Stellar Clusters in Phase Space: Feedback between Dynamical Models and Observations

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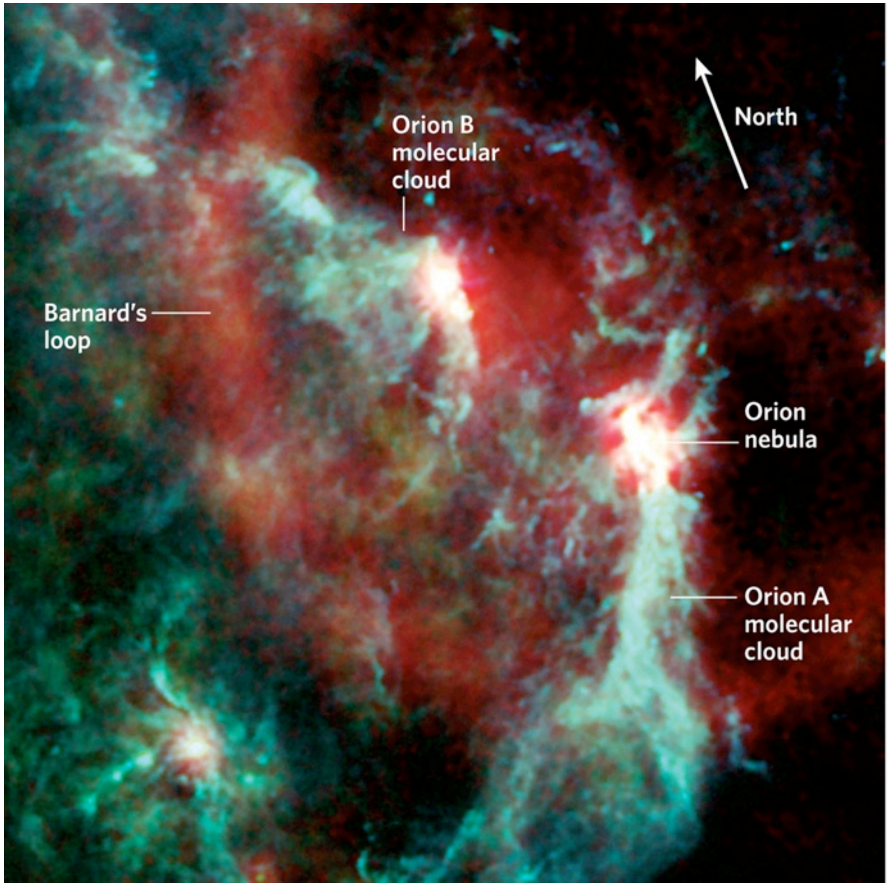
Star Cluster Formation: A Challenging Question



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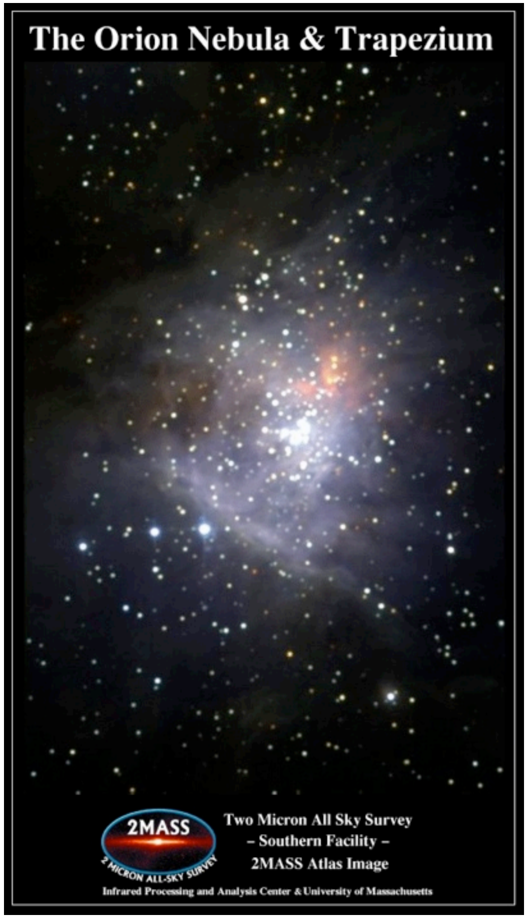
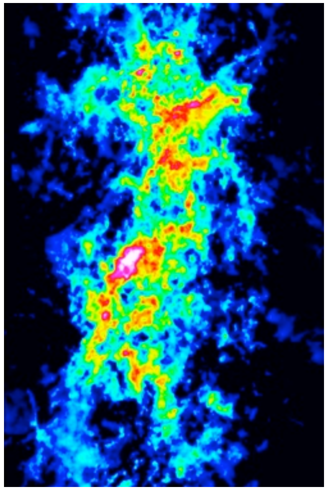
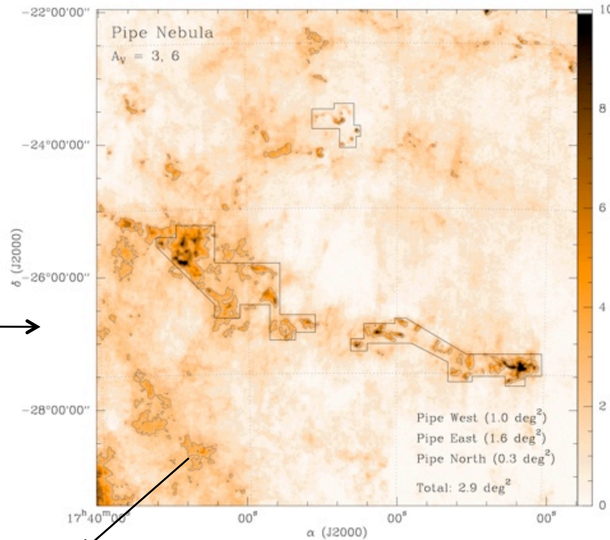


Physical Conditions of the Clouds

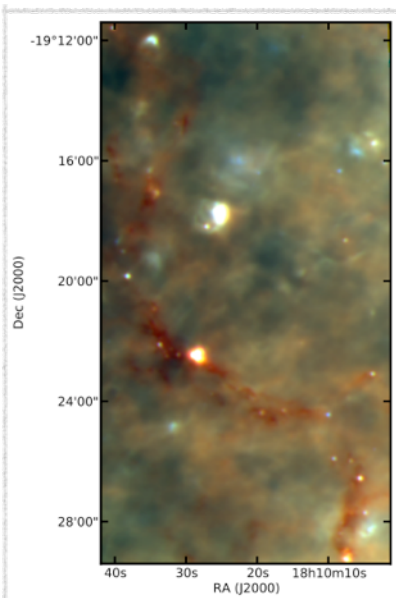
Physical Properties of Stellar Clusters



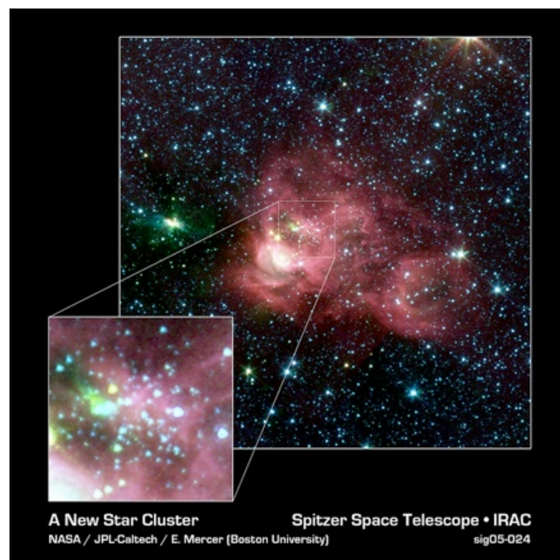
Molecular Clouds



Pre-stellar Cores



Proto-stellar Cores



Embedded Clusters

Visible Clusters

Observational Constraints to Formation and Early Evolution of Stellar Clusters

Stellar IMF

Universal or Environment Dependent? (Bastian et al. 2010; Ascenso & Alves 2012; Parker 2012)

Mass Segregation

Universal? (Hoerner 1960; Allison & Goodwin 2011; Parker et al. 2011; Er et al. 2013; Delgado et al. 2013)

Primordial? (Maschberger & Clarke 2011; Alfaro & Román-Zuñiga 2014)

Cluster Structure in Phase-Space:

- Spatial and Kinematic Structures
- Evolutionary Models

Spatial & Kinematic Variables

A stellar system is fully described by an evolving phase-space density distribution function, $f(\mathbf{r},\mathbf{v},t)$.

In astronomical coordinates phase-space can be defined by $(\alpha, \delta, r, V_r, \mu_\alpha, \mu_\delta)$ variables

Unfortunately, in most cases we observe only 3 out of 6 variables:
2 positional + radial velocity $(\alpha, \delta + V_r)$

On just a few occasions do we know the other 2 velocity components (μ_α, μ_δ) and rarely the 3rd spatial dimension (r)

And always at a given moment of t. Thus we seek families of stellar systems seen at different evolutionary states

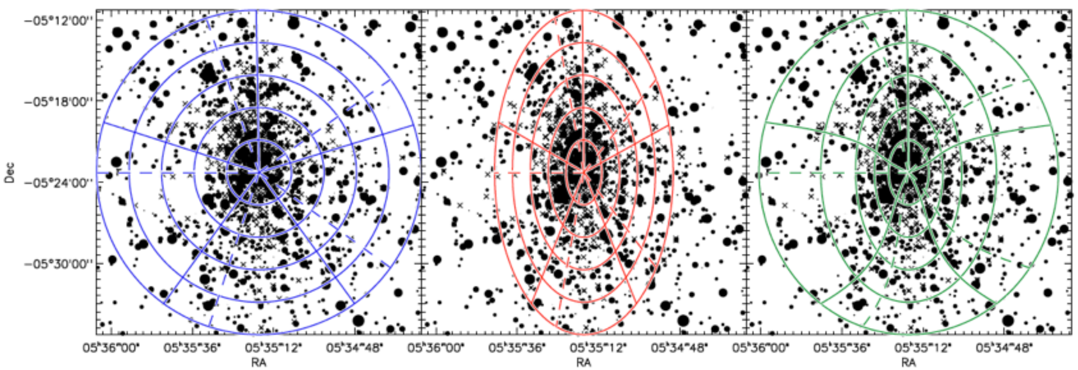
Cluster Spatial Distributions

• Stellar Clusters, in particular young stellar clusters, show a great variety of morphologies which need to be "quantified" to enable a systematic study.

• The fractal character of the star formation pattern in a wide range of scales (Efremov & Elmegreen 1998; Sánchez et al. 2010; Gouliermis et al. 2014) makes the definition of cluster boundaries a subjective task.

• The generation of a given spatial pattern is not associated to a single mechanism. Model degeneracy problem: Two-body relaxation, gas removal, or subclusters merging, can yield the same spatial distribution coming from different initial conditions (i.e. Parker 2014).

Angular Dispersion: Orion Nebula Cluster



$$\delta_{\mathrm{ADP,N}} = \sqrt{\frac{1}{(N-1)\overline{n}}\sum_{i=1}^{N}(n_i-\overline{n})^2} = \sqrt{\frac{\sigma^2}{\sigma^2_{\mathrm{Poisson}}}} \quad (1)$$

ONC: Supervirial SFR with formation time over 10 free-fall time (t_{ff} ~ 3.5 X 10^5 a)

Da Rio et al. 2014

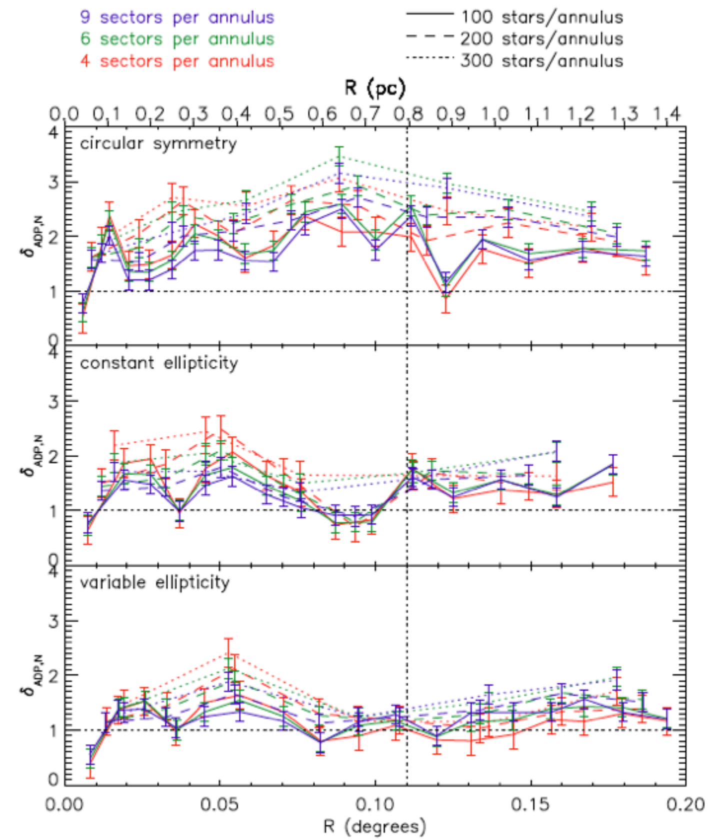


Figure 6. Angular dispersion of stellar counts in sectors normalized on that expected for Poisson statistics, as measured by the ADP, as a function of radial distance from the center of the selected annuli. Lines corresponds to different numbers sectors and stars per annulus, and for the assumption of circular symmetry as opposed to elliptical symmetry. The vertical dotted line at delimits the X-ray complete sample at $r < 0.11°$.

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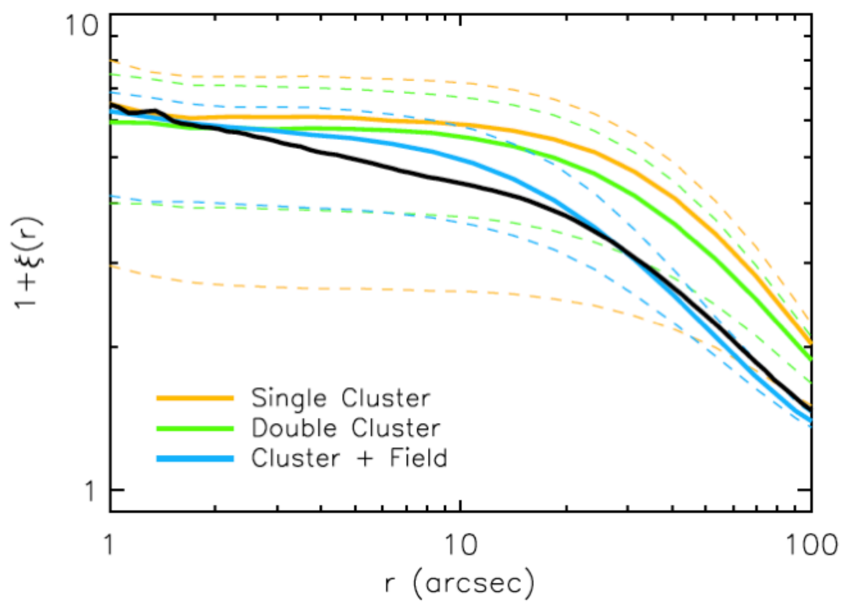
ACF as spatial distribution parameter

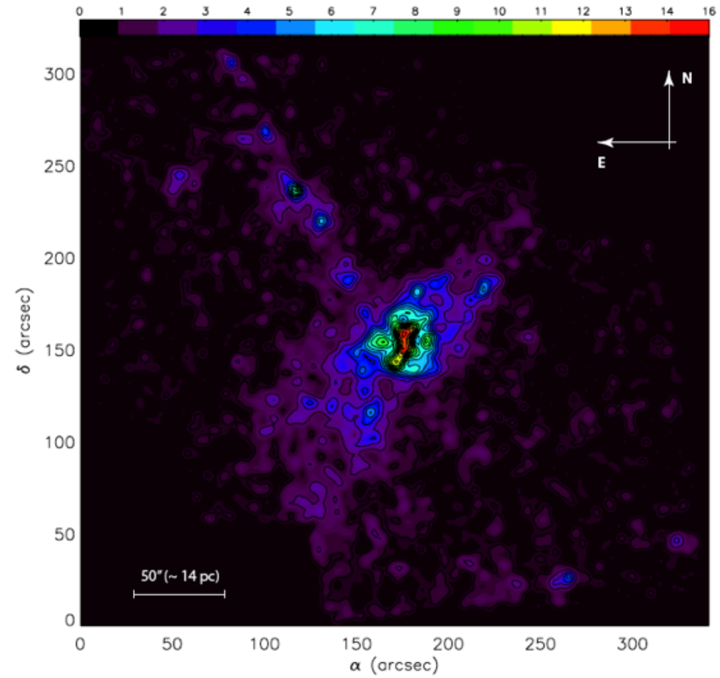
ACF defined as

$$1 + \xi(r) = \frac{1}{\bar{n}N} \sum_{i=1}^{N} n_i(r),$$

↓ Two-Point Correlation Function

Similar to the FCF used by Sánchez et al. 2008, 2010





NGC 346 @ SMC

A central compact cluster +
Fractal underlying stellar population

Gouliermis et al. 2014

Fractal Correlation Function: Star Formation Scales in M33

$$C(r) = \frac{1}{M(N-1)} \sum_{i=1}^{M} n_i(r).$$

Sánchez & Alfaro 2008

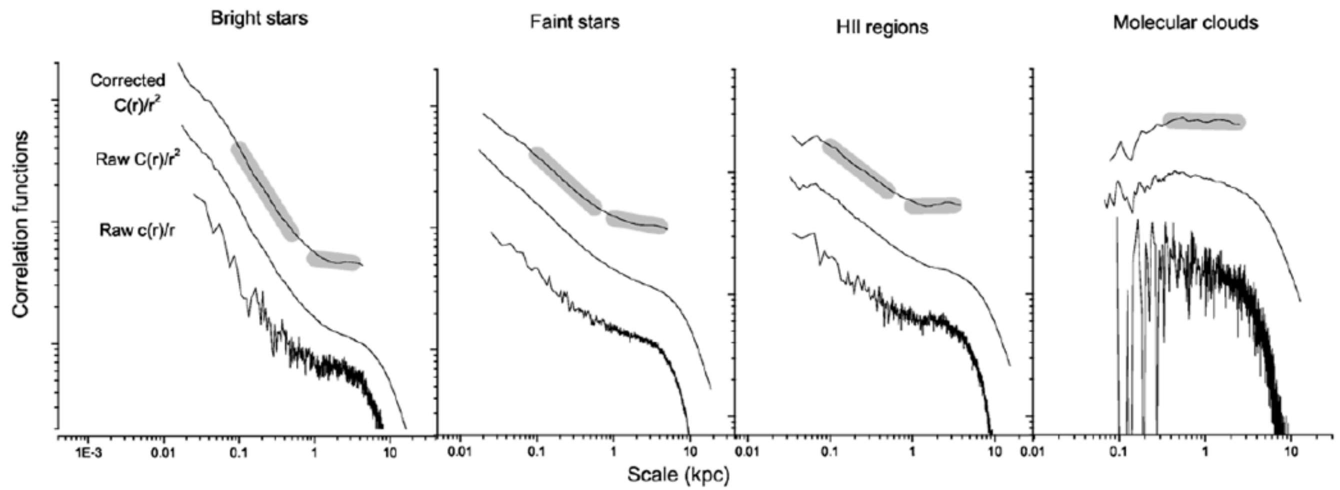


Figure 3. From top to bottom in each panel, the edge-corrected correlation integral $C(r)/r^2$, the raw correlation integral $C(r)/r^2$, and the differential correlation function $c(r)/r$ for the distributions of pointlike objects. The data have been arbitrarily shifted vertically for clarity. Shaded line segments show power-law fits.

The spatial scale for this transition is in the range ~500–1000 pc.
This characteristic scale separates two physical regimes, one where small-scale turbulent motions generate self-similar structures, and another dominated by large-scale galactic dynamics (Sánchez et al. 2010)

Mean Surface Density of Companions

Cartwright & Whitworth (2004)

$$p(s_i) = \frac{2\mathcal{N}_i}{\mathcal{N}_{\rm total}(\mathcal{N}_{\rm total}-1)\Delta s}$$

$$\Delta s = 2R_{\rm cluster}/i_{\rm max}$$

where i_{max} is the number of bins

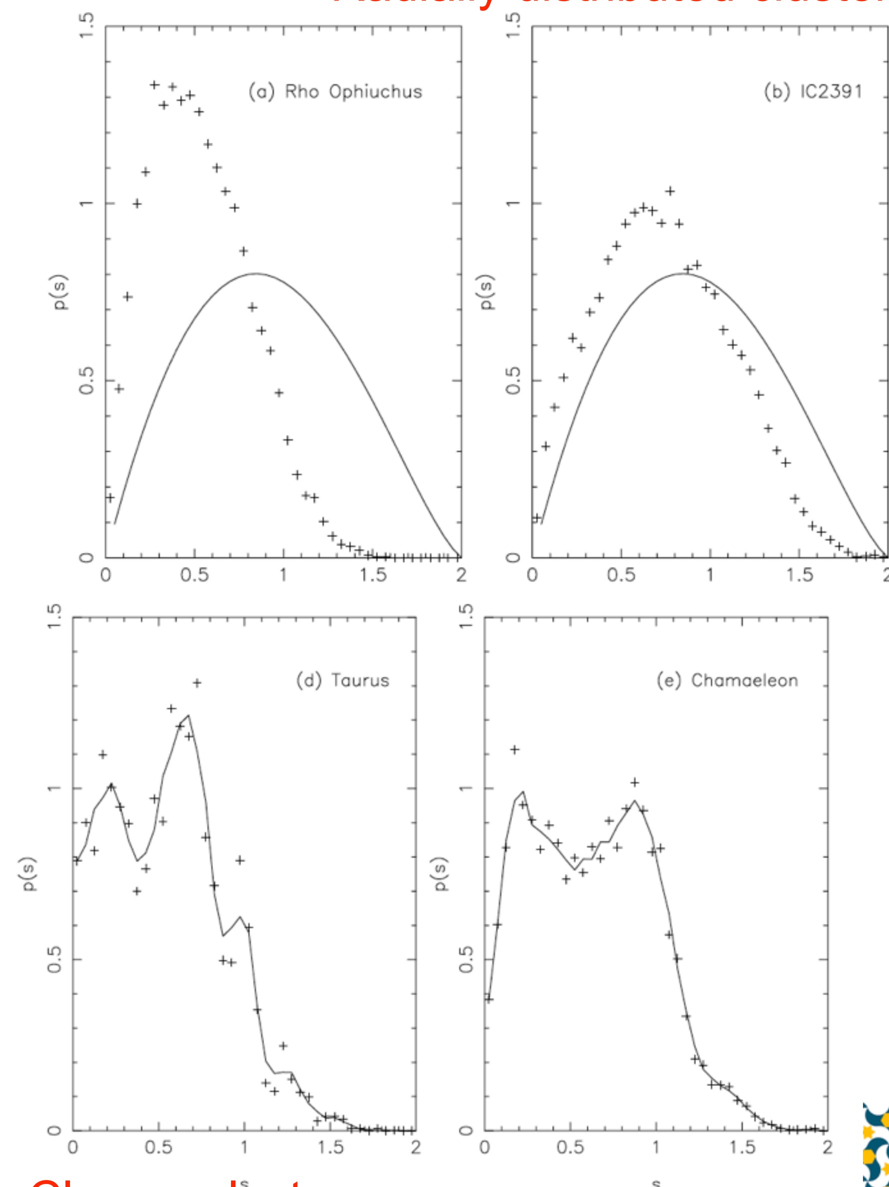
s interval for the *i* bin is given by

$$(i-1)\,\Delta s < s < i\Delta s$$

$$\mathcal{N}_{\rm total}(\mathcal{N}_{\rm total}-1)/2$$

total number of separations

Radially distributed clusters



Clumpy clusters

Euclidean Minimum Spanning Tree: Q parameter

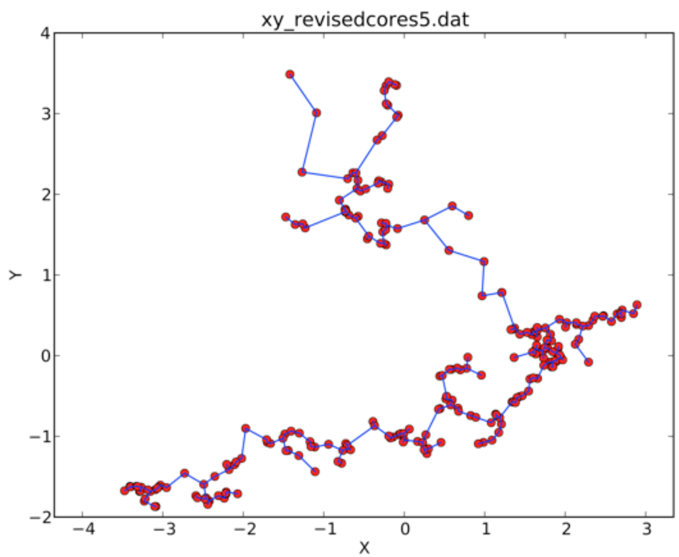
Cartwright & Whitworth (2004)

In Graph's Theory: A tree connecting all the set points with the minimum total weight. When the weight is the Euclidean distance, the solution is given by linking the points with their closest ones.

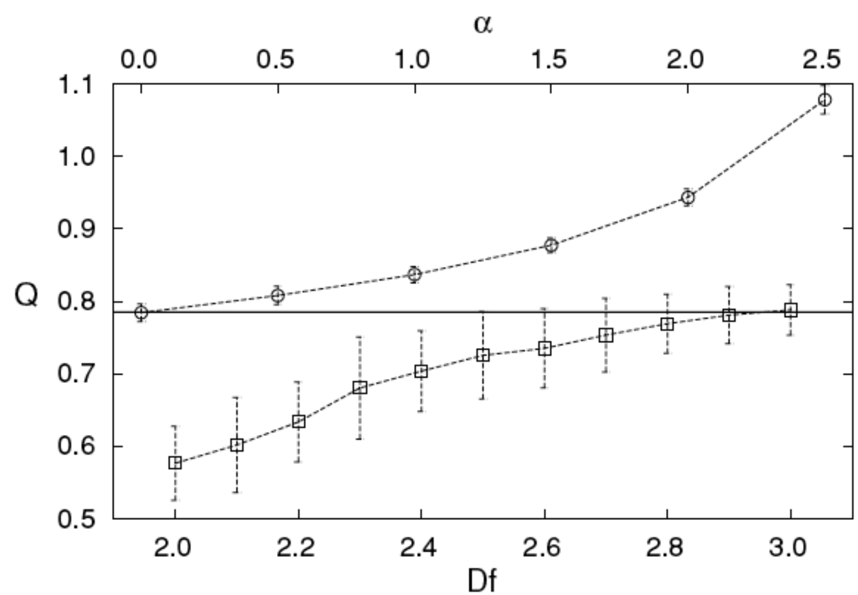
$$Q = \frac{\bar{m}}{\bar{s}}$$

$\bar{m}$ Mean edge length

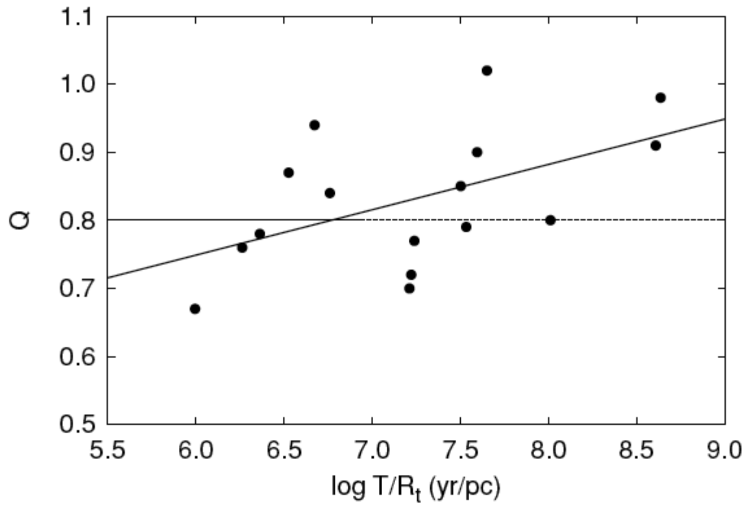
$\bar{s}$ Correlation length as the mean separation normalized by the cluster radius

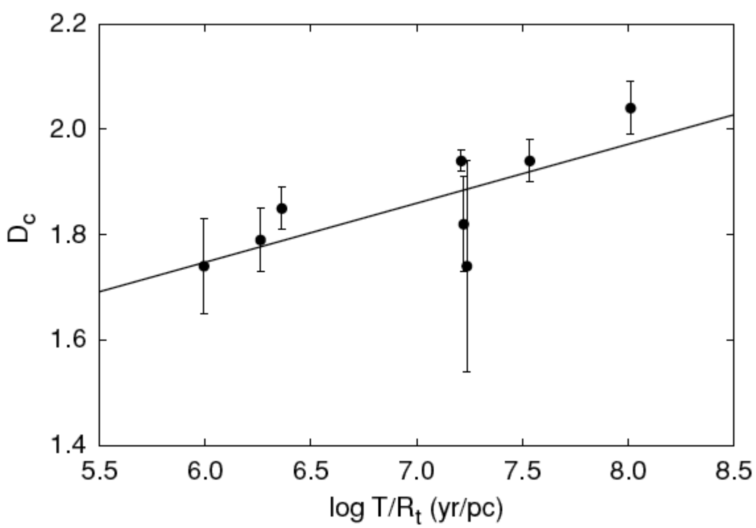


Q = 0.35



Spatial Structure: Evolution





Sánchez & Alfaro 2009

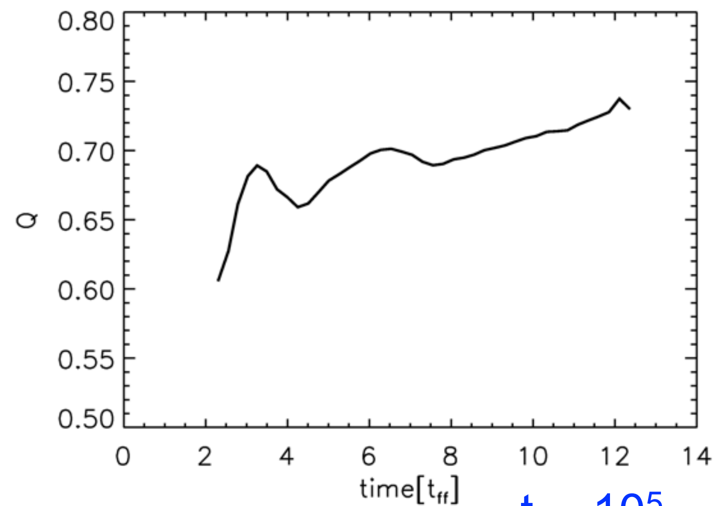
16 stellar clusters (with PM data)

- Membership analysis
- Q, Correlation Fractal Dimension and King model
- Weak correlation between Q and logT
- Fractal Dimension increases (less clumpy) with time
- Clumpy structure observed up to 100 Ma

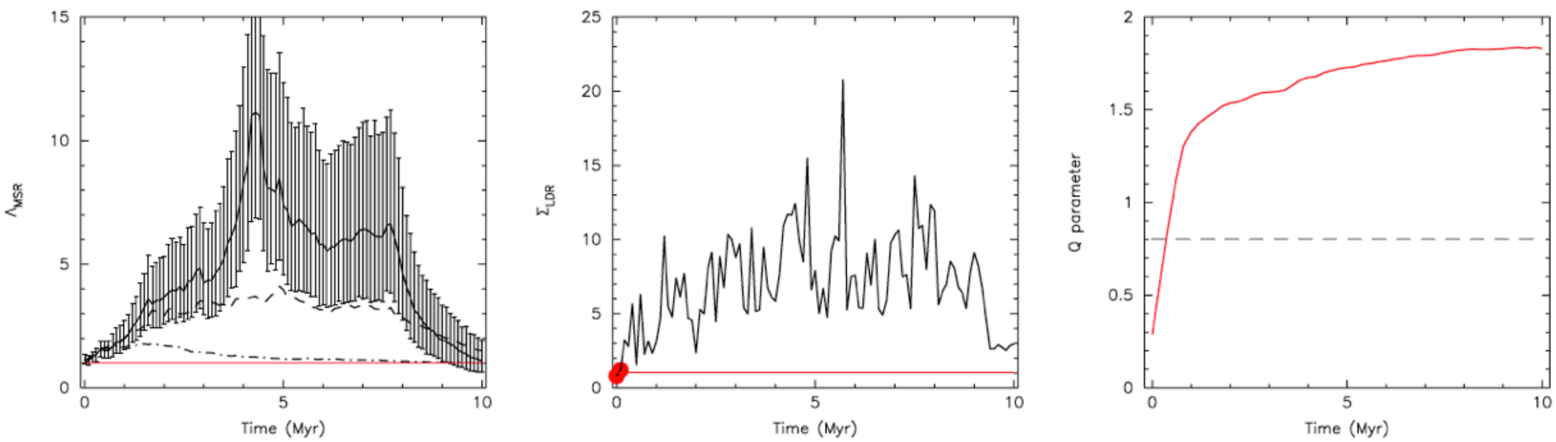
Similar results to those found for Embedded Clusters (Schmeja et al. 2008a), for Star Forming Regions (Kuhn et al. 2014), and for evolutionary models of Star Forming Clouds and Young Stellar Clusters (Schmeja et al. 2008b; Parker et al. 2014)

Models

Schmeja et al. (2008) based on
Schmeja & Klessen (2004) models



t_{ff} ~10^5



(j) Evolution of $\Lambda_{\rm MSR}$ (k) Evolution of $\Sigma_{\rm LDR}$ (l) Evolution of $\mathcal{Q}$–parameter

Parker et al. 2014

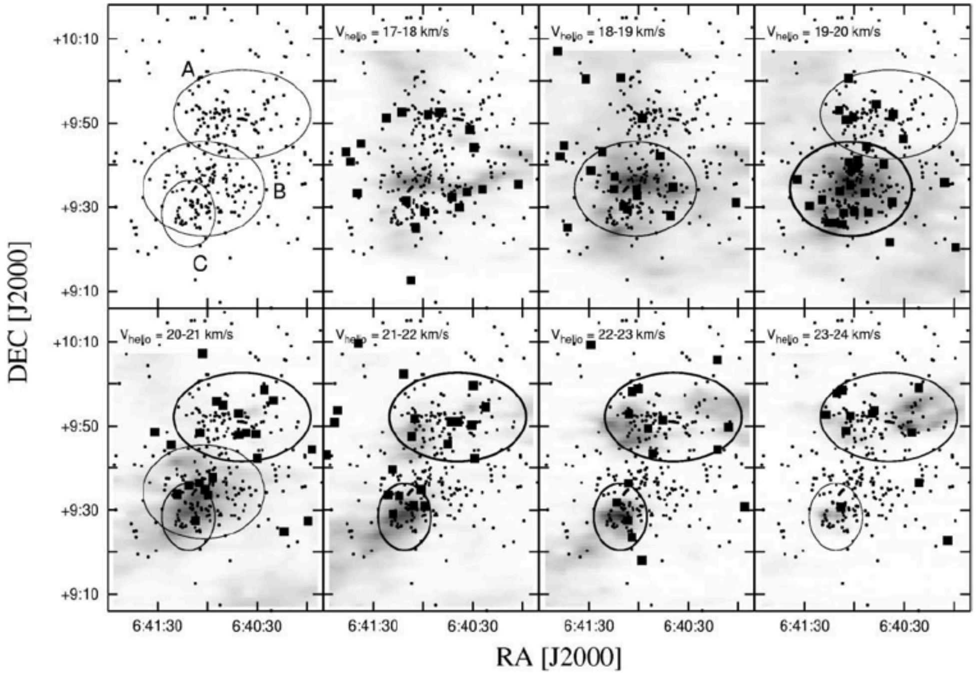
What is happening in the Kinematic Subspace?

- Internal velocity dispersion for some clusters looking for dynamical mass or virial state of the system

- Detection of kinematic substructures in just a few clusters (2 of them with GES data)

- Why? Typical 1D velocity dispersion for open clusters is lower than 1 km/s. We need RVs better than 1 km/s, and PMs with uncertainties of around 1 mas/yr, just for clusters closer than 200 pc.

Data with worse kinematic resolution hide any kind of internal pattern

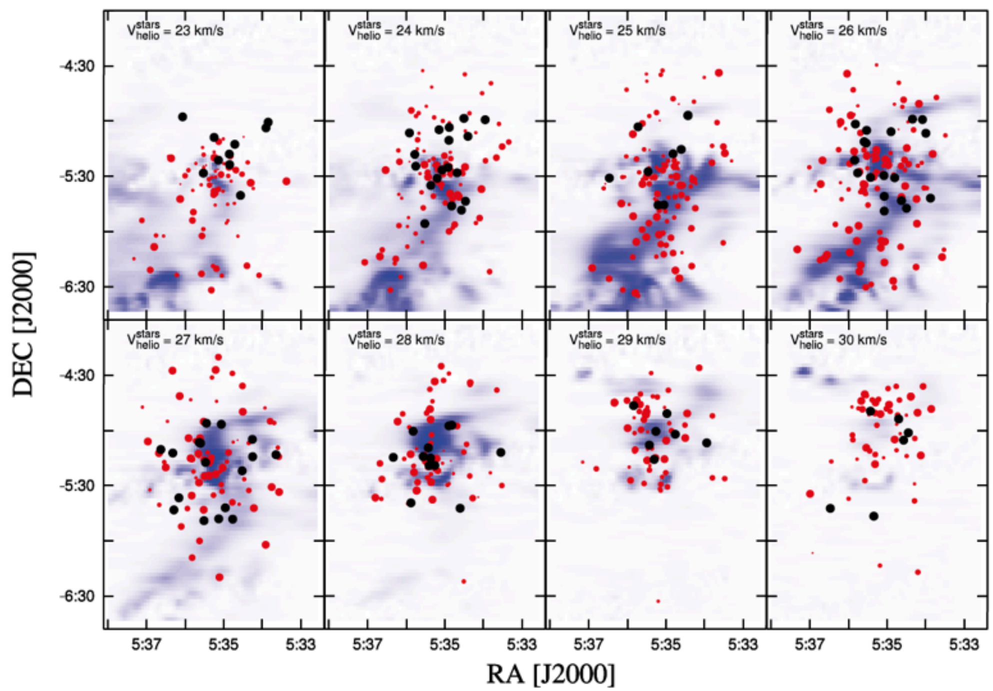


NGC 2264

Fürész et al. 2006

➔ Three RV subclusters

Young stars follow the same velocity pattern as the gas from which they were formed



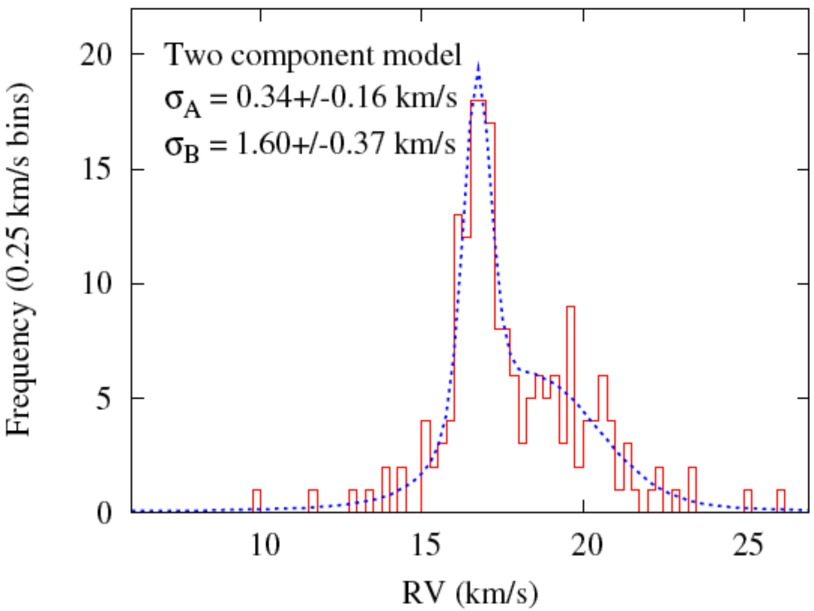
Orion Nebula Cluster

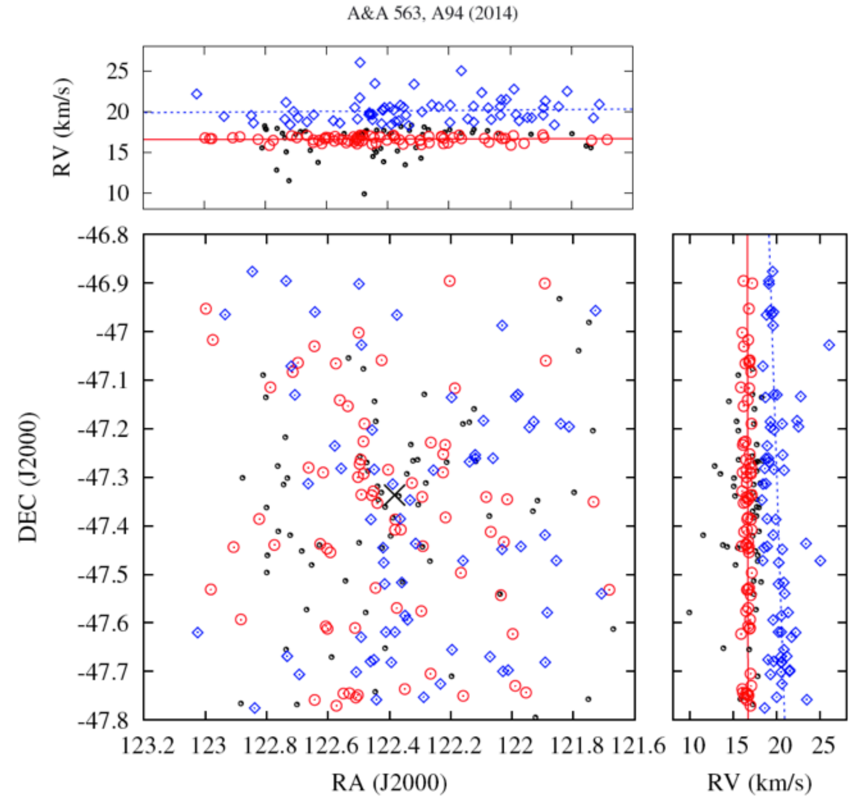
Fürész et al. 2009

GES Vela OB2

Gamma Velorum

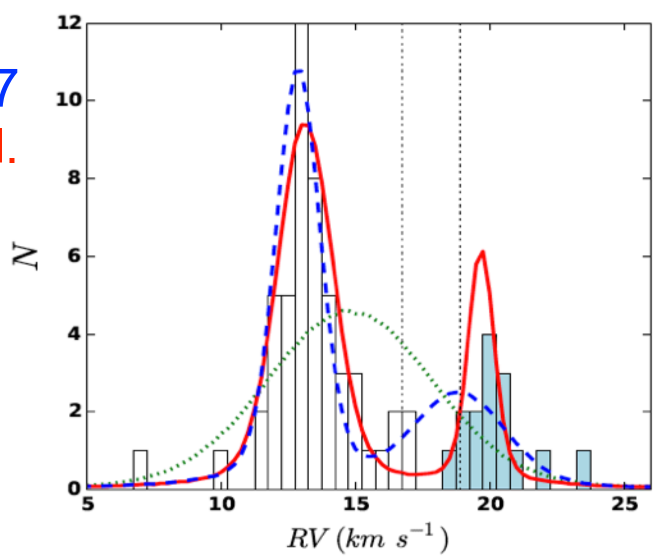
Jeffries et al. 2014





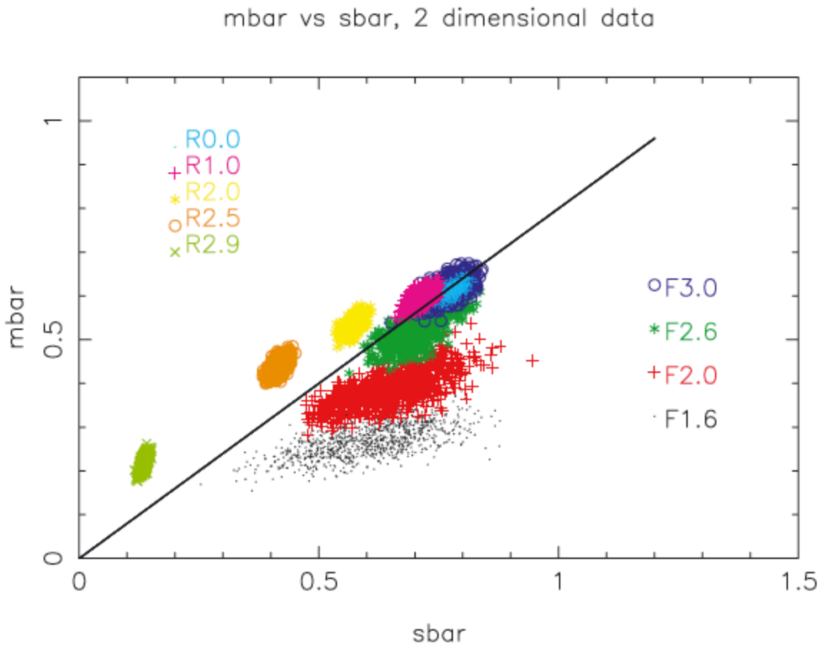
NGC 2547

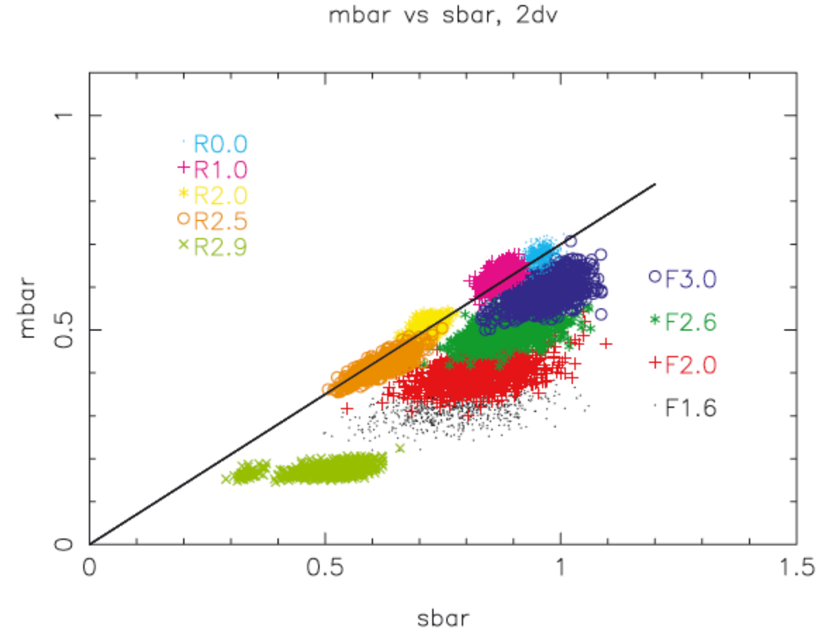
Sacco et al. 2014



Q method for 3D (2dv)

Measuring clustering in 2dv space
(Cartwright 2009)





Including velocity data as a proxy for a third dimension of position results in a degradation of the mbar versus sbar plot, rather than an improvement on the 2d version.

Radial Velocity Groupings: How to detect and measure it?

RV groups: Stars in a RV range which are more densely distributed than the cluster stars are.

Basis: We are looking for RV segregation (Alfaro 2014)

Tool: Λ parameter based on MST algorithm (Allison et al. 2009), but adopting its robust formulation (Maschberger & Clarke 2011) with some specific rules.

$$\tilde{\Lambda}(RV_j) = \frac{\overline{\tilde{l}^{50}_{i,i+R}}}{\tilde{l}_{i,i+R}}$$

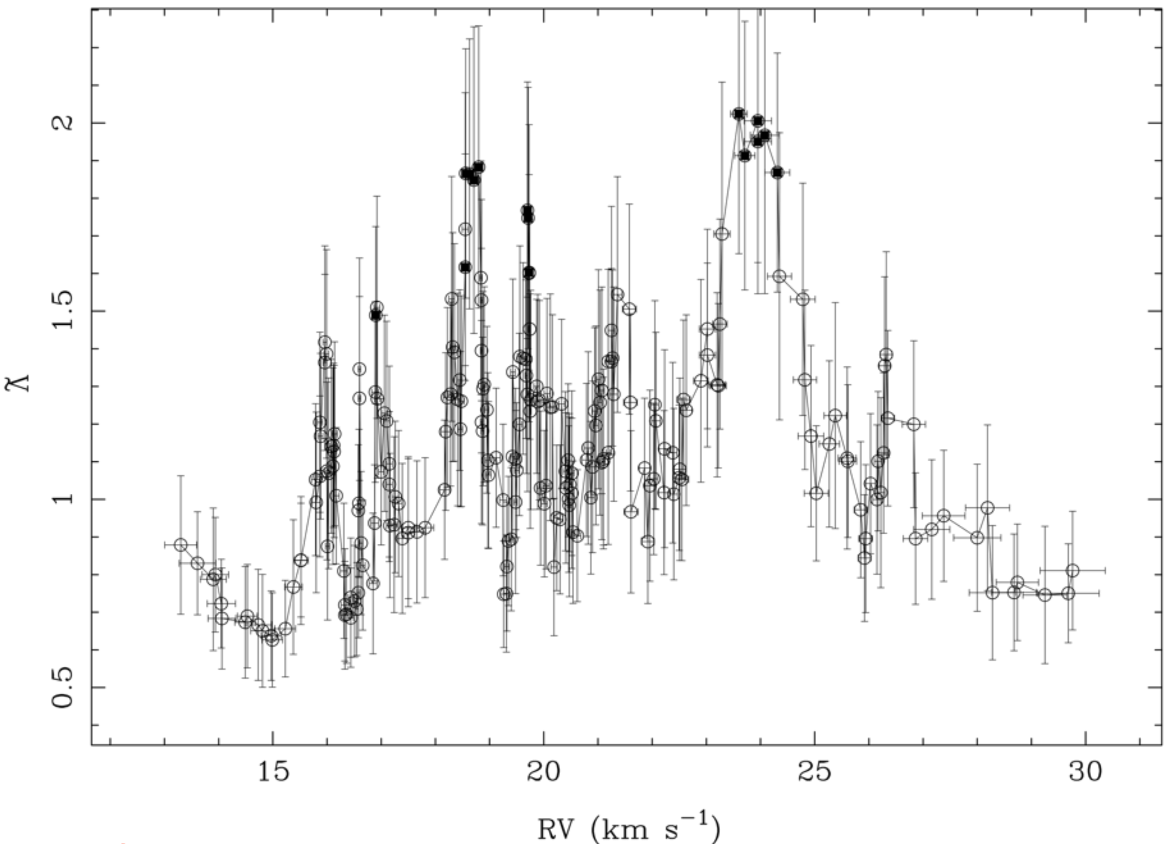
$$i = 1 + (j-1) \times S$$

$$Int(1 + ((N-R)/S))$$

$$\frac{\overline{\tilde{l}^{50}_{i,i+R}}}{\tilde{l}_{i,i+R}} - \frac{2 \times \overline{\tilde{\sigma}^{50}_{i,i+R}}}{\tilde{l}_{i,i+R}} > 1$$

R= number of stars per RV bin
S= displacement between adjacent bins

Spectrum of the Radial Velocity Segregation: NGC 2264



Alfaro 2014

RV from Fürész et al. (2006), taken from Vizier

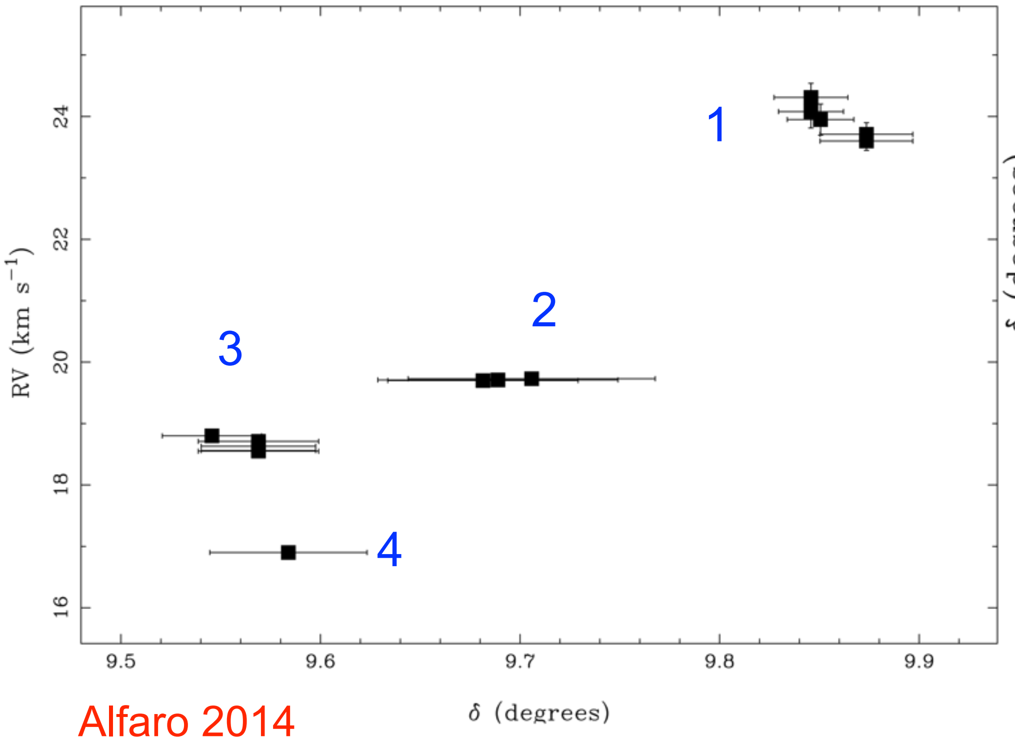
240 members with RV better than 1.5 km/s

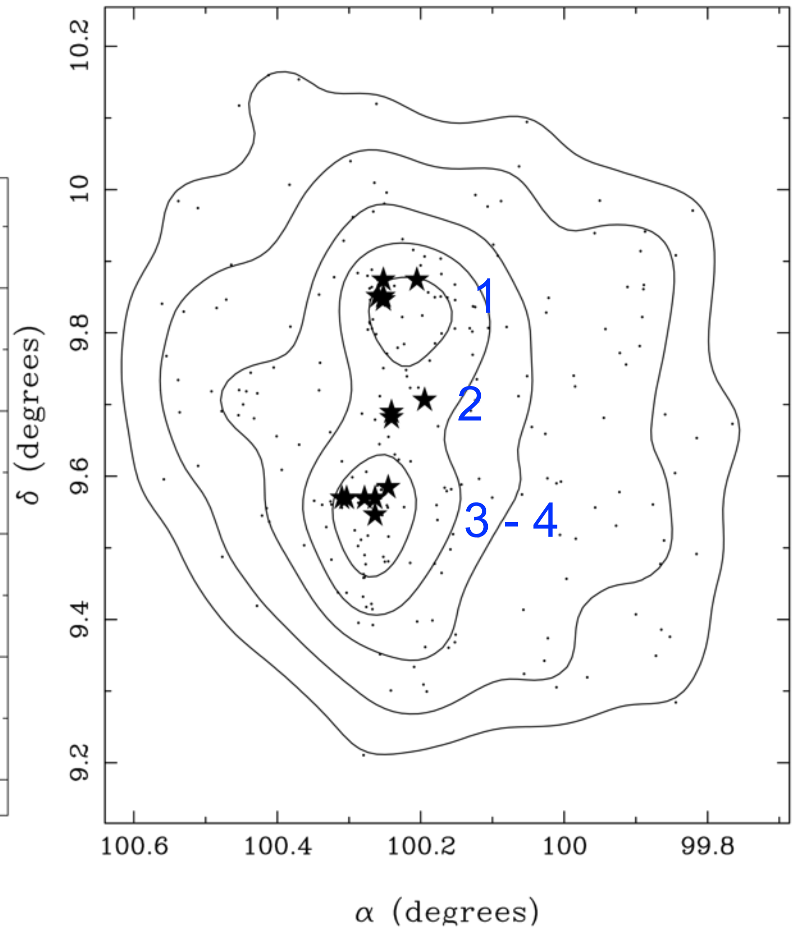
$R = 15 \sim (240)^{1/2}$
$S = 1$

Group	RV	α	δ	Λ
1	17.0	100.25	9.85	2.0
2	18.7	100.22	9.69	1.8
3	19.6	100.29	9.56	1.9
4	24.0	100.25	9.58	1.5

NGC 2264 RV Gradient

Four RV groups arranged along the declination axis





Alfaro 2014

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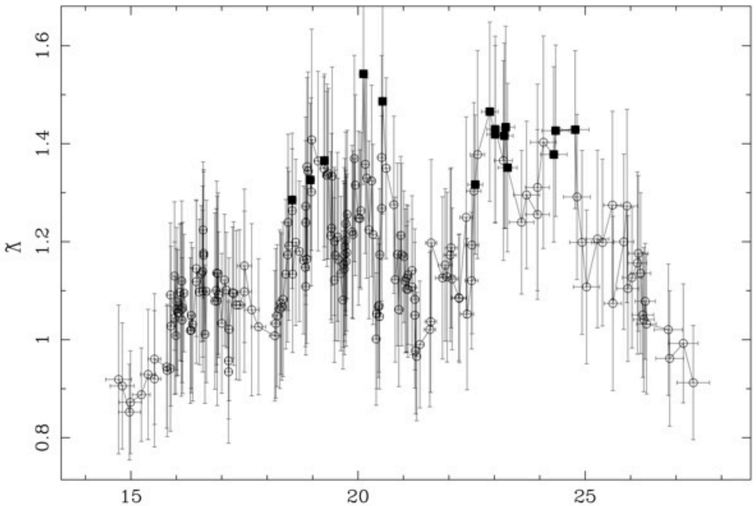
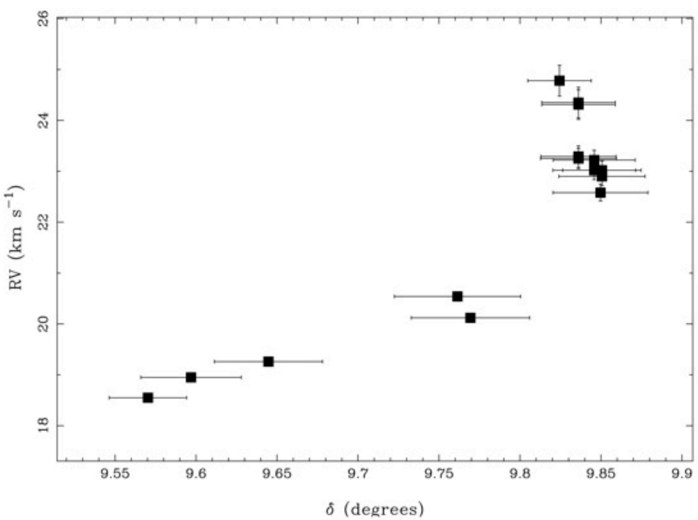
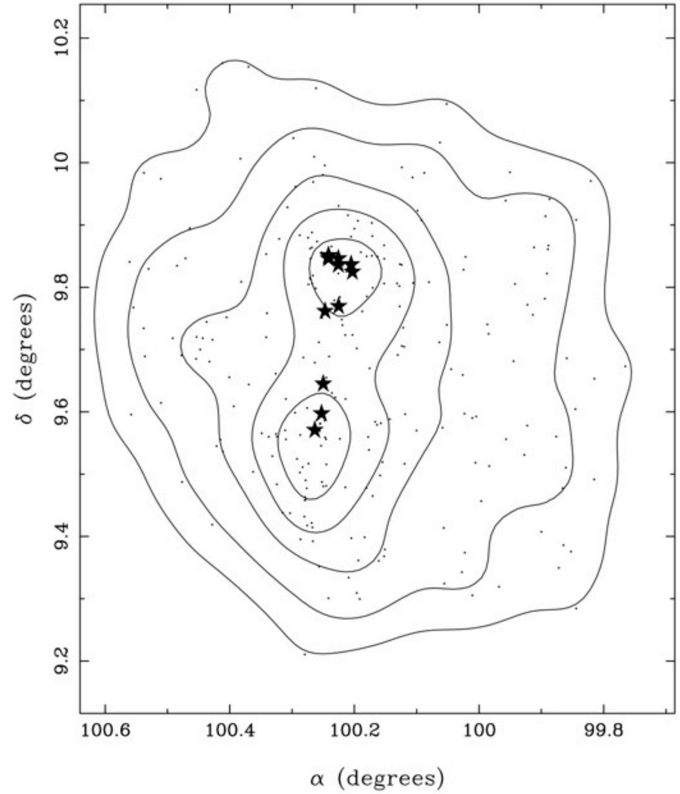
NGC 2264 (Changing *R*) *R* = 31



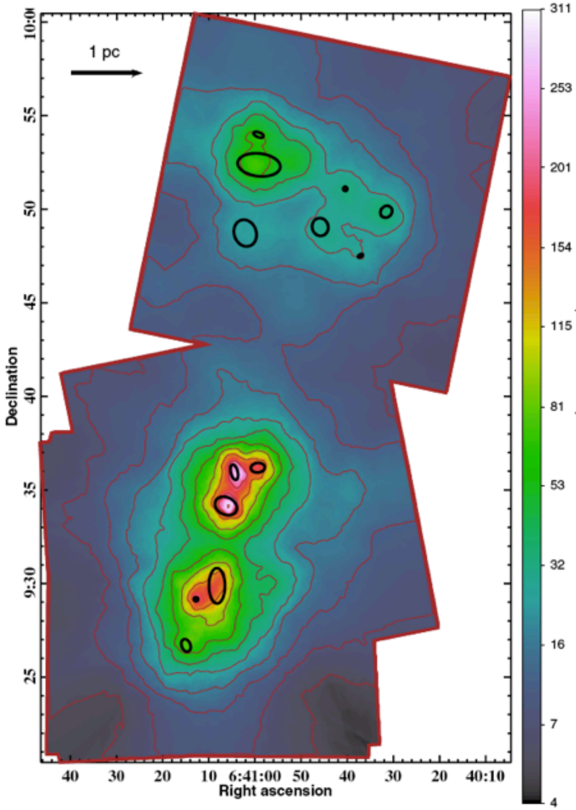




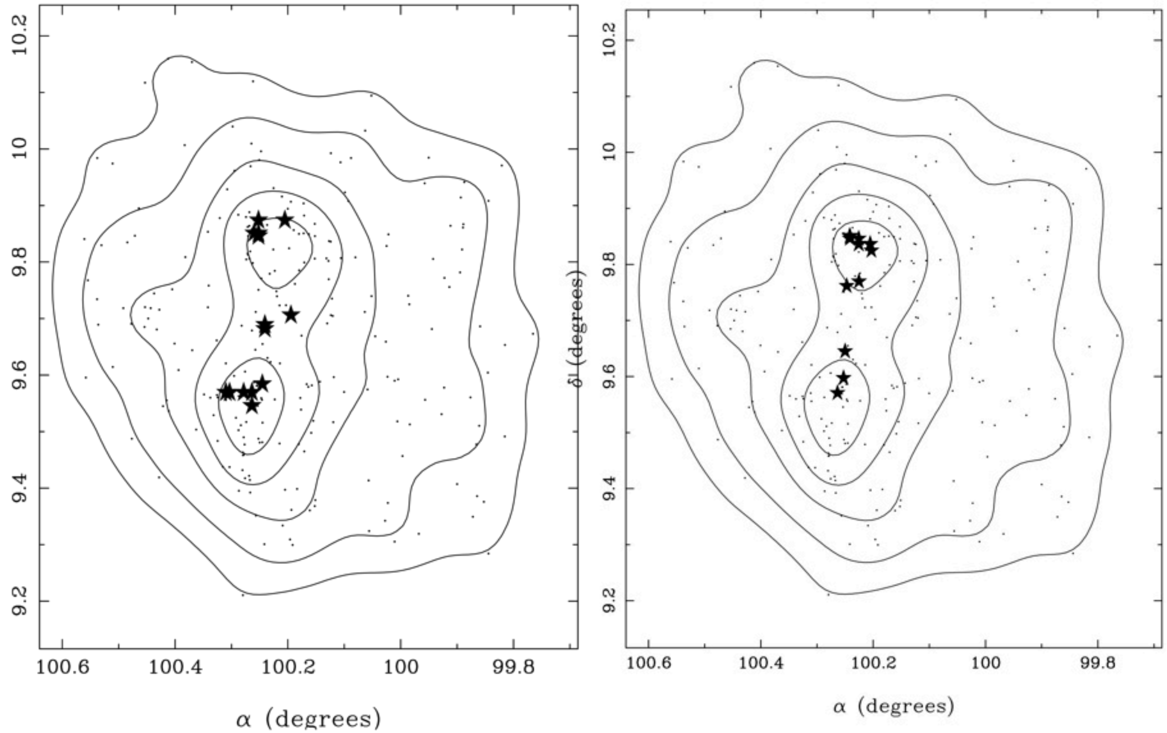
Alfaro 2014

NGC 2264 in the 2dv subspace

Spatial Groupings



2dv Subclusters



Kuhn et al. 2014

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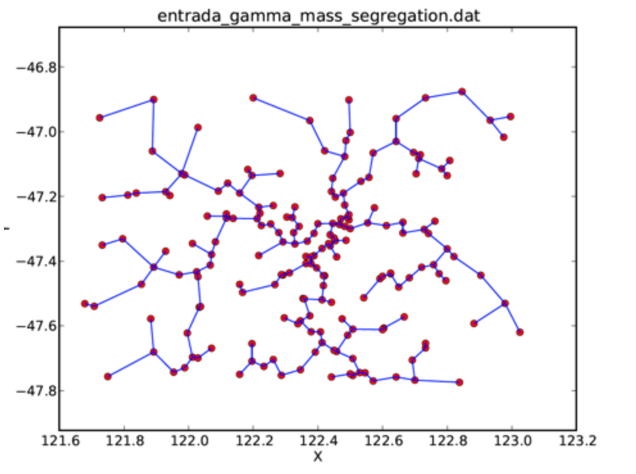
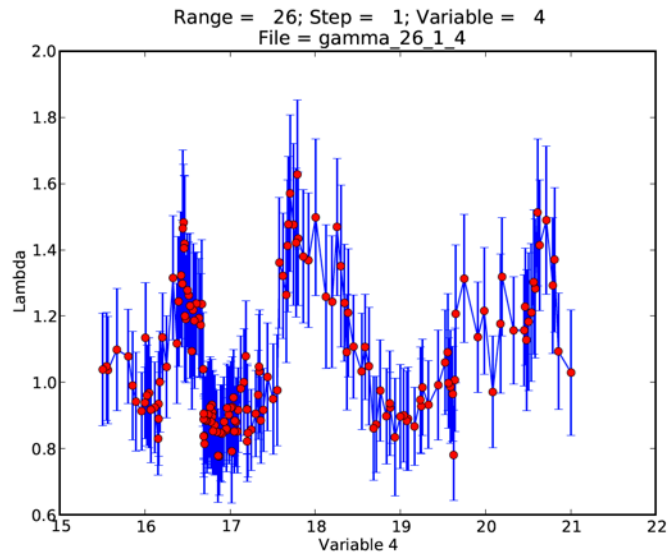
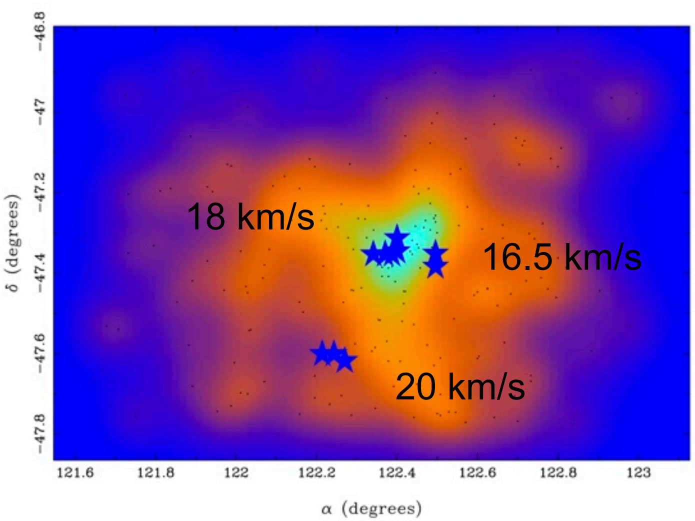
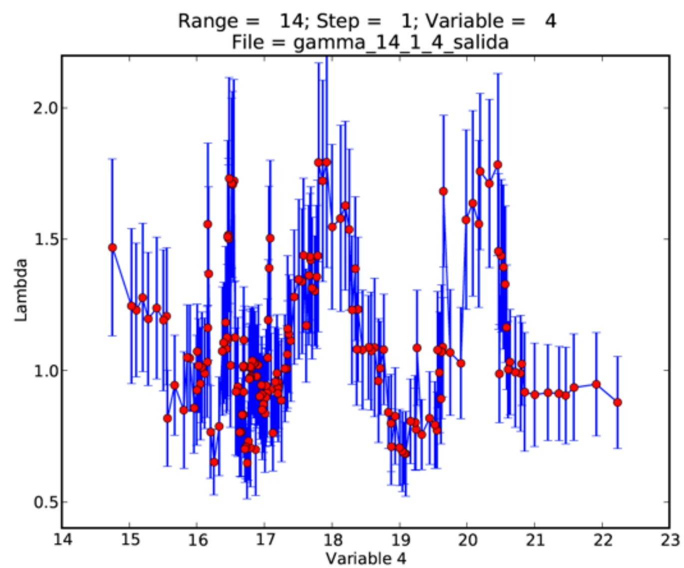
Radial Velocity Segregation in GES clusters

We applied this methodology to a few GES clusters: Gamma Velorum, NGC 2547, and NGC 6705 (Alfaro + GES 2015)



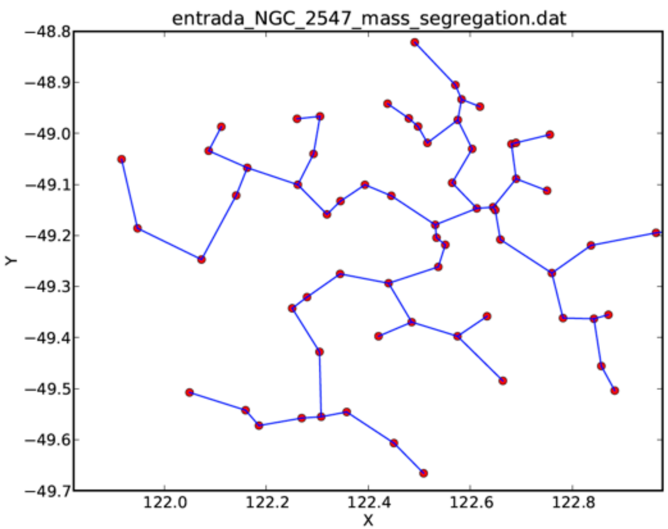


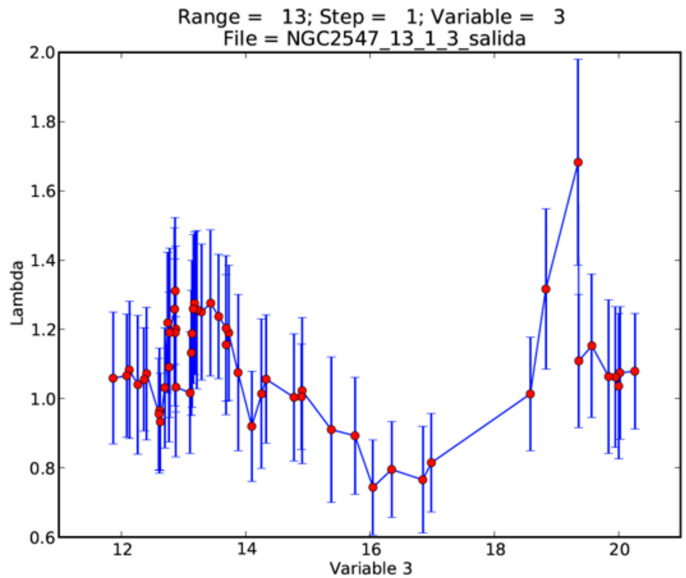


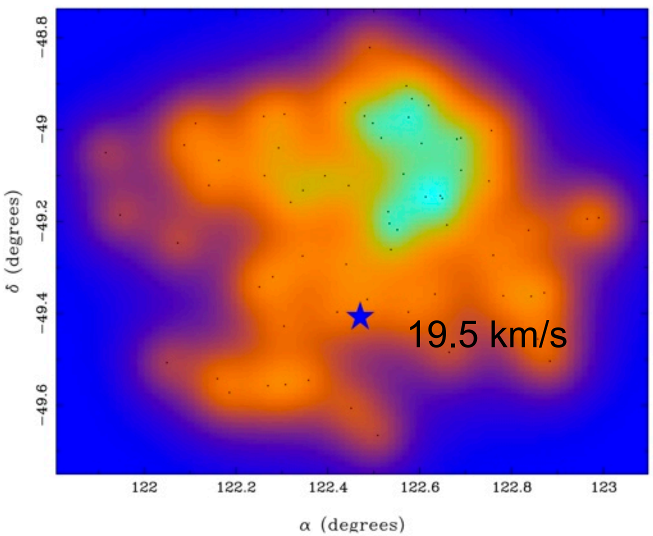


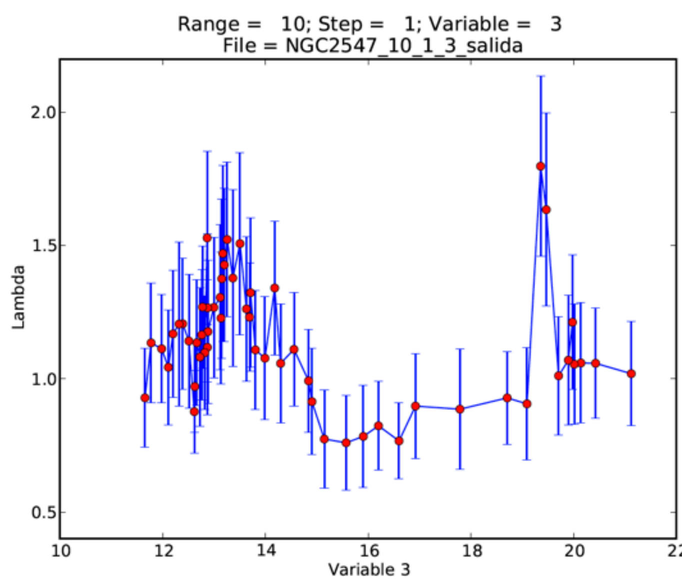
Radial Velocity Segregation in GES clusters

NGC 2547



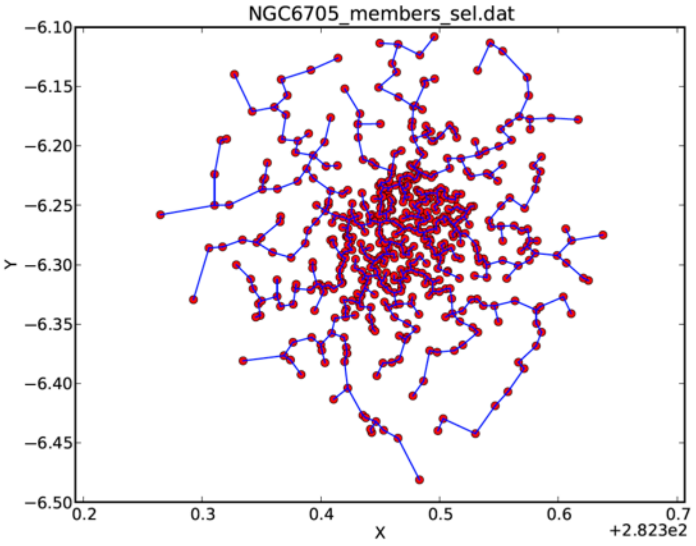


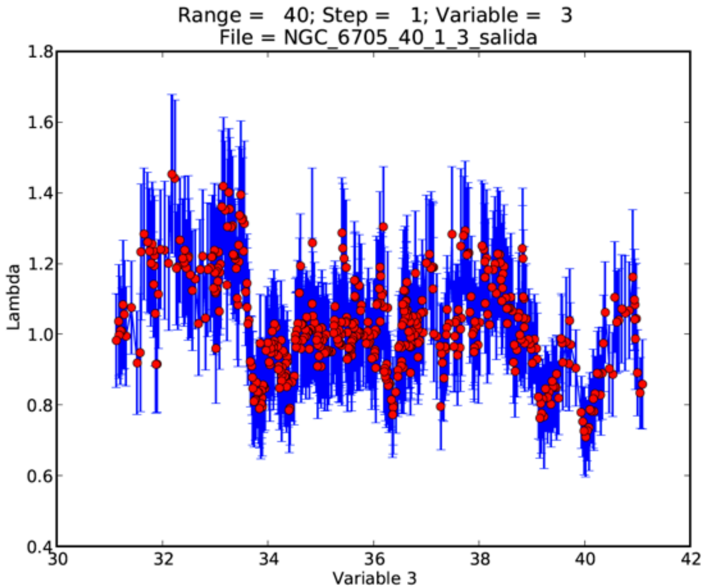


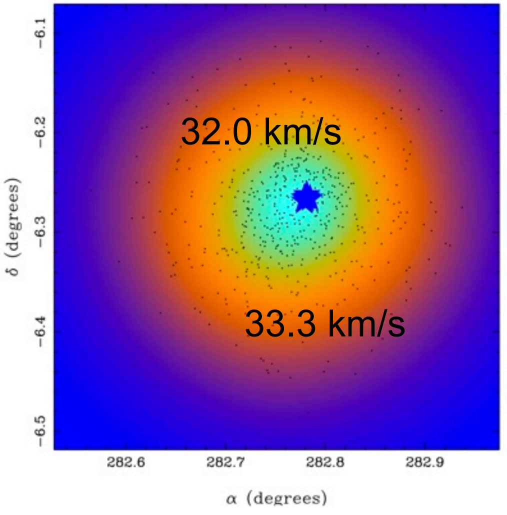


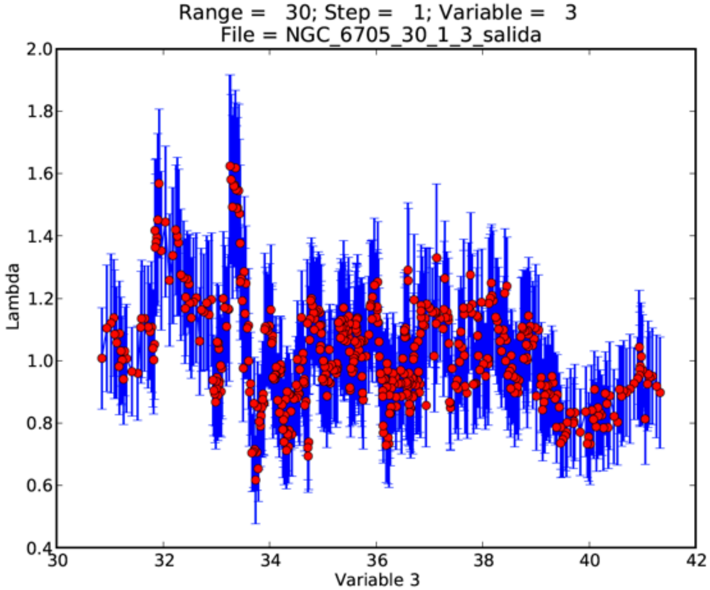
Radial Velocity Segregation in GES clusters

NGC 6705







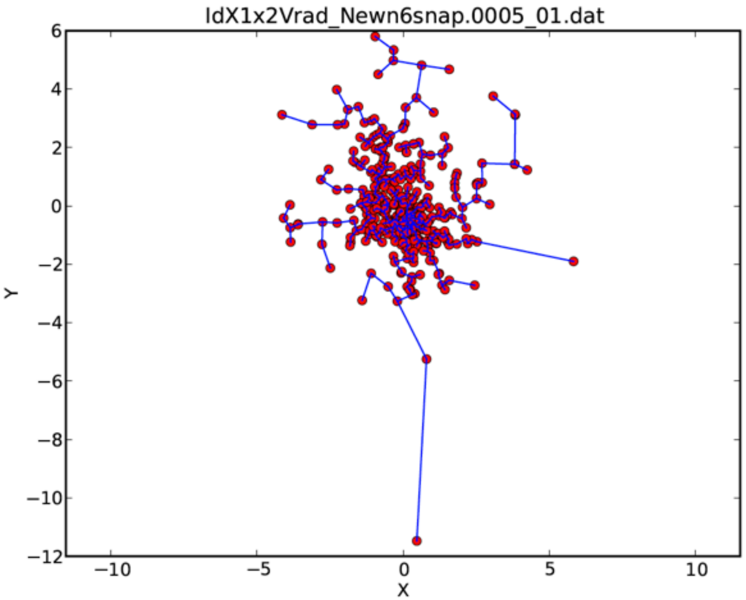


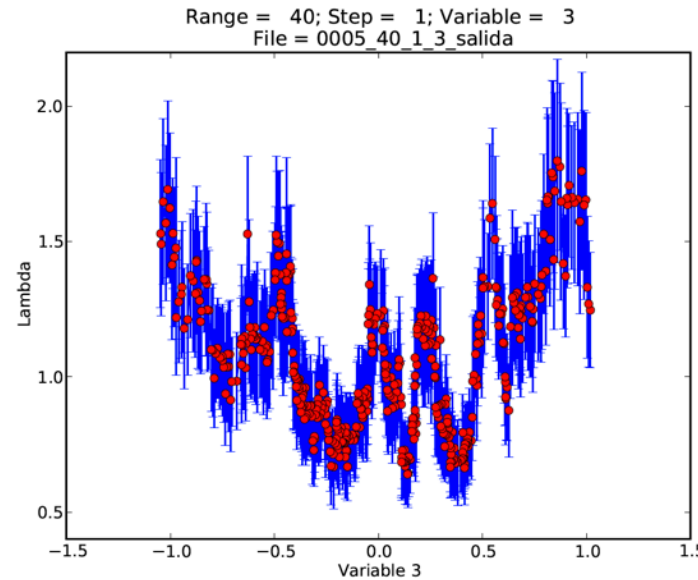
Simulations

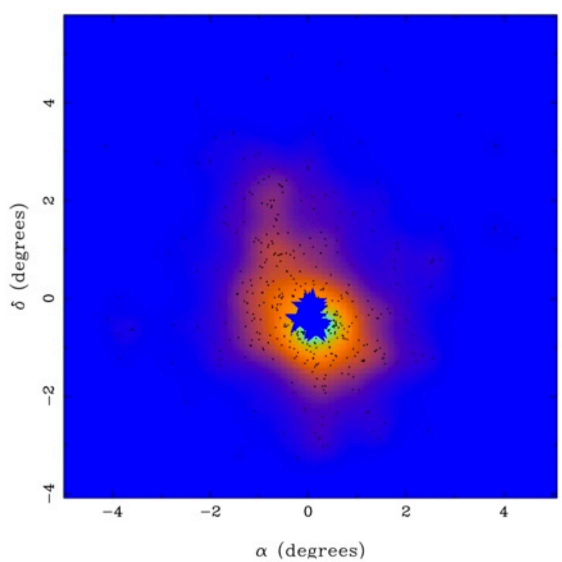
Initial Conditions (Mcluster):

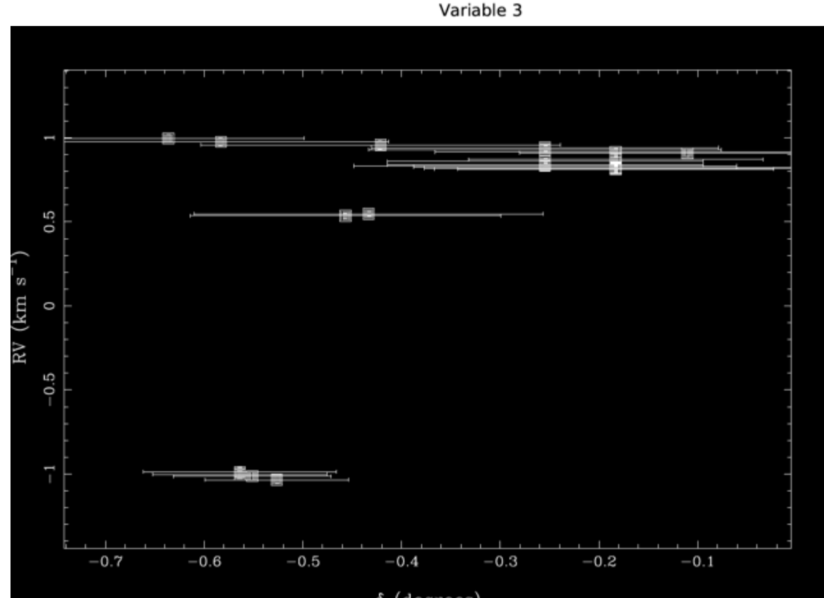
- 500 stars
- Half-mass radius: 2 pc.
- Kroupa's IMF with stars between 0.4 and 120 $M_{\odot}$
- Fractal spatial distribution con D_f = 1.6
- Mass segregation of 0.2
- Virial equilibrium

Radial Velocity Segregation: Simulations

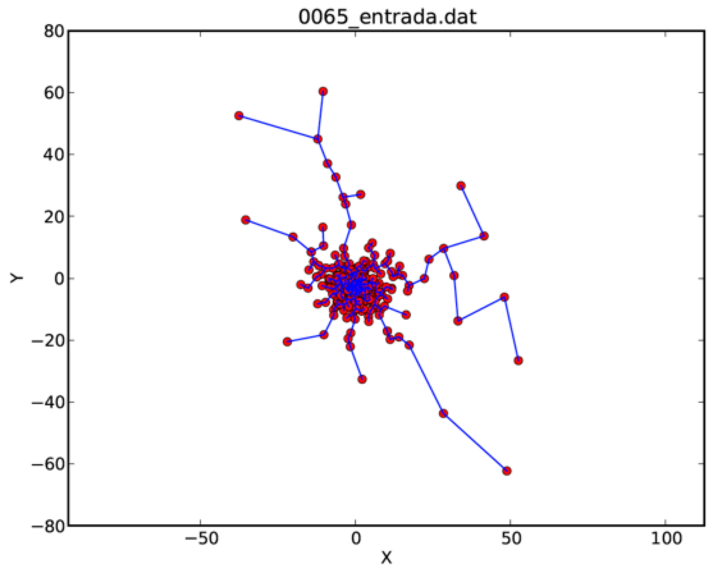


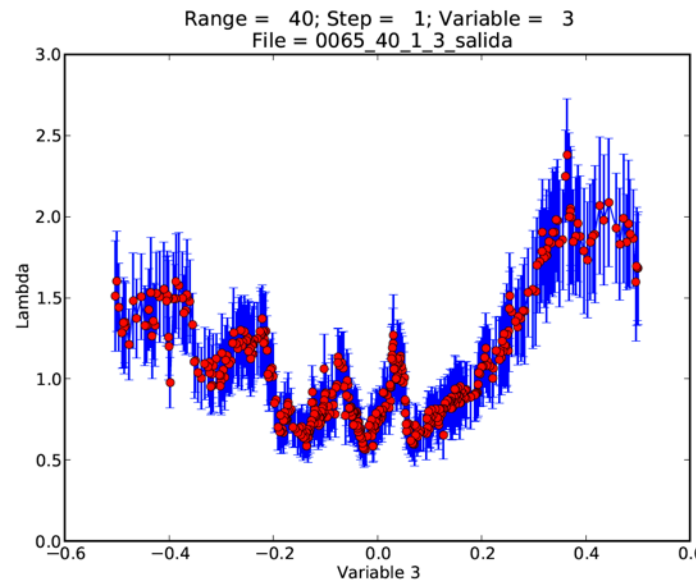


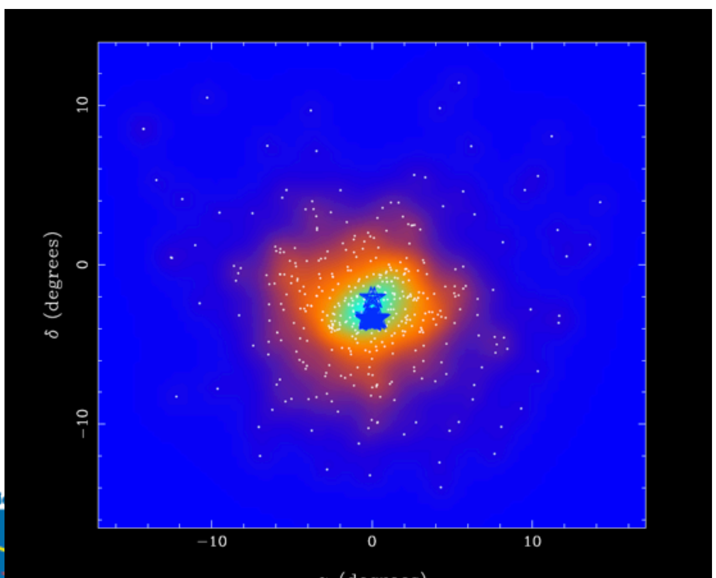


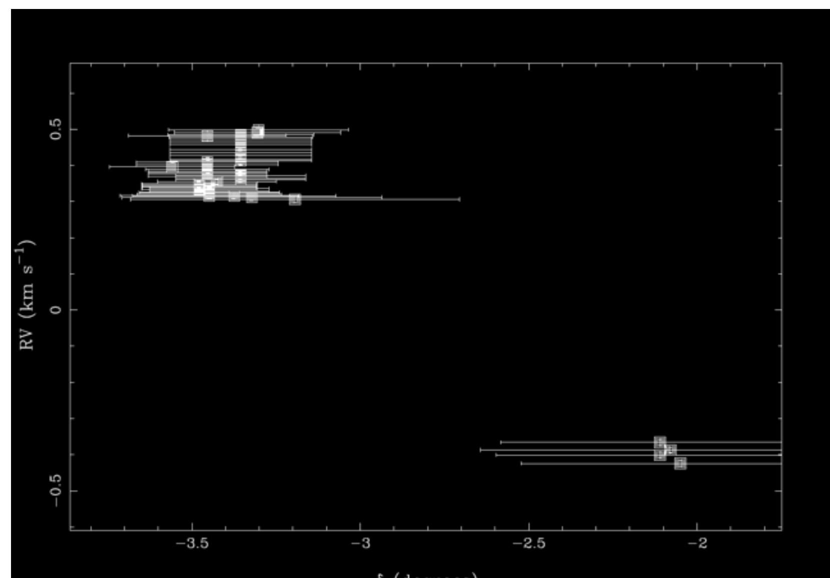


60 TU later 1TU ~ 1 Myr









Conclusions and Future Work

• The search for a predictive theory of stellar cluster formation requires the setting of fundamental observational constraints, such as: IMF, Mass Segregation, and Phase-Space Structures

• While several pattern descriptors have been proposed for analyzing the spatial subspace of the Phase-Space, there is a lack of statistical tools for the pattern analysis of the velocity subspace. Here we propose a new tool, which we call radial velocity segregation, that enables the searching for kinematic patterns in stellar systems.

• The method, based on the MST graph, can be easily implemented in any pipeline developed for mining large databases and leads to a quantitative description of the kinematic pattern allowing a comparative analysis among different clusters, environments and datasets in a homogeneous way.

• GES cluster data constitute, for the time being, the best collection of velocity data for the study of the formation and early evolution of star clusters, a true legacy. WEAVE (for a Northern 4 m telescope) and an extended GES project are the genuine successors of this scientific program.