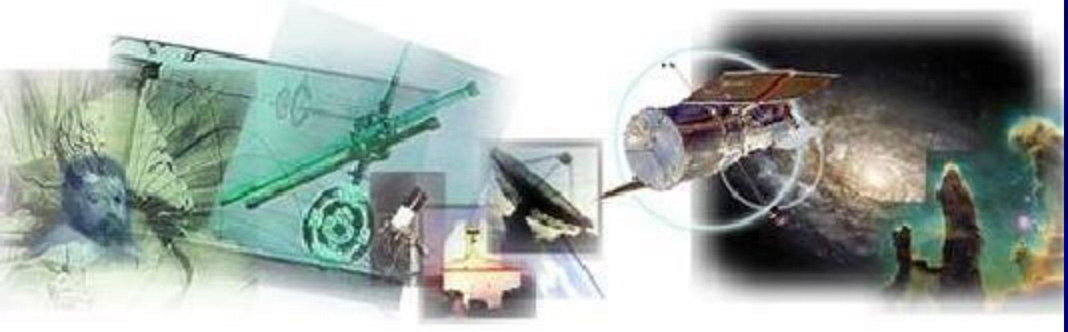
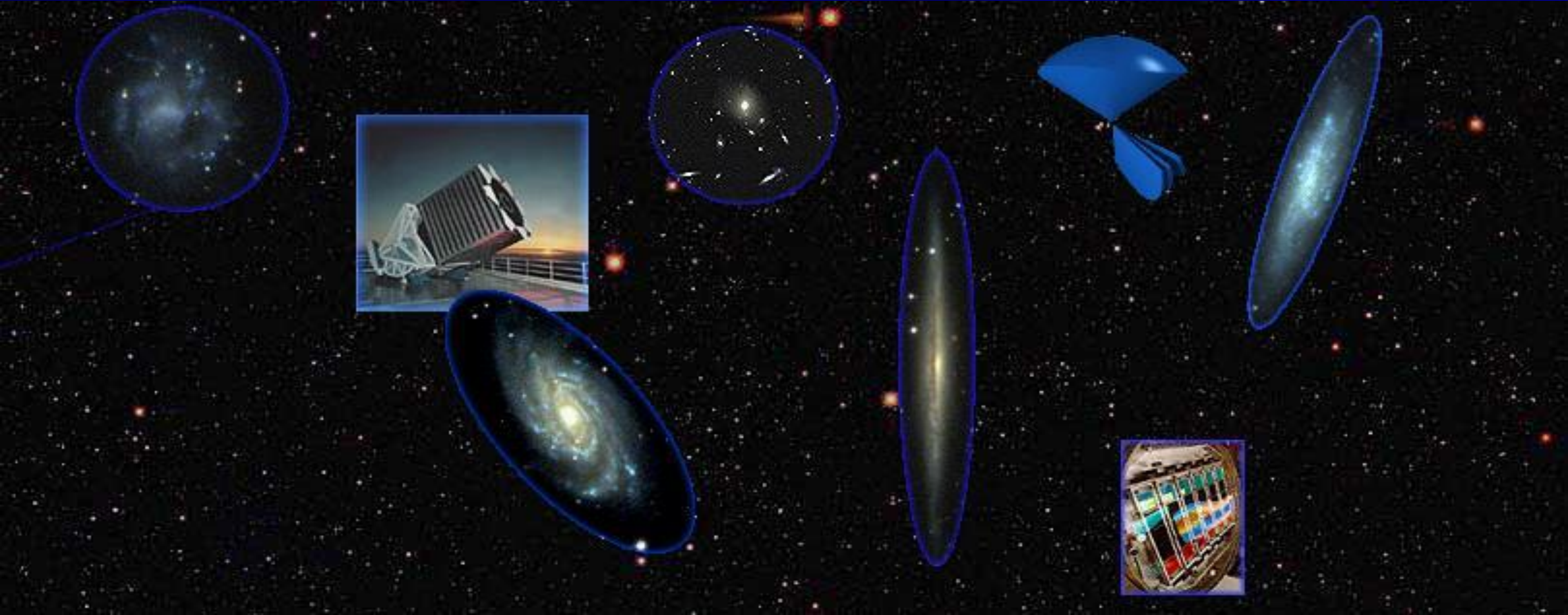


Massive galaxies in massive datasets

M. Bernardi (U. Penn)



OUTLINE

- Introduction
  - – Importance of Early-Type Galaxies
  - – Overview of recent results:
    - Quenching of SF, Merging (dry/wet + major/minor)
- Testing Dry mergers in SDSS

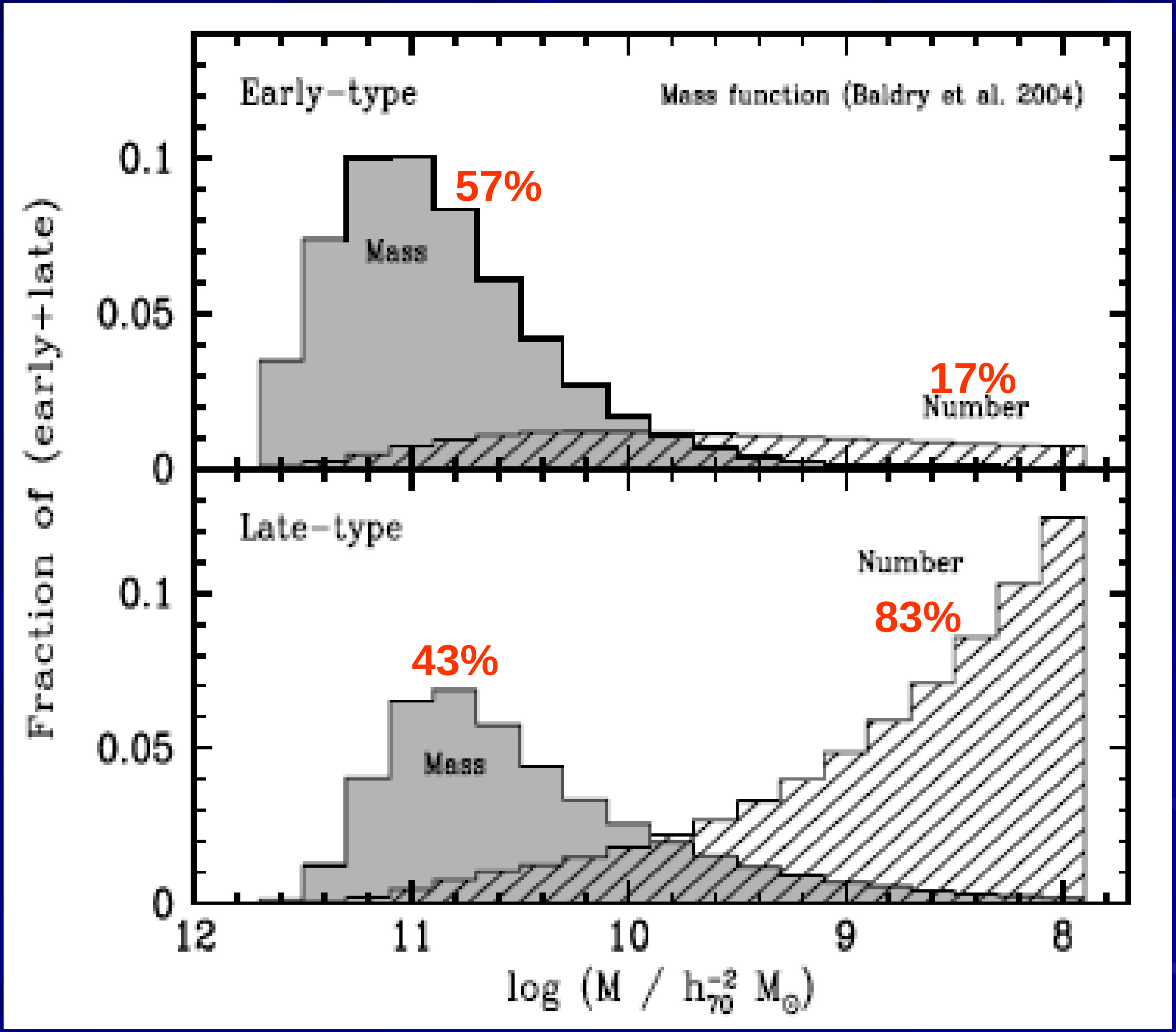
(Luminosities, Sizes, Velocity dispersions, Colors)

– Brightest Cluster Galaxies

– Full Early-type Sample

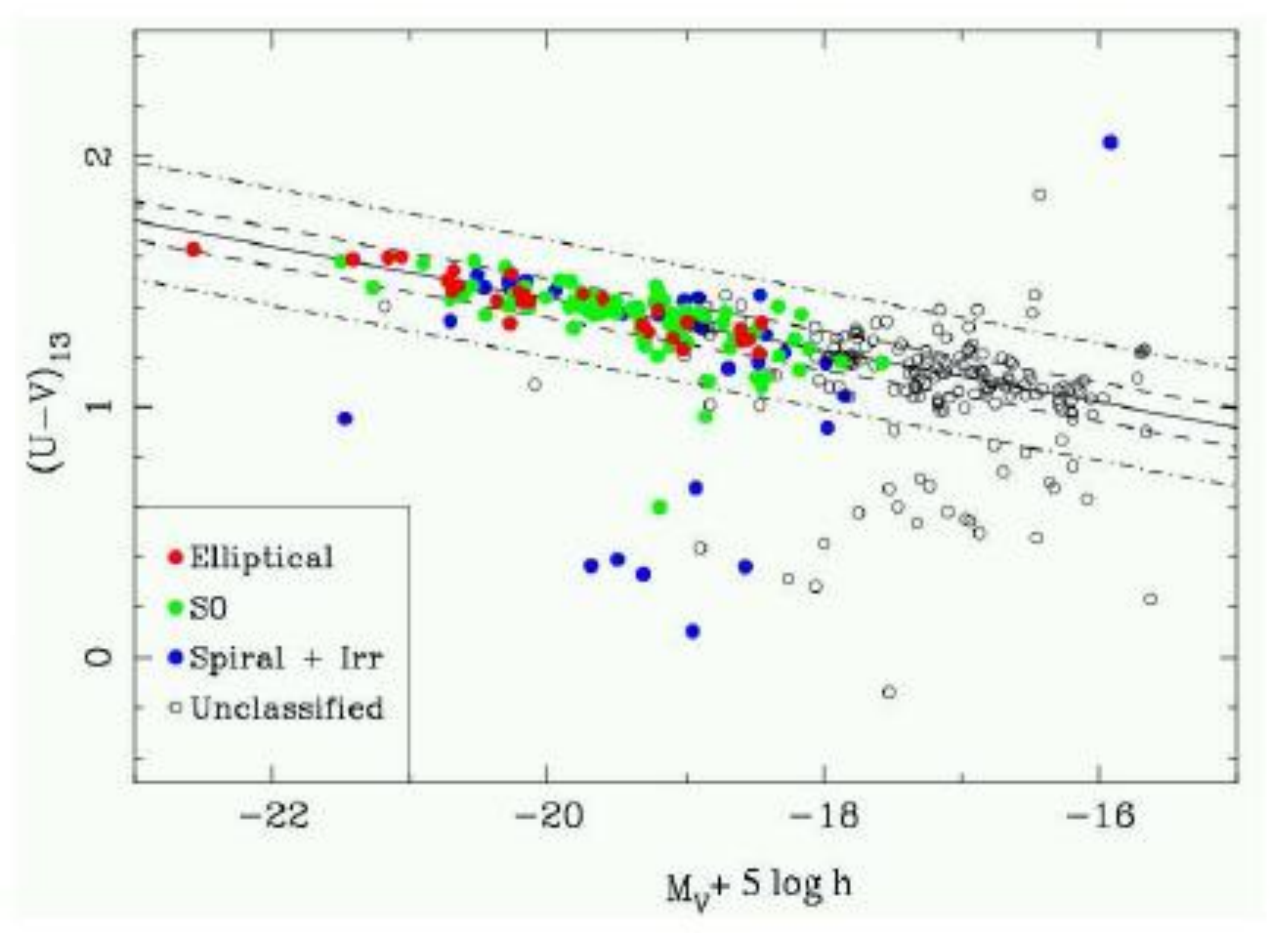
– High σ Galaxies

Early-types don’t dominate number, but they do dominate stellar mass



Renzini 2006

The most massive galaxies are red and dead



Red Color →

← Luminosity

e.g. Bower et al. 1992
Bernardi et al. 2003; 2005

In the hierarchical picture of galaxy formation

We need to find out when ….

- stars were formed
- the galaxy was assembled

- Old stellar population (OK for everybody!!)

- ?? When were galaxies assembled ??
  - Population of massive red galaxies seen even at z >> 0 (e.g. K20, VVDS, COMBO-17, DEEP, MUSYC, MUNIC, COSMOS, MIPSpitzer-24μm-undetected)
  - Still assembling at low z?

- In the hierarchical formation picture …..

(e.g. de Lucia et al. 2006, Bower et la. 2006, Hopkins et al. 2006, Cattaneo et al. 2010)

-- prevent formation of new stars (Quenching):
AGN feedback, Shock heating, dynamical friction
-- assemble the stellar mass:
Dry merging (most of the stellar mass put in place at z < 1
e.g. for $M_* > 10^{11}$ $M_\odot$ 80% of the stellar mass
is only put in place at z~0.3)

About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos -- the most massive halos (> 3 × 10^{13} $M_\odot$) have grown by a factor 2-3 since z ~ 1 (e.g. Sheth & Tormen 1999)
- Are massive red galaxies merging from z~1 to z~0?

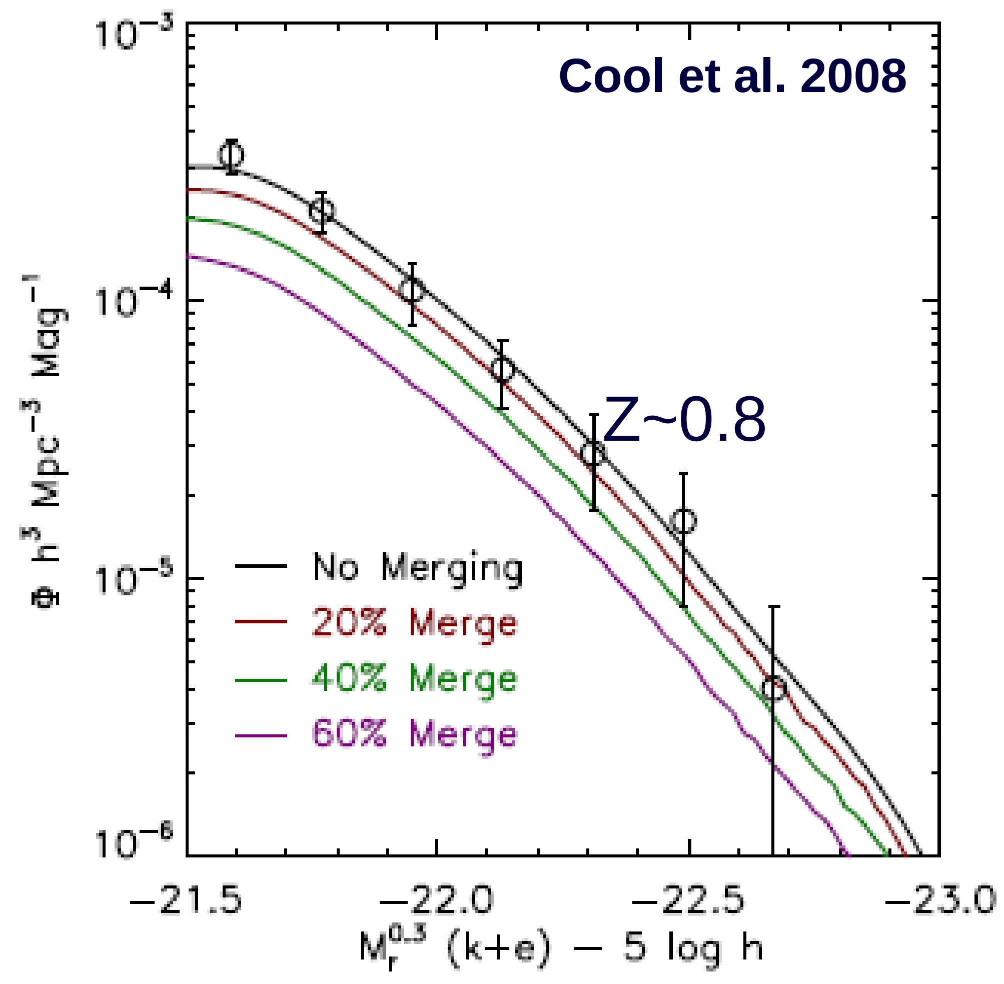
About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos -- the most massive halos (> 3 × 10^{13} $M_\odot$) have grown by a factor 2-3 since z ~ 1 (e.g. Sheth & Tormen 1999)
- Are massive red galaxies merging from z~1 to z~0?
  - Some work says that the total stellar mass must not have grown by more than 30% out to z~0.8 (e.g. Wake et al. 2006; Brown et al. 2007; Cool et al. 2008)

Little evolution in the Luminosity Function

(e.g. Wake et al. 2006; Brown et al. 2007; Cool et al. 2008)

Model where a galaxy has doubled its luminosity through 1:1 mergers between z ~ 0.8 and z ~ 0.1



Using 1:1 mergers
Merger rates > 25% are ruled out with 50% confidence

Using 1:3 mergers
Merger rates up to 40% are allowed at 50% confidence

The total stellar mass in massive red galaxies from z~0.9 must not have grown by more than 50%

(Brown et al. 2007 -> 80% of M_* in $4L_*$ galaxies was already in place at z~0.7

Wake et al. 2006 -> 50% of M_* in LRGs already assembled by z~0.6)

In contrast L* galaxies have increased their stellar mass by a factor of ~2

About the assembling of massive galaxies ….

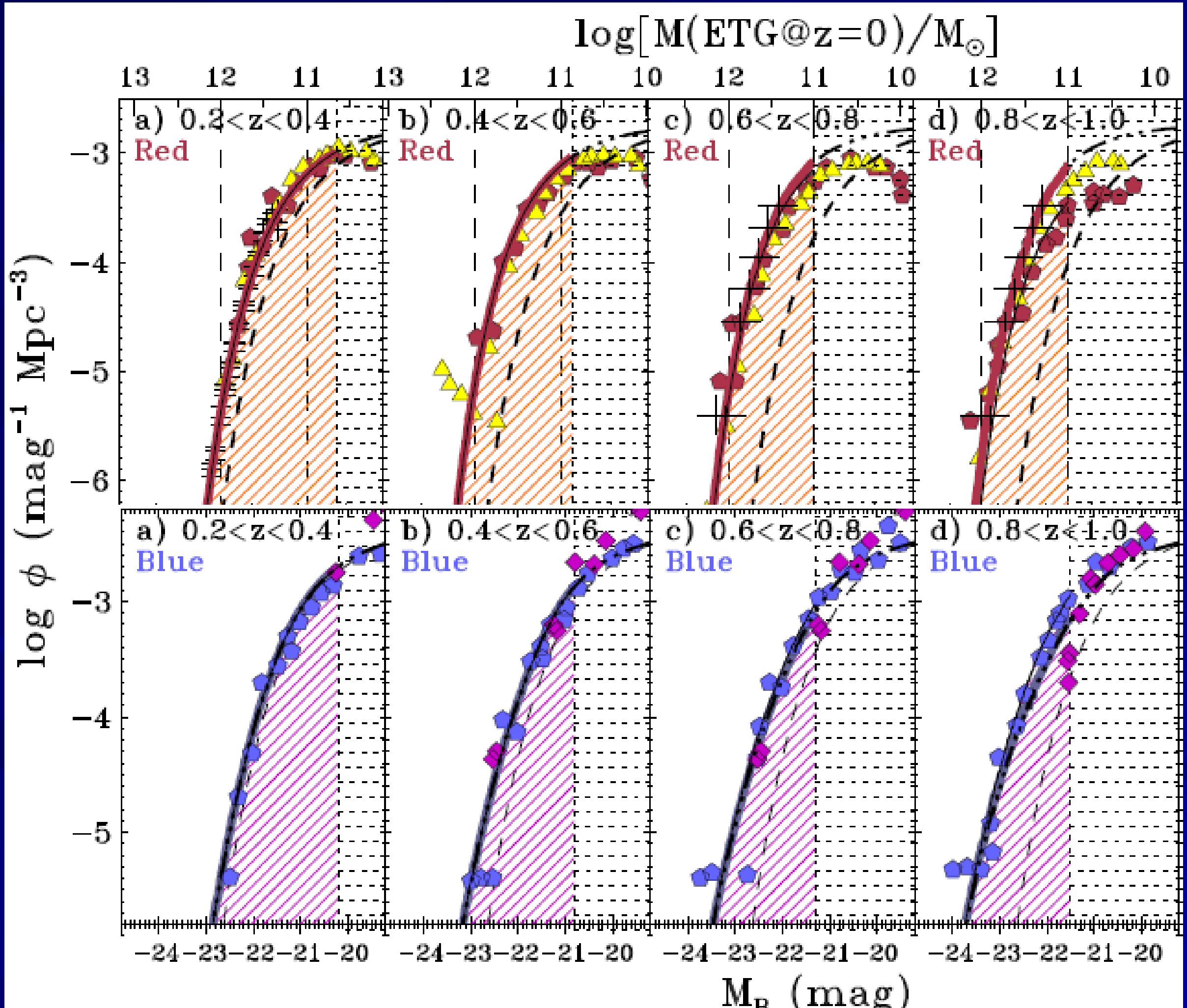
- From ΛCDM -> merging of halos -- the most massive halos (> 3 × 10^{13} $M_\odot$) have grown by a factor 2-3 since z ~ 1 (e.g. Sheth & Tormen 1999)
- Are massive red galaxies merging from z~1 to z~0?
  - Some work says that the total stellar mass must not have grown by more than 30% out to z~0.8 (e.g. Wake et al. 2006; Brown et al. 2007; Cool et al. 2008)
  - Others see an increase in the # density of very massive galaxies between z~1 and z~0.8

    (accounting for Dust Star Forming galaxies)

The discrepancy in the number evolution reported by different studies for bright, red galaxies up to z ~1 could be due to the inclusion of a significant amount of DustySFs into the red galaxy sample

▲ Bell et al. 2004
\+ Cool et al. 2008
⬟ Faber et al. 2007

The bulk of the more recent mETG assembly occurs over ~ 1Gyr around 0.8<z< 1

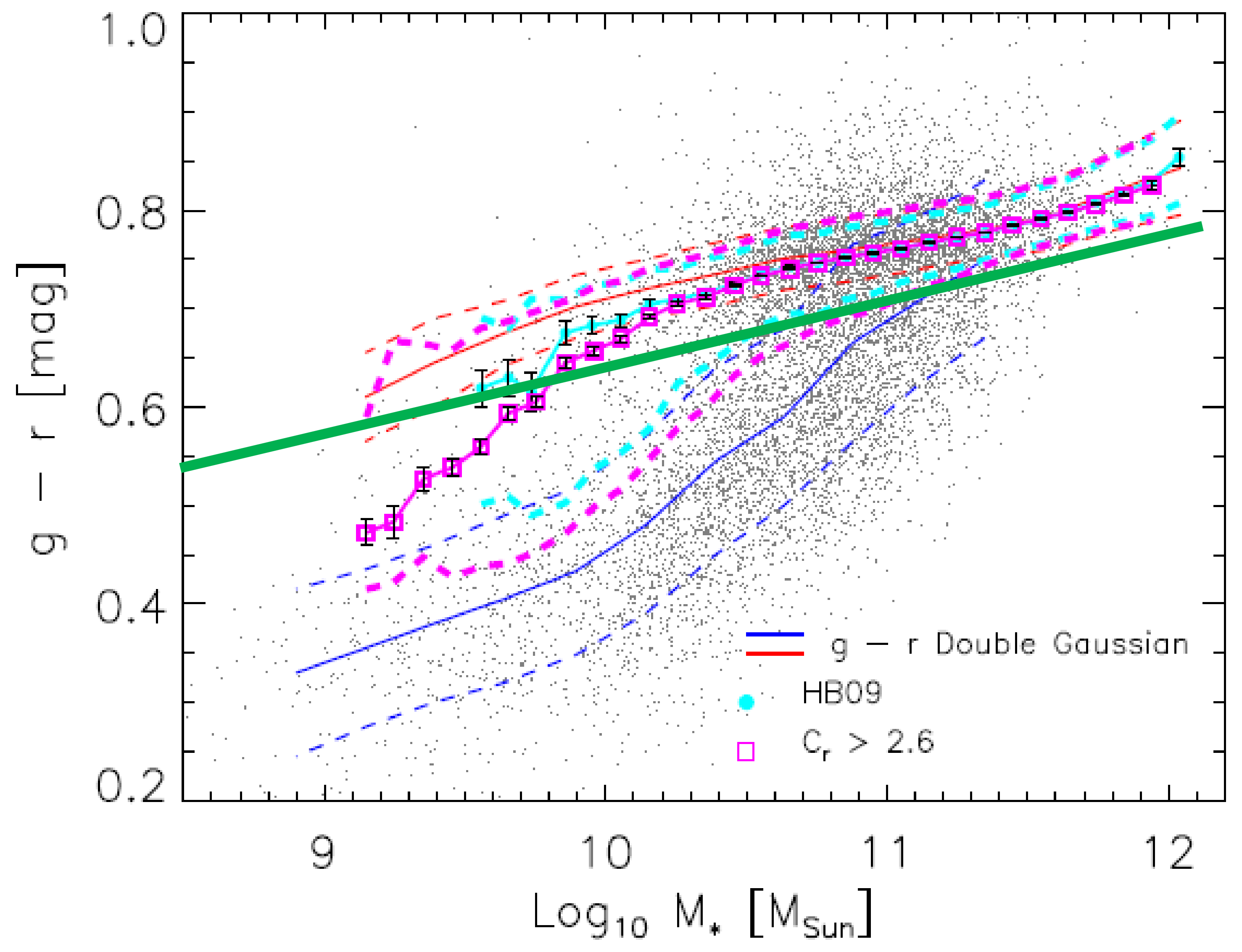


Eliche-Moral et al. 2010a

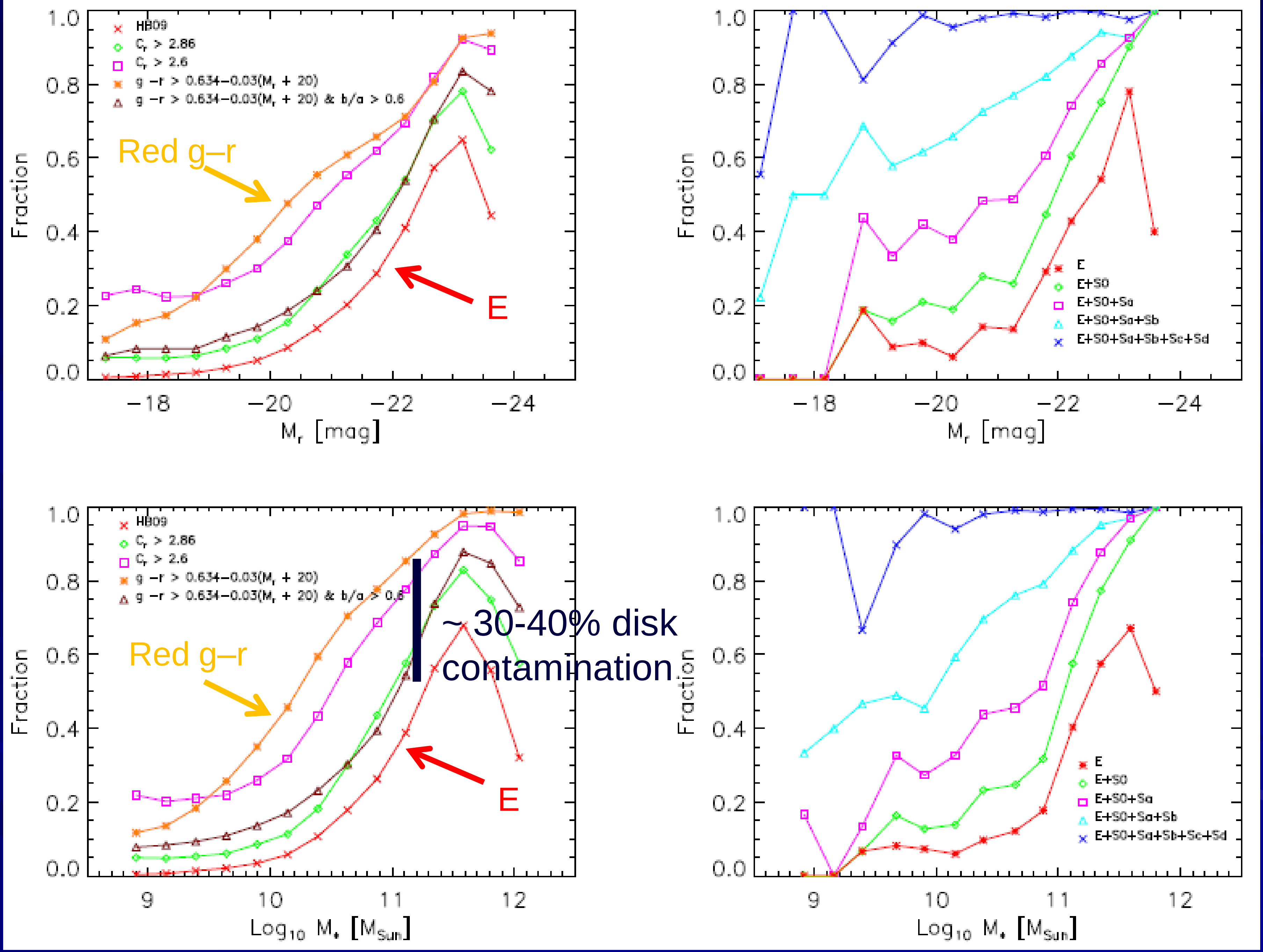
Decrease ~ 30-*40% of # density of blue galaxies since z~1 to z~0, just considering the transformation of disks into ETGs driven by the major mergers at z~1*

⬟ Faber et al. 2007
◇ Ilbert et al. 2006

Red Fraction or Early-type Fraction?



Bernardi et al. 2010



Red g–r

E

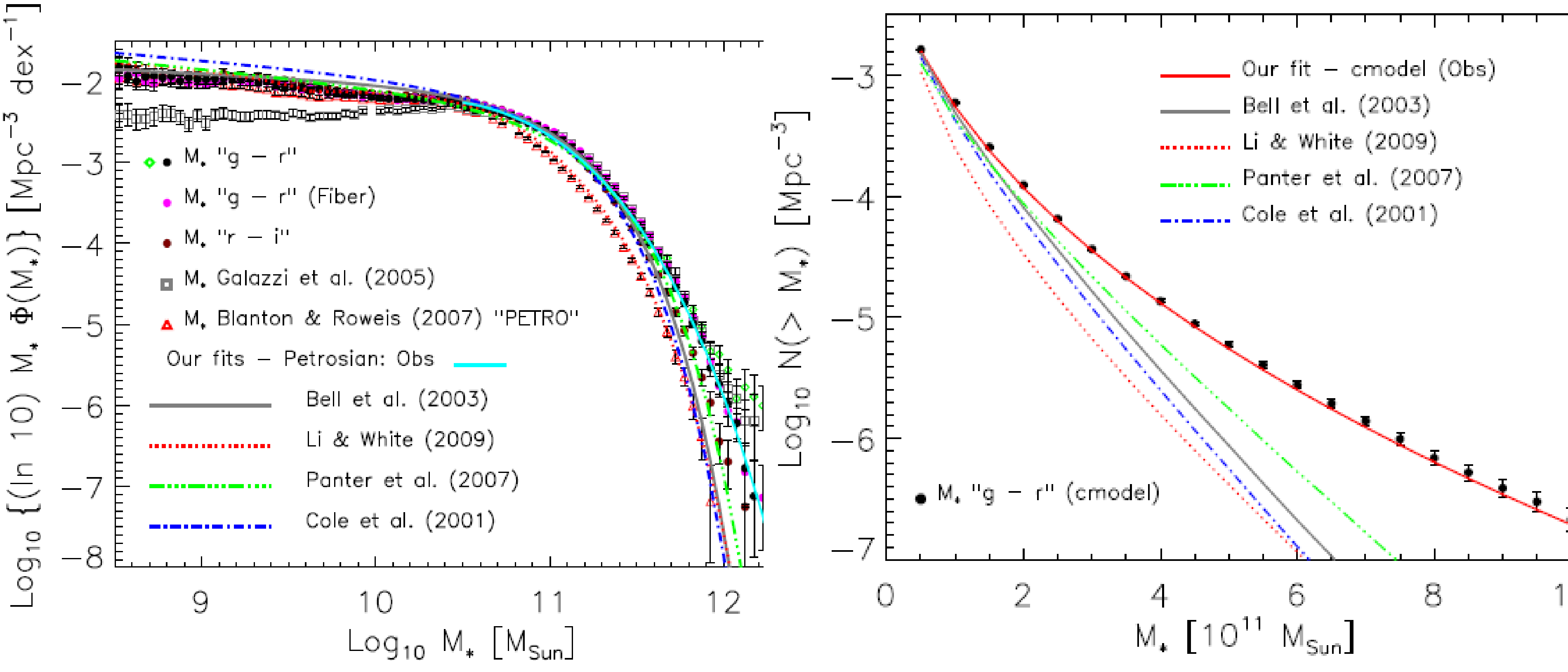
Red g–r

E

~ 30-40% disk contamination

Bernardi et al. 2010

Uncertainties in the local M_*F



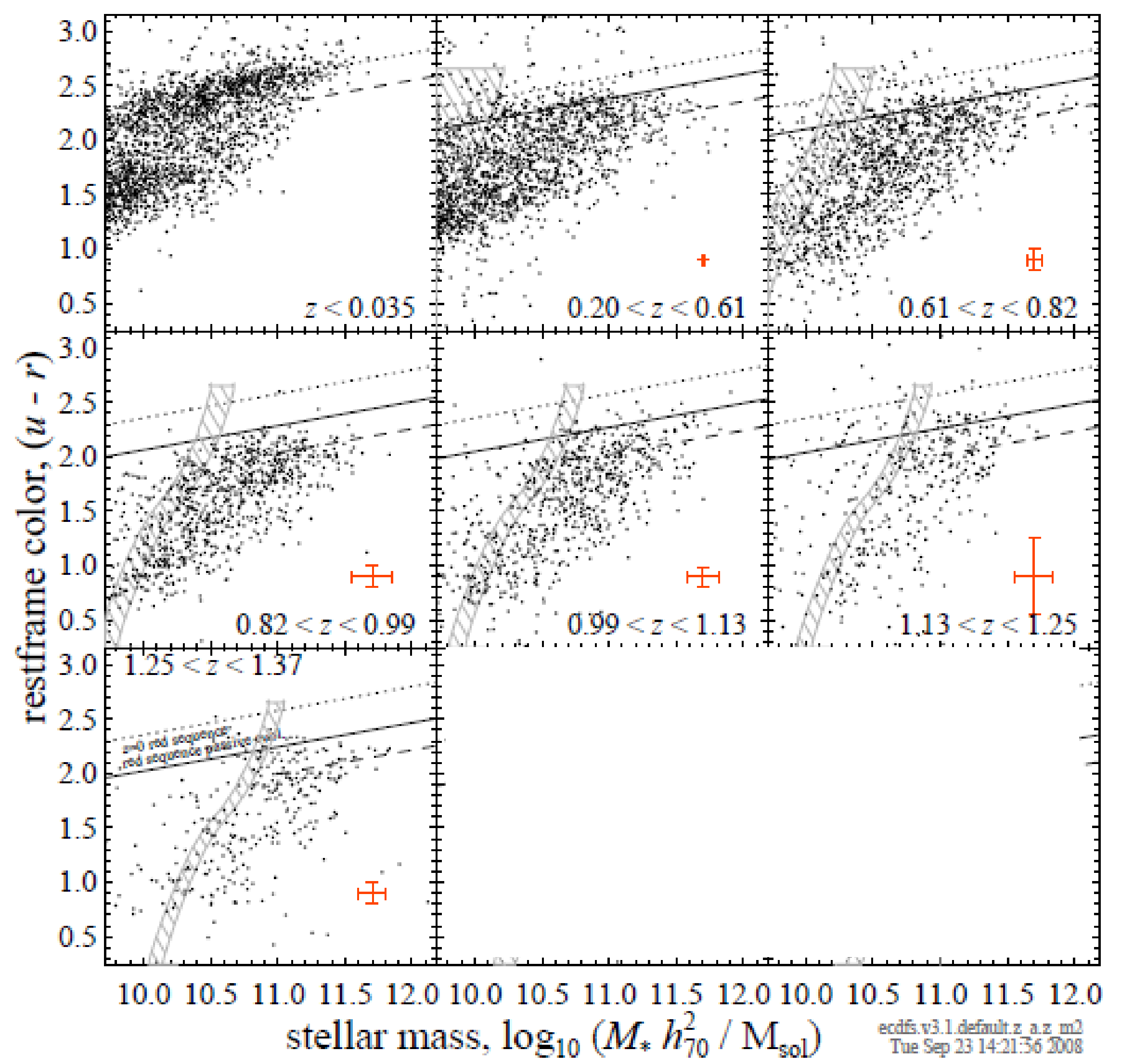
Bernardi et al. 2010

About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos
- Merging of massive red galaxies from z~1 is still debated
  - In contrast, L* galaxies have increased their stellar mass by a factor of ~2-4
- Quenching of star formation important – are red massive galaxies formed only by quenching and passive evolution or do we need merging (wet or dry / major or minor)?

Quenching of star formation important

The truncation of star formation in blue galaxies and subsequent passive fading of stellar population can explain the growth of L* galaxies in the red-sequence since z ~ 1



The lack of very massive blue galaxies at z~1

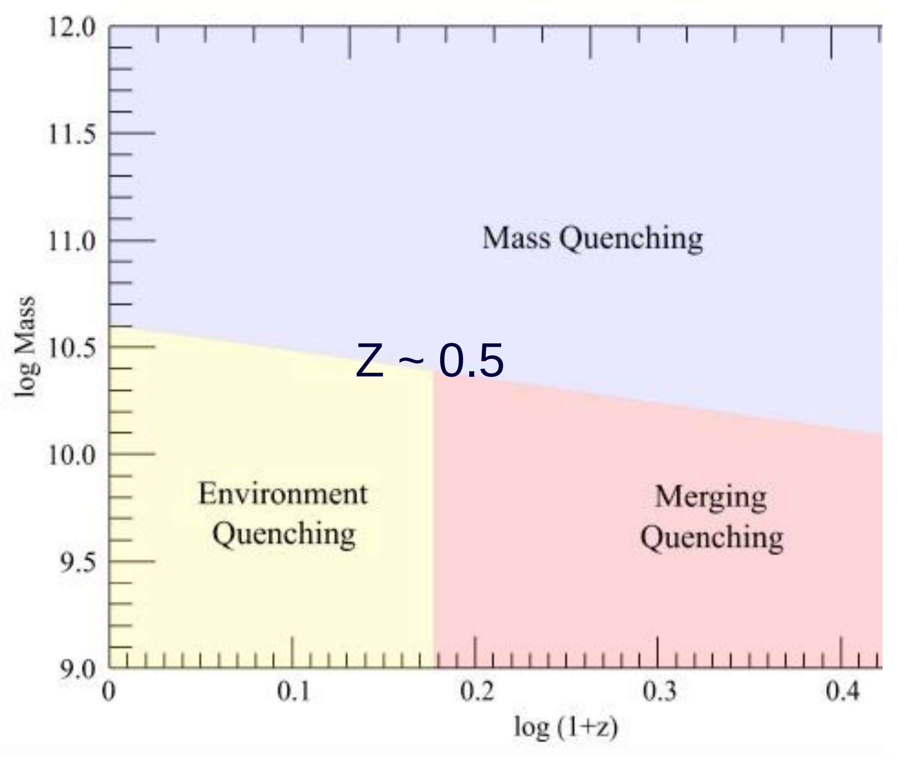
⇓

Most massive galaxies must be fueled by merges of less luminous red-galaxies

Taylor et al. 2008

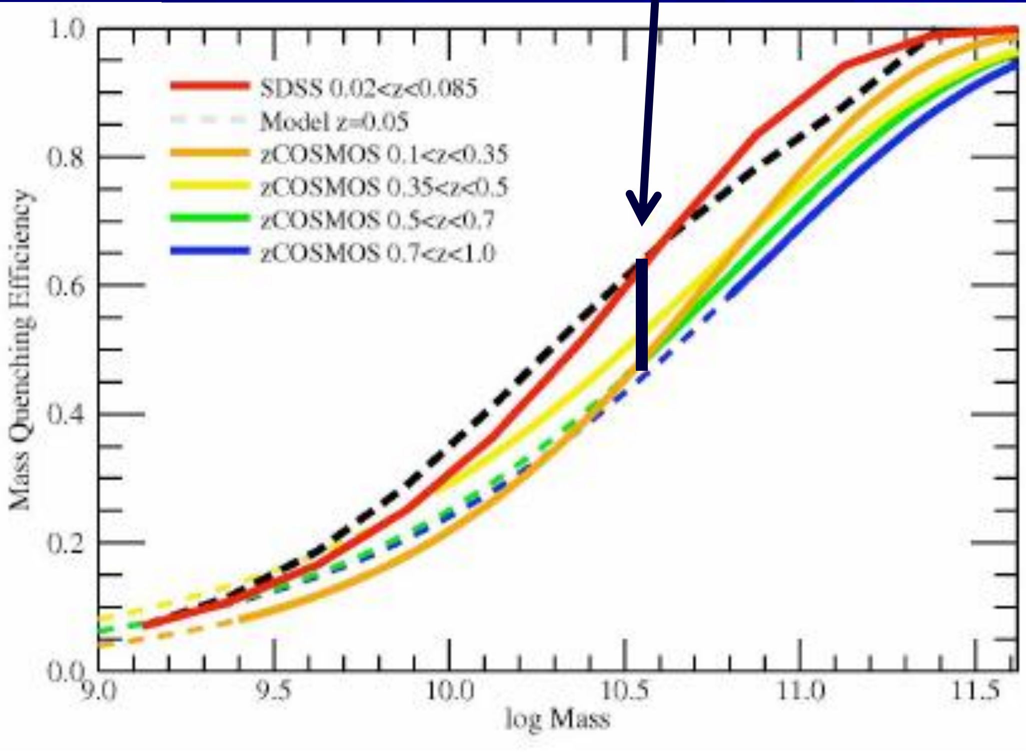
Three processes of quenching dominate the evolution of galaxies "mass-quenching" + "environment-quenching" + some additional "merging-quenching"

(SDSS + zCOSMOS)



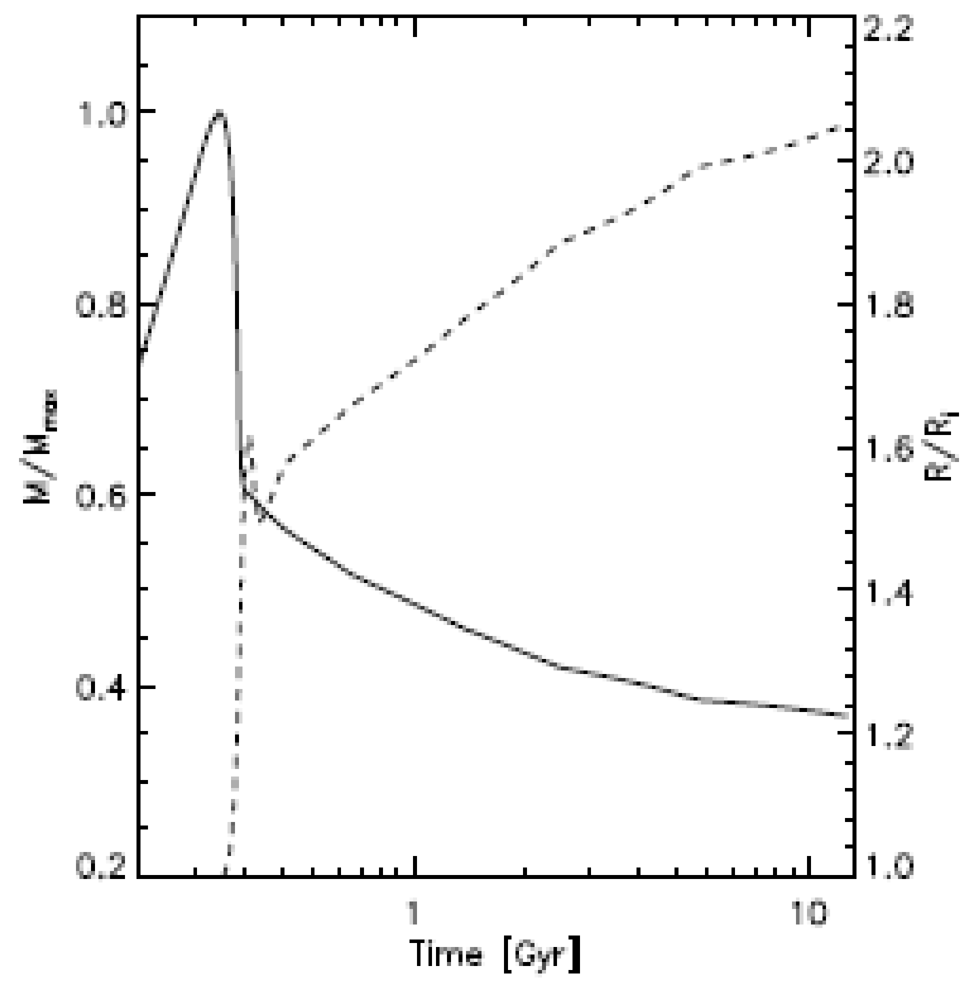
Z ~ 0.5

Mass quenching is more efficient at low z



Peng et al. 2010

The evolution in Re at fixed mass between z ~ 1 and the present is a factor of 1.97 ± 0.15



The size expansion achieved after the epoch in which stellar populations are older than ~ 0.5 − 1 Gyr is 25% - 20%

This needs merging
not only quenching
with
“dry” not “wet” merging
Major or Minor?

OR

A puffing up related to large scale galactic winds (e.g. Fan et al. 2008; Ragone & Granato 2011)

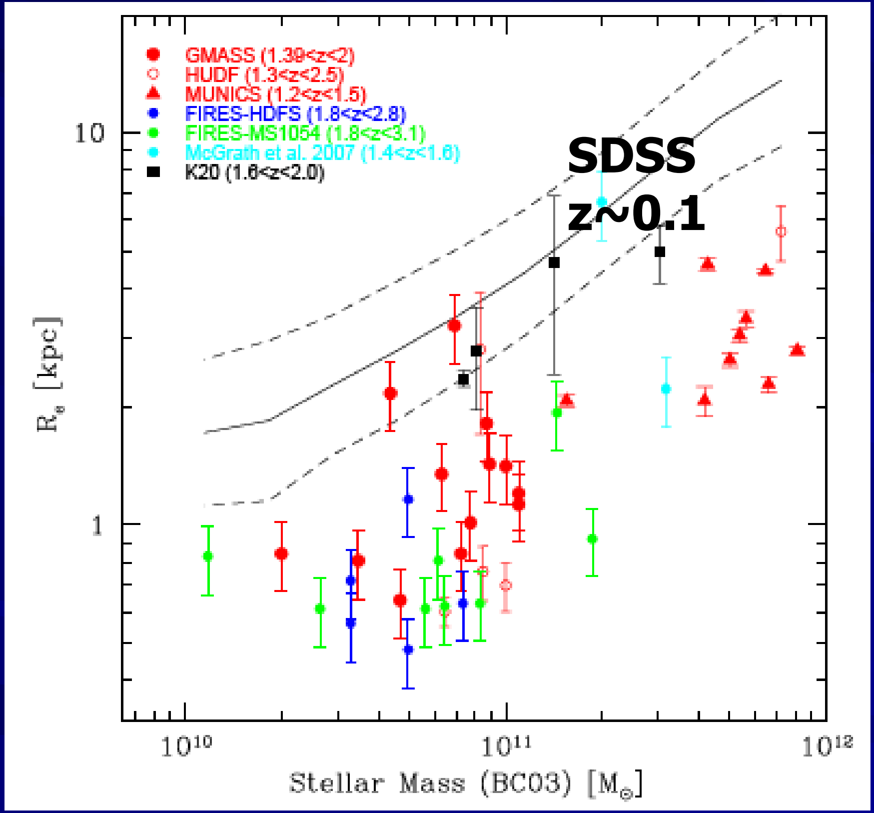
About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos
- Merging of massive red galaxies from z~1 is still debated
  - Differently L* galaxies have increased their stellar mass by a factor of ~2-4
- Quenching of star formation important + merging (wet / dry)?
- The size evolution of massive and passive galaxies is still debated

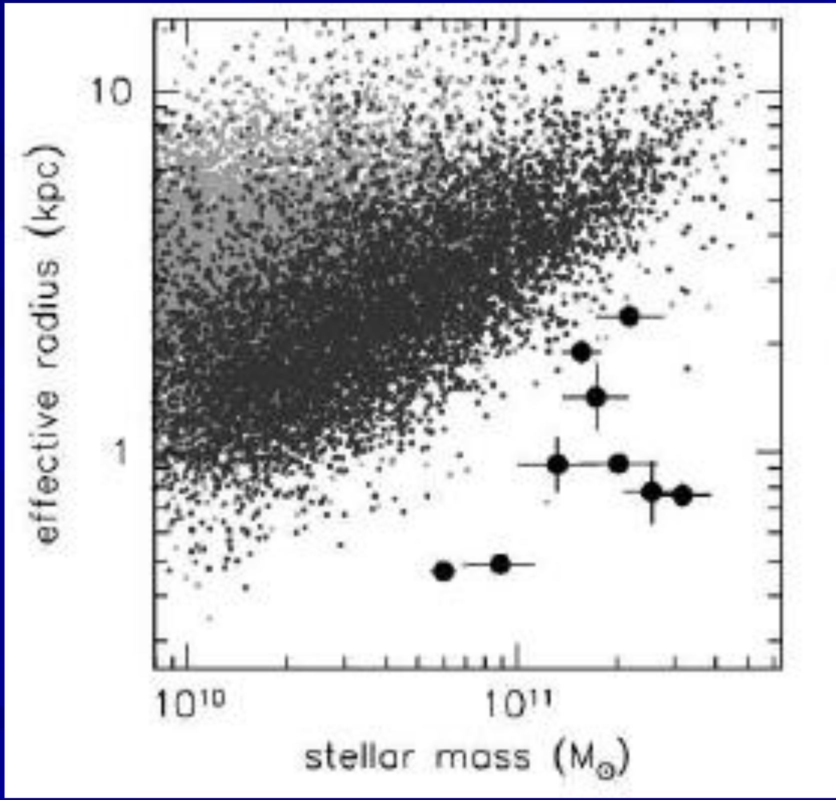
At fixed stellar mass, high-z sizes are smaller by $(1+z)^{-1}$ or more (e.g. Trujillo et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008; Saglia et al. 2011)

Z ~ 1.8

Z ~ 2.3

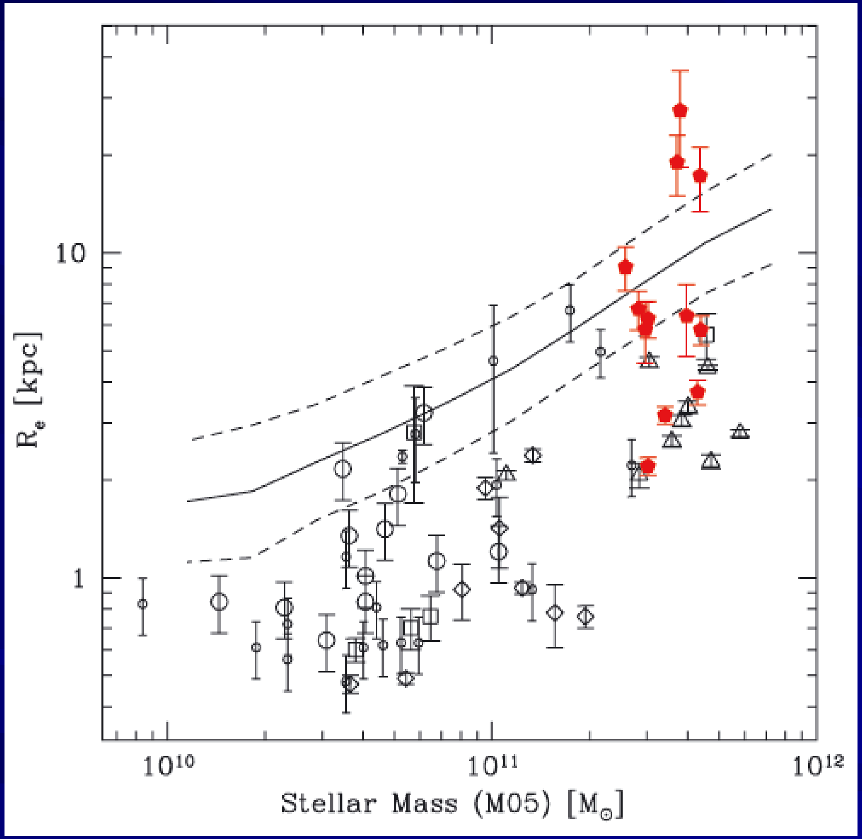


Cimatti et al. 2008



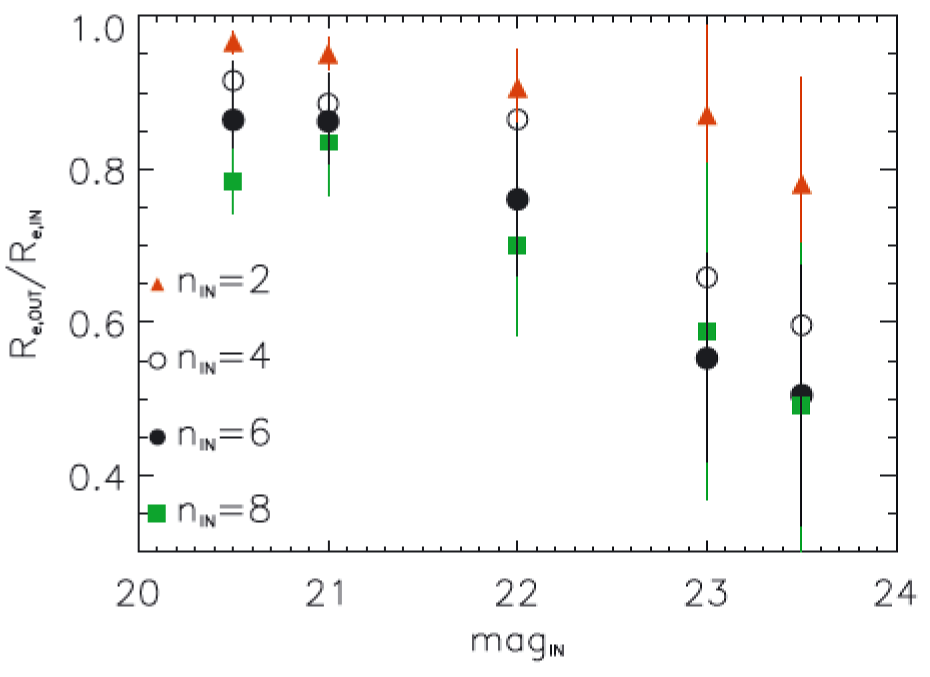
5 kpc @ z~0 → 0.9 kpc @ z~2.3
van Dokkum et al. 2008

However …



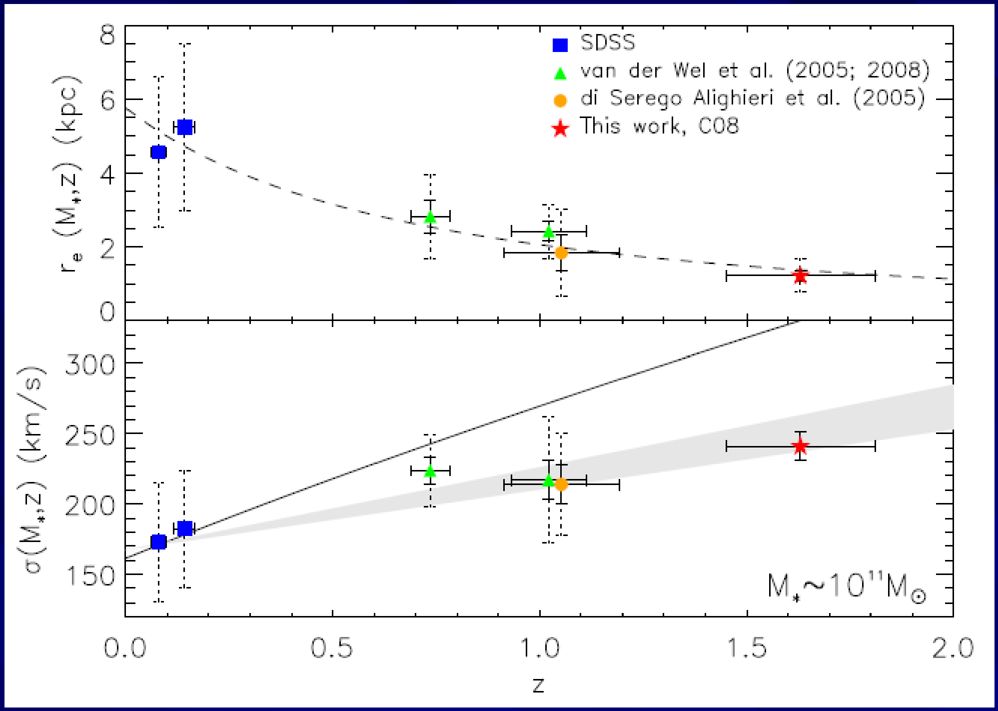
Mancini et al. 2010

Measurements could be biased



Another e.g. Stott et al. 2011

“The scale sizes of BCGs at $z = 1$ are $\simeq$ 30% smaller than at $z = 0.25$”



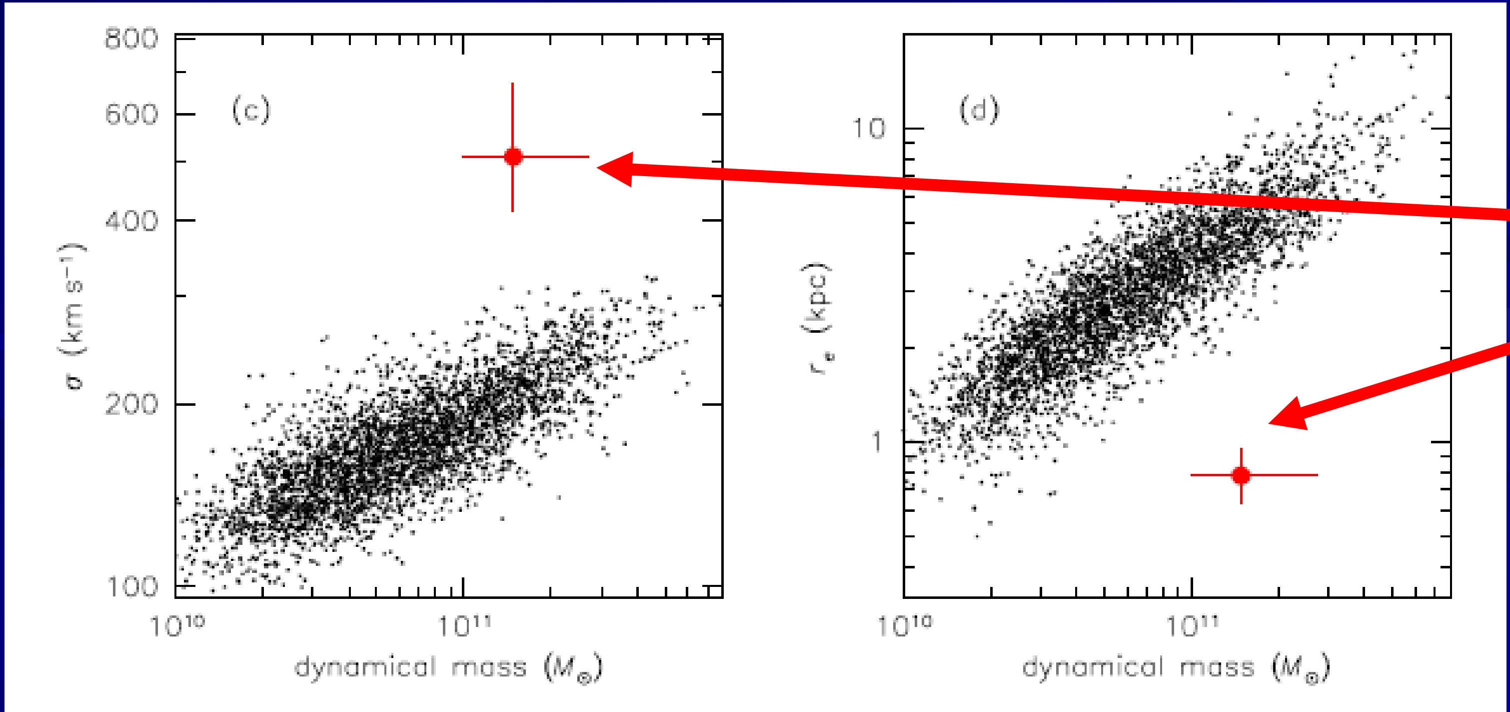
$M \sim R \; x \; \sigma^{2}$

Cenarro & Trujillo 2009

At z~2:
R_e ~ factor 6 smaller
σ ~ factor 1.5 larger

z = 2.186
$\sigma = 510^{+165}_{-95}$ km s^{-1}

Van Dokkum et al. 2009



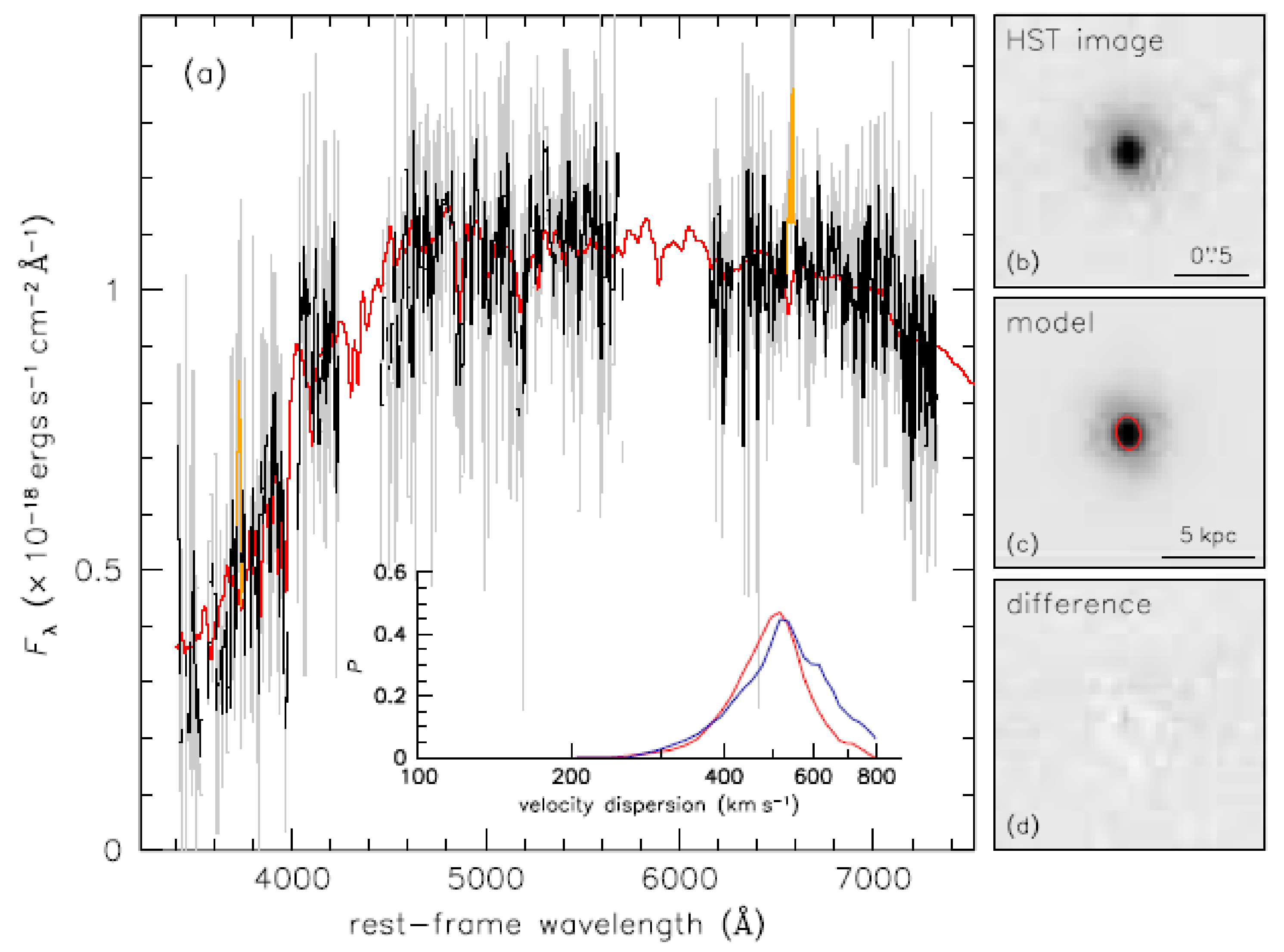
σ ~ factor 2.5

R_e ~ factor 6

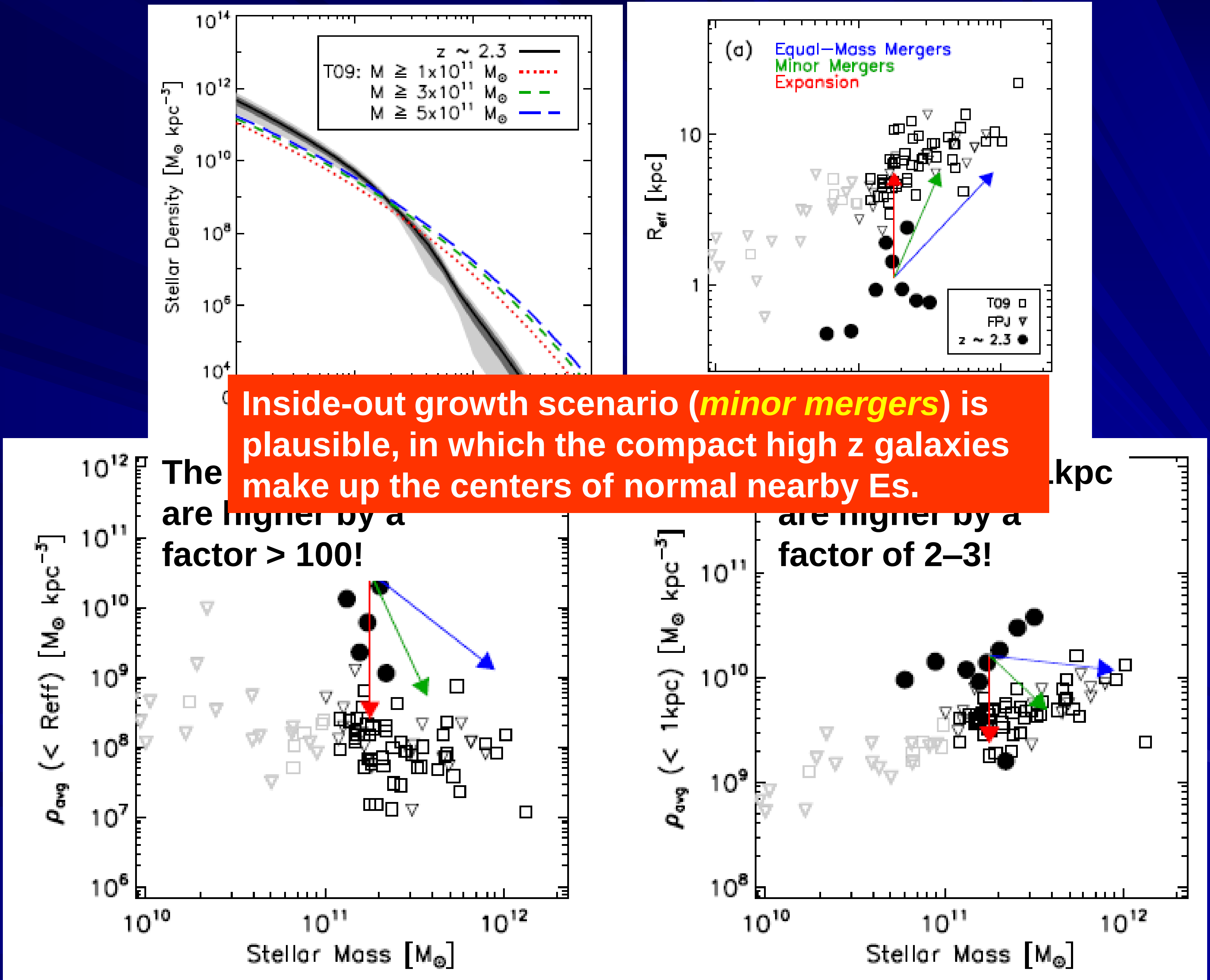
Gemini spectrum and HST images of 1255–0 at z = 2.186

29 hours integration for a S/N ~ 5-8!

Cost of $200k!!



Bezanson et al. 2009



Inside-out growth scenario (*minor mergers*) is plausible, in which the compact high z galaxies make up the centers of normal nearby Es.

The

are higher by a

factor > 100!

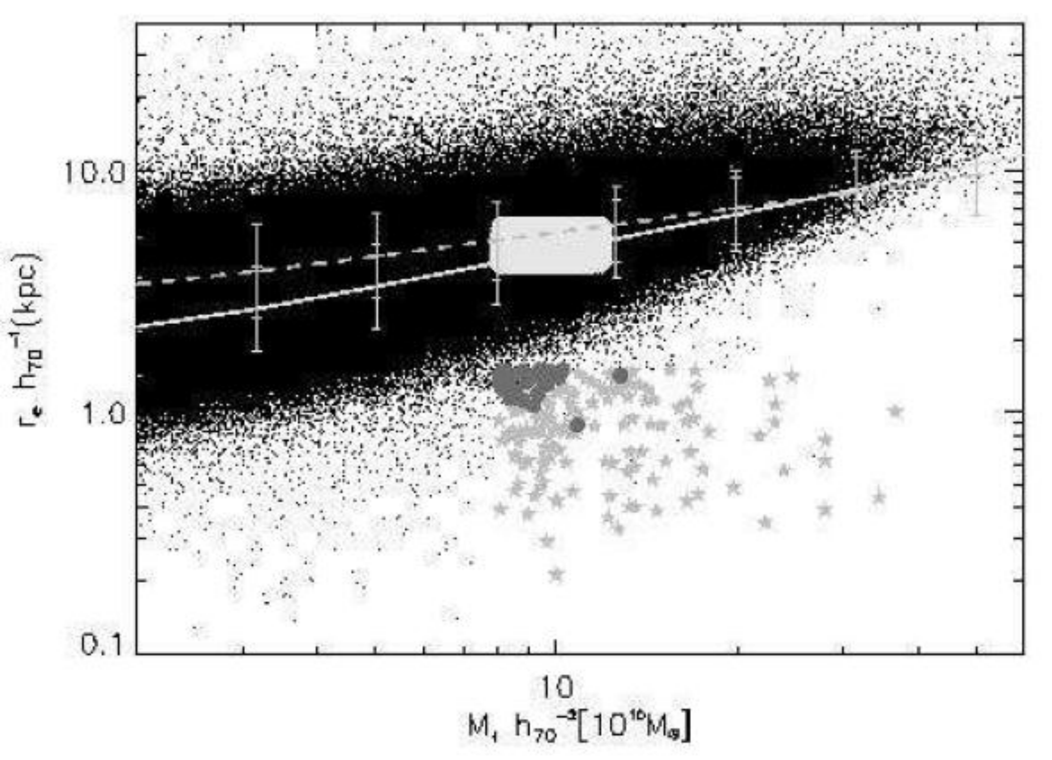
kpc

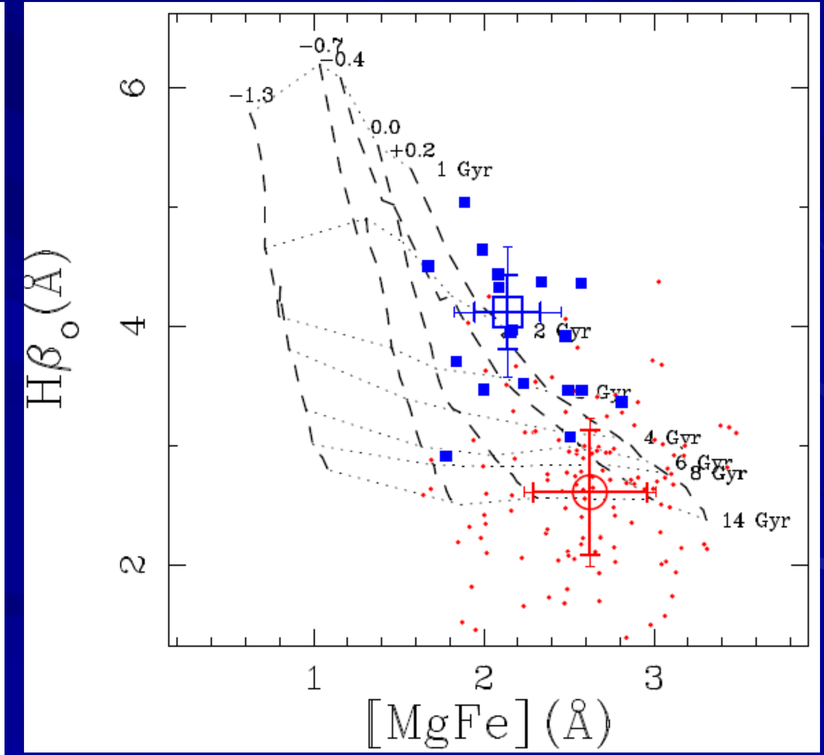
are higher by a

factor of 2–3!

- Models with major mergers predict that the fraction of superdense massive galaxies which survived intact since their formation at z > 2 to be 1-10%
- Observations find no old massive compact galaxies at z~0

Role of minor mergers and small accretion can be very relevant

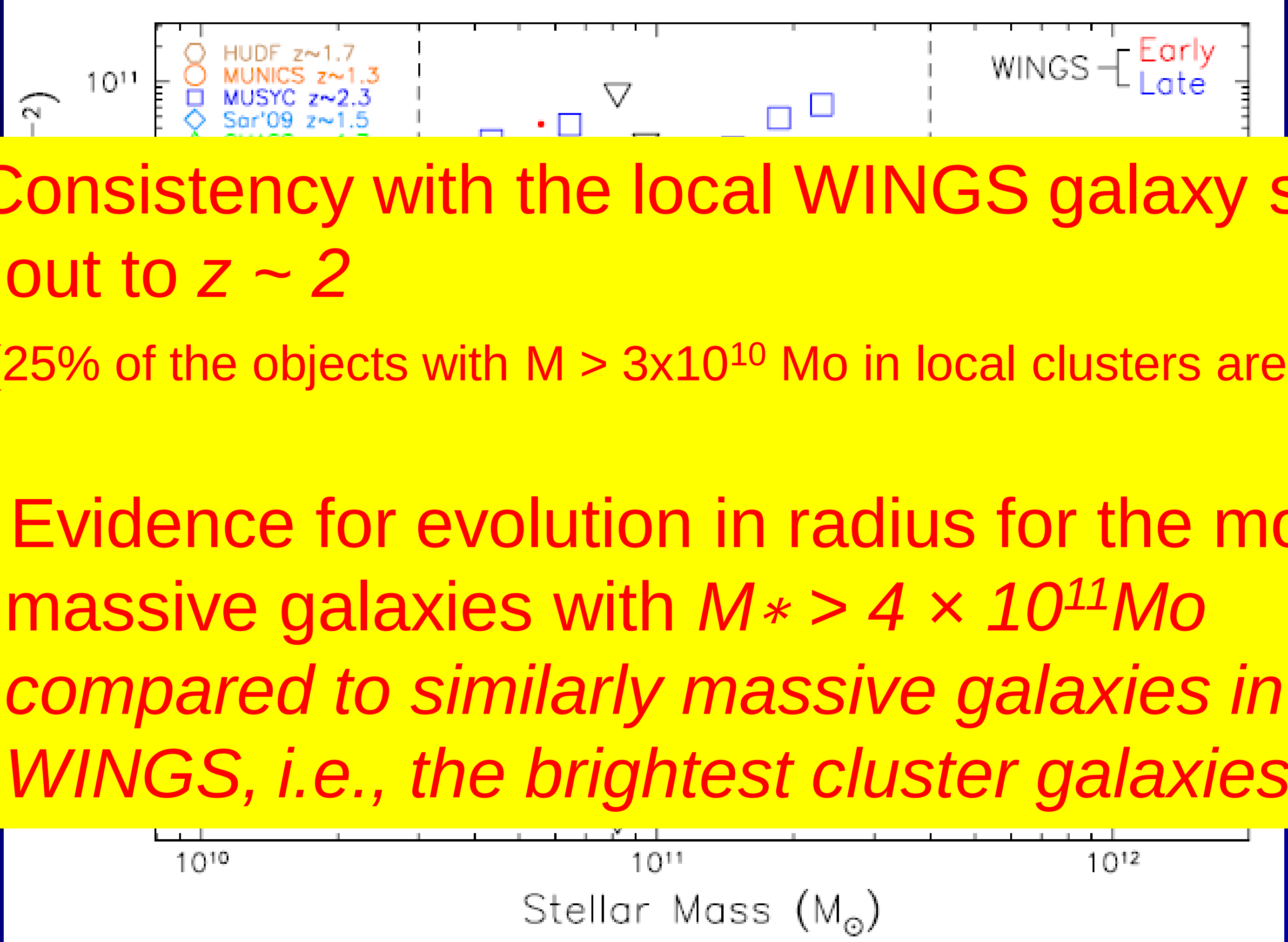




Trujillo et al. 2009

However ….

Superdense Galaxies in WINGS



- Consistency with the local WINGS galaxy sizes out to *z* ~ 2

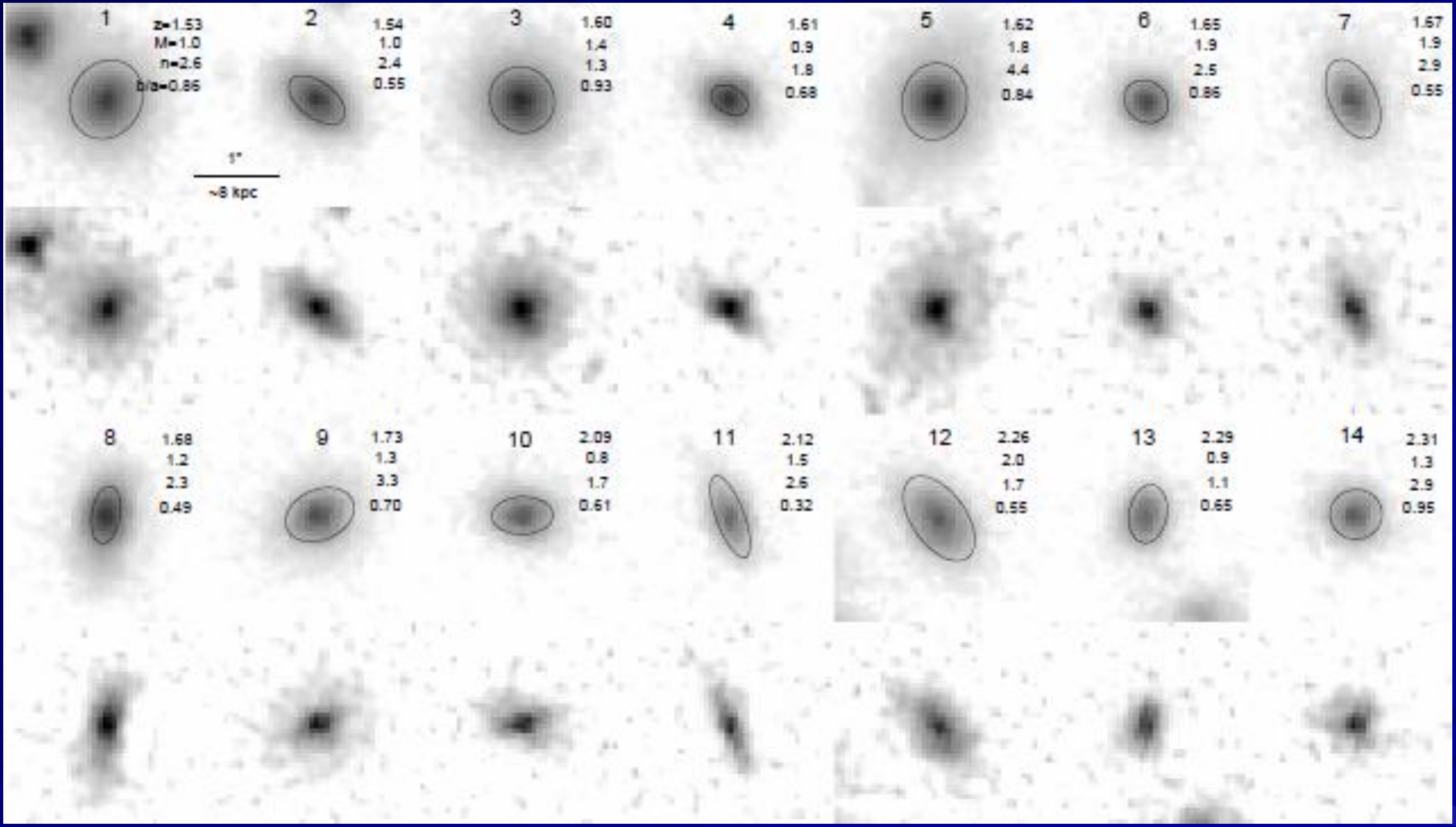
(25% of the objects with M > 3x10^{10} Mo in local clusters are SDG)

- Evidence for evolution in radius for the most massive galaxies with *$M_* > 4 \times 10^{11}$Mo compared to similarly massive galaxies in WINGS, i.e., the brightest cluster galaxies*

Valentinuzzi et al. 2009

65%±15% of the population of massive, quiescent z ~ 2 galaxies are disk-dominated

van der Wel et al. 2011



“The much-discussed ultra-dense high-redshift galaxies should generally be thought of as disk-like stellar systems with the majority of stars formed from gas that had time to settle into a disk”

About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos
- Merging of massive red galaxies from z~1 is still debated
  - Differently L* galaxies have increased their stellar mass by a factor of ~2-4
- Quenching of star formation important + merging (wet / dry)?
- The size evolution of massive and passive galaxies is still debated
- Major vs Minor Dry mergers

Dry mergers: Major & Minor

- $E_i = E_f$
- $E_i = E_{virial} + \cancel{E_{orbit}} = KE_{virial} + W_{virial}$

  $= m_1\sigma_1^2/2 + m_2\sigma_2^2/2 – G\ m_1^2/r_1 – G\ m_2^2/r_2$
- $E_f = (m_1+m_2)\sigma_f^2/2 – G\ (m_1+m_2)^2/r_f$

- **Major merger**: $m_1 = m_2 = m_i$ and $m_f=2m_i$

  $\sigma_i^2 – G\ (2\ m_i)/r_i = \sigma_f^2 – G\ m_f/(r_f/2)$

  ➔ double mass, double size, no change in σ

- **Minor merger**: $m_f = (1+f)\ m_i$

From Virial Theorem (2KE = -W) $m \sim r\ \sigma^2$

$r_f\ \sigma_f^2 = (1+f)\ r_i\ \sigma_i^2 = (1+f)^2\ r_i\ \sigma_i^2\ /\ (1+f)$

when $f << 1$ $m_f = (1+f)\ m_i \sim (1+2f)\ r_i\ \sigma_i^2\ (1-f)$

➔ larger change in size than mass and decrease in σ

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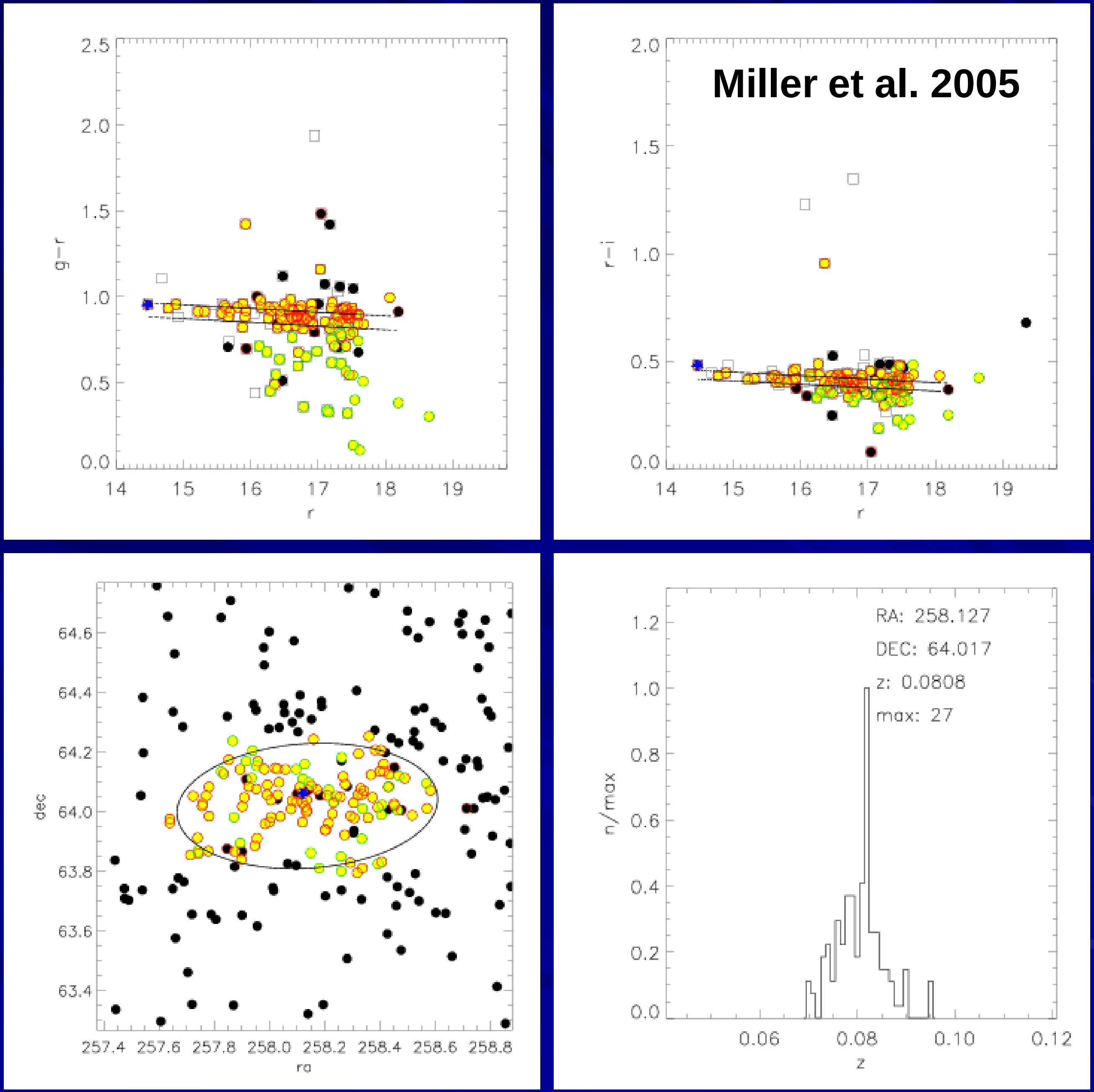
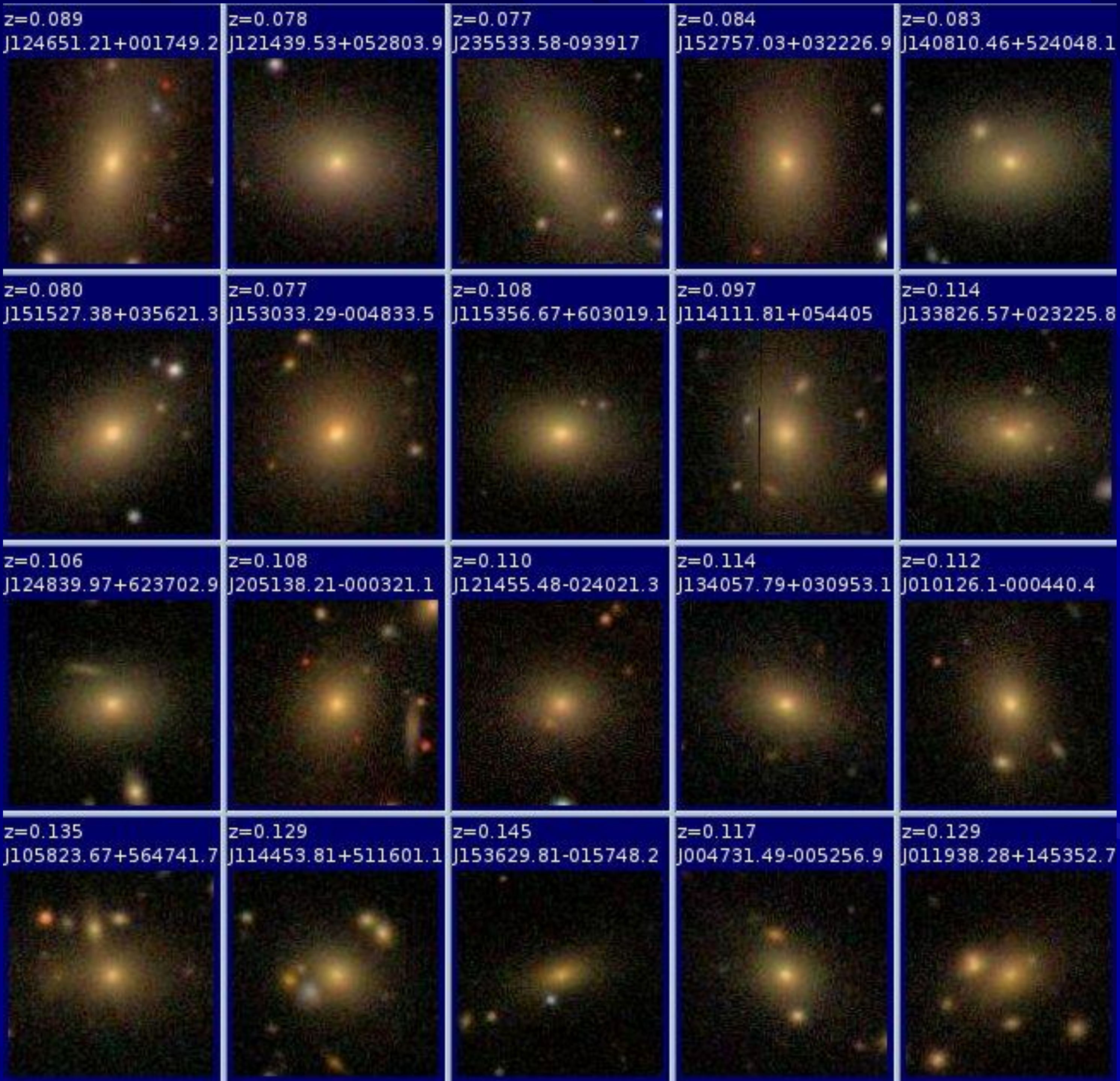
(Luminosities, Sizes, Velocity dispersions, Colors)

- Brightest Cluster Galaxies
- Full Early-type Sample
- High σ Galaxies

Brightest Cluster Galaxies

- C4 cluster catalog (Miller et al. 2005)
- MaxBCGs (Koester et al. 2007)




z=0.089
J124651.21+001749.2
z=0.078
J121439.53+052803.9
z=0.077
J235533.58-093917
z=0.084
J152757.03+032226.9
z=0.083
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z=0.077
J153033.29-004833.5
z=0.108
J115356.67+603019.1
z=0.097
J114111.81+054405
z=0.114
J133826.57+023225.8
z=0.106
J124839.97+623702.9
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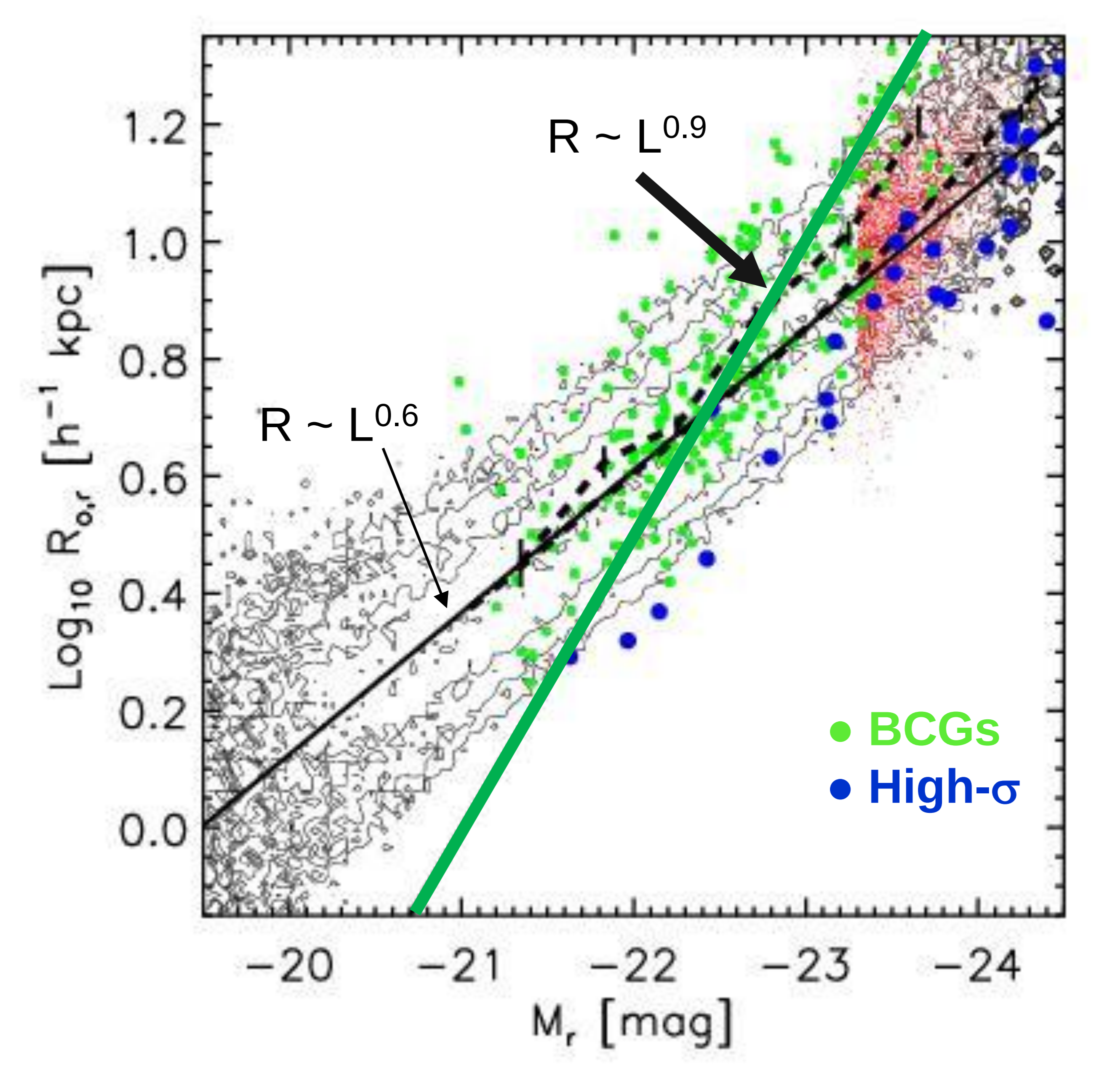
z=0.145
J153629.81-015748.2
z=0.117
J004731.49-005256.9
z=0.129
J011938.28+145352.7

Luminosity-Size relation

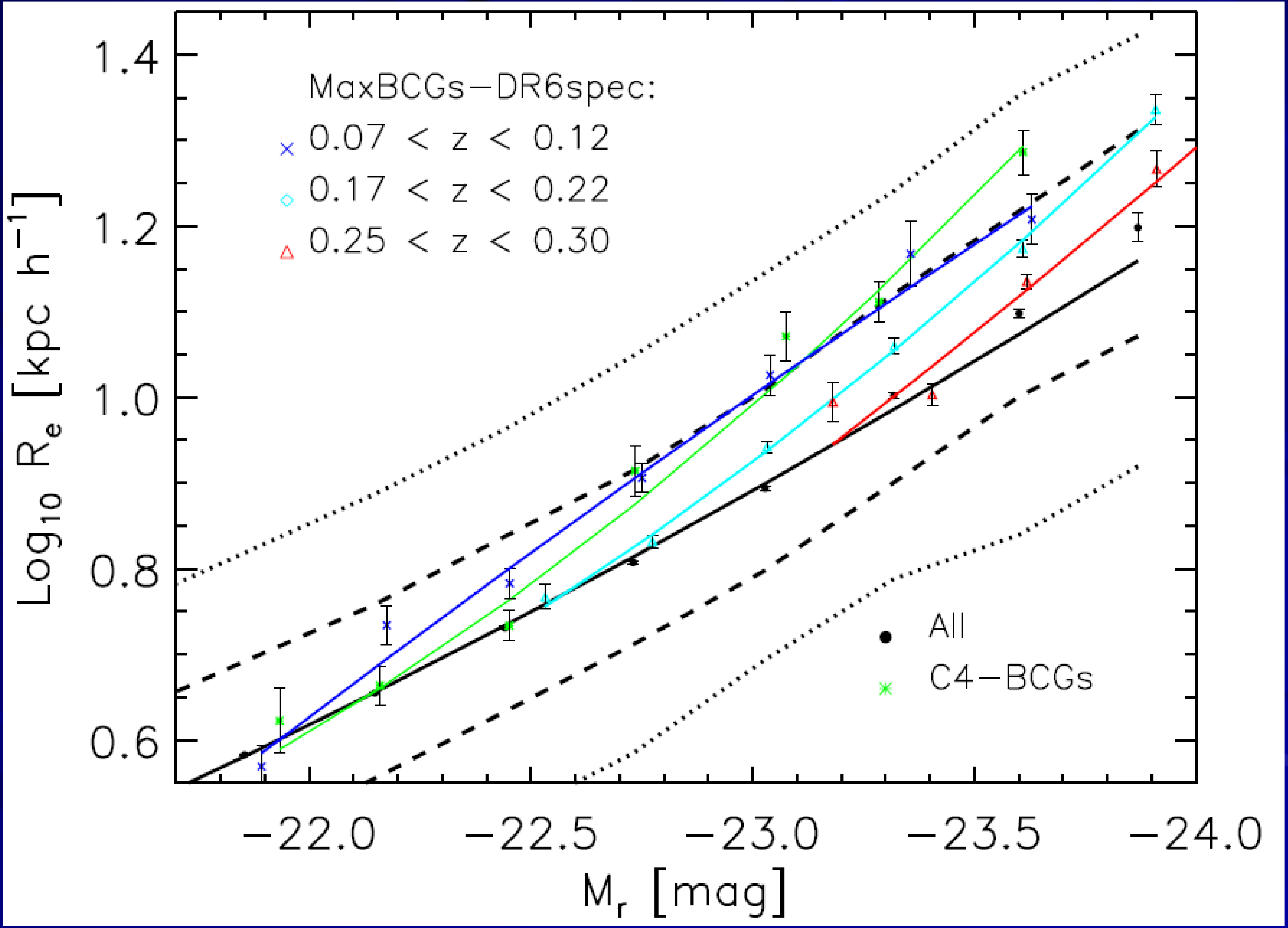
- Upturn to larger sizes at large luminosities
- Why?

Dry merging?

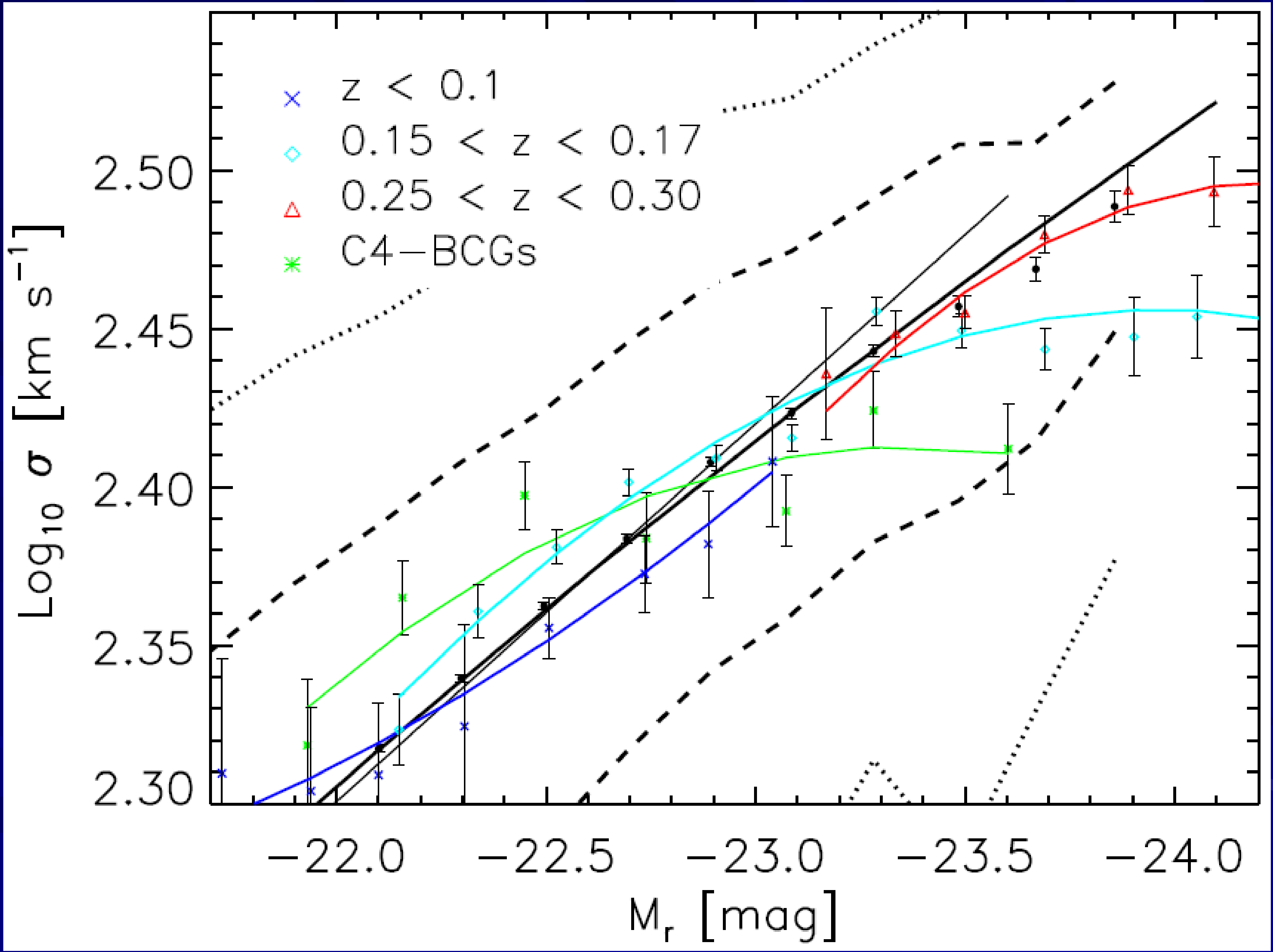
Oegerle & Hoessel 1991
Bernardi et al. 2007
Lauer et al. 2007

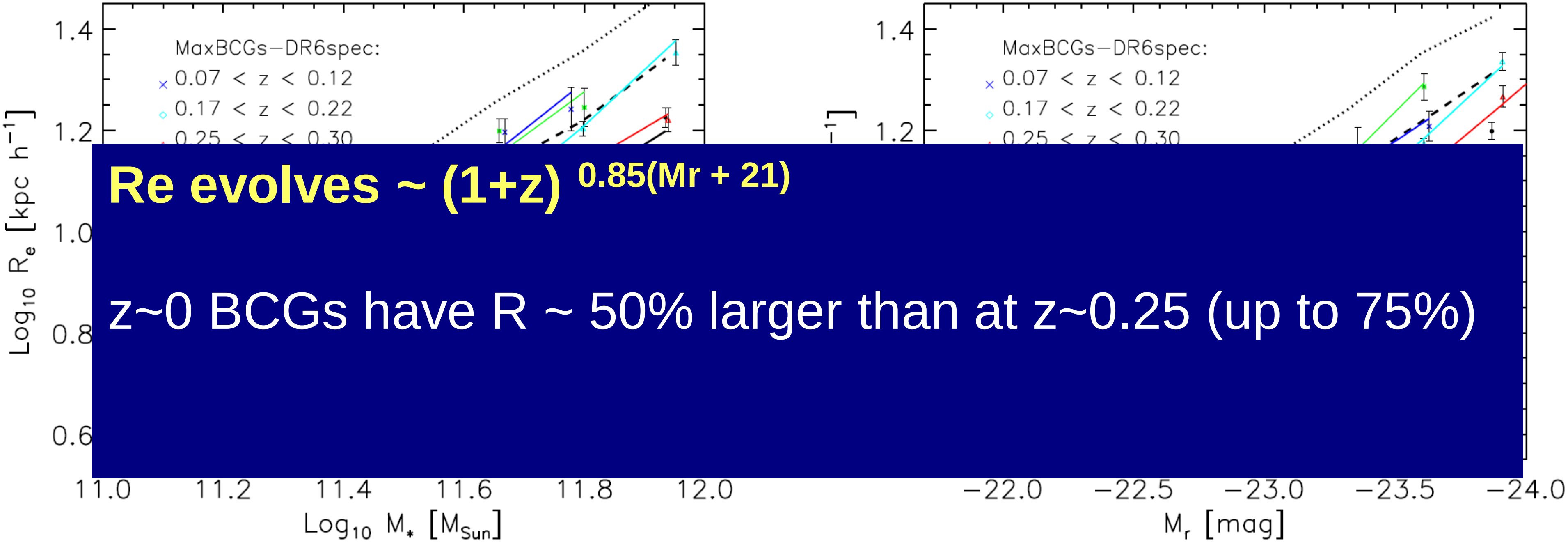


Testing evolution ….



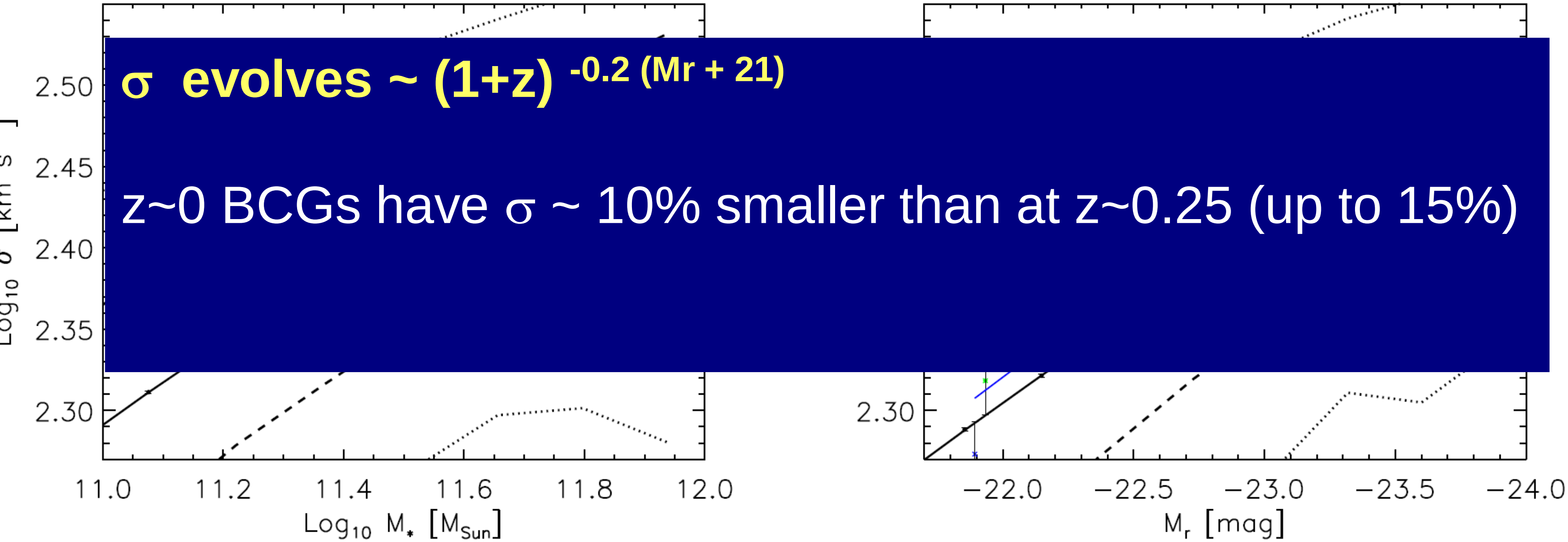
Bernardi 2009


z < 0.1
0.15 < z < 0.17
0.25 < z < 0.30
C4−BCGs
2.50
2.45
2.40
2.35
2.30
Log$_{10}$ σ [km s^{-1}]
−22.0
−22.5
−23.0
−23.5
−24.0
M$_r$ [mag]



Re evolves ~ $(1+z)^{0.85(Mr + 21)}$

z~0 BCGs have R ~ 50% larger than at z~0.25 (up to 75%)



σ evolves ~ $(1+z)^{-0.2\ (Mr + 21)}$

z~0 BCGs have σ ~ 10% smaller than at z~0.25 (up to 15%)

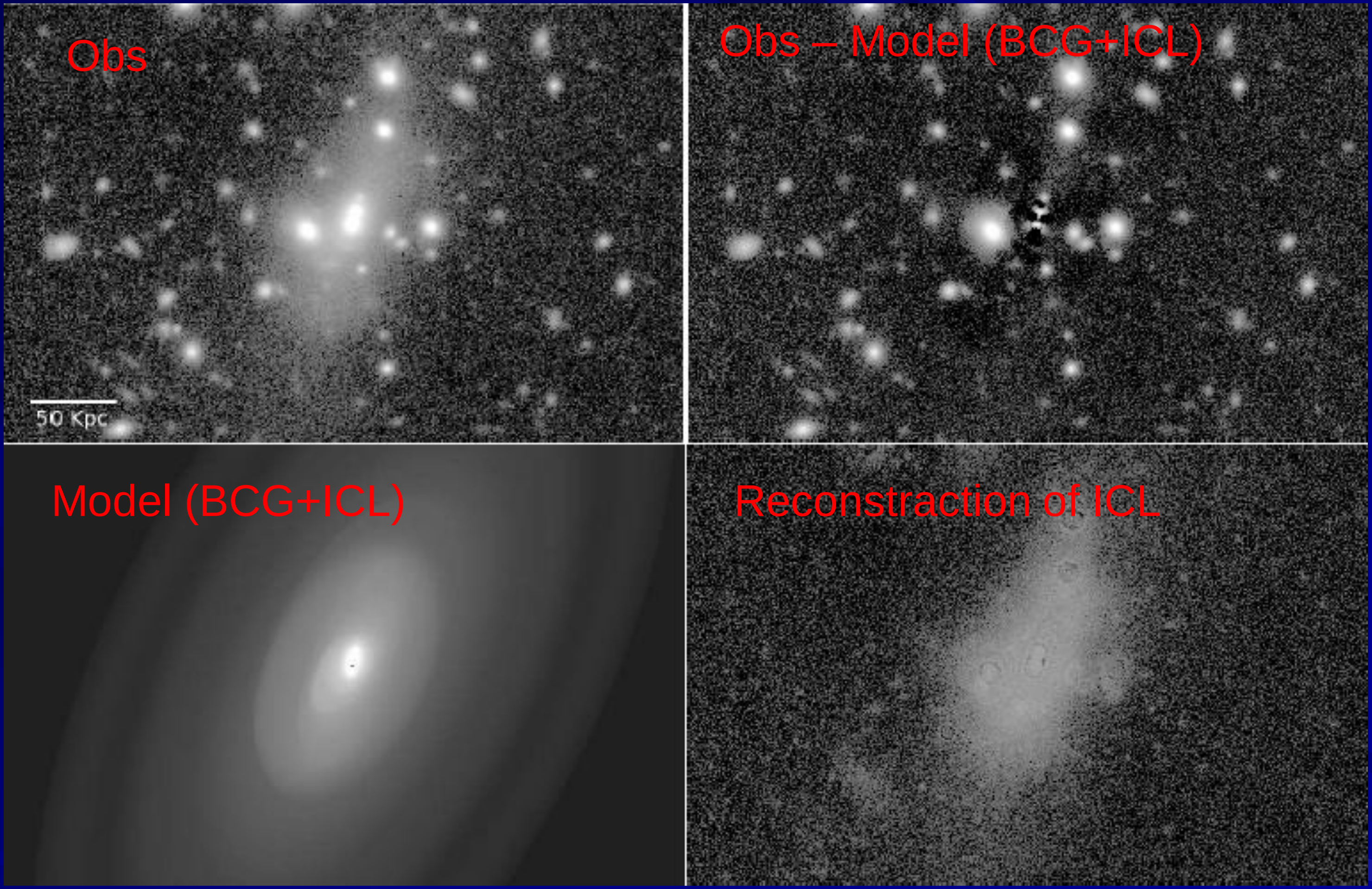
About BCGs …

Need some *minor* mergers at low z!

- -- increase in size more than mass and decrease σ
- -- some of the added stellar mass must make the ICL (Skibba et al. 2007; Conroy et al. 2007)

Could explain the low (??) growth in M* of massive red galaxies since z~0.8

BCG + ICL



Toledo et al. 2011

“The bluer color and shallower spectral indexes of the ICL, and its chaotic motions are consistent with the idea that the ICL originates from tidally disrupted galaxies”

About BCGs …

Need some *minor* mergers at low z!

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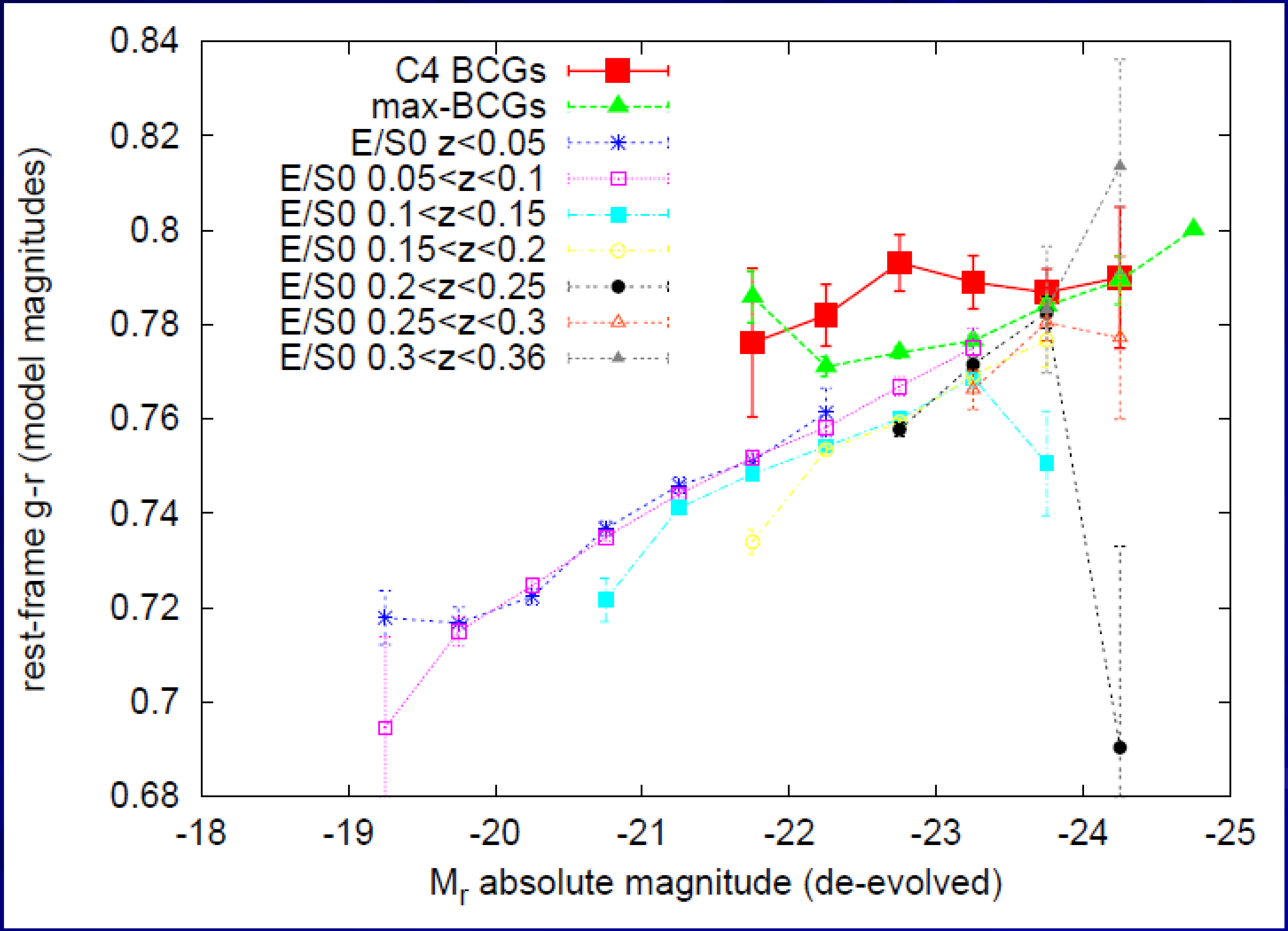
- -- some of the added stellar mass must make the ICL (Skibba et al. 2007; Conroy et al. 2007)

Could explain the low (??) growth in M* of massive red galaxies since z~0.8

HOWEVER

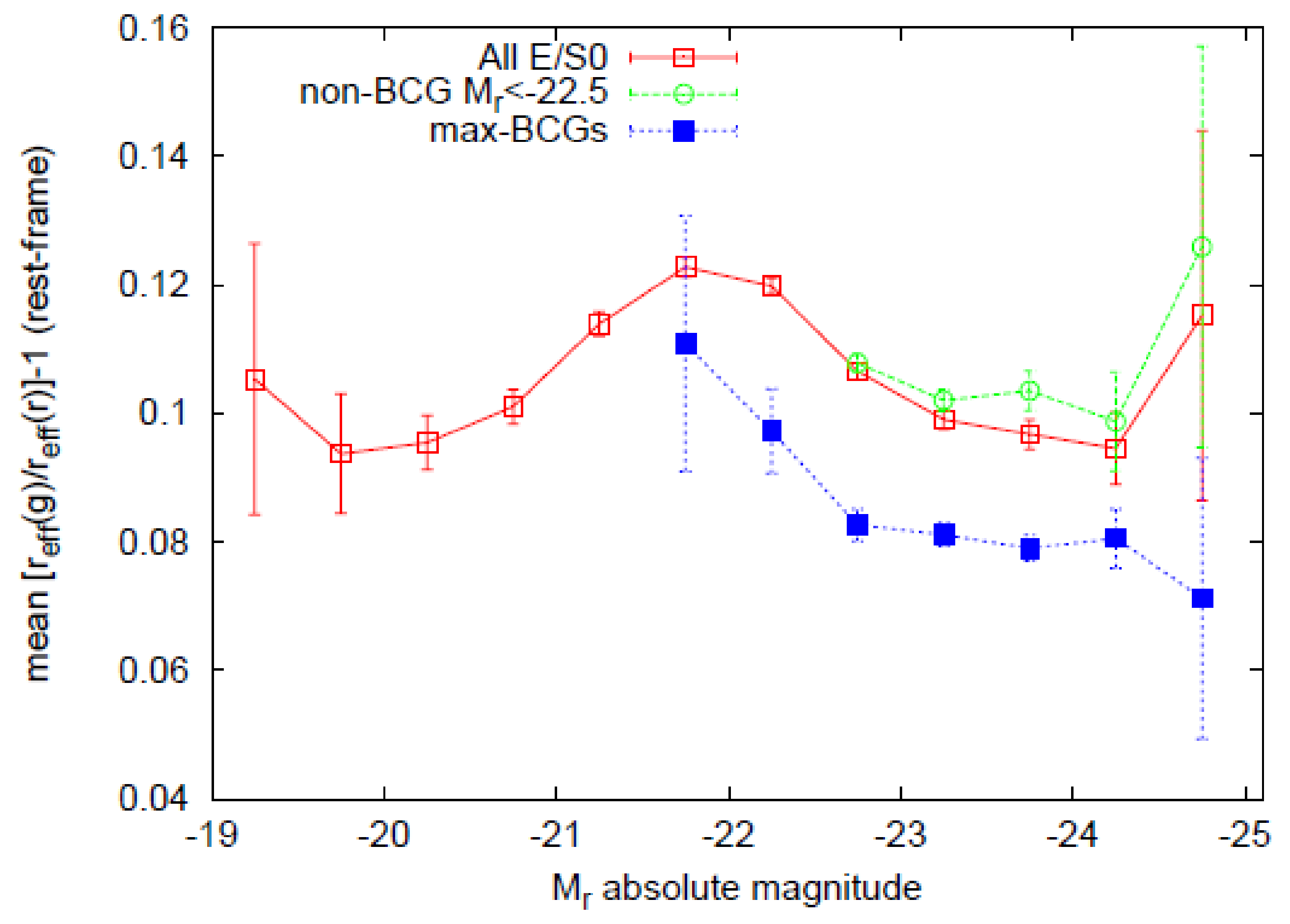
- We need to explain more properties …..

BGCs are redder ….



Roche, MB & Hyde 2010

BCGs have lower color gradients



Roche, MB & Hyde 2010

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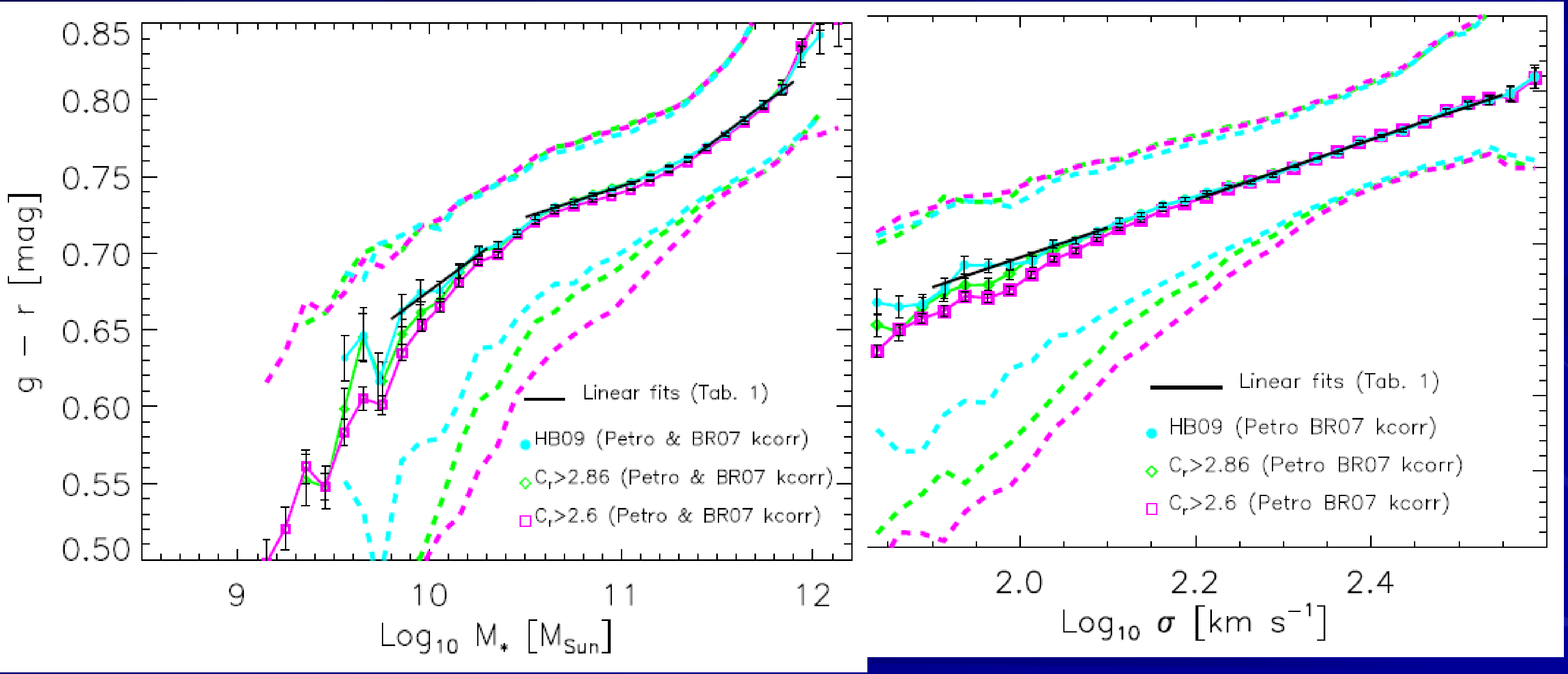
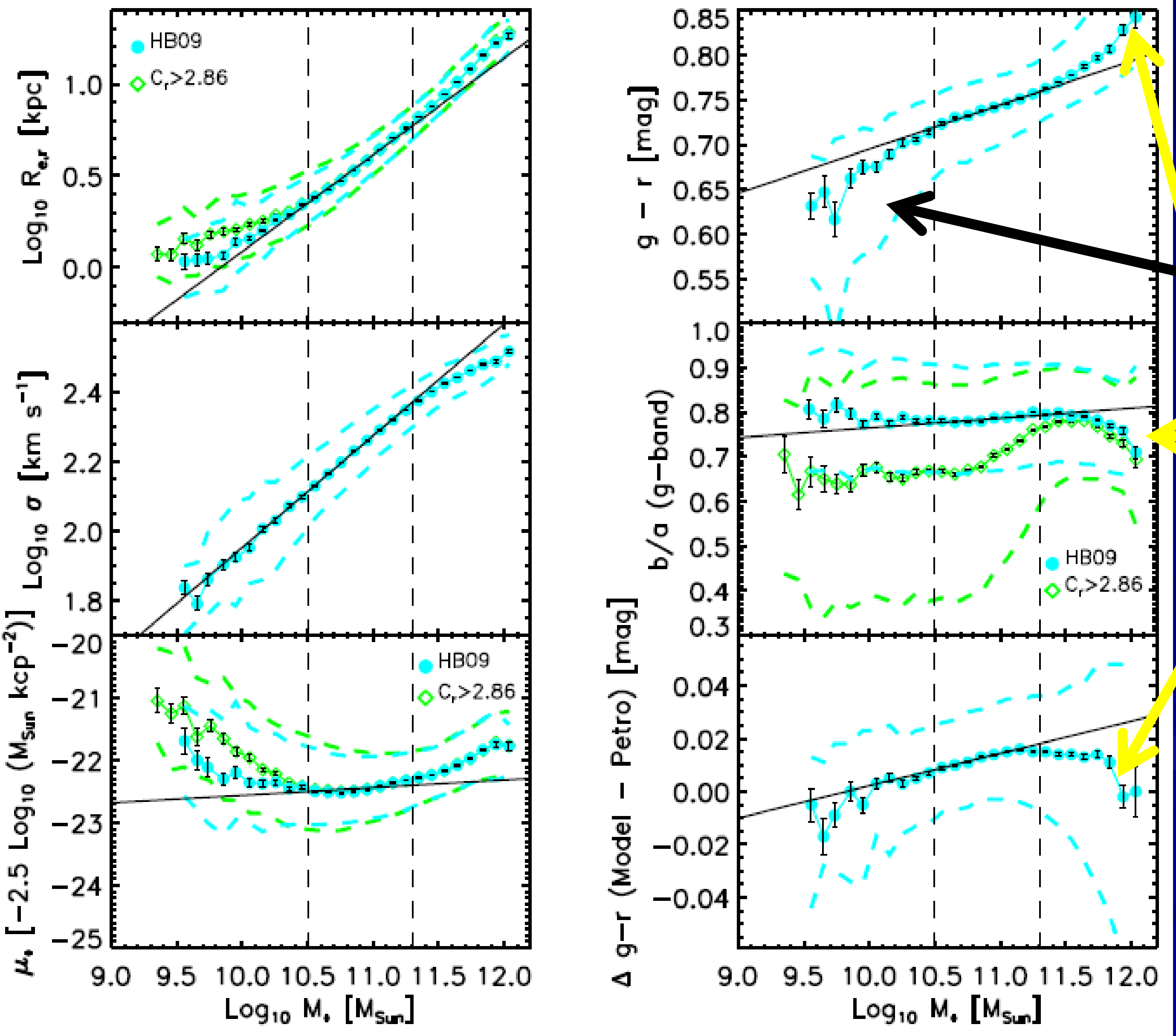
Curvature in the Color-M_* but Power Law for Color-σ



Bernardi et al. 2011a

Major dry mergers change M_* but not σ or color

Impact of Major Dry Mergers at $M_* > 2$ x 10^{11}



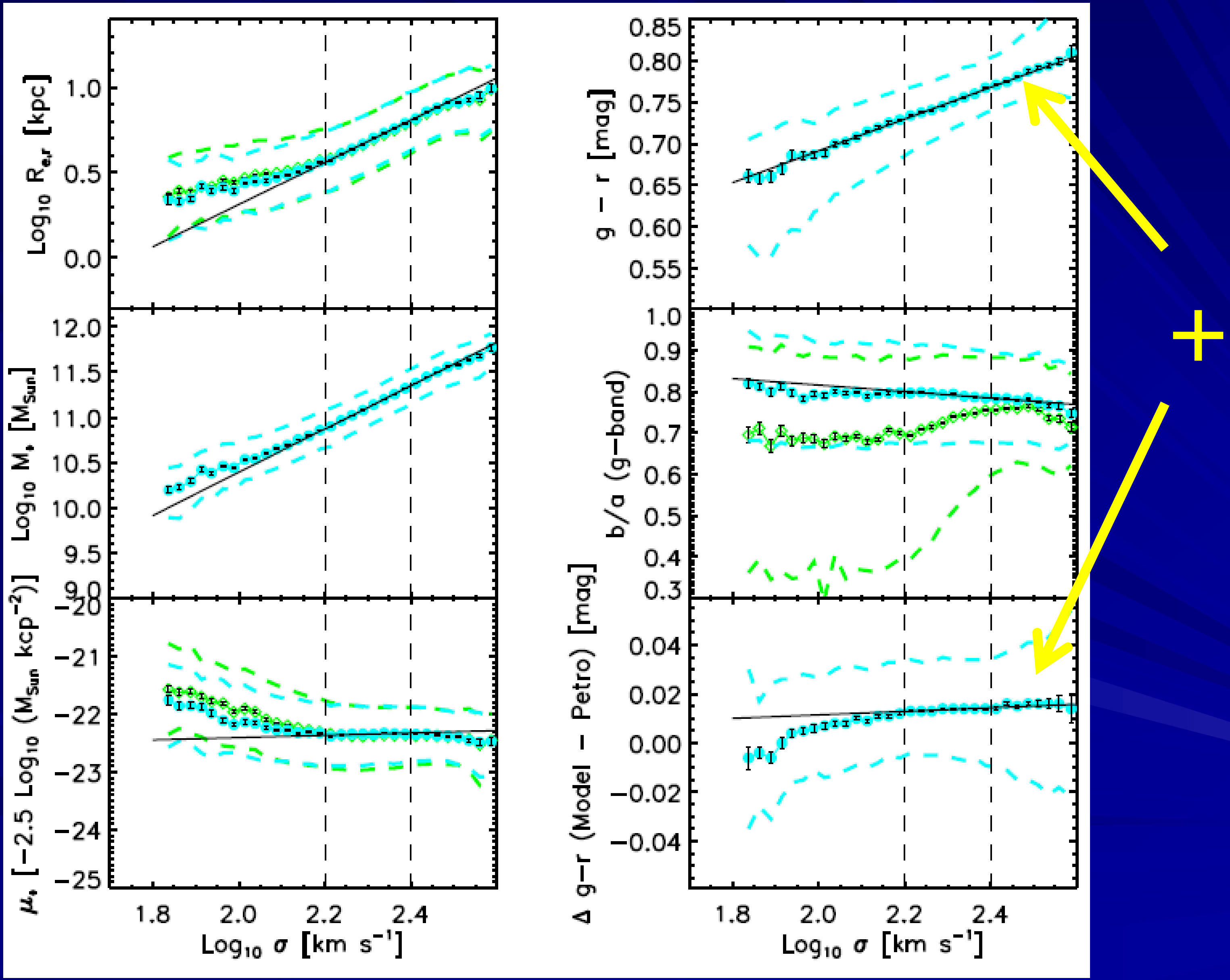
Two scales:
3×10^{10} and
2×10^{11} M_{Sun}

Wet mergers

Evidence of
Major dry mergers

Bernardi et al. 2011b

Less curvature with σ



About $M_* > 2 \times 10^{11} M_o$ …

Need some *major* mergers at some high z!

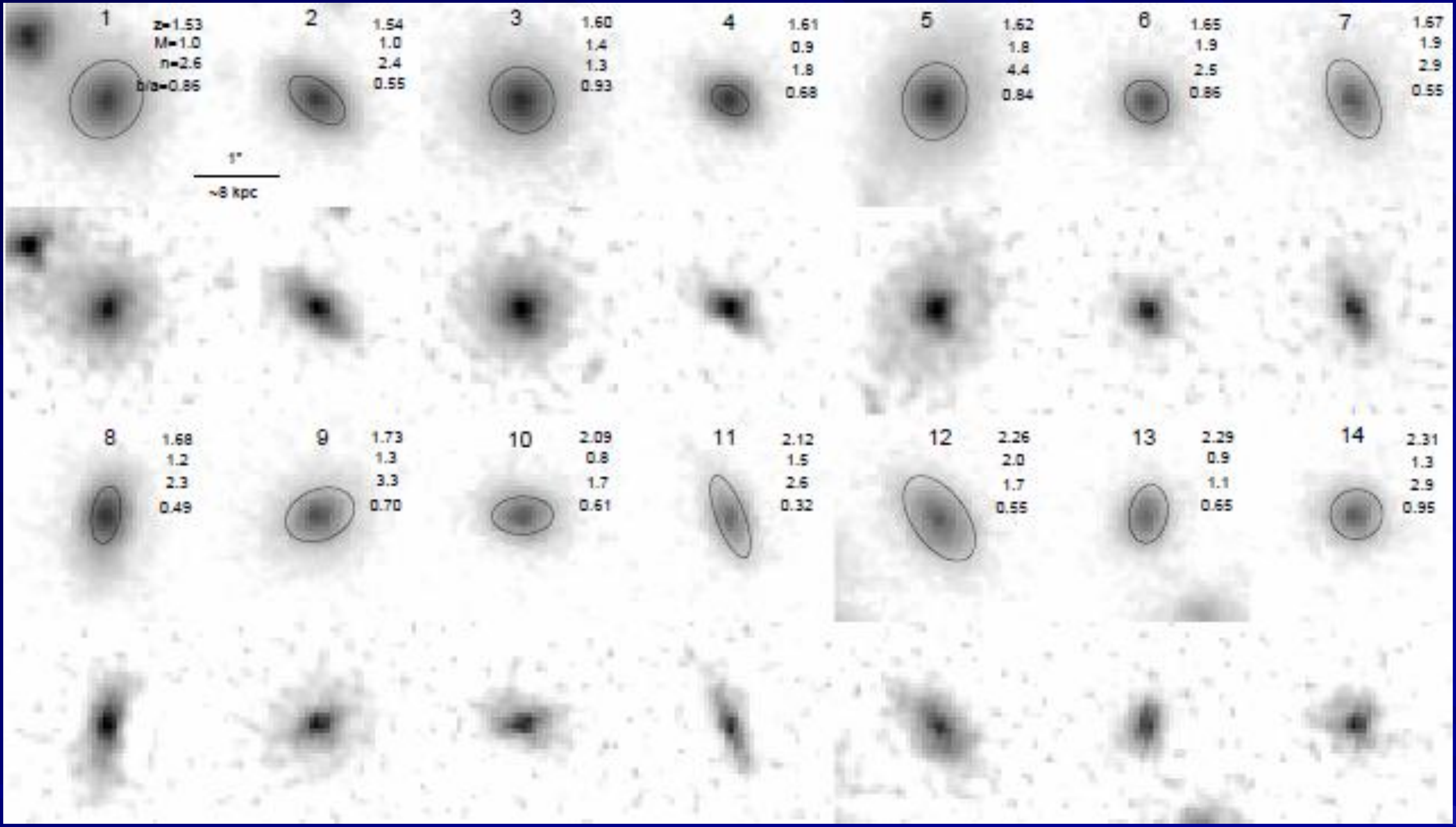
- -- redder Color, lower b/a, lower Col. Gradients (M*)
- -- power law of Color-σ or Col. Gradients-σ

$+$

- -- more room for evolution in the M_* function?

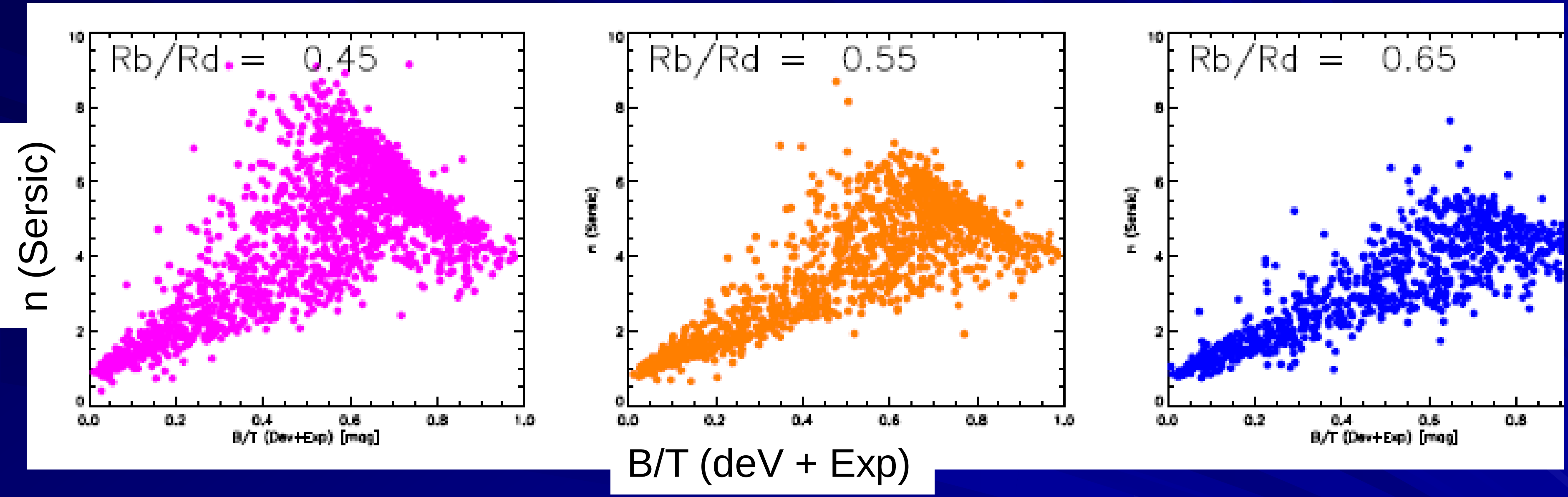
65%±15% of the population of massive, quiescent z ~ 2 galaxies are disk-dominated

van der Wel et al. 2011

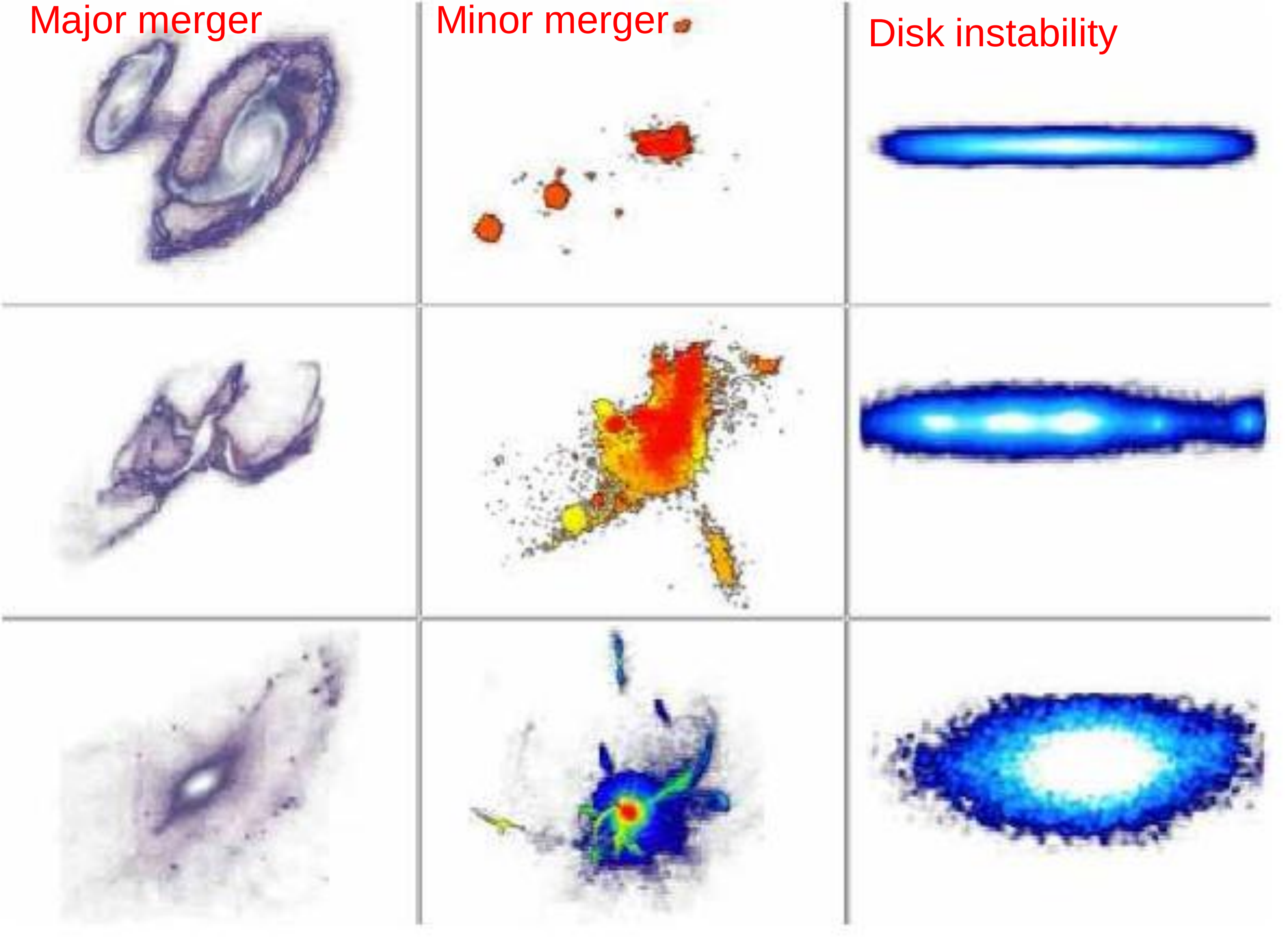


“The much-discussed ultra-dense high-redshift galaxies should generally be thought of as disk-like stellar systems with the majority of stars formed from gas that had time to settle into a disk”

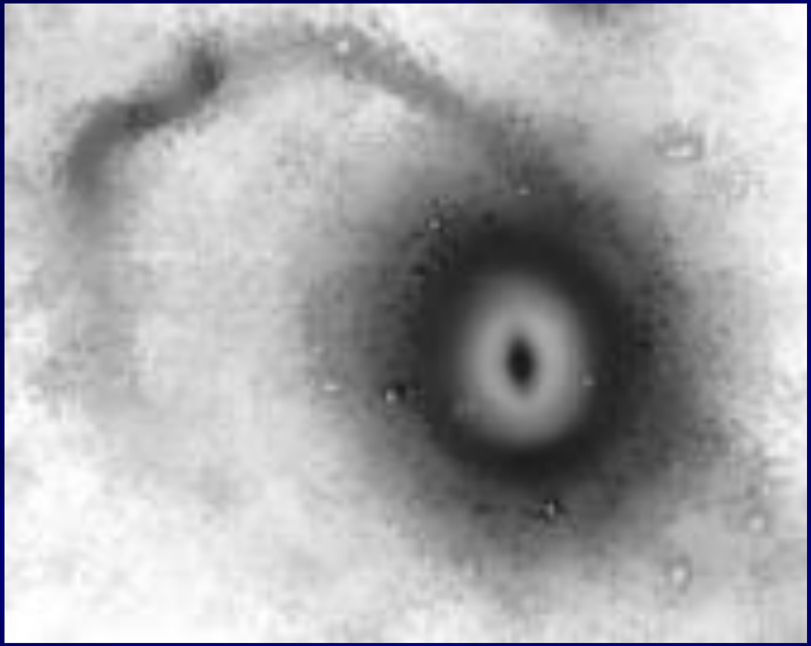
Systems with a disk component can have very high n!!



Another way …..

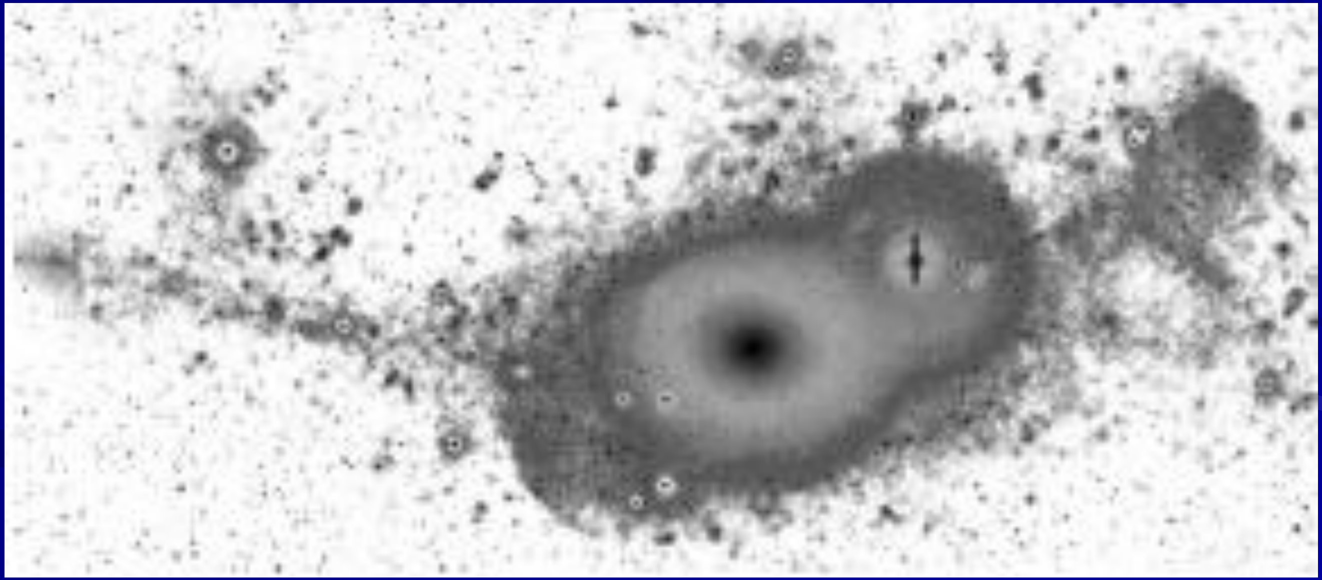


Duc et al. 2011



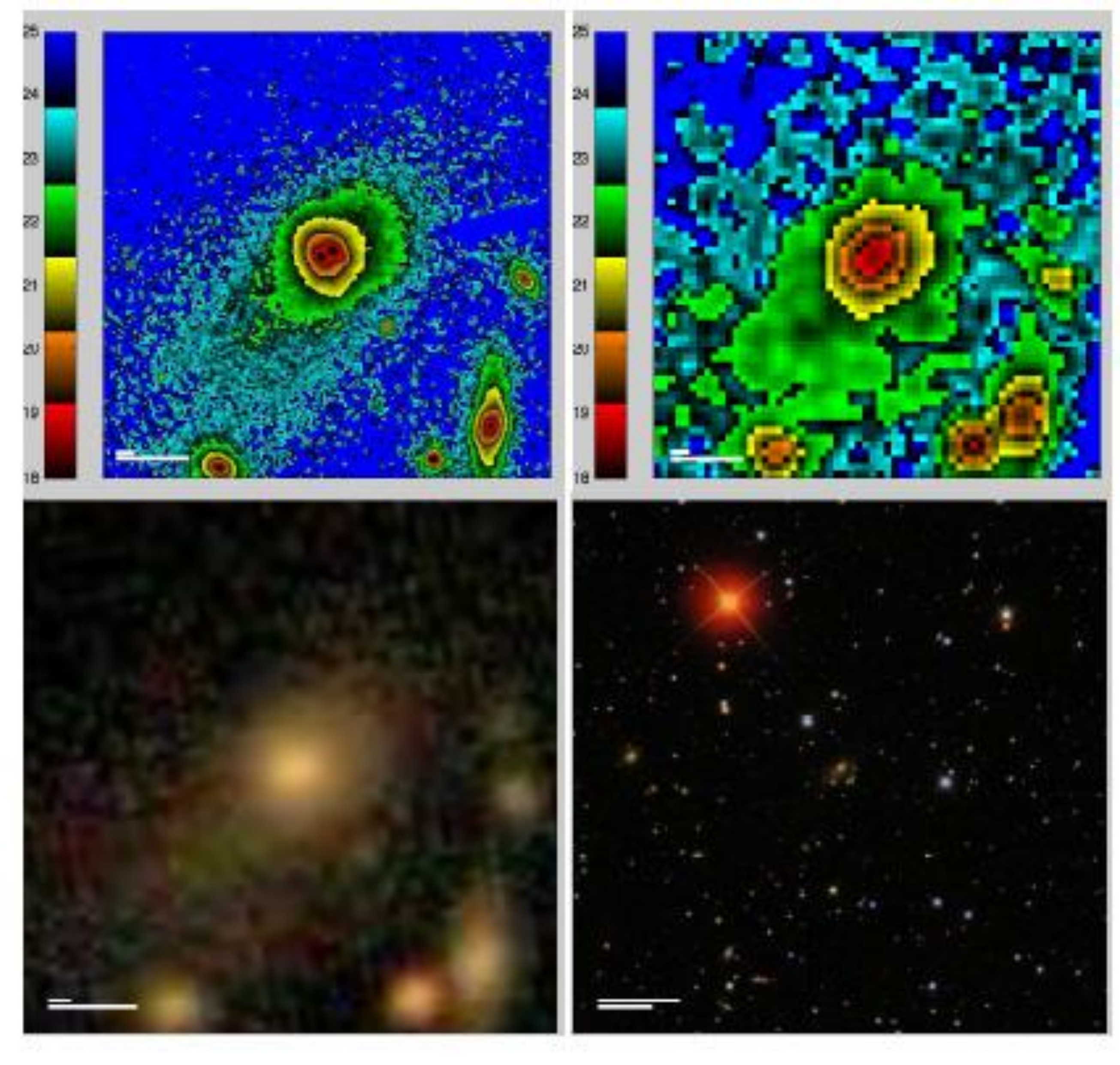
Minor dry merger

Major dry merger (a bit wet?)



Duc et al. 2011

SDSS galaxies in super-position may be nice sample dry-merger population!



About the assembling of massive galaxies ….

- From ΛCDM -> merging of halos
- Merging of massive red galaxies from z~1 is still debated
  - Differently L* galaxies have increased their stellar mass by a factor of ~2-4
- Quenching of star formation important + merging (wet / dry)?
- The size evolution of massive and passive galaxies is still debated
- Major vs Minor Dry mergers: Major dry mergers needed at $M_* > 2 \times 10^{11} M_o$ (Wet mergers important at $M_* < 3 \times 10^{10} M_o$)

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- BCGs built through major dry mergers -- minor dry mergers are dominant at low z (z < 0.8?)

⇨ formation of ICL ⇨ low evolution in M_*

OUTLINE

- Introduction
  - – Importance of Early-Type Galaxies
  - – Overview of recent results:
    - Quenching of SF, Merging (dry/wet + major/minor)
- Testing Dry mergers in SDSS

(Luminosities, Sizes, Velocity dispersions, Colors)

– Brightest Cluster Galaxies

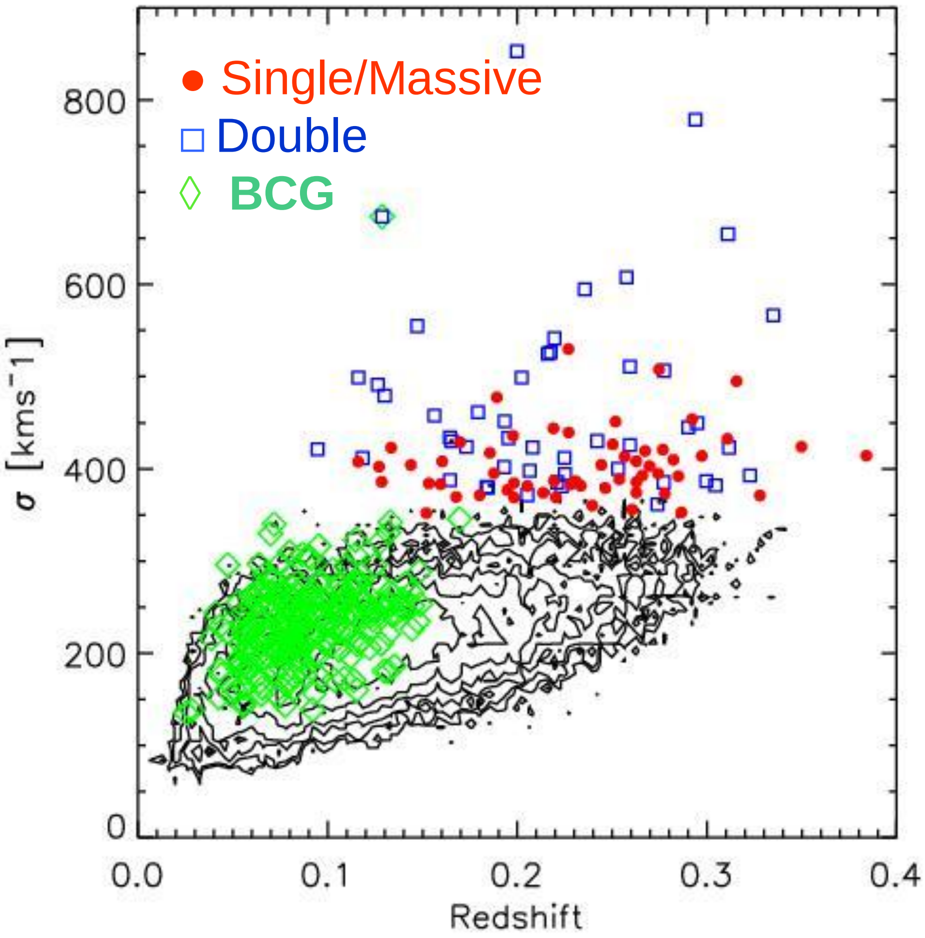
– Full Early-type Sample

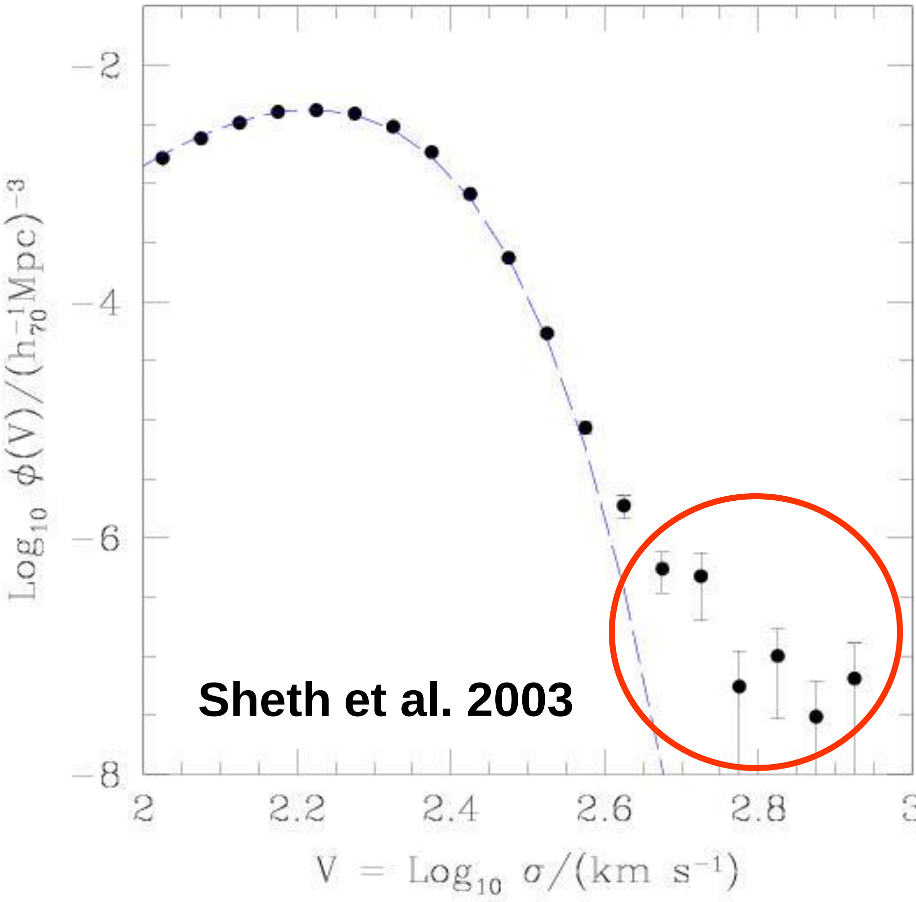
– High σ Galaxies

BigSigs:
Another class of massive galaxies?

- Search SDSS for $\sigma > 350$ km/s
  - – these host the most massive BHs
  - – constraints on formation mechanism (cooling cutoff)
- Eliminate superpositions on basis of images or spectra
  - – expect 1/300 is superposition

Galaxies with the largest velocity dispersion

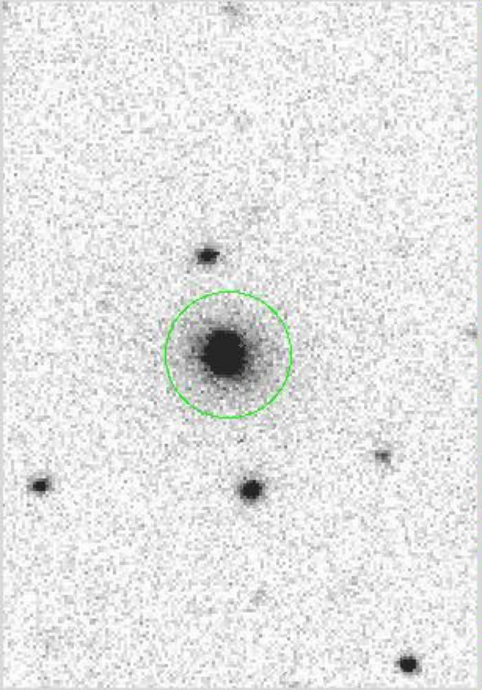


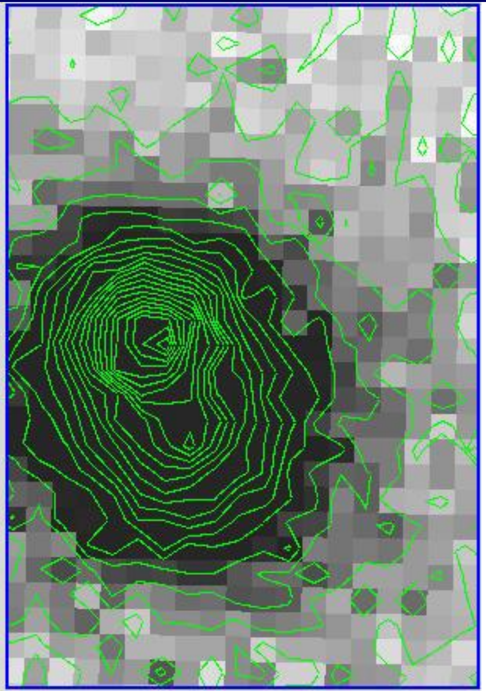


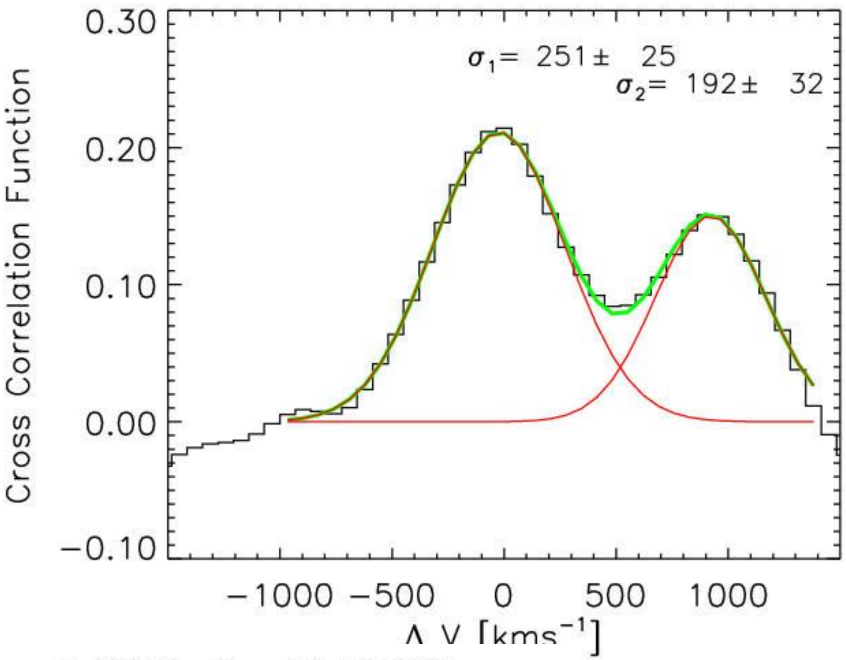
Sheth et al. 2003

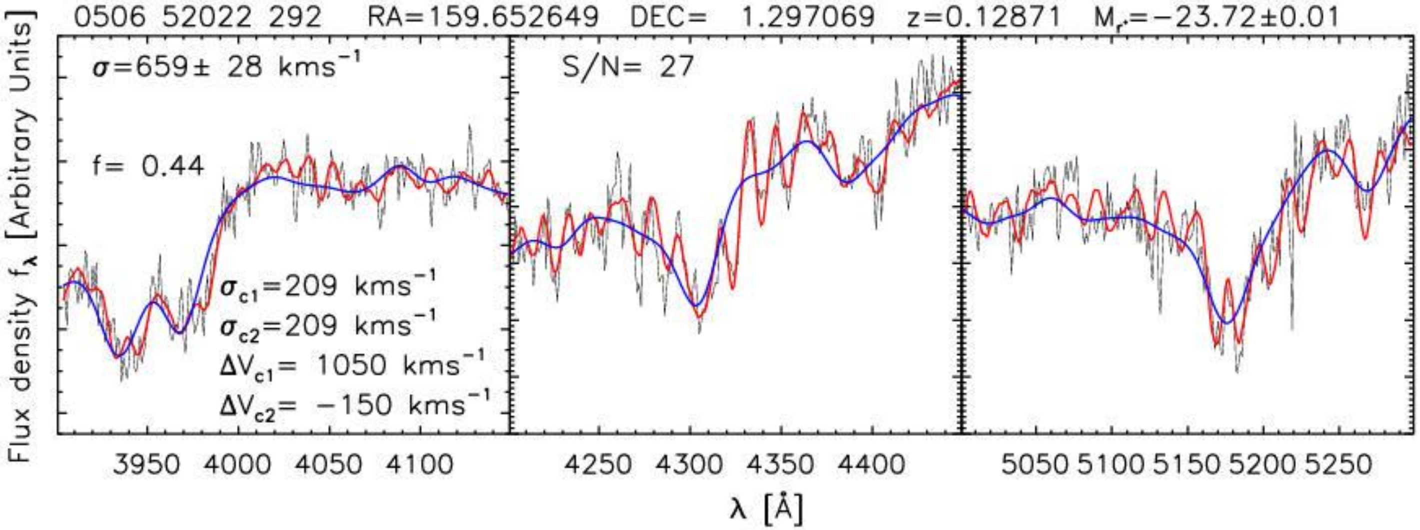
Bernardi et al. 2006

‘Double’ from spectrum and image

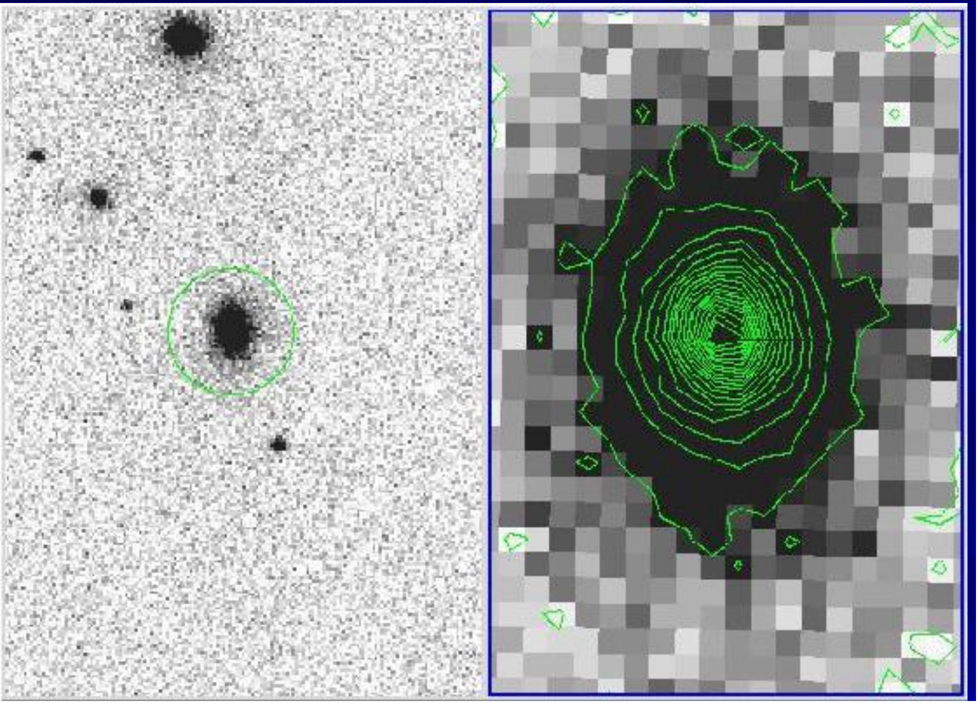


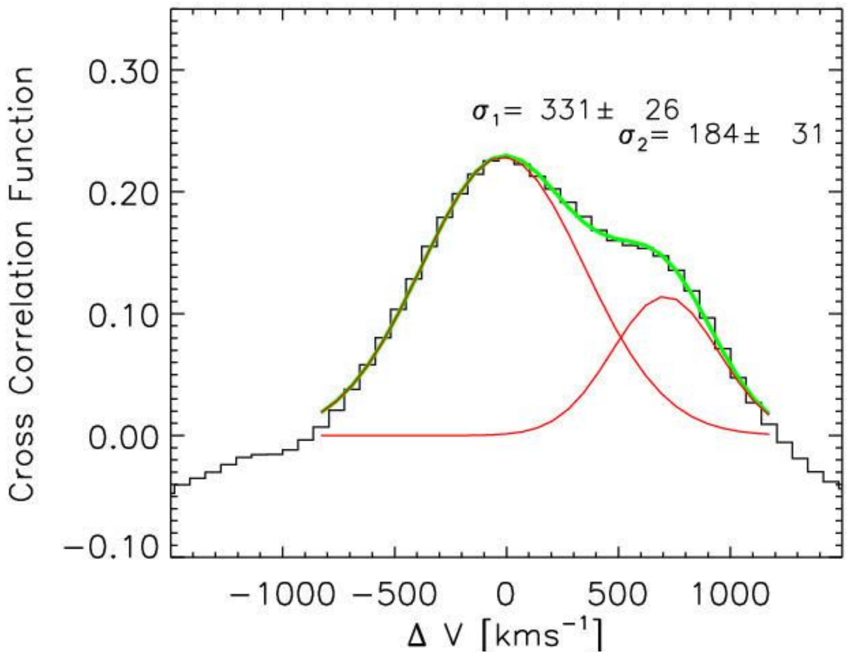


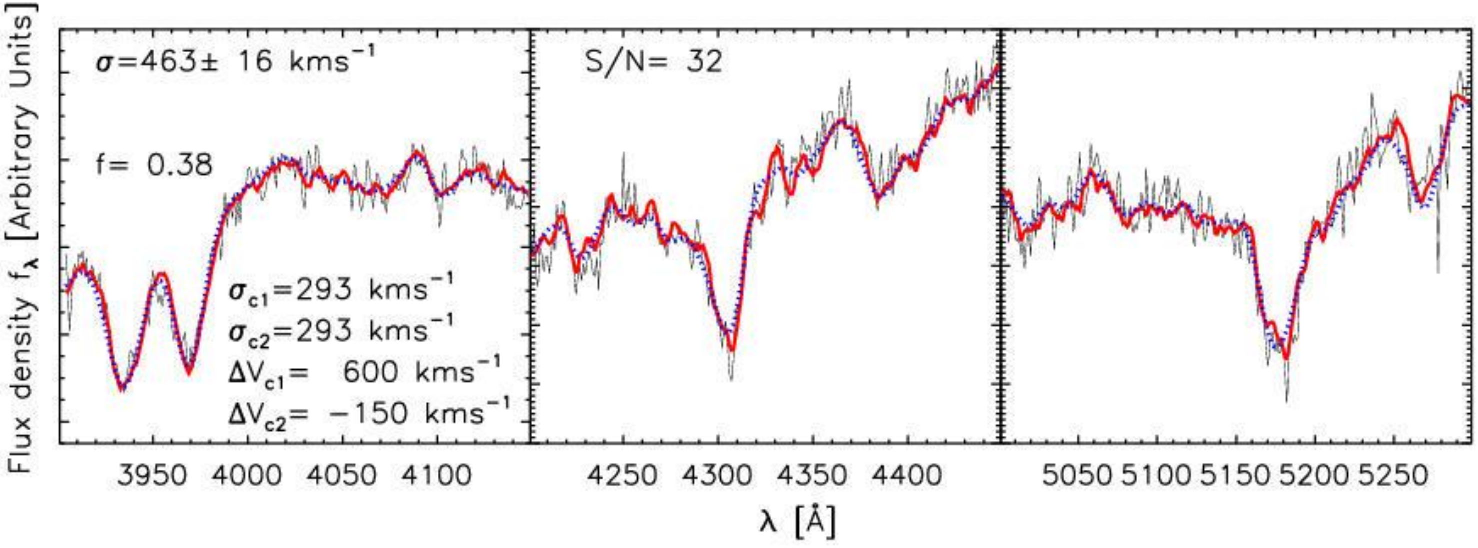




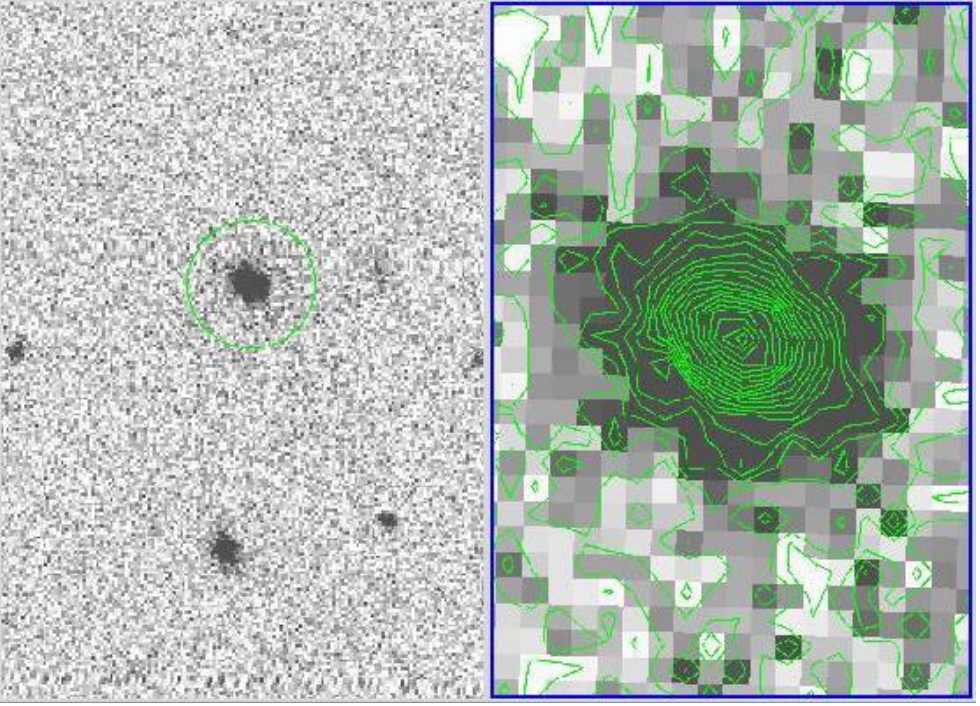
‘Double’ from spectrum, not image

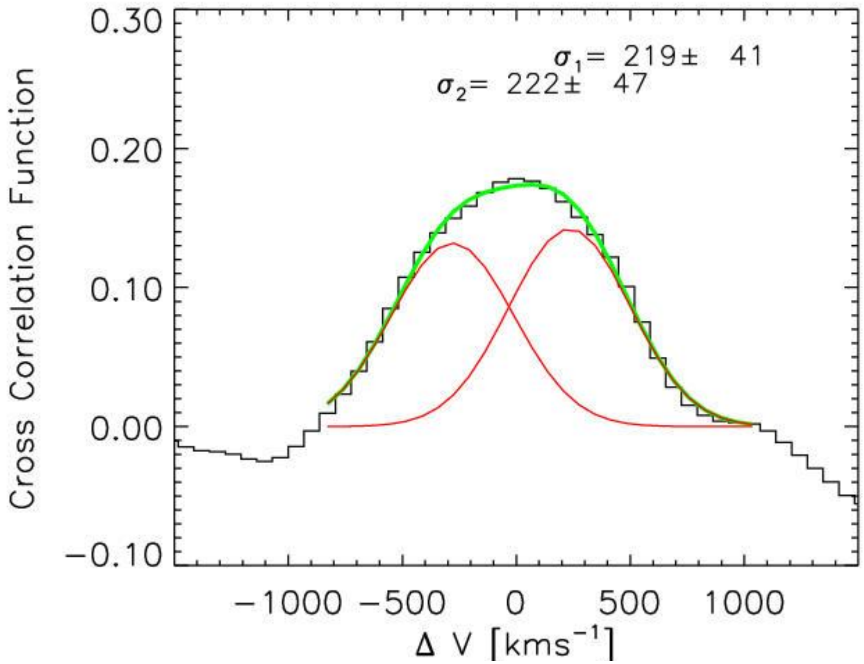


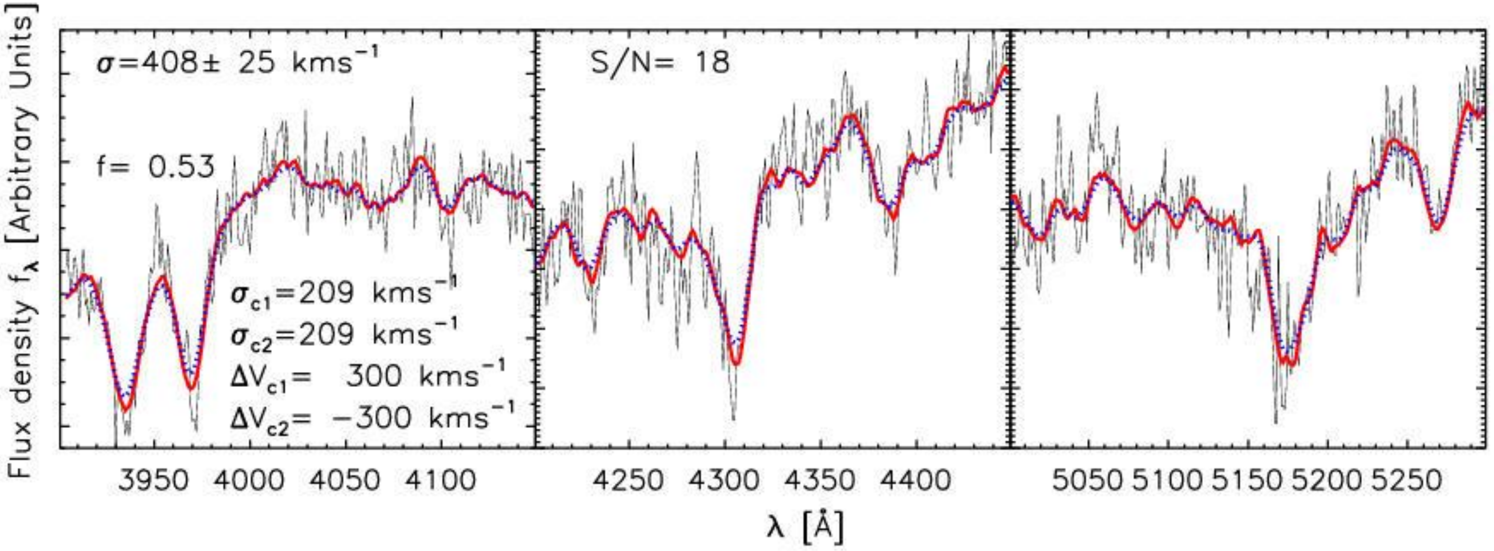




‘Single?’

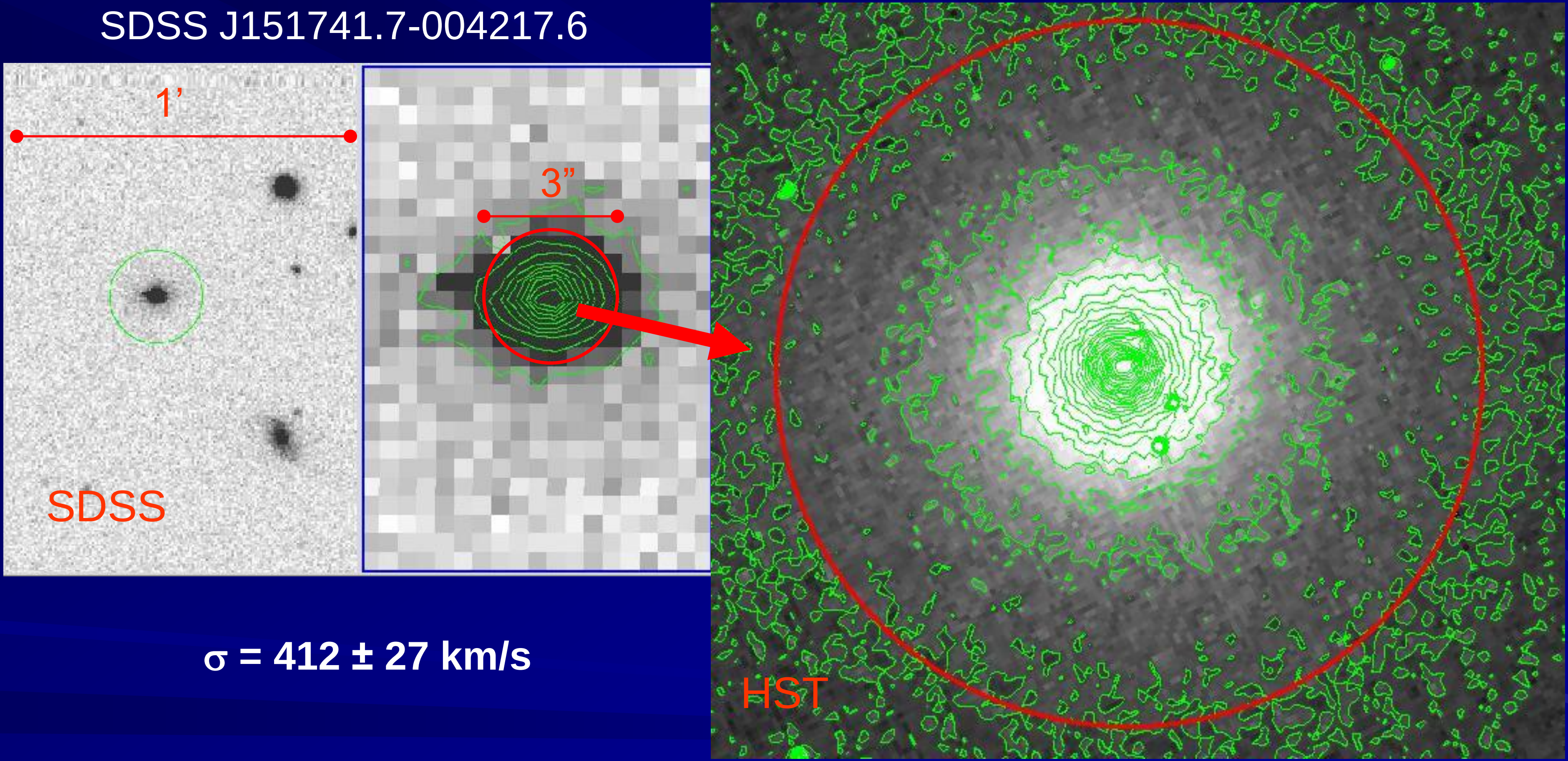



σ_1= 219± 41
σ_2= 222± 47
Cross Correlation Function
0.30
0.20
0.10
0.00
−0.10
−1000 −500 0 500 1000
Δ V [kms^{-1}]


σ=408± 25 kms^{-1}
S/N= 18
f= 0.53
σ_{c1}=209 kms^{-1}
σ_{c2}=209 kms^{-1}
ΔV_{c1}= 300 kms^{-1}
ΔV_{c2}= −300 kms^{-1}
Flux density f_λ [Arbitrary Units]
3950 4000 4050 4100
4250 4300 4350 4400
5050 5100 5150 5200 5250
λ [Å]

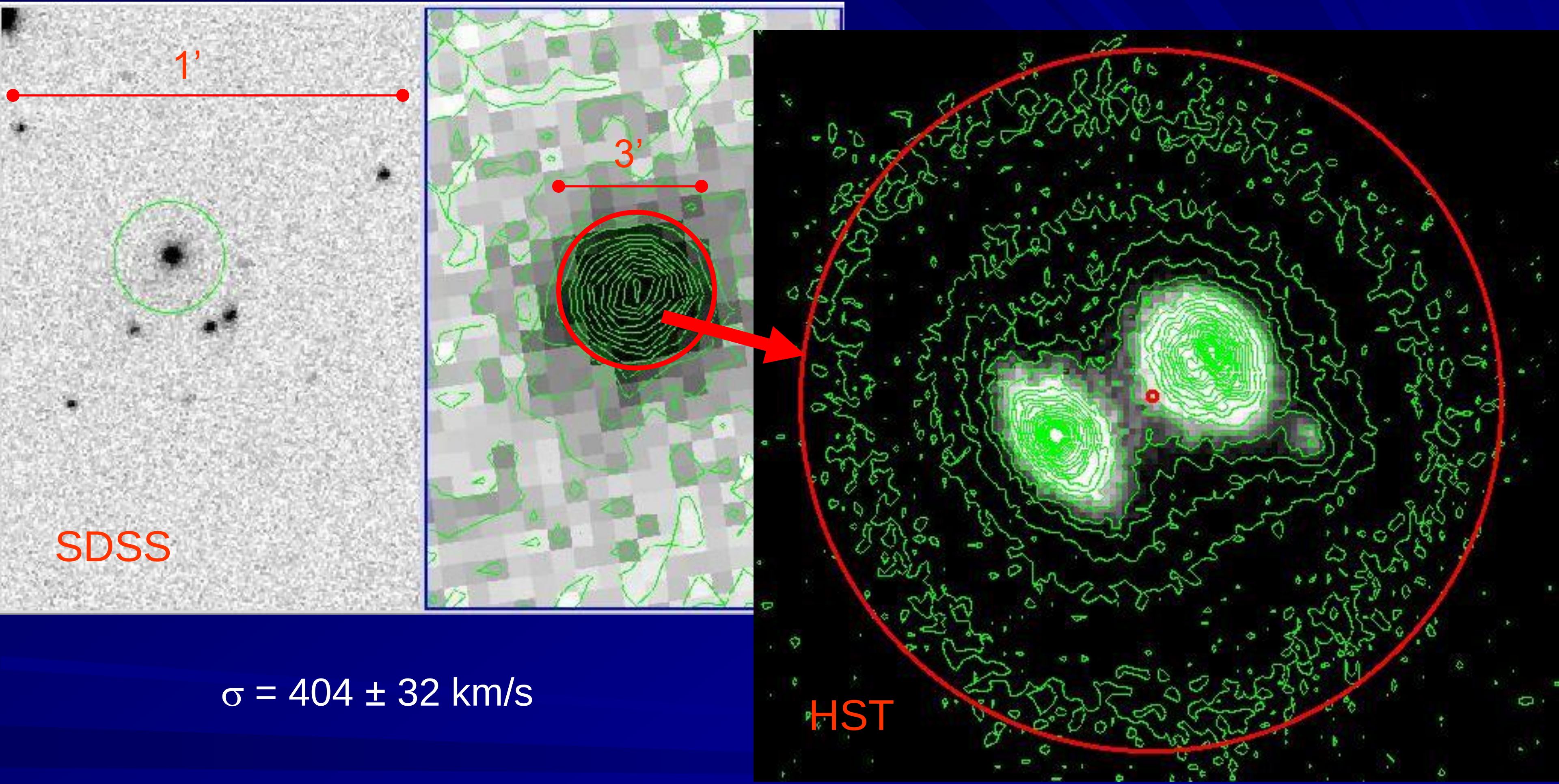
HST images: with ACS-HRC

SDSS J151741.7-004217.6

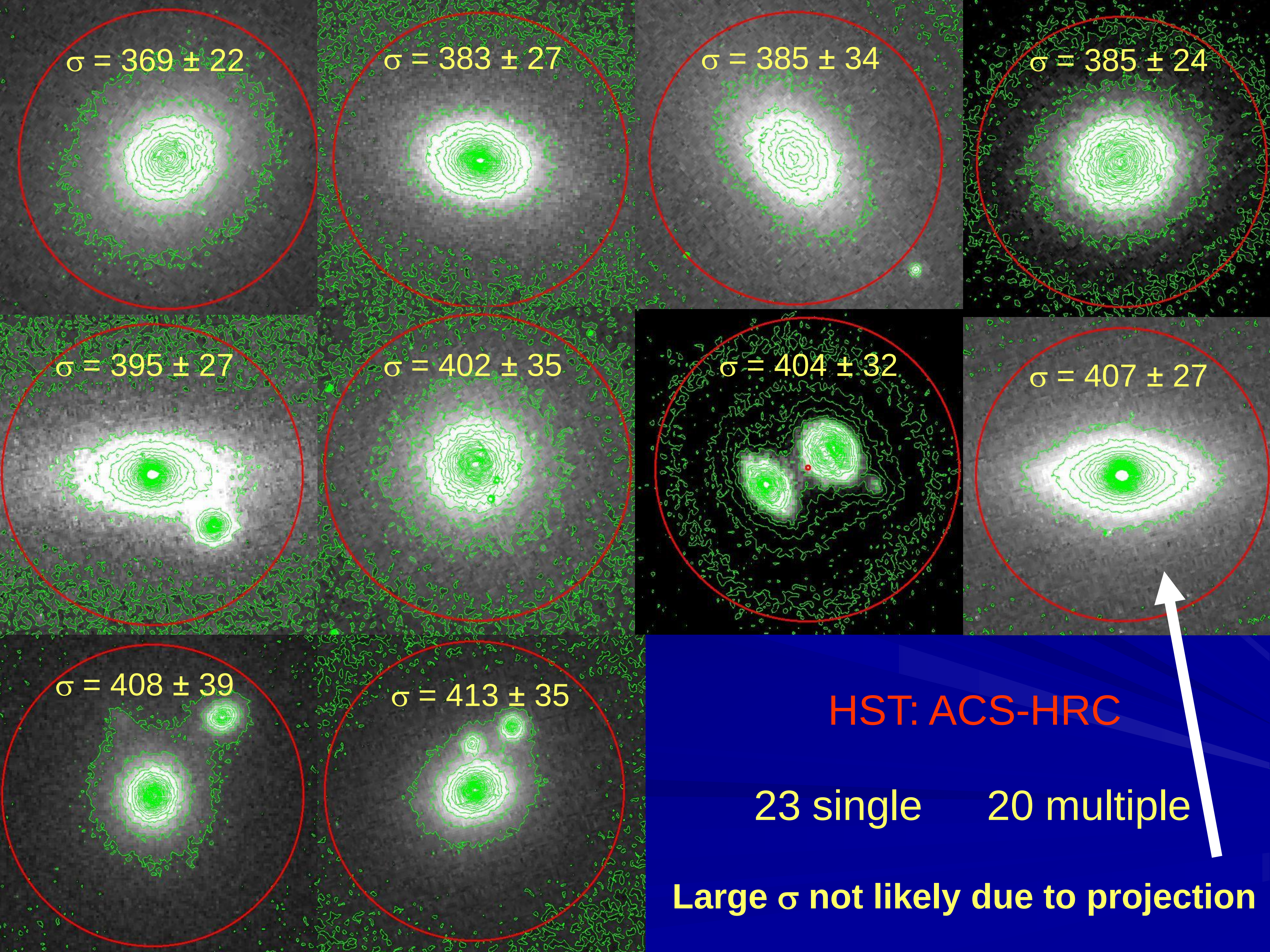


σ = 412 ± 27 km/s

SDSS J204712.0-054336.7



σ = 404 ± 32 km/s



HST: ACS-HRC

23 single 20 multiple

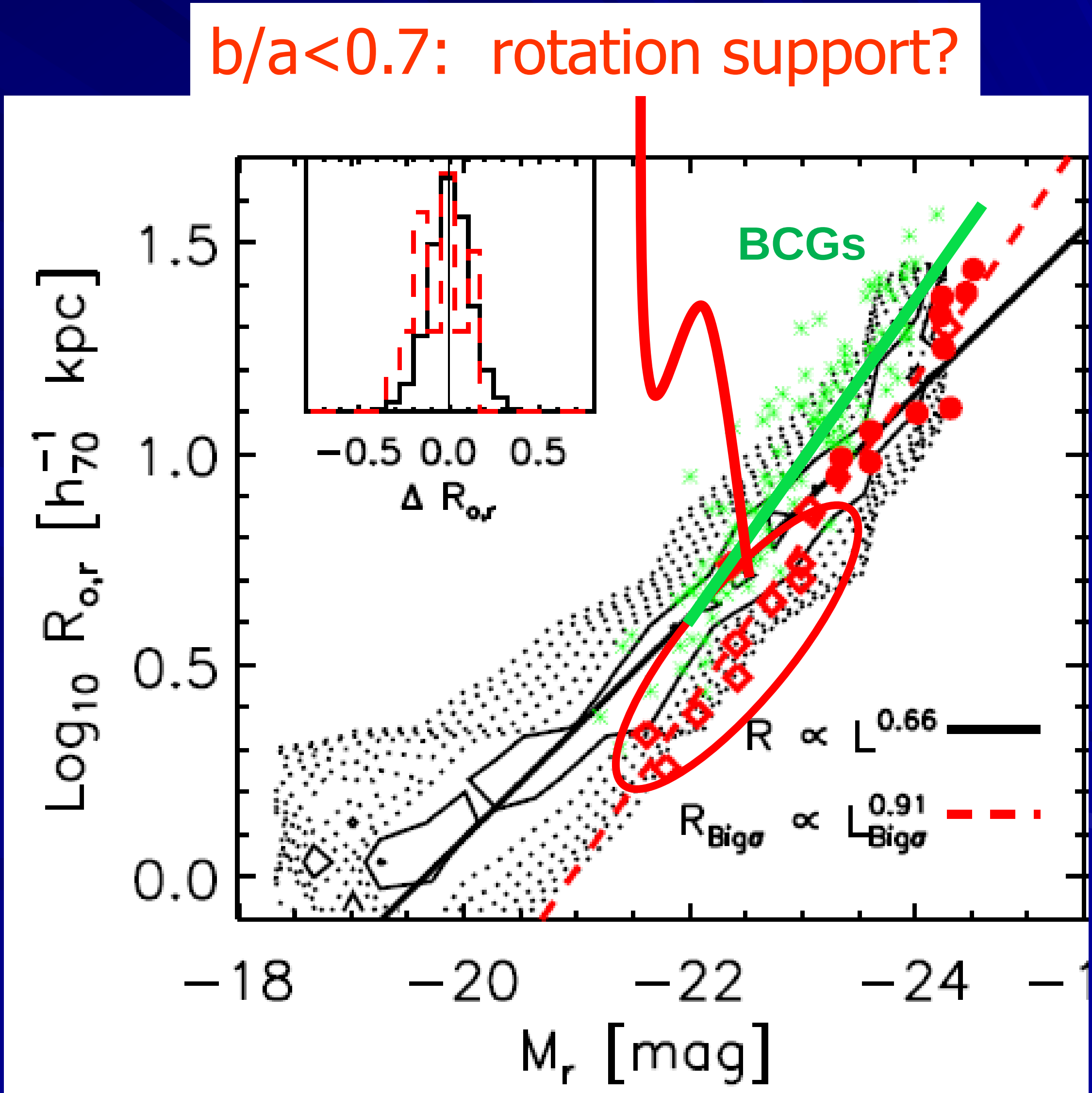
Large σ not likely due to projection

Luminosity-size relation

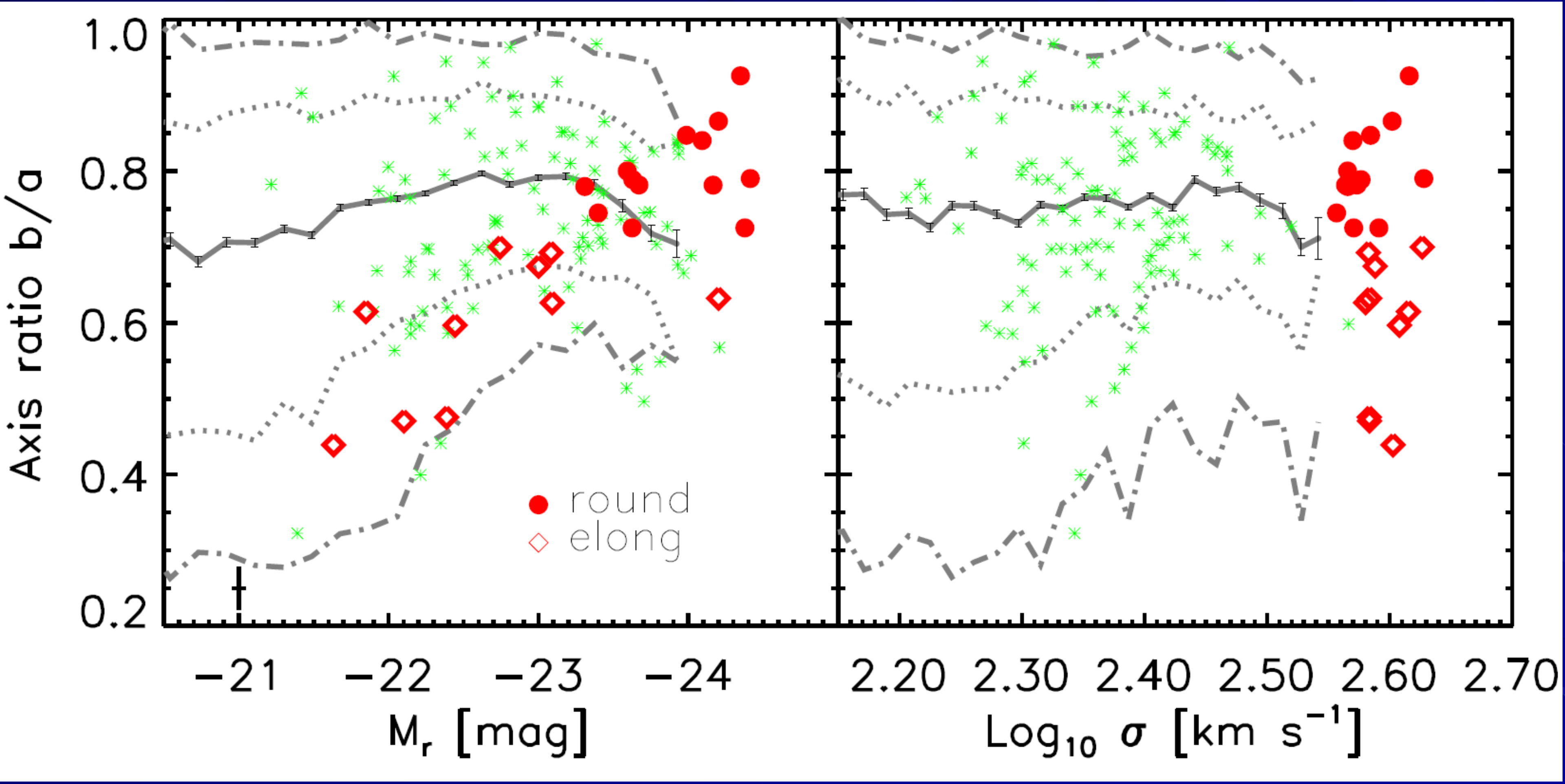
Compared to BCGs, large σ sample has smaller sizes

Large σ from extreme dissipation?

Bernardi et al. 2008

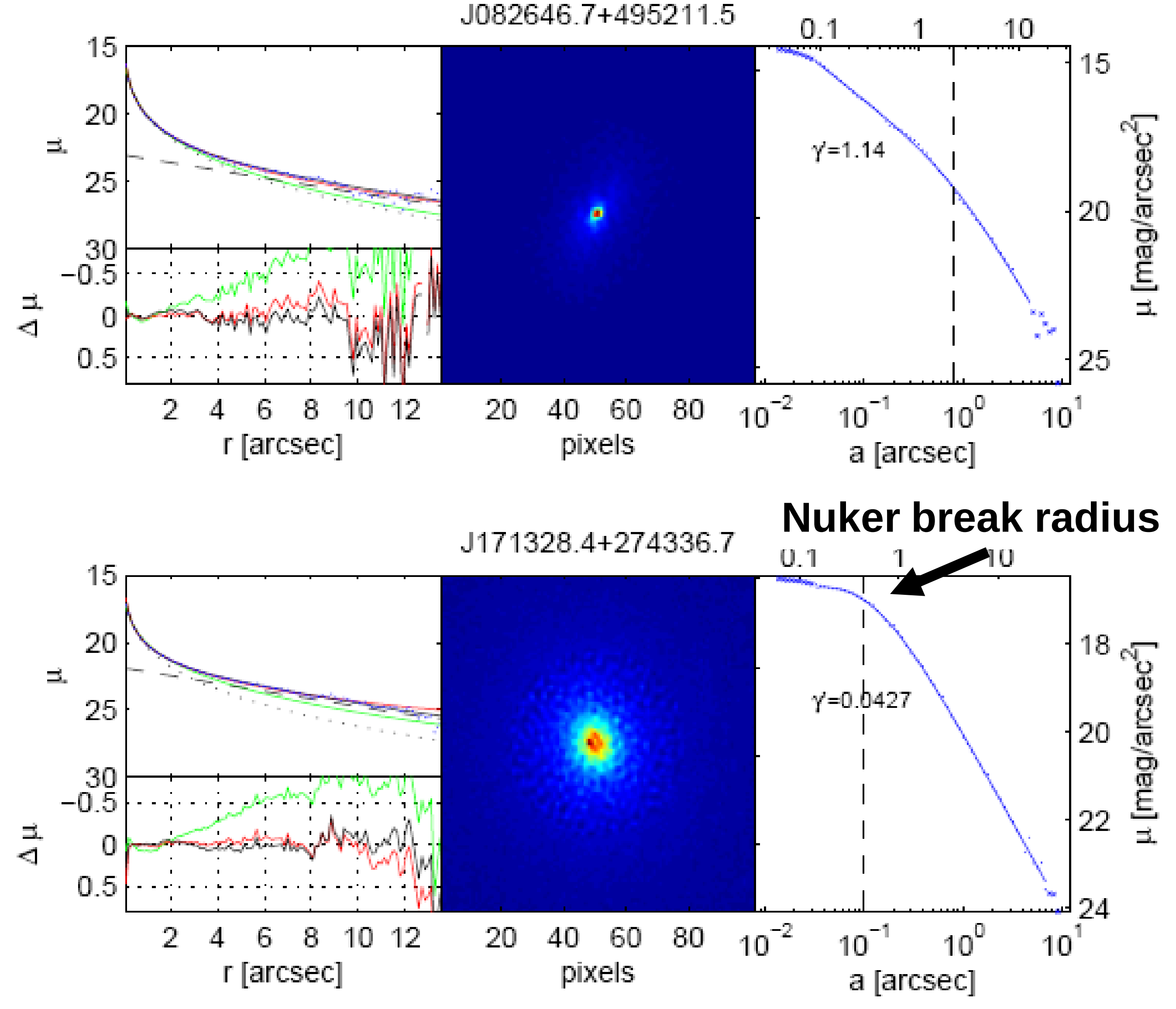


BCGs are less round; BigSigs are rounder!!



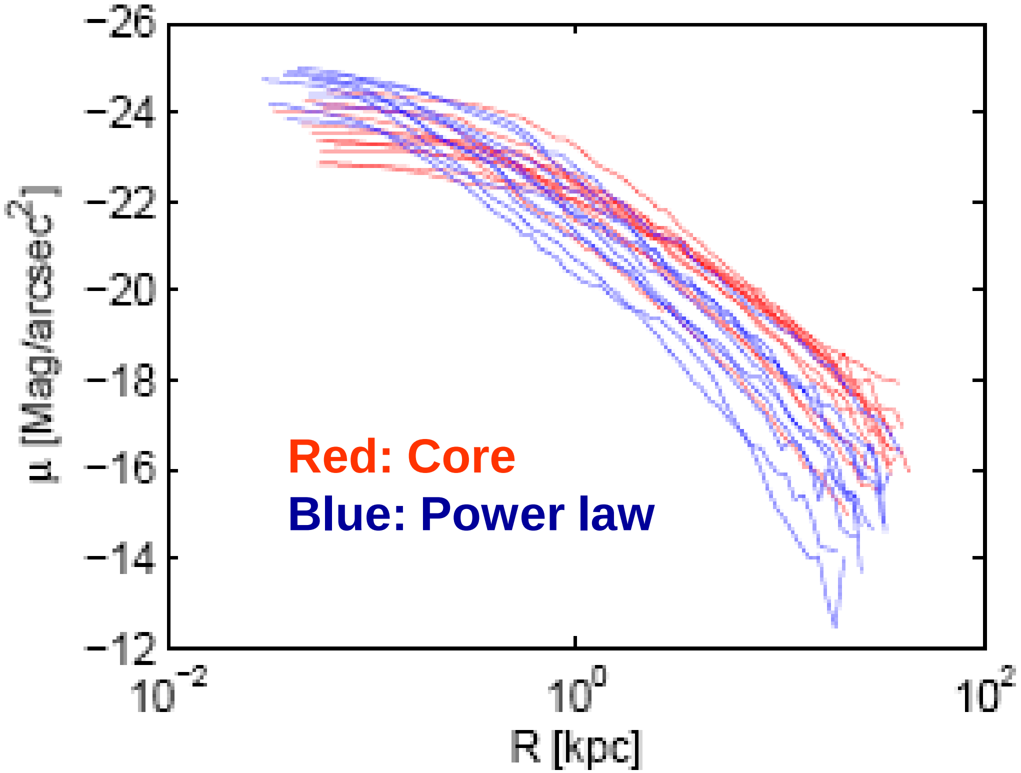
From the HST images we get more info …..

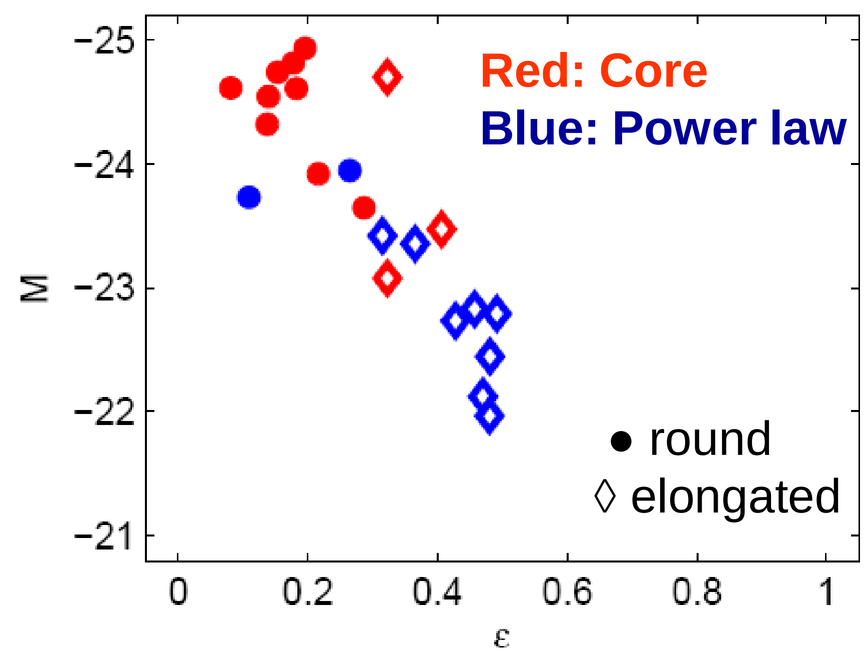
Hyde et al. 2008

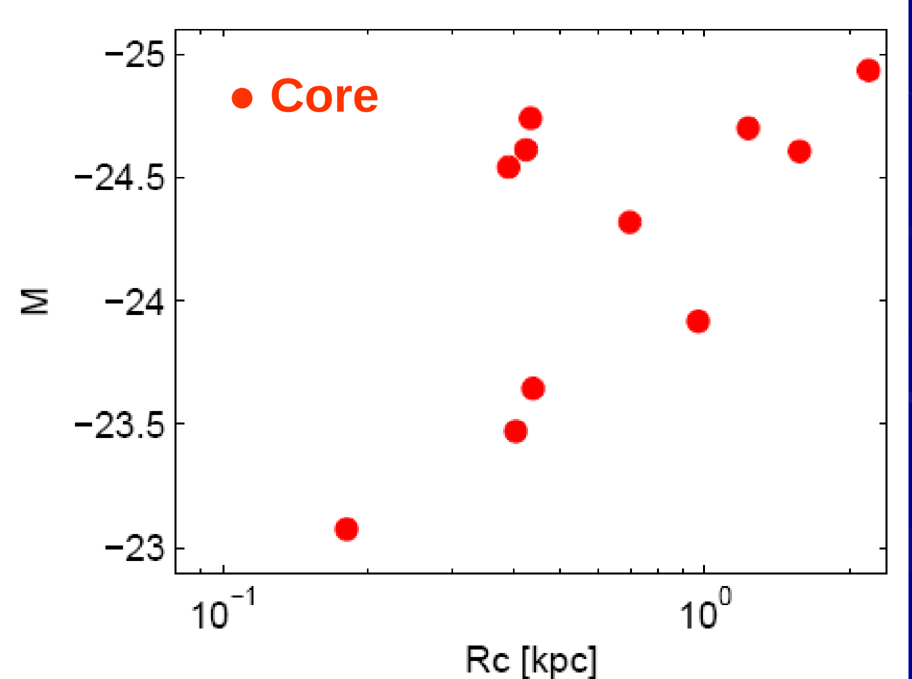


Nuker break radius

Hyde et al. 2008



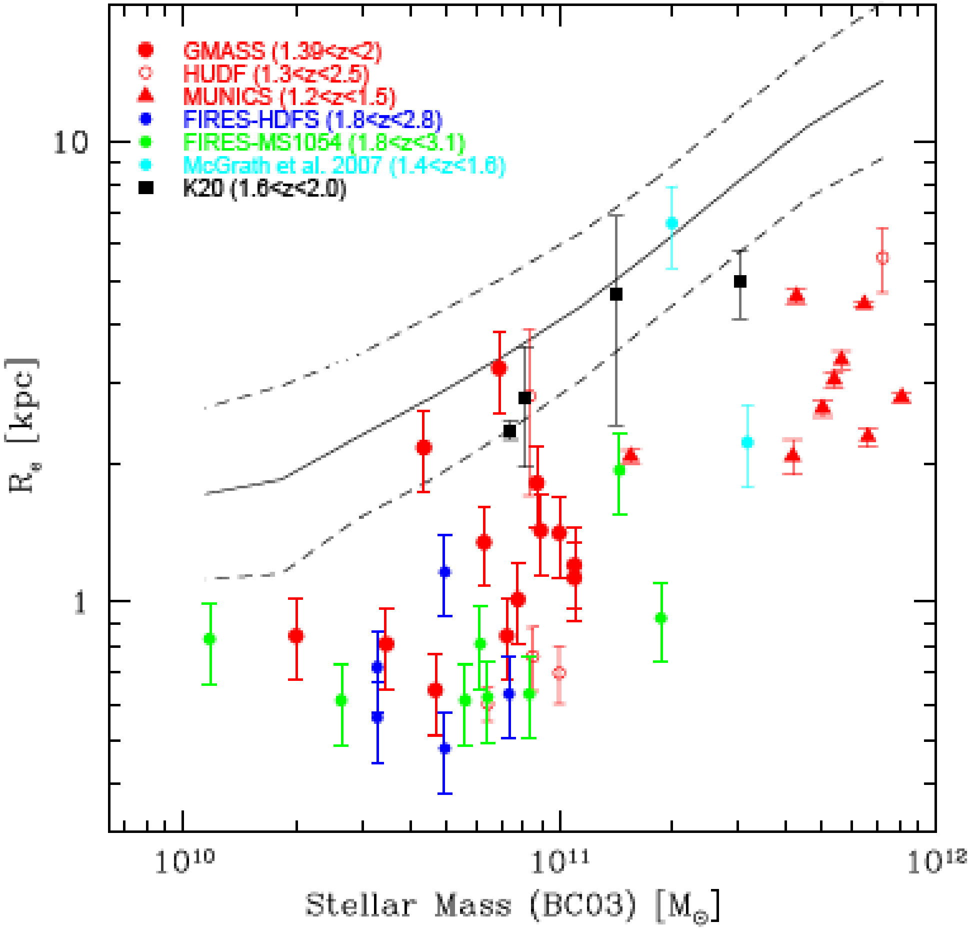


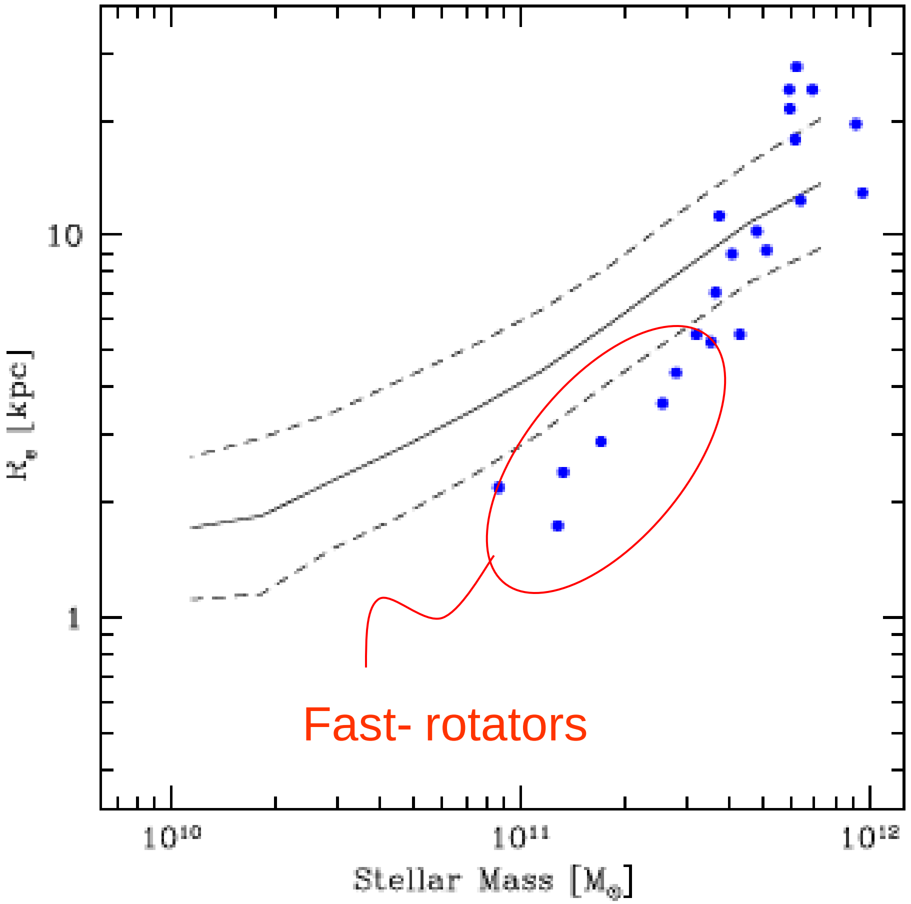


About the smaller sizes at high-z

z~1.8 z ~ 0.2

Cimatti et al. 2008





Fast- rotators

Conclusions

- BCGs have larger than expected sizes, smaller than expected σ, and decreasing b/a with L
- Detected BCGs size evolution at low z -- evolution in σ!
- Curvature in Color, b/a, Col. Grad. vs M_* relation but NOT vs σ at $M_* > 2 \times 10^{11} M_o$
  - Consistent with dry merger formation history
  - Most easily understood if massive early-types grew from *major mergers* at some earlier time while BCGs can have had more dry *minor mergers* recently
- BigSigs – two types:
  - M_r<-23 Prolate BCGs seen along the longer axis (core central profile)
  - M_r>-23 Fast rotators – extremely dense – red color & high Mg2 (power-law central profile)

    -> large amount of dissipation

    -> high metallicity & dust