Galaxy Structural Transformations During Star Formation And After Quenching

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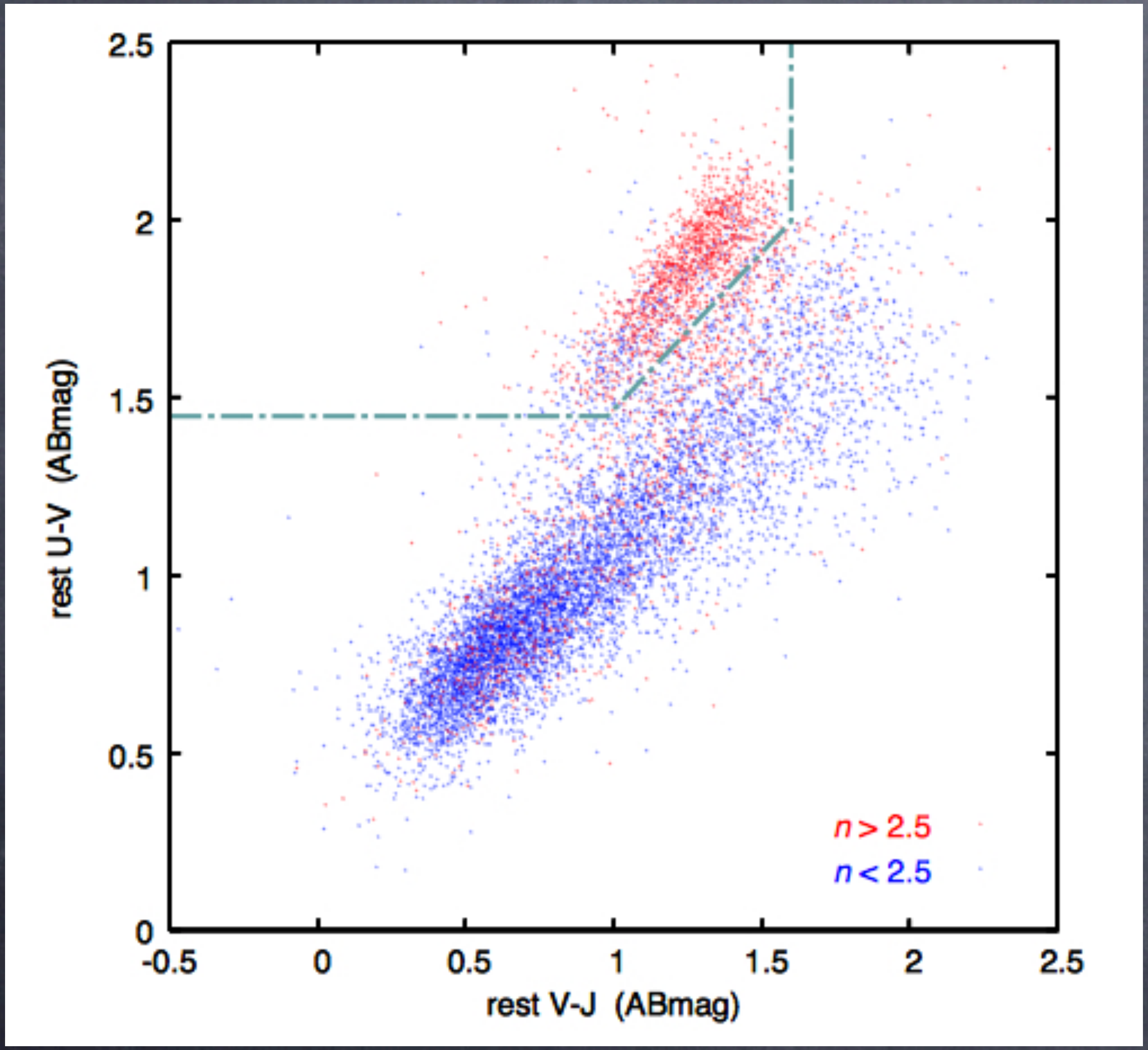
At any redshift, quenched galaxies have "spheroidal-like" features; star forming are "disk-like".

Kajisawa+ 2015, galaxies up to z≈1.5



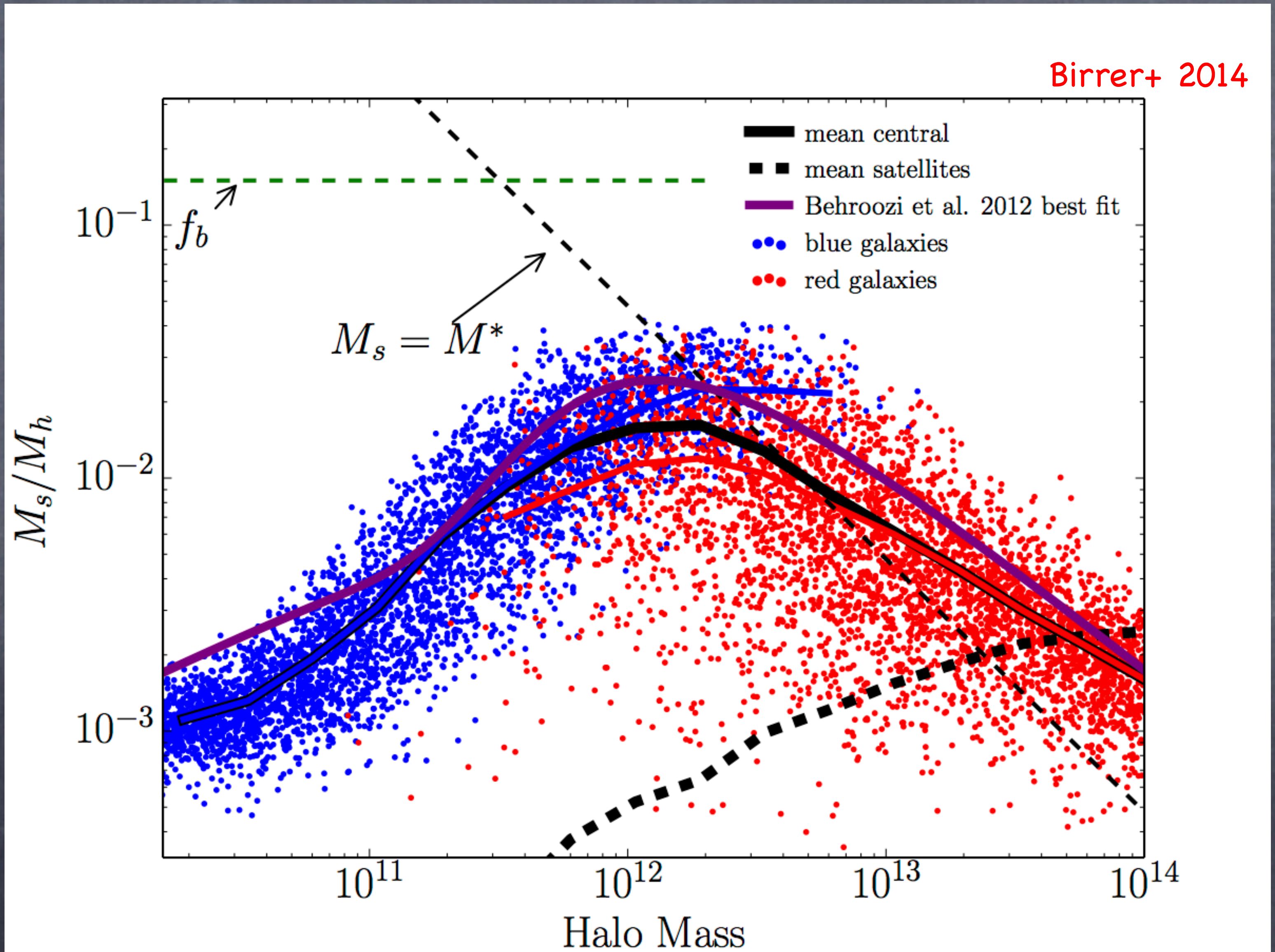
Exponential disk: n = 1

De Vaucouleurs spheroid: n = 4

See also Bell+ 2012; Carollo+ 2013; Teimoorinia+ 2015

Mass Quenching: $p_q \approx \exp(-M/M^*)$, the inevitable doom?

- Galaxies quench when they grow too big (≈M^{12} $M_\odot$), too efficient in forming stars (≈10% of f_b)
- Is stellar morphology ≈conserved during the quenching phase?



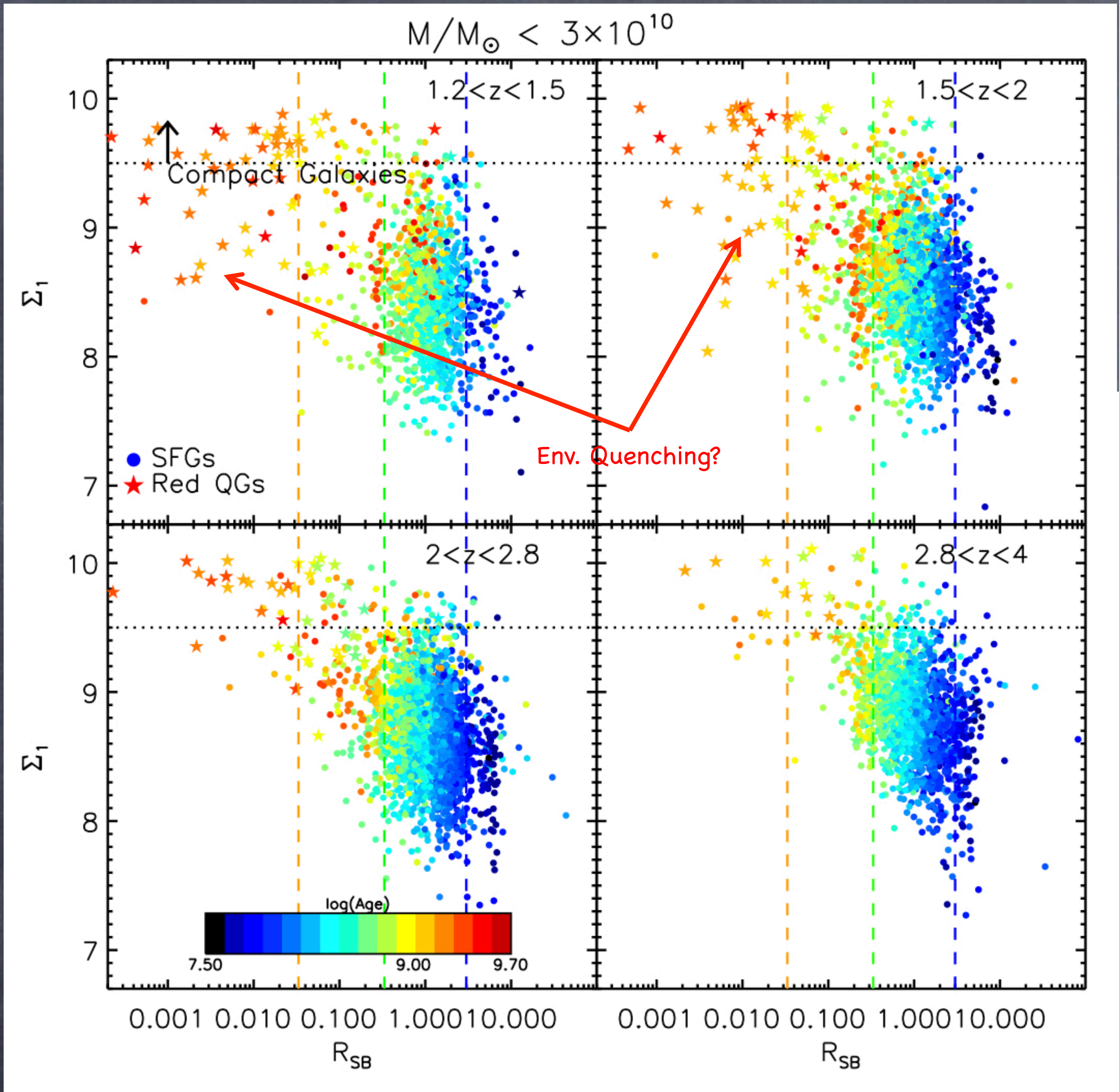
Consistent with, in fact implied by, LF of SF and Q galaxies; evolution of M^*; overall evolution of SFRD and MS

Peng+ 2010, 2015; Lilly+ 2013; Behroozi+ 2012; Moster+ 2013

The Questions

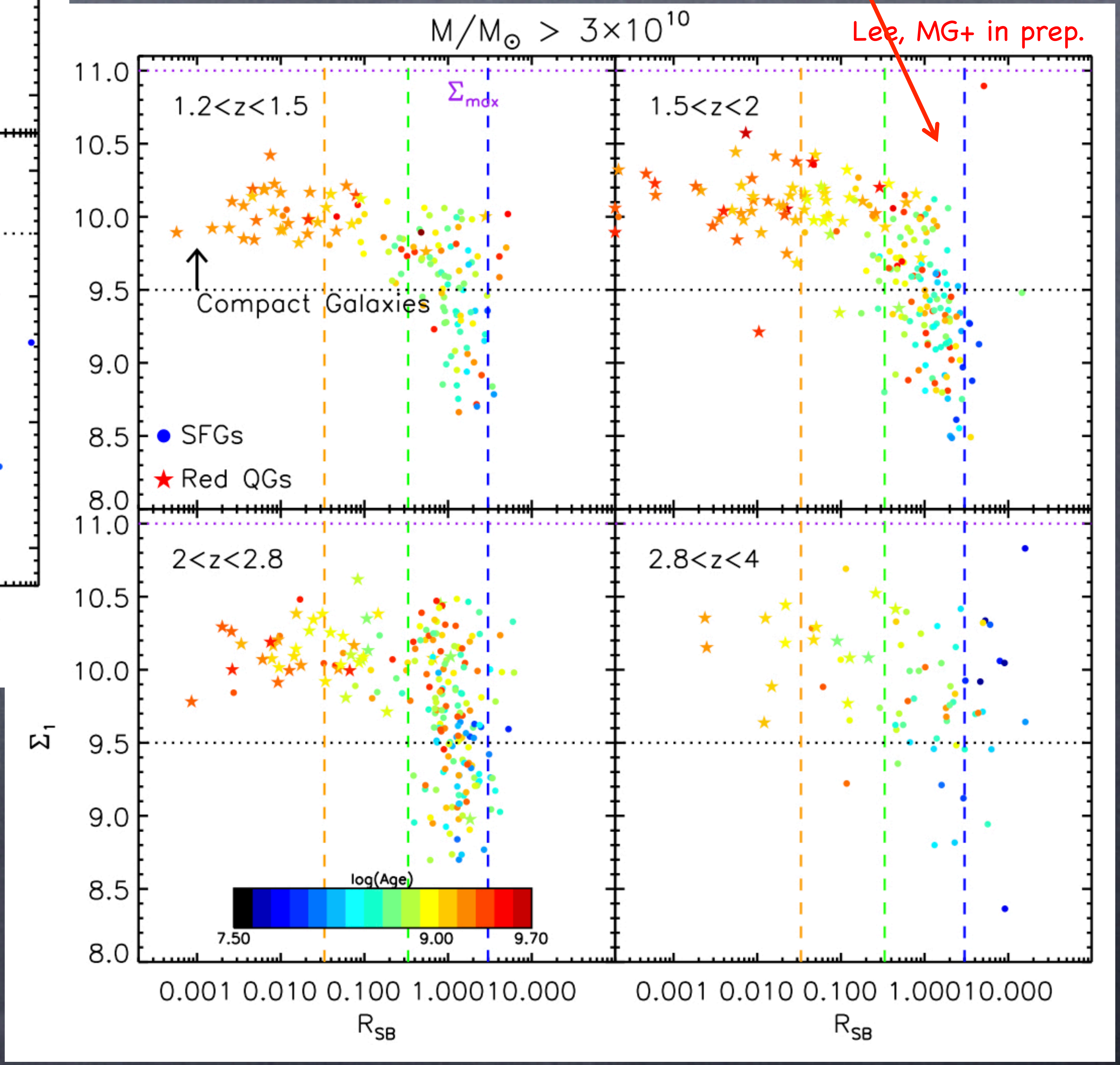
- Do galaxies undergo structural transformation as they evolve?
- Do galaxies keep their morphology as they quench?
- Is quenching the culmination of structural transformations or a "phase transition" during these transformations?
- Is a high stellar density a "quenching agent" or the result of some feedback-driven regulation (Hopkins+ 2010, Diamond-Stanic+ 2010)?
- Or just progenitor bias, i.e. older galaxies are more compact and/or more dissipative (Lilly & Carollo 2016; this work) or both?

Projected core mass density: Σ_1 vs R_{sb} and Age



Lee, MG+2017

Lack of compact massive SFG at lower redshift (see also Van Dokkum+15)



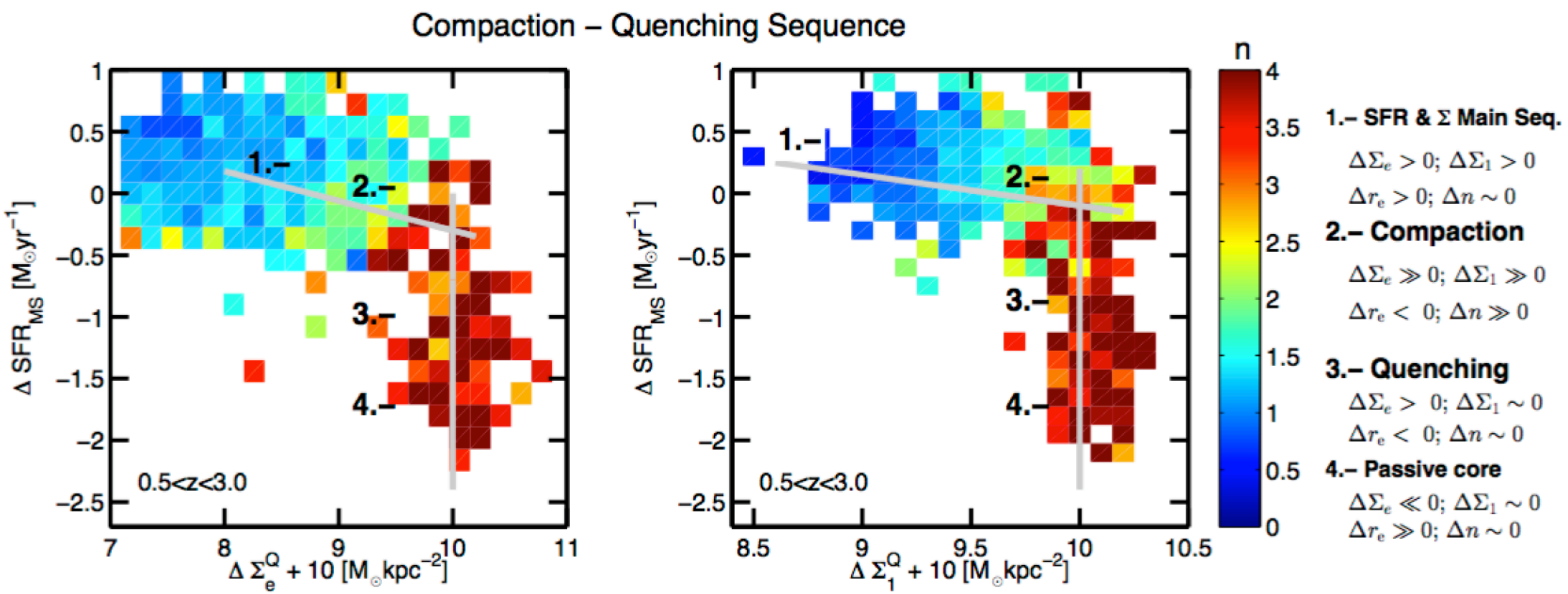
MS galaxies have full range of Σ_1; Q ones do not

Core of more massive QG always very dense

Less massive QG have broader range of Σ_1

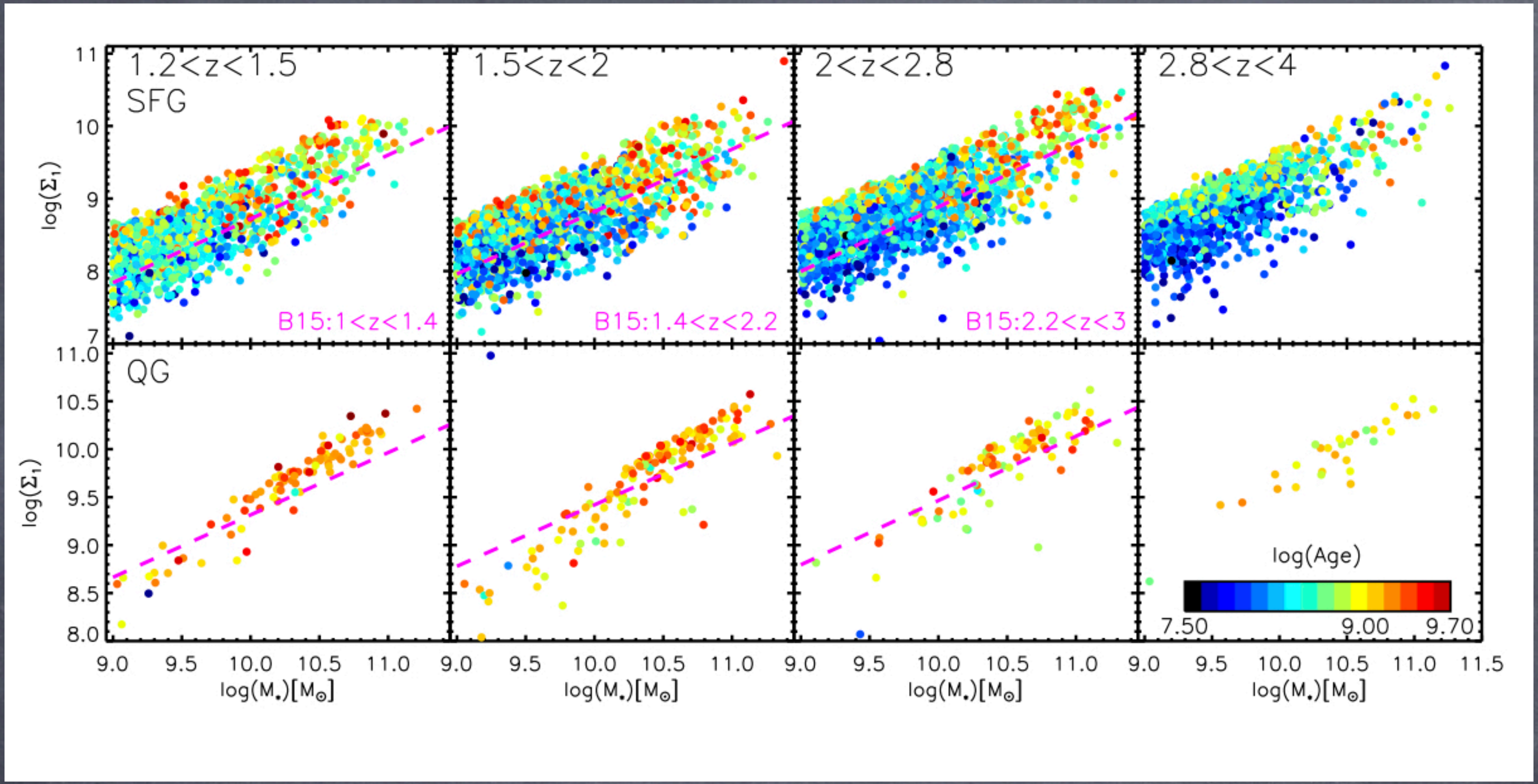
Others find the same result:

1. the central density of quenched galaxies tops at a threshold of ≈10^{11} $M_{\odot} kpc^{-2}$ (see Hopkins et al. 2009, 2010)
2. It spans ≈1/3 of the range of the central density of SF galaxies



Barro et al. 2015,7

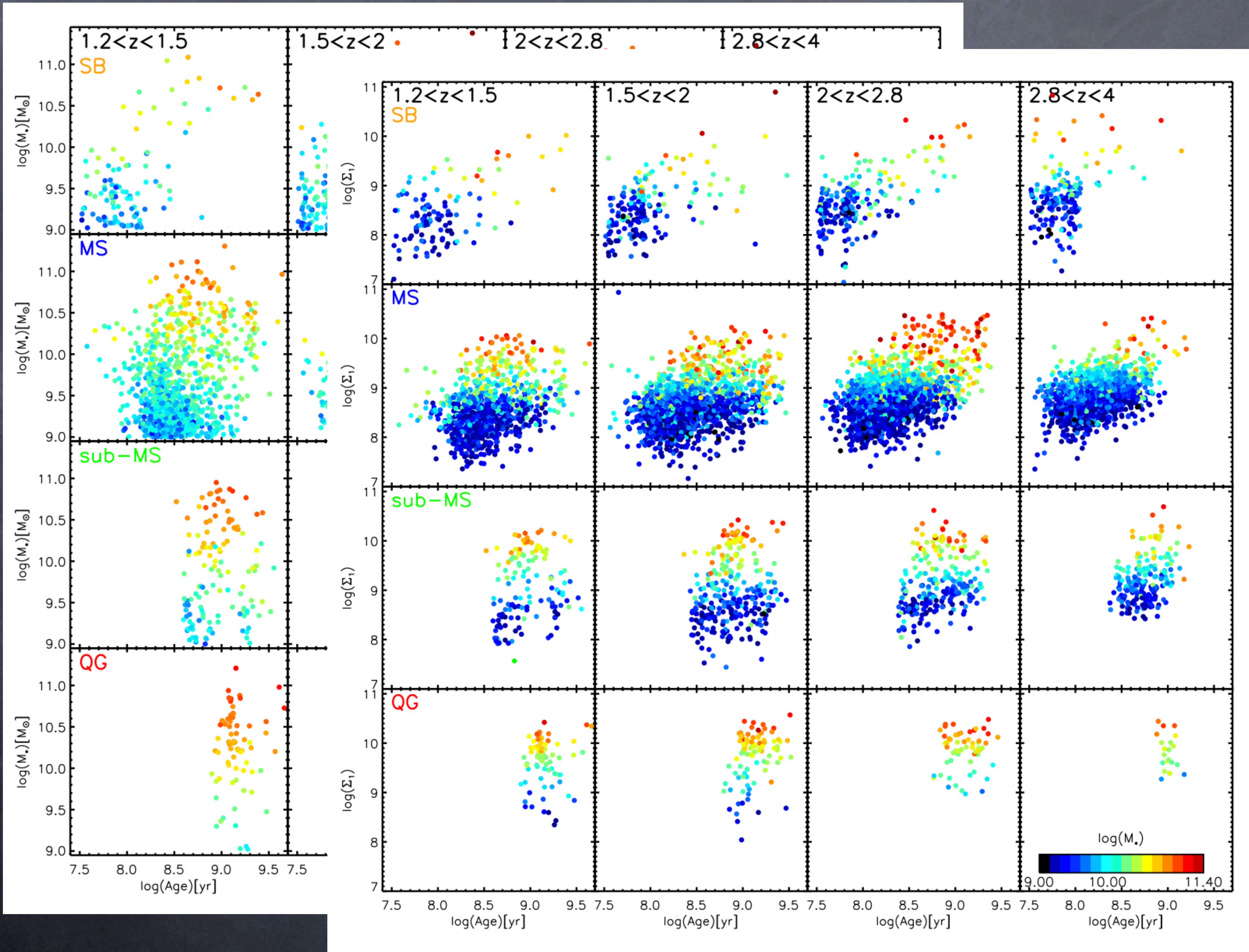
M_*, Σ_1 and Age



- Three variables: Age, M_*, and Σ_1
- Age is independent variable, but measures are very noisy:
  - Correlations washed out a bit
- Strong correlation between Σ_1 and M_*
  - Both grow as galaxies evolve
- Σ_1 gradient with age:
  - Older galaxies have larger Σ_1

- M_*: diagnostic of history of baryon accretion and star formation
- Σ_1: diagnostic of highly dissipative accretion
- But more massive galaxies can be more dissipative

Fang+13; Barro+15,17; Lee+17
See also Williams+17; Fagioli+17



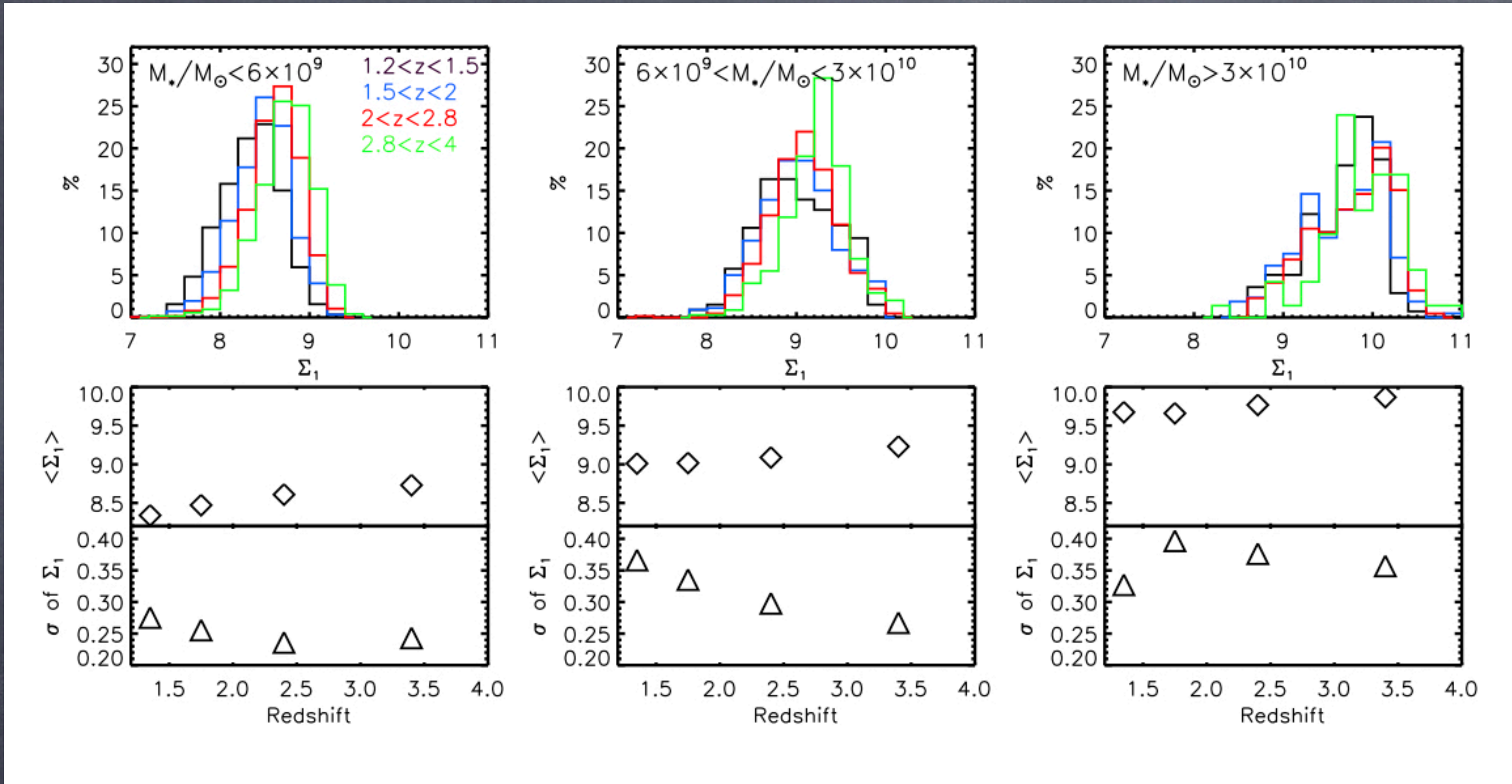
1.2<z<1.5
1.5<z<2
2<z<2.8
2.8<z<4
SB
MS
sub−MS
QG
log(M*)[M⊙]
log(Age)[yr]
log(Σ1)
log(M*)
9.00
10.00
11.40

Galaxies with a compact core are not necessarily compact galaxies

- Σ_1 is a *local* metric of density; it only informs us on the structure of the innermost volume of a galaxy
  - Σ_1 does not really tell us about a galaxy's global transformation, or if it becomes compact; only if it grows a high-density central structure

- Gini and M_{20} are *global* metrics; they describe the overall light (mass) distribution of the whole galaxy
  - Absolute values of Gini and M_{20} difficult to calibrate and interpret; **variations are more informative**

- Gini and M_{20} as tracers of structural transformations as galaxies grow in size and stellar mass: independent on light profile
  - define a compact galaxy not based on Σ_1 alone but rather based on Gini, M_{20} and Σ_1. Compact Galaxy:
    - $G > 0.55$
    - $M_{20} < -1.6$
    - $\Sigma_1 > 9.5$ (Log scale)

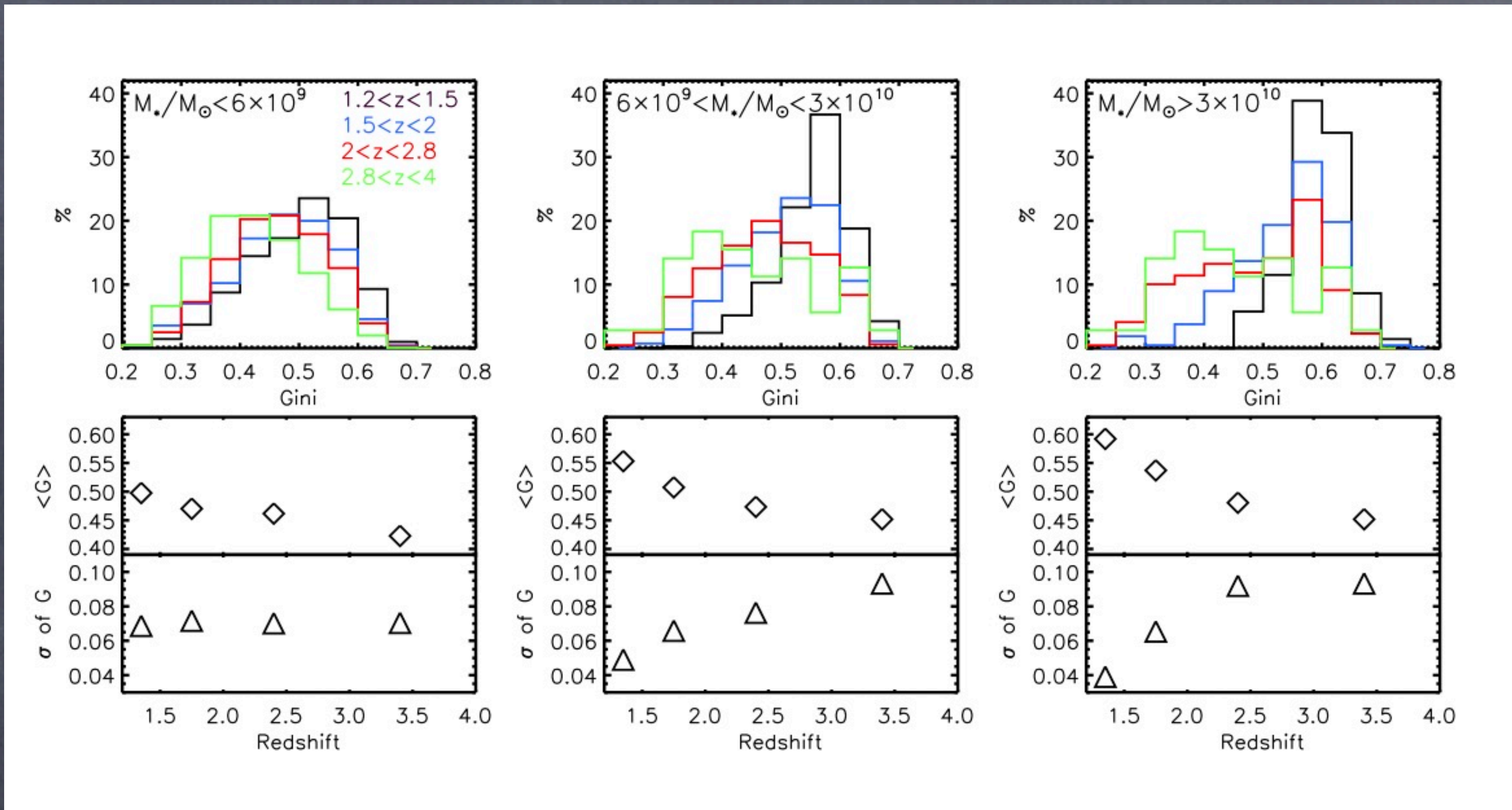


Very mild evolution of Σ_1 with redshift: in fact, Σ_1 slightly decreases with redshift, due to addition of galaxies with lower central density

The highest value, $\Sigma_1 \approx 11$, does not decrease (but it is mass dependent)

"Compactification" is mass dependent: more massive galaxies compactify more

"Compactification" may help or even drive quenching via gravitational heating (e.g. Johnasson, Naab & Ostriker 09, 12)

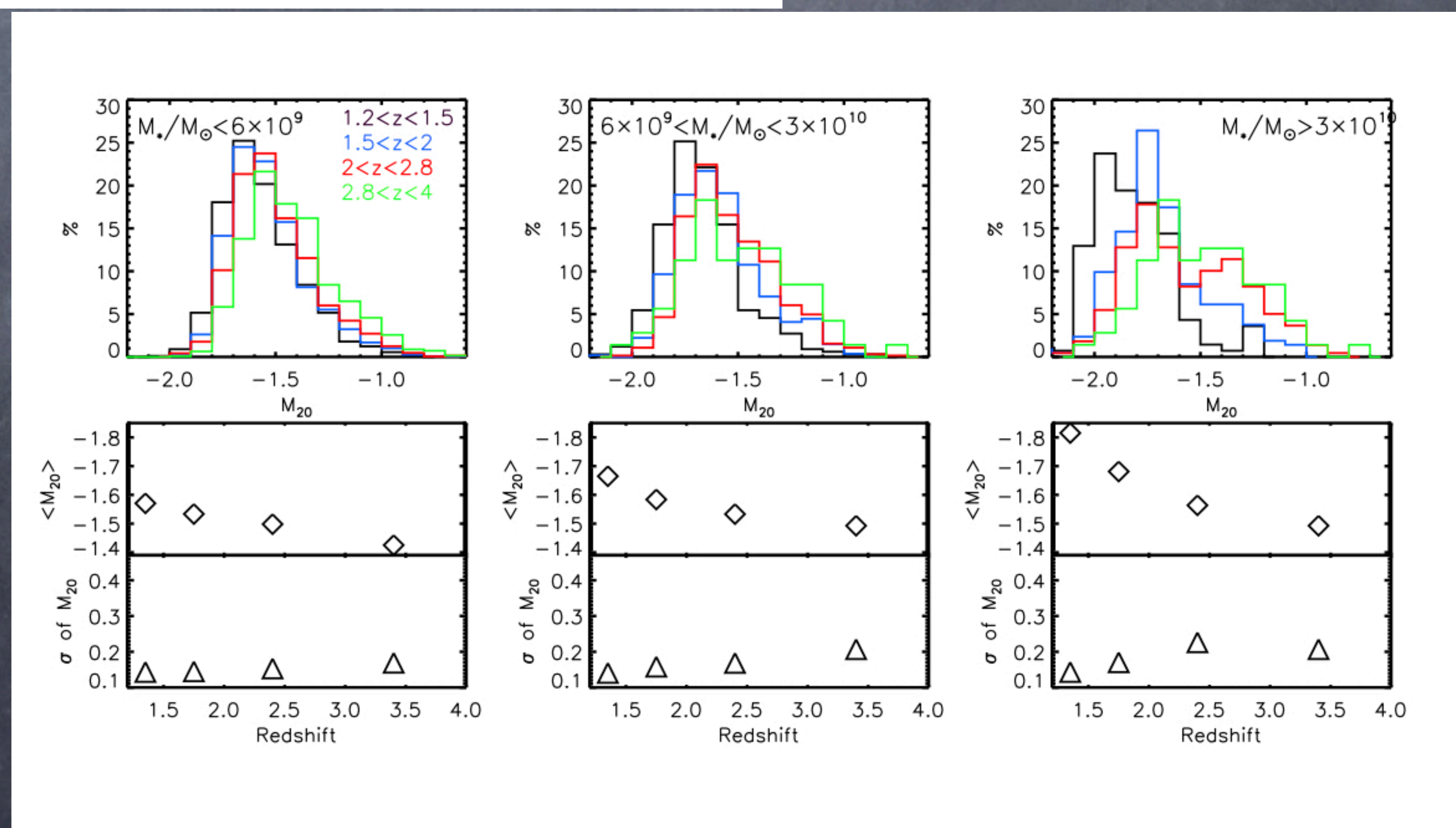


Gini and M_{20} both show strong evolution with redshift:

Gini increases: galaxies become more compact

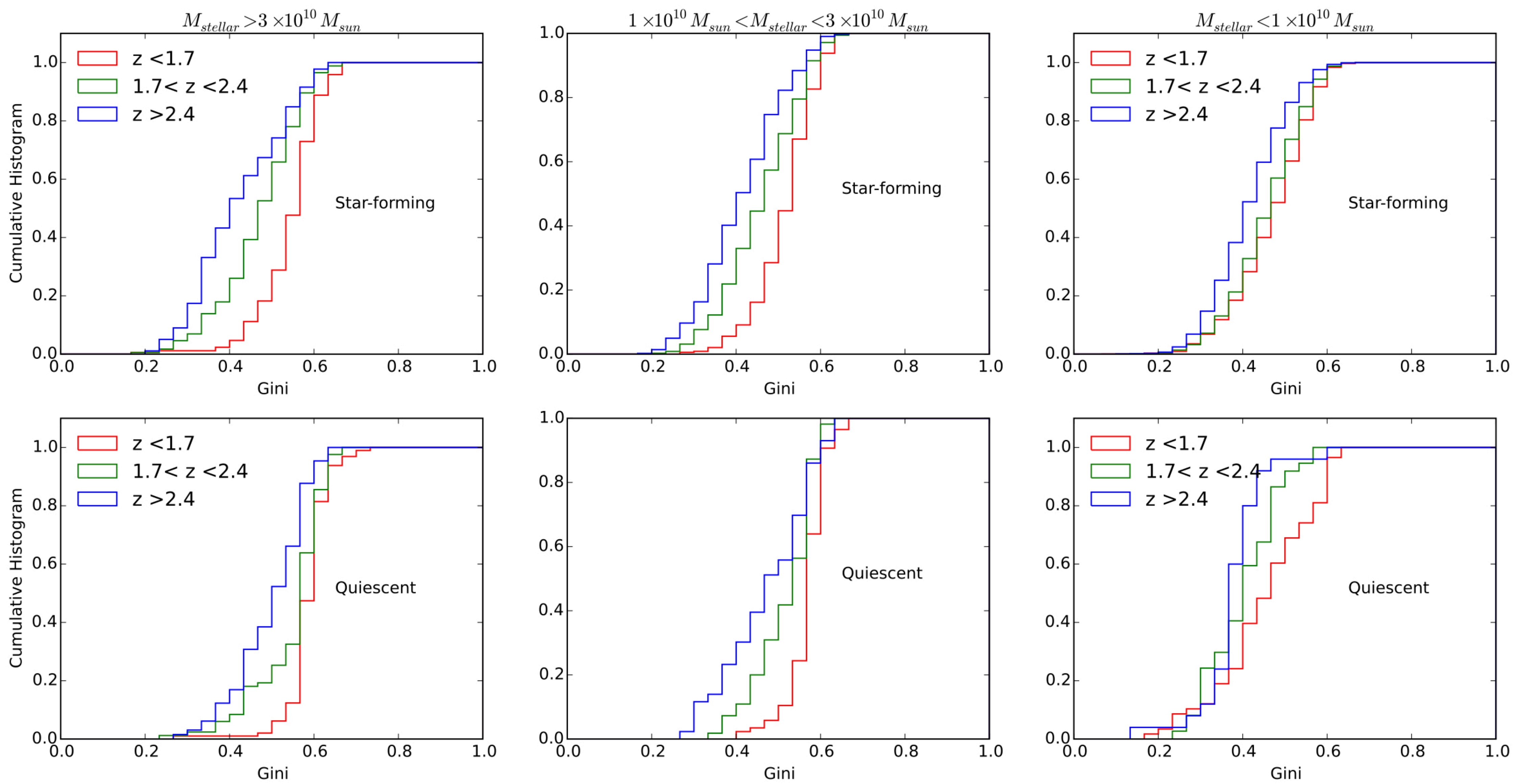
M_{20} decreases: galaxies become more nucleated

COMPACTIFICATON



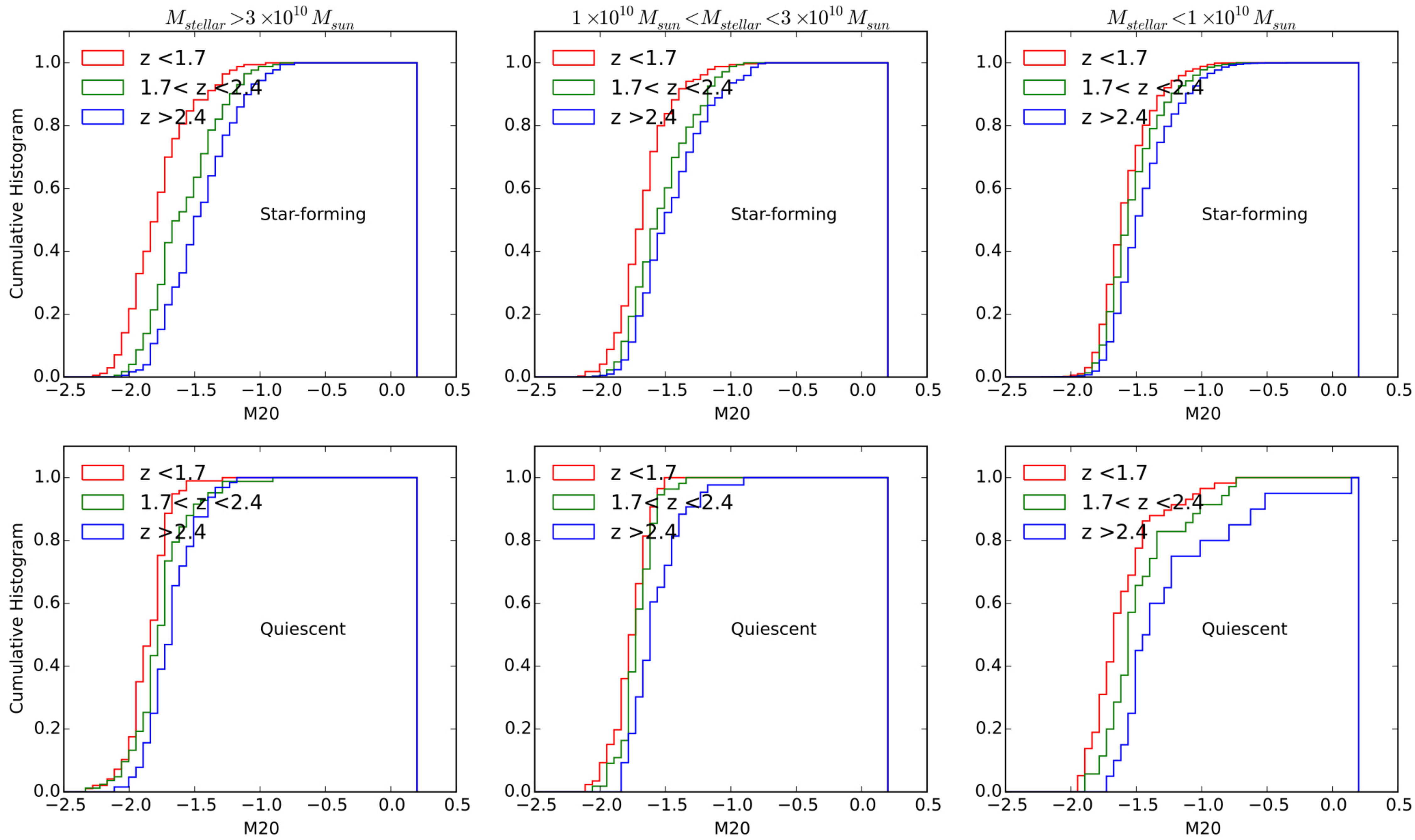
The cumulative distribution of Gini

Strong, mass-dependent evolution with redshift



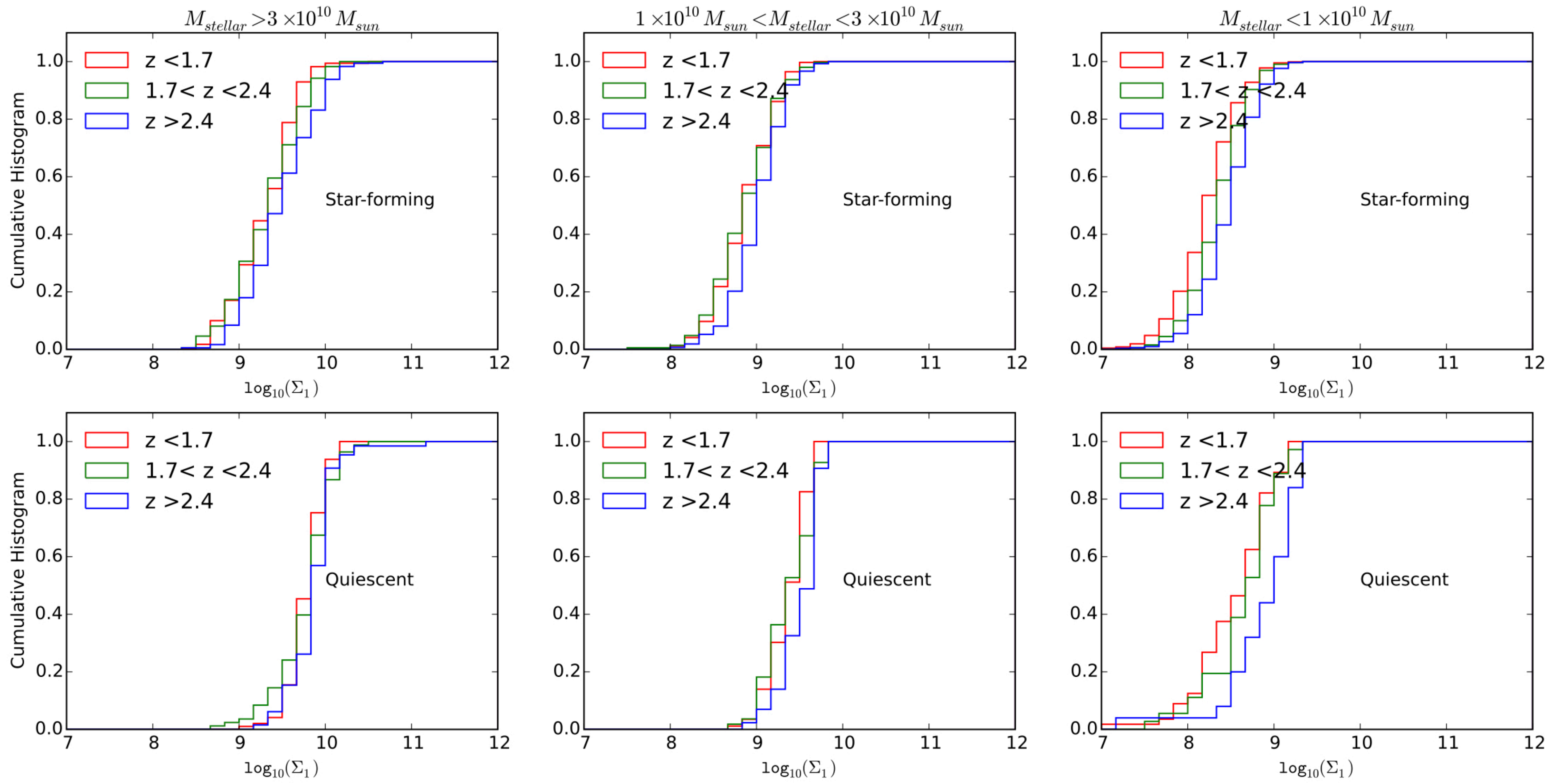
The cumulative distribution of M_{20}

Mass-dependent evolution with redshift



The cumulative distribution of Σ_1

No evolution with redshift



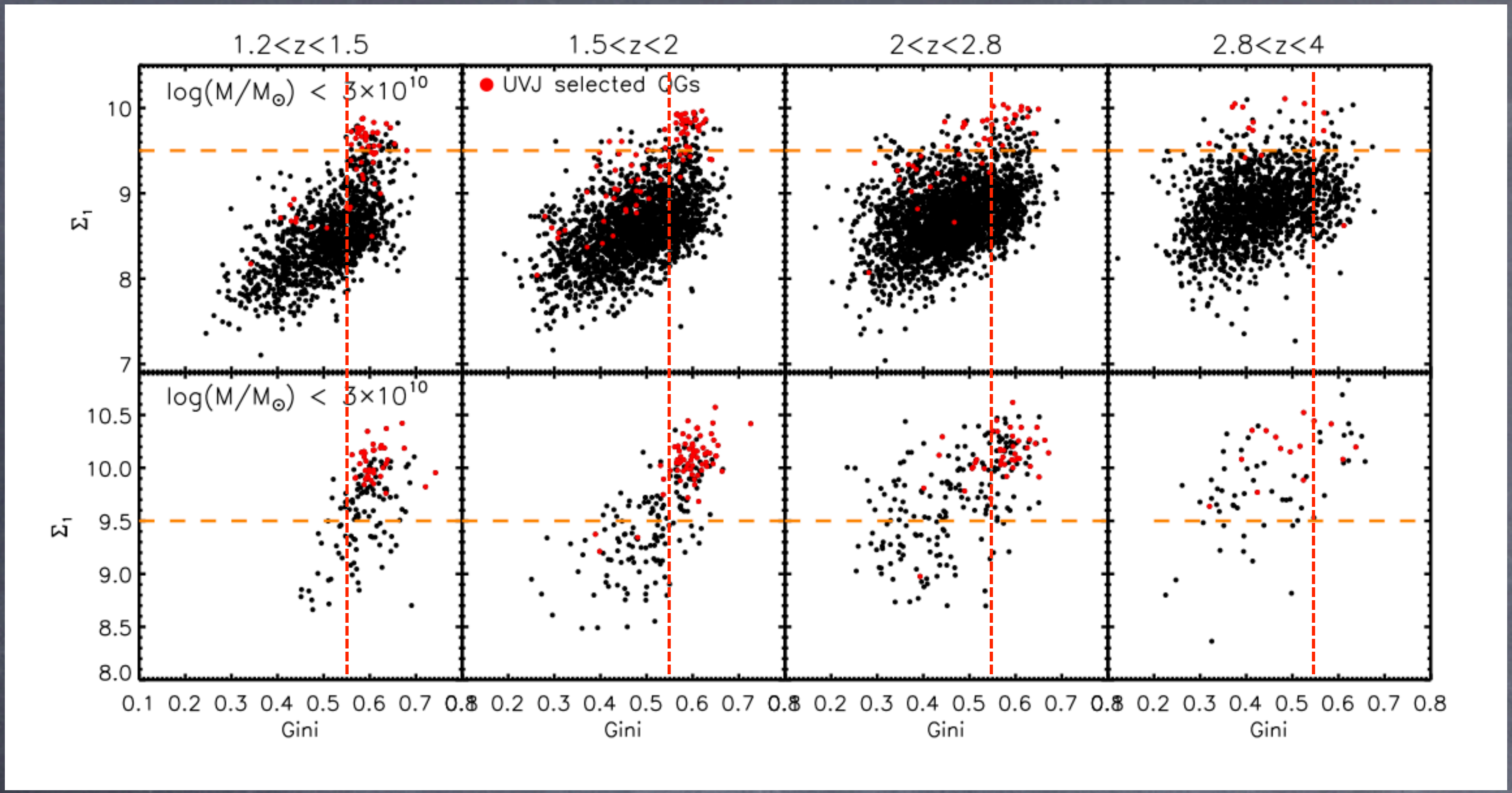
We carefully considered redshift-dependent bias (see Lotz+ 04, 06; Peth+15):

1. It is not wavelength-dependent morphology, because that would go the opposite way: galaxies are more nucleated and compact at bluer wavelengths
2. It is not an angular resolution effect because:
   ① It gets stronger for brighter galaxies, which are larger
   ② It goes the opposite direction (limited resolution causes M_{20} to become more negative), but signal gets stronger at lower redshift, where effects of fixed resolution ameliorate
3. It is not due to differential surface-brightness sensitivity because:
   ① Signal more pronounced for brighter galaxies, which have more pixels at higher surface brightness
   ② M_{20} largely independent of such bias, but the evolution of Gini largely consistent with that of M_{20}

Σ_1 alone does not inform us on global structural transformations, only those of the central regions

- The dependence of Gini and M_{20} with R_{SB} is similar to that of Σ_1:
  - all three indicators tell us that evolved galaxies are, at any epoch, concentrated, nucleated and with a relatively narrow range of central density
- But Σ_1 is a local diagnostic (a "clock", see Barro+17): it informs us on the dissipative history of the galaxy (baryons):
  - the distribution of Σ_1 does not evolve much with time: it is in place at least since $z \approx 3$ (Barro+17, Lee+17): little information on global structural transformations
- The evolution of Gini and M_{20} contains information on the evolution of overall gravitational potential (DM and baryons)

Morphology transformation



Gini and M_{20} evolve with redshift;

Σ_1 does not evolve

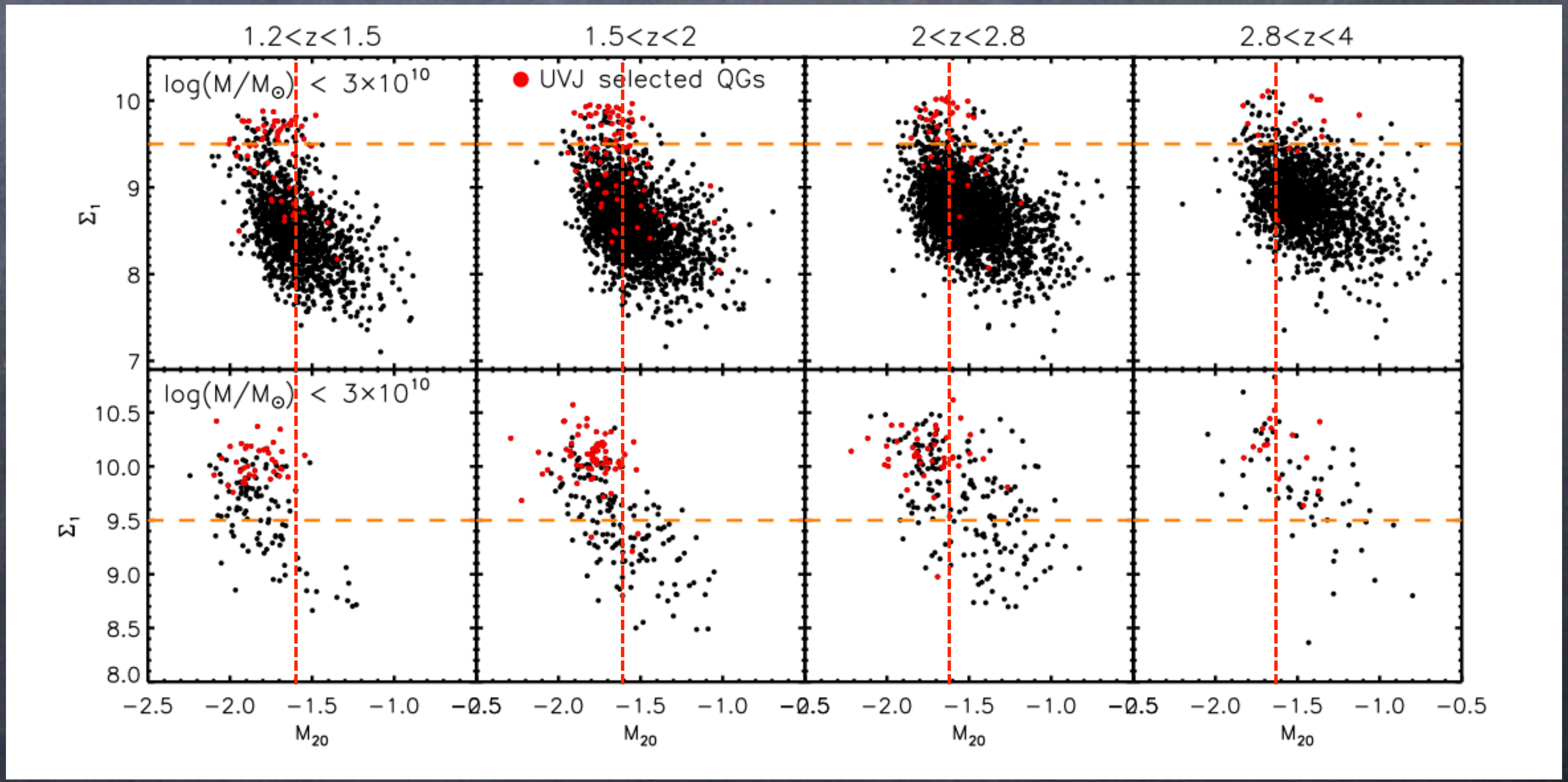
Both SF and Q galaxies evolve with time by becoming more concentrated and more nucleated ("compactification"), even if the central density DOES NOT evolve

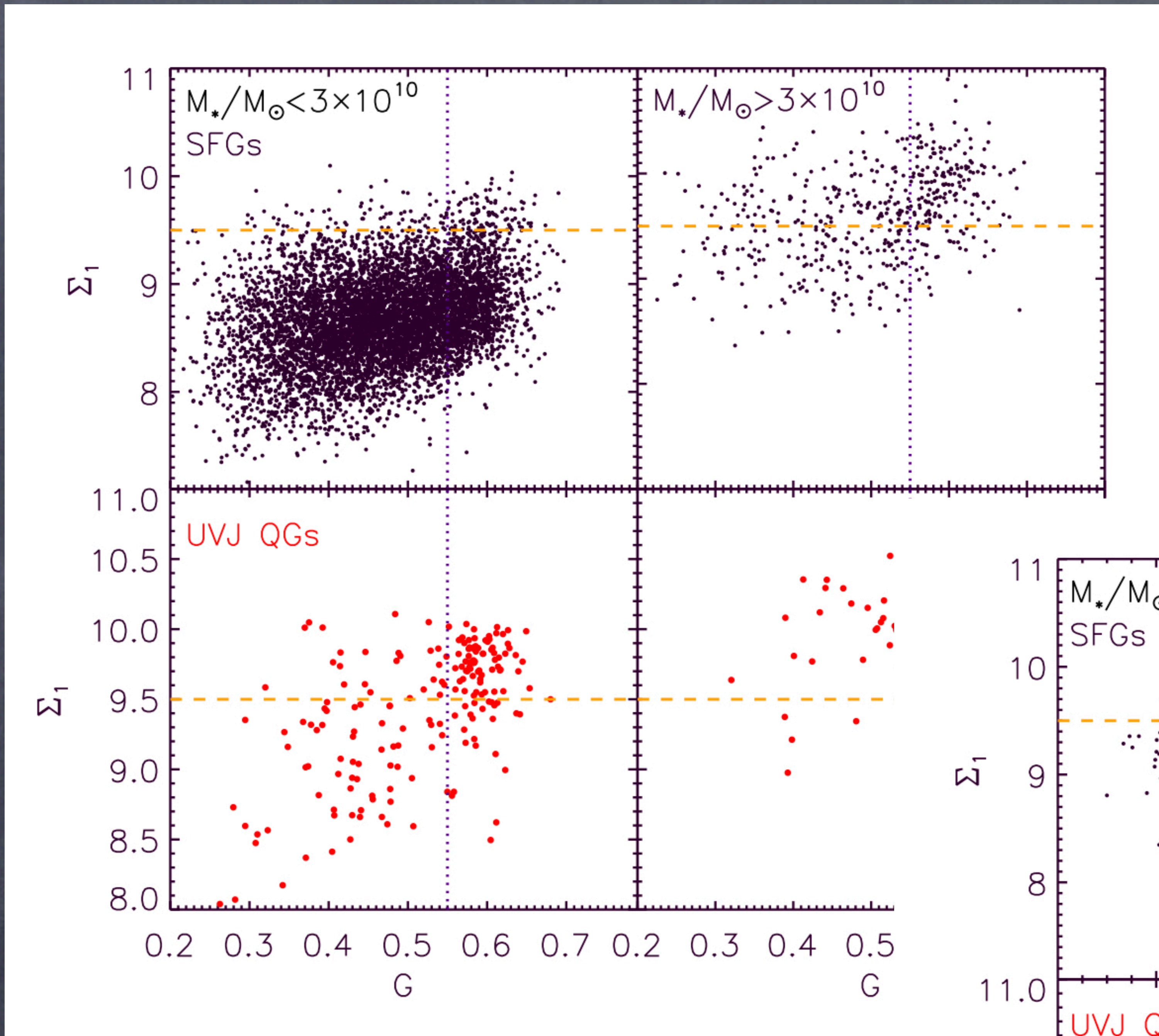
At z≈3.5, only a minority of massive galaxies have G>0.55 and M_{20}<-1.6

By z≈1.2, most massive galaxies (all Q ones) have G>0.55 and M_{20}<-1.6

Morphology transformations observed only through G and M_{20}

Both Q and SF galaxies undergo morphology transformation



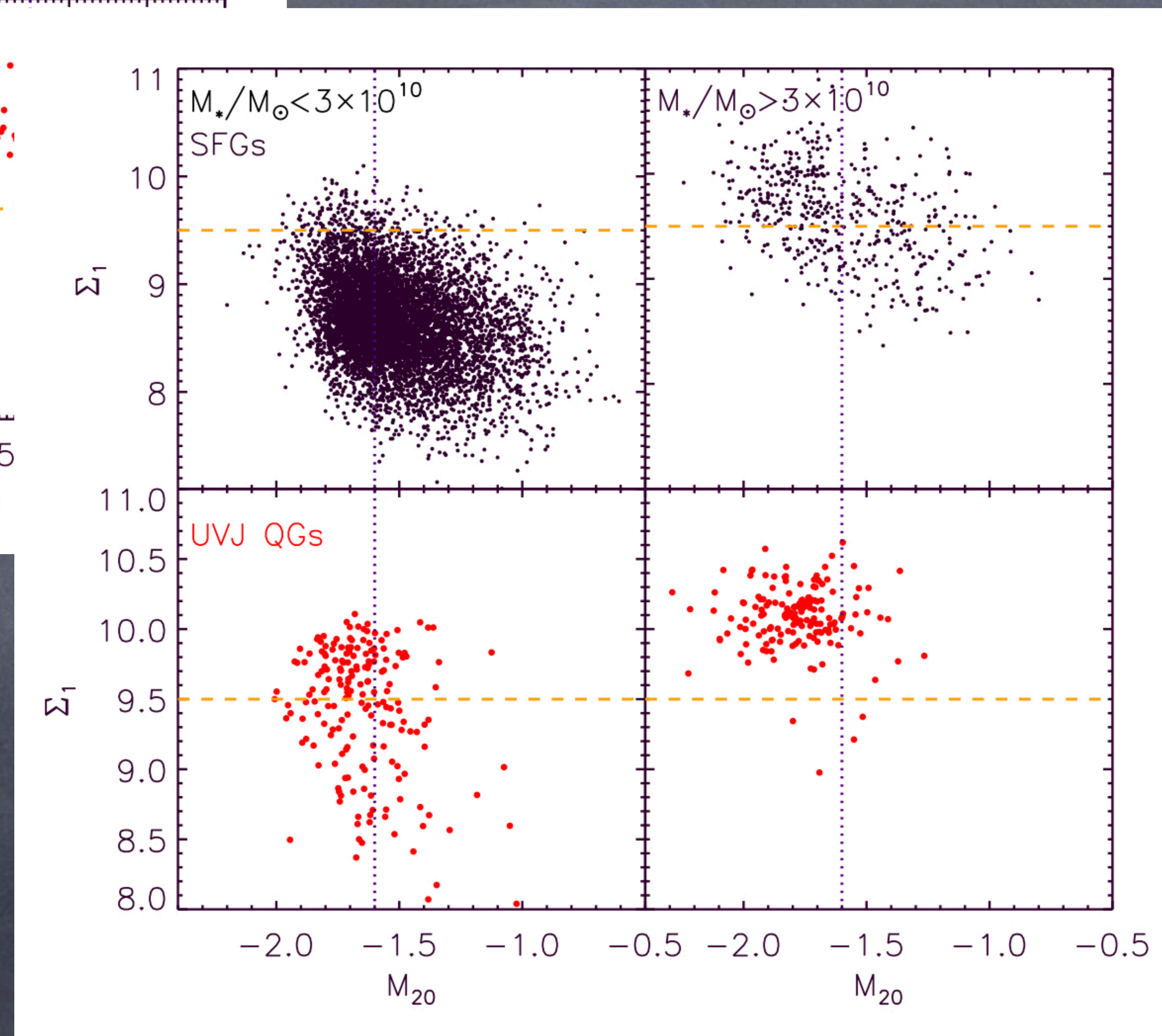


Compact galaxies defined based on the position of the galaxies that are the most compact (high G), the most nucleated (more negative M_{20}) and with the highest-density core (Σ_1)

$G > 0.55$

$M_{20} < -1.6$

$\Sigma_1 > 9.5$



As before, both Q and SF galaxies can be *compact*

Only Q galaxies can be only all *compact*

The most massive galaxies are the most compact

What are we seeing?

- Here we are seeing the rest-frame light at λ>4000 Å, the bulk of the stellar mass: the non-dissipative baryon component
- DM matter should behave like the stars
- As they grow in size and mass, galaxies constantly re-adjust their overhole structure by becoming more concentrated and nucleated ("global compactification")
- Compactification releases gravitation energy (5×10^{59} erg from z≈2 to 1 for a 10^{12} $M_\odot$ halo); ½ of it goes into heat (VT). Does this quench SF?
- IMPORTANT: compactification takes place both before and after quenching
- Two time-scales regulate variations of the gravitational potential:
  - Fast: driven by gas accretion. Process ends at quenching
  - Slow: driven by dynamical friction? It continues…

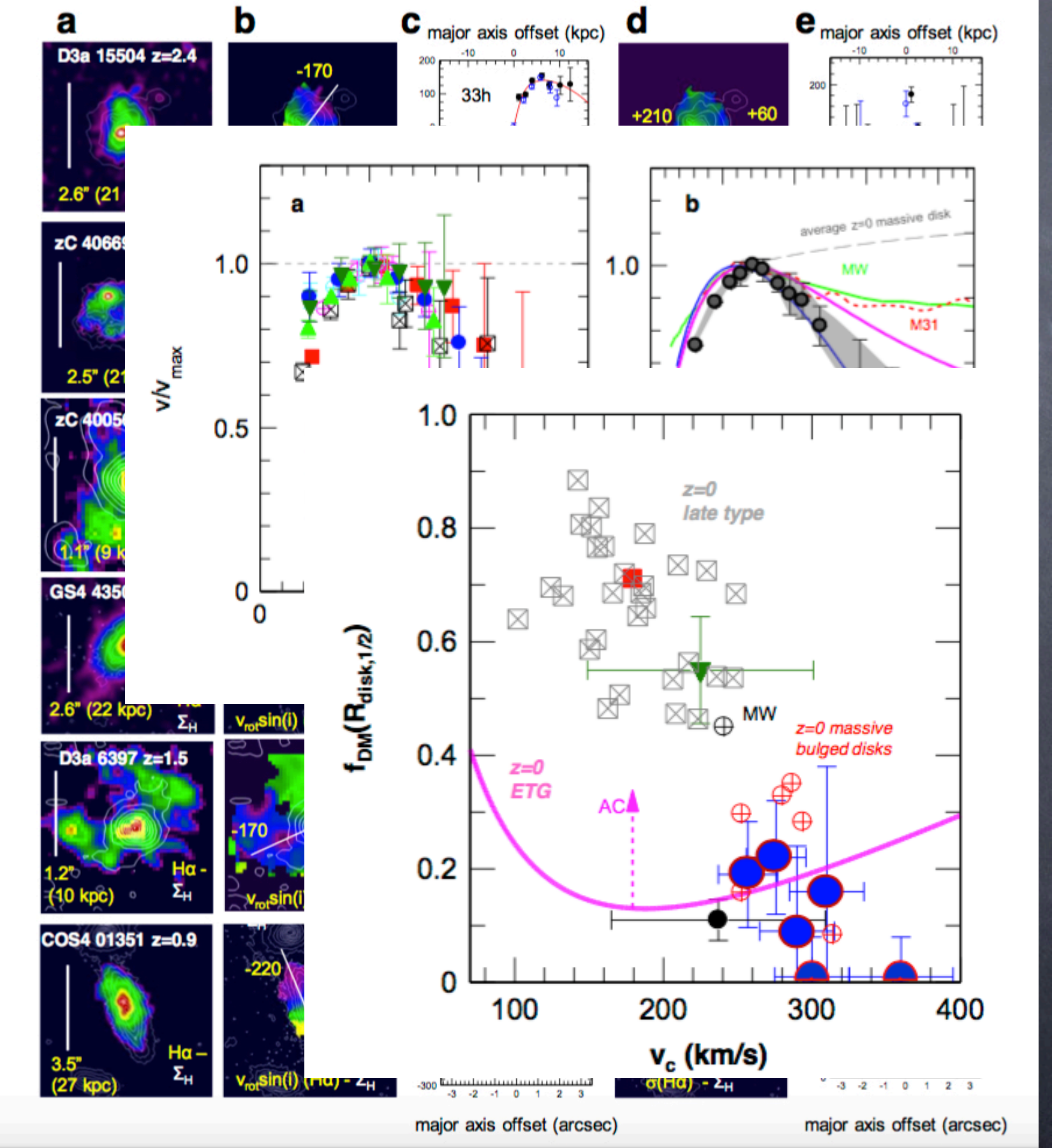
Genzel et al. 2017:

At redshift 1<z<2.5 the rotation curves of massive disks turn downward over the same scales where, in the local universe, they remain flat

→ **strongly baryon dominated**

Seems to imply a profound rearrangement of the relative distribution of dark matter and baryons

Does this imply non-homologous evolution?



Different, mass dependent quenching mechanisms at z≈2

- Based on the following evidence:
  - There are quenched galaxies both of low and high stellar mass, i.e. mass is not the only parameter; and…
  - …dispersion of Σ_1, Gini and M_{20} larger at low masses; and…
  - …quenched fraction varies with mass; it peaks at about $\approx 10^{11}\ M_{\odot}$, where quenching efficiency is the highest; and…
  - …quenching of galaxies depends on the environment; quenched galaxies cluster around other quenched galaxies, effect stronger for lower-mass galaxies

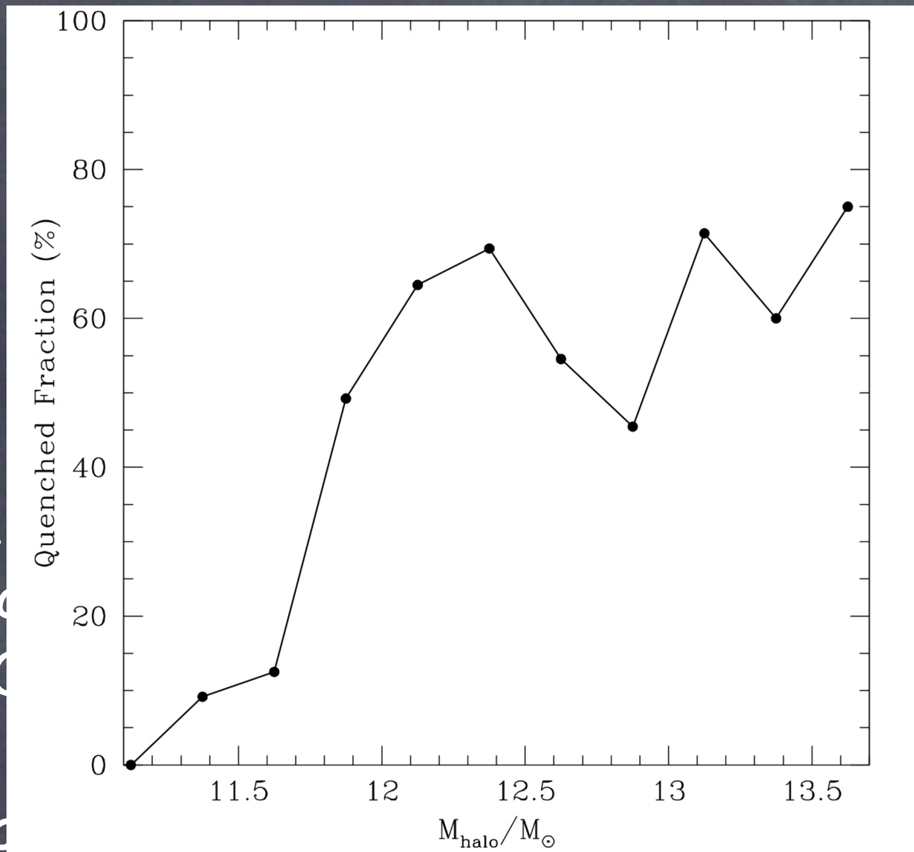
Star formation efficiency at high redshift

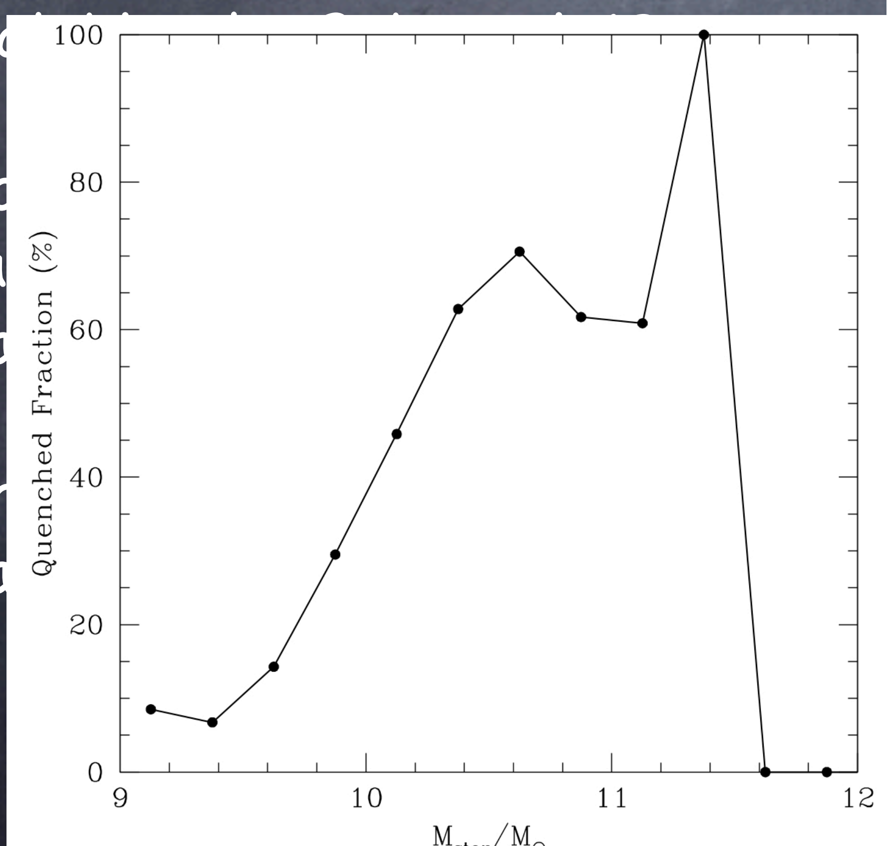
The probability that a galaxy quenches becomes high at ≈3×10^{10} $M_\odot$

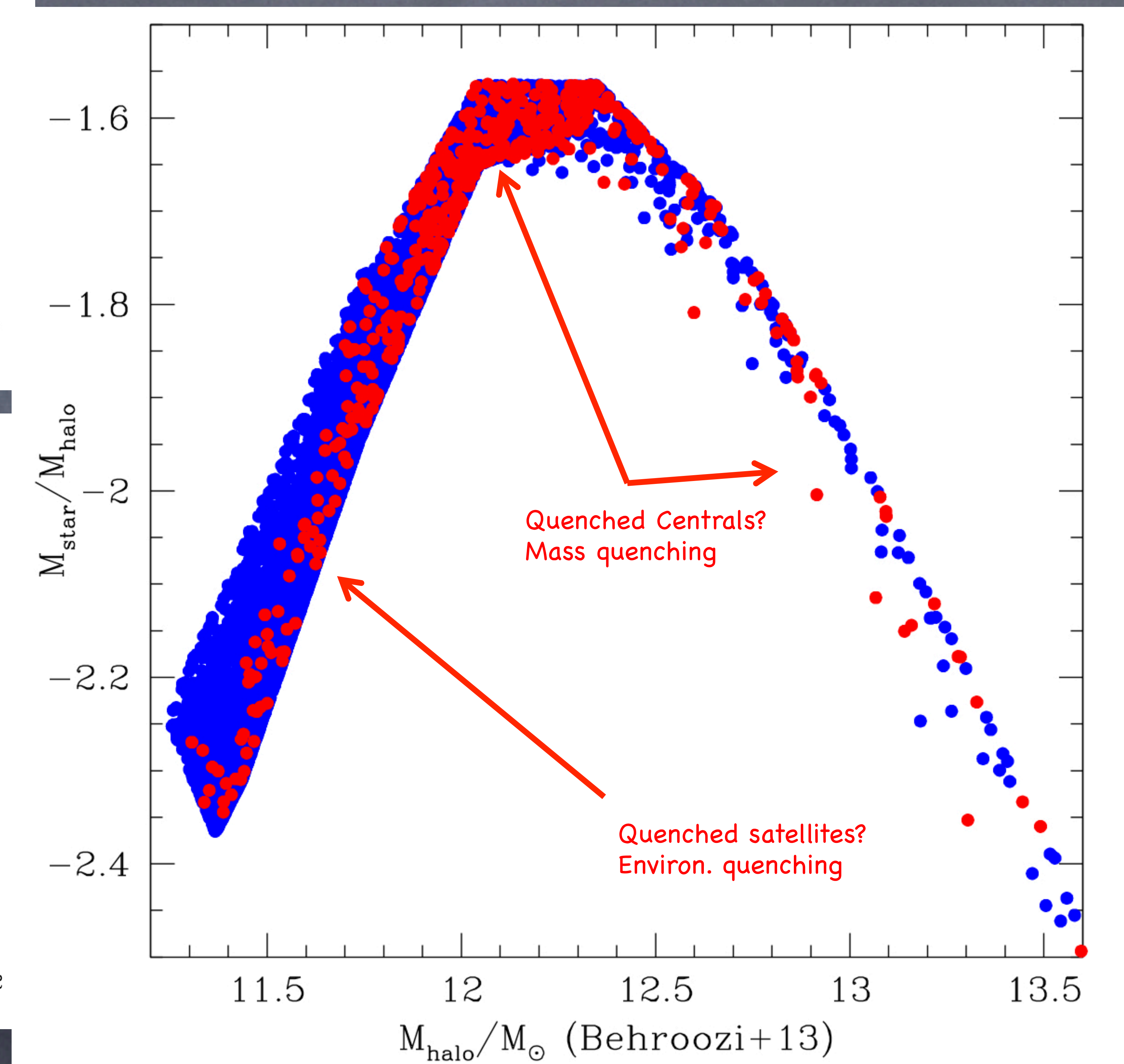
→ mass quenching

There are quenched galaxies at lower mass

There are SF galaxies at larger mass







Al
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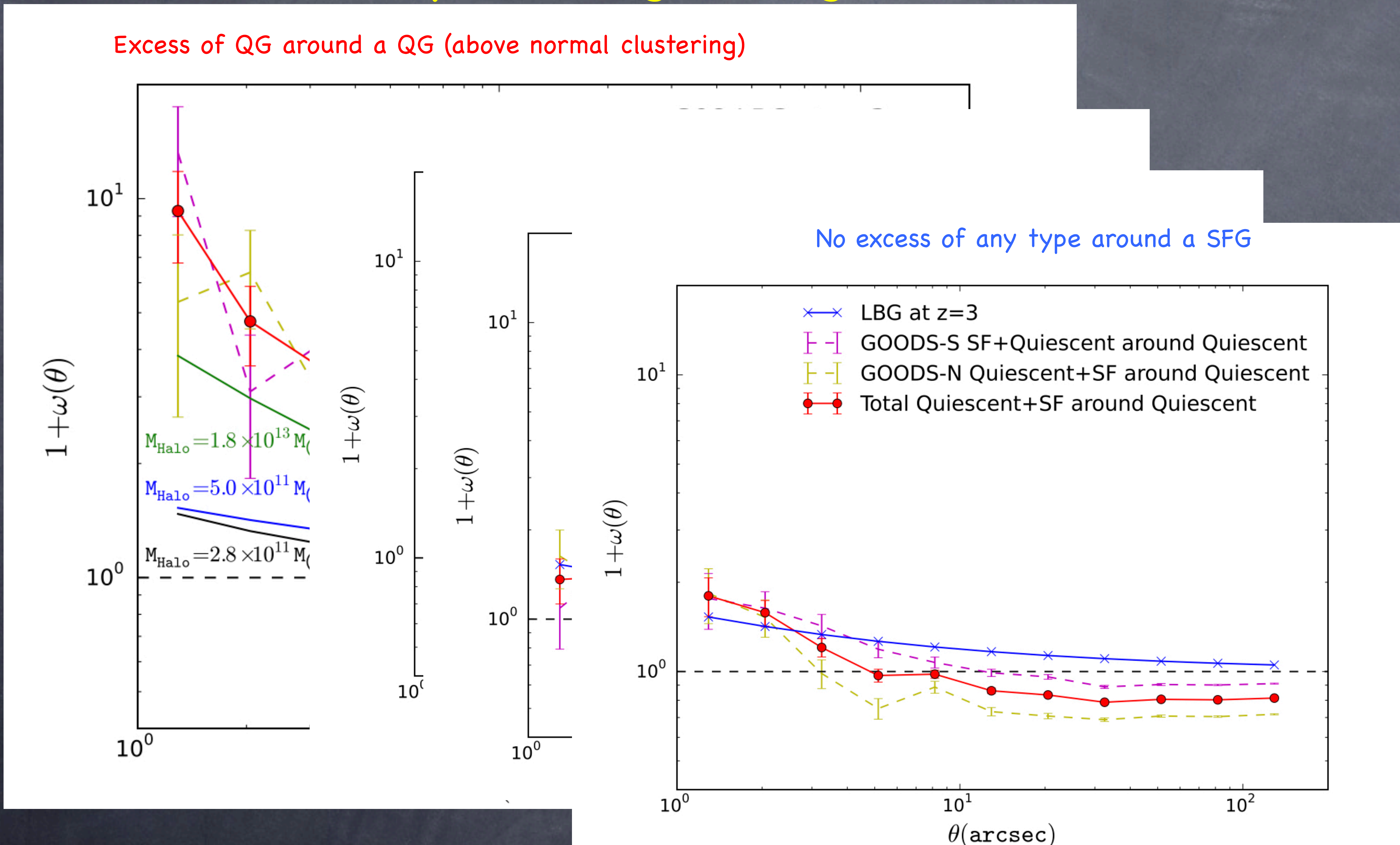
If low-mass QG are satellites, we should see environmental quenching at high redshift ($1.2<z<2.5$)

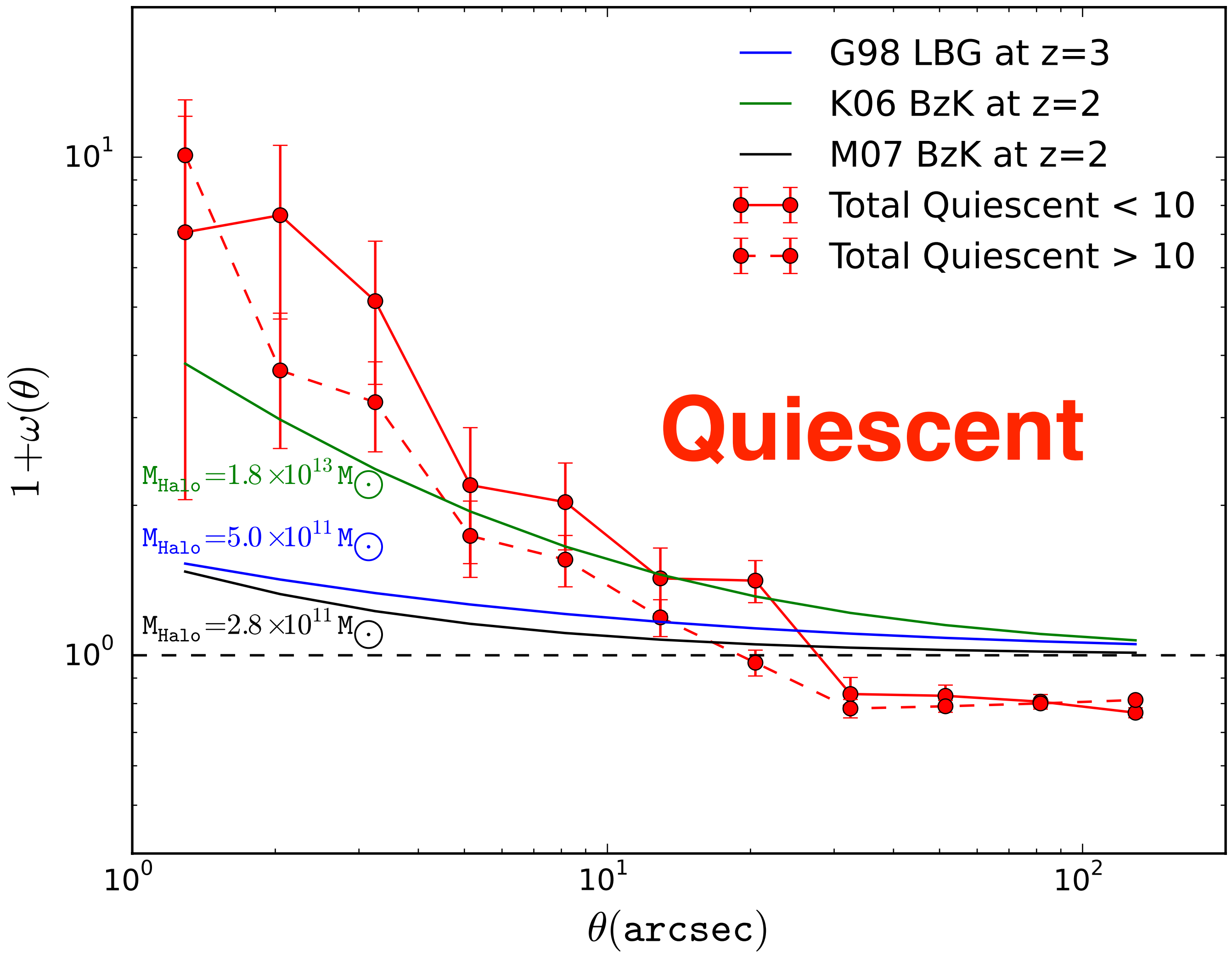


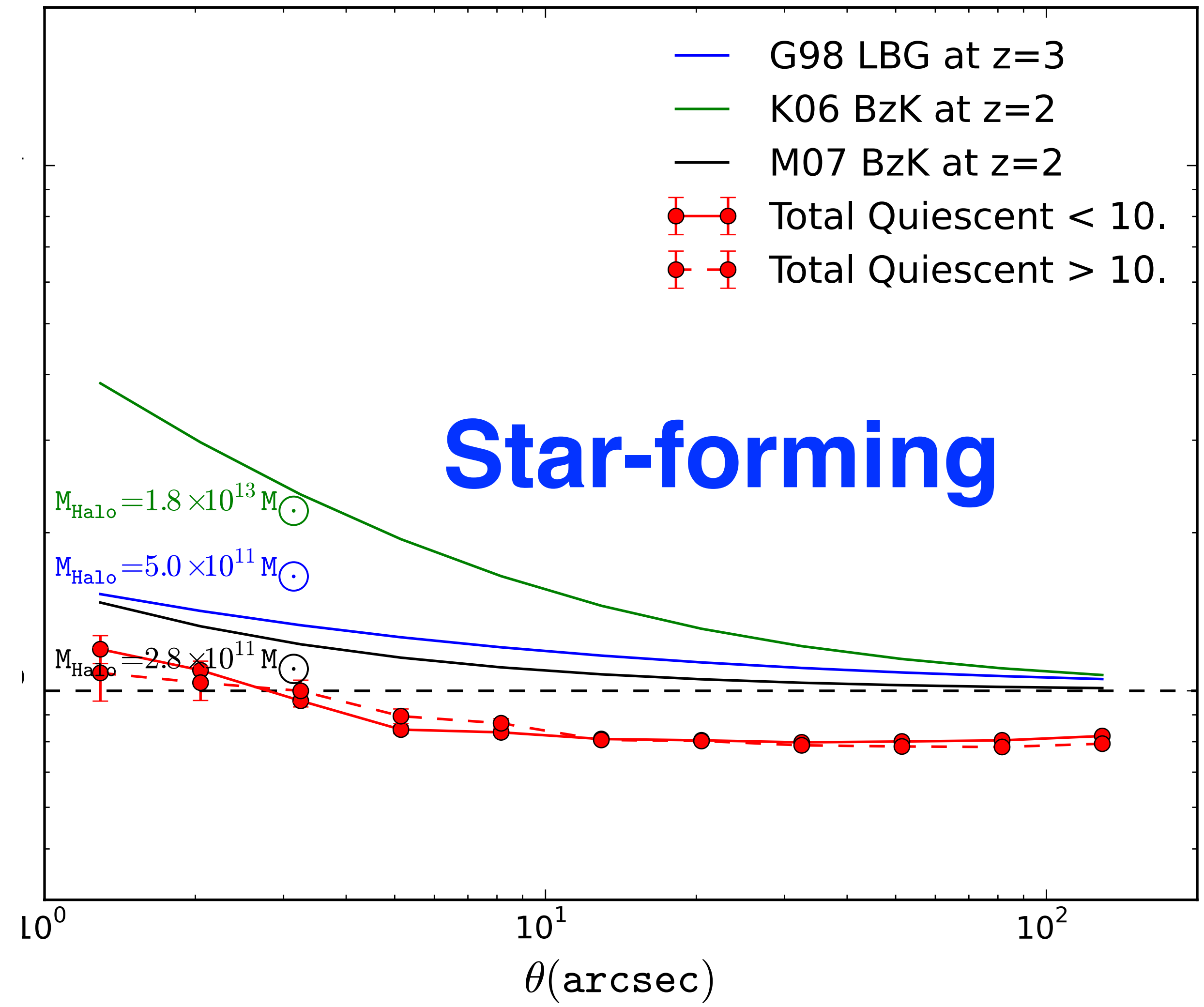
20 arcsec: ≈160 kpc (proper) at $1.2<z<2.5$
about the size of the virial radius of a $\approx10^{12}\ M_{\odot}$ halo

Ji, MG 2017, ApJ, subm.
Guo et al. 2017, subm.

Is this Environmental Quenching the same as Satellite Quenching?

Simple test: two stellar mass bins: >1e10 Msun and <1e10 Msun





Low mass bin shows higher clustering.
Opposite trend then galaxy clustering

Undistinguishable

It suggests we are observing satellite quenching
Different physical mechanism, path to quenching

Conclusions

- **Galaxies change their structure as they evolve (even in absence of major merging)**
  - As their grow in size, DM and stellar mass, galaxies globally become more compact, nucleated
  - Process is likely driven by accretion of lots of dissipative matter (gas)
- **Both SF and Q galaxies "compactify" as they evolve, regardless of the density of the central region. Compactification continues after quenching**
  - Do to the different dissipation time scale of gas and of DM and stars?
  - Gravitational heating a mechanism to help or even cause quenching?
- **Compactification is mass-dependent: more massive galaxies compactify more and earlier**
  - The stars of more compact QG are older (by 0.7 to 1.5 Gyr), i.e. they quenched sooner and evolved faster: progenitor bias, no obvious causal link between central "nugget" and quenching
  - Density of central region has nothing to do with quenching. When the galaxy has quenched, the nugget density has simply reached its "maximum" value of, $\mathrm{Log}(\Sigma_1)\approx 11$ for massive galaxies
- **Quenching happens as compactification proceeds. The formation of a compact nuclear component (nugget) also takes place during compactification**
  - There is a "critical" mass ($M\approx 3\times 10^{10}\ M_\odot$) above, which galaxies quench quite effectively