Structure and substructure of galaxy clusters

Why studying galaxy clusters?

Constrain cosmological models

e.g. through N(M,z), M/L, dM/dt

Constrain dark matter properties

e.g. through M(r), M(r)/L(r)

Constrain galaxy evolution

e.g. through f(R,vel)

Why studying galaxy clusters?

Constrain cosmological models

e.g. through N(M,z), M/L, dM/dt

Constrain dark matter properties

e.g. through M(r), M(r)/L(r)

Constrain galaxy evolution

e.g. through f(R,vel)

Why studying galaxy clusters?

Constrain cosmological models

e.g. through N(M,z), M/L, dM/dt

Constrain dark matter properties

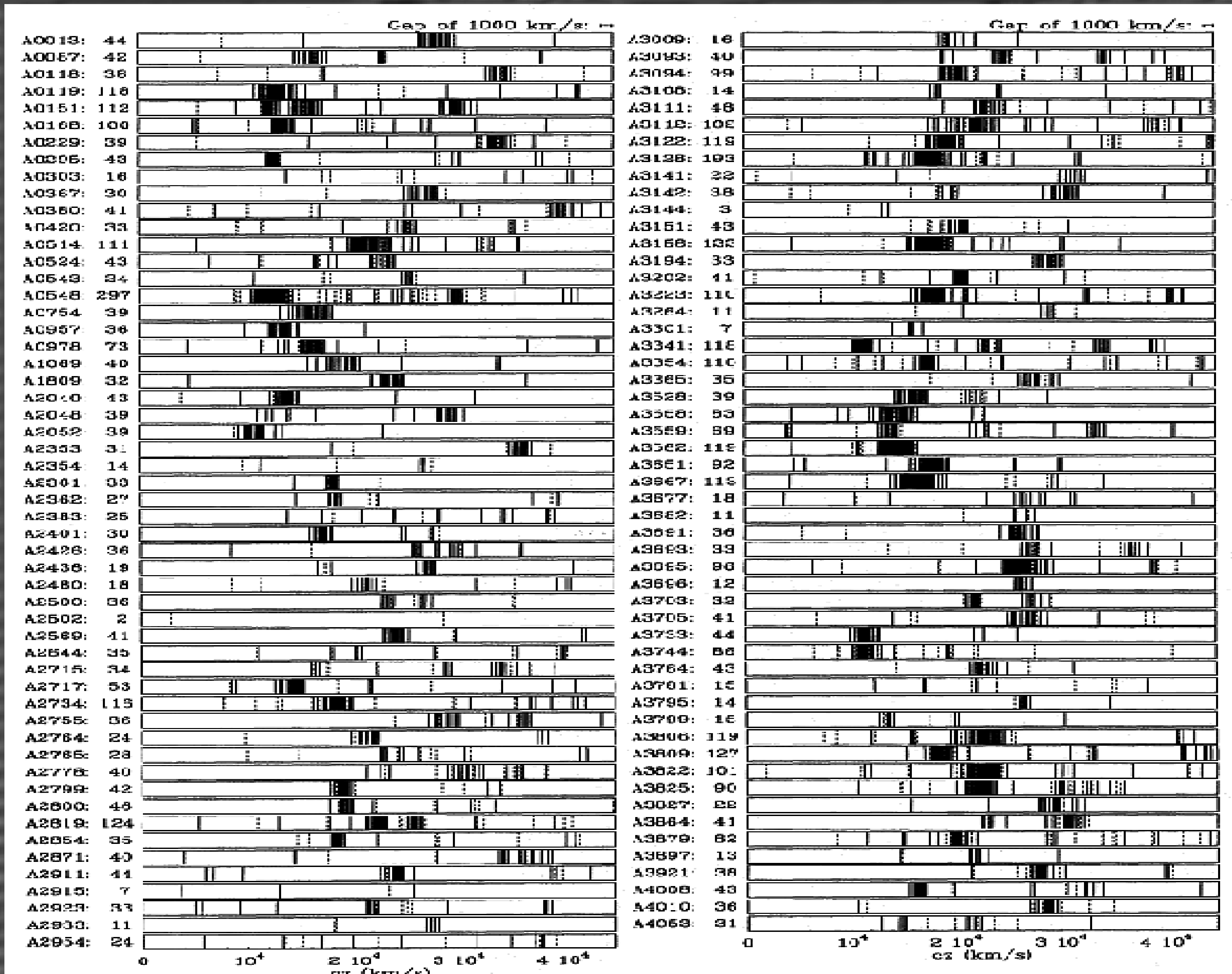
e.g. through M(r), M(r)/L(r)

Constrain galaxy evolution

e.g. through f(R,vel)

The ESO Nearby Abell Cluster Survey: a young 20-years old survey

1st observing run in 1989



(1996, ENACS I; den Hartog's thesis)

The ESO Nearby Abell Cluster Survey: a young 20-years old survey

~3000 galaxies with redshifts
in the virial regions of 59 massive clusters

CIRS *(Rines & Diaferio 2006)*:
drawn from SDSS DR4, is only 10% larger

WINGS *(Cava et al. 2009)*:
a new cluster-dedicated survey, is only 20% larger

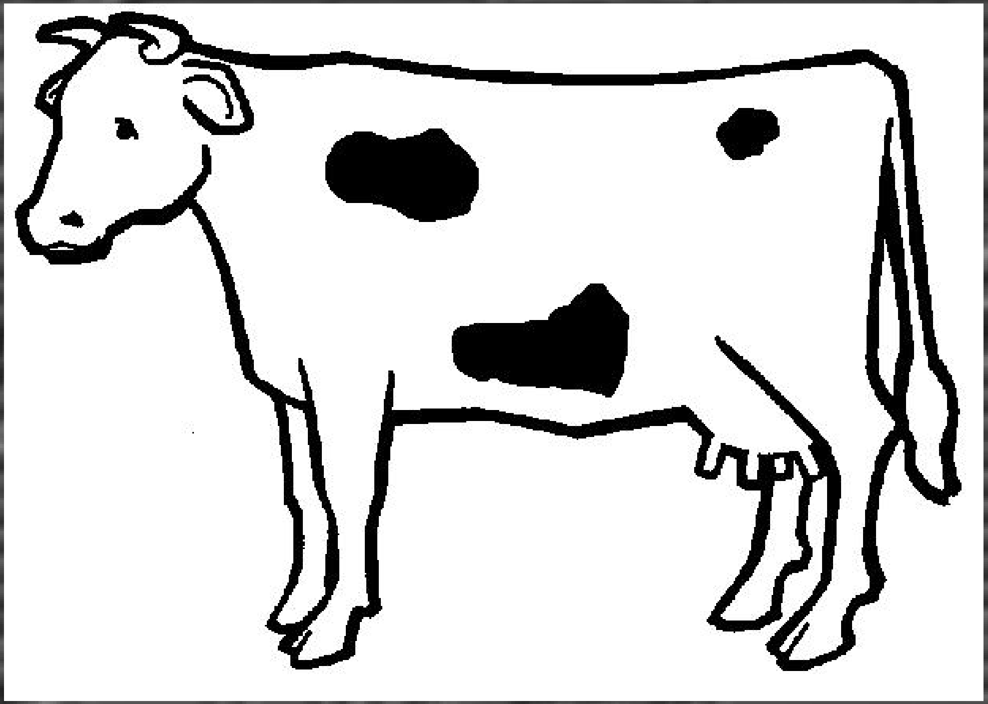
The ESO Nearby Abell Cluster Survey: a young 20-years old survey

~3000 galaxies with redshifts
in the virial regions of 59 massive clusters

CIRS *(Rines & Diaferio 2006)*:
drawn from SDSS DR4, is only 10% larger

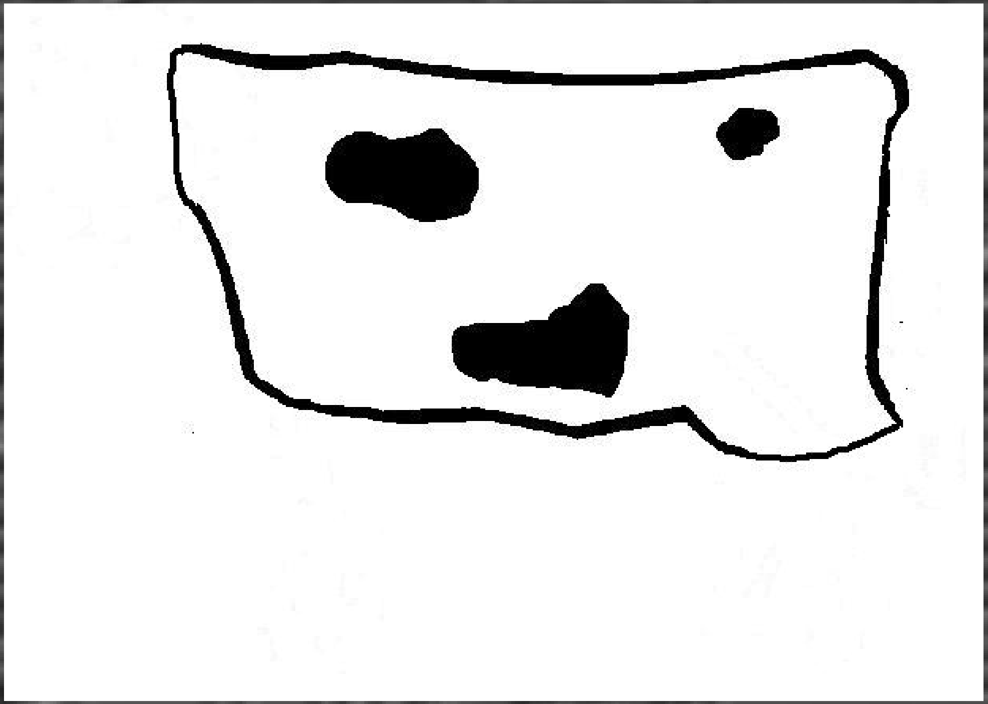
WINGS *(Cava et al. 2009)*:
a new cluster-dedicated survey, is only 20% larger

How do we analyse the structure of galaxy clusters



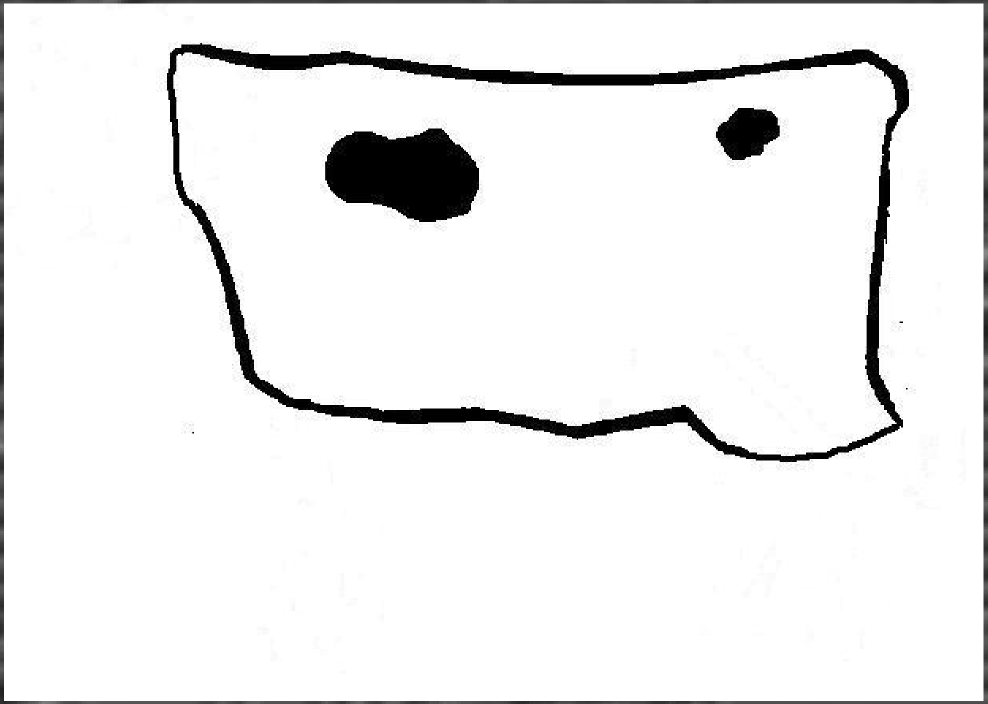
Take a cluster...

How do we analyse the structure of galaxy clusters



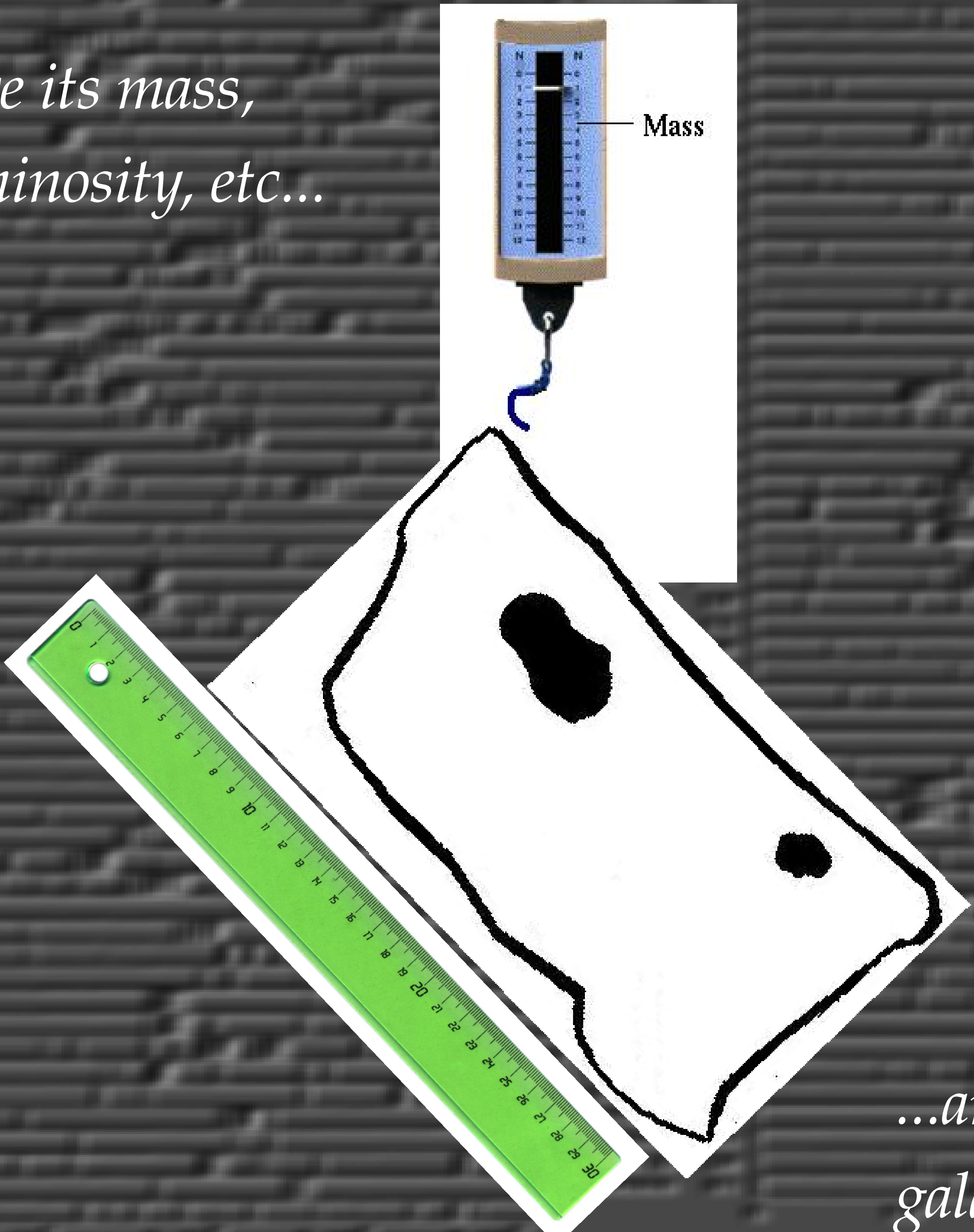
...select its virial region...

How do we analyse the structure of galaxy clusters



...remove 'evident' substructures (by looking at the velocity distributions of galaxies in local density peaks)

...measure its mass, size, luminosity, etc...

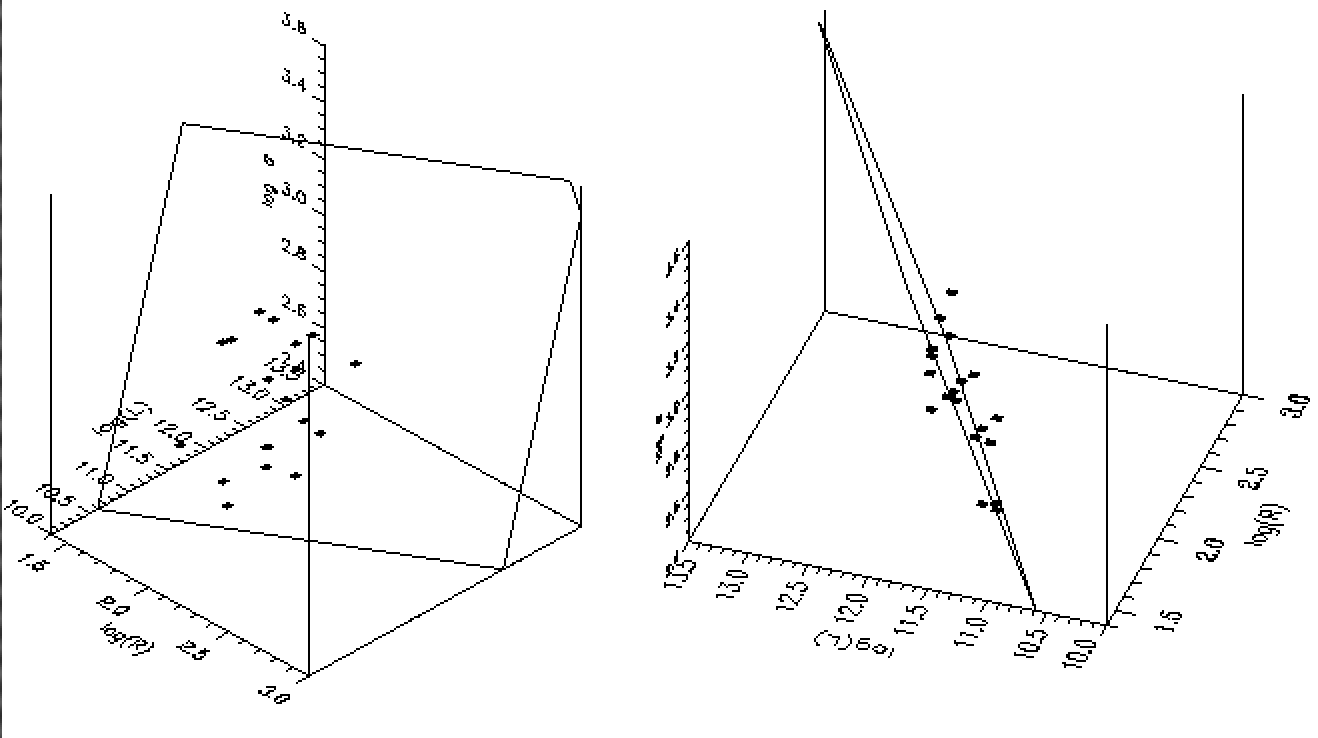


...and do it for many galaxy clusters

Structure: global properties

Average cluster M/L ⇒ $\Omega_m \sim 0.3 < 1$

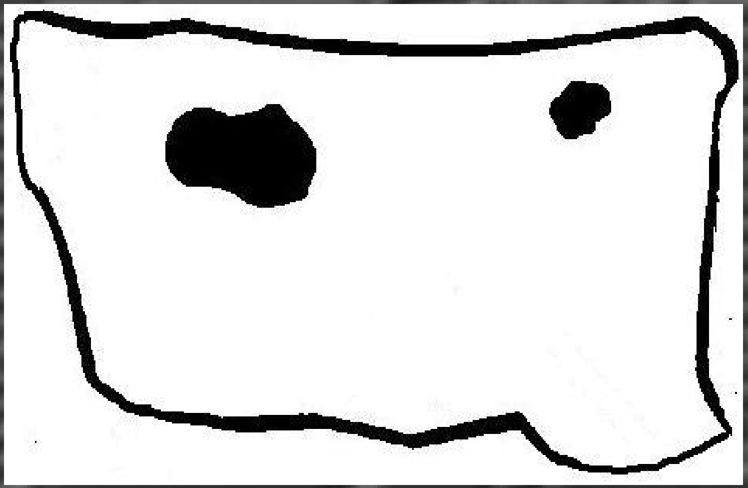
(1998, ENACS VII)

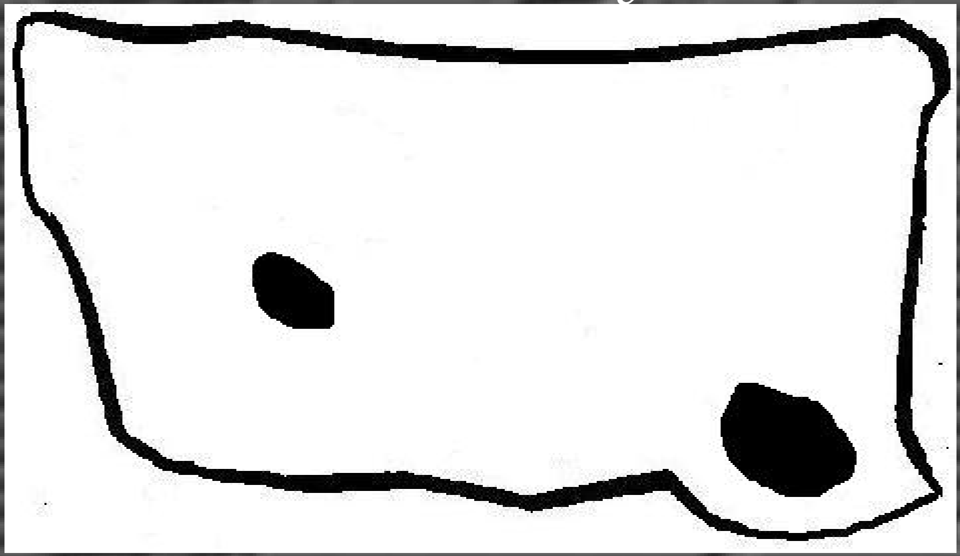


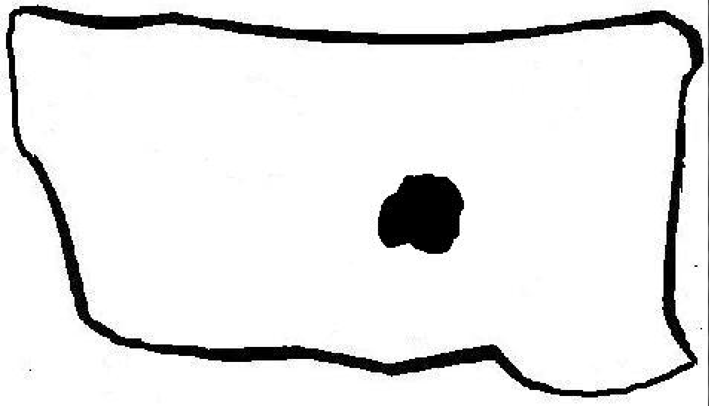
The fundamental plane relating size, luminosity, velocity dispersion ⇒ M/L ↑ with M

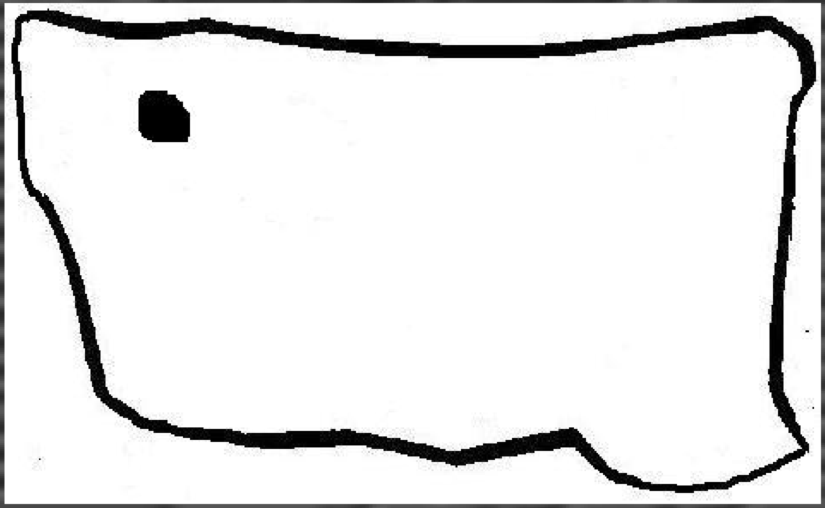
(1998, ENACS IV)

Beyond global cluster characteristics:
to determine the internal structure we need a better statistics:
must stack several clusters (in a suitable way)

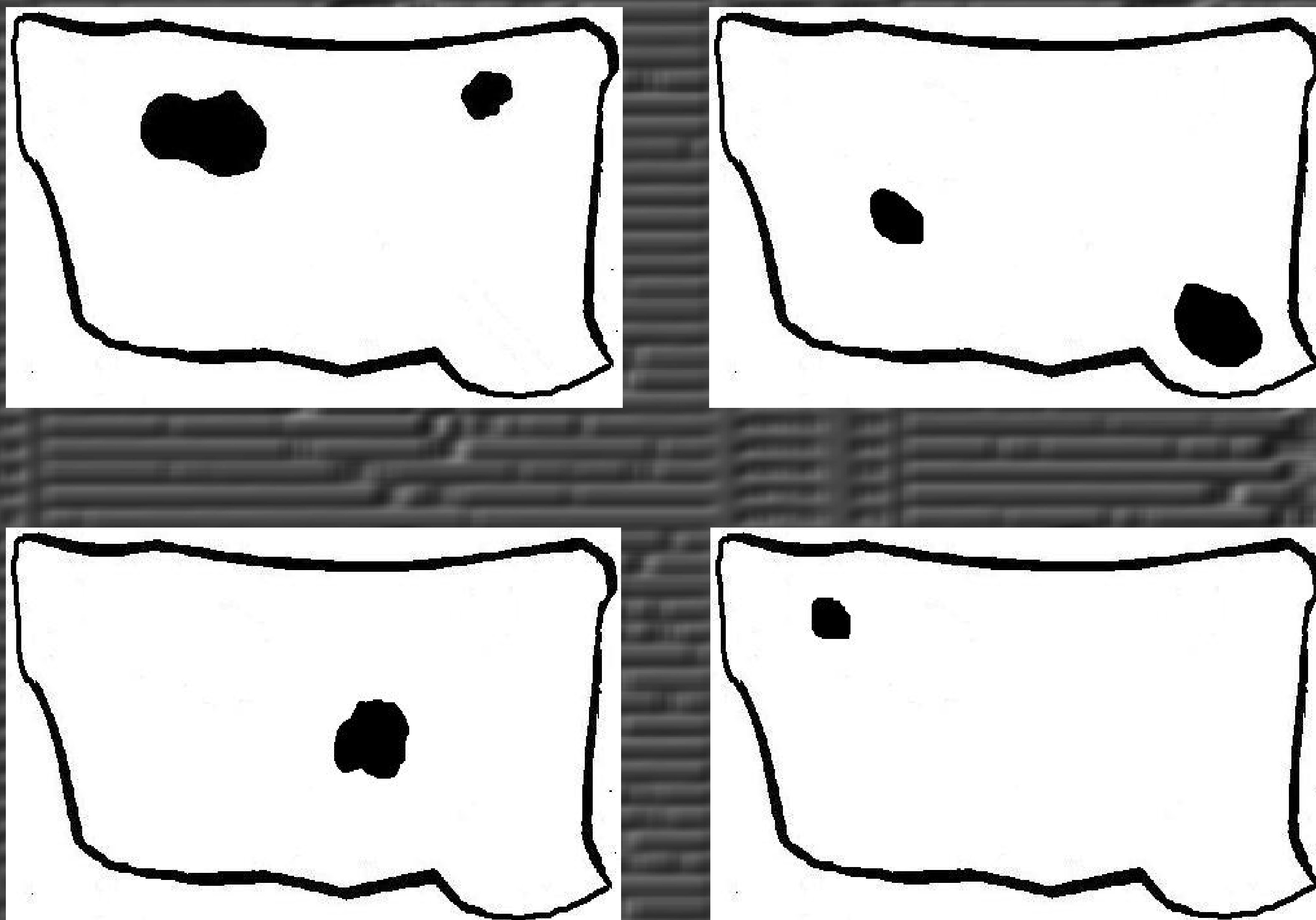




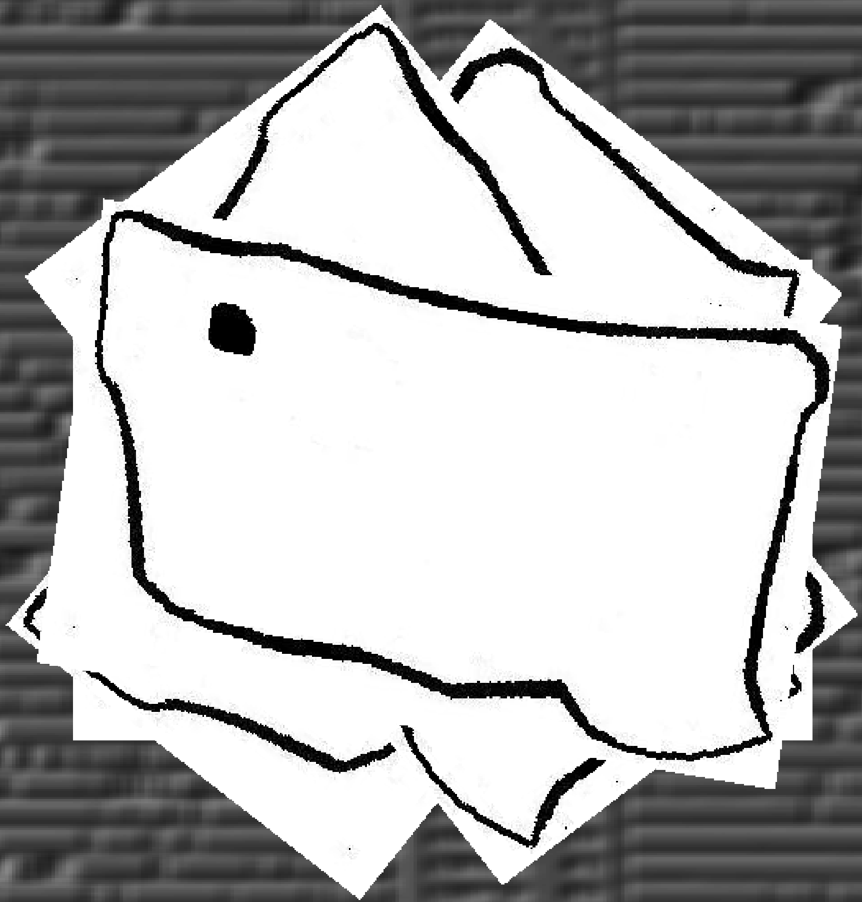




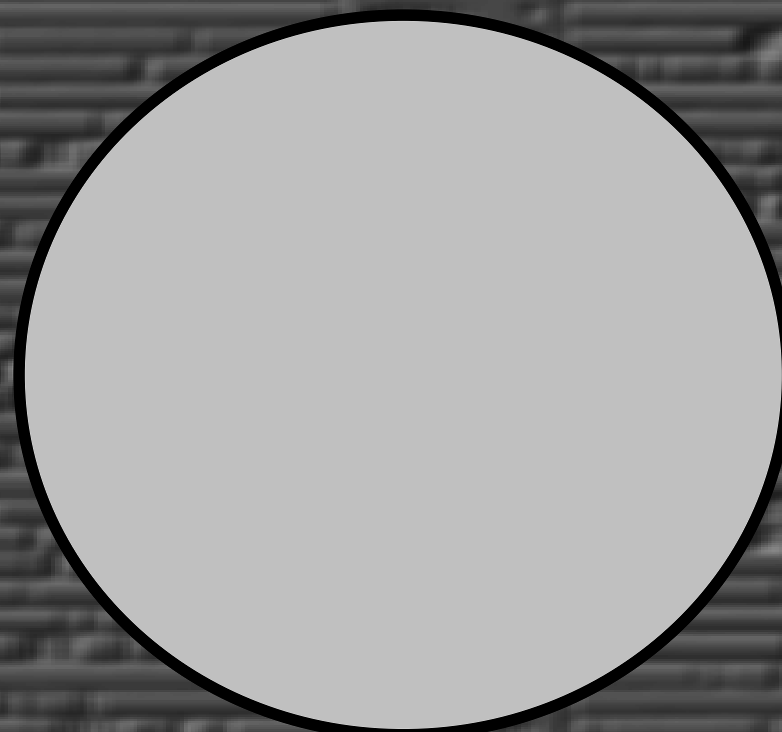
1) Scale by mass...



2) … and stack irrespective of their original orientation



… so to obtain the spherical *cluster*
of which we determine the internal structure!



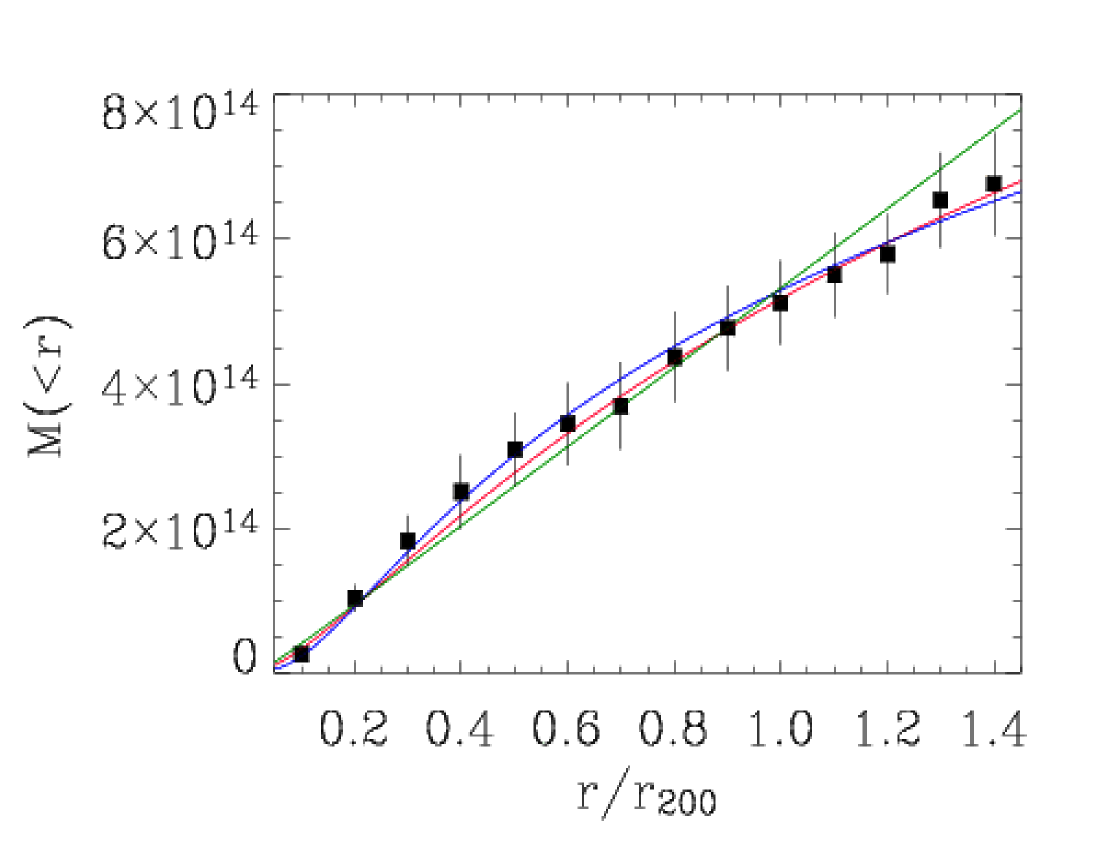
Internal structure

Average cluster M(r):

CDM numerical simulations' favorite (NFW) is OK

Isothermal sphere model not so good

(2004, ENACS XII)



Red=NFW cuspy model

Blue=core model

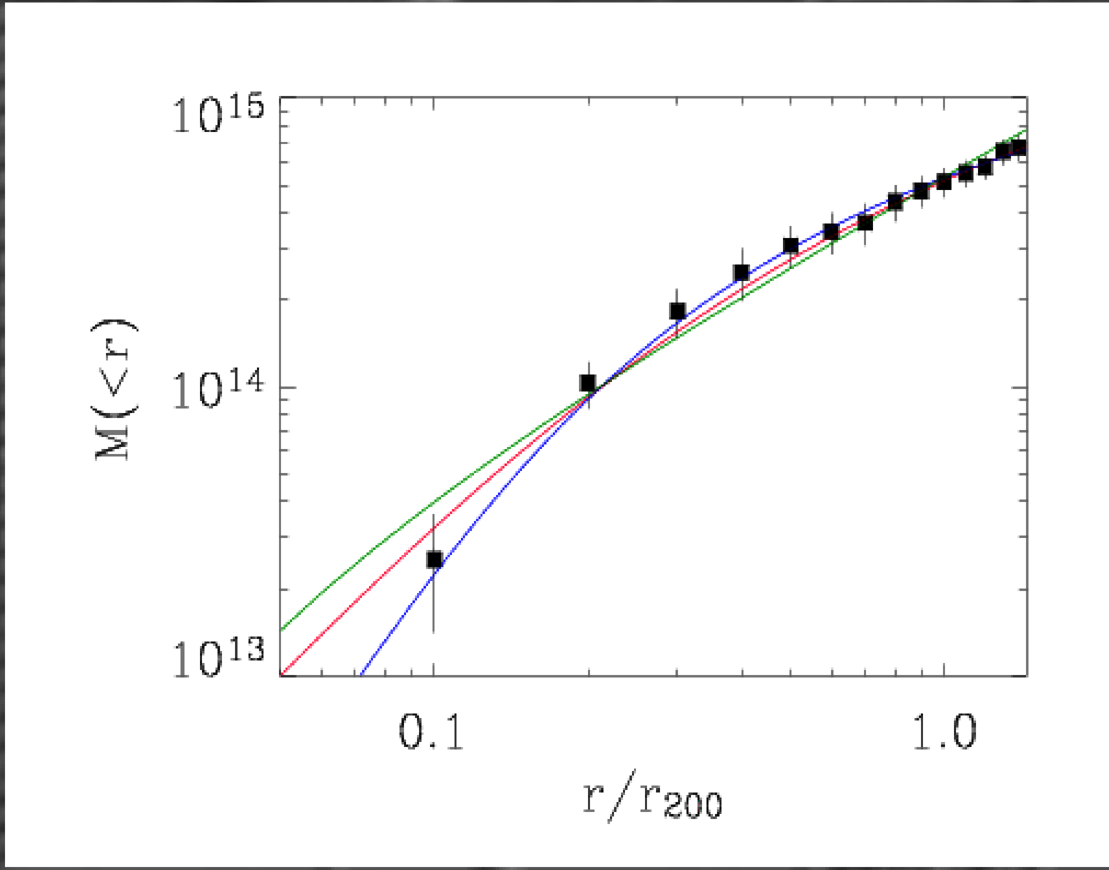
Green=Isothermal Sphere

Internal structure

Average cluster M(r) ⇒ Core radius small <0.1 Mpc

(constrains dark matter particle cross section)

(2004, ENACS XII)



Red=NFW cuspy model

Blue=core model

Green=Isothermal Sphere

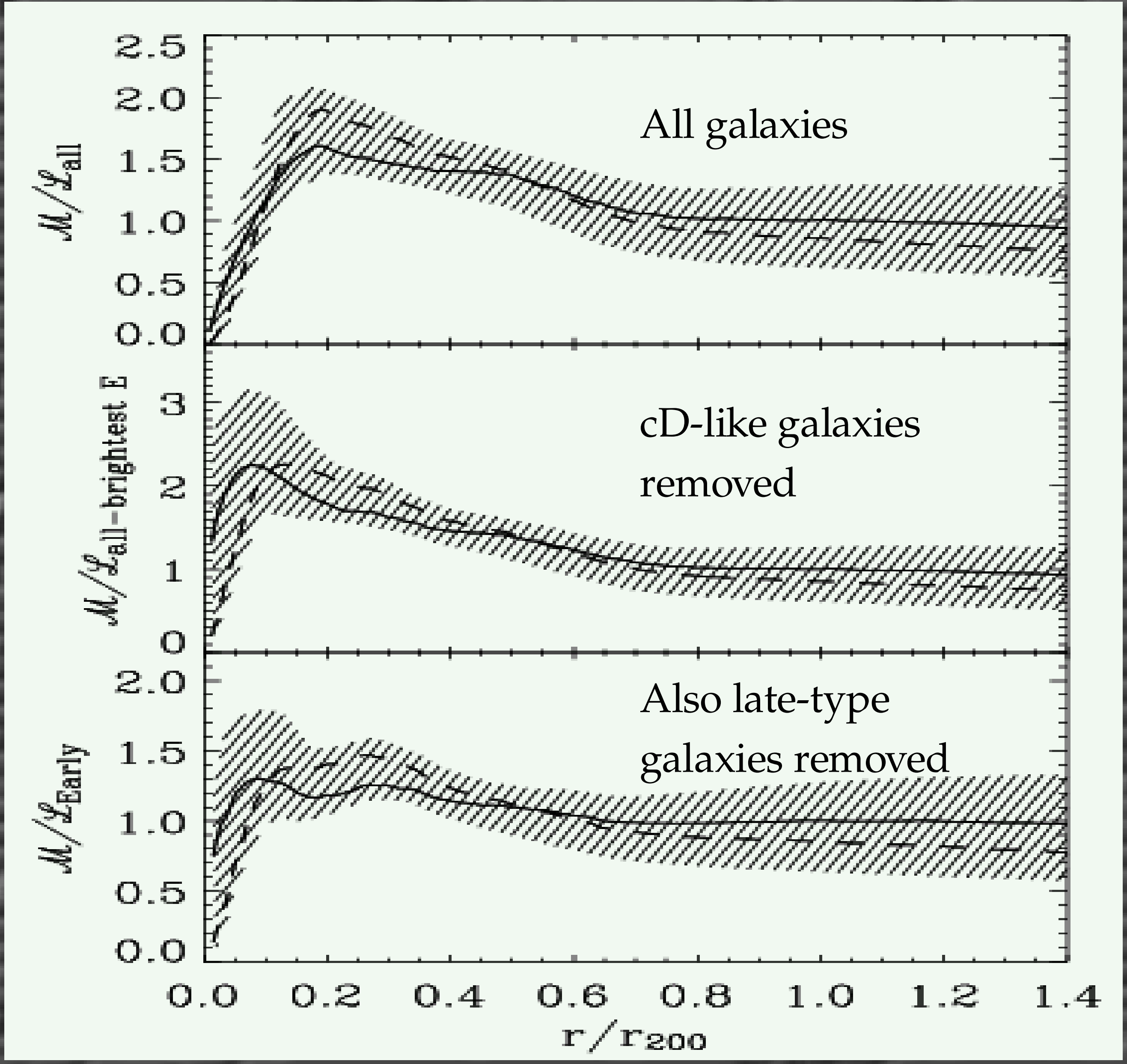
Internal structure

M/L profile:

Does Mass follow Light?

Yes,
the light of E/S0

(2004, ENACS XII)



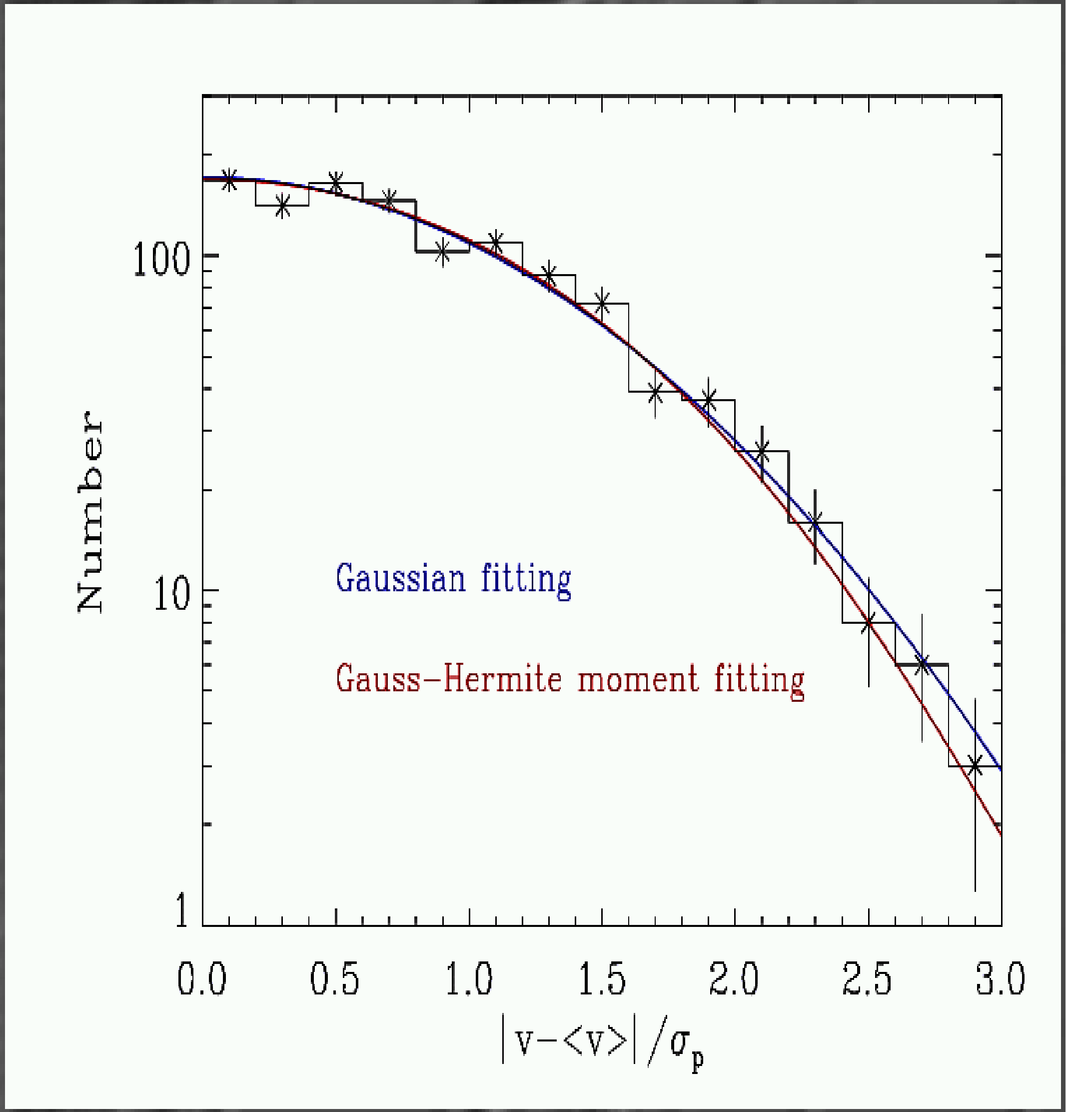
Internal structure

Orbits of galaxies in clusters:

E and S0 move along isotropic orbits,

$$\left(\langle v_r^2\rangle / \langle v_t^2\rangle\right)^{1/2} \simeq 1.0^{+0.05}_{-0.2}$$

(2004, ENACS XII)

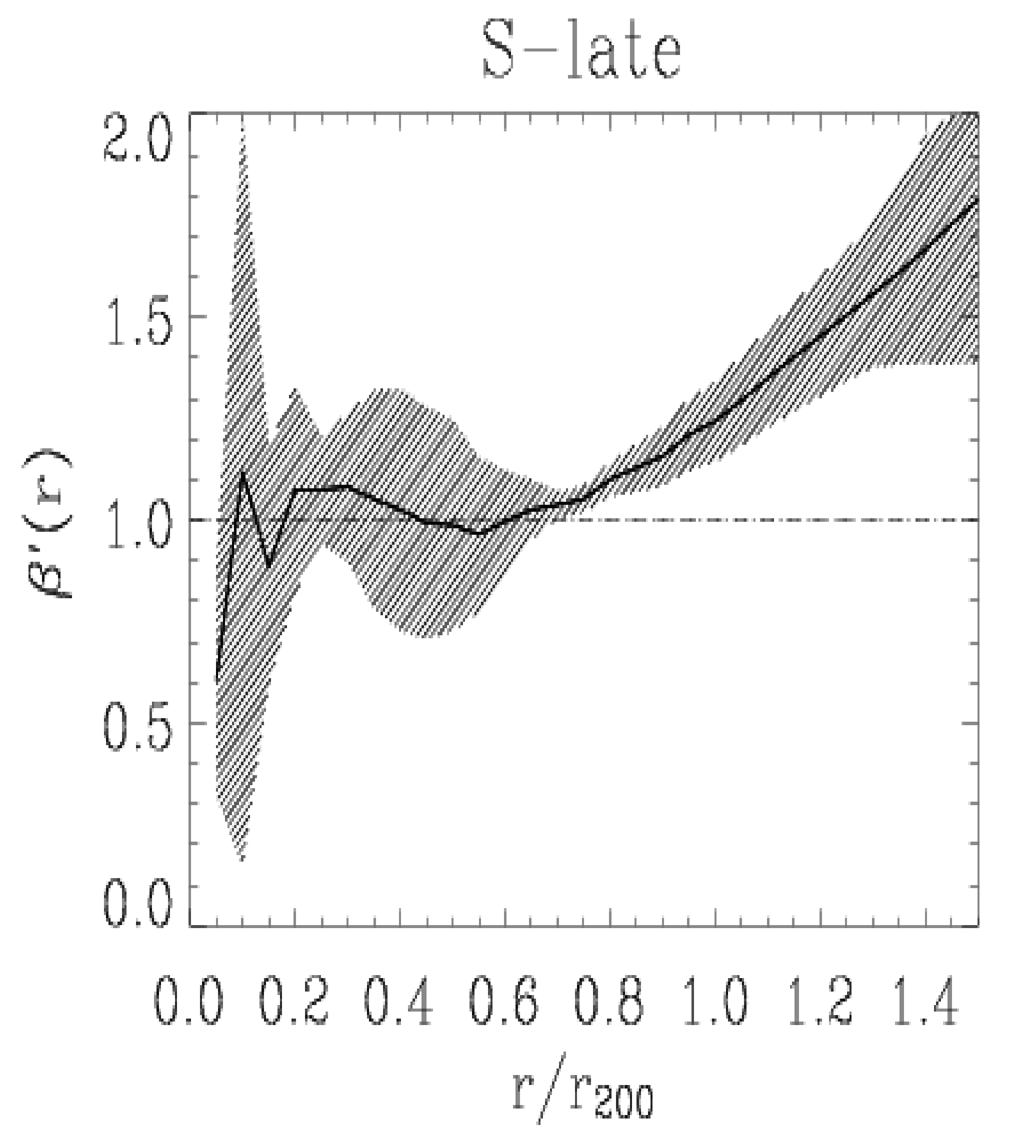


Internal structure

Orbits of galaxies in clusters:

Late-type S move along increasingly radial orbits with increasing distance from the cluster center

(2004, ENACS XIII)



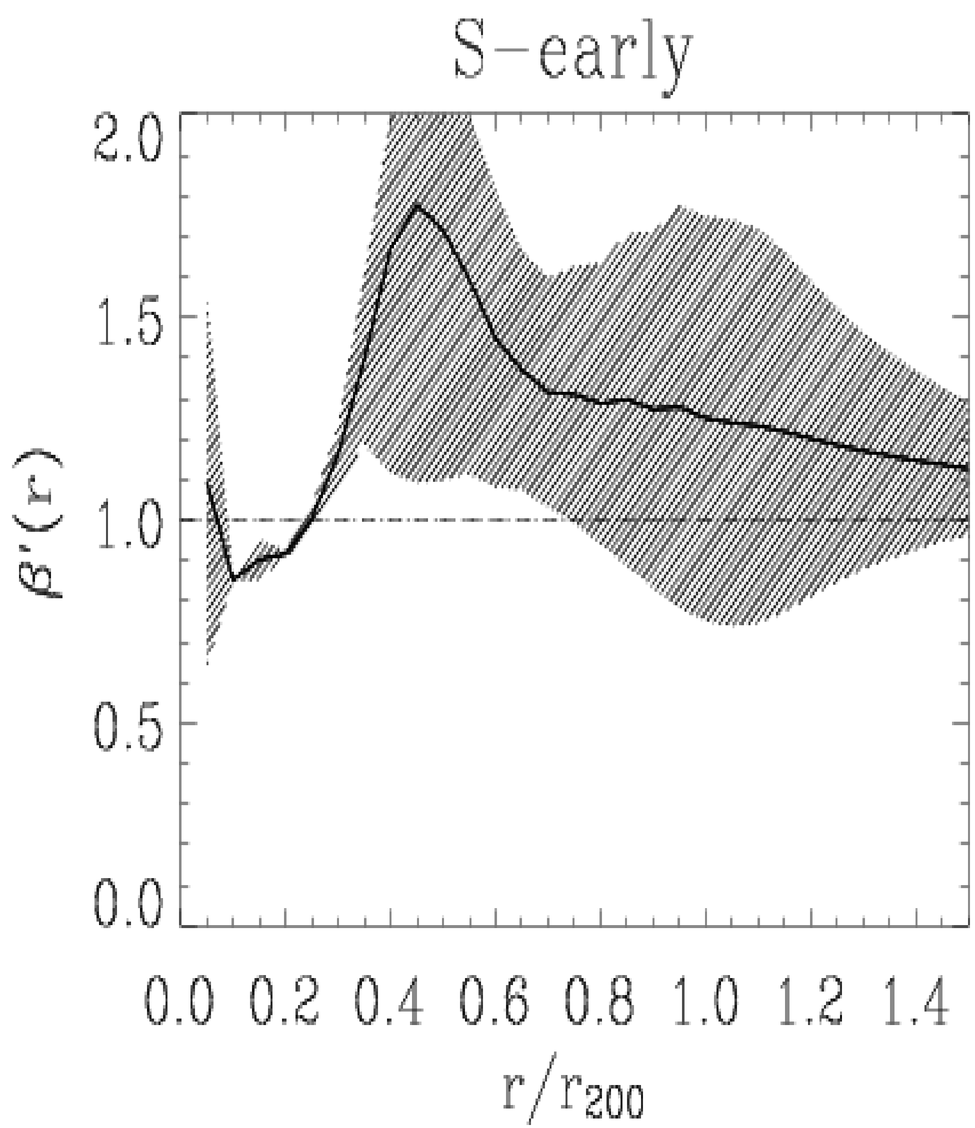
$$\beta'(r) = \left(\frac{< v_r^2 >}{< v_t^2 >}\right)^{1/2}$$

Internal structure

Orbits of galaxies in clusters:

Early-type S move along mildly radial – almost isotropic orbits

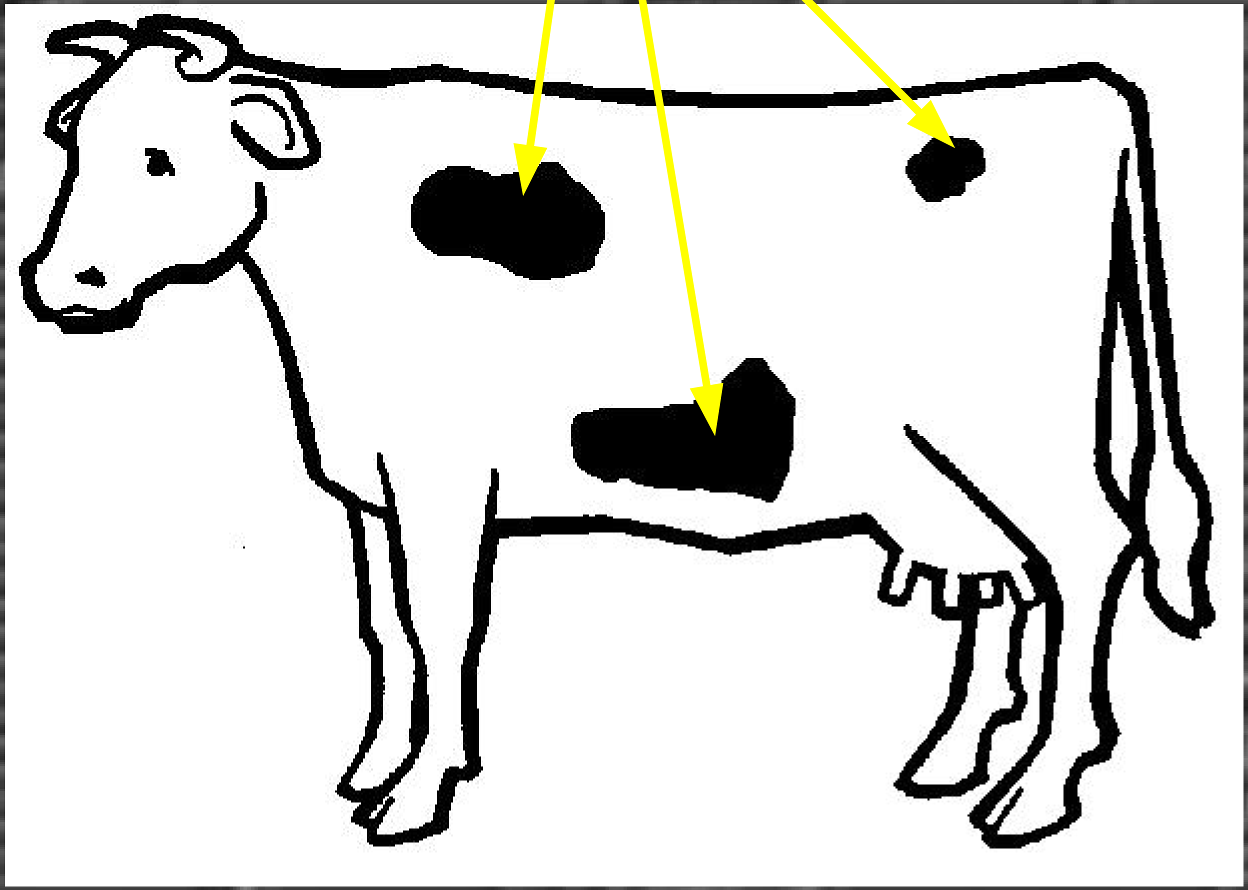
(2004, ENACS XIII)



$$\beta'(r) = \left(\frac{< v_r^2 >}{< v_t^2 >} \right)^{1/2}$$

So far, so good, but what about…

… Substructure ?



Why studying cluster substructure?

Constrain cosmological models

through dM/dt, i.e. accretion history:

do clusters accrete matter from the field in clumps?

how long do these clumps survive the cluster tidal field?

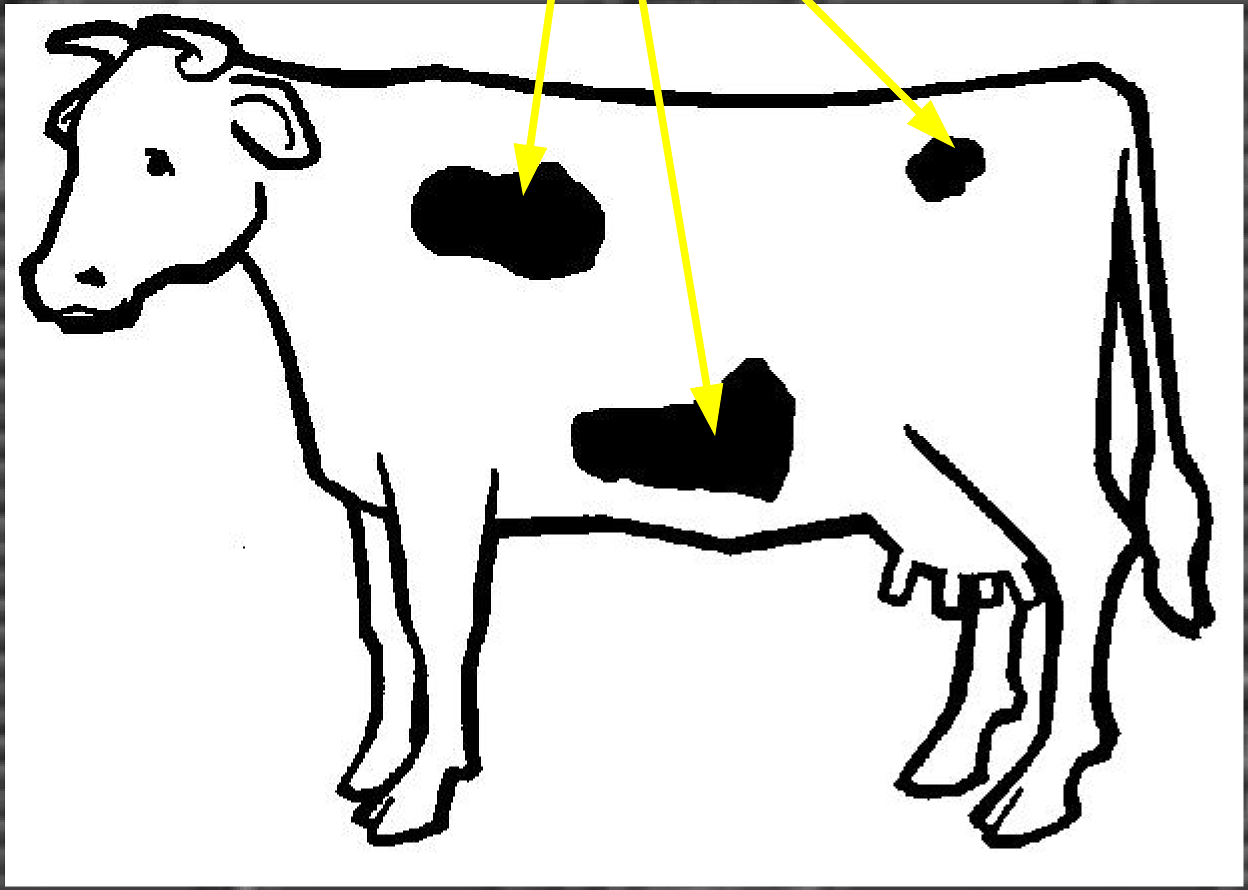
Constrain galaxy evolution

do galaxies evolve in groups before they join clusters?

do cluster tidal field stimulates evolution in groups?

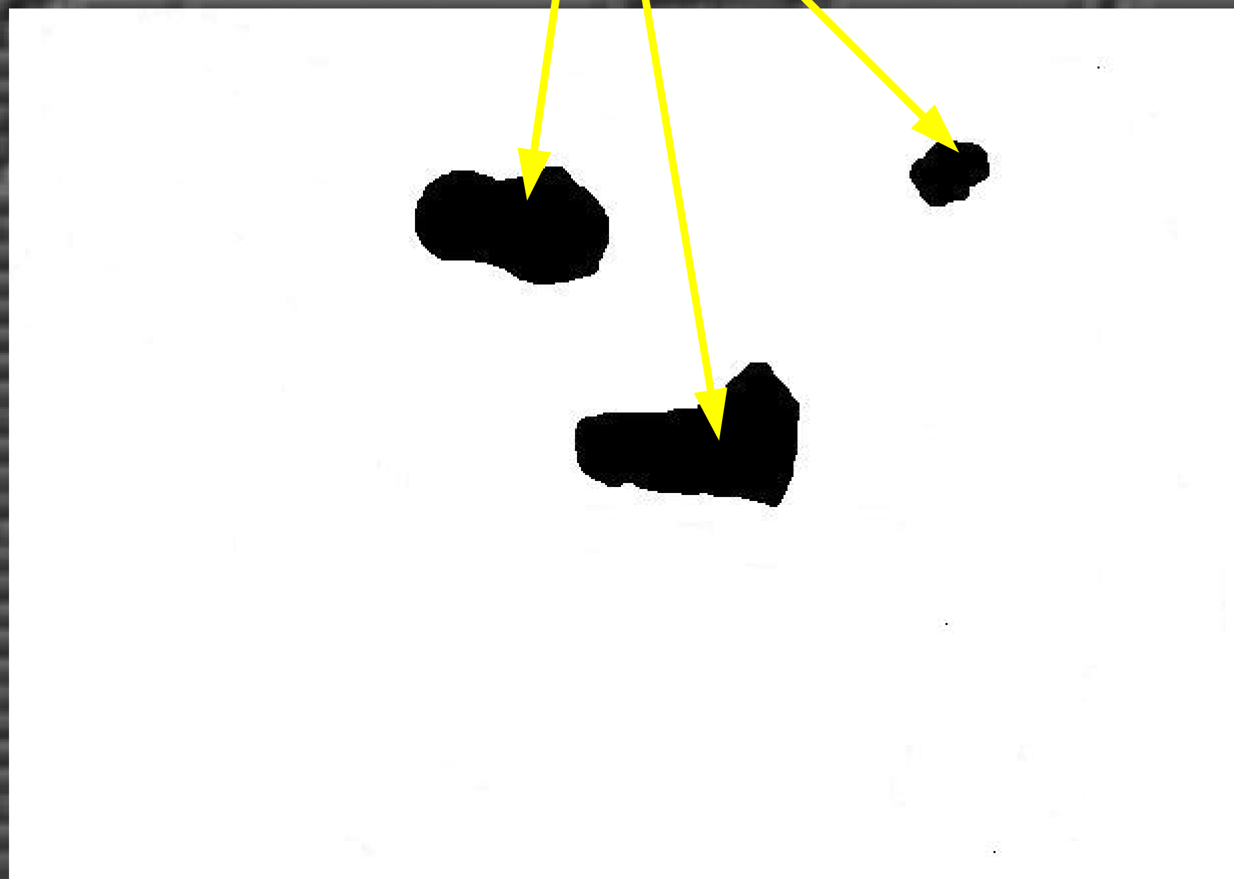
So, how can we study

… Substructure ?



In order to study

... Substructure



...must get rid of the 'contaminating' structure!

How do we analyse the *sub*structures of galaxy clusters?

1) Identify local 2nd order overdensities in the galaxies distrib.

How do we analyse the *sub*structures of galaxy clusters?

1) Identify local 2nd order overdensities in the galaxies distrib.

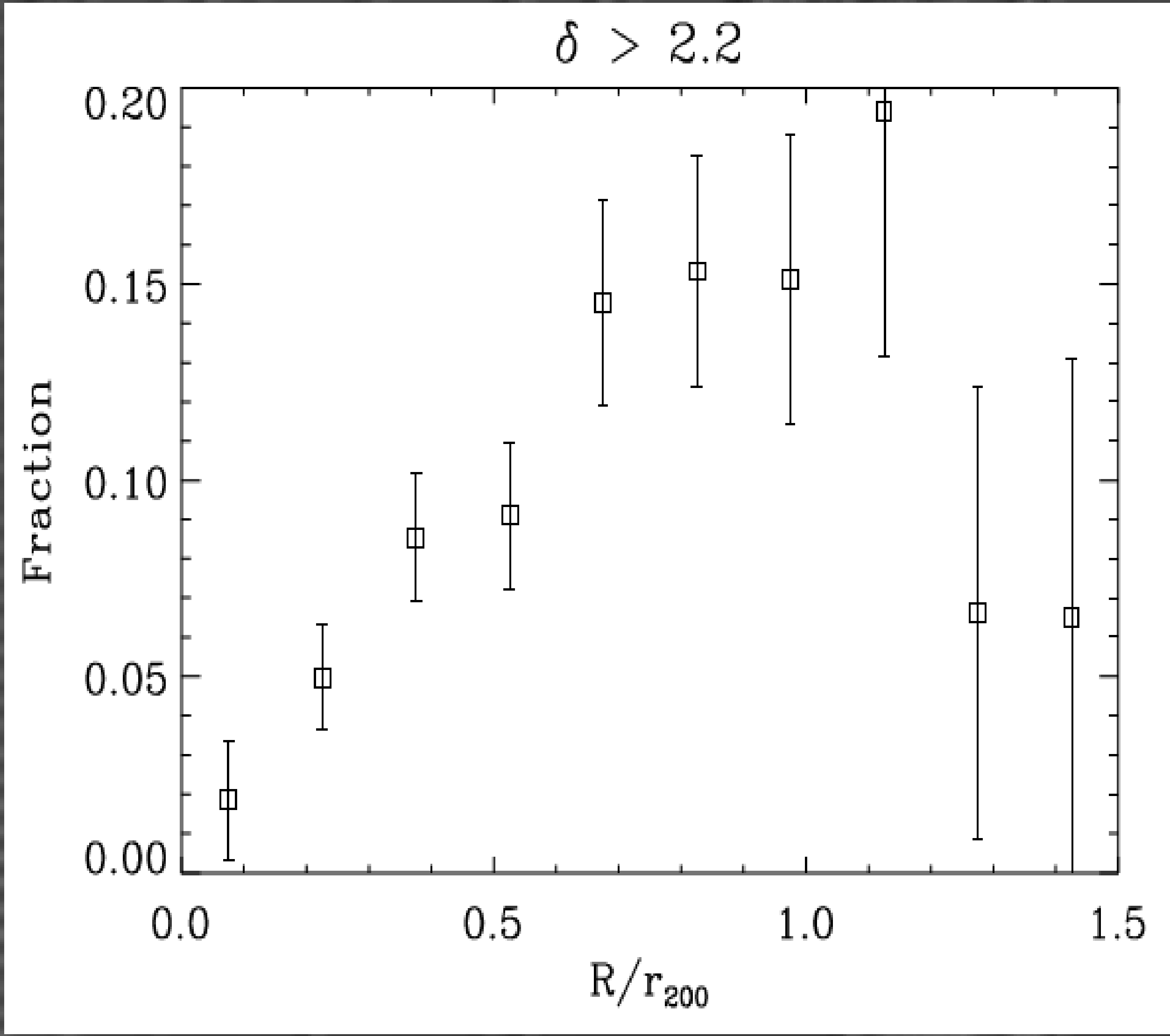
2) Look for deviations of the velocity distributions of galaxies in these overdensities from the global velocity distribution of the cluster

$$\delta = \frac{1}{\sigma_{\rm p}(R)}\sqrt{\frac{n_{\rm loc}\delta_v^2}{[t_{n_{\rm loc}-1}]^2} + \frac{\delta_\sigma^2}{\left[1-\sqrt{(n_{\rm loc}-1)/\chi^+_{n_{\rm loc}-1}}\right]^2}}$$

with $\delta_{\rm v} = \mid \overline{v}_{\rm loc} - \overline{v}_{\rm glob} \mid$, and $\delta_\sigma = \max(\sigma_{\rm p} - \sigma_{\rm loc}, 0)$

(2002, ENACS XI)

Substructure



Distribution:

Are subclusters destroyed as they get close to the cluster center?

(2002, ENACS XI)

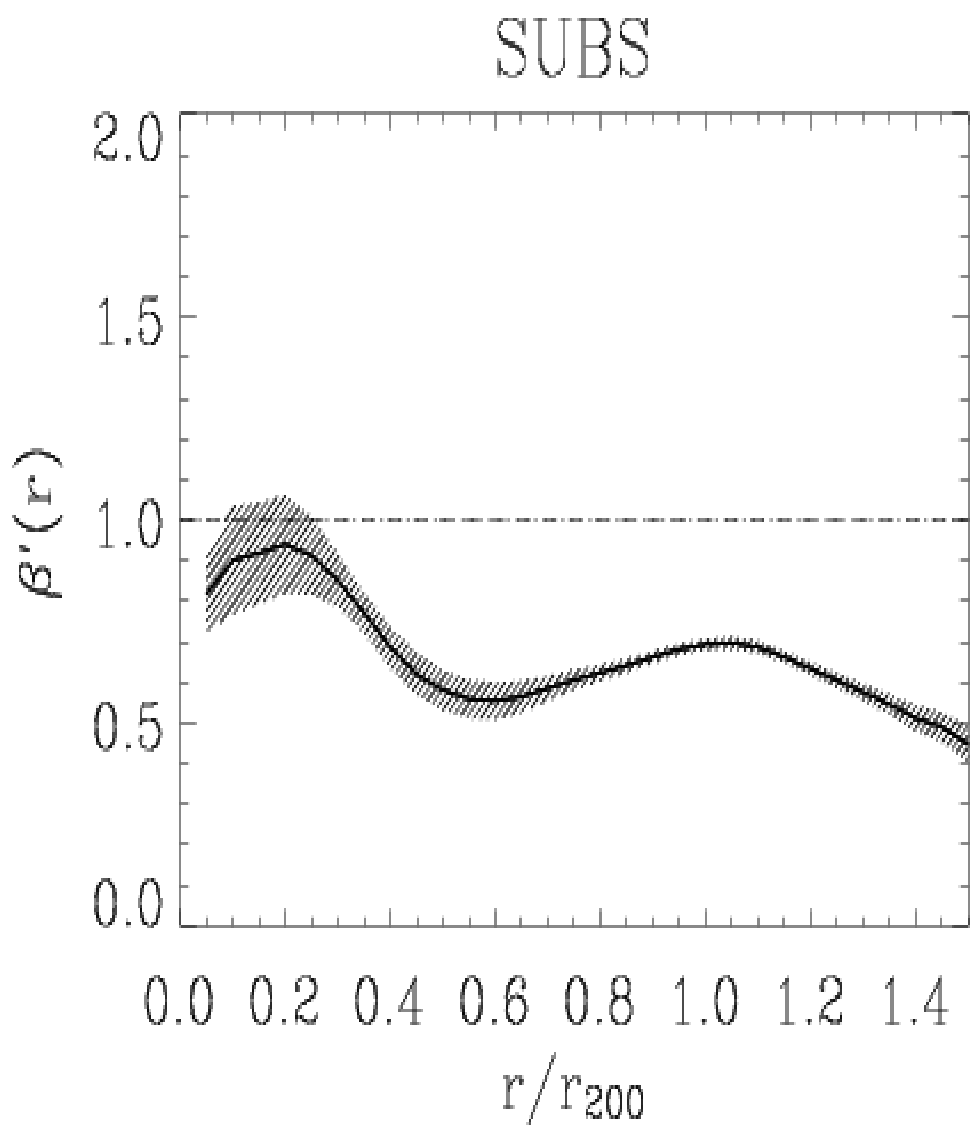
Substructure

Orbits:

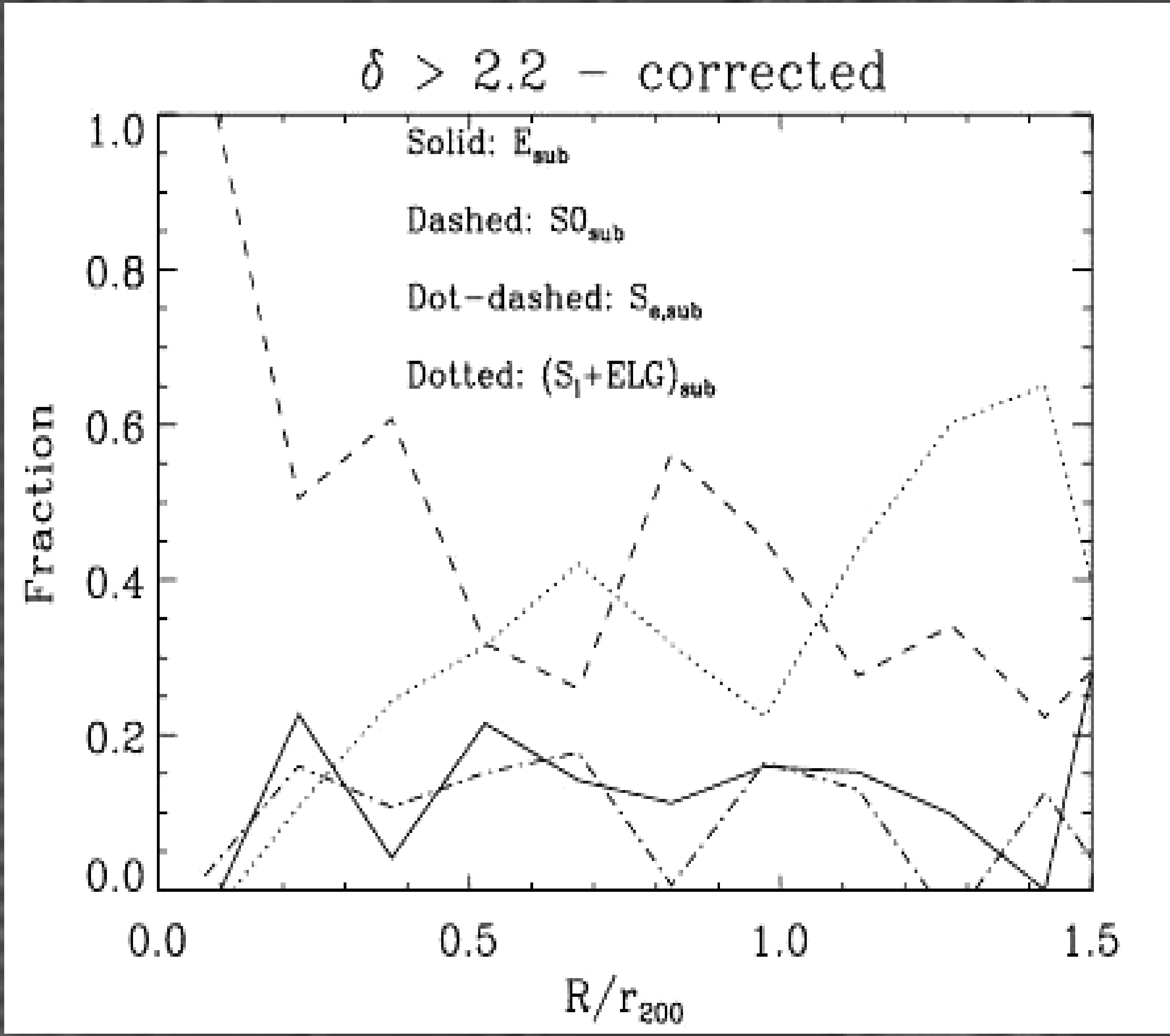
Do subclusters that manage to survive do so because they move on tangential orbits?

(2004, ENACS XIII)

$$\beta'(r) = \left(\frac{< v_r^2 >}{< v_t^2 >} \right)^{1/2}$$



Substructure



Composition:

Do S0s form in subclusters as they get close to the cluster center?

(2002, ENACS XI)

Substructure: a new start!

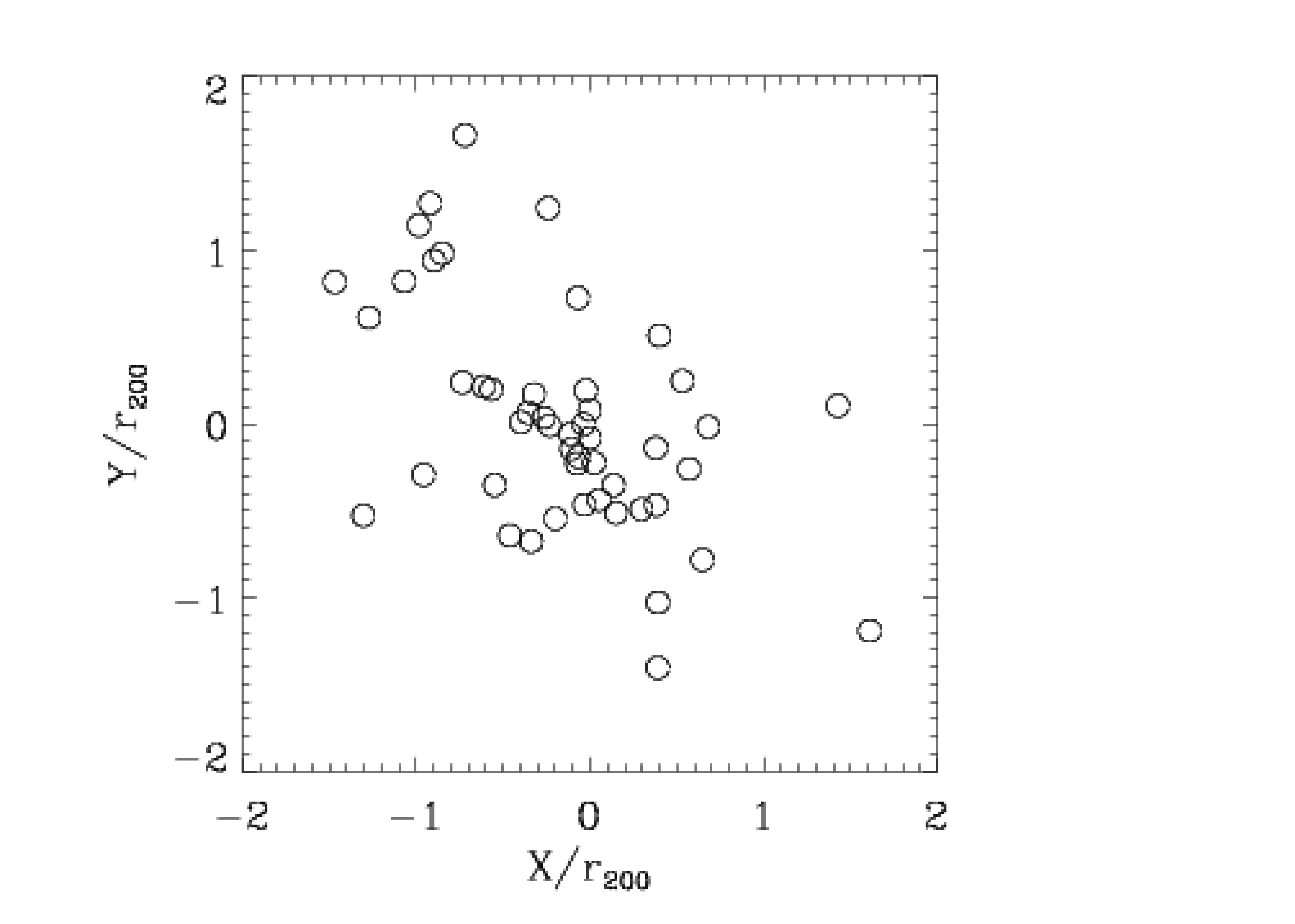
Several issues to re-consider:

1) define independent substructures in a 'unique way'

2) estimate probabilities of observed δ, p_δ

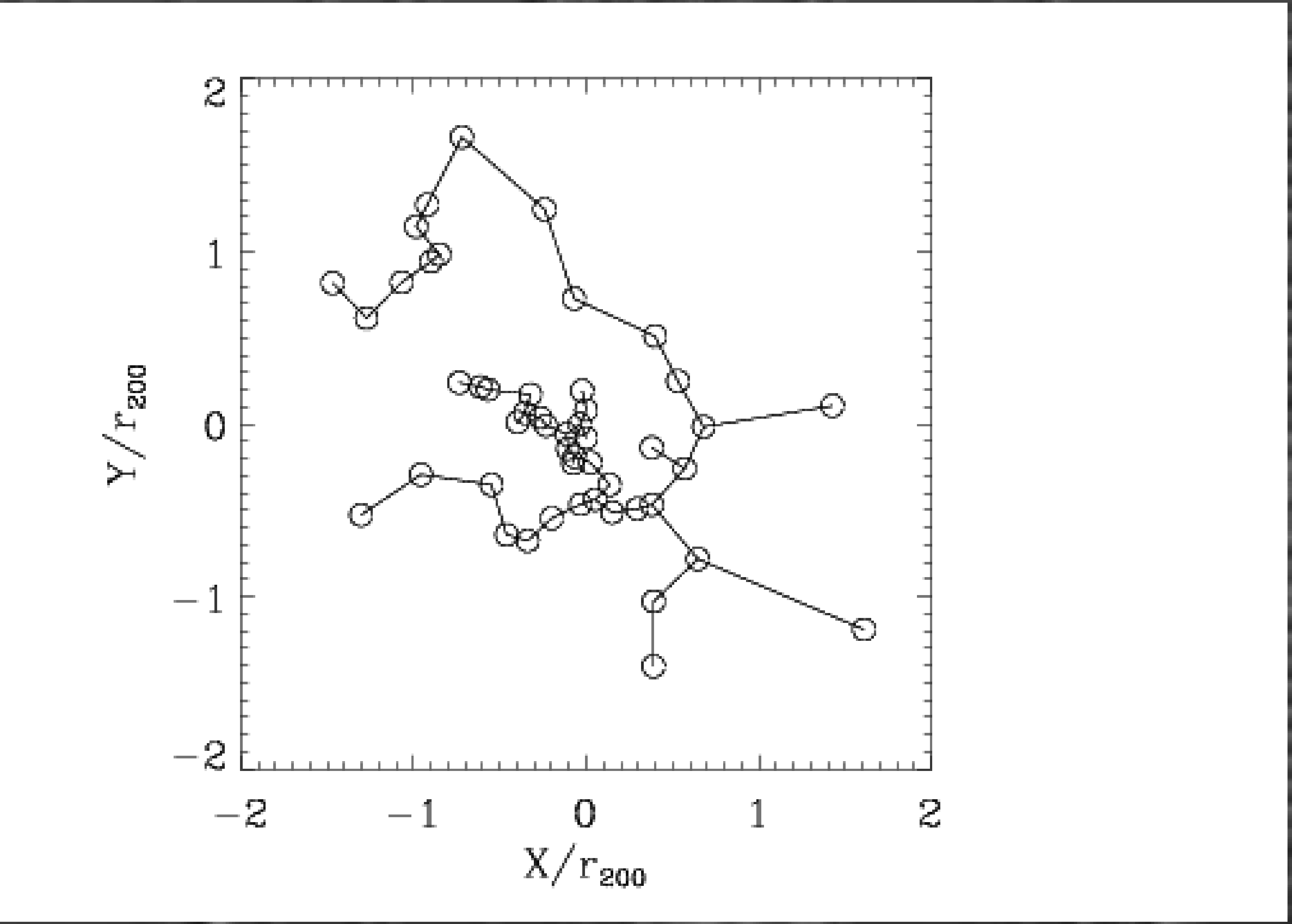
3) estimate the dilution and contamination effects due to projection (i.e. relate 6d-p_δ to p_δ)

Use the Minimal Spanning Tree:

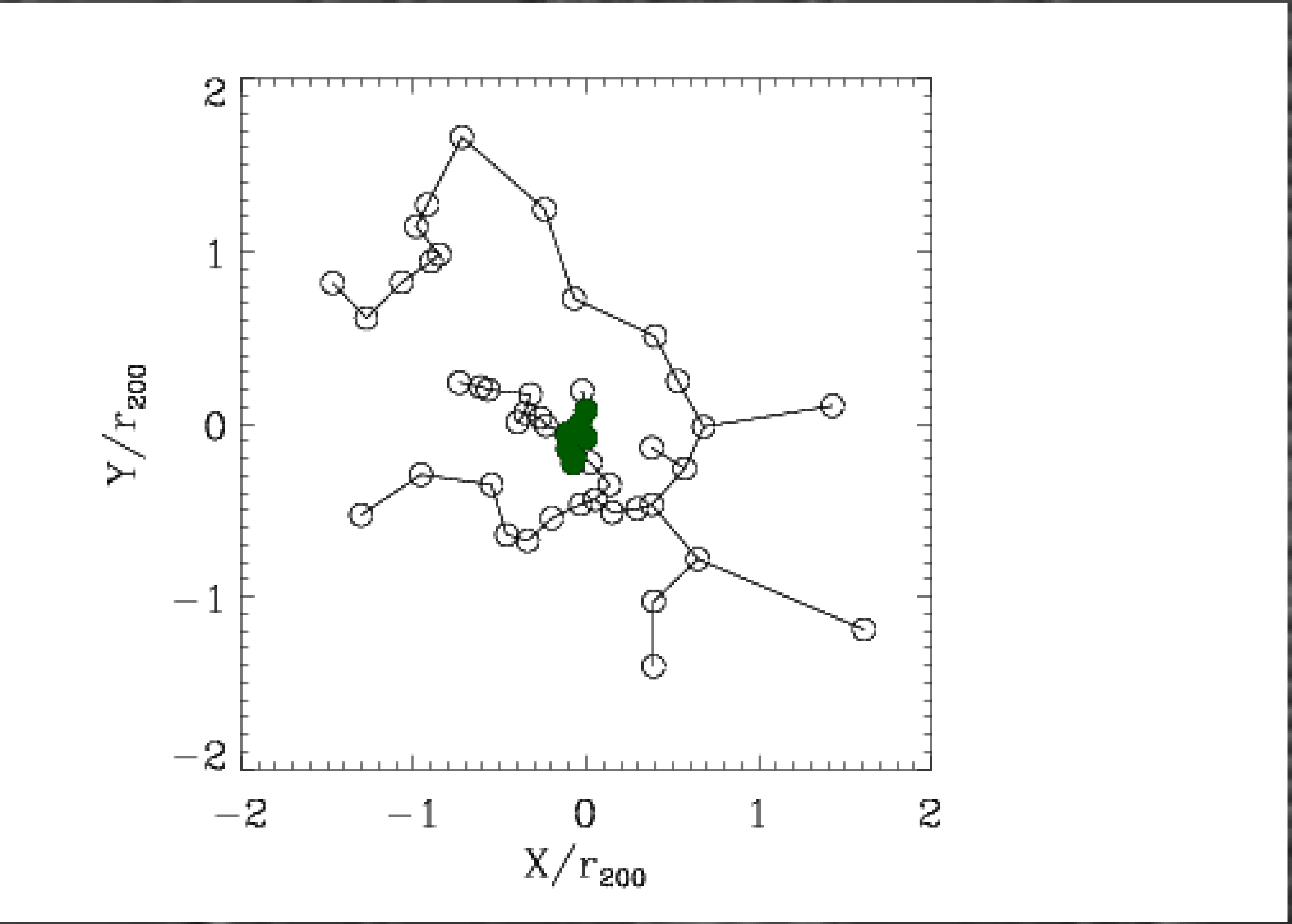


The projected distribution of galaxies in an ENACS cluster

Use the Minimal Spanning Tree:

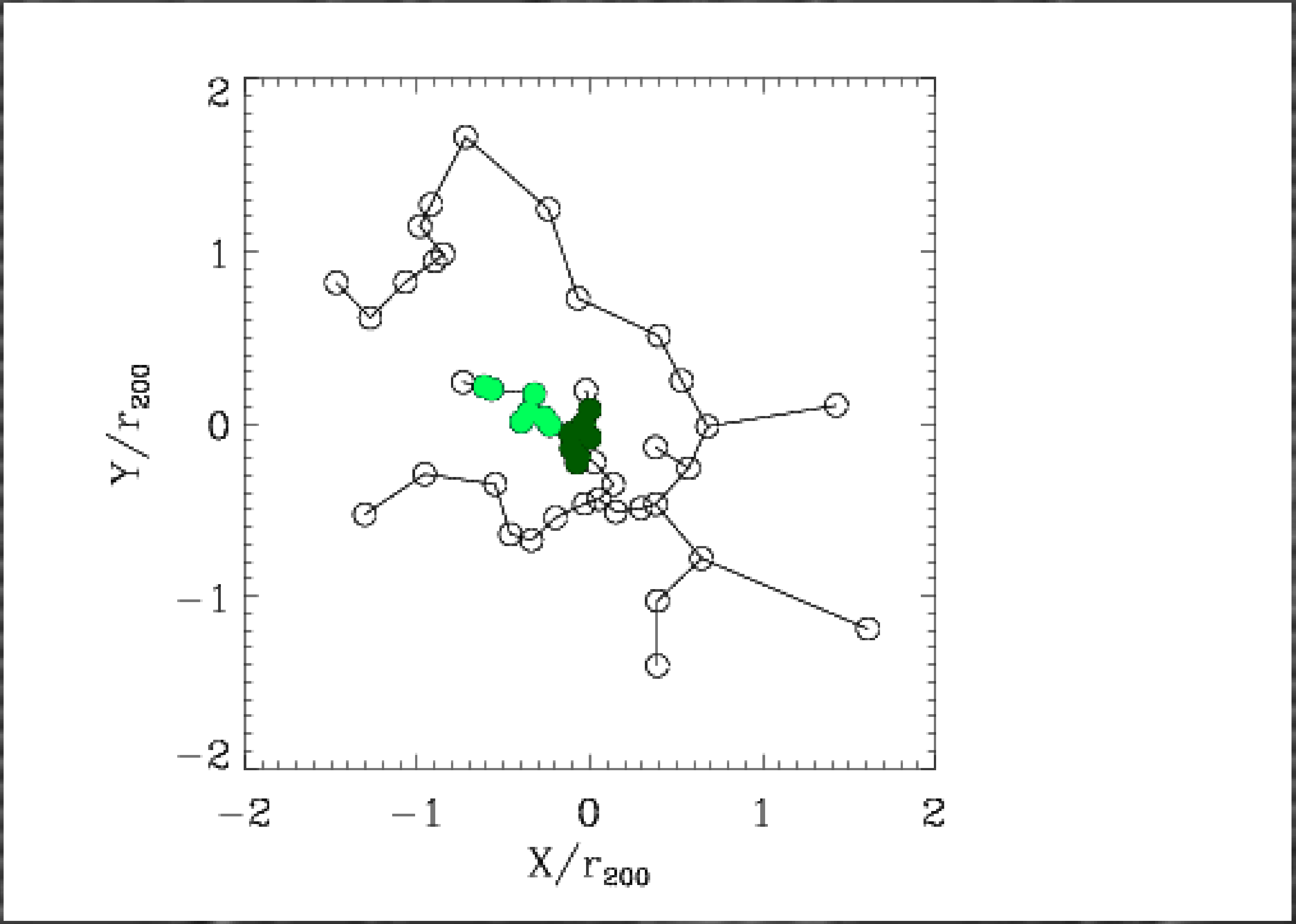


Split the MST into subclusters of given multiplicity (e.g. 7):



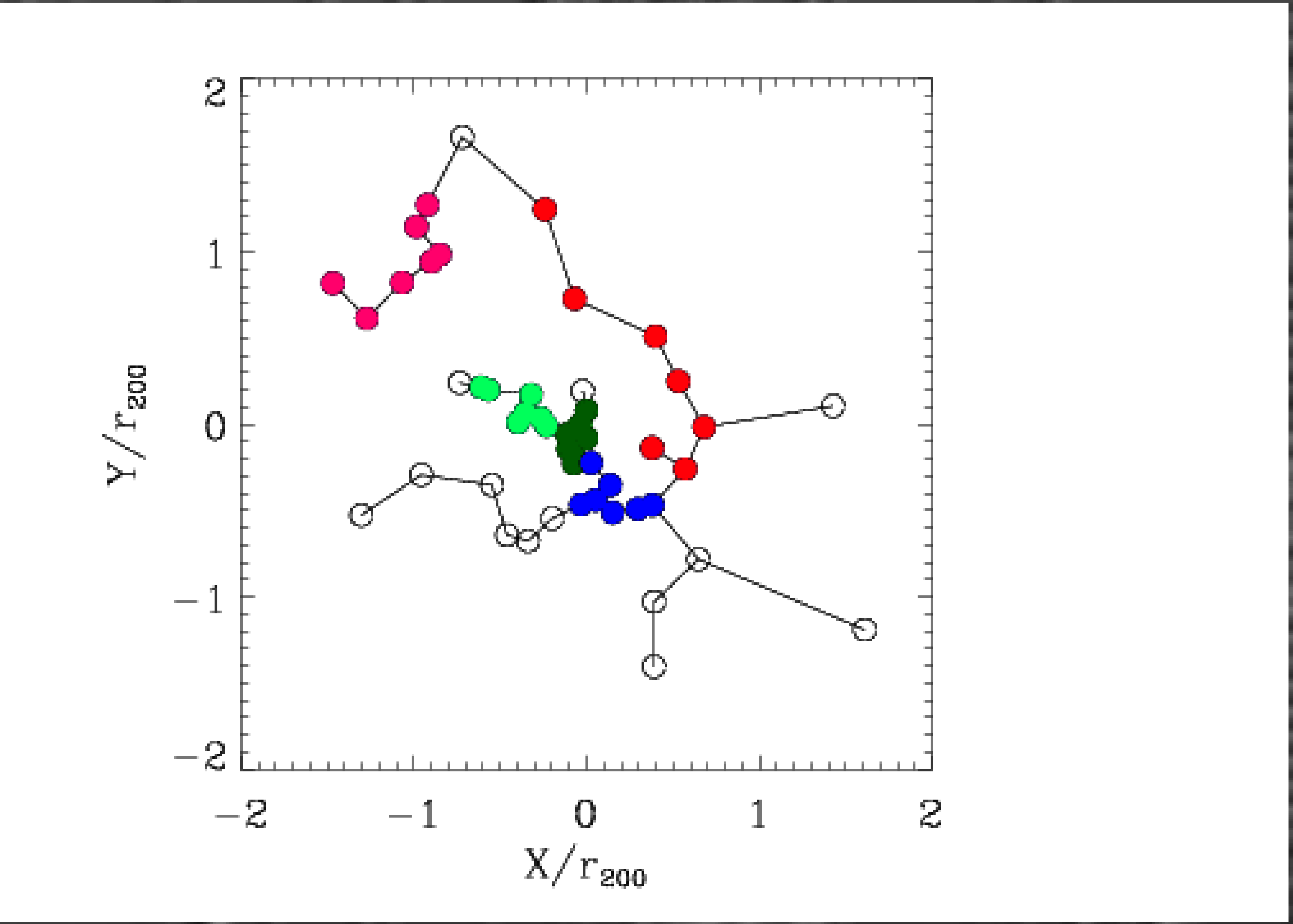
Select the minimum-length N=7 subcluster in the MST...

Split the MST into subclusters of given multiplicity (e.g. 7):



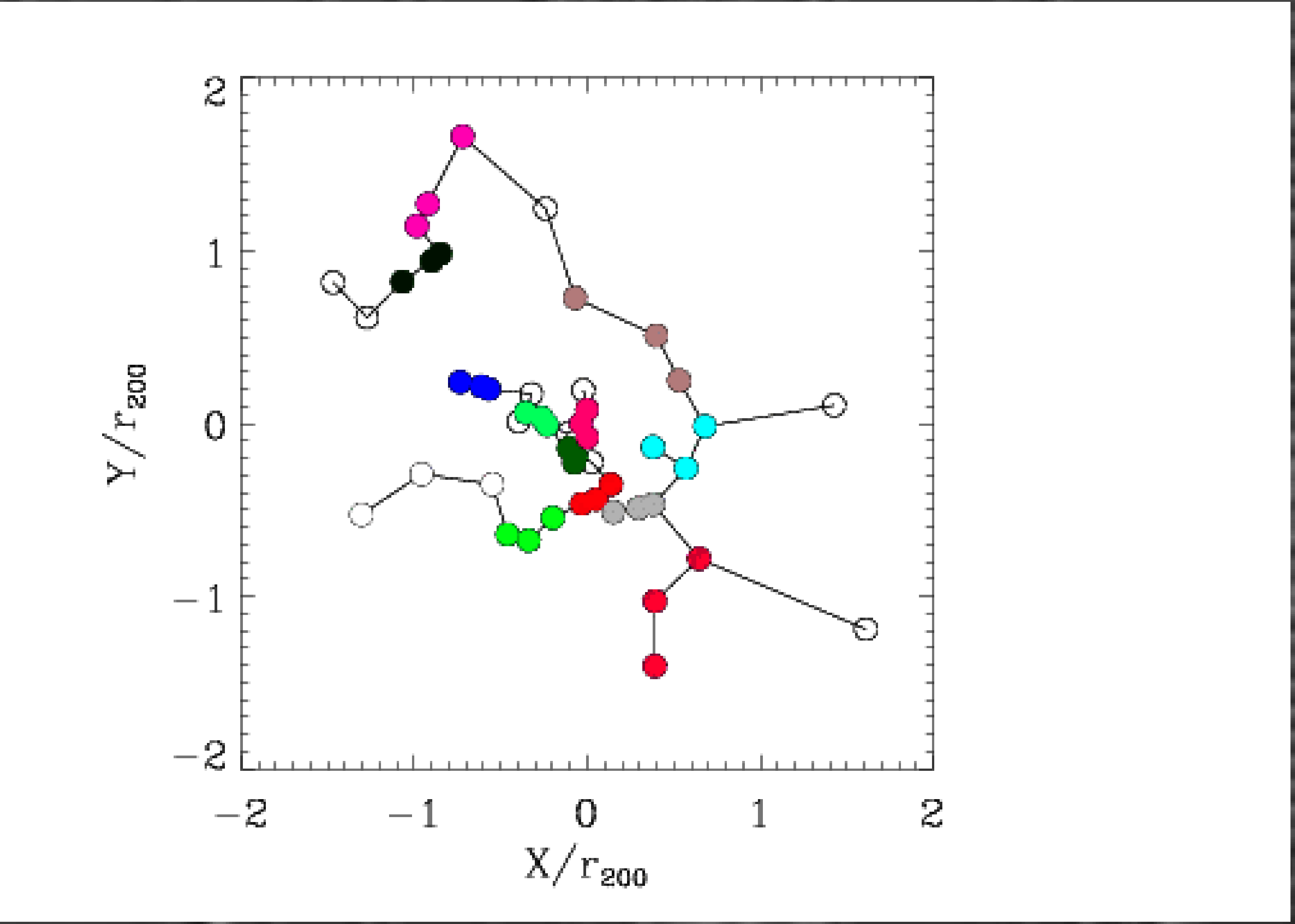
… then select the 2^{nd} minimum-length subcluster...

Split the MST into subclusters of given multiplicity (e.g. 7):



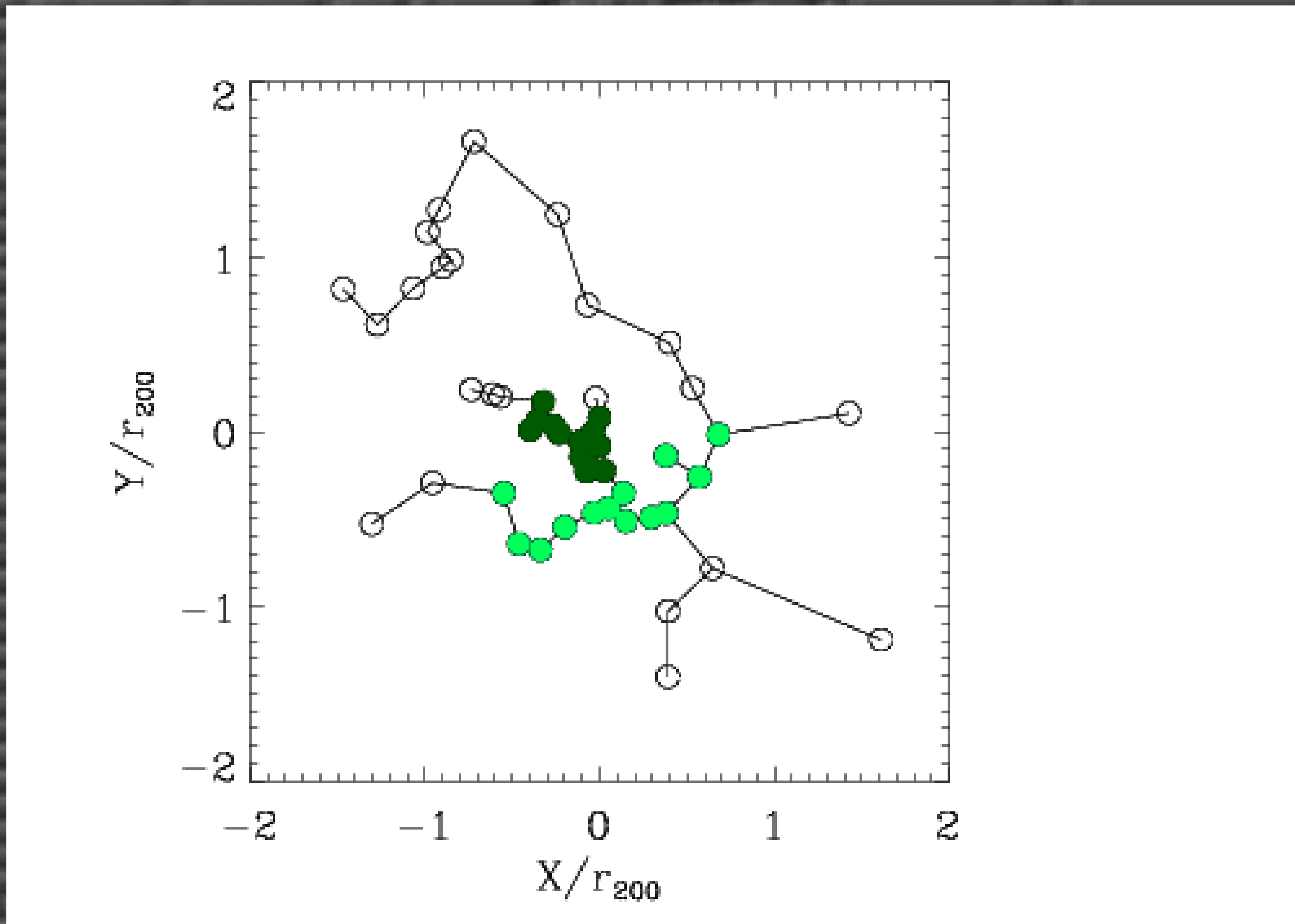
… and so on, until no other N=7 subcluster can be defined.

Do the same for all multiplicity subclusters:



E.g.: subclusters of N=3 identified in the MST

Do the same for all multiplicity subclusters:



E.g.: subclusters of N=13 identified in the MST

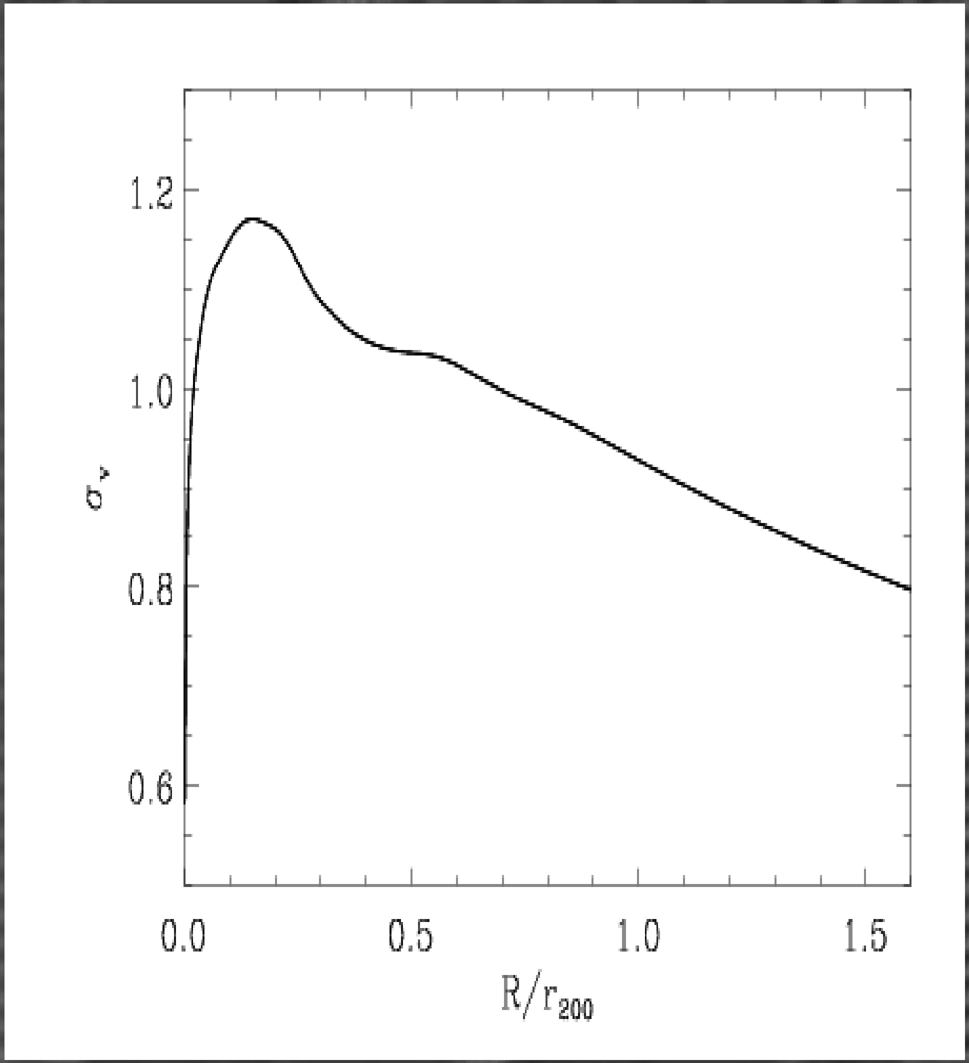
Substructure: a new start!

Several issues to re-consider:

1) define independent substructures in a 'unique way'

2) estimate probabilities of observed δ, p_δ

3) estimate the dilution and contamination effects due to projection (i.e. relate 6d-p_δ to p_δ)



Define a model cluster:

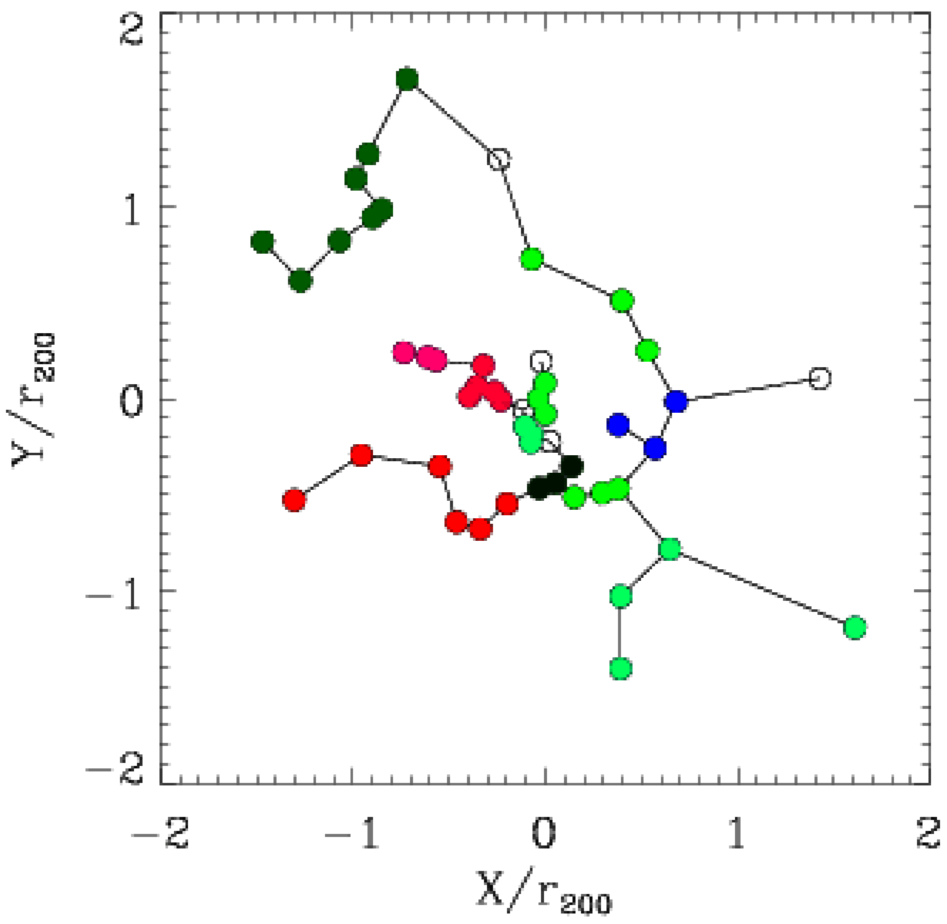
Global σ_v = σ_v of the cluster being analysed;

$\sigma_v(R)$ = average of all clusters.

Take 1000 random draws of the galaxy velocities in each cluster from a Gaussian of zero average and $\sigma_v(R)$ dispersion [where R is the distance of the galaxy from the cluster center]

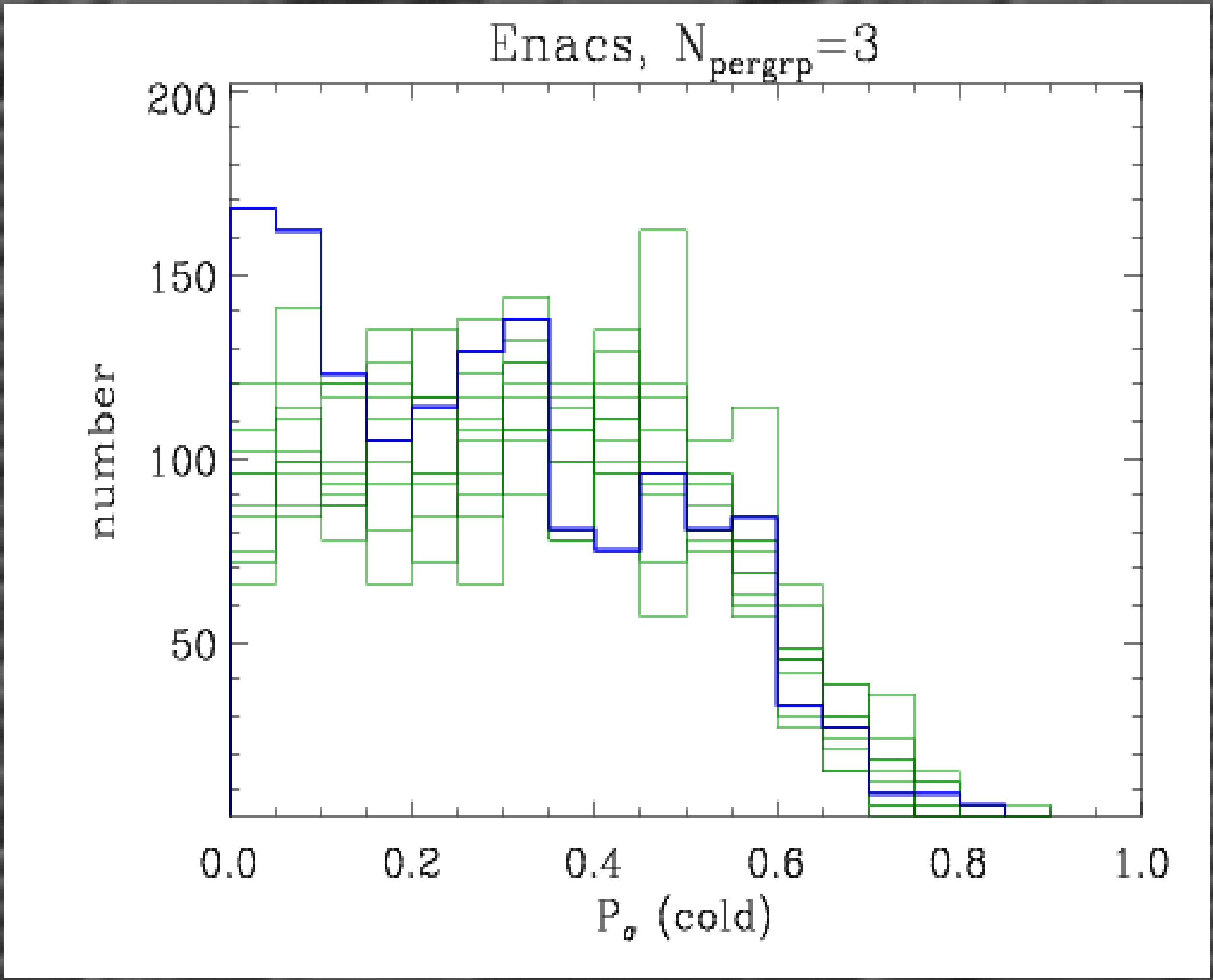
p_δ = fraction of times simulated δ > observed δ

Select the substructures less likely
to be chance occurrences (i.e. with smaller p_δ):



Use the model cluster to generate several mock 'reference' clusters without substructuctures

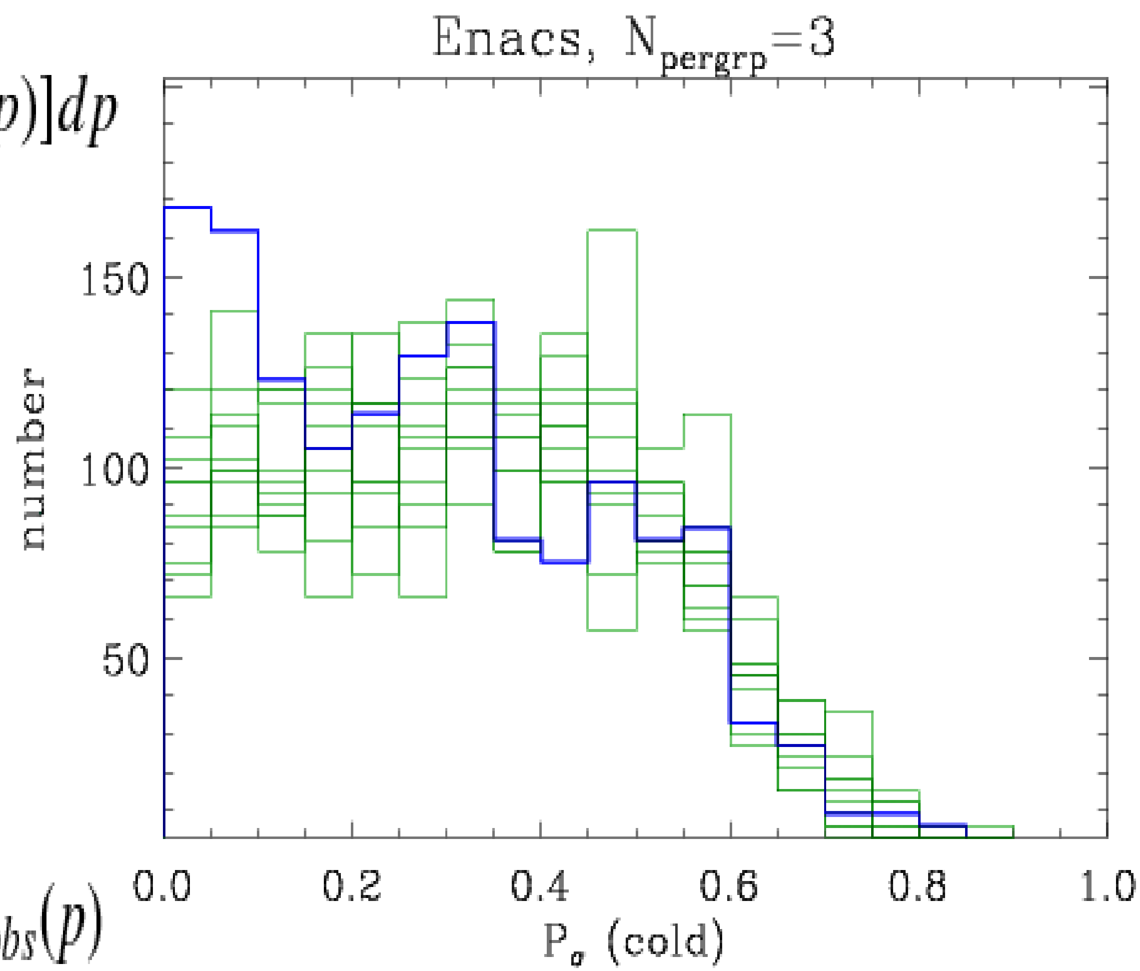
Randomly draw the velocities of the cluster galaxies but keep their positions fixed, so the same MST subclusters are defined, but with different δ and p_δ



Compare the p distributions of real and mocks

$$N_{sub,tot} = \int [N_{obs}(p) - f * N_{mock}(p)]dp$$

Total number of galaxies in substructure



From probabilities to 'reliabilities'

$$\Re(p) = [N_{obs}(p) - f * N_{mock}(p)]/N_{obs}(p)$$

Substructure: a new start!

Several issues to re-consider:

1) define independent substructures in a 'unique way'

2) estimate probabilities of observed δ, p_δ

3) estimate the dilution and contamination effects due to projection (i.e. relate 6d-p_δ to p_δ)

Select 59 cluster-sized halos from a cosmological numerical simulation so that their properties *in projection (including interlopers)* resemble those of the 59 ENACS clusters

Determine the substructures of the parent 59 simulated halos *in full phase-space* (6-D: x, y, z, v_x, v_y, v_z)

For given definition of 'substructure' in 6-D (*e.g. using a limiting* p_δ *in 6-D)* determine the selection parameter in projection *(e.g. a limiting* p_δ*)* so as to optimize completeness & purity of the substructures identified in projection

Select 59 cluster-sized halos from a cosmological numerical simulation so that their properties *in projection (including interlopers)* resemble those of the 59 ENACS clusters

Determine the substructures of the parent 59 simulated halos *in full phase-space* (6-D: x, y, z, v_x, v_y, v_z)

For given definition of 'substructure' in 6-D (*e.g. using a limiting p_δ in 6-D)* determine the selection parameter in projection *(e.g. a limiting p_δ)* so as to optimize completeness & purity of the substructures identified in projection

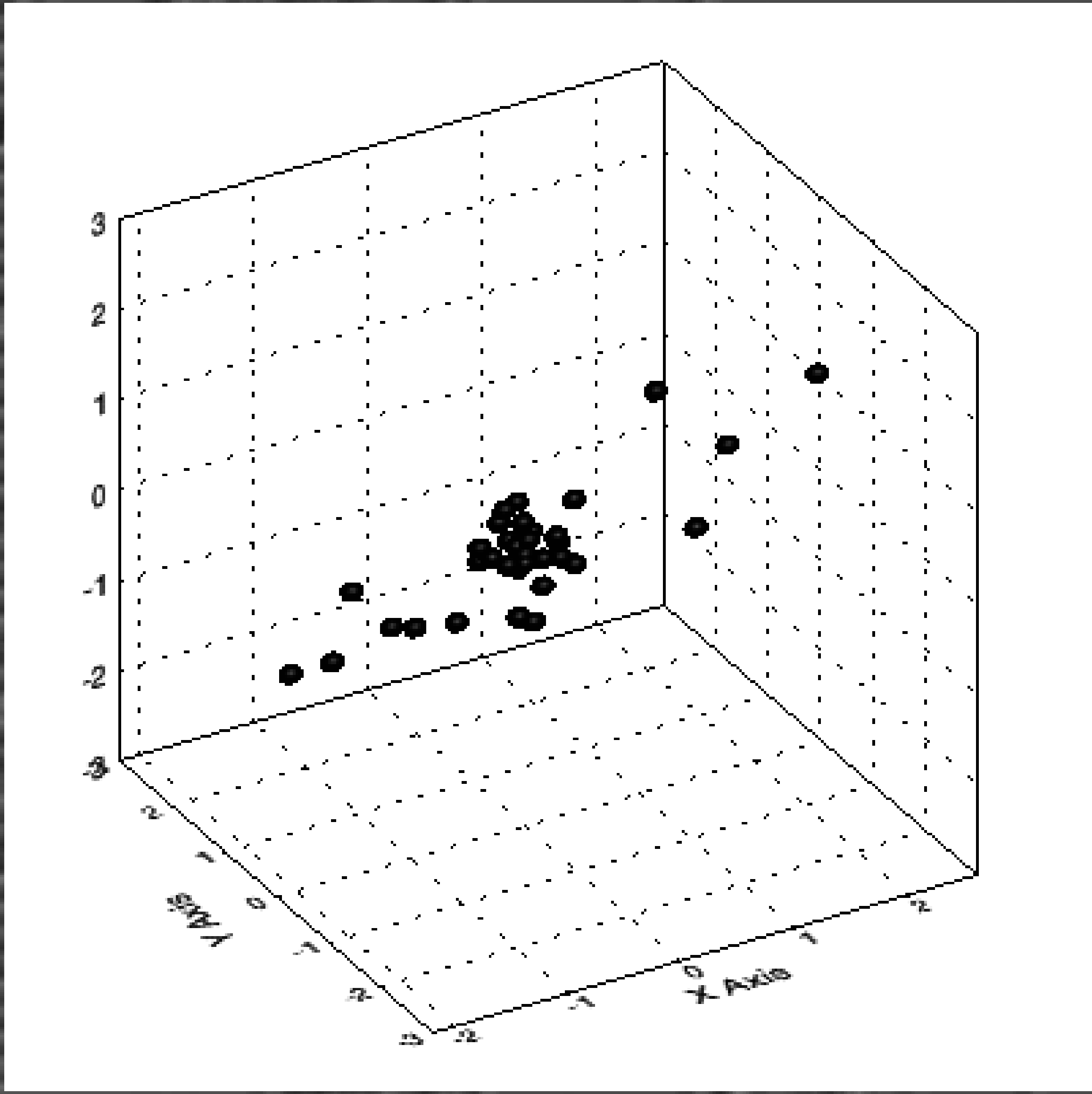
Select 59 cluster-sized halos from a cosmological numerical simulation so that their properties *in projection (including interlopers)* resemble those of the 59 ENACS clusters

Determine the substructures of the parent 59 simulated halos *in full phase-space* (6-D: x, y, z, v_x, v_y, v_z)

For given definition of 'substructure' in 6-D *(e.g. using a limiting p_δ in 6-D)* determine the selection parameter in projection *(e.g. a limiting p_δ)* so as to optimize completeness & purity of the substructures identified in projection

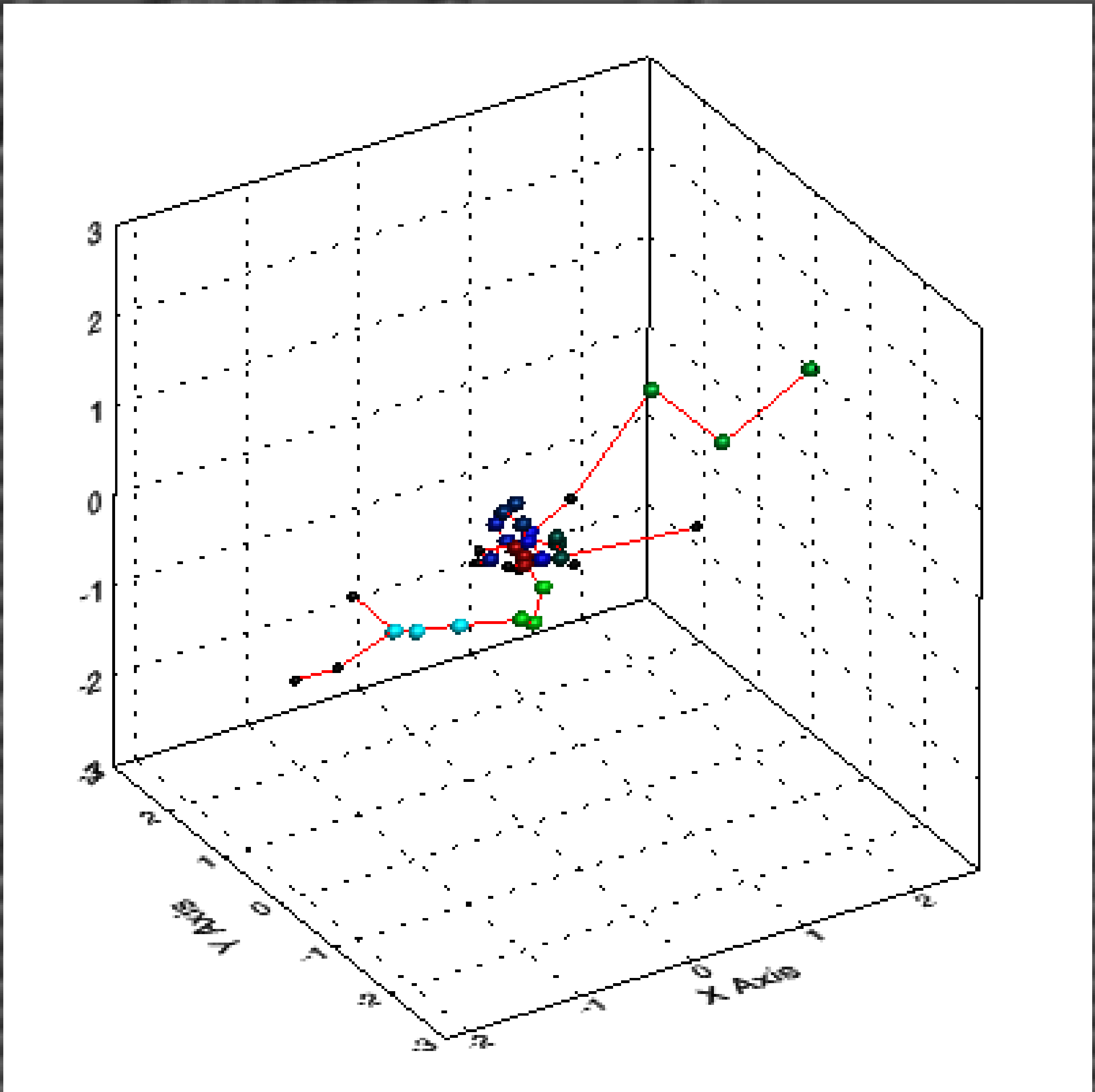
The effects of projection on the identification of substructure

A simulated halo in 6-d, displaying only particles within turnaround that have also been selected in projection



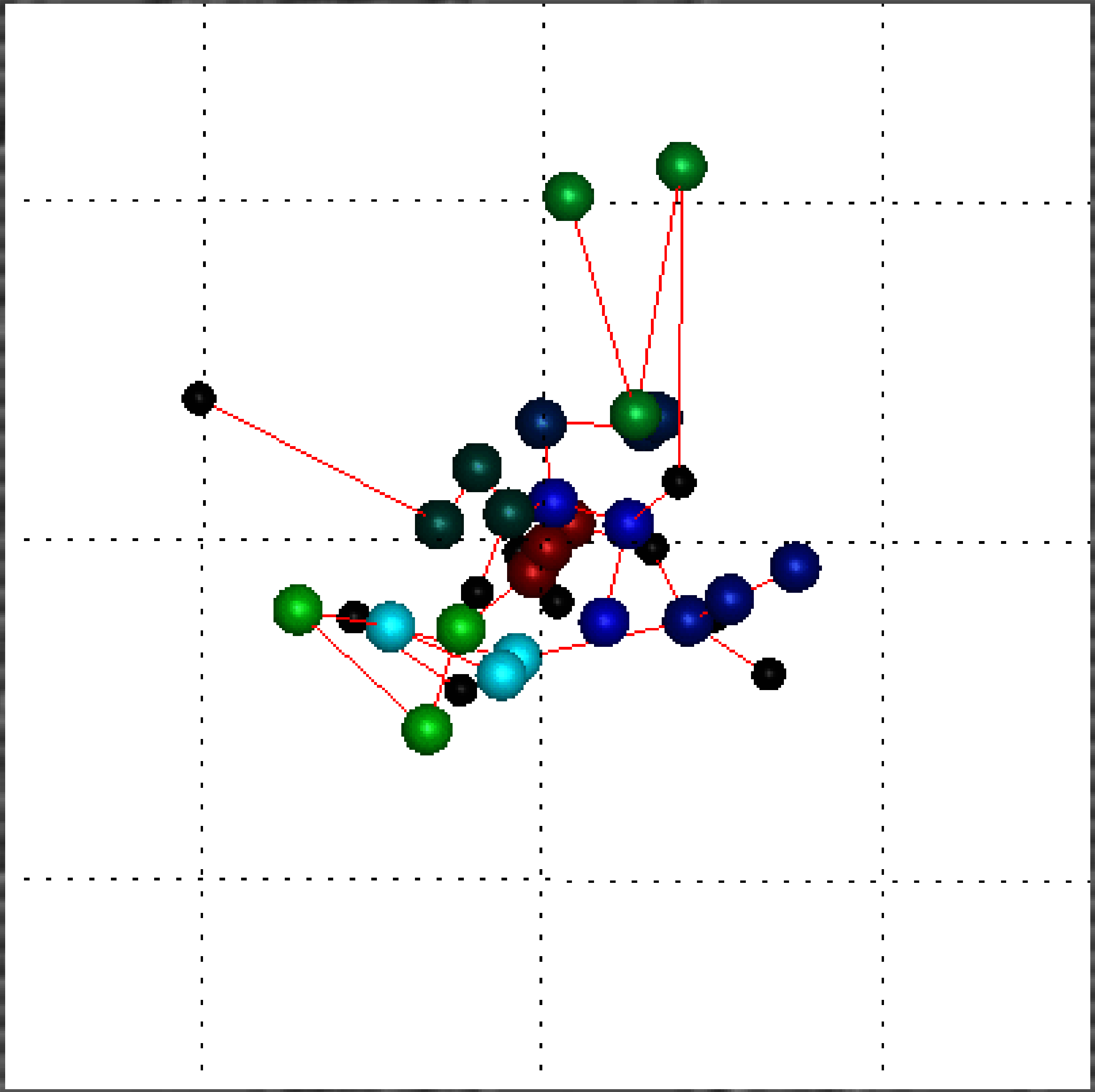
The effects of projection on the identification of substructure

Minimum Spanning Tree in 6-d, with identification of N=3 subclusters (just an example)

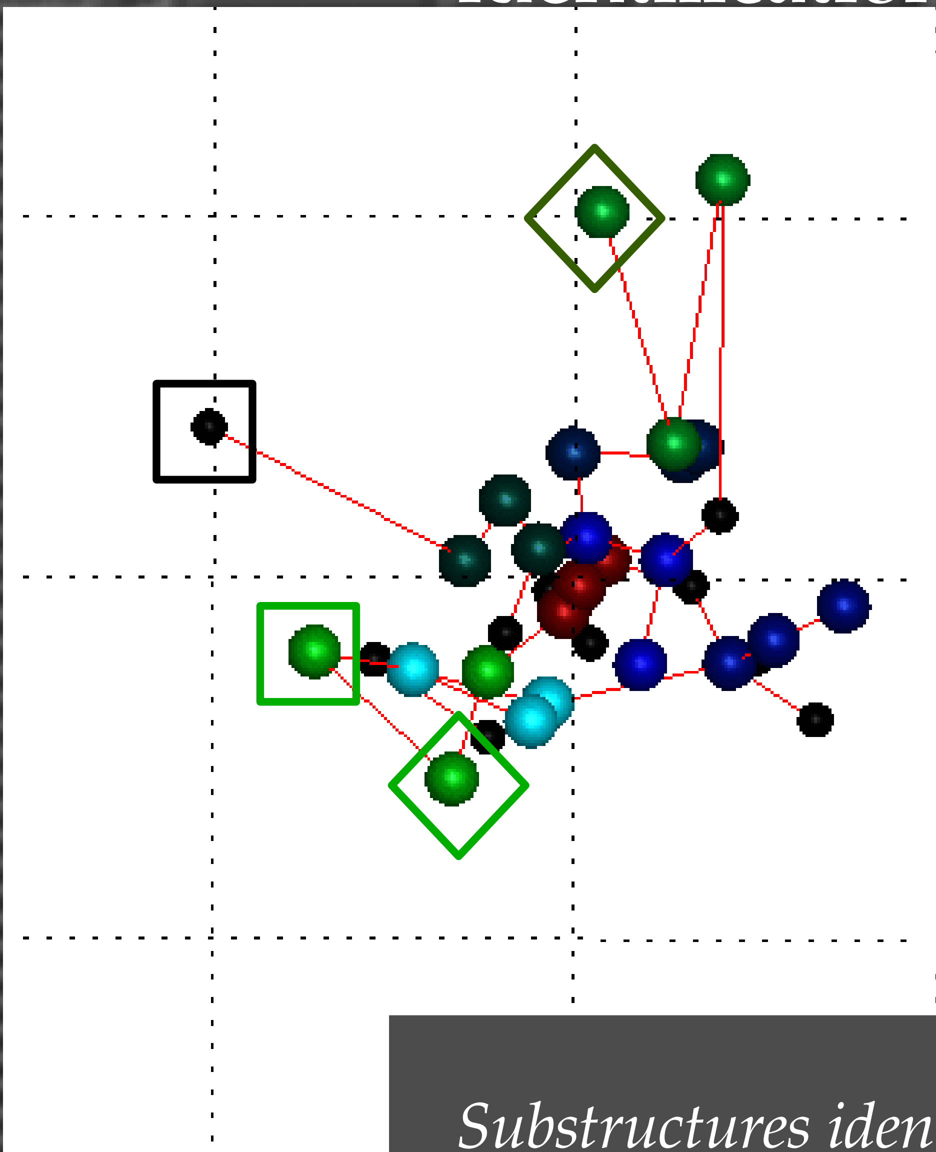


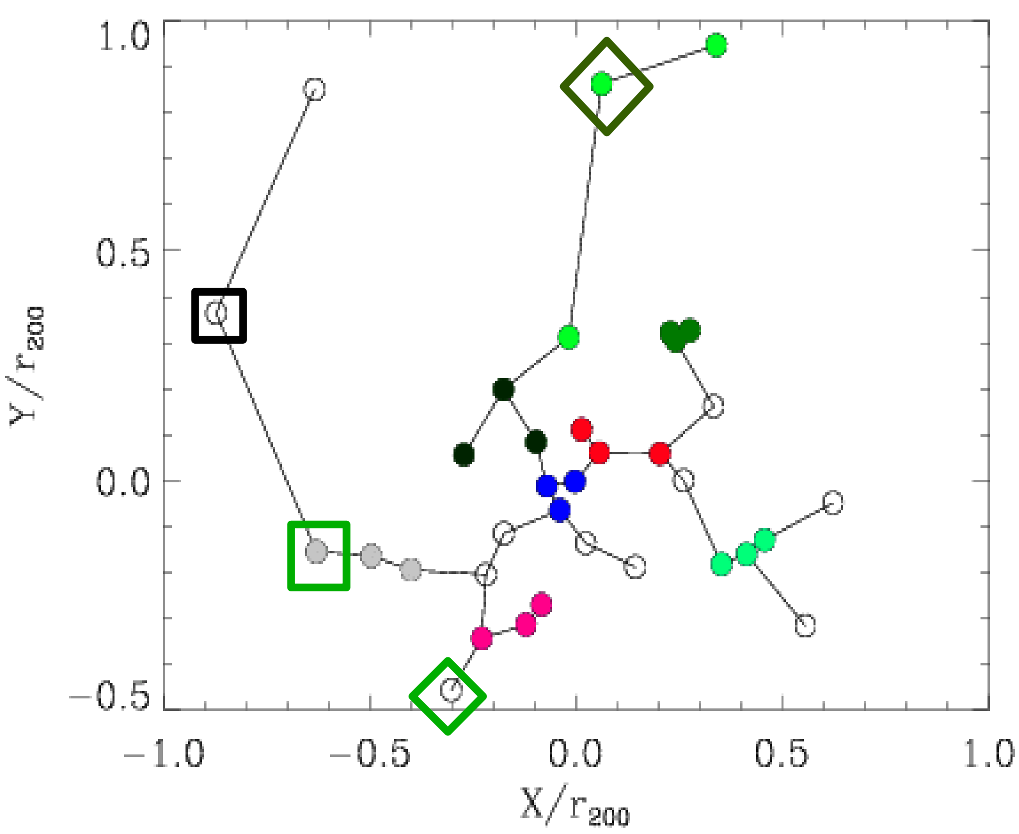
The effects of projection on the identification of substructure

Minimum Spanning Tree in 6-d, with identification of N=3 subclusters, as it appears projected along the x-axis



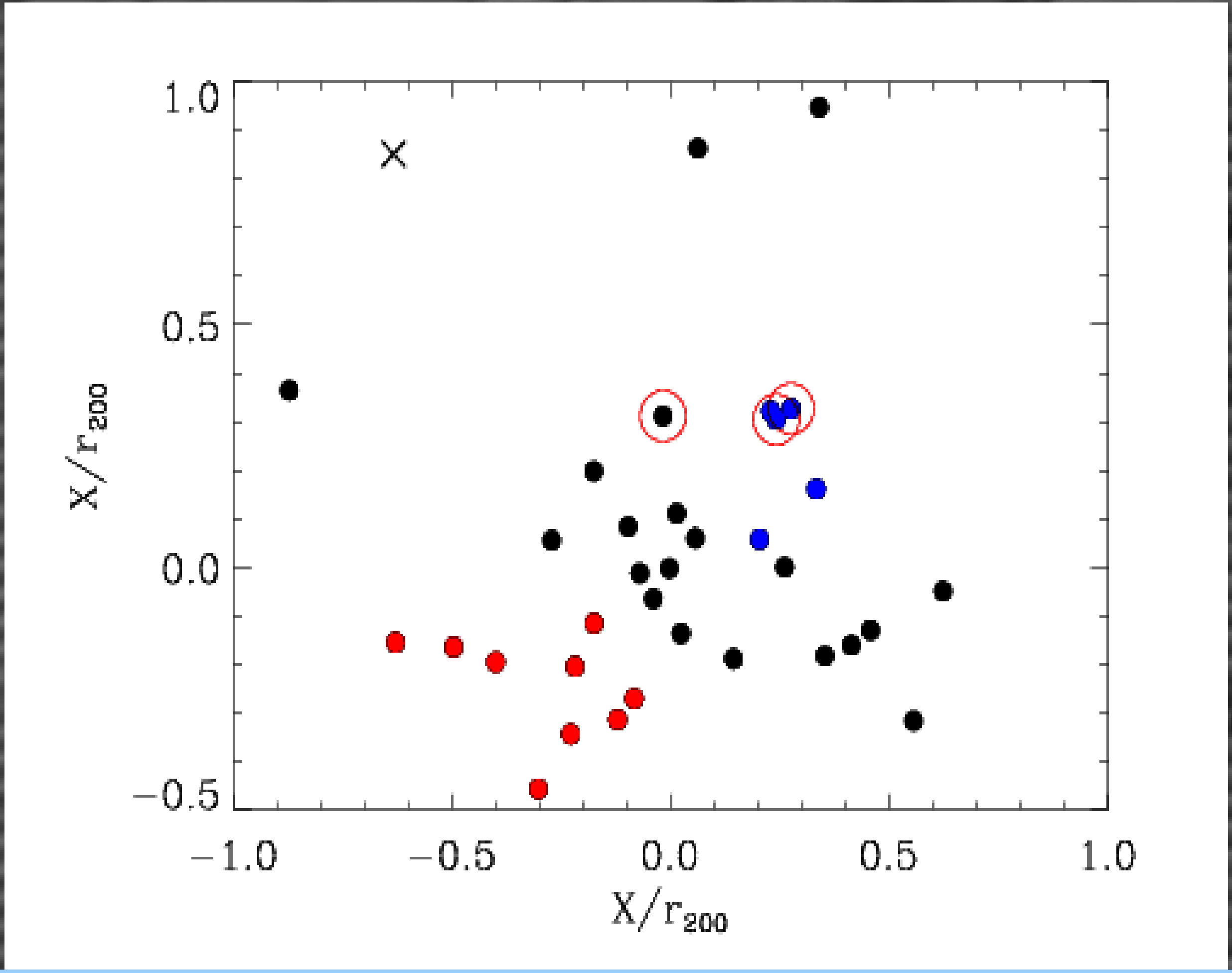
The effects of projection on the identification of substructure





Substructures identified in the 6-d MST differ from those identified in the projected MST

The effects of projection on the identification of substructure



Selecting only the lowest p_δ substructures improves the purity of the sample

Cross: galaxy outside the cluster in real space, but assigned to the cluster in projection
Colored circles: galaxies assigned to significant substructures in real space
Colored dots: galaxies assigned to significant substructures in projection

...sorry, we have not finished yet...

The best has yet to come!

The Intergalactic Humane Association monitored the animal action.

No animal was harmed in the making of this talk

INTERGALACTIC
HUMANE
ASSOCIATION.