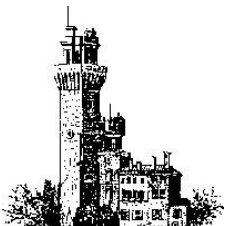


# MORPHOLOGICAL PROPERTIES OF YOUNG CLUSTERS

## The case of Gamma Velorum

**Tristan CANTAT-GAUDIN**

with A. Vallenari, E. Alfaro, M. Mapelli



Gaia-ESO survey 2<sup>nd</sup> Science Meeting  
10-13 November 2014, Porto





# INTRODUCTION

- Young clusters may retain some of the primordial properties of the molecular cloud they originate from and tell us how they assembled: multiple vs single cluster formation events?
- Different scenarios predict a variety of forms for young clusters, e.g. quiescent star formation with age spread among the same cloud (Krumholz & Tan 2007) or competitive accretion on short timescales (Clark et al. 2007).

**We want to study the star formation process in the Gamma Velorum region**



# VELA-PUPPIS STAR-FORMING REGION

$\lambda$  velorum

$\zeta$  puppis

$\gamma^2$  velorum

10 pc (at 350 pc)

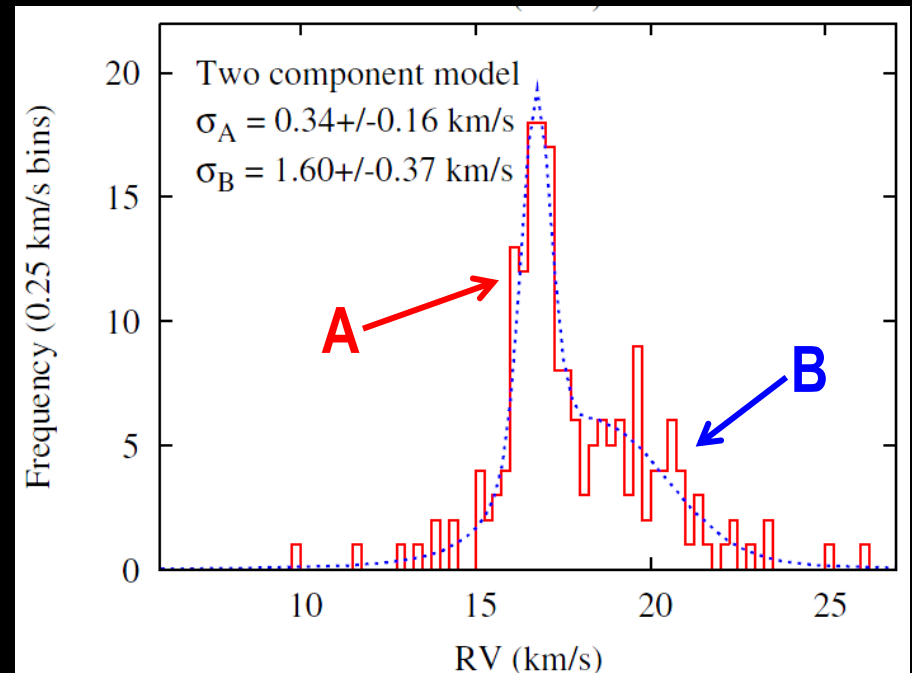
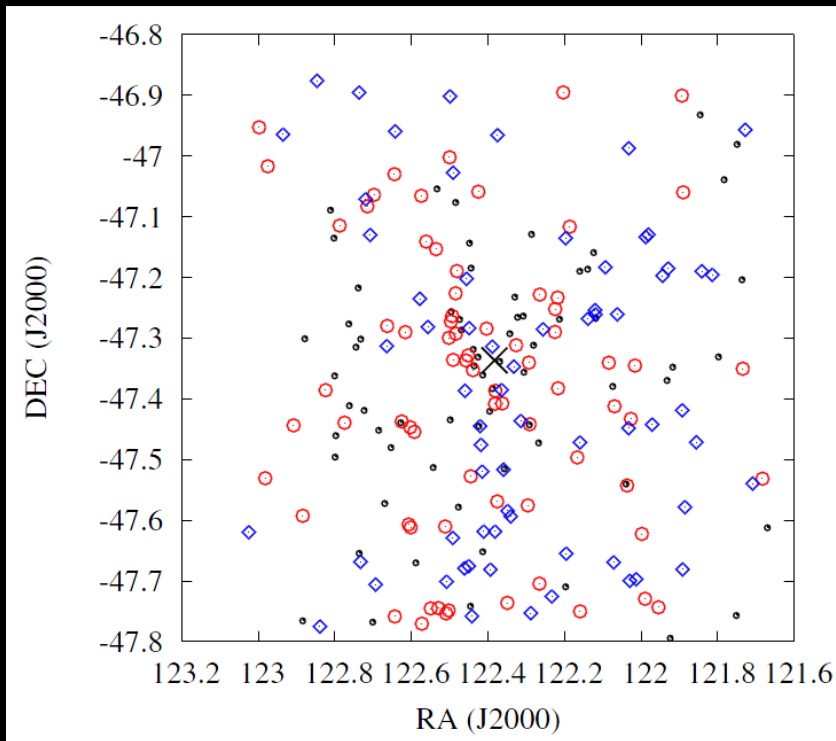
NGC 2547





# GAMMA 2 VELORUM CLUSTER – OBSERVATIONAL SITUATION

- Distance 350-400pc
- Made up of two populations (A and B) with 2 km/s radial velocity offset
- A is richer and more concentrated than B
- Age difference/different distance along the line of sight?
- Offset between two population centroids



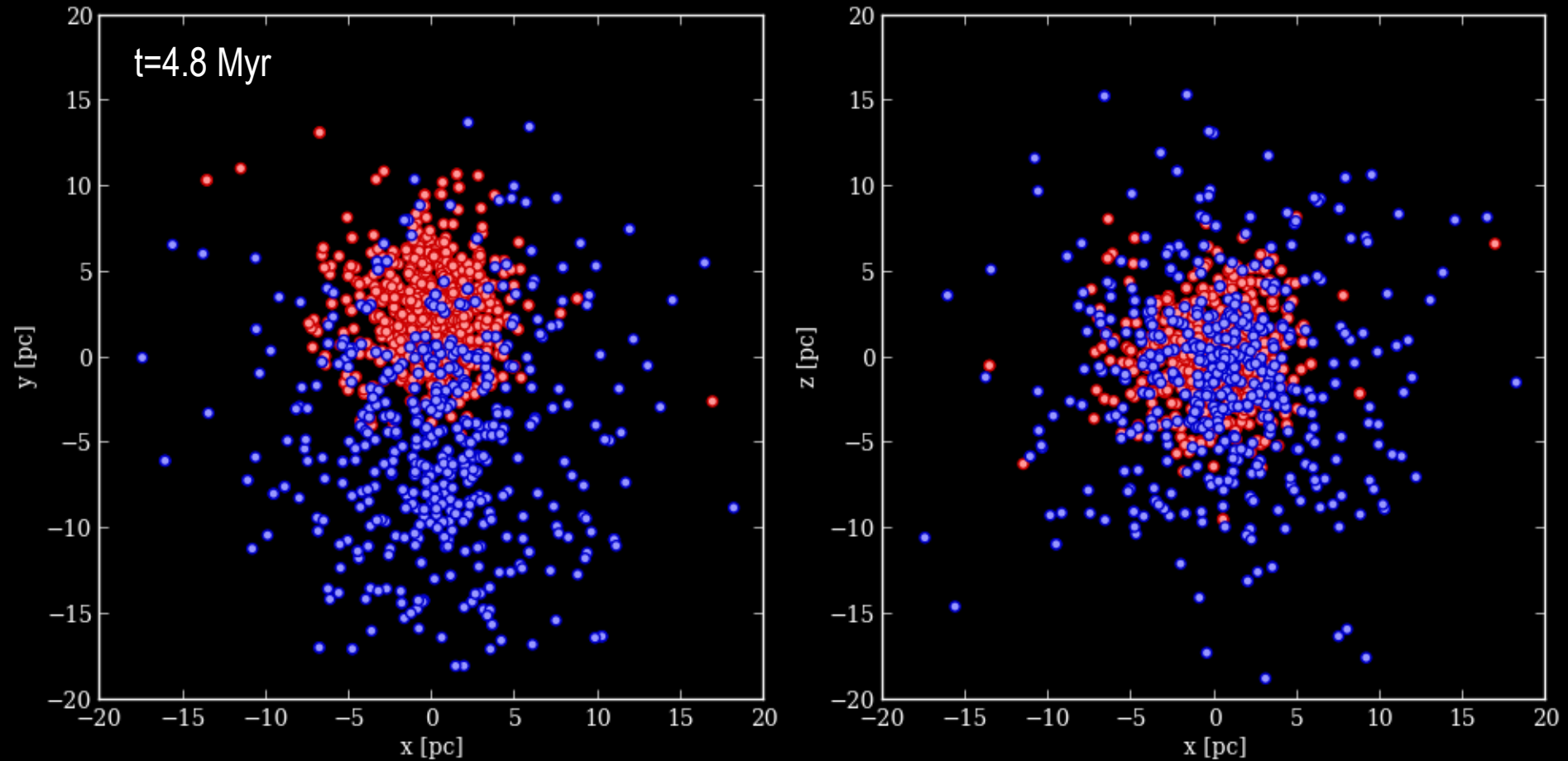
[Jeffries et al. 2014]

# N-BODY SIMULATIONS

Observational properties best reproduced when pop. B is very supervirial ( $Q > 4.5$ ).

# N-BODY SIMULATIONS

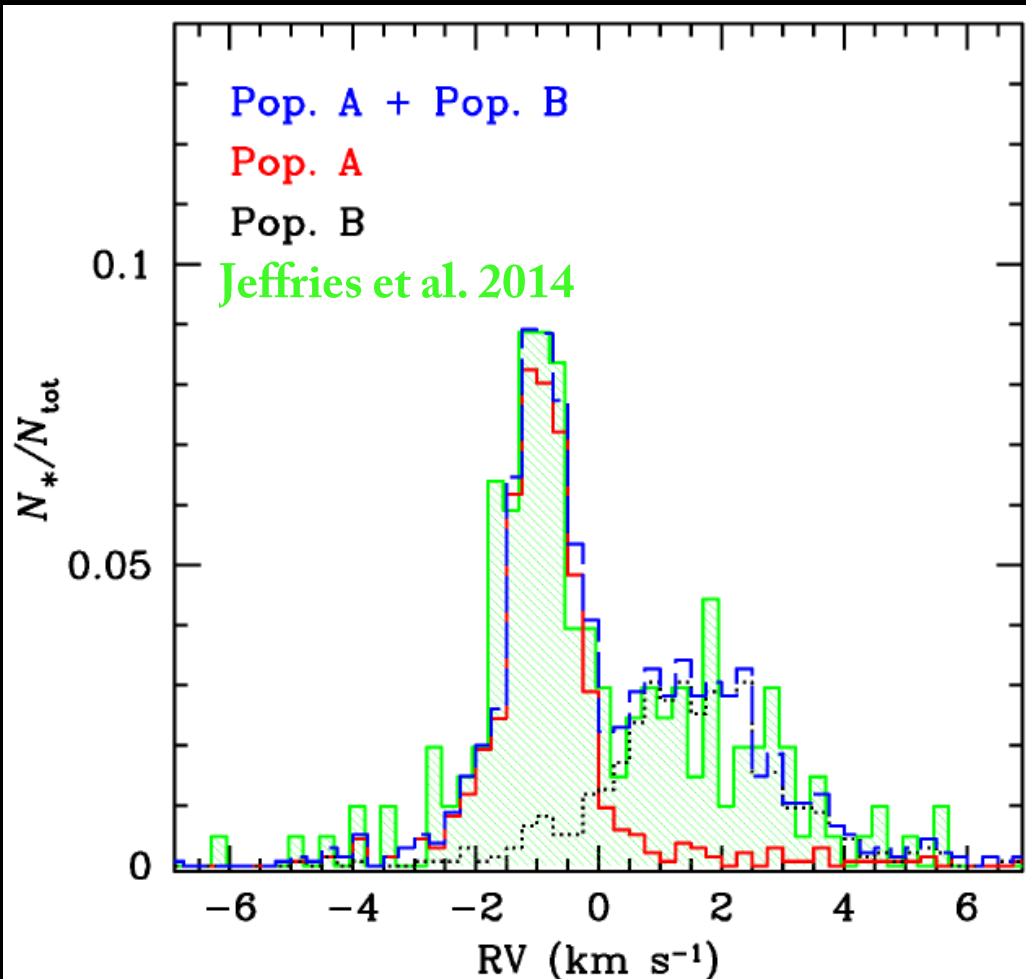
Observational properties best reproduced when pop. B is very supervirial ( $Q > 4.5$ ).



Mapelli et al. (in prep. GES manuscript #31 and poster)

# N-BODY SIMULATIONS

## Simulated radial velocity distribution:



## N-body simulations of the Gamma Velorum cluster

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**Abstract:** The Gaia-ESO Survey has recently unveiled the complex kinematic signature of the Gamma Velorum cluster: this cluster is composed of two kinematically distinct populations (henceforth, Pop. A and B), showing two different velocity dispersions and a relative  $\sim 2 \text{ km s}^{-1}$  radial velocity (RV) shift. We propose that the two populations of the Gamma Velorum cluster originate from two different sub-clusters, born from the same parent molecular cloud. We investigate this possibility by means of direct-summation N-body simulations. Our scenarios likely reproduce not only the RV shift and the different velocity dispersions, but also the slightly different centroid ( $\sim 0.5 \text{ pc}$ ), the different spatial concentration and the different line-of-sight distance ( $\sim 5 \text{ pc}$ ) of the two populations. The observed 1-2 Myr age difference between the two populations is also naturally explained by our scenario, in which the two sub-clusters formed in two slightly different star formation episodes. Our simulations suggest that Pop. B is strongly superstellar, while Pop. A might be close to virial equilibrium.

### Introduction:

GES data (Jeffries et al. 2014) show that the Gamma Velorum cluster (distance  $\sim 350 - 400 \text{ pc}$ ) is composed of two populations, pop. A and pop. B, which have a different kinematics (a  $2 \text{ km/s}$  RV shift and two distinct velocity dispersions), two different concentrations, and a slightly different age (1-2 Myr).

Motivated by the results of molecular cloud simulations (e.g. Bate 2006; Girichidis et al. 2011), we propose that the two populations of the Gamma Velorum cluster originated in two sub-clusters born in the same molecular cloud, but in two different star formation episodes (Mapelli et al., in prep.). We investigate this possibility by means of direct-summation N-body simulations, with stellar and binary evolution (Fig. 1).

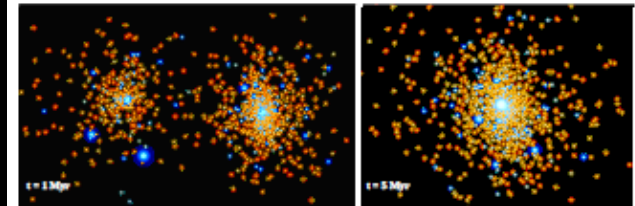


Fig. 1: Two snapshots of a direct-summation N-body simulation. Left-hand panel:  $t=1 \text{ Myr}$ , the two sub-clusters (Pop. A and B) are about to collide. Box size:  $10 \times 6 \text{ pc}$ . Right-hand panel:  $t=5 \text{ Myr}$ , the two clusters have already collided. Box size:  $4 \times 3 \text{ pc}$ . Particle colors indicate stellar temperature, while particle size corresponds to the stellar luminosity.

### KEY RESULTS:

- Our simulations reproduce the kinematics of the Gamma Velorum cluster, provided that Pop. A is approximately in virial equilibrium, while Pop. B is strongly superstellar, with virial ratio  $Q > 2$ . Fig. 2 compares the RV distribution of an N-body simulation (in which pop. B has  $Q \approx 4.5$ ) with the observed RV distribution of the Gamma Velorum cluster (Jeffries et al. 2014). The simulations where convolved with observational uncertainties.
- We predict a  $\sim 0.1 \text{ pc}$  shift between the centroids of pop. A and pop. B in the plane of the sky (consistent with the observations), and a  $\sim 5\text{-}15 \text{ pc}$  shift between pop. A and pop. B along the line of sight. Gaia will provide constraints on our prediction.
- Jeffries et al. (2014) find that pop. B is 1-2 Myr younger than pop. A, on the basis of Lithium depletion. Our simulations naturally account for this difference, since we assume that pop. A and pop. B formed in two different star formation episodes.
- A strongly superstellar pop. B expands and becomes unbound very fast. In our simulations, several members of pop. B are as far as  $15 \text{ pc}$  from the centroid of pop. A, at time  $> 5 \text{ Myr}$  (Fig. 3). This agrees with the recent claim that members of pop. B are superimposed to NGC 2547, which lies at a distance of  $\sim 2 \text{ deg}$  ( $\sim 10 \text{ pc}$ ) from the Gamma Velorum cluster (Sacco et al., in prep.).

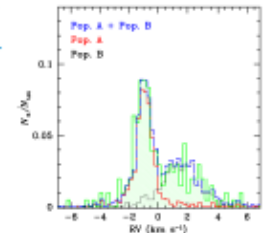


Fig. 2: RV distribution of the simulated cluster in one of our N-body models. Red line: pop. A; black line: pop. B; the line: sum of the two populations. Gauss Mixtures: data from Fig. 6 of Jeffries et al. (2014).

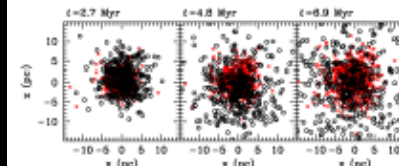


Fig. 3: Position of simulated stars belonging to pop. A (red crosses) and pop. B (black open circles), projected in the plane of the sky (the  $xz$ -plane of the simulation), at three different times ( $t=2.5, 4.8$  and  $6.9 \text{ Myr}$  since the beginning of the simulation). We notice that pop. B expands much faster than pop. A, given its super-stellar conditions.

- A superstellar nature for pop. B implies that this population formed with low star-formation efficiency and/or that the parent molecular gas evaporated very fast.

This result gives important clues to understand the process of star formation and cluster formation in the Milky Way.

**References:**  
 - Bate M. R. 2006, MNRAS, 362, 590  
 - Girichidis P., et al. 2011, MNRAS, 413, 2741  
 - Jeffries R. D., et al. 2014, A&A, 563, 94  
 - Mapelli M., et al., GES manuscript # 31  
 - Sacco G. G., et al., GES manuscript # 30

See M. Mapelli's poster.

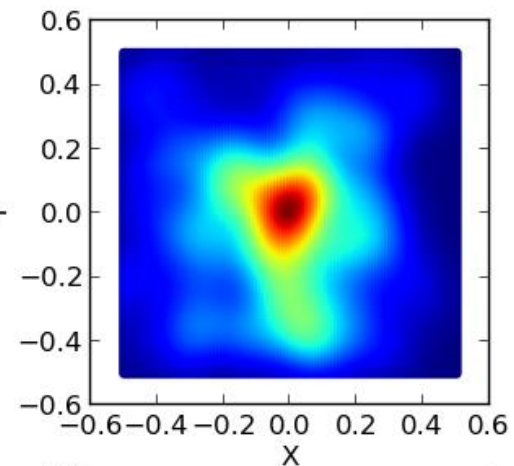
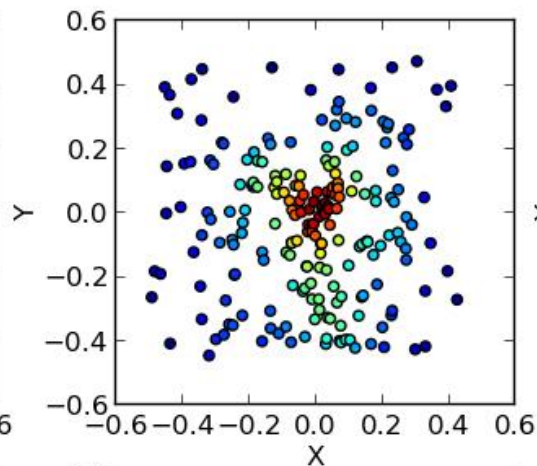
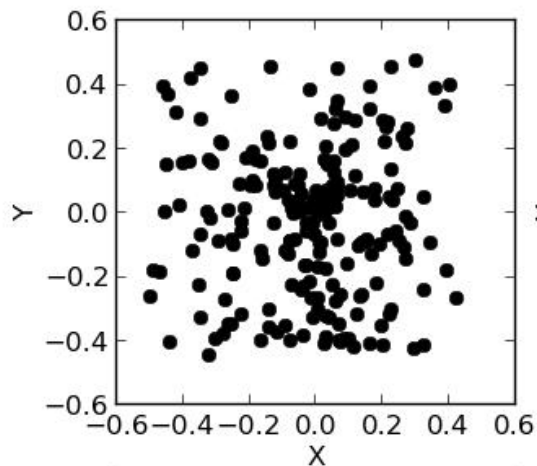
# WORKING ON OBSERVATIONAL DATA: THE DIFFERENT MORPHOLOGY OF A AND B

If A and B are in two different dynamical states, it must impact the spatial distribution of their stars.

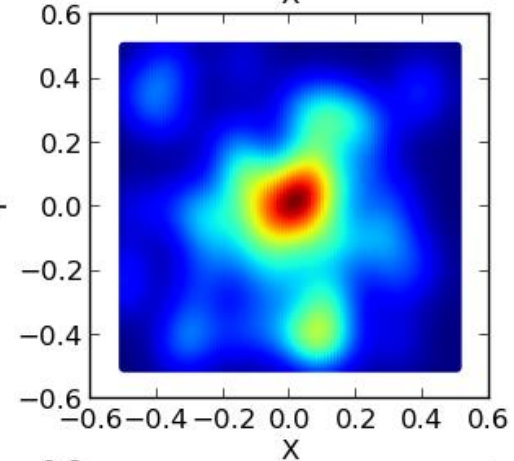
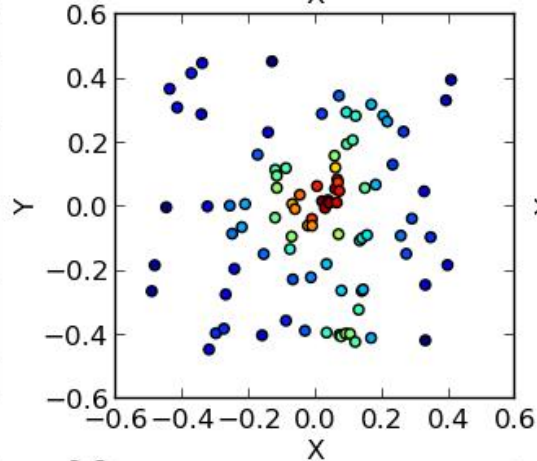
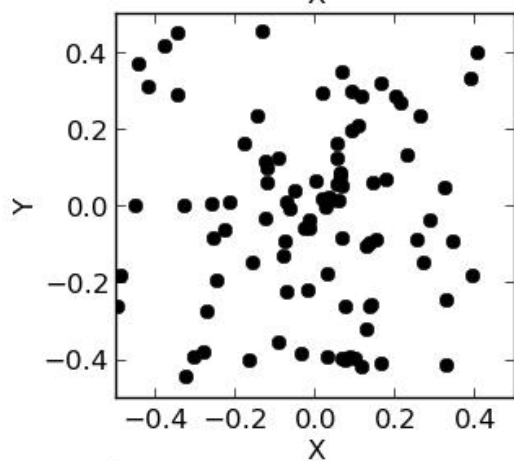
- Density maps
- Density profiles
- Two-point separation function
- Mass segregation:  $\Lambda$  parameter
- Fractality: Q parameter



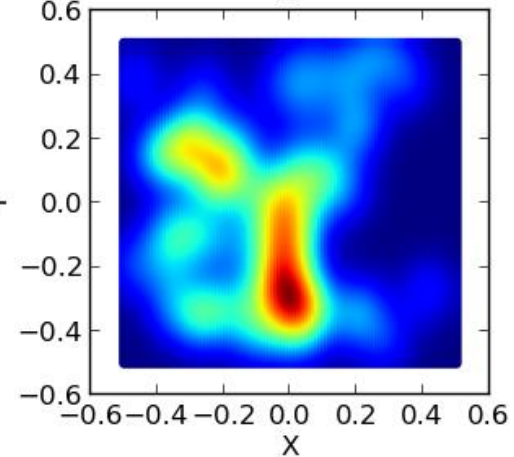
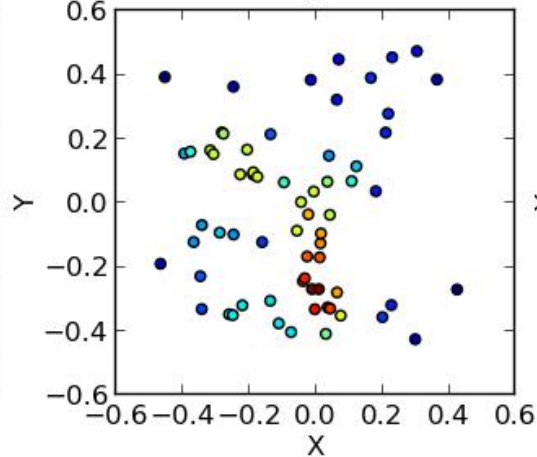
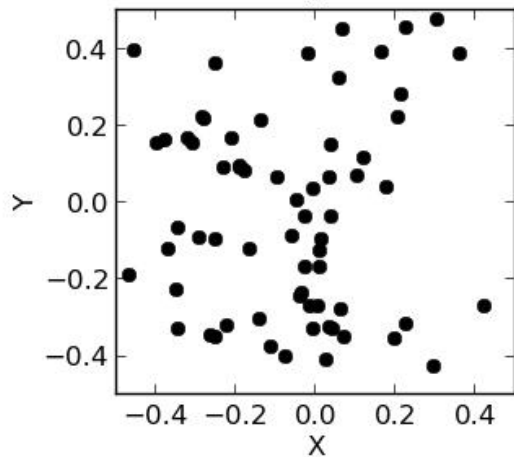
208  
cluster  
members



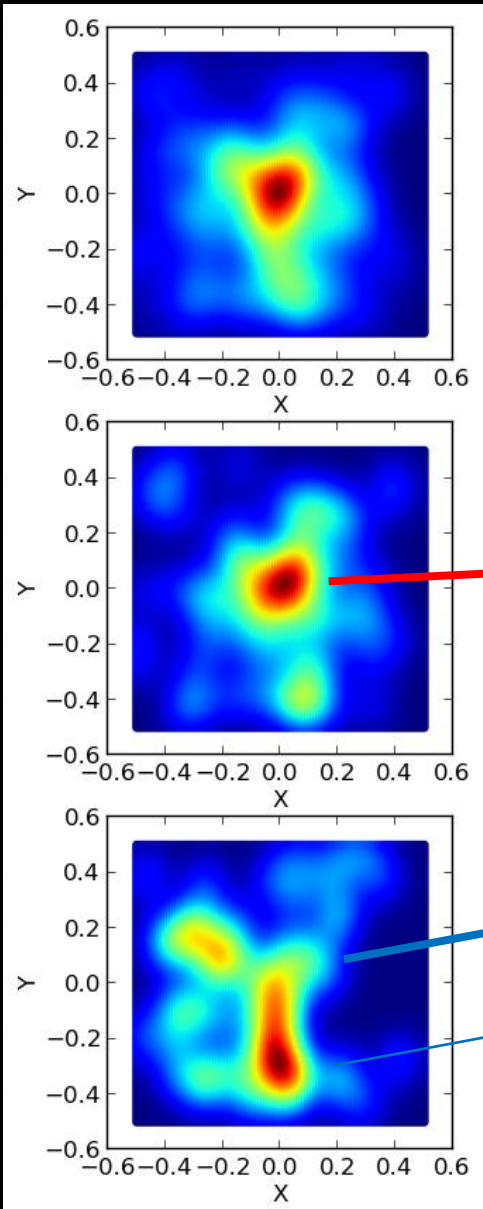
Pop. A  
( $p_A > 75\%$ )



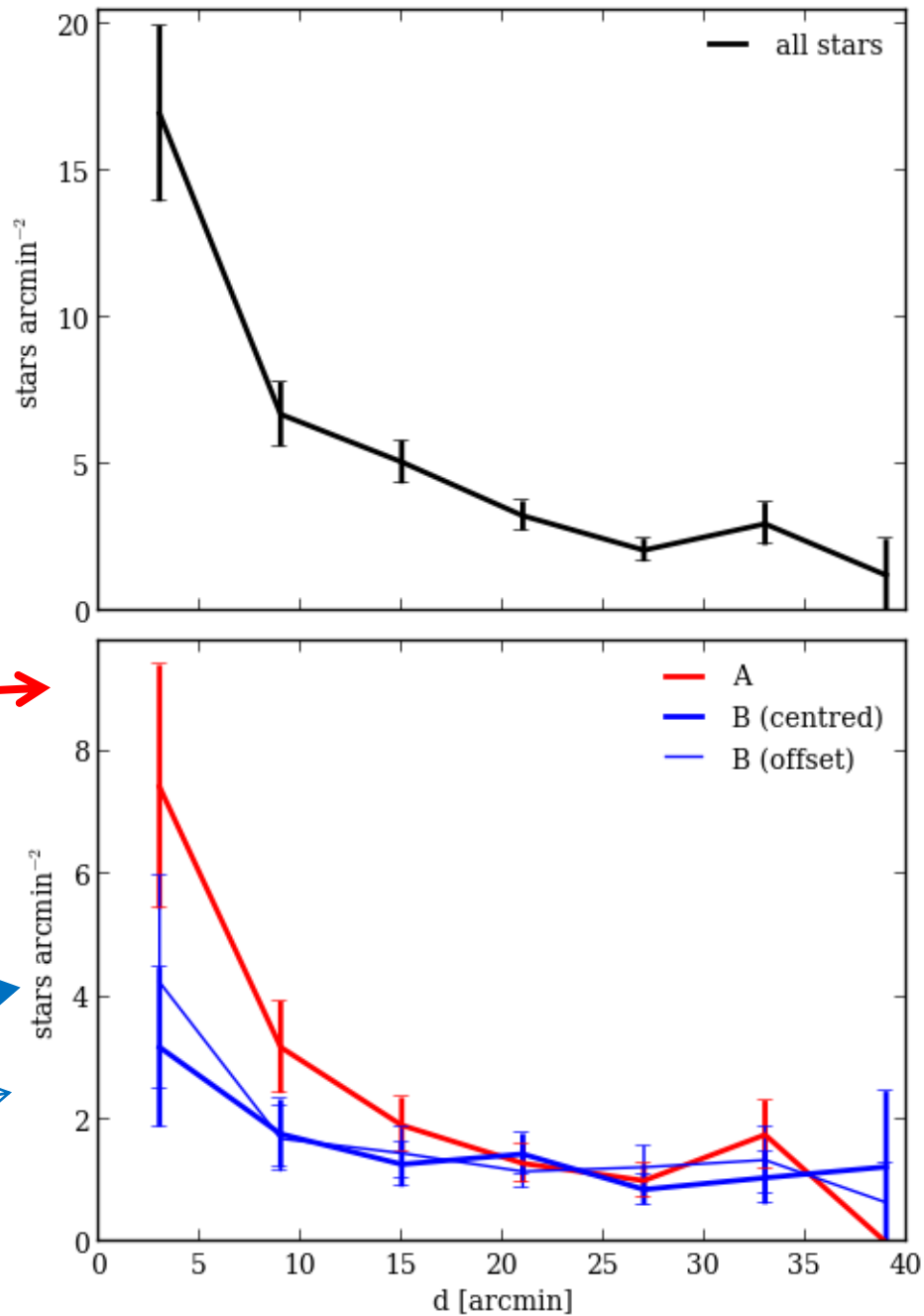
Pop. B  
( $p_A < 25\%$ )



# RADIAL DENSITY PROFILES

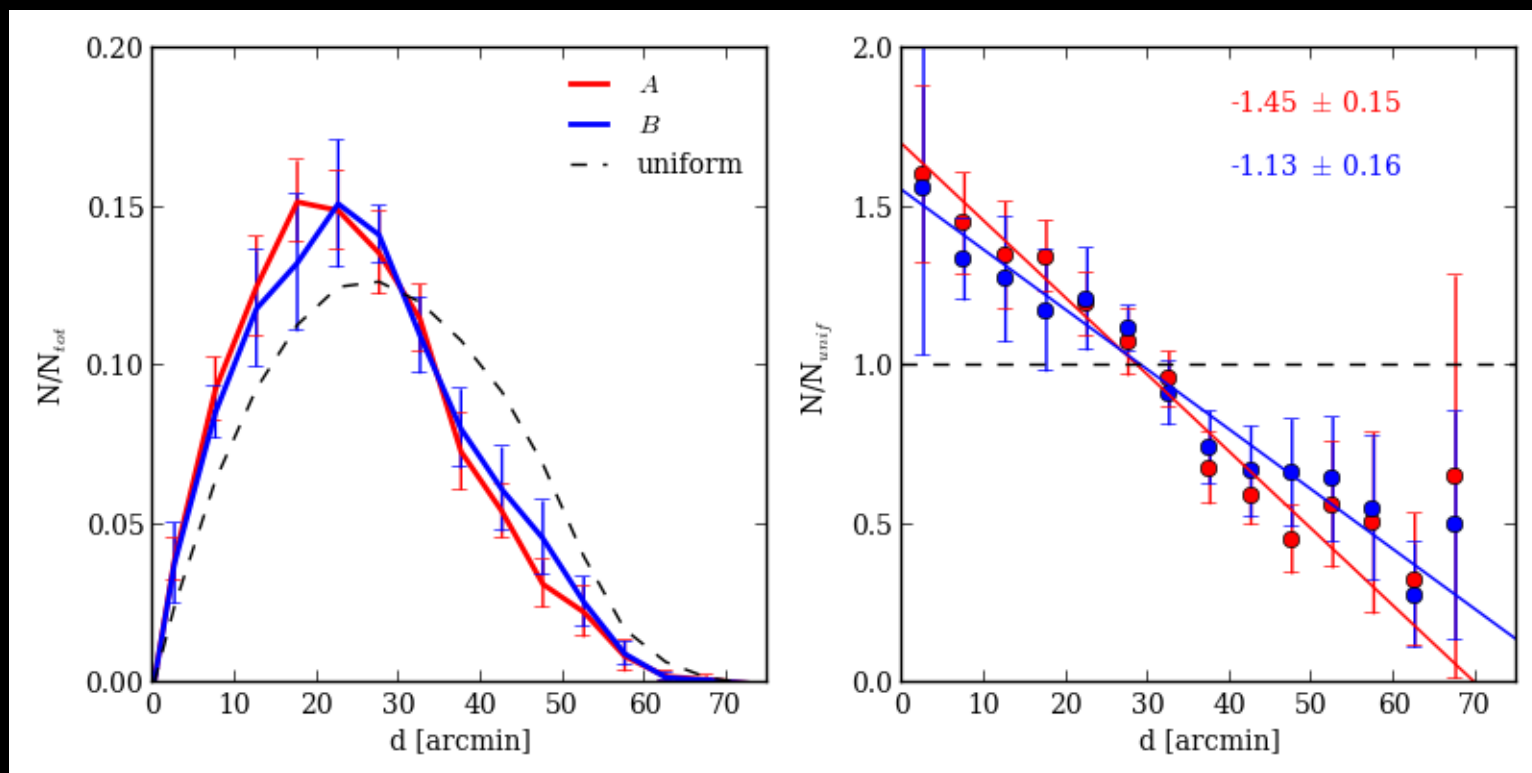


(two different choices of centre)





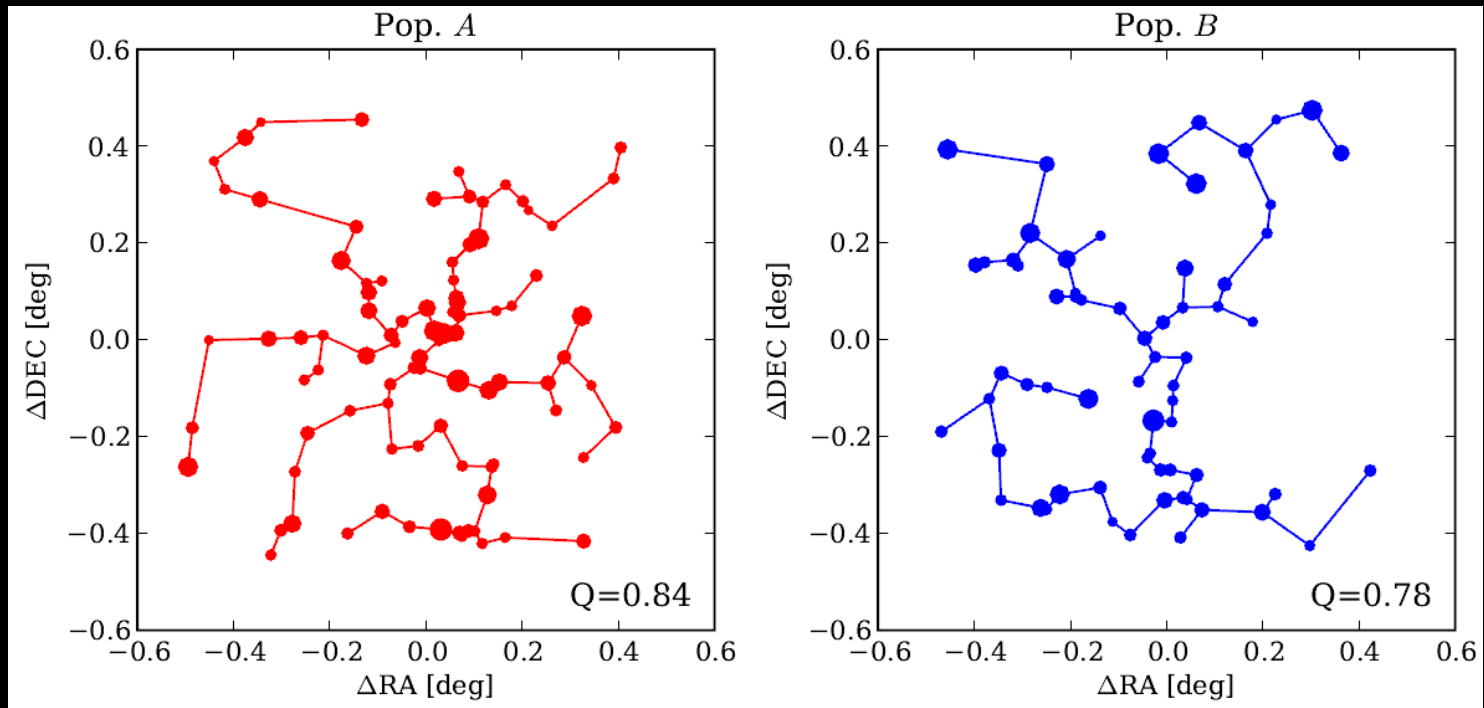
# FOR NON-CENTRALLY CONCENTRATED DISTRIBUTIONS, TWO-POINT SEPARATION FUNCTION BETTER THAN RADIAL DENSITY PROFILE



Ratio between two-point separation of population and a uniform distribution: steeper slope for population A.  
A is not just denser, it is also more concentrated.

# FRACTALITY AND MASS SEGREGATION

- Clusters evolve from a primordial fractal structure to a radial one (Klessen 2011, Maschberger & Clarke 2011).
- A supervirial cluster undergoes a **warm collapse** (Parker & Meyer 2012) and retains some of its primordial substructure for a longer time (5-10 Myr).
- Fractality can be quantified through parameter  $Q$  (Cartwright & Whitworth 2004):  
 **$Q > 0.8$ : centrally distributed**       **$Q < 0.8$ : fractally distributed**
- Mass segregation can be either primordial or appear dynamically.  
**segregation + high  $Q$  = cold collapse** (Delgado et al. 2013)

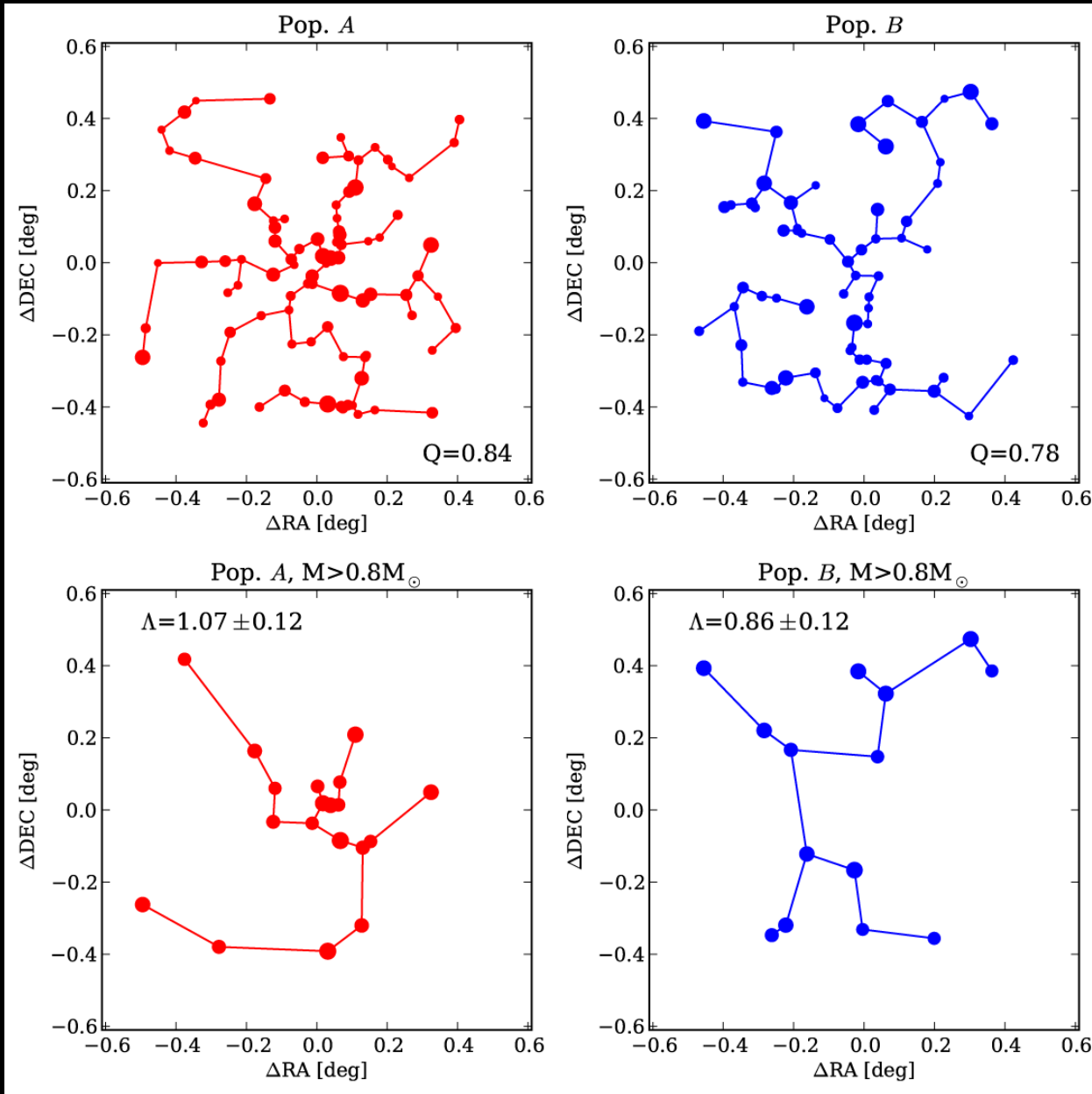




# FRACTALITY AND MASS SEGREGATION

## A

Mass-segregated and less fractal?



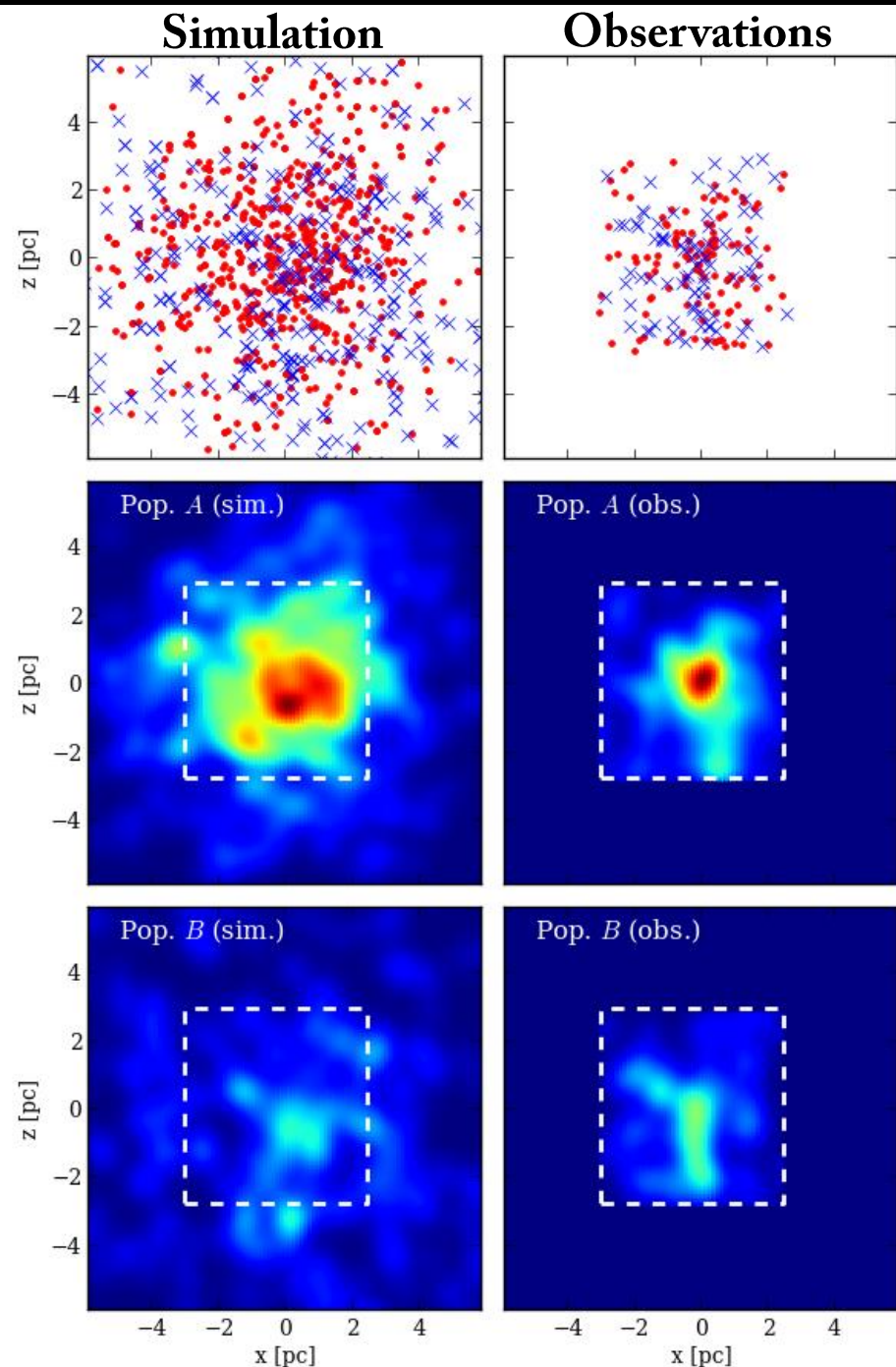
## B

Not segregated and more fractal?

# WE ONLY COVER THE INNER REGION OF THE CLUSTER

We expect B to be sparser,  
less concentrated, less mass-  
segregated, and more fractal.

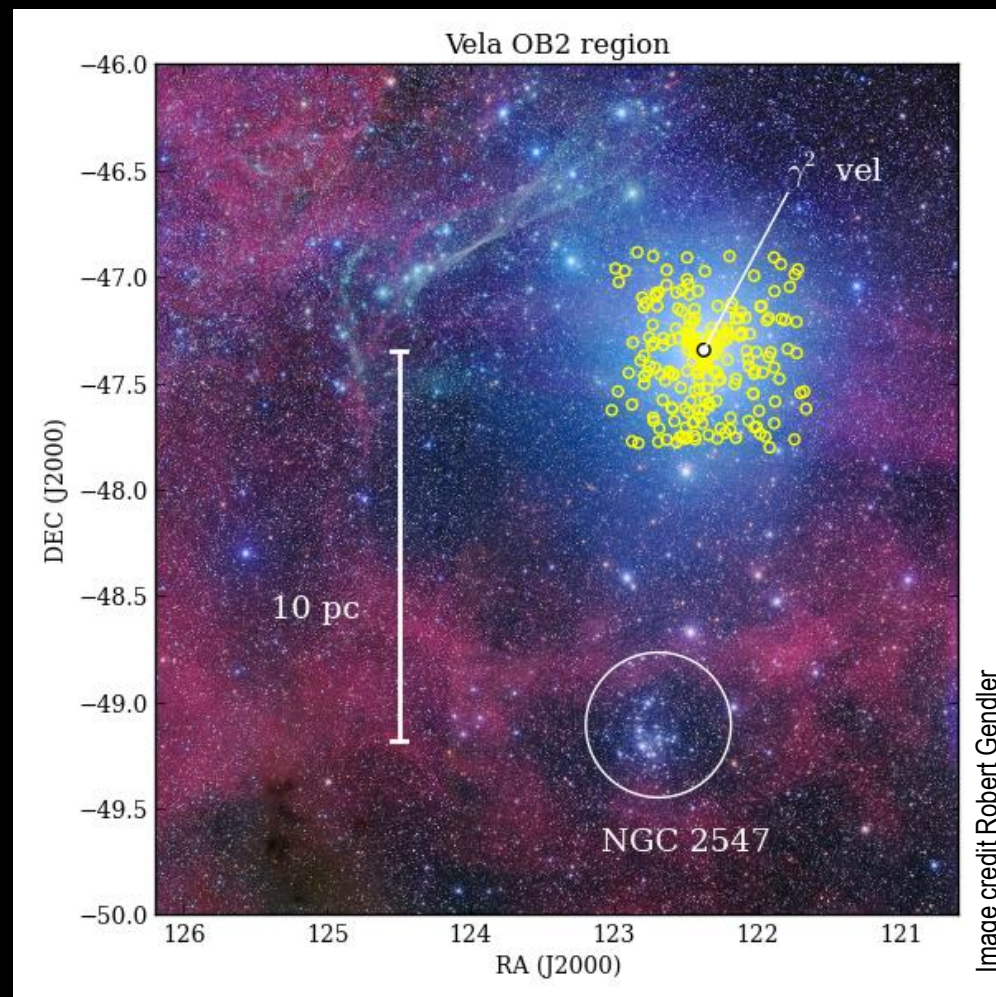
Observations seem to point in  
that direction, but  
characterising the morphology  
of populations A and B would  
require studying them on a  
larger scale because we only  
see the core of the system.





# THE BRIDGE TO NGC 2547

In the simulations, subcluster B expands rapidly to distances of **15 pc**.



This expansion can explain the peculiar dynamical structure observed by Sacco et al. (GES manuscript #30) in **NGC 2547**.

# SUMMARY

- A and B present a different dynamical state, radial velocity distribution, density profile, and spatial distribution.
- They might have been formed in two different episodes/environments (multiple clustering has been observed in the MW e.g. Megeath et al. 2012, Feigelson et al. 2011).
- B is sparser than A due to its supervirial state: formed in a less dense environment, or lost more gas?
- This scenario naturally explains the kinematic signature of B in the NGC 2547 region.

# PROSPECTS

- Spectroscopy on a larger field would improve our characterisation of the morphology of A and B.
- Line-of-sight distribution from Gaia parallaxes can solve the question of the physical link between subclusters A and B.
- The massive, young binary system  $\gamma^2$  Vel needs to be inserted in the puzzle.

