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 $f(R,vel)$
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The ESO Nearby Abell Cluster Survey: a young 20-years old survey

1st observing run in 1989
(1996, ENACS I; den Hartog's thesis)
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~3000 galaxies with redshifts in the virial regions of 59 massive clusters

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

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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=\textit{NFW cuspy model}
Blue=\textit{core model}
Green=\textit{Isothermal Sphere}
Internal structure

Average cluster $M(r) \Rightarrow$ 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,

\((<v_r^2>/<v_t^2>)^{1/2} \approx 1.0^{+0.05}_{-0.2}\)

(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

\( \beta'(r) = \left( \frac{\langle v_r^2 \rangle}{\langle v_t^2 \rangle} \right)^{1/2} \)

(2004, ENACS XIII)
Internal structure

Orbits of galaxies in clusters:

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

(2004, ENACS XIII)

\[
\beta'(r) = \left( \frac{\langle v_r^2 \rangle}{\langle v_t^2 \rangle} \right)^{1/2}
\]
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 substructures of galaxy clusters?

1) Identify local 2\textsuperscript{nd} order overdensities in the galaxies distrib.
How do we analyse the *substructures* of galaxy clusters?

1) Identify local 2\textsuperscript{nd} 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

\[
\delta = \frac{1}{\sigma_p(R)} \left[ \frac{n_{\text{loc}} \delta_v^2}{[t n_{\text{loc}} - 1]^2} \right] + \left[ 1 - \sqrt{\frac{n_{\text{loc}} - 1}{\chi_{n_{\text{loc}} - 1}^+}} \right]^2
\]

with \( \delta_v = |\bar{v}_{\text{loc}} - \bar{v}_{\text{glob}}| \), and \( \delta_\sigma = \max(\sigma_p - \sigma_{\text{loc}}, 0) \)

(2002, ENACS XI)
Substructure

Distribution:

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

(2002, ENACS XI)
Orbits:

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

(2004, ENACS XIII)

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

3) estimate the dilution and contamination effects due to projection (i.e. relate $6d-p_\delta$ to $p_\delta$)
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\textsuperscript{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 $\delta, p_\delta$

3) estimate the dilution and contamination effects due to projection (i.e. relate $6d-p_\delta$ to $p_\delta$)
Define a model cluster:
Global $\sigma_v = \sigma_v$ of the cluster being analysed;
$\sigma_v(R) = \text{average of all clusters.}$

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]

$p_\delta = \text{fraction of times simulated } \delta > \text{observed } \delta$
Select the substructures less likely to be chance occurrences (i.e. with smaller $p_S$):
Use the model cluster to generate several mock 'reference' clusters without substructures.

Randomly draw the velocities of the cluster galaxies but keep their positions fixed, so the same MST subclusters are defined, but with different $\delta$ and $\rho_\delta$.

Compare the $p$ distributions of real and mocks.
Total number of galaxies in substructure

From probabilities to 'reliabilities'
Substructure: a new start!

Several issues to re-consider:

1) define independent substructures in a 'unique way'

2) estimate probabilities of observed $\delta$, $p_{\delta}$

3) estimate the dilution and contamination effects due to projection (i.e. relate $6d-p_{\delta}$ to $p_{\delta}$)
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 \( \rho_\delta \) in 6-D) determine the selection parameter in projection (e.g. a limiting \( \rho_\delta \)) so as to optimize completeness & purity of the substructures identified in projection.
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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 $p\delta$ 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
The Intergalactic Humane Association monitored the animal action.

No animal was harmed in the making of this talk.