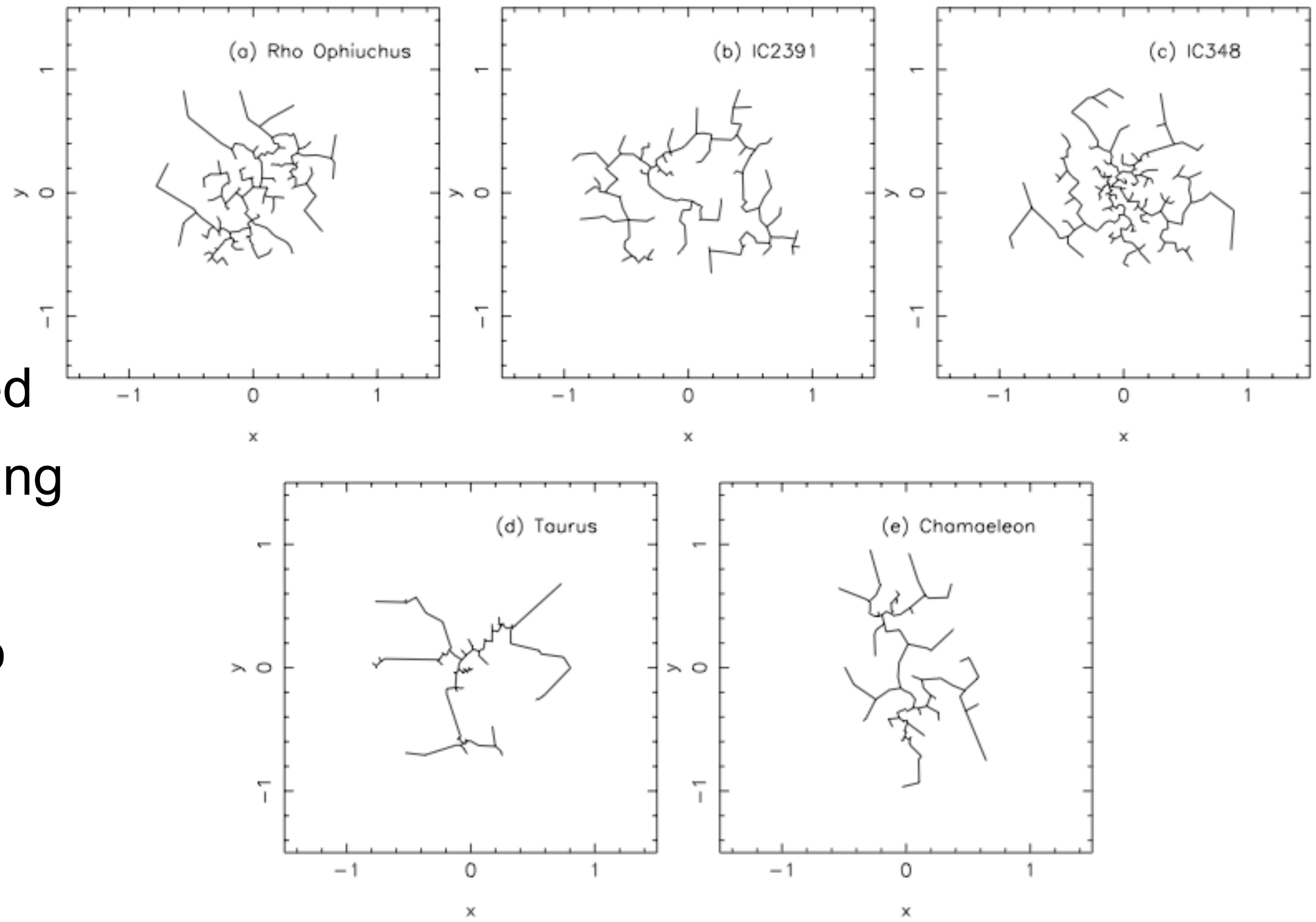
Clusters: structure and morphology

- Measuring structure: the Q-parameter - Cartwright & Whitworth (2004)
- Divides mean MST length by mean separation length

$$\mathcal{Q} = \frac{\bar{m}}{\bar{s}}$$

- Q > 0.8 = radially concentrated
- Q < 0.8 = substructured
- Many young star-forming regions substructured (e.g. Sanchez & Alfaro (2009))



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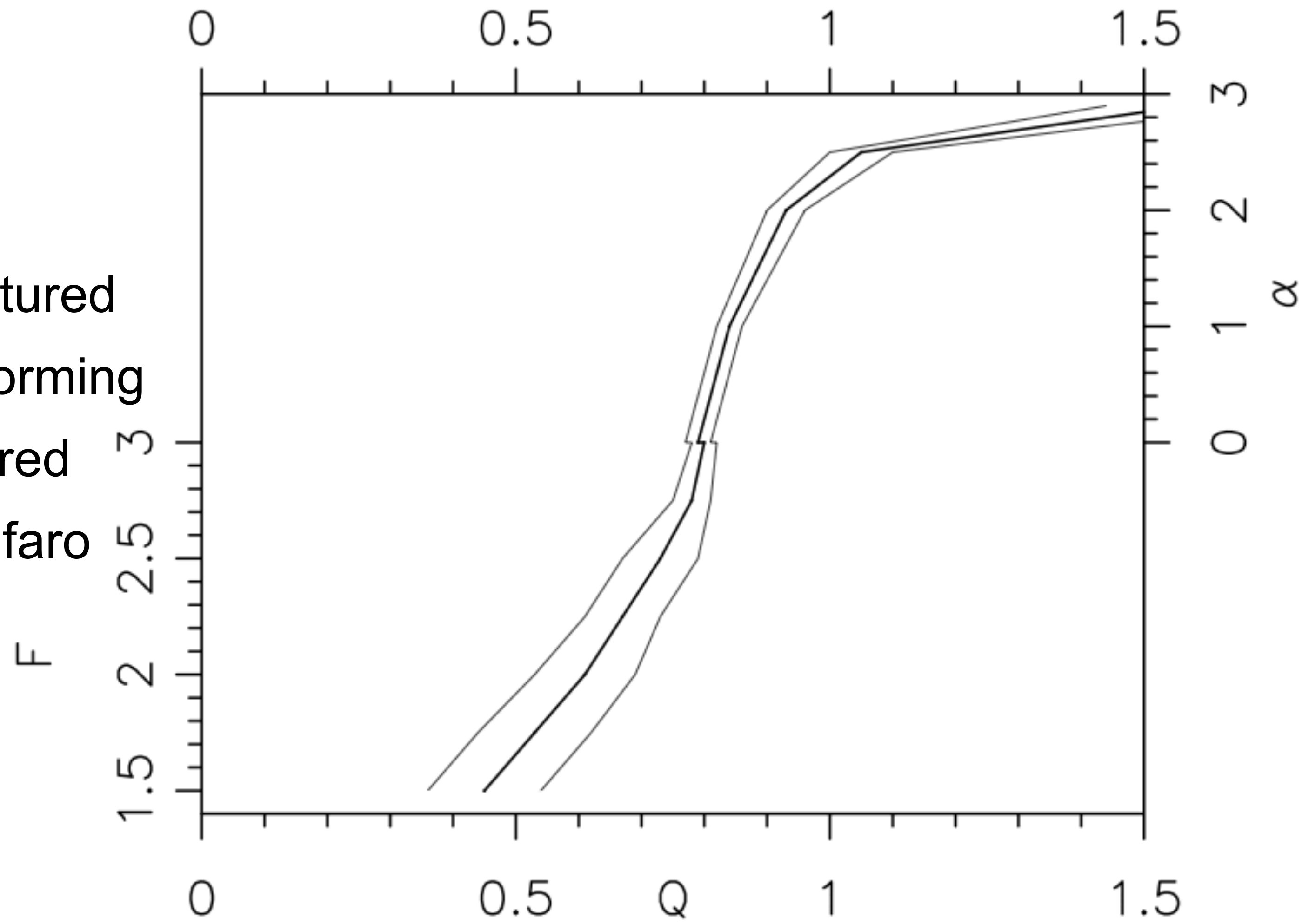

Substructure

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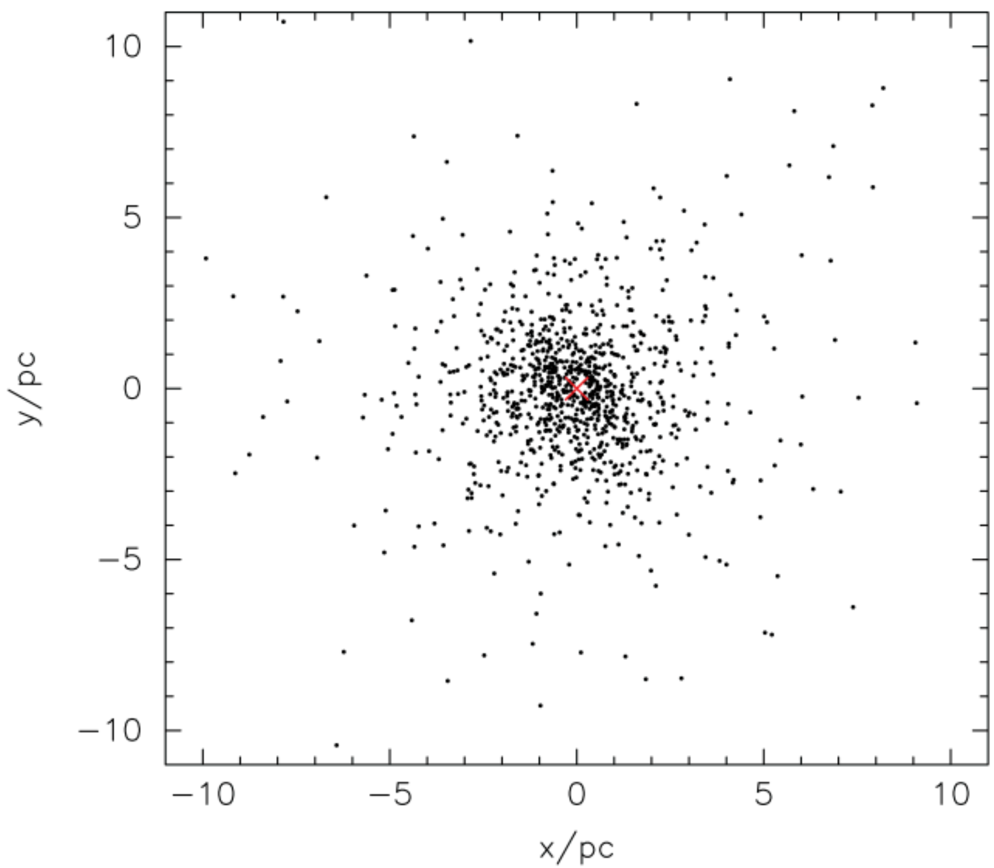
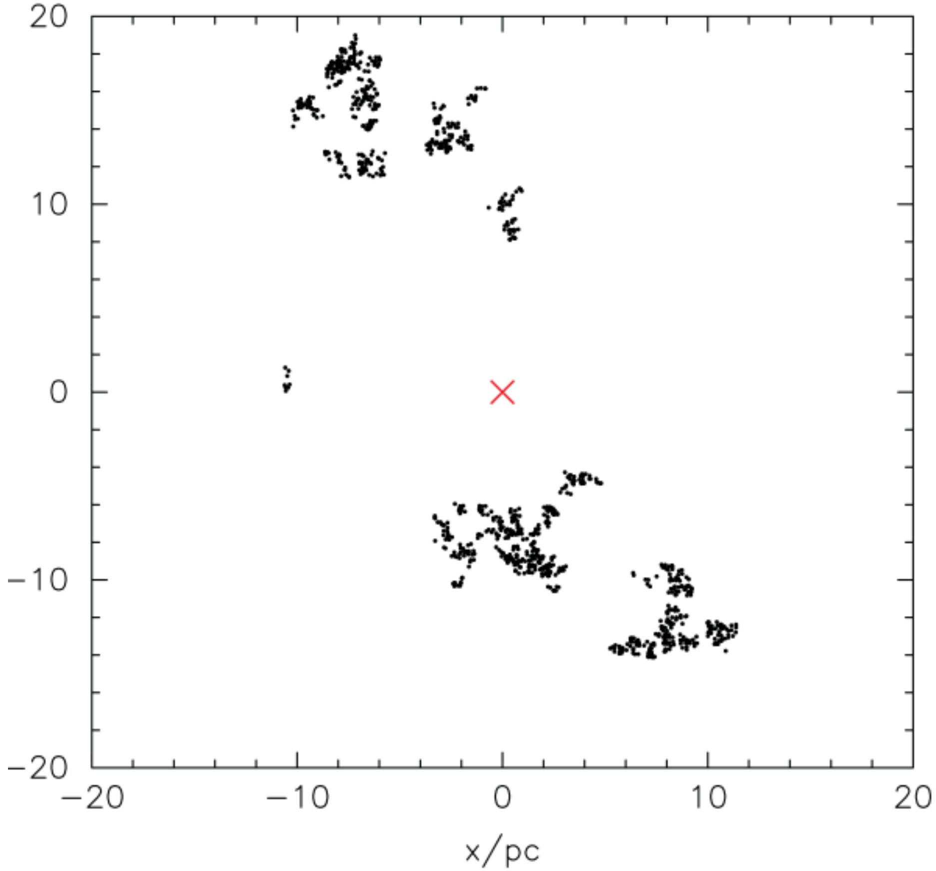
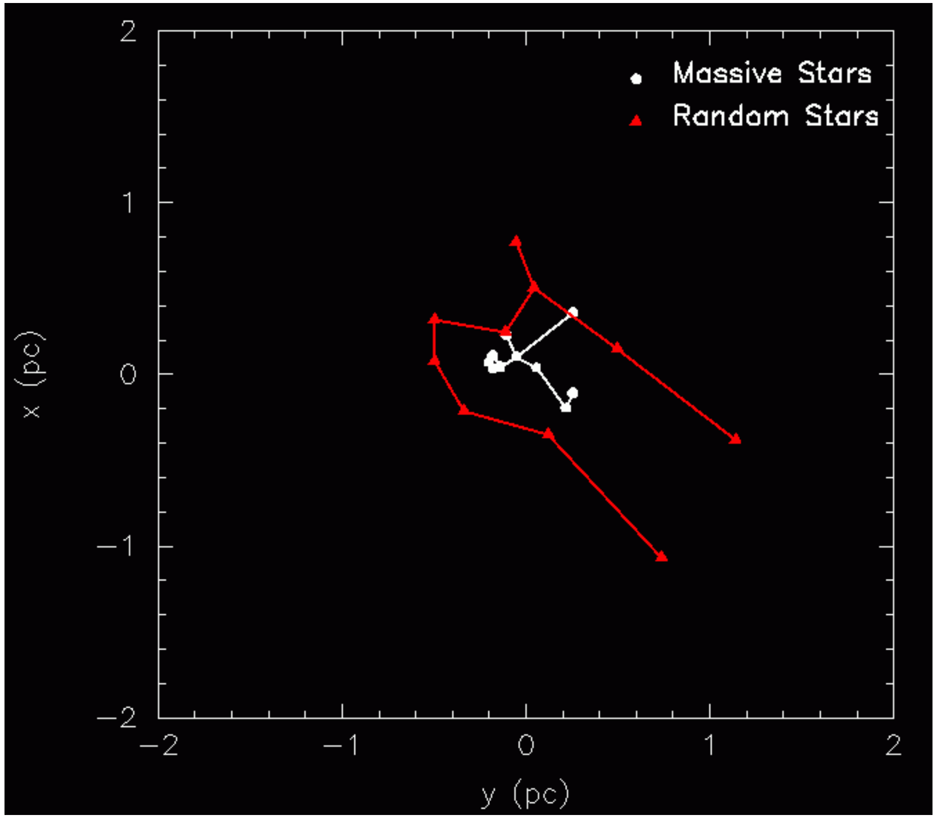
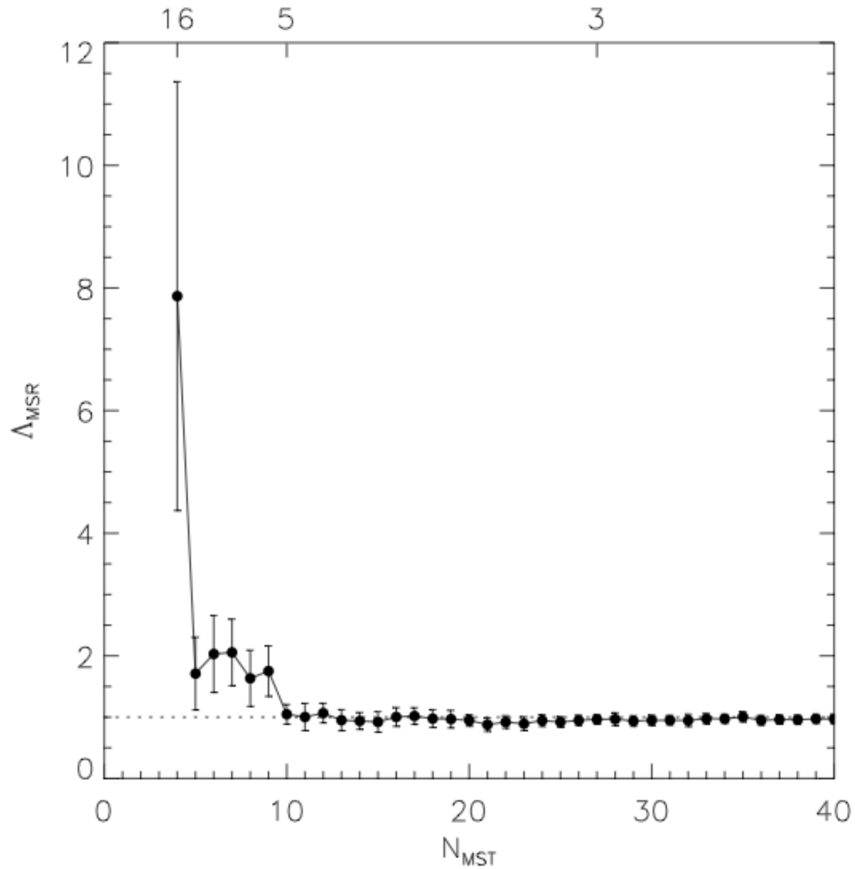




(a) Plummer (Q=1.1) (b) fractal (Q = 0.4)

Mass segregation





Allison et al (2009)

(also Maschberger & Clarke 2011, Olczak et al 2011)

$$\Lambda_{\mathrm{MSR}} = \frac{\langle l_{\mathrm{norm}} \rangle}{l_{\mathrm{massive}}} \pm \frac{\sigma_{\mathrm{norm}}}{l_{\mathrm{massive}}}$$

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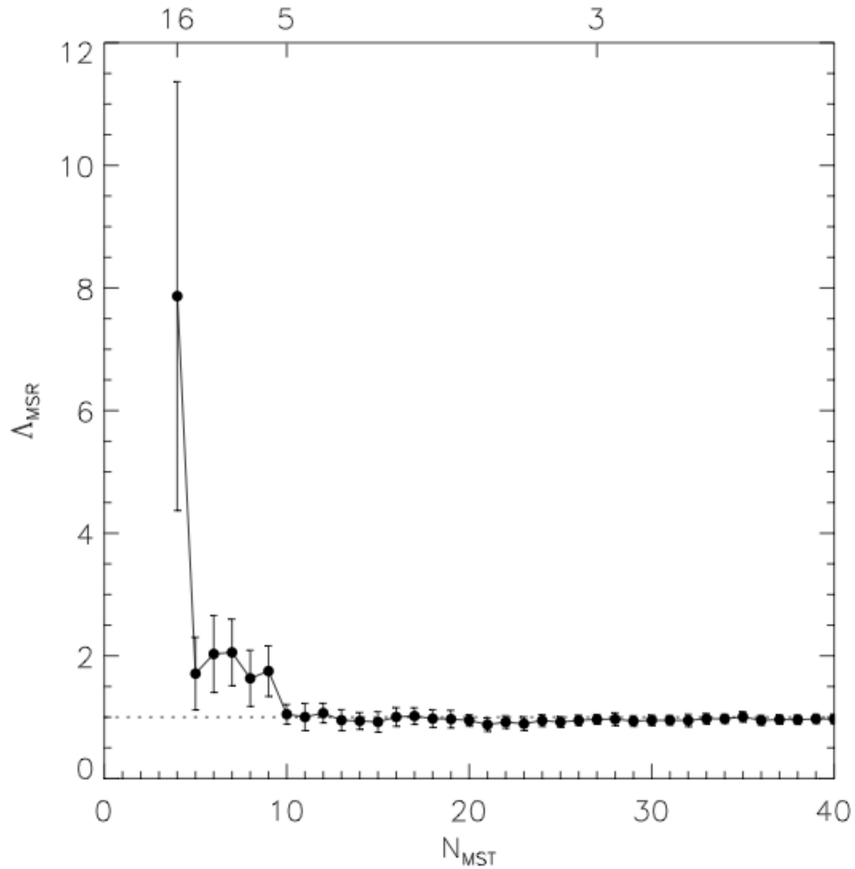

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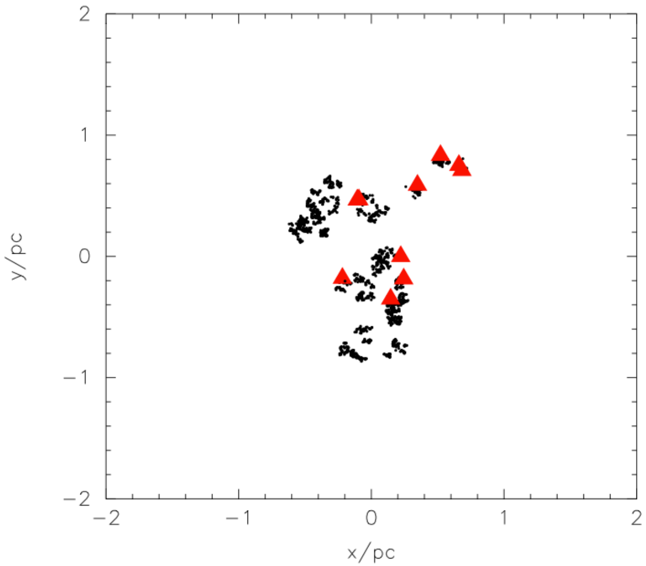
N-body simulations

- Cool and clumpy (Virial ratio = 0.3, fractal dimension 1.6)
- Hot and clumpy (Virial ratio = 1.5, fractal dimension 1.6)
- Tepid and smooth (Virial ratio = 0.5, fractal dimension 2.6)

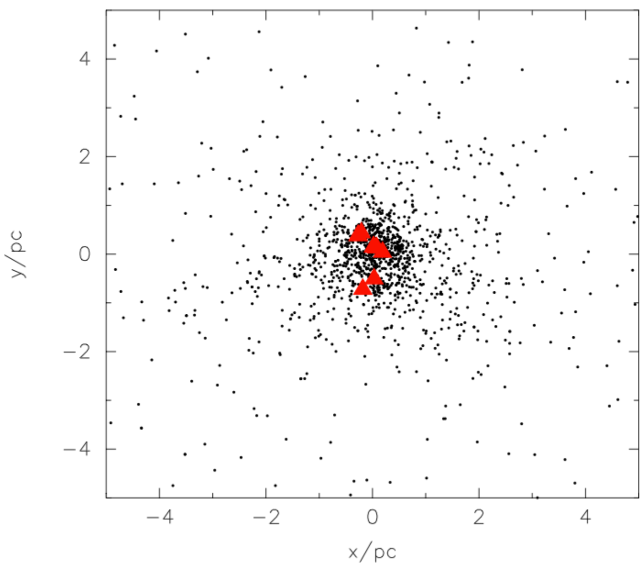
- Simulations: 1500 stars in a cluster
- Maschberger (2013) IMF
- Evolved for 10 Myr with **Starlab** (Portegies Zwart et al 1999)
    a) All single stars
    b) Field-like binaries (Raghavan et al 2010, Bergfors et al 2012, Janson et al 2012, Duchene & Kraus 2013)

Evolution of structure and morphology

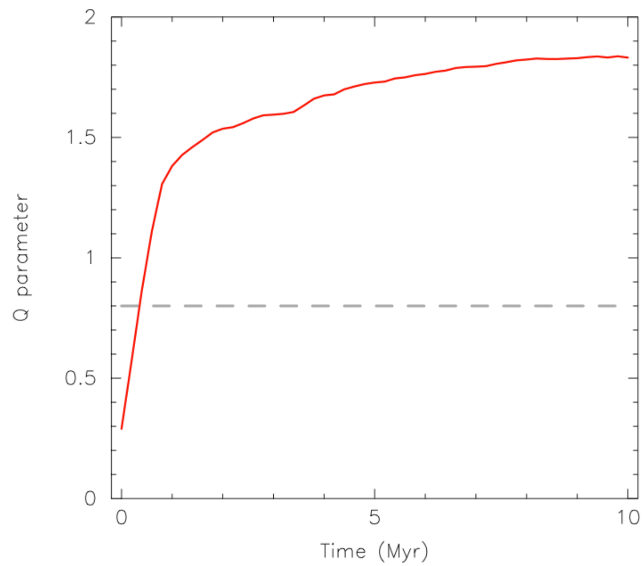
- Measuring structure - evolution of the Q-parameter in a collapsing (cool) fractal cluster:



0 Myr



5 Myr



Q-parameter

- Dynamics rapidly erases substructure (Scally & Clarke 2002; Goodwin & Whitworth 2004; Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer, submitted)

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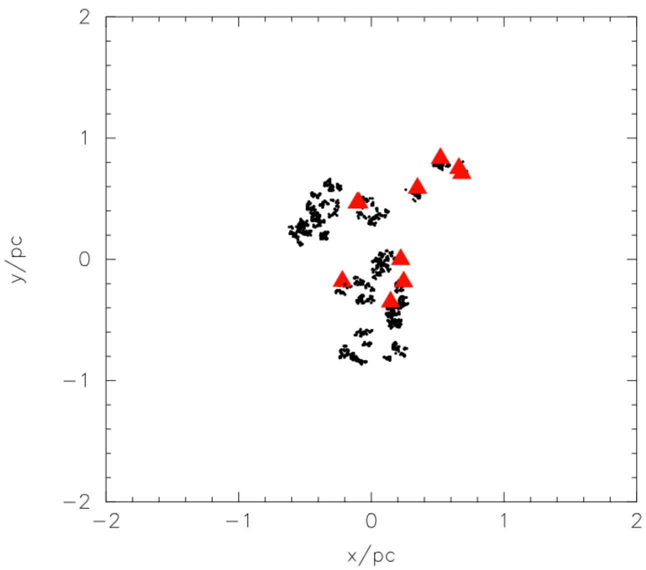

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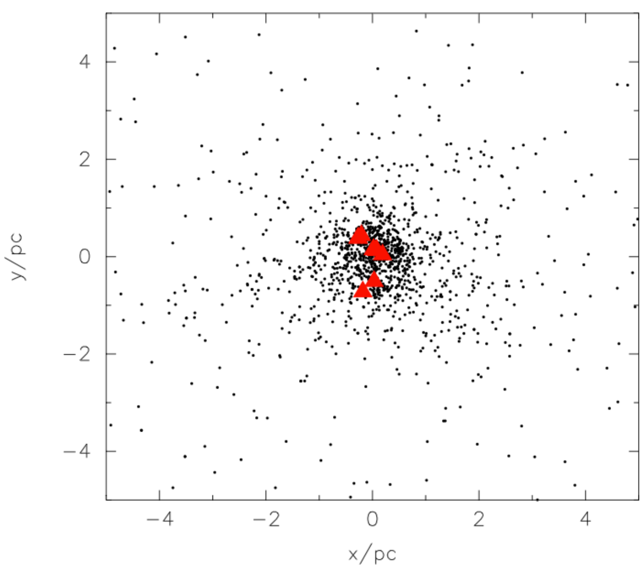

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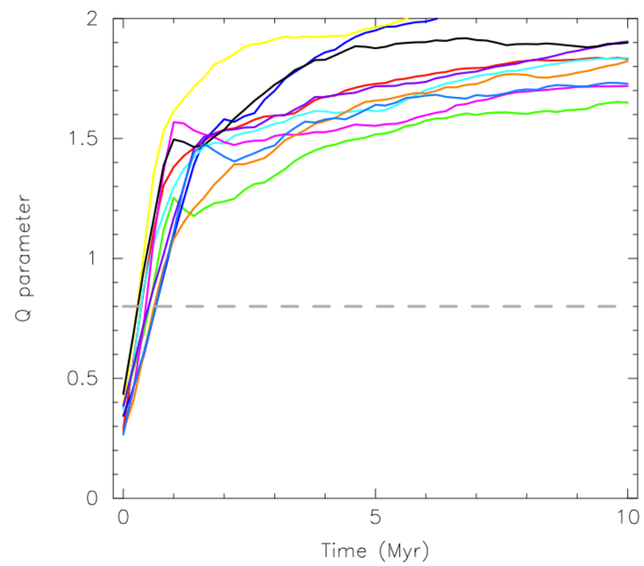

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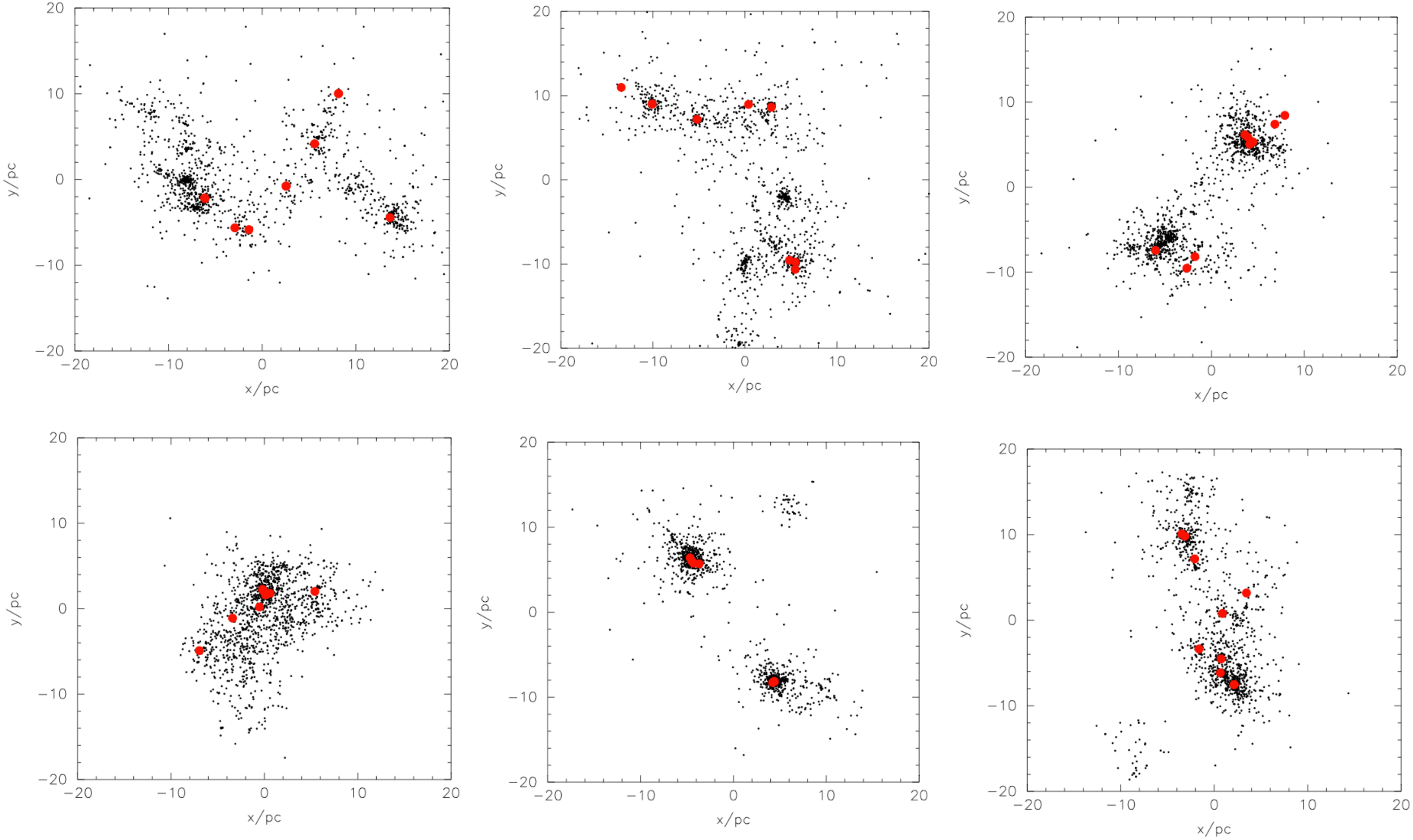
Supervirial stochasticity



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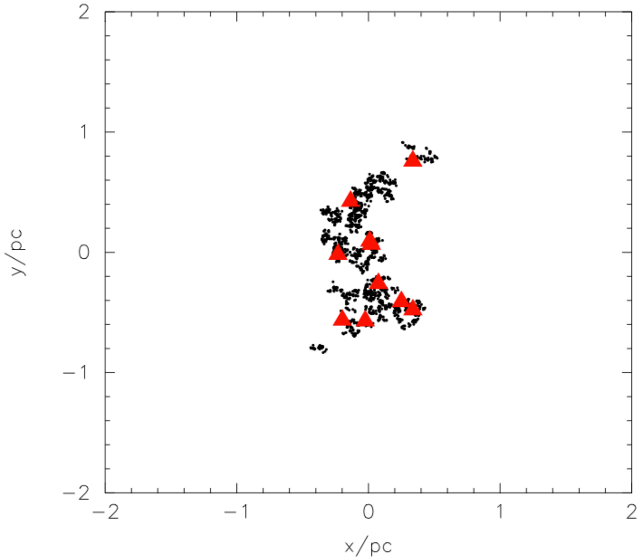
Evolution of structure and morphology

- Measuring structure - evolution of the Q-parameter in an unbound (hot) association:



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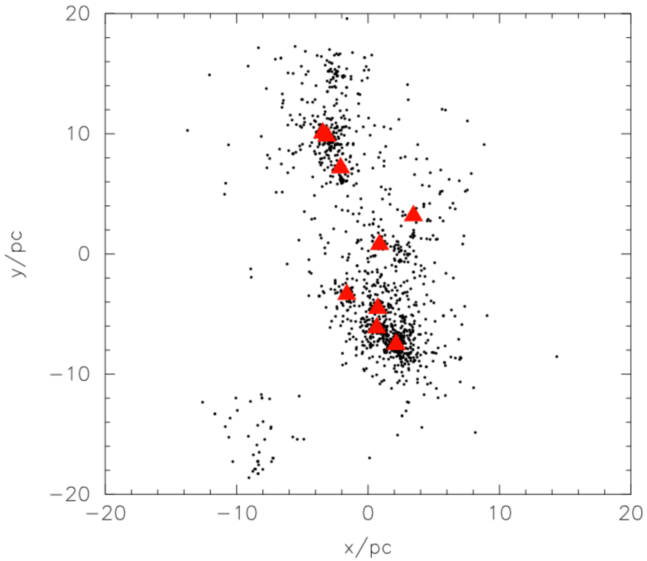

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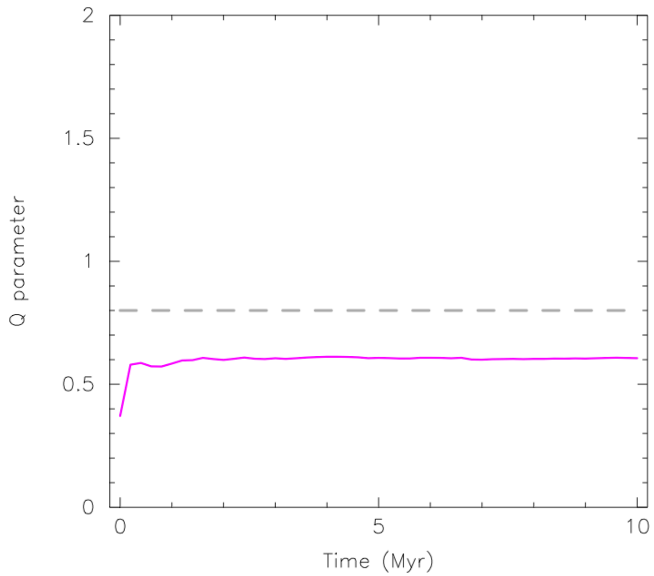

Q-parameter

(Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer, submitted)

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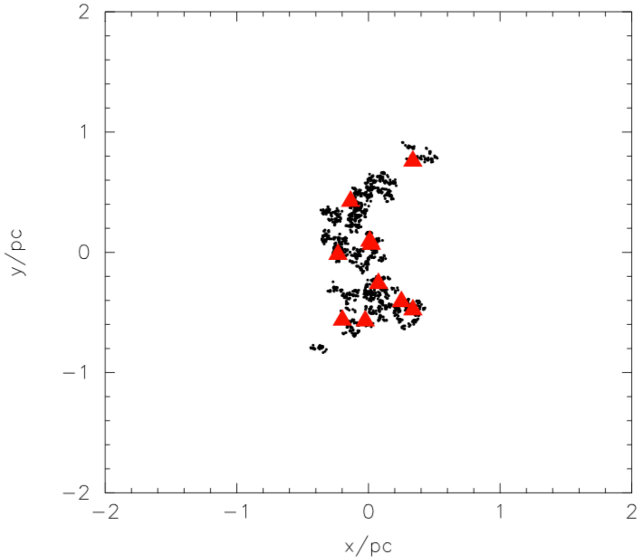

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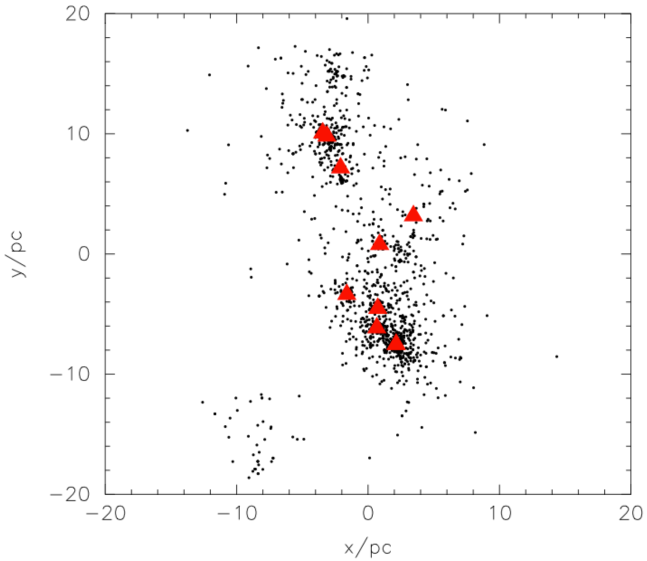

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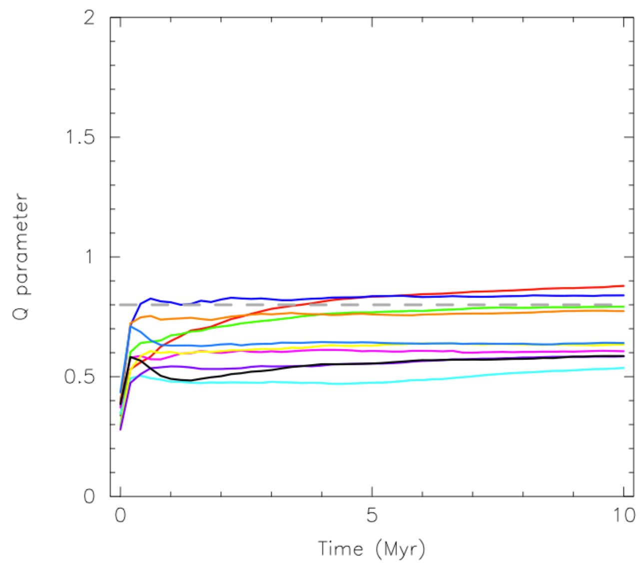

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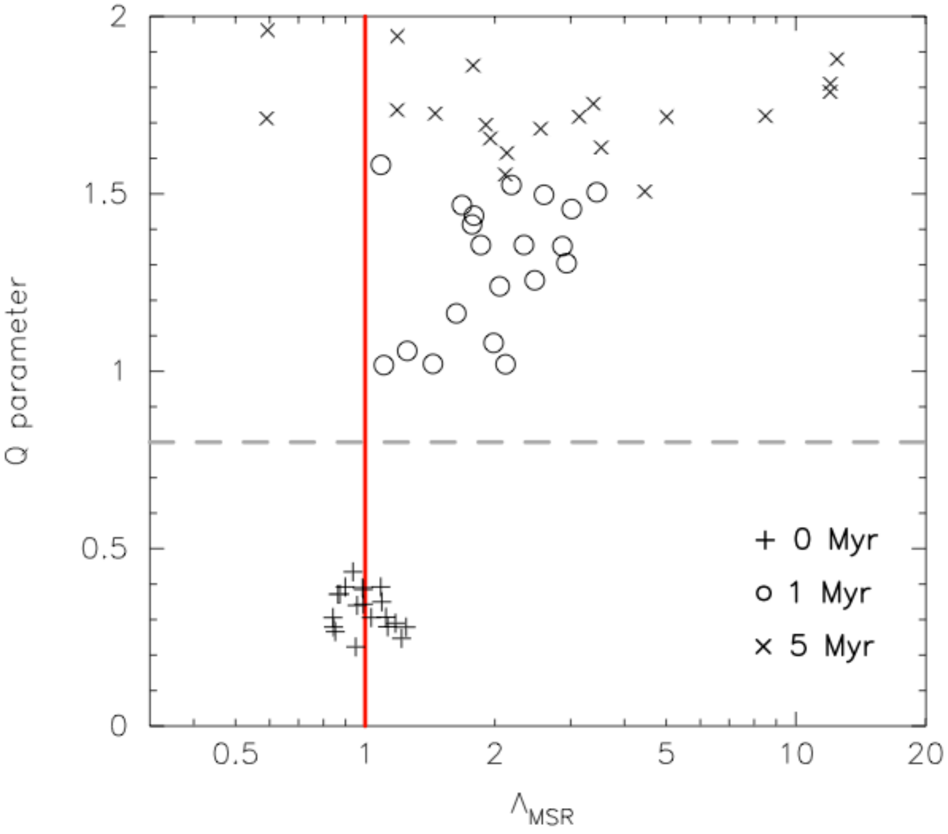
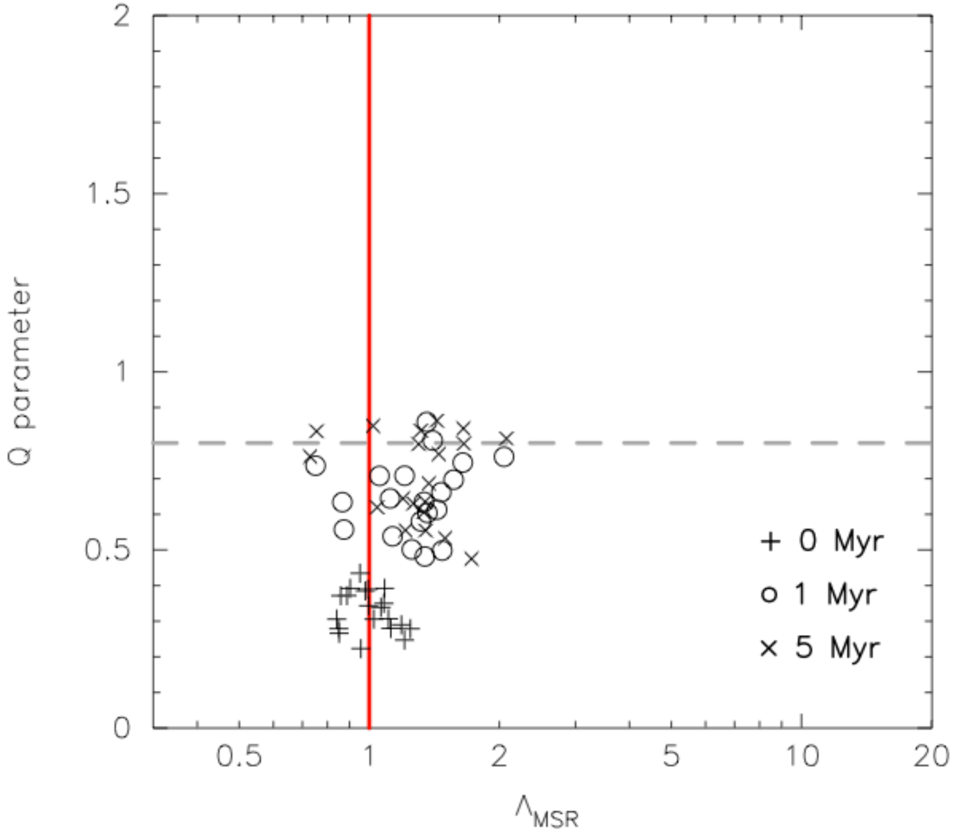
Structure versus mass segregation



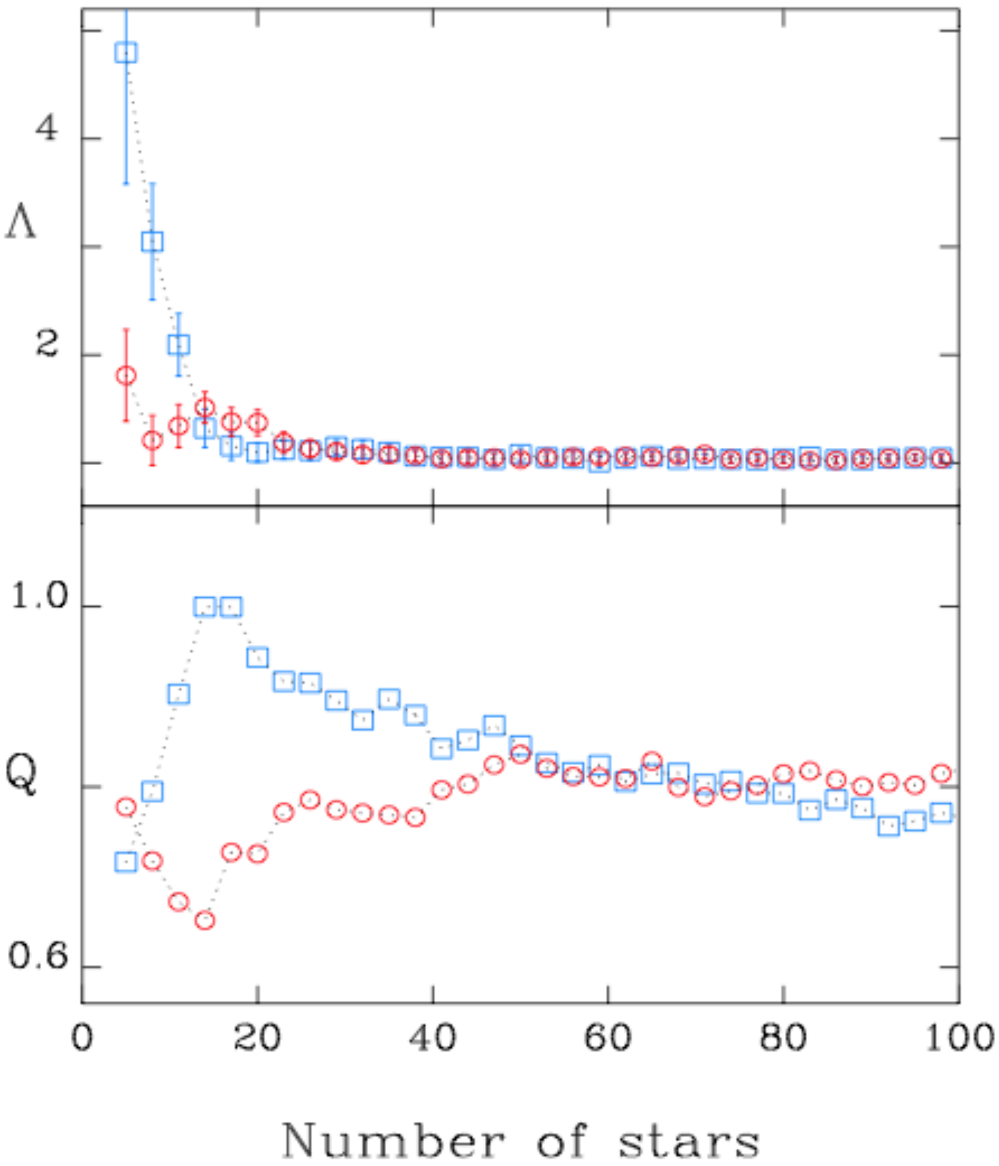
Cool



Hot

(Parker, Wright, Goodwin & Meyer, submitted)

Structure versus mass segregation



Different dynamical histories?

Blue: Ber96
Red: Ber94

(Delgado et al 2013)

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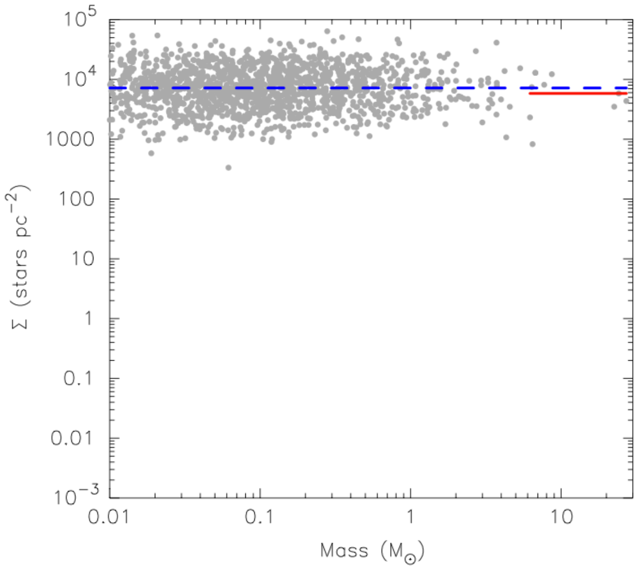
Using surface density to probe evolution



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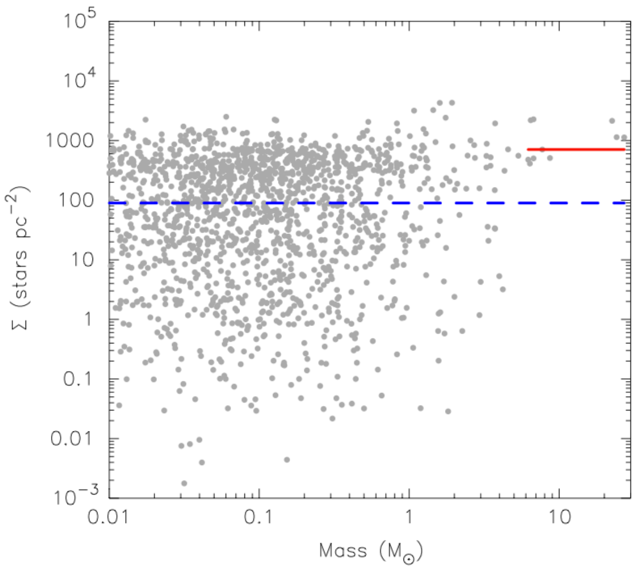
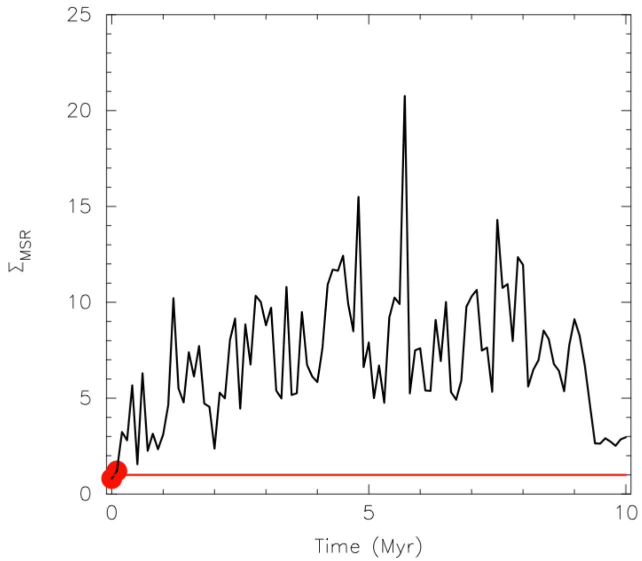


5 Myr



Σ_{LDR}

The Σ – m technique (Maschberger & Clarke 2011):

- Determine the local density of every star.
- Compare to the local density of the massive stars:

$$\Sigma_{LDR} = \Sigma_{massive}/\Sigma_{cluster}$$

(Parker, Wright, Goodwin & Meyer, submitted)

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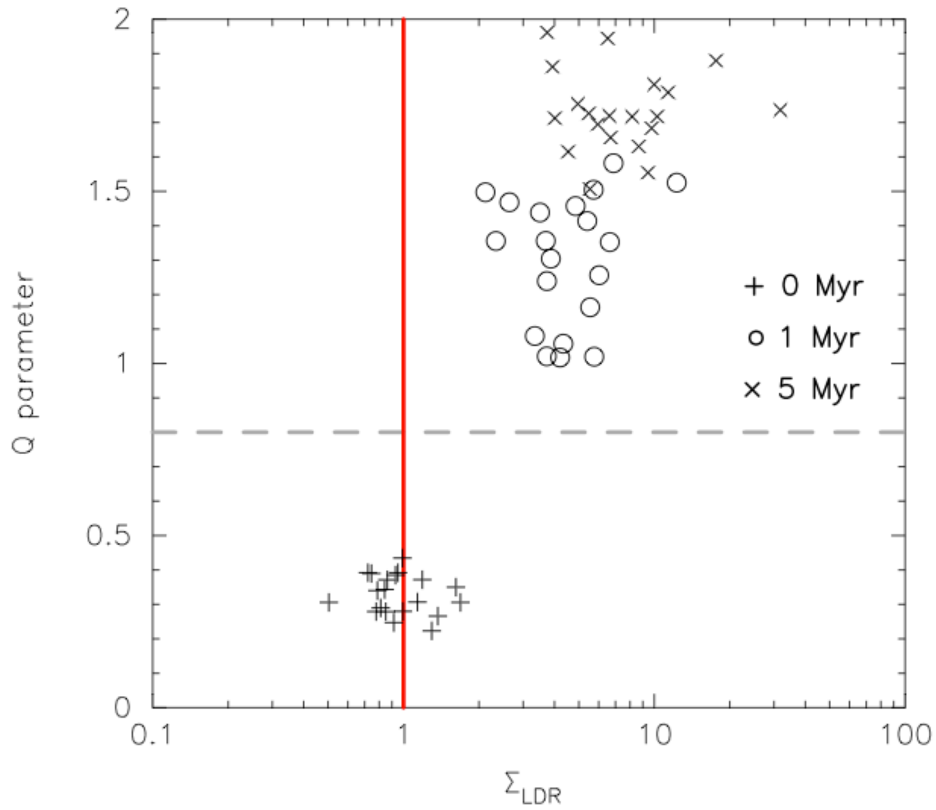
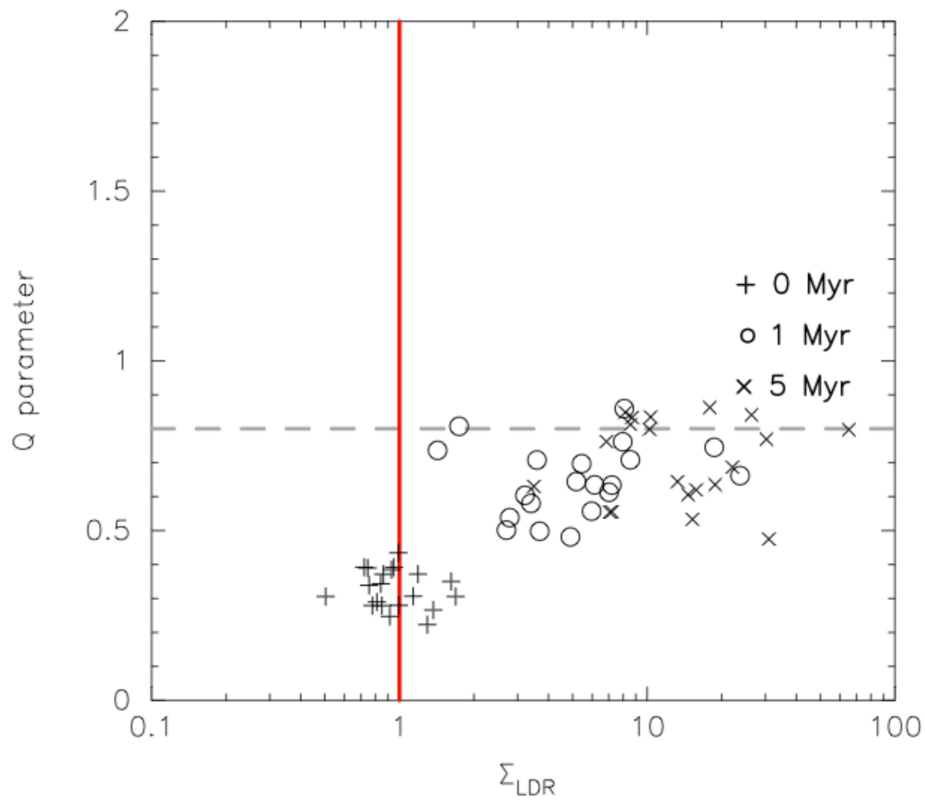
Structure versus surface density



Dense and cool



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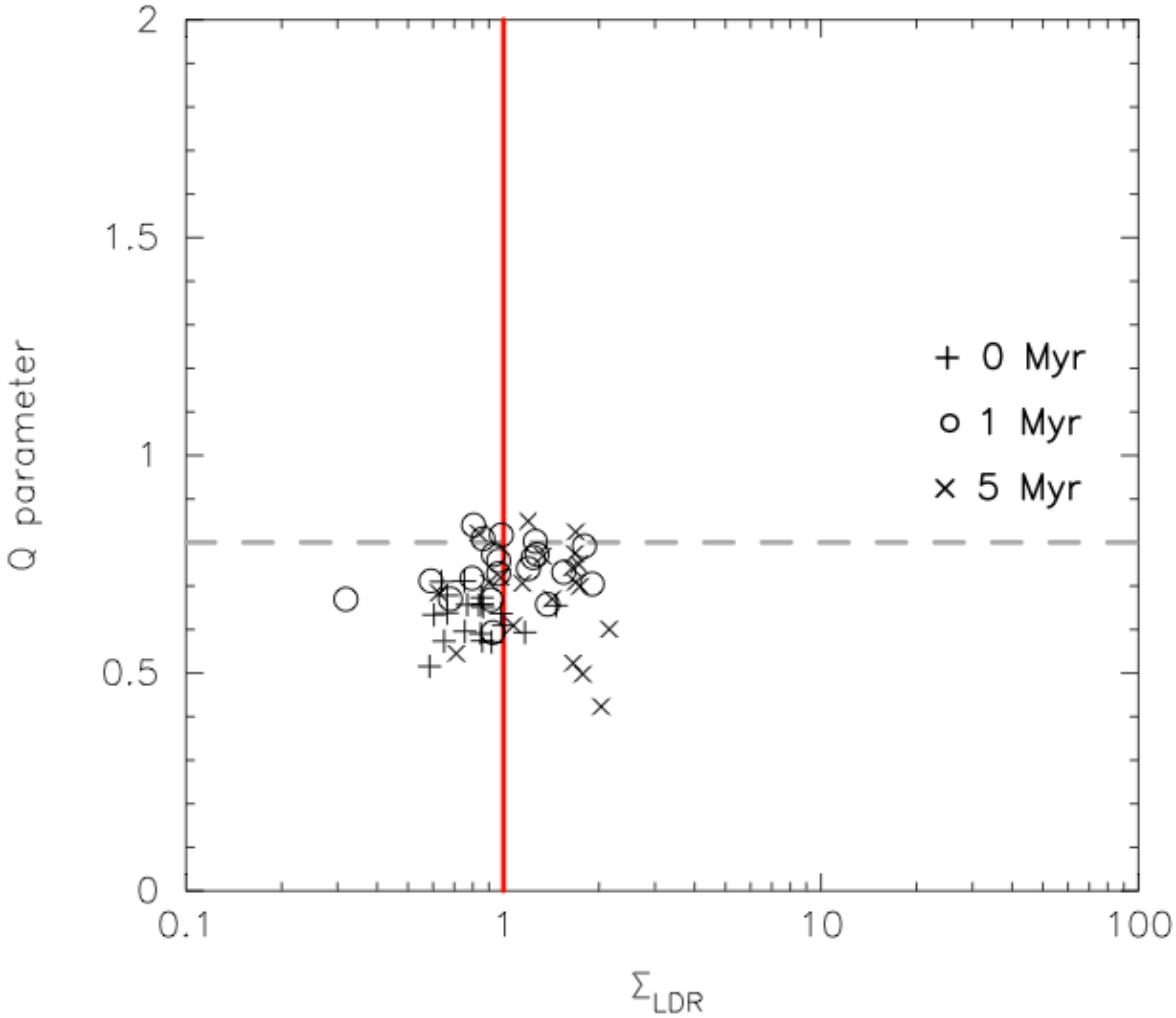
Structure versus surface density



Evolution of a low-density region

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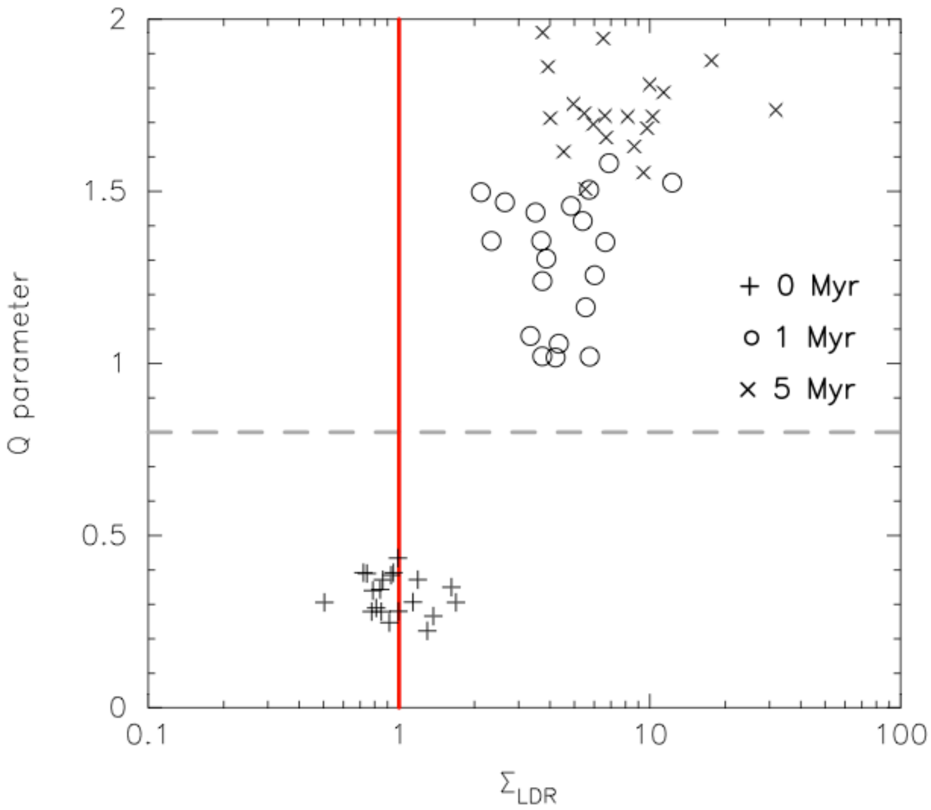
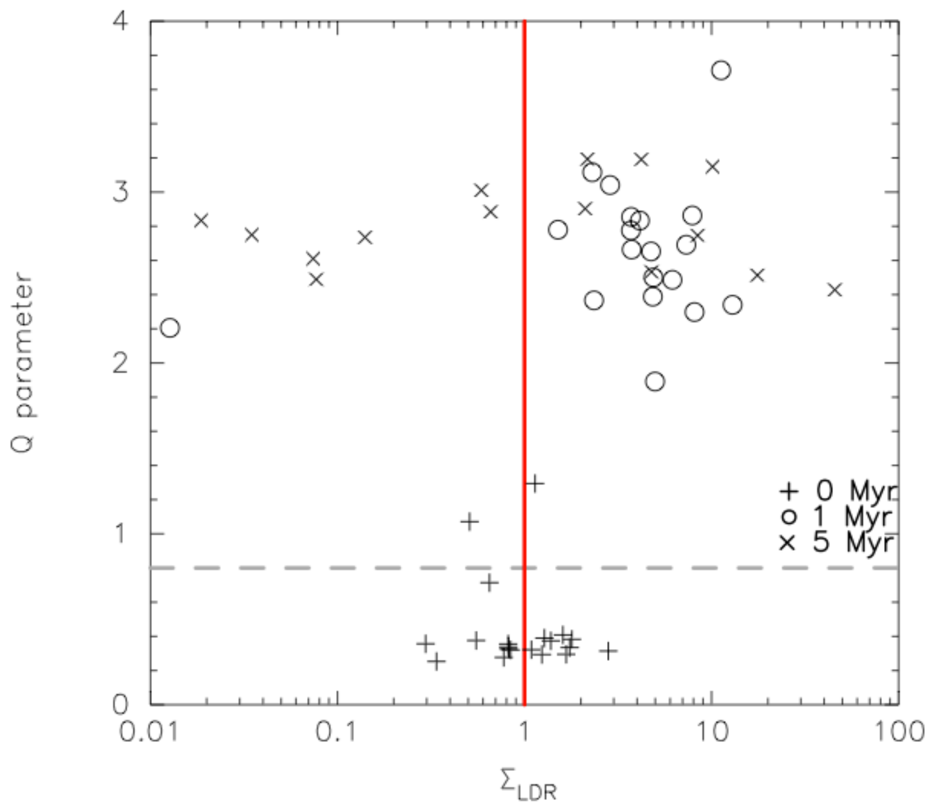
The influence of binaries



Single stars



primordial binaries

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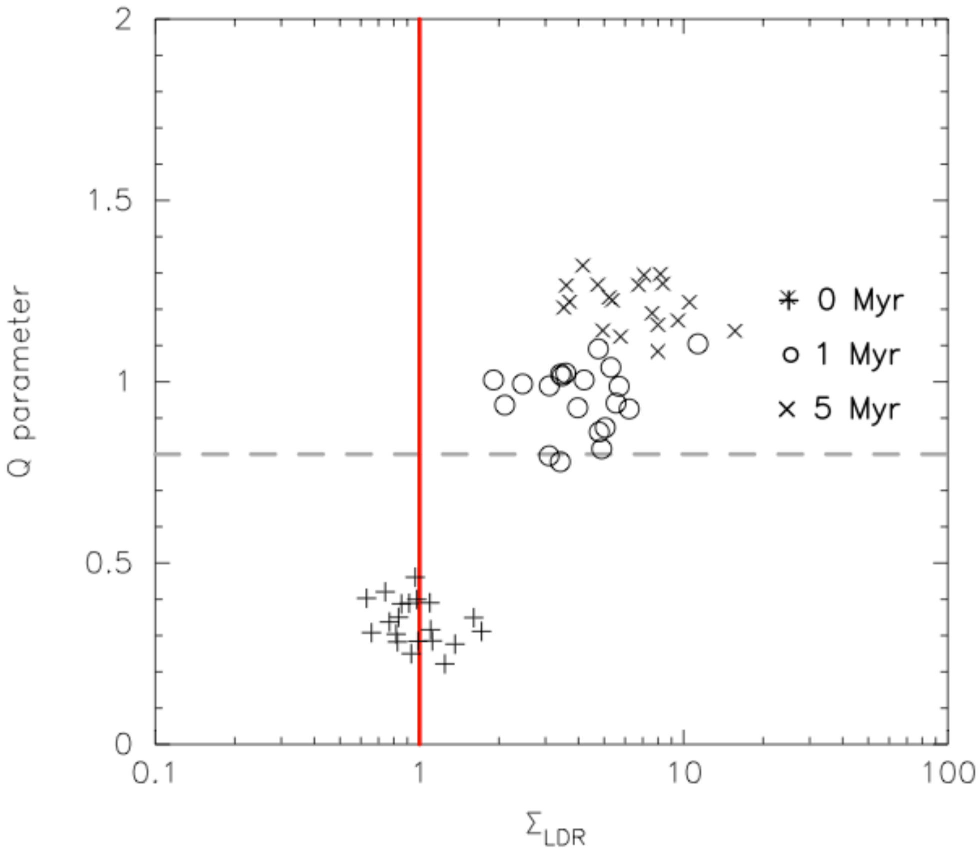
Removing outliers



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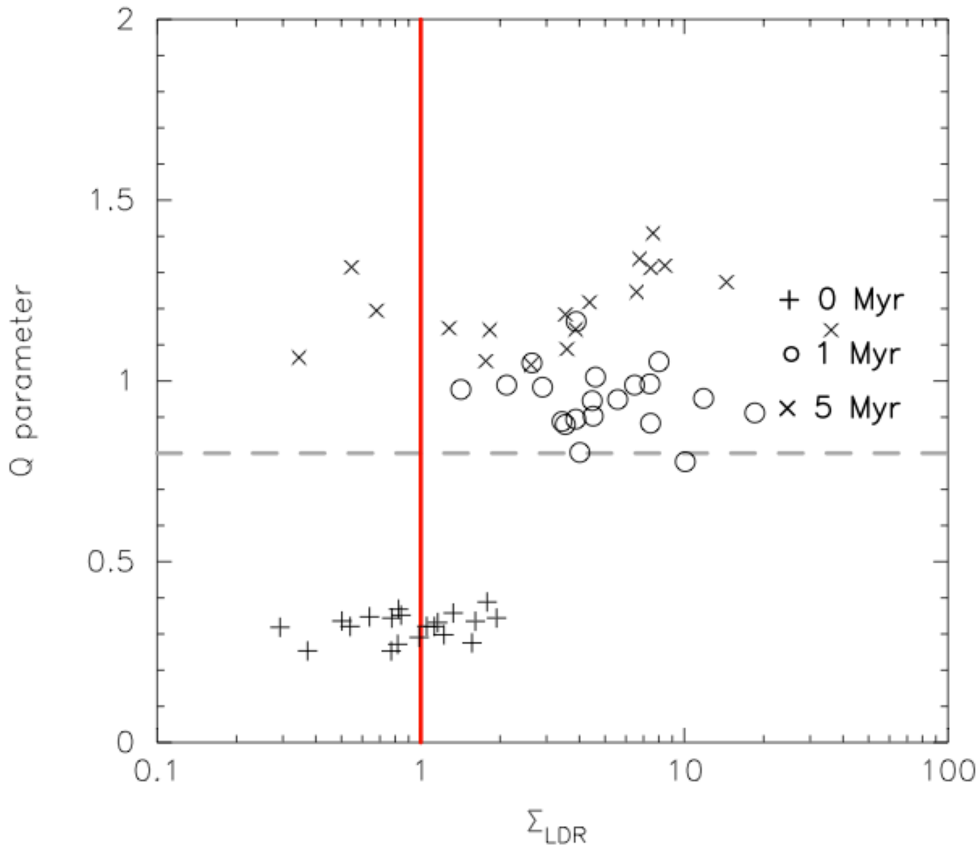
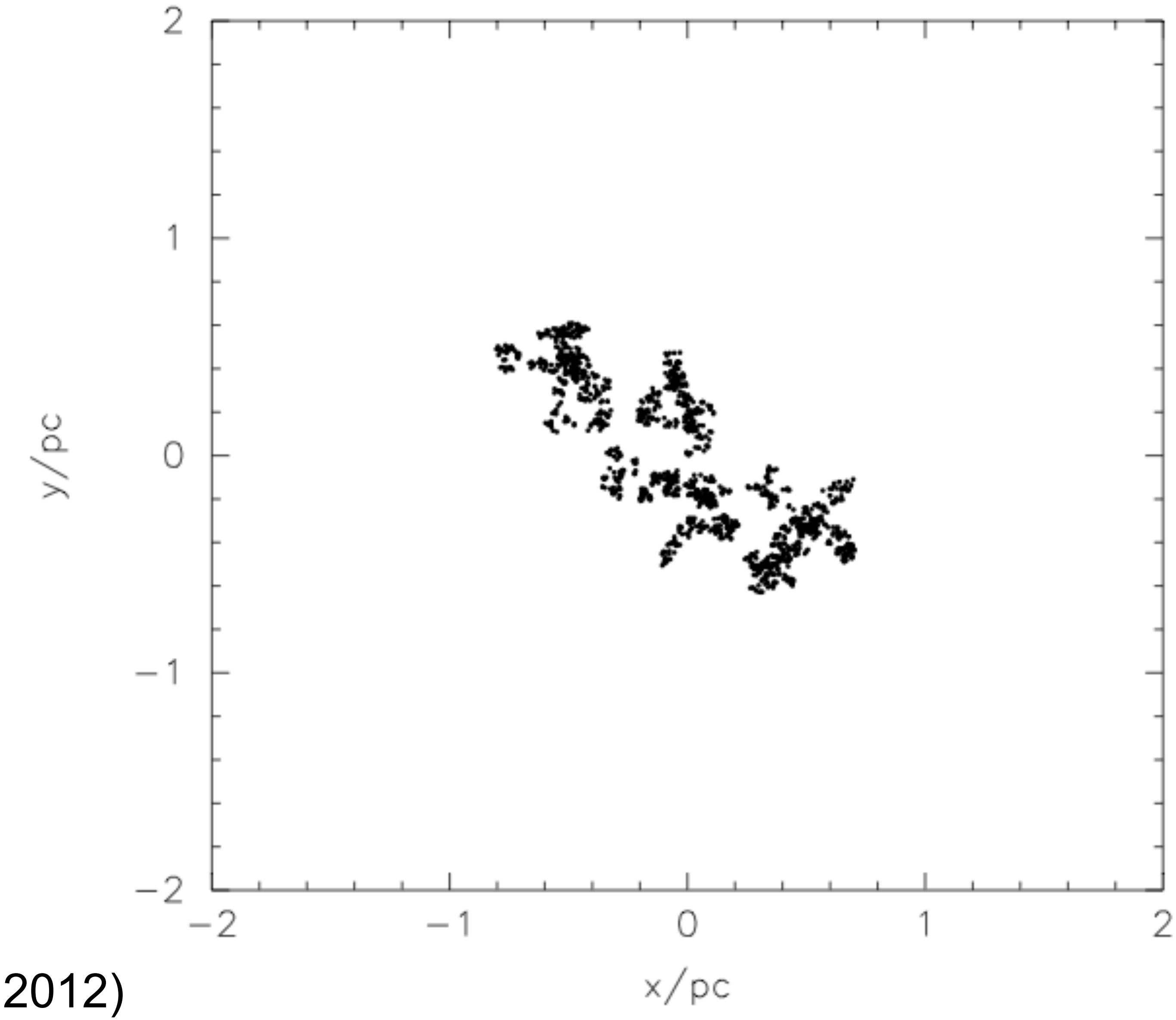


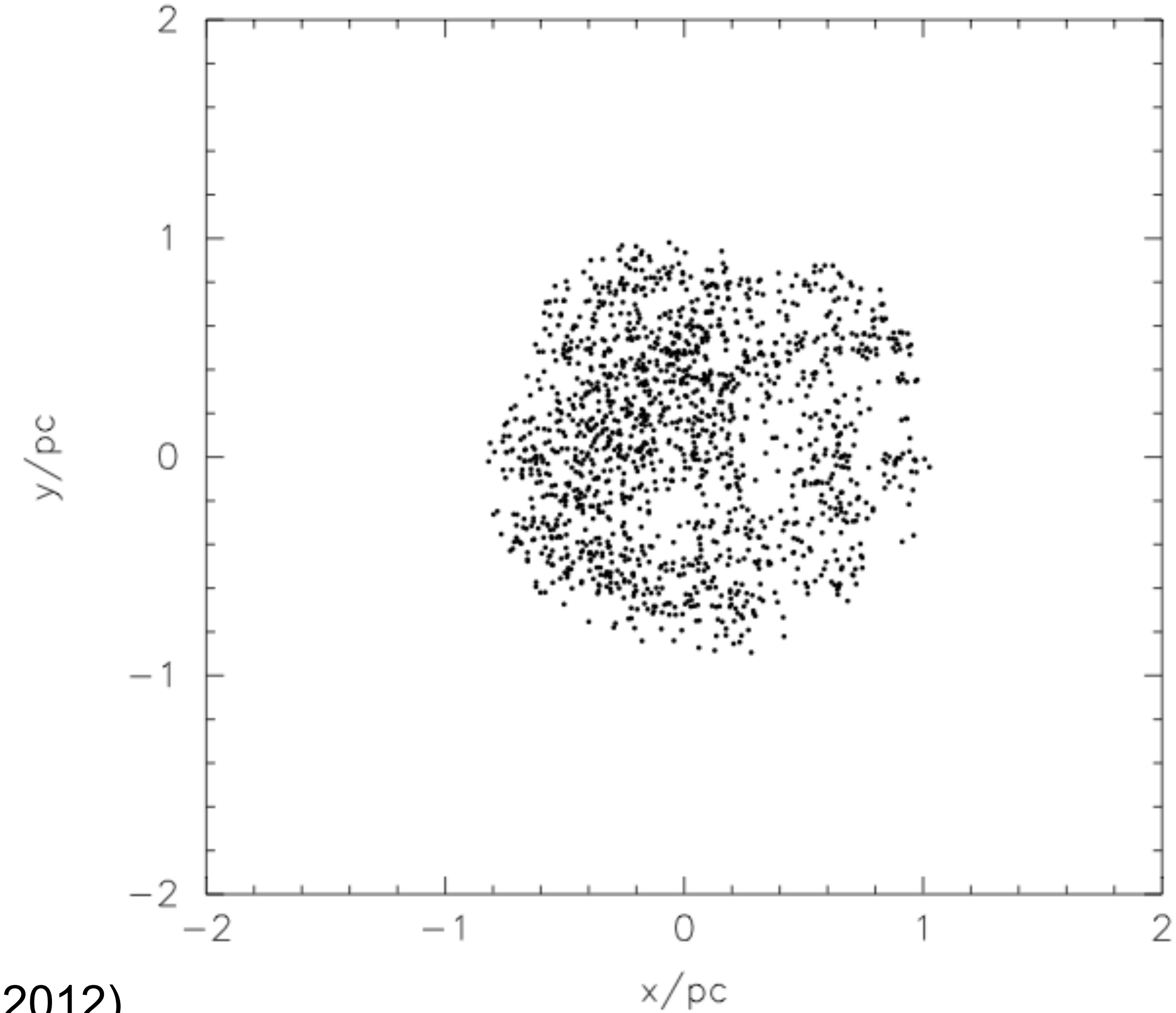
primordial binaries

Cool & clumpy; 0Myr



(Allison 2012)

Tepid & smooth; 0Myr



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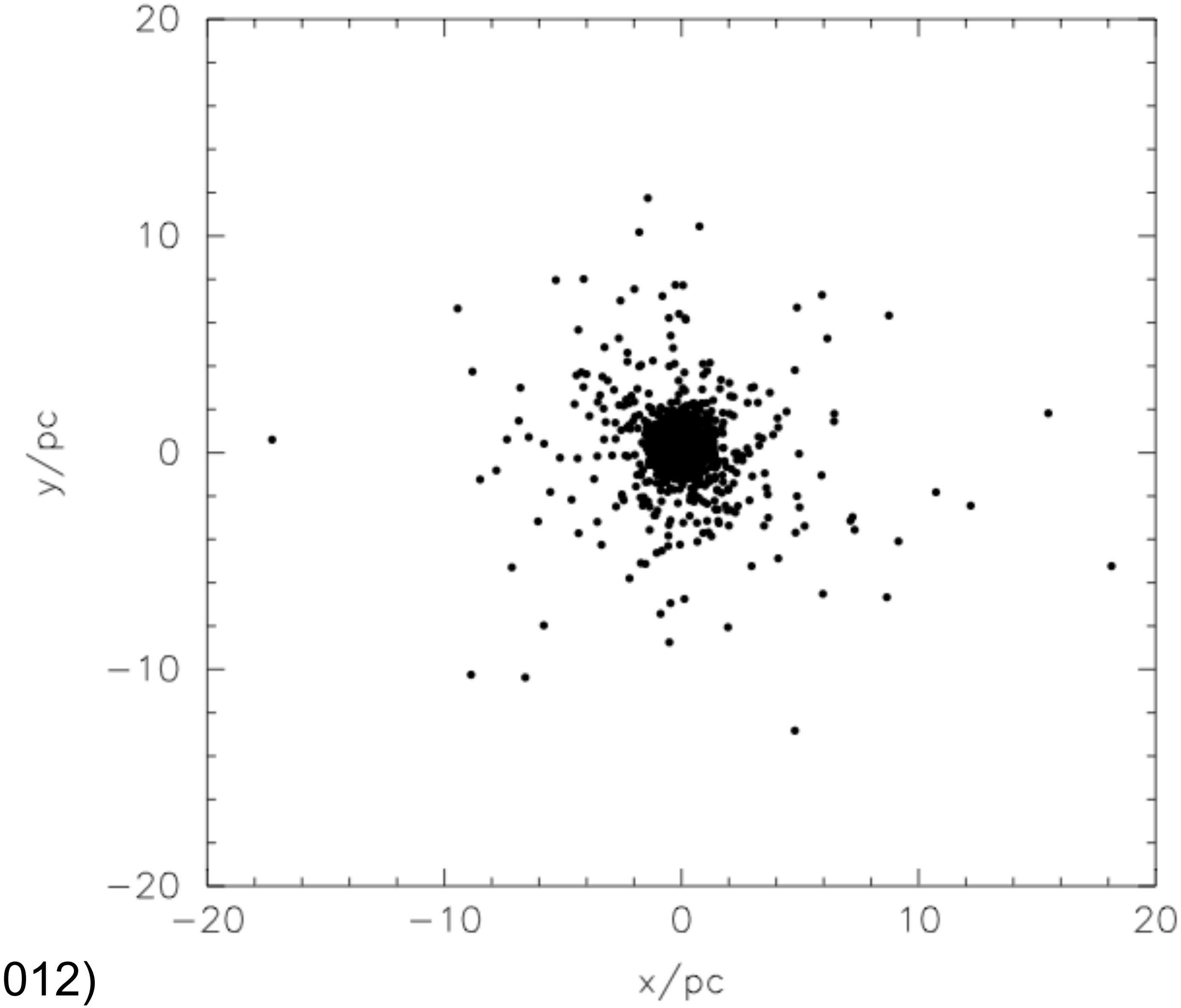
Cool & clumpy; 4Myr



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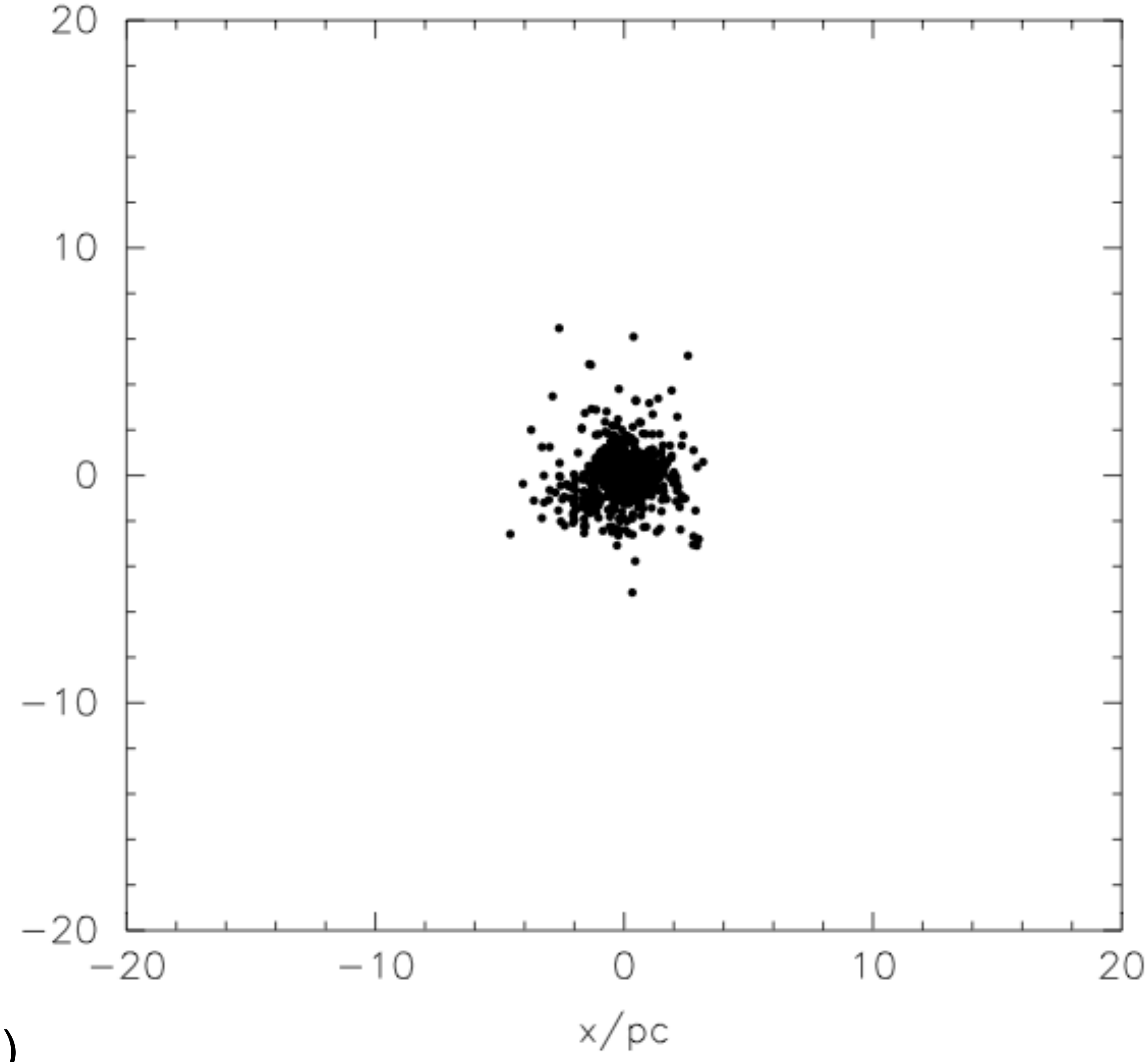
Tepid & smooth; 4Myr



(Allison 2012)

Ejected stars with *Gaia*

- Define an ejection:

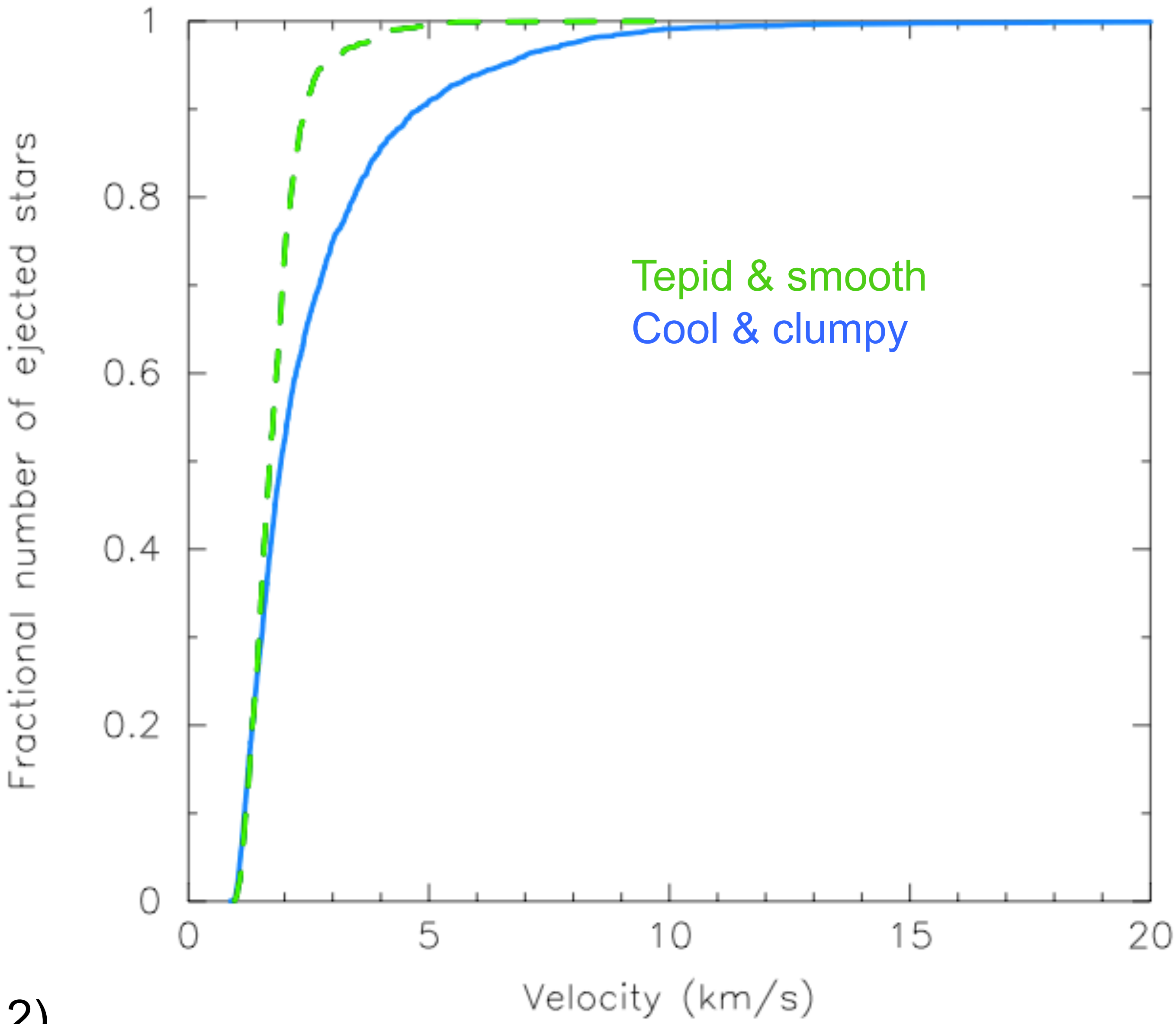
  - velocity magnitude > escape velocity

  - radial velocity > tangential velocity

  - position is beyond a cropping distance

(moving fast enough, in right direction, and far enough away)

Ejected velocities; 4Myr



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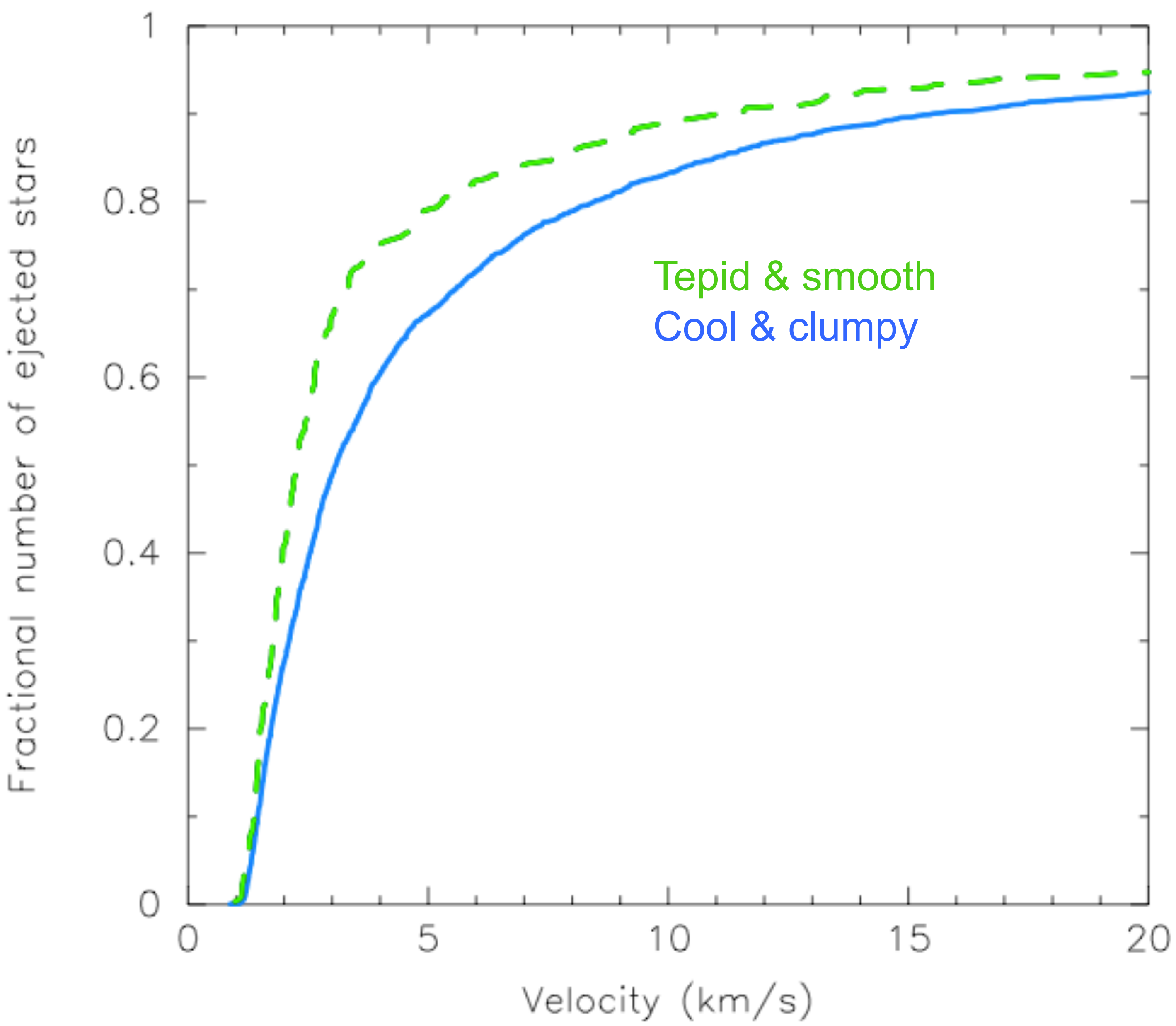

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Summary

- Different initial conditions for star formation give very different spatial distributions in clusters/associations
- Strong dynamical evolution betrayed by mass segregation and high local surface densities around massive stars
- More observational data would be **very** helpful ☺
- What will *Gaia* (and ground-based surveys) give us?