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Probing brown dwarf formation mechanisms with *Gaia*

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Open questions:

1. Do brown dwarfs form more “like stars”, or “like planets”?
2. How can we test their formation mechanism(s)?
    a) Spatial distributions
    b) Velocity information

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1. Do brown dwarfs form more “like stars”, or “like planets”?
2. How can we test their formation mechanism(s)?
    a) Spatial distributions
    b) Velocity information

- We need to apply consistent methods for a)
- We need *Gaia* for b)
- We need N-body simulations to test both a) and b)

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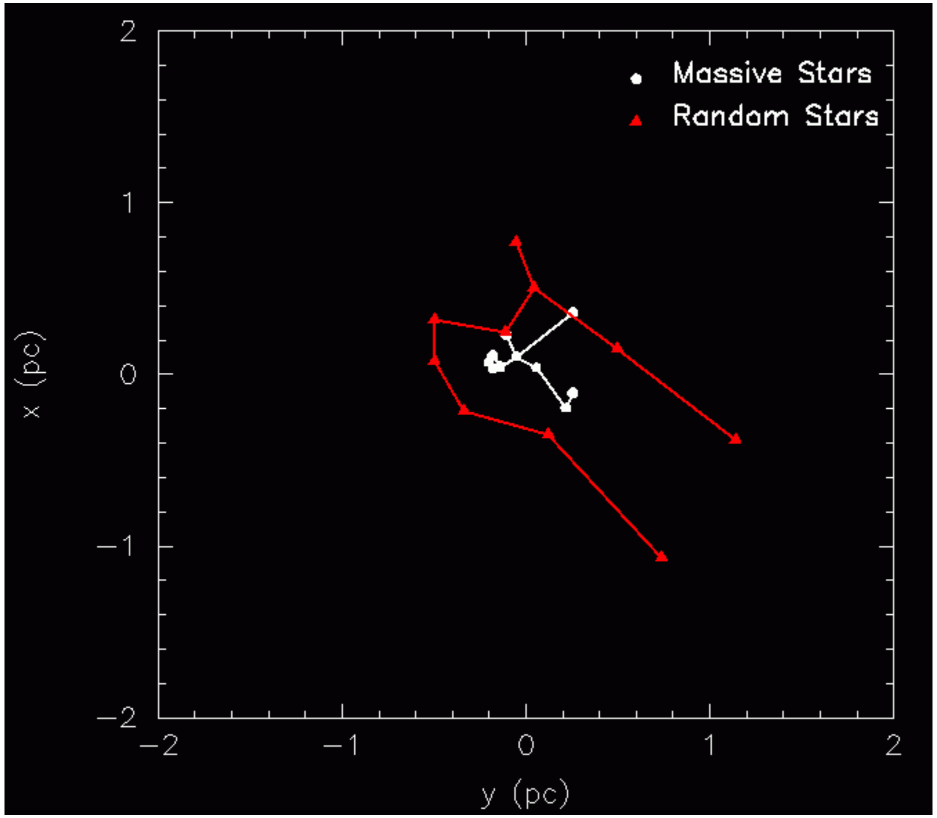
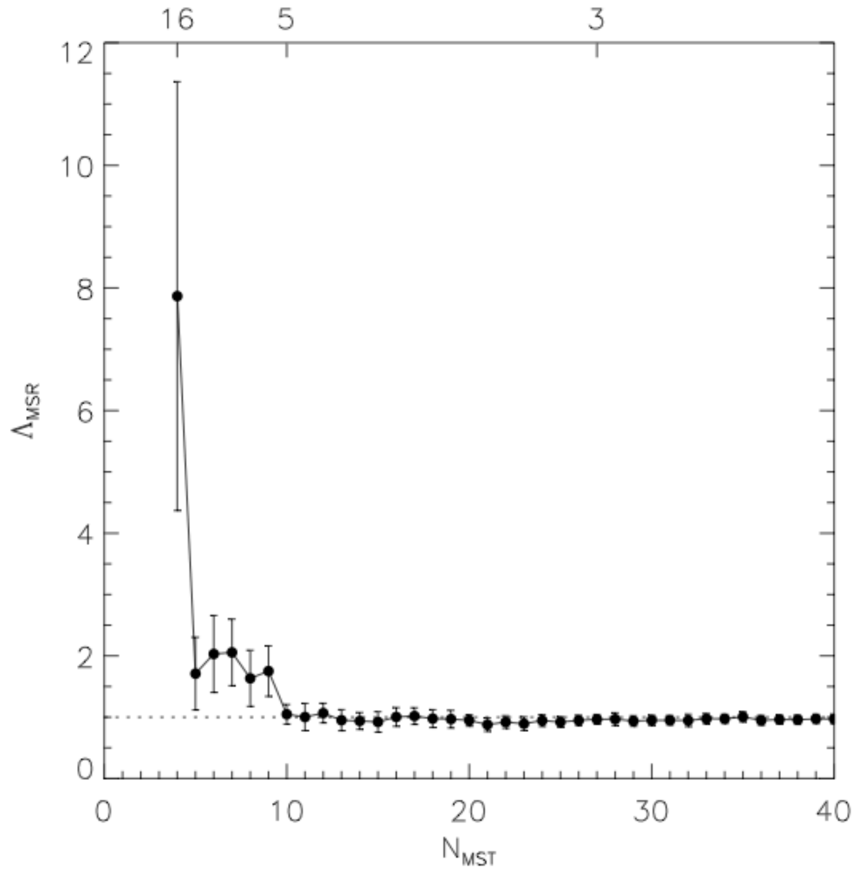
Mass segregation: Λ_{MSR}





Allison et al 2009

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

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

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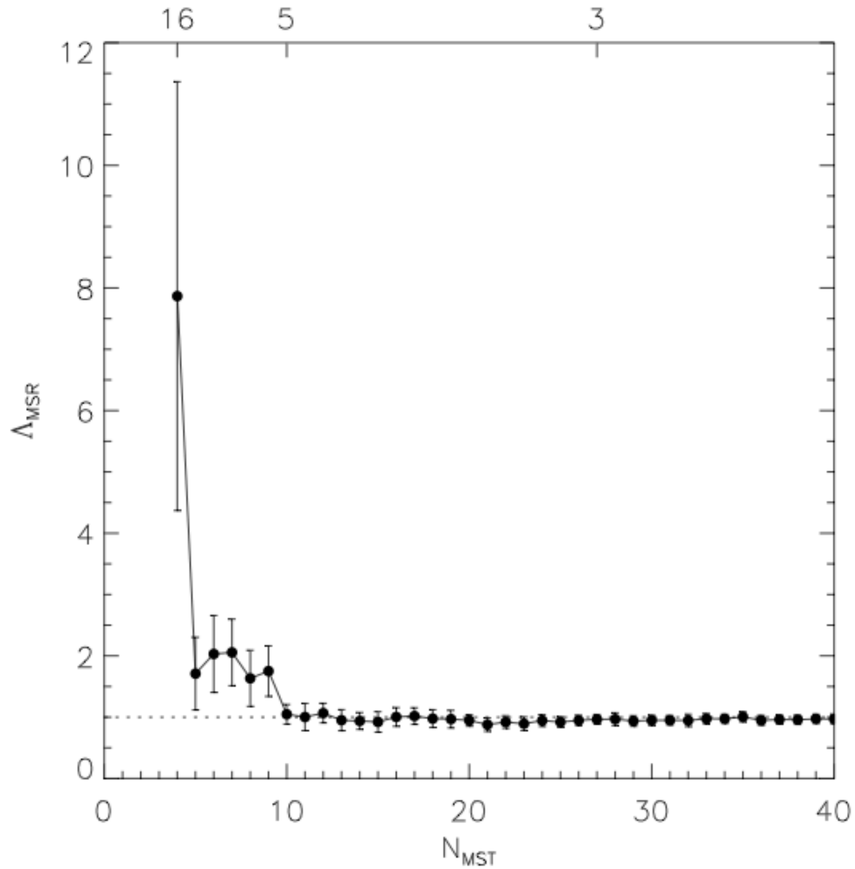
Mass segregation: Λ_{MSR}

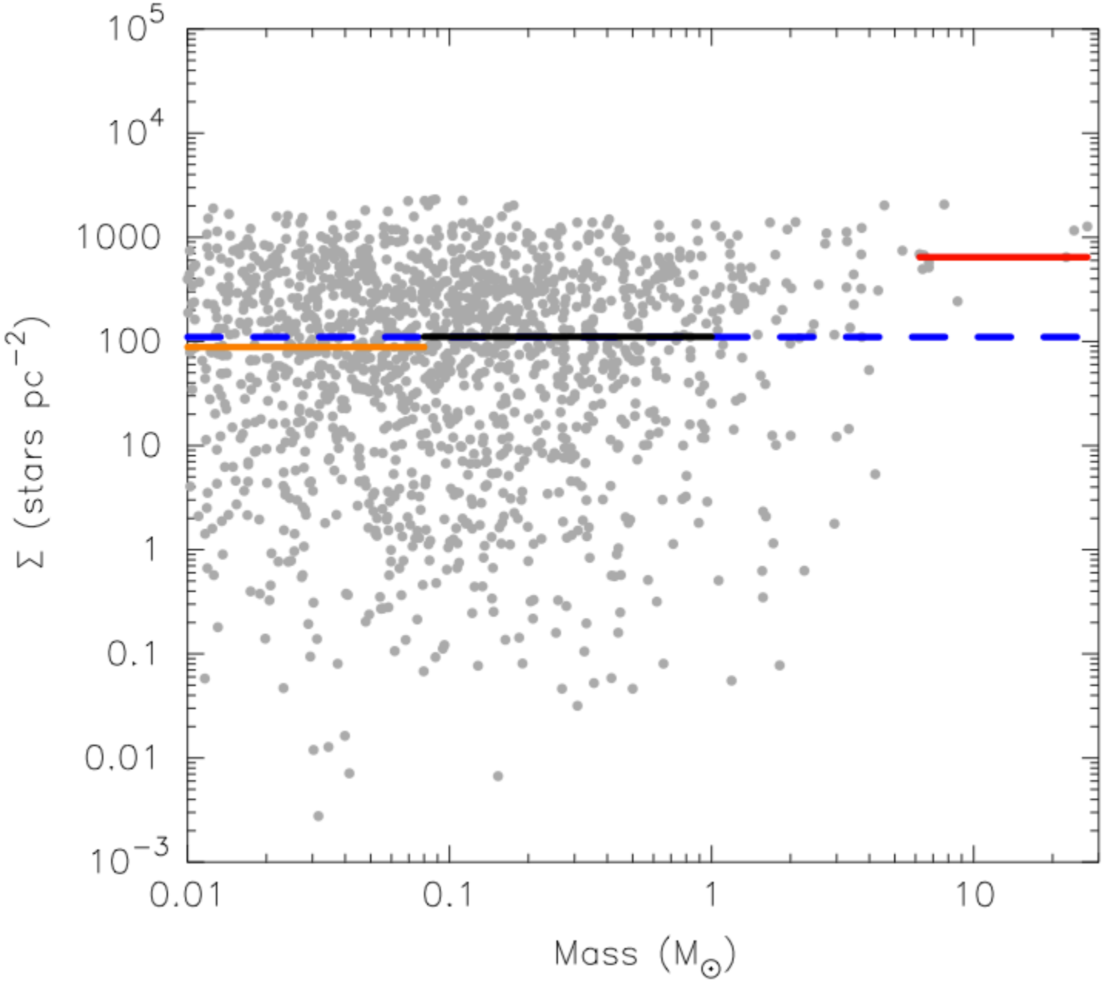
(M. McCaughrean/ESO 2001)



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

Allison et al 2009

Local surface density: Σ - m

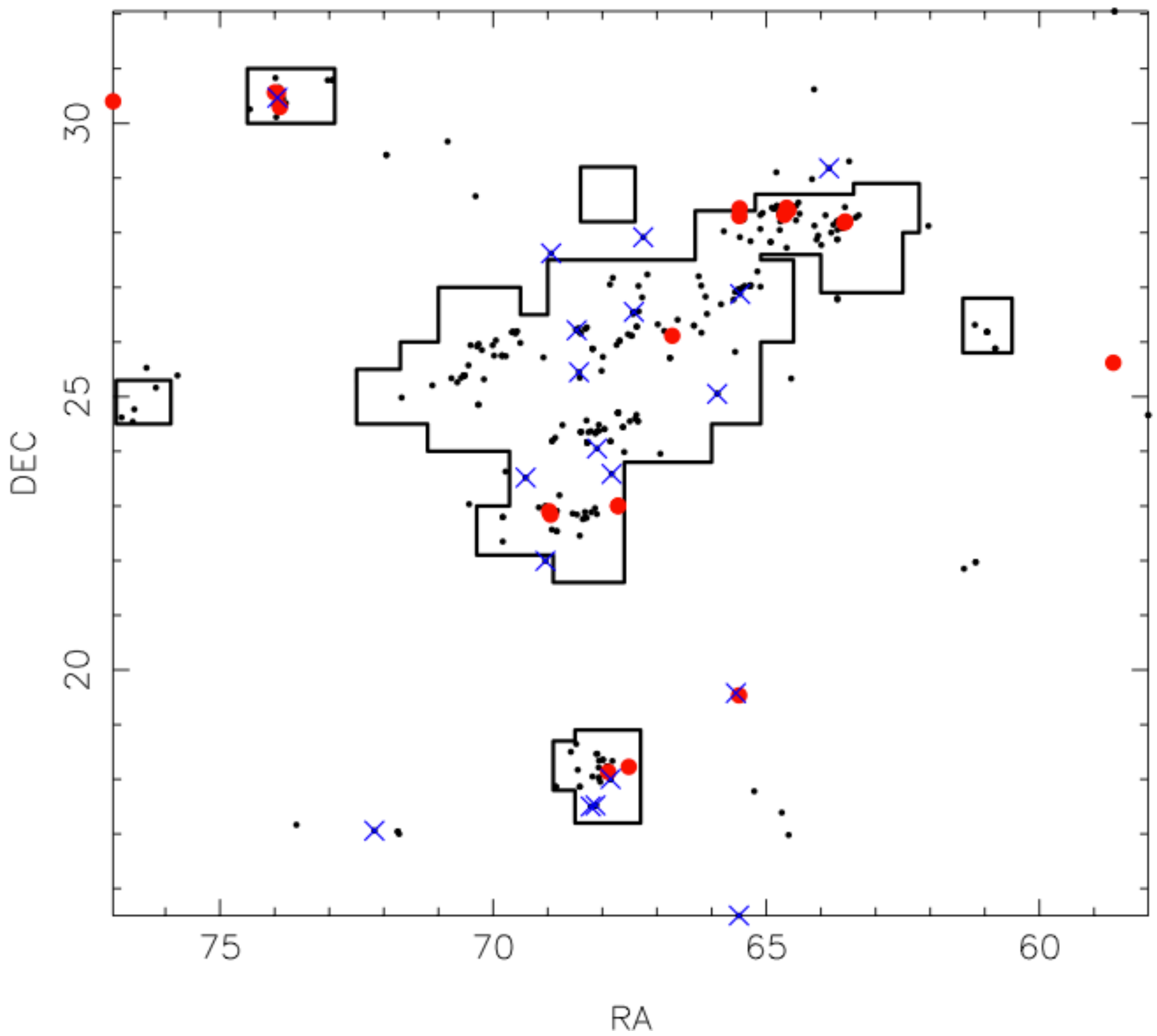


$$\Sigma = \frac{N-1}{\pi r_N^2}$$

Maschberger & Clarke 2011

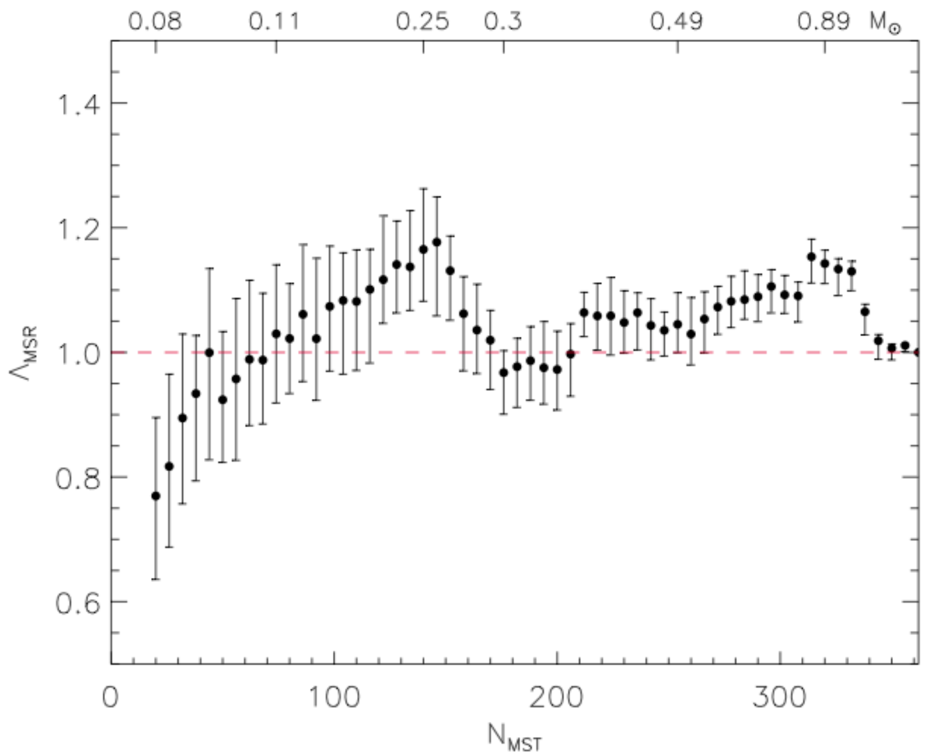
BDs in nearby regions: Taurus

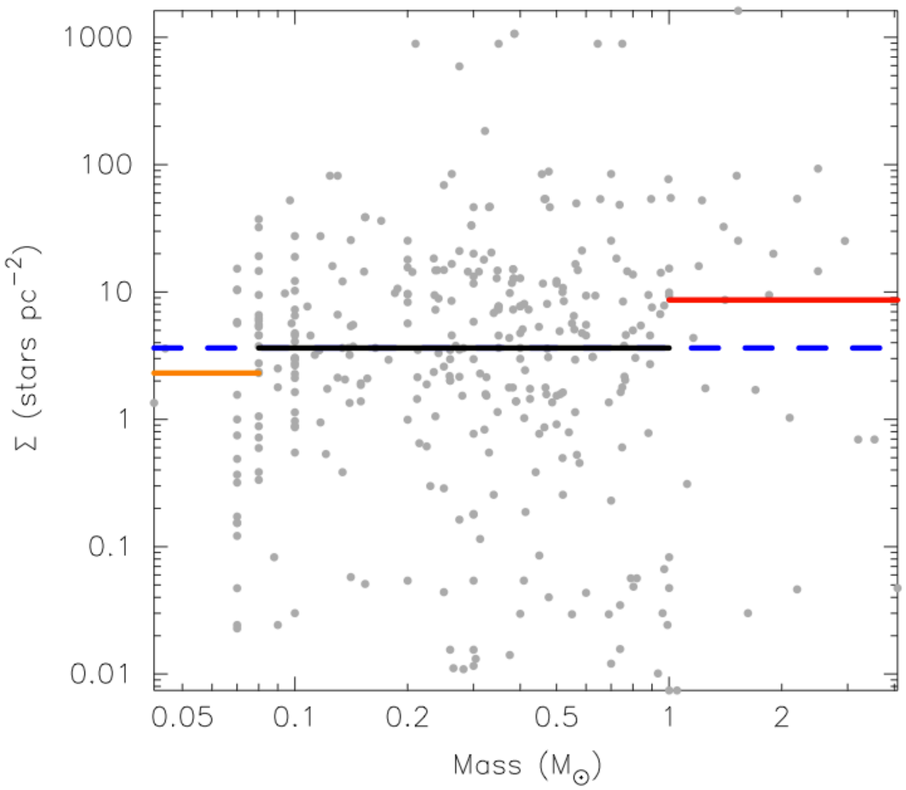
- Data compiled for XEST survey & updated from recent surveys (Güdel et al 2007).
- Red = 20 most massive objects.
- Blue = 20 least massive objects.



BDs in nearby regions: Taurus

Both Λ_{MSR} and Σ – m consistent with stars





Parker et al 2011

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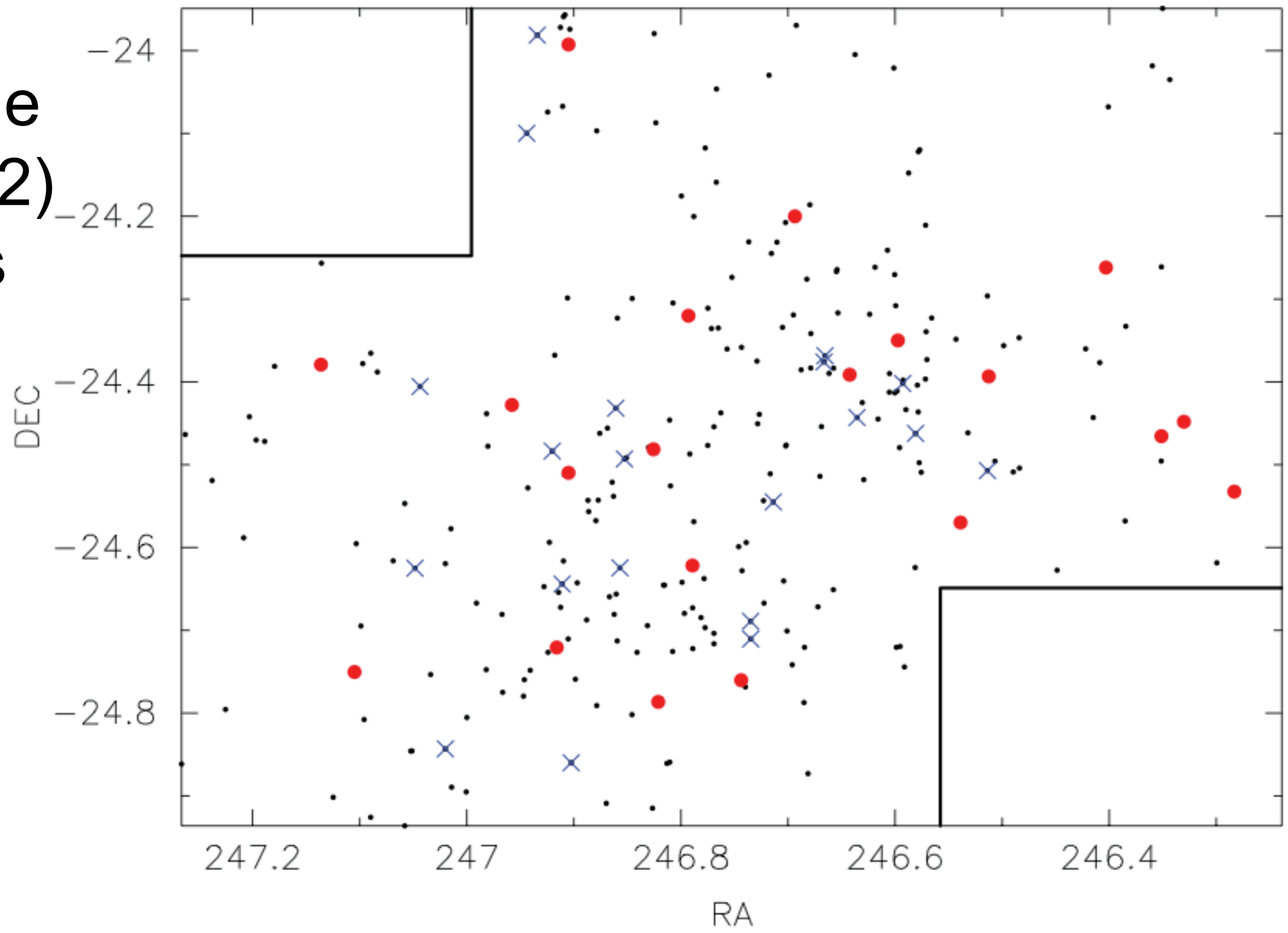
BDs in nearby regions: ρ Oph

- Data from Alves de Oliveira et al (2012) and other sources
- Red = 20 most massive objects.
- Blue = 20 least massive objects.



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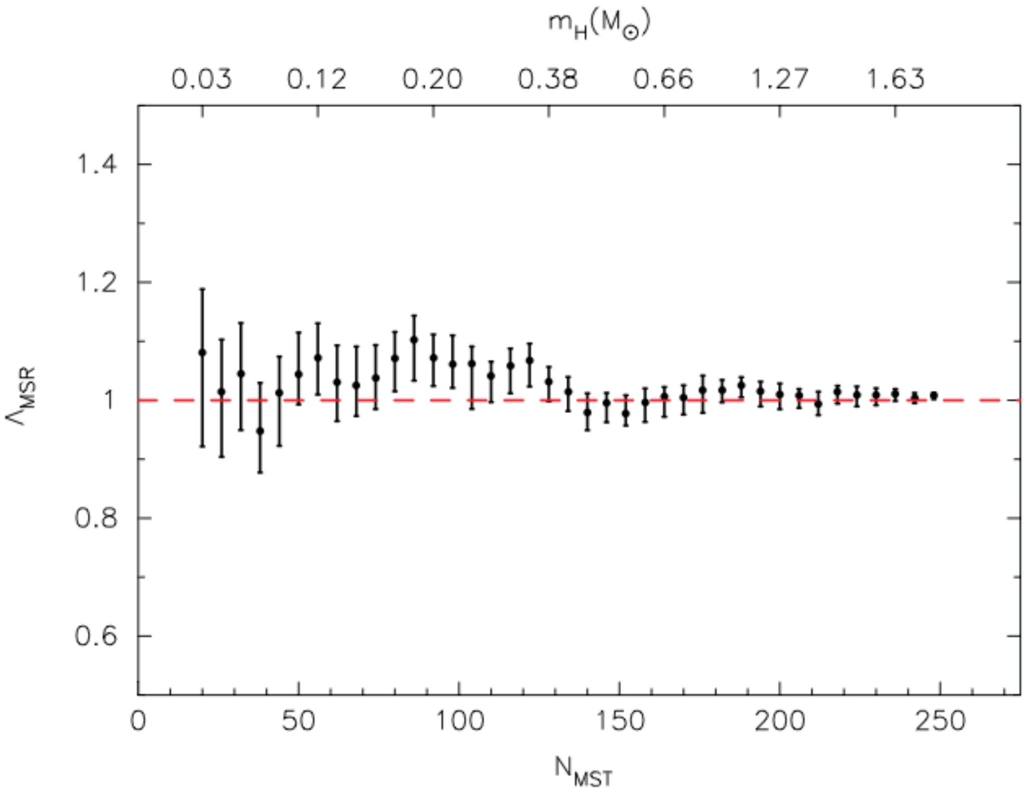
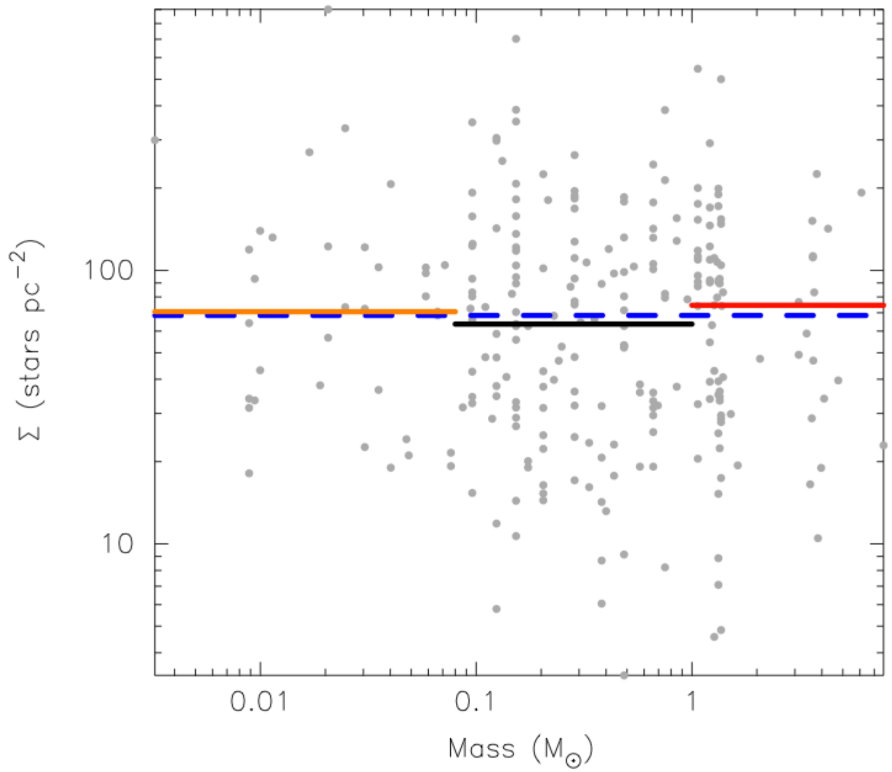
BDs in nearby regions: ρ Oph

Both Λ_{MSR} and Σ – m consistent with stars





Parker, Maschberger & Alves de Oliveira 2012

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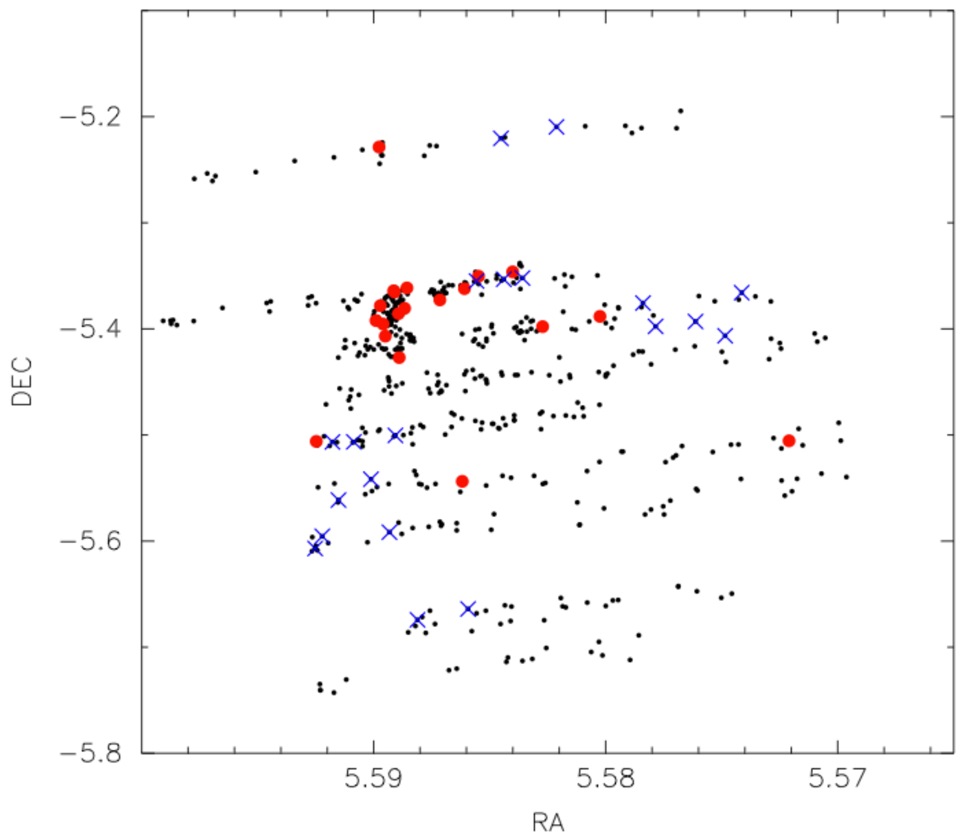
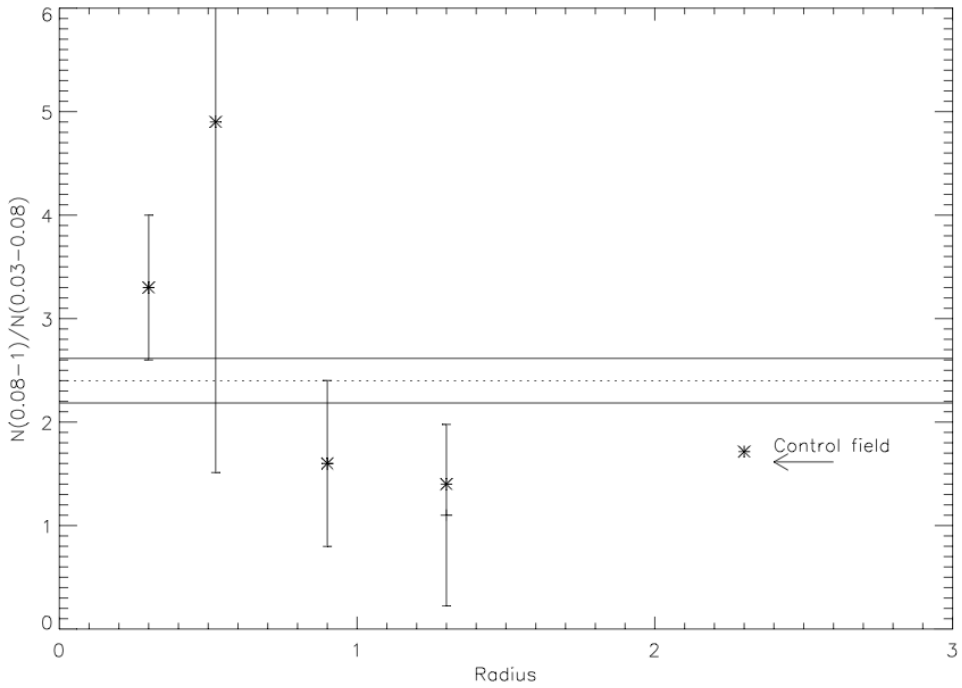
BDs in nearby regions: ONC (some of it)





- Data from Andersen et al 2011
- Decreasing fraction of stars/BDs (R_{SS})
- Brown dwarfs have different spatial distribution?

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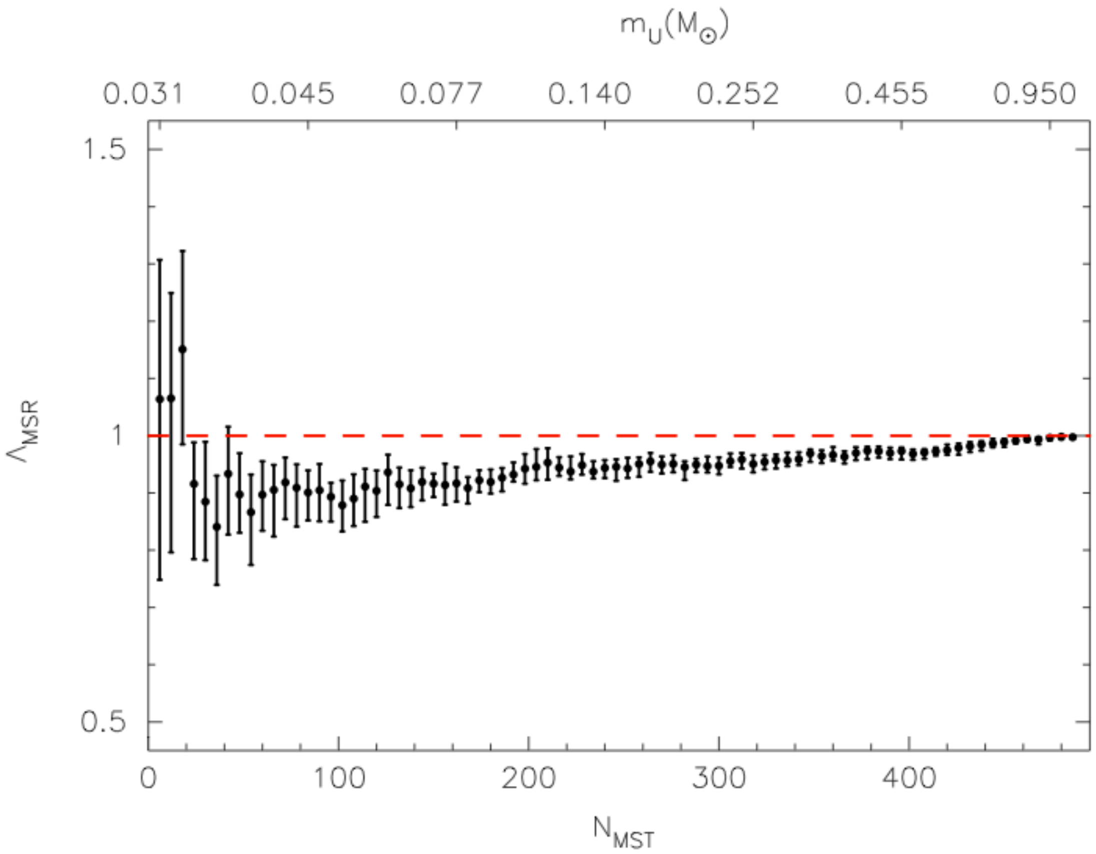
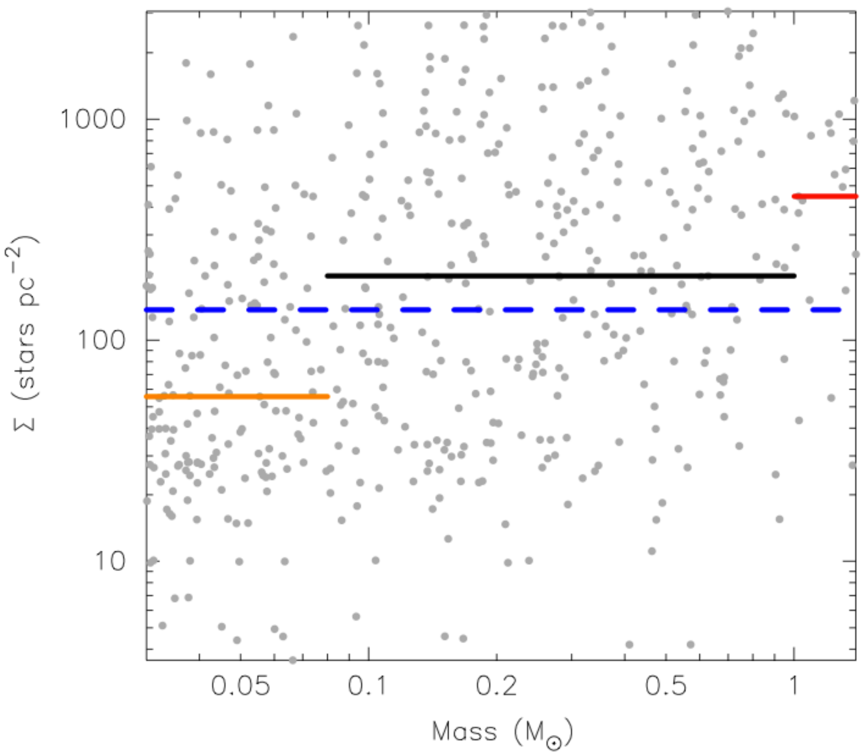
BDs in nearby regions: ONC (some of it)

Λ_{MSR} consistent with stars, Σ - m shows differences





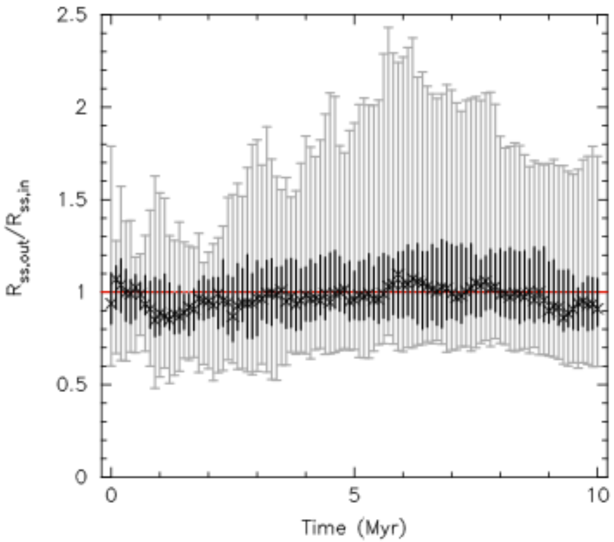
Parker & Andersen (in press)

N-body simulations

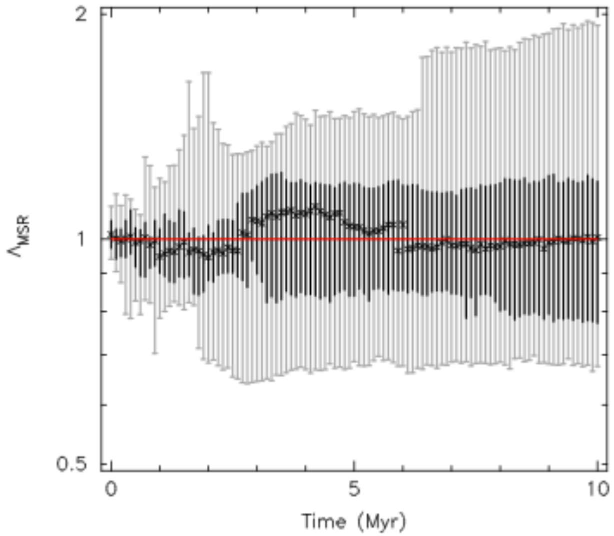
- Cool and clumpy (Virial ratio = 0.3, fractal dimension 1.6)
- Hot and clumpy (Virial ratio = 1.5, fractal dimension 1.6)
- Tepid and smooth (Virial ratio = 0.5, fractal dimension 2.6)

- 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)

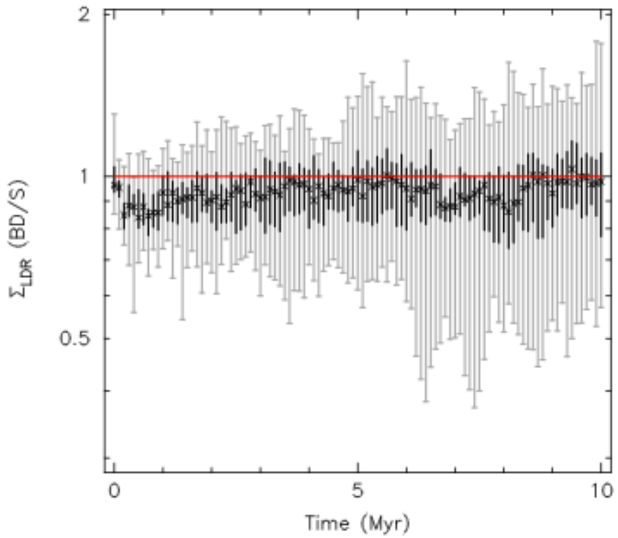
N-body simulations



(a) $\mathcal{R}_{ss,out}/\mathcal{R}_{ss,in}$



(b) $\Lambda_{\rm MSR}$ (BDs)



(c) $\Sigma_{\rm LDR}$ (BDs/stars)

- Dynamical evolution *can* give different spatial distributions (Parker & Andersen, in press)
- To determine whether the differences are *only* due to dynamical evolution, we need more information on the region's evolution

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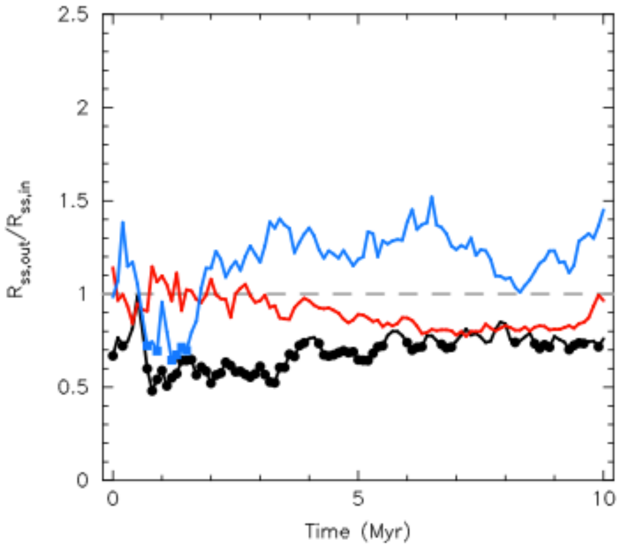
N-body simulations



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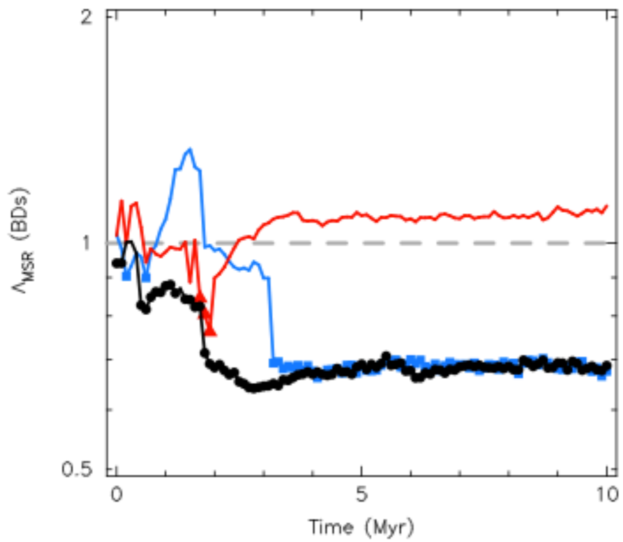

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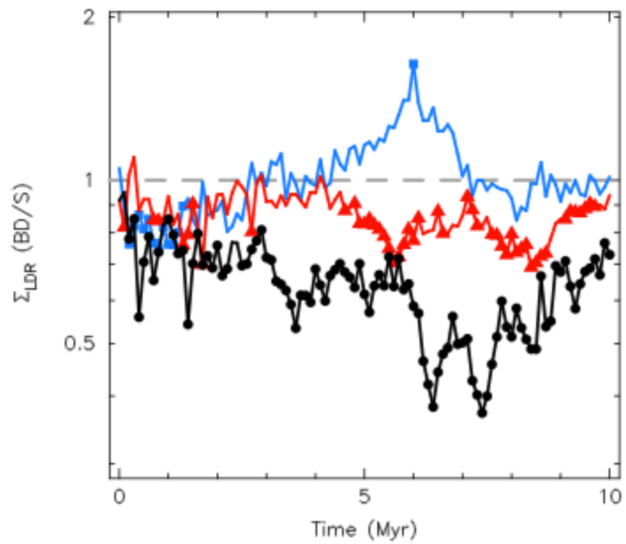

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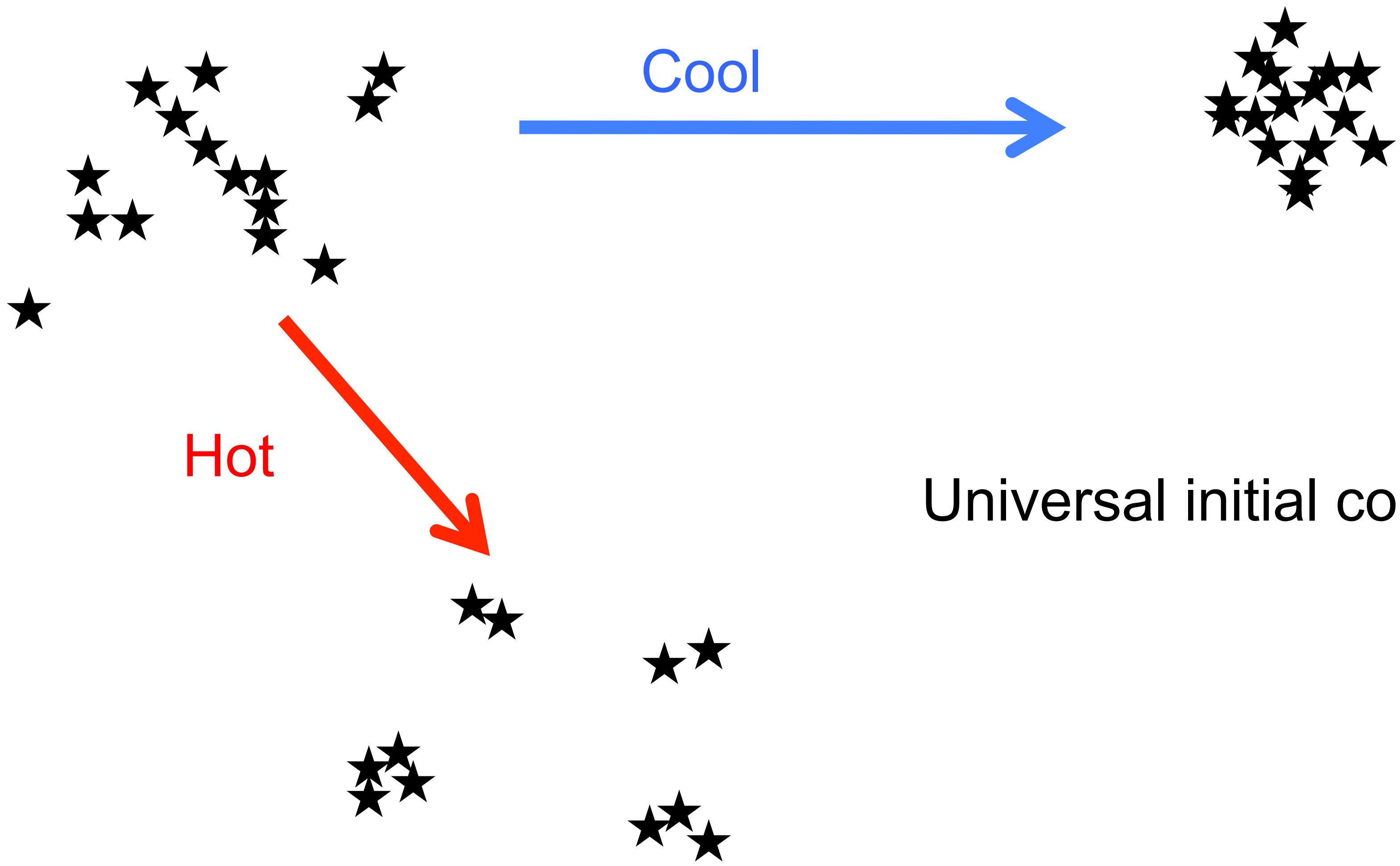
Clusters versus associations?



Universal initial conditions?

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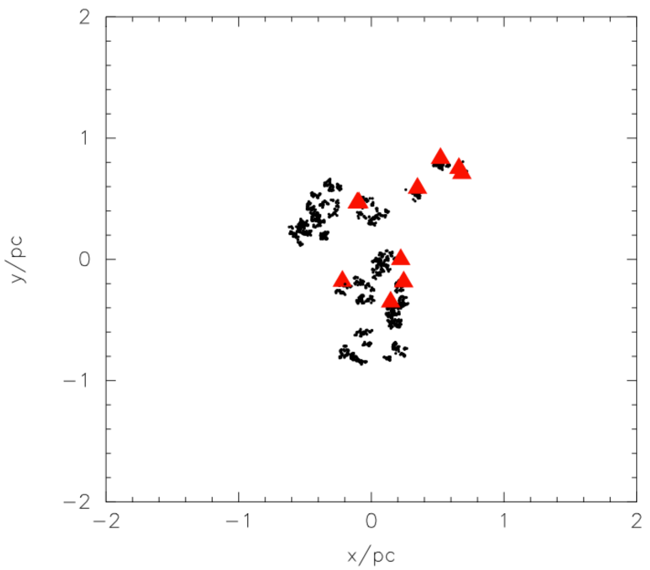
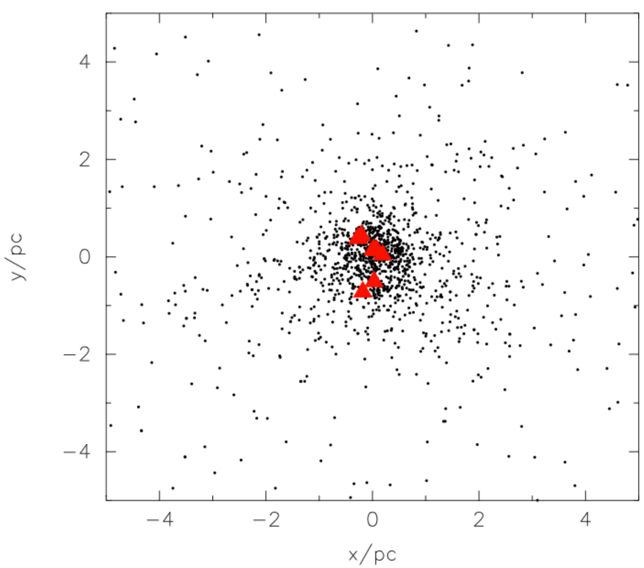
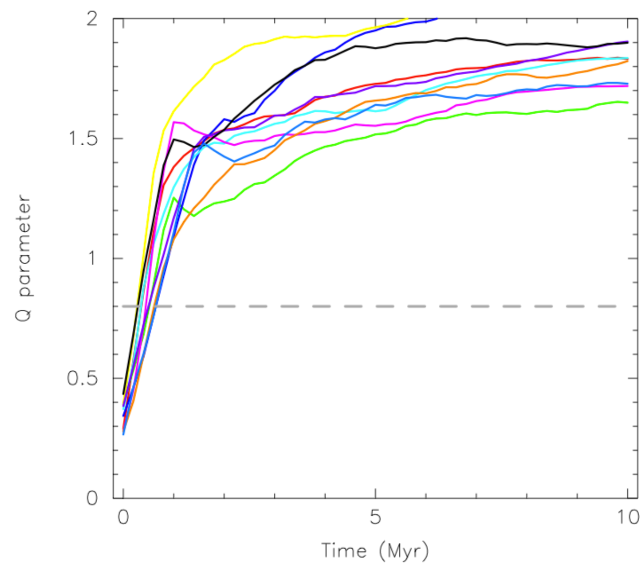
Evolution of structure and morphology

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







0 Myr

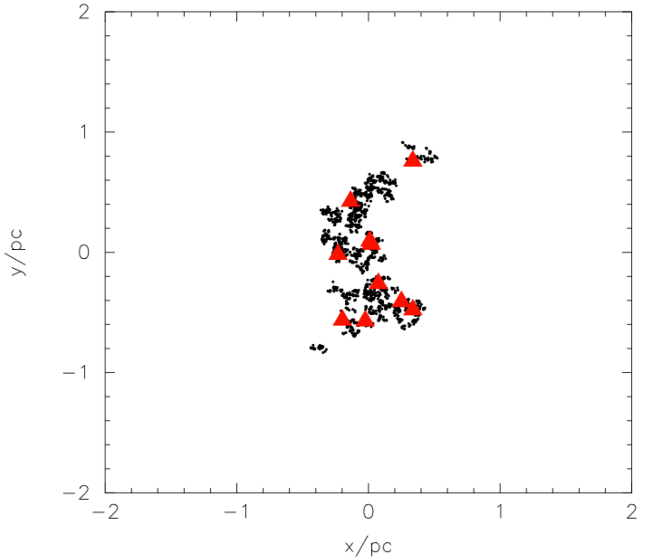
5 Myr

Q-parameter

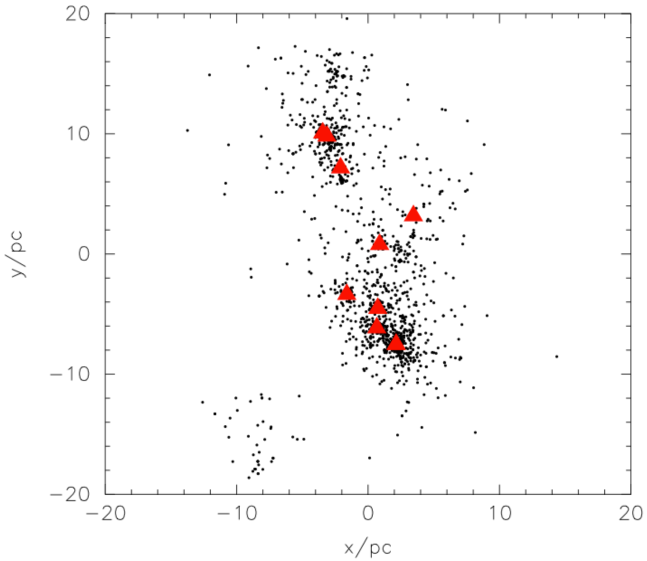
- Dynamics rapidly erases substructure (Scally & Clarke 2002; Goodwin & Whitworth 2004; Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer 2014)

Evolution of structure and morphology

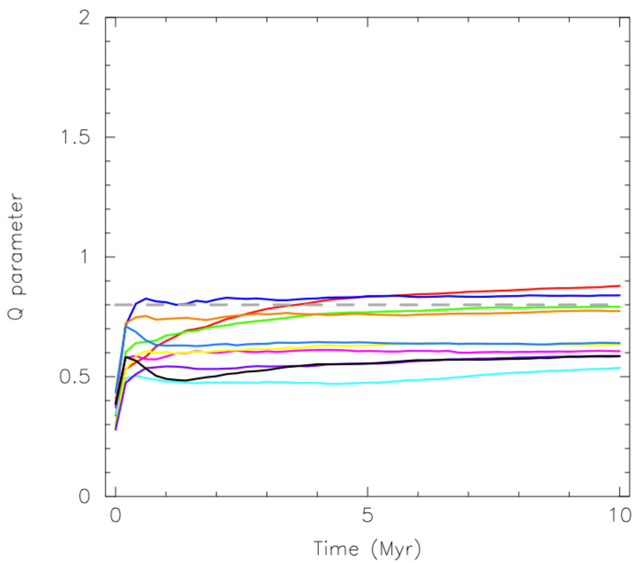
- Measuring structure - evolution of the Q-parameter in an unbound (hot) association:



0 Myr



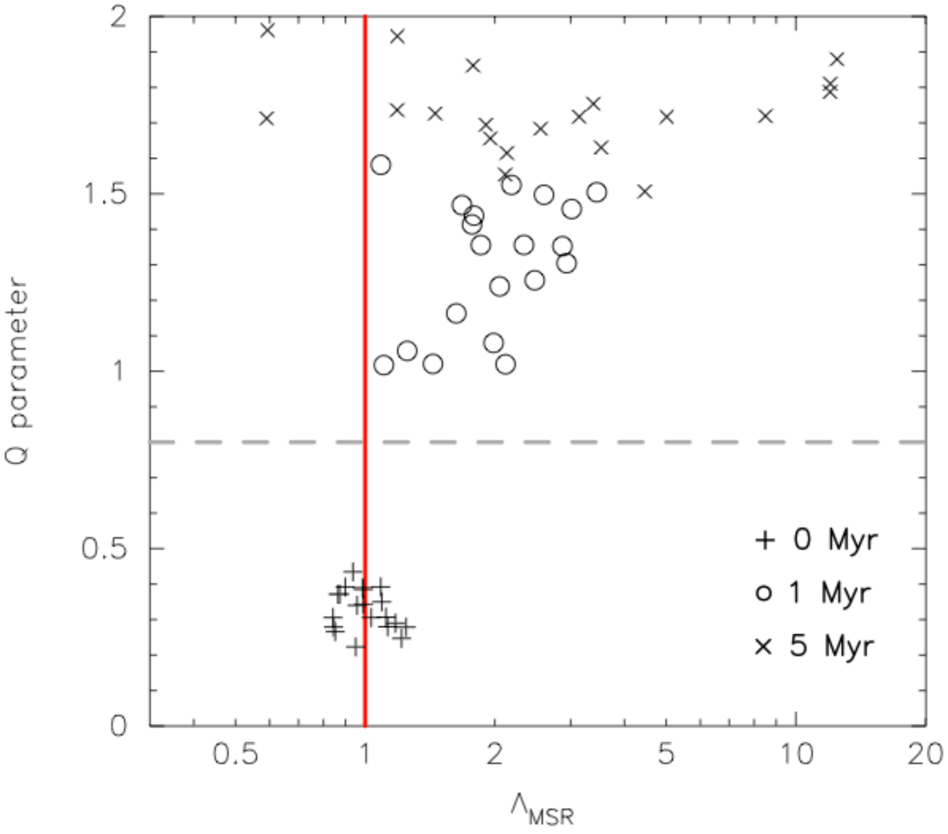
5 Myr



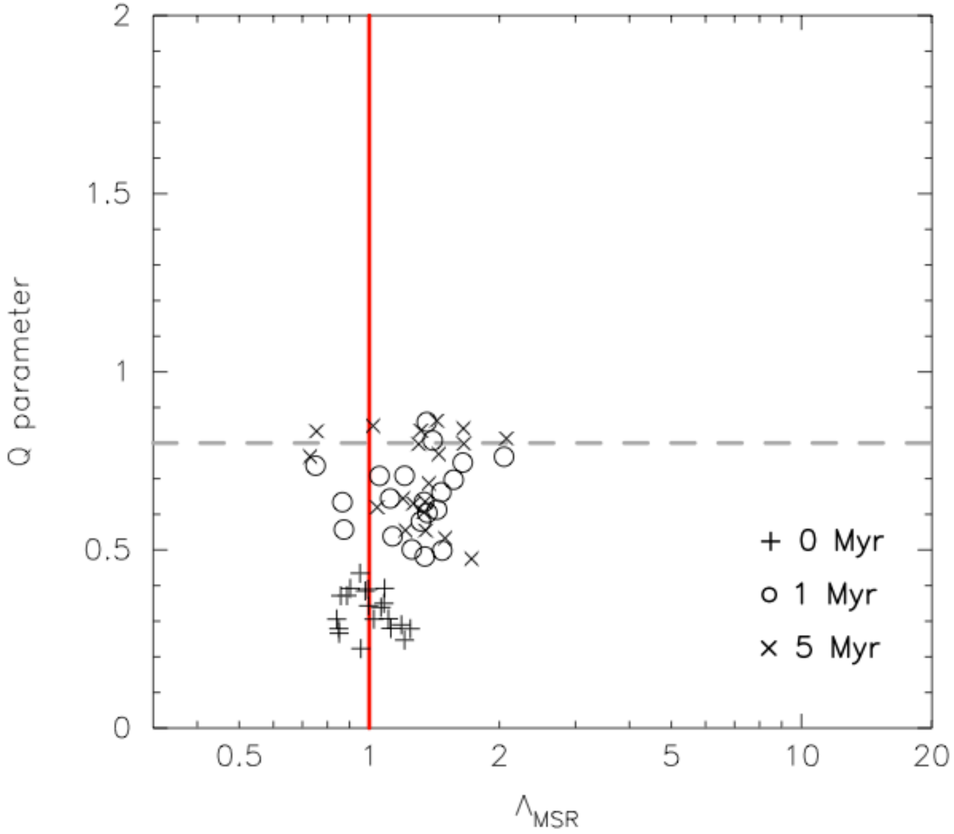
Q-parameter

(Parker & Meyer 2012; Parker, Wright, Goodwin & Meyer 2014)

Structure versus mass segregation



Cool



Hot

(Parker, Wright, Goodwin & Meyer 2014)

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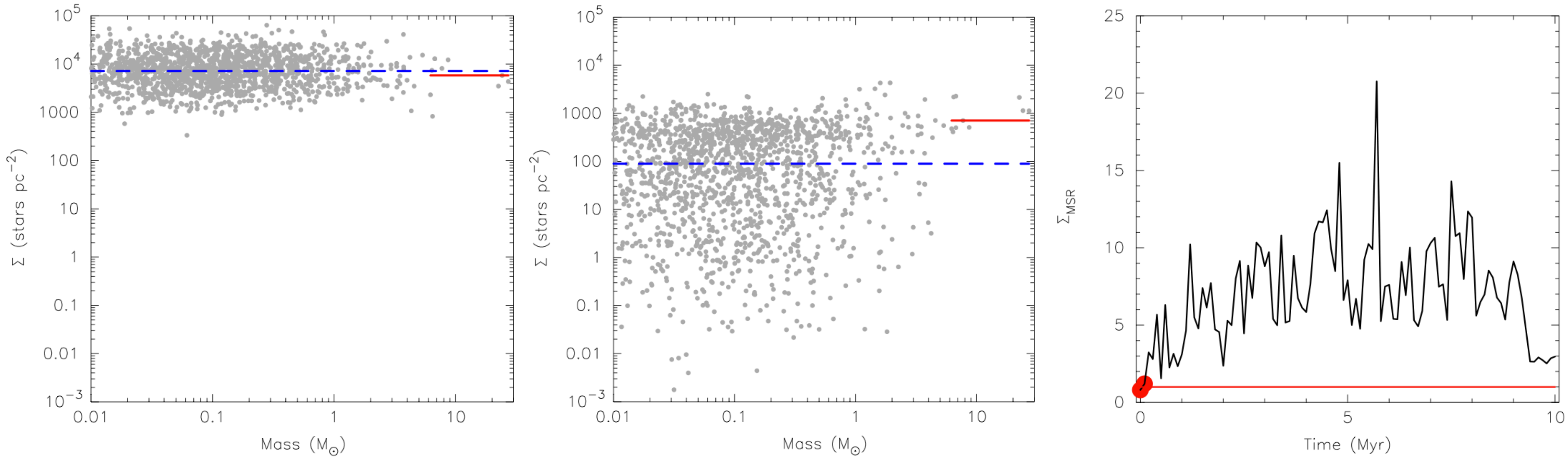
Using surface density to probe evolution



0 Myr   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:

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

(Küpper et al 2011, Parker, Wright, Goodwin & Meyer 2014)

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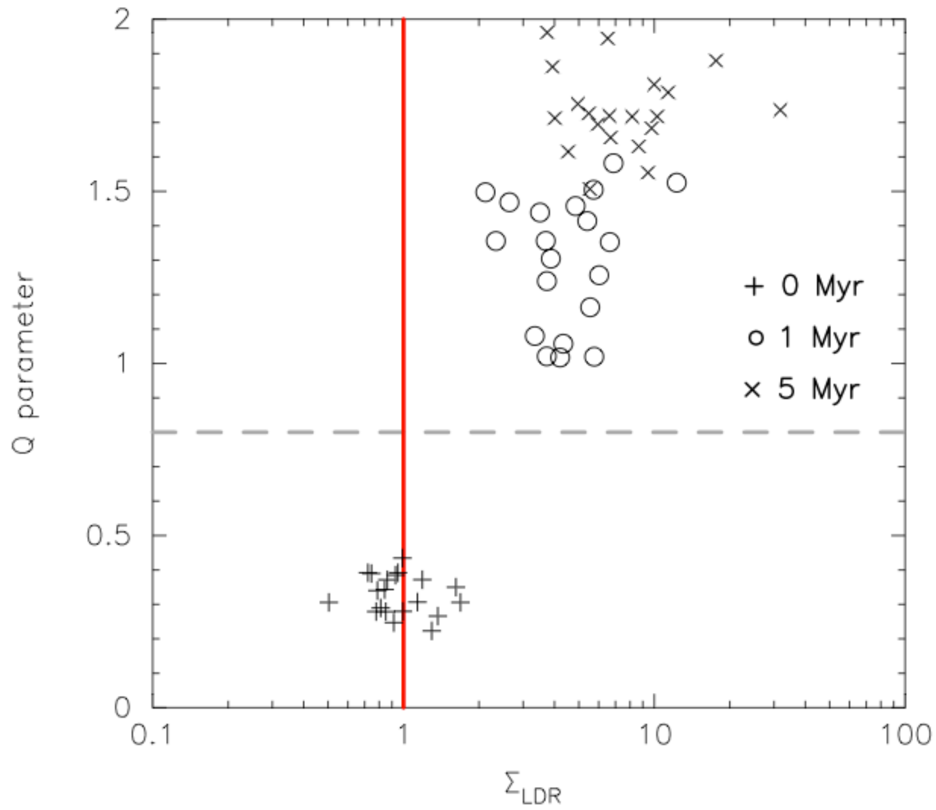
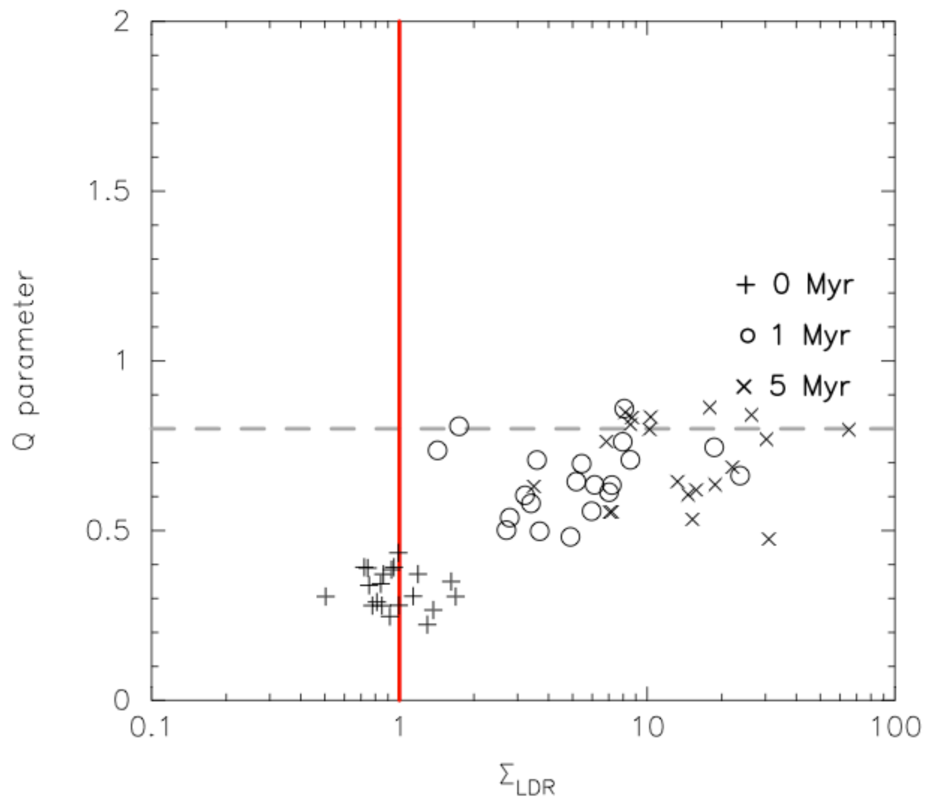
Structure versus surface density



Dense and cool



Dense and hot

(Parker, Wright, Goodwin & Meyer 2014)

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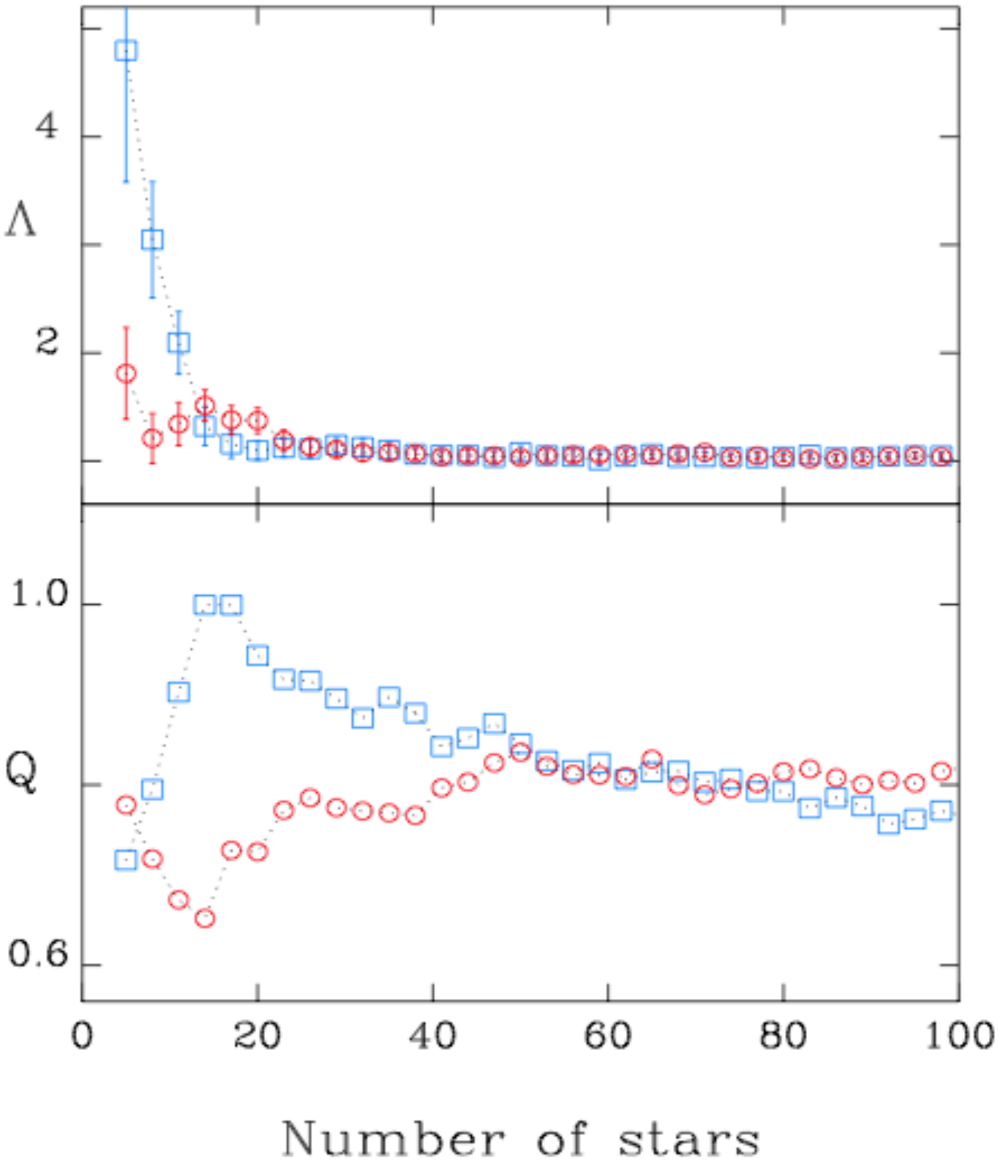
Structure versus mass segregation



Different dynamical histories?

Blue: Ber96
Red: Ber94

(Delgado et al 2013)

Ejected stars with *Gaia*

- Define an ejection:

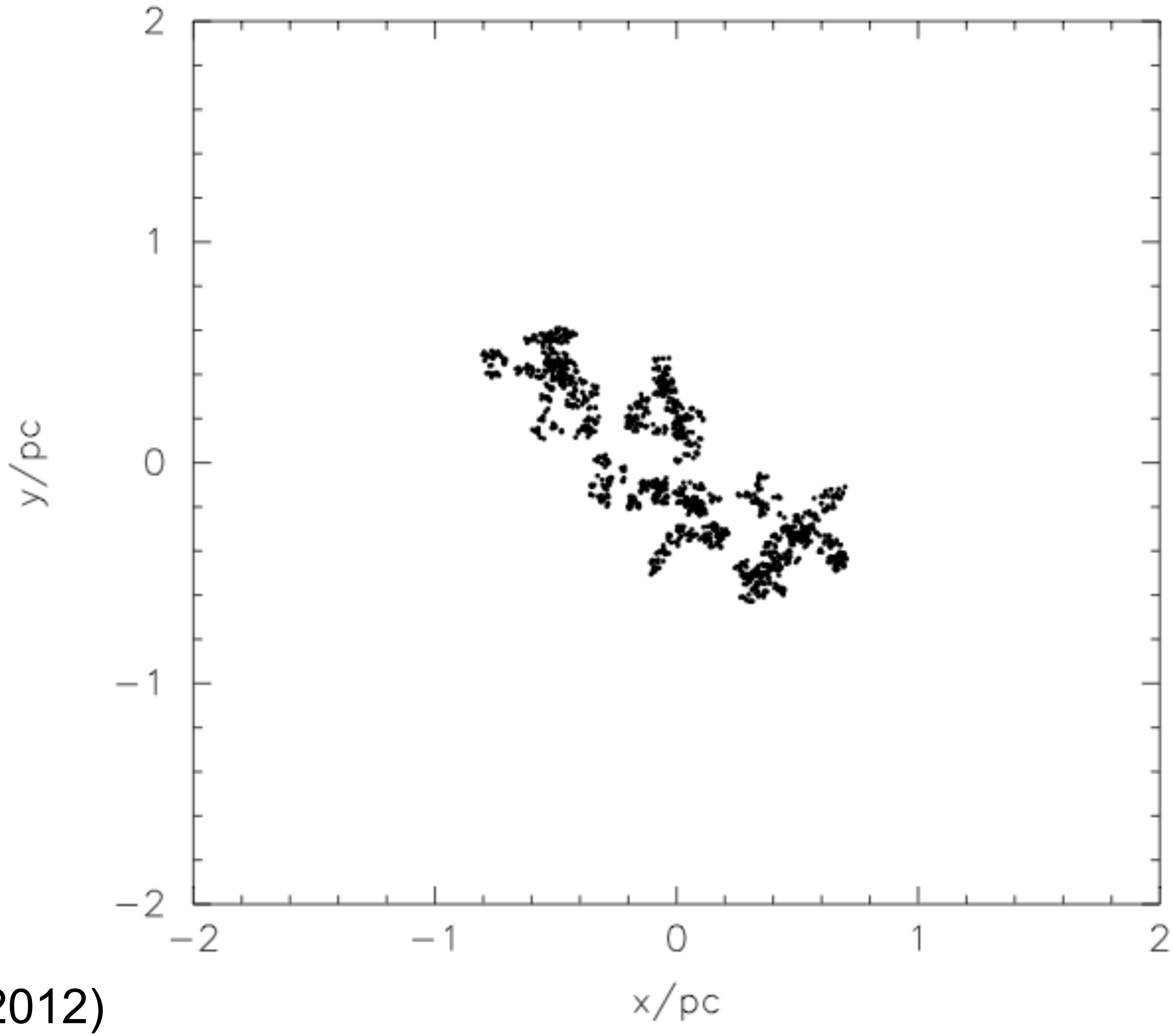
  - velocity magnitude > escape velocity

  - radial velocity > tangential velocity

  - position is beyond a cropping distance

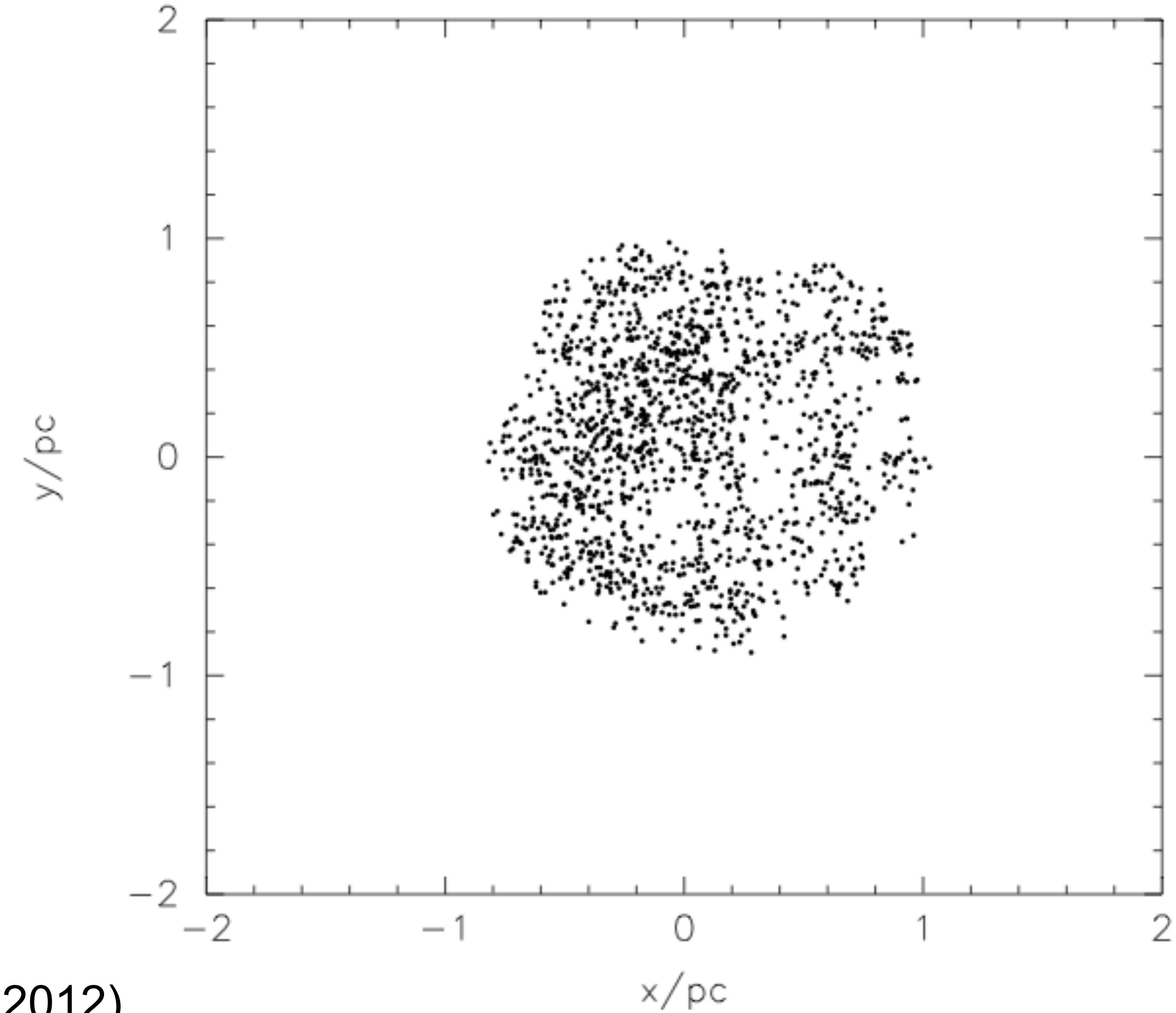
(moving fast enough, in right direction, and far enough away)

Cool & clumpy; 0Myr



(Allison 2012)

Tepid & smooth; 0Myr



(Allison 2012)

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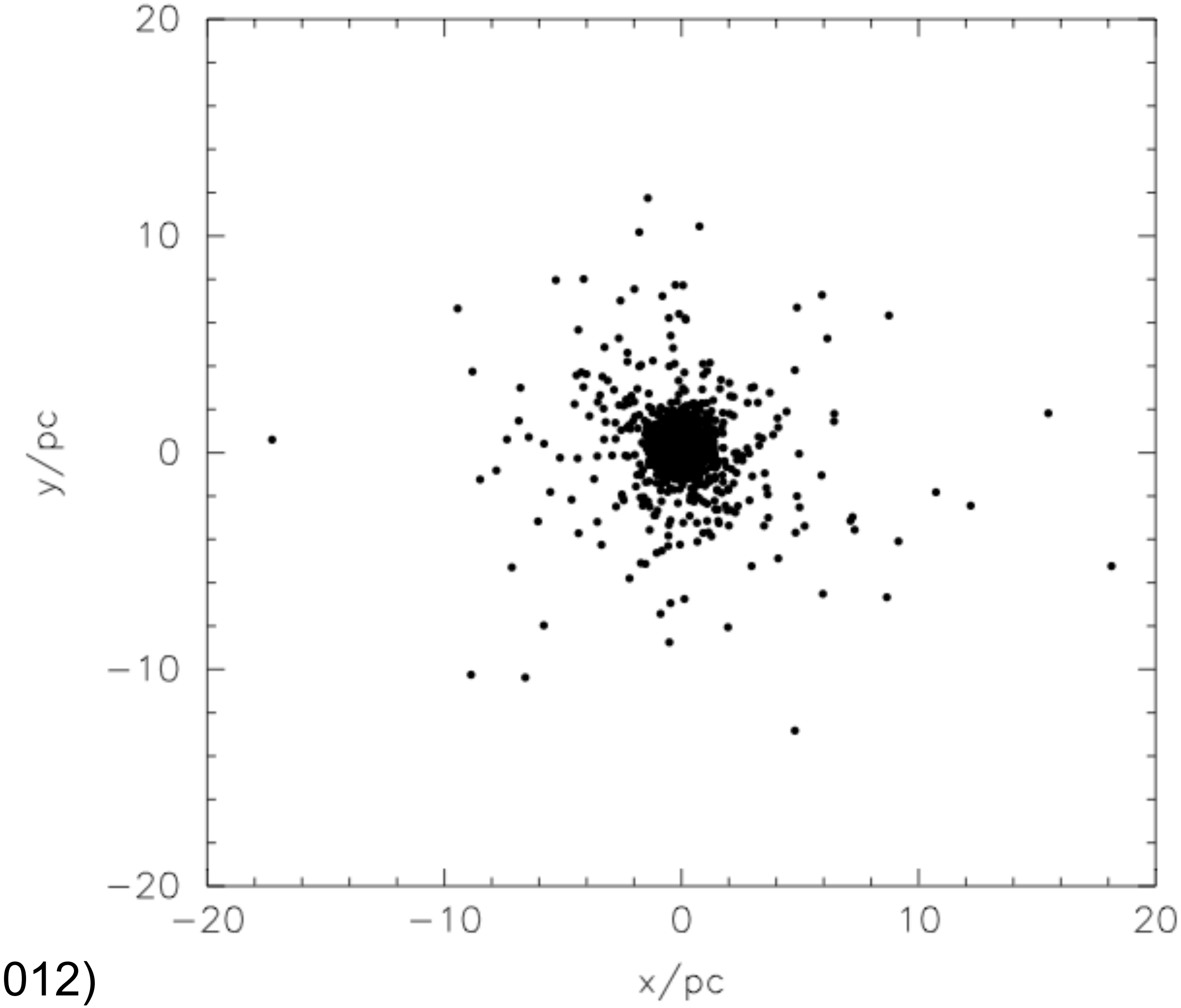
Cool & clumpy; 4Myr



(Allison 2012)

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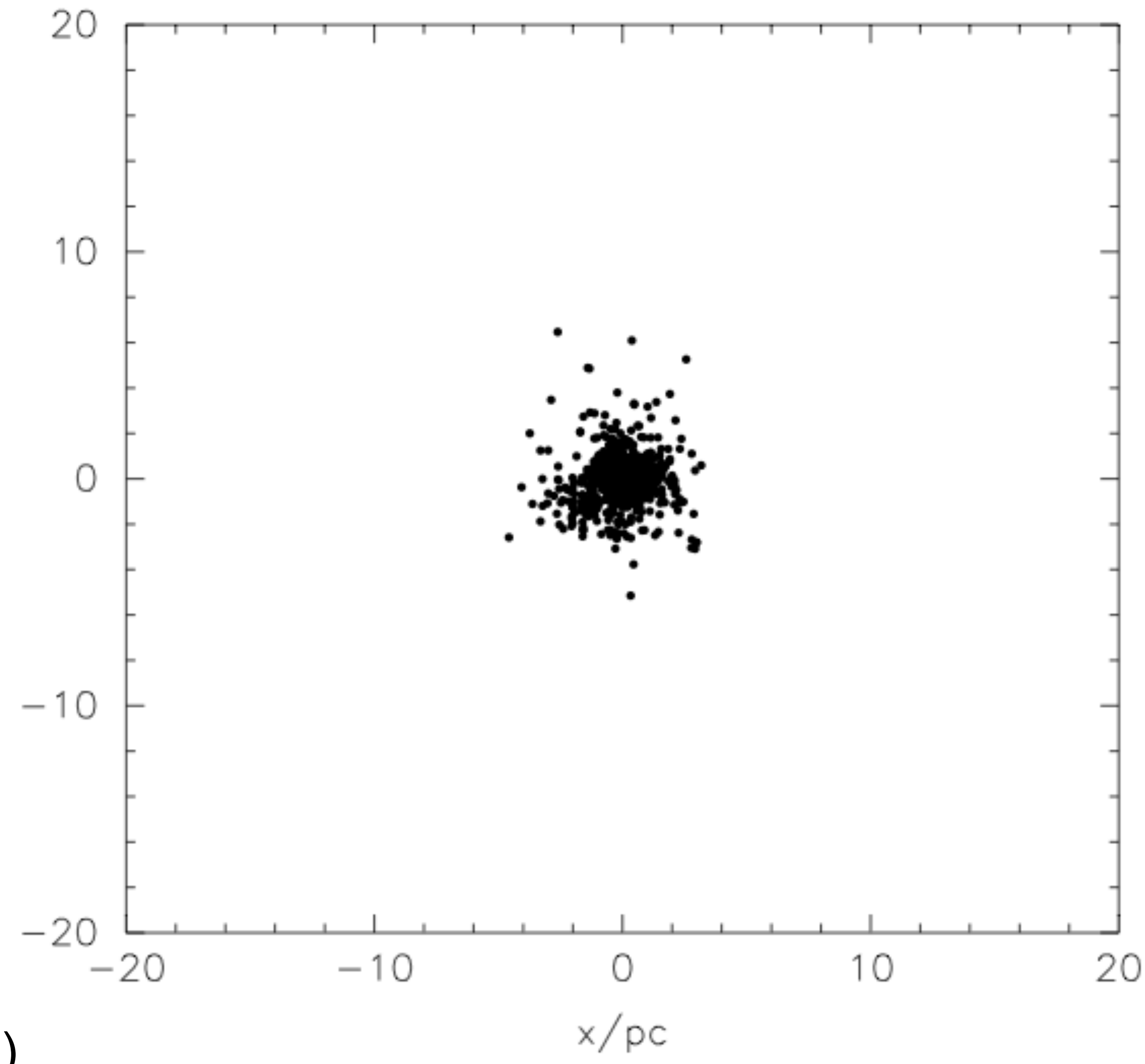
Tepid & smooth; 4Myr



(Allison 2012)

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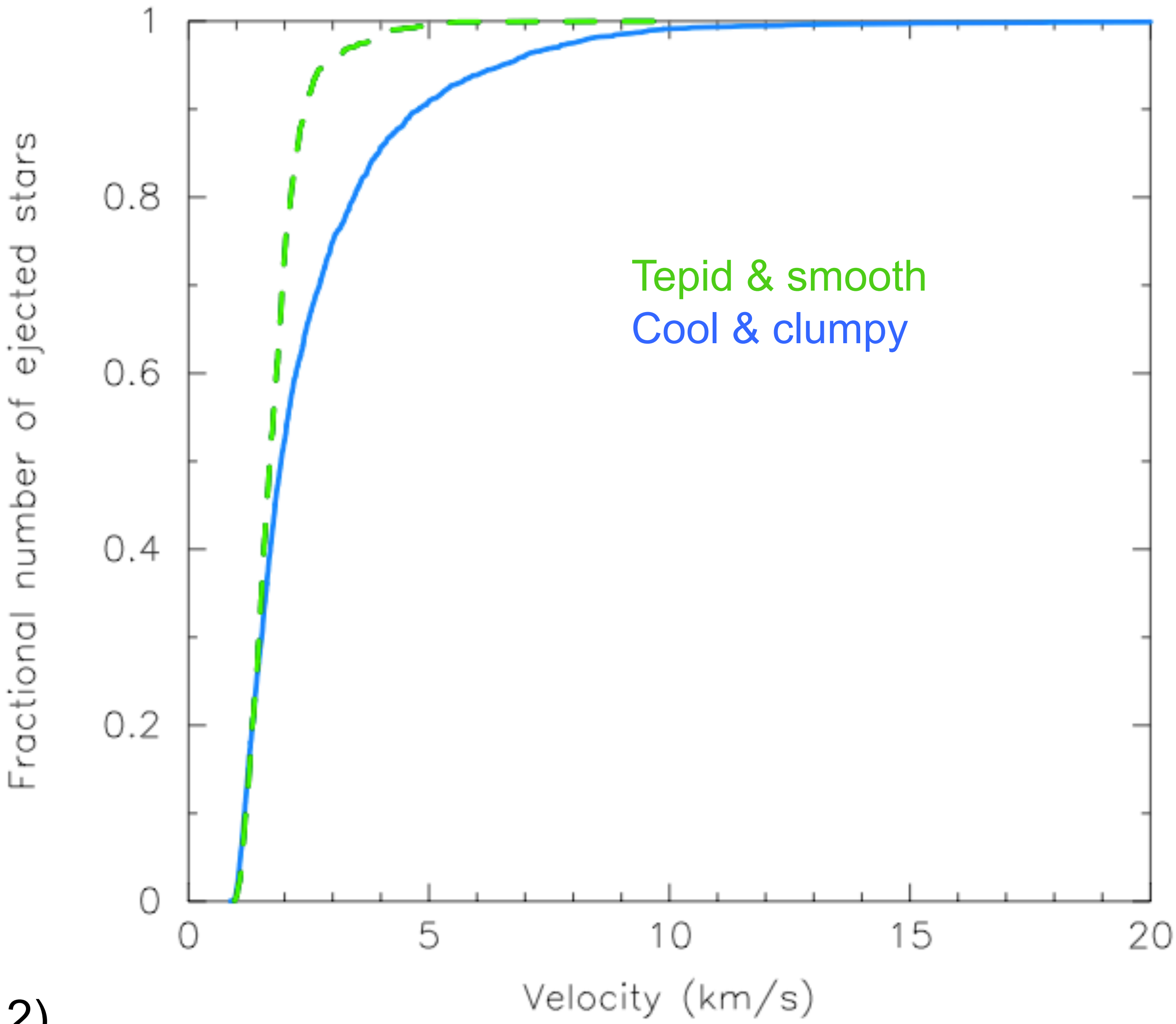
Ejected velocities; 4Myr



(Allison 2012)

Summary

- BDs may have different spatial distributions to stars in some nearby star-forming regions, but not all
- More than one measure should be used to look for differences
- Dynamical evolution can lead to differences
- However, 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
- *Gaia* will help us to probe formation mechanisms