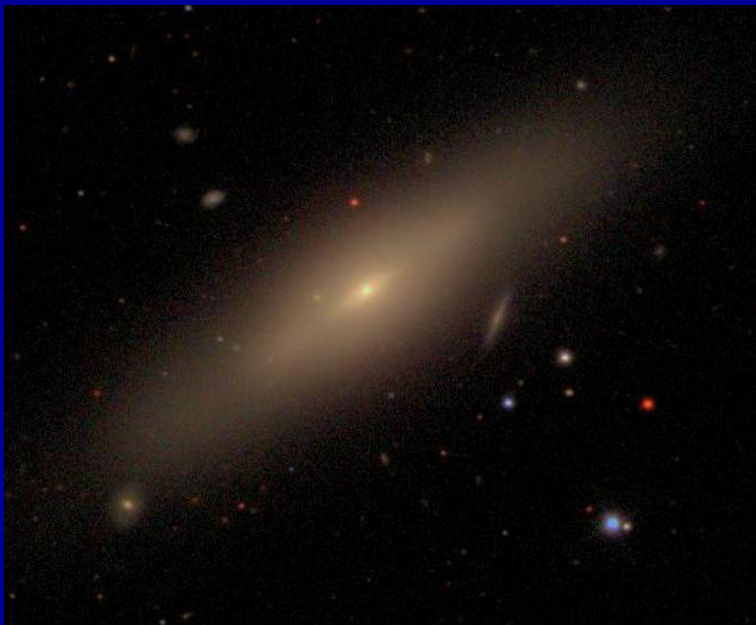




Transforming Spirals into S0s



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Collaborators:

Steven Bamford

Bo Milvang-Jensen

Alejandro García Bedregal

Michael Merrifield

Osamu Nakamura

Jordi Barr

Nicolas Cardiel

Nobuo Arimoto

Chisato Ikuta

Yara Jaffé

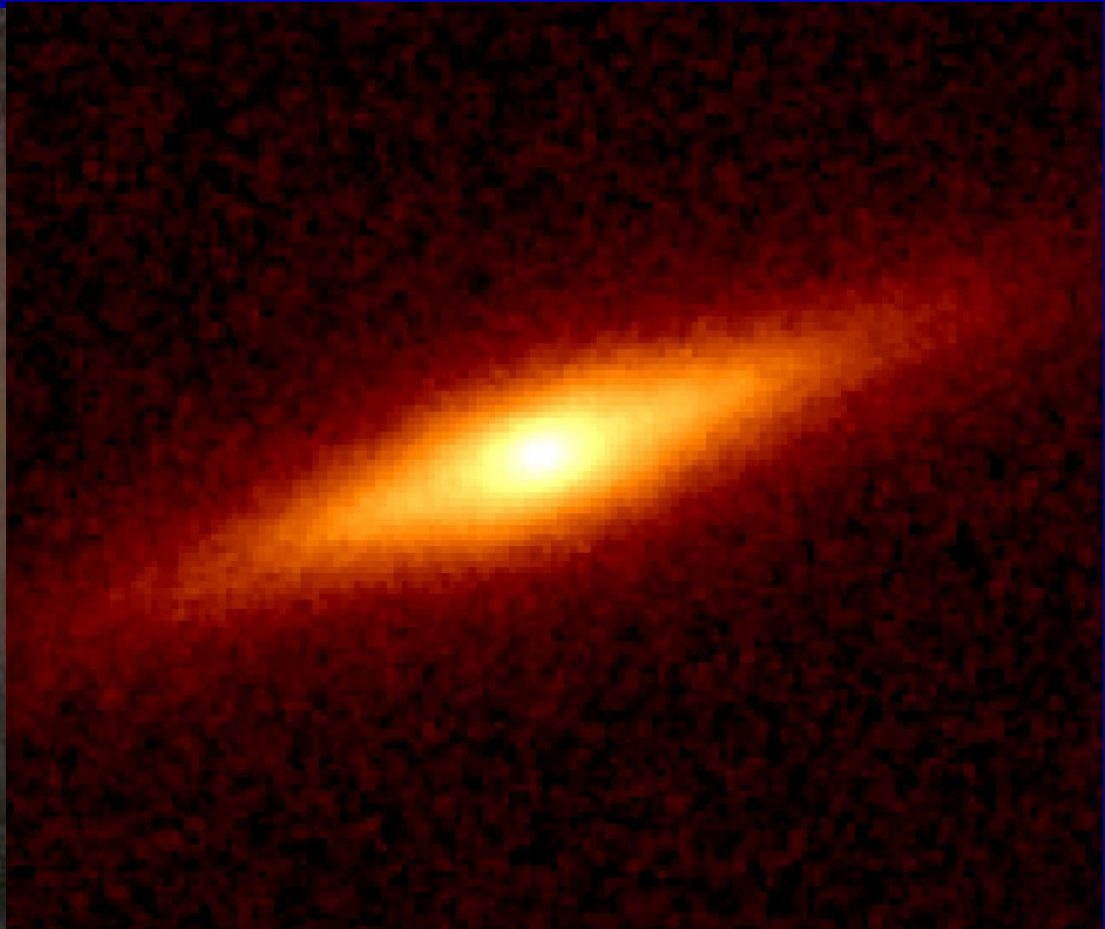
+

EDisCS and STAGES collaborations

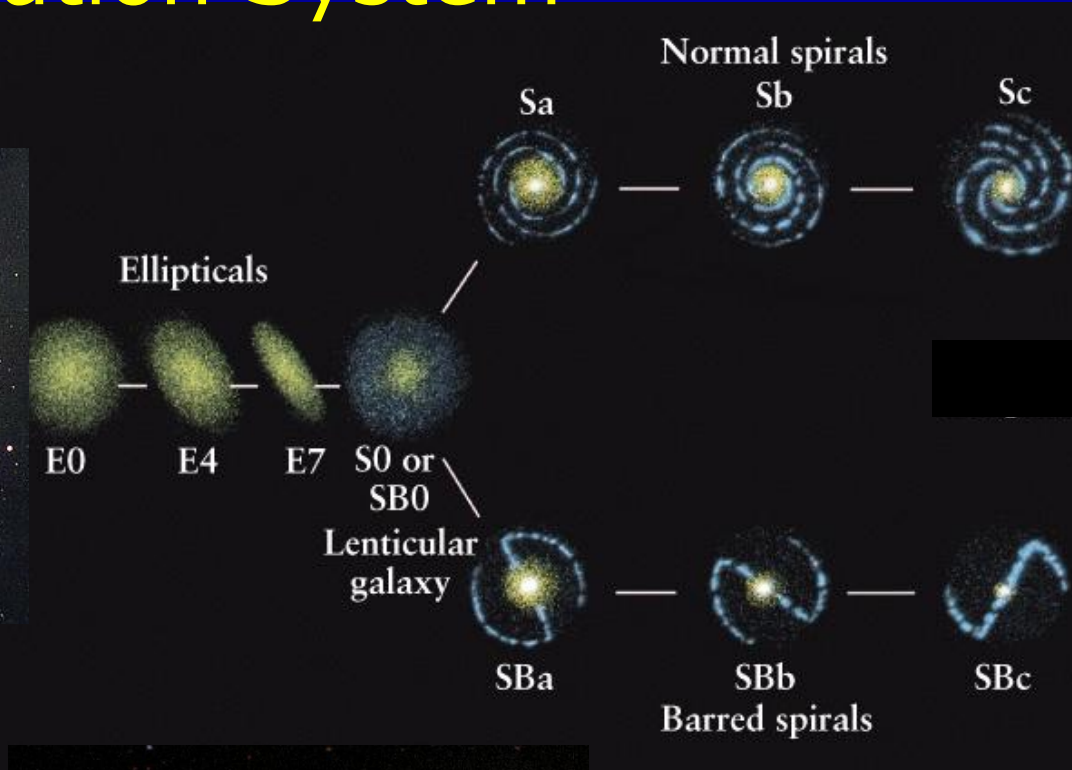
Overview:

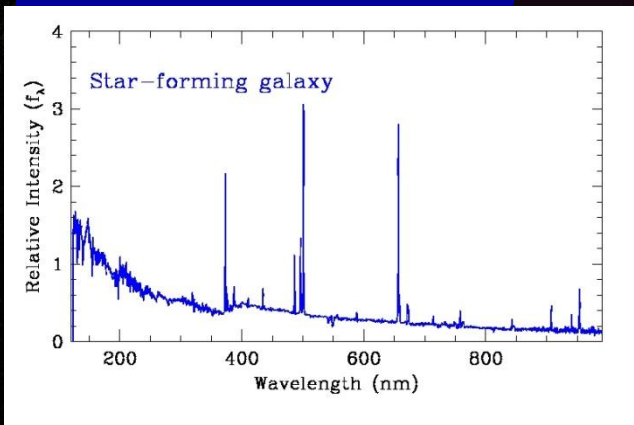
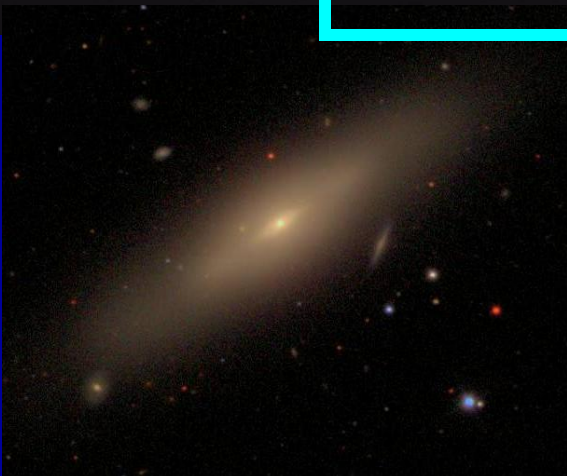
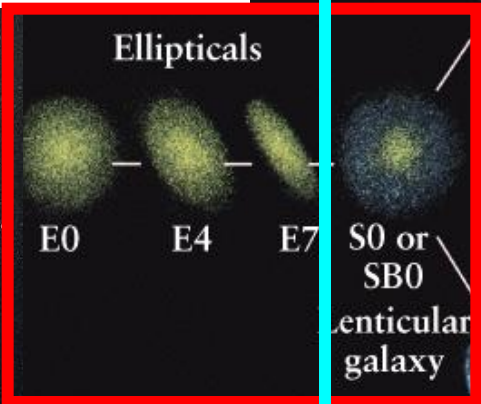
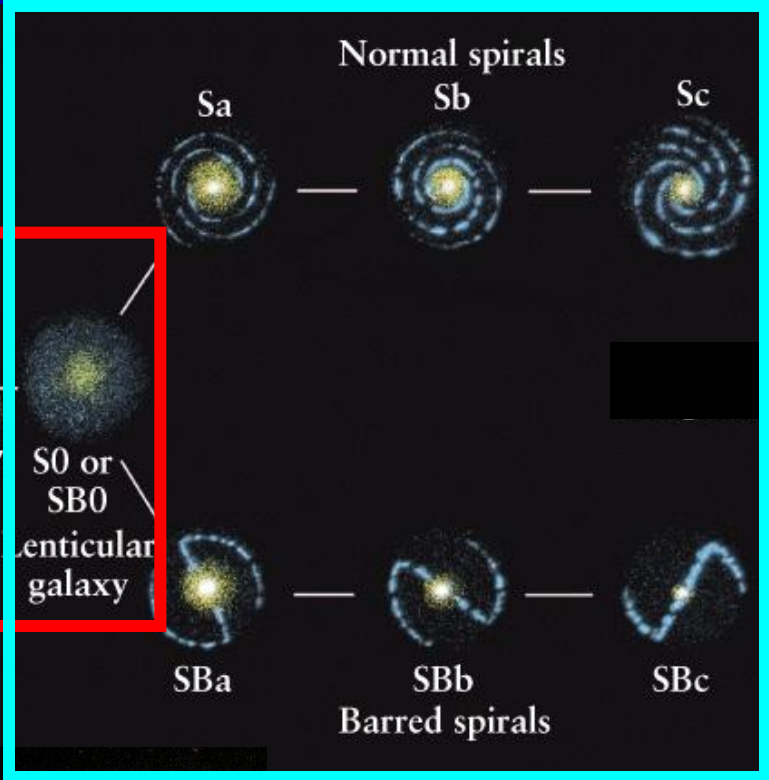
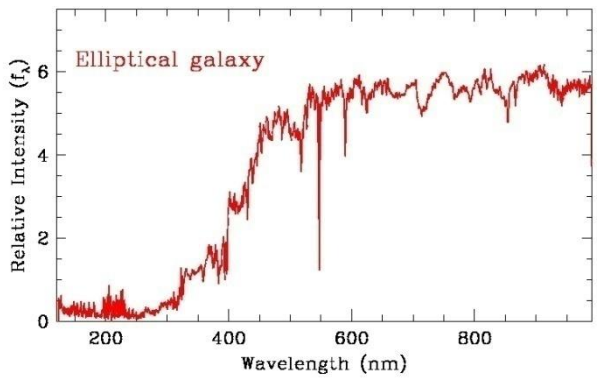
- Motivation
- Some ideas on the formation of S0 galaxies
- Tully-Fisher relation and gas kinematics for high- z cluster and field spirals
- Tully-Fisher relation for low- z S0s
- Stellar populations in S0s
- Globular Clusters and S0 formation
- Conclusions and future work

Lenticular (S0) Galaxies

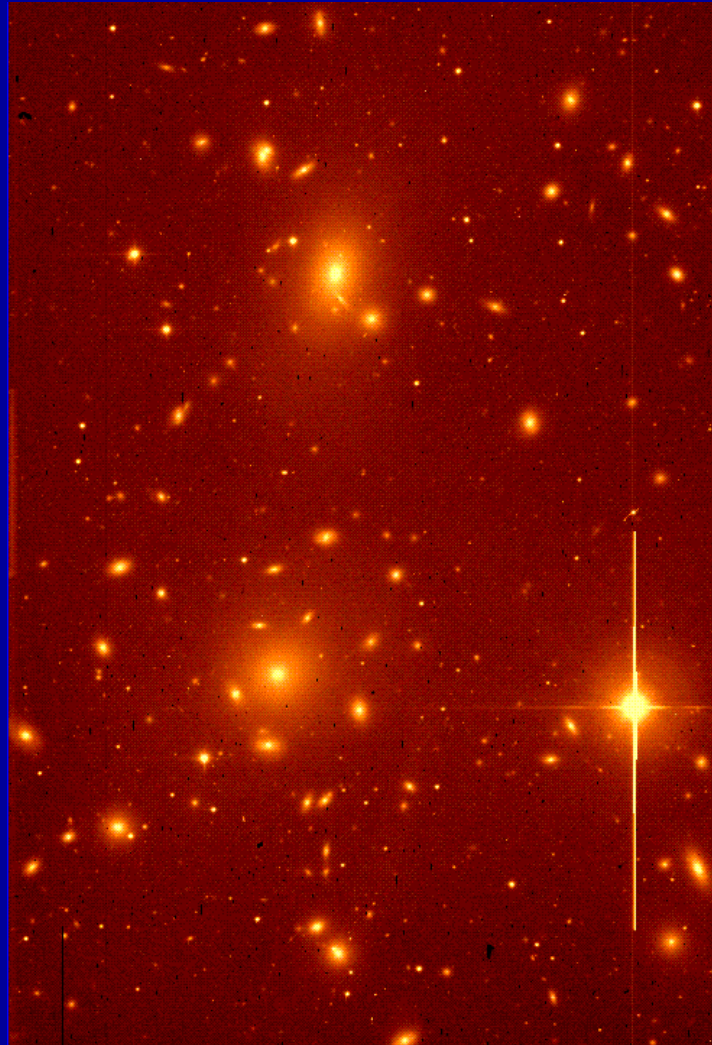
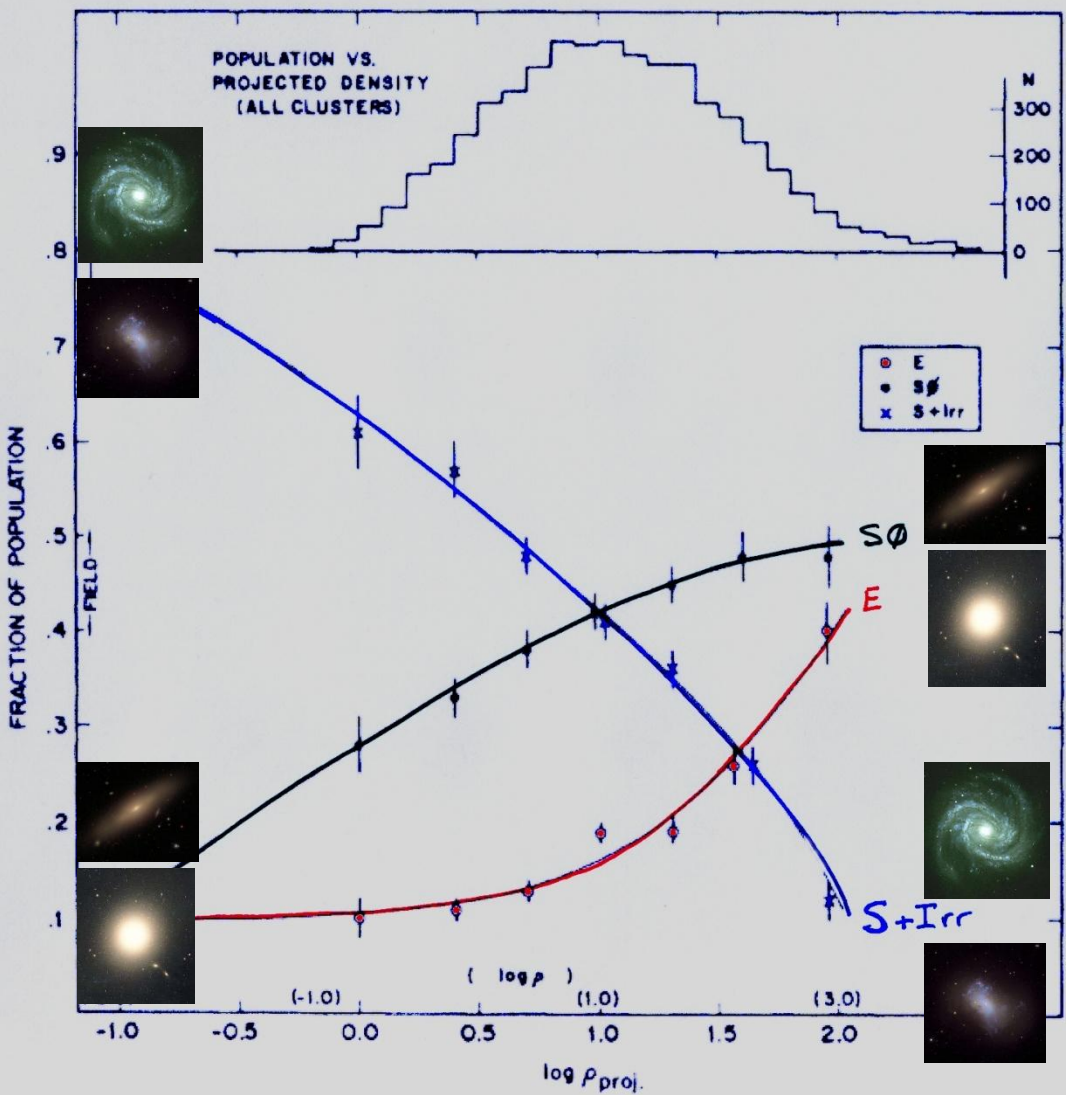


Hubble Morphological Classification System





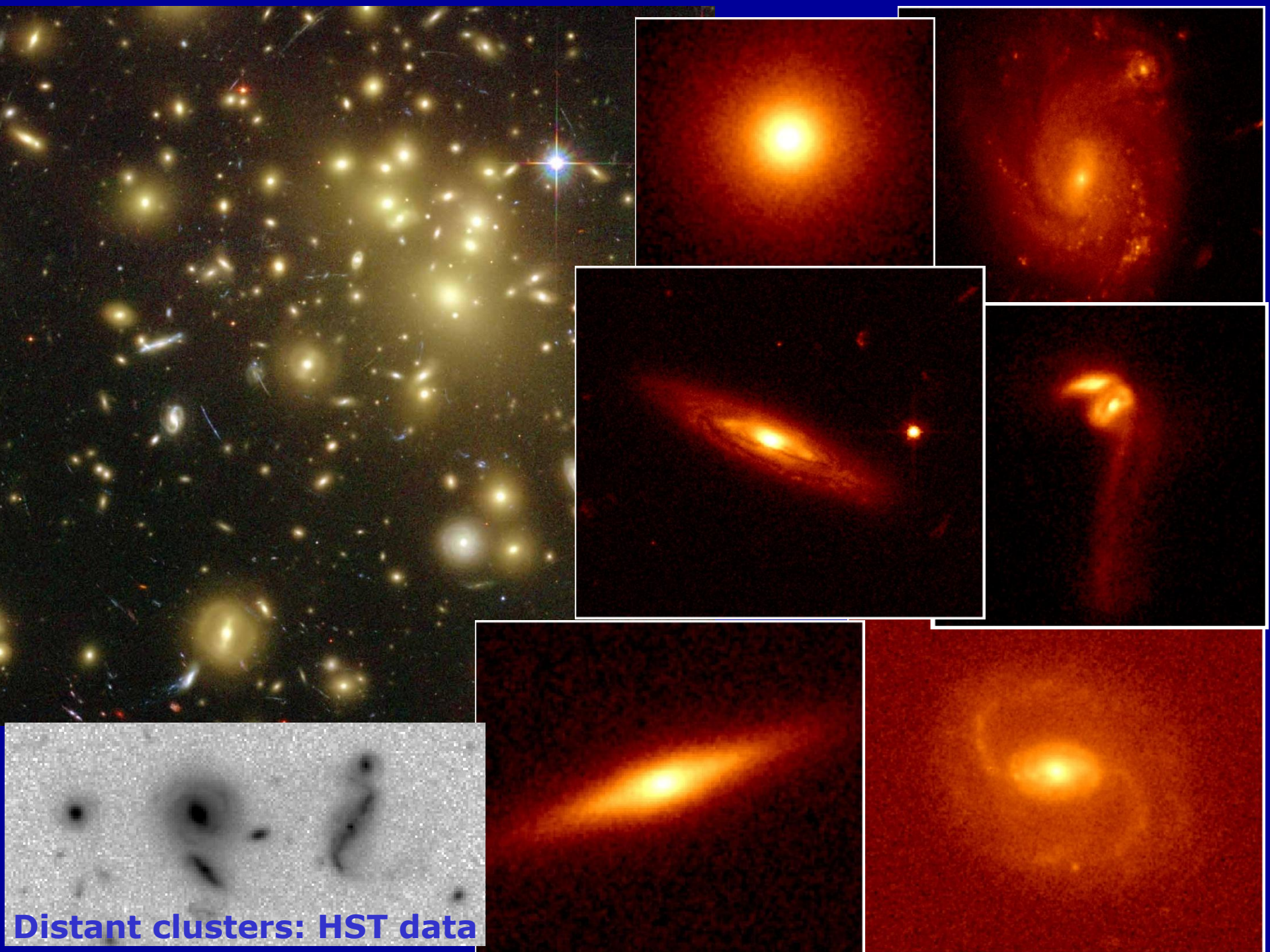
Morphology-Density Relation at $z \sim 0$



Hubble & Humason (1931)

Dressler (1980)

Density



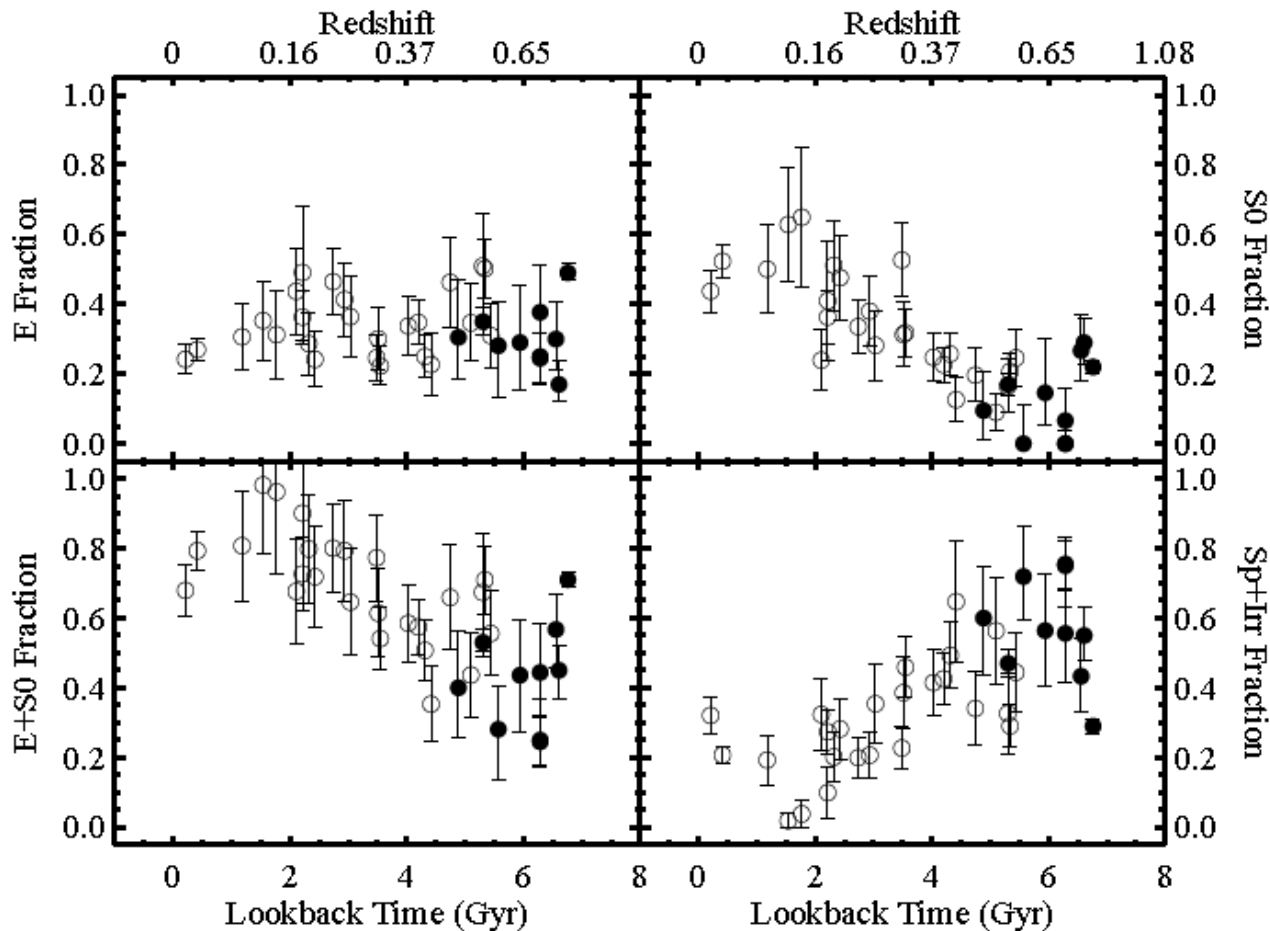
Distant clusters: HST data

At $z \sim 0$
(Present time)

Many S0s in clusters
Few Spirals in clusters

At $0.36 < z < 0.6$
(~ 5 Billion years ago)

Many Spirals in clusters
Few S0s in clusters

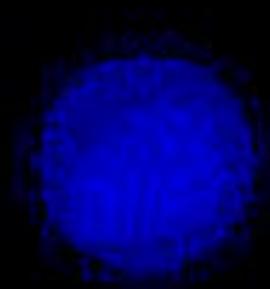


ESO Distant
Clusters Survey
(EDisCS)

Desai et al. (2007)

(cf. Dressler et al.
1997)

$z=49.000$

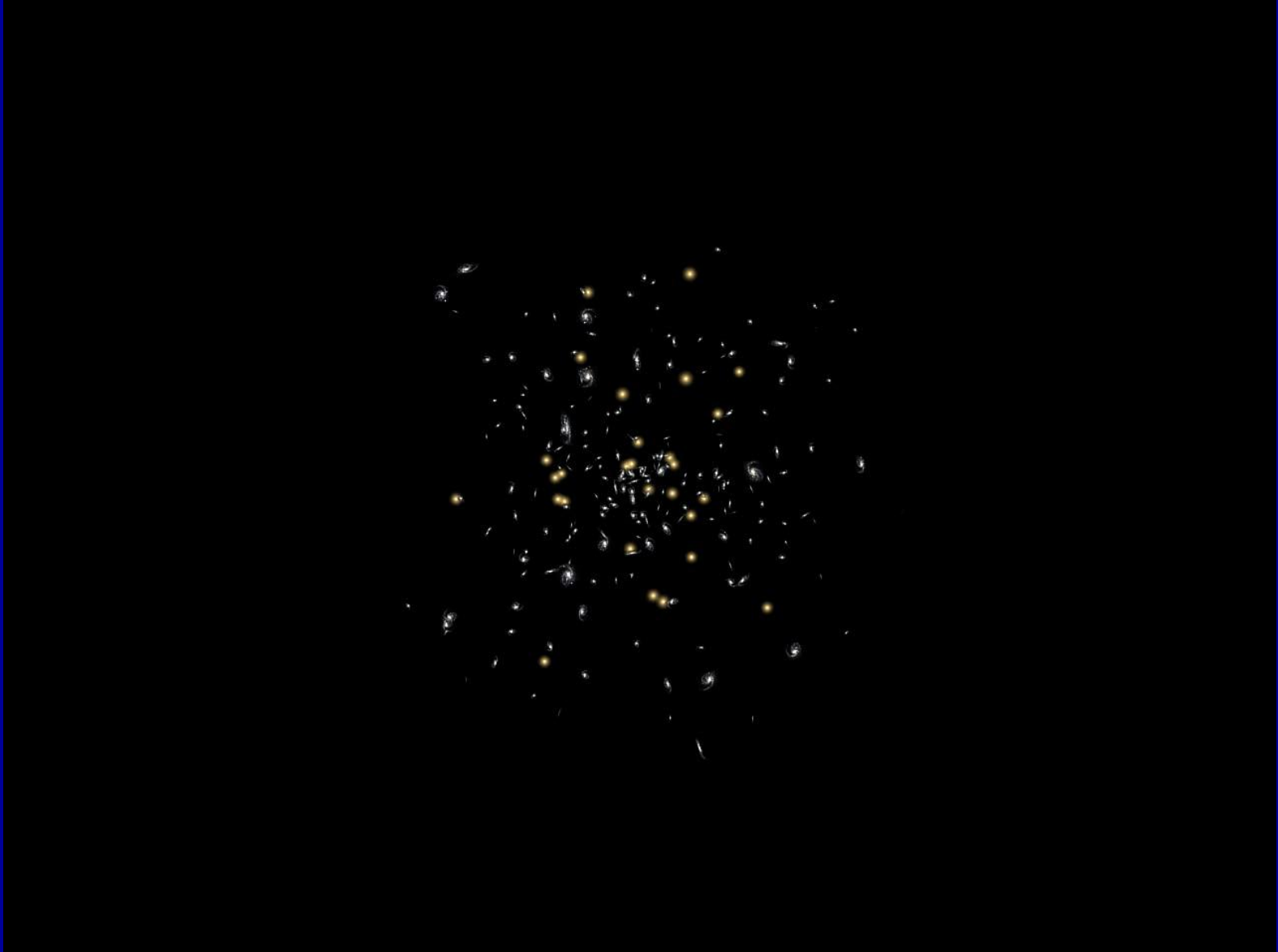


Cluster
Formation
(Cold Dark
Matter
Cosmogony)

B. Moore

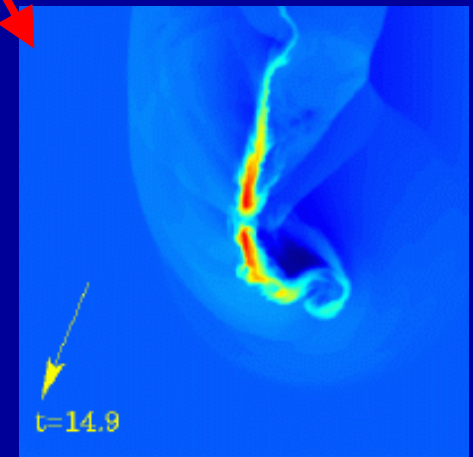
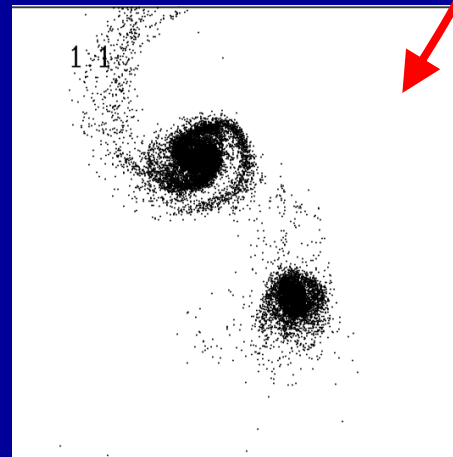
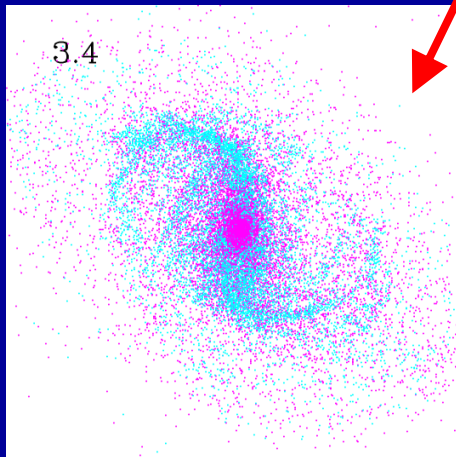
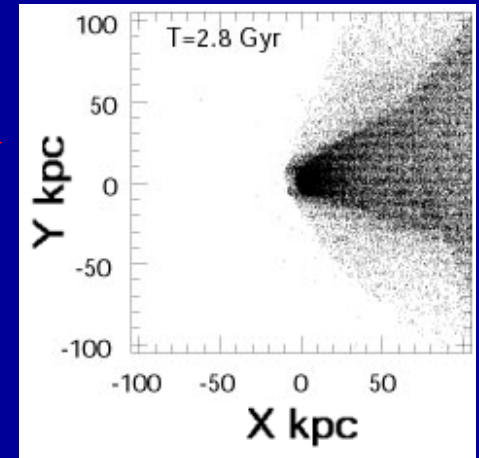
Galaxy falling into Virgo cluster

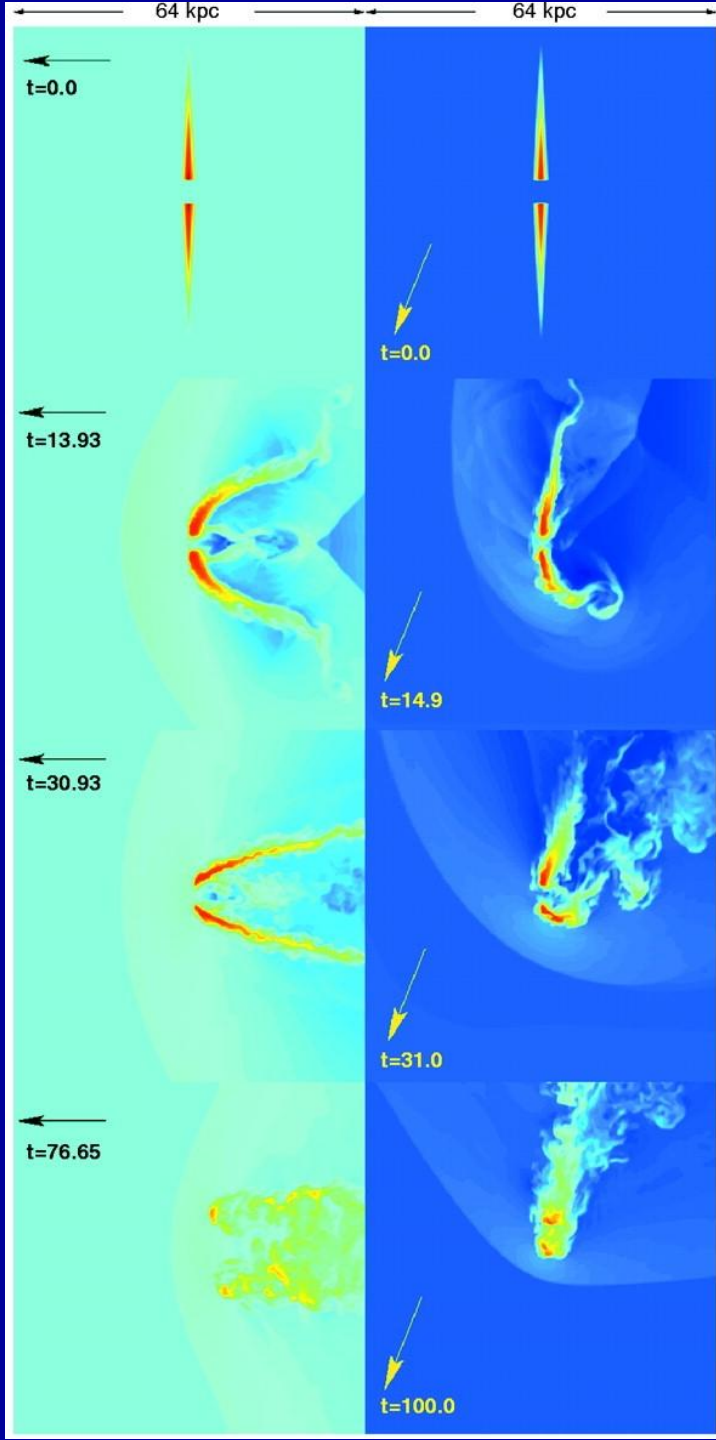
Cardiff Numerical Simulations Group (2009)



Clusters are Laboratories of Galaxy Evolution

- Physical processes:
 - ram-pressure stripping
 - of gas halo (Larson et al. 1980, Bekki et al. 2002)
 - of disk gas (Gunn & Gott 1972, Quilis et al. 2000)
 - galaxy-galaxy interactions
 - harassment (Moore et al. 1998)
 - mergers (Bekki 1998)
 - cluster tidal field (Bekki 1999)
 - &cetera





Ram Pressure:

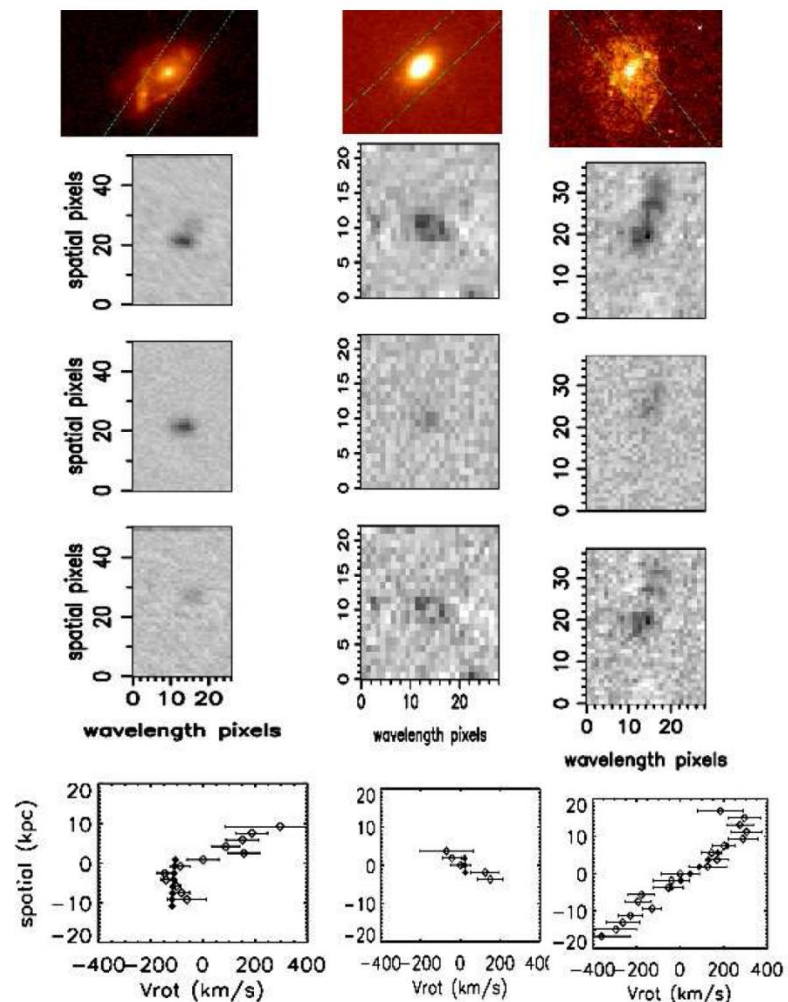
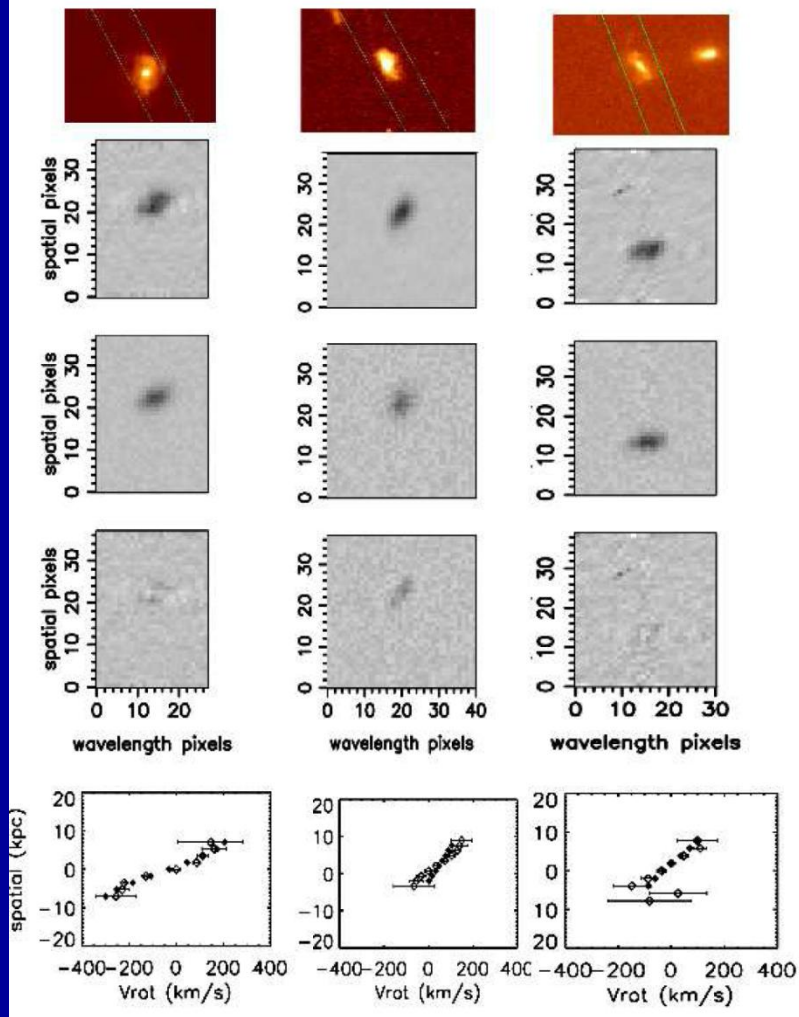
Gas disk interacting with hot intracluster medium

Cardiff Numerical Simulations Group (2009)

Quilis, Moore & Bower (2000)

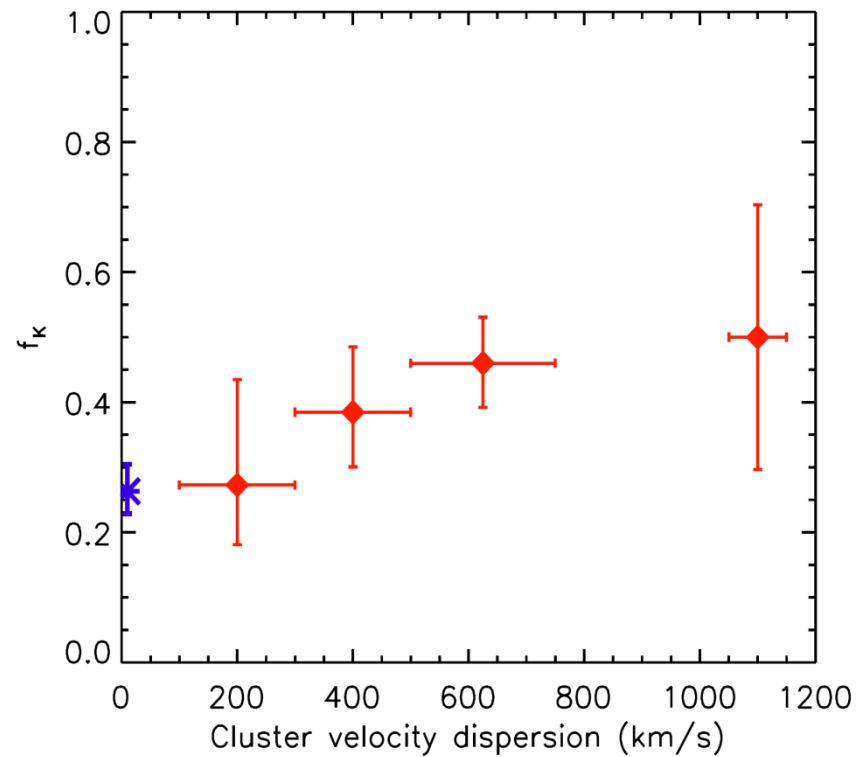
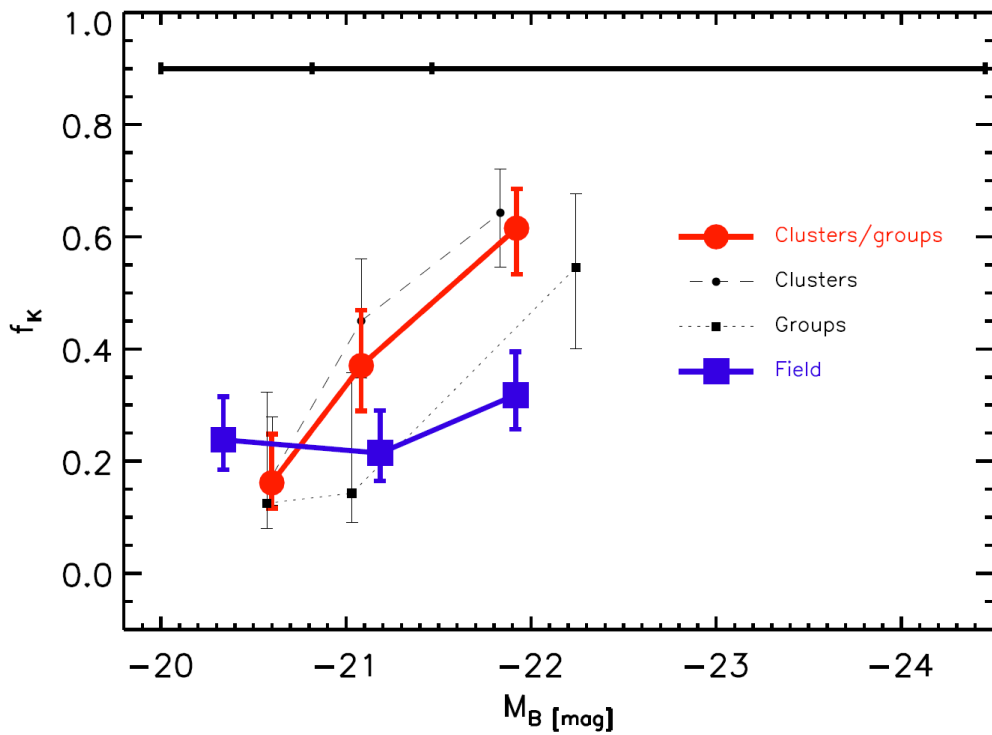
good fits

bad fits



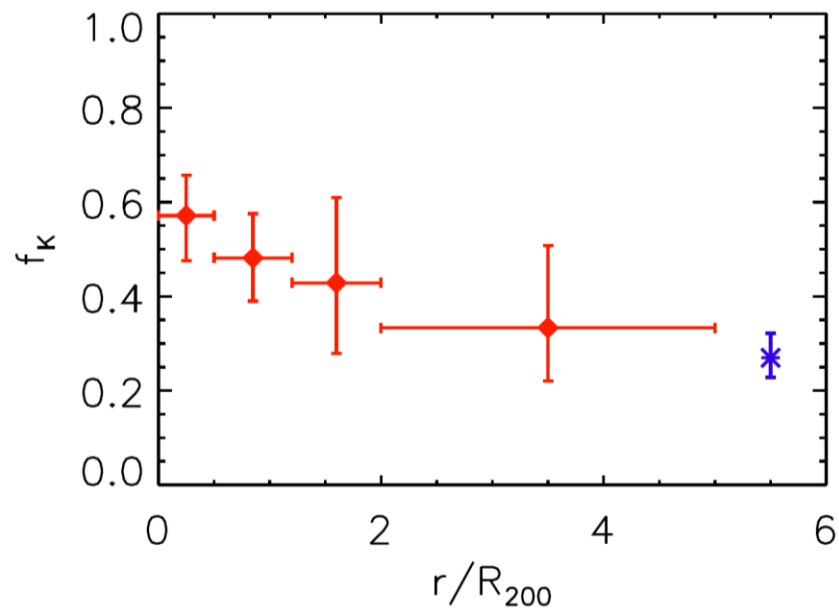
Gas kinematics in cluster spirals

Yara Jaffé et al. 2011

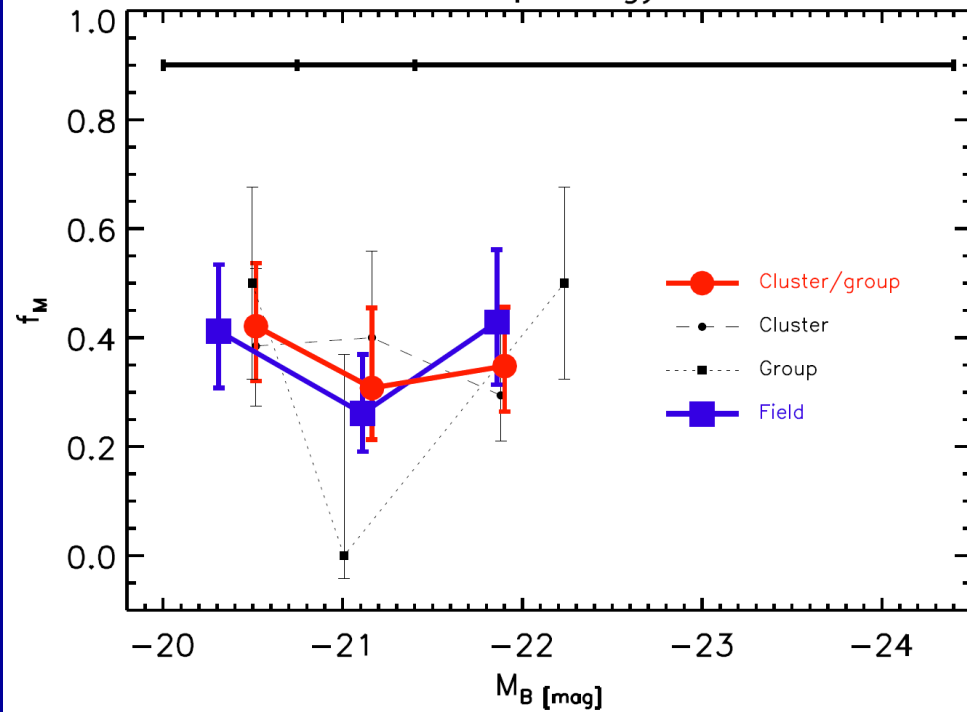


Gas kinematics in cluster spirals

Yara Jaffé et al. 2011



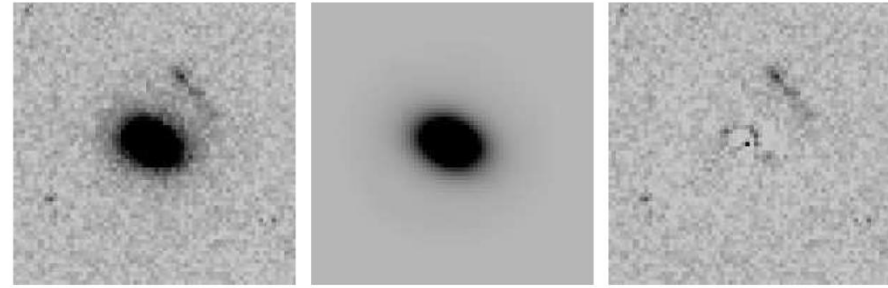
morphology



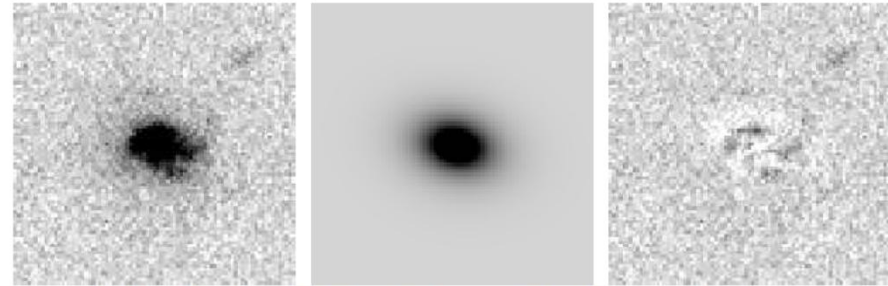
(Un)disturbed
morphology of cluster
spirals

Yara Jaffé et al. 2011

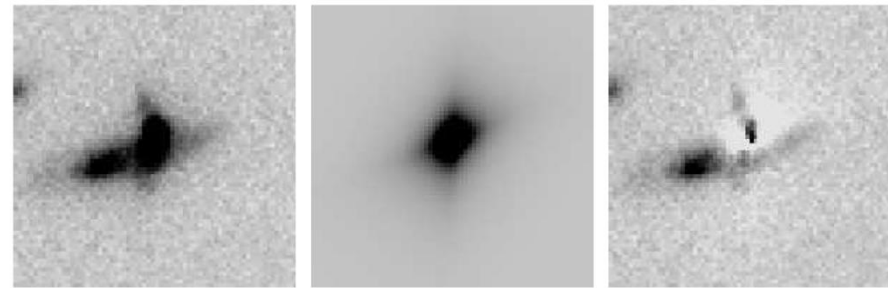
EDCSNJ1040443-1158045. $M_V = -21.4$ $Re = 0''.23$



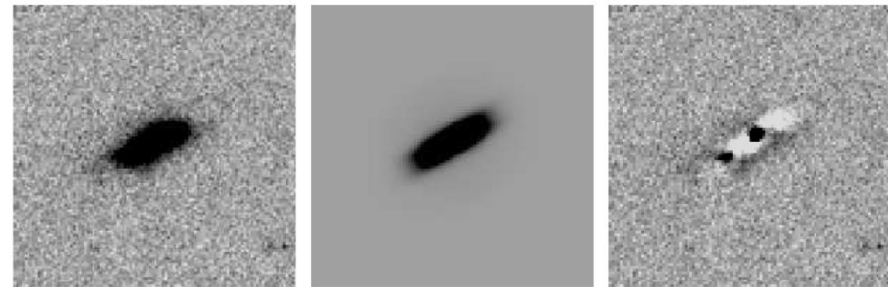
EDCSNJ1138064-1134297. $M_V = -19.16$ $Re = 0''.47$

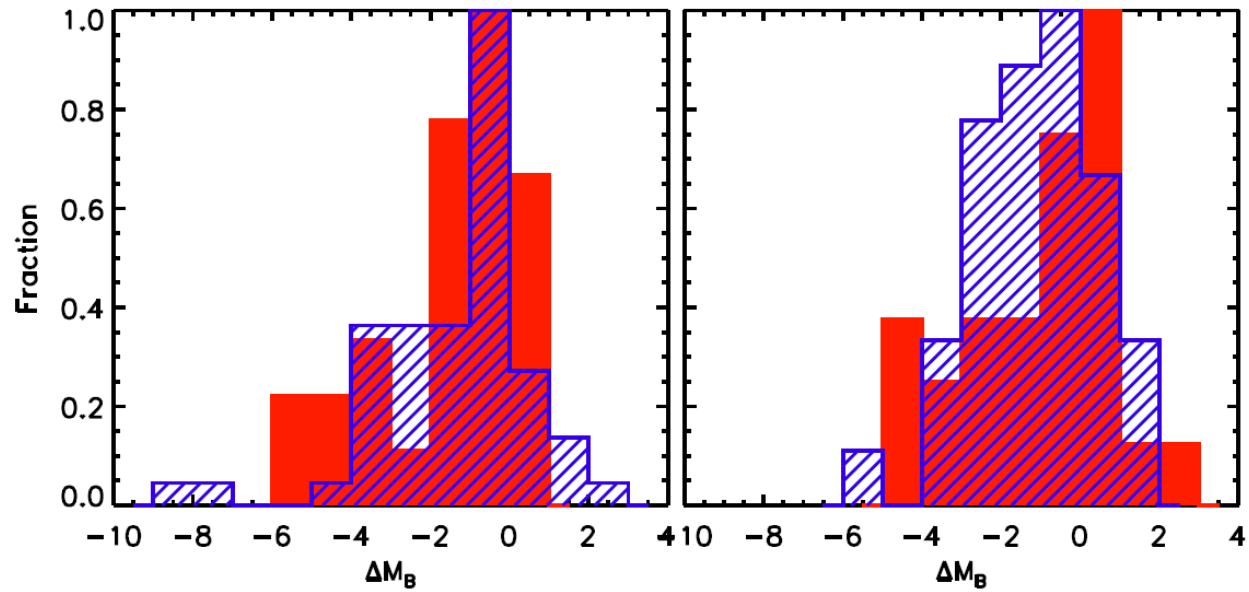
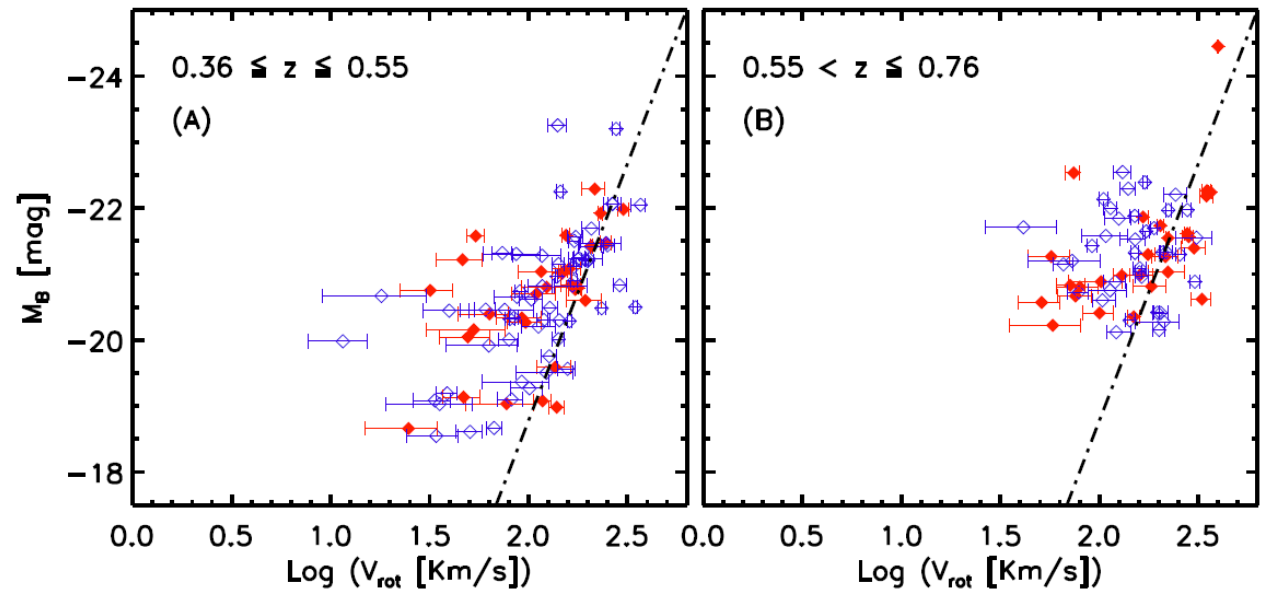


EDCSNJ1040420-1155092. $M_V = -21.15$ $Re = 0''.64$



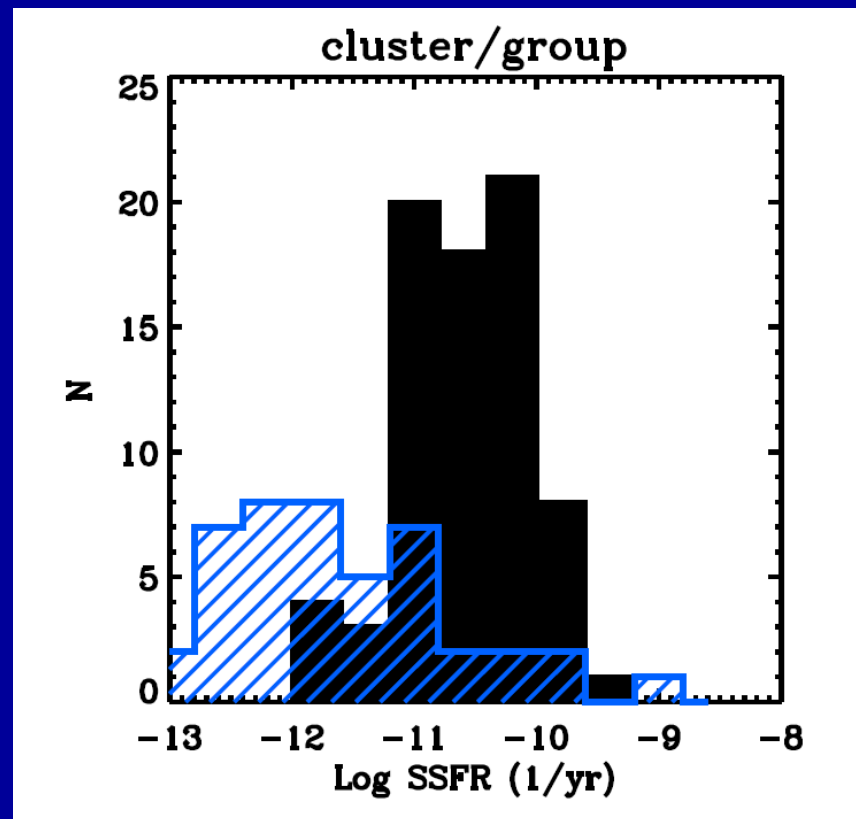
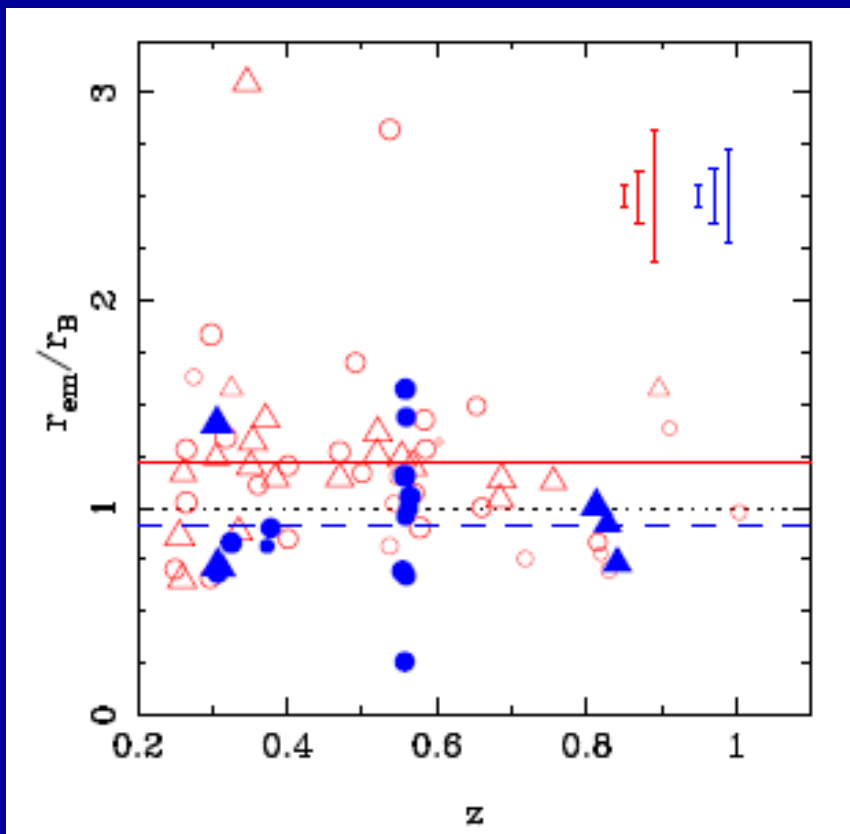
EDCSNJ1216434-1202128. $M_V = -21.0$ $Re = 0''.40$





Tully-Fisher Relation (Yara Jaffé et al. 2011)

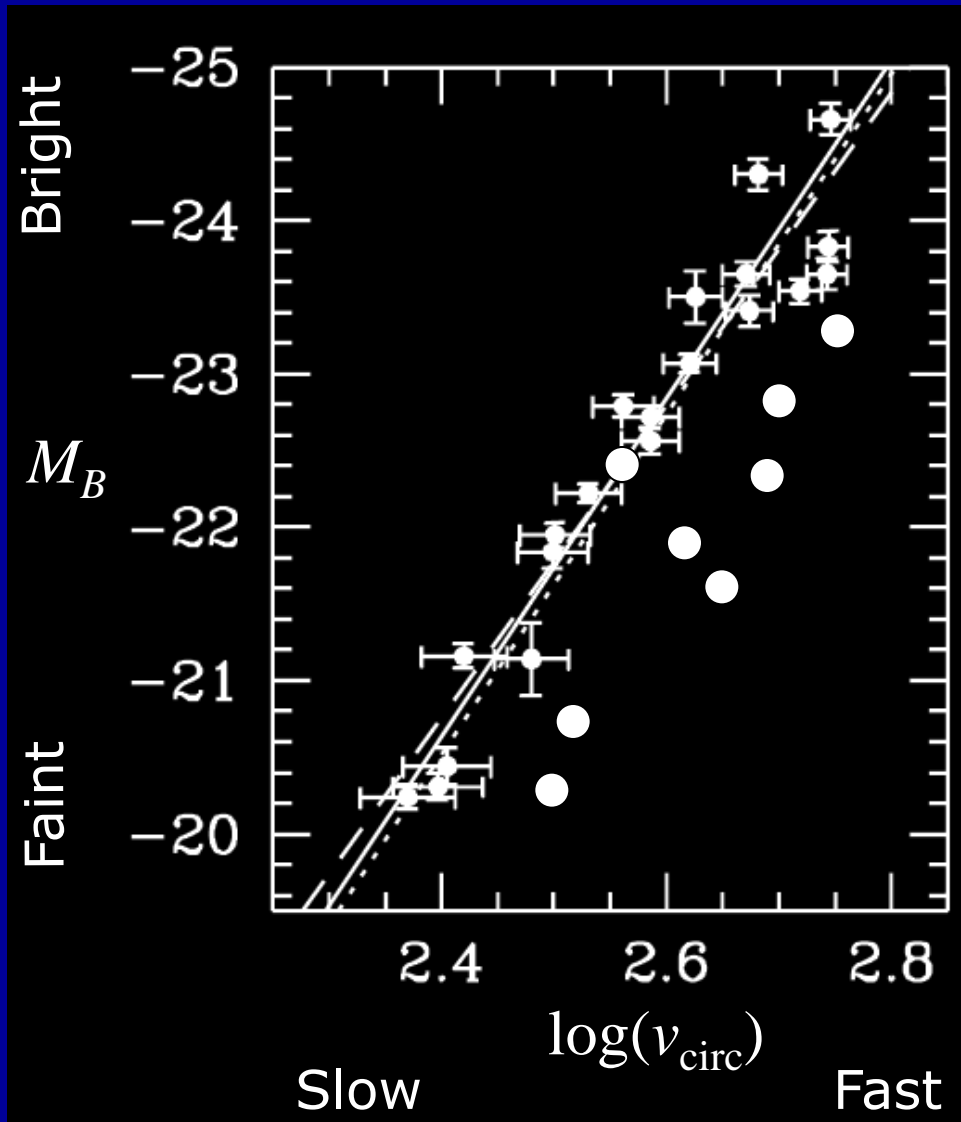
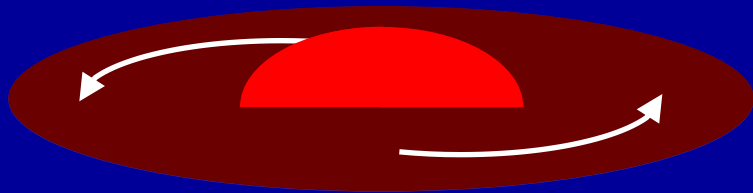
Size and sSFR of disc galaxies in intermediate-z clusters



- Star formation is more concentrated in cluster disc galaxies than in field ones
- sSSR is lower in galaxies with disturbed gas

Bamford et al. 2007; Jaffé et al. 2011

Evolution of a Fading Disc Galaxy



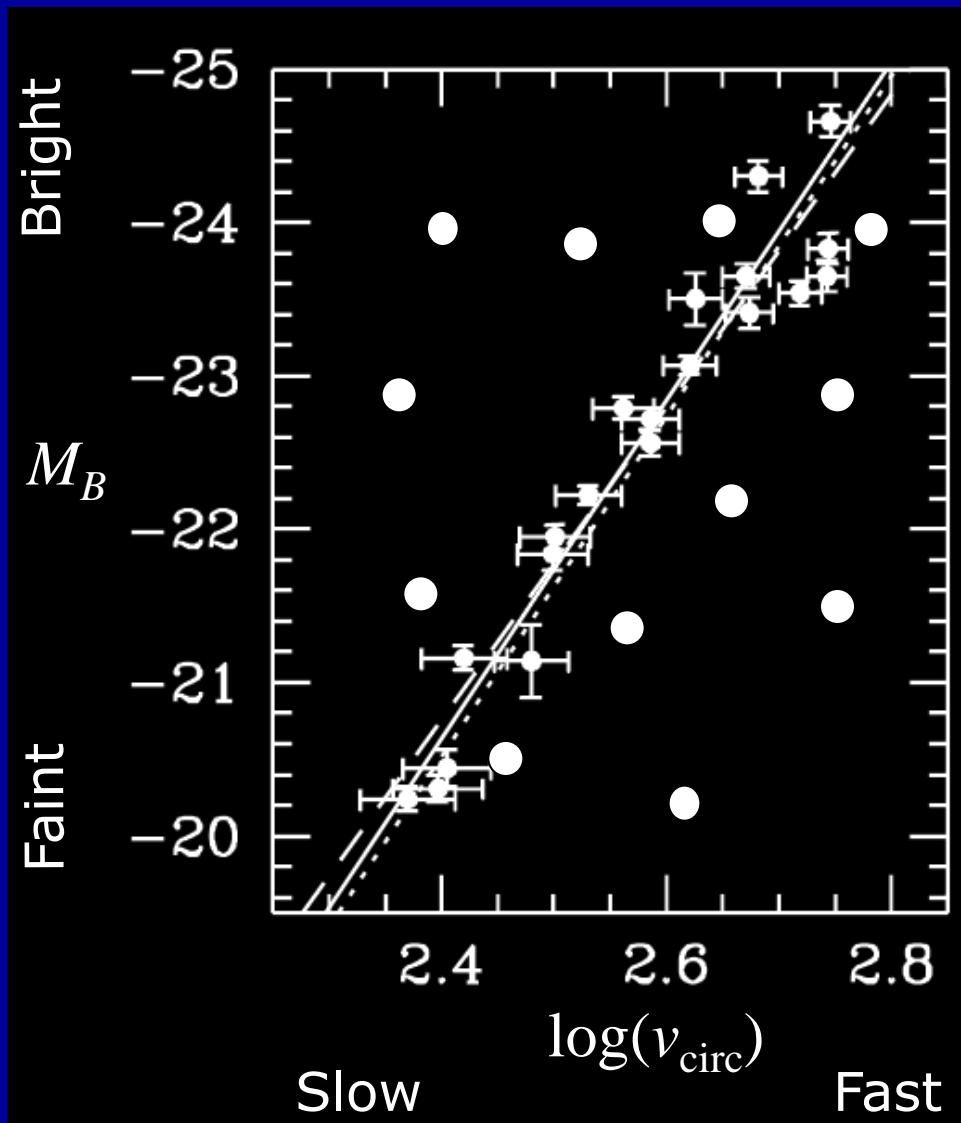
Other Formation Mechanisms

Mergers?

Gas-Rich Collapse?

Gas-Poor Collapse?

Something
Complete Different?



Fornax Galaxy Cluster

NGC 1380

NGC 1382

NGC 1381

NGC 1375

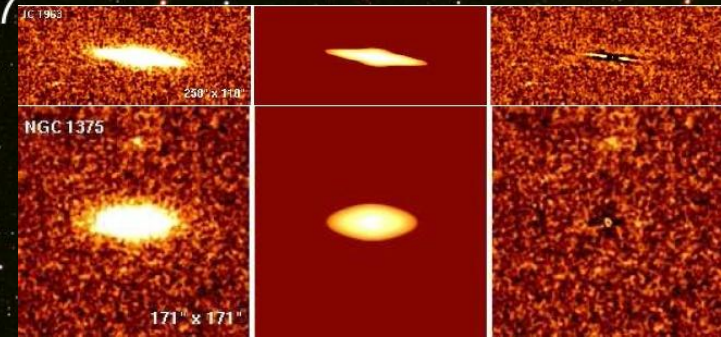
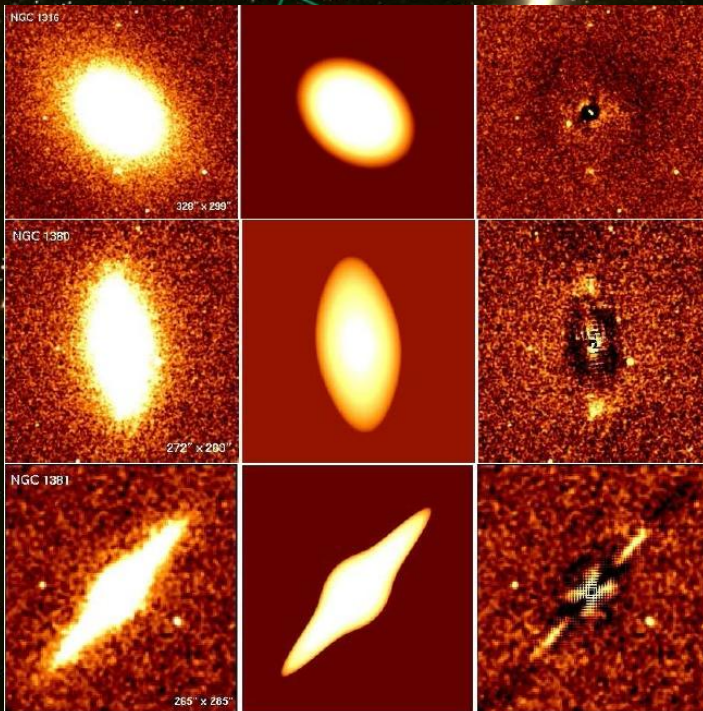
NGC 1399

NGC 1379

NGC 1427A

NGC 1387

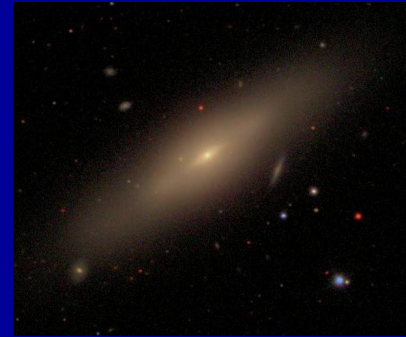
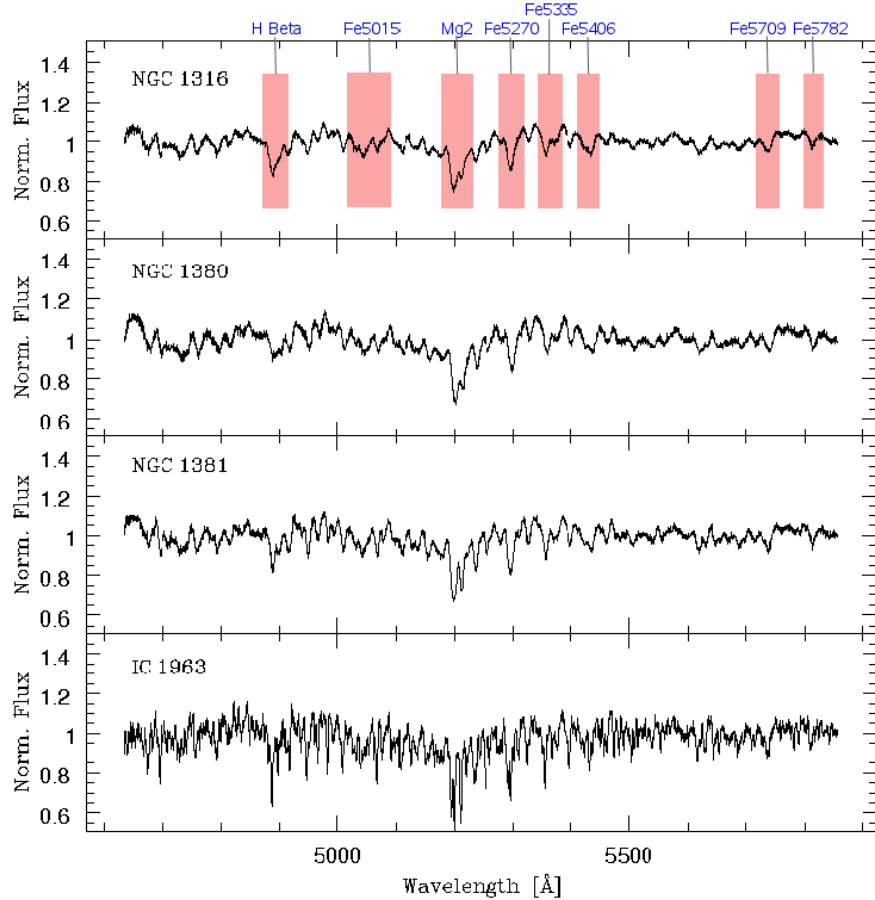
404



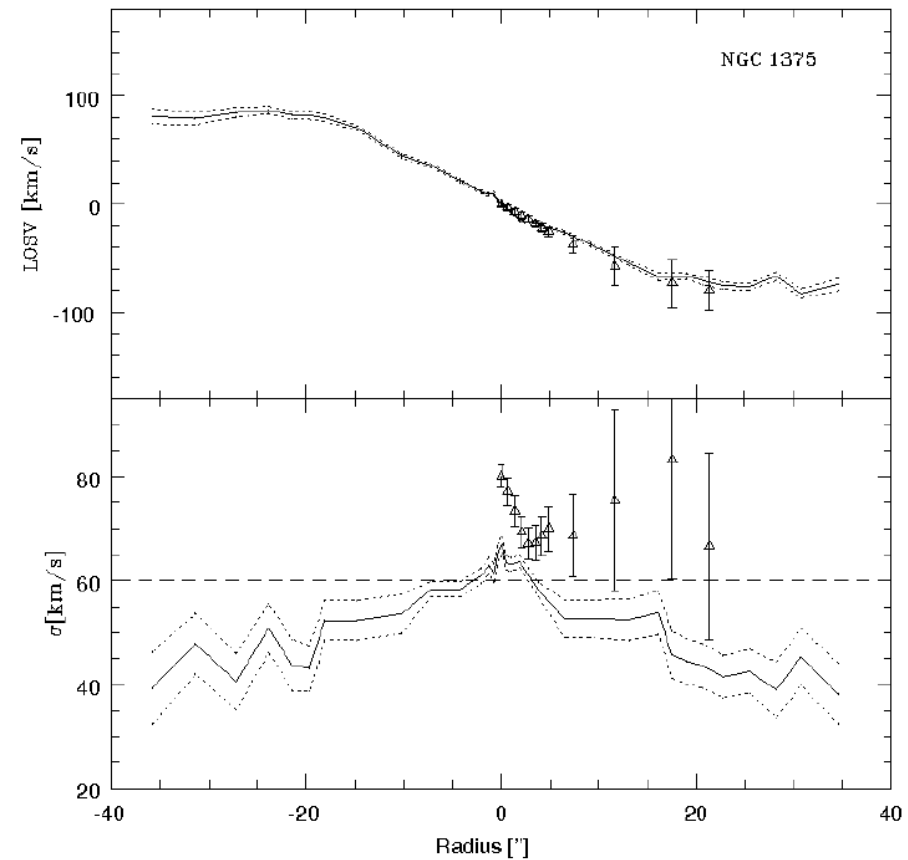
NGC 1389

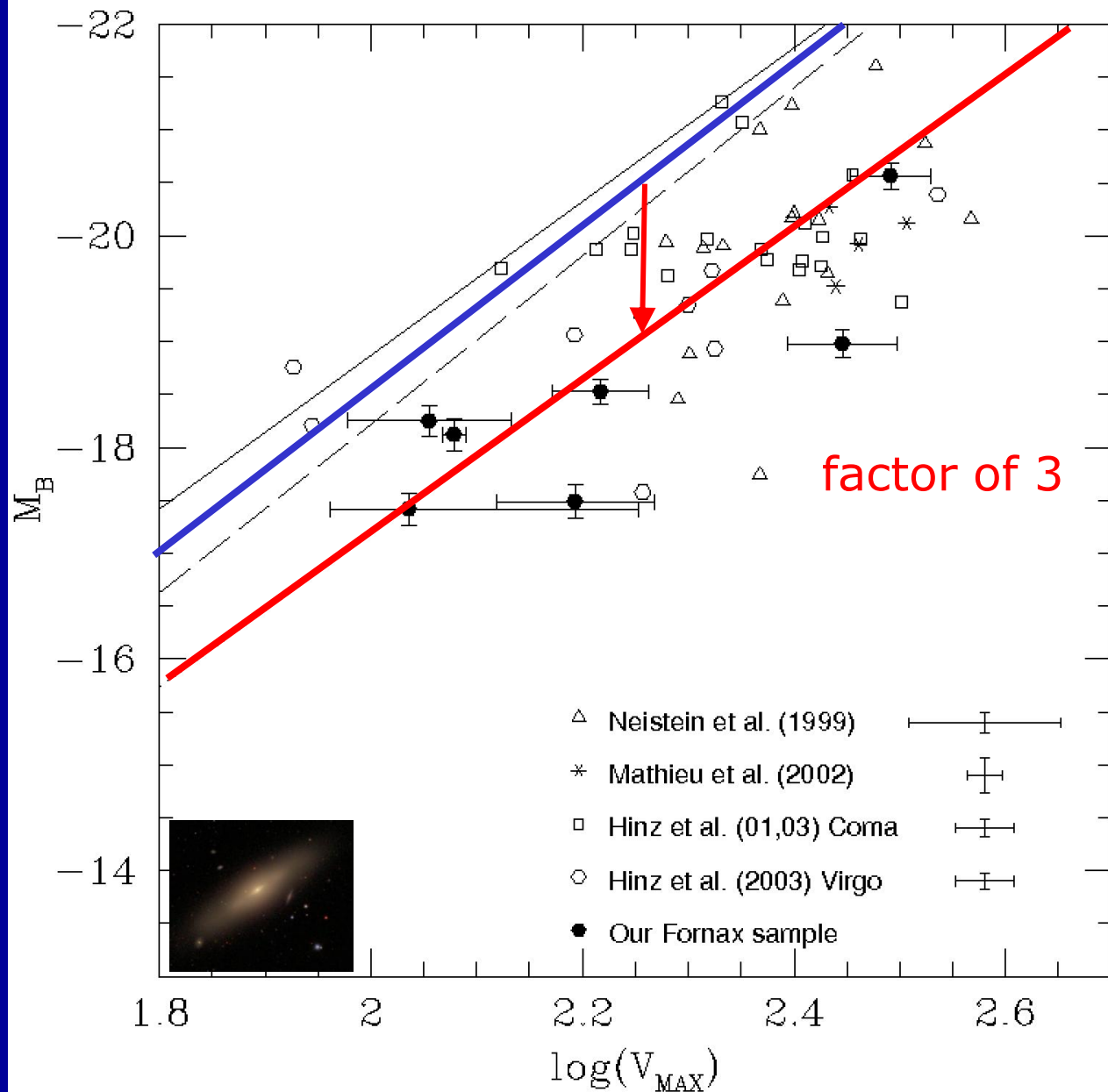
NGC 1365

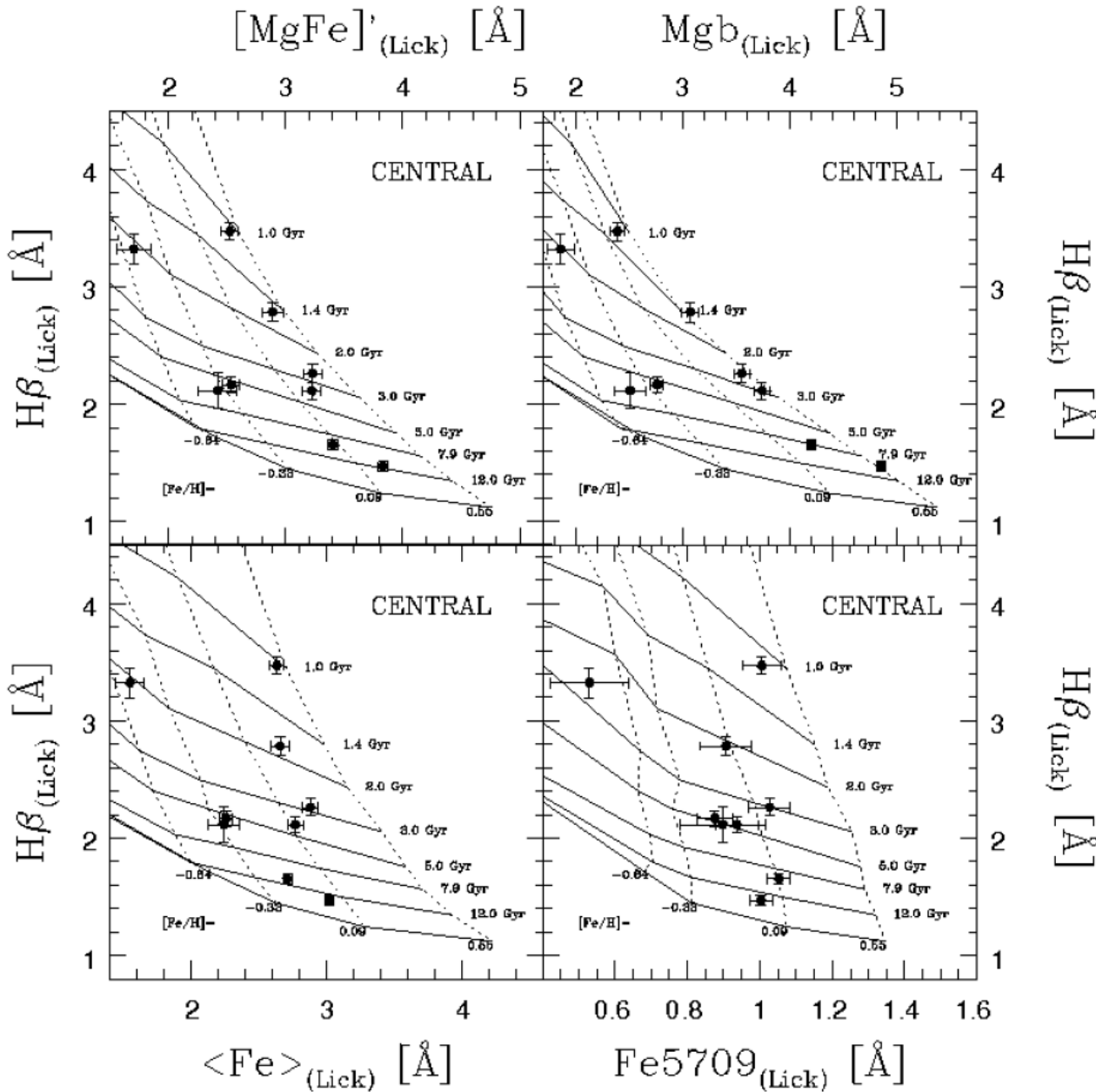
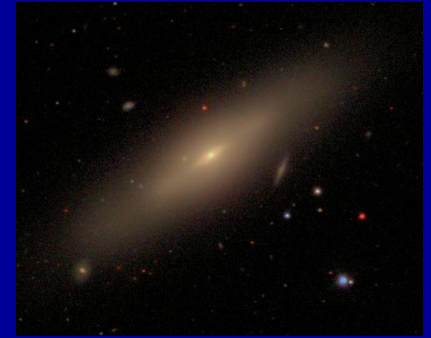
(M. Drinkwater)



Fornax Cluster Data

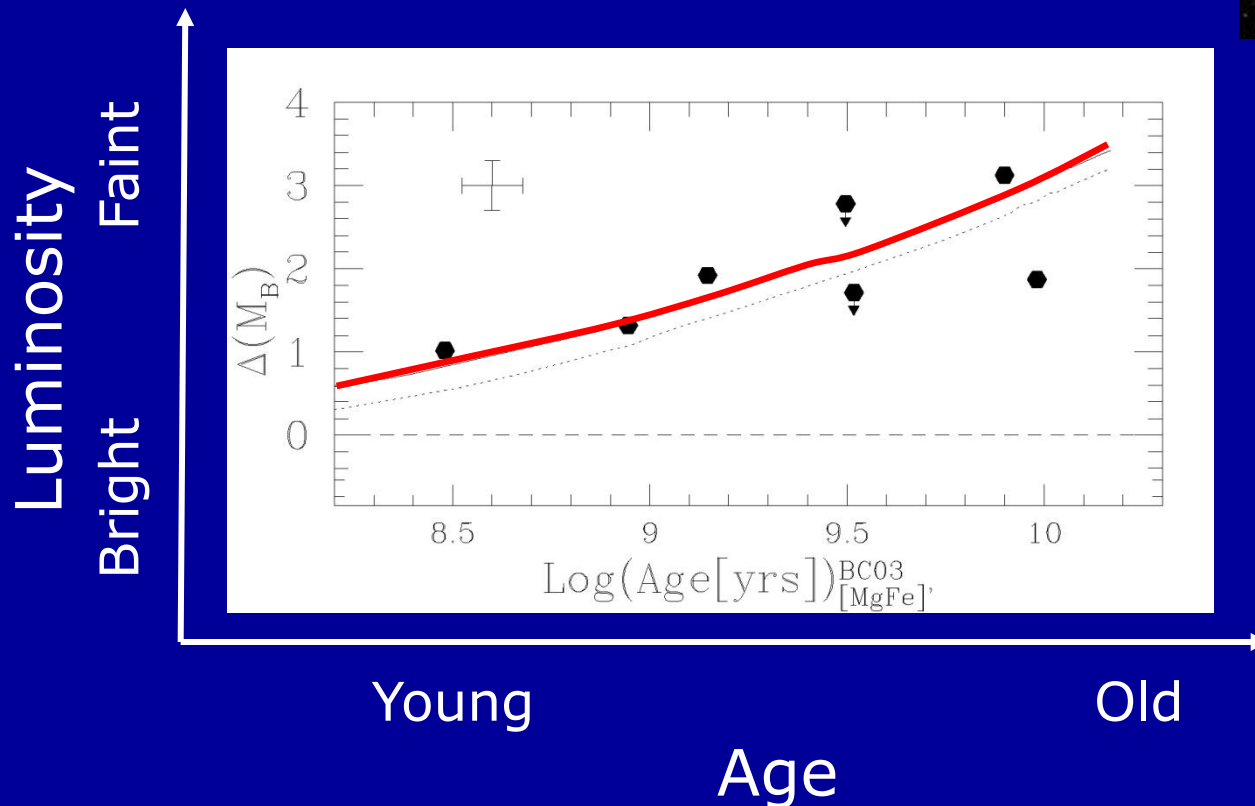
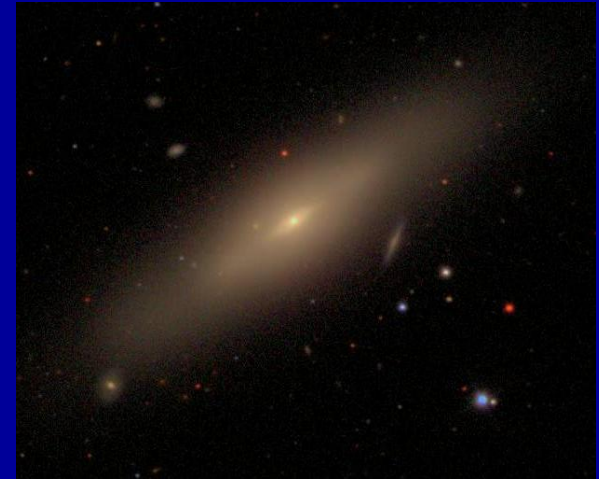




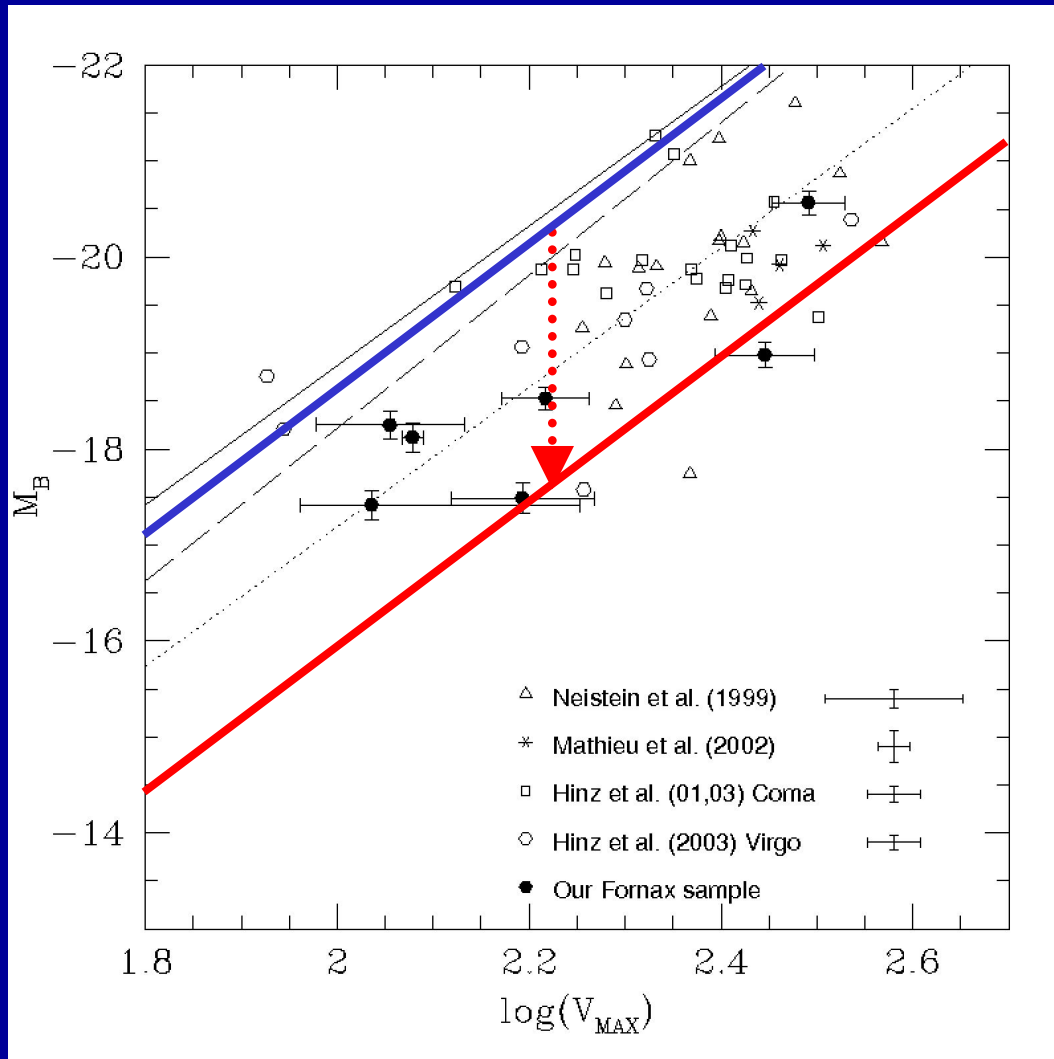


S0 Tully-Fisher offsets vs. age

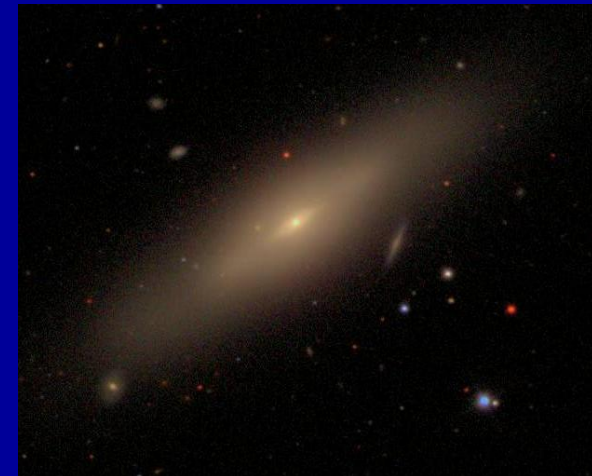
Bedregal, Aragón-Salamanca,
Merrifield & Cardiel 2007



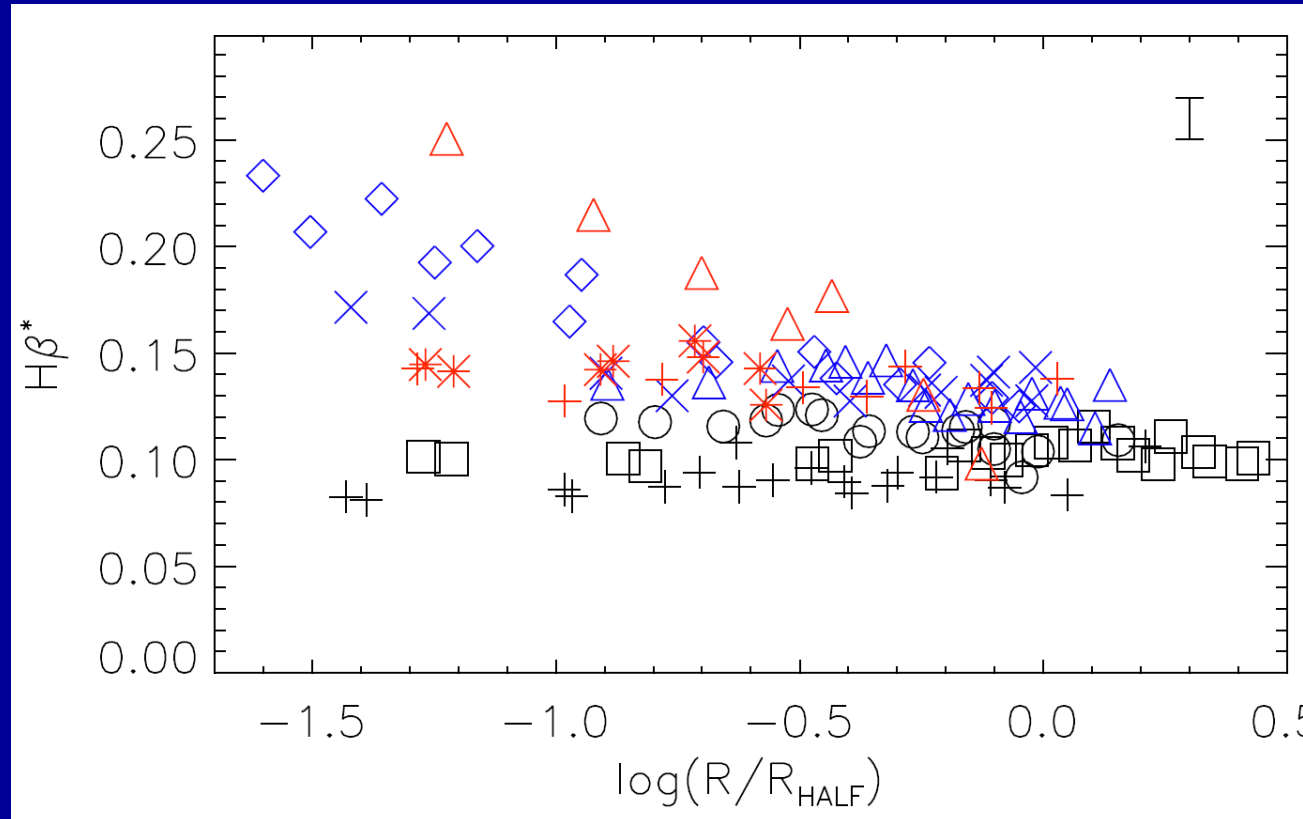
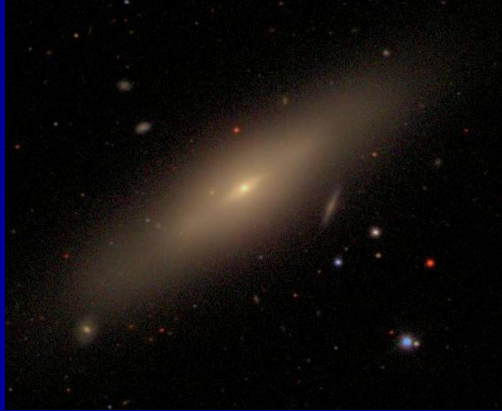
Prediction: Maximum Tully-Fisher offset for S0s



$\Delta M_B(\text{max}) \sim -2.5 \text{ mag}$



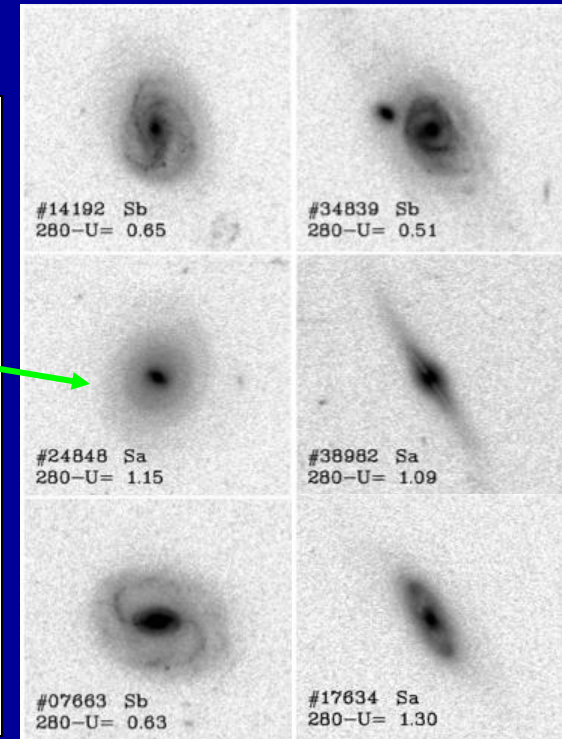
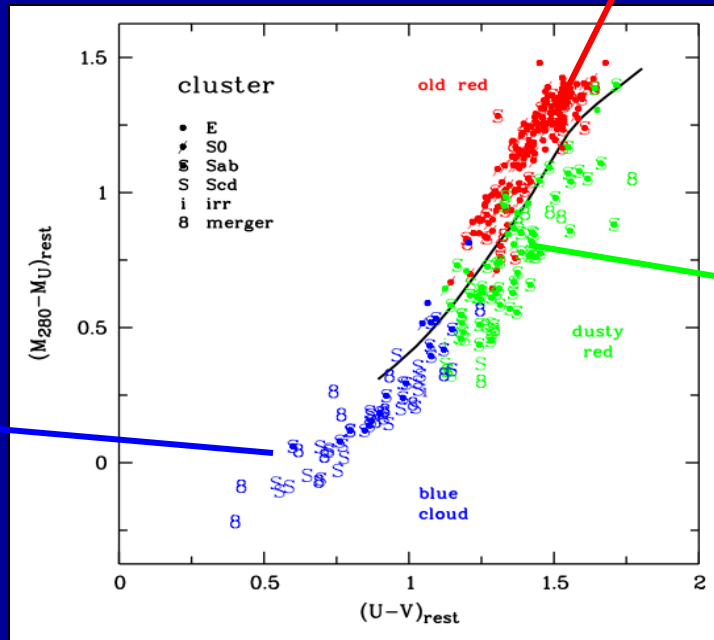
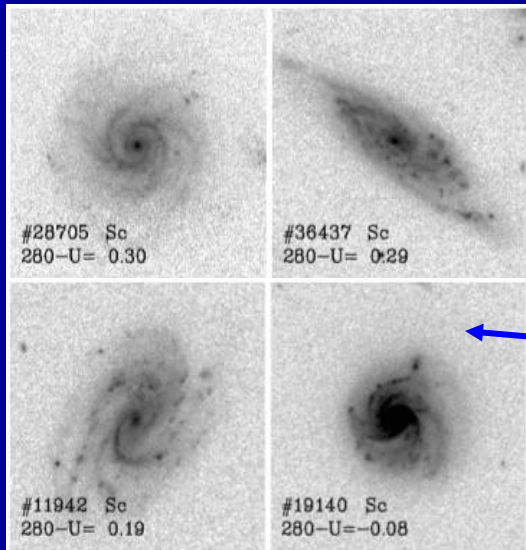
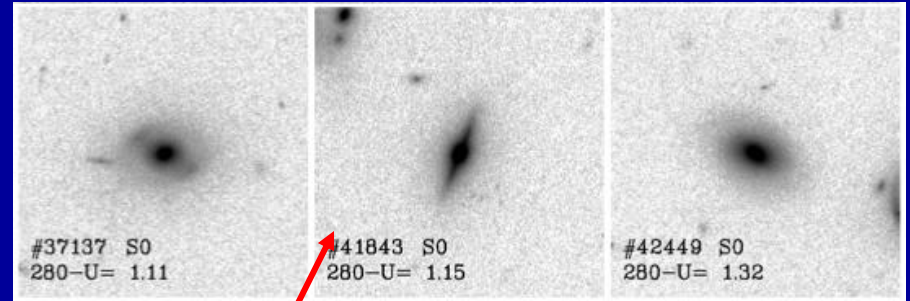
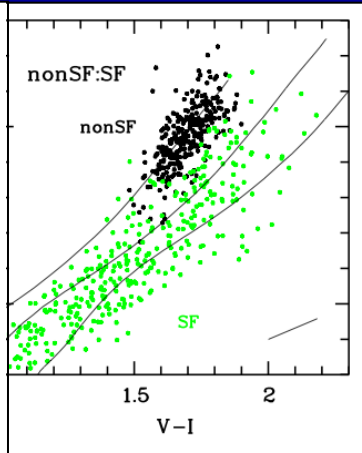
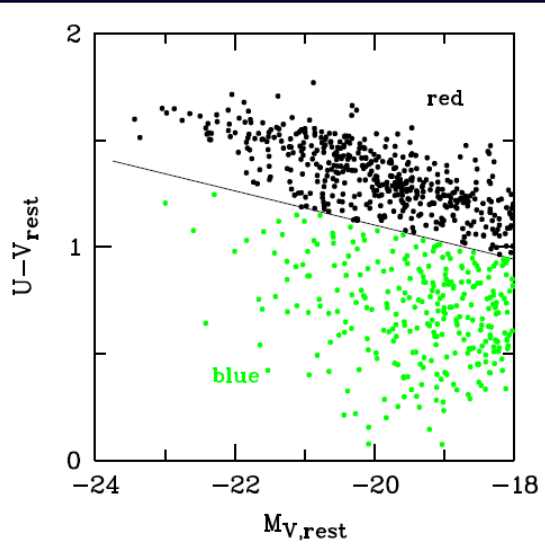
Age gradients in S0 galaxies

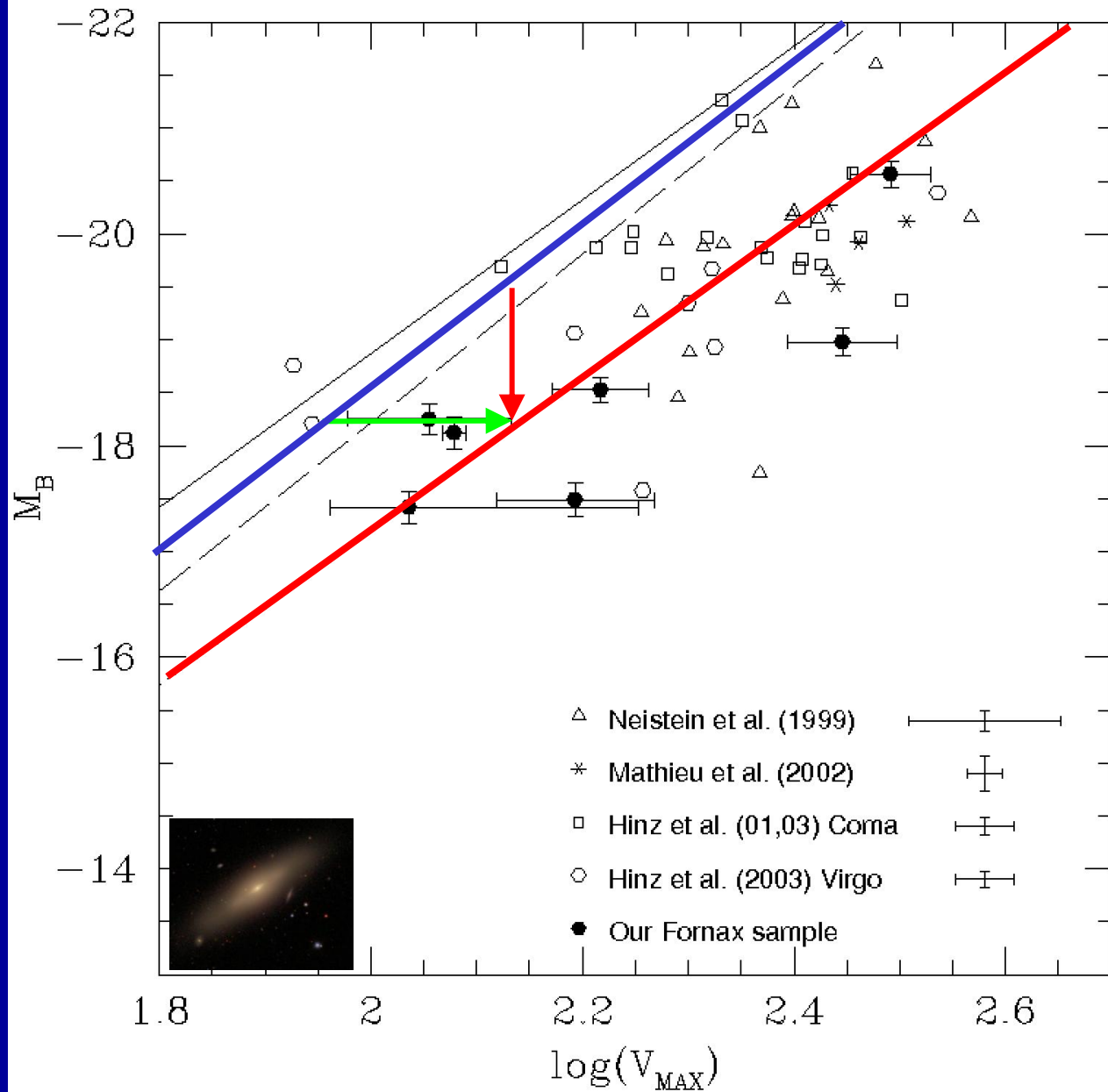


Bedregal et al 2011

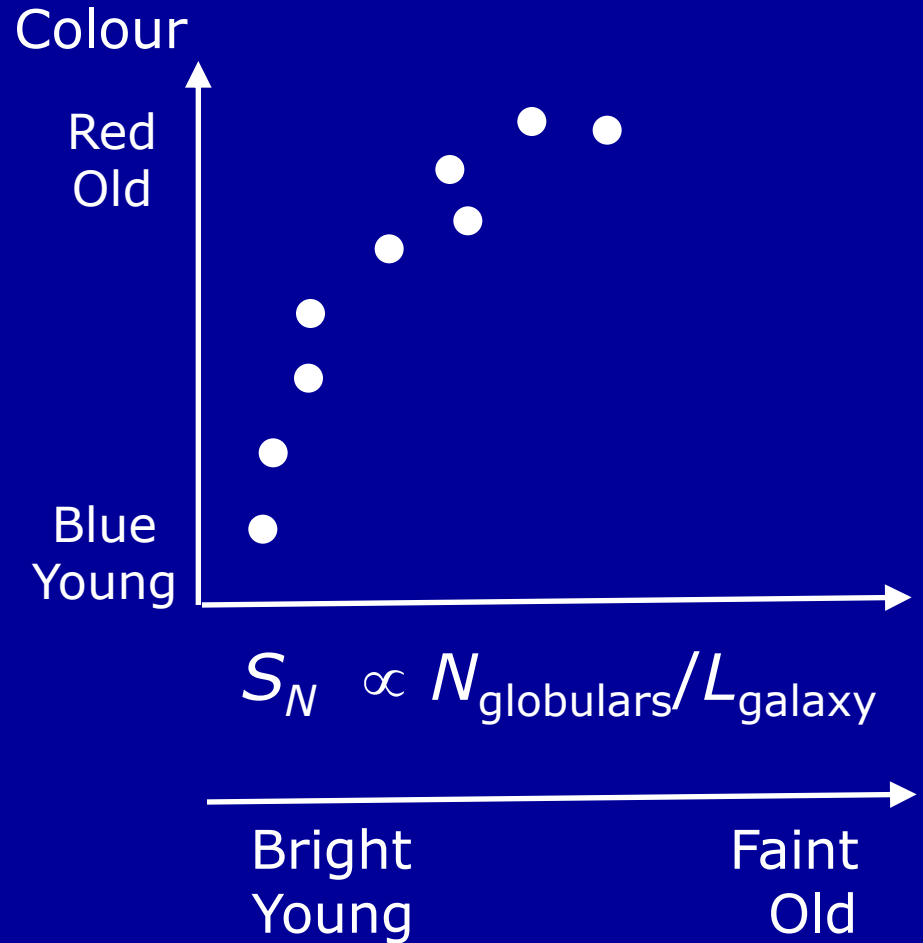
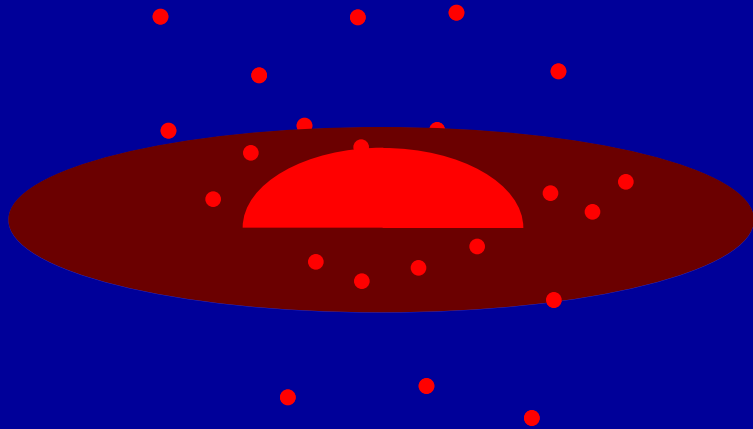
Old Red & Dusty Red Galaxies

Chris Wolf, Alfonso Aragón-Salamanca, et al. 2009

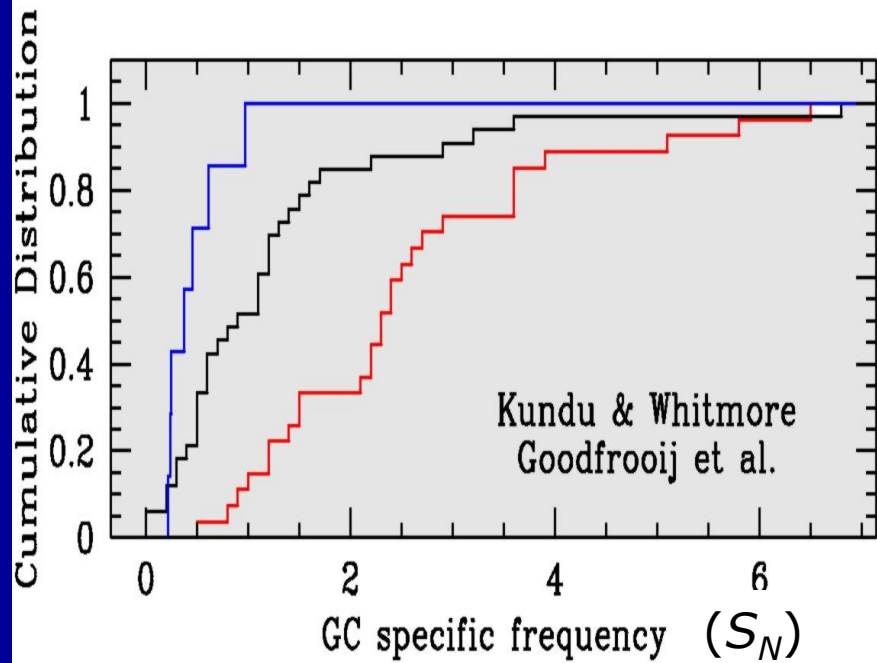




Evolution of a Fading Galaxy



Globular Cluster Systems

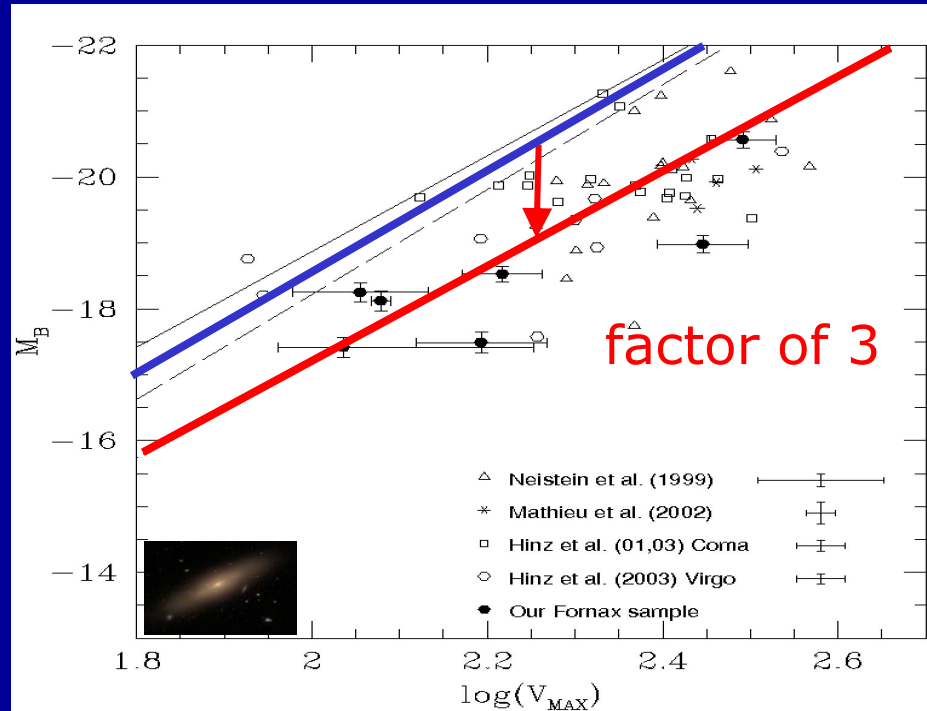


$$\frac{\langle S_N \rangle_{S0}}{\langle S_N \rangle_{\text{Spiral}}} \approx 2.8 \pm 0.9$$

$$S_N \equiv N_{\text{GCs}} 10^{0.4(M_V+15)}$$

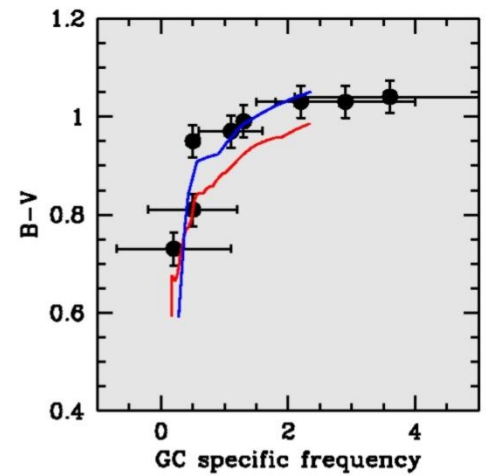
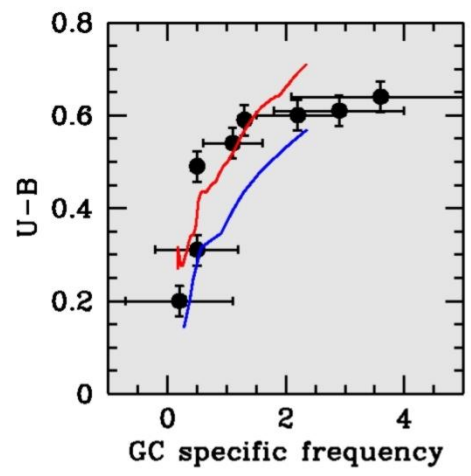
$$S_N \propto N_{\text{GCs}}/L_{\text{galaxy}}$$

Tully-Fisher Relation

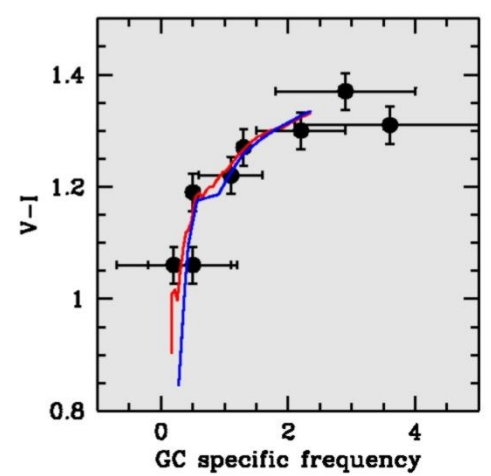
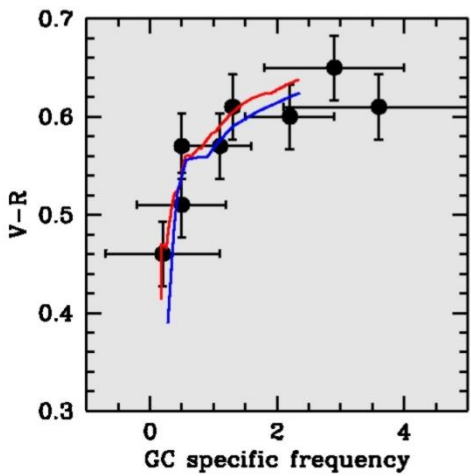


GC Specific Frequency vs. Galaxy Colours

Red
Old



Blue
Young

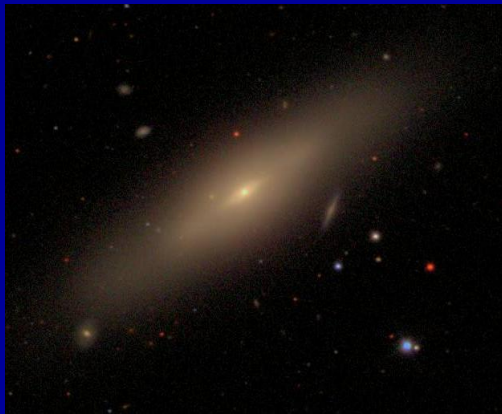
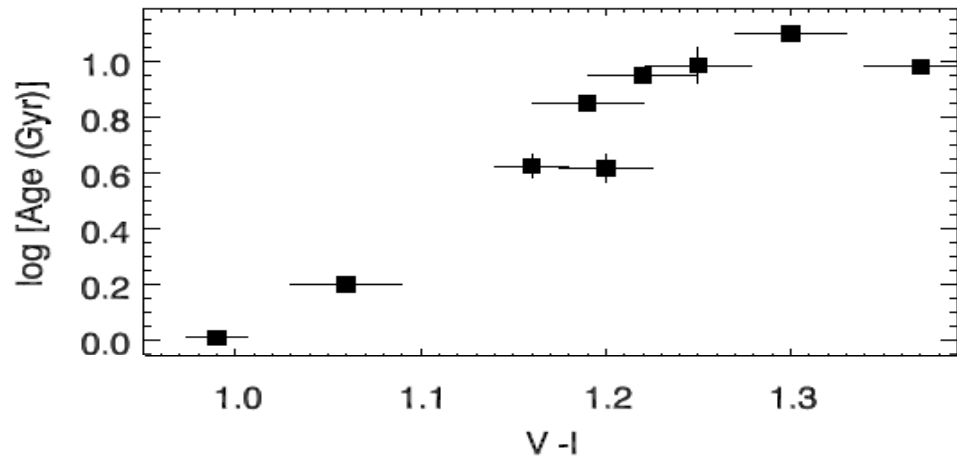


Bright
Young

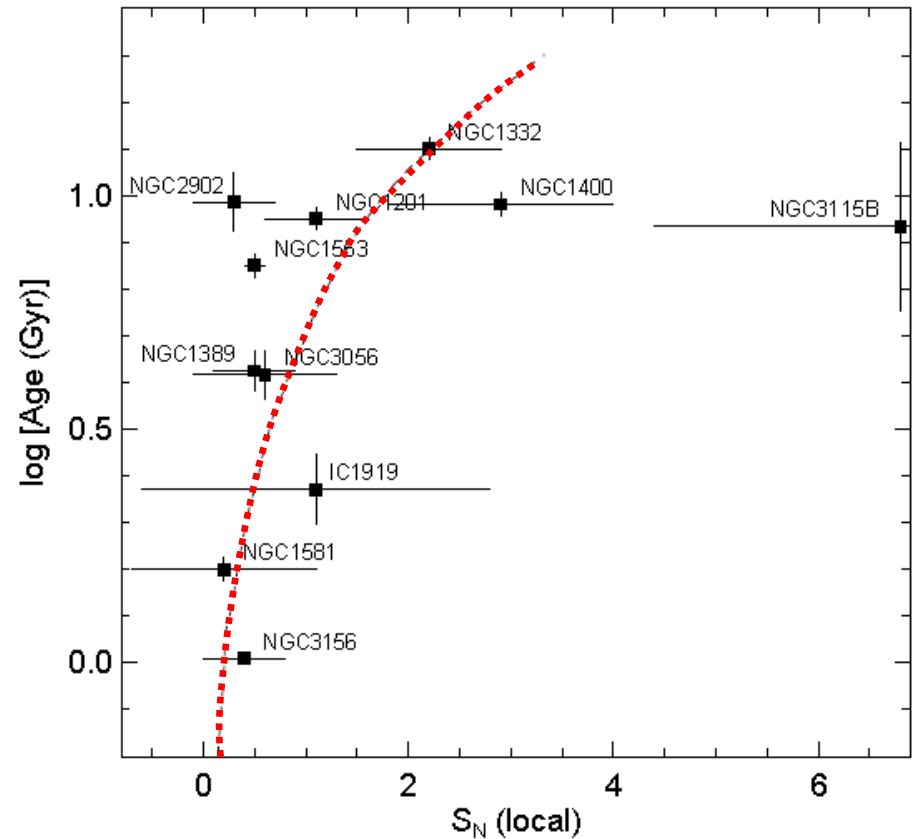
Faint
Old

Aragón-Salamanca,
Bedregal &
Merrifield 2006

GC Specific Frequency vs. Galaxy Age



Barr, Bedregal,
Aragón-Salamanca, Merrifield
& Bamford 2007



Conclusions

- Indirect evidence indicates that spirals evolve into S0s in clusters
- The disturbed structure and kinematics of the gas in spiral galaxies falling into intermediate- z clusters, coupled with the lack of morphological disturbance, indicate that the process responsible for the transformation is “gentle”.
- The Tully-Fisher relation of low- z S0s suggests that S0 galaxies are fading spirals.
- The stellar populations of S0 galaxy bulges and disks provide additional evidence on the formation history the S0s: SF ended last in the central regions, helping to build the bulges.
- The properties of the Globular Cluster systems of S0 galaxies are consistent with the idea that S0s are formed from spiral galaxies whose star formation has ceased.

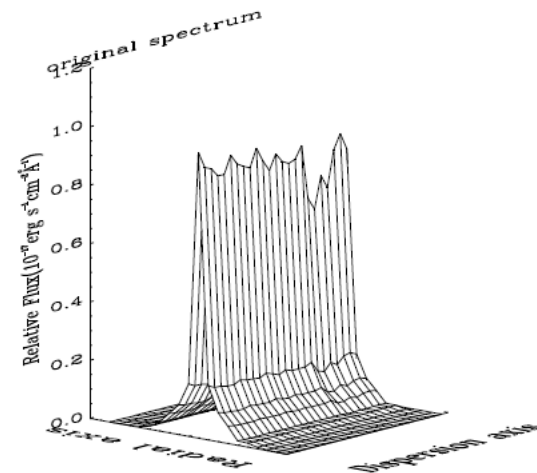
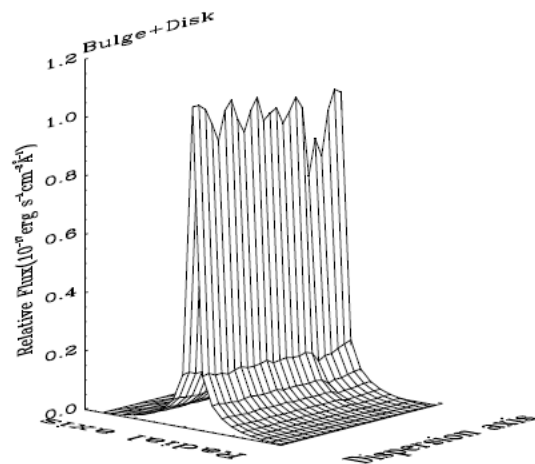
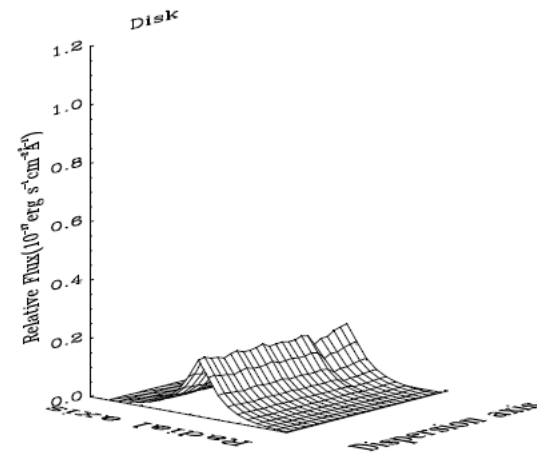
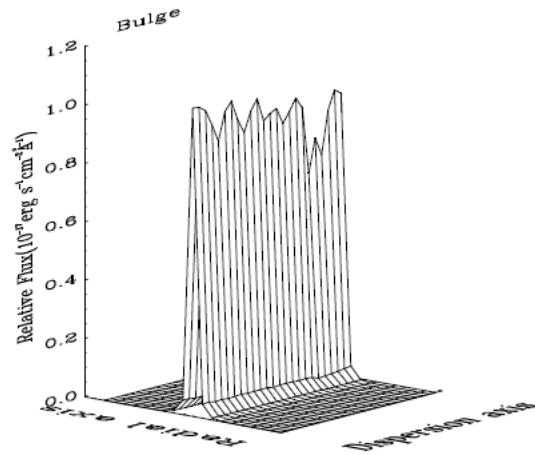
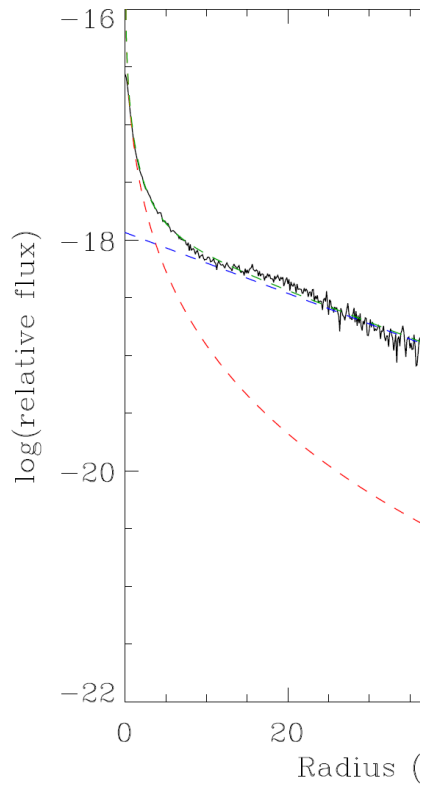
S0s are dead spirals

(and we can now provide an approximate time of death)

Future Work

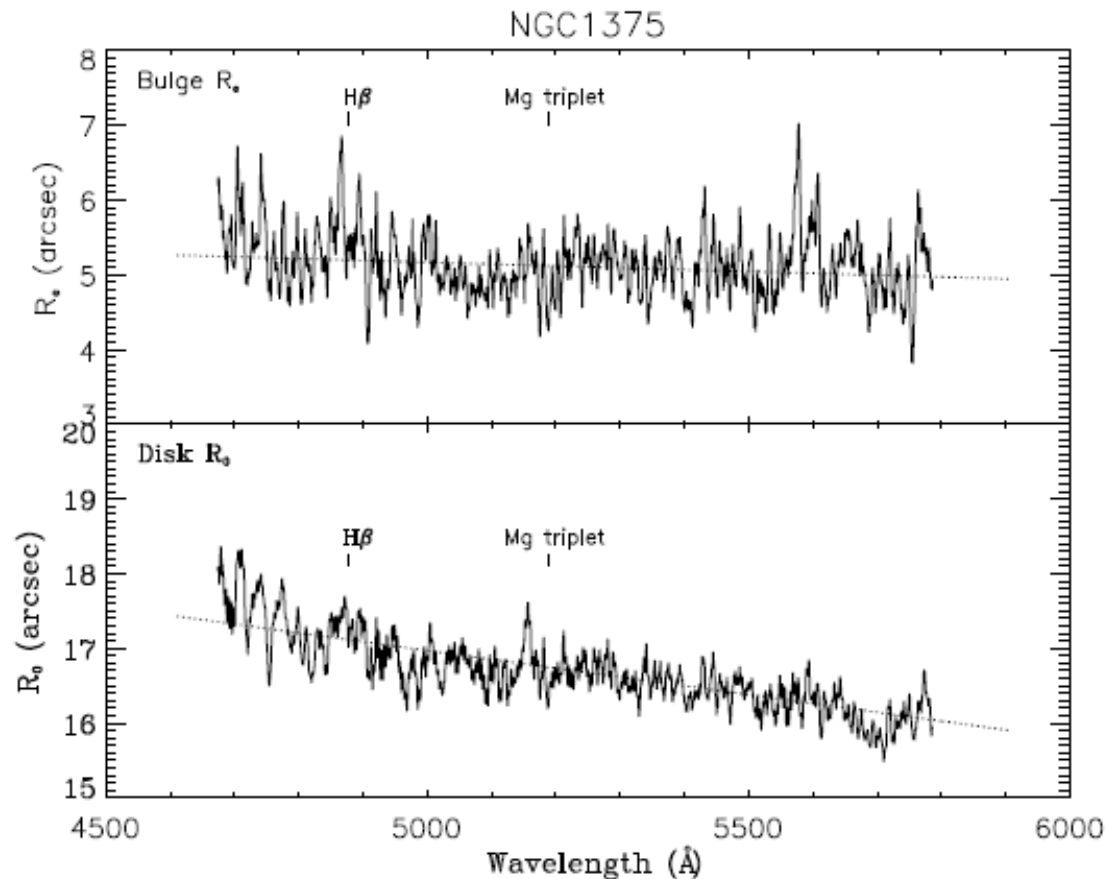
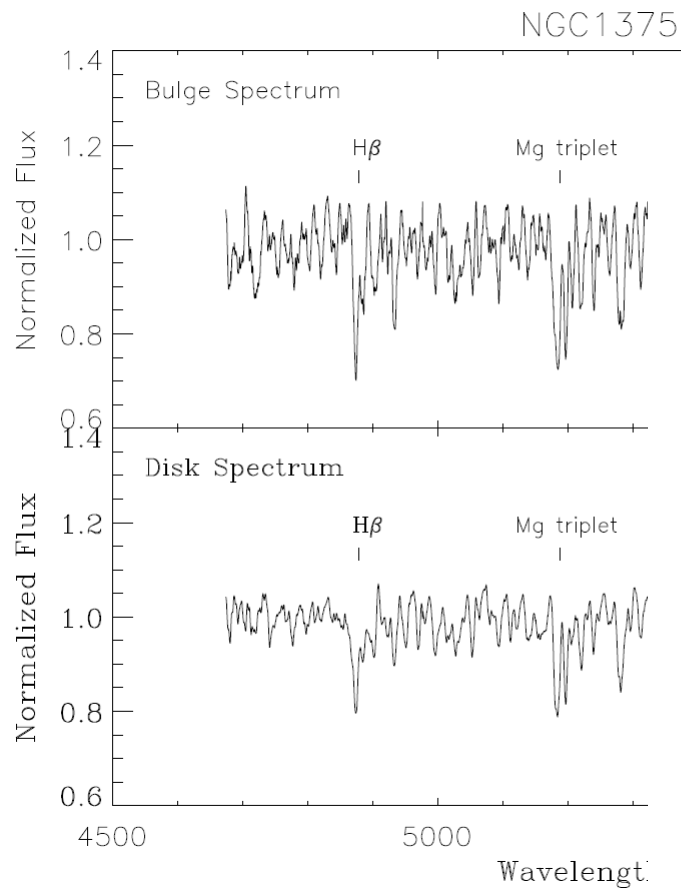
- At low z , extend Tully-Fisher and stellar-population studies of S0s in different environments and over a large range of luminosities/masses.
- Spectral bulge-disk decomposition.
- IFU observations of $z \sim 0.3$ E+A galaxies with S0 morphology (using VLT/FLAMES).

Spectral Bulge-Disk decomposition



Evelyn Johnston,
Alfonso Aragón-Salamanca,
Michael Merrifield

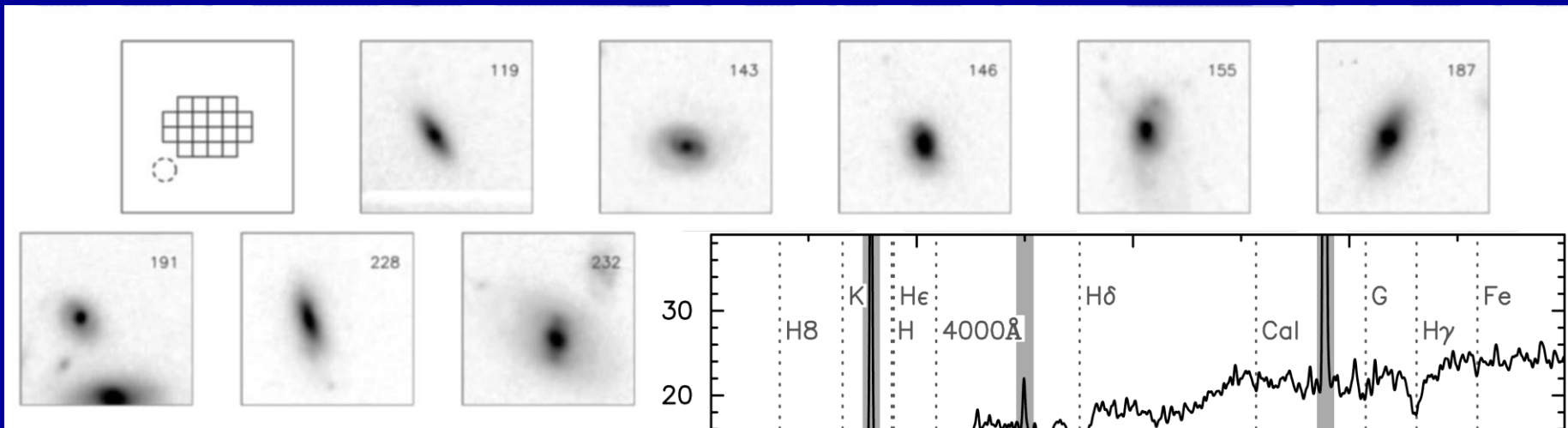
Spectral Bulge-Disk decomposition



Evelyn Johnston,
Alfonso Aragón-Salamanca,
Michael Merrifield

Catching them in the act

- Observed all E+A galaxies with disk morphology and $M_R > -20.5$ in one $z=0.31$ cluster (AC114)
- Used FLAMES at the VLT: 15 deployable 3x2" IFUs
- Examine the distribution and dynamics of the separate old and recent stellar populations



Bruno Rodriguez del Pino,
Alfonso Aragón-Salamanca,
Steven Bamford