Astronomy 580-galaxies in Clusters

Outline

1) Evolution of ellipticals

2) The morphology-density relation

3) The Butcher-Oemler effect

4) The S0 Problem

5) Merging/Interactions

Evolution of Cluster Galaxies

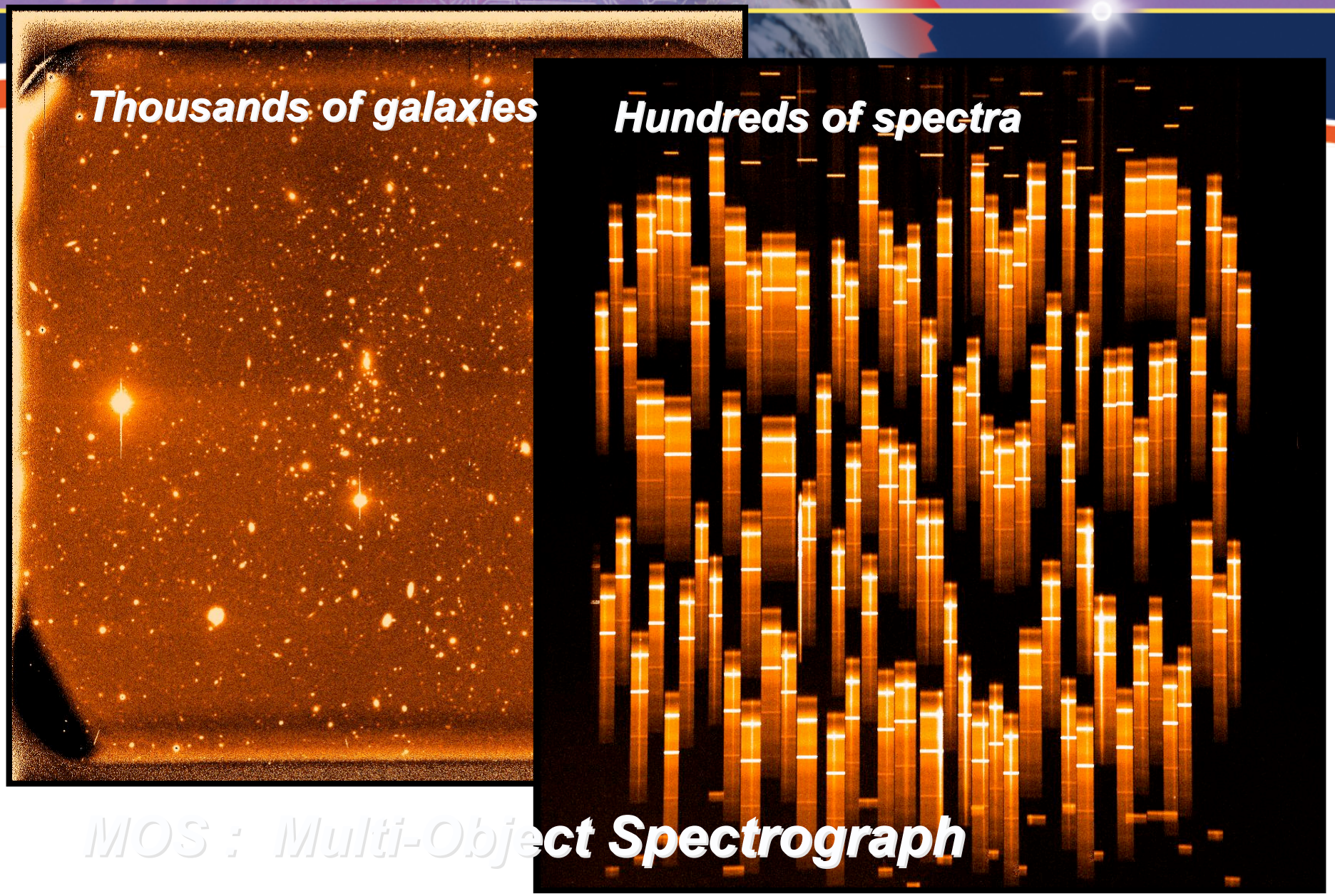
Environment

Why study the evolution of galaxies ?

- Find the physical organizing principles that govern galaxy formation
- Determine the “Origin of the Hubble Sequence”
- What are galaxy-scale influences on star formation?
- What are the global-scale influences on star formation?

Why study cluster galaxies ?

- It is efficient
- The interactions of the environment with the galaxies reveals something about both
- The galaxy populations in clusters are interesting
- Some types of galaxies live mostly in clusters
- Galaxy kinematics give us a handle on cluster mass
- Lensing reveals cluster and galaxy masses


Thousands of galaxies
Hundreds of spectra
MOS : Multi-Object Spectrograph

Cluster fundamentals: Abell clusters

- Abell (1958) compiled a sample of 2712 rich clusters of galaxies
- Based on visual examination of red Palomar Sky Survey plates
- Limit on third brightest cluster member ~ 17.5
- Richness based on number of galaxies not more than 2 mag. Fainter than the third brightest member
- Much work on local ($z < 0.1$) clusters is based on the Abell catalog

TABLE 4

RICHNESS-GROUP INTERVALS

Richness Group	Counts	Richness Group	Counts	Richness Group	Counts
0	30–49	2	80–129	4	200–299
1	50–79	3	130–199	5	300 or over

Cluster fundamentals: Abell clusters

- The number of Abell clusters falls very steeply with increasing richness

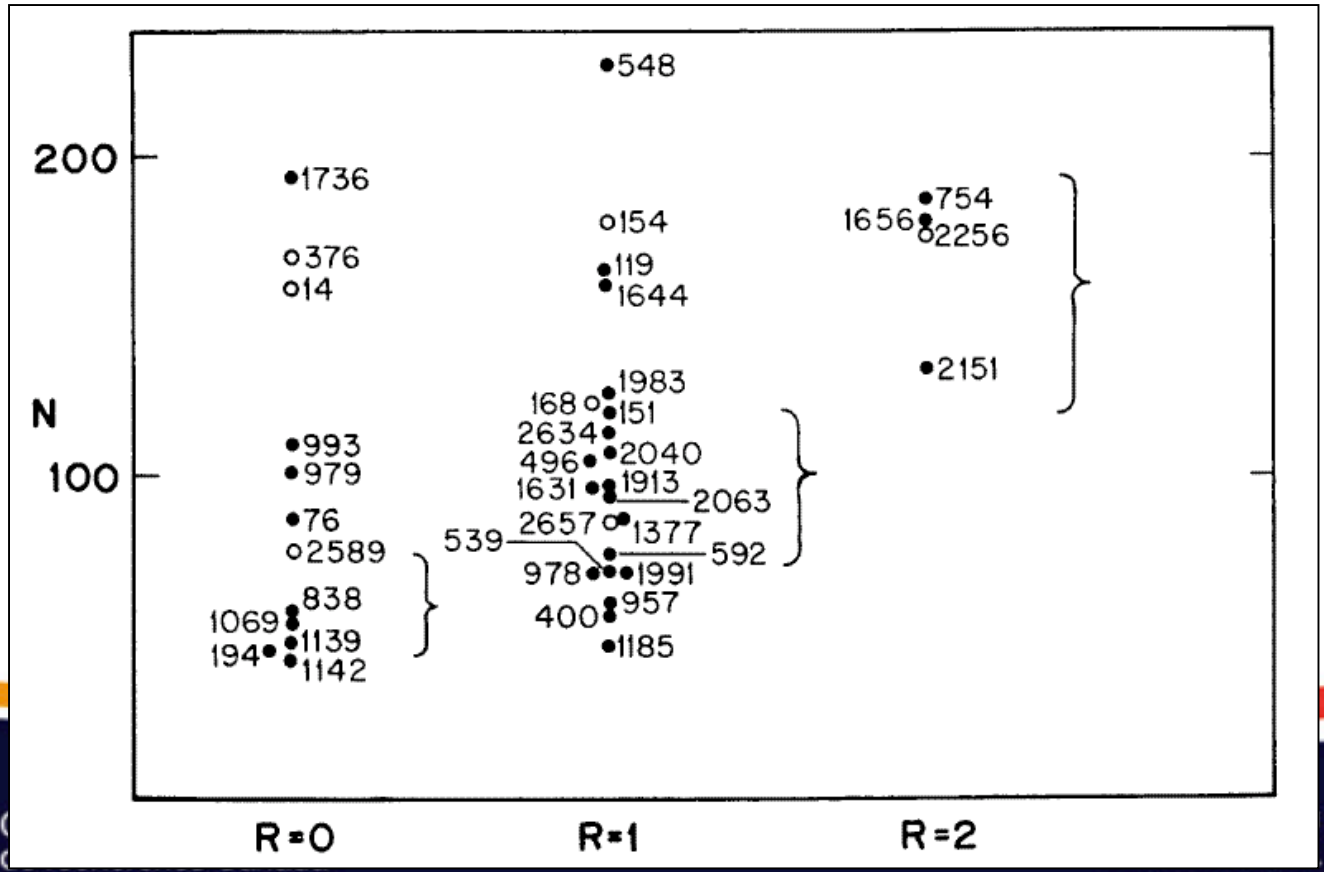
TABLE 7

DISTRIBUTION ACCORDING TO RICHNESS CLASSIFICATION

Richness-Group No.	No. of Clusters $N(n)$	Logarithm of Number $\log N(n)$
1	1224	3.088
2	383	2.583
3	68	1.832
4	6	0.778
5	1	0.000
Total	1682	3.226

Cluster fundamentals: Dressler catalogs

Dressler (1980) produced a catalog of 55 clusters and morphological types and redshifts for clusters to z ~ 0.06



Cluster fundamentals: HST Sample of clusters

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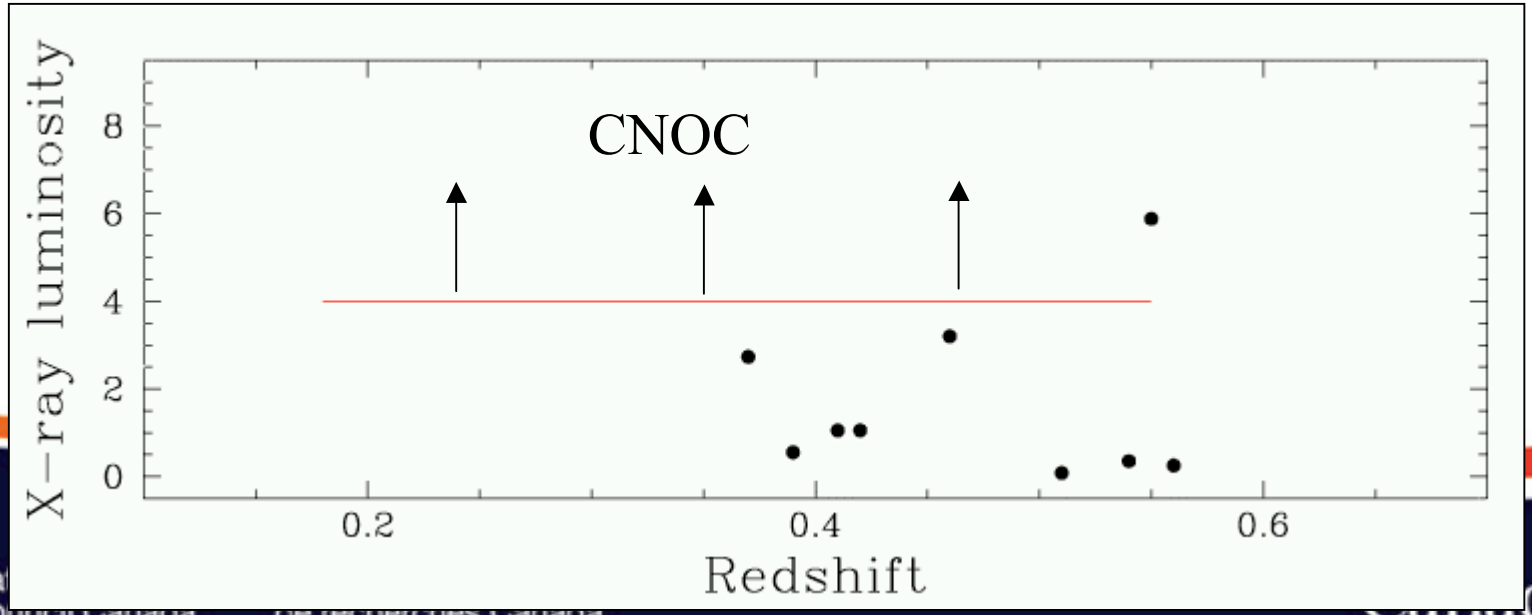
From Discovery to Innovation...

- HST Sample: Relatively small number of clusters
- Dressler et al. 1994-1997
- Couch et al. 1994
- Oemler 1997



Cluster fundamentals: CNOC cluster sample

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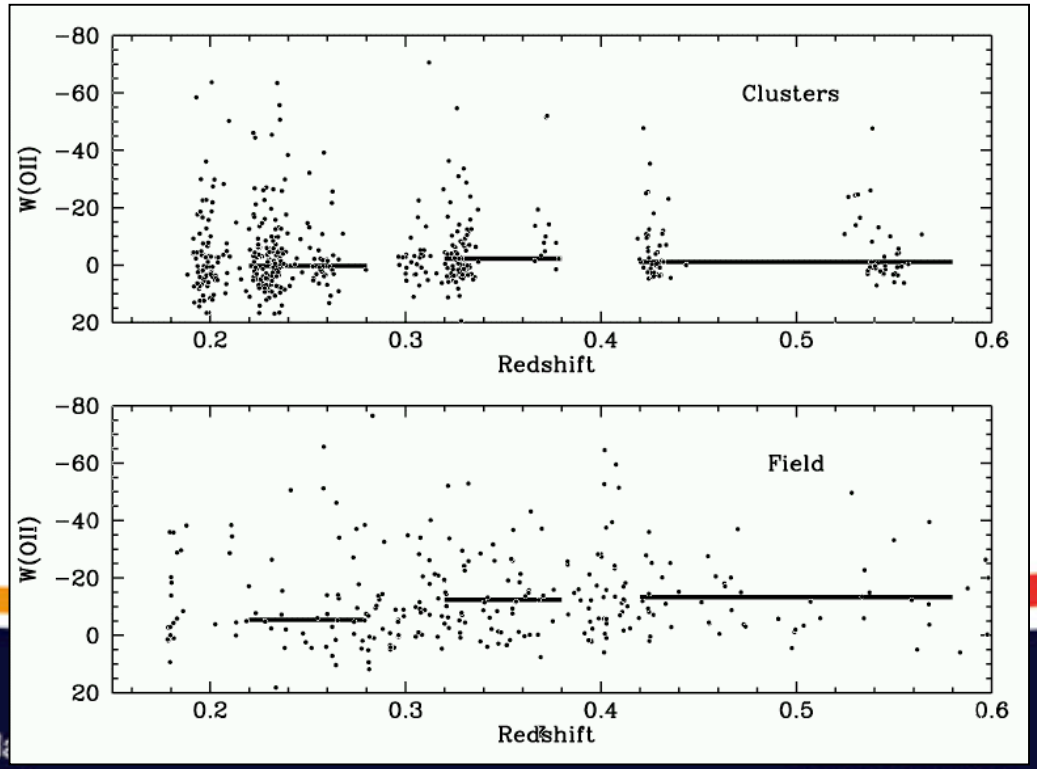
- Selected by X-ray luminosity: Lx > 4 x 10^44 ergs/s
- 16 clusters 0.2 < z < 0.55
- Fair sample of galaxies subjected to spectroscopy
- Range of X-ray luminosity



Observed Phenomena of Cluster Galaxies

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- Morphology-Density relation
- Old (co-eval) ellipticals
- Butcher-Oemler effect
- E+A galaxies
- S0 problem

- cD galaxies
- Suppression of SFR
- Disk galaxies
- Dwarf galaxies
- Interactions/Mergers

Early Processes ?

Formation of Initial Generation of Cluster Galaxies

- Morphology-Density relation
- Old (co-eval) ellipticals
- Interactions/Mergers

Late Processes ?

Infall of Field Galaxies

- S0 problem
- Butcher-Oemler effect
- E+A galaxies
- Suppression of SFR
- Interactions/Mergers

Observed Phenomena of Cluster Galaxies

Early-type galaxies

- Morphology-Density relation
- Old (co-eval) ellipticals

Disk galaxies

- Morphology-Density relation
- Butcher-Oemler effect
- E+A galaxies
- Suppression of SFR
- S0 problem
- Interactions/Mergers

The colour-magnitude relation in clusters

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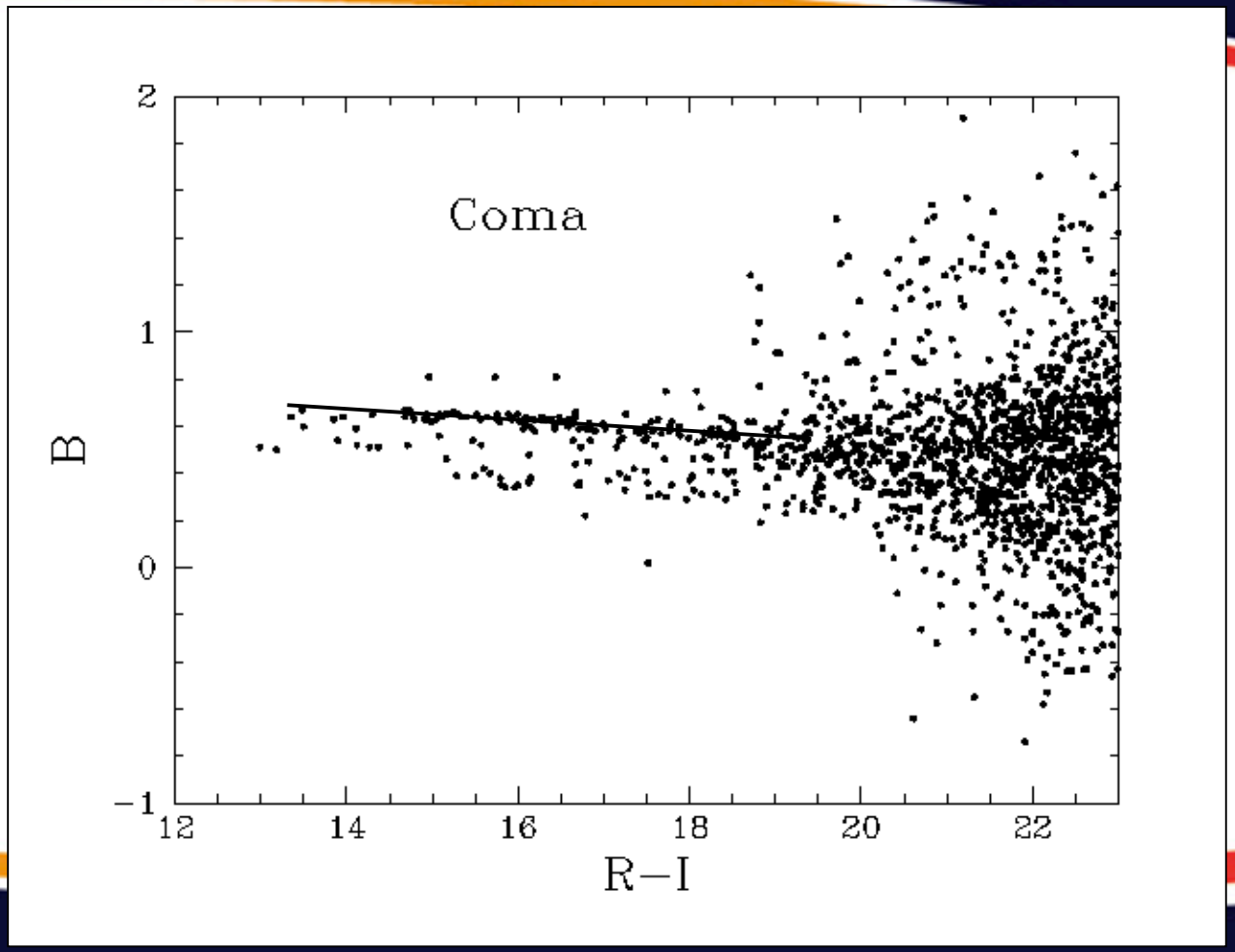
E/S0 galaxies form a tight red sequence

There are also galaxies that scatter to bluer colors



Lopez-Cruz (1999)

Homogeneity of the elliptical population

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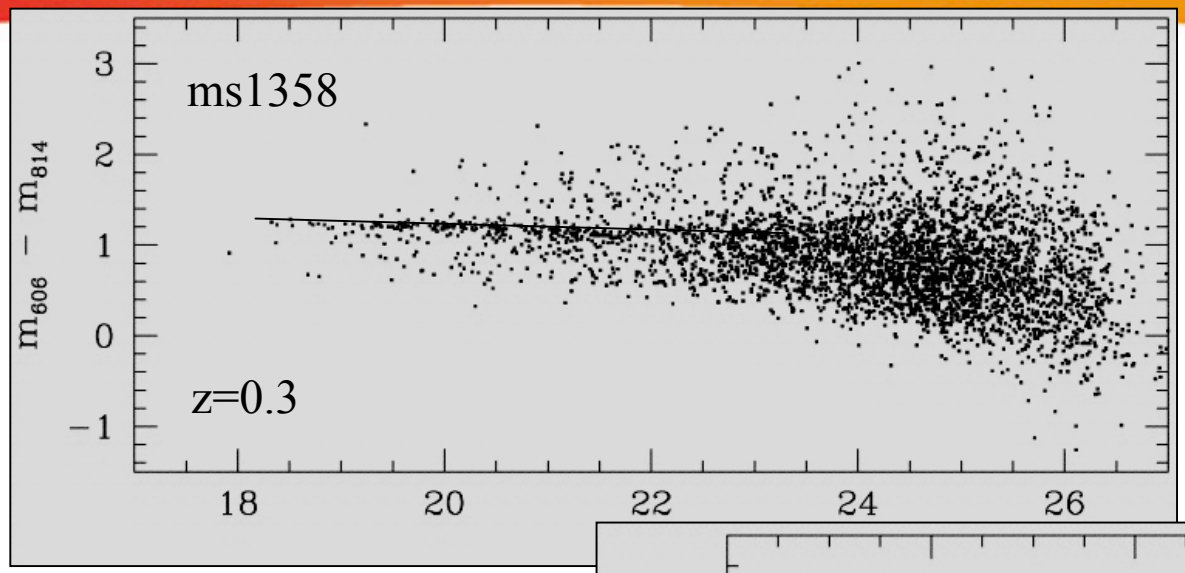

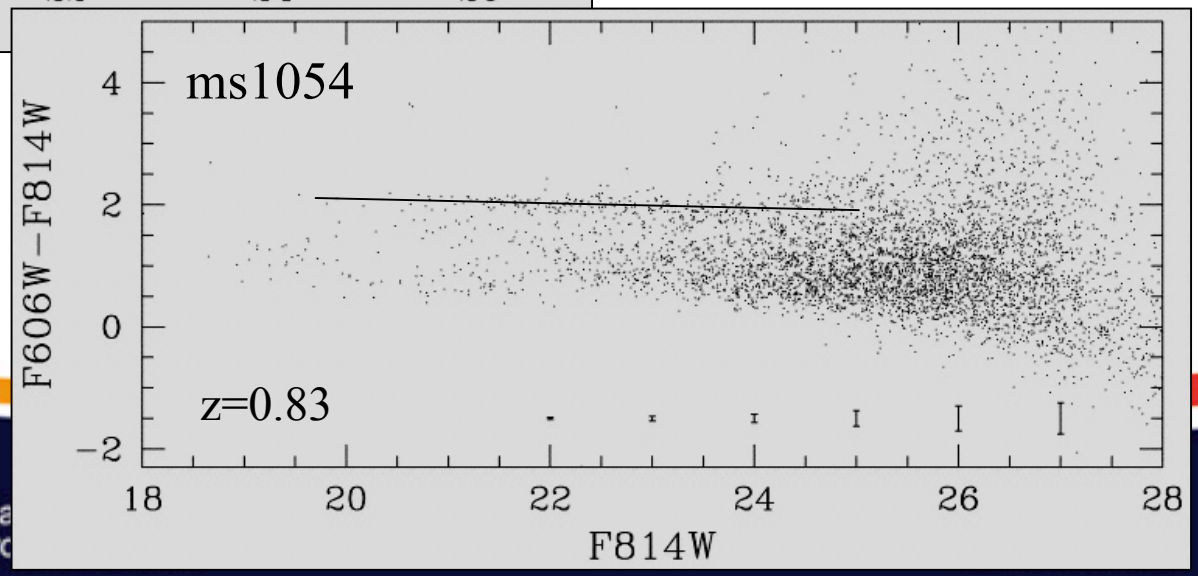

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The core population: old elliptical galaxies

- The color of a galaxy alone does not directly yield the age
- Age-metallicity degeneracy: $d \log(Z) = -2/3\, d \log(Age)$
- Star-formation history can be buried

The core population: old elliptical galaxies

- Cluster E/S0 galaxies are very red and display a C-M relation
- E and S0s colors are identical in clusters and are identical in the field (Sandage & Visvanathan 1978)
- Homogeneity of E/S0 population: very tight C-M relations
- Comparison of stellar synthesis models yields large ages
- Elliptical population is in place in clusters at the highest redshifts yet observed

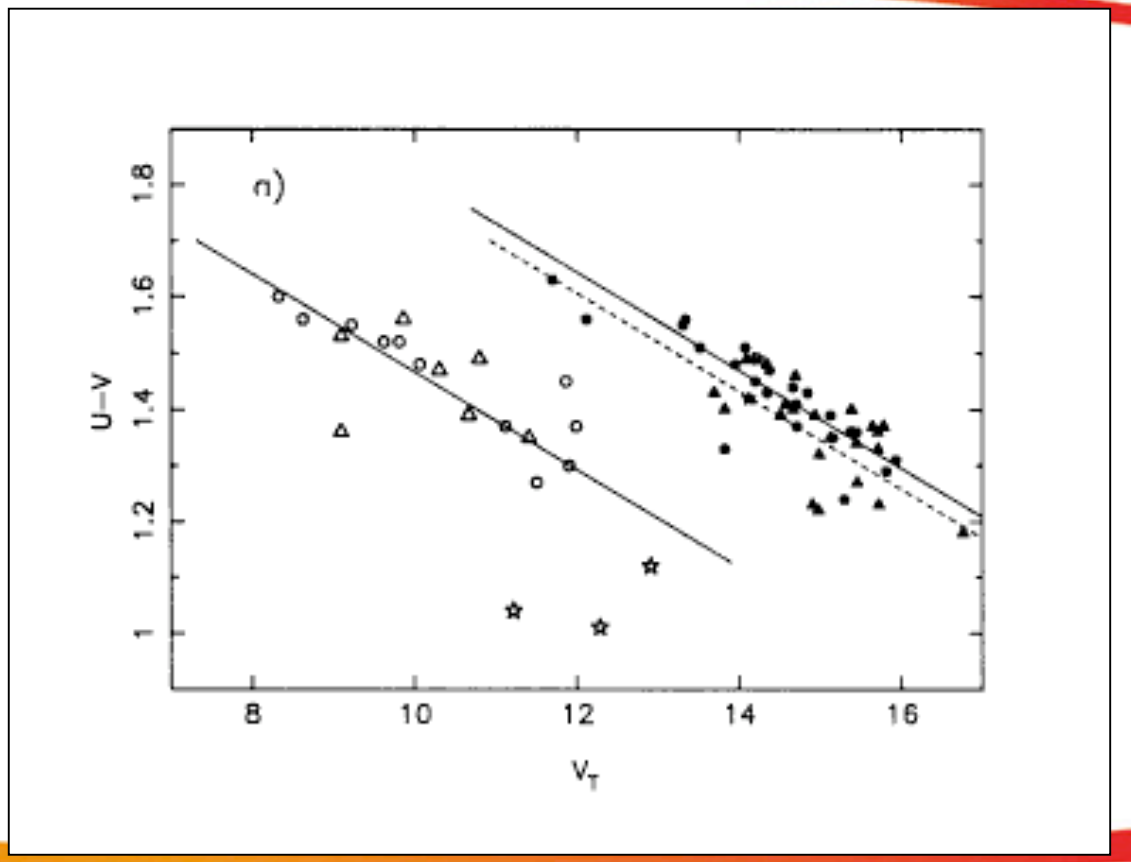
[It can be difficult to discriminate between E and S0 galaxies when doing galaxy classifications]

Homogeneity of the elliptical population : Local Universe

Comparison of Virgo and Coma (Bower, Lucey, Ellis)

The similarity in color and the small dispersion in color of the E/S0 population implies a large age and a similar formation epoch for all of the E/S0 galaxies in the clusters.

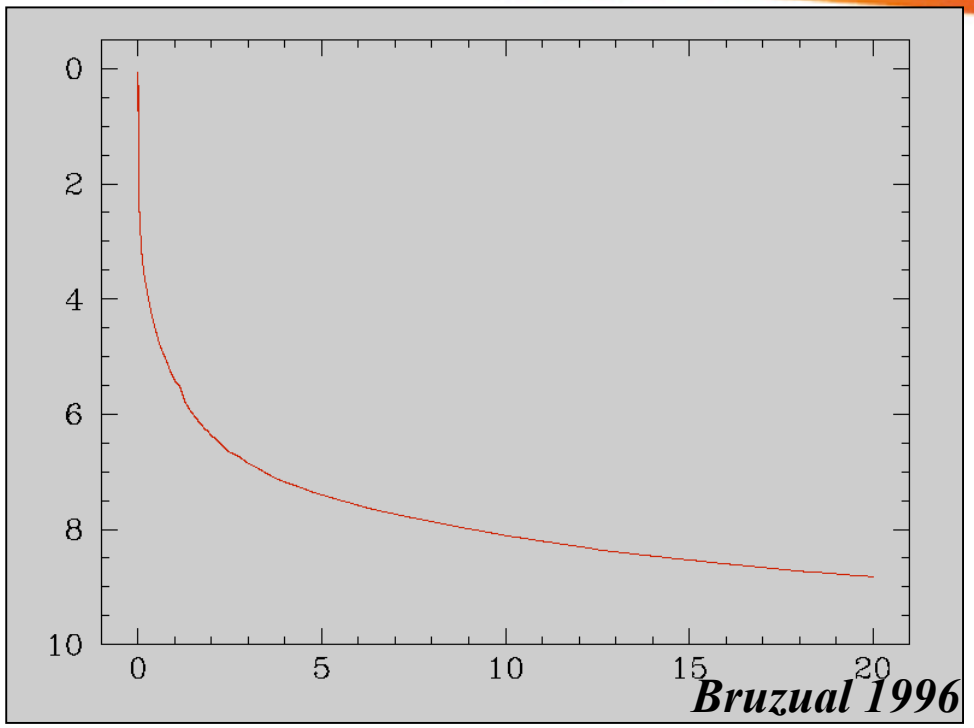
Intrinsic scatter ~ 0.04 mag in U-V



Spectral synthesis models of elliptical galaxies

B magnitude

Luminosity changes rapidly during early phases, slower later



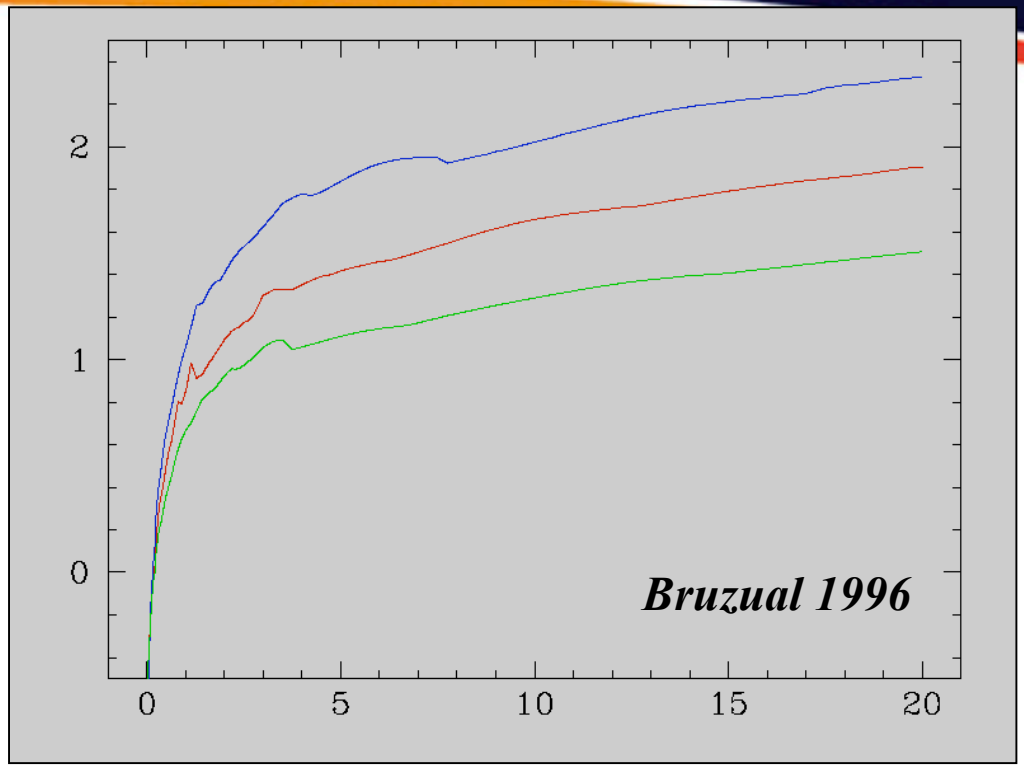
Age of the galaxy (Gyr)

Spectral synthesis models of elliptical galaxies

U-V color

Strong variation in color with metallicity

Variation in color with age

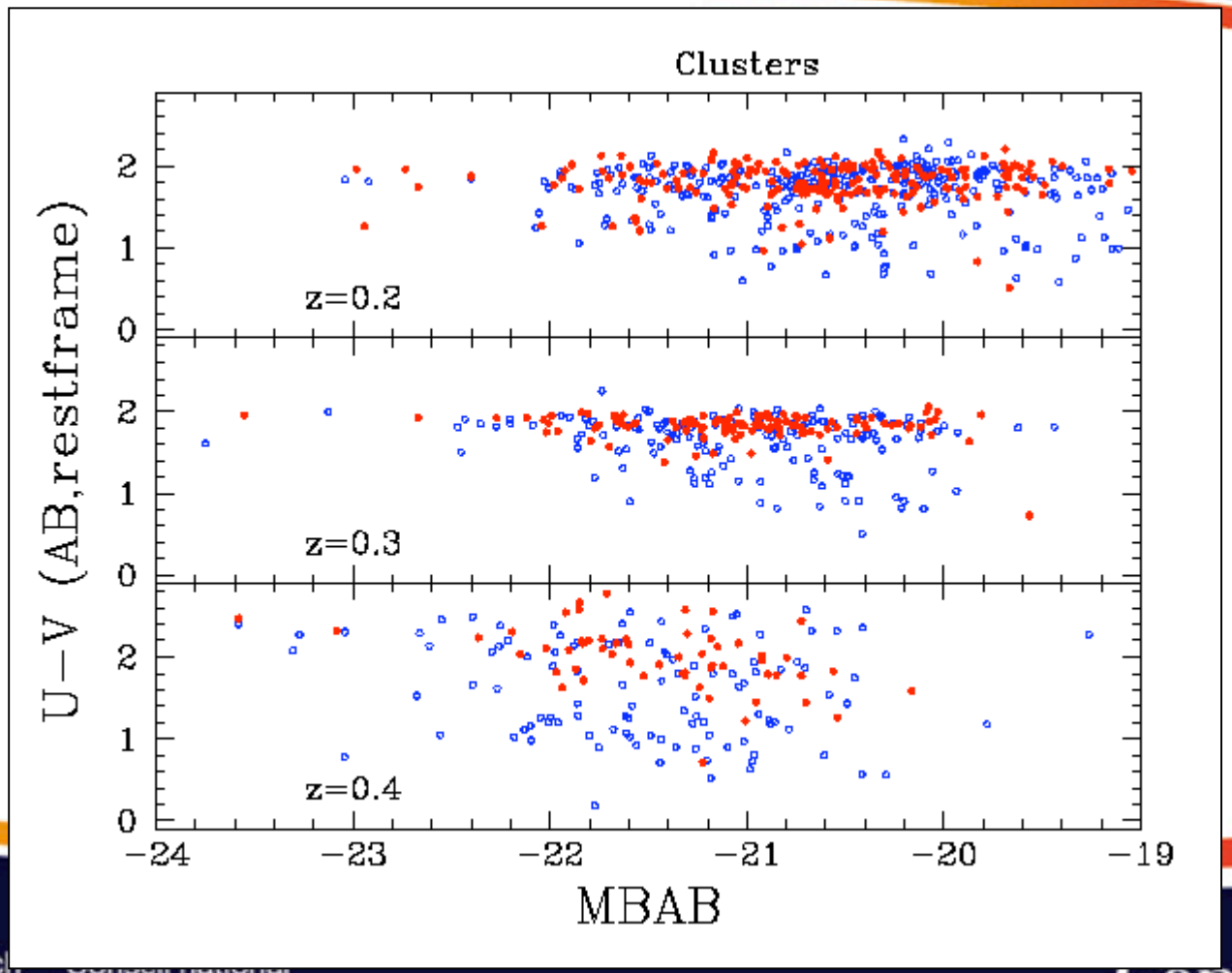


Age of the galaxy (Gyr)

Observe clusters at higher redshifts

Clusters at higher redshift will provide much stronger contraints on formation epoch from the color-magnitude relation

Homogeneity of the elliptical population: CNOC



The elliptical/S0 population at z=0.5

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HST imaging --- visual classification

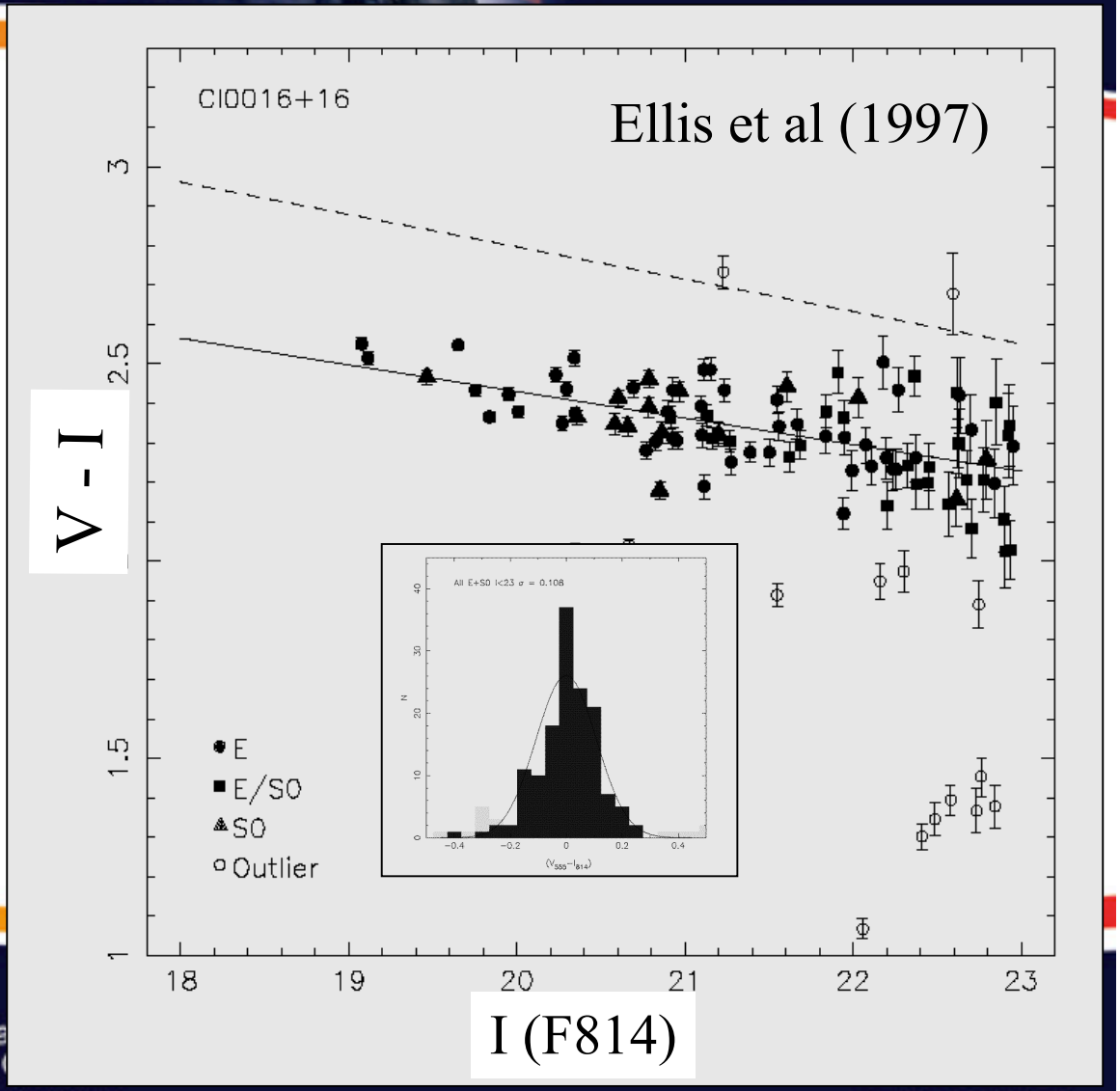
3 clusters (few redshifts)

CL0016+16

rms (E) = 0.082

rms(S0) = 0.080

Intrinsic scatter < 0.1 mag



Homogeneity of the elliptical population

$$\delta(U-V) = \frac{d(U-V)}{dt}\,\beta(t_H - t_F) \leq \sigma$$

t_H = cosmic age at time of the observations

t_F = lookback time to end of single burst of star formation

b = factor ~ 1 if star formation history was distributed uniformly from t=0 to t_F

b = factor << 1 if galaxies all formed nearly simultaneously

s = dispersion in U-V color

For any b > 0.3 (and conventional cosmology) most spheroidal stars formed at z > 3

Conclusions from color-magnitude relation at z=0.54

- E and S0 galaxies have identical colors at z = 0.54
- Scatter in C-M relation is small (< 0.07 mag)
- Cluster-to-cluster scatter in mean color is small (< 0.03 mag) for 3 three clusters (despite differences in X-ray luminosity, richness)
- Small bluing of the U-V colors, consistent with passive evolution
- Bulk of the stars formed 5-6 Gyr earlier than the epoch of the observations

Luminosity evolution of cluster ellipticals

- Fundamental plane: relationship between size, surface brightness, and velocity dispersion

- M-log Re relation (projection of the fundamental plane)

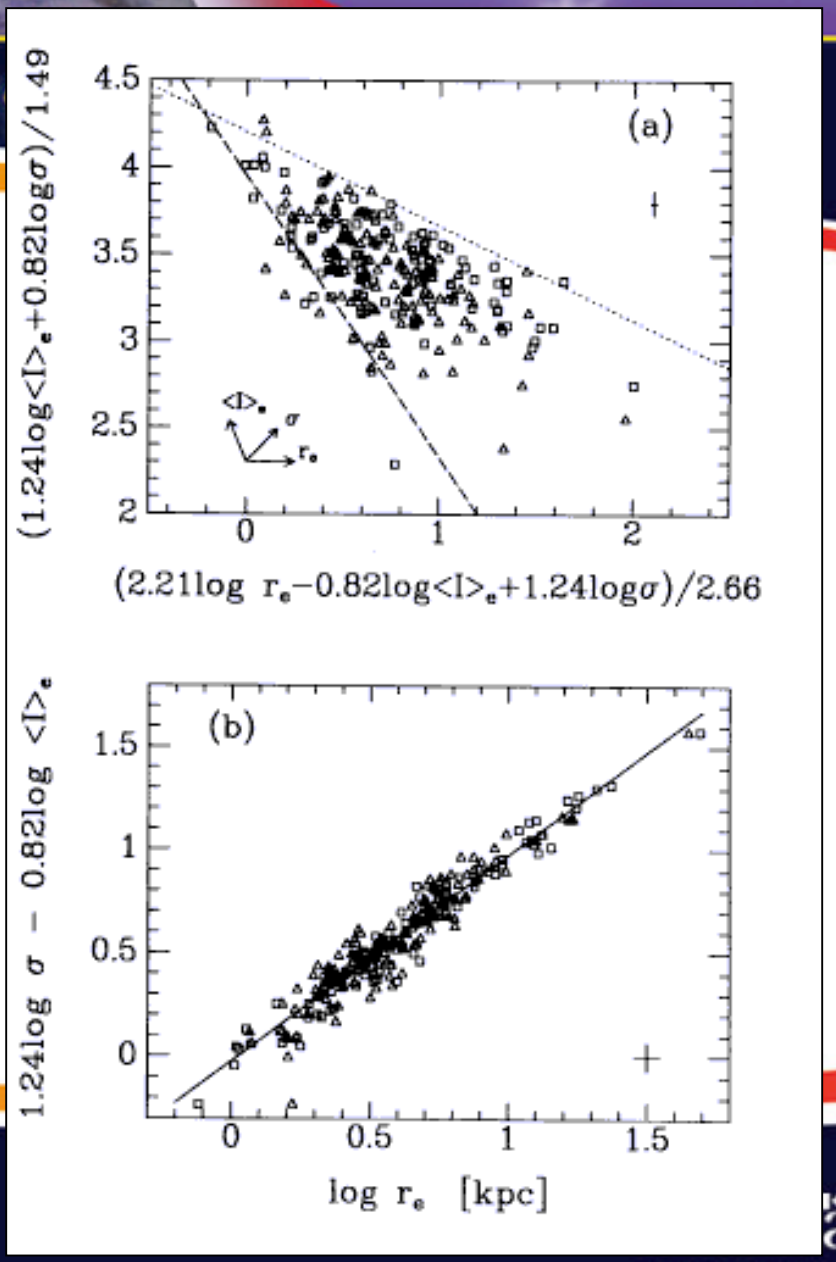
Assume that there is no dynamical evolution so that size and mass are constant. Then evolution is simply a fading with time of the stellar population, revealed as a change in surface brightness or luminosity

Evolution of ellipticals

The local FP of cluster ellipticals

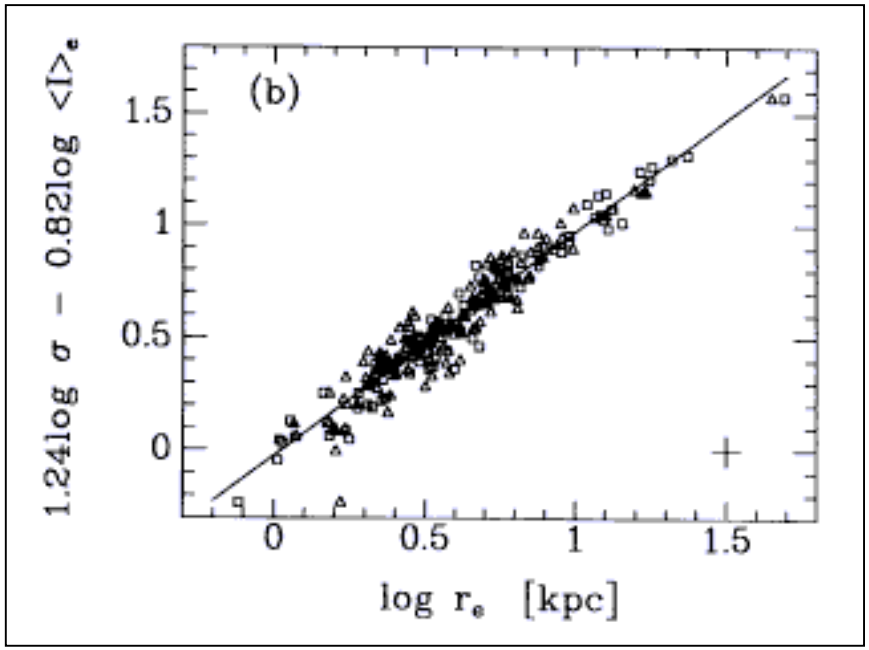
from Jorgensen et al.(1996)

Note that S0 galaxies follow the fundamental plane

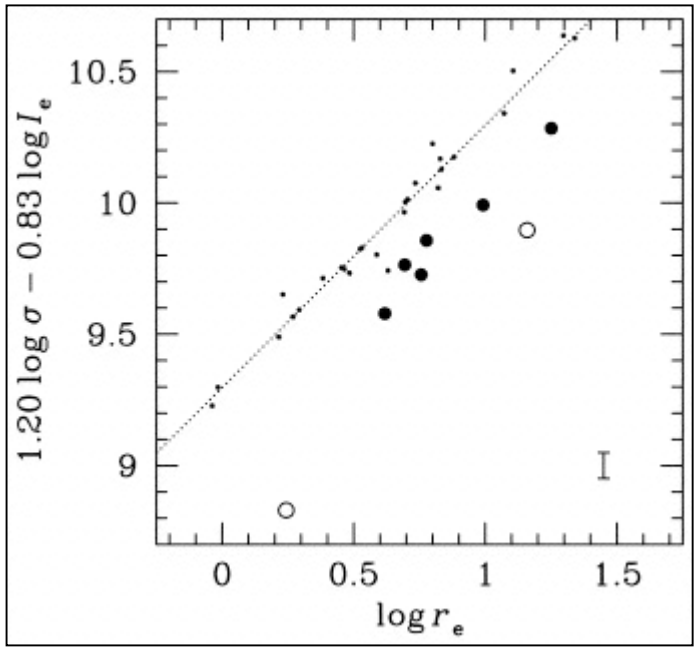


Evolution of ellipticals: the fundamental plane (FP)

local FP in clusters



FP at z=0.83

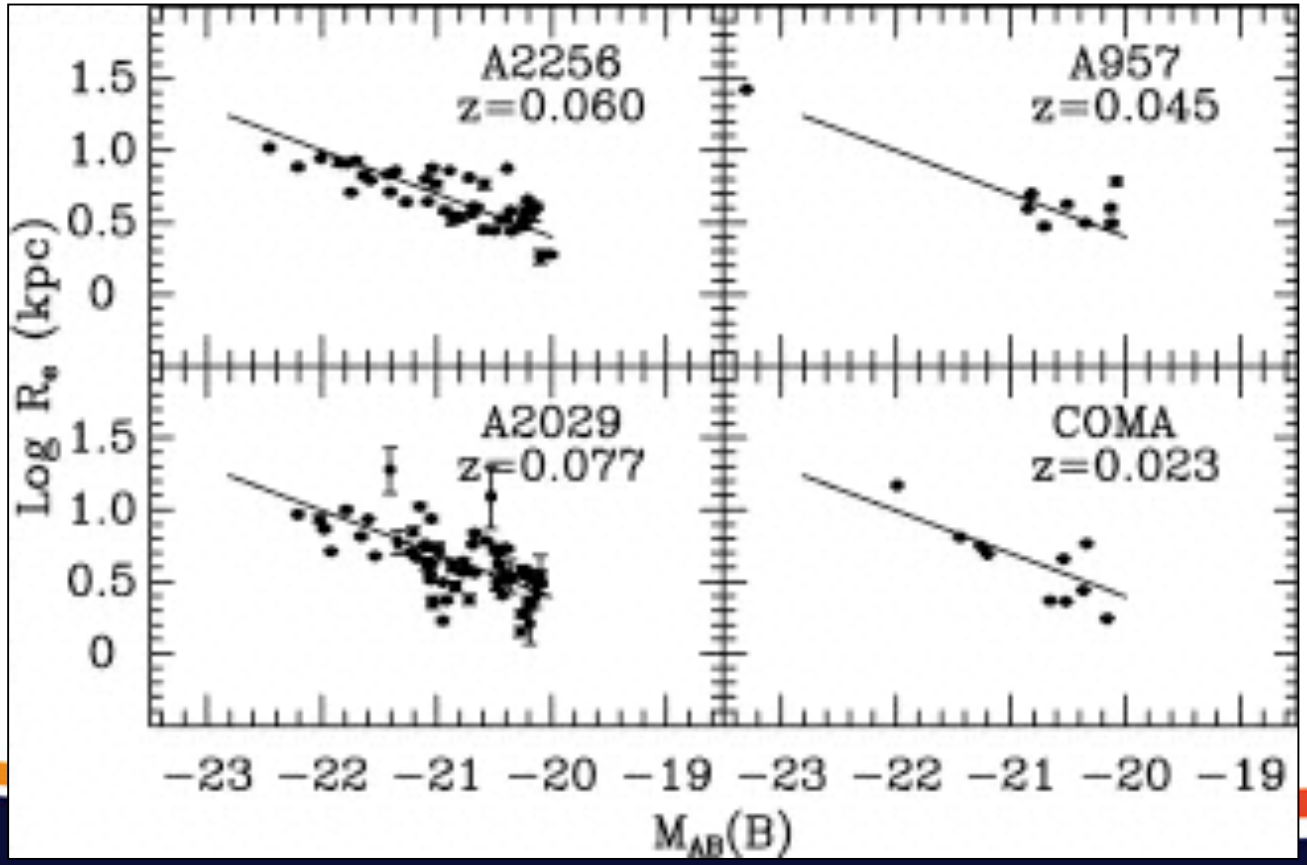


van Dokkum et al 1998

The FP requires high quality imaging (HST) and spectroscopy to obtain the central velocity dispersions. Very costly.

Evolution of cluster elliptical galaxies

The M-log Re relation



Schade, Barrientos, Lopex-Cruz (1997)

Evolution of cluster elliptical galaxies

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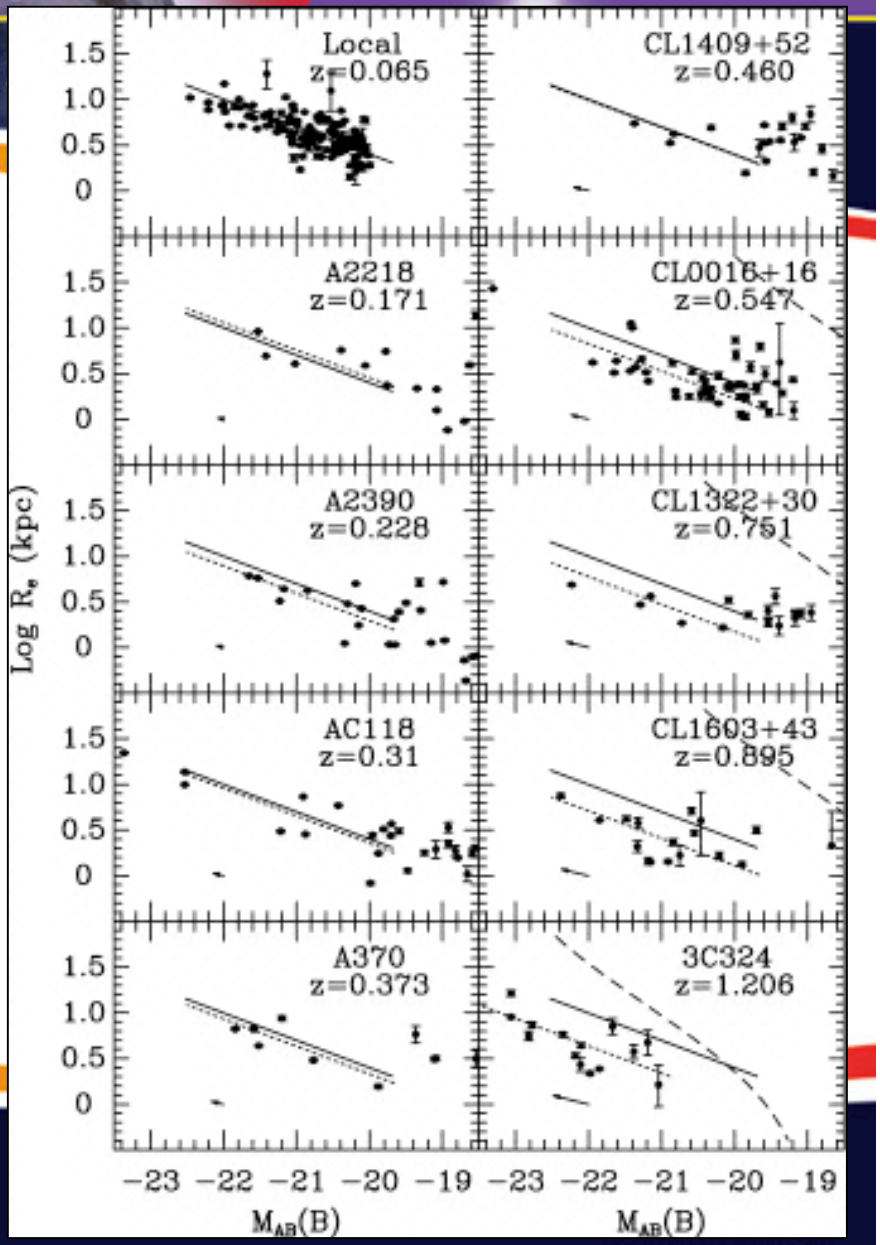
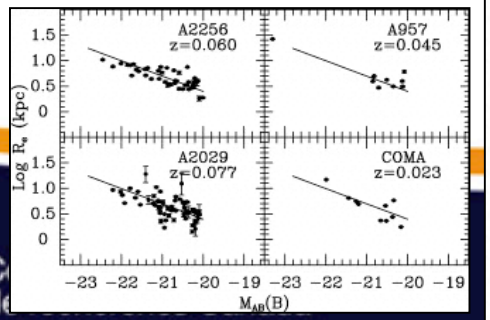
The M-log Re relation requires high-quality imaging

HST imaging of 9 clusters with redshifts $0.2 < z < 1.2$ (Schade et al. 1997)

Requires careful matching of methods of data reduction between high and low redshift

Two-dimensional surface photometry using parametric models (deVaucouleurs and exponential)





Schade, Barrientos, Lopez-Cruz (1997)

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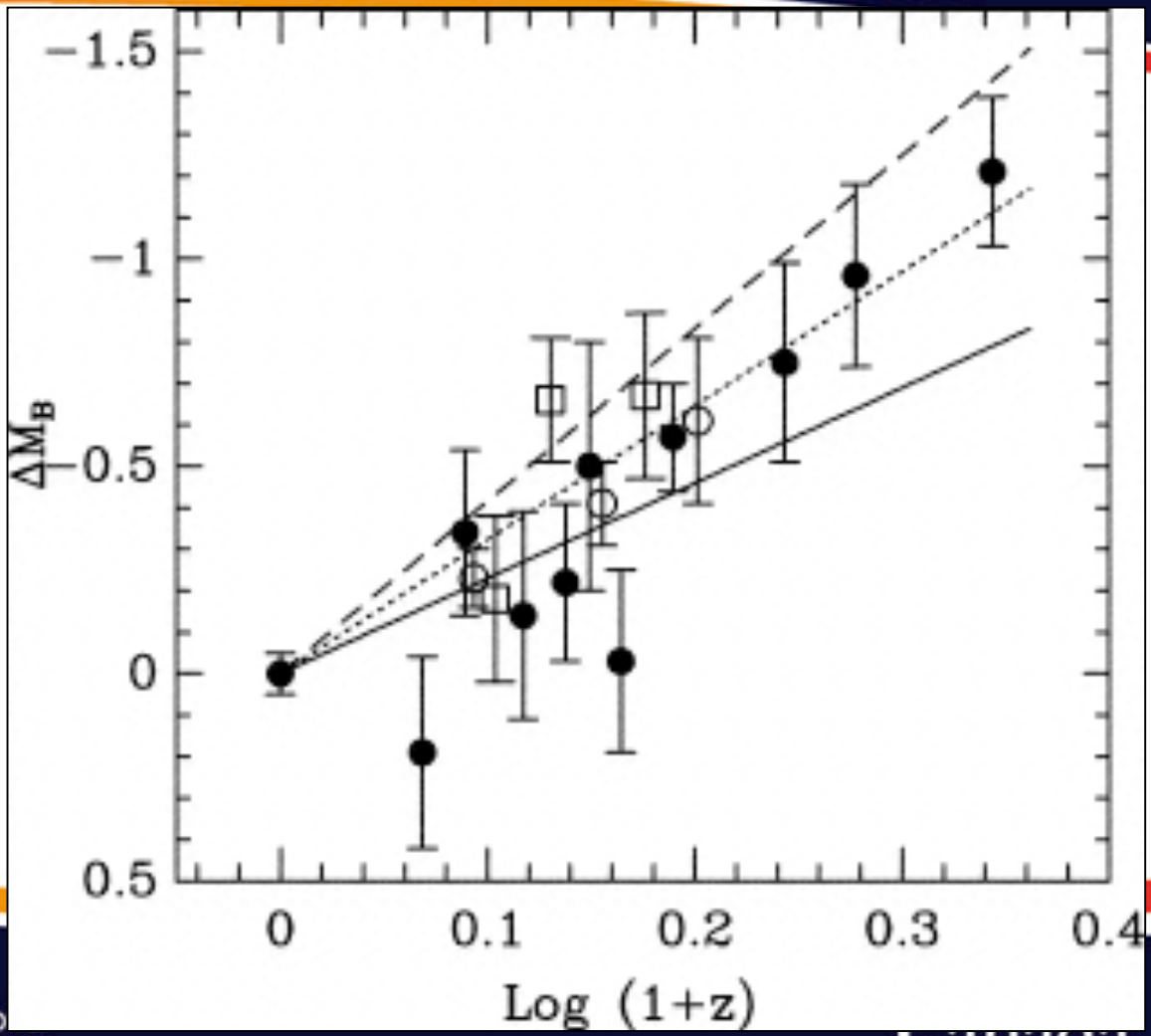
Evolution of cluster elliptical galaxies

Luminosity evolution of cluster ellipticals is consistent with passive evolution of old stellar populations

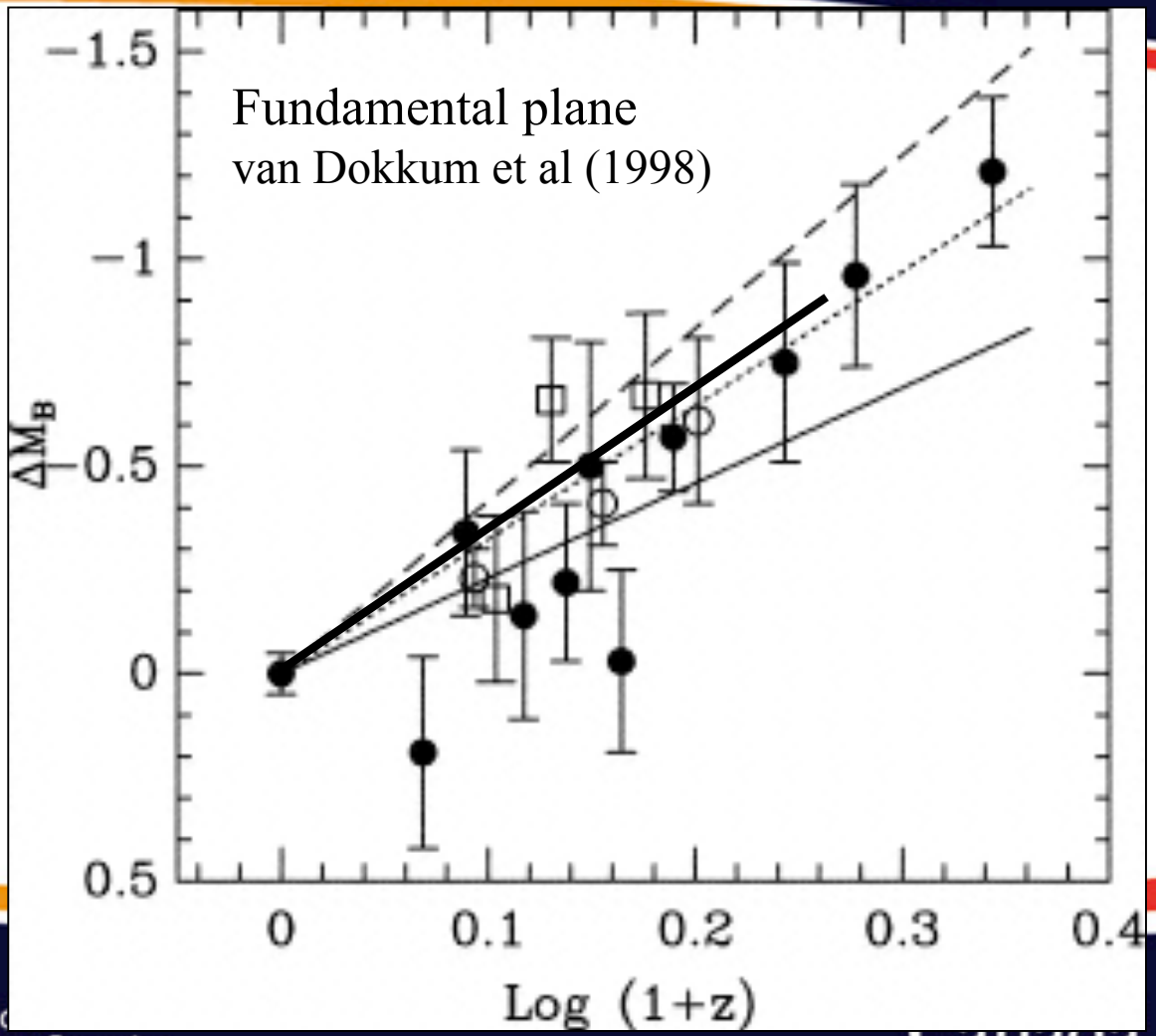
Luminosity evolution of ellipticals to z = 1 is similar in clusters and the field

Schade, Lilly,.. 1999



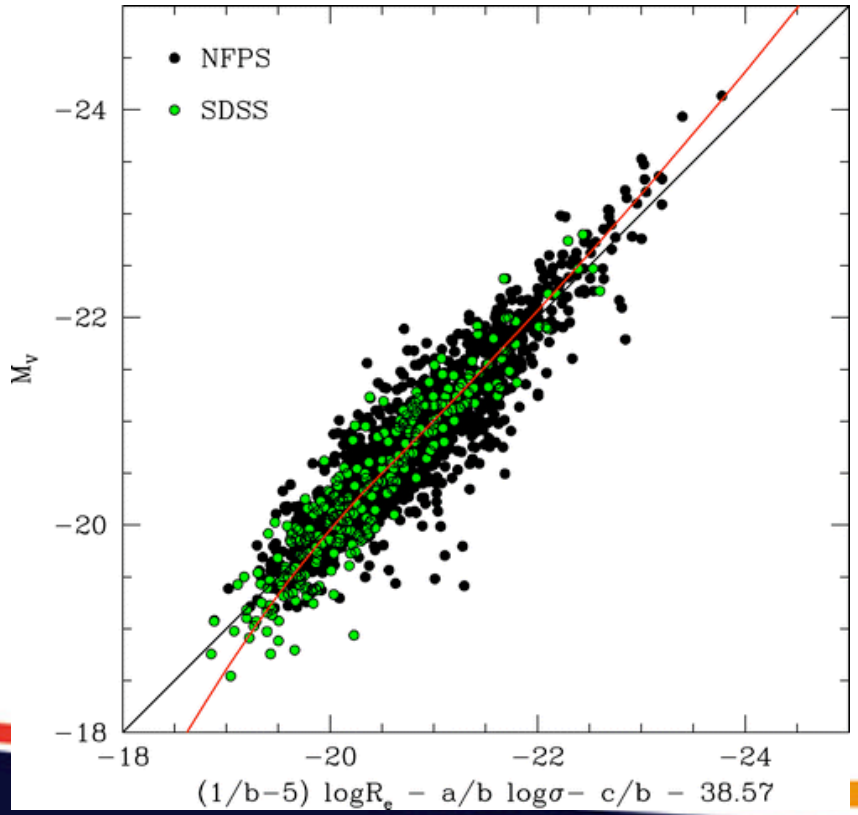
Evolution of cluster elliptical galaxies

Fundamental plane and M-log Re methods give the same result



The local fundamental plane (FP)

FP at z=0.83



Fundamental plane Dressler et al (2008) in 59 clusters (SDSS/other) z< 0.07

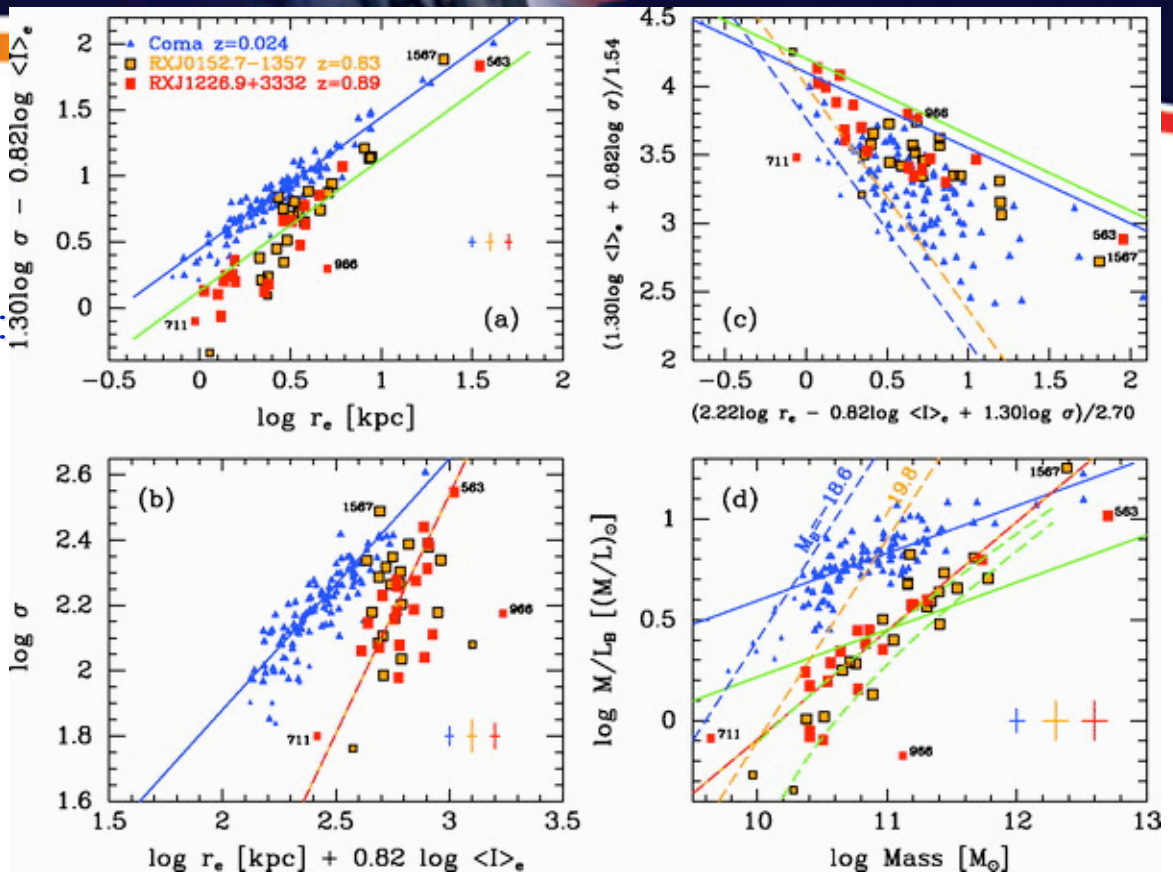
Some dependence on Lum

and environment

van Dokkum et al 1998

Jorgensen 2006

- 2 rich clusters (z=0.82 and 0.89)
- Passive evolution OK
- High=z FP is shifted and rotated:
- Mass dependency of SFR
- Low-mass galaxies had more recent star-fromation



The FP requires high quality imaging (HST) and spectroscopy to obtain the central velocity dispersions. Very costly.

Summary of evolution of cluster elliptical galaxies

- The color-magnitude diagrams of rich clusters are dominated by a red sequence of E and S0 galaxies
- The E are indistinguishable from the S0 galaxies in color or scatter in color
- The red sequence has the same color in all clusters studied (at a given z)
- The homogeneity of the E/S0 populations persists to $z = 0.5$ and implies a formation epoch at least a few Gyrs earlier ($z > 1$)
- The color of the ellipticals evolves in a manner consistent with the implied ages and with passive evolution
- Cluster (and field) ellipticals evolve in luminosity in a manner consistent with the implied ages and with passive evolution

The field galaxy population is evolving