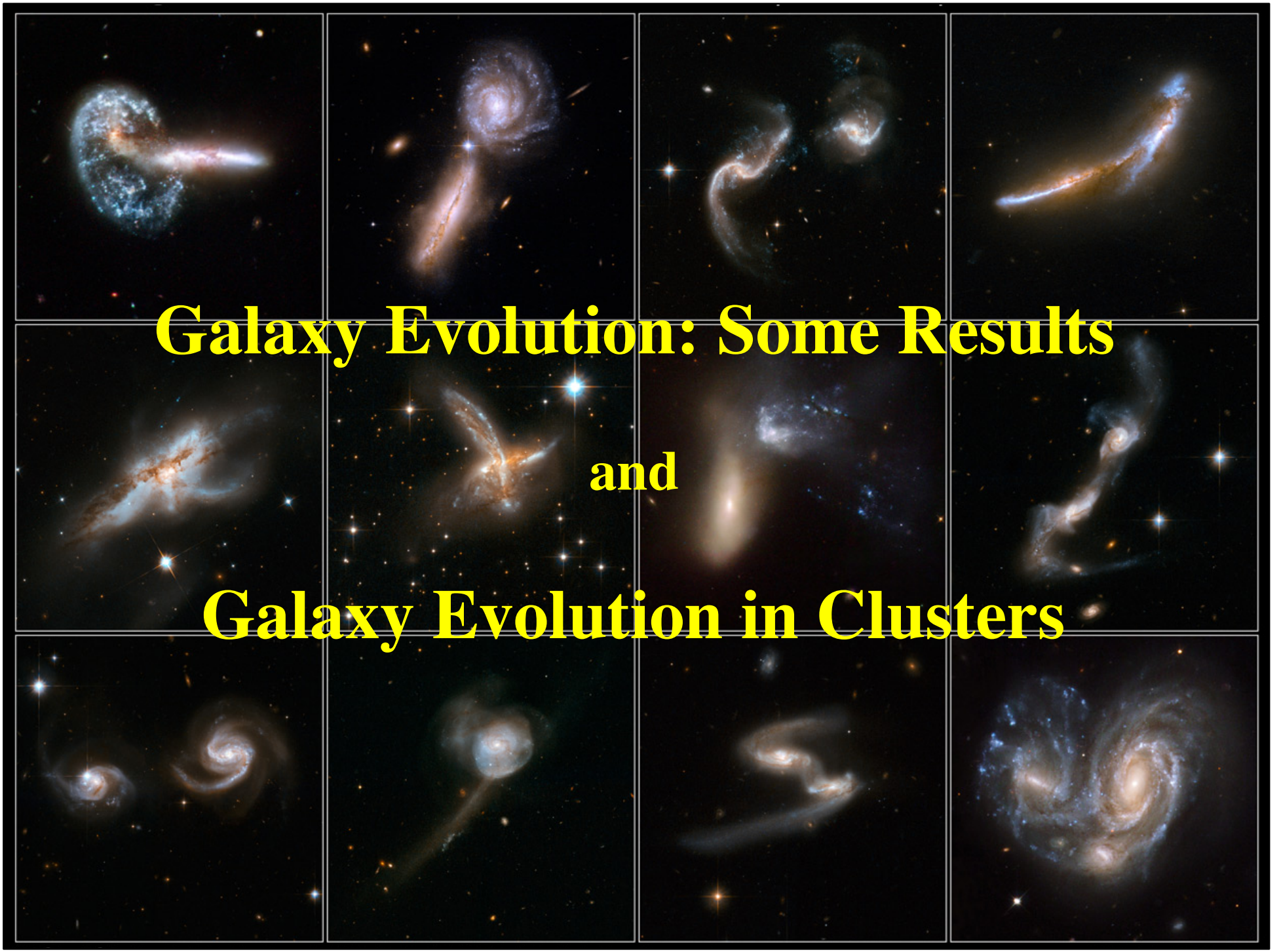
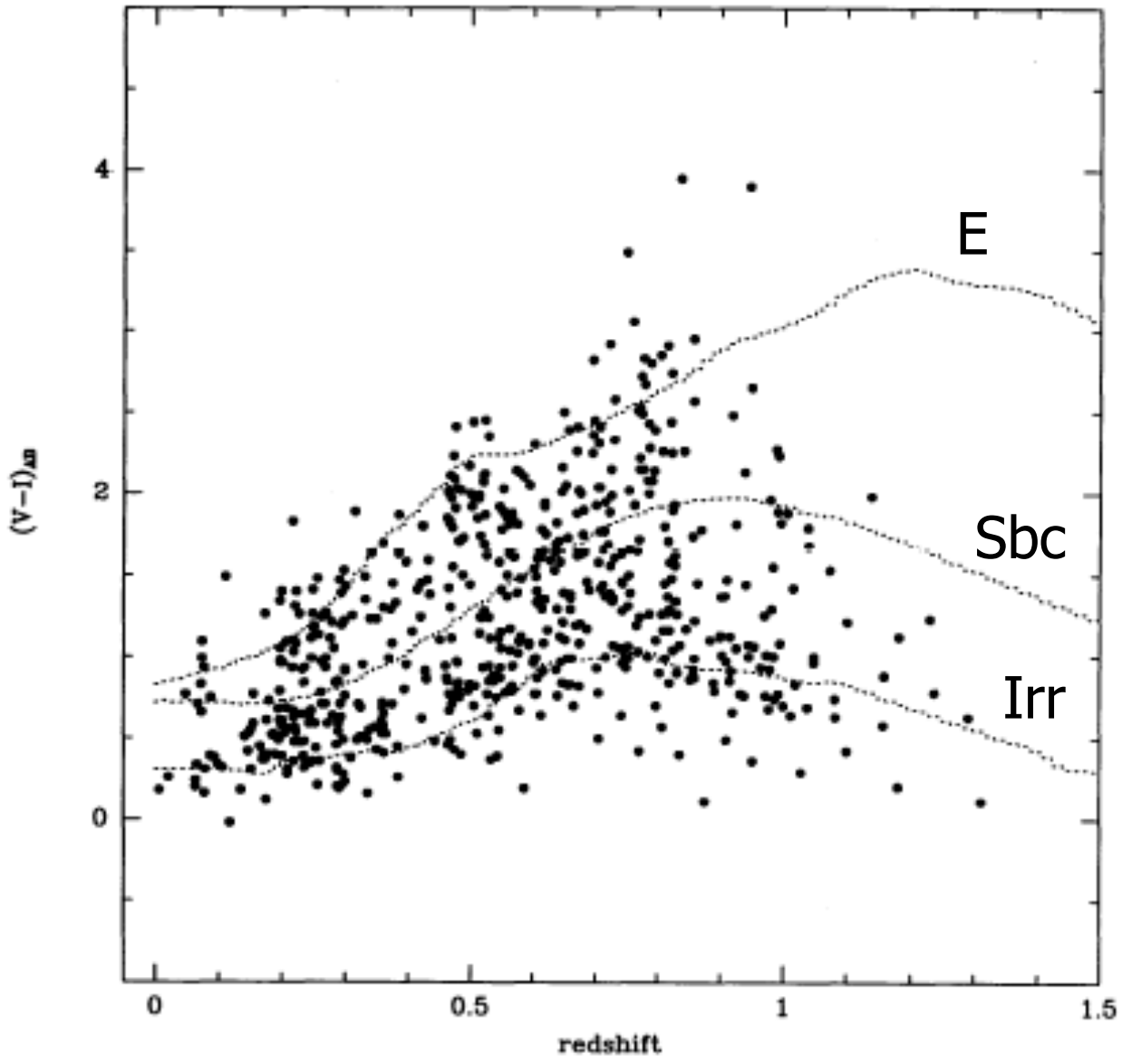

Galaxy Evolution: Some Results
and
Galaxy Evolution in Clusters

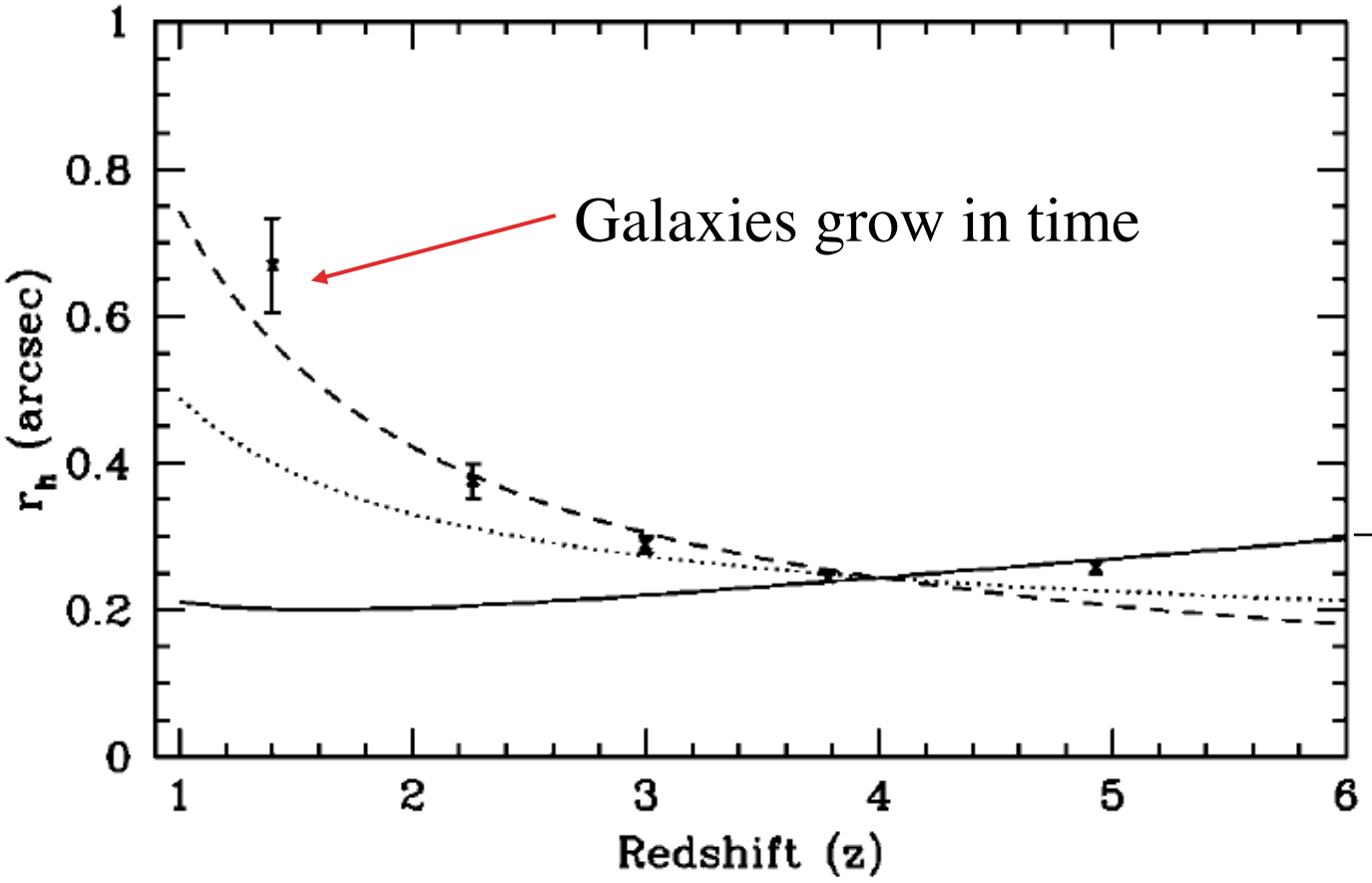
# Galaxy Colors vs. Redshift




Morphological mix comparable to that at z ~ 0 extends out to z ~ 1, with little apparent evolution

# Evolution of Galaxy Sizes

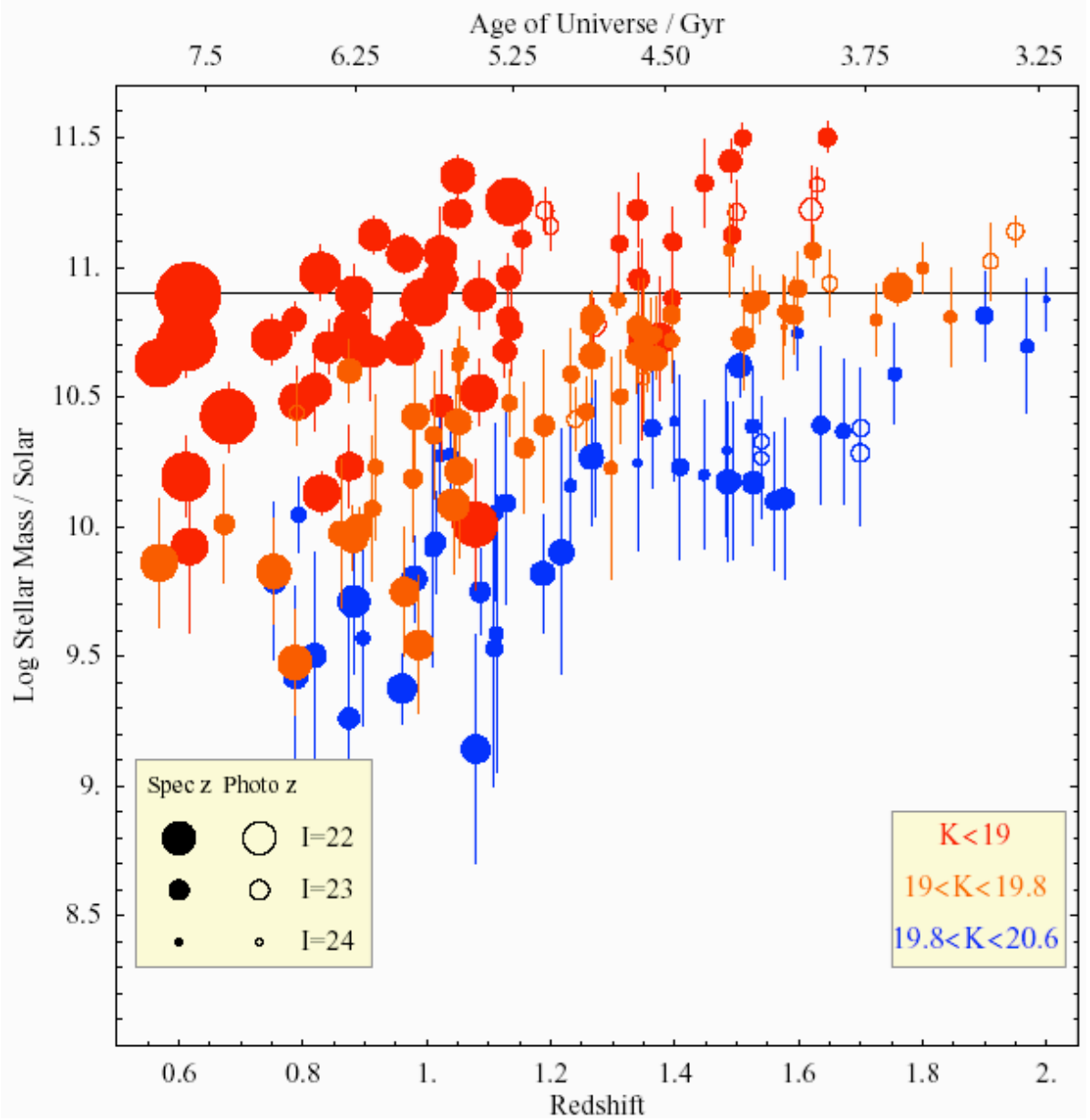
HST imaging suggests that galaxies were smaller in the past




Solid line: Expected if galaxies have a fixed size in proper coordinates

# Evolution of Galaxy Masses

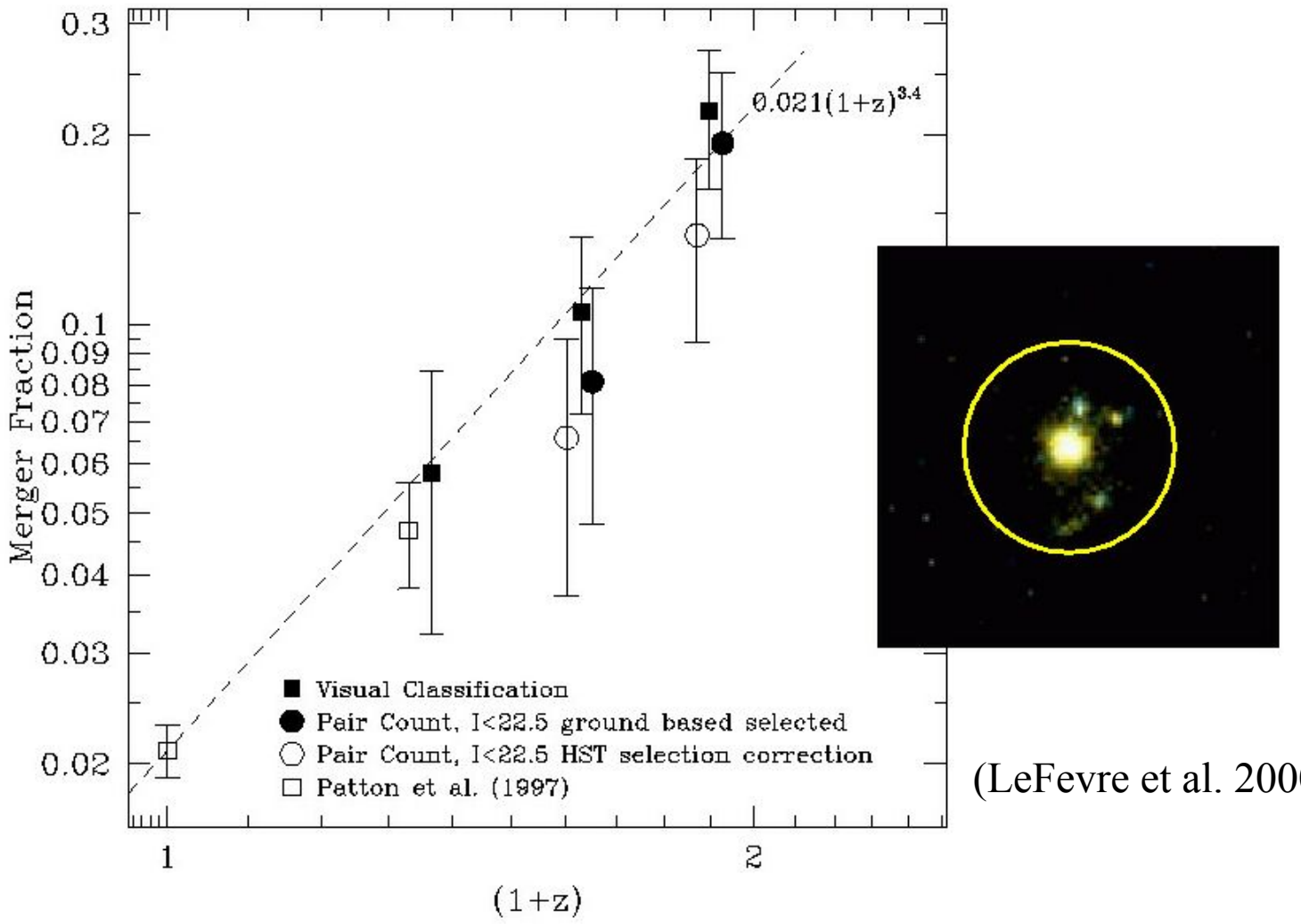
The more massive galaxies evolve less, i.e., they are already in place at $z \sim 1$ - 2, whereas most of the evolution at lower $z$'s is for the low mass systems - seemingly opposite from what one may expect in the hierarchical scenario! (this is caled "galaxy downsizing")



# Evolution of the Merger Rate

***Merger fraction***

***~ (1 + z)*** $^{3.4}$

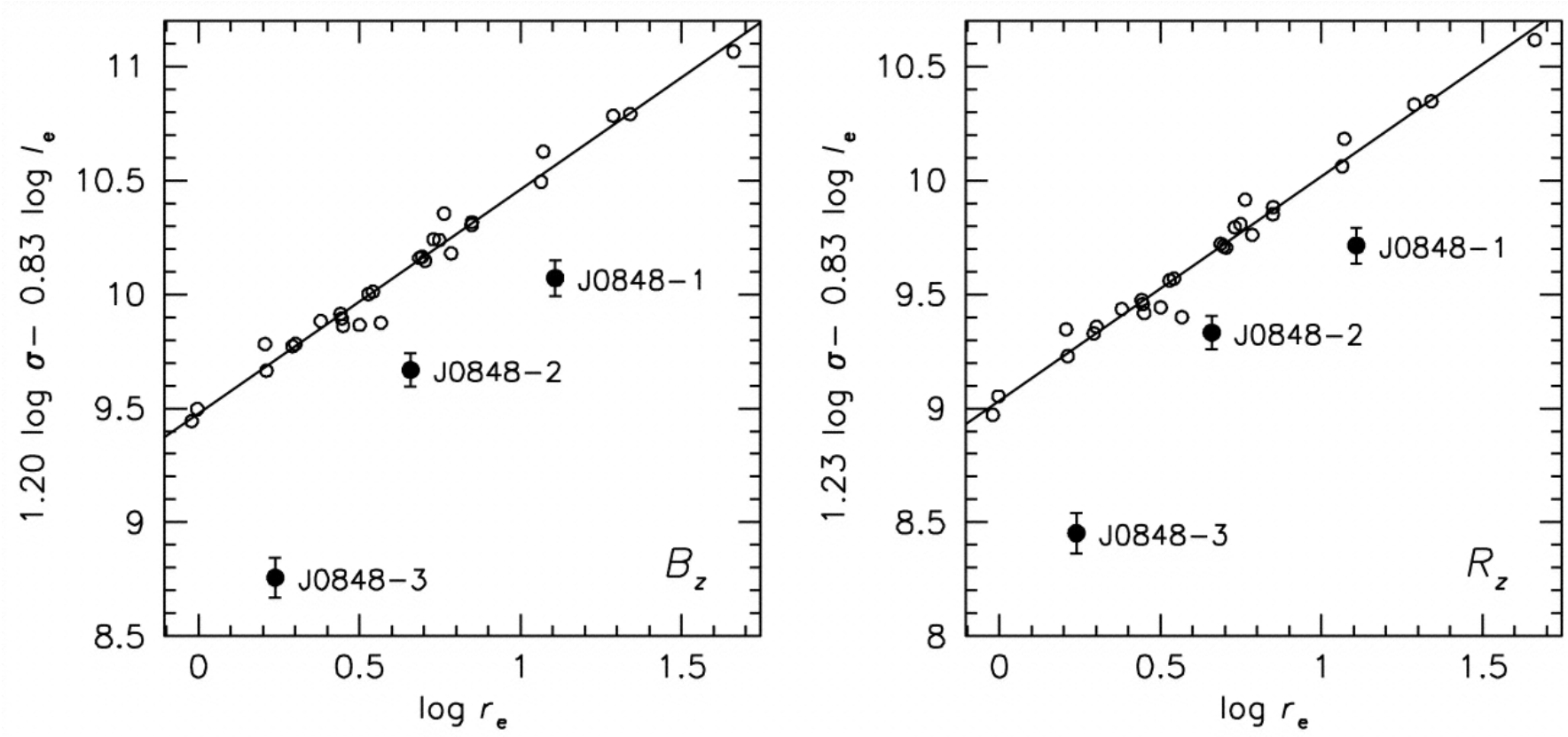



(LeFevre et al. 2000)

Good evidence for a rapid rise in merging fraction at higher z's, but conversion to mass assembly rate is not straightforward

# Scaling Relations as Evolution Probes

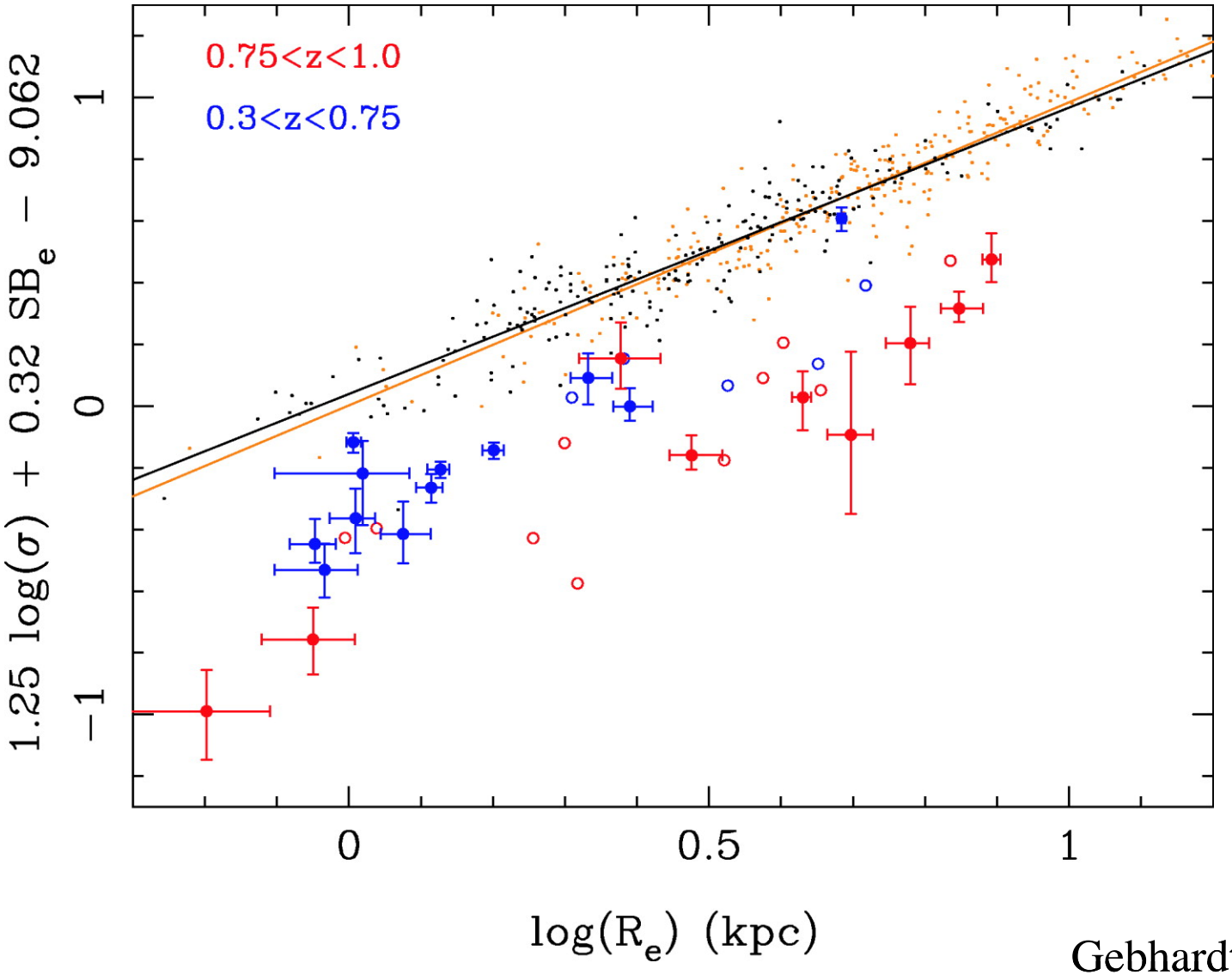
By design, they are our sharpest probe of galaxy properties - and thus potentially of galaxy evolution (note that the relations themselves may be evolving!)




Cluster at z =1.27

van Dokkum & Stanford, 2003

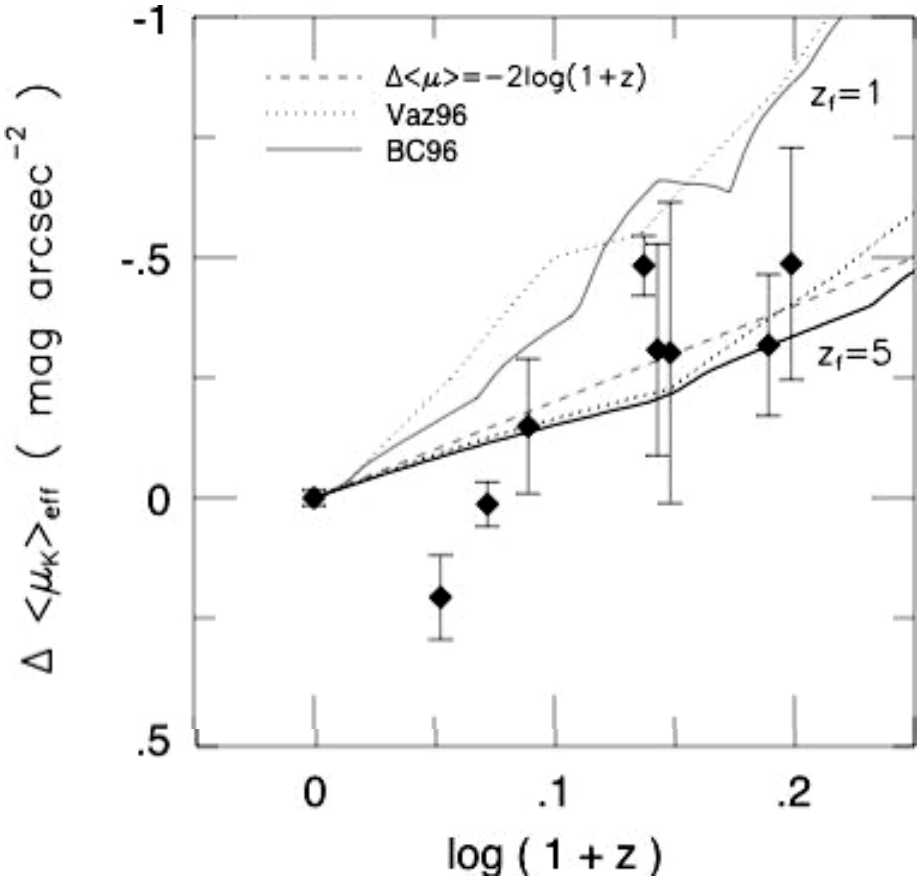
# Evolution of the FP of Field Ellipticals

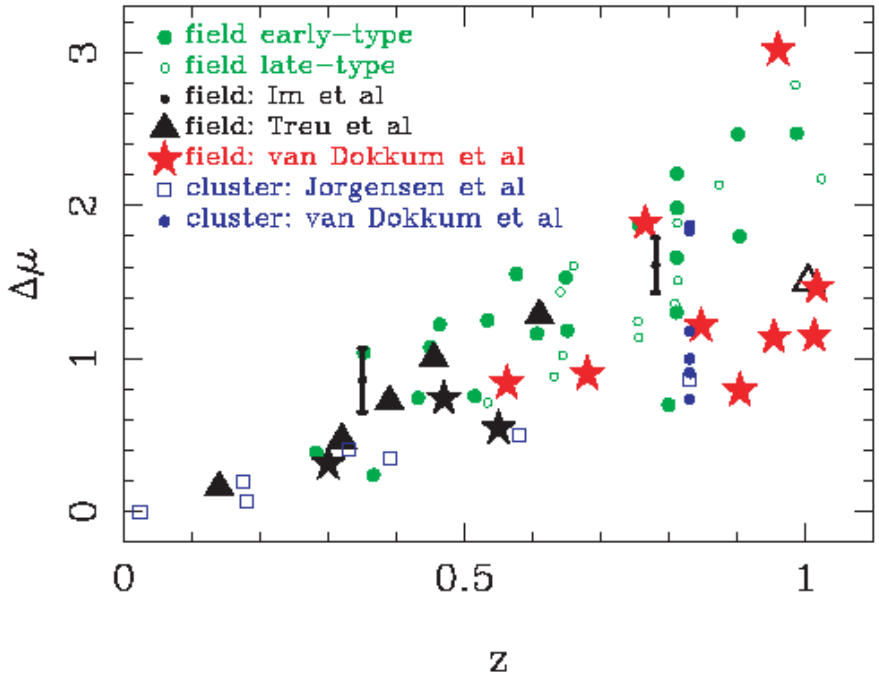



Gebhardt et al. 2004

# Fundamental Plane Evolution

The data indicate a brightening of E's at higher redshift, as reflected in their surface brightness at a fixed $r_e$ and $\sigma$. The brightening rate is consistent with passive evolution starting at a high redshift



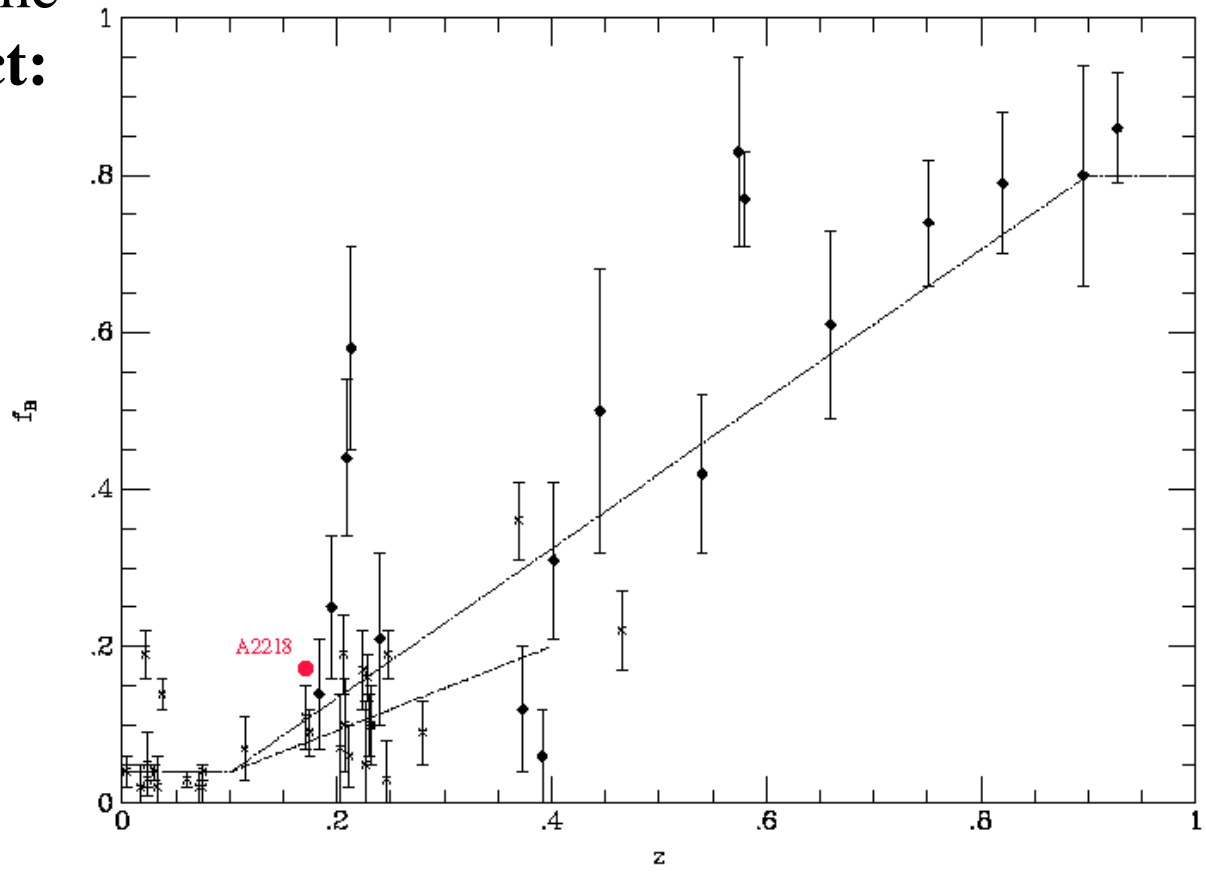
# Scaling Relations as Evolution Probes

- Studies of the FP in both clusters and field out to $z > 1$ indicate that ellipticals were brighter in the past, but the data are consistent with a model where they are formed at high redshifts ($z > 3$, say) and evolve nearly passively since then
- Data on galaxy colors and line strengths are also consistent with that picture
- There is a gradual rotation of the FP, in the sense that the lower mass E's are younger - galaxy downsizing again
- Studies of the ***Tully-Fisher relation*** at high z's are much less conclusive: the TFR appears to be noisier in the past, and spirals somewhat brighter, but the situation is not clear yet

# Galaxy Evolution in Clusters

Generally, we may expect a systematic difference in galaxy evolution processes in very different large-scale environments, mainly due to different dynamical effects.

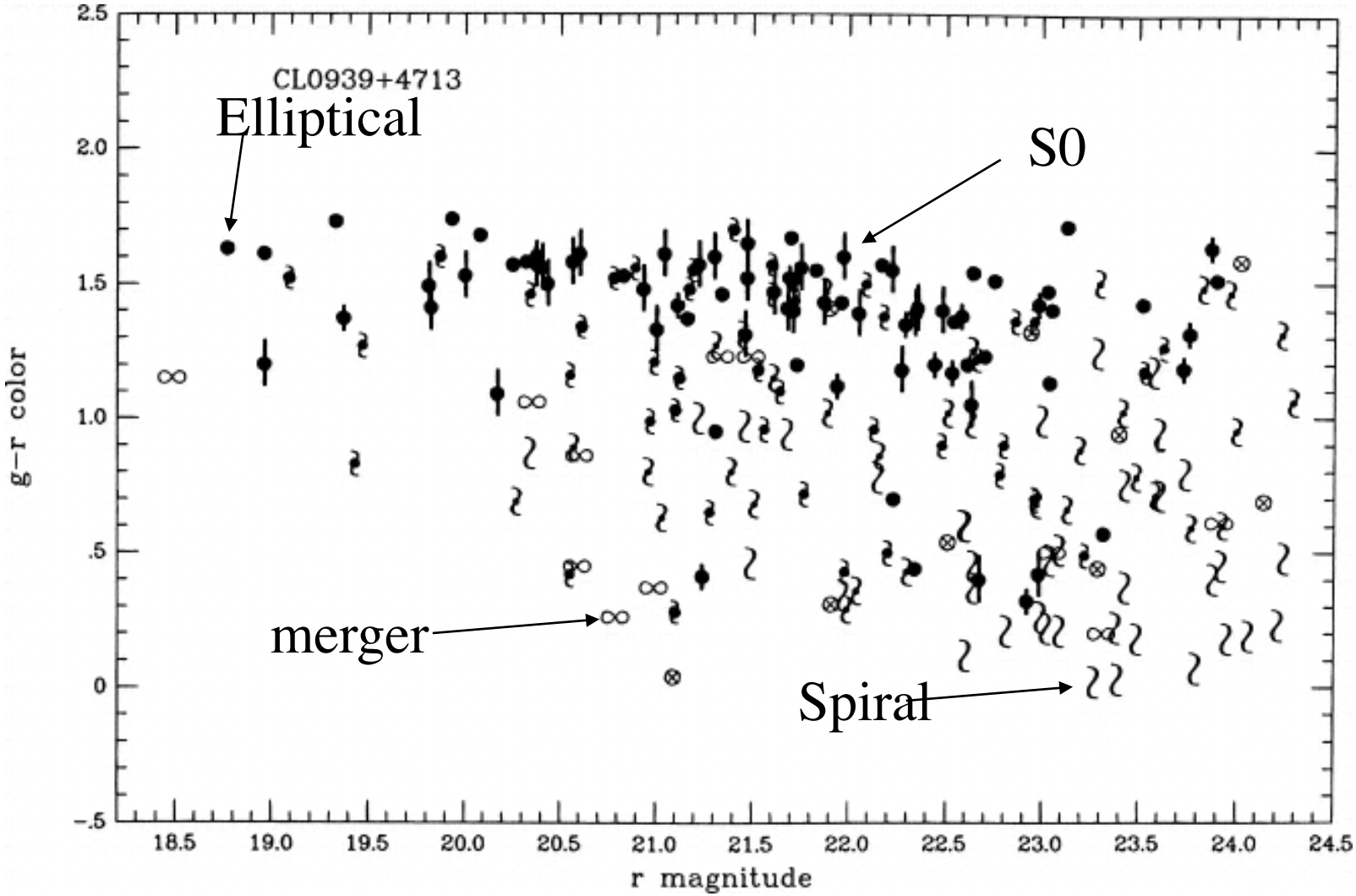
The first of these was the **Butcher-Oemler effect:** the fraction of blue galaxies in clusters increases dramatically at higher redshifts



# Galaxy Harassment

- Some encounters will not lead to mergers, but will disturb the tidally interacting galaxies
- First proposed by Moore et al. in 1996 as frequent high speed galaxy encounters (too fast for merging to occur) driving the morphological transformation of galaxies in clusters
- Galaxies will interact with both other galaxies in the cluster and with the cluster potential
- Galaxy harassment will transform Sc/Sd/dIrr galaxies into dE or dSph galaxies over the timescale of several billion years
- Tidal heating of disks may form S0's
- Tidally stripped debris is probably the source of intracluster stars
- In addition, gas may be stripped, leaving little fuel for star formation

# Color-magnitude diagram for CL0939+4713, z ~ 0.41



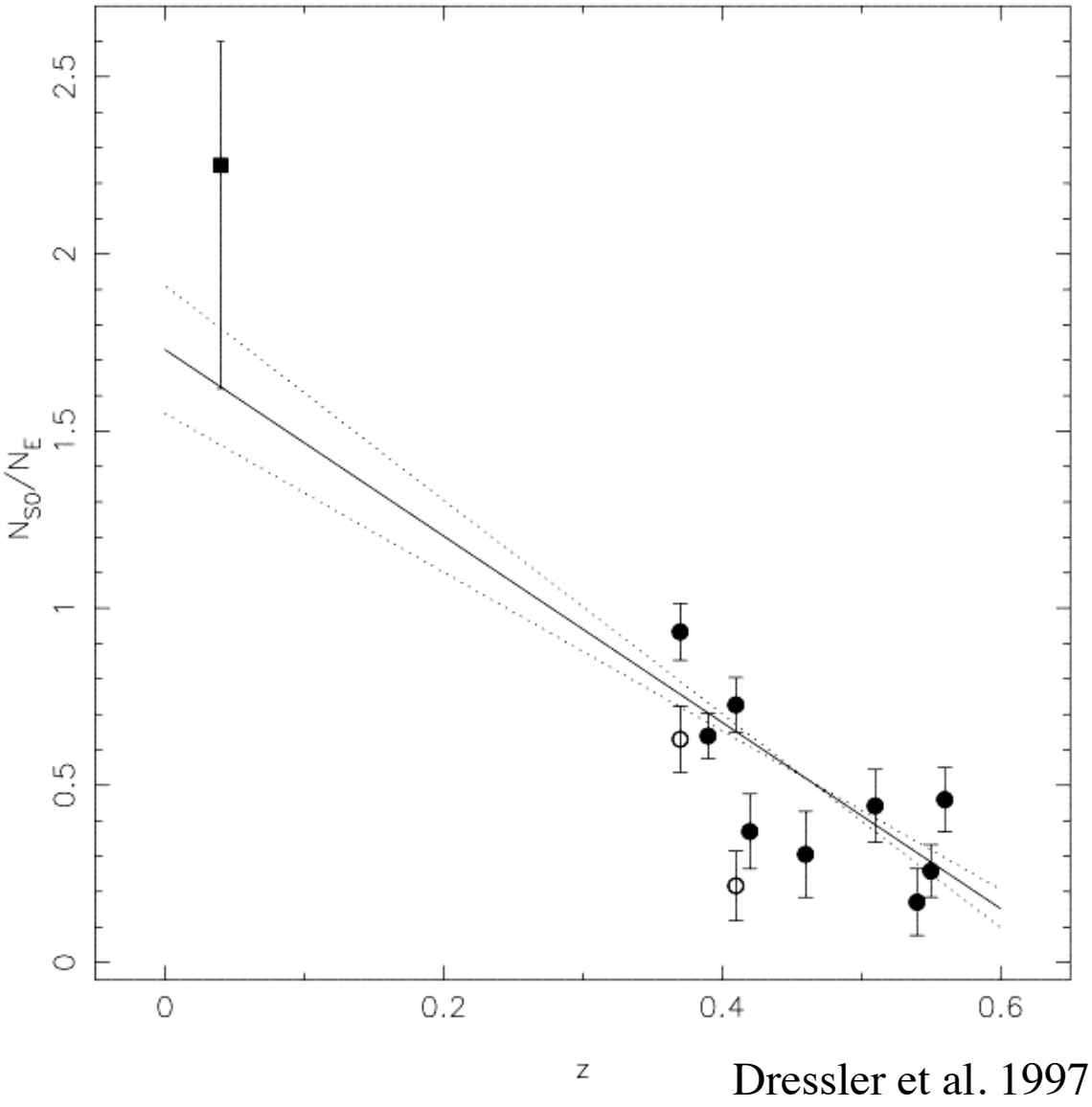

Oemler et al. 1997

# Post-Starburst Galaxies

- These blue galaxies in distant clusters are a mix of regular star-forming spirals, some AGN, and a new type:
- There is a significant population of ***post-starburst galaxies*** in distant clusters (~20%), these have K+A (or E+A) spectrum, showing both the features of a K-star (typical E galaxy spectrum) plus the strong Balmer absorption lines of an A star
- This would only be seen in a galaxy that was forming stars in the recent past (<1.5 Gyr) but the star formation was truncated
- This is probably related to the conversion of S0 to S galaxies (morphology density) and the Butcher-Oemler effect

# S0/E galaxy fraction as a function of redshift

The data indicate that there is a systematic conversion of regular spirals into S0 and E galaxies in time, but at any fixed redshift, richer and denser clusters have fewer spirals




Dressler et al. 1997

# Evolution of Spirals in Cluster Environment

- Possible scenario for spirals transforming into S0's:
  - Infalling spiral galaxies @ z~0.5
  - Triggering star formation
  - Starburst (emission-line galaxies)
  - Gas is stripped by intracluster medium
  - Post-starburst galaxies
  - Tidal interactions heat disk
  - Stars fade
  - The products are S0's at z~0
  - Morphological segregation proceeds hierarchically, affecting richer, denser clusters earlier. S0's are only formed after cluster virialization
- But there are S0's also in group environments, so this is not the only way to make them


Next:
Dust Obscured Galaxies