The Evolution of Early-Type Galaxies Since z=1

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E+S0 Galaxies at z<0.7:

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E+S0 Galaxies z<1:

I. Jørgensen (Gemini), R. L. Davies (Oxford), K. Chiboucas (IfA), R. P. Schiavon (Gemini)

GEE2 Meeting, Milano, November 8th, 2011

Outline

- Introduction
  - Context and Scaling Relations
  - Hierarchical Galaxy Formation
- Motivation
  - Stellar Population Differences?
  - Environmental Dependences?
- Results

  Part I. *Early-Type Galaxies at Low-z*

  Part II. *Early-Type Galaxies at High-z*
- Summary
- Outlook

Why?

- Early-Type Galaxies are important!

- *Observations*:

  o Cluster Galaxies: E+S0 old $z_f \geq 2$

  e.g. van Dokkum & Franx 1996, Bender et al. 1998, Scodeggio et al. 1998, Jørgensen et al. 1999, van Dokkum & Stanford 2003, La Barbera et al. 2003

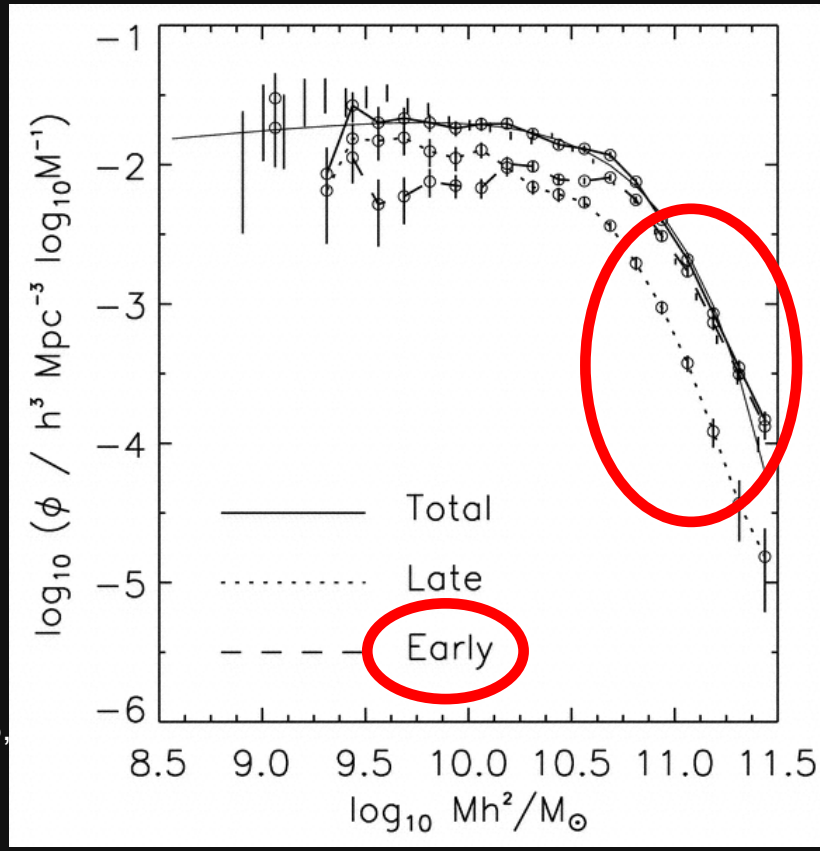
  o Field Galaxies:

  Similar to Cluster ↔ Assembly $z_f \sim 1$

  e.g. Treu et al. 2001,van de Ven et al. 2003, Gebhardt et al.03, di Serego Alighieri et al. 2005, Saracco et al. 2005

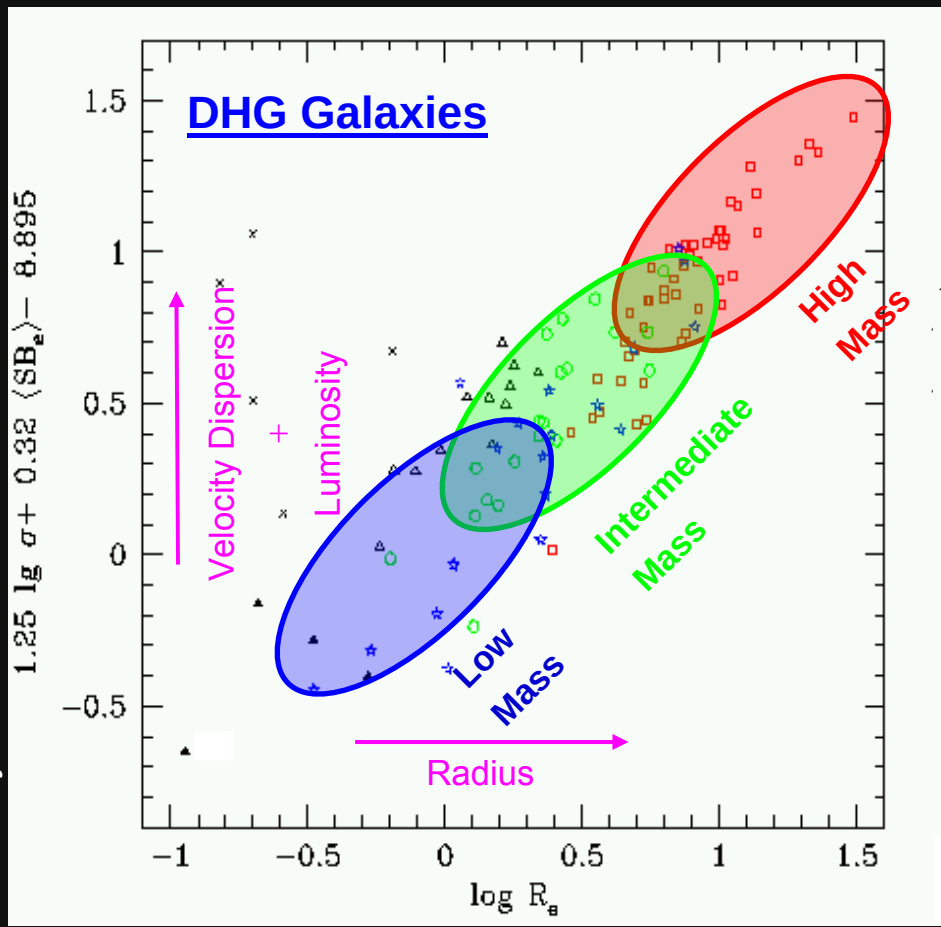
  o *Nearby* E+S0: Sub-structure/*complex*

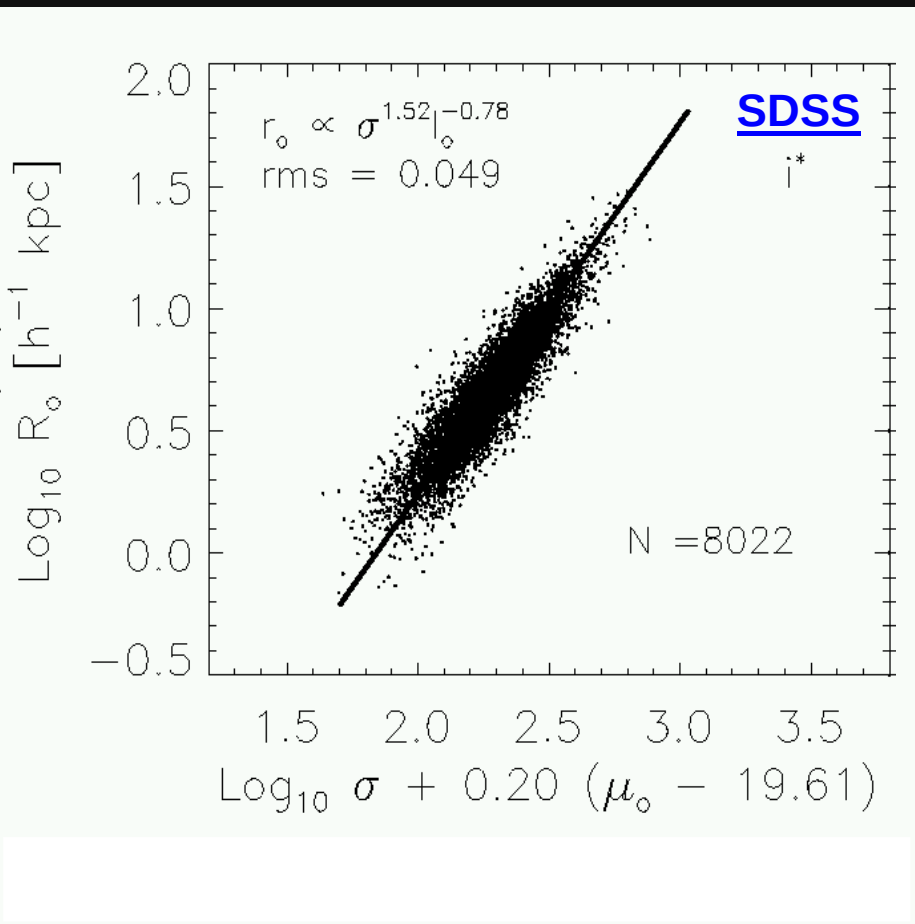
  e.g. van Dokkum 2005, McDermid et al. 2006, Cappellari et al. 2011



K-band MF for SDSS/2MASS Bell et al. 2003

Fundamental Plane





Luminosity effects →

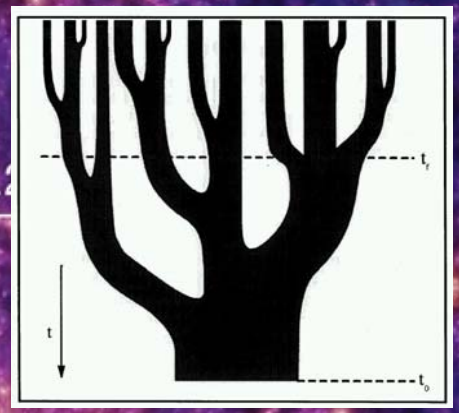
FP in B-band — Bender et al. 1992 — FP in i-band — Bernardi et al. 2003

Structural size →

$$\log R_e = \alpha \log \sigma + \beta \langle \mu_e \rangle + \gamma$$

Results of FP studies (N<15) at $0 \le z \le 1$ → Majority of stars formed at $z_f \ge 2$

Hierarchical Galaxy Formation



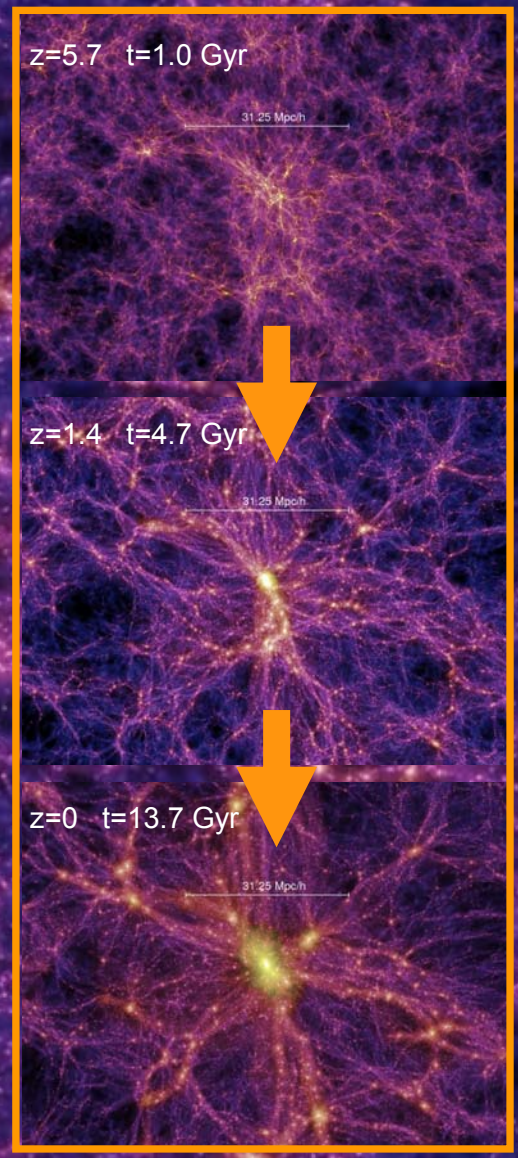
CDM Simulations:

- Small Structures first
- Large Structures later

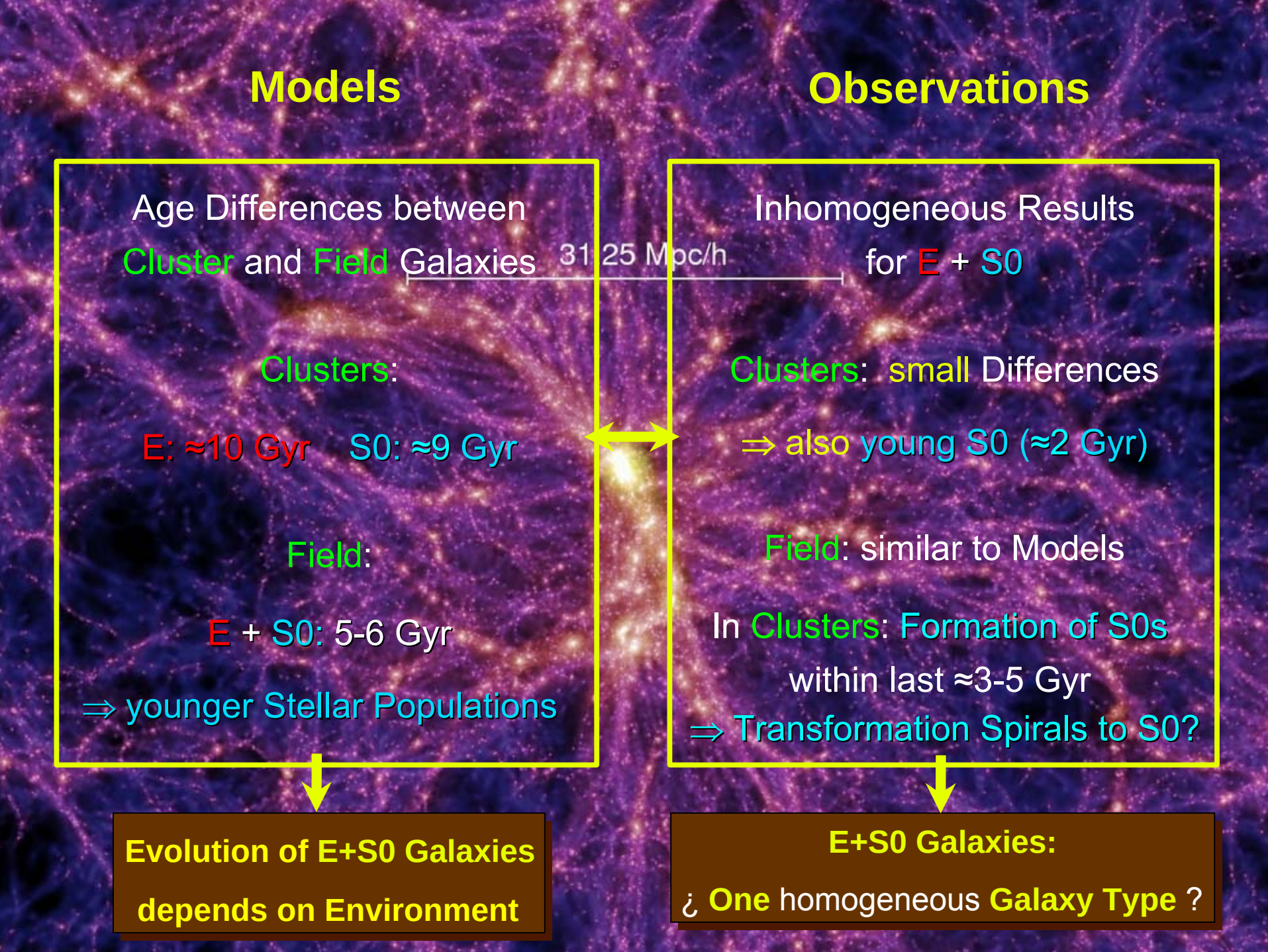
⇒ *Lower-mass* (small) Galaxies *older* than Higher-mass (larger) Galaxies

Environment affects Galaxy Evolution

Diaferio et al. 2001, De Lucia et al. 2004



Springel et al. 2005


Models
Observations
Age Differences between
Cluster and Field Galaxies
31.25 Mpc/h
Clusters:
E: ≈10 Gyr S0: ≈9 Gyr
Field:
E + S0: 5-6 Gyr
⇒ younger Stellar Populations
Evolution of E+S0 Galaxies
depends on Environment
Inhomogeneous Results
for E + S0
Clusters: small Differences
⇒ also young S0 (≈2 Gyr)
Field: similar to Models
In Clusters: Formation of S0s
within last ≈3-5 Gyr
⇒ Transformation Spirals to S0?
E+S0 Galaxies:
¿ One homogeneous Galaxy Type ?

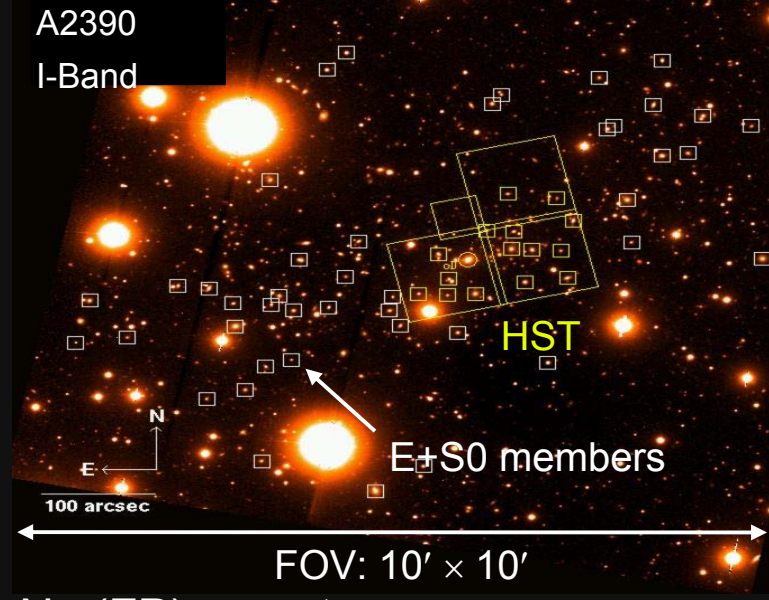
Motivation

Sample Criteria

- ✓ Different Environment
- ✓ High S/N Spectra (S/N ≥ 20) ⇒ SP Analysis
- ✓ *Large Number* of Objects (N~50)
- ✓ Wide Luminosity Range (down to M_*+2)
- ✓ Field-of-view for Clusters: ~10′ × 10′
- ✓ Deep Photometry

FORS Deep Field
BRI composite

Datasets



- E+S0 Galaxies at low-z: N = 121

  VLT/FORS and CA MOSCA spectra

  UBV*g*RI Multi-colour and *HST*-Photometry

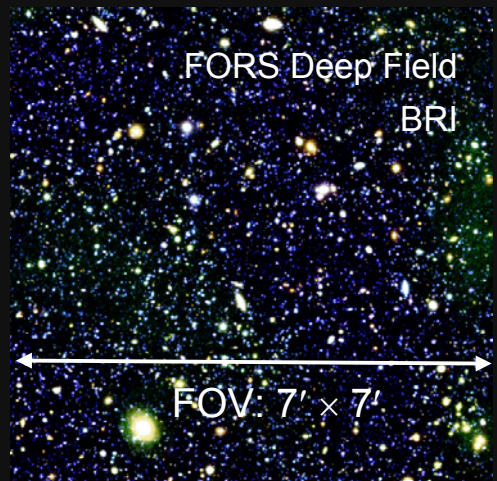
	N_G	N_G (FP)	t_{LB}	
Cluster Galaxies ($0.22 < z < 0.3$):				
Rich: A2218 + A2390	96	34	3 Gyr	Fritz et al. 2005
Poor: CL0849 + CL1701 + CL1702	27	11	3 Gyr	Fritz & Ziegler 2009 Fritz et al. 2011
Field Galaxies ($0.21 \leq z < 0.75$):				
FORS + William Herschel Deep Field	24	21	4 Gyr	Fritz et al. 2009a

- E+S0 Galaxies at high-z: N = 72

  Gemini/HST Galaxy Cluster Project:
  HST/ACS + High S/N GMOS Spectra
  (S/N ≥ 25 per Å in rest-frame)

  RXJ1415.1+3612 (z=1.01): N=14+38 Fritz et al. 2009b

  Field Galaxies (0.5<z<1): N=20 (50) Fritz et al. 2011



Surface Brightness Profiles

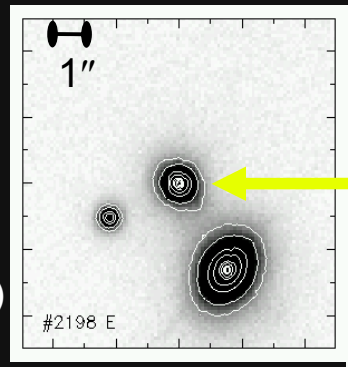
HST/ACS+WFPC2:

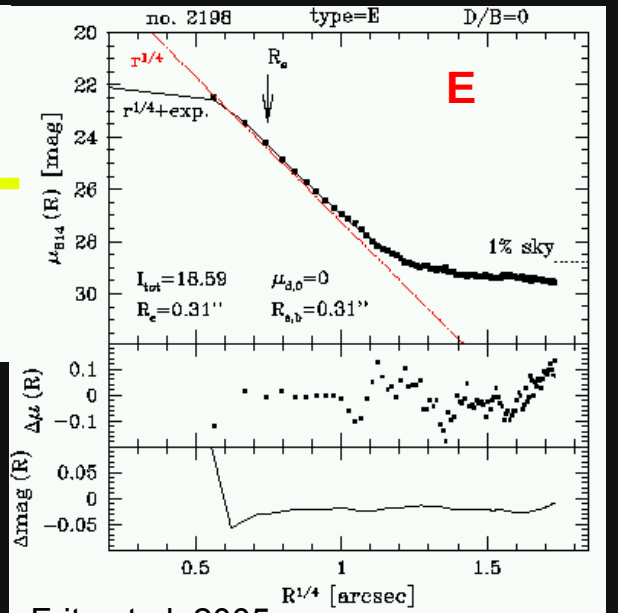
108 Galaxies (30 @ z=1) :

Luminosity Profiles and structural Parameters (Saglia et al. 1997, Peng et al. 2002)

Model each Galaxy:

- PSF Convolution
- $r^{1/4}$ Profile / $r^{1/4}$ + Disk
- Detailed Error Analysis

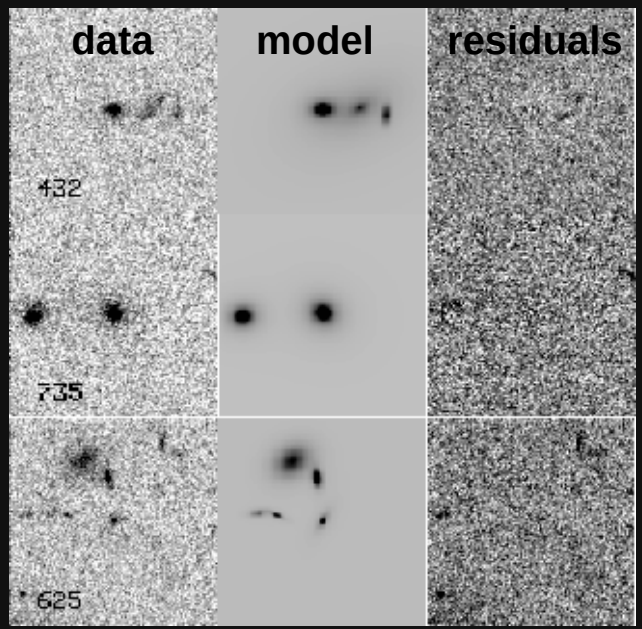


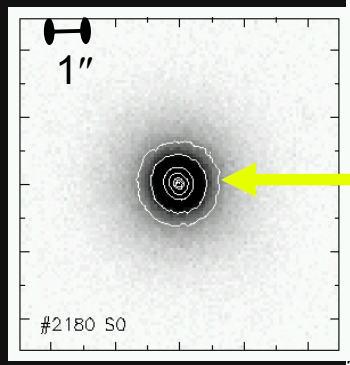


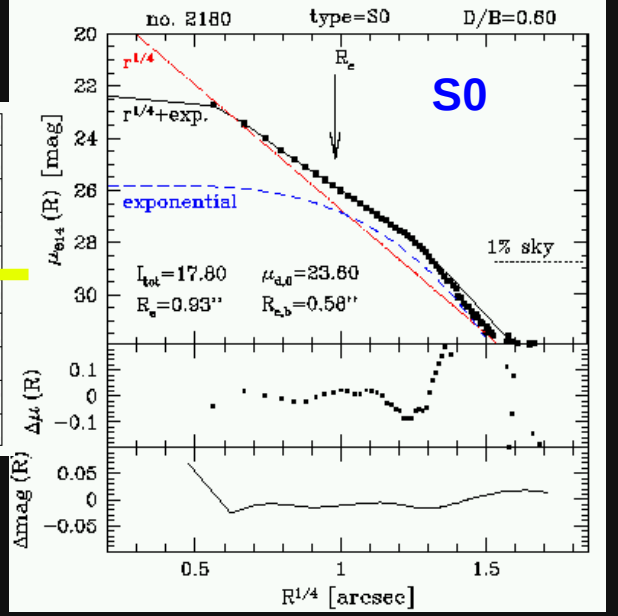
Fritz et al. 2005

$$\mu(R) = \mu_e \exp\left\{-7.67\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right]\right\}$$

$$\mu(R) = \mu_0 \exp\left(-\frac{R}{h}\right)$$







RXJ1415.1+3612: z=1

Fritz et al. 2009b

Kinematics

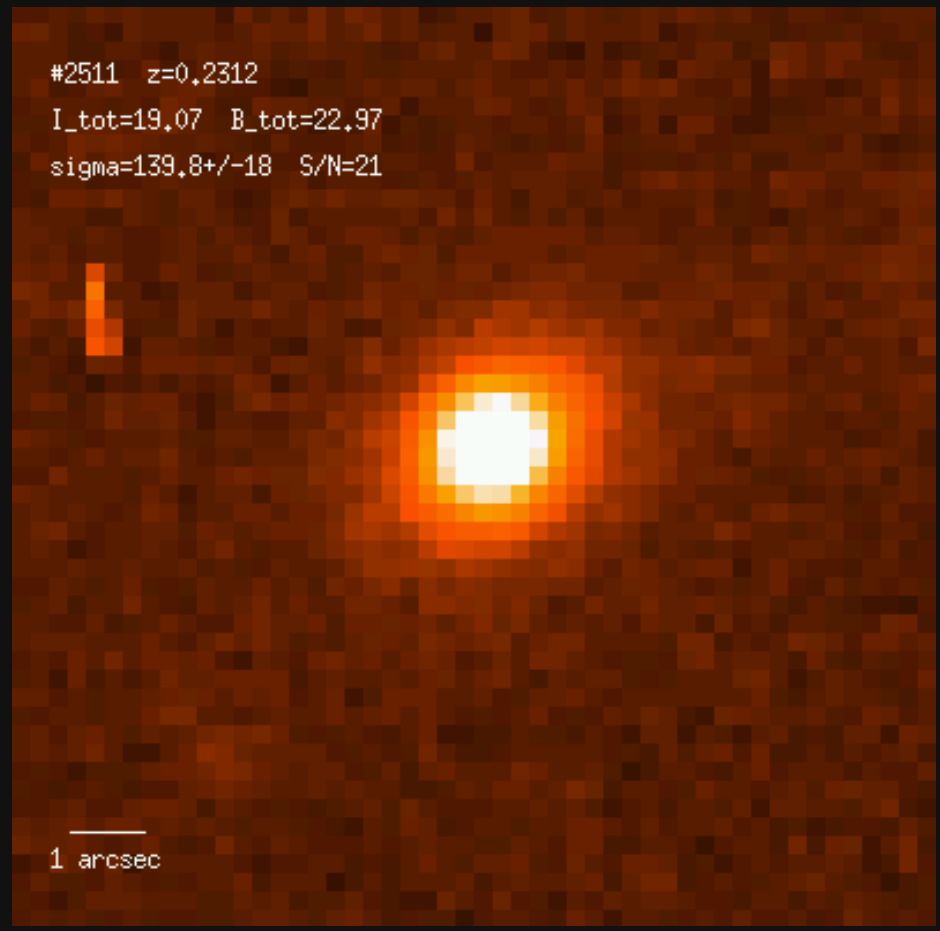
Spectroscopy of *distant* Galaxies:

- low-luminosity Objects:

  $\Rightarrow$ 1-2 mag fainter than M^*

- small apparent Sizes:

  Extension: 3-4" R_e : 0.2"<R_e<2.3"



Fritz et al. 2009a

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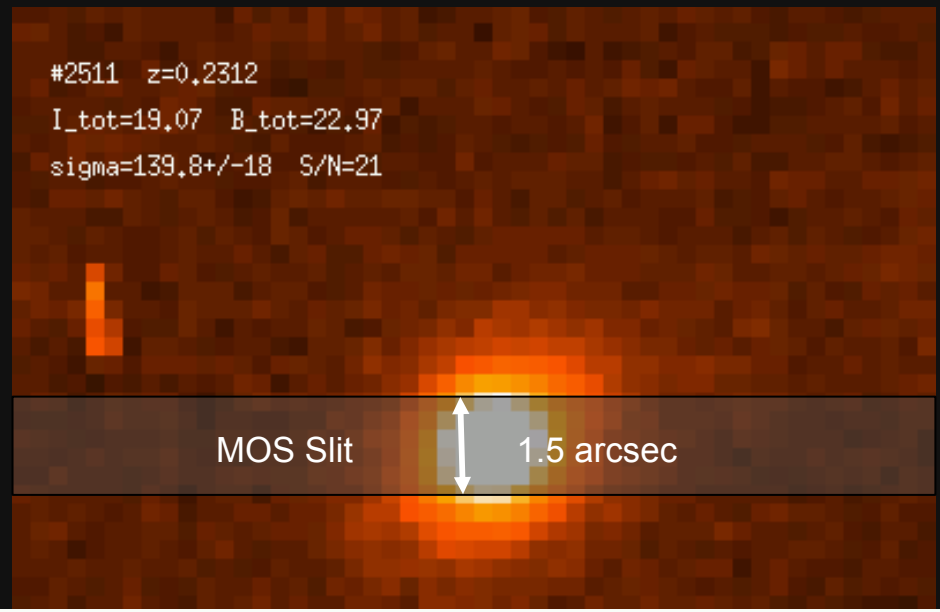
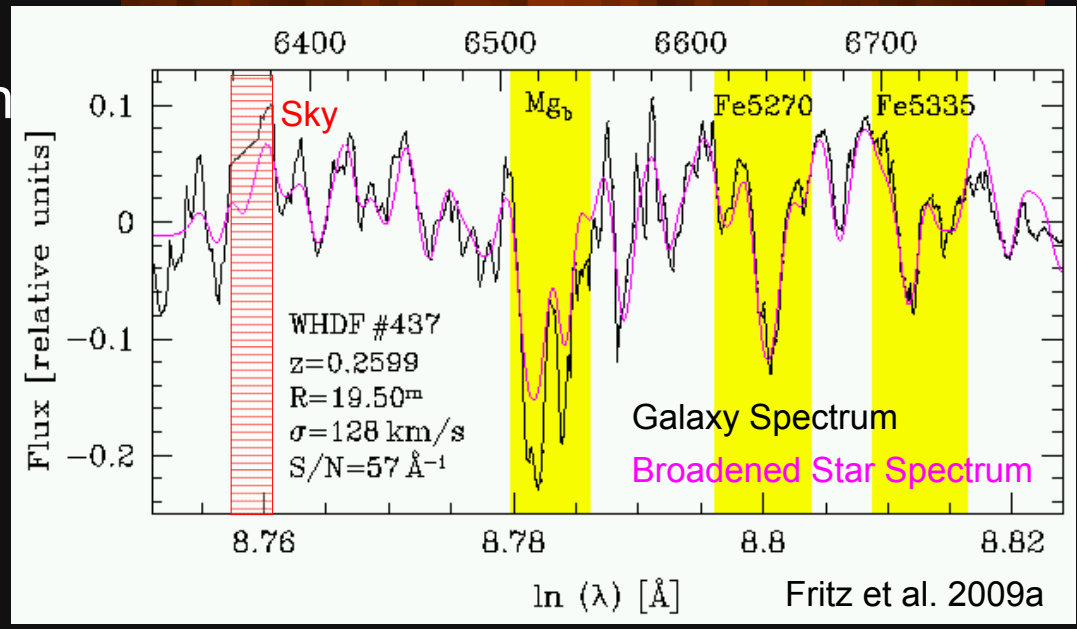
- *integrated* Velocity Dispersion

  ⇒ Aperture Correction of σ

- FCQ Method (Bender 1990)

  - LOSVD *a posteriori*
  - Insensitive to Template Mismatch
  - Consistency checks and MC sims





Fritz et al. 2009a

Faber-Jackson Relation

Rich Clusters:

A2218 + A2390: 96 E+S0s

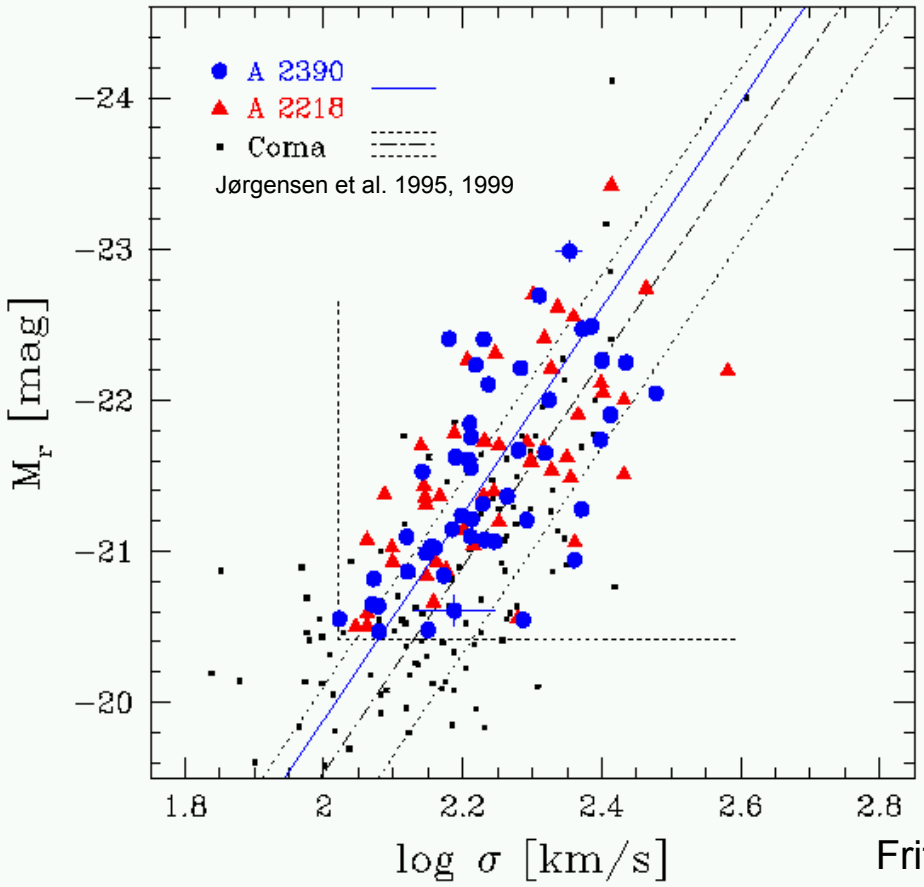
Gunn r: $\Delta\langle M_r\rangle$=–0.35 mag

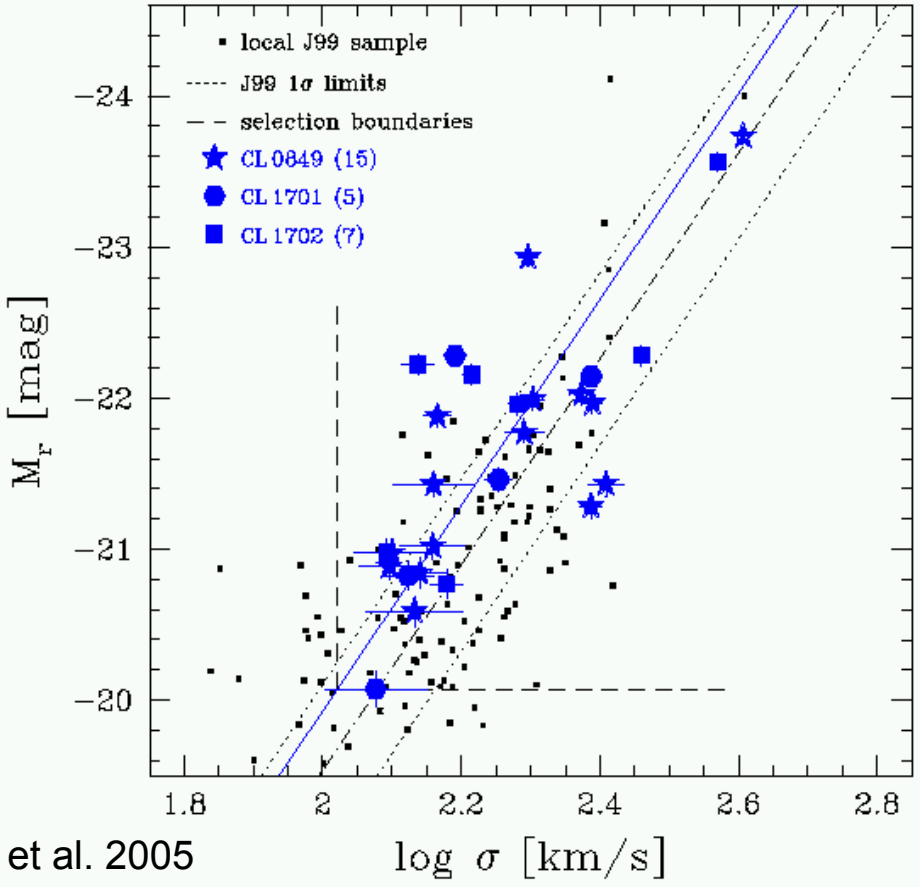
Poor *Low Mass* Clusters:

CL0849 + 1701 + 1702: 27 E+S0s

Gunn r: $\Delta\langle M_r\rangle$=–0.38 mag

$\Rightarrow$ early Formation Epoch and passive Evolution





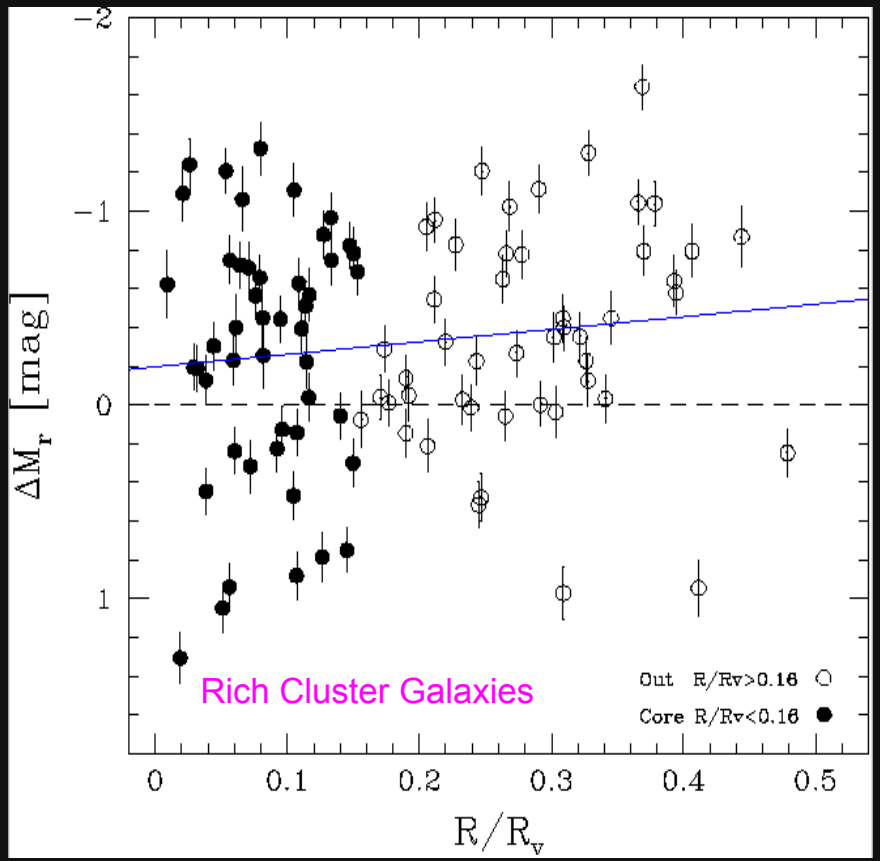
Fritz et al. 2005

Environmental Dependence

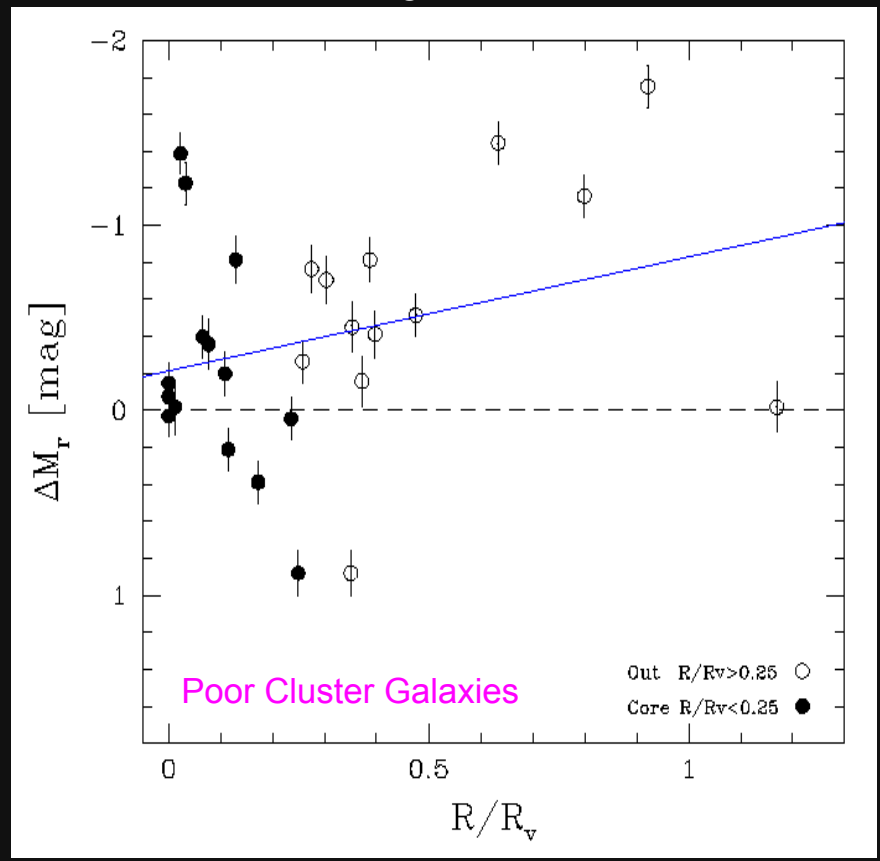
FJR Offsets:

- Luminosity Dependence *low-L* $\Delta\langle M_r\rangle$=–0.3 mag ↔ *high-L* $\Delta\langle M_r\rangle$=–0.4 mag
- *Radial Dependence* *core* $\Delta\langle M_r\rangle$=–0.25 mag ↔ *outskirts* $\Delta\langle M_r\rangle$=–0.4 mag

Fritz et al. 2005



Fritz & Ziegler 2009, Fritz et al. 2011



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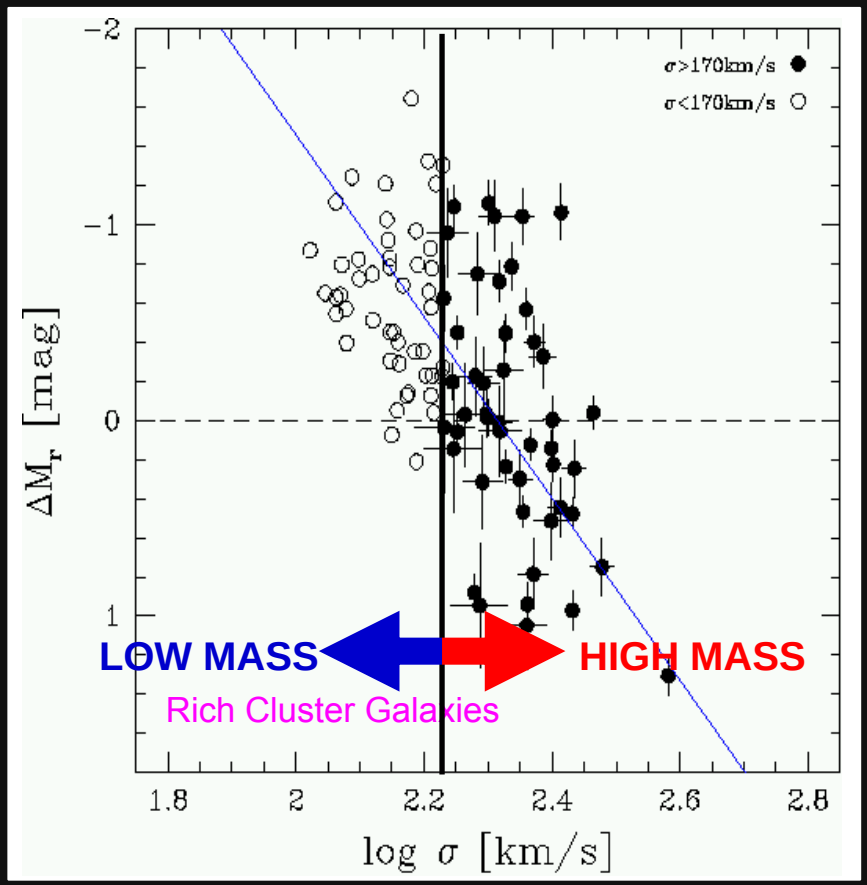
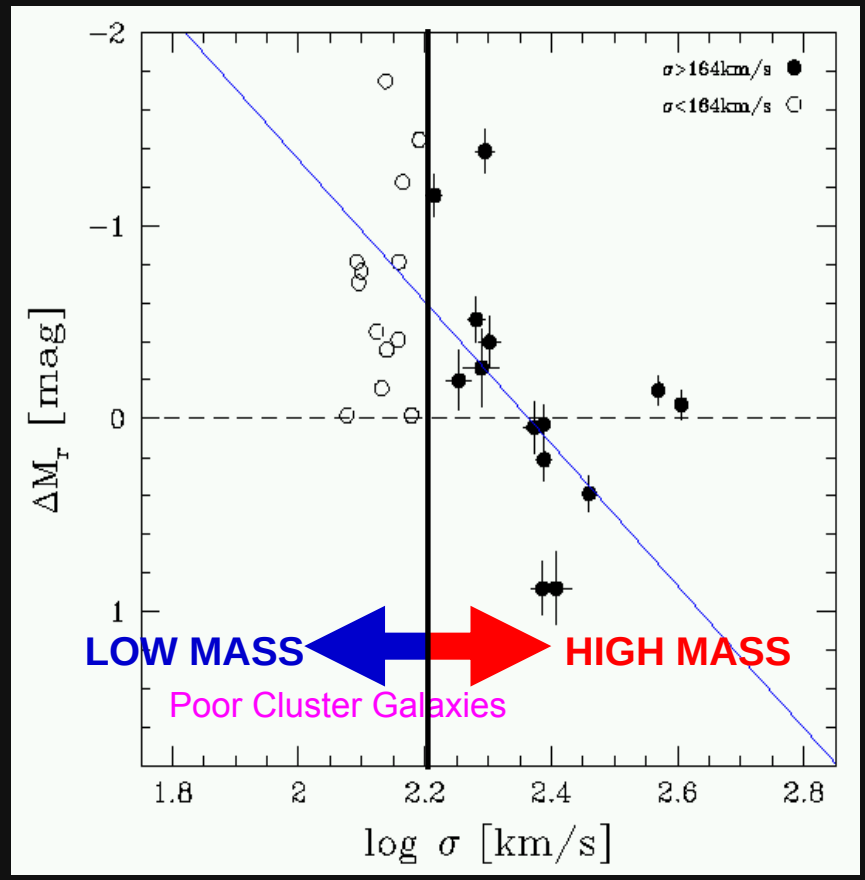
- *Radial Dependence* *core* $\Delta\langle M_r\rangle$=–0.25 mag ↔ *outskirts* $\Delta\langle M_r\rangle$=–0.4 mag
- *Mass Dependence* *low-M* $\Delta\langle M_r\rangle$=–0.6 mag ↔ *high-M* $\Delta\langle M_r\rangle$=–0.05 mag





Environmental Dependence

FJR Offsets:

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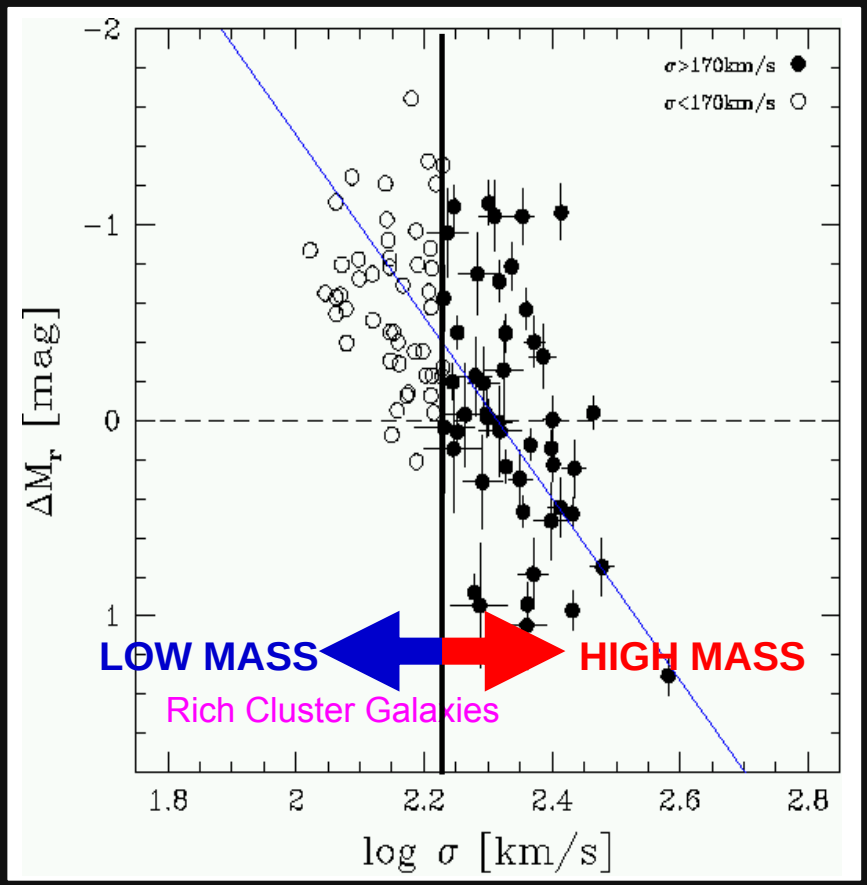
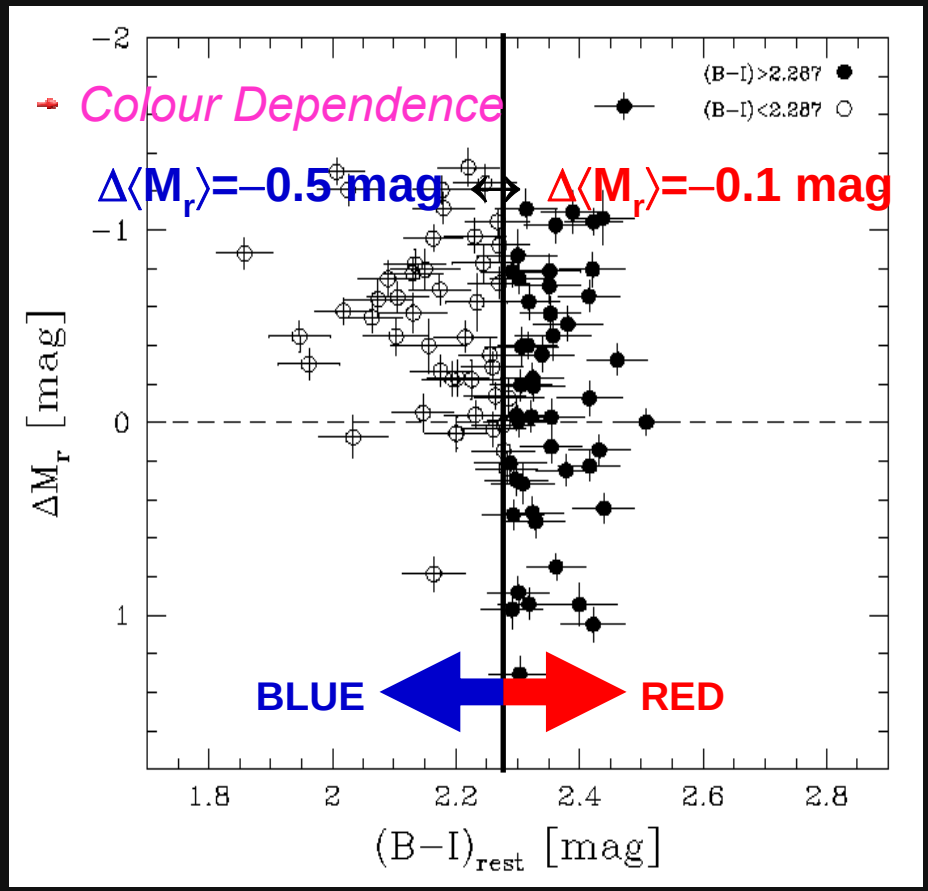
- *Mass Dependence* *low-M* $\Delta\langle M_r\rangle$=–0.6 mag ↔ *high-M* $\Delta\langle M_r\rangle$=–0.05 mag



- *Colour Dependence*



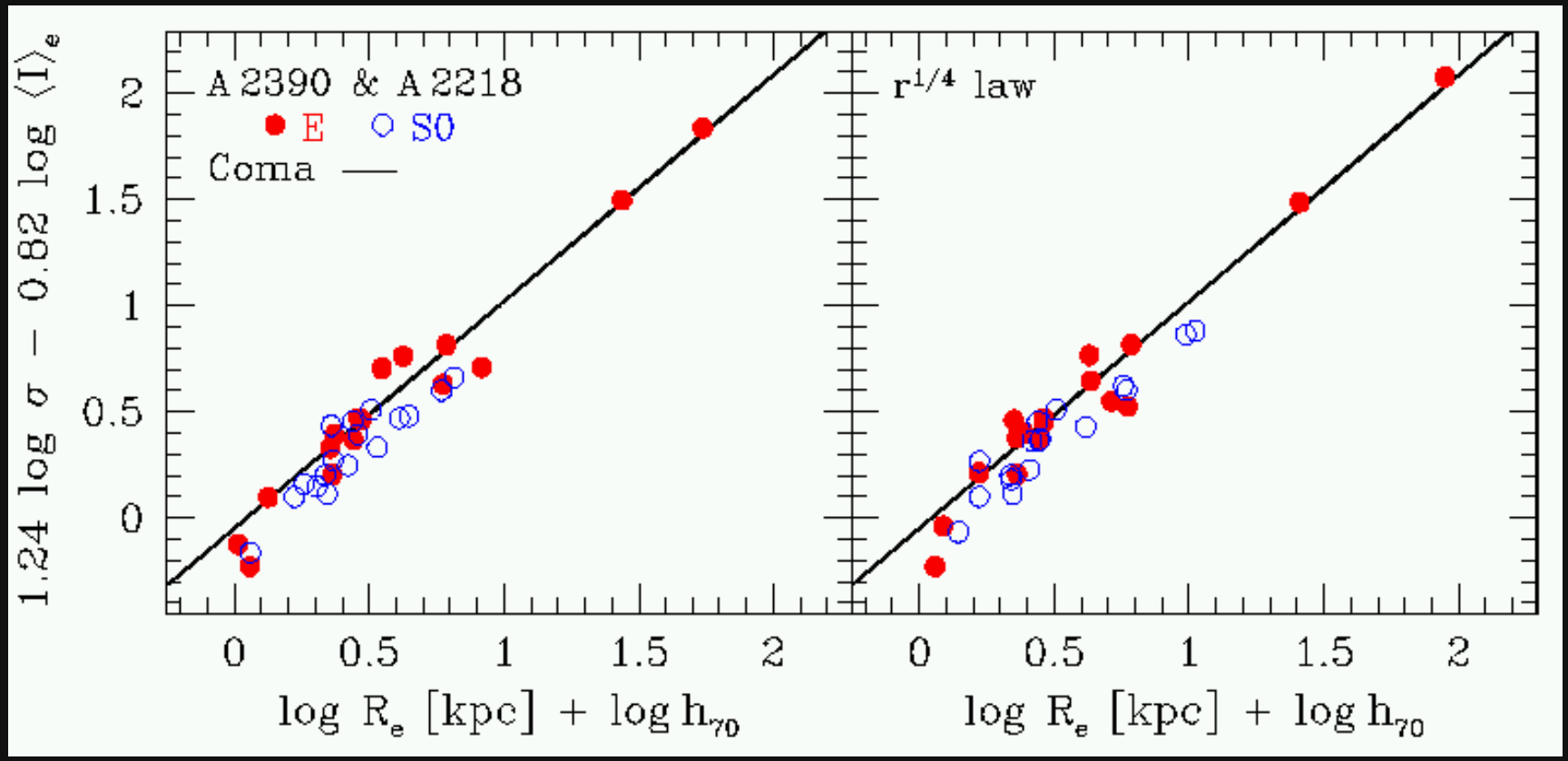
FP Rich Galaxy Clusters

Stellar Population Differences ⇒ S0s stronger Evolution

17 E : $\Delta\langle M_r\rangle$=–0.02 mag

17 S0 : $\Delta\langle M_r\rangle$=–0.44 mag

Fritz et al. 2005



Field Galaxies

- SP Differences:

S0 : $\Delta\langle M_B \rangle = -0.64$ mag

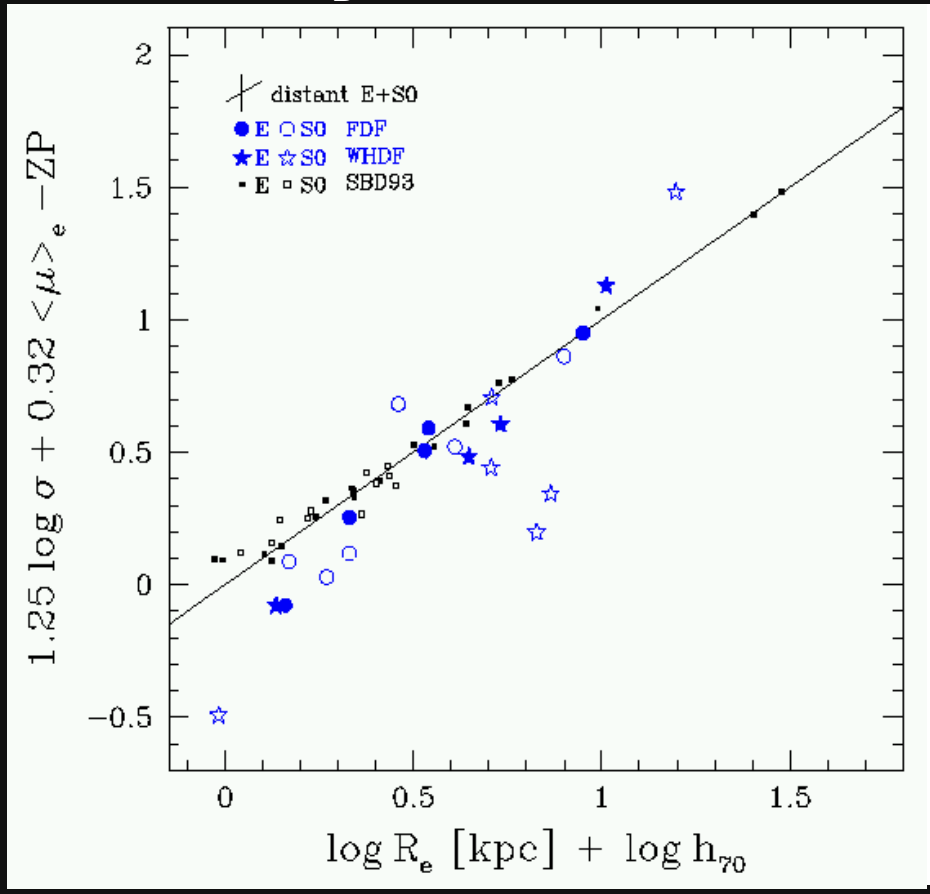
E : $\Delta\langle M_B \rangle = -0.23$ mag

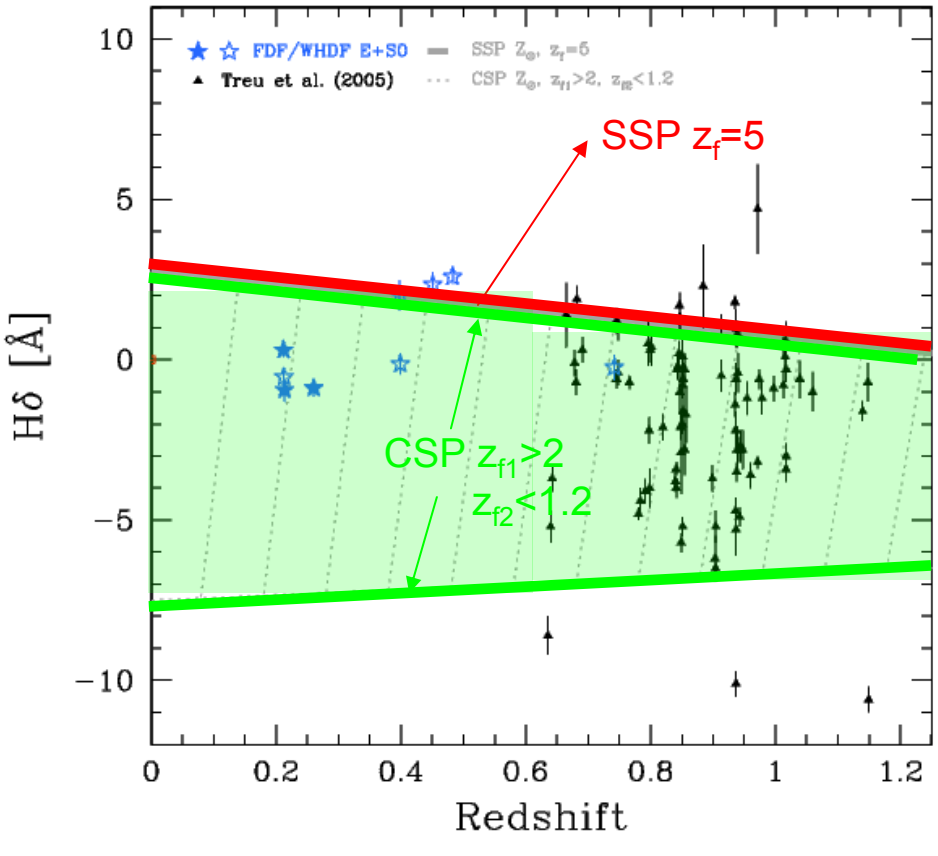
- Recent SF since z~1

SFR(OII) ~ 4 M_o yr^{-1}

$\Rightarrow$ 3 - 10% M_*

Fritz et al. 2009a





Local Sample: Saglia, Bender & Dressler (1993)

SSP Models for Cluster Galaxies

Fritz et al. 2009a

FP zero-point Evolution

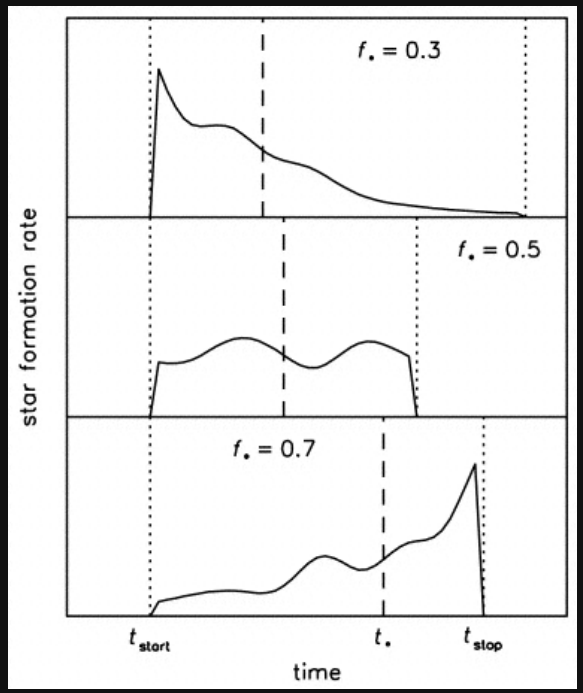
$\Rightarrow$ Evolution of Mass-to-Light Ratio

Comparison with SSP Models

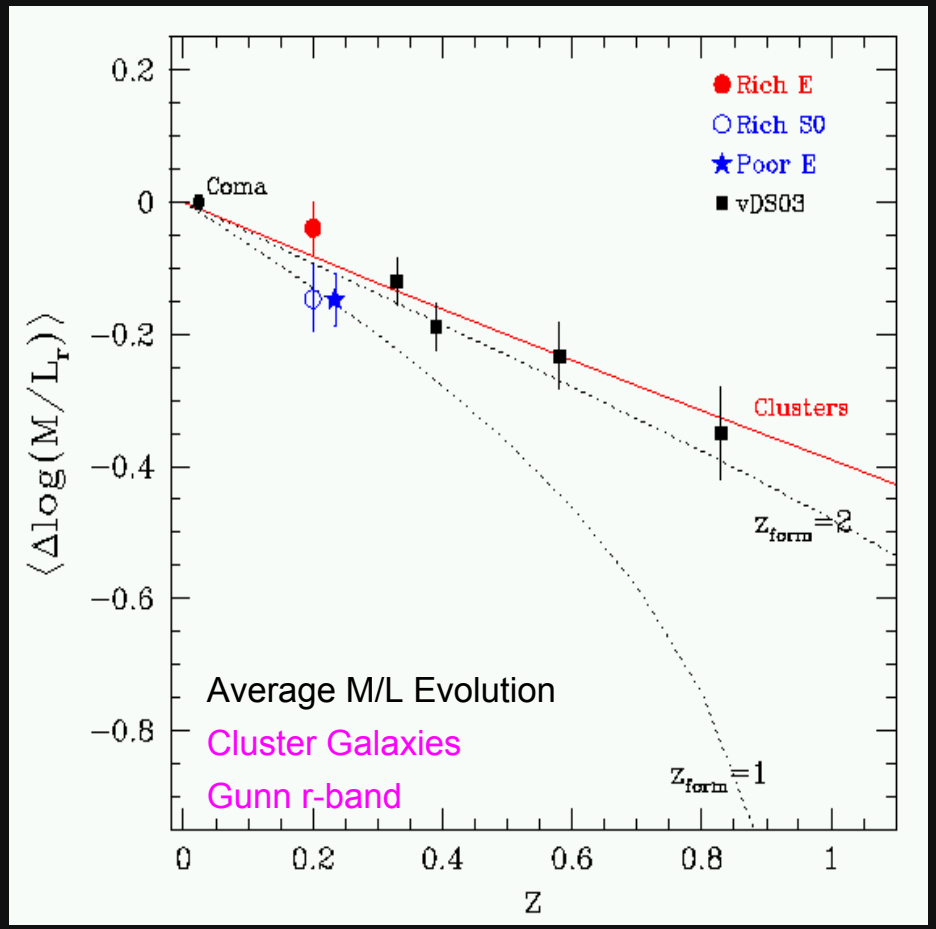
$$L \propto \frac{1}{(t - t_{\rm form})^{\kappa}}$$

van Dokkum & Franx 2001

$\Rightarrow$ Formation Redshift $z_{\rm form}$



van Dokkum & Franx 2001



Comparison Sample: van Dokkum & Stanford 2003

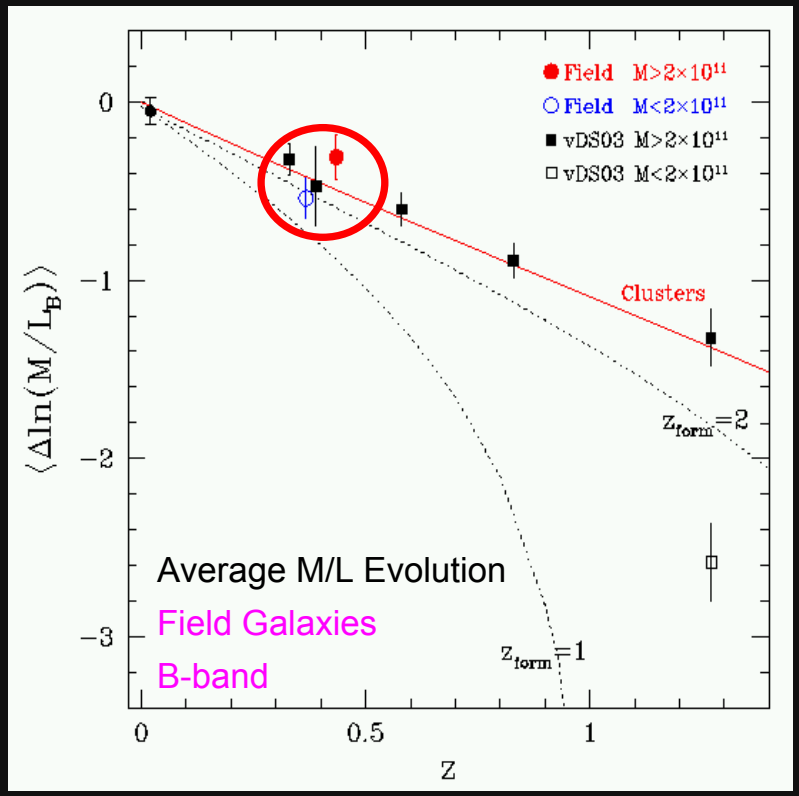
SSP Models for Field Galaxies

Mass-dependent Evolution already visible at t_{LB}~5 Gyr!

less-massive $M<2\times10^{11}\ M_{sun}$: $z_{form}=1.9\pm0.5 \Rightarrow$ 10.1 Gyr

more-massive $M>2\times10^{11}\ M_{sun}$: $z_{form}=3.5\pm1.3 \Rightarrow$ 11.8 Gyr

Fritz et al. 2009a



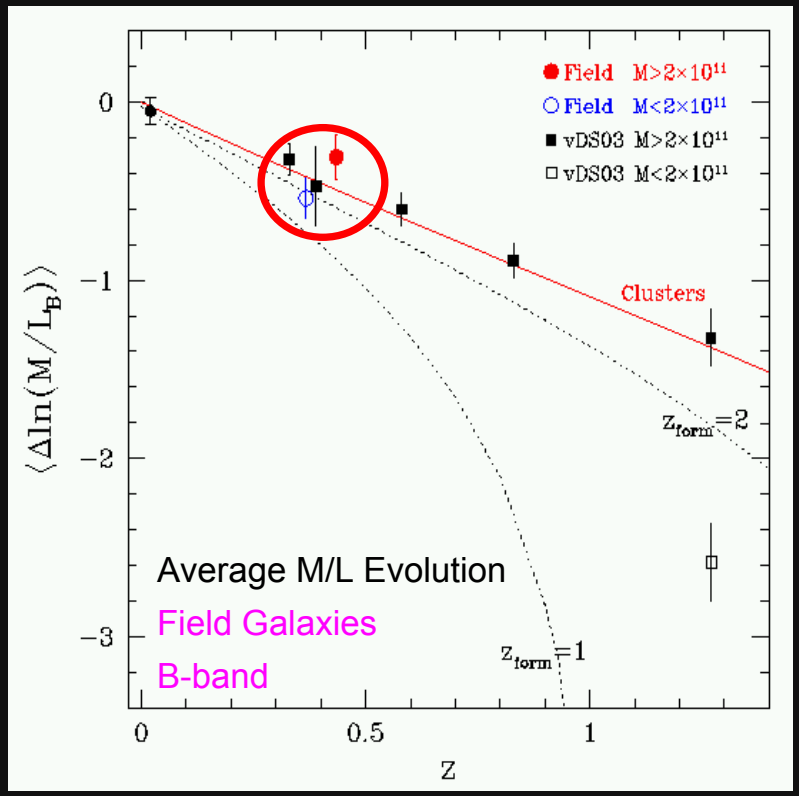
Masses of Field Galaxies

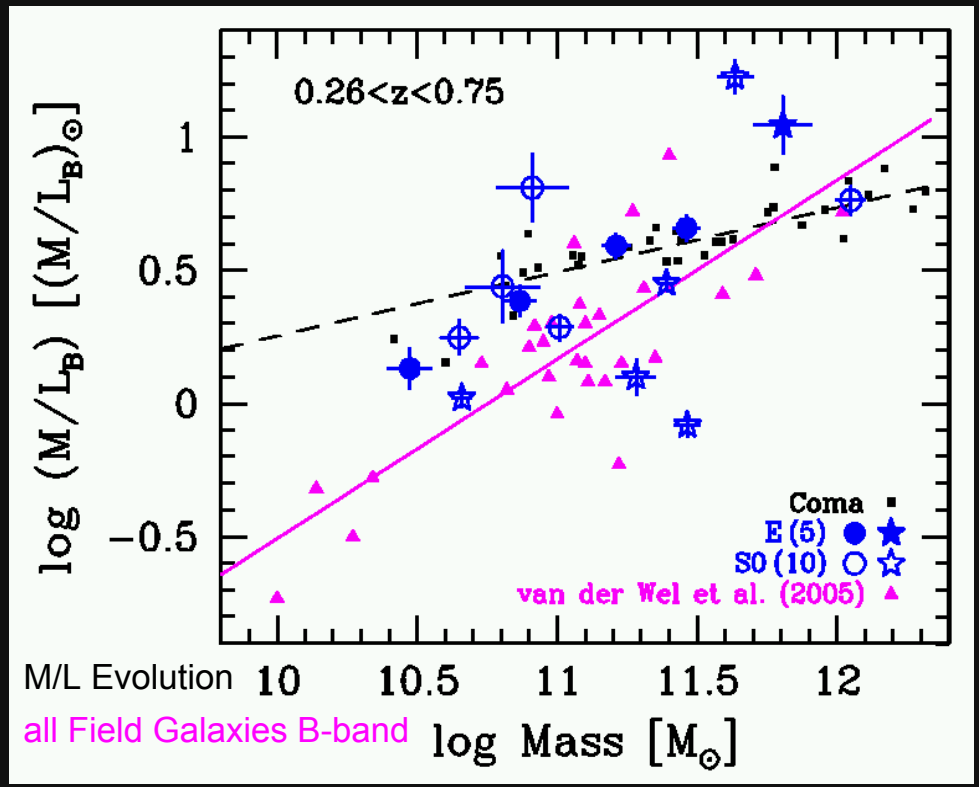
Continuous assembly of Field Galaxies since z~1

less-massive $M<2\times10^{11}\ M_{sun}$: $z_{form}=1.9\pm0.5 \Rightarrow$ 10.1 Gyr

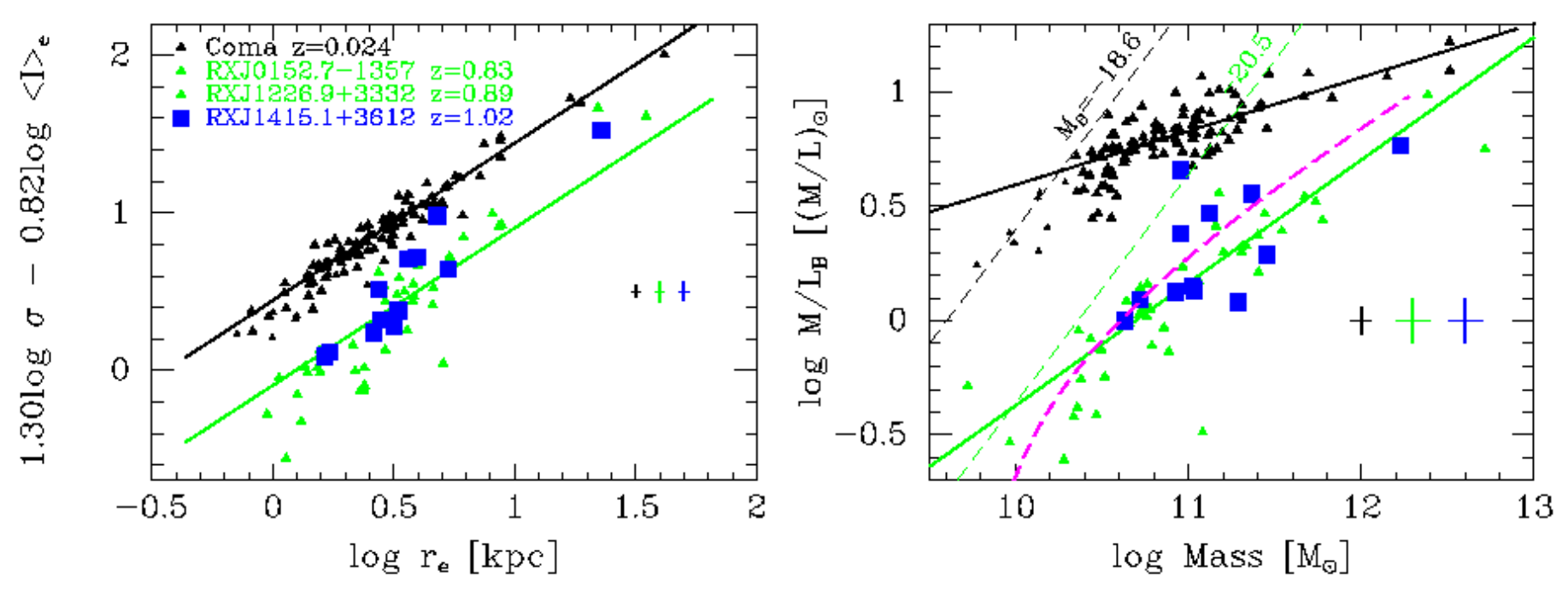
more-massive $M>2\times10^{11}\ M_{sun}$: $z_{form}=3.5\pm1.3 \Rightarrow$ 11.8 Gyr

Fritz et al. 2009a





Cluster E+S0 FP at z=1



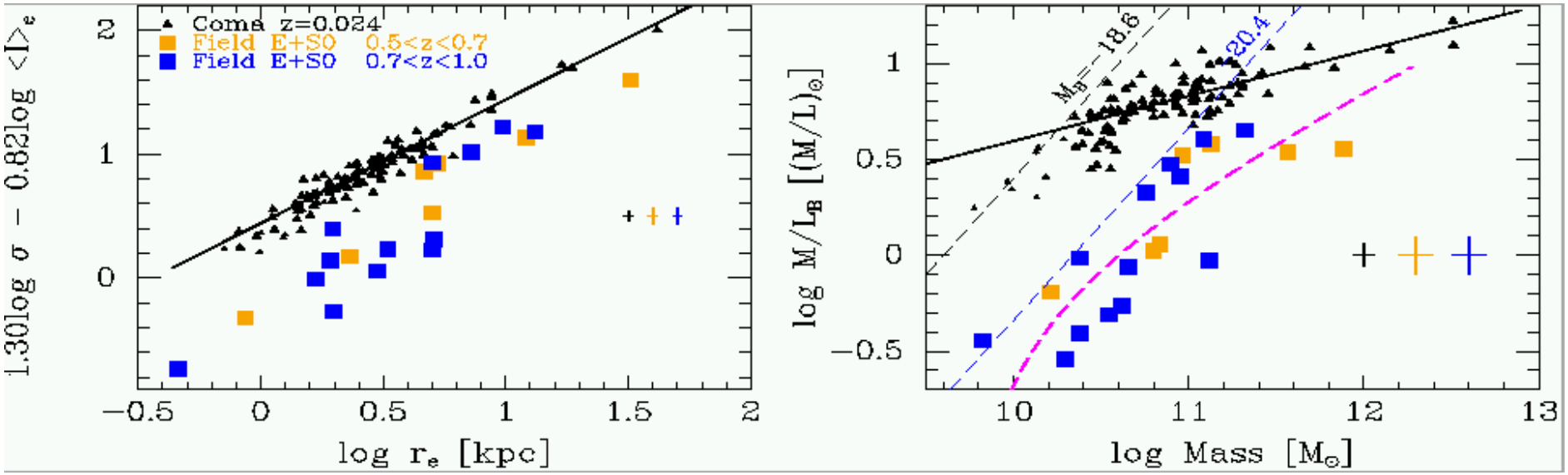
Fritz et al. 2009b

- First *detailed* Fundamental Plane of cluster E+S0 galaxies at z=1
- FP for z=0.8-1.0 has different slope than z=0 FP
- Mass-dependent evolution ⇒

  Lower-Mass M*~3 ×10^{10} M_{sun} : z_f ~ 1.1

  Higher-Mass M*>2 ×10^{11} M_{sun} : $z_f \geq 1.6$ ⇒ Down-sizing Cowie et al. 1996, Kodama et al. 2004

Field E+S0 FP at z=1



Fritz et al. 2010, 2011

- Study FP slope and scatter of field E+S0 galaxies at z=1
- FP at z=0.7-1.0 has different slope than FP at z=0
- Similar to Cluster E+S0 FP at z=1

Summary

- E+S0s at z<0.7:
  - Scaling Relations: *mild* Evolution in *all Environments*
  - Elliptical and S0 Galaxies are different
    ⇒ S0 faster Evolution and younger
  - Weak Environmental Dependence of the Evolution
    ⇒ Internal Galaxy Properties more important ⇒ SP Analysis
- E+S0s at 0.5<z<1.0:
  - First detailed FP at z=1
  - Distant FP has steeper slope
    Lower-Mass $M^* \sim 3 \times 10^{10} M_{sun}$: $z_f \sim 1.1$
    Higher-Mass $M^* > 2 \times 10^{11} M_{sun}$: $z_f \geq 1.6$
  - Mass-dependent Evolution since z=1
    ⇒ SF Efficiency mass-dependent ⇒ Down-sizing Theory