Cluster density profiles: galaxies

Bahcall ARA&A

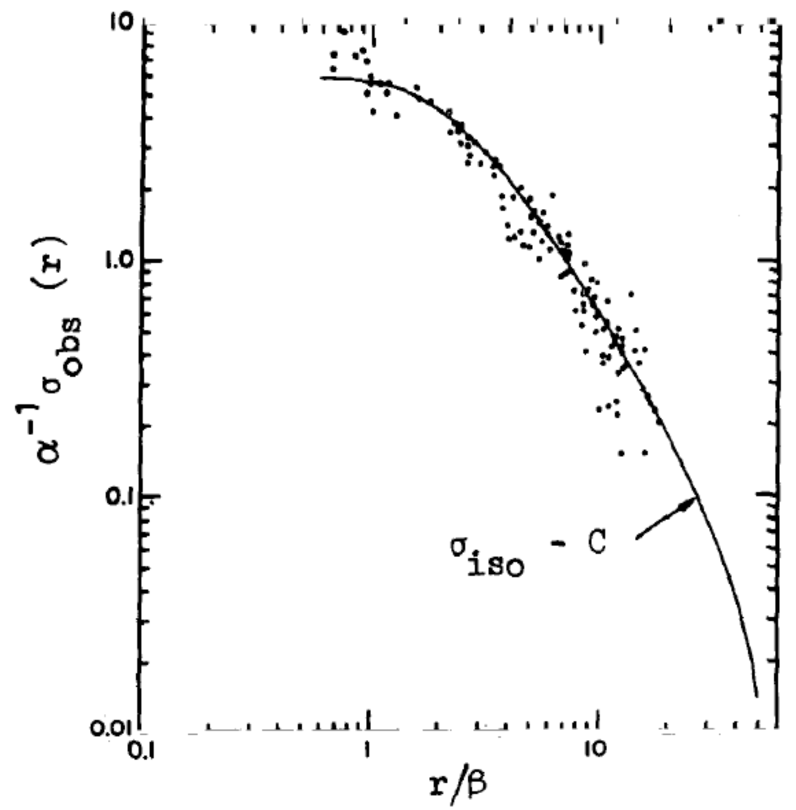


Figure 2 Projected galaxy distributions in 15 regular clusters (studies by Bahcall 1975a) plotted as a function of distance from the cluster centers. All distributions are normalized with their best fit parameters α (density normalization) and β (distance scale). The solid line is the projected bounded Emden isothermal gas sphere model with a cutoff $C = 0.1$.

Cluster density profiles: galaxies

Carlberg et al 1997:
15 CNOC clusters

The average projected galaxy number density profile, $\Sigma(R)$, is fit with the projection of the volume density function,

$$\nu(r) = \frac{A}{r(r + a_\nu)^p}, \quad (2)$$

where p is fixed at either $p = 2$ (NFW) or $p = 3$ (Hernquist). The results for $p = 2$ are shown in Figure 1 as the solid line. The dashed lines are described below. Both the $p = 2$ and $p = 3$ forms are statistically acceptable fits by the χ^2 test. We will consider only the $p = 2$ form for the rest of this paper. The fitted scale radius is $a_\nu = 0.27$, with a 95% confidence range of 0.13–0.43 from the χ^2 distribution.

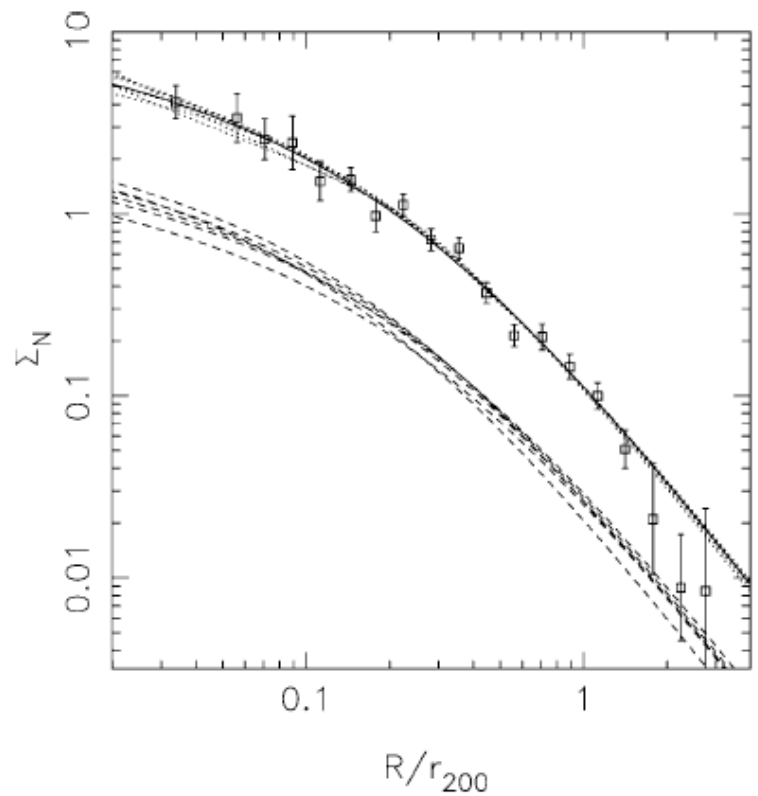


FIG. 1.—Average galaxy density profile of the clusters using the BCG as the center. In the text, we demonstrate that this galaxy number density profile is statistically equal to the projected average mass profile. The solid line is the projection of the NFW function. The dotted lines are the projection of the product of an assumed NFW mass profile with the dynamically derived local light-to-mass ratio, $\nu(r)/\rho(r)$. The dashed lines are the projected NFW mass profiles themselves, offset by downward half a dex.

Physical processes:

The gravitational radius of a cluster may be defined as

$$R_G \equiv \frac{2GM}{3v_r^2} \simeq 3h_{50}^{-1}\ \mathrm{Mpc} \times (M/10^{15}\ M_\odot)/(v_r/10^3\ \mathrm{km\ sec^{-1}})^2, \tag{10}$$

where M is the cluster mass and v_r is the observed radial velocity dispersion. R_G, defined as in (10), is the radius at which the gravitational energy approximately equals the kinetic energy of a galaxy moving in the cluster.

with an appropriate analytic function. Fits with a bounded isothermal model with a typical cutoff of $C \simeq 0.015\ \sigma_{\mathrm{iso}}(0)$ (Bahcall 1975a) yield a cutoff (or halo) radius $[\sigma_{\mathrm{iso}}(R_h/\beta) \equiv C]$

$$R_h \simeq 20\, R_c \simeq 5\, h_{50}^{-1}\ \mathrm{Mpc}. \tag{12}$$

Physical processes: crossing time

A galaxy travelling through a cluster with a velocity v will cross a radius R in a cluster in a crossing time given by

$$T_{CR} = R/v \simeq 6 \times 10^8 \text{ yr} \times [(R/\text{Mpc})/(v_r/10^3 \text{ km sec}^{-1})], \quad (15)$$

where v_r is the observed radial velocity (spherical symmetry, $v^2 = 3v_r^2$, is assumed throughout). The crossing time for a typical distance of 10 Mpc is $\sim 6 \times 10^9$ yr, only slightly shorter than the Hubble time (2×10^{10} yr). Galaxies at the outer regions of large superclusters ($R \gtrsim 35$ Mpc) have crossing times $\gtrsim 2 \times 10^{10}$ yr and therefore have not yet had time to travel through the center of the cluster.

Galaxies in the outer regions of clusters have not crossed once.

Two-body relaxation time: Bahcall ARA&A

The two-body relaxation time for galaxies in clusters, which measures the time in which collisions can produce a large alteration in the original velocity distribution, is given by (see Chandrasekhar 1942, Spitzer & Hart 1971)

$$T_R = v^3/4\pi G^2 M_g^2 N \ln\Lambda \tag{16}$$
$$\sim 2 \times 10^{10}\,\text{yr} \times [(v_r/10^3\,\text{km sec}^{-1})^3/(M_g/10^{12}\,M_\odot)^2(N/10^3\,\text{gal Mpc}^{-3})\ln\Lambda],$$

where v and M_g are the galaxy velocity and mass, N is the number density in the cluster, and $\ln\Lambda$ is the ratio of maximum to minimum impact parameters. If relaxation is due to the dynamical friction of a galaxy moving through a homogeneous and isotropic background distribution of lighter bodies, the term NM_g in Equation (16) should be replaced by ρ_{bg}, the background mass density in the cluster; thus $T_{DF} = v^3/(4\pi G^2 M_g \rho_{bg} \ln\Lambda)$. The dynamical friction time is related to the two-body relaxation time through the ratio of mass density in bright galaxies to the density in the background of lighter bodies. Galaxies relax faster the larger their mass and the higher the galaxy density is in their vicinity. In the central parts of regular clusters, where $N \sim 3 \times 10^3$ gal Mpc^{-3} [see (9)], the two-body relaxation time may be $\sim 10^9$ yr for the massive galaxies ($M_g \sim 10^{12}$ $M_\odot$); some relaxation could have occurred in these central regions. No appreciable two-body relaxation is expected for much lighter galaxies.

Galaxies relax faster the larger their mass and the higher the galaxy density

Physical processes: collision time

The average time between successive collisions of a galaxy with other cluster members is given by

$$T_{\rm coll} = [2^{1/2} v N \pi R_g^2]^{-1} \sim 10^9\ {\rm yr} \times [(v_r/10^3\ {\rm km\ sec^{-1}})(N/10^3\ {\rm gal\ Mpc^{-3}})(R_g/10\ {\rm kpc})^2]^{-1}, \qquad (17)$$

where R_g is the galaxy radius. The effect of gravitational focusing is negligible since $v^2 \gg GM_g/R_g$. In the dense central regions of a regular cluster, the collision time is typically 10^8 to 10^9 yr for a galaxy with a radius of ~ 10 kpc. In the lower density parts of a regular cluster (or in irregular clusters), where $N \lesssim 100$ gal Mpc^{-3}, the time between collisions is much longer ($> 10^{10}$ yr). For a galaxy radius larger than 10 kpc, the collision time is reduced considerably.

Physical processes: ICG Cooling time

The cooling time of the intracluster gas by bremsstrahlung emission is given by

$$T_{BR} = 9 \times 10^7 \text{ yr} \times T_8^{1/2} n_e^{-1}, \tag{18}$$

where T_8 is the gas temperature in 10^8 K, and n_e is the electron density in particles cm^{-3}. For a typical gas temperature of 10^8 K, as expected from the observed velocities in the cluster and as suggested by the observed X-ray emission, and a typical density of $\sim 10^{-3}$ cm^{-3} (see Section 5), the cooling time is rather long ($\sim 10^{10}$–10^{11} yr). Therefore, gas of this density that is heated to 10^8 K will stay hot for roughly the cluster lifetime.

Physical process: Disk Galaxies

Collisions and Interactions

- Response of a galaxy depends on internal structure and encounter speed
  - Fast encounter: moderate, disk-wide response
  - Slow encounter: instabilities that result in strong nuclear activity
- Tidal effects of cluster potential
  - Strip off warm halo gas
- Ram pressure stripping
  - •Pram ~ density_gas v^2 galaxy
  - infalling galaxies create shock wave
  - strips gas out of halo and disk

$$P_{RAM} \propto \rho_{gas} V^2$$

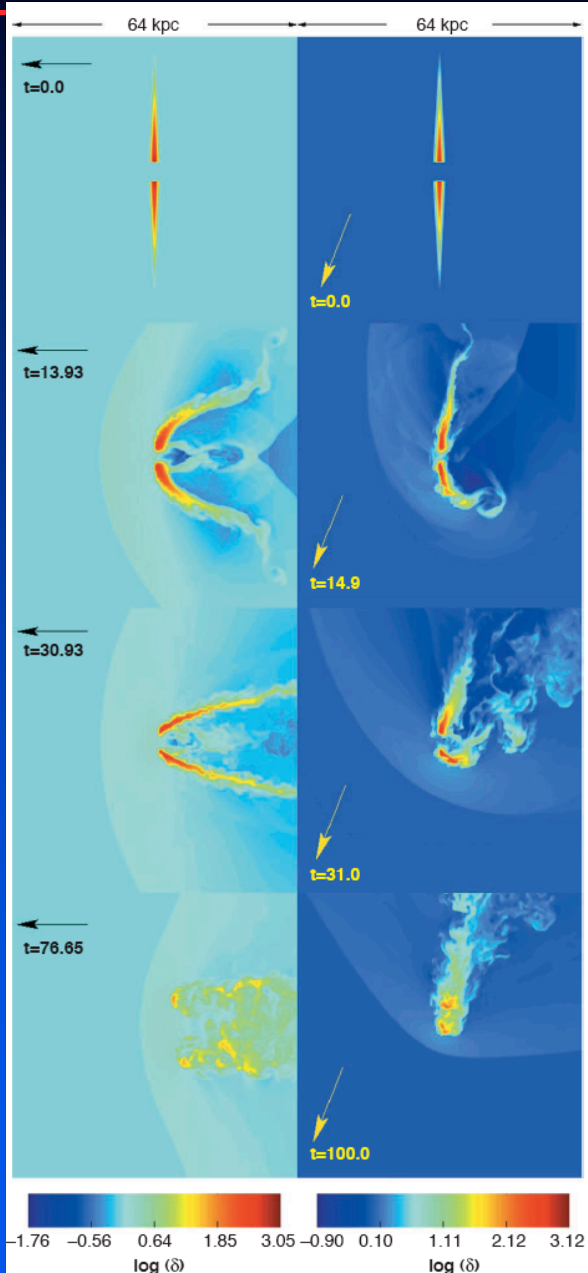
Physical process: Group environment

Infalling groups may be the site of much interaction

- Low velocity encounters more important
- substructure in X-ray maps

BUT REPEATED fast encounters in CLUSTERS can drive strong response in galaxies

- galaxy harassment
- harassment is important only for low-luminosity galaxies



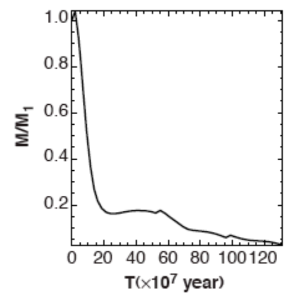


Fig. 1 (**left**). The evolution of the gaseous disk of a spiral galaxy moving face-on (left column) and inclined 20° to the direction of motion (right column) through a diffuse hot intracluster medium. Each snapshot shows the density of gas ($\delta = \rho/\rho_{ICM}$) within a 0.2-kpc slice through the center of the galaxy and each frame is 64 kpc on a side. Note how rapidly the disk material is removed: within 100 My, 100% of the HI is lost. We do not show the stellar disk, bulge, or dark matter halo, which remain unaffected by the loss of the gaseous component. The box size is 64 kpc and the hydro grid has 256^3 cells. **Fig. 2** (**right**). Mass loss as a function of time for the model including 10 little holes and inhomogeneous density. We plot the evolution of the gaseous mass within a cylindrical slice of 25-kpc radius and 2-kpc thickness, centered on the center of mass of the stellar disk. Initially, ram-pressure stripping dominates the gas-loss process and the entire outer disk is removed in a very rapid time scale. Viscous and turbulent stripping operates continuously, but over a longer time scale, resulting in a roughly linear rate of mass loss. We stop this simulation after 130 My, by which time 97% of the gas disk has been removed.

Quilis et al (2000)

- Disk of spiral galaxy
- Diffuse ICM
- Milky Way like galaxy
- Ram pressure and turbulent and viscous stripping
- All HI stripped in 0.1 Gyr
- Depends on details of the simulation

Physical process: Disk Galaxies

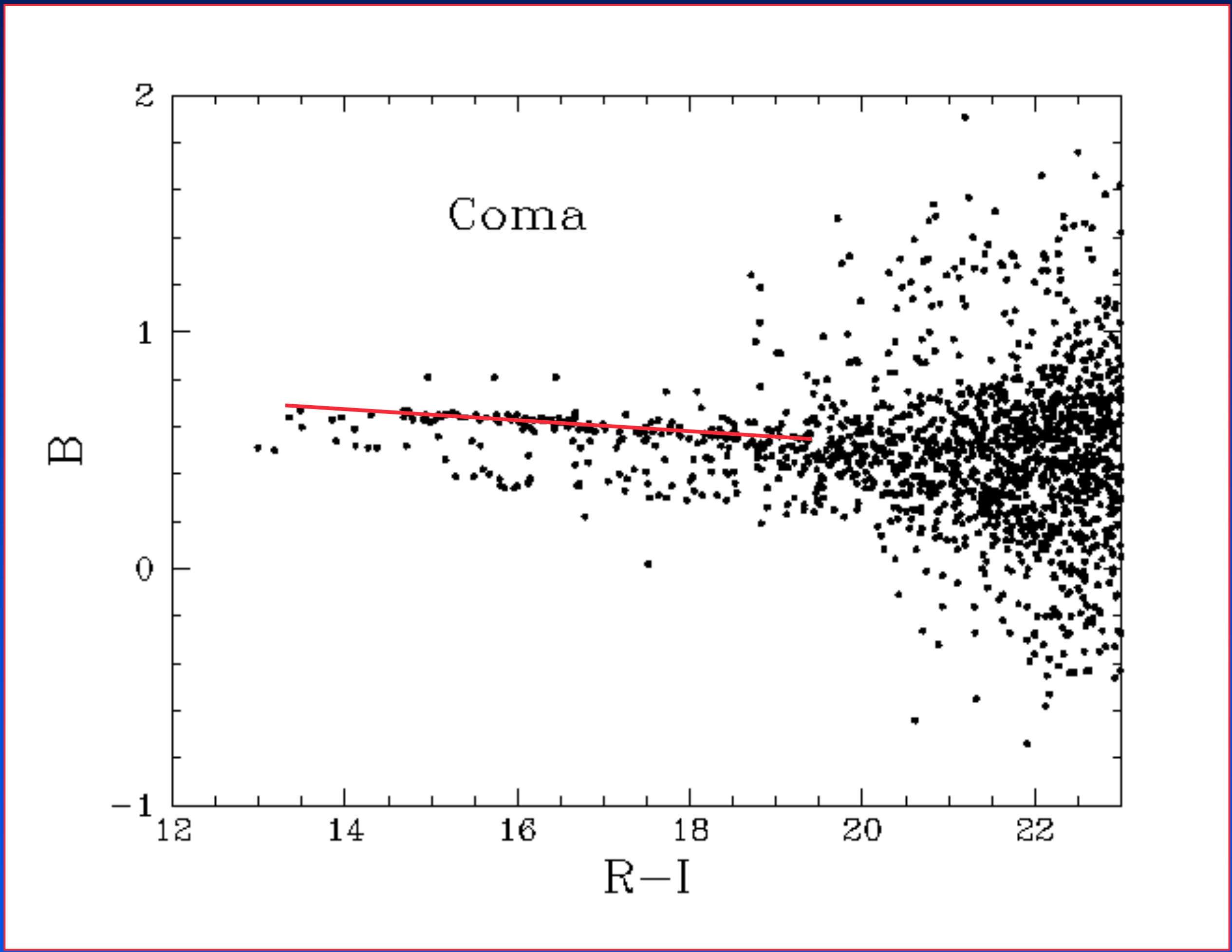
Strangulation of star-formation

- Infalling spirals have the warm gas in their outer halos stripped off by tidal interaction with the cluster potential.
- Slowly starves star formation.
- Balogh, Navarro, Morris 2000, Diaferio et al 2001.

The colour-magnitude relation in clusters

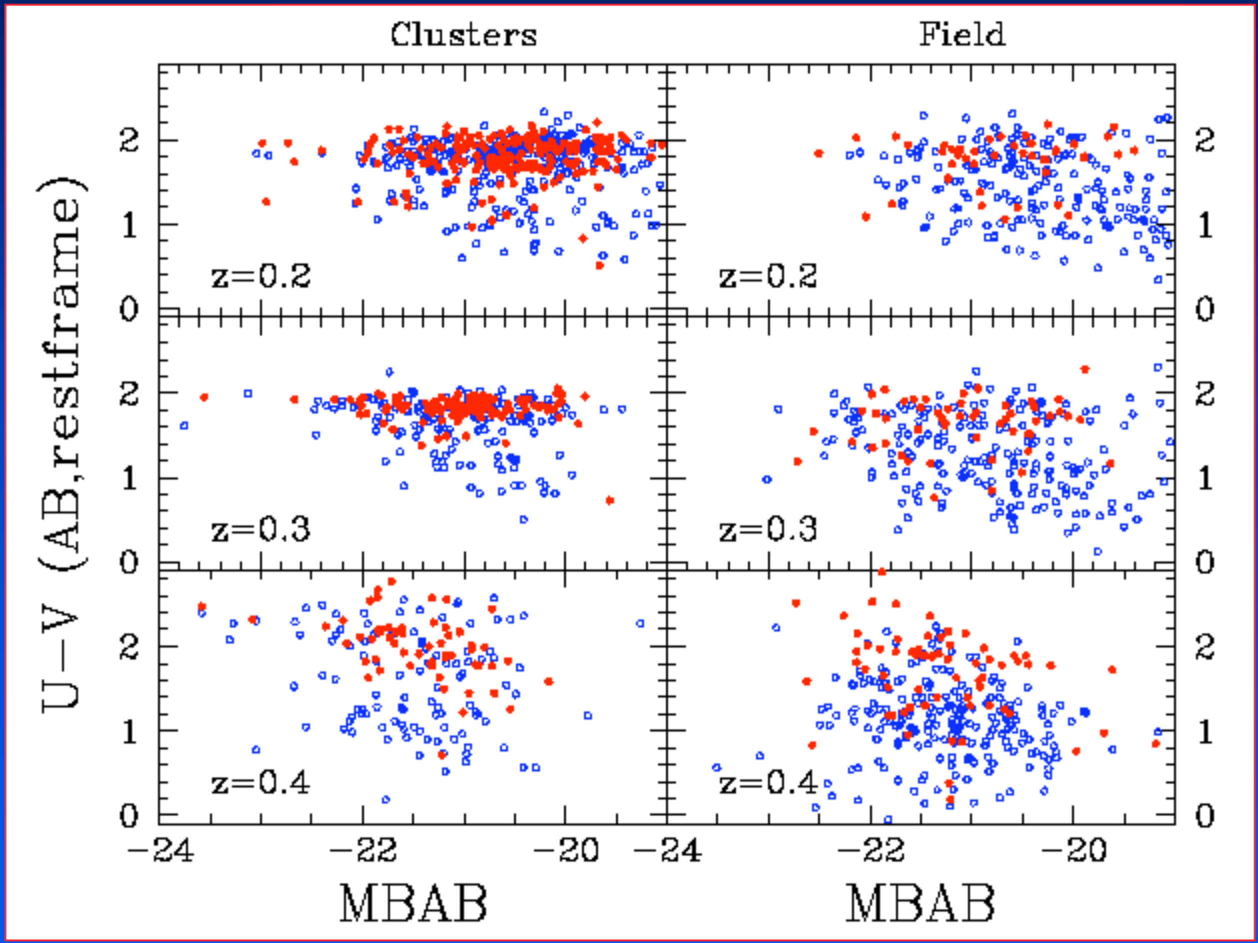
E/S0 galaxies form a tight red sequence

There are also galaxies that scatter to bluer colors



Lopez-Cruz (1999)

The field galaxy population is evolving



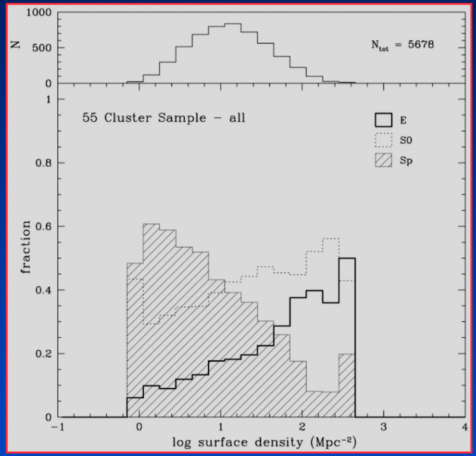
The Local Morphology-Density Relation

There exists a well-defined relation between the local galaxy density (or cluster-centric radius) and the mix of morphological types

In high-density regions the population is dominated by ellipticals, in low density regions, spirals.

Alternatively:

Near the cluster center the population is dominated by ellipticals, in the outer regions, spirals.



Dressler (1980)

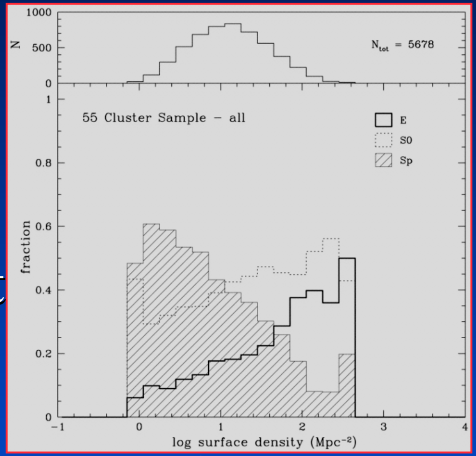
Dressler et al (1997)

The morphology-density relation in local clusters

The effect was discovered as a morphology-radius relation in clusters by Melnick & Sargent (1977)

For "irregular" clumpy clusters, the effect was absent but it is difficult to define the cluster center in these cases.

Dressler (1980) looked for the correlation with local galaxy density



Dressler 1980

Dressler et al 1997

The primacy of either the morphology-density relation or the morphology-radius relation continues to be debated (e.g., Whitmore et al (1991,1993)

The morphology-density relation

Visual classification of galaxies to some magnitude limit ($M_v = -20$)

Select comparable cluster areas at high and low redshift

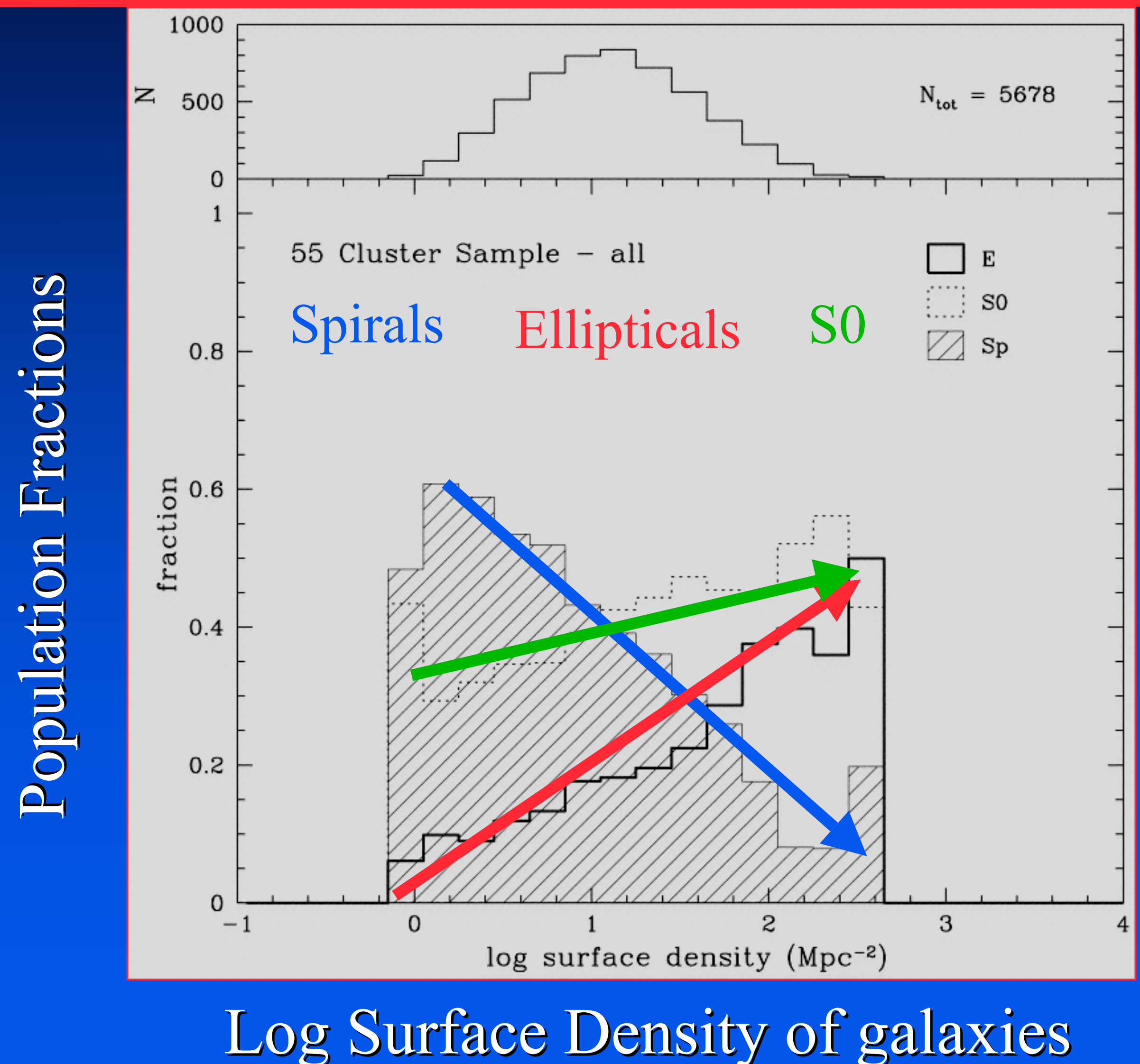
Make a morphologically-dependent field galaxy correction

Determine distance to 10th nearest galaxy, then compute area

and projected density in galaxies /Mpc^2

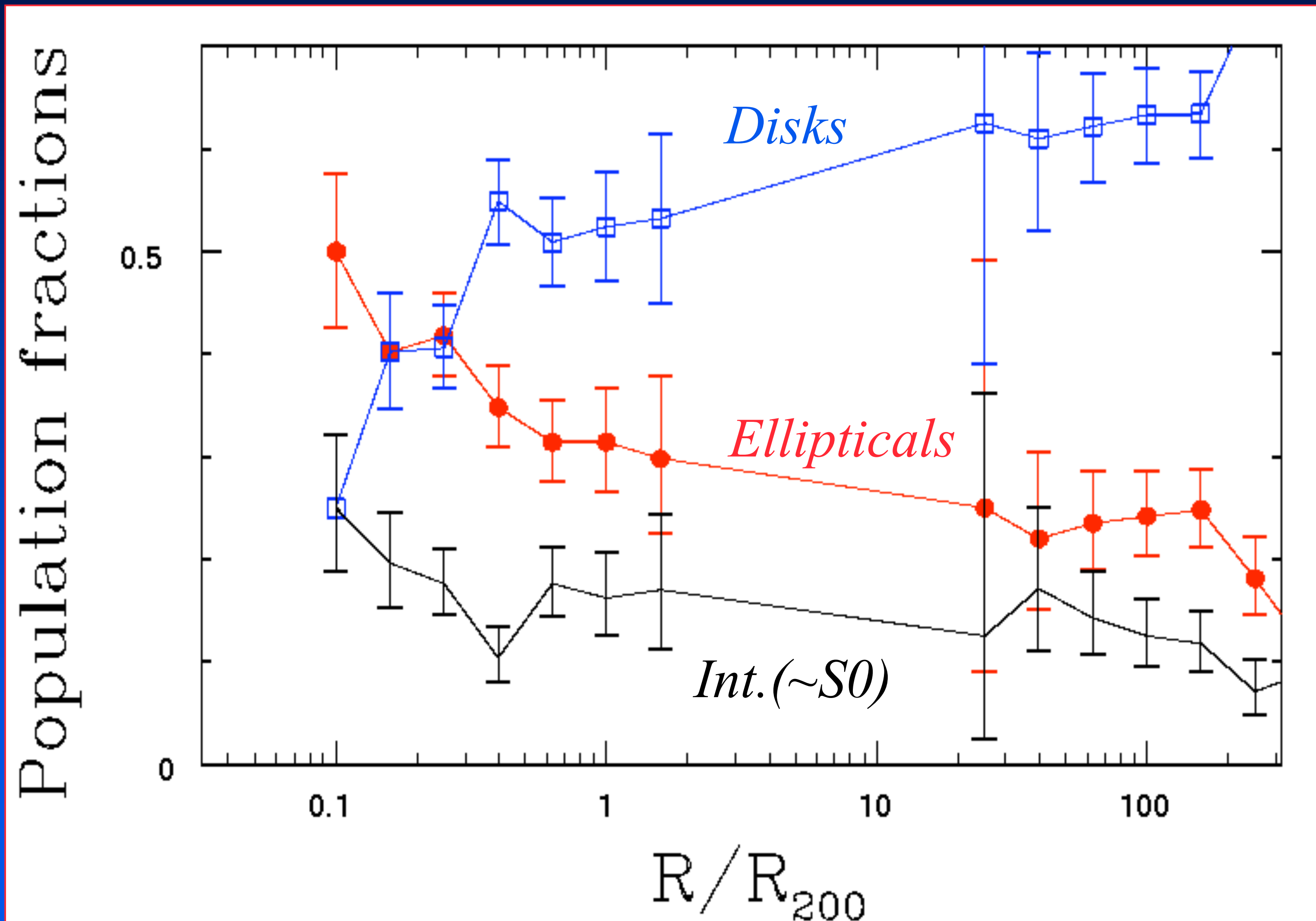
Dressler et al 1997

The morphology-density relation in local clusters



Dressler et al 1997

The morphology-radius relation at z = 0.2-0.5 : CNOC

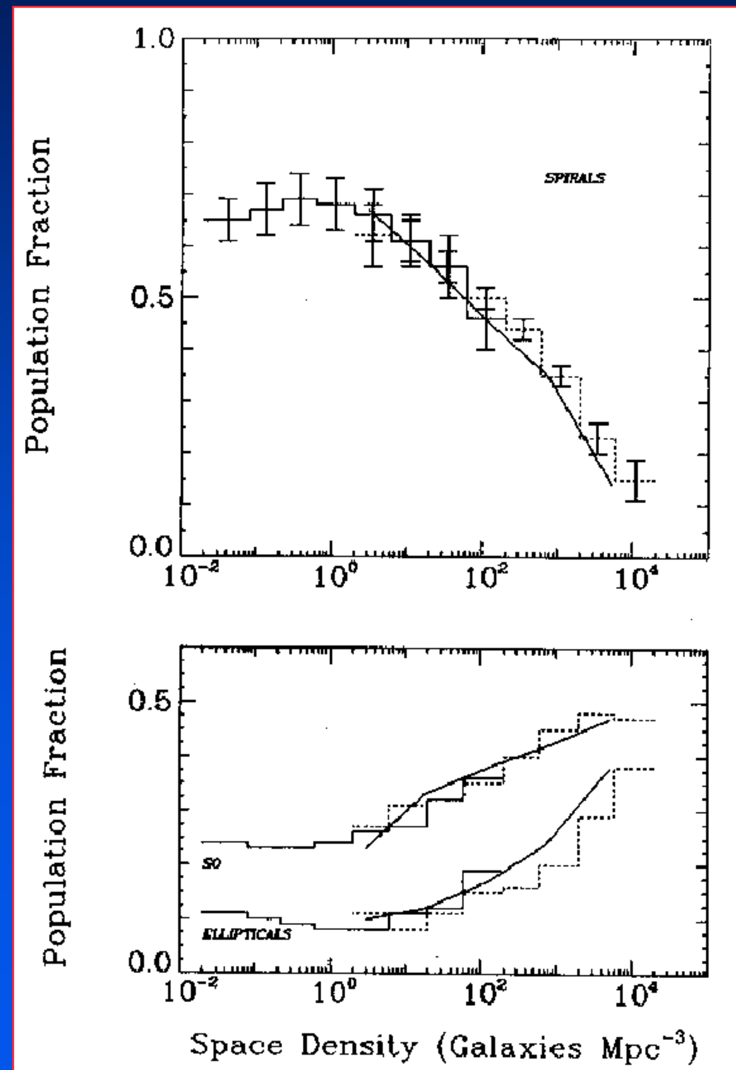


Schade et al 2001

The morphology-density relation in groups

The morphology-density relation extends to groups of galaxies

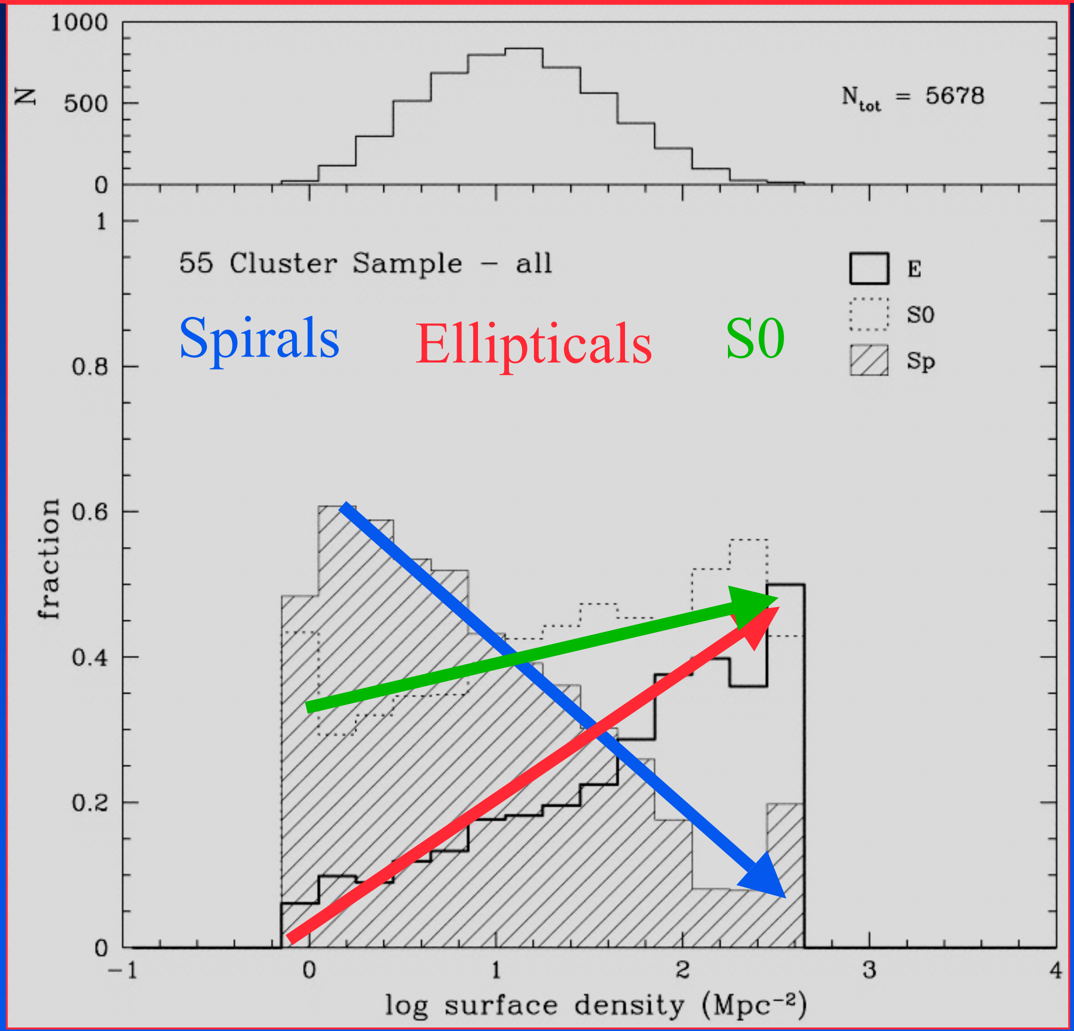
Morphological segregation is also seen in the local group.



Postman and Geller (1984)

The morphology-density relation in local clusters

Population Fractions



Dressler et al 1997

Log Surface Density of galaxies

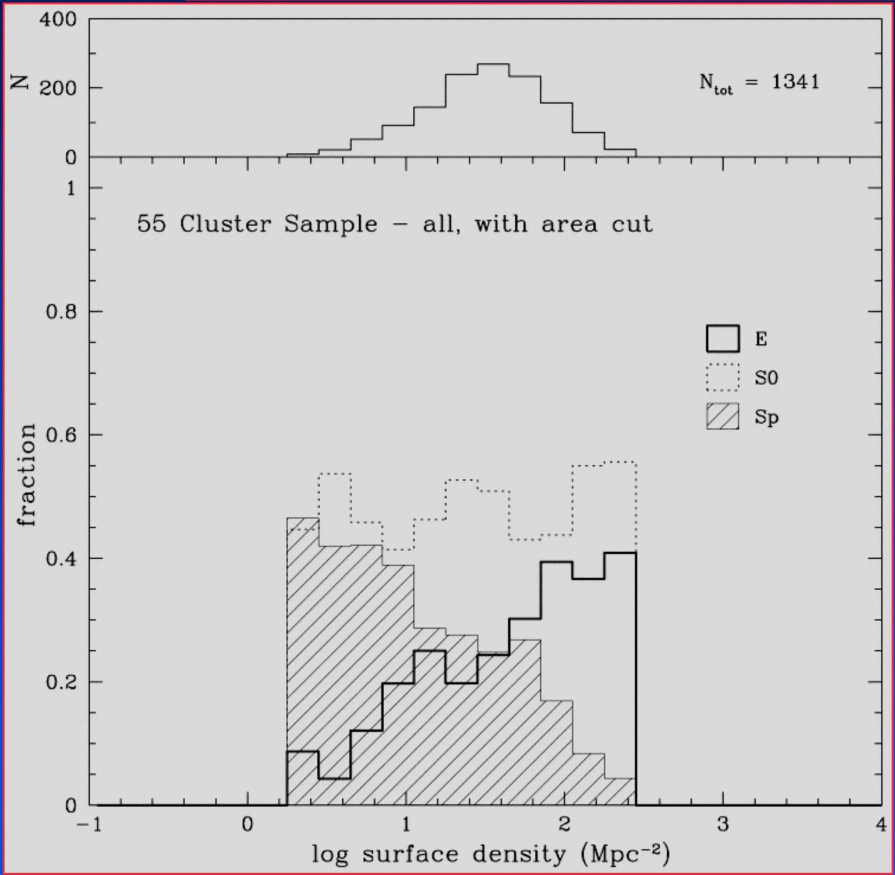
The morphological content of clusters

Oemler (1974) classified cluster galaxies and found that there exist spiral-rich, spiral-poor, and cD clusters, a continuous range of cluster types

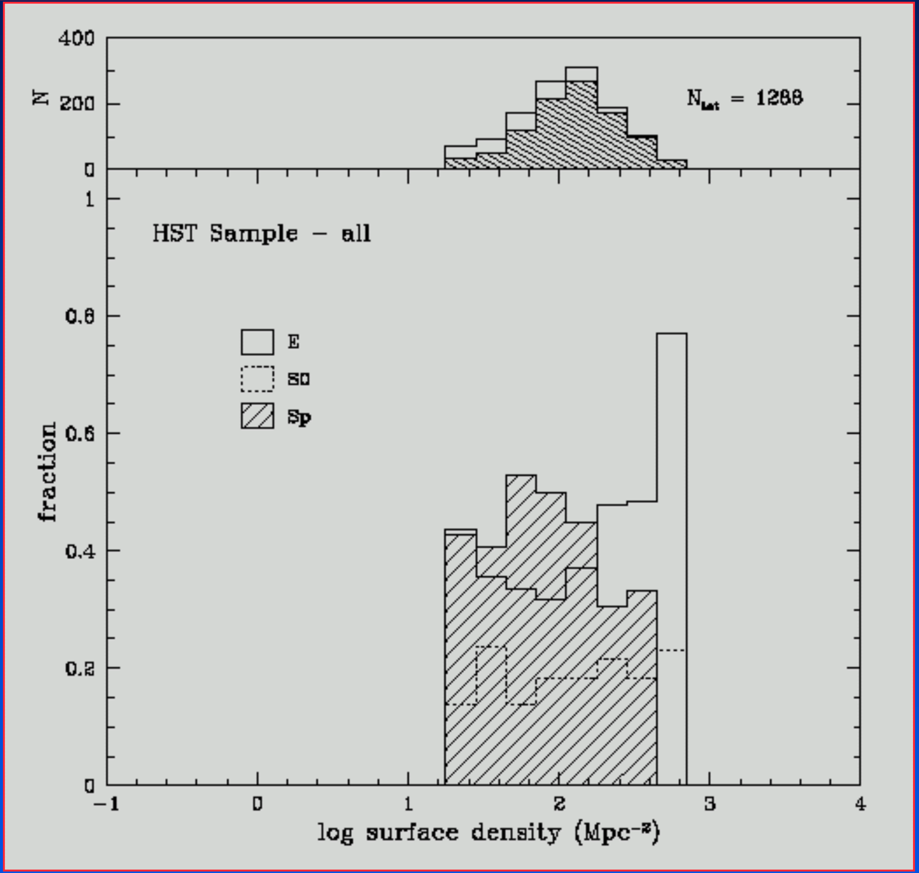
There are concentrated, regular clusters, and irregular clusters without well-defined centers.

There exists a wide range in cluster populations. (In contrast to ellipticals where one cluster is the same as another.)

The morphology-density relation for all clusters



Z=0



Z=0.5

Dressler et al 1997

The morphology-density (T-Σ) relation at $z=0.5$

Surprise:

There exists no morphology-density relation in the full HST sample at $z=0.5$ with the exception of the highest density bins where there is an excess of elliptical galaxies.

Dressler et al 1997

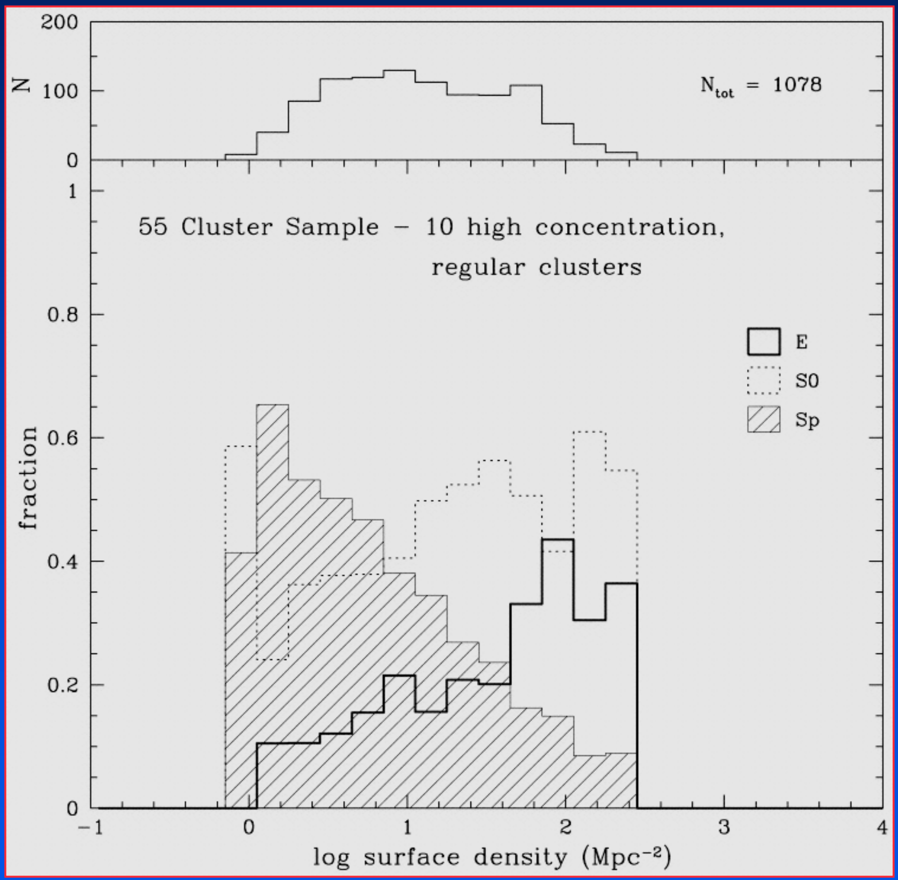
The morphology-density (T-Σ) relation at z=0.5

Try breaking the sample into sub-samples of :

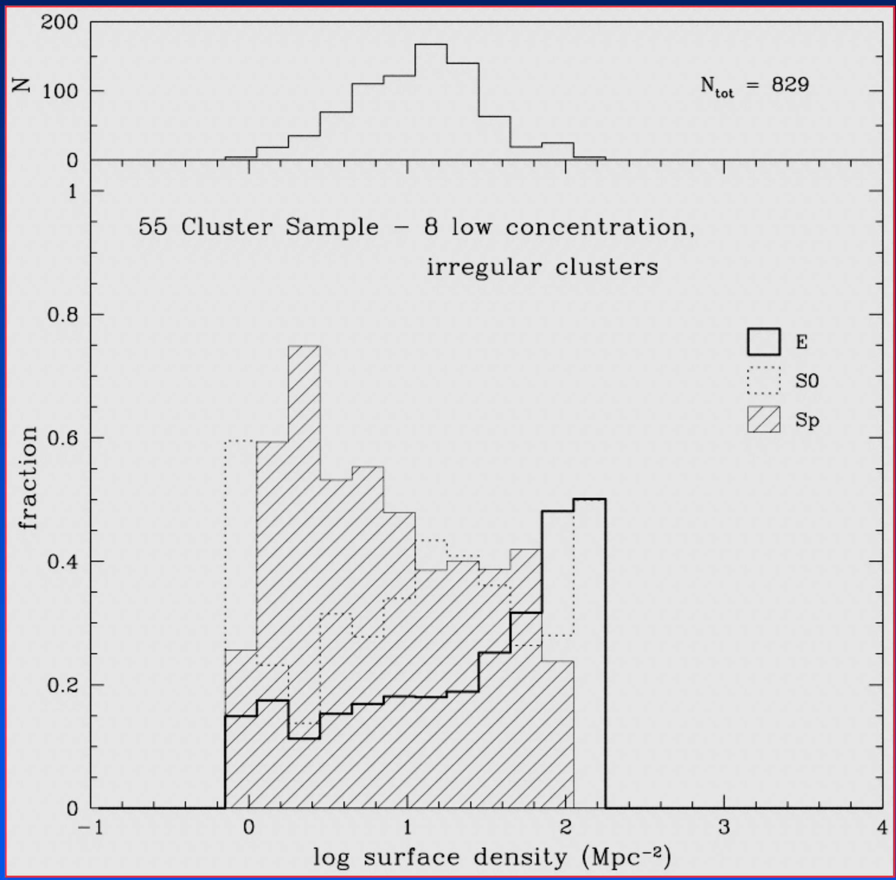
a) high-concentration regular clusters and

b) low-concentration irregular clusters

The morphology-density relation in local clusters



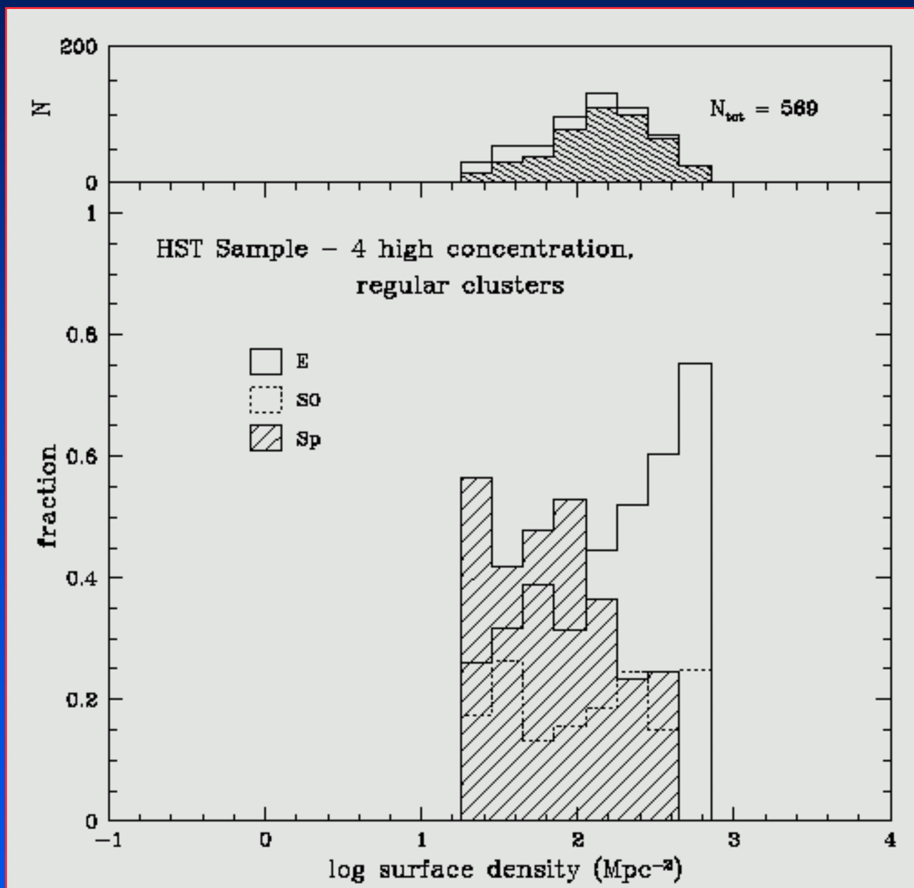
Regular clusters



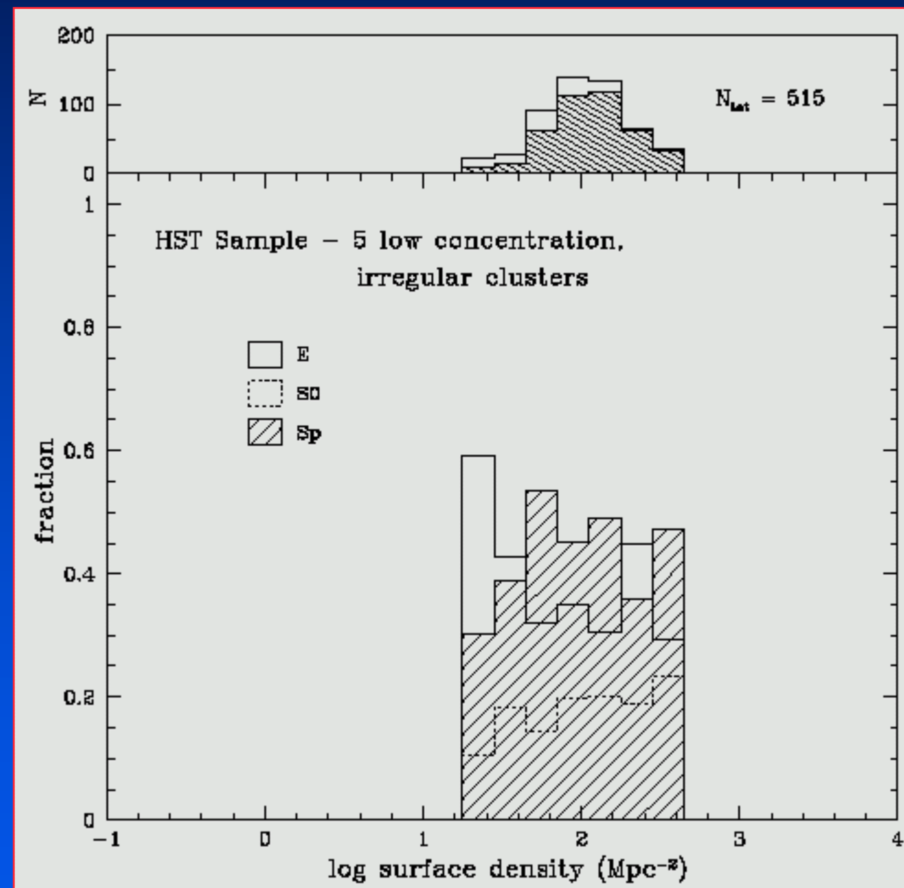
Irregular clusters

Dressler et al 1997

The morphology-density relation at z=0.5



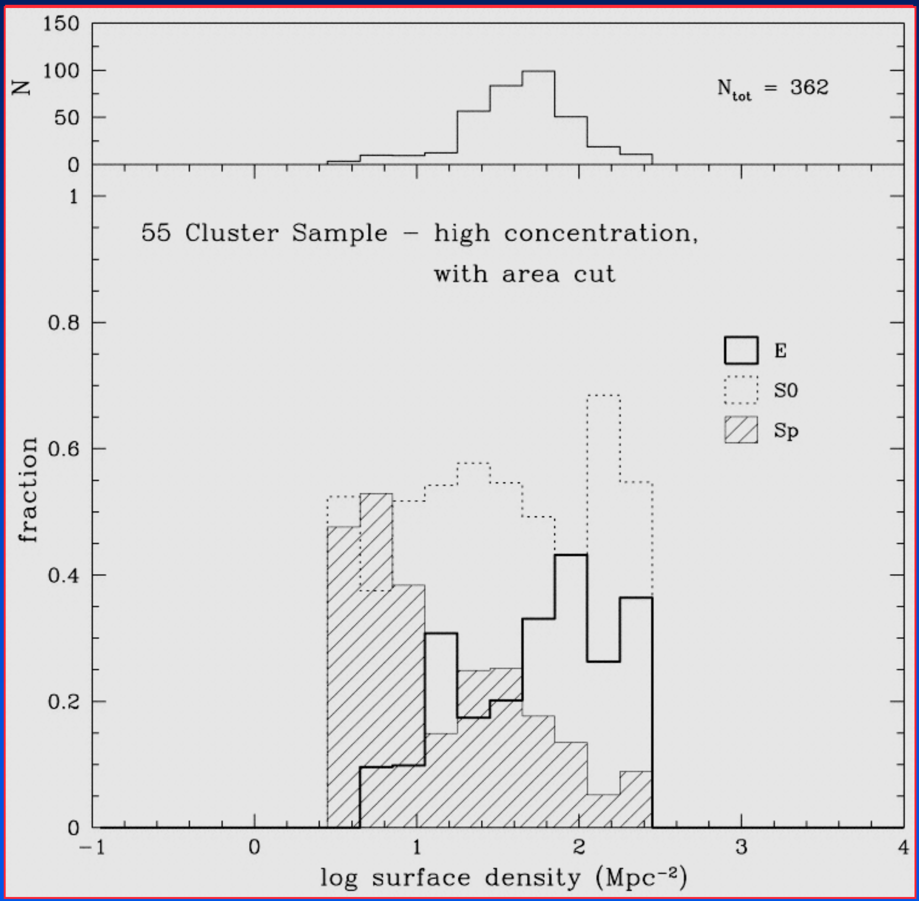
Regular clusters



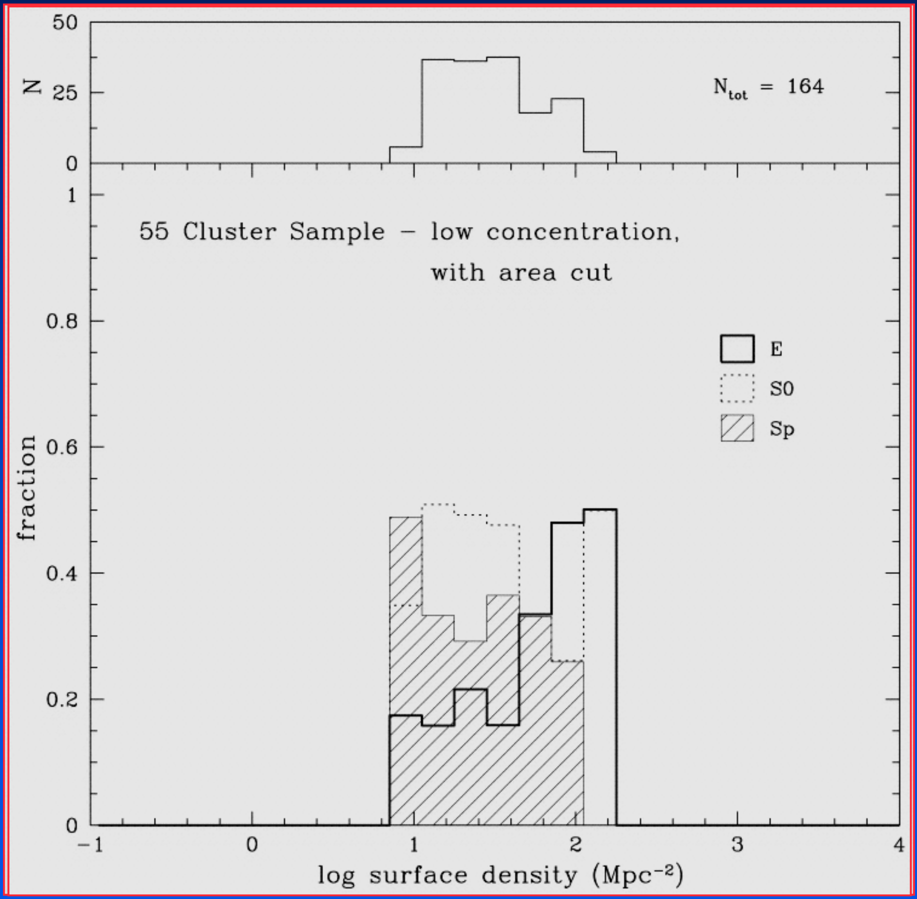
Irregular clusters

Dressler et al 1997

The morphology-density **local clusters**



Regular clusters



Irregular clusters

Dressler et al 1997

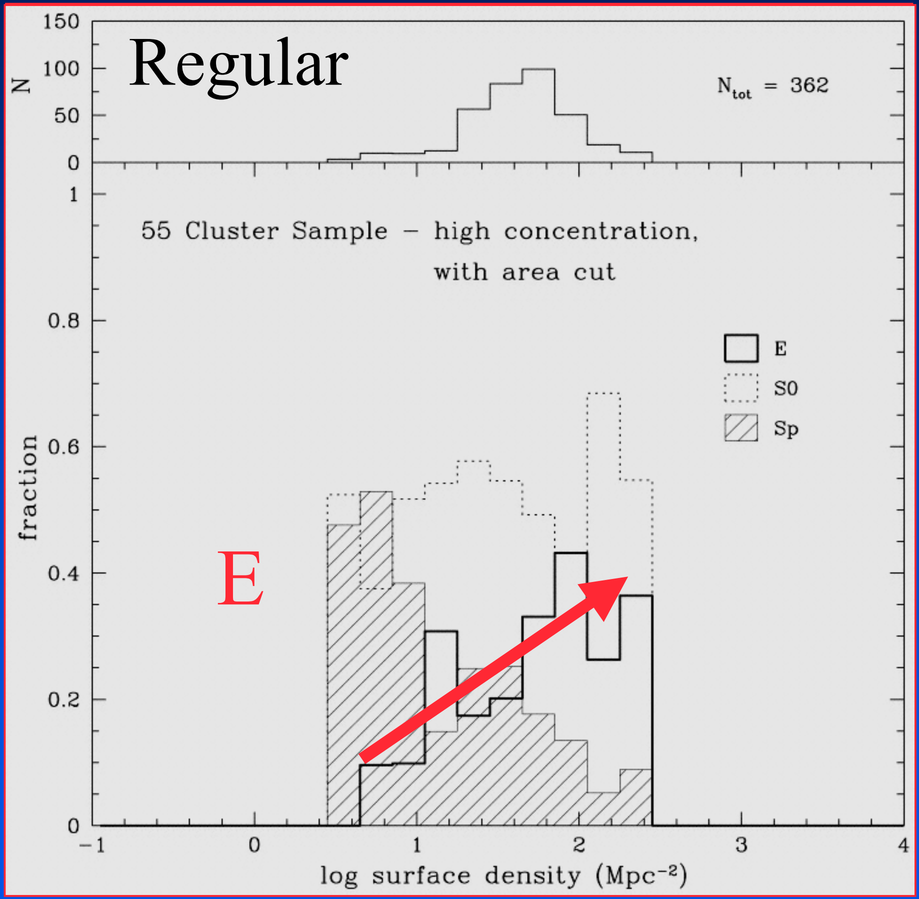
The morphology-density (T-Σ) relation at z=0.5

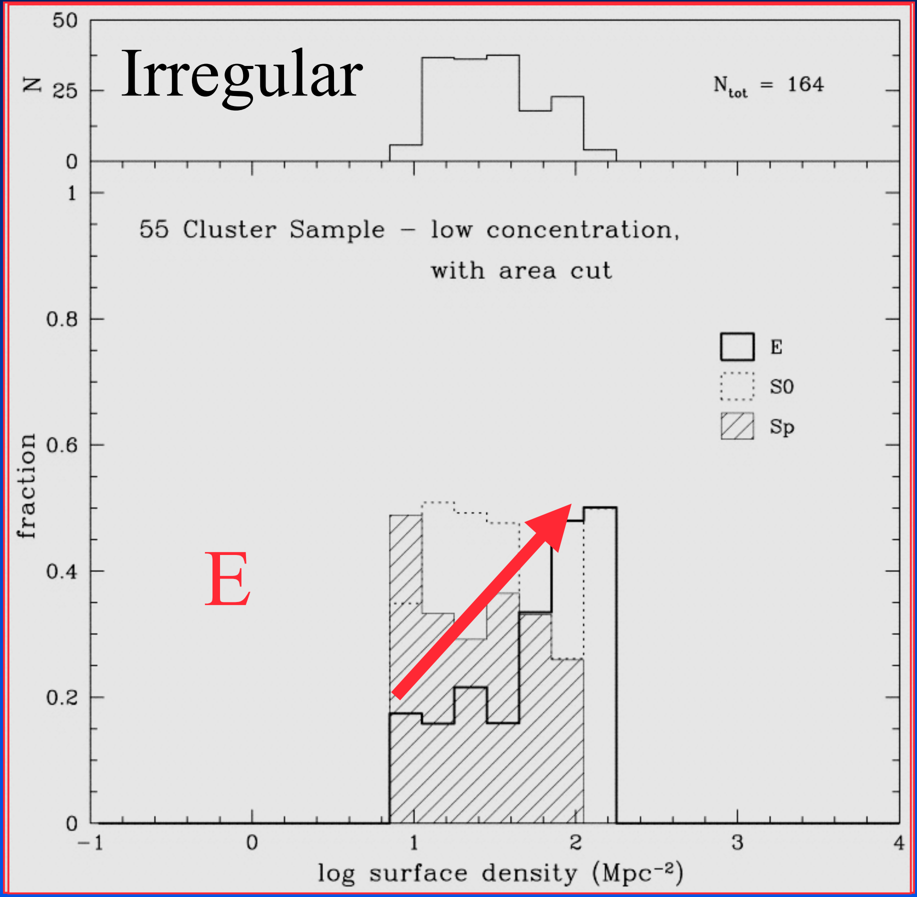
There is a systematic shift to higher densities in the high-redshift sample. This reflects the fact that these high-redshift clusters are richer than the typical clusters in the low-redshift sample. However, there is considerable overlap in density (75% of the galaxies lie in the same range of projected density).

If local density is truly the controlling factor in the morphology-density relation then this is irrelevant. If global cluster properties (for example cluster richness) are important then the systematic difference between the cluster samples could be a severe problem.

Dressler et al 1997

The morphology-density **local clusters**

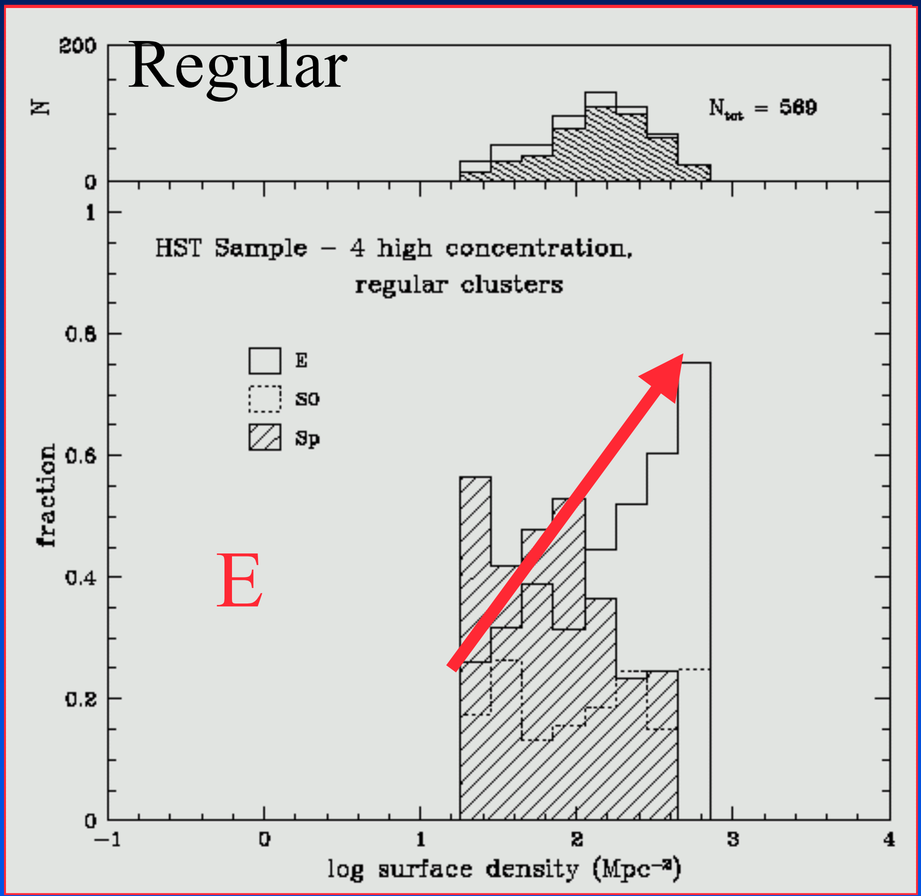


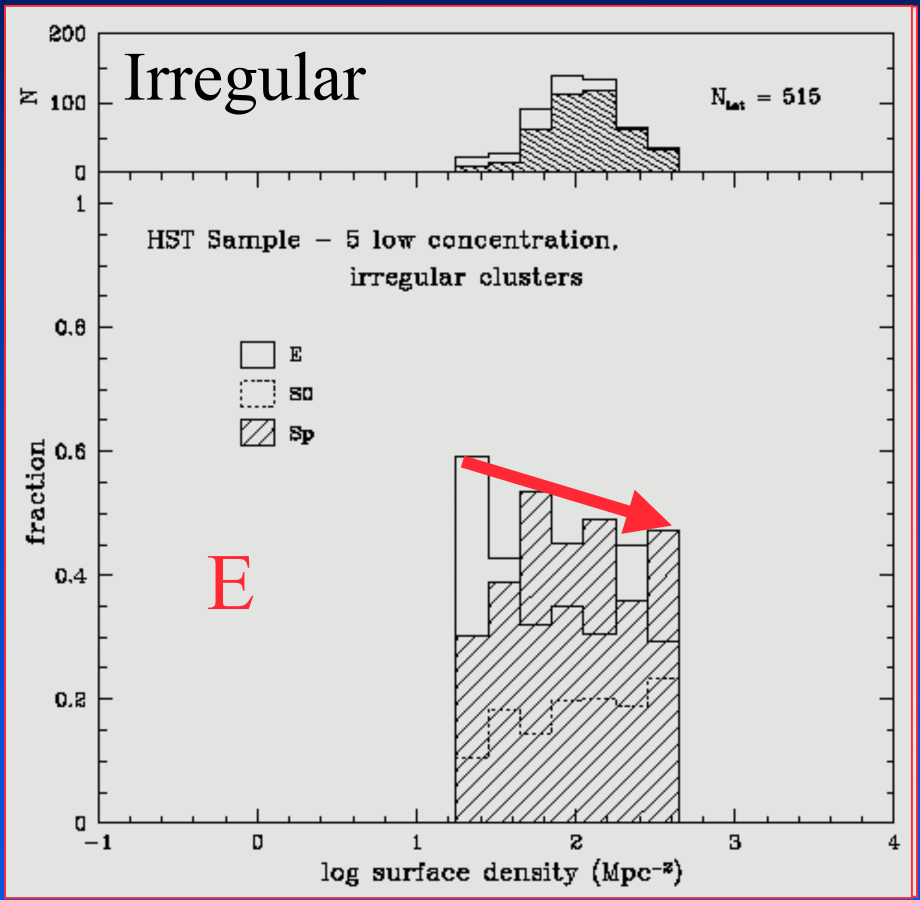


Ellipticals

Dressler et al 1997

The morphology-density relation at **z=0.5**

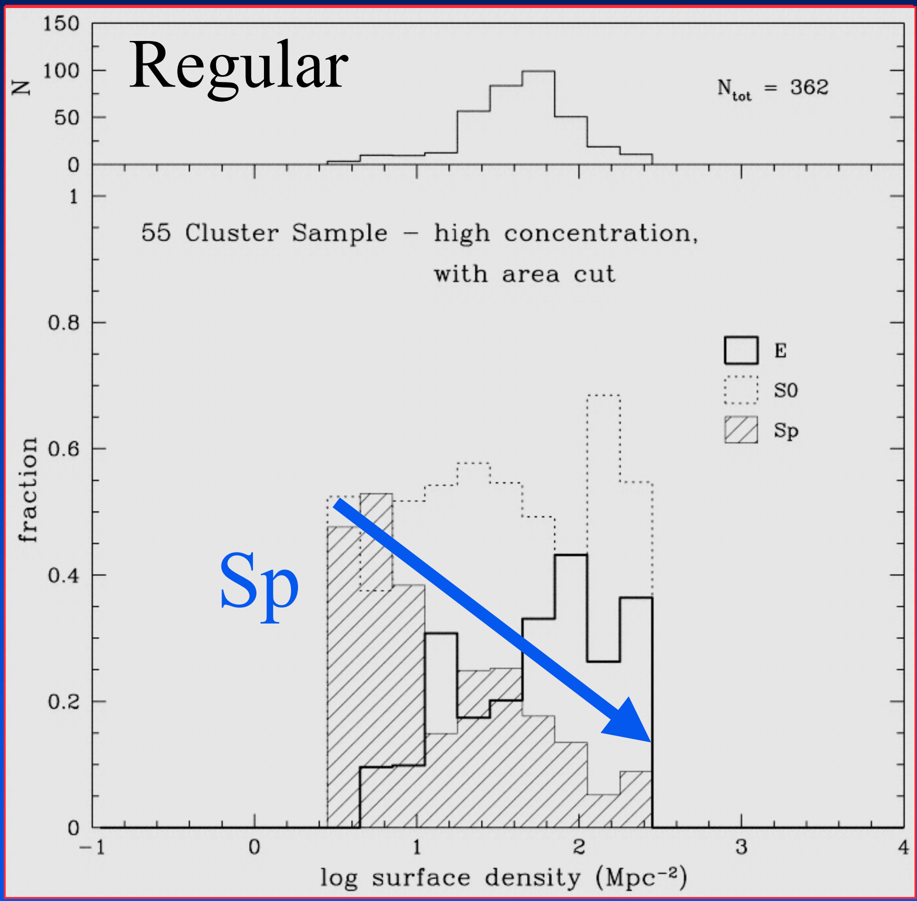


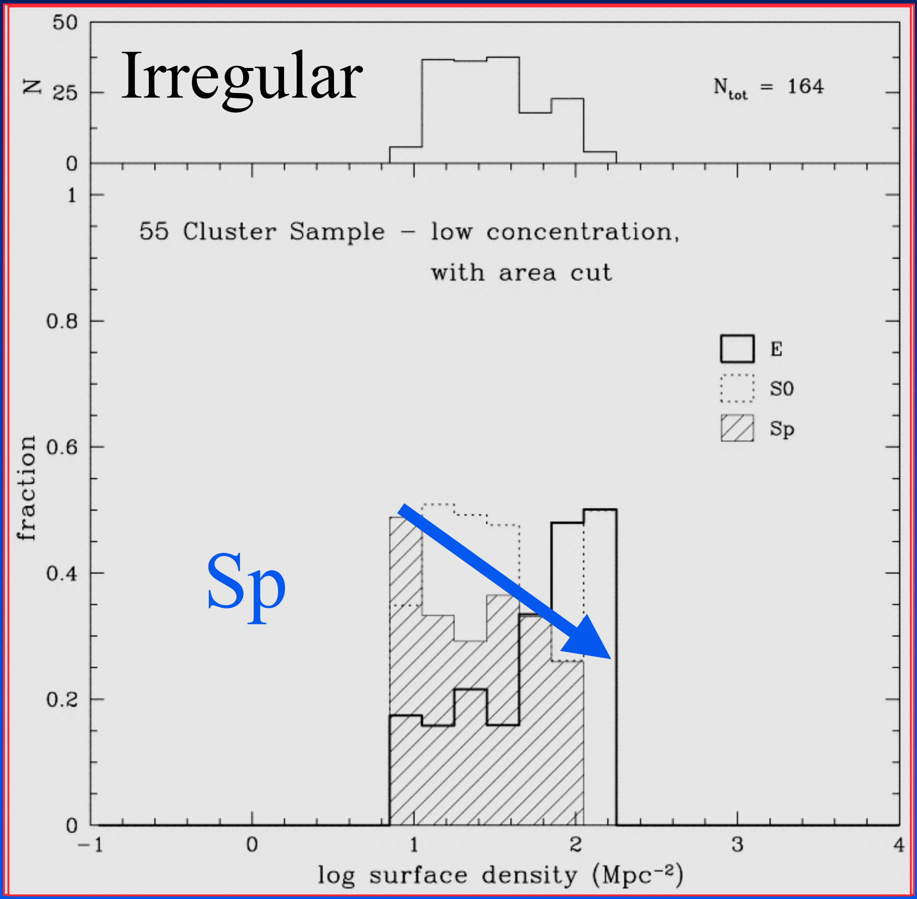


Ellipticals

Dressler et al 1997

The morphology-density **local clusters**

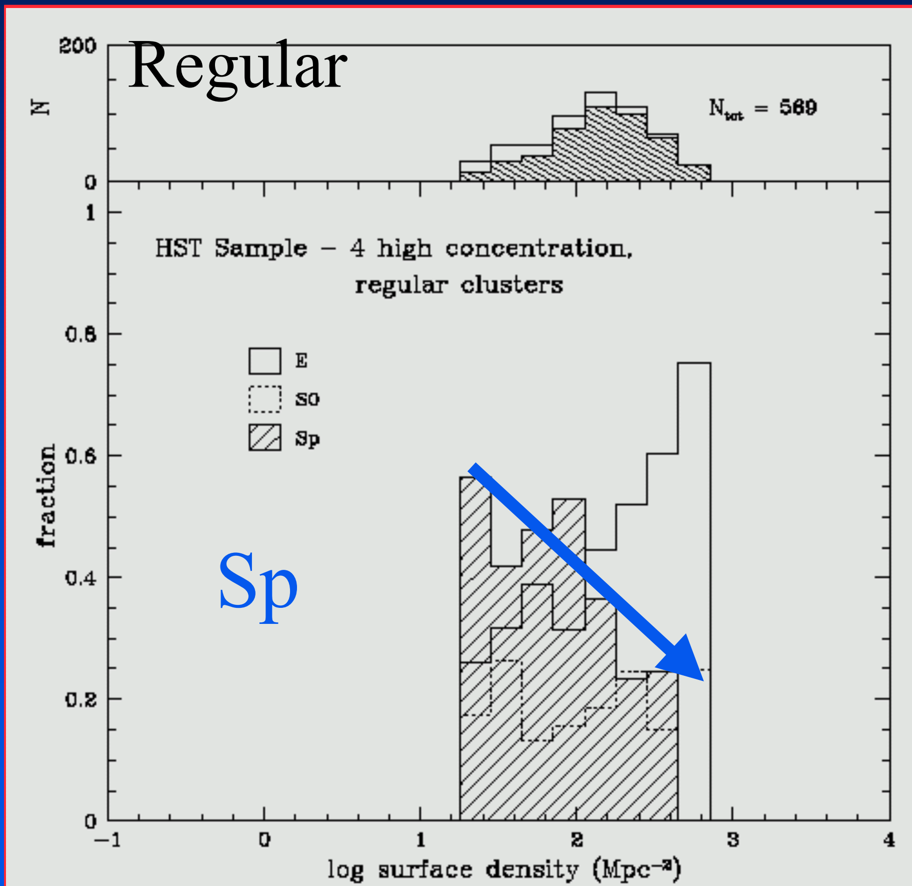


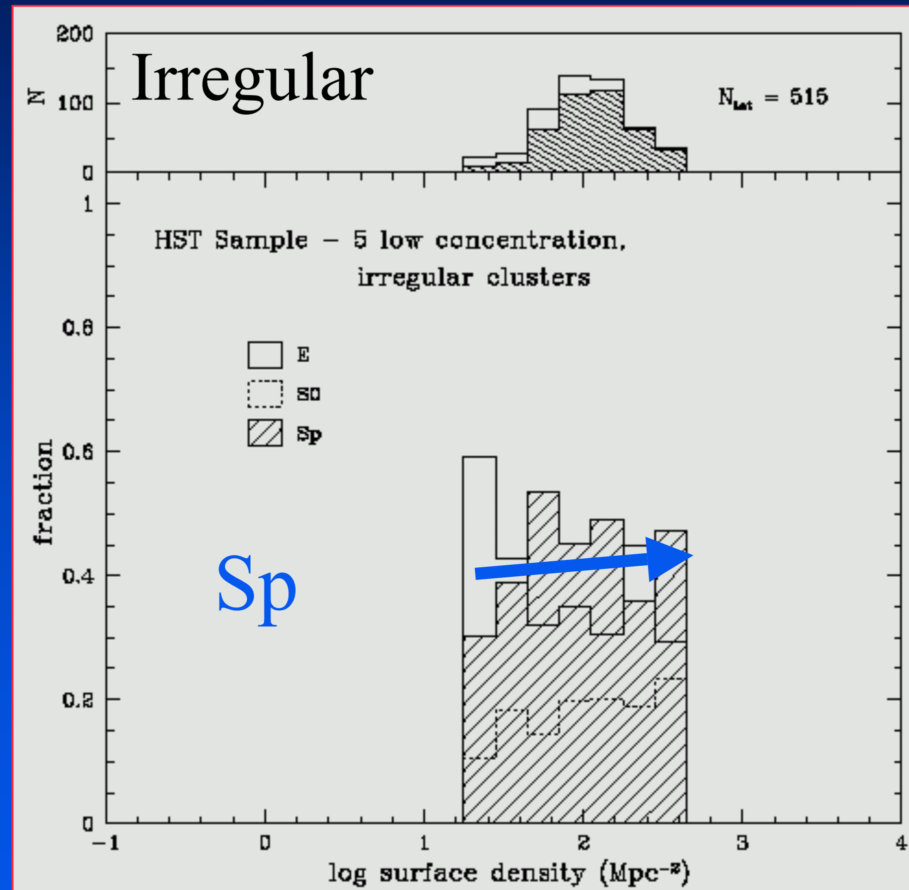


Spirals

Dressler et al 1997

The morphology-density relation at <u>**z=0.5**</u>

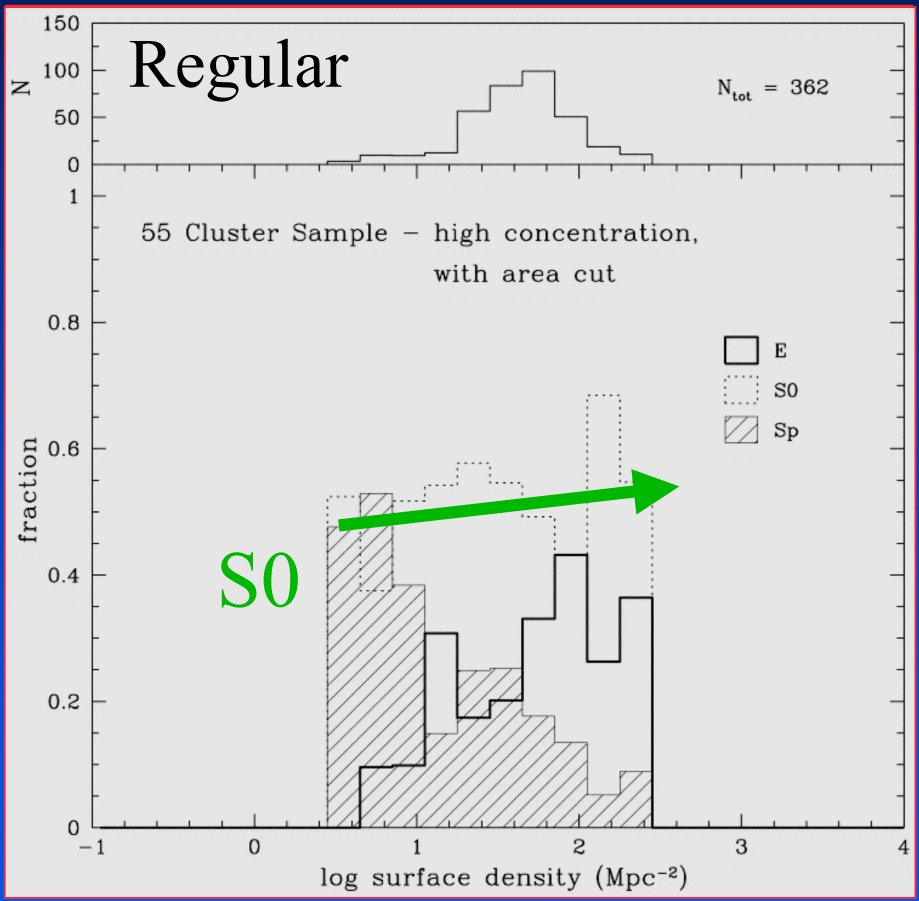


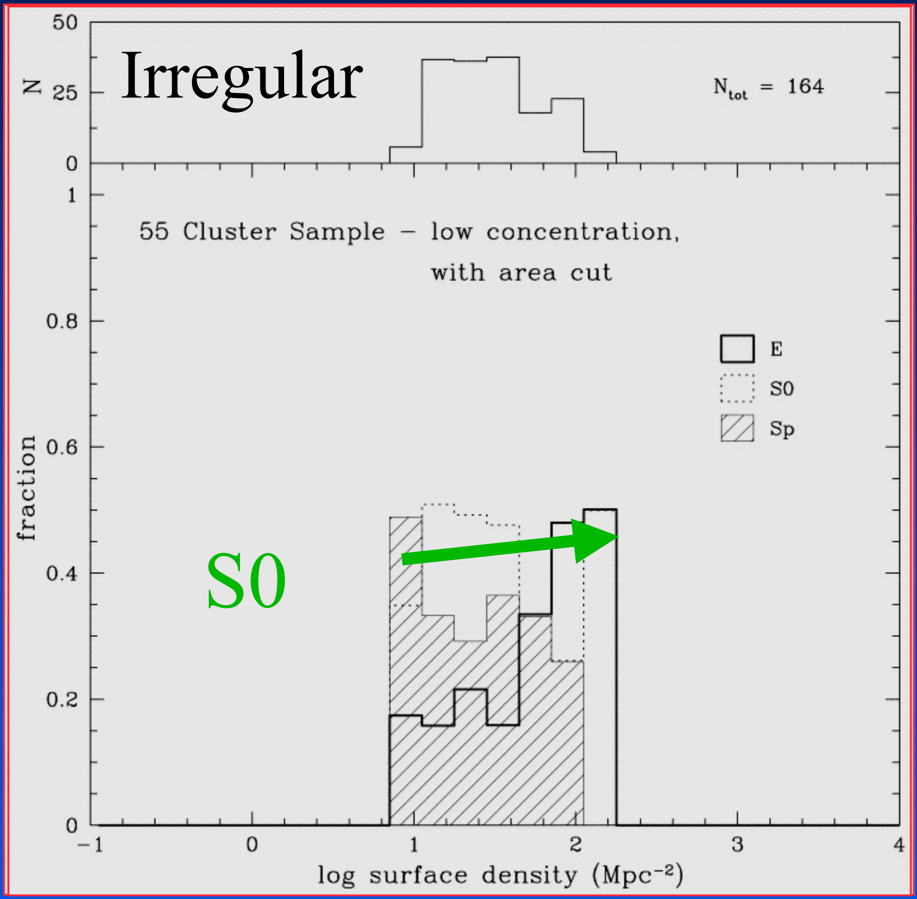


Spirals

Dressler et al 1997

The morphology-density **local clusters**

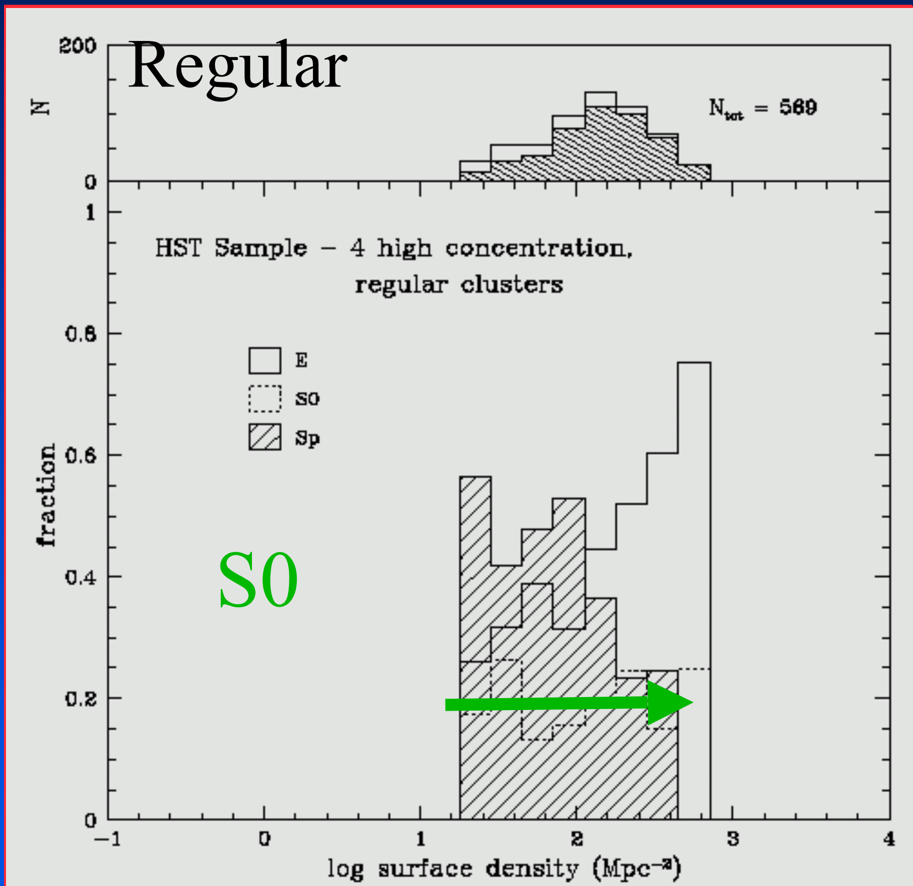


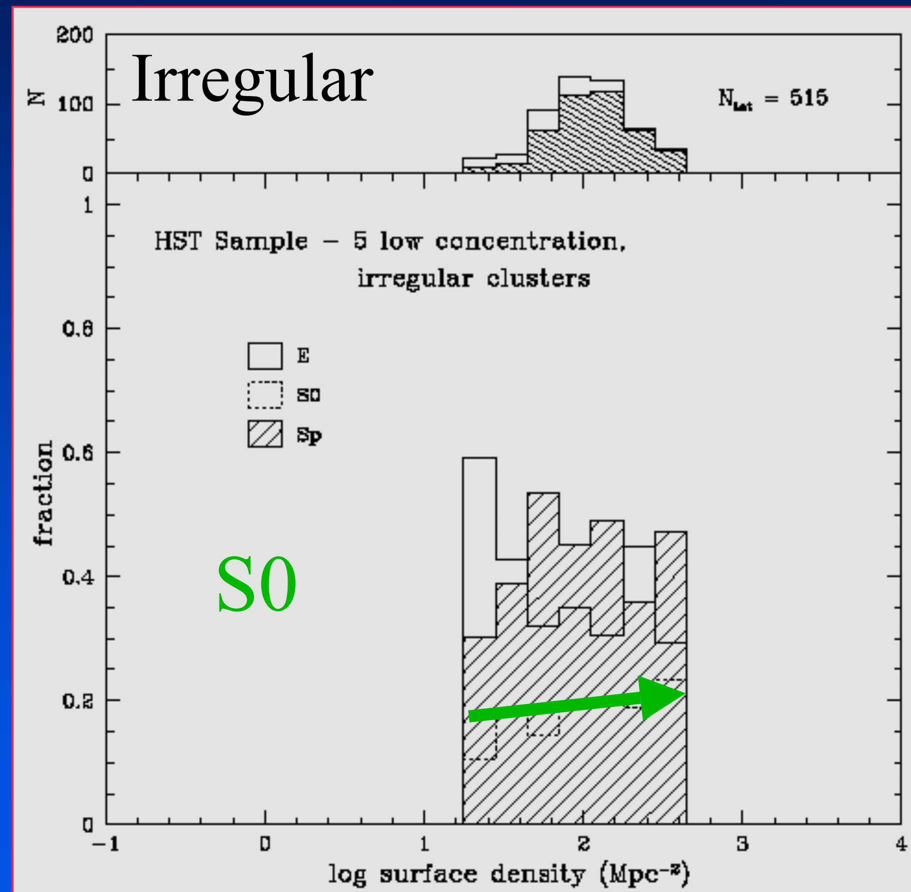


S0

Dressler et al 1997

The morphology-density relation at **z=0.5**





S0

Dressler et al 1997

Evolution of the morphology-density relation

Dressler et al (1997)

• In local clusters there is a well-defined relationship between local density (clustercentric radius) and population fractions of E/S0/Sp+Irr galaxies. The relation is identical (similar) for rich, regular, highly-concentrated clusters and for irregular clusters which are not highly concentrated

• At z=0.5 there is a well-defined morphology-density relation for the rich, highly-concentrated clusters but NOT for irregular clusters.

Perhaps dynamical processes which produce the relation take place earliest in the densest systems.

Evolution of the morphology-density relation

Dressler et al (1997)

• In every cluster the fraction of ellipticals is as large as at low-redshift

• The S0 fractions at z = 0.5 are 2-3 times smaller

• The spiral fractions are larger

Interpretation

• The elliptical population is in place and probably predates virialization

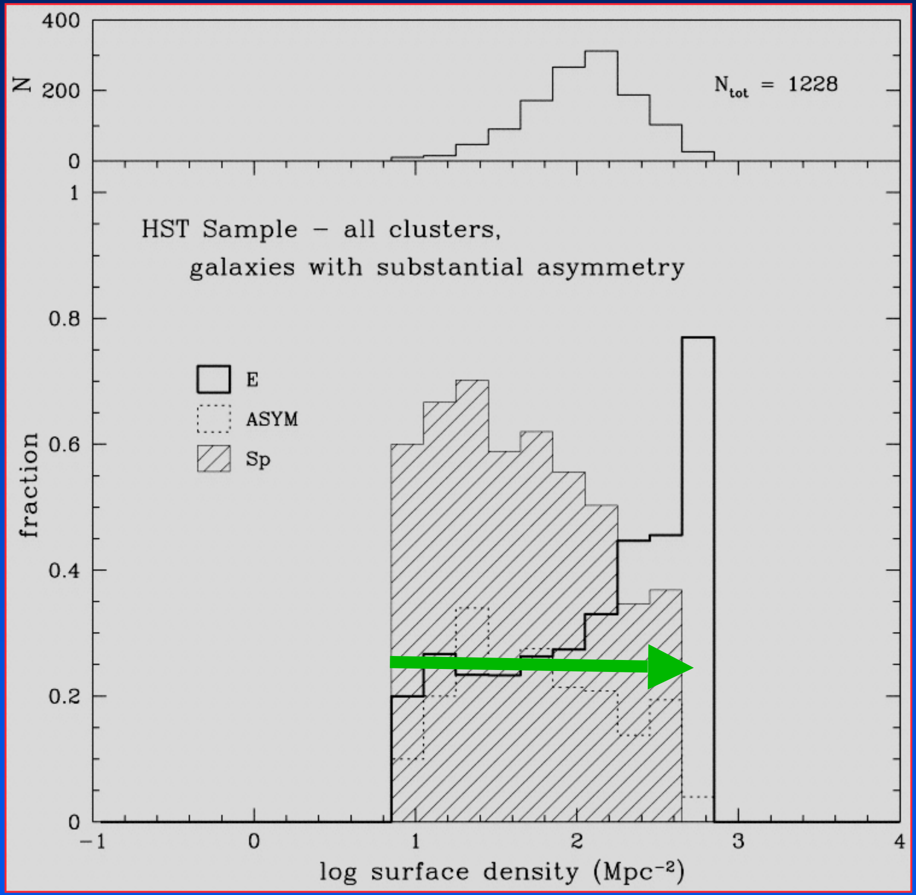
• The spiral population provides a reservoir of galaxies which must undergo a morphological transformation to produce S0s in present-day clusters

This is the "S0 Problem"

The morphology-density relation at z=0.5

The morphology-density relation for “asymmetric” galaxies follows the trend seen for S0s.

Suggests these evolve into S0s rather than ellipticals.



Dressler et al 1997

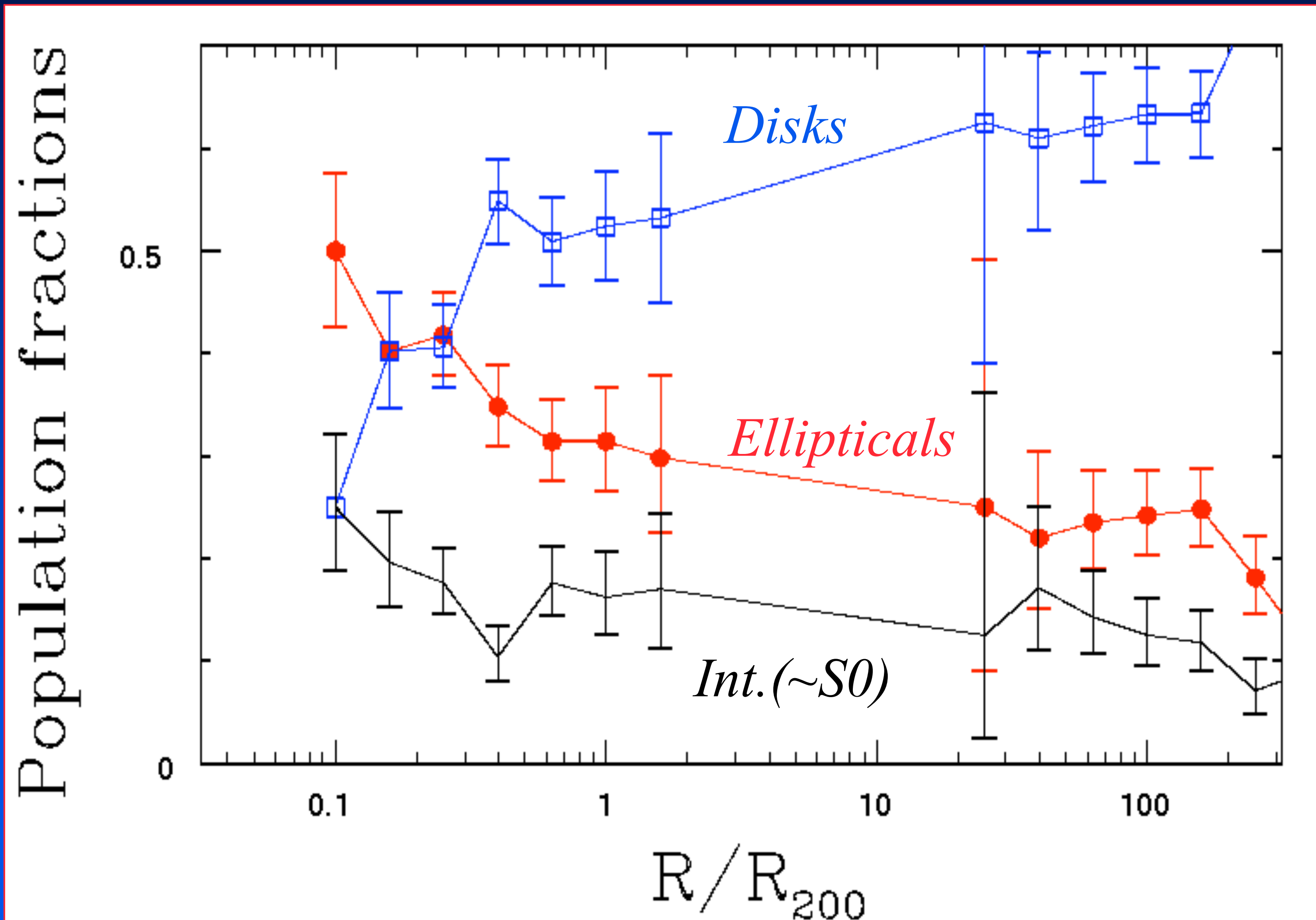
Evolution of the morphology-density relation

Dressler et al (1997)

• The population fractions for ASYMMETRIC galaxies follows the same relation as the S0s

•The asymmetric or interacting population are unlikely to produce elliptical galaxies but rather S0s

The morphology-radius relation at z = 0.2-0.5 : CNOC



Schade et al 2001

The morphological content of clusters

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