GALAXY CLUSTER
FORMATION, MORPHOLOGY, SUBSTRUCTURE, MERGER

MORPHOLOGY

ROOD-SASTRY CLASSIFICATION based on the brightest galaxies
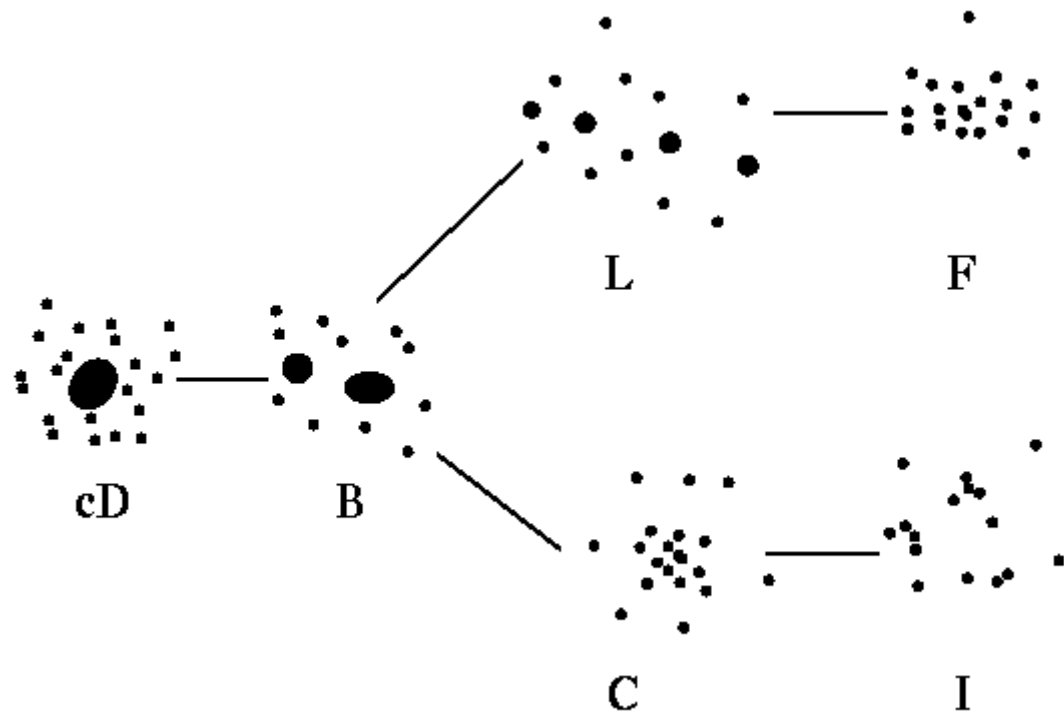
Clusters with cD central Do

Binary clusters,

Linear,

Flat,

Core,

Irregular

Within hierarchical cosmological scenario, clusters are though to form through the merger of smaller systems, likely at the intersection of the large scale structure (LSS).

Cluster merger is an ongoing process, with a lot of
 observational evidence in both local and distant Universe.
A connected feature is the presence of SUBSTRUCTURE.

OPTICAL STUDIES FROM GALAXIES >50%
of clusters show substructure
(small substructure ~10% of the total mass)
Major substructure (=major merger) only in 10% of clusters.
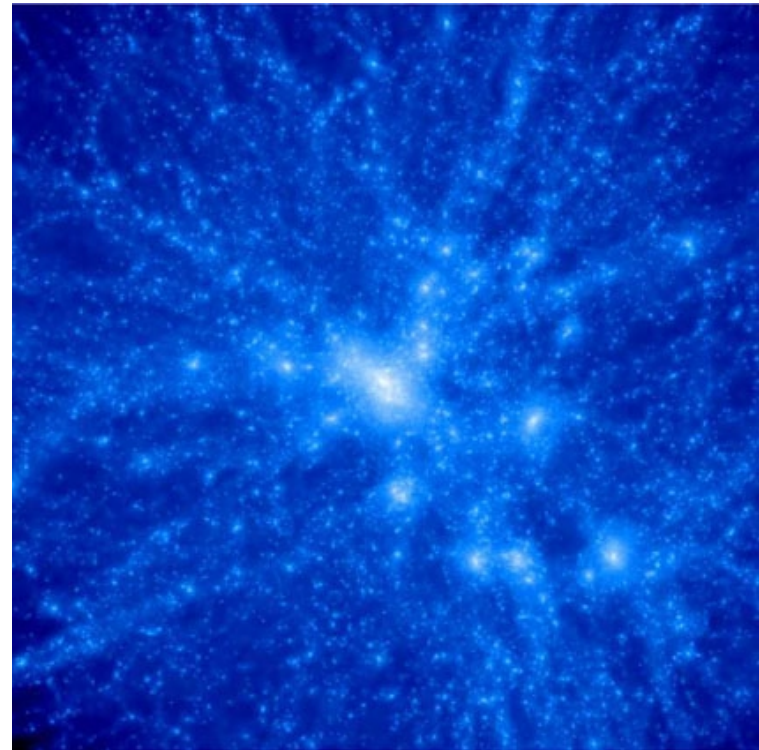
Methods of detection:
1D in the velocity space
2D gals density onto the sky
3D correlation between position and velocity

SUBSTRUCTURE MAY BE:
*cluster mergers,
*subsystems with system already relaxed (remnant),
*bound group that will merge,
*unbound group, projected onto the cluster.

Since the violent relaxation theory → Gaussian 1D velocity distribution
1D – tests often based on Gaussian.
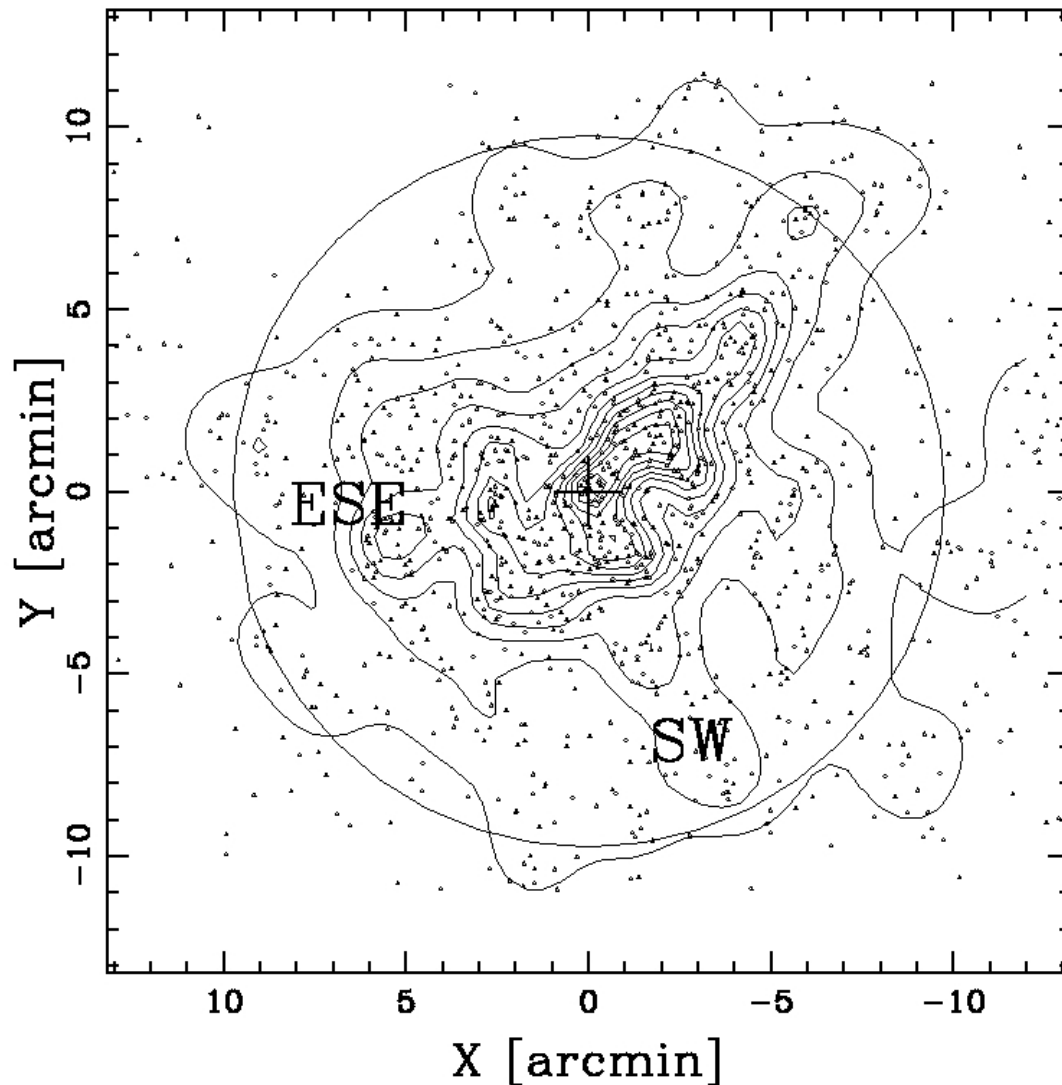This is instead the result for a non-parametric adaptive method of galaxy density.

A 10% OF CLUSTERS ARE FAR FROM DYNAMICAL EQUILIBRIUM →
MASS ESTIMATE VARIES BY A FACTOR 2

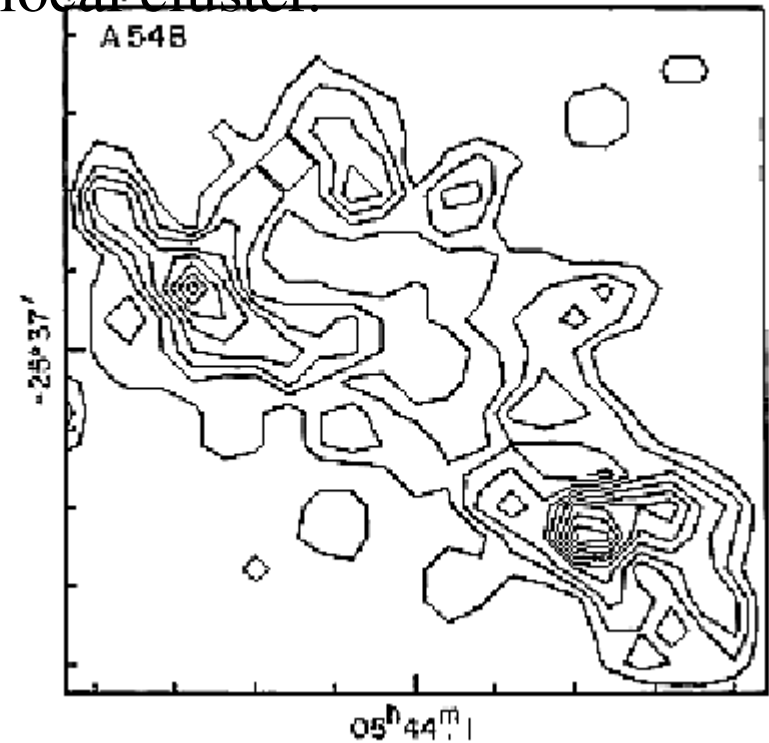σv estimate increases during the merger!
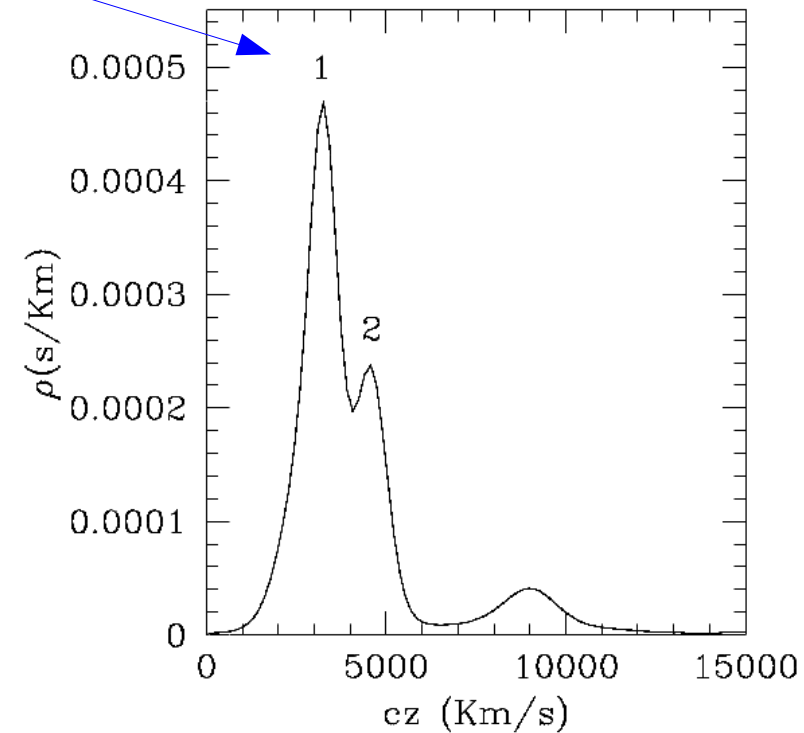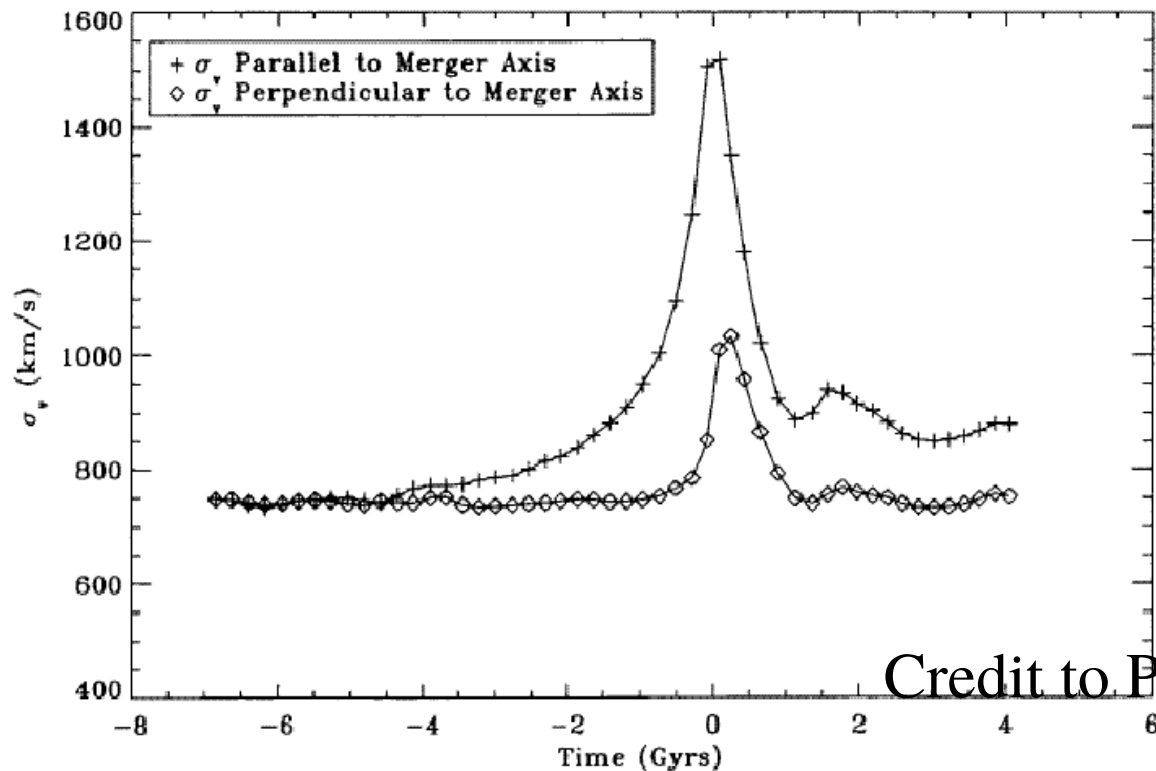
Credit to Pinkney 1996

2D analysis.

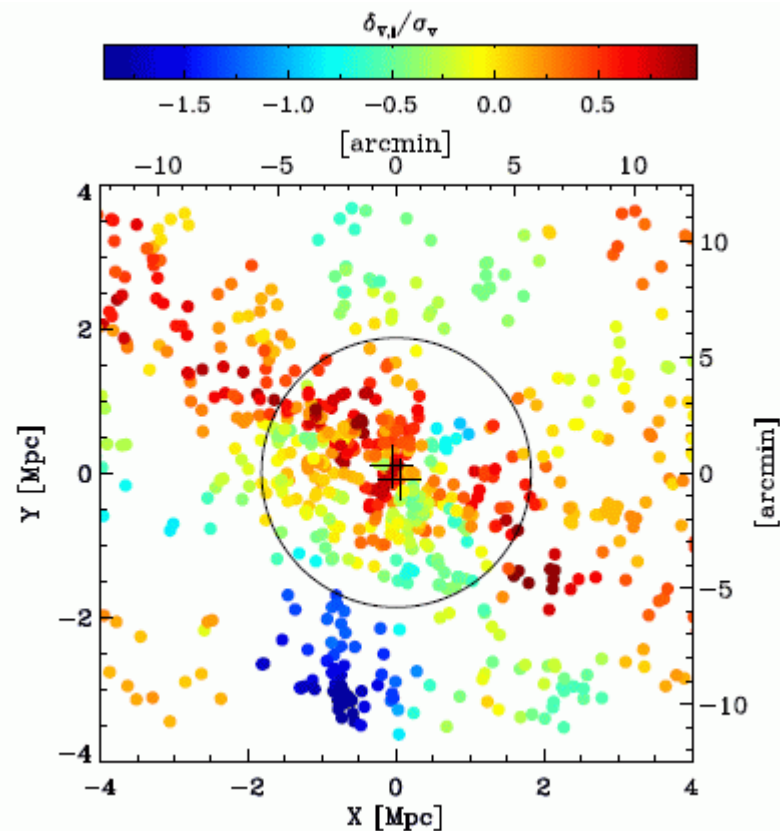Galaxy density isocontours.

Geller 1982.

For a local cluster.
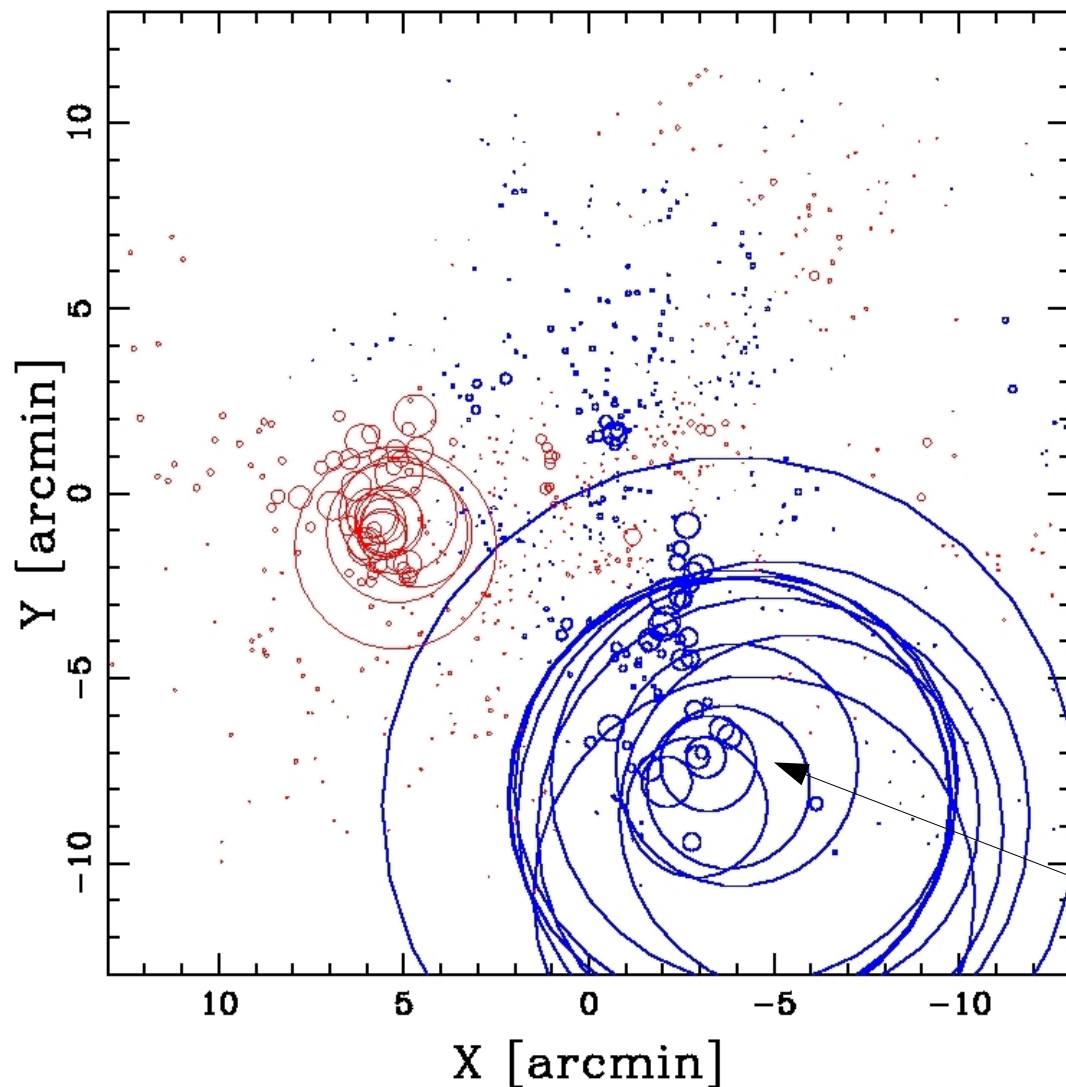

Ongoing work on Abell 209
CLASH-VLT data for >1000 gals
At z=0.2. 1116 cluster gals.
PI Piero Rosati.
In TS, MG,A.Biviano,M.Nonino,
+others and postdocs

CLASH-VLT data MACS J0416 at z=0.4 and Abell 209 at z=0.2

3D-analysis. Dessler-Schectman test
For departure of the local mean velocity
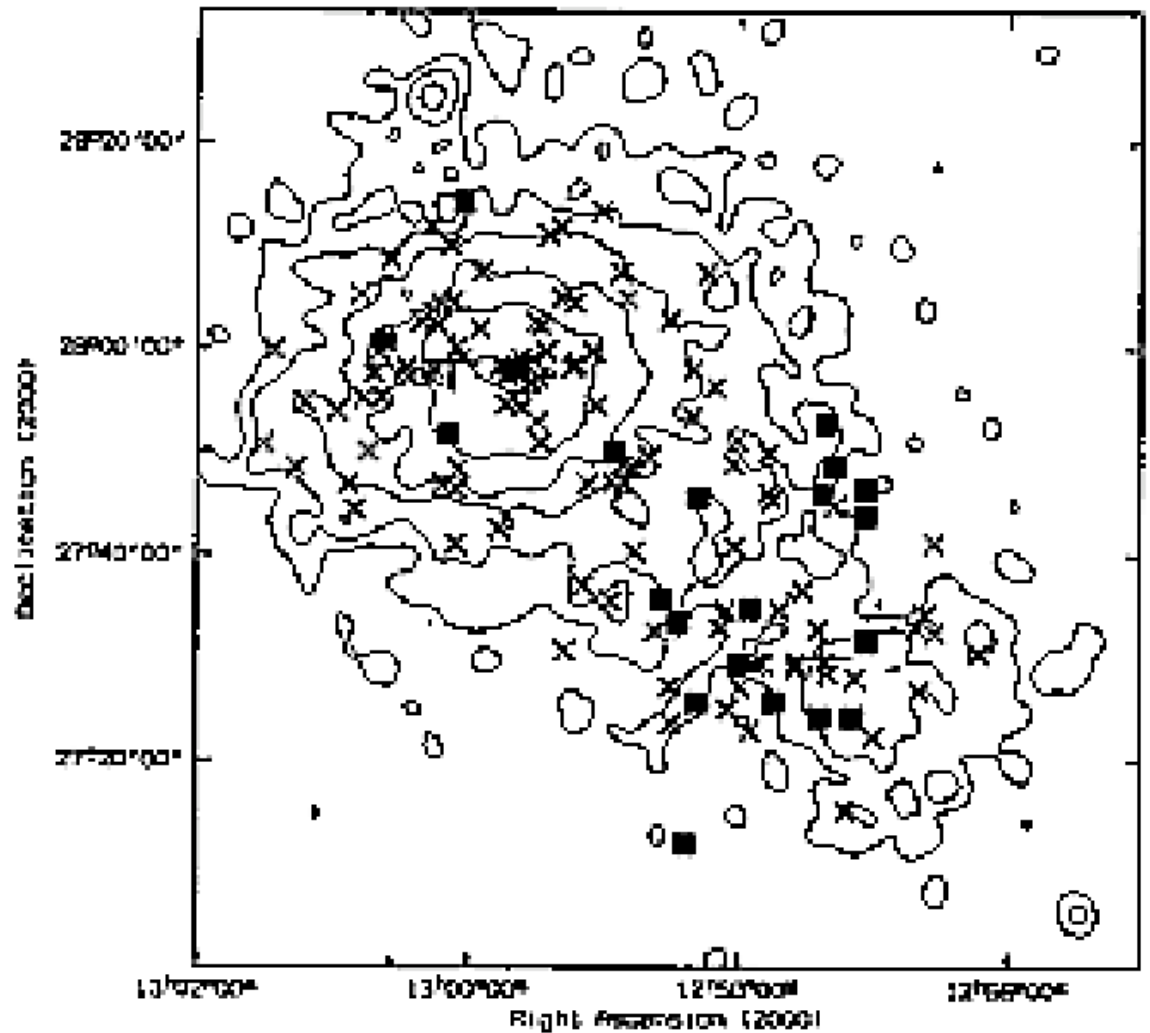From global mean velocity.
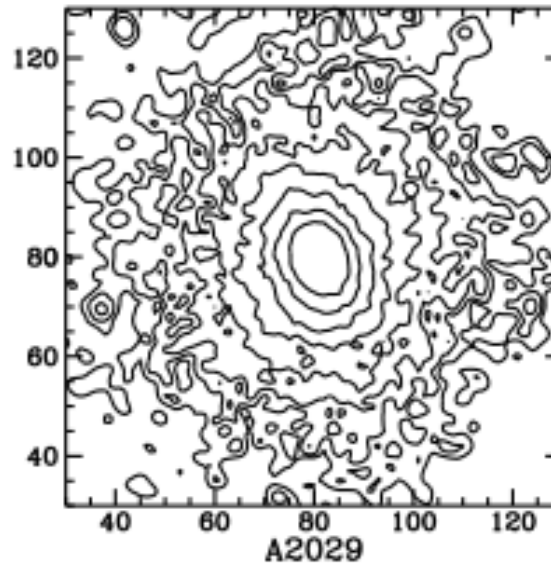

Statistical sign. through
Montecarlo simulations.

Low mean velocity

Cluster mergers can stop or enhance the star formation in galaxies.
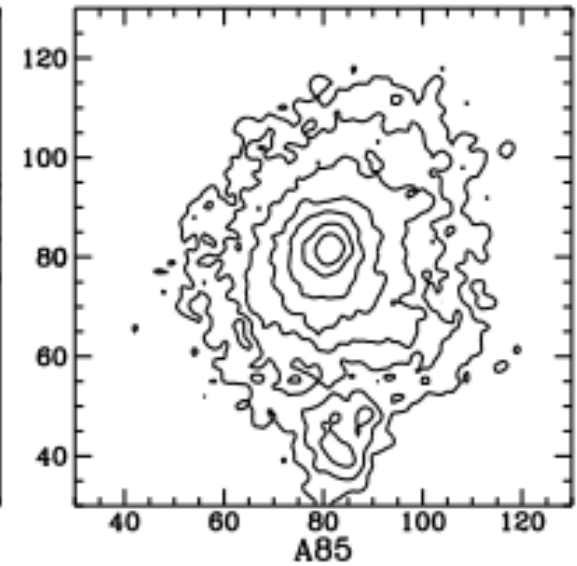
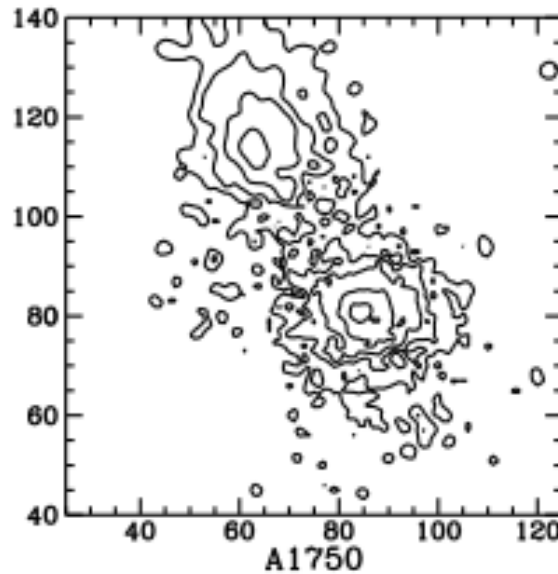Caldwell+1993   Post Starbust (PSB) galaxies and cluster mergers

X-ray morphology
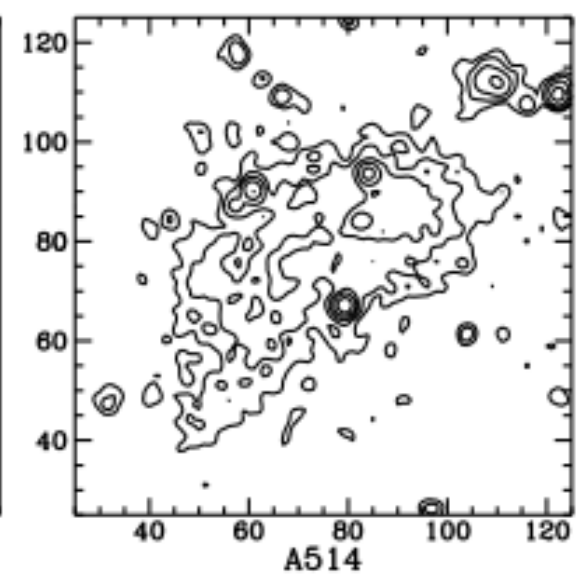Forman 1984
Rosat data.
Surface brightness
contours.

A2029
SINGLE

A85
PRIMARY WITH
SMALL SECONDARY

A1750
DOUBLE

A514
COMPLEX

2.1.   METHODS

Perhaps the most common approach used to quantify the morphologies of a large number of X-ray cluster images has been with a measure of the X-ray ellipticity (e.g., McMillan et al. 1989; Davis 1994; Mohr et al. 1995; Gómez et al. 1997; Gómez et al. 2000; Kolokotronis et al. 2001). This method is not a particularly good indicator of the dynamical state since both relaxed and disturbed clusters can have significant ellipticity. And even disturbed clusters can have small ellipticity if the substructure is distributed symmetrically about the cluster center. Moreover, even if both the ellipticity and associated position angles are considered they only provide a crude measurement of cluster morphology and have never been shown to provide an interesting distinction between the variety of morphologies exemplified by the Jones & Forman classes.

A better method is the center-shift introduced by Mohr et al. (1993). This popular method has been applied in various forms to X-ray cluster images in several studies (e.g., Mohr et al. 1995; Gómez et al. 1997, 2000; Rizza et al. 1998; Kolokotronis et al. 2001). The basic idea is to divide up a cluster image into a series of circular annuli having different radii but with centers located initially at a guess for the cluster center. The center-shift is then given by the rms difference between the centroid computed for each of these annuli and the weighted average centroid for all annuli.

Since the center-shift is sensitive only to asymmetries in the X-ray images (in particular non-ellipsoidal configurations) it is much more reliable than the ellipticity as an indicator for when a cluster is relaxed. However, it is not transparent how the center shift translates into a physical measure of the dynamical state. And since the center-shift is most sensitive to mergers of equal-mass subclusters, it cannot by itself distinguish the full range of structures exhibited by the Jones & Forman morphological classes.

If the only objective were to distinguish the full range of cluster morphologies then the logical procedure would be to decompose cluster images into a set of orthogonal basis functions of which wavelets (see § 1) are the probably best example. The wavelet coefficients would then define the parameter space of cluster morphologies. Unfortunately, there is no obvious connection (of which I am aware) between wavelet coefficients and a physical measure of the dynamical state.

One method that is both closely related to the cluster dynamical state and provides a quantitative description of the full range of Jones & Forman morphological classes is the "power ratio" method (Buote & Tsai 1995, 1996; Buote 1998). The power ratios are constructed from

the moments of the two-dimensional gravitational potential. Specifically, one evaluates the square of the moments over a circle of radius, R, where the origin is located at the center of mass or at the largest mass peak. The ratio of term, m, to the monopole term is called a "power ratio",

$$\frac{P_m}{P_0} \equiv \frac{\langle (\Psi_m^{int})^2 \rangle}{\langle (\Psi_0^{int})^2 \rangle}, \tag{1}$$

where Ψ_m^{int} is the mth multipole of the two-dimensional gravitational potential due to matter interior to the circle of radius, R, and $\langle \cdots \rangle$ represents the azimuthal average around the circle. In detail we have,

$$P_0 = [a_0 \ln(R)]^2, \tag{2}$$

for $m = 0$,

$$P_m = \frac{1}{2m^2 R^{2m}} \left(a_m^2 + b_m^2 \right) \tag{3}$$

for $m > 0$. The moments a_m and b_m are given by,

$$a_m(R) = \int_{R' \leq R} \Sigma(\vec{x}') (R')^m \cos m\phi' d^2 x',$$

$$b_m(R) = \int_{R' \leq R} \Sigma(\vec{x}') (R')^m \sin m\phi' d^2 x',$$

where $\vec{x}' = (R', \phi')$.

These ratios are directly related to the 2D gravitational potential if one has a map of the 2D surface mass density such as provided by weak gravitational lensing studies. For X-ray studies Σ is replaced with the X-ray surface brightness, Σ_x, and therefore the power ratios in X-ray studies are really derived from a pseudo potential. These ratios are most sensitive to structures on the same scale as the aperture radius, R.

When the aperture is located at the peak of the X-ray emission the dipole power ratio, P_1/P_0, provides structural information similar to the center shift discussed above (see also Dutta 1995). For an aperture located at the centroid of the surface brightness the dipole moment vanishes. In this case the quadrupole power ratio, P_2/P_0, is sensitive to the degree of flattening and is related to the ellipticity. But unlike ellipticity P_2/P_0 is also sensitive to the radial profile of the X-ray emission.

set of basis functions for the (pseudo) potential and thus are well suited to classify the wide range of observed cluster morphologies.

To get a feel for the power ratios let us see how they behave on the *ROSAT* PSPC images of clusters in the different Jones & Forman morphological classes shown in Figure 3.2. The four clusters inhabit the extreme Jones & Forman classes. A2029 is a smooth, single component system apparently in a relaxed state. A85 has a regular dominant component but with a small structure ~ 0.6 Mpc to the S. A1750 is a double cluster consisting of two roughly equal-sized components separated by ~ 1 Mpc. A514 is a highly irregular aggregation of structures.
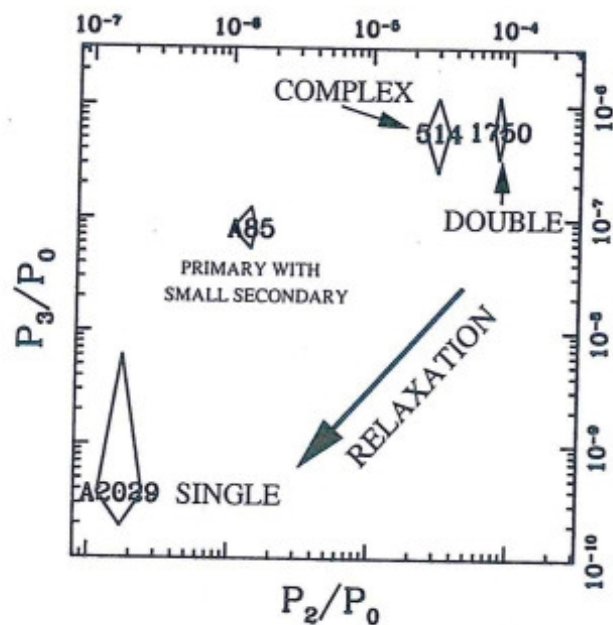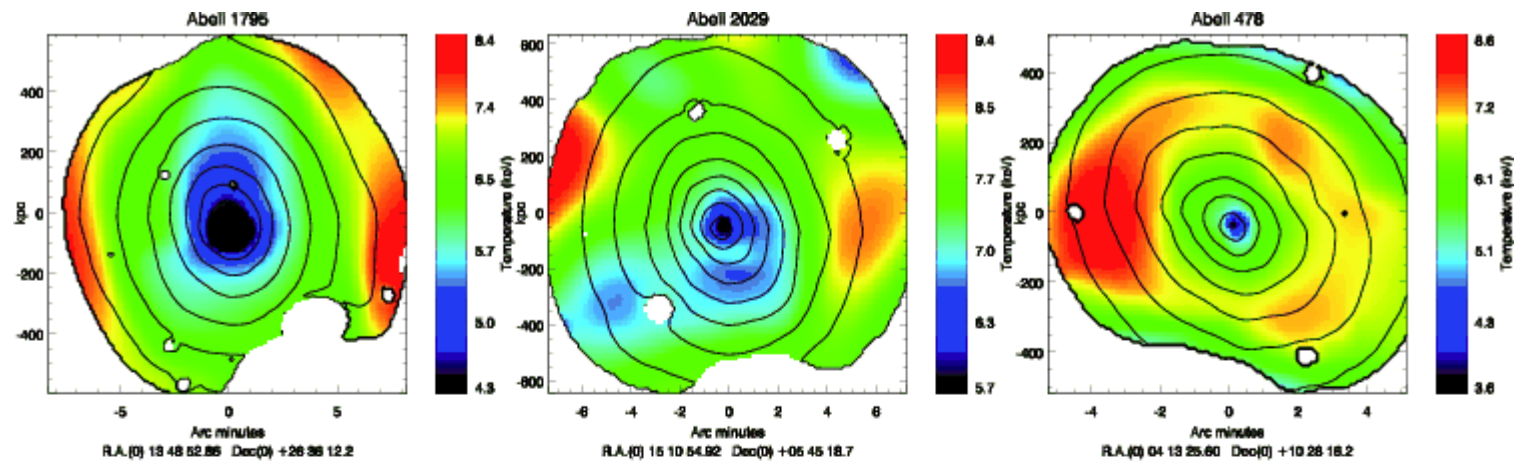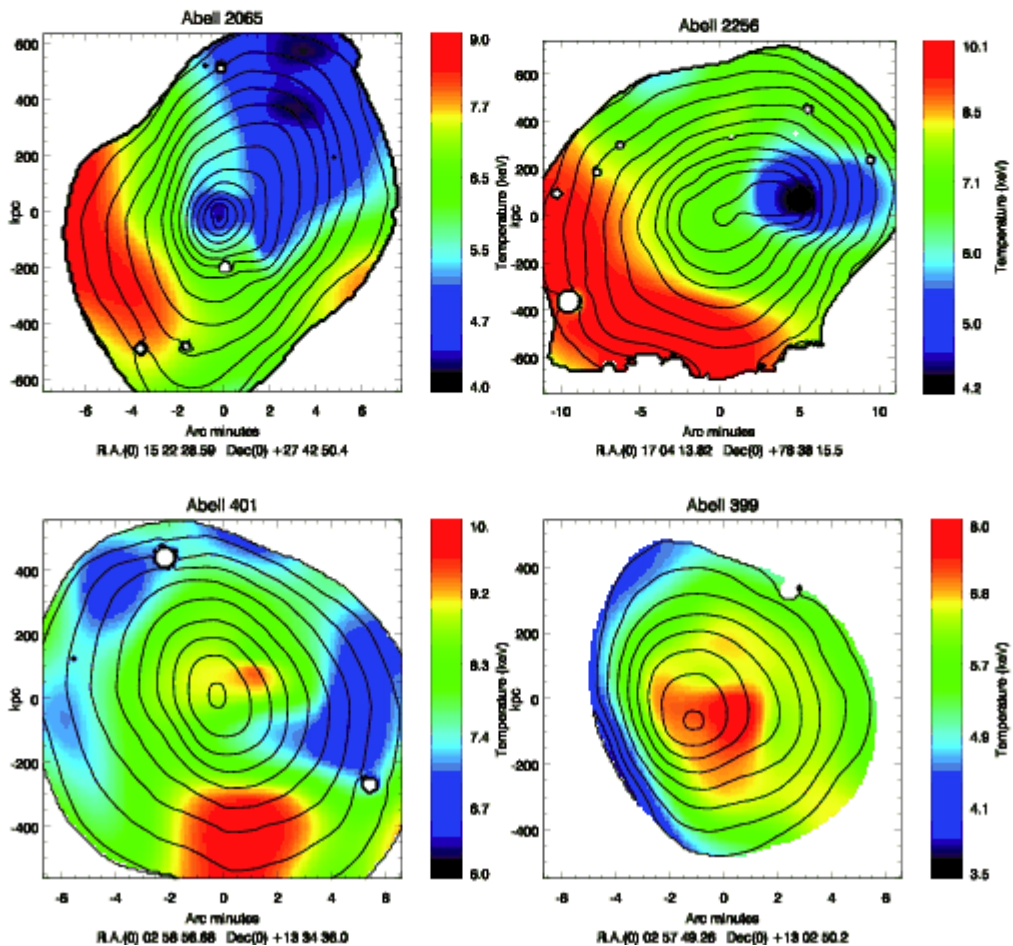

Figure 3.6. Power ratios (from Buote & Tsai 1996) for the clusters in Figure 3.2 computed within a circular aperture of 1 Mpc radius located at the centroid of the X-ray emission.

In Figure 3.6 I show the power ratios, P_2/P_0 and P_3/P_0, of these clusters computed for a 1 Mpc aperture[2] where the aperture is located at the centroid of the X-ray emission (i.e., analog of the center of mass).

Temperature
maps overlaid
To brightness
Isocontours.
Bourdin and
Mazzotta 2008.

A cool core
is a sign
of a relaxed cluster.

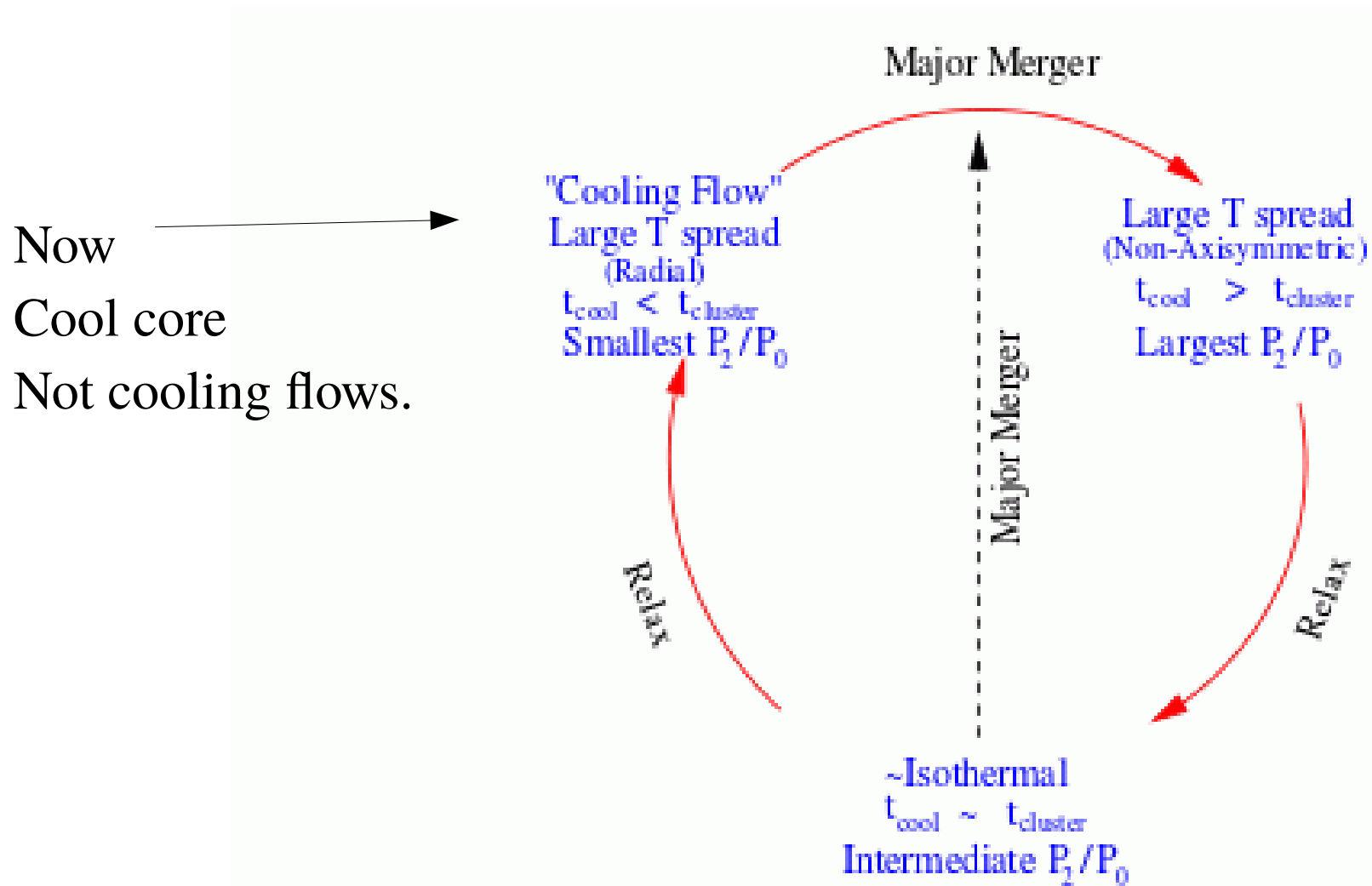Buote 2002. A scenario for cluster evolution.

Now

Cool core

Not cooling flows.

Major Merger

"Cooling Flow"
Large T spread
(Radial)
$t_{cool} < t_{cluster}$
Smallest P_2/P_0

Large T spread
(Non-Axisymmetric)
$t_{cool} > t_{cluster}$
Largest P_2/P_0

Major Merger

Relax

Relax

~Isothermal
$t_{cool} \sim t_{cluster}$
Intermediate P_2/P_0

Figure 1.17. A possible description of the evolution of the X-ray temperature structure and image morphology during the formation and evolution of a cluster.
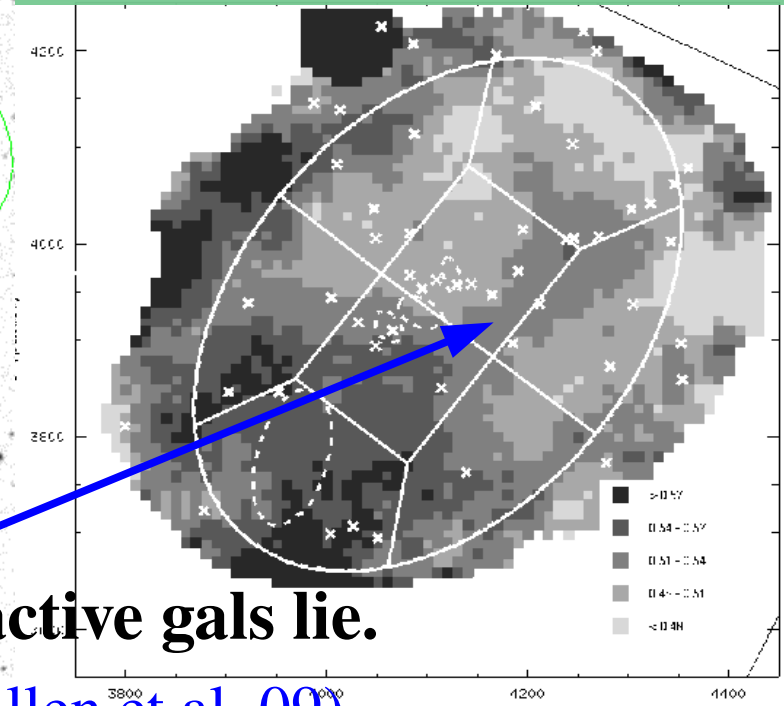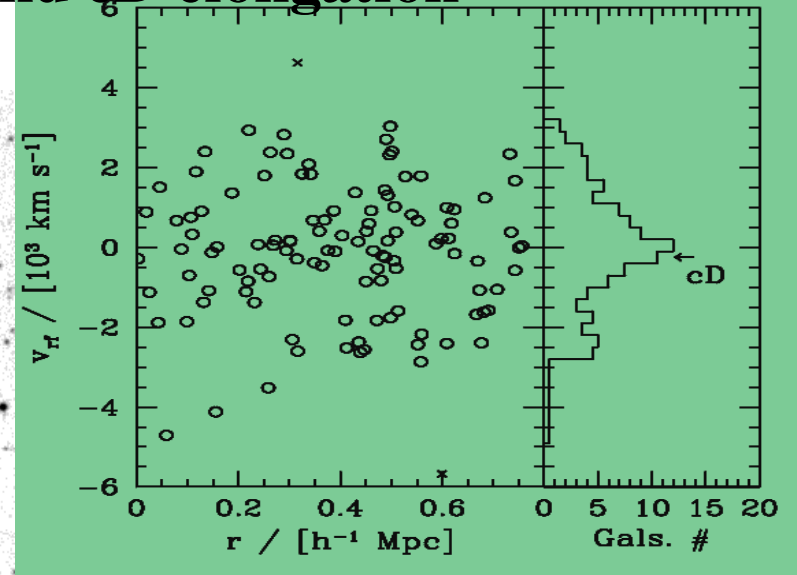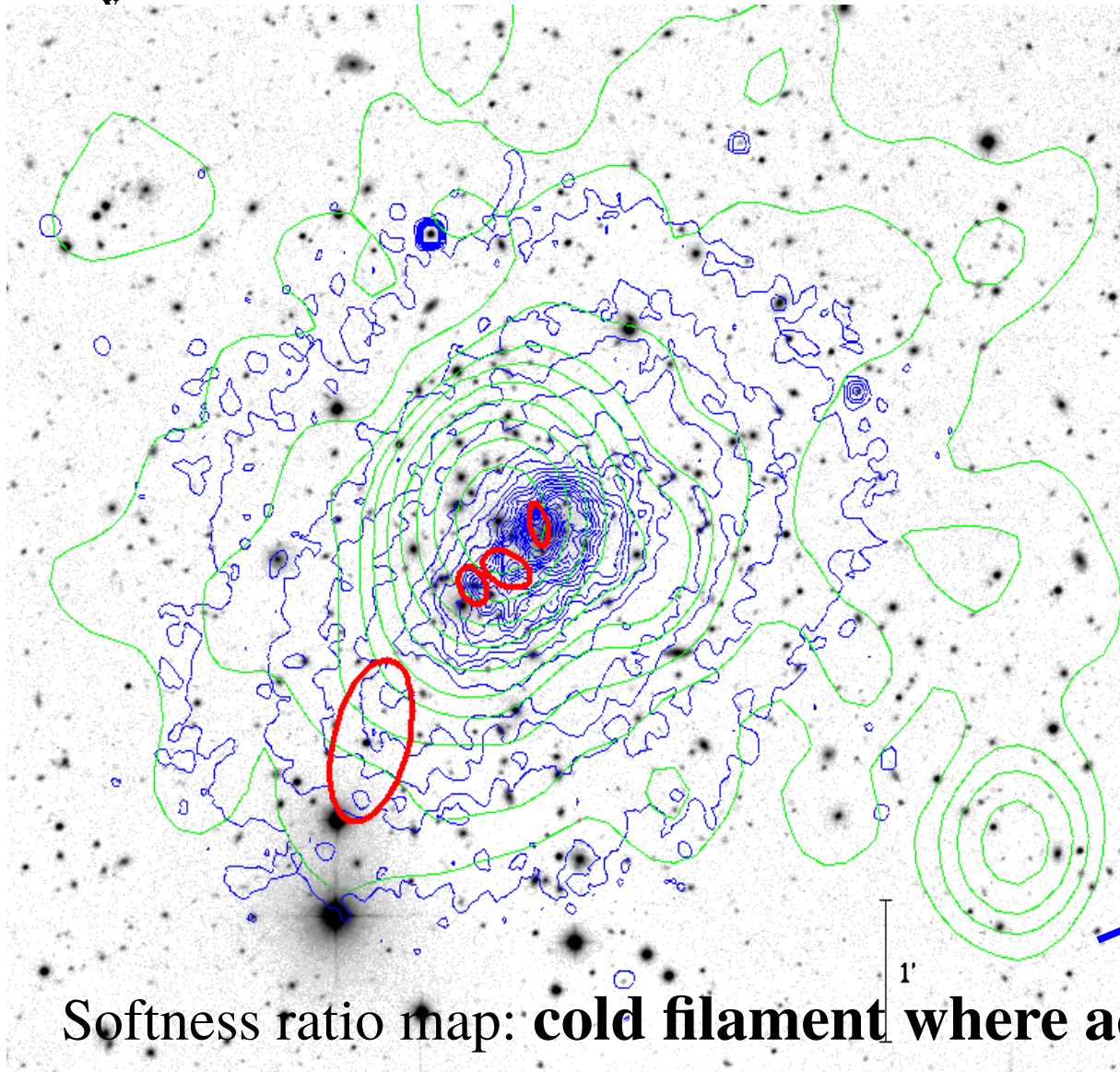
A2219, z~0.22
Radio halo

(Boschin, MG, Barrena, et al. 2004, AA, 416, 839)
TNG/Dolores +CFHT multiobject spectroscopy

SE-NW cluster and cD elongation

σ_v ~1400 kms-1

Softness ratio map: **cold filament where active gals lie.**

Recent discover of a cold front (Million & Allen et al. 09).