A short (and not complete) journey in the early-type galaxy's realm

-an informal talk on the recent discoveries on spheroidal galaxies both at high and low redshift -

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Outline

Why are ETGs so interesting?

What we know about them from local studies;

What we know about them form high-z studies;

} Constraints on the evolutionary picture

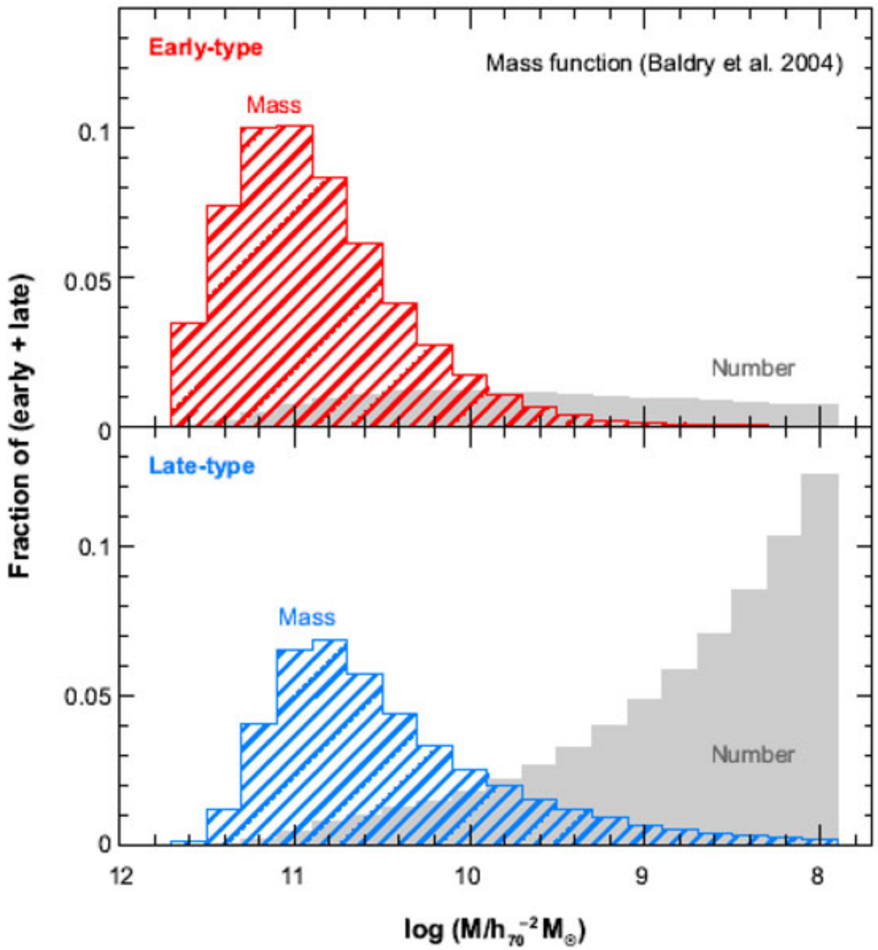
The stellar Initial Mass Function (IMF) of dense high-z ETGs

Why studying the early –type galaxies?

In local Universe,

ETGs are just 25%-30% of the total number of galaxies

but contain 50%-70% of the total stellar mass.

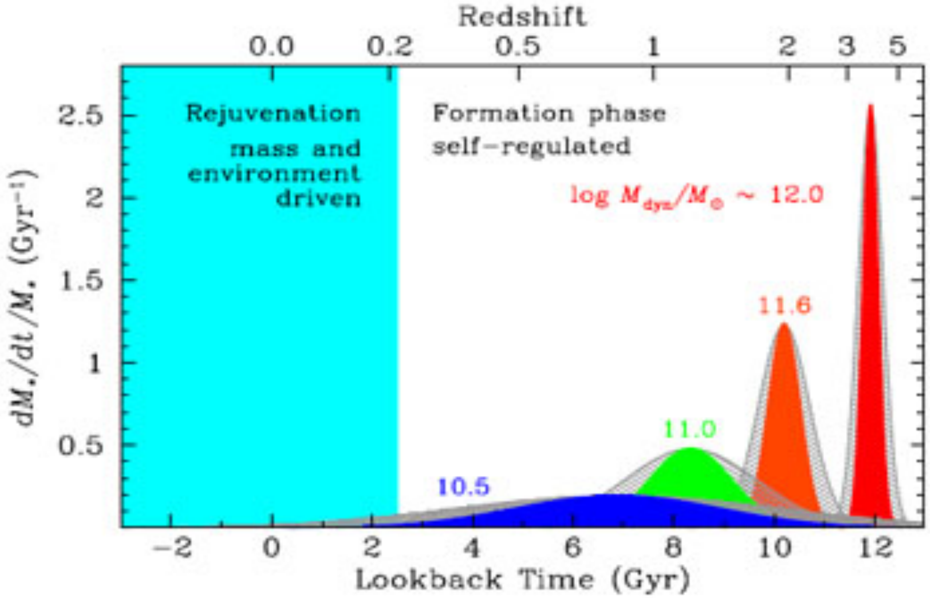


Renzini 2006

How they form and evolve?

What we know: observative evidences – local universe.

The formation redshift (z_{form}) and timescale of the star formation (Δt) depend on stellar mass (or σ): massive galaxies form first ($z_{form} > 3$) and over shorter time-scales with respect to less massive ones.



Thomas et al. 2010

Age → z_{form} [α/Fe] → Δt

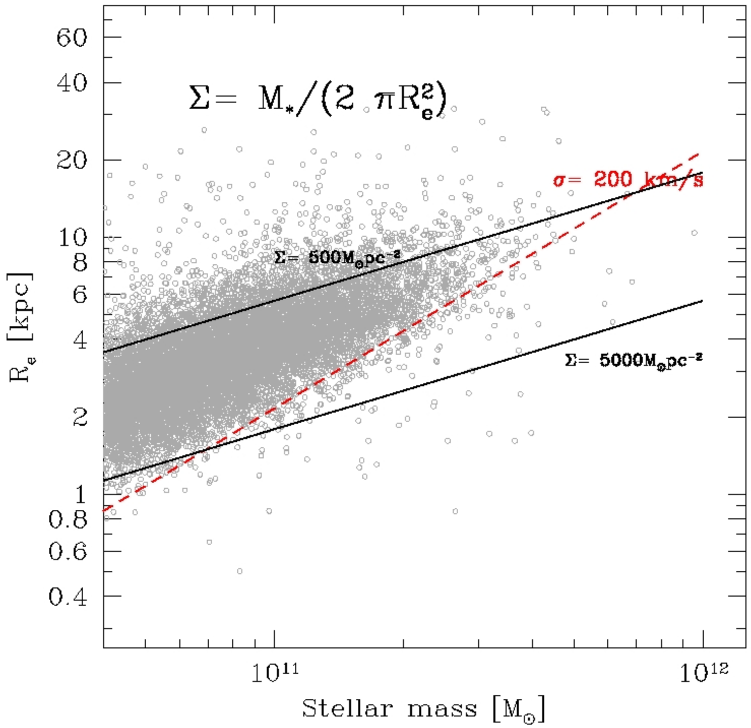
α elements mainly from SN type II (from stars with mass *m* > 9Msol)
Fe mainly from DELAYED SN Type Ia (from low mass stars)

High value of [α/Fe] → stars formed from a gas that have had no time to be enriched in Fe → SHORT timescale of star formation

What we know: observative evidences – local universe.

z_{form} and Δt depend on M_{star} (or σ) → are ETGs with similar stellar mass ….similar?

No.



At fixed M_{star} or σ, ETGs span an order of magnitude in Re →
More than 2 orders of magnitude in mean surface stellar mass density Σe

What we know: observative evidences – local universe.

In what differ the stellar population properties of normal and dense ETGs?
Variation of stellar properties across the Fundamental Plane

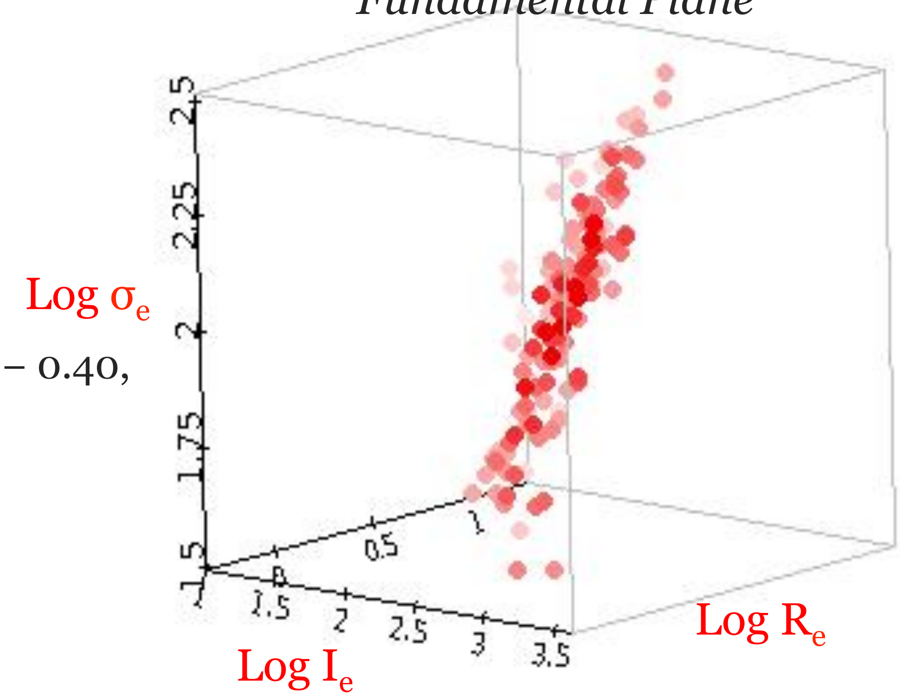
Mean surface stellar mass density Σe → mean surface light density Ie

For galaxies with σ > 100 km/s :

Log Re = 1.35 ± 0.11 Log σ_0 – 0.81 ± 0.03 Log I e – 0.40,

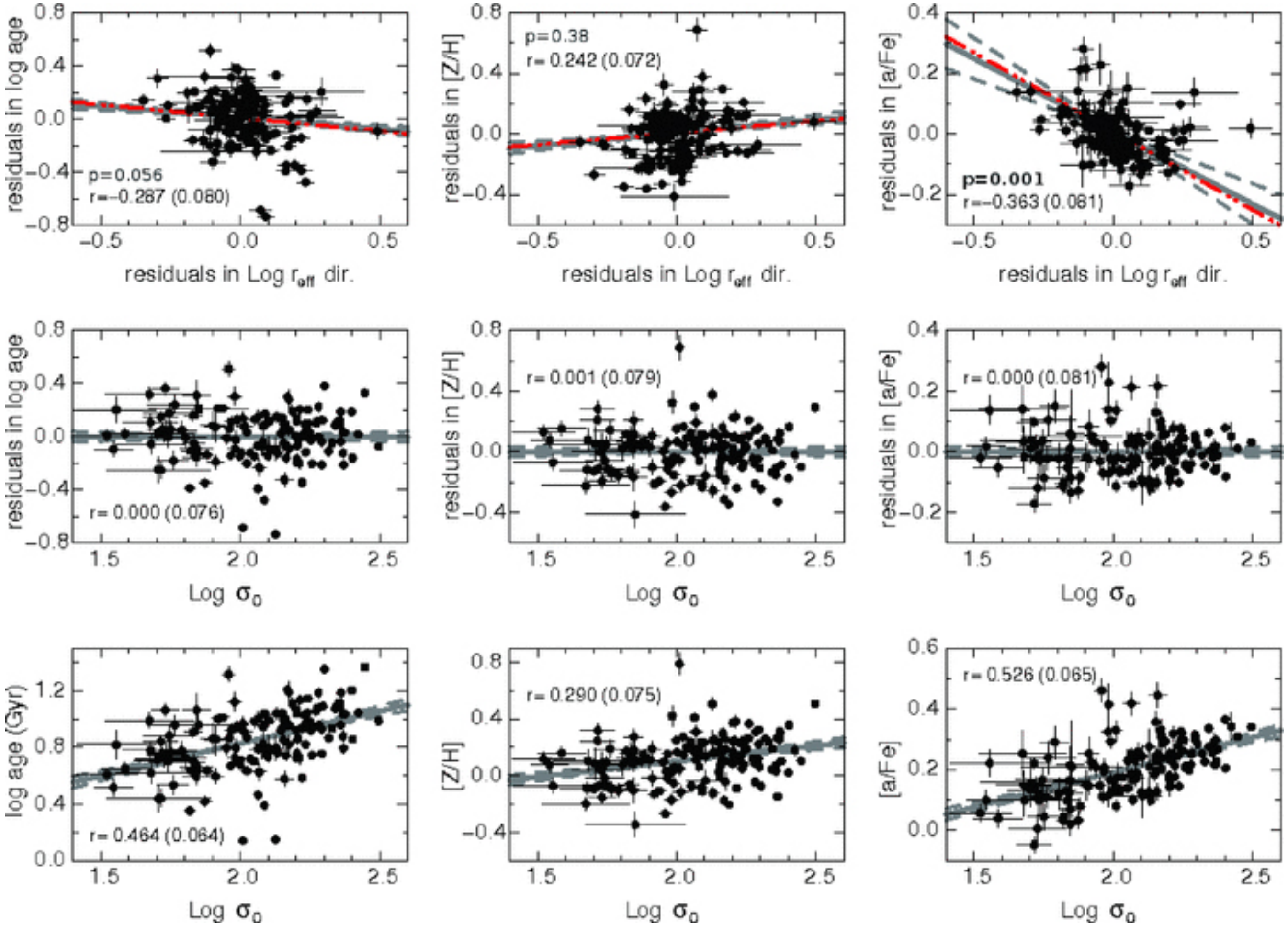
σ_{int} = 0.09 in log Re direction

Shapley supercluster core
Fundamental Plane



Gargiulo et al. 2009

What we know: observative evidences – local universe.

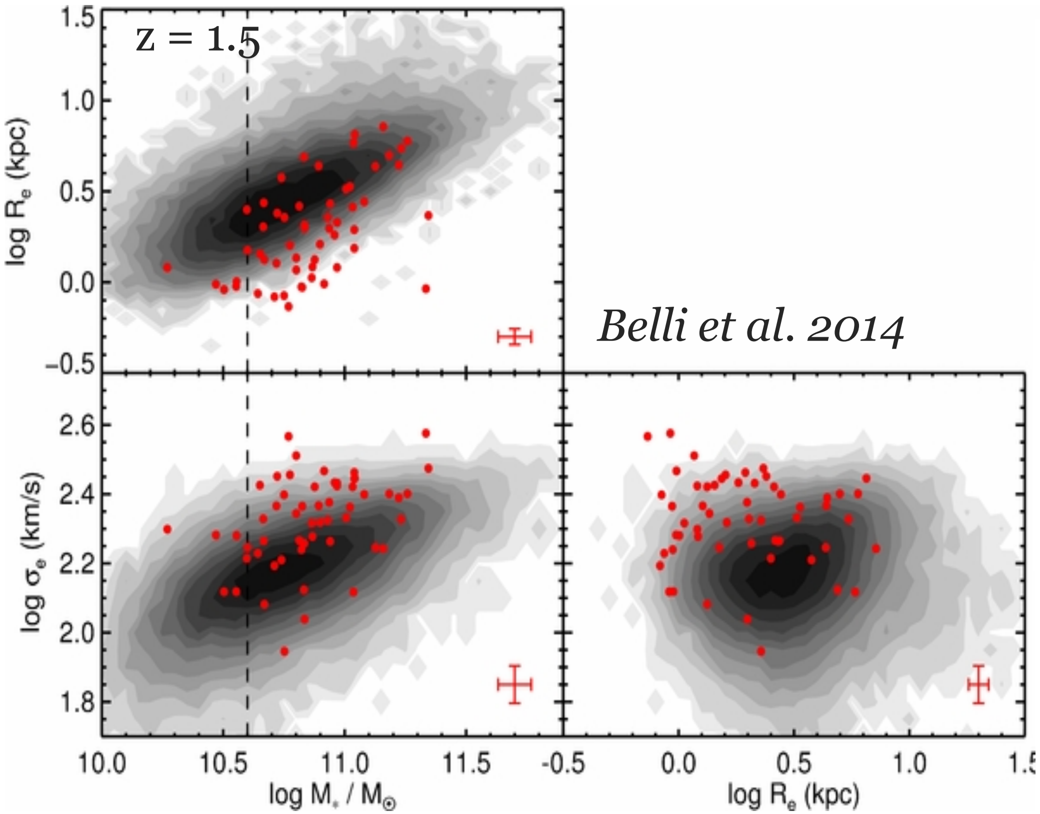


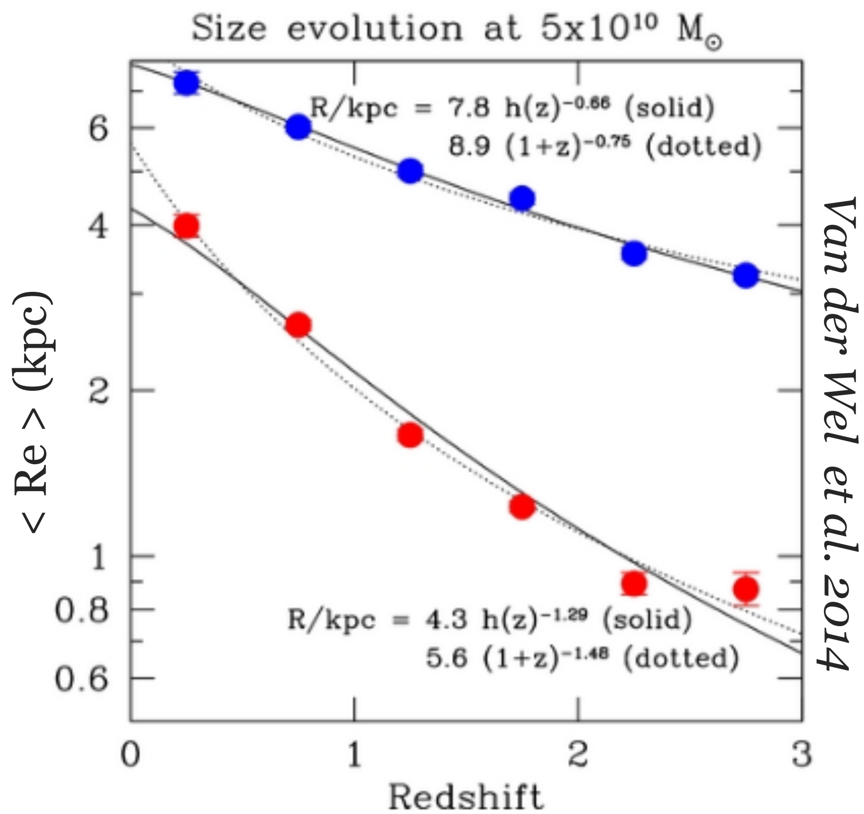
Gargiulo et al. 2009

On average, the denser the ETGs,
the higher the α enhancement and the stellar age.
Dense ETGs are older and have shorter star formation timescales
(see also Graves et al. 2009, Springob et al. 2012)

What we know: observative evidences – high –z universe.

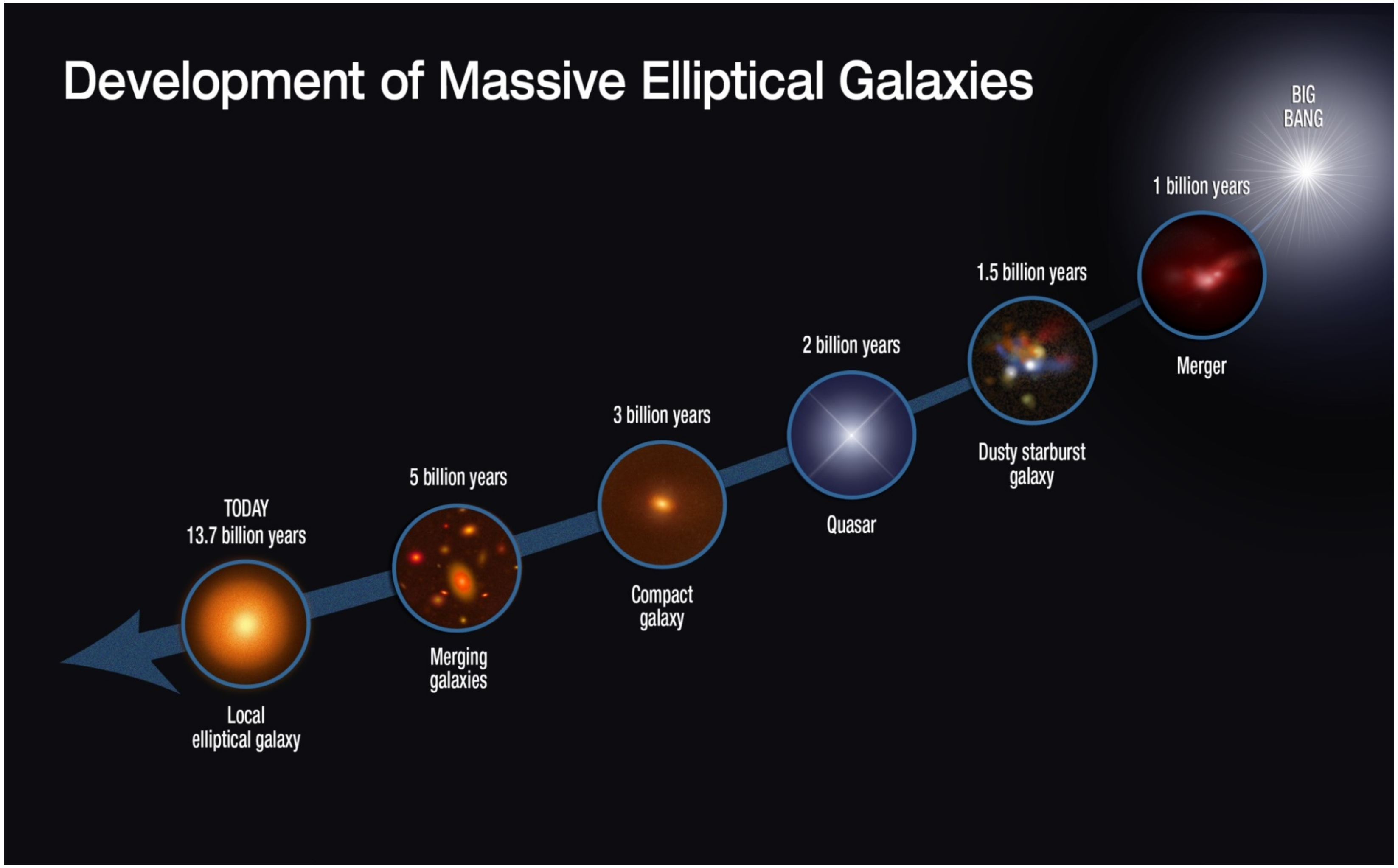
High –z observations show that massive ETGs are already in place at z ~ 2 and beyond, but, at fixed stellar mass, they are on average, smaller and with high velocity dispersion with respect to local ETGs of similar stellar mass.





See also Buitrago et al. 2008, Cassata et al. 2013, Cimatti et al. 2012

The new paradigma of ETGs formation and evolution: the “inside-out” scenario

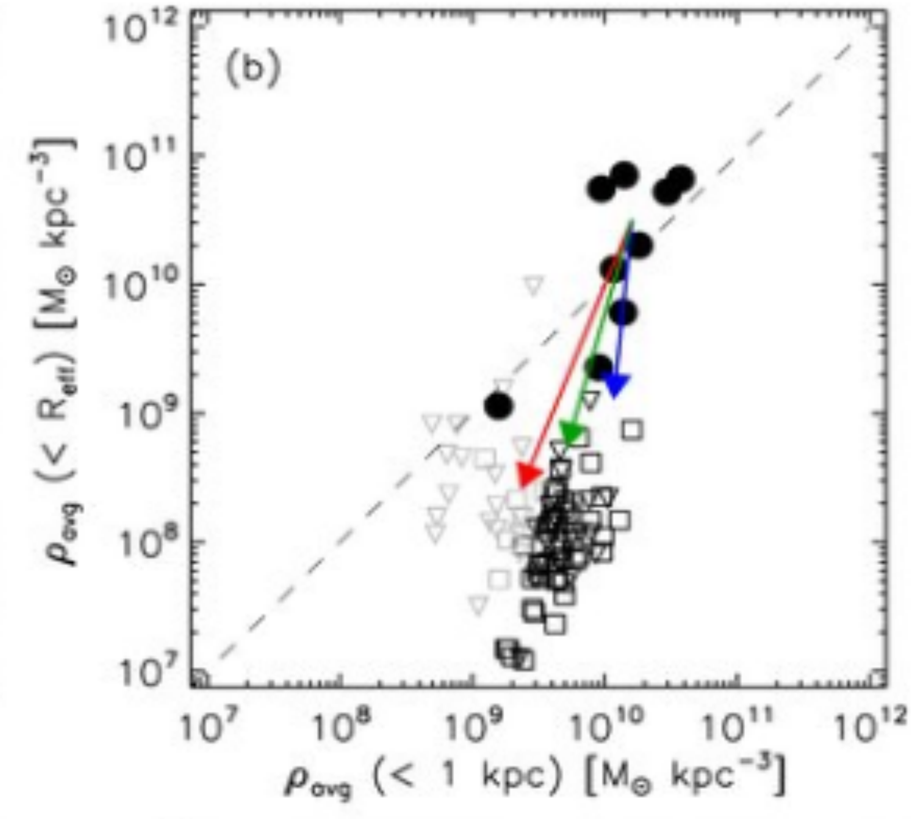


Credits: NASA

The largest galaxies are the final evolutionary step of high-z dense ETGs

The central stellar mass density of high-z and local ETGs

The central (R < 1kpc) stellar mass density of high-z (dense) ETGs
is similar to the central stellar mass density of typical (normal) local ETGs



Bezanson et al. 2009

Evidence of an inside – out mass accretion:
the central regions of local ETGs "fossil" of the compact core ….

The central stellar mass density of high-z and local ETGs

Or not?

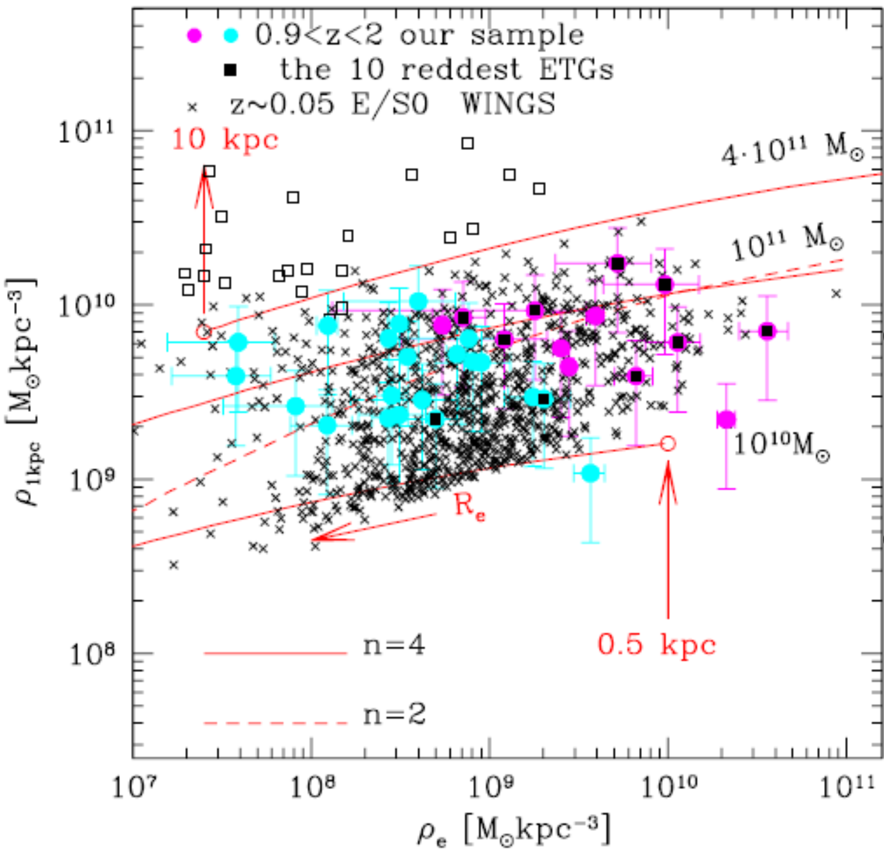
stellar mass profile = surface brightness profile x M/L

Sersic profile

$$I(r) = I_e \exp\left[-b\left(\left(\frac{r}{r_e}\right)^{1/n} - 1\right)\right]$$

ρ1kpc_dense = ρ1kpc_normal

evolutionary connection
between the two types of galaxies



Saracco, Gargiulo, Longhetti 2012

Color gradients in high-z ETGs

To discriminate the assembly path(s) of stellar mass in ETGs with different mean stellar mass density Σ_e

↓

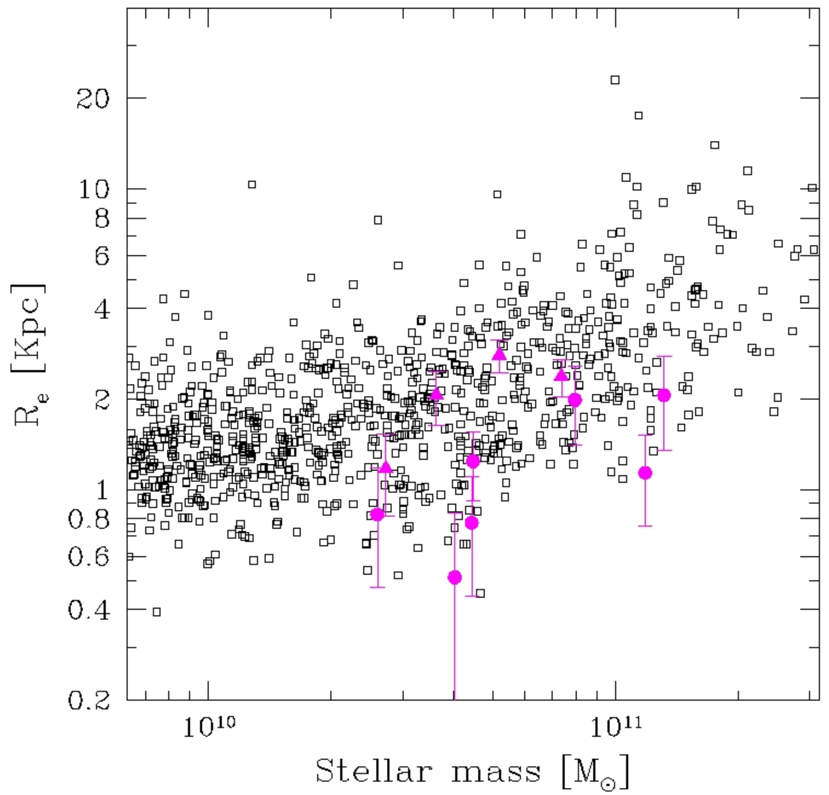
investigate the radial properties of ETGs stellar content
as a function of mean stellar mass density
as close as possible to their formation epoch

↓

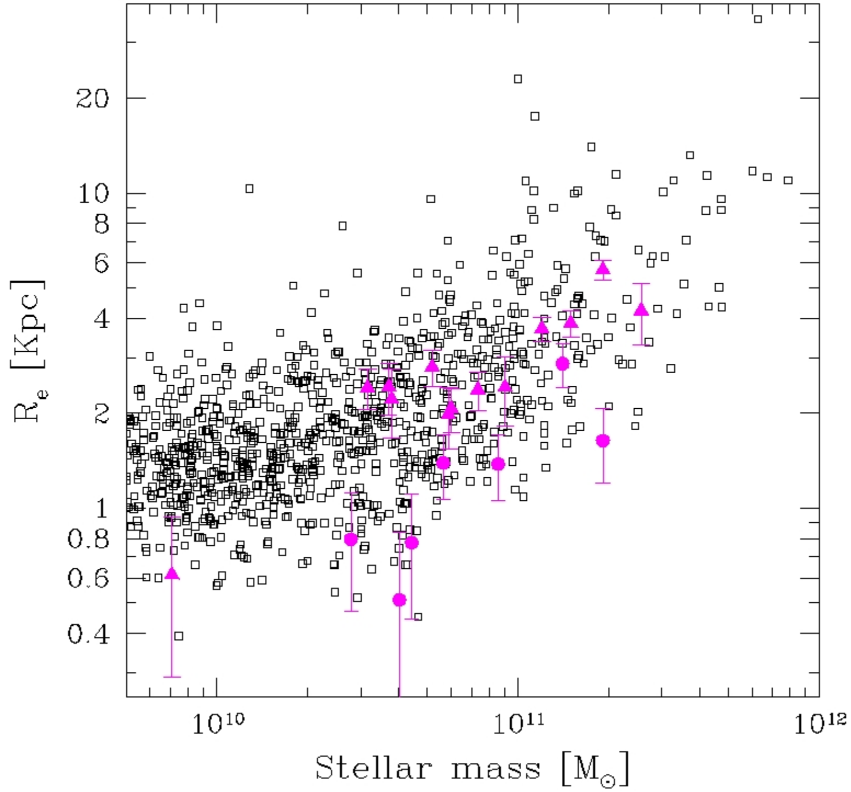
Color gradients → Radial variation of color → radial variation in stellar population properties

Color gradients in ETGs at <z> = 1.5

$(U\text{-}R)_{restframe}$ color gradients of for 11 ETGs (out of the 34) at 1<z<1.9 on GOODS-S field



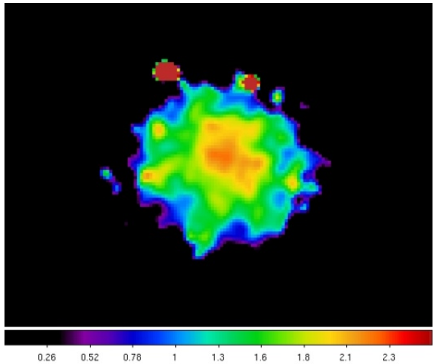
$(UV\text{-}U)_{restframe}$ color gradients of 20 ETGs (out of the 34) at 1<z<1.9 on GOODS-S field

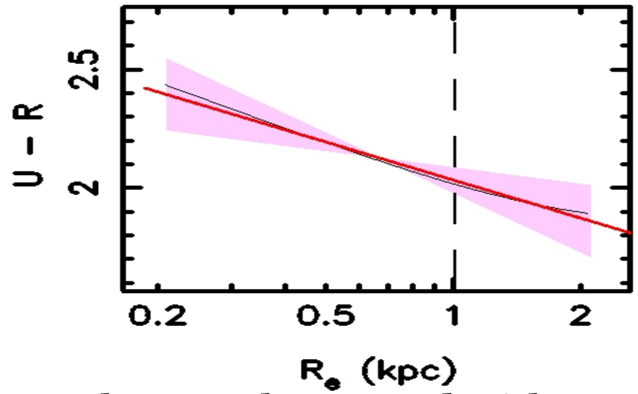


Gargiulo et al. 2011, 2012

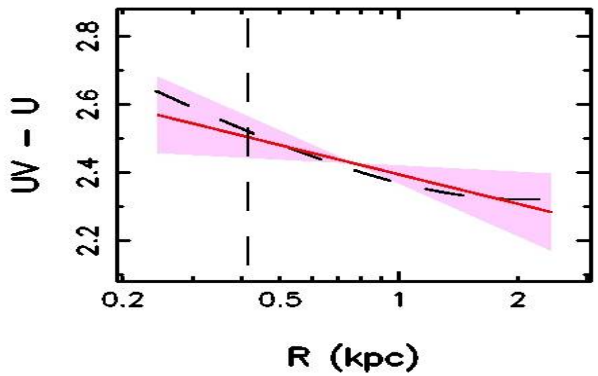
Color gradients in ETGs at <z> = 1.5

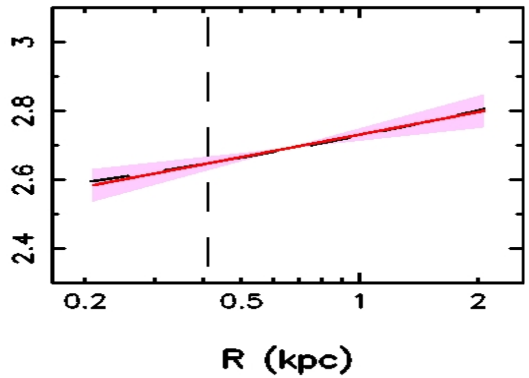
Irrespective of their stellar mass density, all the ETGs of the sample show negative U-R color gradients





Both negative and positive UV-U color gradients, but no clear trend with Σe

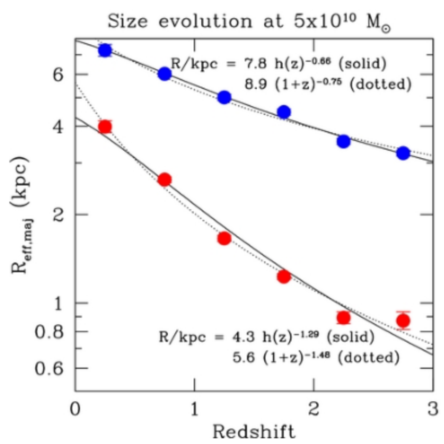


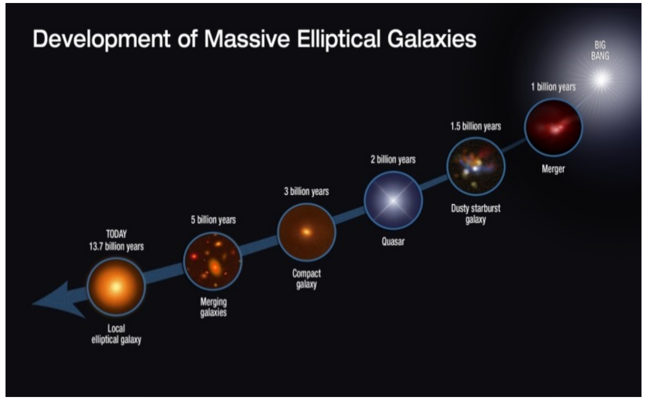


No trend of color gradients with Σ_e

→ radial distribution of stellar population do not correlate with mean stellar mass density

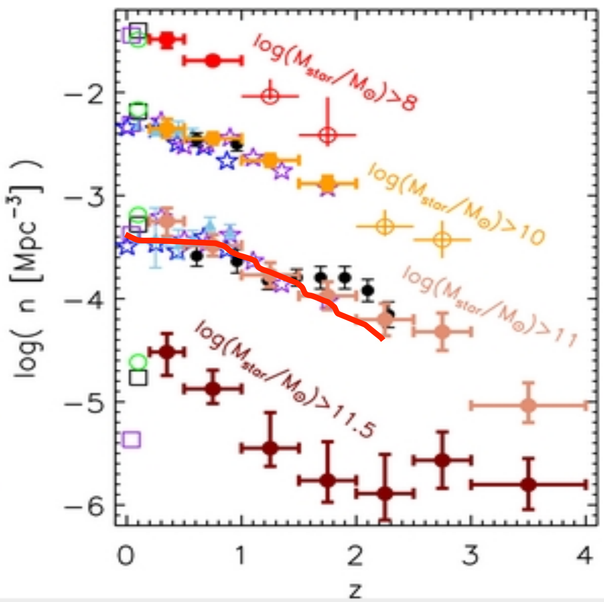
The origin of the mean size growth: brief summary





But…number density of ETGs increases of a factor 10 in the last ~ 10 Gyr → mean size growth main driver

Size growth of individual ETGs



Addition of new and larger ETGs over the cosmic time

The origin of the mean size growth: number density of massive dense ETGs

How many dense massive ETGs at high and low-z?

Hydrodynamical simulations show that, typically, massive ($M_{star} > 10^{11} M_{sun}$) passive galaxies are the central galaxies of massive halos and evolve mainly through minor mergers.

→ individual size growth more significant

Number density of massive dense quiescent galaxies at $0.2 < z < 1.0$ on COSMOS

NEWLY QUENCHED GALAXIES AS THE CAUSE FOR THE APPARENT EVOLUTION IN AVERAGE SIZE OF THE POPULATION

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ABSTRACT

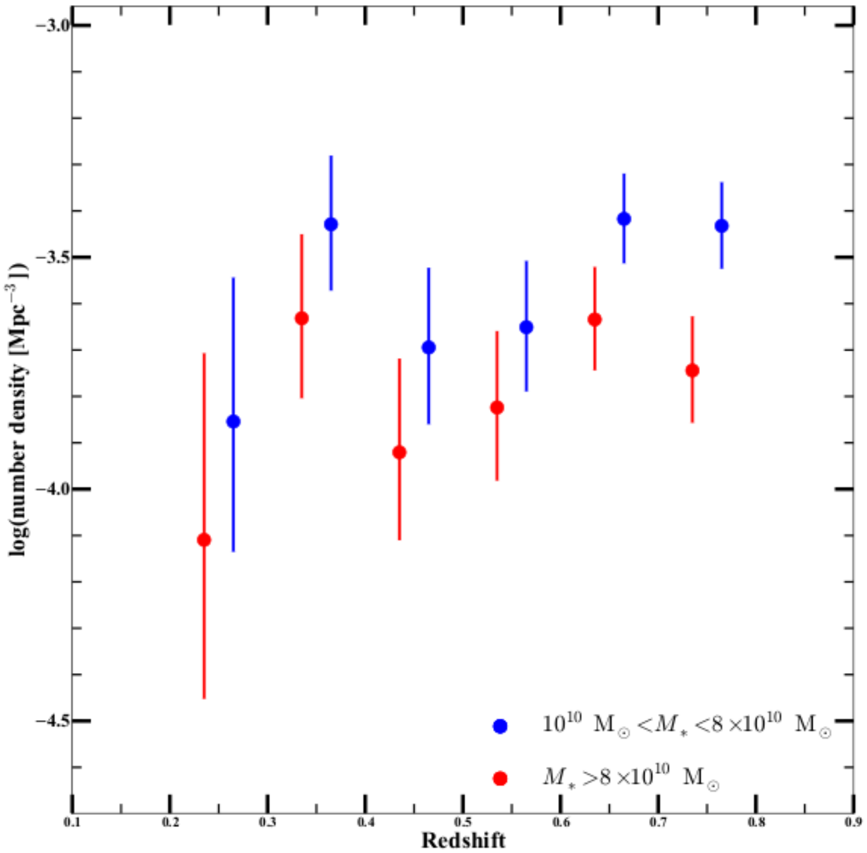
We use the large COSMOS sample of galaxies to study in an internally self-consistent way the change in the number densities of quenched early-type galaxies (Q-ETGs) of a given size over the redshift interval $0.2 < z < 1$ in order to study the claimed size evolution of these galaxies. In a stellar mass bin at $10^{10.5} < M_{galaxy} < 10^{11} M_{\odot}$, we see no change in the number density of compact Q-ETGs over this redshift range, while in a higher mass bin at $>10^{11} M_{\odot}$, where we would expect merging to be more significant, we find a small decrease, by ~30%. In both mass bins, the increase of the median sizes of Q-ETGs with time is primarily caused by the addition to the size function of larger and more diffuse Q-ETGs. At all masses, compact Q-ETGs become systematically redder toward later epochs, with a $(U - V)$ color difference which is consistent with a passive evolution of their stellar populations, indicating that they are a stable population that does not appreciably evolve in size. We find furthermore, at all epochs, that the larger Q-ETGs (at least in the lower mass bin) have average rest-frame colors that are systematically bluer than

The origin of the mean size growth: number density of massive dense ETGs

Damjanov at al. 2015:

Constant number density for $M_{star} > 8x10^{10}$ M_{sun} compact ETGs in the range $0.2 < z < 0.8$

Log $[M_{star}/R_e^{1.5}] > 10.3$ M_{sun}/ kpc $^{1.5}$



Damjanov et al. 2015, submitted

The origin of the mean size growth: number density of massive dense ETGs over the last 10 Gyr, from z = 0 up to 1.6

Morphological ETGs with $\Sigma > 2500\ M_{sun} pc^{-2}$ and $M_{star} > 10^{11} M_{sun}$

THE SAMPLES:

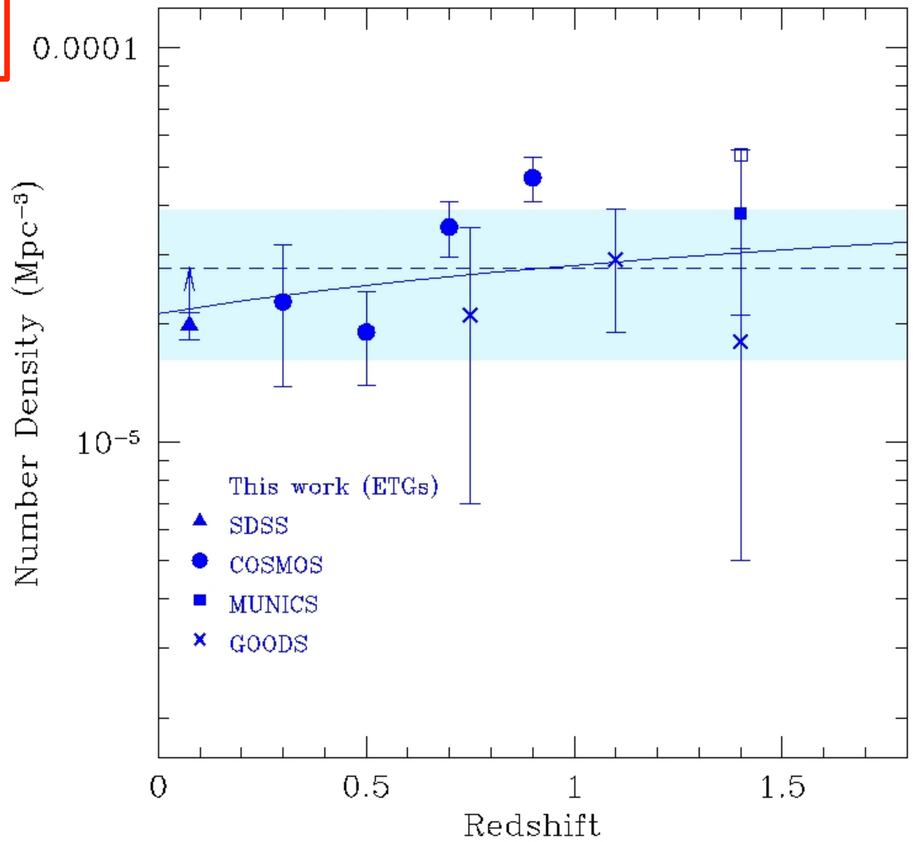
z ~ 0.1 → SDSS DR4 (Thomas et al. 2010)
Morphology: Thomas et al. 2010
Re: NYU release (r band)
M_{star} : Kauffmann et al. 2003
spectroscopic incompleteness

0.2 < z <1 → COSMOS
Morphology: Scarlata et al. 2007
Re: Sargent et al. 2007
M_{star} : Ilbert et al. 2013

1.2 < z < 1.6 MUNICS + GOODS South

MUNICS: morphology , Re: Longhetti et al. 2007
M_{star} Saracco et al. 2009

GOODS South: morphology, Re , M_{star} Tamburri et al. 2014



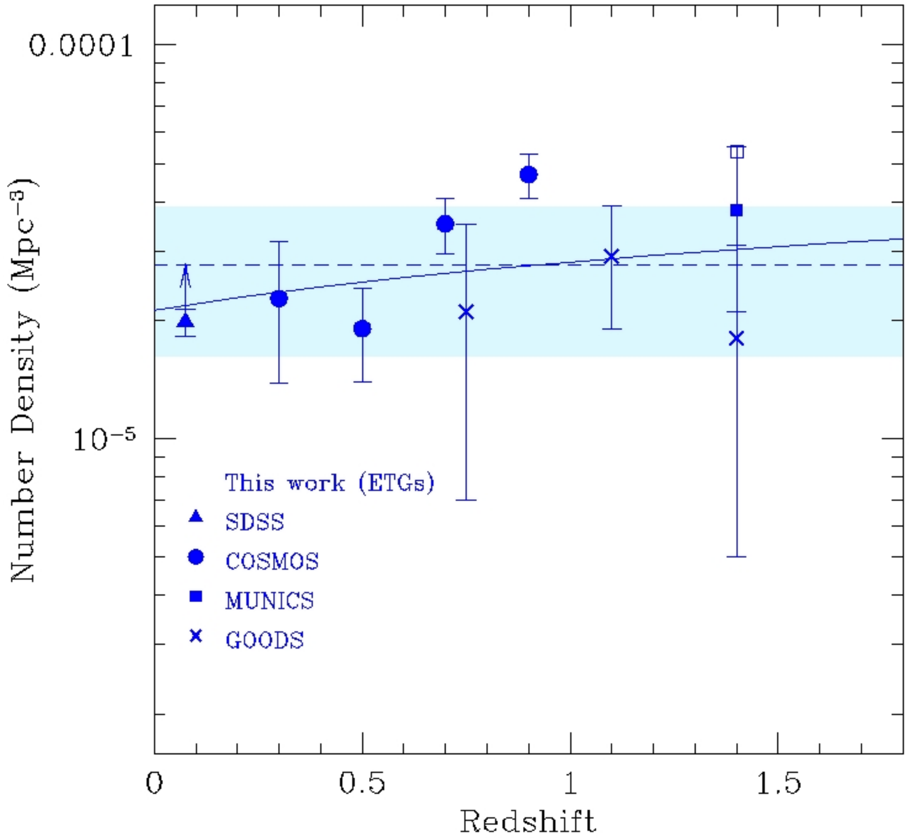
The origin of the mean size growth: number density of massive dense ETGs over the last 10 Gyr, from z = 0 up to 1.6

From z =1.6 to zero number density of massive dense ETGs decrease of a factor 1.5

$$\rho = K\,(1+z)^{-0.4}$$

ρ decrease by a factor ~ 1.5 from z = 1.6 to ~0

What about the properties of high-z and local ETGs?



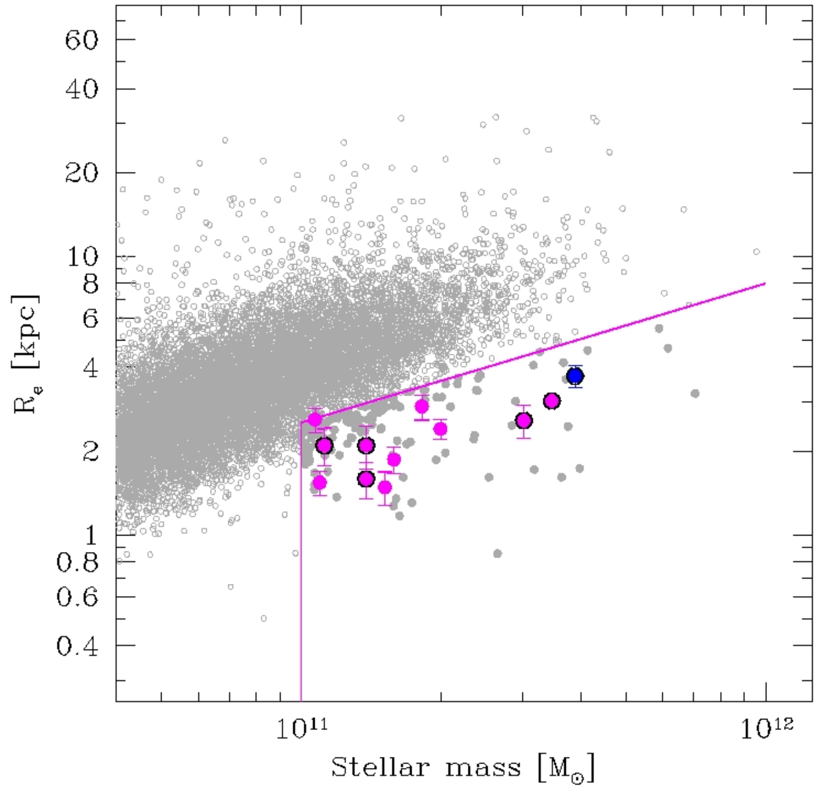
Gargiulo et al. 2015 submitted

The origin of the mean size growth: Comparison of structural and dynamical parameters of massive ETGs over the last 10 Gyr

Local sample: ETGs from Thomas et al. 2010 sample with $M_{star} > 10^{11}\ M_{sun}$, and $\Sigma > 2500\ M_{sun}\ pc^{-2}$

High-z sample: all the massive ETGs at $1.2 < z < 1.6$ with available Re and σ_e and with $\Sigma > 2500$ Msun pc^{-2} (11 ETGs).

For four out of 11 ETGs VLT- FORS2 spectra for velocity dispersion measurements.



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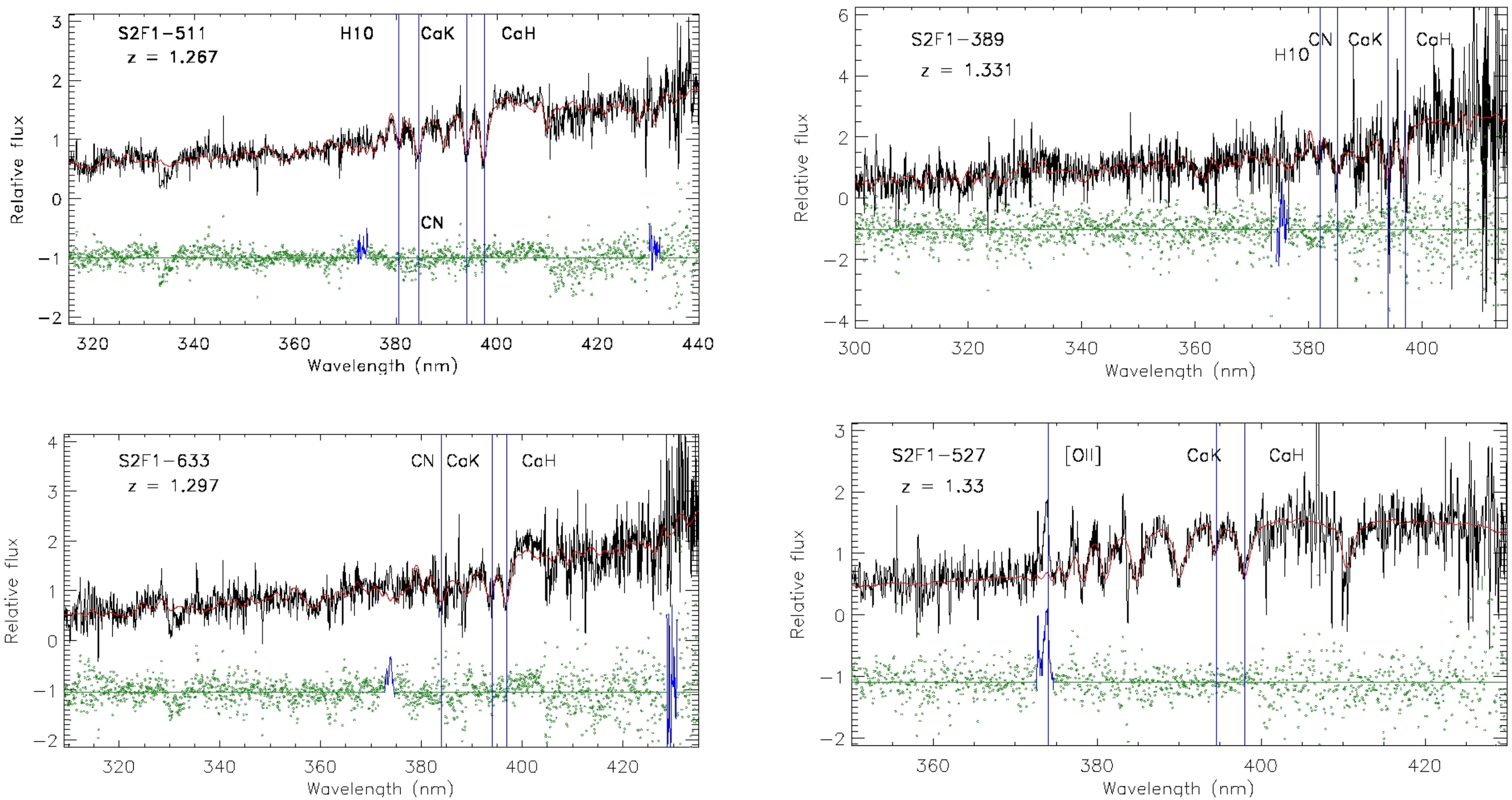
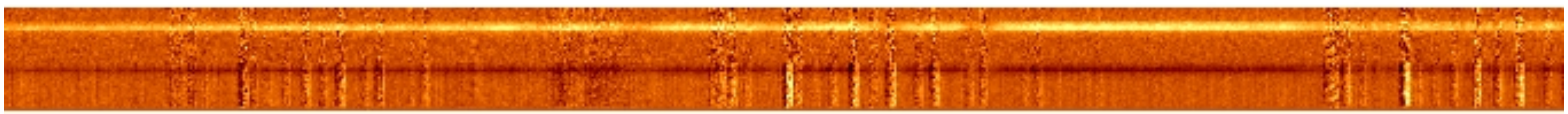


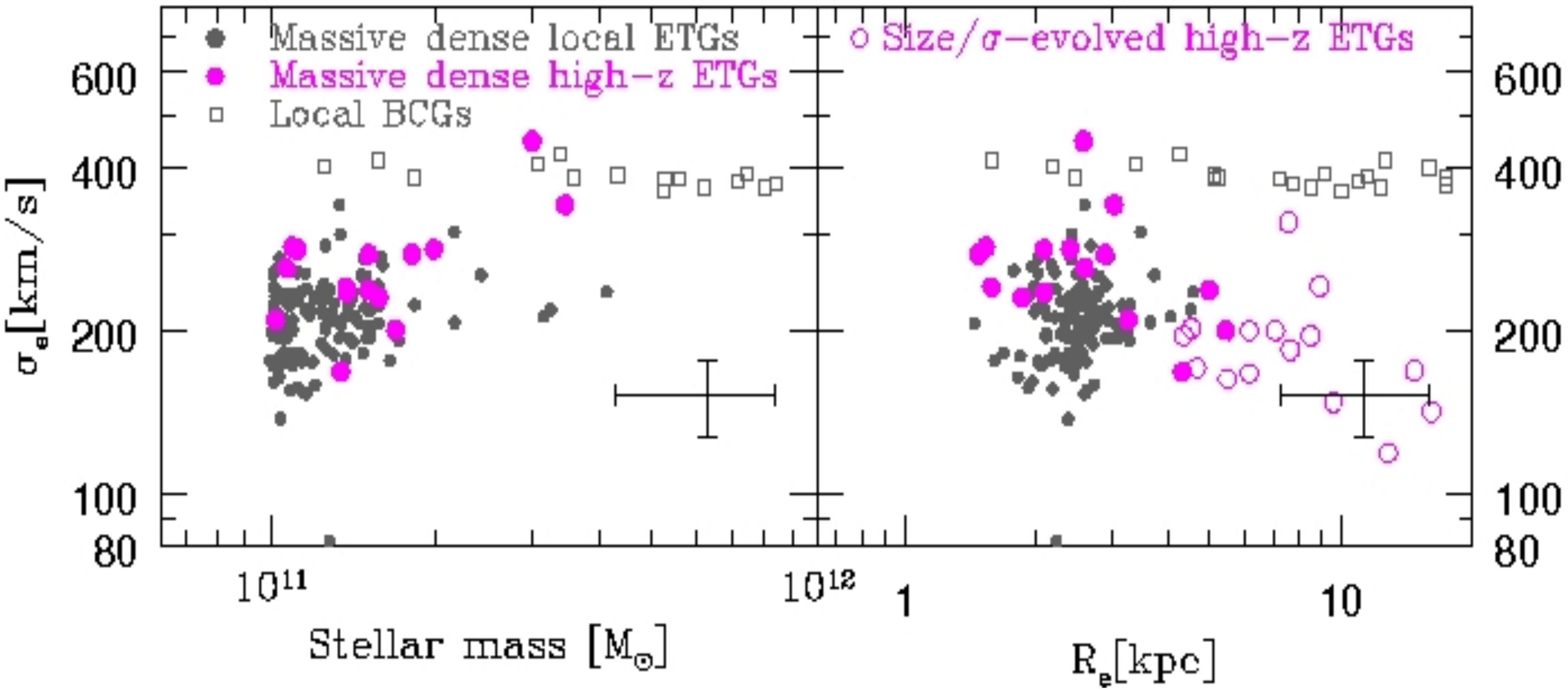
Gargiulo et al. 2015 submitted



8100 Å

10000 Å

The origin of the mean size growth:
Comparison of structural and dynamical parameters of massive ETGs over the last 10 Gyr



Gargiulo et al. 2015 submitted

$< Re > = K\,(1+z)^{-1.4}$

$$\frac{\langle \sigma(z \mid M_*) \rangle}{\langle \sigma(0 \mid M_*) \rangle} = \frac{1}{\sqrt{1+\gamma}} \sqrt{\gamma + \frac{\langle R_e(0) \rangle}{\langle R_e(z) \rangle}},$$

γ is the relative fraction of the central potential contributed by the dark matter at $z = 0$

The origin of the mean size growth: brief summary

- Number density of massive dense ETGs decrease of a factor ~1.5 from z = 1.6 to 0;
- All the massive dense high-z ETGs have a counterpart in local universe with similar structural and dynamical properties

(1) The majority of massive dense ETGs at z = 1.4 have already completed their mass accretion and their shaping.

↓

Mean size growth → new larger ETGs

(2) A significant fraction of massive dense ETGs at z = 1.4 evolves in size, sustaining the mean size growth, *BUT* new dense ETGs form at z < 1.6 to maintain the number density almost constant.

↓

Mean size growth → individual size growth

↓

Inside – out accretion : possible not necessary

The origin of the mean size growth: brief summary

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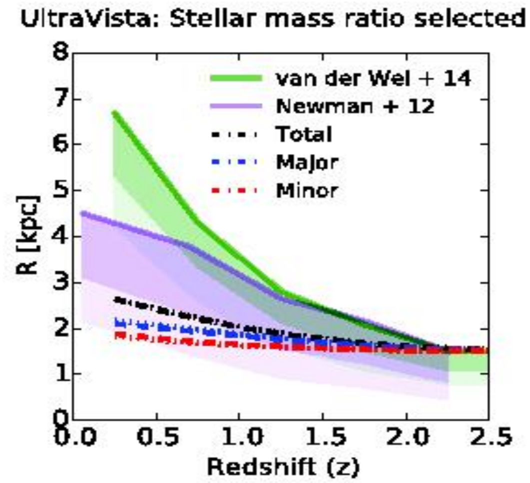
Mean size growth → individual size growth



Man et al. 2014

The Initial Mass Function (IMF)

Constraints on mass accretion of ETGs are all based on a fundamental assumption: the universality of the stellar initial mass function (IMF) over the cosmic time.

mass spectrum of a stellar generation at birth

Fix the relative number of low- and high- mass stars →
Define the chemical enrichment, the total light, the color,
and the evolution of all these quantities with time

Direct stars counts in MW :

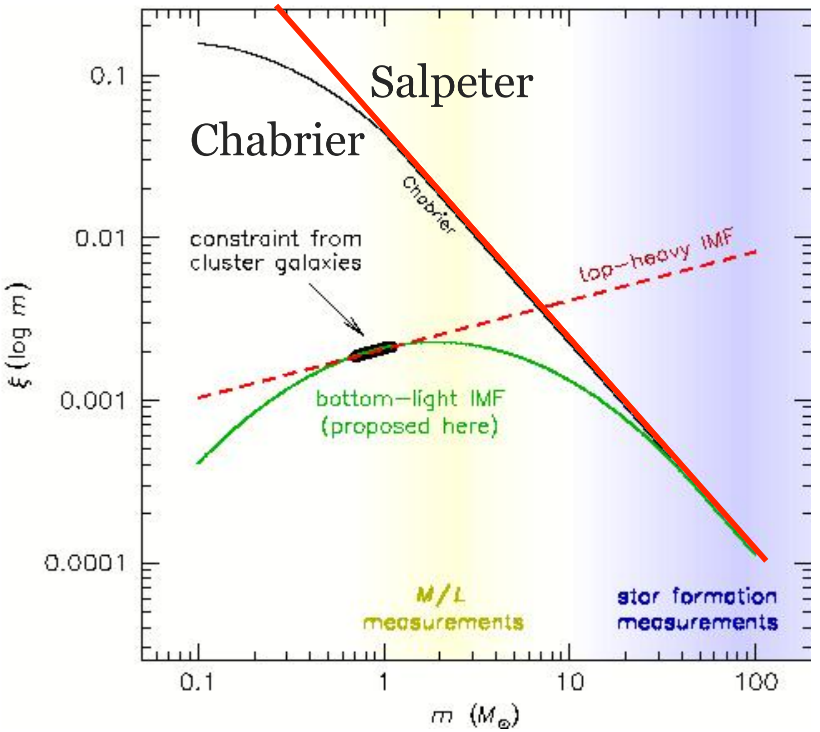
$dN / dm \propto m^{-x}$, x = - 2.3 , Salpeter (1955)

then revised from Chabrier (2003) (Kroupa 2001):
turn over at low masses

the same across different MW environment

⬇

UNIVERSALITY OVER THE TIME AND SPACE



Van Dokkum 2008

Is the IMF universality a reasonable assumption?

$$\mathbf{M_J} \propto \mathbf{T}^{3/2}\ \rho^{-1/2}$$

T temperature of the gas,
ρ density of the gas

T related to metallicity Z : at fixed heating rate, the gas cooling efficiency is reduced in absence of metals, and consequently the gravitational collapse of low-mass stars is inhibited in metal poor gas

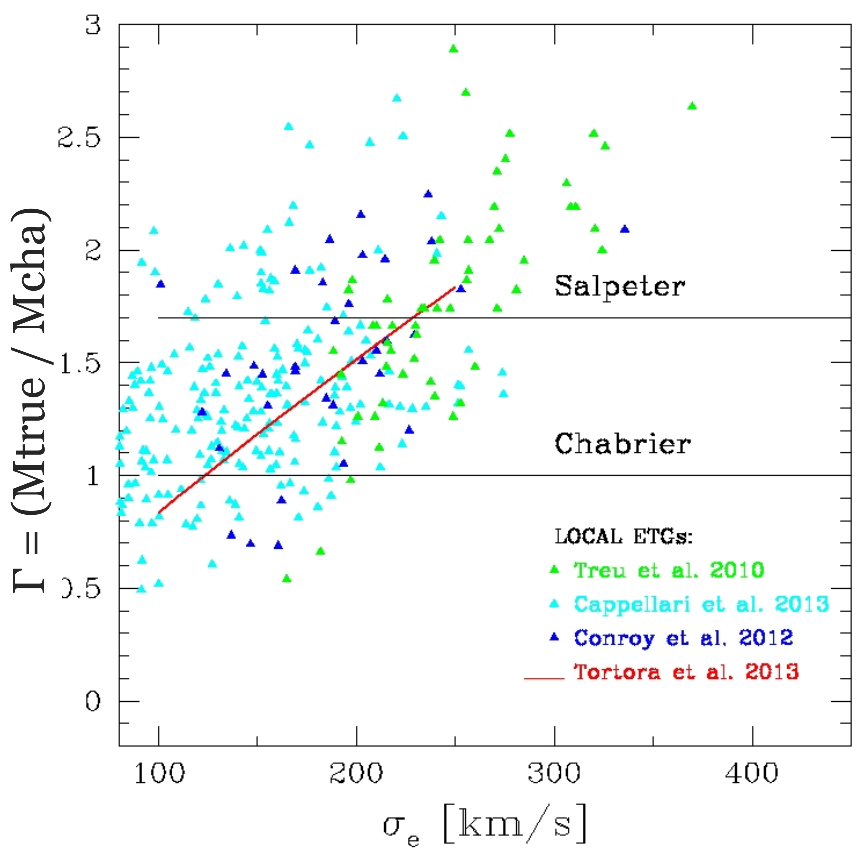
(e.g. Larson 2005; Bate & Bonnell 2005; Bate 2005; Bonnell et al. 2006).

<u>Mass spectrum of stars formed in a burst of star formation is deeply connected to the properties of the gas cloud</u>

Among galaxy types: initial condition in which galaxies form are expected to be different.

At high redshift: the temperature was higher , primordial gas was metal poor → disfavour the formation of low-mass stars

The variation of IMF in local ETGs



Strong systematic variation of IMF in ETGs with velocity dispersion

Compare:

Mtrue (IMF indep.) → the stellar mass derived through :

2D dynamical model

simpler 1D dynamical models (Tortora et al. 2013)

lensing (Treu et al. 2010)

spectral feature sensitive to low mass stars (Conroy et al. 2012)

with

Mcha → the stellar mass derived through SED fitting using SPS models and fixed IMF (Chabrier)

The IMF in dense ETGs at z =1.4

High-z dense massive ETGs the first to form → provide insight on the early "IMF"
On the basis of the local findings and constraints
→ Γ – σ trend in high-z massive dense ETGs at z =1.4

Spectral energy distribution fitting with the Chabrier IMF → Mcha

Mtrue = Mdyn = $(\beta R_e \sigma_e{}^2) / G$

where $\beta = 8.87 - 0.831 \times n + 0.0241 \times n^2$

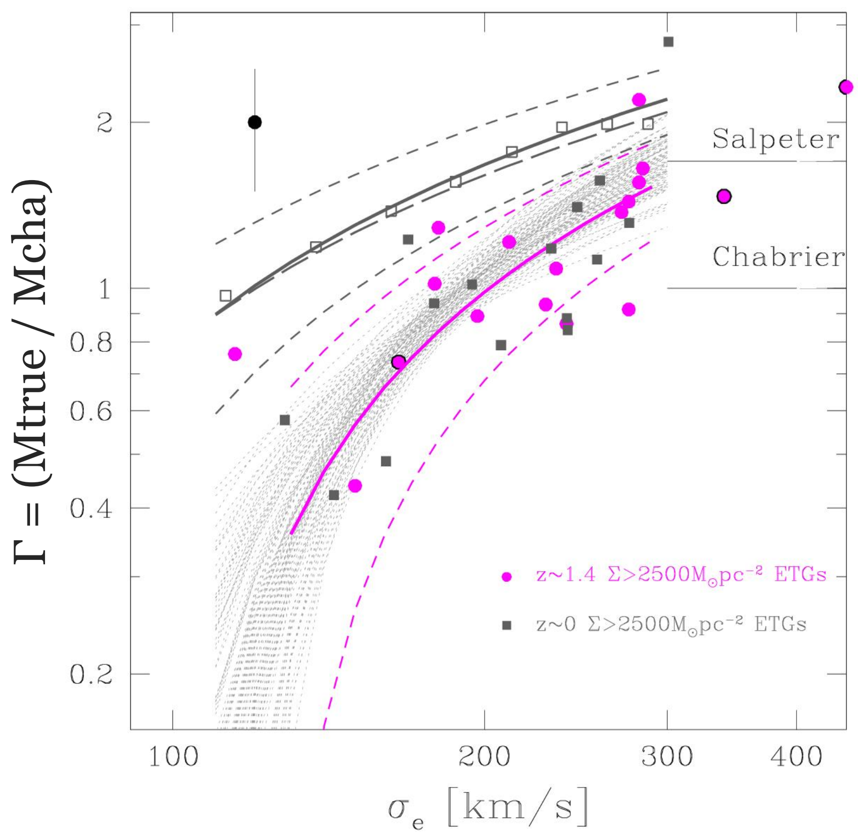
hp: spherical and isotropic
(Cappellari et al. 2006)

→ no DM
(reasonable assumption : dense ETGs stellar matter dominated)

High-z dense ETGs:
lower stellar mass normalization with respect to local ETGs

↓

higher ratio of high- to low-mass stars than the IMF of typical ETGs of similar σ_e



Gargiulo et al. 2015

The IMF in high-z dense ETGs

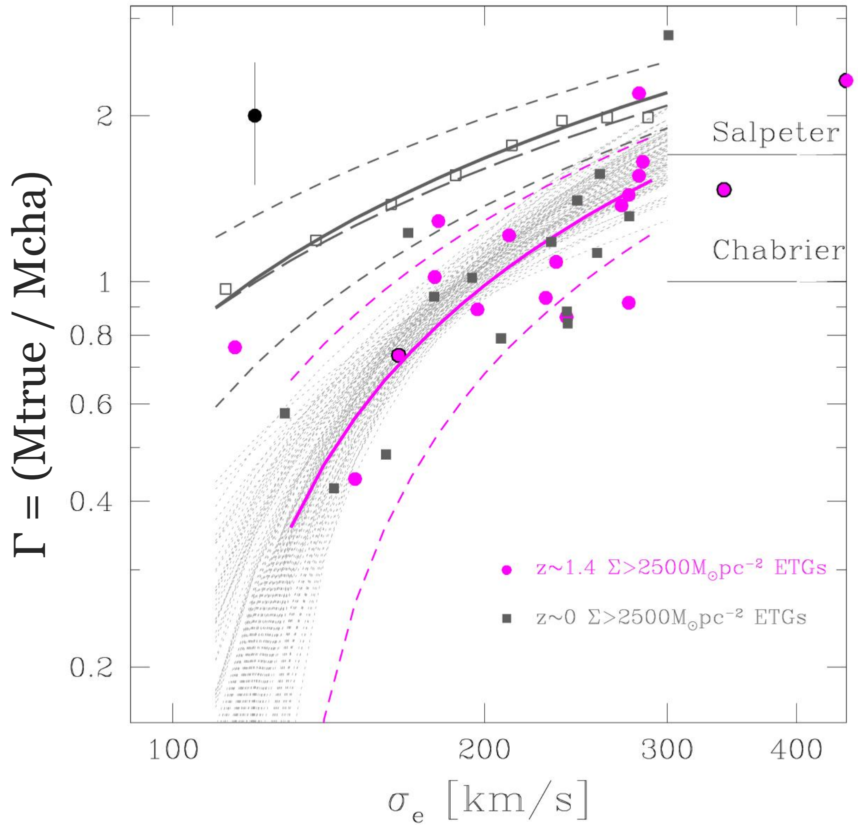
The lower mass normalization of high-z dense ETGs could be an evidence of an evolution of the IMF with time or of a correlation with Σ.

Γ-σ_e trend of dense ETGs at $z = 1.4$ consistent with that of local ETGs with similar velocity dispersion and mean stellar mass density.

AT ANY REDSHIFT: the IMF of massive dense ETGs

↓

higher ratio of high- to low-mass stars with respect to typical ETGs of similar σ.



Gargiulo et al. 2015

The IMF in ETGs

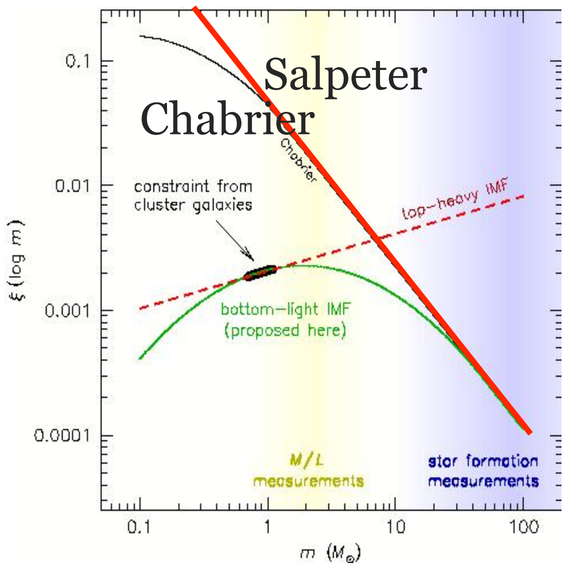
Both high-z and local massive dense ETGs have a lower mass normalization

If all massive dense ETGs form at high-z (thus local massive dense ETGs are mostly the descendants of high-z dense ETGs) → the conditions of the early universe produce a lower ratio of high- to low- mass stars

$$\frac{\text{High mass stars}}{\text{Low mass stars}}$$

Top heavy IMF → not able to reproduce the Z of local ETGs

Bottom light IMF → in agreement with theoretical predictions



Van Dokkum 2008

The IMF in ETGs

Both high-z and local massive dense ETGs have a lower mass normalization

If all massive dense ETGs form at high-z (thus local massive dense ETGs are mostly the descendants of high-z dense ETGs) → the conditions of the early universe produce a lower ratio of high- to low- mass stars → main factor is the time.

If massive dense ETGs form at any z → the same conditions of the early universe occur at lower redshift.