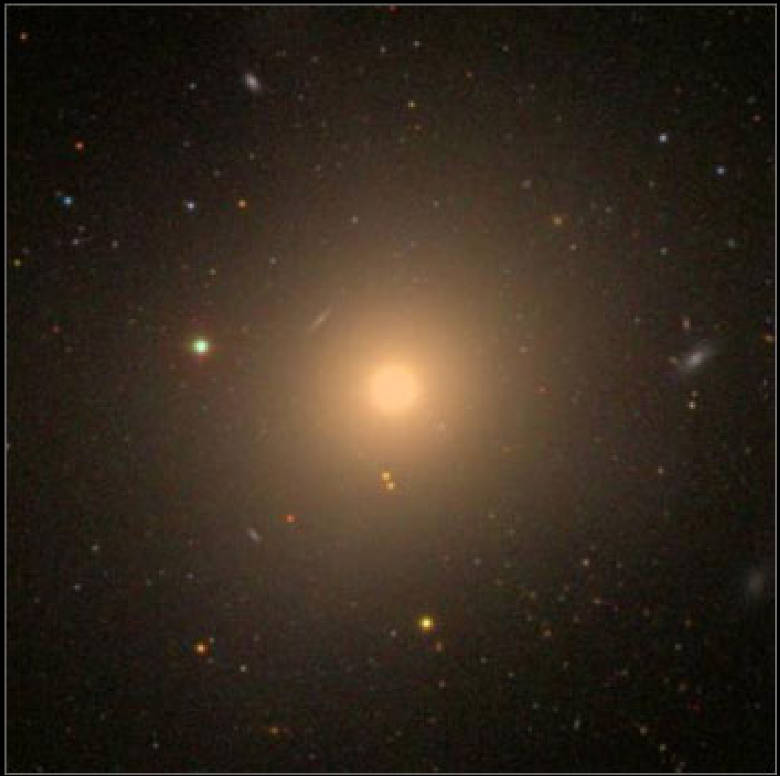
How have the massive galaxies evolved over cosmic time?

Nacho Trujillo

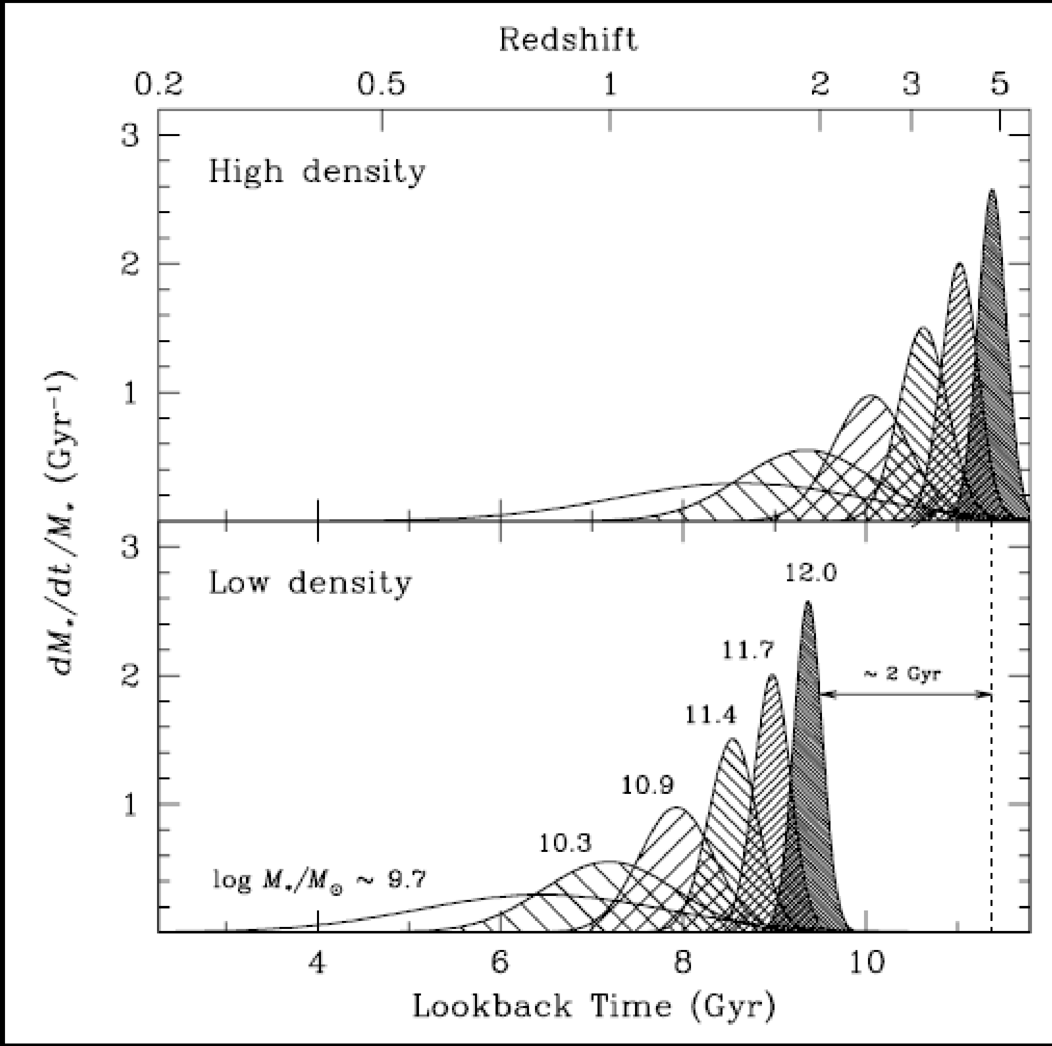
Instituto de Astrofísica de Canarias

Massive galaxies today



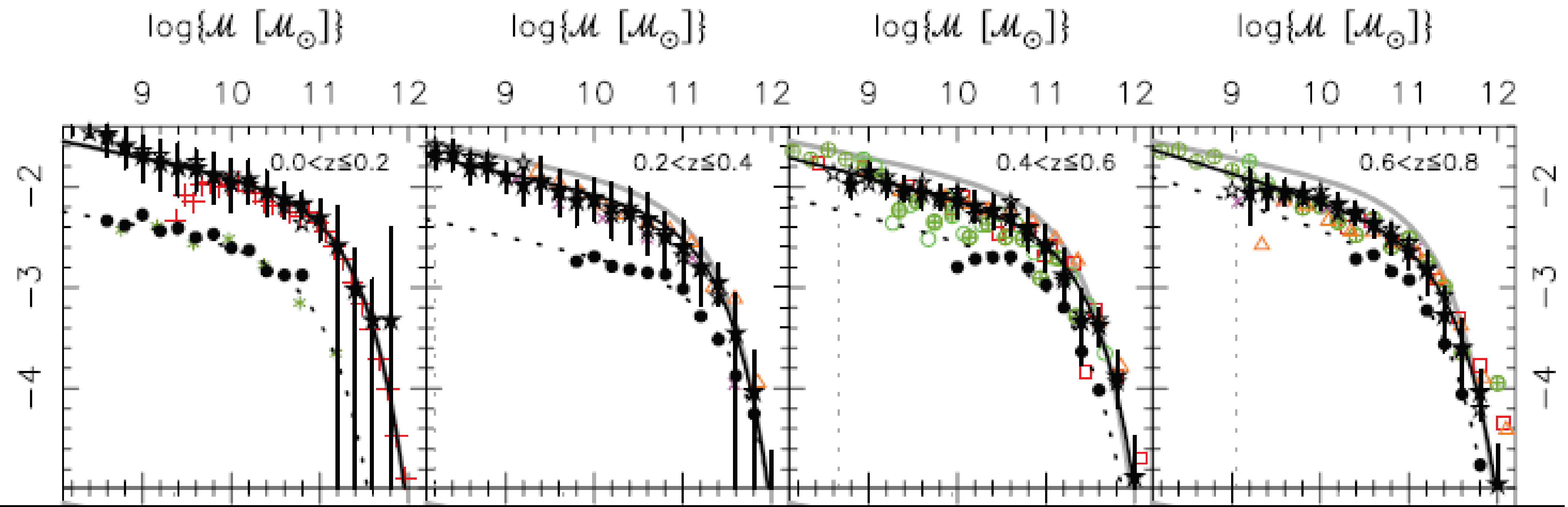
$M_* \geq 10^{11} M_{sun}$ galaxies:

- Morphological Type: 75% early-type
- Stellar populations: old, metal rich, short formation time scale
- Sizes: big objects r_e~5 kpc



Thomas et al. (2005)

Mild stellar mass function evolution for the most massive galaxies since z~0.8



Pérez-González et al. (2008)

Just a passive evolution of the most massive galaxies?

The evidence both from:

-Stellar population analysis in the present Universe

-Number density evolution of massive galaxies

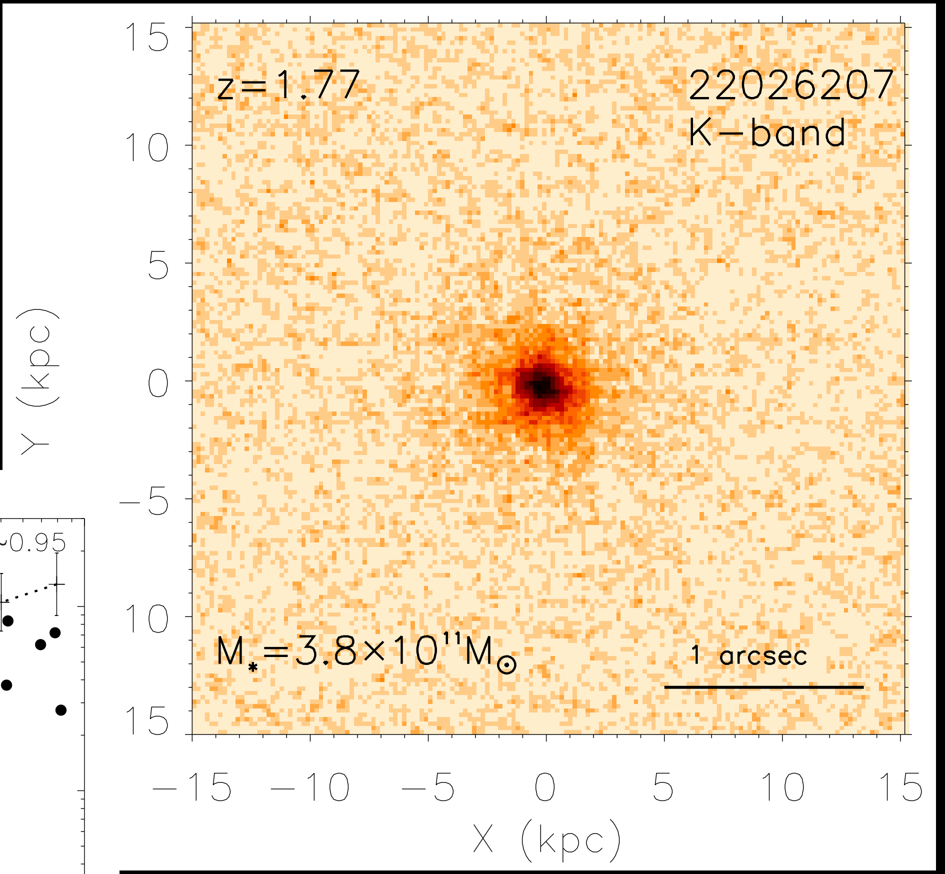
Suggest a monolithic-like formation and passive evolution scenario…

However…

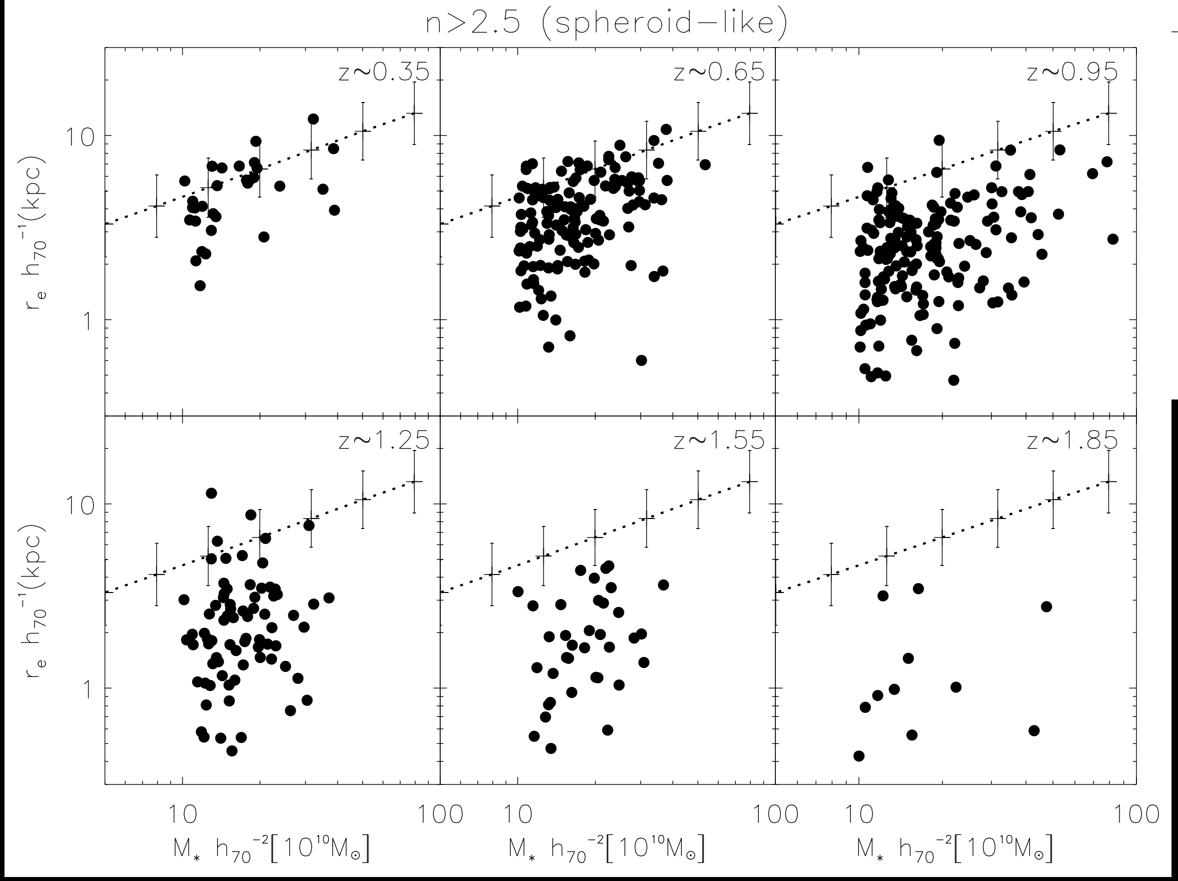
Massive galaxies at z~1.8

$M_{*} \geq 10^{11}$Msun galaxies:

- Morphological Type: mixed
- Stellar populations: ~1 Gyr, metal rich?, short formation time scale?
- Sizes: compact objects r_e~1.5 kpc



Carrasco et al. (2010)

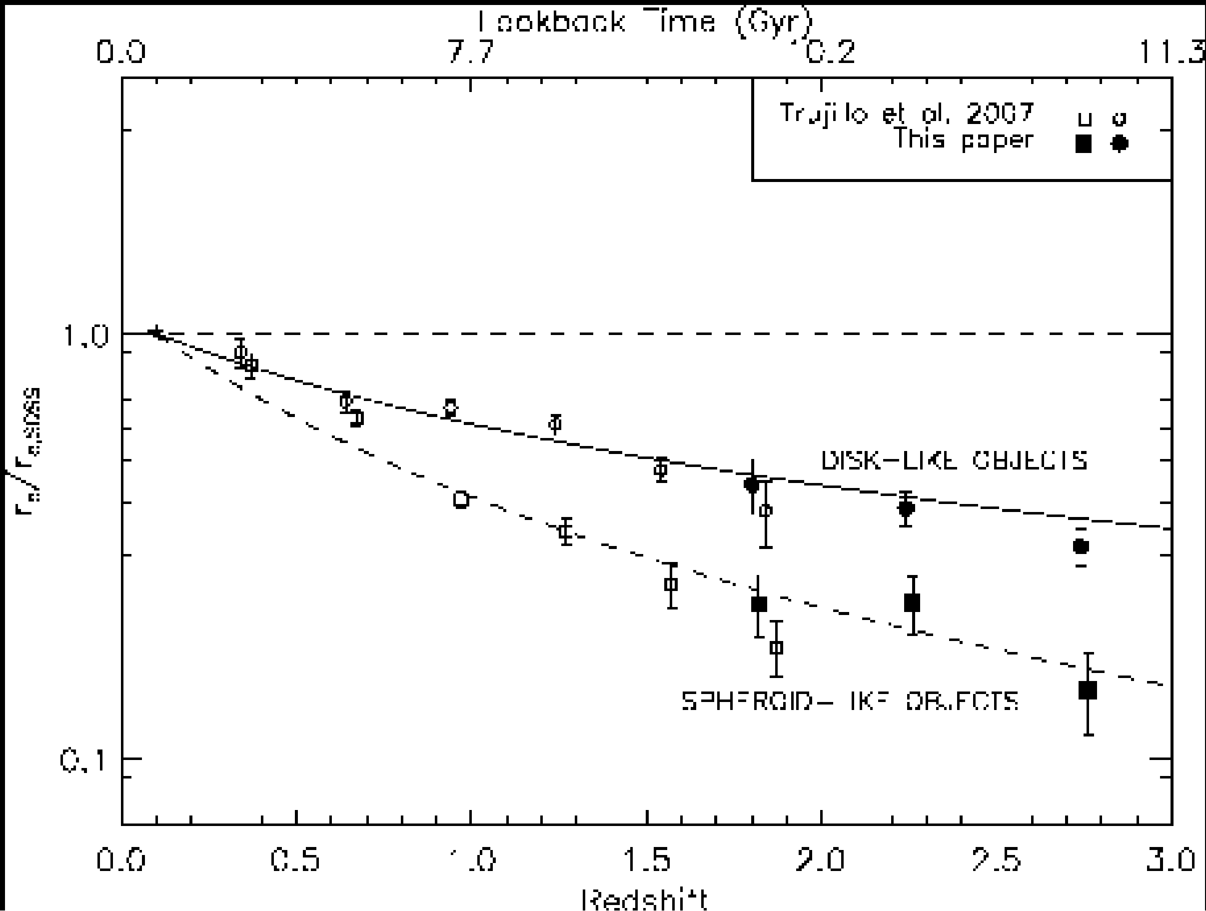


Trujillo et al. (2007)

Massive galaxies at z~1.8

$M_* \geq 10^{11} M_{sun}$ galaxies:

- Morphological Type: mixed
- Stellar populations: ~1 Gyr, metal rich?, short formation time scale?
- Sizes: compact objects r_e~1.5 kpc



Stellar density at z~2:
~2x10¹⁰Msun/kpc³
(Buitrago al. 2008)

How robust is the size evolution result?

How robust is the size evolution result?

The two possible sources of uncertainty are the size and the stellar mass estimates (e.g. see a critical discussion in Mancini et al. 2010).

Size estimates:

1. *Repeatability*:

-Daddi et al. (2005); HST ACS (Hubble Ultra Deep Field)

-Trujillo et al. (2006); Ground-based NIR

-Trujillo et al. (2007); HST ACS and NICMOS

-Cimatti et al. (2008); HST ACS

-Zirm et al. (2007); Toft et al. (2007); Longhetti et al. (2007); Damjanov et al. (2008); van Dokkum et al. (2008); Buitrago et al. (2008)… HST NICMOS

-Cassata et al. (2009); Szomoru et al. (2010); HST WFC3 (Hubble Ultra Deep Field)

-Carrasco et al (2010); K-band Gemini AO imaging

… and many more…

How robust is the size evolution result?

The two possible sources of uncertainty are the size and the stellar mass estimates.

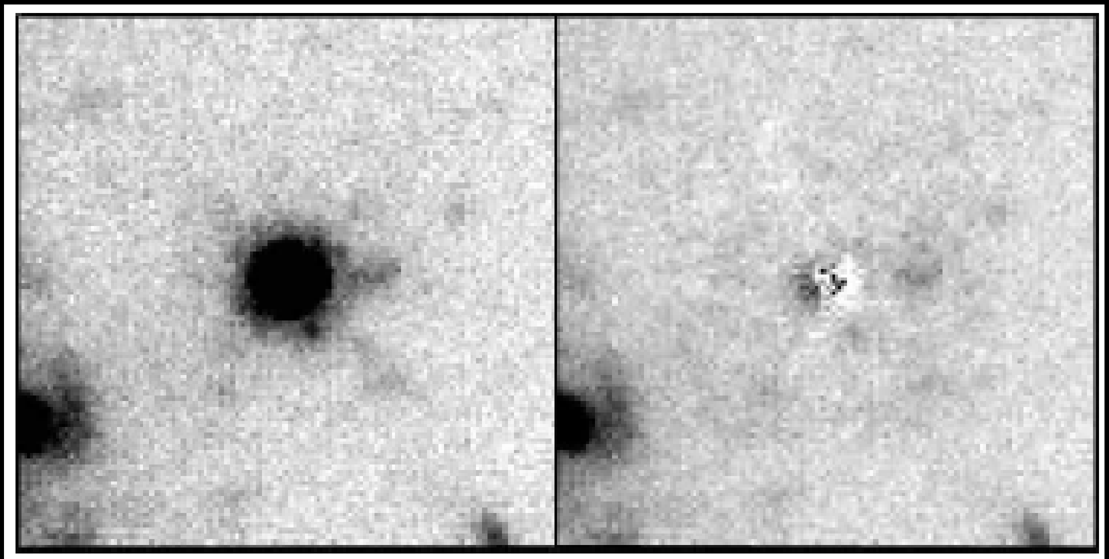
Size estimates:

2. *No evidence for large-scale diffuse halo (after stacking)*:

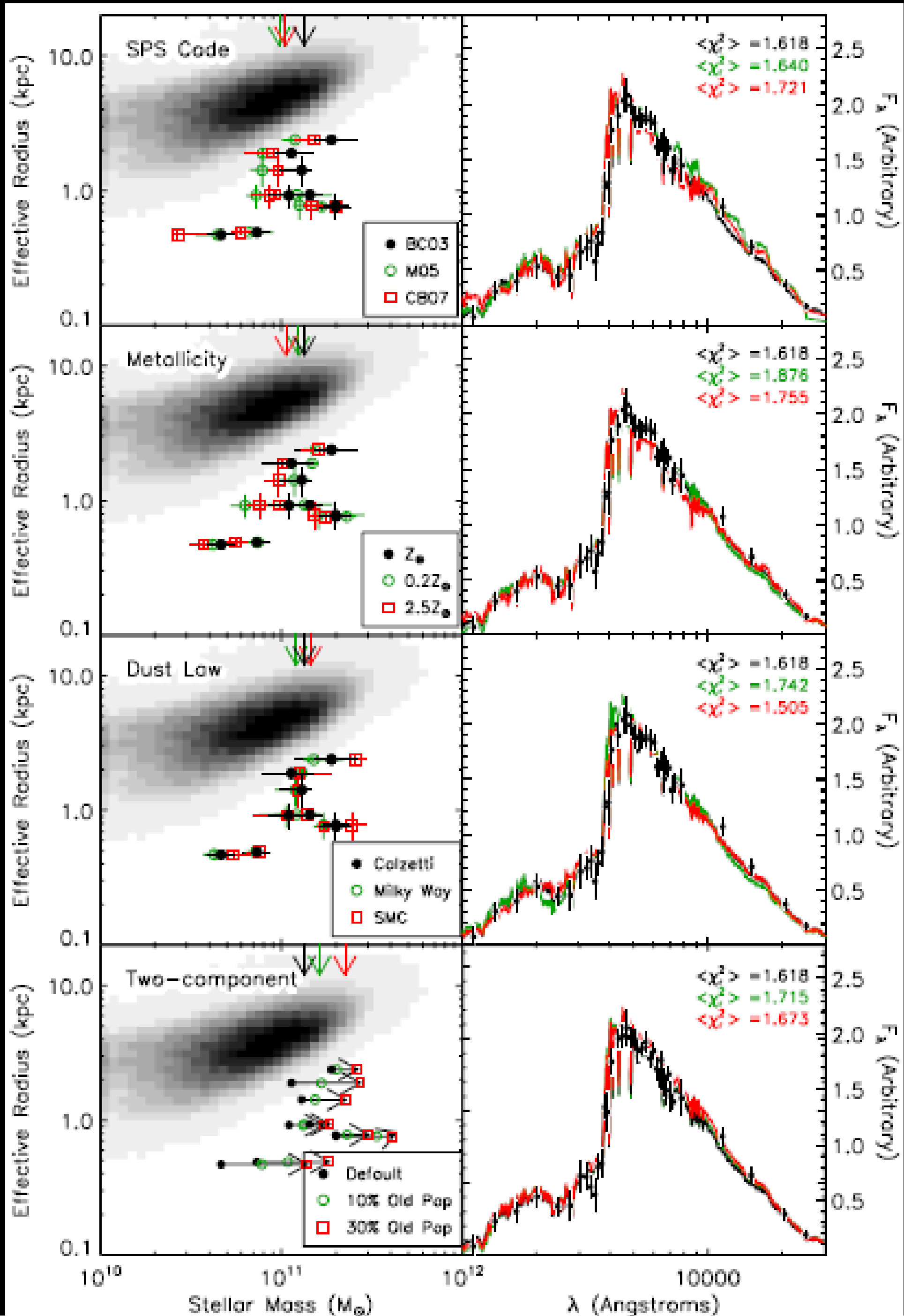
-Zirm et al. (2007); HST NICMOS 14 objects (~26 mag/arcsec^2)

-van Dokkum et al. (2008); HST NICMOS 9 objects (~27 mag/arcsec^2)

-Cassata et al. (2009); HST WFPC3 (~26.3 mag/arcsec^2 per object)



How robust is the size evolution result?



The two possible sources of uncertainty are the size and the stellar mass estimates.

Stellar mass estimates:

3. *Robust to changes in metallicities, dust laws, different stellar population codes* *(Muzzin et al. 2009)*

How robust is the size evolution result?

The two possible sources of uncertainty are the size and the stellar mass estimates.

4. Dynamical mass estimates:

-The first velocity dispersion estimate (Cenarro & Trujillo 2009) found ~240 km/s

-Later estimates have found similar values (e.g. Cappellari et al. 2009; Onodera et al. 2010; van de Sande et al. 2011) or even larger (~500 km/s; van Dokkum et al. 2009)

Models for spheroid size evolution

Models for spheroid size evolution

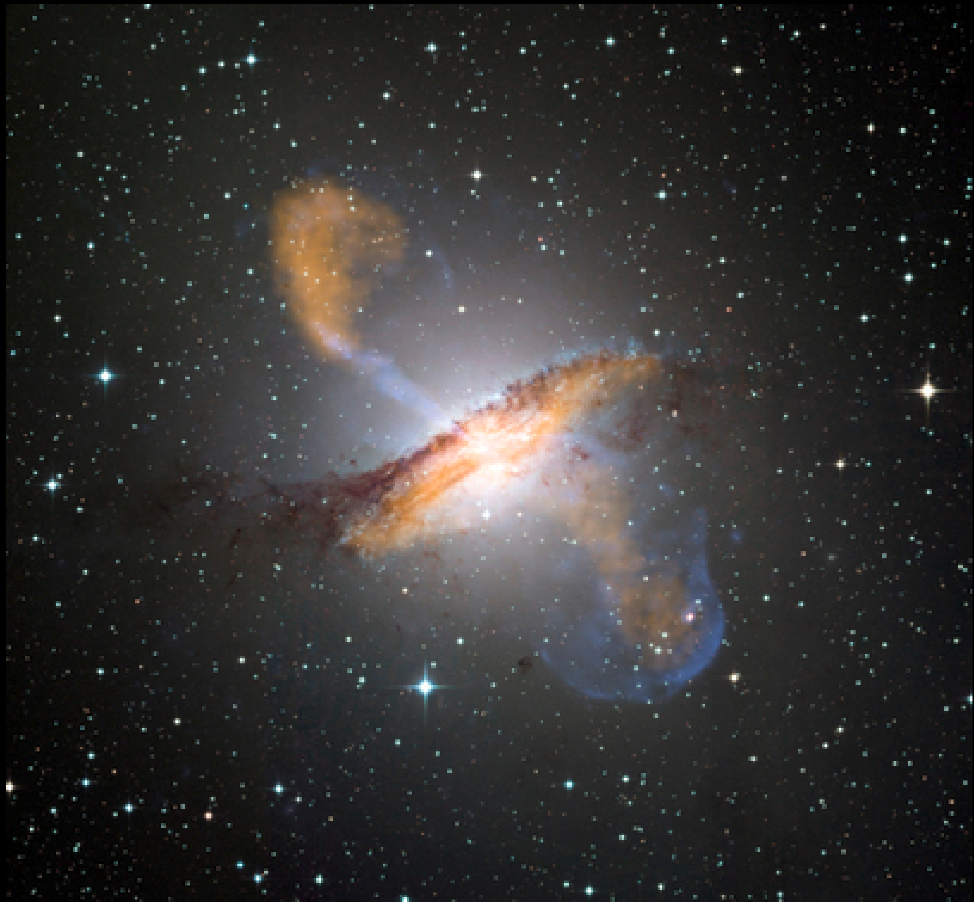
a) Puffing-up: AGN activity removes gas from the galaxies and puff-up their structures (Fan et al. 2008;2010)

b) Major dry mergers: spheroid-spheroid re-mergers (e.g. Ciotti & van Albada 2001; Boylan-Kolchin et al. 2006; Naab et al. 2007; Nipoti et al. 2010)

c) Minor/Late merging: progressive infall of minor satellites with low-effective density (e.g. Khochfar & Burkert 2006; Maller et al. 2006; Hopkins et al. 2009; Naab et al. 2009; Oser et al. 2010)

Models for spheroid size evolution

Puffing-up (Fan et al. 2008;2010):AGN activity removes gas from the galaxies and puff-up their structures.

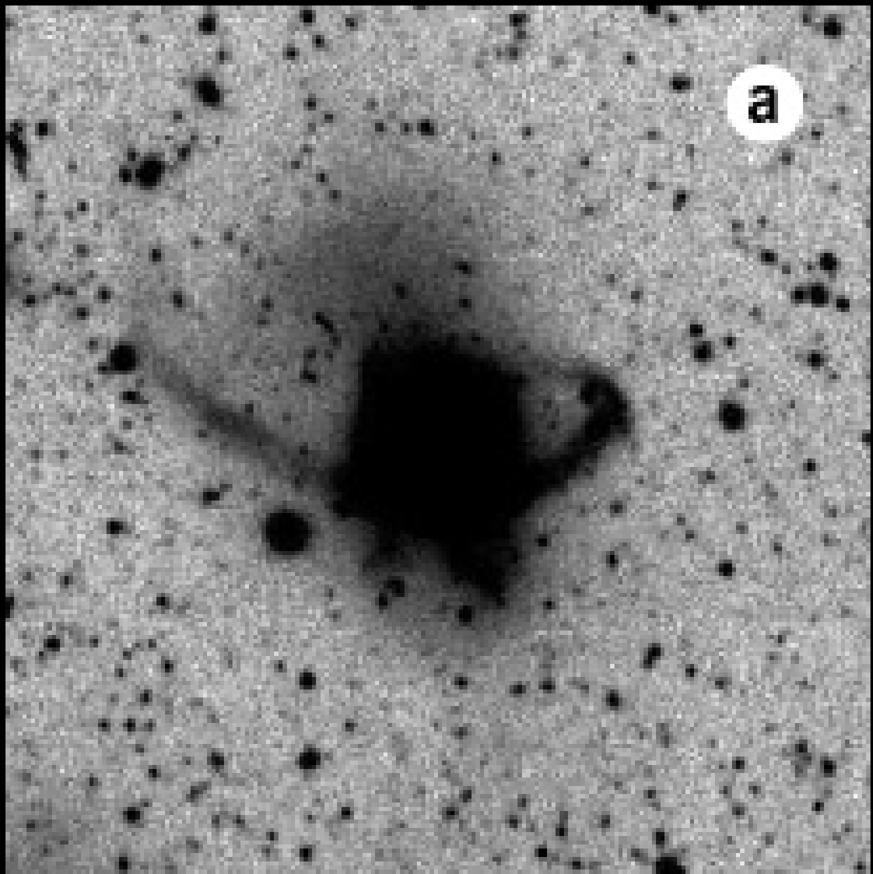


Predictions:

- No stellar mass increase
- Very fast (<1 Gyr) size evolution
- Strong decrease in the velocity dispersion (400 km/s -> 200 km/s)
- Difference in size between “old” (>1 Gyr) and “young” (<1 Gyr) spheroids at a given redshift

Models for spheroid size evolution

Minor/Late accretion: progressive infall of minor satellites with low-effective density (e.g. Khochfar & Burkert 2006; Naab et al. 2009)



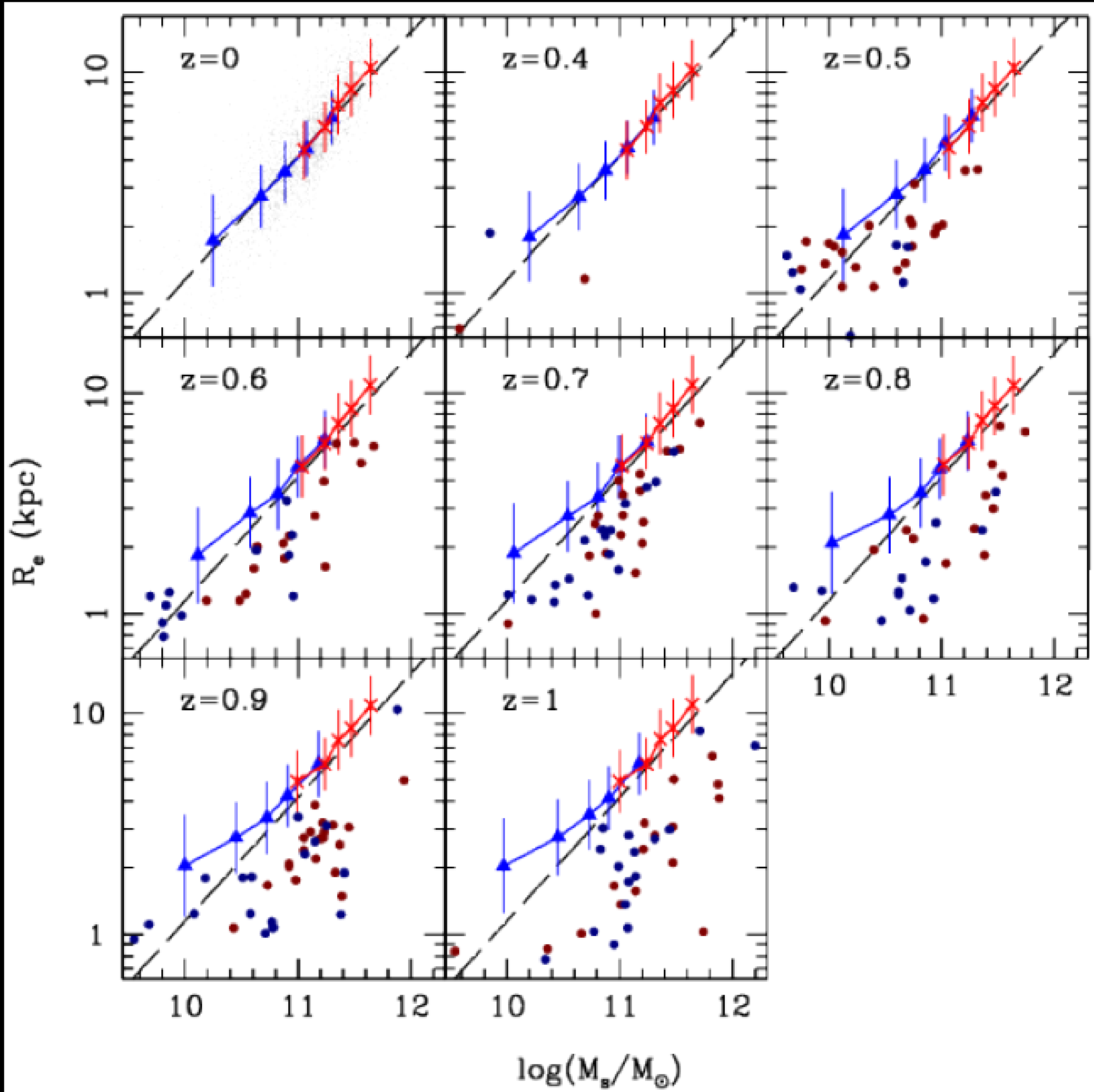
Predictions:

- Stellar mass increase
- Continous size evolution
- Mild decrease in the velocity dispersion
- No difference in size between old and young spheroids at a given redshift

Observational Constraints

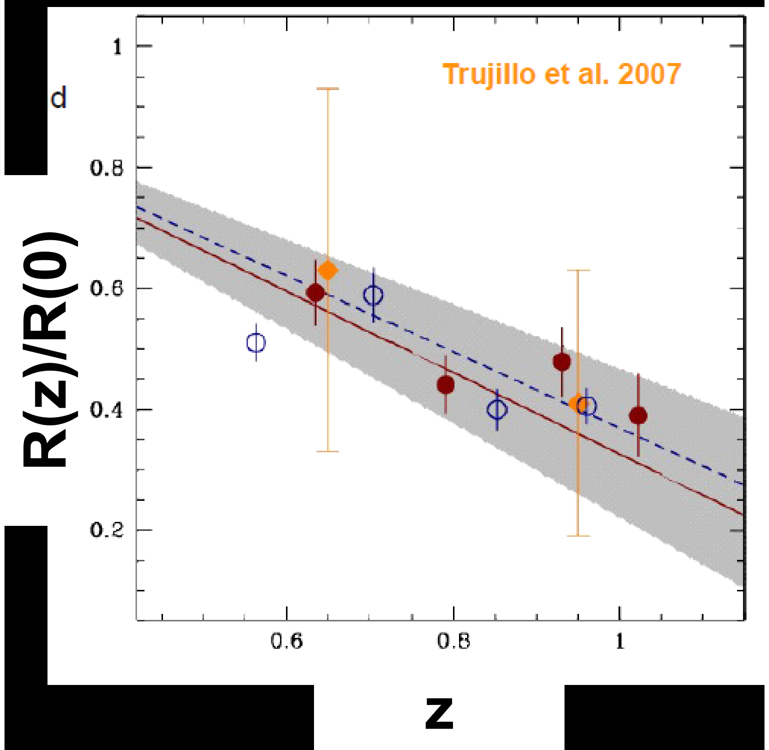
Size and stellar population age dependence

Size and stellar population age dependence



No mean size difference between old and young spheroids at each z

Disfavour puffing-up model

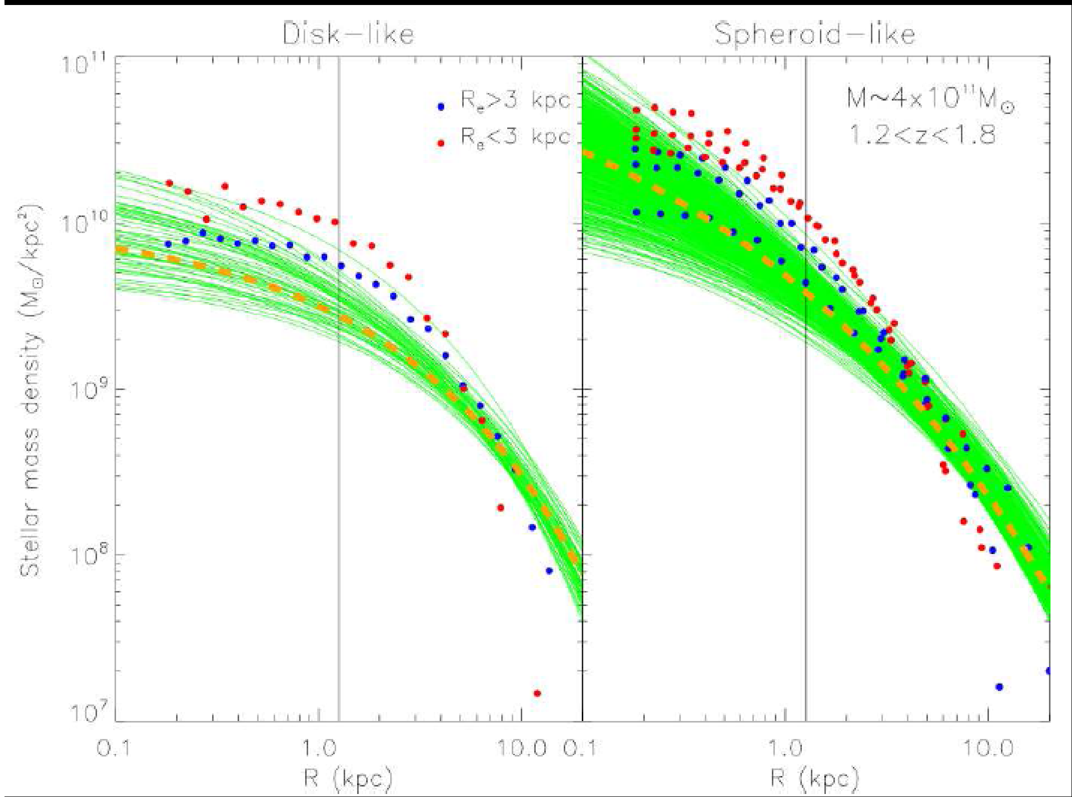


Trujillo et al. (2011); but see a critical view in Saracco et al. (2011)

Stellar mass density profile evolution

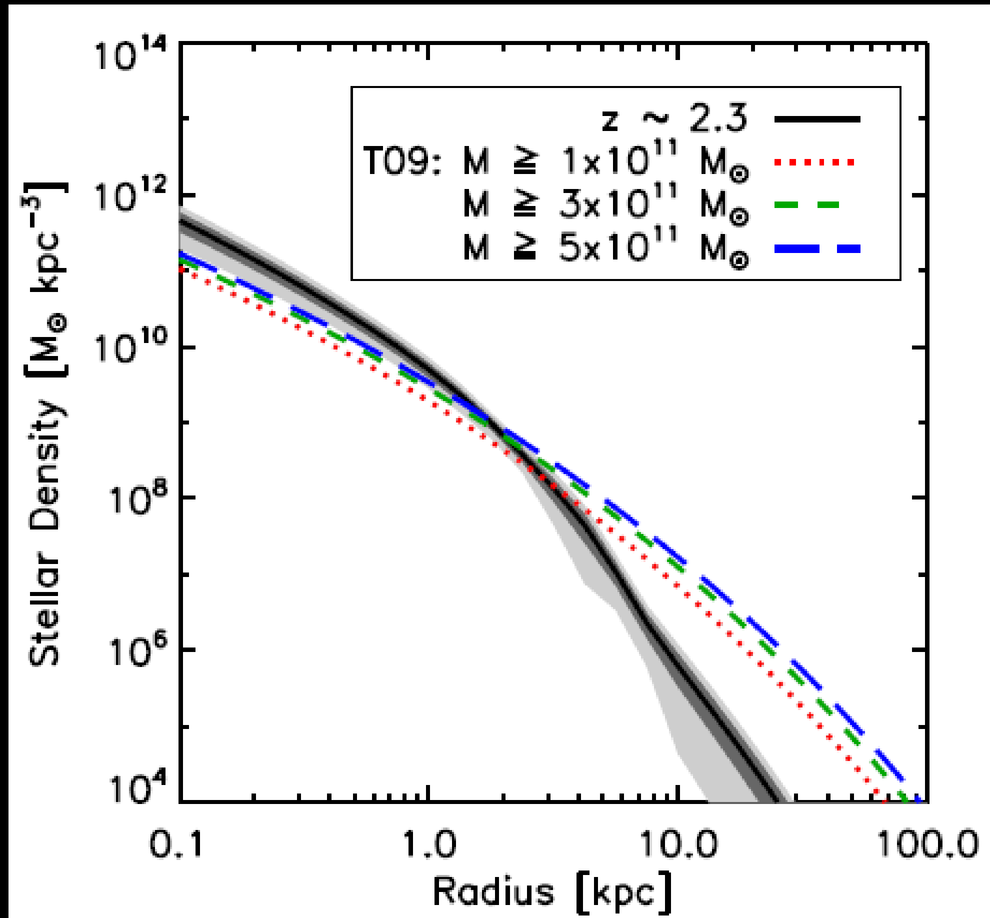
Stellar mass density profiles evolution

Individual galaxies



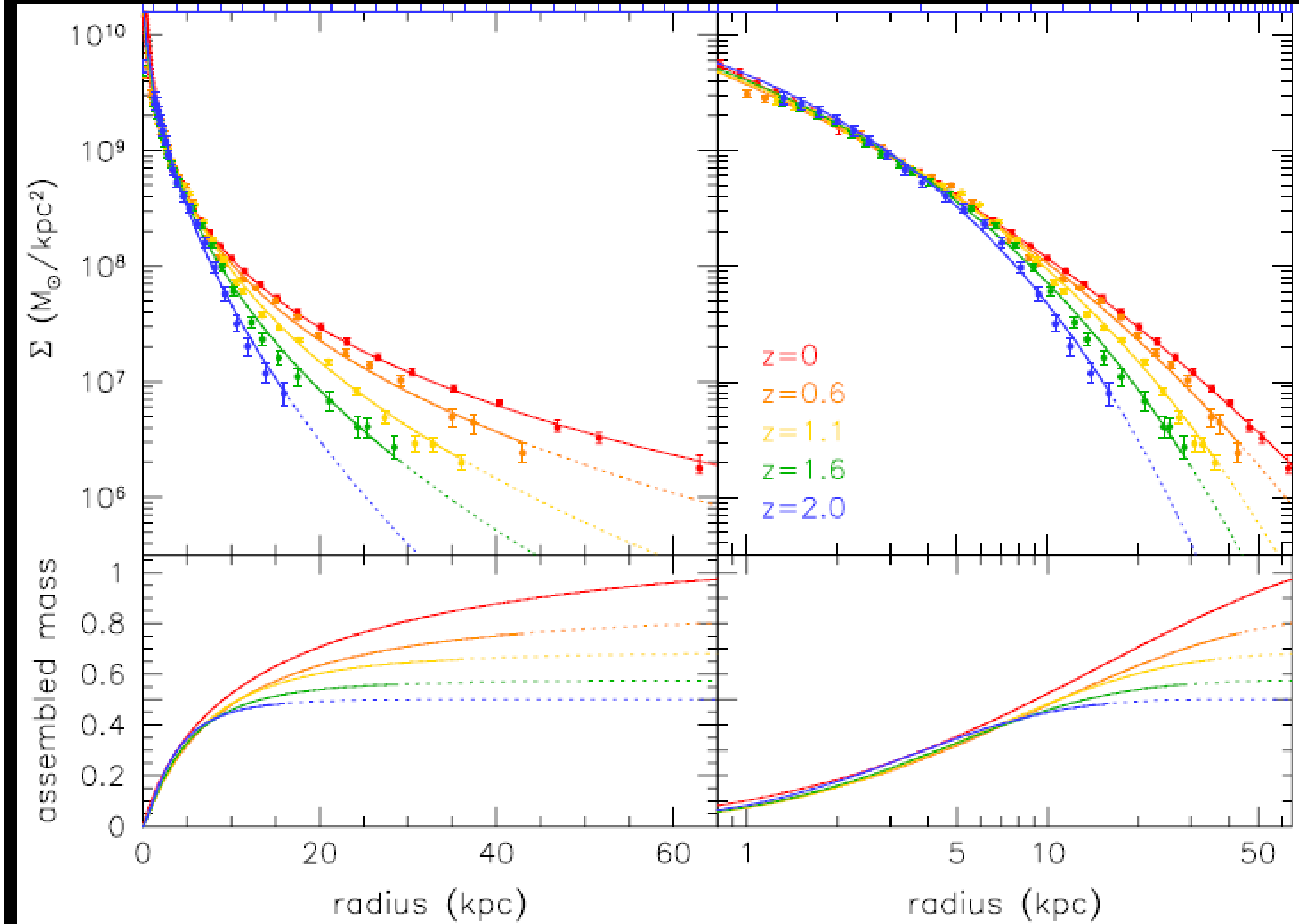
Carrasco et al (2010)

Stacked galaxies



Bezanson et al. (2009); Hopkins et al. (2009)

Stellar mass density profiles evolution



Progressive and steady formation of outer galaxy envelopes

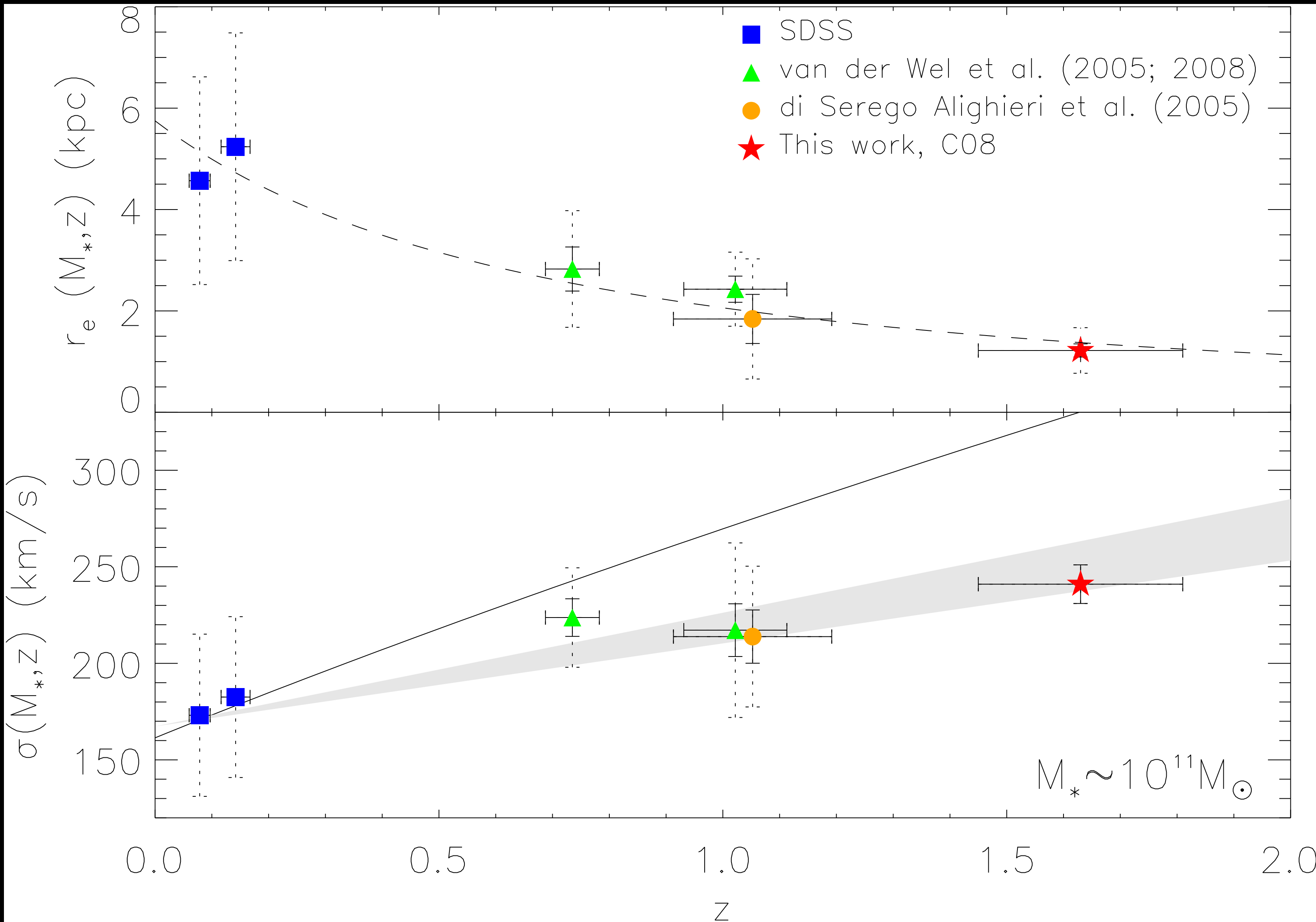
Disfavour puffing-up model

Favour merging model

van Dokkum et al. (2010)

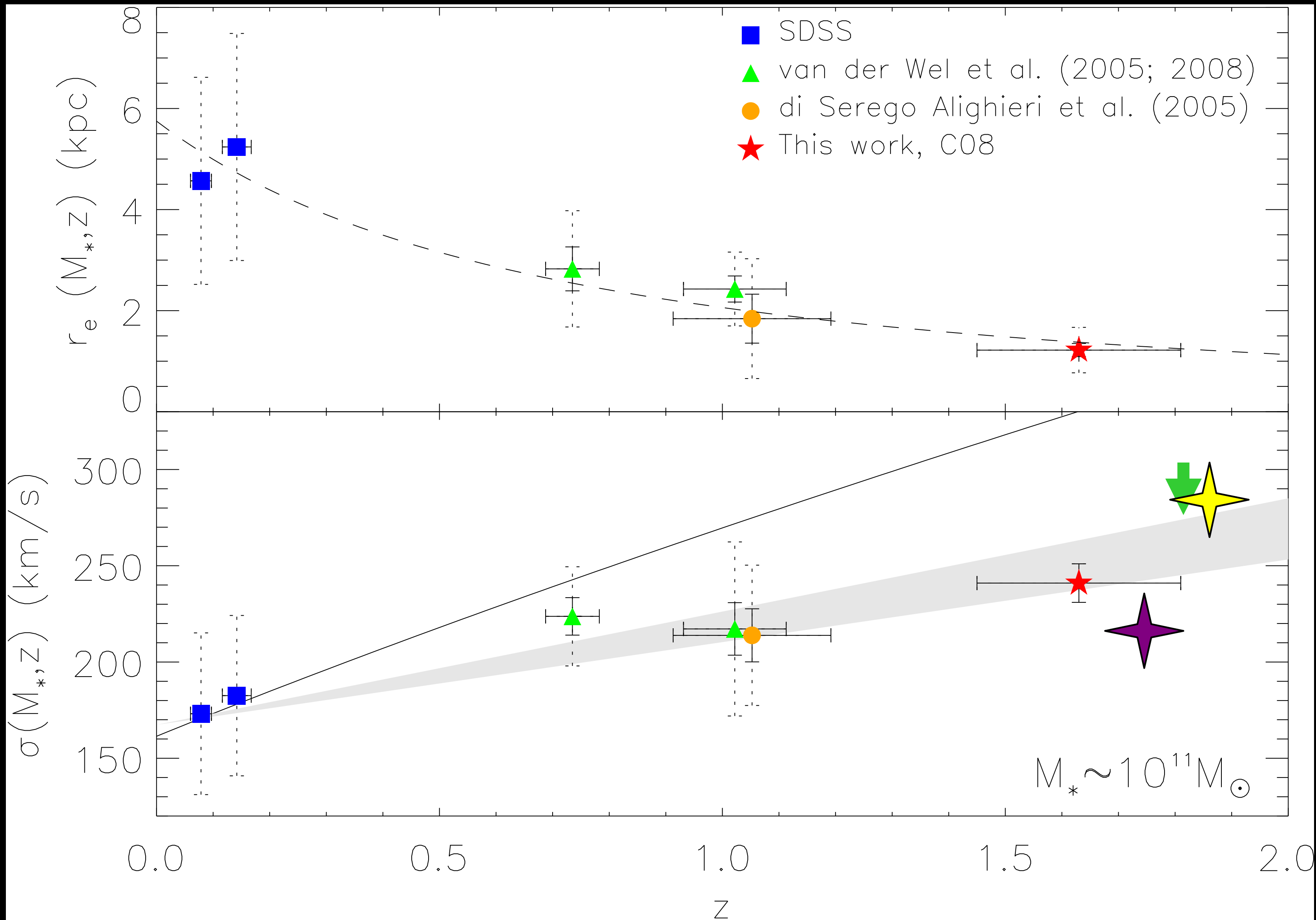
Velocity dispersion evolution

Velocity dispersion evolution



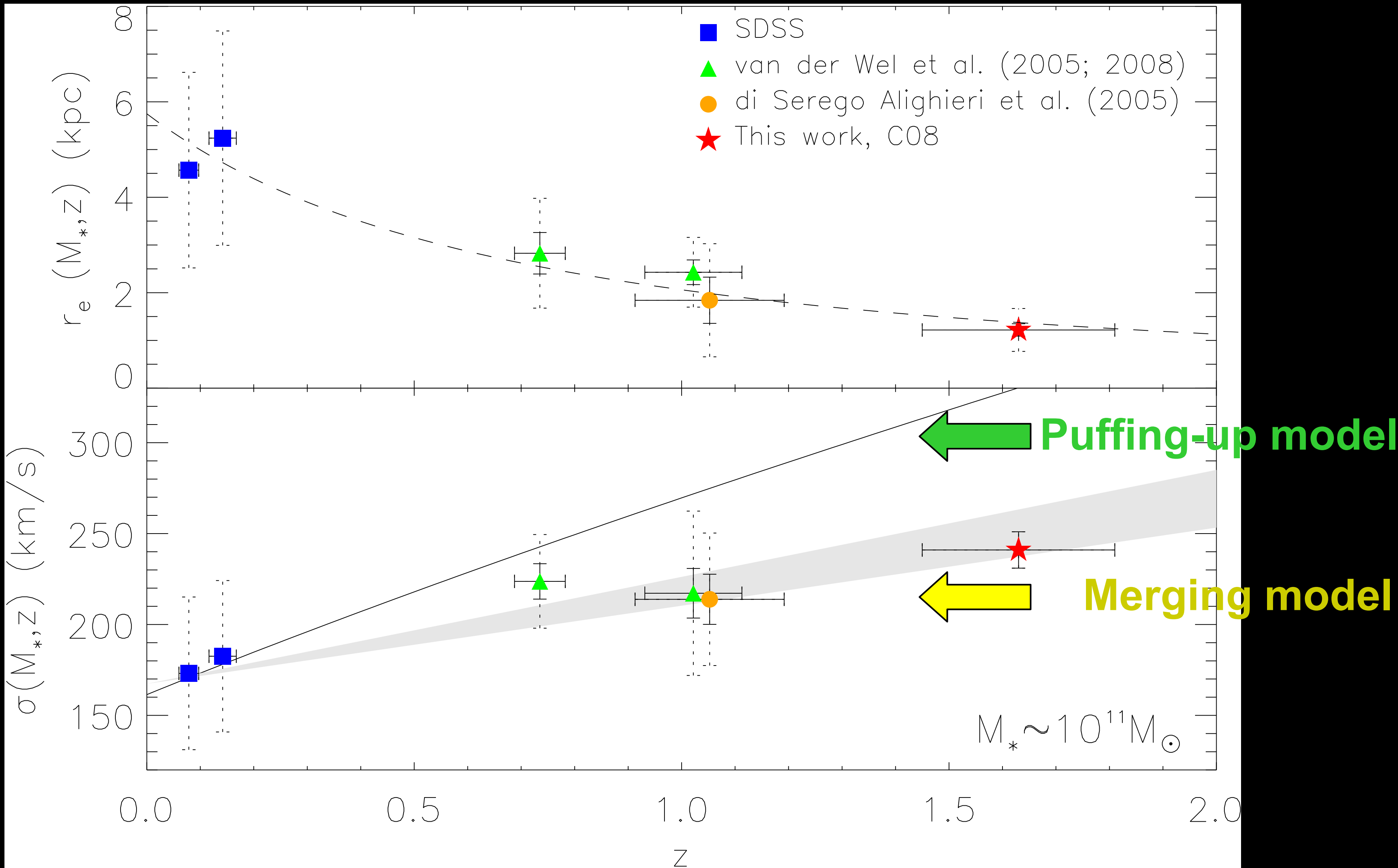
Cenarro & Trujillo (2009)

Velocity dispersion evolution



Cenarro & Trujillo (2009); Onodera et al. (2010);
Cappellari et al. (2009); van de Sande et al (2011)

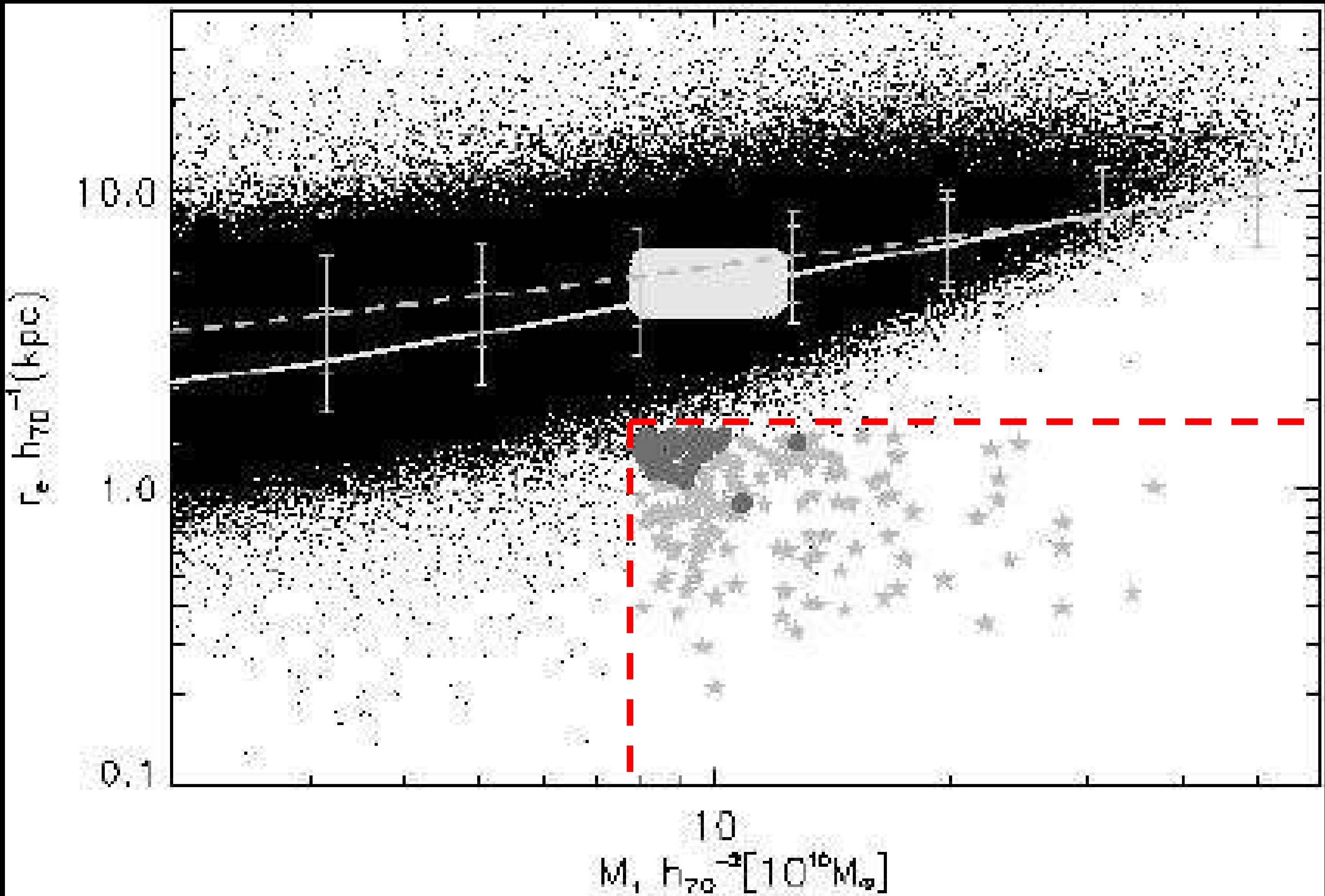
Velocity dispersion evolution



Cenarro & Trujillo (2009)

Compact massive galaxies at $z\sim0$

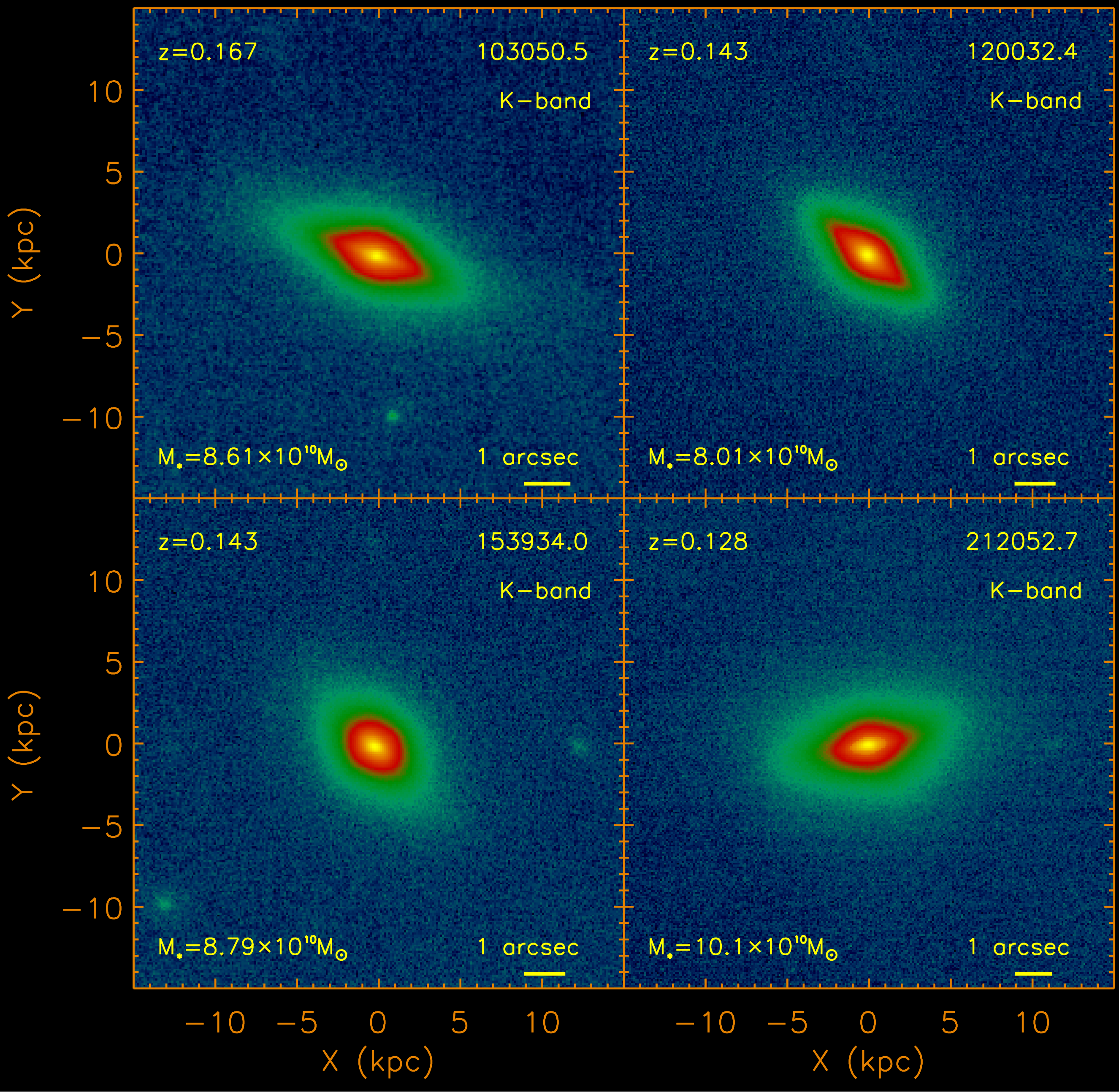
Compact massive galaxies at z~0



<0.03% of today massive galaxies are compact

Trujillo et al. (2009); Taylor et al (2010); but see Valentinuzzi et al (2010)

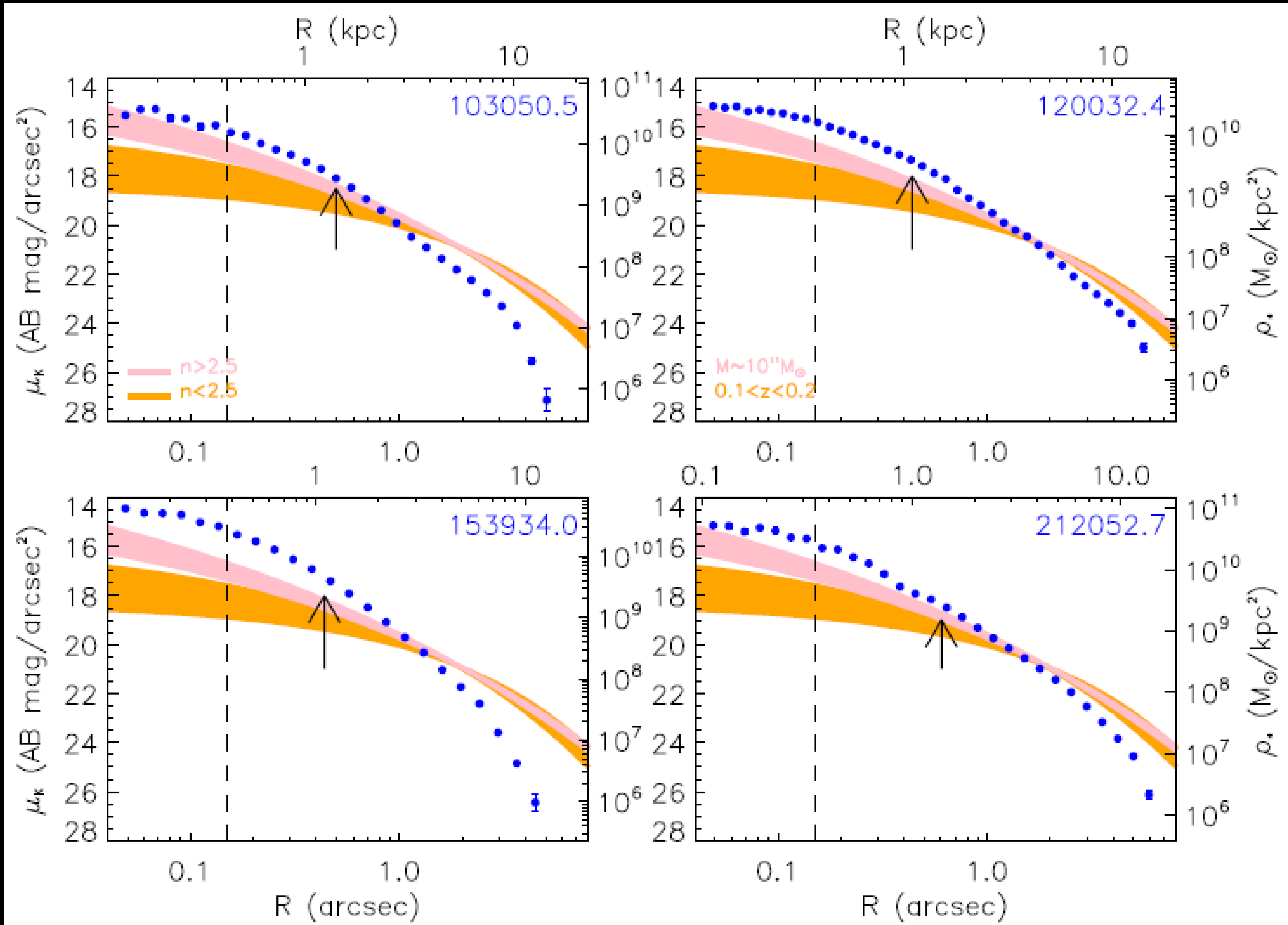
A high resolution view of local compact massive galaxies



-K-band imaging at 0.15 arcsec resolution with Gemini AO

Trujillo et al. (2011; in preparation)

A high resolution view of local massive compact galaxies

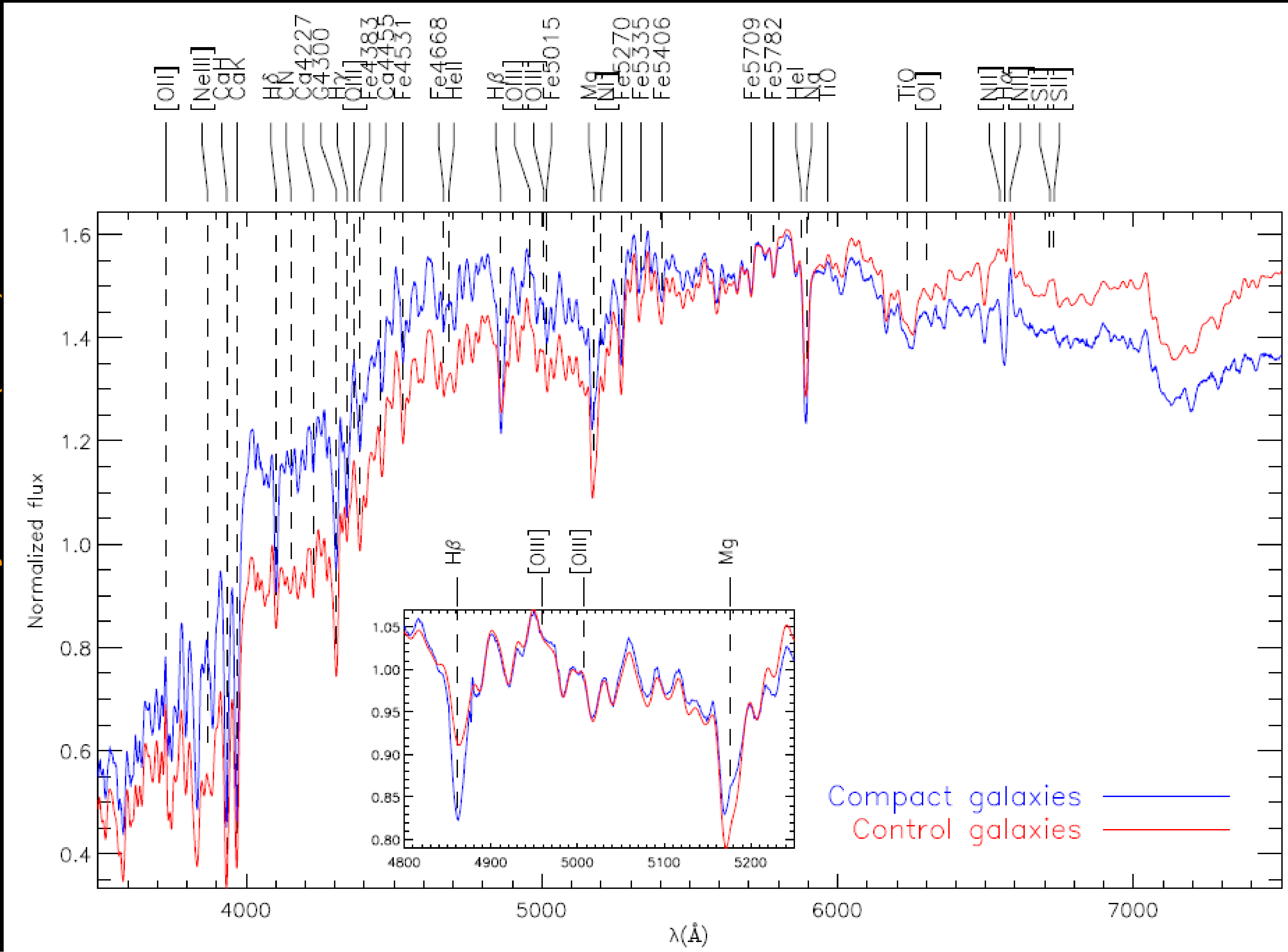


- Stellar mass density profile of massive compact galaxies compared to nearby normal massive galaxies

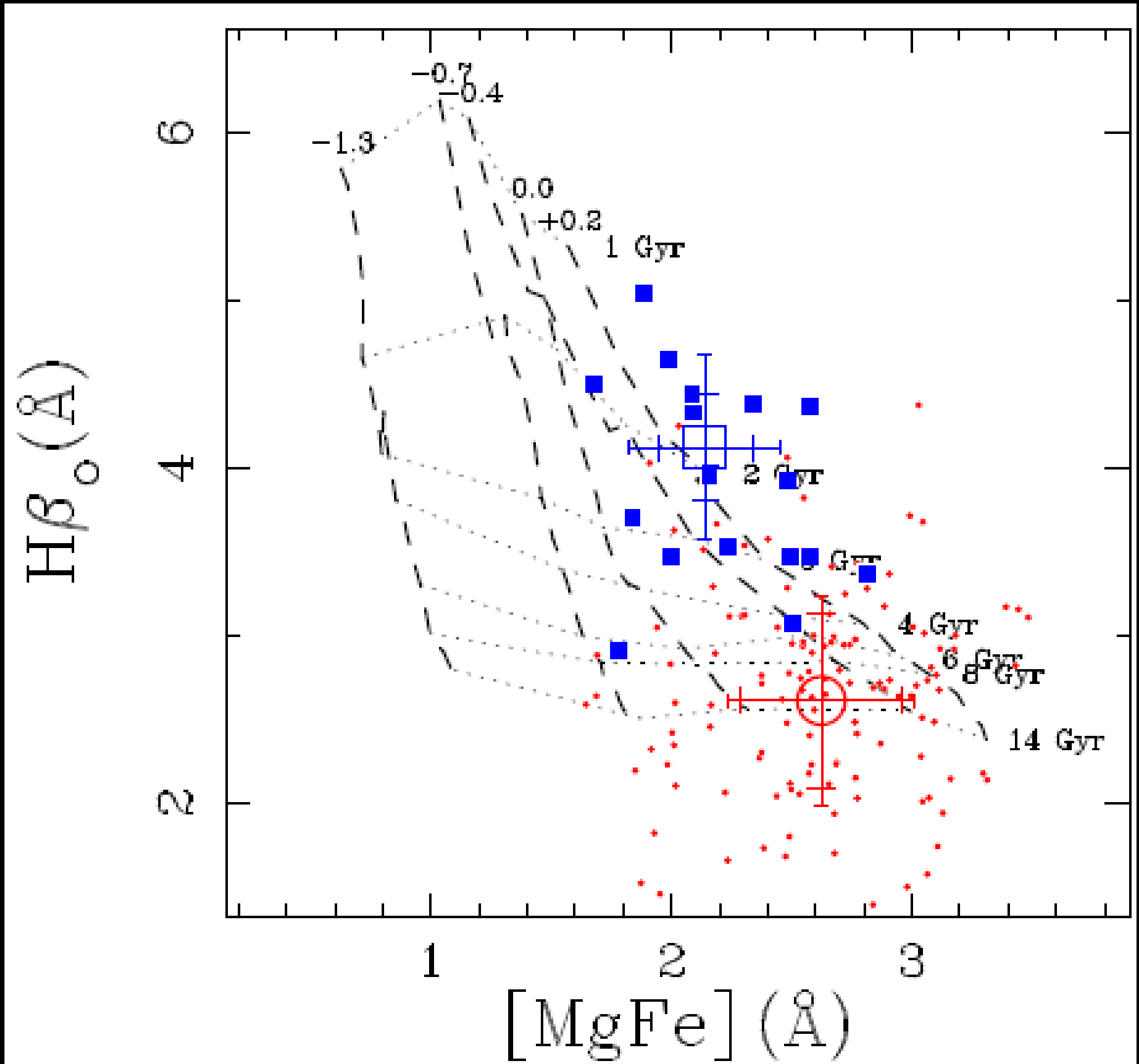
Trujillo et al. (2011; in preparation); Shih & Stockton (2011)

Compact massive galaxies at z~0

Trujillo et al. (2009)



Compact massive galaxies at z~0



-Massive compact galaxies at z~0 are relatively young (~2 Gyr)

Disfavour puffing-up model

-There are not compact massive relics today from the early universe

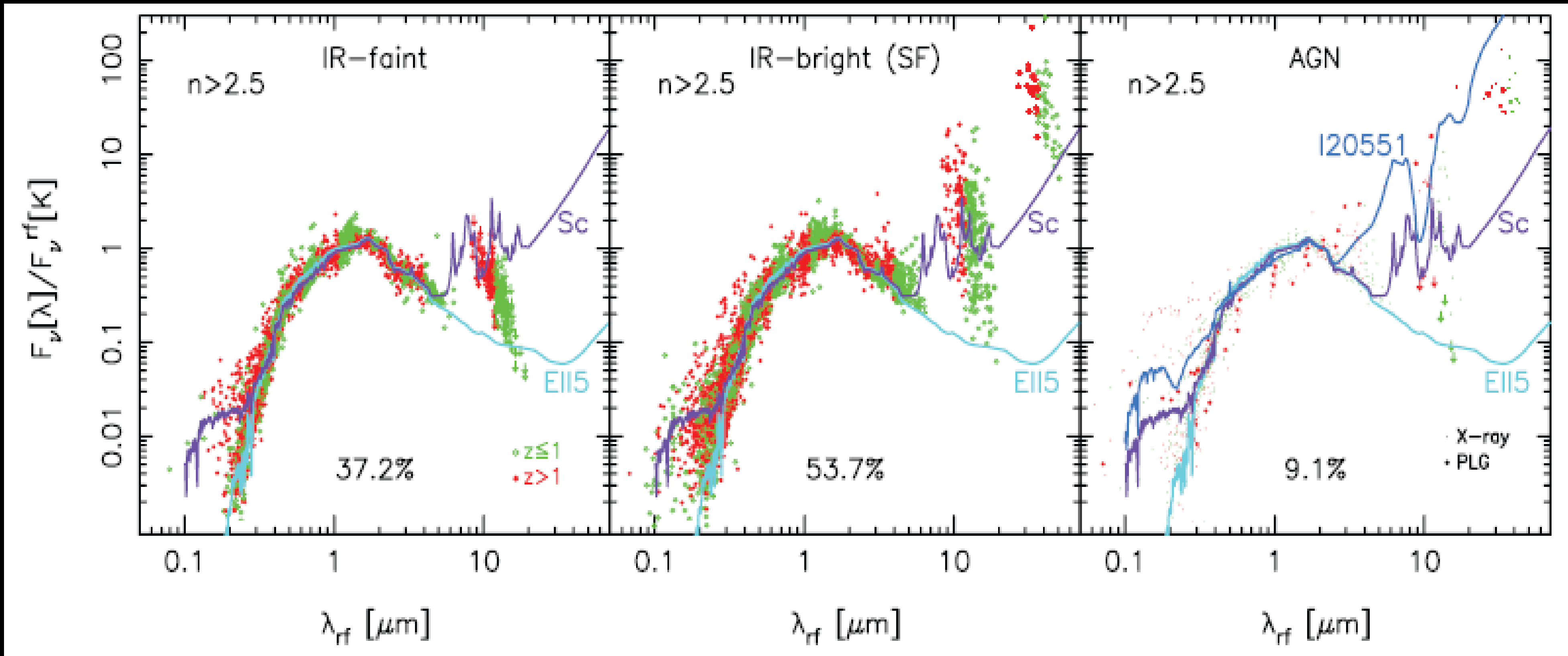
Disfavour merging model

Trujillo et al. (2009); Ferre et al. (2011; in prep)

Star formation histories of massive galaxies

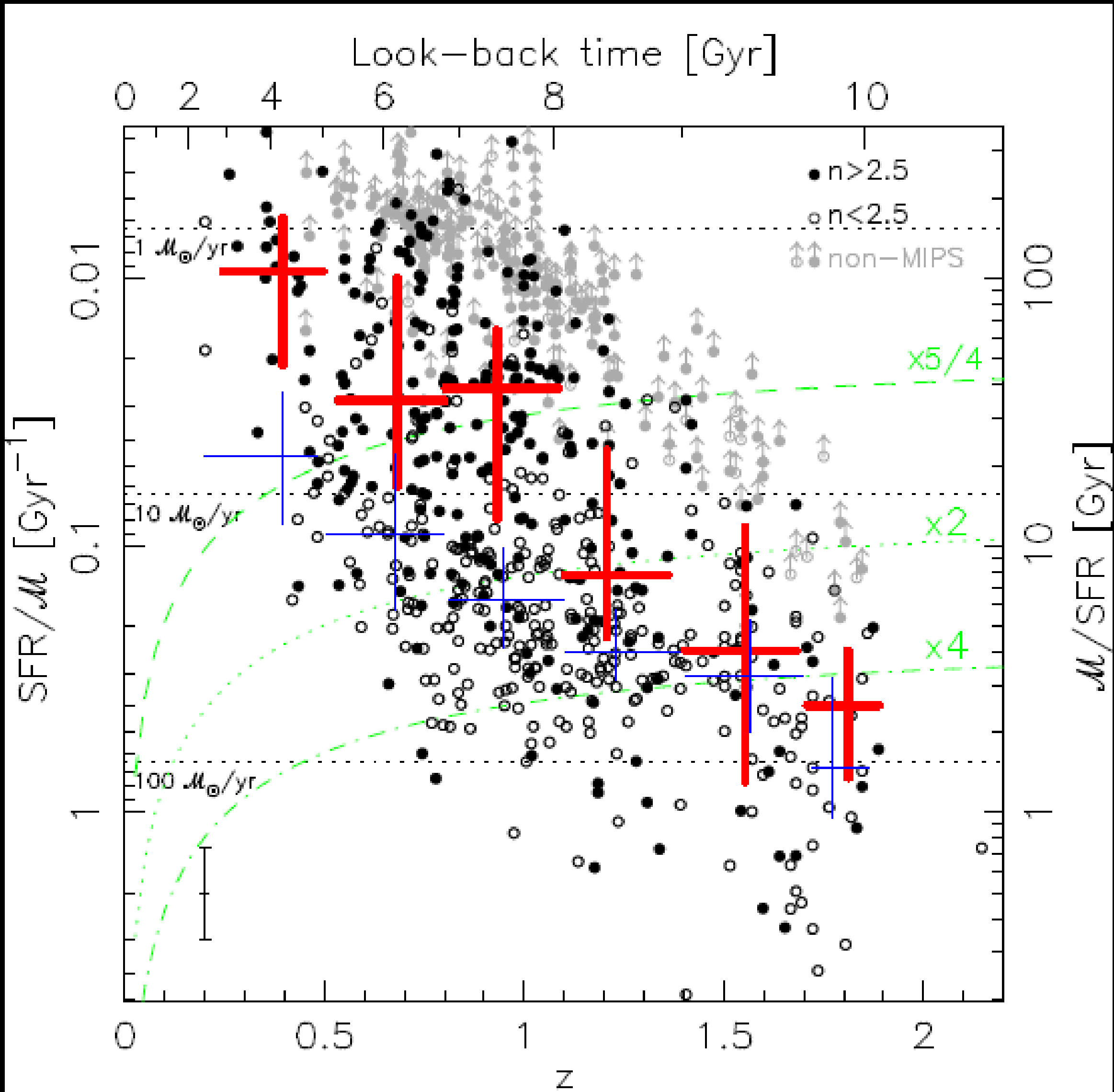
Star formation histories

Average SEDs for spheroid-like objects since z~2



Pérez-González et al (2008); Kriek et al. (2009)

Star formation histories



Pérez-González et al. (2008)

Disk-like galaxies:

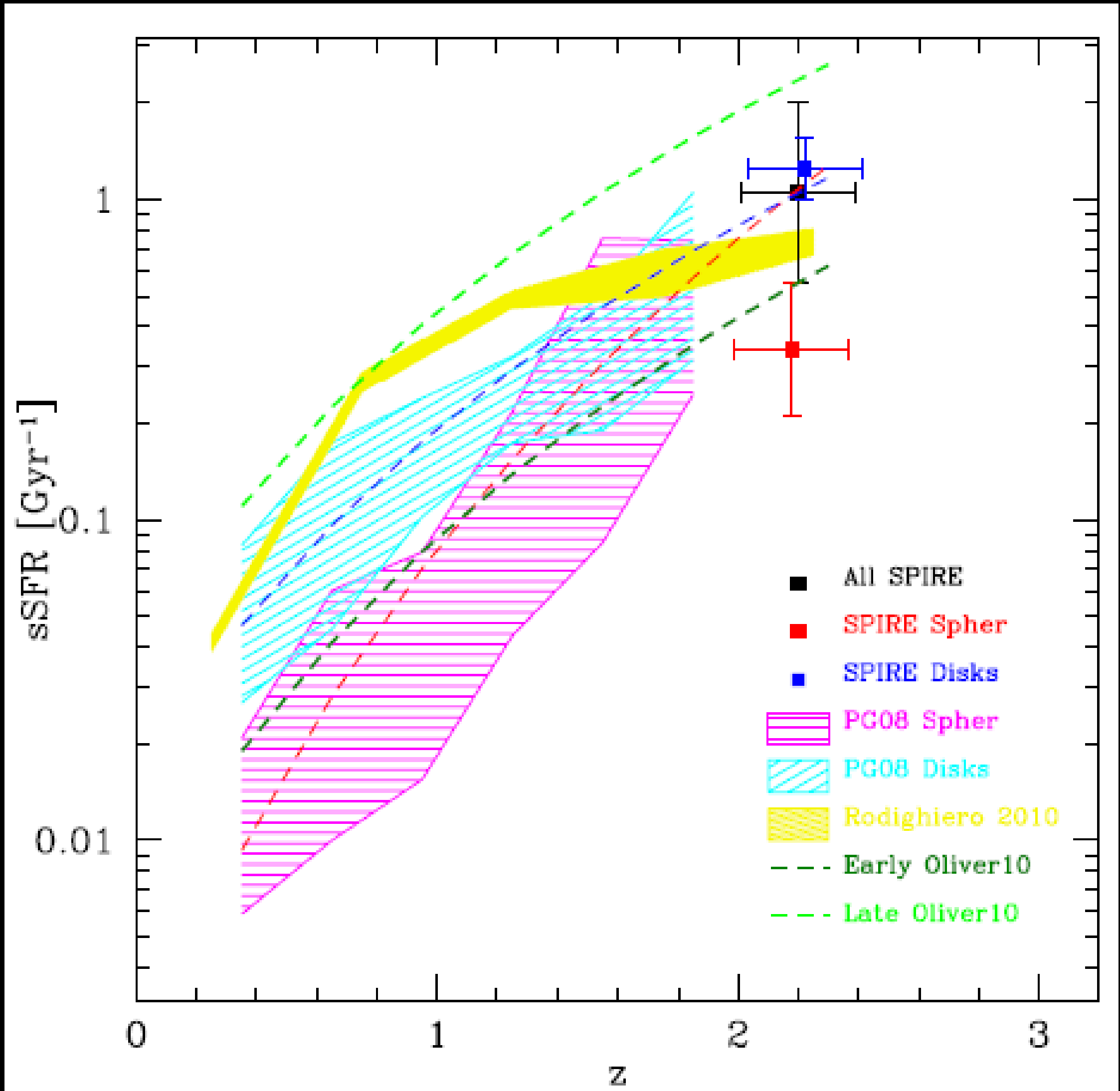
At the most they have tripled their stellar mass content since z=2

Spheroid-like galaxies:

At the most they have doubled their stellar mass since z=2

Star formation histories

New results at 2<z<3



Cava et al. 2010 (SPIRE at Herschel) and Viero et al. 2011 (Spitzer, BLAST + LABOCA) consistent results:

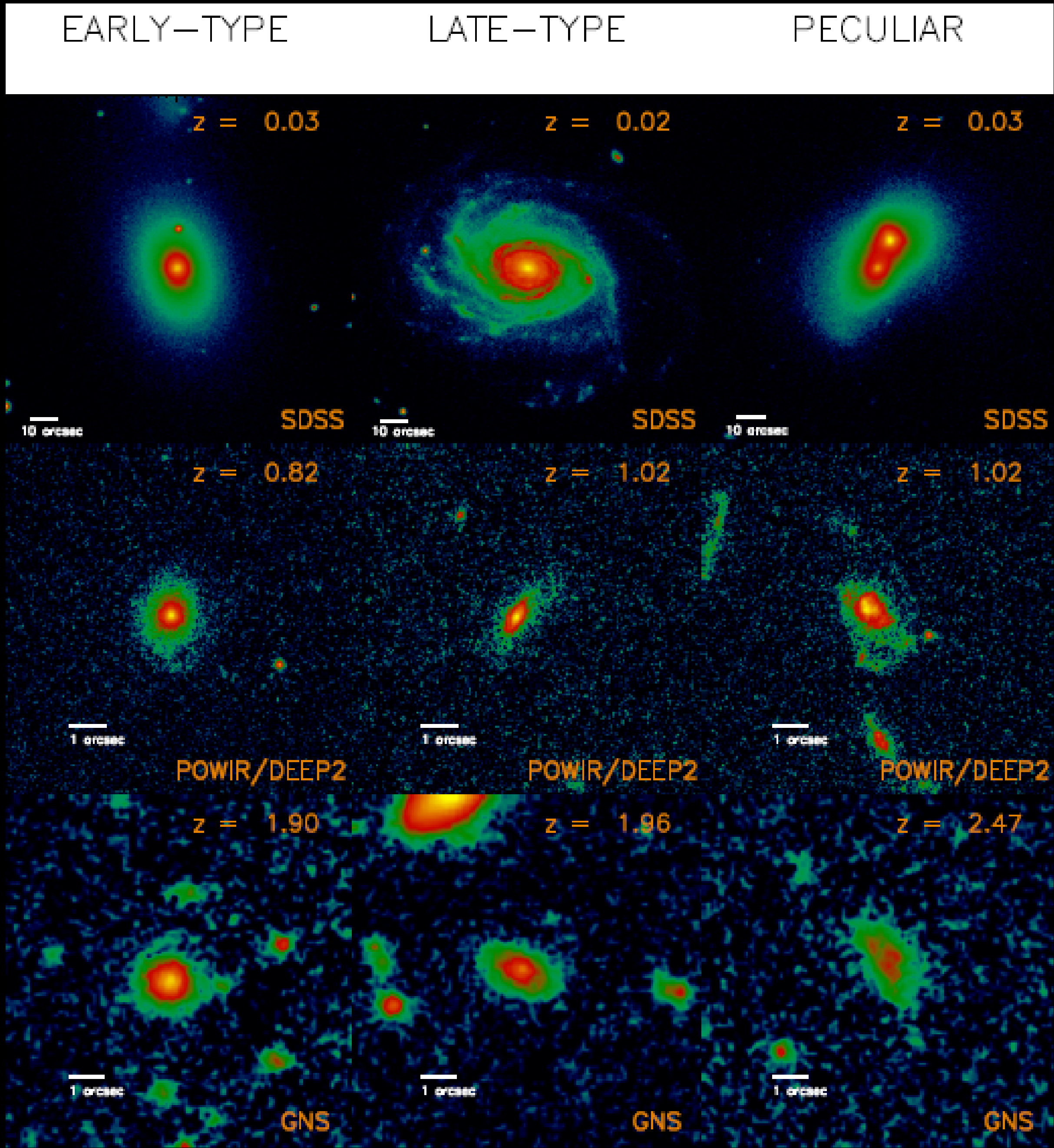
Disk-like galaxies: ~200-300 M/yr

Spheroid-like galaxies: ~100 M/yr

Disfavour puffing-up models

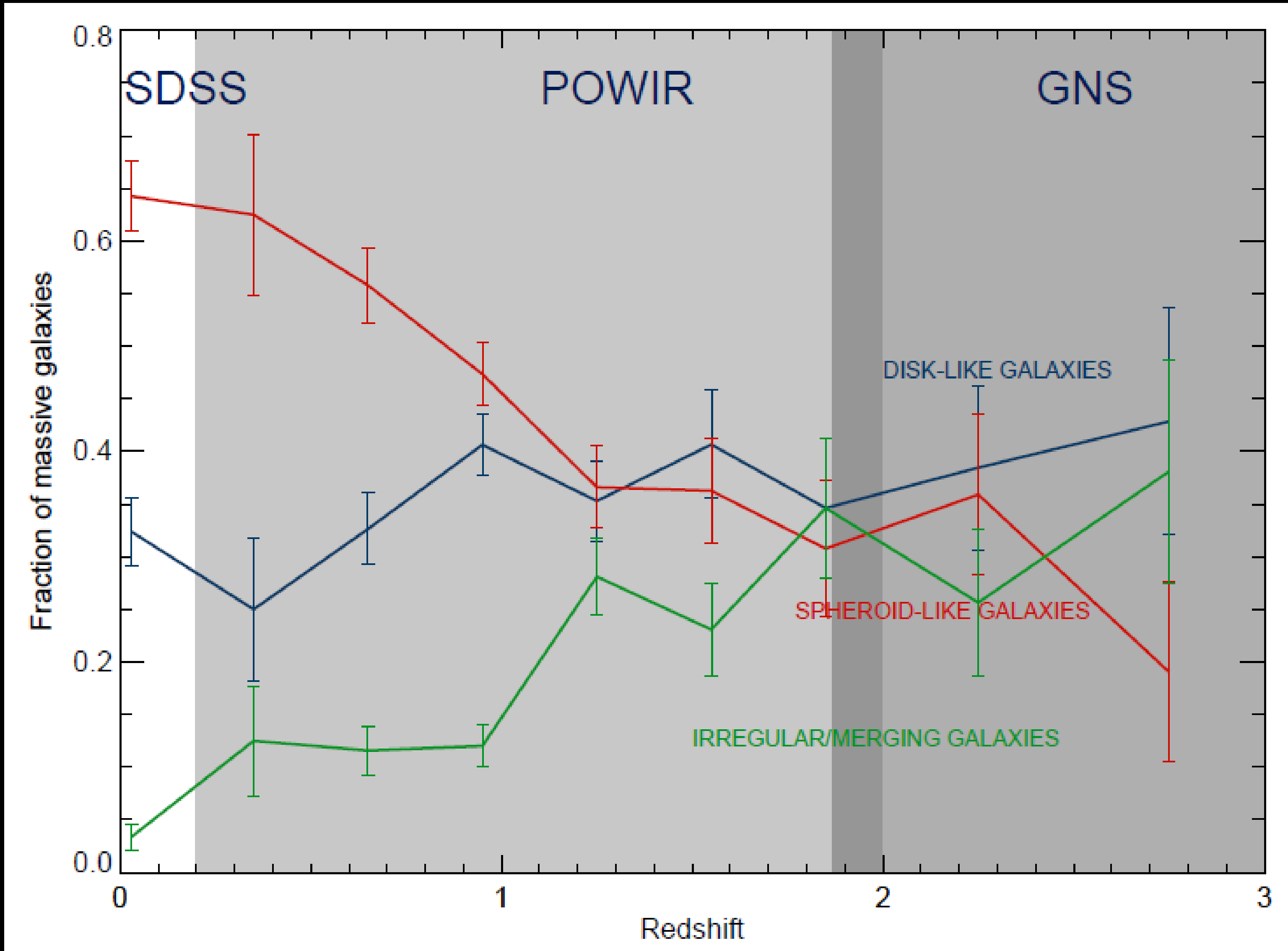
Morphological transformation

Strong morphological transformation



Buitrago et al. (2011; in preparation); van der Wel et al. (2011)

Strong morphological transformation



Elliptical galaxies are the dominant morphological class among the massive galaxies only since z~1.5

Buitrago et al (2011; in preparation)

Models for spheroid size evolution: Likelihood

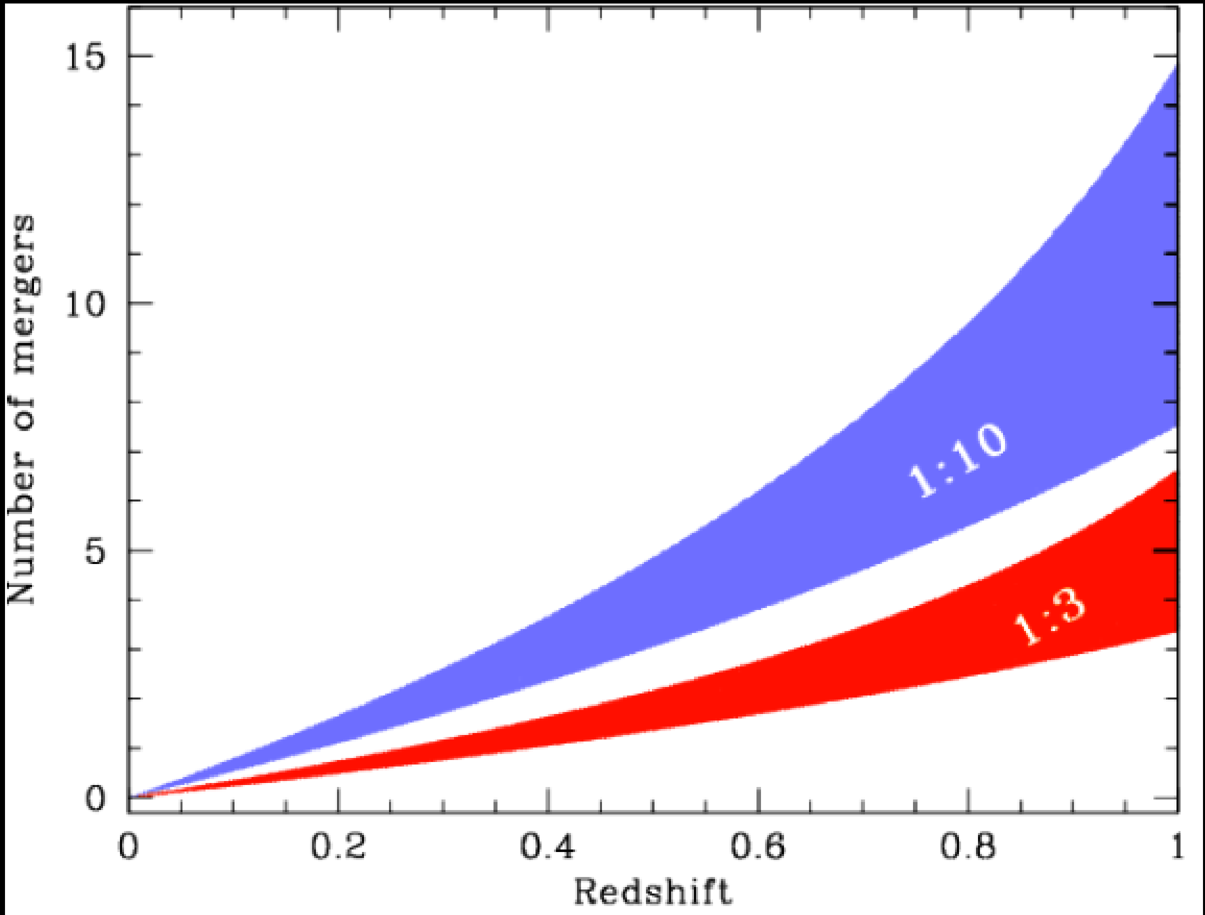
a) Puffing-up: AGN activity removes gas from the galaxies and puff-up their structures. X

b) Major dry mergers: spheroid-spheroid re-mergers (X; e.g. López-SanJuan et al. 2010)

c) Minor/Late merging: progressive infall of minor satellites with low-effective density √

Towards direct evidence of the minor merging scenario

Expected size and mass evolution through merger channel



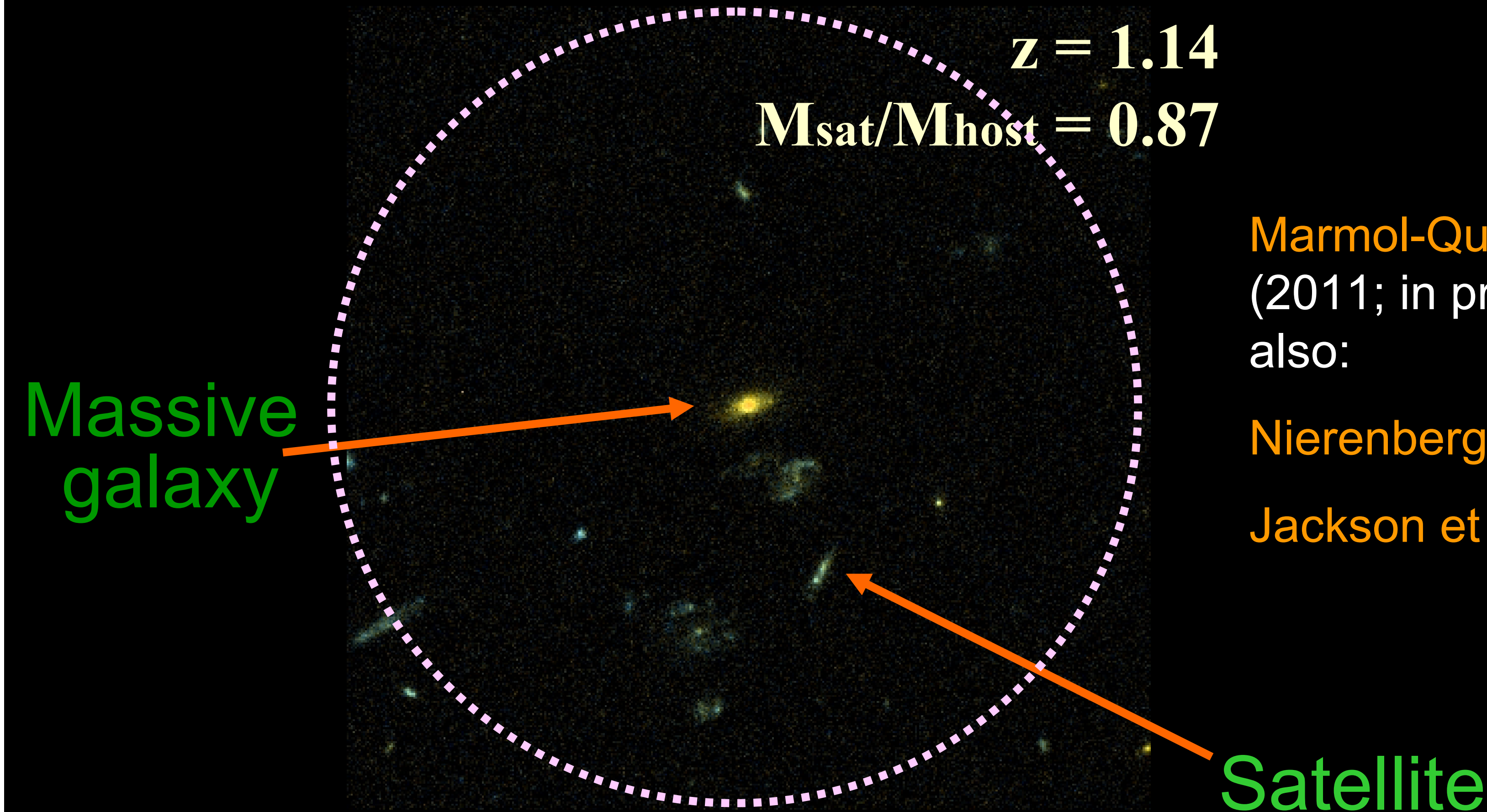
$$\frac{R_f}{R_i} = \left[\frac{(1+\eta)^2}{1+\eta^{2-\alpha}}\right]^N$$

$$\frac{M_f}{M_i} = (1+\eta)^N$$

Naab et al. (2009)

Trujillo et al (2011)

Direct counting of satellites

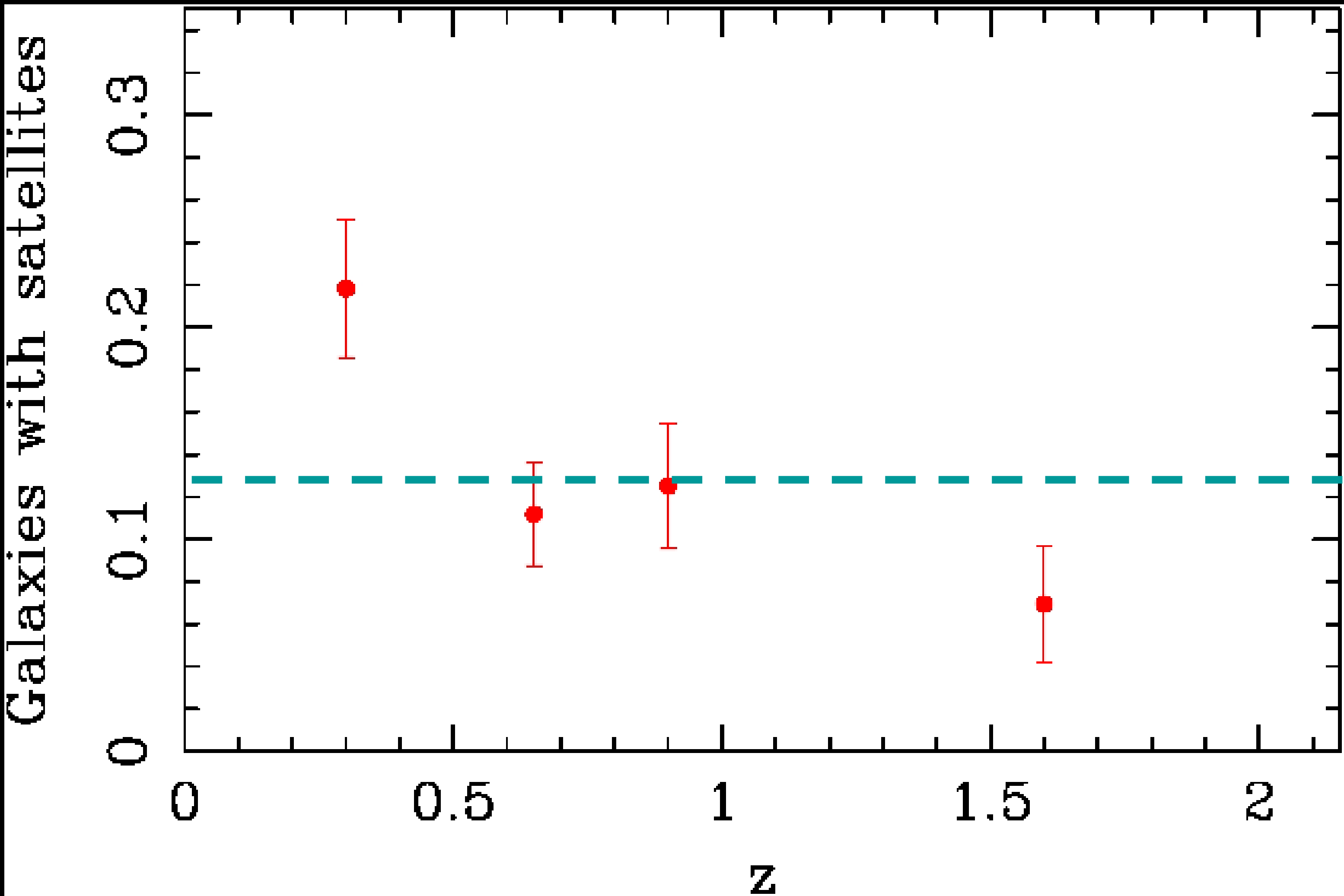


Marmol-Queralto et al (2011; in preparation); See also:

Nierenberg et al. (2011)

Jackson et al. (2010)

Direct counting of satellites



Host galaxies:

$M_* > 10^{11}\ M_{sun}$

Search Radius:

100 kpc

Satellite galaxies:

$0.1 < M_{sat}/M_{host} < 1$

Marmol-Queralto et al (2011; in preparation)

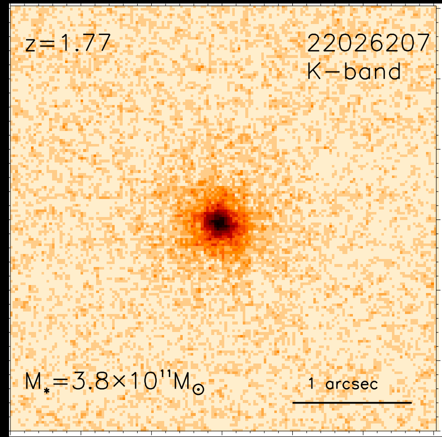
Summary

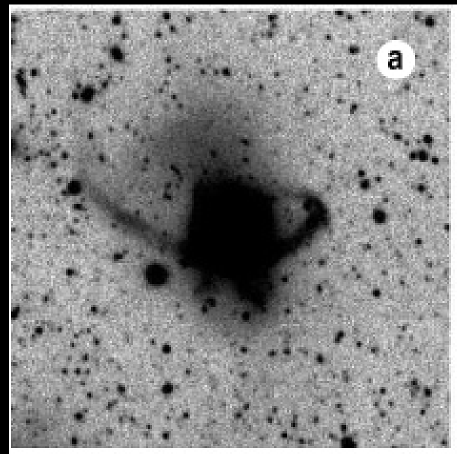
Present-day most favored picture

Bulk (core) of massive galaxies (~10^{11} M_{sun}) is formed very early-on (z~4-5) in a dissipative event (see e.g. Ricciardelli et al. 2010)

+

Continuous accretion of minor satellites create the outer envelopes and enlarge the size of the galaxies





Cosmic Time

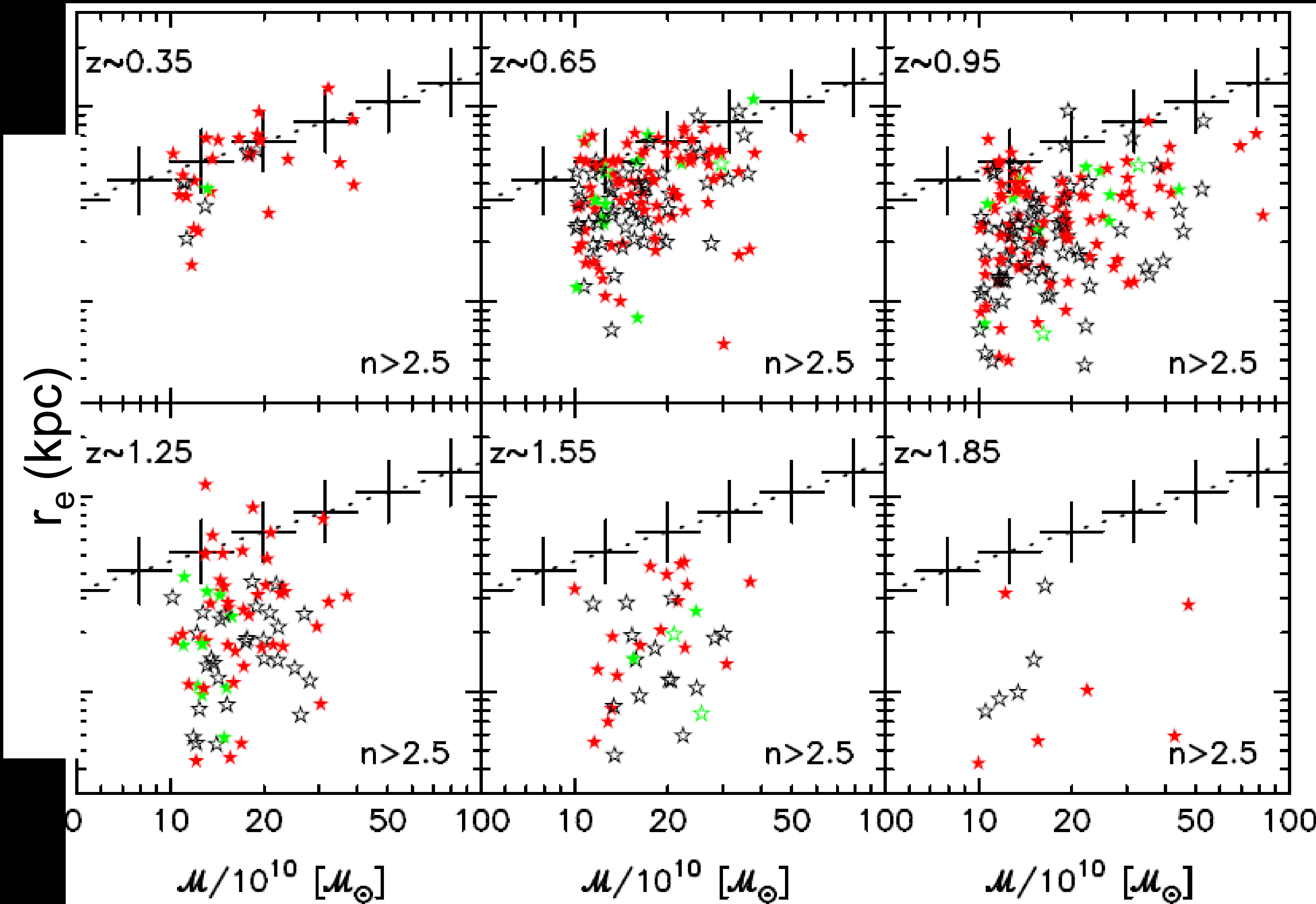
Open issues from the observational point of view:

The most favored evolutionary scenario is the accretion of minor satellites, however, still to observationally check:

- An estimation of the minor merging rate in massive galaxies since z~4-5
- Ages and stellar metallicities gradients of the present-day most massive galaxies to explore their wings properties (see e.g. Coccato et al. 2010)

[redacted]

Observational constraints: Star Formation Histories



Pérez-González, Trujillo et al. (2008)

How the massive compact galaxies form?

How the massive compact galaxies form?

Are the massive compact galaxies the final stages of the merging of gas-rich disk galaxies? (Hopkins et al. 2007;2009; Cimatti et al. 2008)

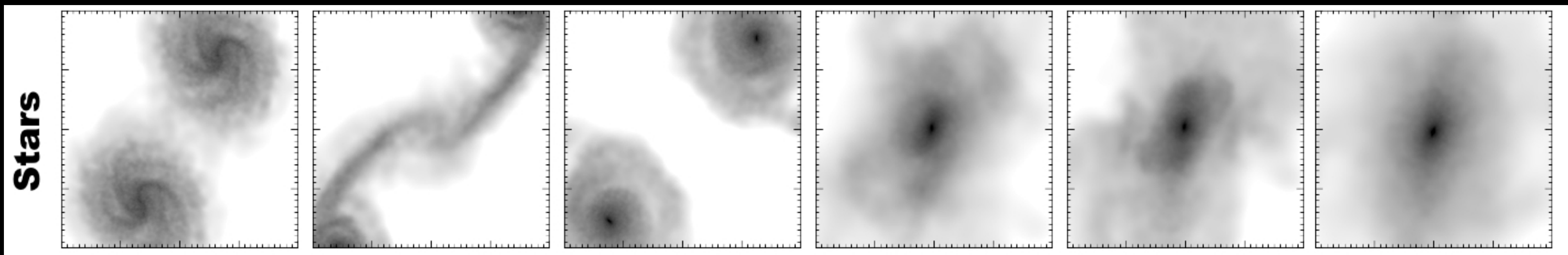


Figure from TJ Cox

How the massive compact galaxies form?

Characteristics of the candidates to be progenitor of the compact massive galaxies at high-z:

-Gas rich

-Very massive ($M \sim 10^{11} M_{sun}$)

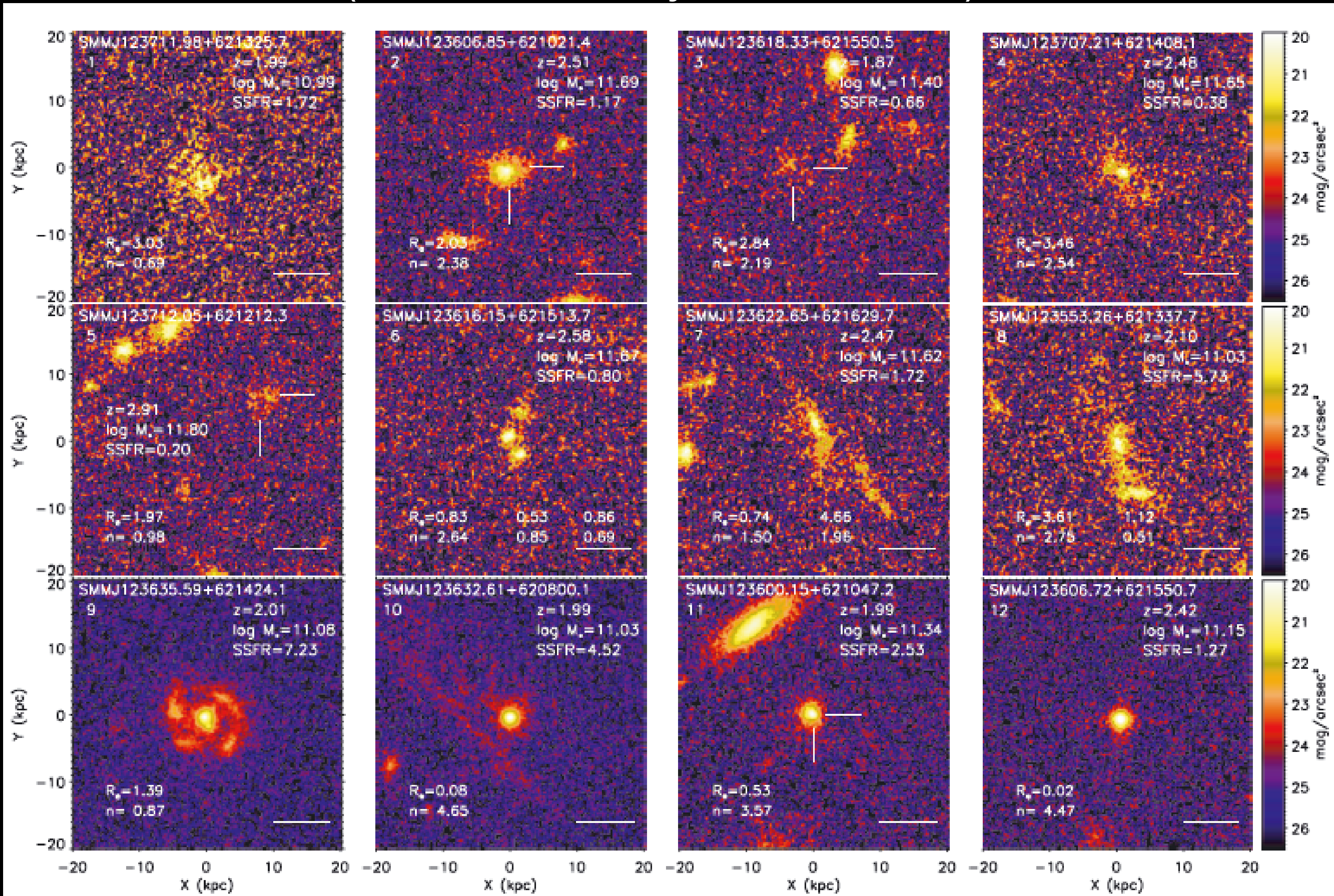
-High redshift ($z>2$)

A likely candidate are the submillimetre galaxies.

We explore whether the morphologies and sizes fit within the theoretical scheme

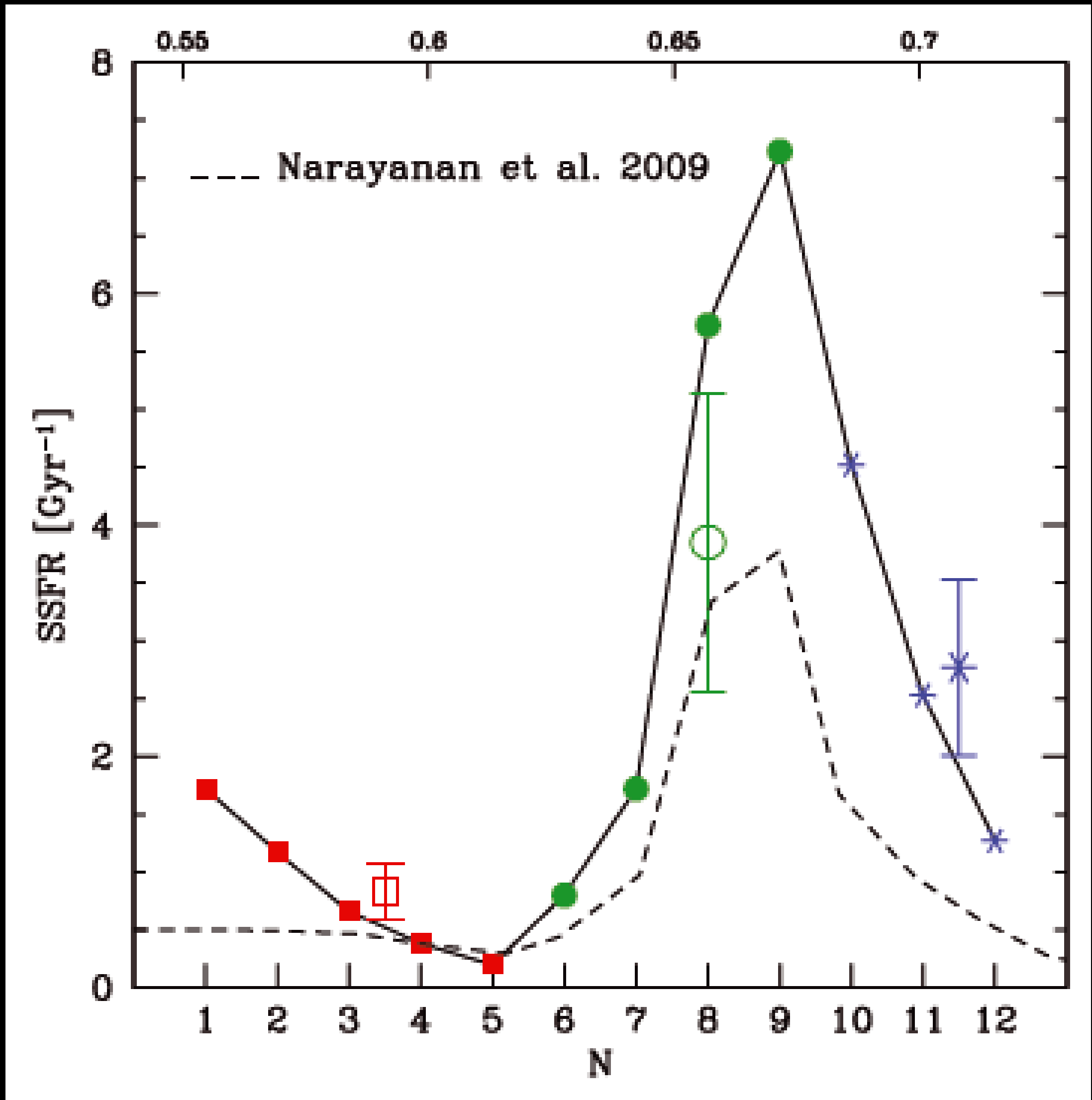
How the massive compact galaxies form?

Our sample: 12 star forming submillimetric galaxies ($M>10^{11}M_{sun}$) at 1.8<z<3 observed with NICMOS & ACS @ GOODS-North (Ricciardelli, Trujillo et al. 2010)



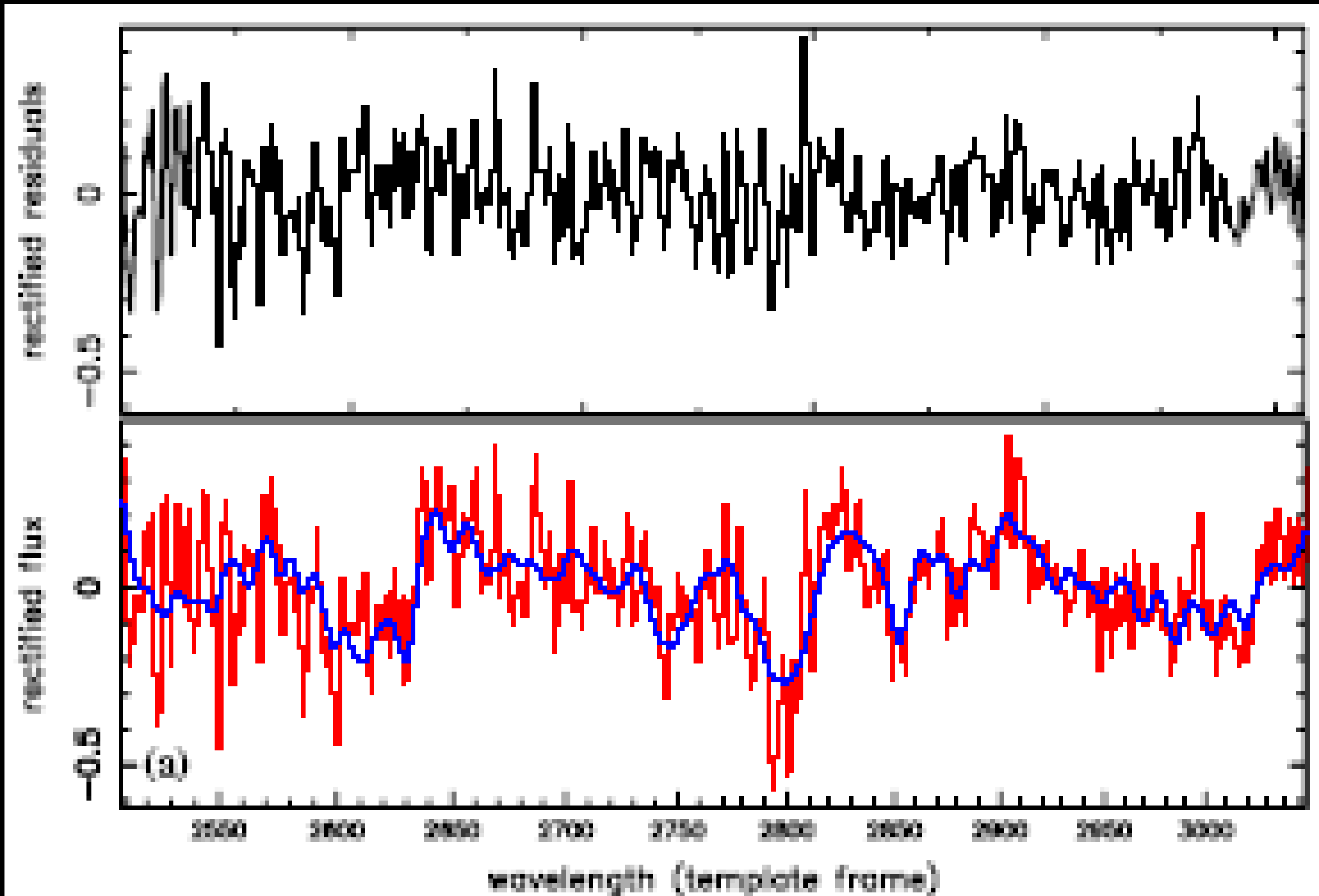
How the massive compact galaxies form?

Can the morphologies of the observed submillimetre galaxies be accommodated into the theoretical scheme?



Disk-like phase Merger phase Compact phase

Observational constraints: velocity dispersion evolution



Template:

CoolCAT stars

Spectral Range:

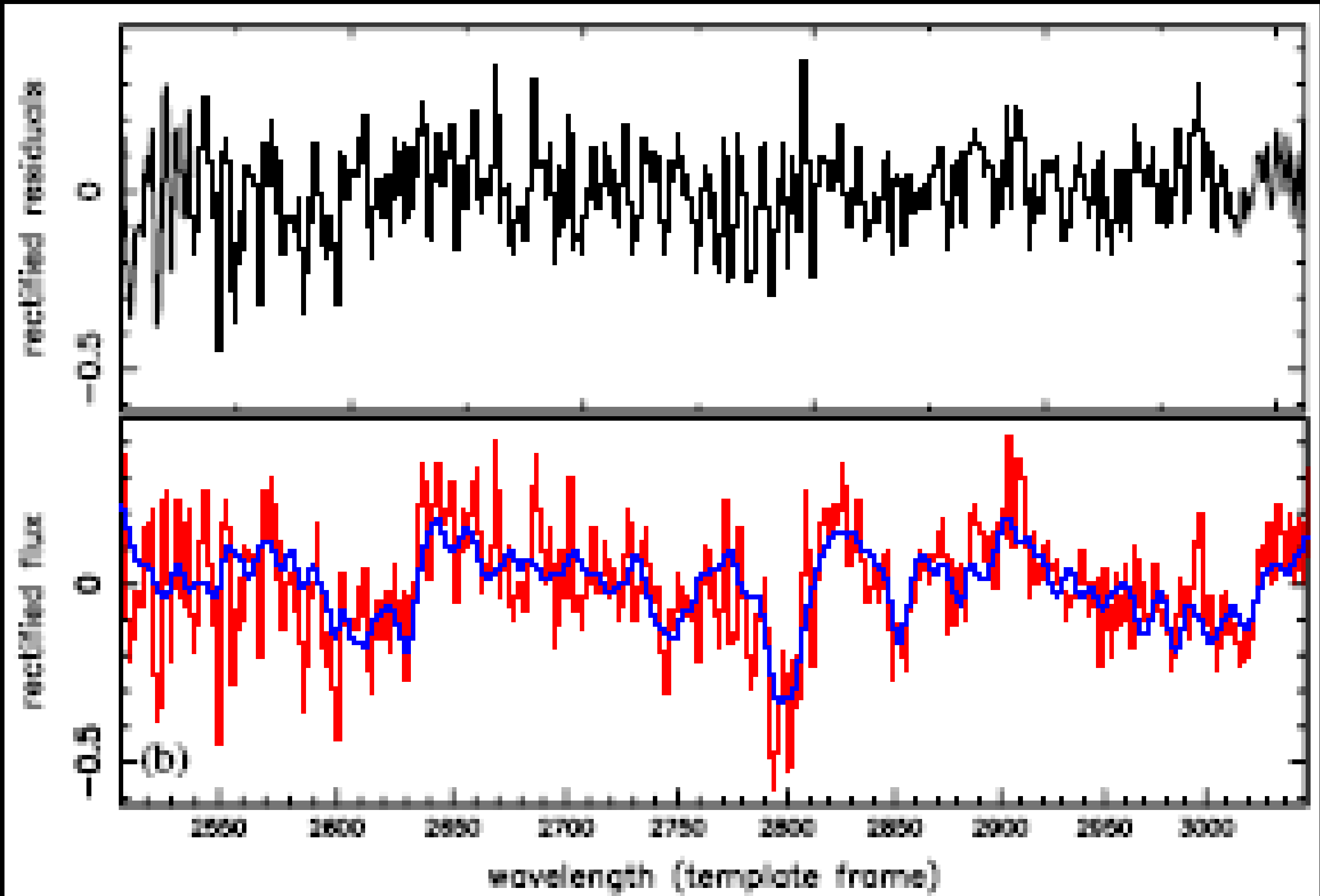
2510-3050 Å

σ_*(km/s):

258±21

Cenarro & Trujillo (2009)

Observational constraints: velocity dispersion evolution



Cenarro & Trujillo (2009)

Template:

BC03+NGSL SSP models

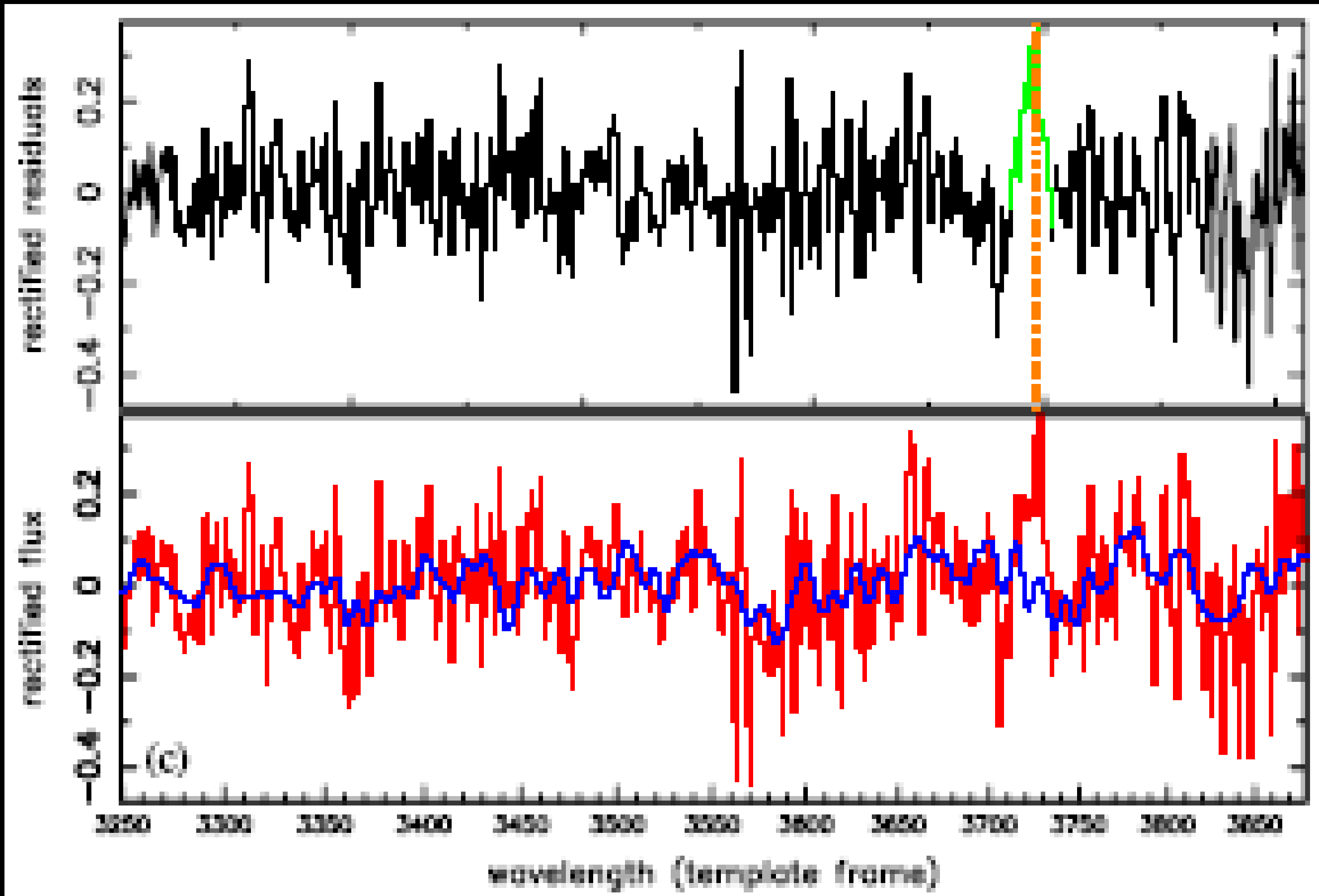
Spectral Range:

2510-3050 Å

σ_*(km/s):

236±18

Observational constraints: velocity dispersion evolution



Cenarro & Trujillo (2009)

Template:

Keck/LRIS stars

Spectral Range:

3250-3880 Å

σ_*(km/s):

236±15

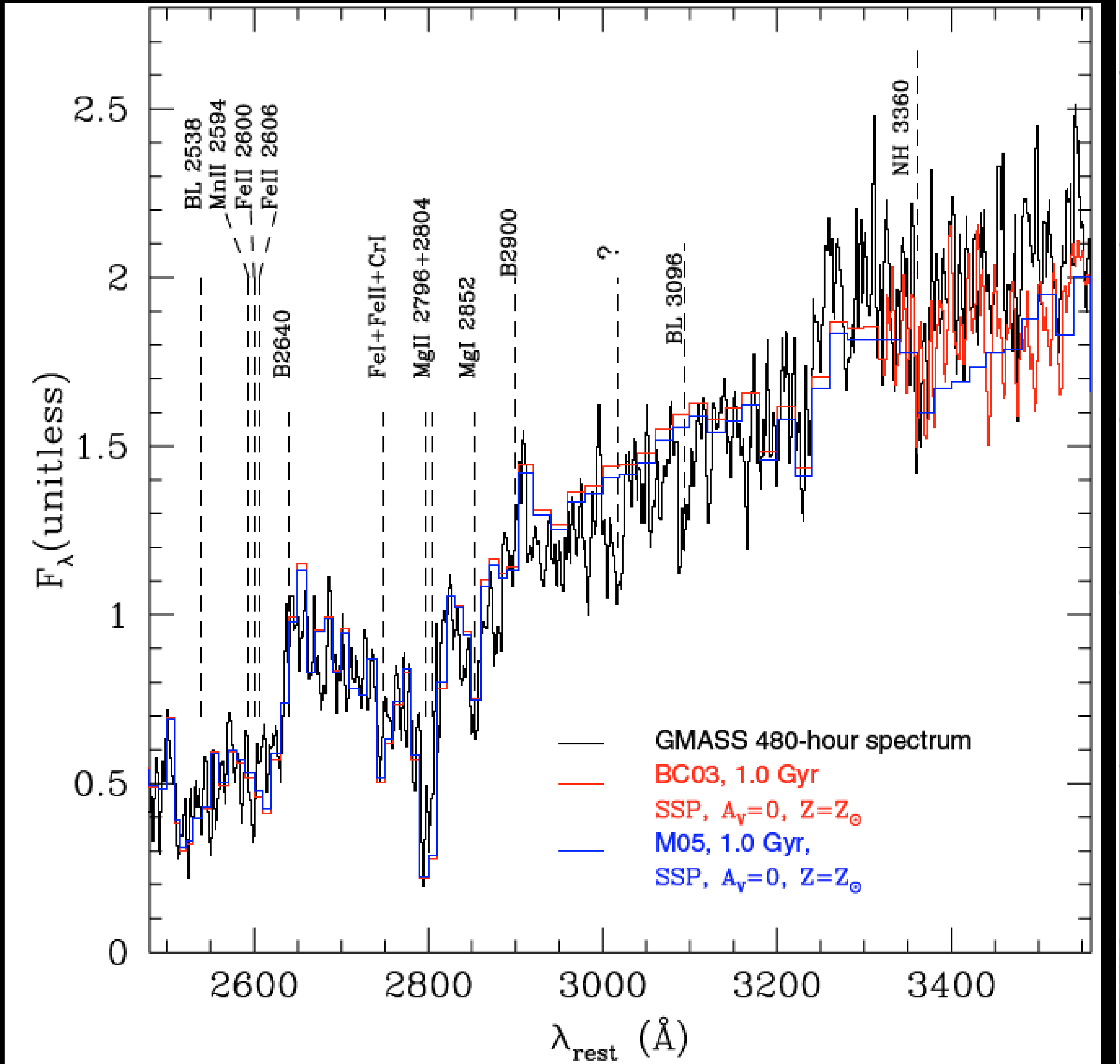
Velocity dispersion evolution

$$\sigma \propto \sqrt{\frac{GM}{r_e}}$$

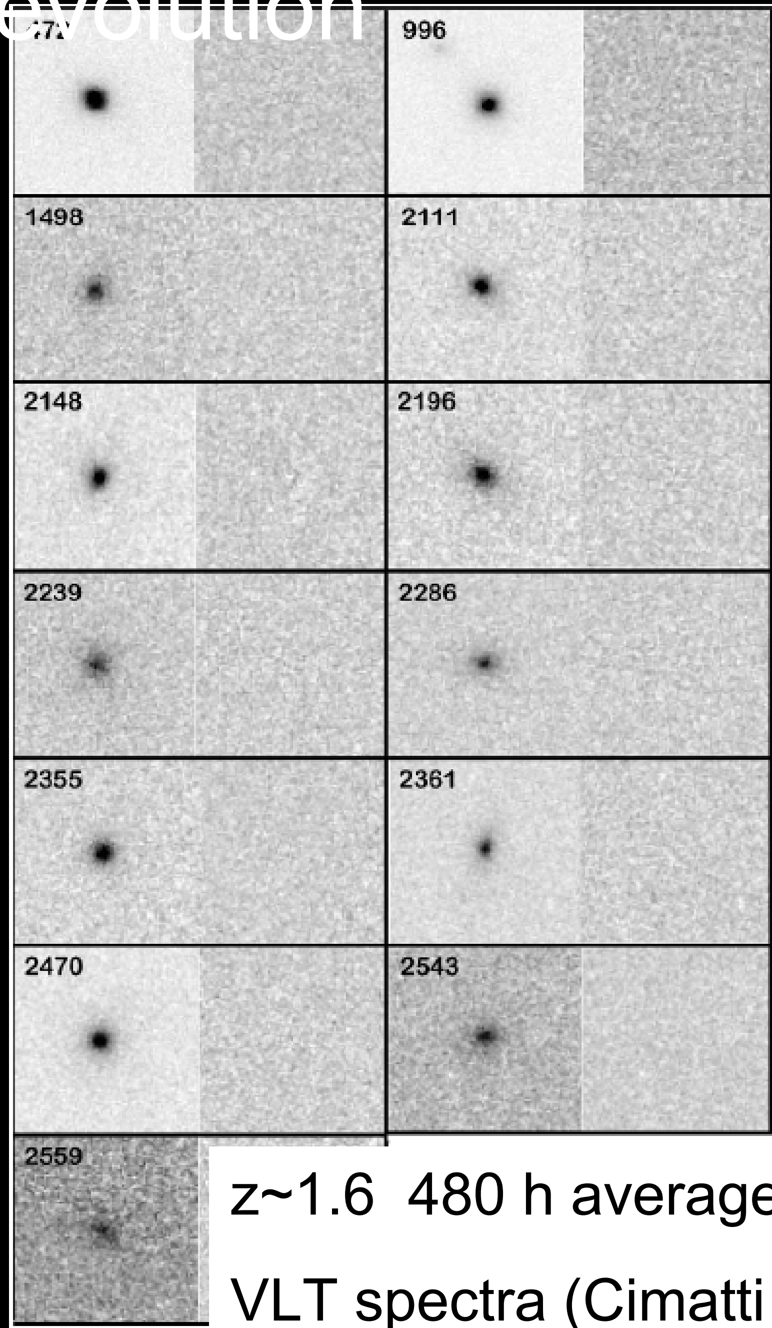
Naïve expectations at a fixed stellar mass:

- $r_e(z=0) = 4\, r_e(z=2) \Rightarrow \sigma(z=2) = 2\, \sigma(z=0)$

Velocity dispersion evolution



Cenarro & Trujillo (2009)



z~1.6 480 h averaged

VLT spectra (Cimatti et al. 2008)