Quenching And New evidence of Structural Transformations Of Galaxies (From CANDELS)

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Outline

1. The properties of star-forming and quenched galaxies and correlations with morphology
2. Physics of quenching and structural transformations
3. Observations at high-redshift: evidence of structural transformations on large scales. **This is the new part**
    1. Comparison with simulated (TNG) galaxies suggests it is due to baryon accretion
4. Speculative discussion

CANDELS:
Cosmic Assembly Near-infrared Deep Extra-galactic Legacy Survey

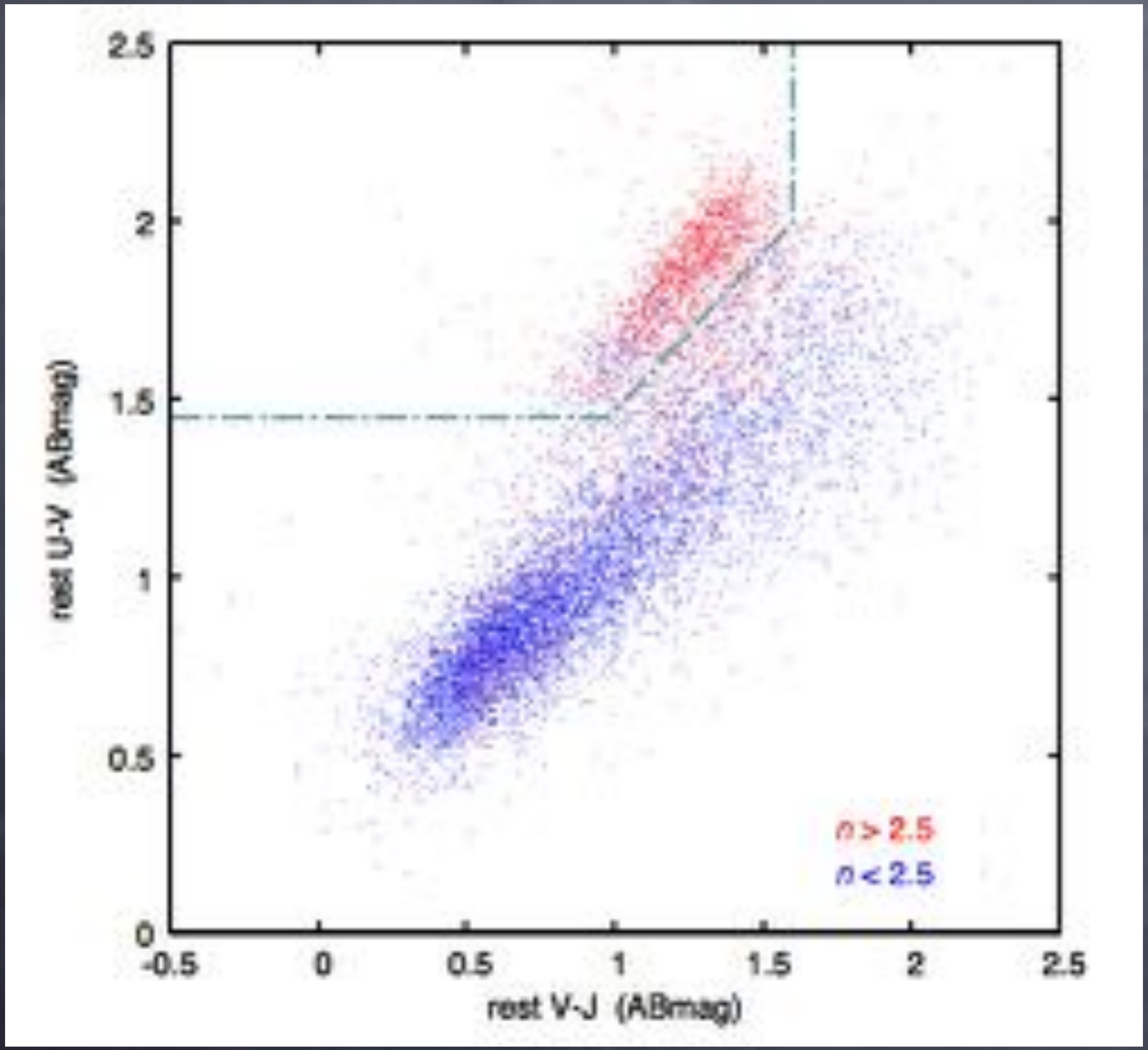
(Grogin et al. 2011; Koekemoer et al. 2011)

1. A large-area survey of high-redshift (z>0.5) galaxy survey with HST (WFC3 and ACS)
2. The largest HST program ever: 902 primary WFC3 orbits (J+H) and ACS parallels (mostly F814)
3. Two teams: Aegis and GOODS. Co-PI's: **S. Faber** and **H. Ferguson**
4. Covers about 0.7 sq. degree over 5 legacy fields: COSMOS, EGS, UDS, GOODS-N, GOODS-S
5. Medium-deep survey in COSMOS, EFS and UDS
6. Deep survey in the GOODS fields
7. Completed by 2016 (incl. high-level data product releases and all panchromatic ancillary data)

At any redshift, the mix of galaxies exhibits "BIMODALITY(ies)" of properties: "star-forming-like" features vs. "early-type-like" features

Galaxy bimodality: **Blue Cloud** vs. **Red Sequence**

Galaxies undergo structural transformations as they go through quenching



Kajisawa+ 2015, galaxies up to z≈1.5

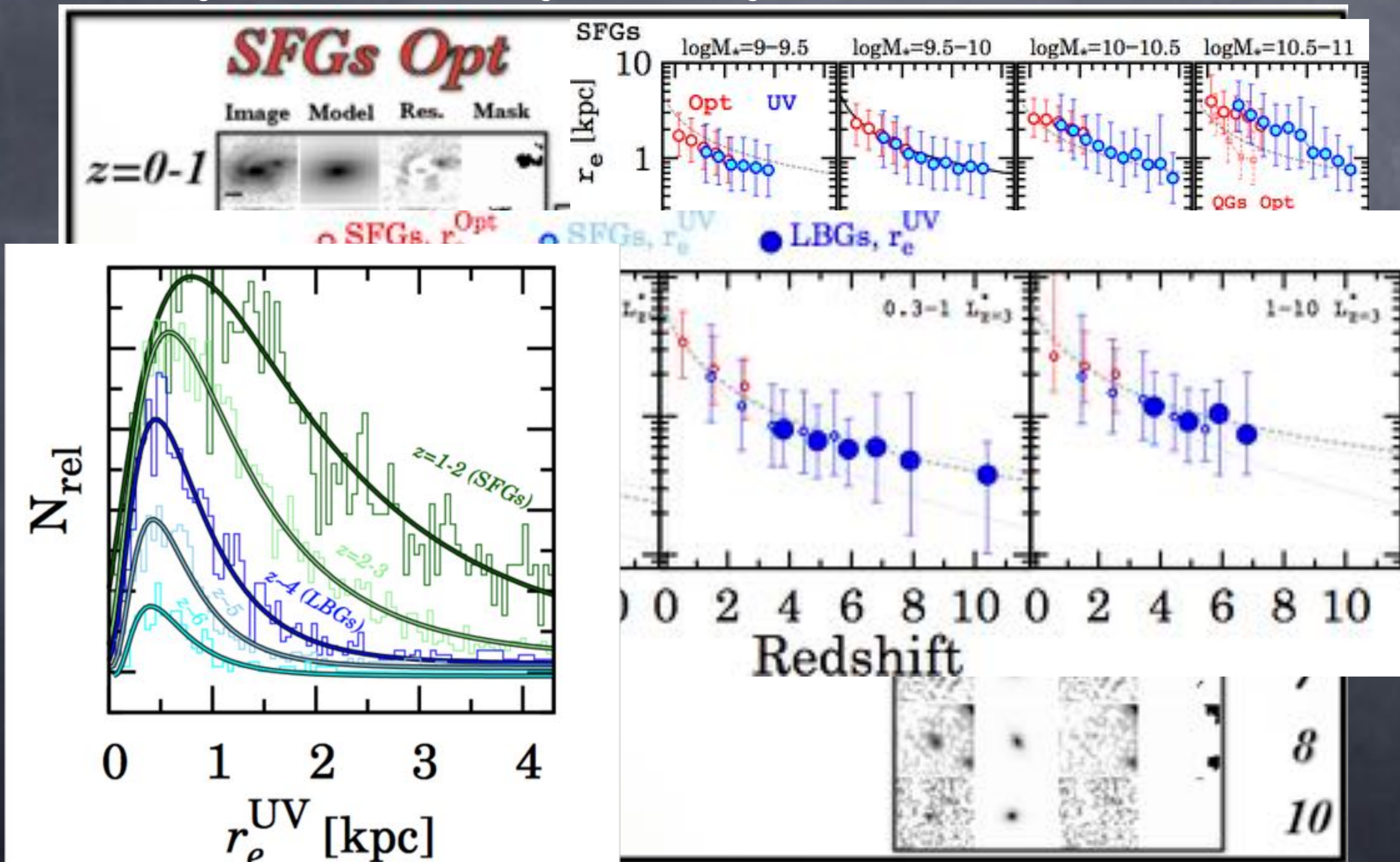
Disks vs. Spheroids

Exponential disk: n=1

De Vaucouleurs spheroid: n = 4

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

- Systematic study of ≈200,000 SF galaxies at 0<z<10 from all HST deep fields (Shibuya+ 2015): morphology, evolution of size of SFG s consistent with **DISKS and TTT. Important!**
- Passive galaxies have much larger Sersic n: galaxy transformation

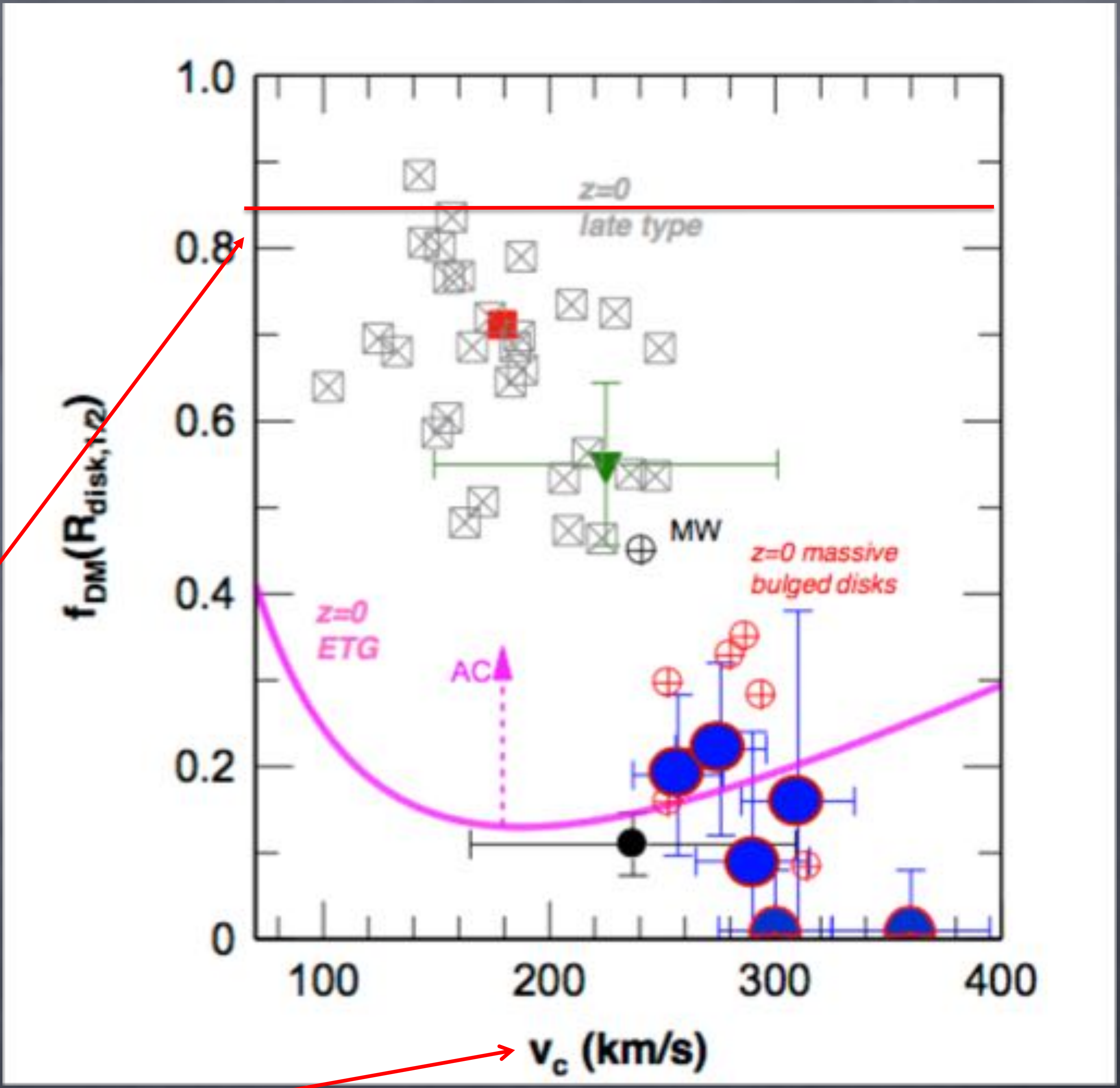


Shibuya+ 2015

Another (most likely) key structural "bimodality" at z=0 …

- Spheroids/ETG have a small DM fraction
- Disks/SFG have a large DM fraction, ≈5x larger
- Strong correlation with SF properties (like in blue cloud vs. red sequence and spheroids vs. disks
- Structural transformations must include DM re-arrangement

f_{DM}(cosm)=0.842



A proxy for the total mass
For spheroids, replace with $\sqrt{V_{rot}^2 + \sigma^2}$

From a compilation by Genzel et al. 2017

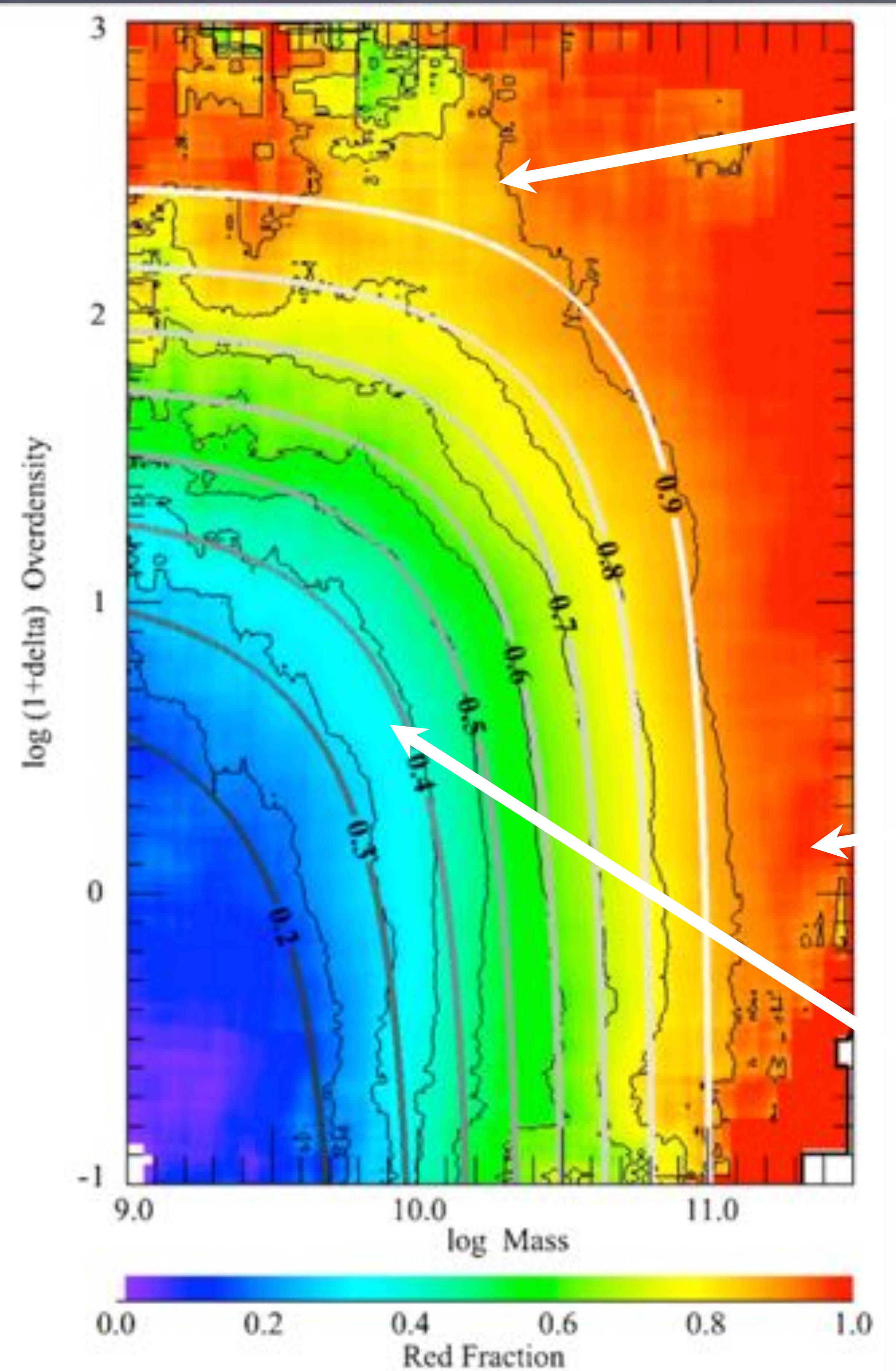
The Questions

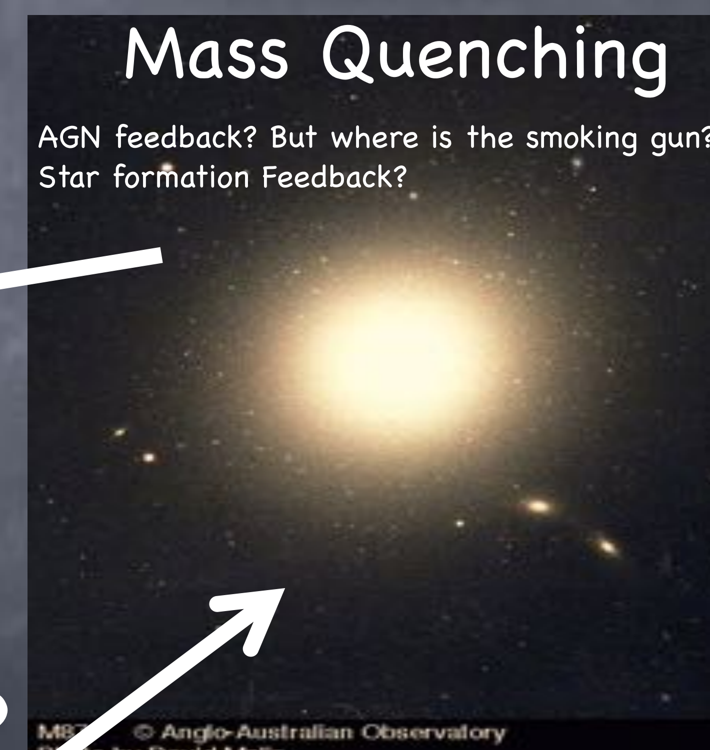
- ✓ Quenching appears to be the big divide between before and after the transformation. Why? What does quench a galaxy?

- ✓ Is quenching the culmination of structural transformations or a "phase transition" that takes place during these transformations, which continue after quenching?
  - ✓ Do galaxies transform or keep their structure as they quench?
  - ✓ Quenching is about feedback and the thermodynamics of ISM
  - ✓ Structural Transformations must have to do with changes in the gravitational potential. What does drive them?
  - ✓ <u>What is the interplay between baryons and dark matter?</u>
    - ✓ <u>Is f_{DM} a useful diagnostic?</u>

Quenching and Transformation

Peng et al. 2010, 2013; Renzini 2009





???

Do galaxies transform their morphology as they quench? How?

We always think of merging, but it is likely much more complicated than that... And it is likely mass dependent

What does quench a galaxy? (and what does have quenching to do with structural transformations?)

- Feedback by AGN and star formation are two key mechanisms:
  - ISM is heated/expelled (✗)
  - Simulations adopt either one or the other or both, but…
    1. Implementation is crude; results critically depend on assumptions:
    2. Isotropic vs. anisotropic AGN coupling
- Gravitational heating (✓)
- Merging and interactions with galaxies (✓)
- Interactions with IGM/ICM (✗)
- Other…

✓: Changes stellar morphology
✗: Does not change stellar morphology

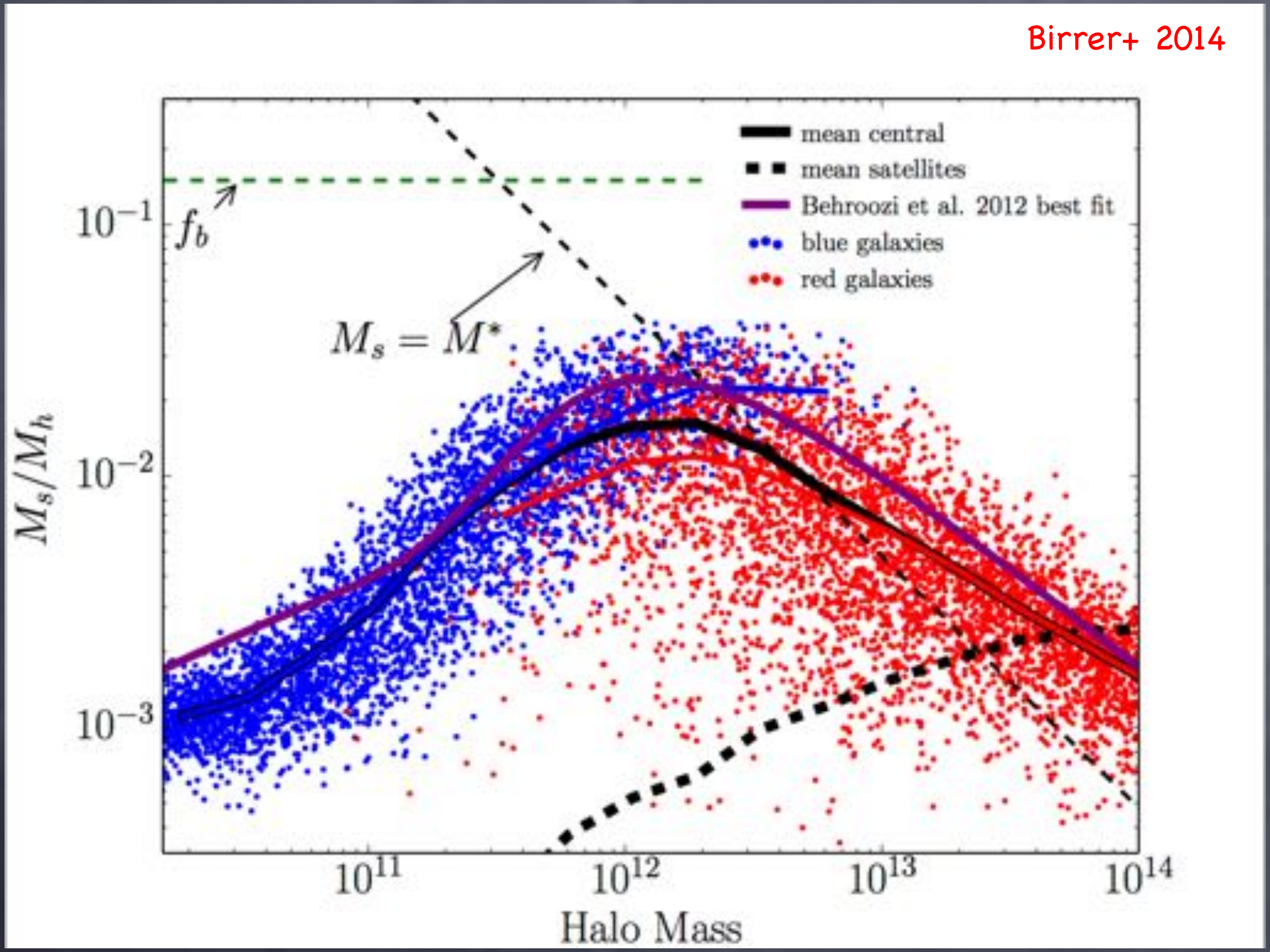
- Points to ponder:

  simulations do not self-consistently come up with star formation (e.g. ϵ_{ff}) which is added by hand (typically $\epsilon_{ff} \simeq 0.2-0.4$). Time evolution not tracked (e.g. see Zanella+ 2018)

  i. Star formation happens by "fiat" following K-S
  ii. Feedback (stellar or AGN) also added by hand
- What does the gas do? Does it mostly stay where stars are made and makes more stars? Changes phase? Is it expelled? Does accretion continue?
  i. If it stays there (see Daddi+ 2010: $f_{cold\ gas}$ up to 0.8), gravity can increase dramatically. DM does not relax with the same time scale of the baryons. Are these the seeds of the structural transformations or even of quenching?
- What do observations suggest?
  i. Lots of dissipation by the time of quenching:
     i. High-z massive galaxies baryon dominated
     ii. High-z galaxies have huge (cold) gas fraction

A simple phenomenological model for Quenching: $p_q \approx \exp(-M/M^*)$

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



Not the whole story: strong correlations with morphology...

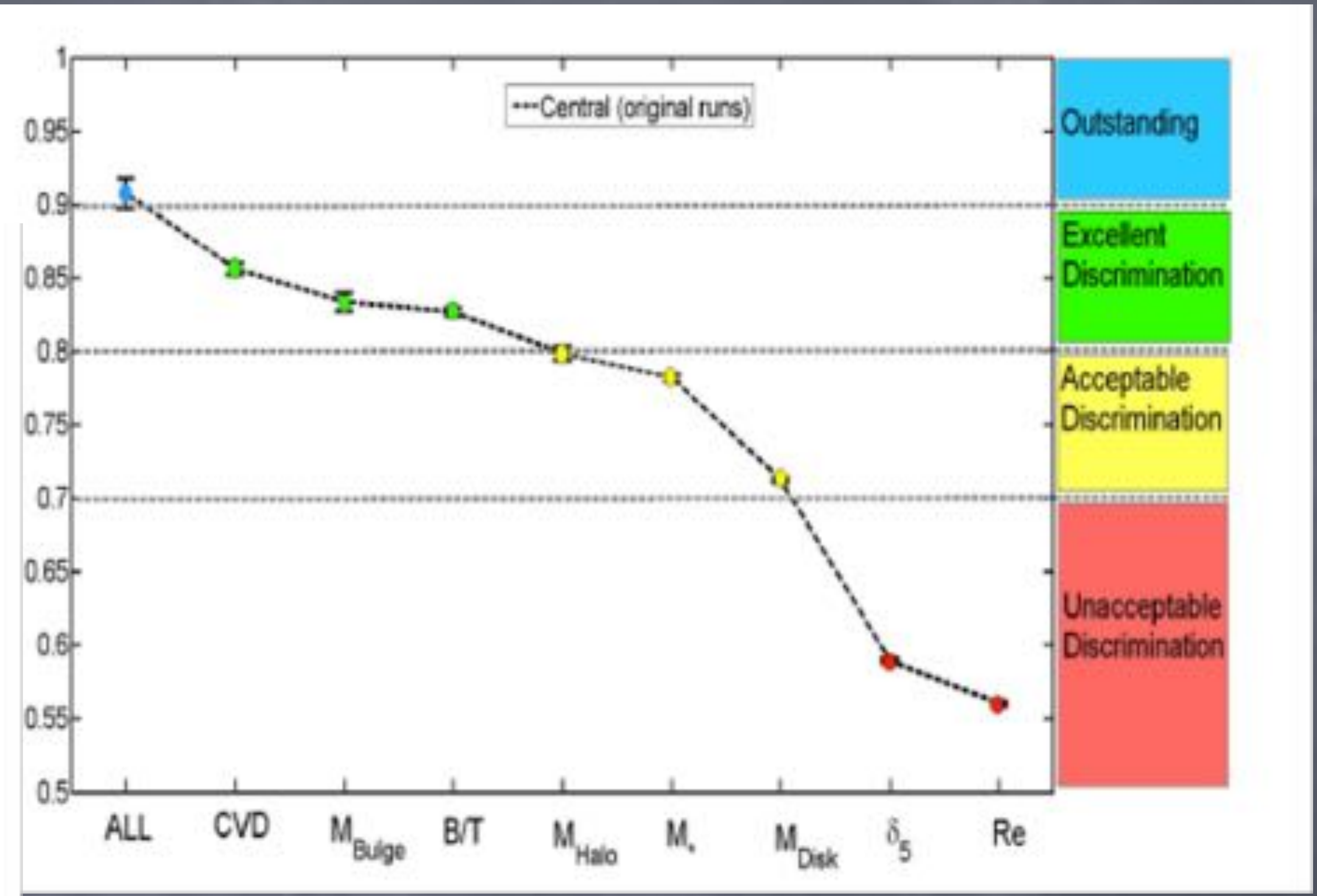
Consistent wit hshape and evolution LF of SF and Q galaxies; overall evolution of SFRD and MS

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

At z≈0: empirical predictors of passivity (quenched status)

Table 3. ANN AUC ranking of single parameters for central galaxies.

Rank	Property	AUC	Success Label*
	ALL	0.9074 ± 0.0106	Outstanding
1	CVD	0.8559 ± 0.0039	Excellent
2	M_{bulge}	0.8335± 0.0060	Excellent
3	B/T	0.8267 ± 0.0028	Excellent
4	M_{halo}	0.7983 ± 0.0045	Acceptable
5	M_*	0.7819 ± 0.0025	Acceptable
6	M_{Disk}	0.7124 ±0.0016	Acceptable
7	δ_5	0.5894 ± 0.0015	Unacceptable
8	Re	0.5599± 0.0013	Unacceptable



General trend in predictive power from central/internal parameters to outer/external parameters:

Quenching of central galaxies originates in the mass concentration of inner regions; Age gradients of ETG minor; accretion

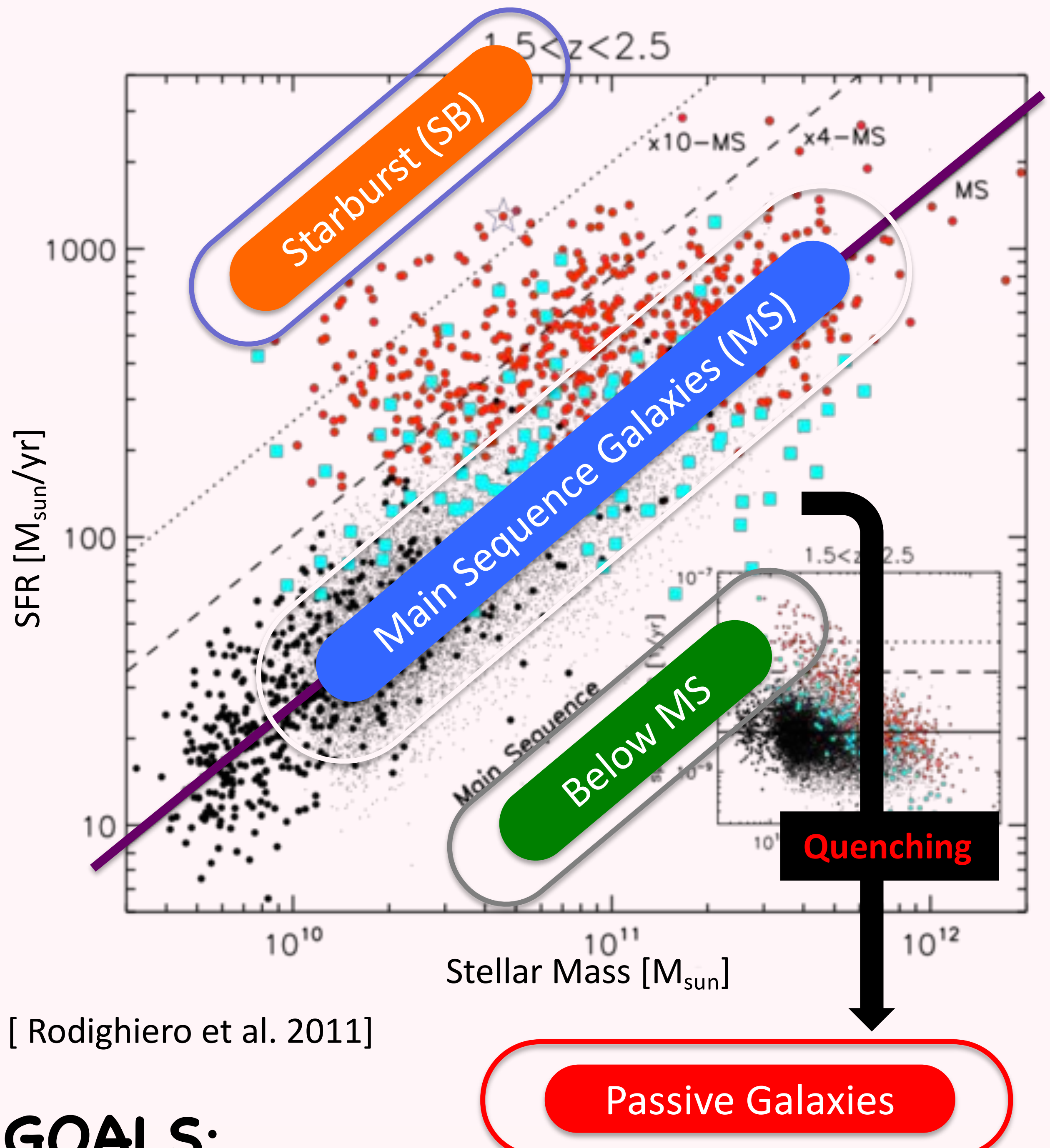
Largely unrelated to their extended structures or environments

Teimoorinia, Bluck & Ellison 2016
See also, Carollo+ 2013; Bell et al. 2012

We need to explore quenching when massive galaxies were forming: z≈1-3

- ETG have been quenched since z≈2 (Renzini 2006): can we see quenching in action at high-z?
- There is evidence of more than one quenching mechanism:
  - There are quenched galaxies both of low and high stellar mass:
    - mass is not the only parameter
  - quenched fraction varies with mass:
    - it peaks at about $\approx 10^{11}\ M_{\odot}$, where quenching efficiency is the highest
  - quenching of galaxies depends on the environment:
    - quenched galaxies cluster around other quenched galaxies, effect stronger for lower-mass galaxies

Star Formation and Quenching at High Redshift: New measures from CANDELS (Lee, MG et al. 2018)



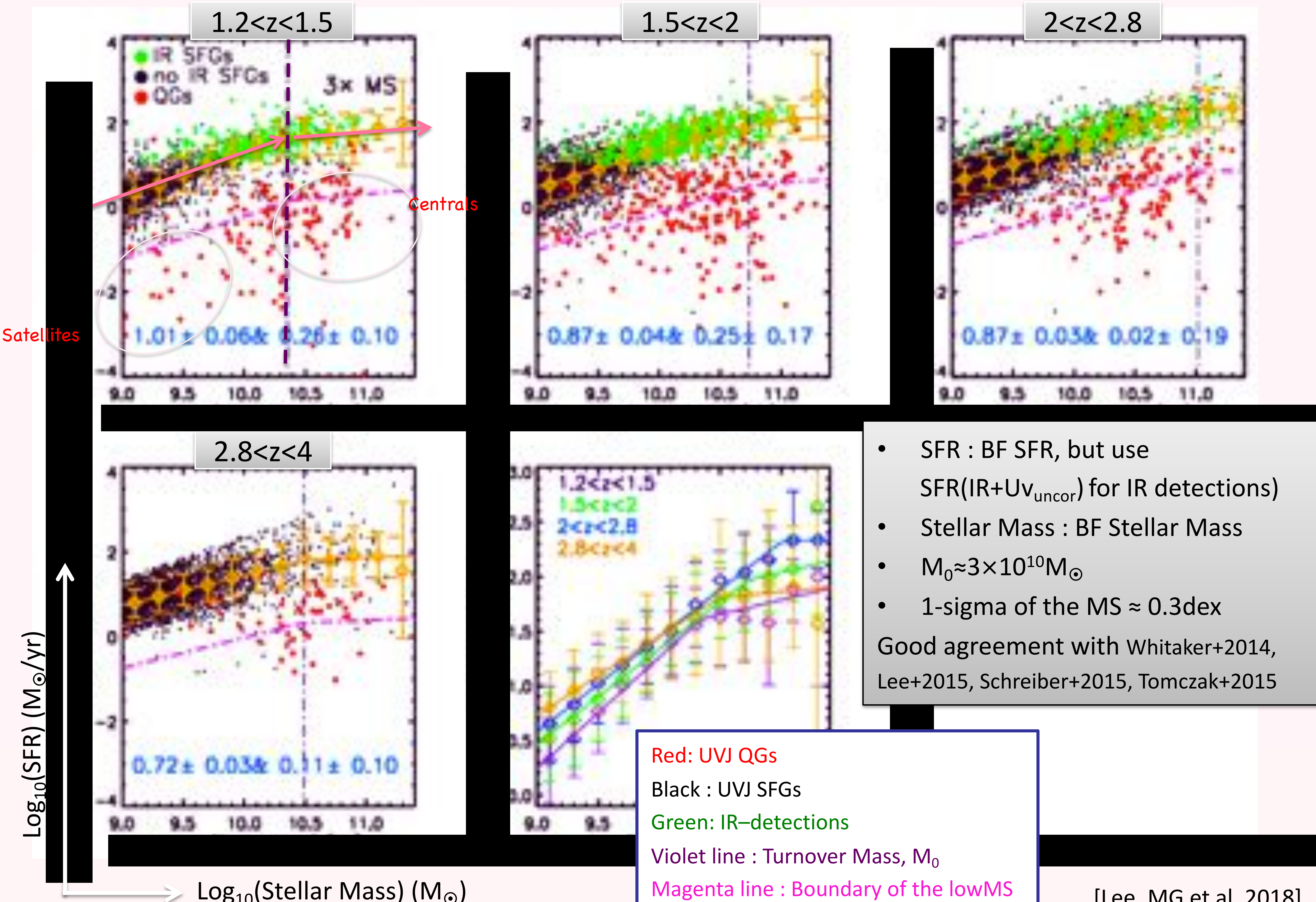
[Rodighiero et al. 2011]

- Main Sequence of Star Formation: tight Correlation between SFR and M_*
  → MS of dM/dt (SFR) ~ M_*^{β} (β~0.7-1.0)
  [Noeske+2007, Daddi+2007, Elbaz+2007]
- Various Galaxy Populations in SFR-M_*
- Not all galaxies have same star formation histories (SFHs) [Renzini 2009, Daddi+2010]
- SFH key to measure SFR for fainter galaxies and to measure the stellar Age
- We left the SFH as a free variable

GOALS:

1) obtain as clean and controlled a sample of SF and QG as possible from z>1 up to z≈3 with HST rest-frame optical morphology
2) Add the information of the mean (mass-weighted) age of the galaxies

SFR vs. Stellar Mass Diagram at 1.2<z<4: the Main Sequence



- SFR : BF SFR, but use SFR(IR+$\mathrm{Uv_{uncor}}$) for IR detections)
- Stellar Mass : BF Stellar Mass
- $M_0 \approx 3\times10^{10} M_\odot$
- 1-sigma of the MS ≈ 0.3dex

Good agreement with Whitaker+2014, Lee+2015, Schreiber+2015, Tomczak+2015

Red: UVJ QGs
Black : UVJ SFGs
Green: IR–detections
Violet line : Turnover Mass, M_0
Magenta line : Boundary of the lowMS

[Lee, MG et al. 2018]

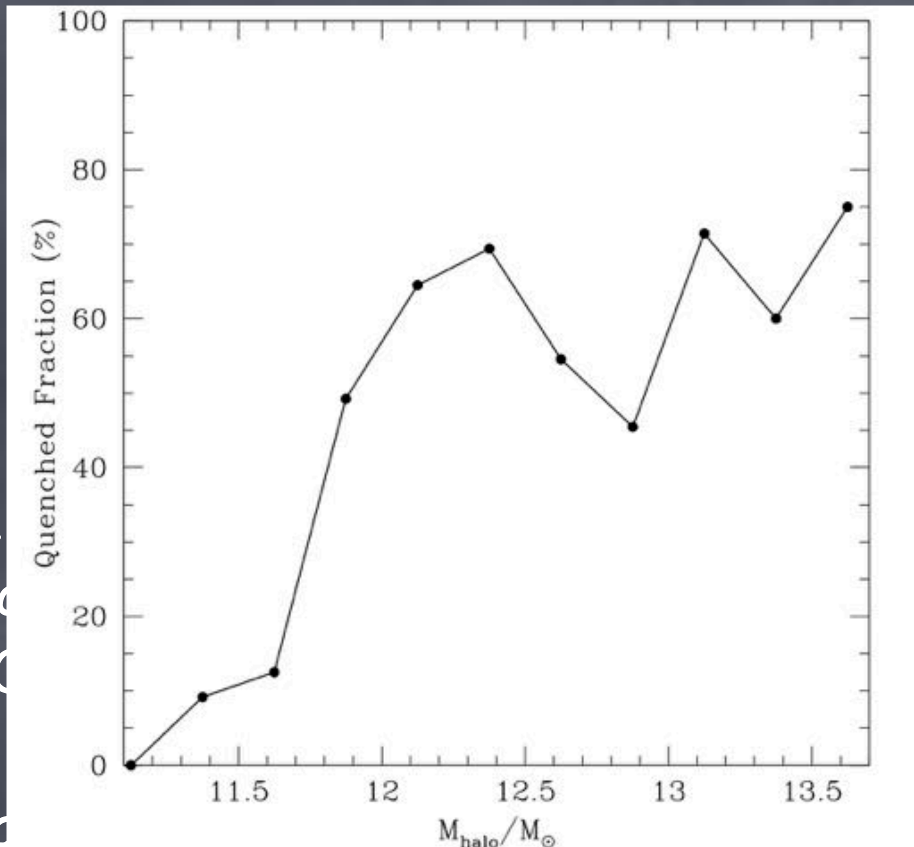
Observations at high redshift: 1<z<3

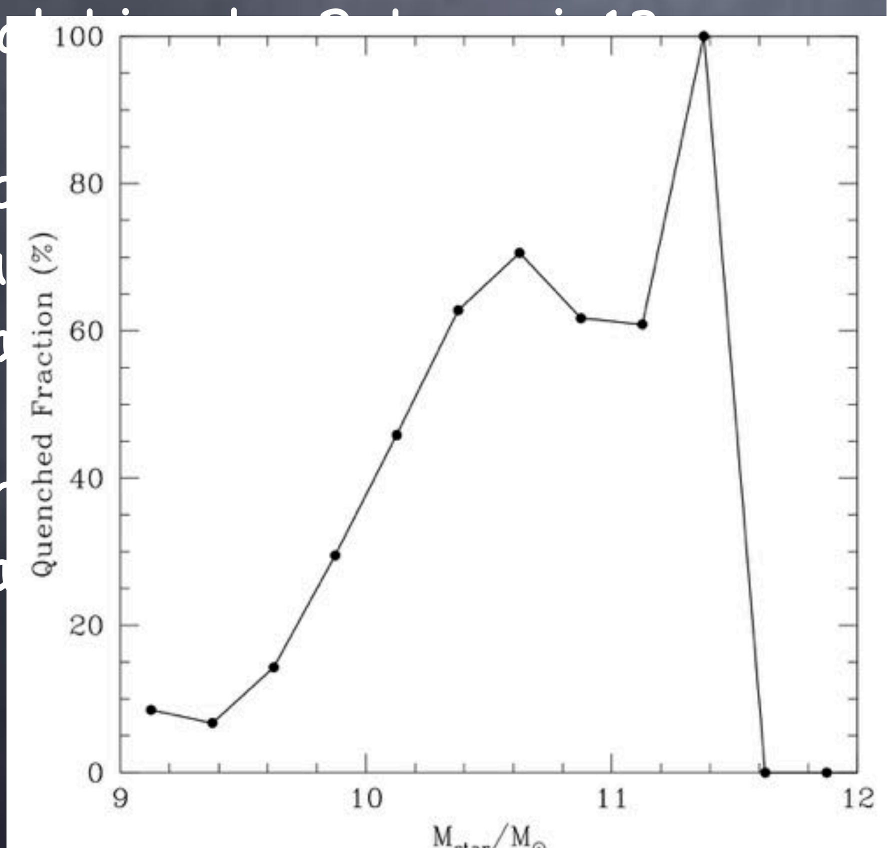
The probability that a galaxy quenches becomes high at ≈3×10^{10} $M_\odot$

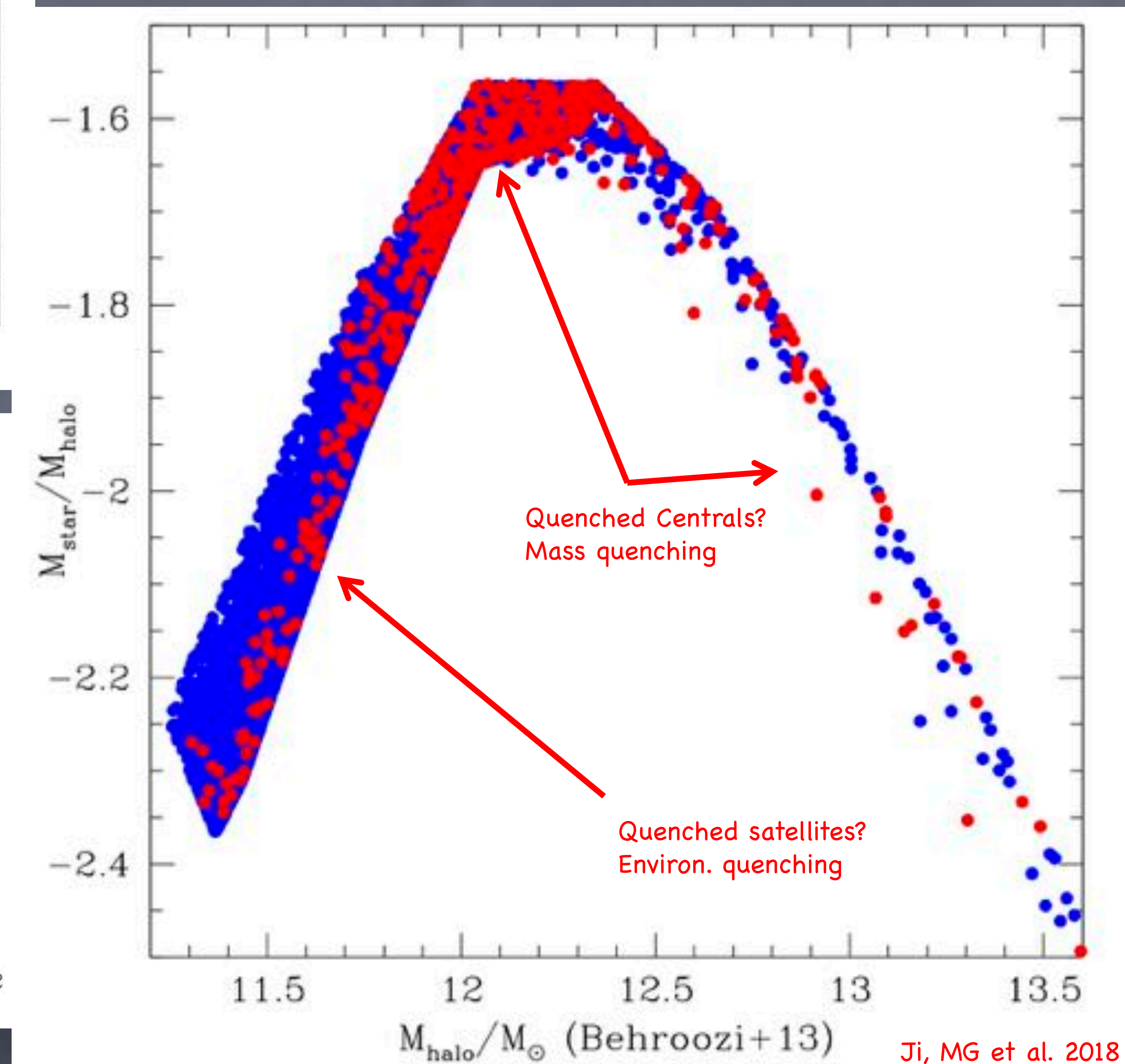
→ mass quenching. The theory gets something right. But…

there are quenched galaxies at lower mass

there are SF galaxies at larger mass







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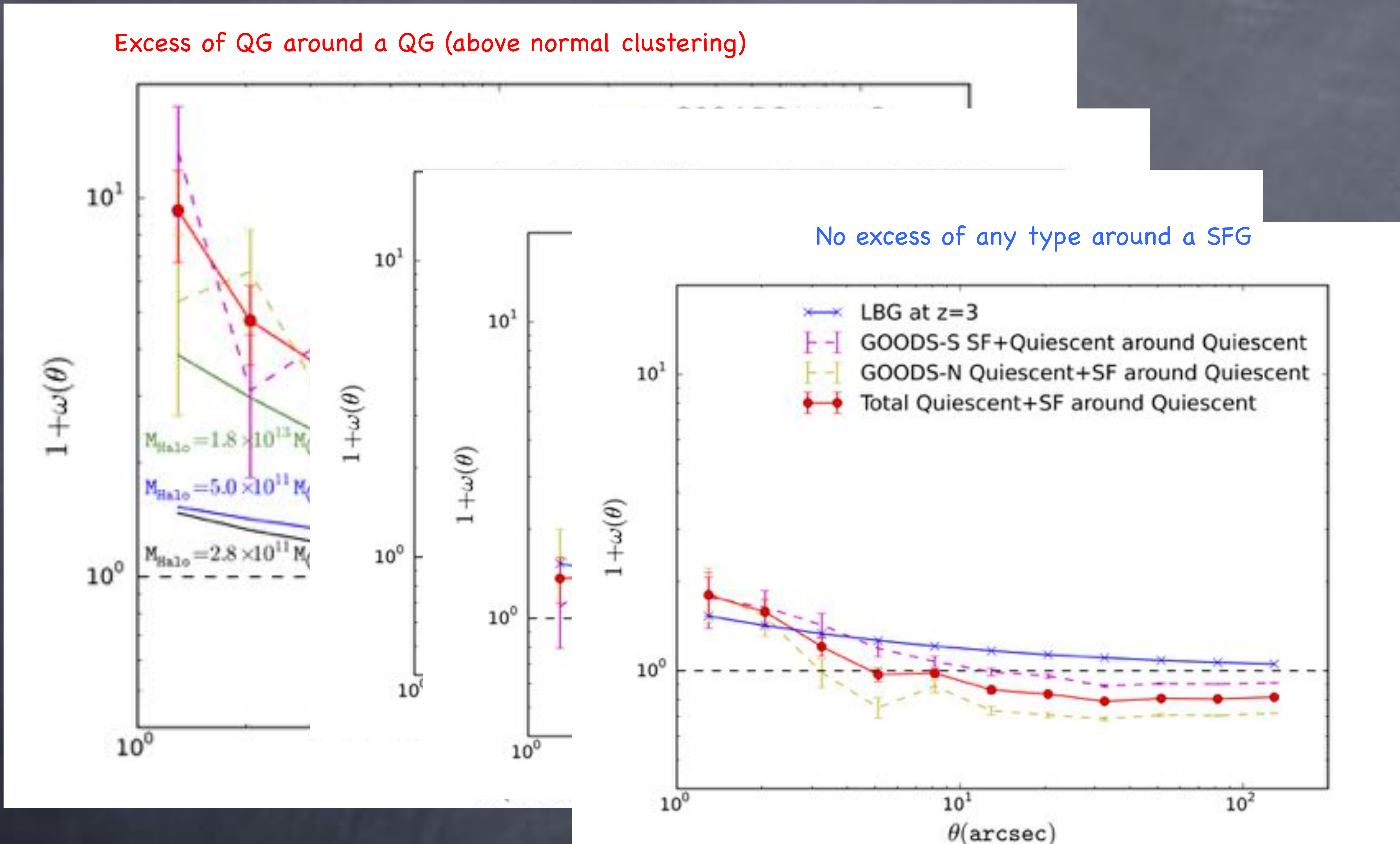
If low-mass QG are satellites, we should see environmental quenching at high redshift (1<z<3)



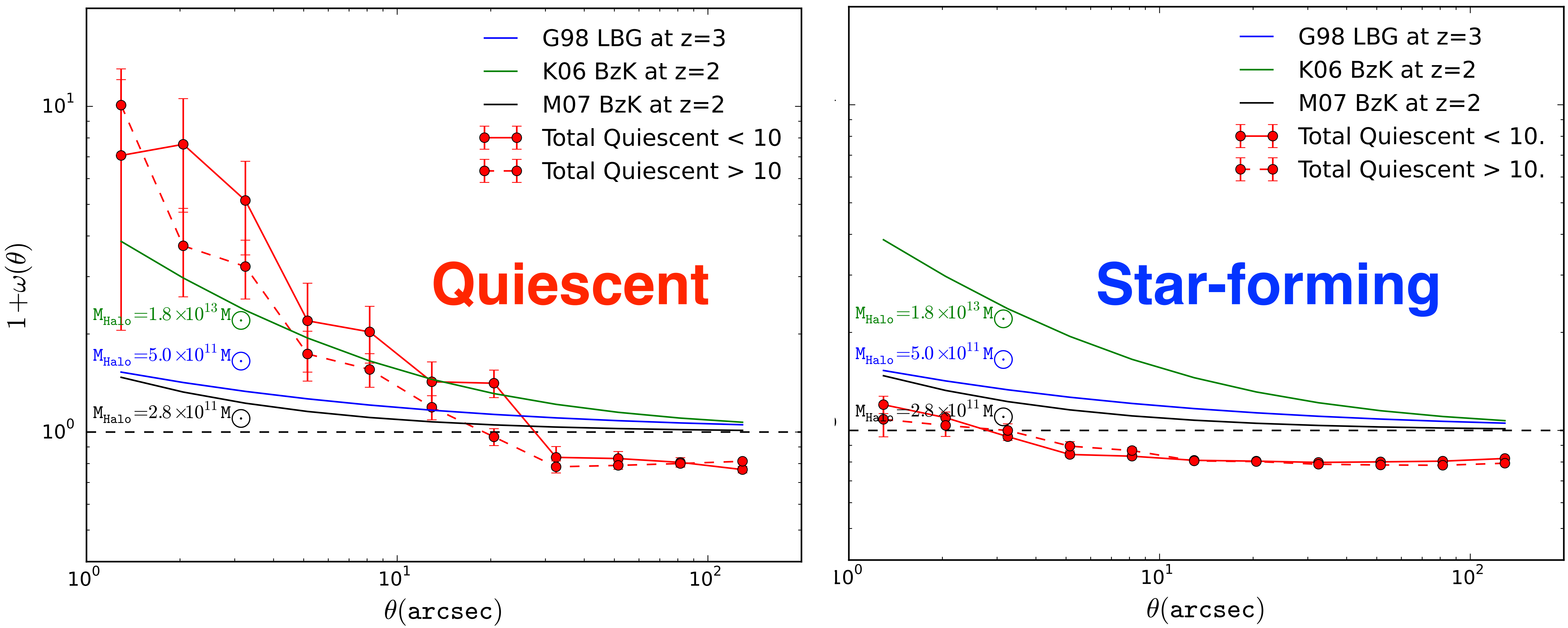
20 arcsec: ≈160 kpc (proper) at 1<z<3

about the size of the virial radius of a ≈10^{12} $M_\odot$ halo

Ji, MG et al. 2018

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

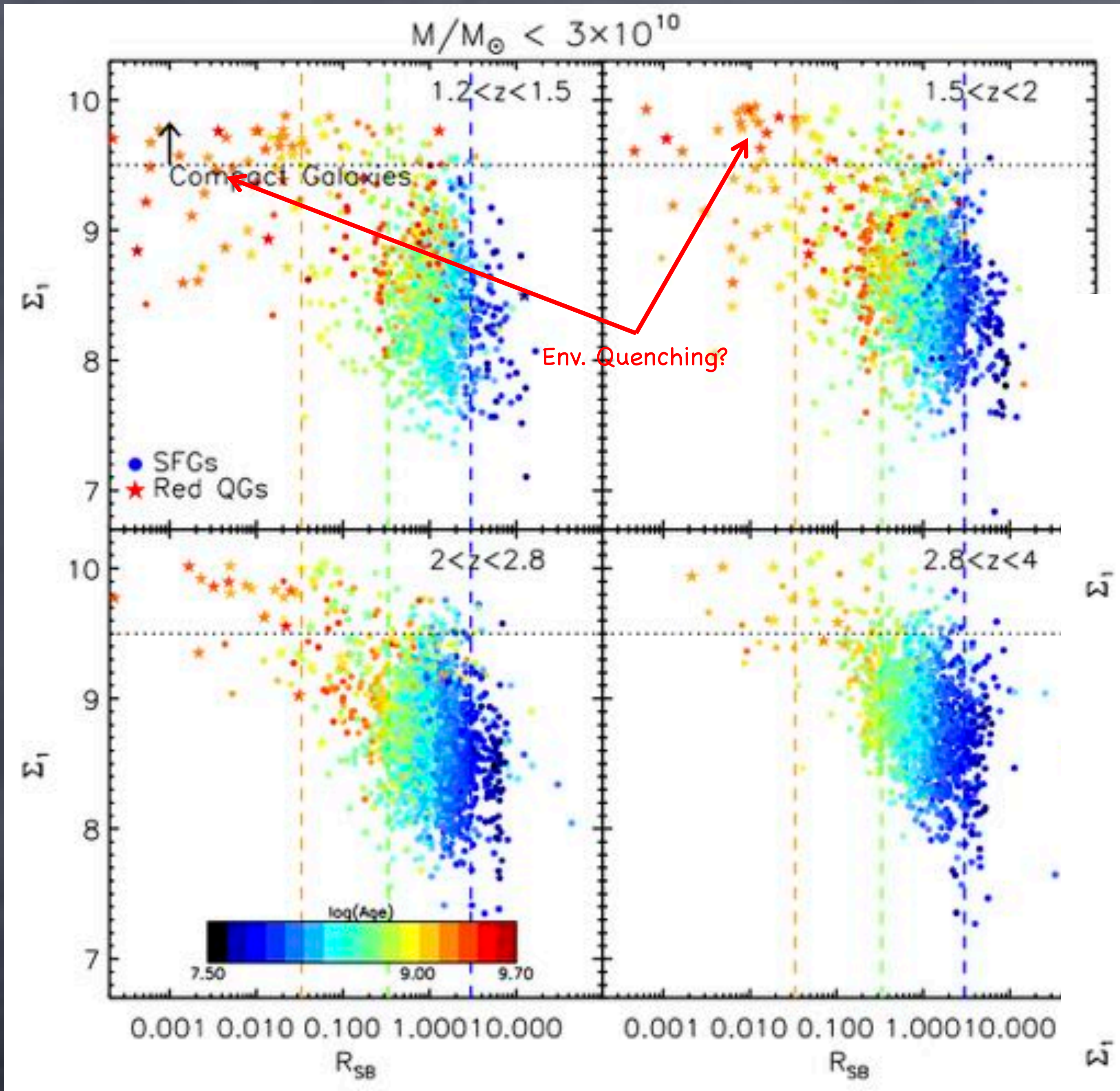
Undistinguishable

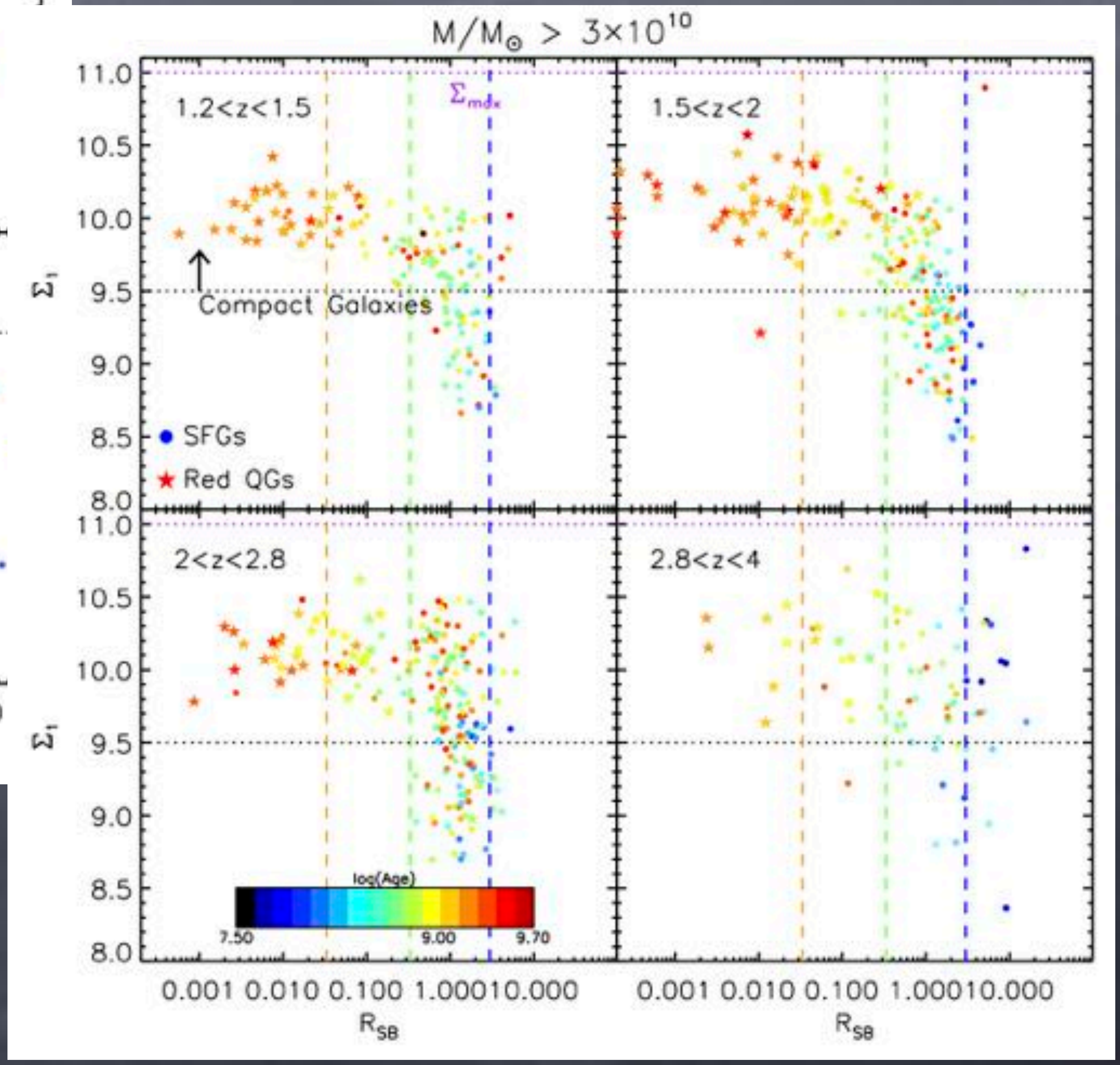
It suggests we are observing satellite quenching
Different physical mechanism, path to quenching

Ji, MG et al. 2018

As galaxies quench, they develop dense stellar cores: Σ_1 traces the history of dissipative accretion

Lee, MG+2018
Barro et al. 2027





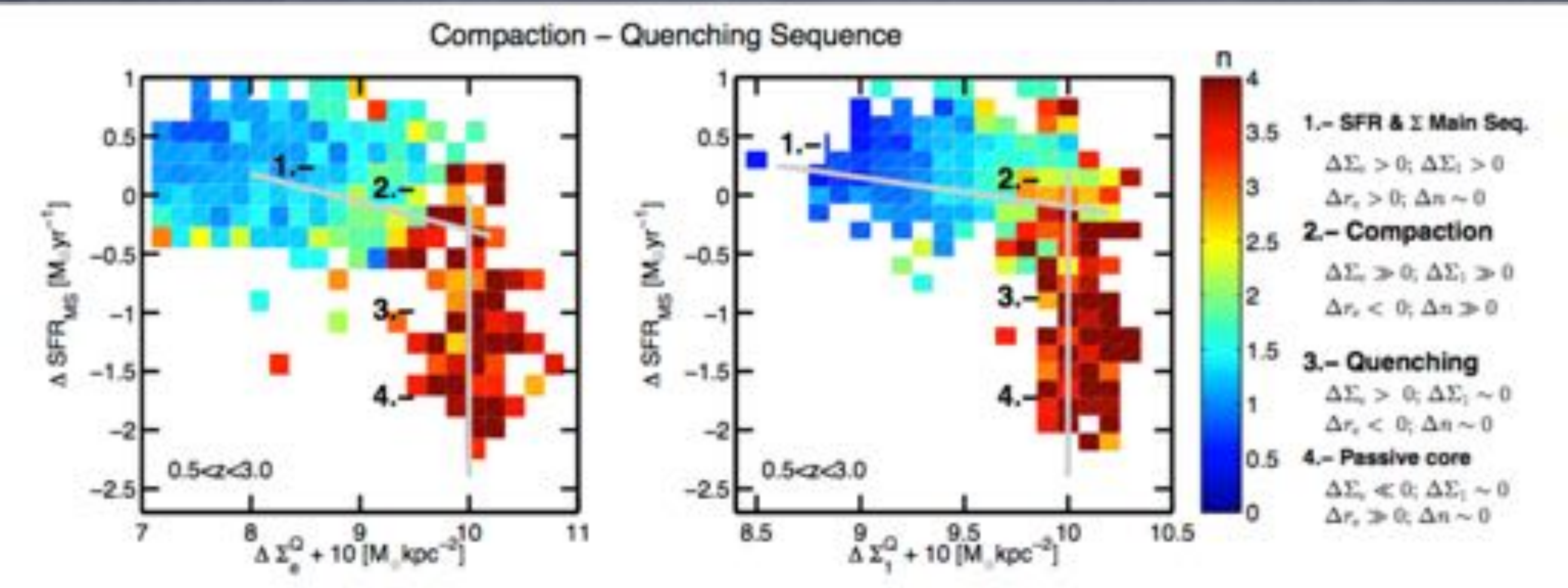
MS galaxies have full range of Σ_1; QG ones do not

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



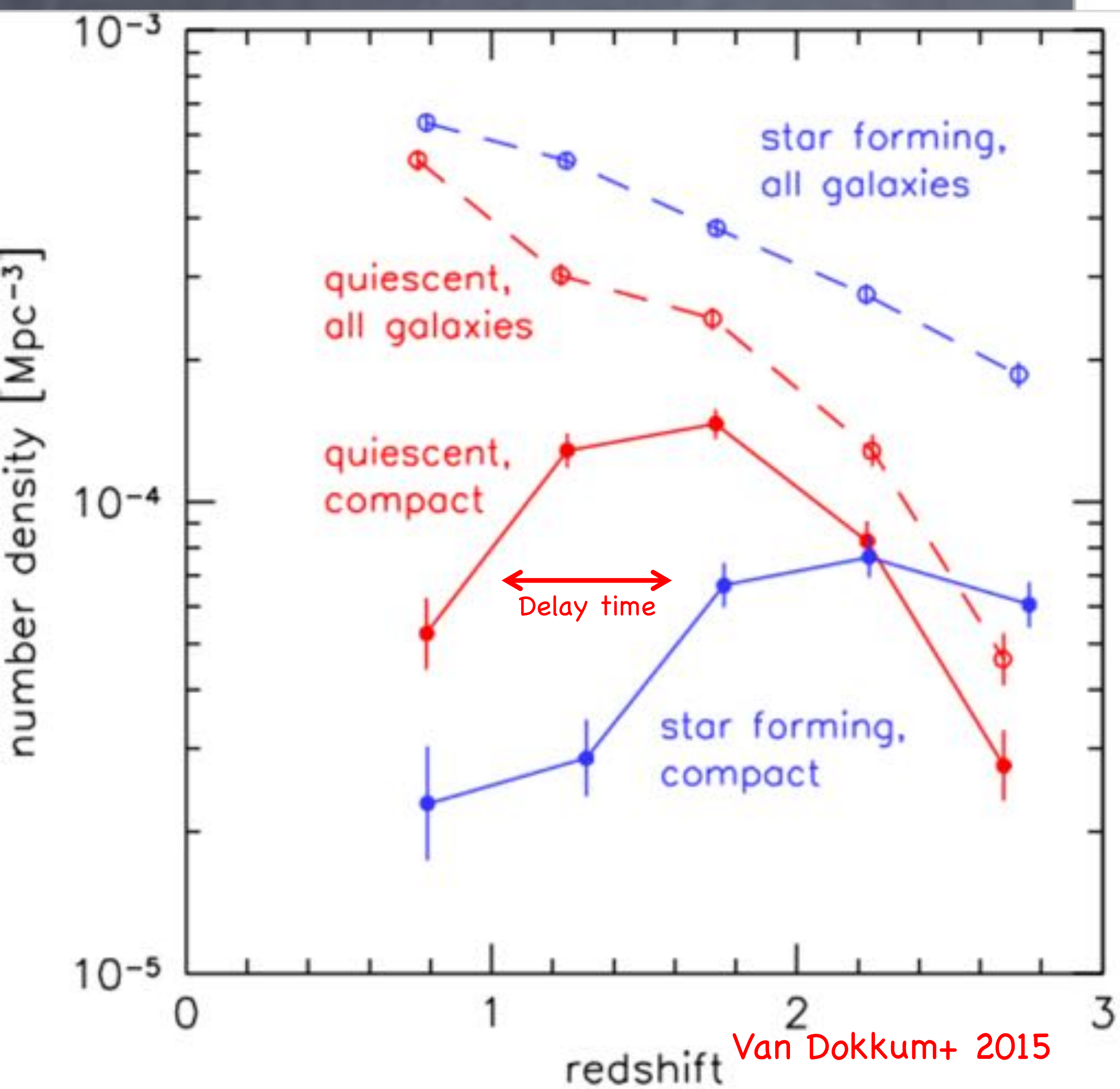
Barro et al. 2015,8

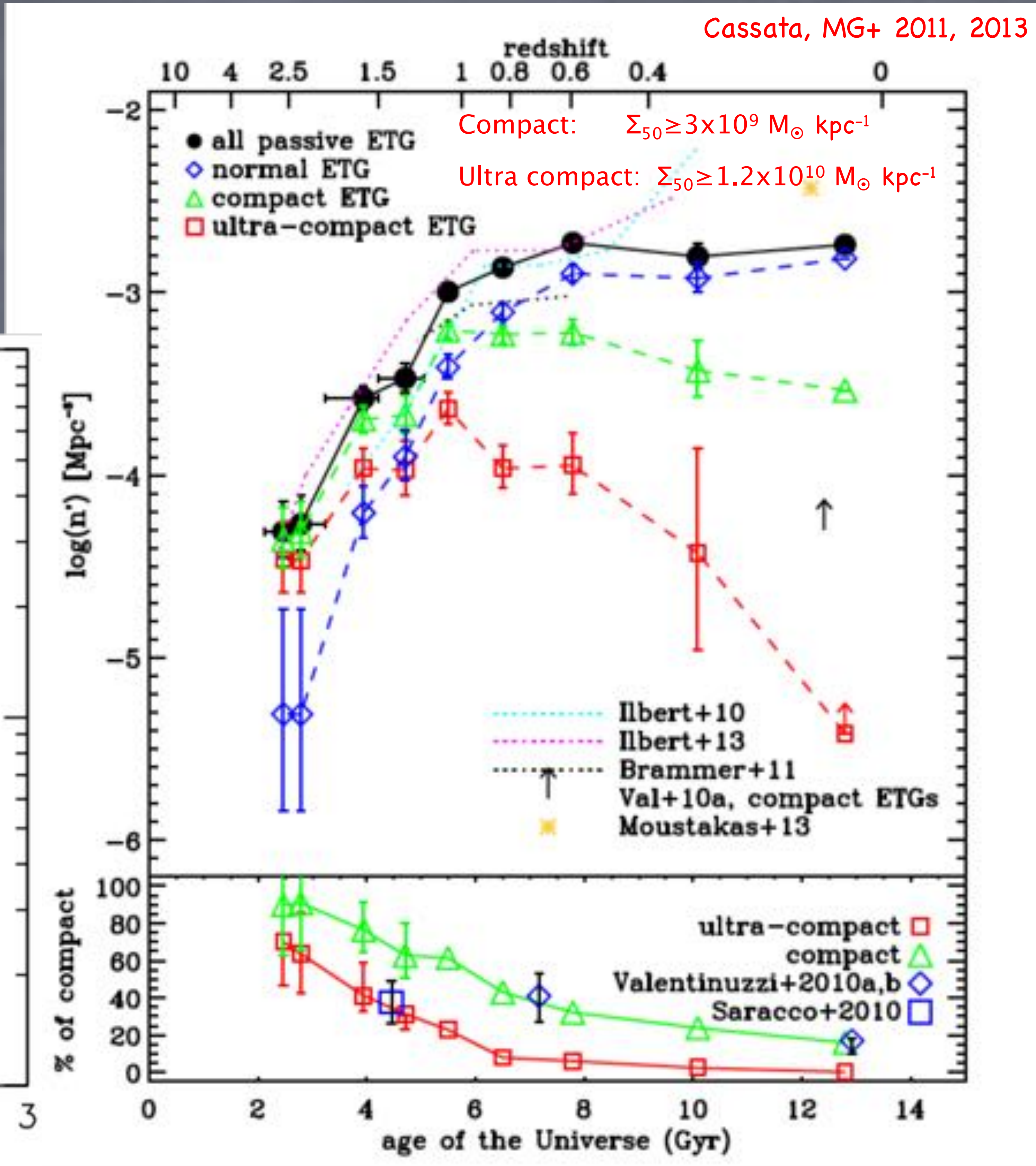
First galaxies to quench are (mostly) compact

SF galaxies of similar mass have a larger dispersion of morphologies

Why are there not more diffuse quenched galaxies at high redshift? (there are at lower redshift -see Carollo et al. 2013)

Does quenching imply morphological transformation?





Early compact quenched galaxies different from local ETG

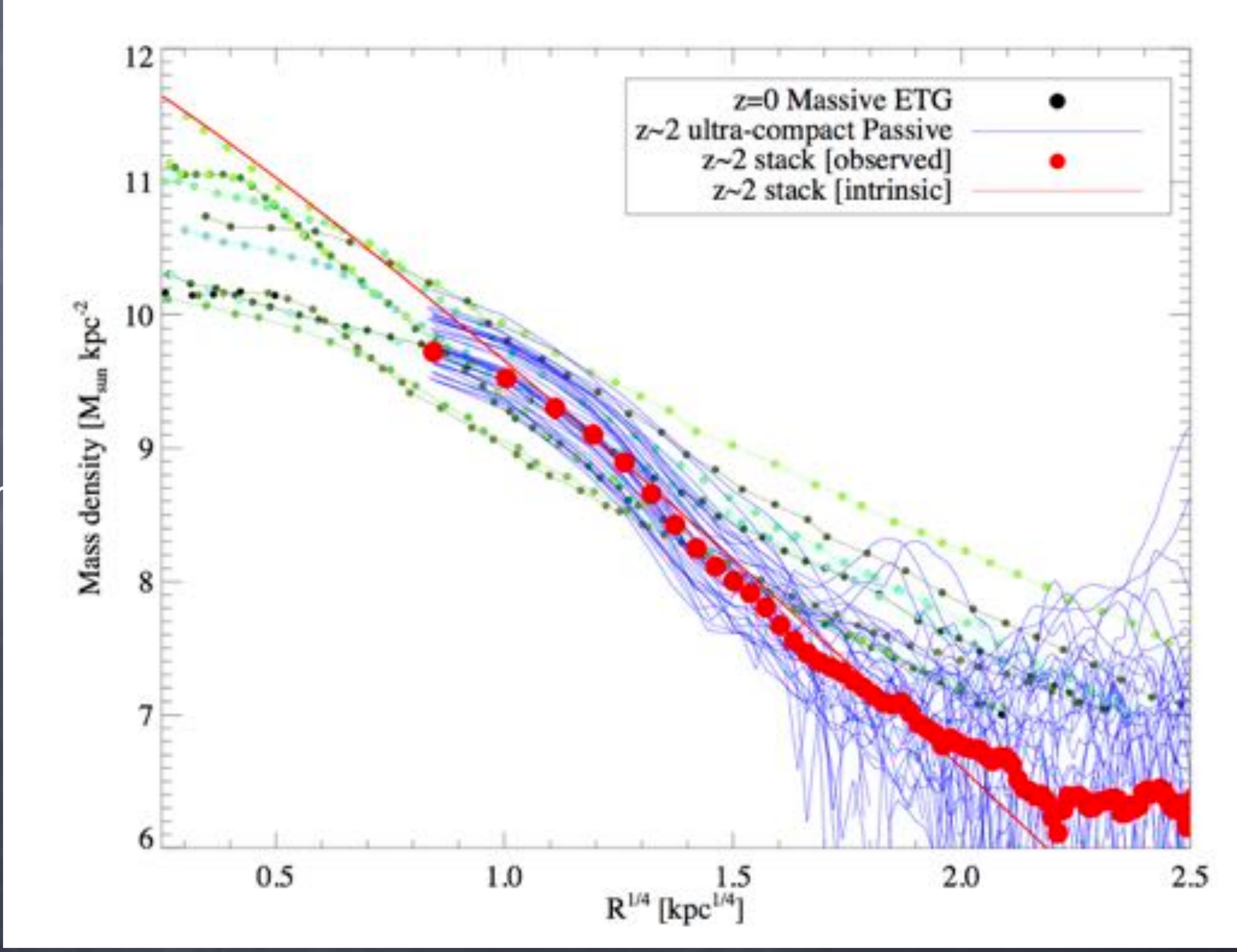
The z≈2 CETG are generally denser than the core of local cuspy ellipticals, from a factor of a few up to 10^2

Do not have more diffuse outer regions (halo or envelope)

Comparison to local ellipticals:
(data from Kormendy+ 2009; CANDELS)

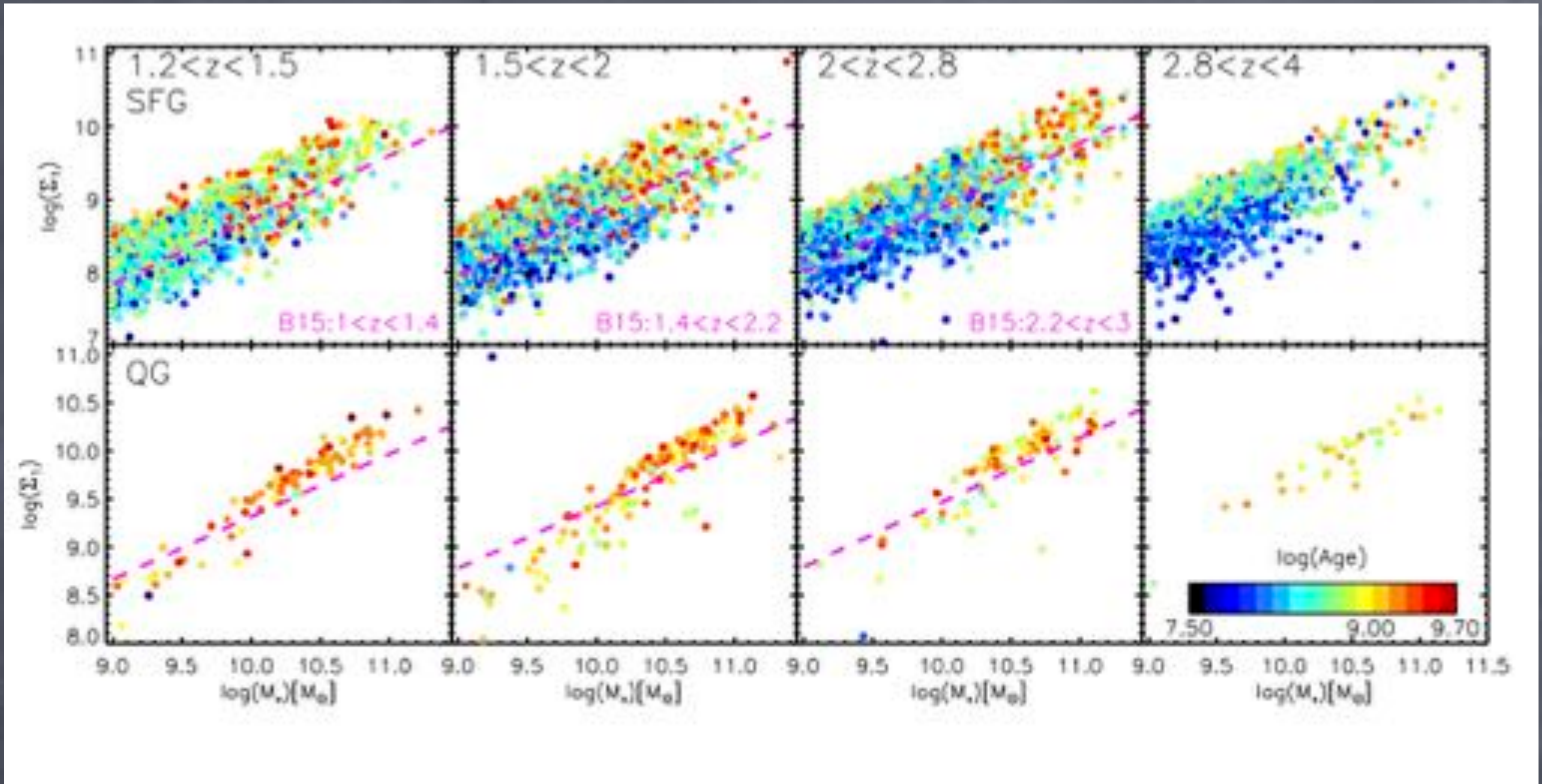
Compact galaxies have n=2.5-3.5, more compact than local, violently-relaxed merger remnants of same mass

If formed via wet mergers of galaxies, a more "diffuse" n=4-4.5 light profile would be expected from the violent relaxation of the dissipation-less component, i.e. the stars (e.g. Hopkins et al. 2008; 2009; 2010)



Age, M_*, Σ_1

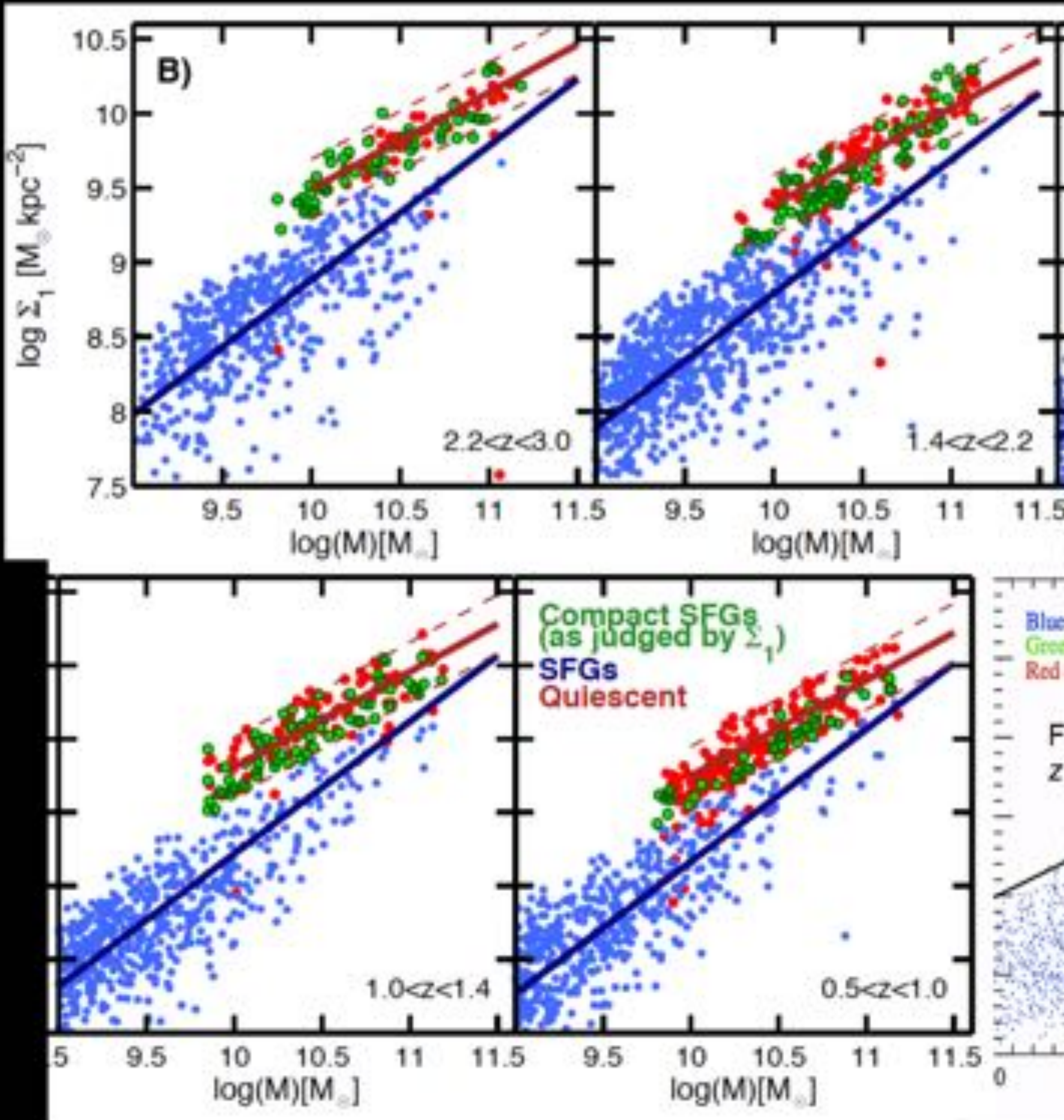
Lee, MG+2017



- Three variables: Age, M_*, and Σ_1
- Age is independent variable, but measures 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
- $\Sigma_1 \approx M_*^{\beta}$, ($\beta_{SF}=0.9$; $\beta_Q=0.66$)

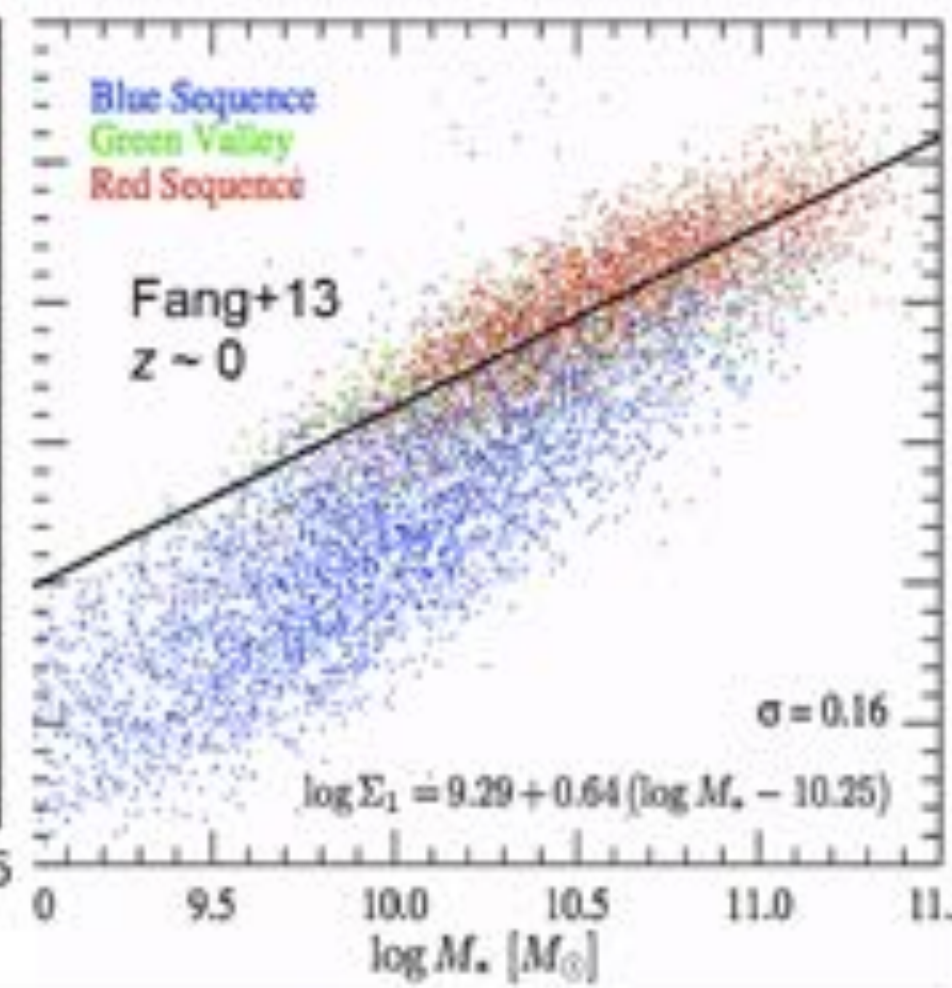
Lee+17; Fang+13; Barro+15,17; Tacchella+17
See also Williams+17; Fagioli+17



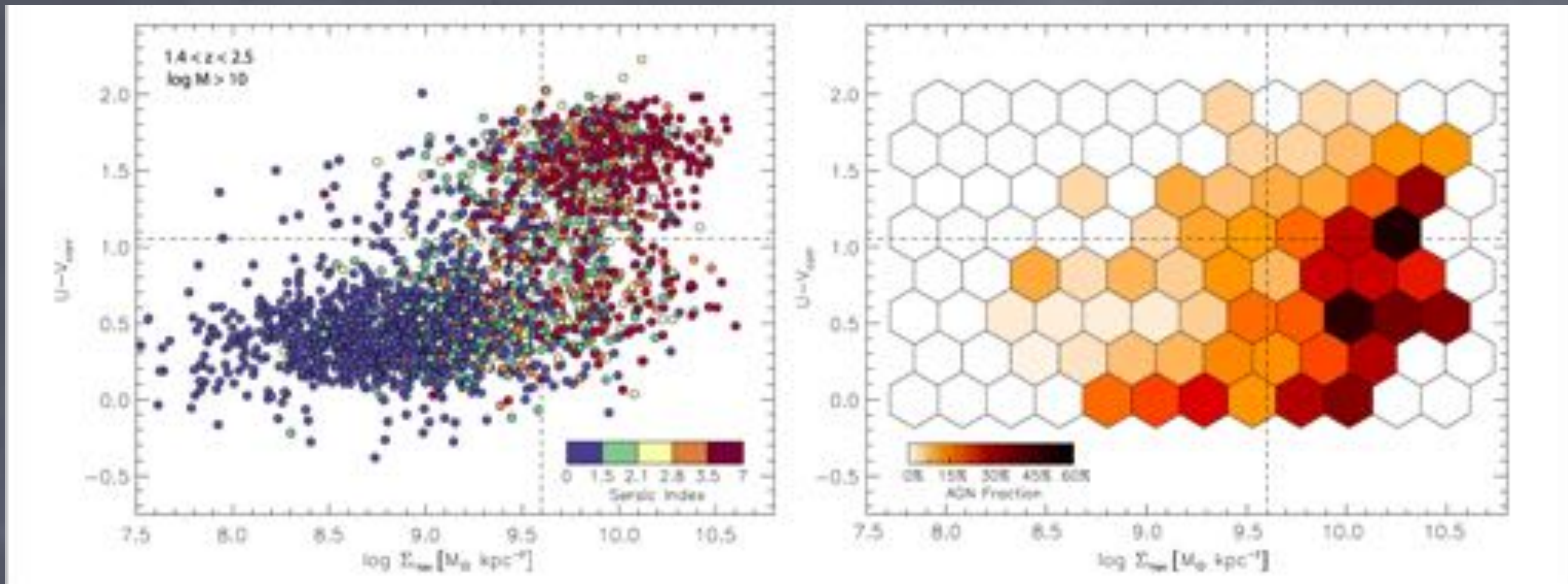
The Σ_1-M* relations are **same at all z's** except for declining zerpt by 0.3 dex

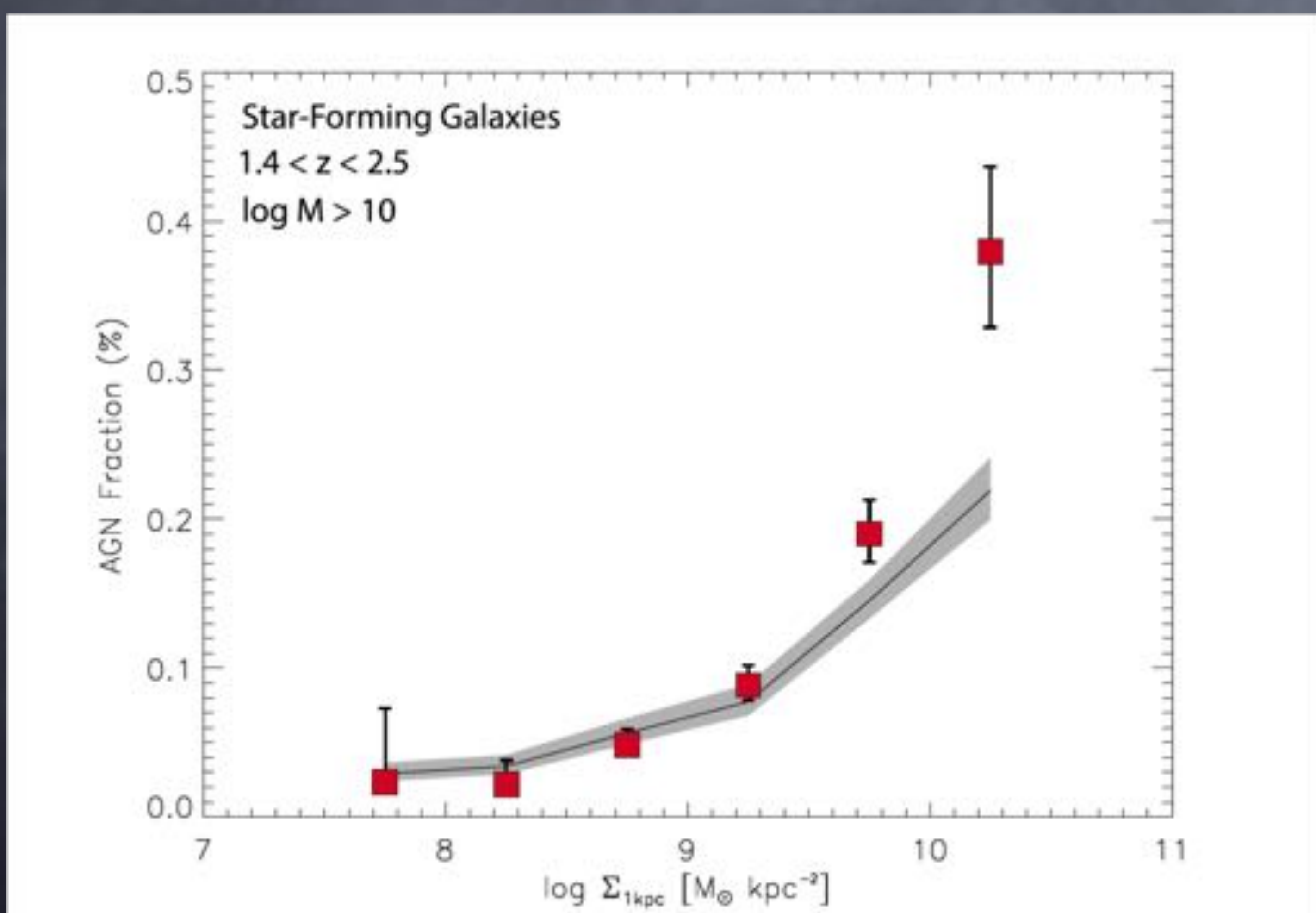
Barro et al. 2017

$\Sigma_1 \sim \sigma^2$, equivalent to $M_{BH} \sim M_*$ or $M_{BH} \sim \sigma^2$



Correlations with AGN activity



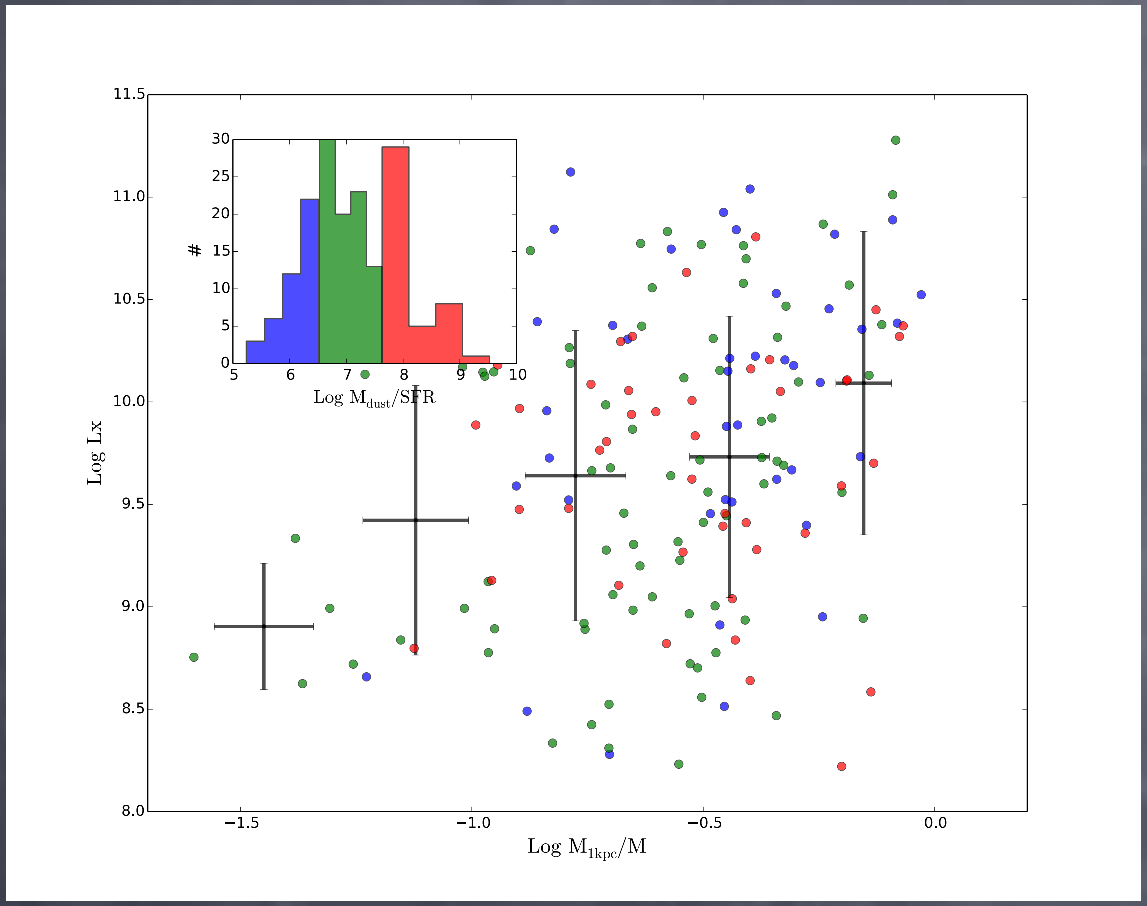


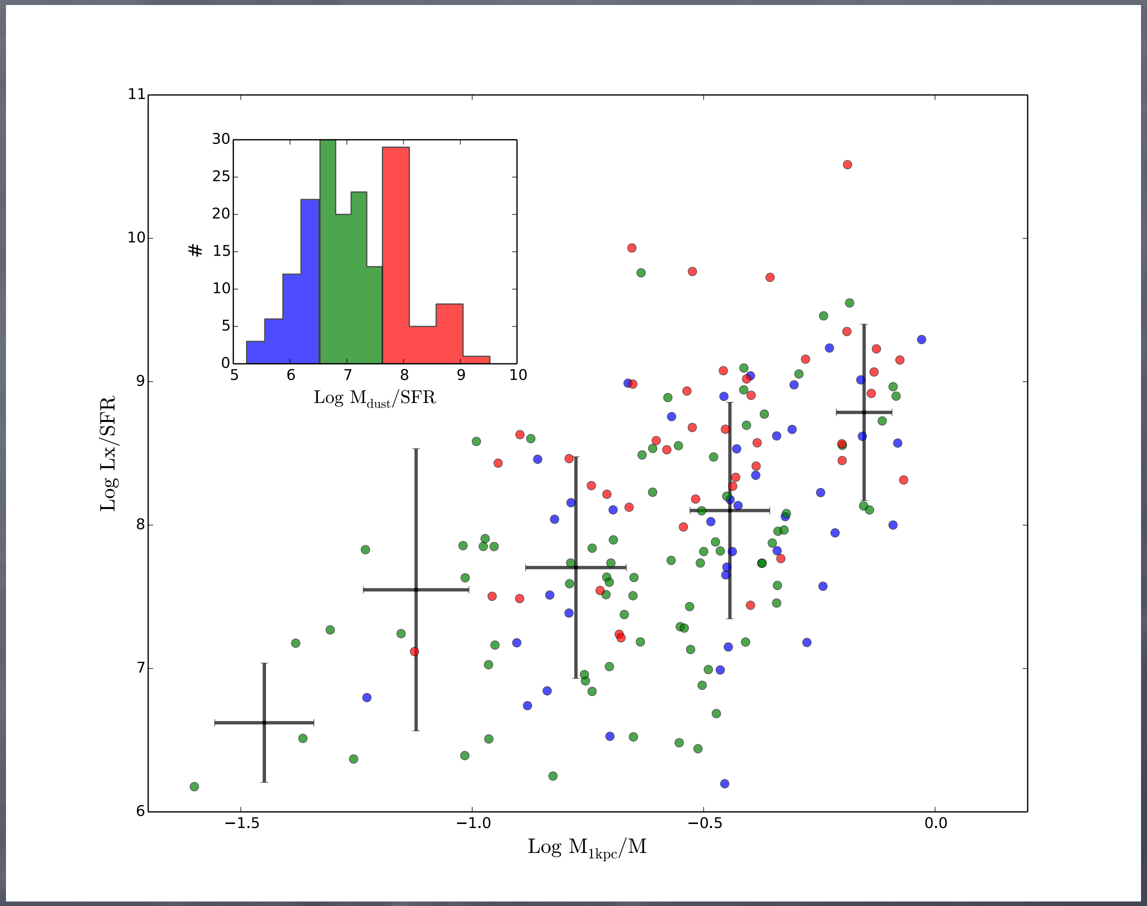
Green valley, more compact galaxies have higher AGN fraction

Caution: it does not imply causation: enhanced AGN activity and compactness could be due to common cause

Wang et al. 2017
Kochevski et al. 2018

AGN output relative to SFR depends on mass concentration:
Likely an effect of dissipative accretion





Ji, MG et al. in prep.
See also Wang et al. 2017

Current Summary

- As galaxies quench, they develop dense central source (scale $\sim$1 kpc): dissipation
- AGN consistent with playing key role in quenching
- Quenching happens when central source is formed, after significant dissipation took place
  - In itself, not evidence of large-scale structural transformations
  - Also remember that in general a big bulge stabilizes the disk

But ....

Stars quenching stars: how photoionization by local sources regulates gas cooling and galaxy formation

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Accepted 2009 December 20. Received 2009 December 10; i

ABSTRACT
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Key words: galaxi

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CHANDRA OBSERVATIONS OF THE MASSIVE STAR-FORMING REGION ONSALA 2

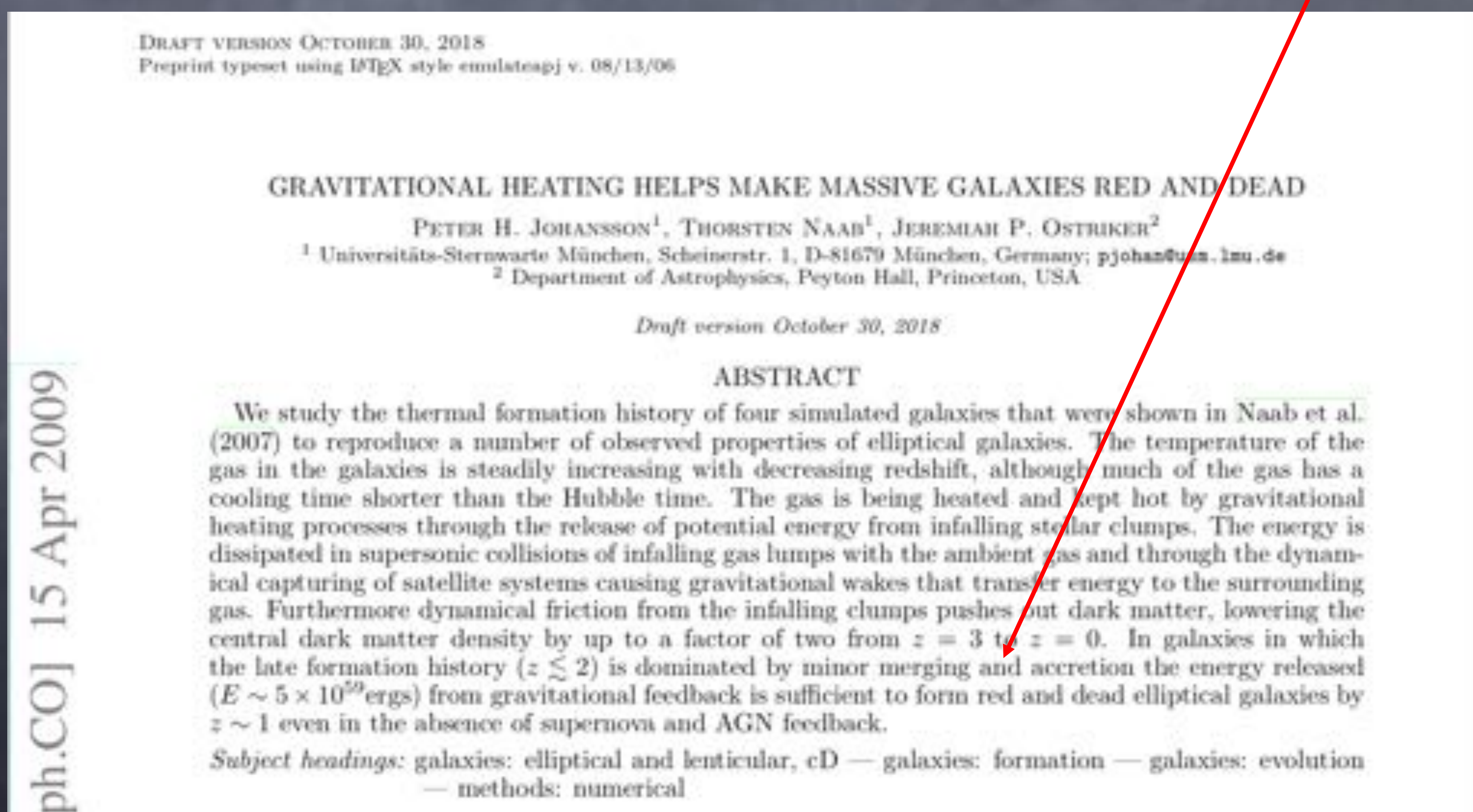
STEPHEN L. SKINNER,[1] KIMBERLY R. SOKAL,[2] AND MANUEL GÜDEL[3]

4. Diffuse X-ray emission is present near G75.77+0.34 and G75.84+0.40. The diffuse spectrum of G75.77+0.34 shows high-temperature emission lines including Fe K (6.67 keV) indicative of hot thermal plasma. It is unlikely that a population of faint X-ray sources can account for the diffuse emission. Shocked winds from the embedded massive stars offer a plausible explanation.

mation in Cygnus known as Onsala 2 (ON 2). Within this region lies the optically-revealed young stellar cluster Berkeley 87 which contains several OB stars and the rare oxygen-type Wolf-Rayet star WR 142. Previous radio studies of ON 2 have also discovered masers and several H II regions excited by embedded OB stars. Radio and GAIA parallaxes have now shown that the H II regions are more distant than Berkeley 87. We summarize two *Chandra* X-ray observations of ON 2 which detected more than 300 X-ray sources. Several optically-identified stars in Berkeley 87 were detected including massive OB stars and WR 142, the latter being a faint hard source whose X-ray emission likely arises in hot thermal plasma. Intense X-ray emission was detected near the compact H II regions G75.77+0.34 and G75.84+0.40 consisting of numerous point sources and diffuse emission. Heavily-absorbed X-ray sources and their near-IR counterparts that may be associated with the exciting OB stars of the H II regions are identified. Shocked winds from embedded massive stars offer a plausible explanation of the diffuse emission. Young stellar object candidates in the ON 2 region are identified using near-IR colors, but surprisingly few counterparts of X-ray sources have near-IR excesses typical of classical T Tauri stars.

812.02210v1 [astro-ph.SI

- The release of gravitation energy: from changes of grav. potential
- $5\mathrm{x}10^{59}$ erg from $z\approx2$ to 1 for a $10^{12}\ M_\odot$ halo $\longrightarrow$ $\approx10^{43}$ erg/sec
- ½ of it goes into heat (VT): should helps quenching or even do the job
- Provides a natural "mass quenching" from everywhere inside the galaxy
  - Direct heating of gas (Johnasson, Naab & Ostriker 2009)
  - Soft X-ray from hot gas further inhibit cooling (see Cantalupo 2010)
- The Virial part should be observed in the simulations
  - SAM see it, say it is not sufficient for quenching. Others?



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GRAVITATIONAL HEATING HELPS MAKE MASSIVE GALAXIES RED AND DEAD

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Draft version October 30, 2018

ABSTRACT

We study the thermal formation history of four simulated galaxies that were shown in Naab et al. (2007) to reproduce a number of observed properties of elliptical galaxies. The temperature of the gas in the galaxies is steadily increasing with decreasing redshift, although much of the gas has a cooling time shorter than the Hubble time. The gas is being heated and kept hot by gravitational heating processes through the release of potential energy from infalling stellar clumps. The energy is dissipated in supersonic collisions of infalling gas lumps with the ambient gas and through the dynamical capturing of satellite systems causing gravitational wakes that transfer energy to the surrounding gas. Furthermore dynamical friction from the infalling clumps pushes out dark matter, lowering the central dark matter density by up to a factor of two from $z=3$ to $z=0$. In galaxies in which the late formation history ($z\lesssim2$) is dominated by minor merging and accretion the energy released ($E\sim5\times10^{59}$ergs) from gravitational feedback is sufficient to form red and dead elliptical galaxies by $z\sim1$ even in the absence of supernova and AGN feedback.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: evolution — methods: numerical

Are spheroids (esp. if dense) intrinsically less conducive to sustain star formation? (e.g. Gobat+, Nat2018)

- Disks are cold systems. Collisions between co-rotating systems (e.g. gas clouds) happen more rarely and with slow relative speed
- Spheroids do not have co-rotating orbits. Collisions likely to happen at very high speed (10^2 km/s). Even if gas-rich, gas is shocked in collisions

Local and global (large-scale) structural transformations

- Σ_1 is a *local* metric of density; it only informs us on the structure of the innermost volume of a galaxy.
- PROBLEM: DM relatively unimportant at r<1 kpc
  - 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 due to dissipative baryon accretion
- Gini is *global* metric, if measured within Petrosian radius (to make it insensitive to surf. Birghtness bias), where DM affects dynamics:

$$G = \frac{1}{2\,n(n-1)\,\rho} \sum_{i,j} |\rho_i - \rho_j|$$

  - M_{20} is the second moment of the 20% brightest pixels
- Gini and M_{20} provide non-parametric descriptions of the overall light (mass) distribution independent of the shape of the profile (Abraham+1996; Conselice+ 2000; Scarlata+2007; Lee+2013,2017)
- Absolute values of Gini and M_{20} difficult to calibrate and interpret; **variations are more informative**

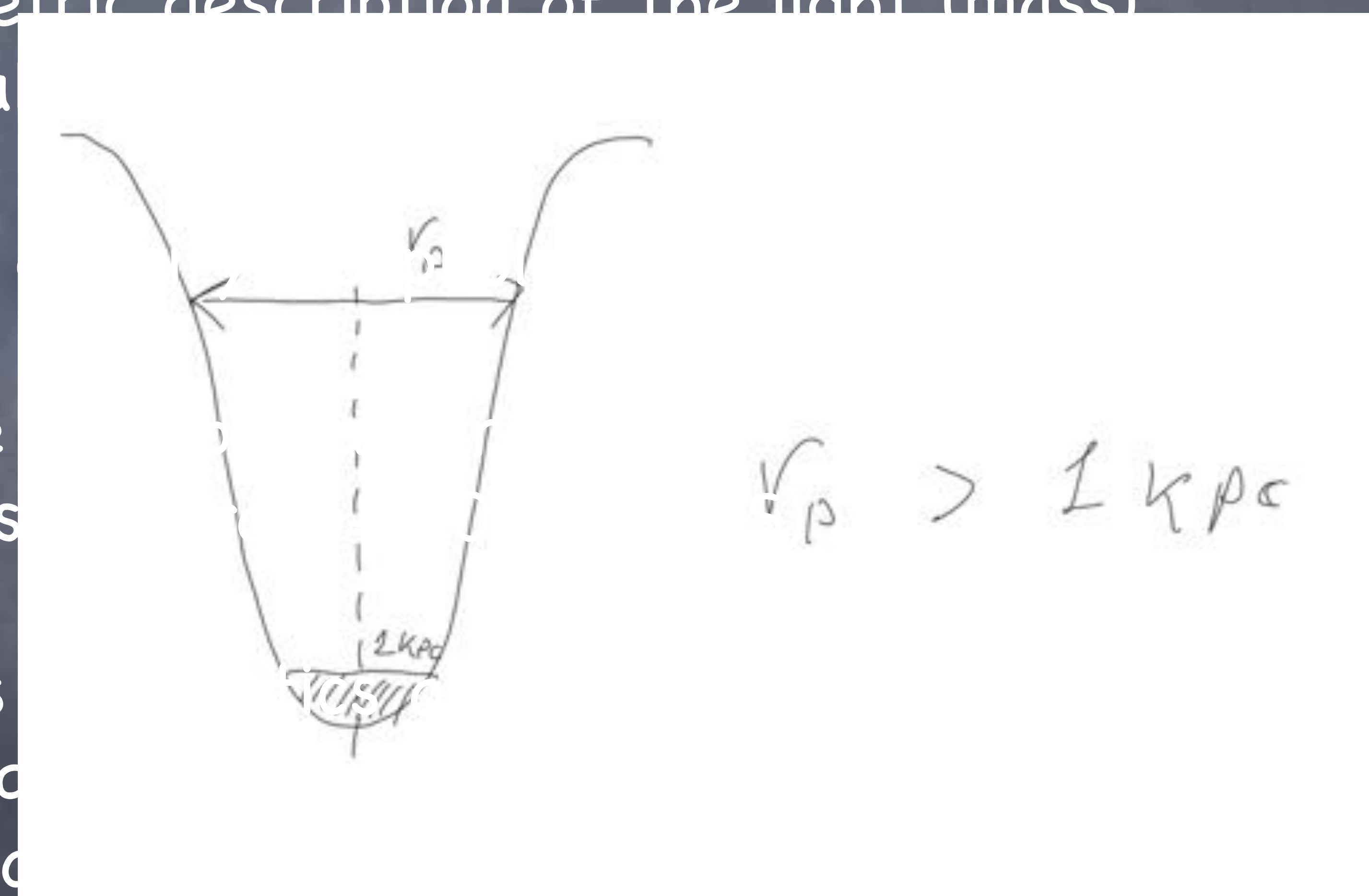
Gini and M_{20} as metrics of (global) morphological transformations:

Measured in elliptical apertures at the (SMA) petrosian radius: $\mu(r_p)/\mu(r<r_p) = 0.2$

Provide a non-parametric description of the light (mass) distribution of the ga

Traditionally, used to
are known for being:

- noisy (i.e. sensitive
- hard to calibrate (s



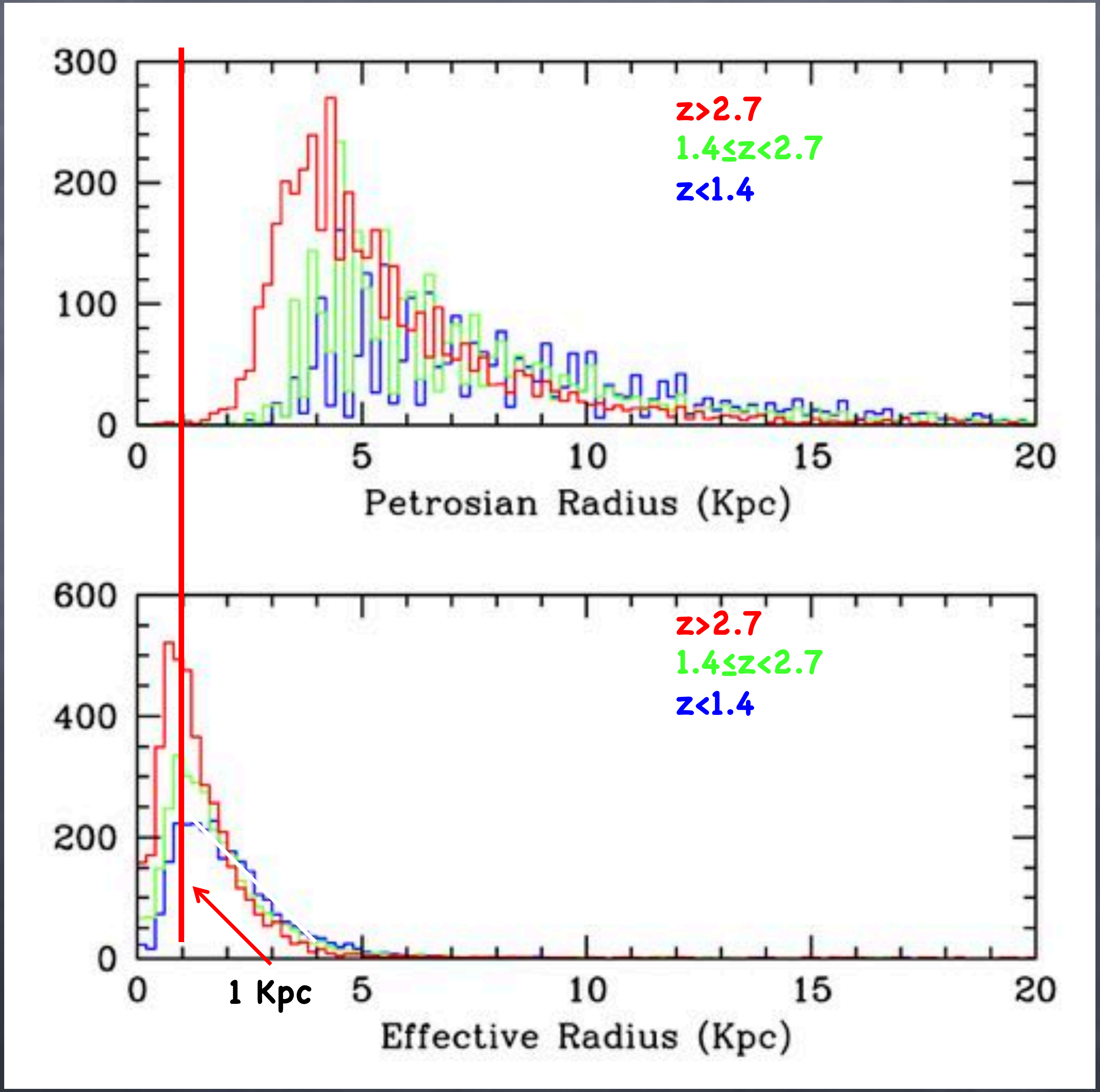
Here we use them as
transformations in a

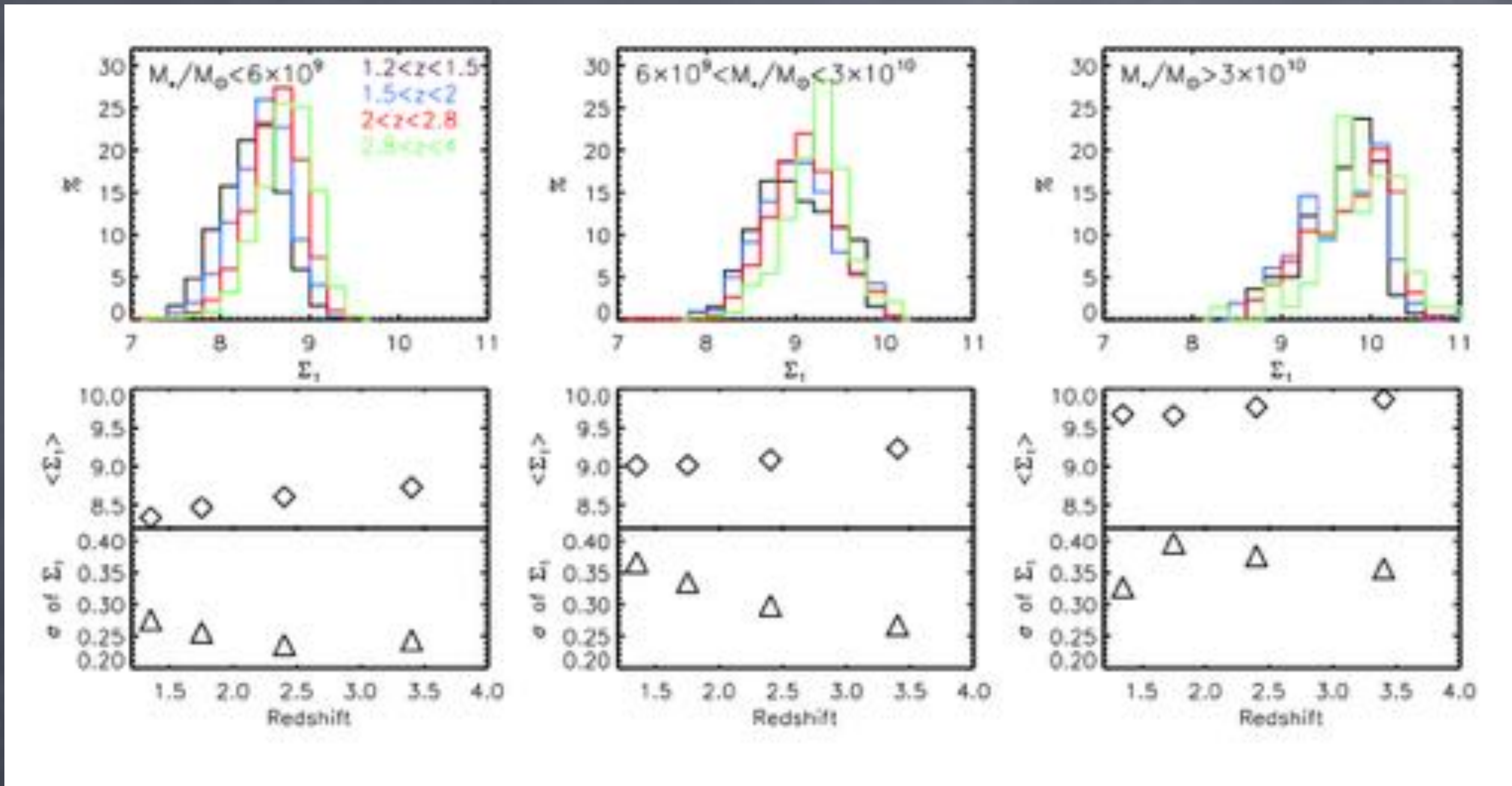
- absolute value is no
- we monitor variations as a function of time

Local scales vs. global scales:

Global = must feel gravity of both baryons and dark matter: representative of the galaxy structural type.

At 1 Kpc, gravity of dark matter is still negligible





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

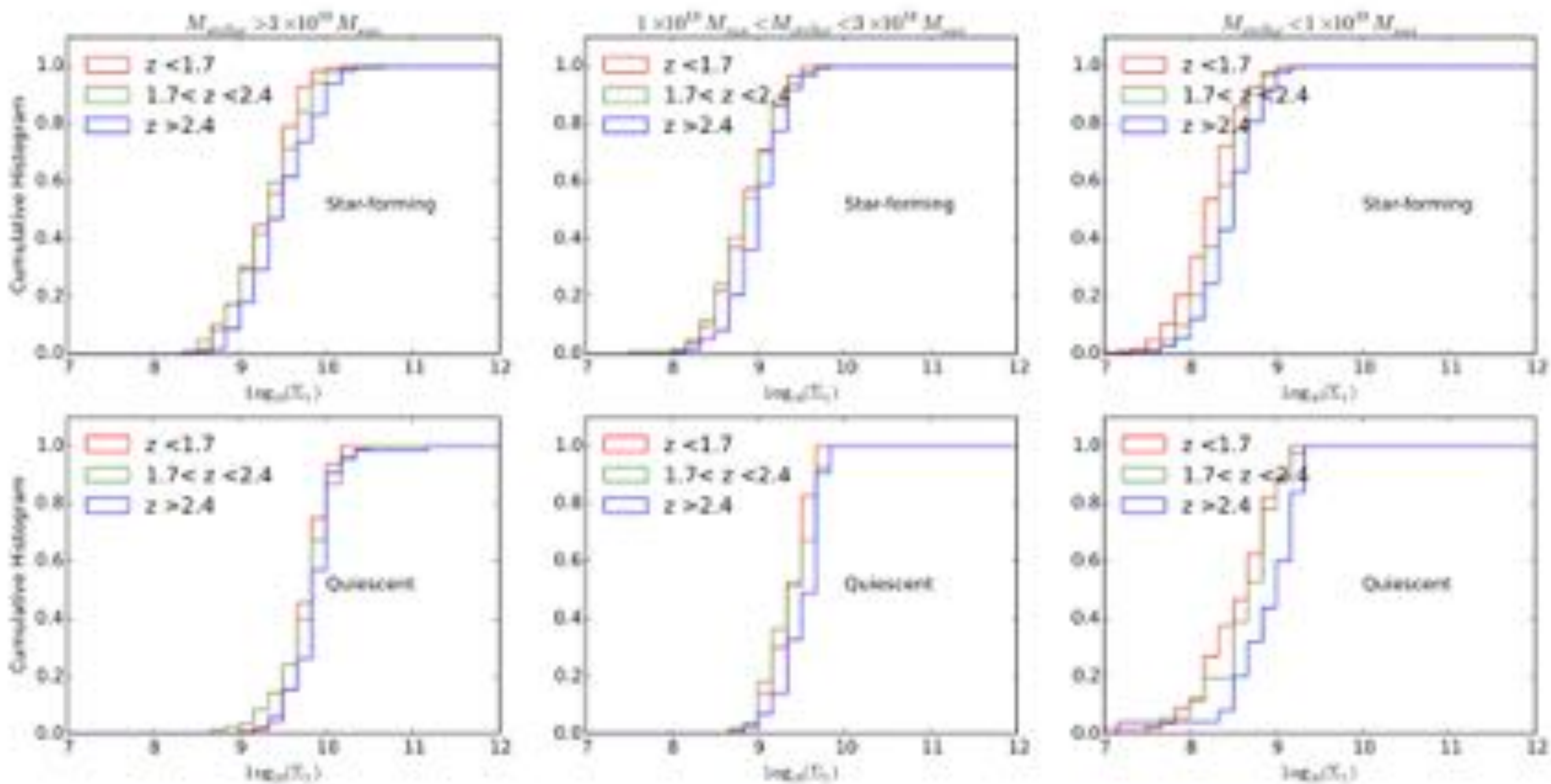
The highest value, $\Sigma_1 \approx 11$, does not decrease (but it is mass dependent)

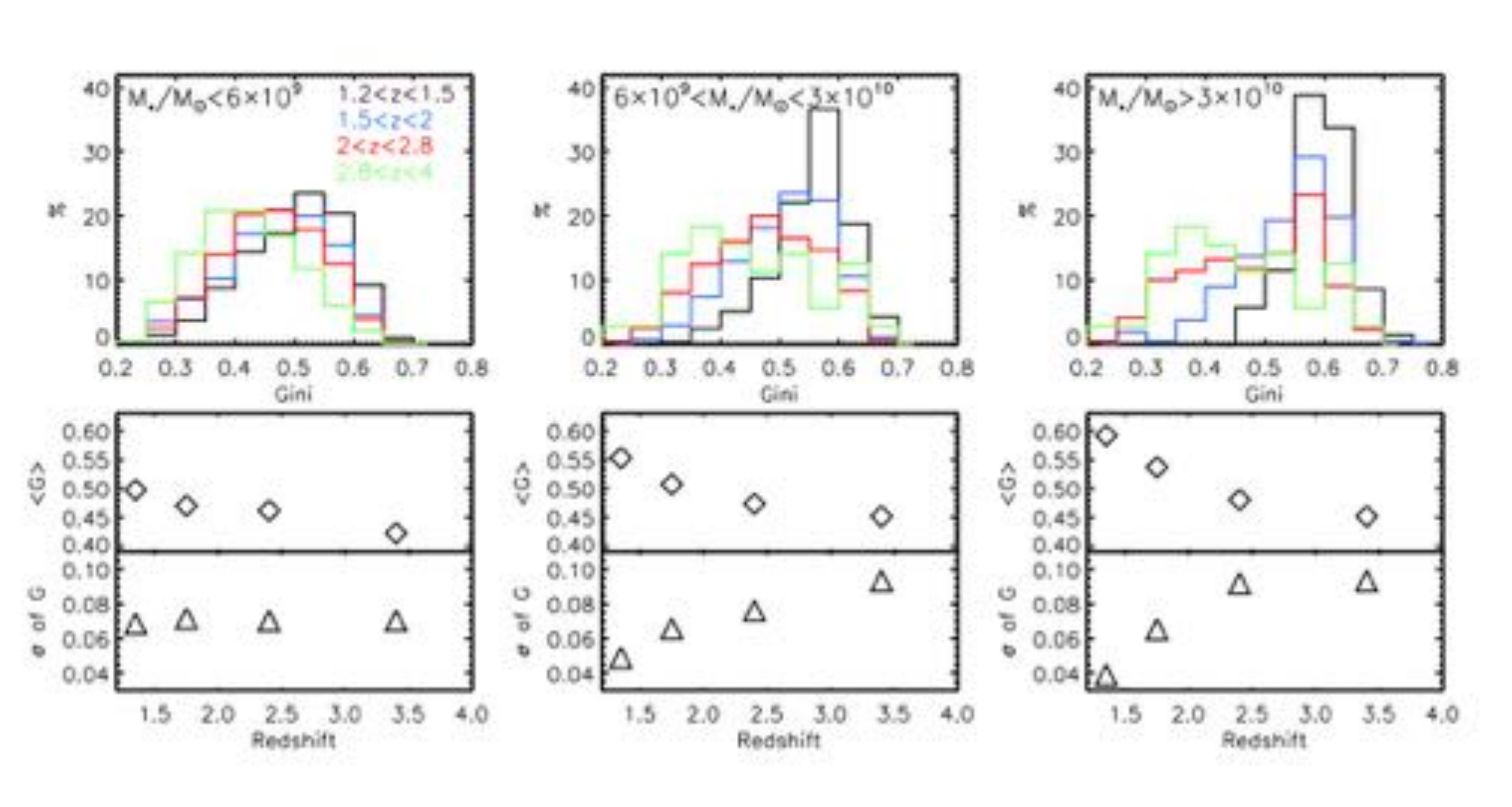
MG+2019, in prep.

The cumulative distribution of Σ_1

MG+2019, in prep.

No big evolution with redshift





Effect is mass dependent: more massive galaxies transform more

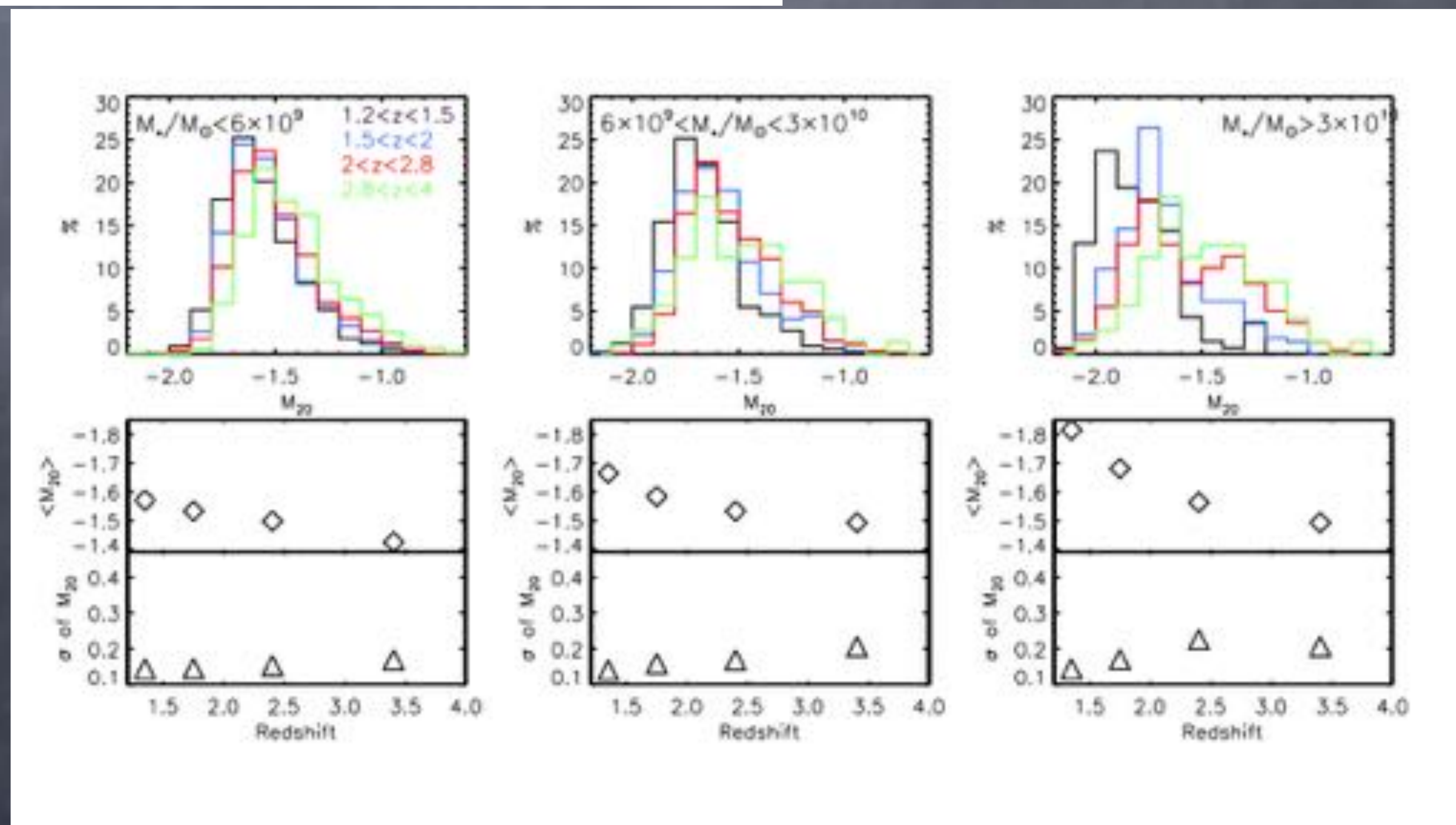
MG+2019 in prep.

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

Gini increases: galaxies place more mass in less volume elements

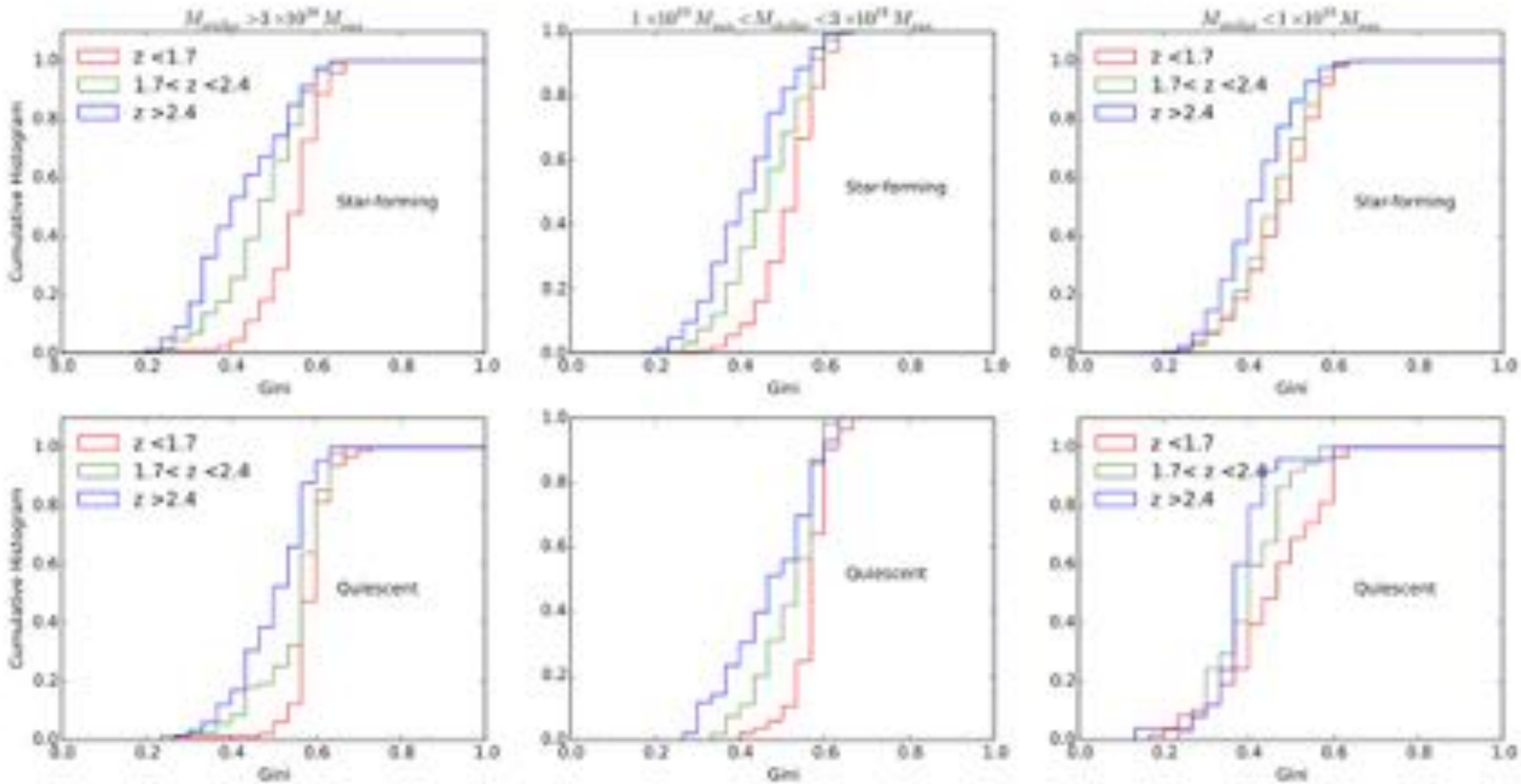
M_{20} decreases: galaxies become more nucleated

Growth of core, structure and accretion may all contribute to this



The cumulative distribution of Gini

Strong, mass-dependent evolution with redshift

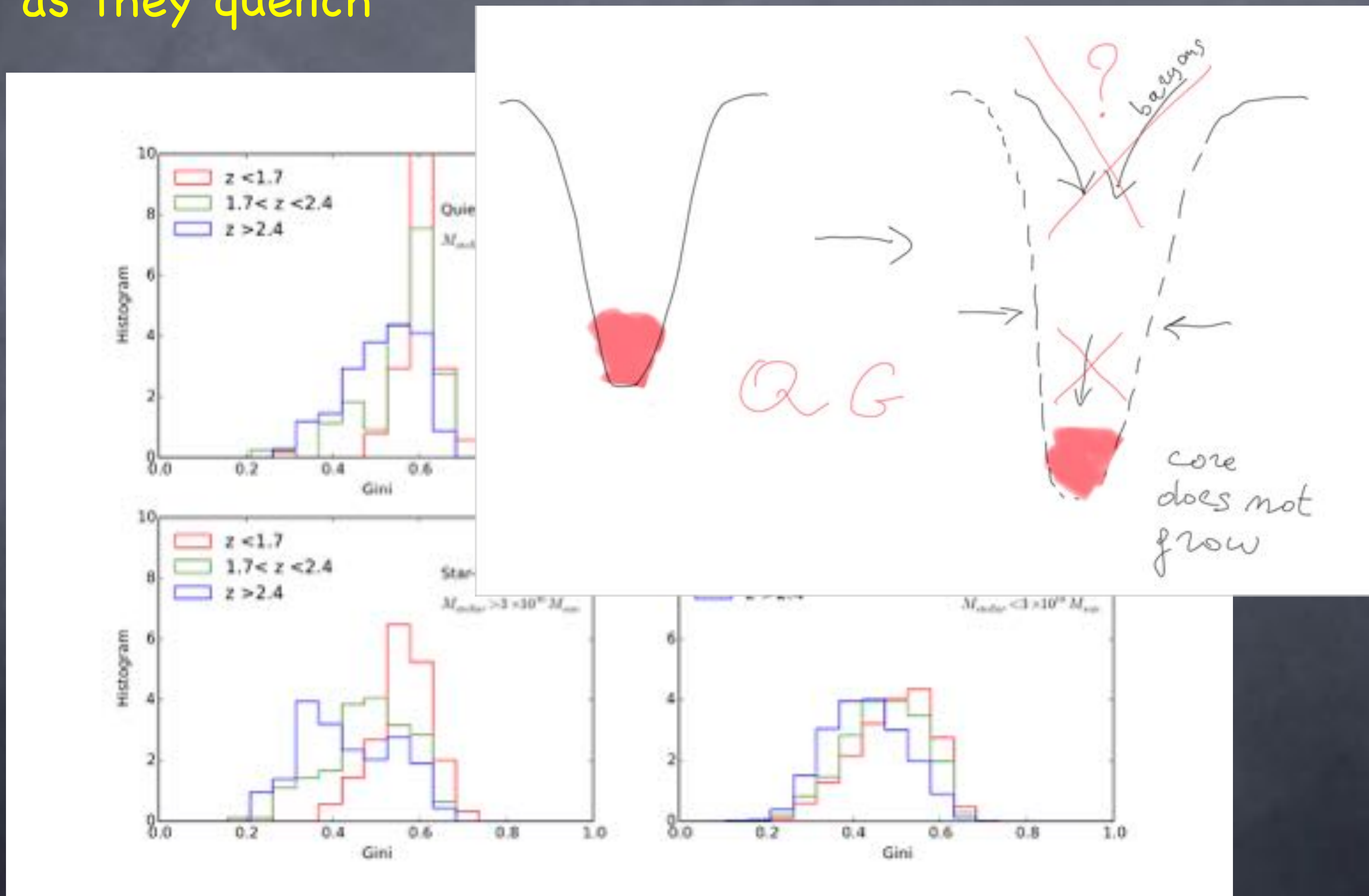


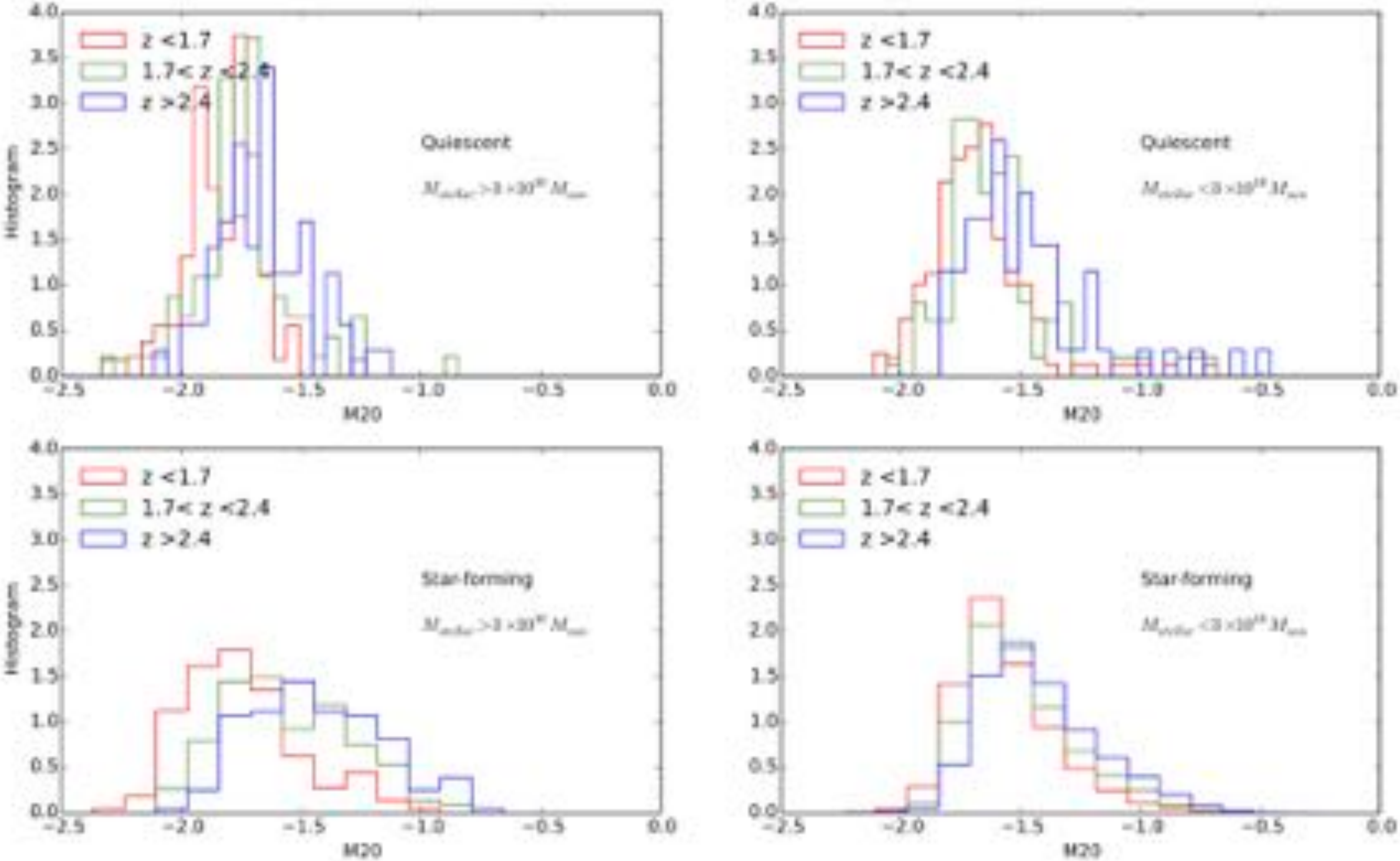
Less Inequality ← → More Inequality

MG+2019, in prep.

The growth of mass inequality "(oligarchy)" seems to continue after quenching: not driven by dissipative gas accretion

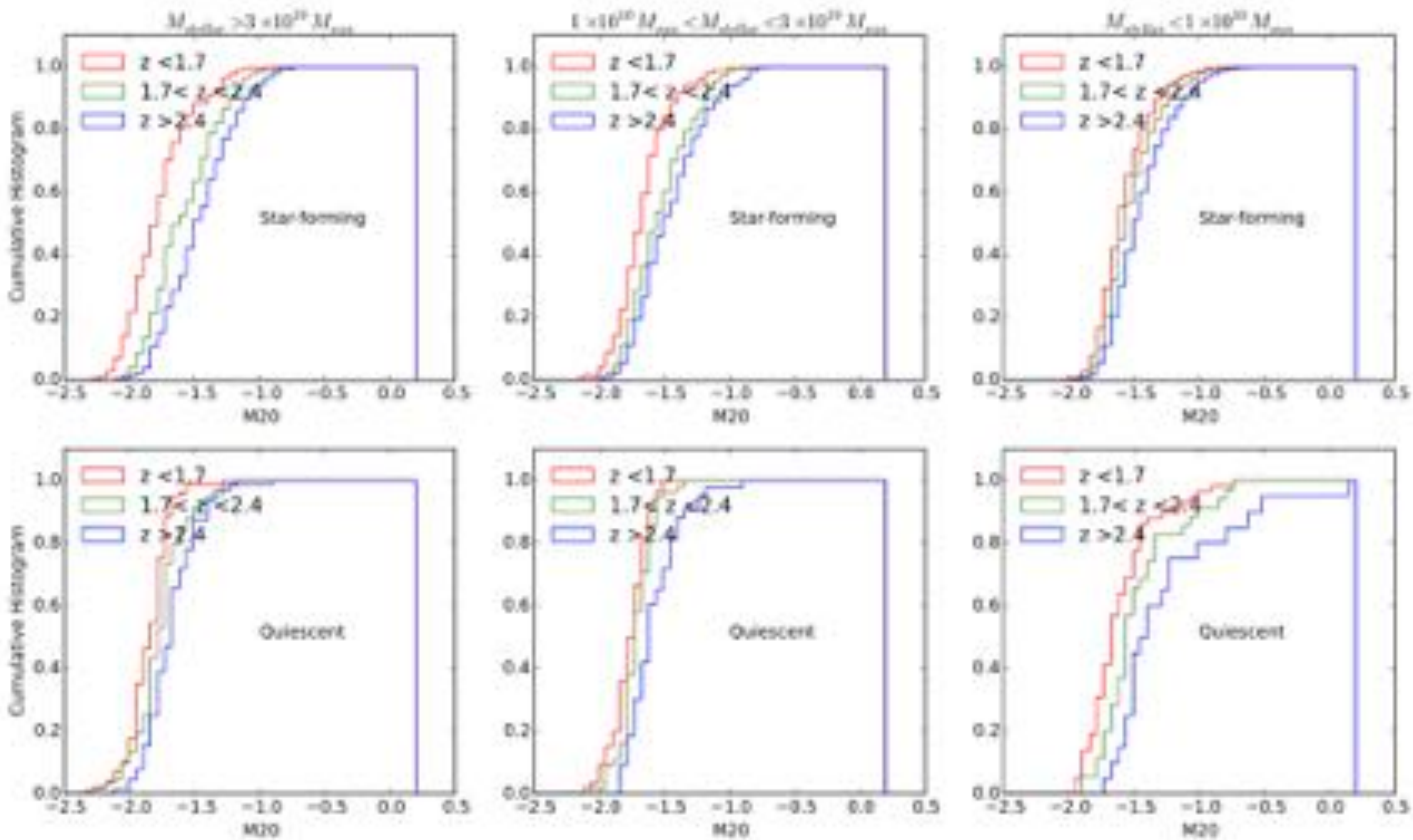
CAVEAT: it could be driven by the addition of new "concentrated" galaxies as they quench



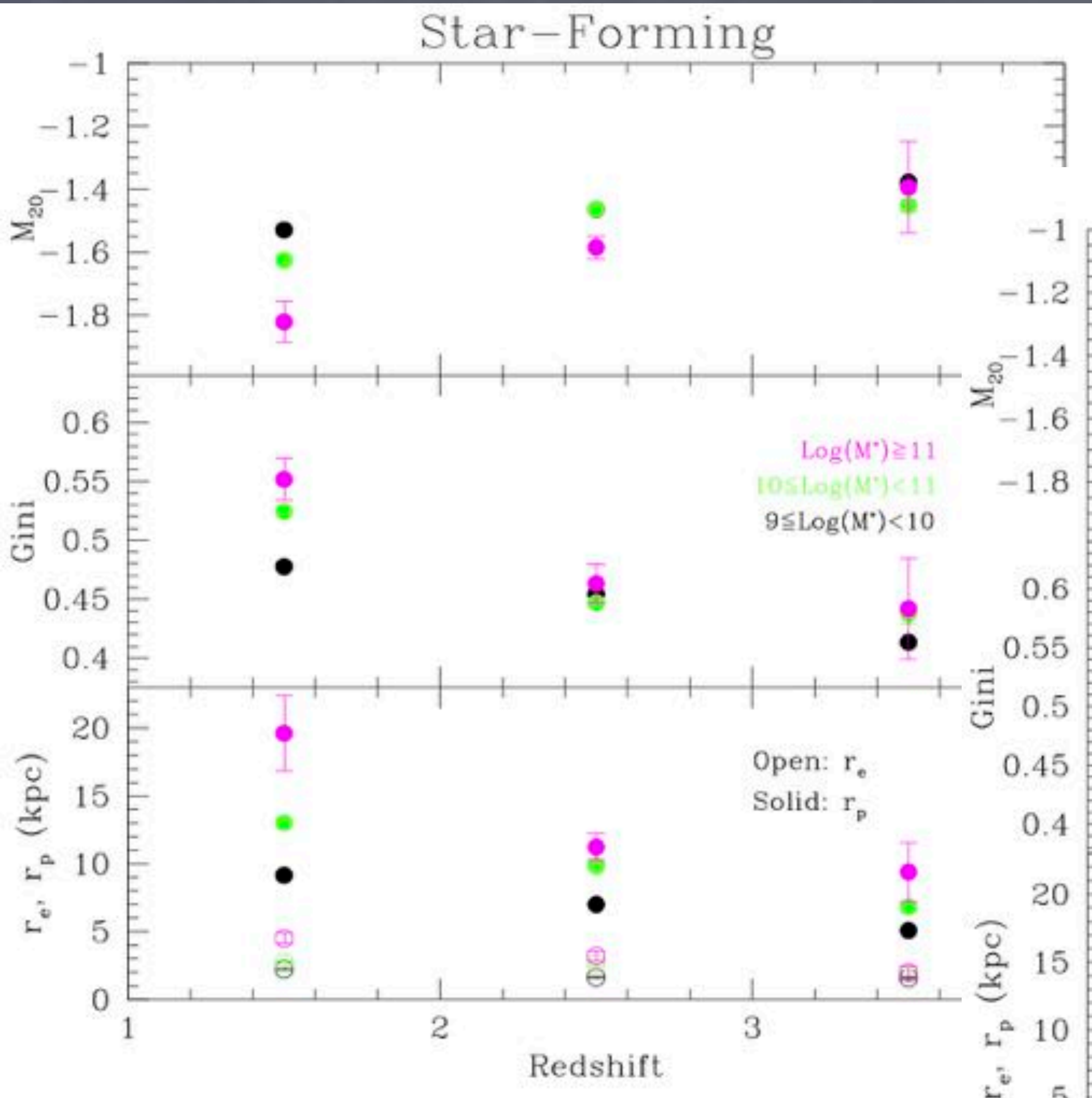

z <1.7
1.7< z <2.4
z >2.4
Quiescent
Histogram
M20
z <1.7
1.7< z <2.4
z >2.4
Quiescent
M20
z <1.7
1.7< z <2.4
z >2.4
Star-forming
Histogram
M20
z <1.7
1.7< z <2.4
z >2.4
Star-forming
M20

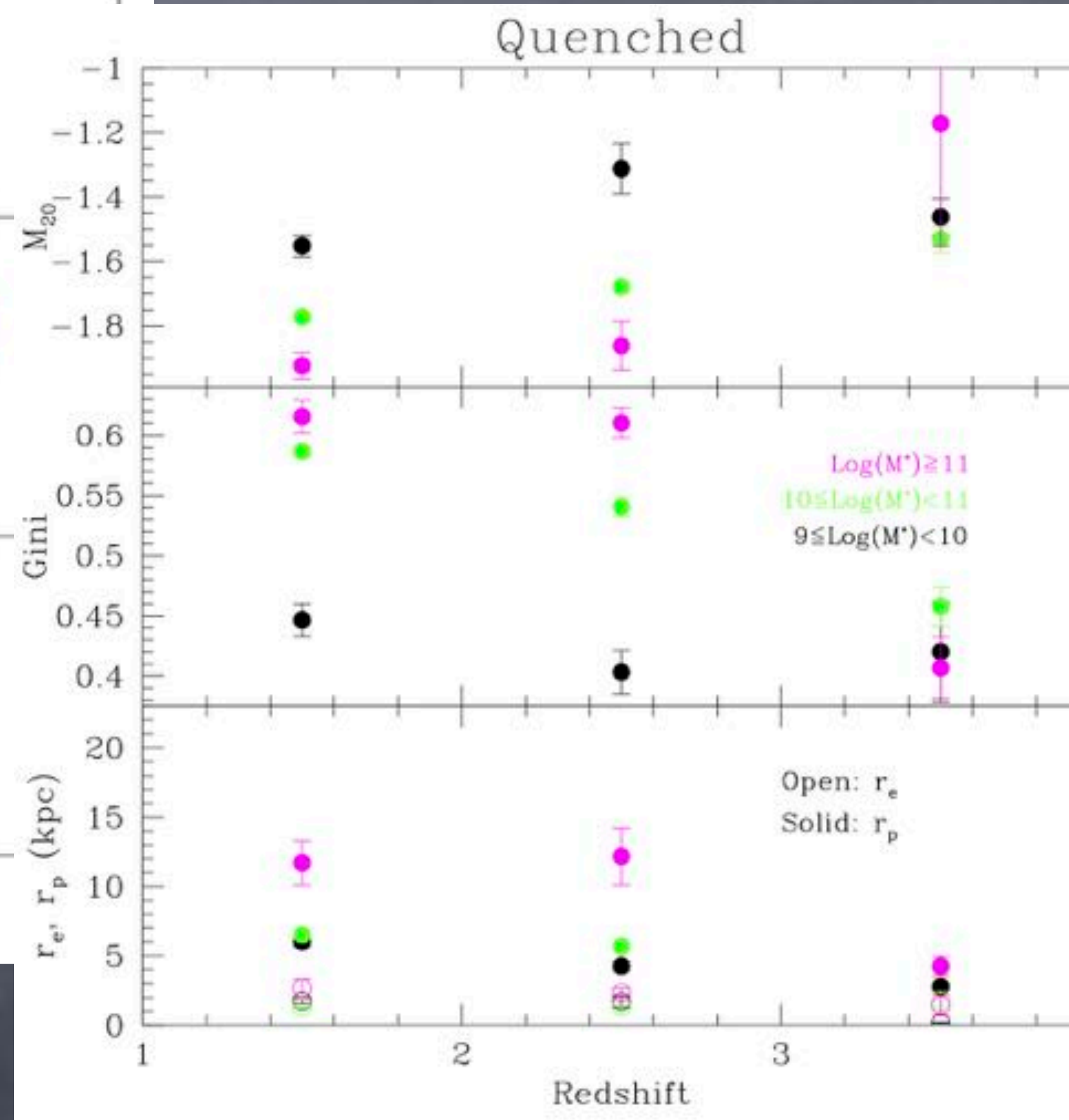
The cumulative distribution of M_{20}

Mass-dependent evolution with redshift



More Nucleated ← → Less Nucleated


Star−Forming
M_{20}
Gini
Log(M*)≧11
10≦Log(M*)<11
9≦Log(M*)<10
r_e, r_p (kpc)
Open: r_e
Solid: r_p
Redshift


Quenched
M_{20}
Gini
Log(M*)≧11
10≦Log(M*)<11
9≦Log(M*)<10
r_e, r_p (kpc)
Open: r_e
Solid: r_p
Redshift

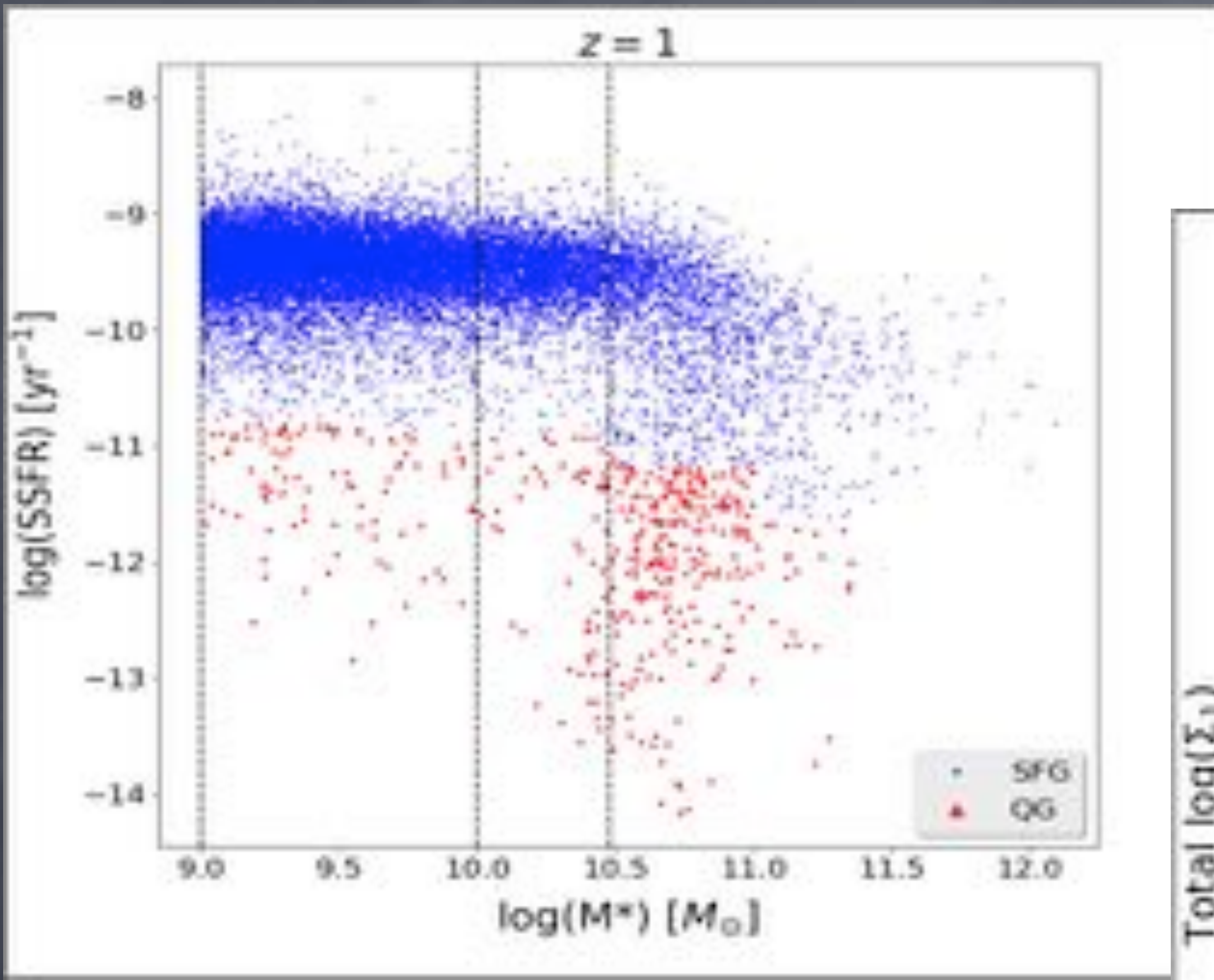
We carefully considered redshift-dependent bias (see Lotz+ 04, 06; Peth+15):

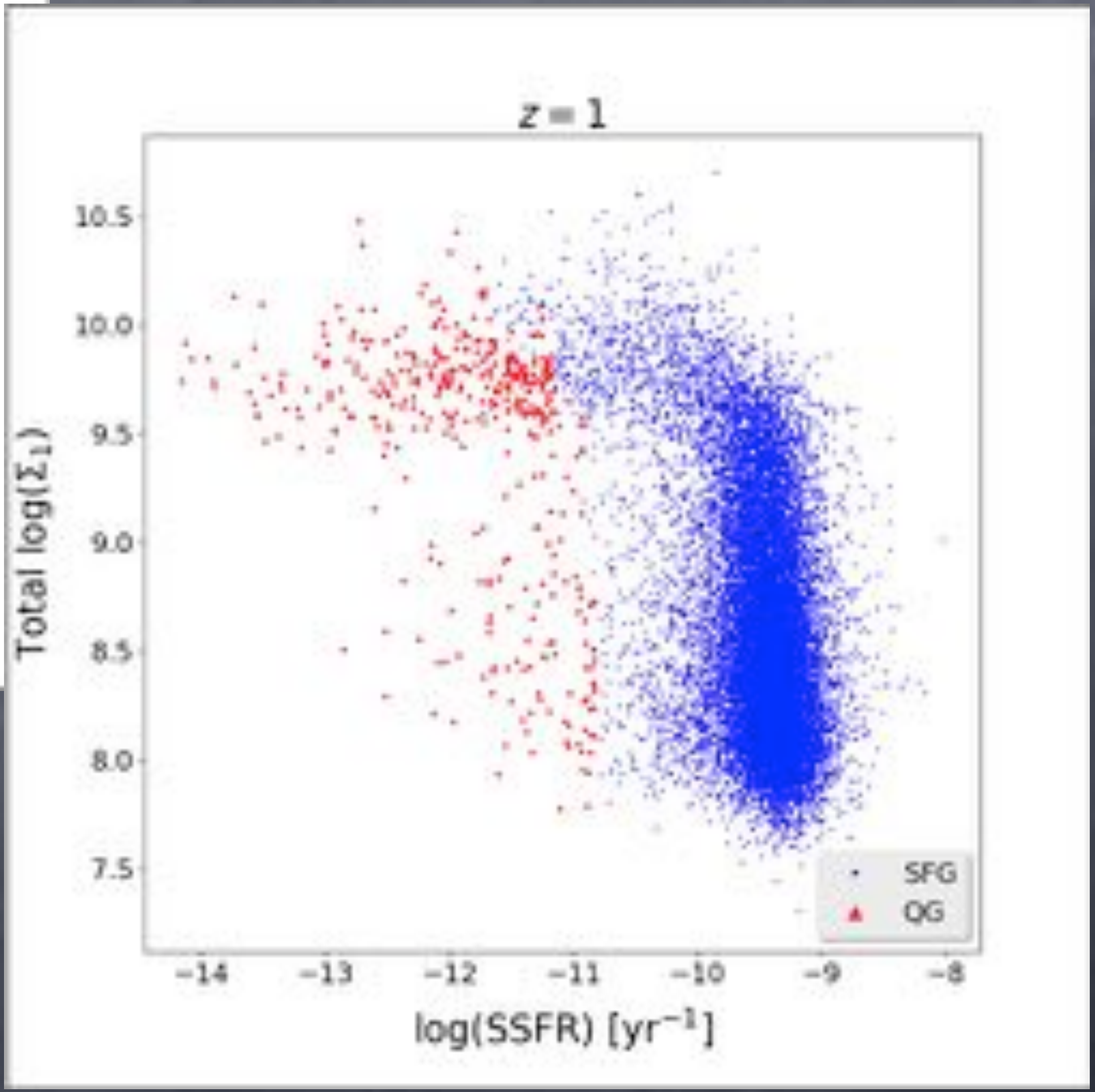
1. It is not wavelength-dependent morphology, because that would go the opposite way: galaxies are more nucleated and compact at bluer wavelengths
2. It is not an angular resolution effect because:
   ① It gets stronger for brighter galaxies, which are larger
   ② It goes the opposite direction (limited 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 consistent with that of M_{20}

What are we seeing? We turned to IllustrisTNG simulations for physical insight

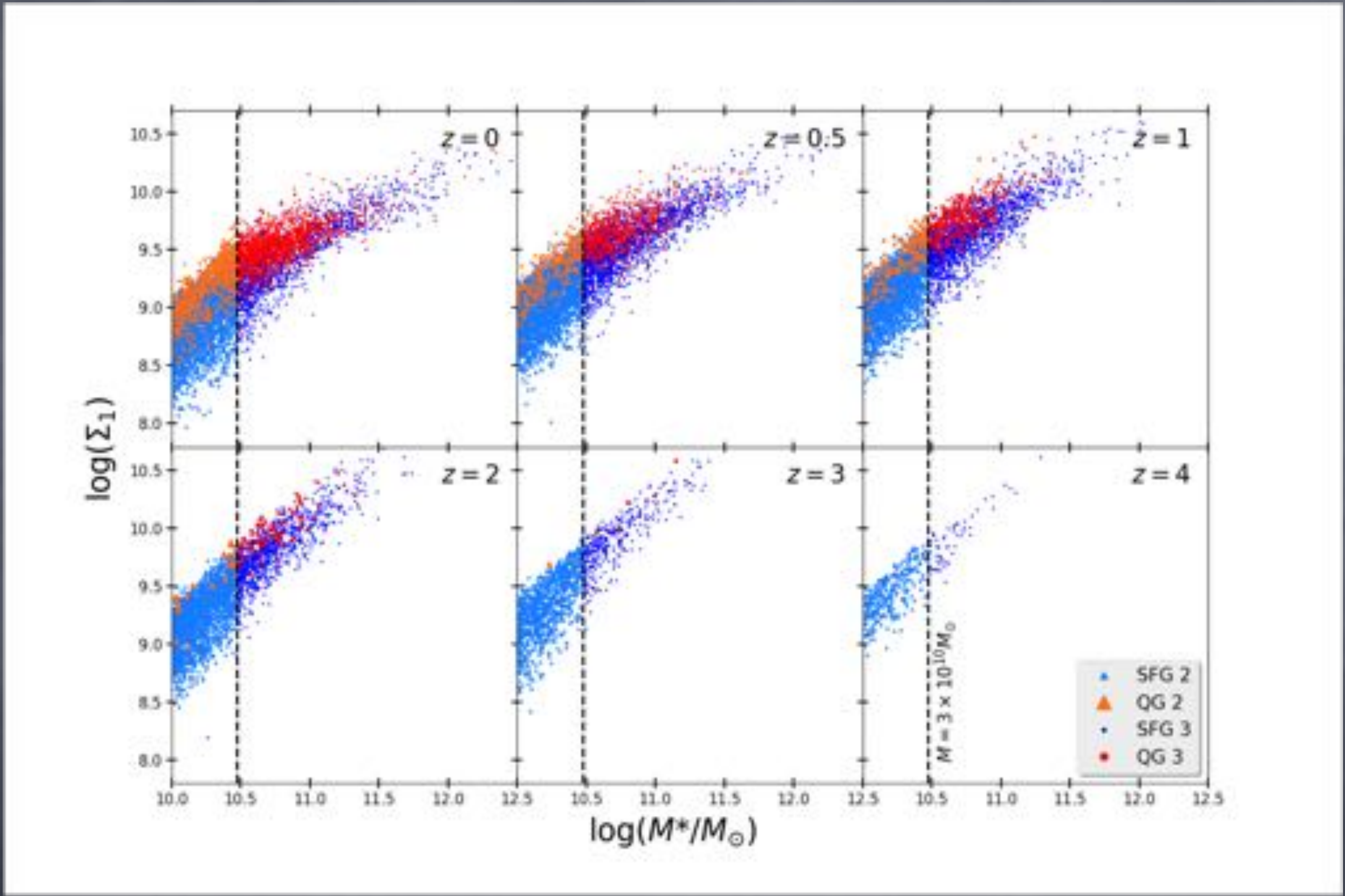
- We see the rest-frame light at λ>4000 Å, the bulk of the stellar mass: the non-dissipative baryon component
- DM matter should behave like the stars
- As they grow in size and mass, galaxies constantly increase **mass inequality**, i.e. re-arrange their mass by placing it in fewer and fewer volume elements, by becoming more concentrated and nucleated.
- IMPORTANT: we need to establish if the "growth of inequality" continues after quenching: if not driven by dissipative gas accretion, it could signal evolution of DM (relaxation?)
- Not clear what drives this process. Also, not clear how it drives f_{DM}
- Two time-scales should regulate variations of the gravitational potential:
  - Fast: dissipative accretion of gas accretion. Ends at quenching
  - Slow: relaxation of non-dissipative component. Driven by dynamical friction?

IllustrisTNG simulations: statistics and resolution



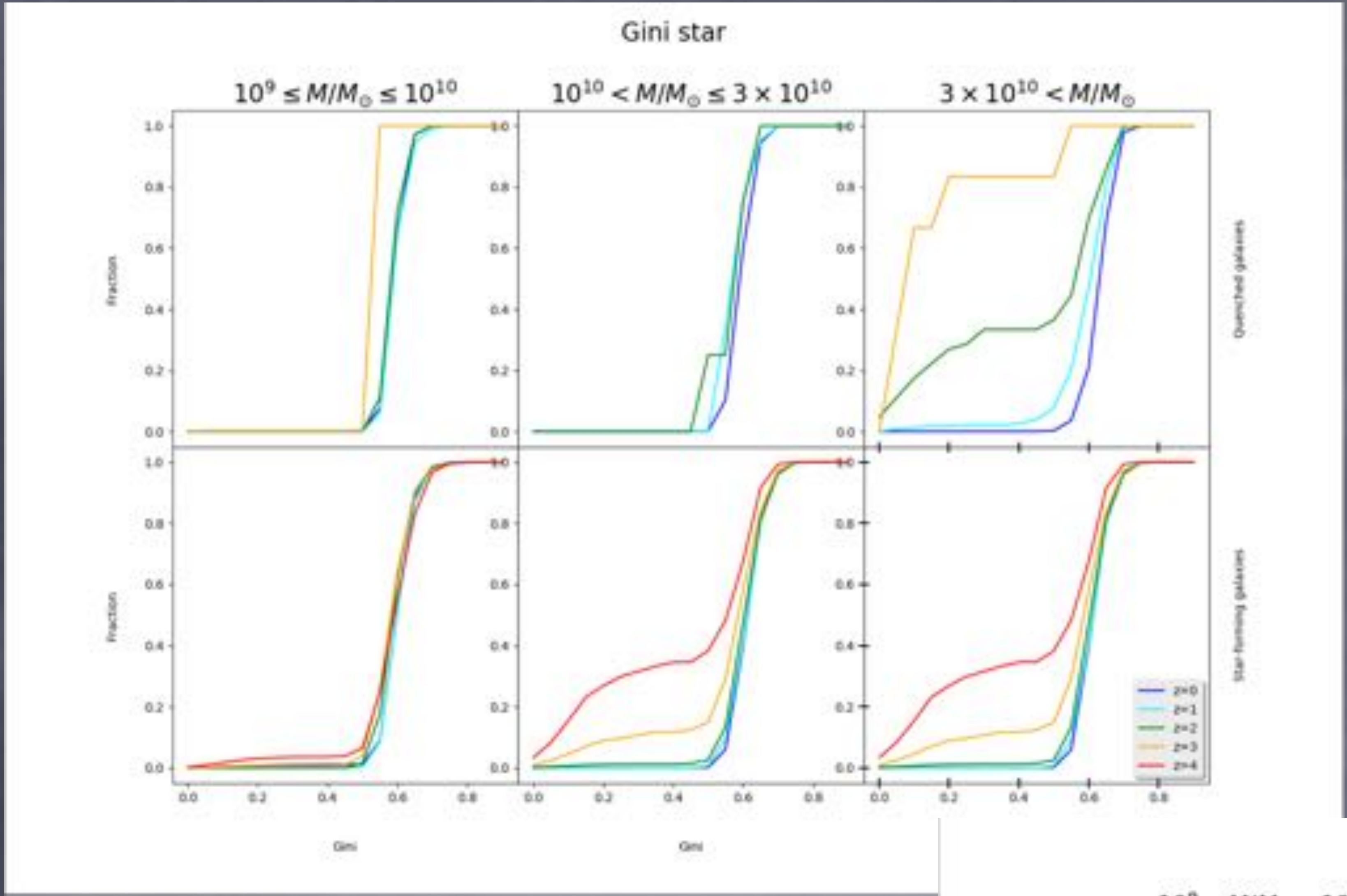


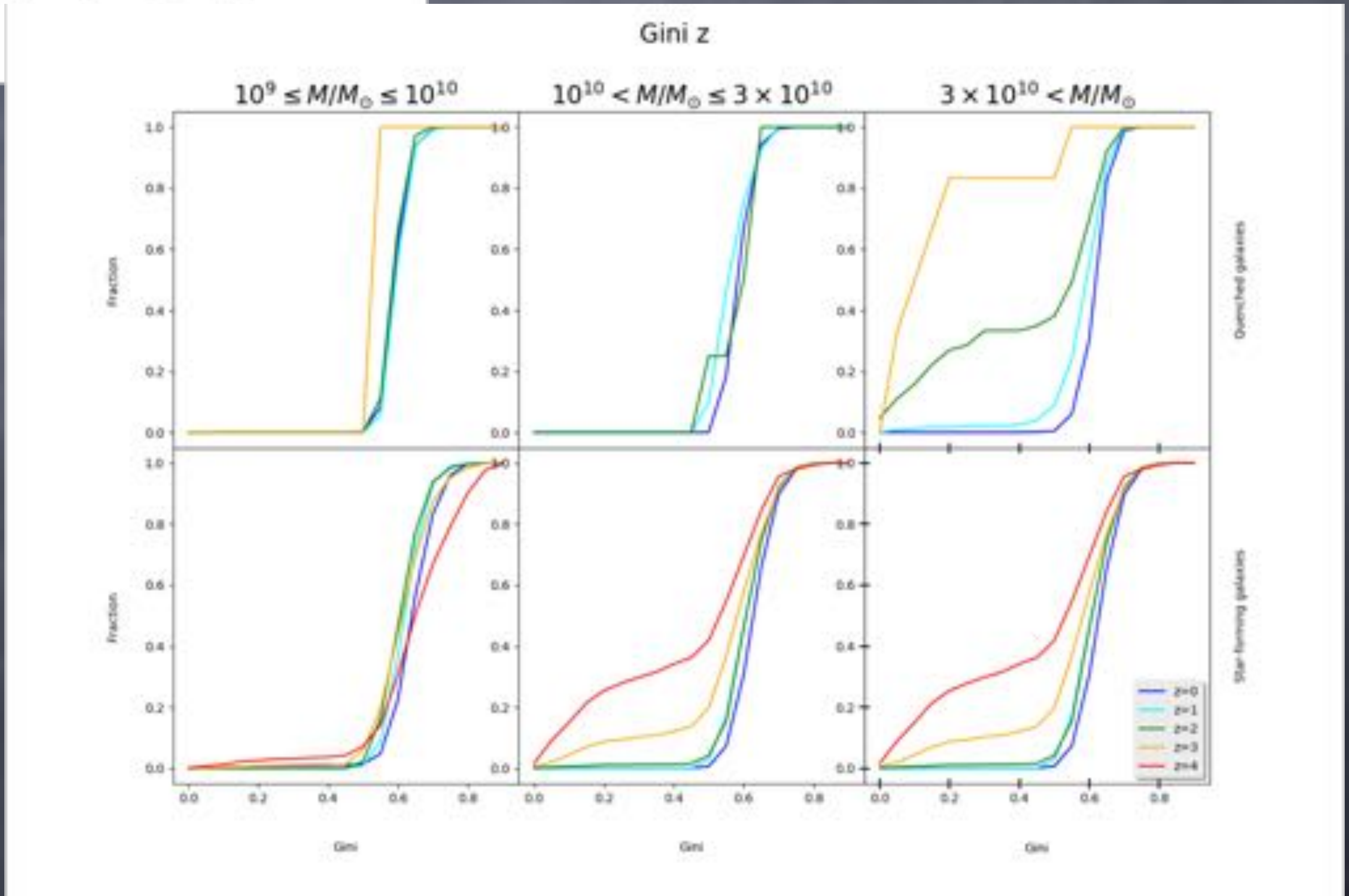
Carman, EDO, MG +19



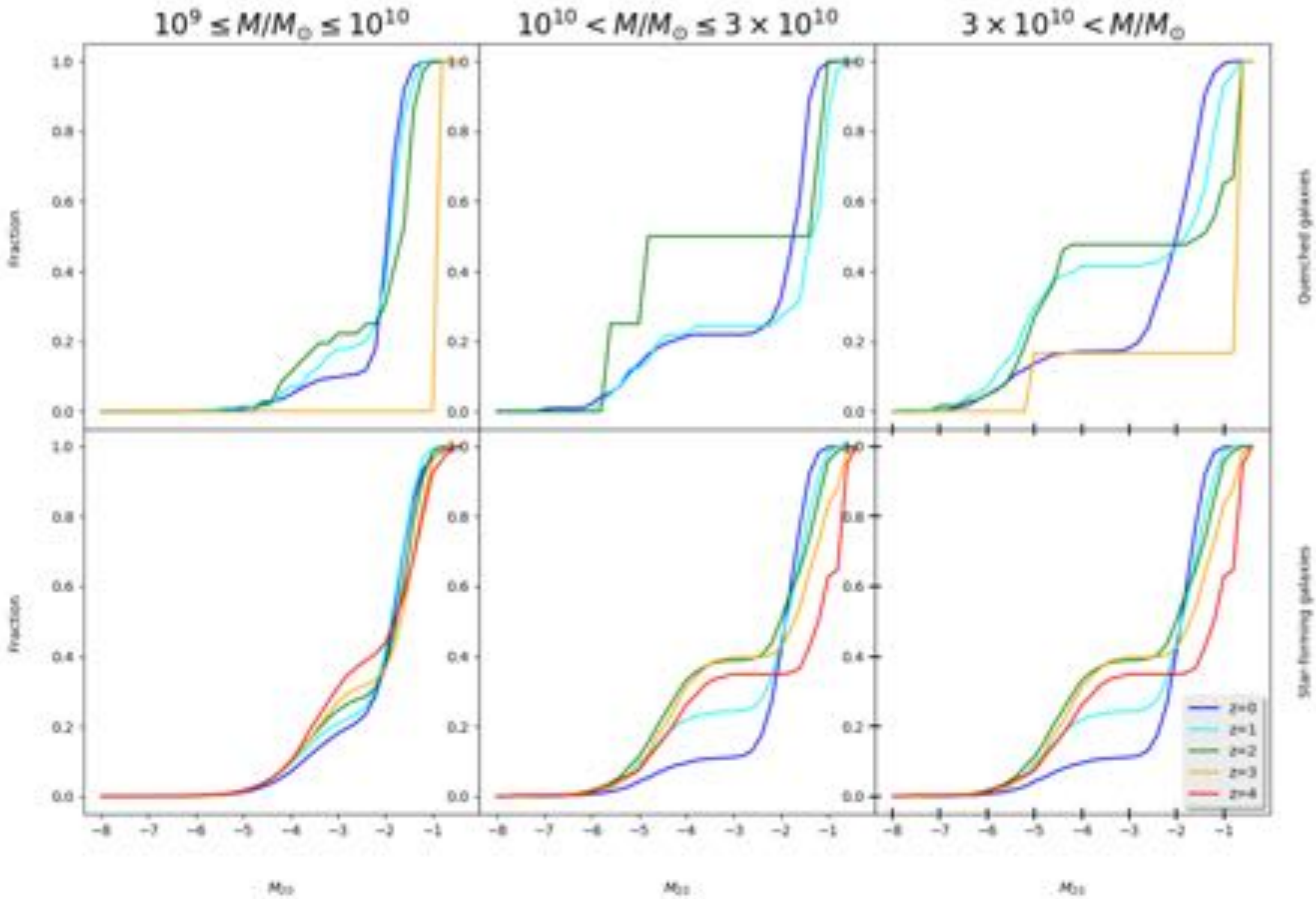
Carman, EDO, MG +19

The same effects is observd in the IllustrisTMG simulations

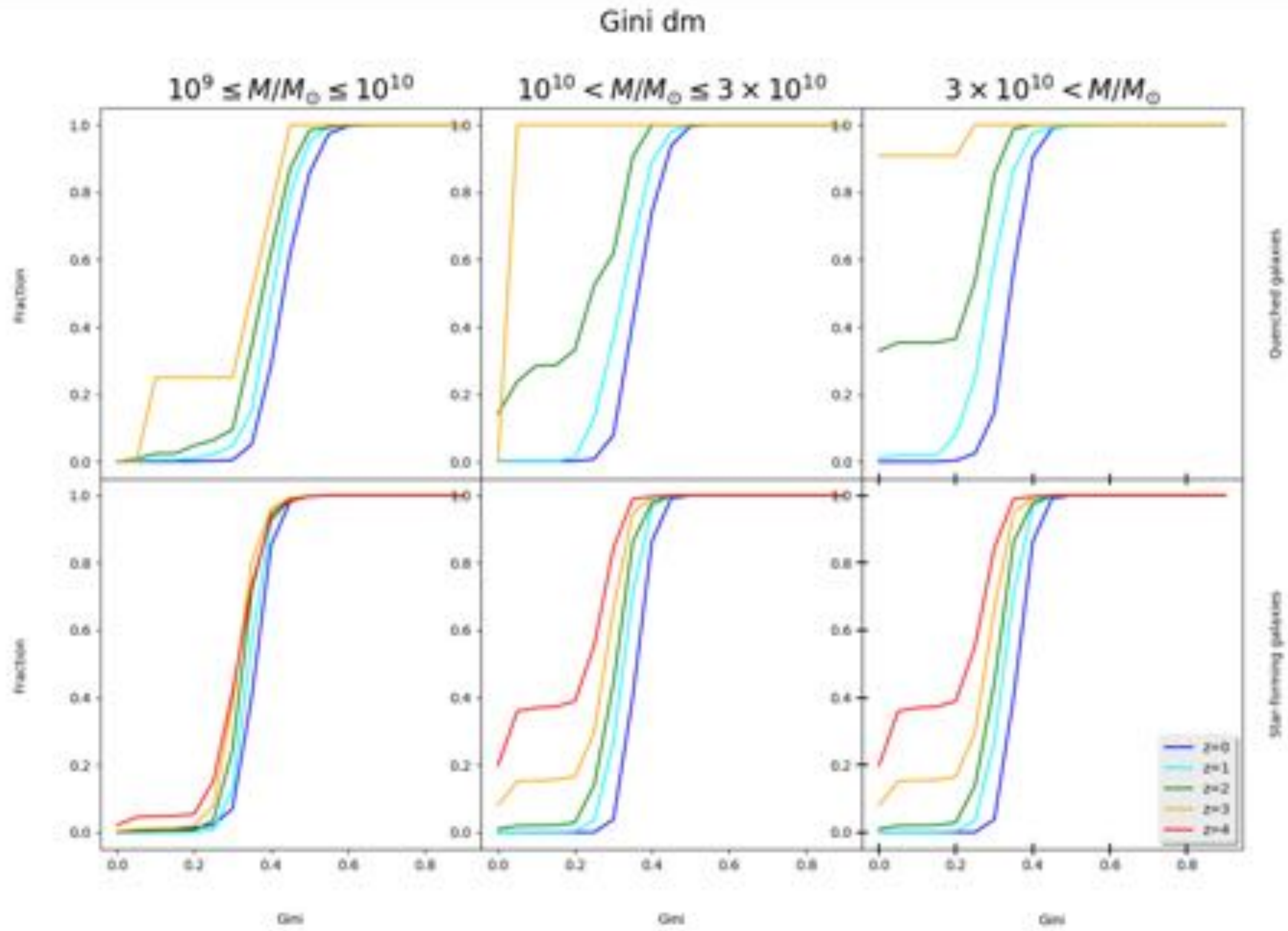




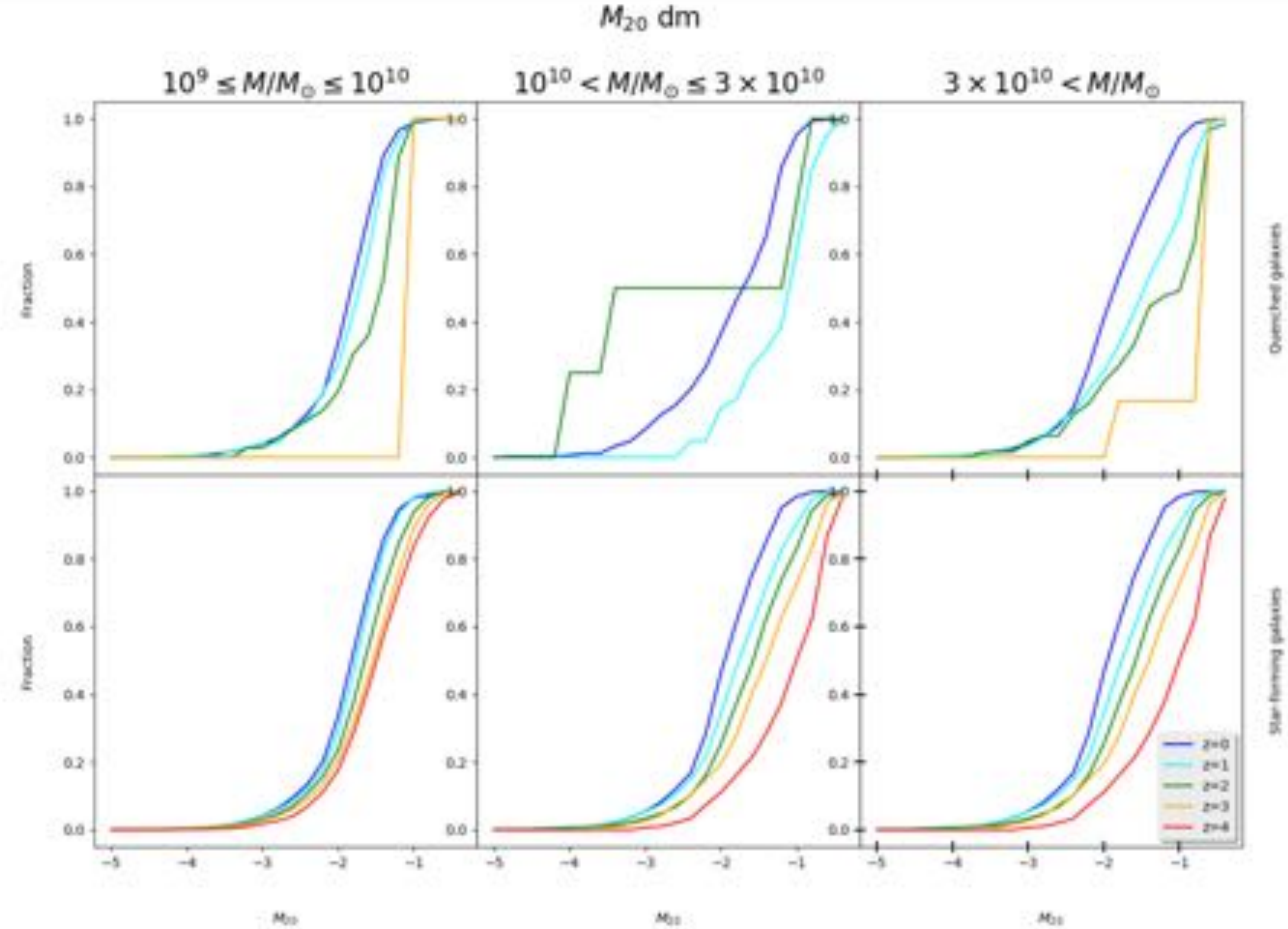
M_{20} z



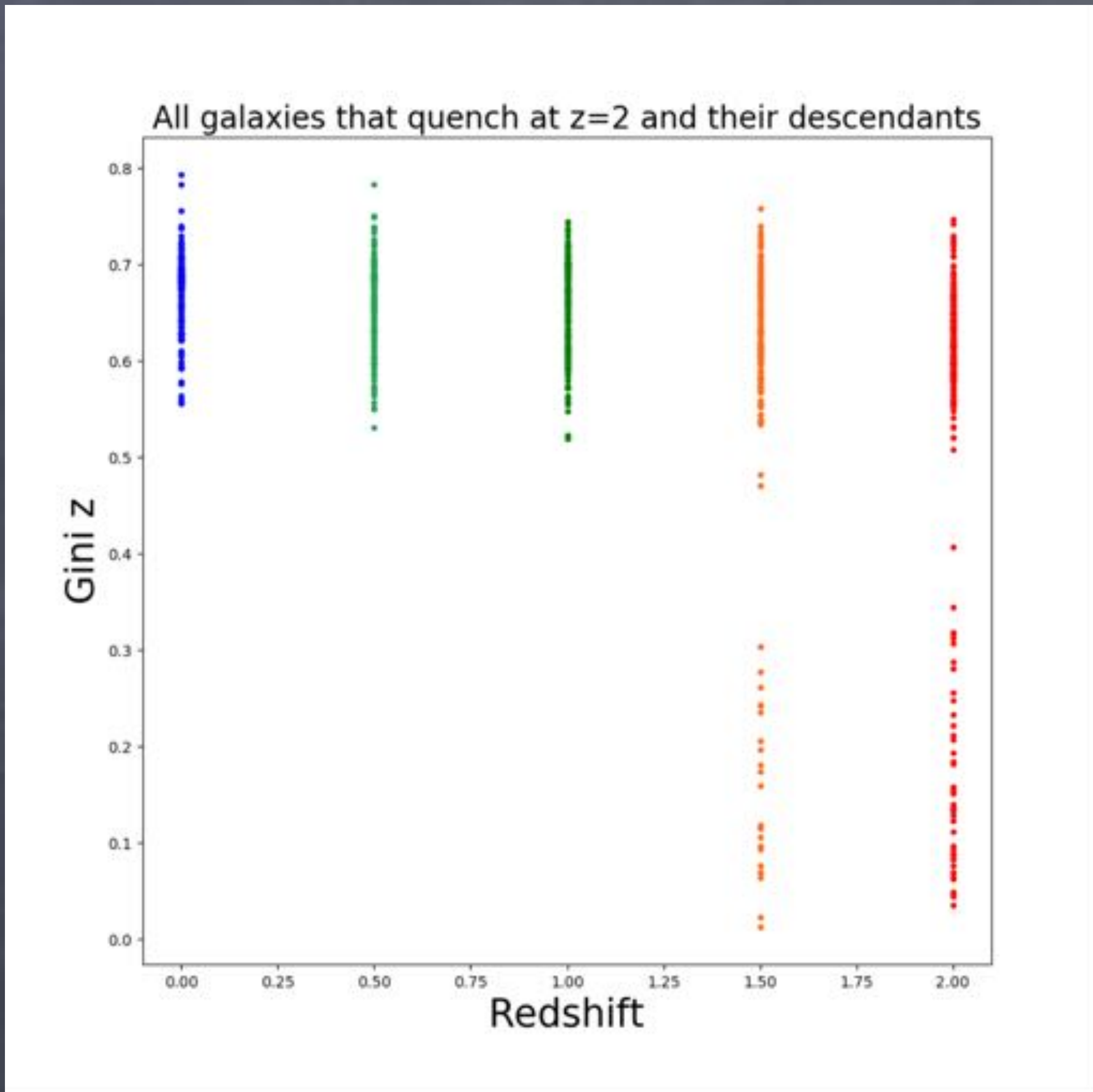
$10^9 \leq M/M_\odot \leq 10^{10}$
$10^{10} < M/M_\odot \leq 3 \times 10^{10}$
$3 \times 10^{10} < M/M_\odot$
Fraction
Quenched galaxies
Star-forming galaxies
z=0
z=1
z=2
z=3
z=4



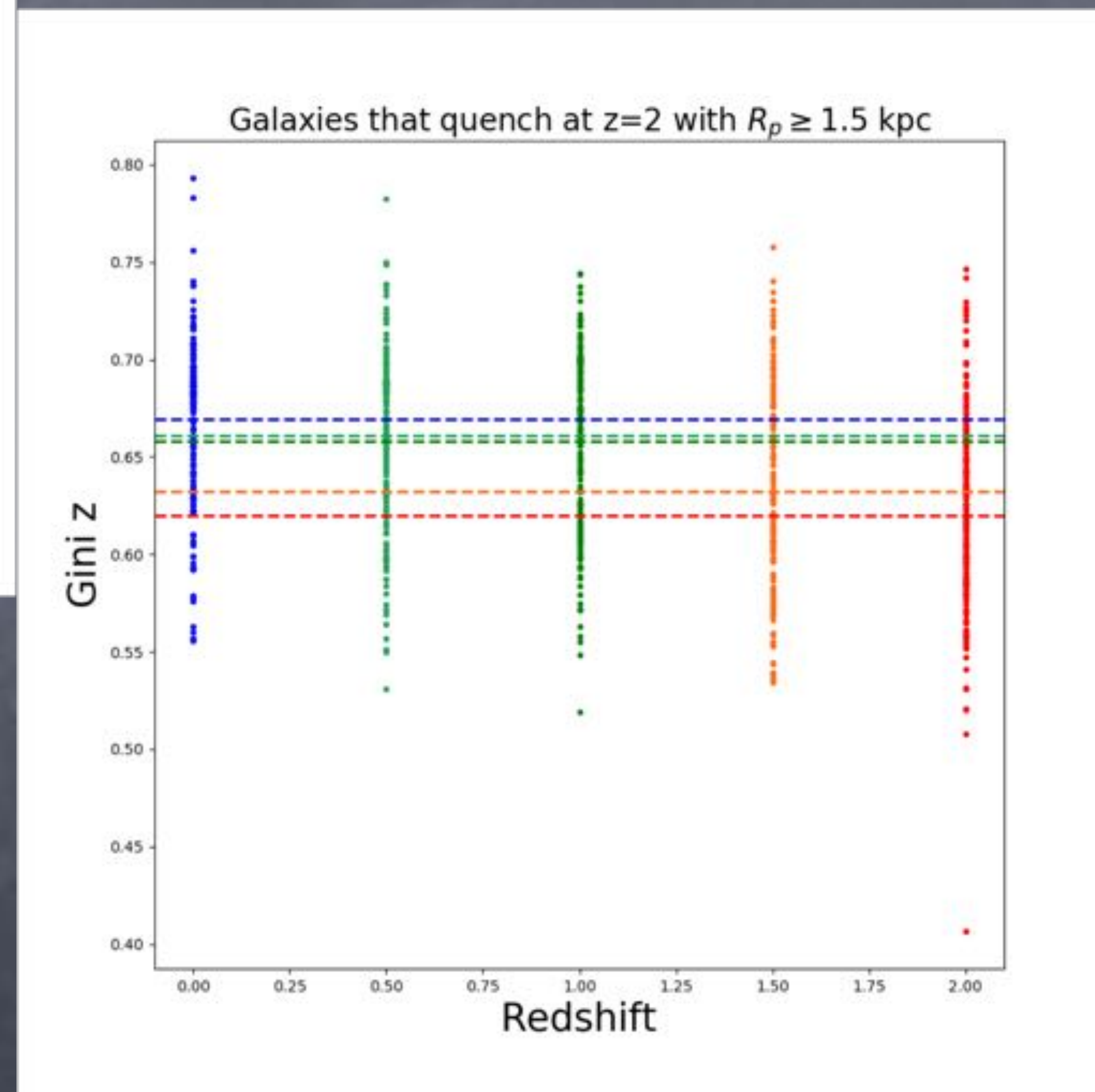
Gini dm
$10^9 \leq M/M_\odot \leq 10^{10}$
$10^{10} < M/M_\odot \leq 3 \times 10^{10}$
$3 \times 10^{10} < M/M_\odot$
Fraction
Quenched galaxies
Star forming galaxies
Gini
z=0
z=1
z=2
z=3
z=4



M20 dm
10^9 ≤ M/M☉ ≤ 10^10
10^10 < M/M☉ ≤ 3 × 10^10
3 × 10^10 < M/M☉
Fraction
Quenched galaxies
Star forming galaxies
z=0
z=1
z=2
z=3
z=4
M20



Quenched galaxies seem to be following, qualitatively, the same trend in the simulations

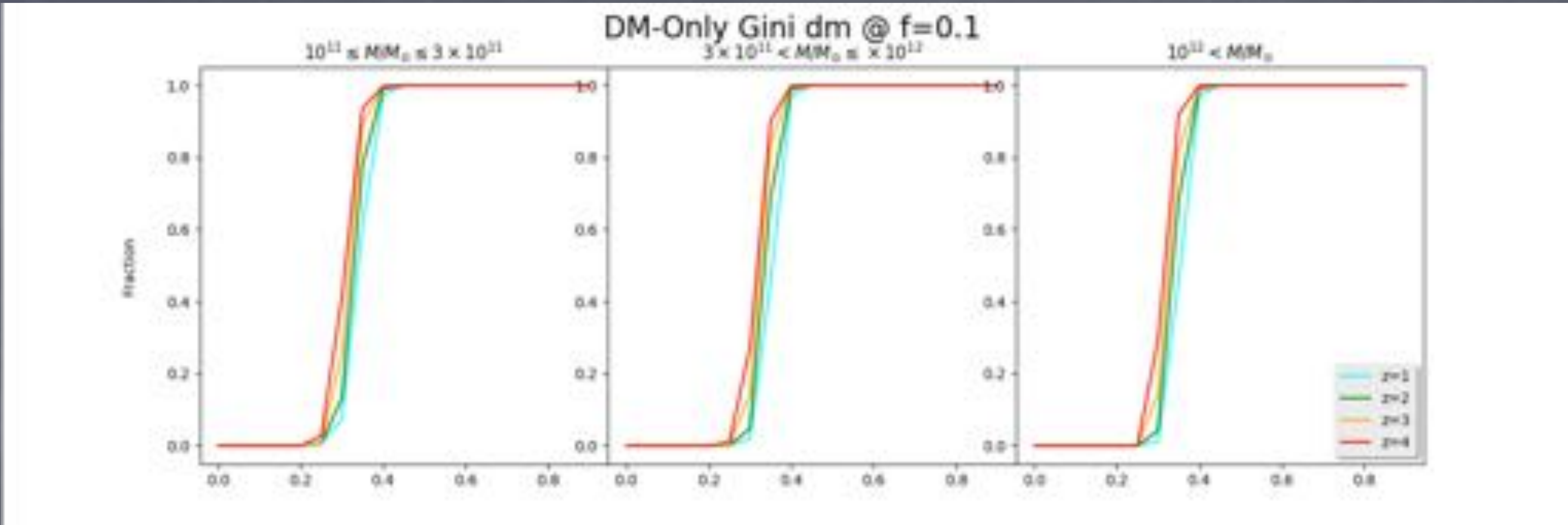


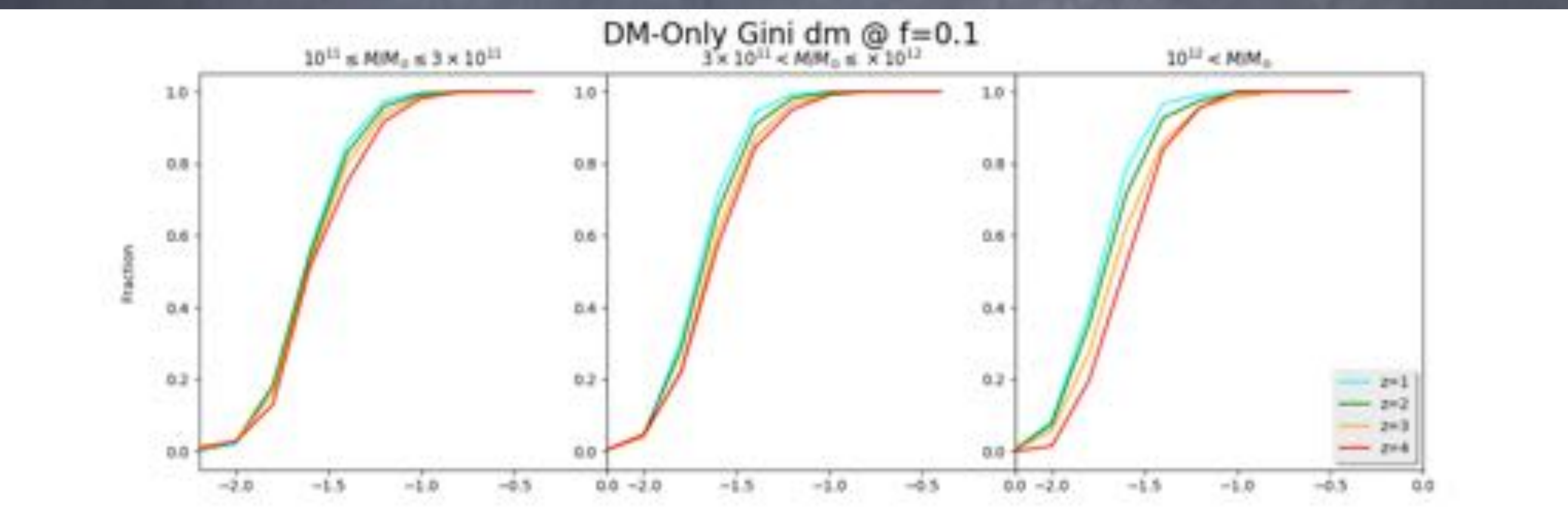
We need to understand what happens in the real galaxies...

The consequences are important: DM relaxation time, which depends on the interaction cross-section...

- At least qualitatively, the same behavior is observed in the simulations
- Both the stars and the DM follow the same general trend

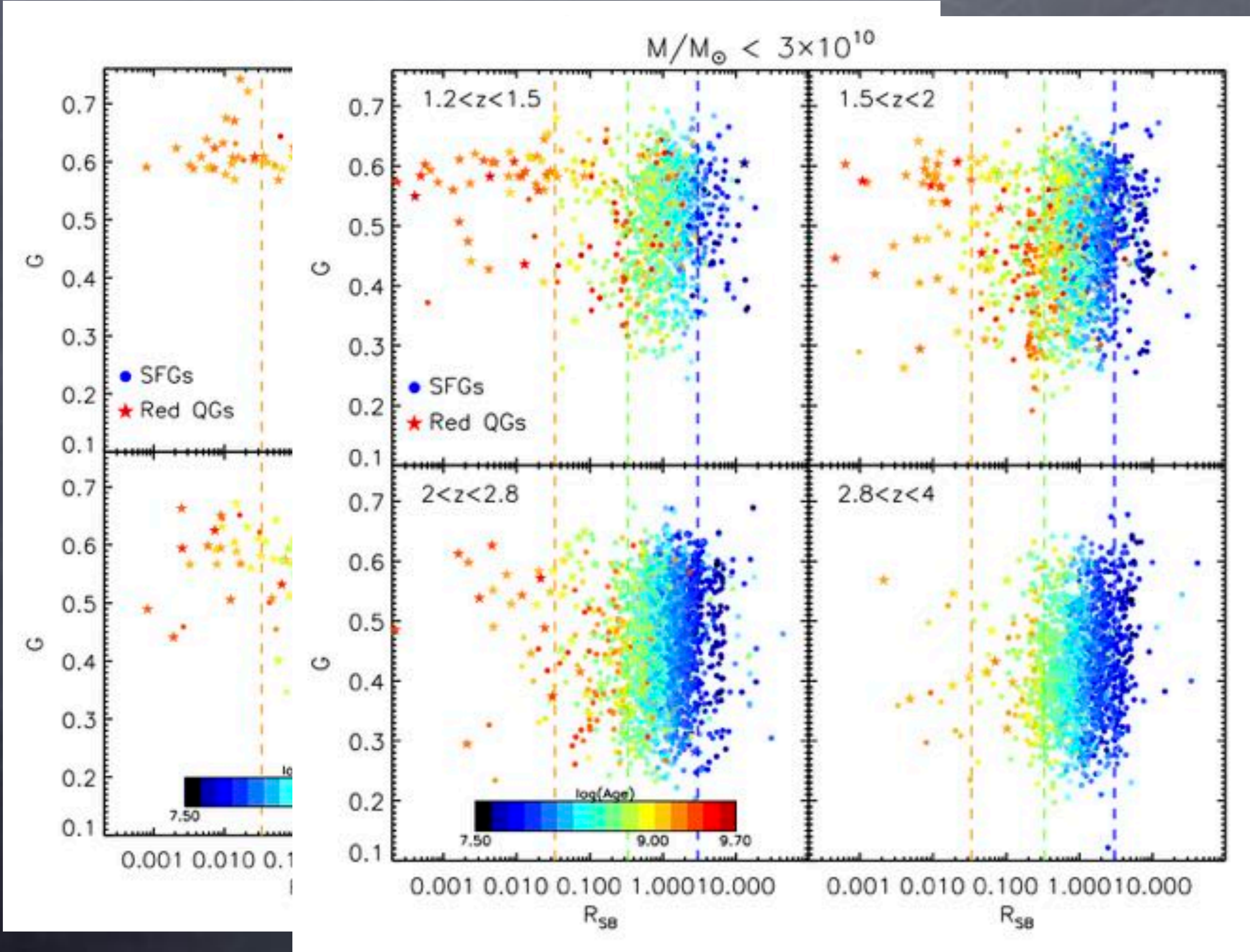
- But... in simulations with DM only, no such effect is observed
  - **<u>The effect appears to be due to the baryons: dissipative gas accretion</u>**

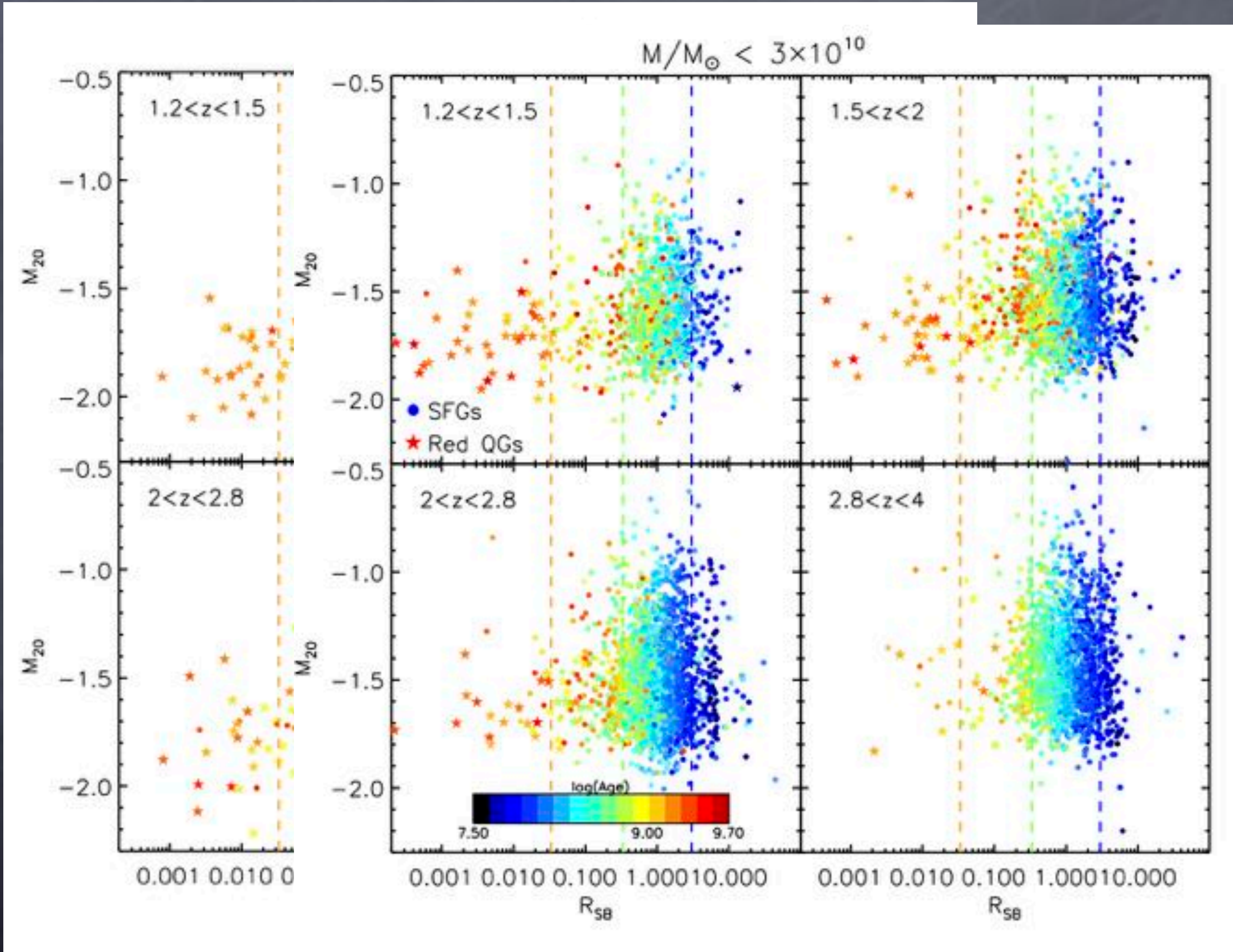

DM-Only Gini dm @ f=0.1
Fraction
z=1
z=2
z=3
z=4


DM-Only Gini dm @ f=0.1
Fraction
z=1
z=2
z=3
z=4

Summarizing these results:

1. Σ_1: the distribution is the same at any epoch
   - a local diagnostic (a "clock", see Barro+17) that reflects the dissipative history of galaxies (baryons) as they evolve (fast time scale)
2. Gini and M_{20}: their distribution changes continuously with redshift, implying large-scale transformations:
   - Gini and M_{20} contains information on the overall distribution of light (mass).
   - Gas accretion likely the primary driver (fast time scale)
   - It causes changes to the overall gravitational potential (DM and stars) of galaxies (slower time scale?)
     - ➢ Could the relaxation be driving the transformation from disk morphology and dynamics into spheroidal ones?


M/M⊙ < 3×10^10
1.2<z<1.5
1.5<z<2
2<z<2.8
2.8<z<4
SFGs
Red QGs
log(Age)
7.50
9.00
9.70
G
R_SB



M/M$_\odot$ < 3×10^{10}
1.2<z<1.5
1.5<z<2
2<z<2.8
2.8<z<4
SFGs
Red QGs
M$_{20}$
R$_{SB}$
log(Age)
7.50
9.00
9.70

Inner gravitational potential evolution: Accretion of satellites (non dissipative) and gas exchanges (dissipative)…

Star formation efficiency ϵ at various scales (at z=0):

$\langle r \rangle \approx$ 20 pc, $\epsilon_6 \approx 0.35 - 0.7\%$

Calzetti et al. 2015; Turner et al. 2015

$\langle r \rangle \approx$ 1.3 kpc, $\epsilon_{ff} \approx 0.01 - 0.1\%$

Utomo et ql. 2018; Leroy et al. 2017

$\langle r \rangle \approx$ 30 kpc, $\epsilon_8 \approx 0.02\%$

Kennicutt & Evans 2012; Utomo et ql. 2018; Leroy et al. 2017

If right, only a small amount of gas converted into stars during each episode of star formation: forming 100 $M_\odot$ of stars requires 5x as much gas! Where is it?

Gas exchanges (in, out, phase change) are crucial! (e.g. Werk et al 2014)

SFE=SFR/M_{gas} (different from ϵ) can also increase with redshift (see Genzel+ 2015; Daddi+ 2015; Zenella+ 2017; Combes+ 2017; Schinnerer+ 2017…)

Feedback and gas exchanges

- Outflows:
  1. Latest measures in massive SF galaxies at $z \approx 2$ suggest winds are bound, moderate mass-loading factors, 0.1 – 0.2, for both
     1. Hot phase (e.g. Forster-Schreieber et al. 2018)
     2. Cold phase (e.g. Tacconi et al. 2018)
  2. AGN seems to be driving winds to $\gtrsim$10 kpc, with much larger mass-loading factors during quenching phase
     1. 0.5 – 3.4, dominated by cold phase (Herrera-Camus et al. 2018)

- Inflows:
  1. Very hard to measure directly…
  2. Gas accretion history vs SFH
     1. do galaxies ever evolve as closed-box systems (aka what is ϵ_9 during and at the end of the MS, see Schreiber+ 2017?)
     2. How does the baryon fraction evolve at $r \gtrsim r_e$?

To further develop: Structure and Quenching

- Growth of structures releases gravitation energy:
- (5×10^{59} erg from $z \approx 2$ to 1 for a $10^{12}\ M_\odot$ halo);
- ½ of it goes into heat (VT)
- This energy should help quenching or even do the job
  - **SF, AGN, Gravity, all contribute ≈the same (e.g. Heckman+ 1990)**
- Provides a natural "mass quenching" from everywhere inside the galaxy
  - Heats gas (Johnasson, Naab & Ostriker 2009)
  - Prevents gas from cooling (see Cantalupo 2010)

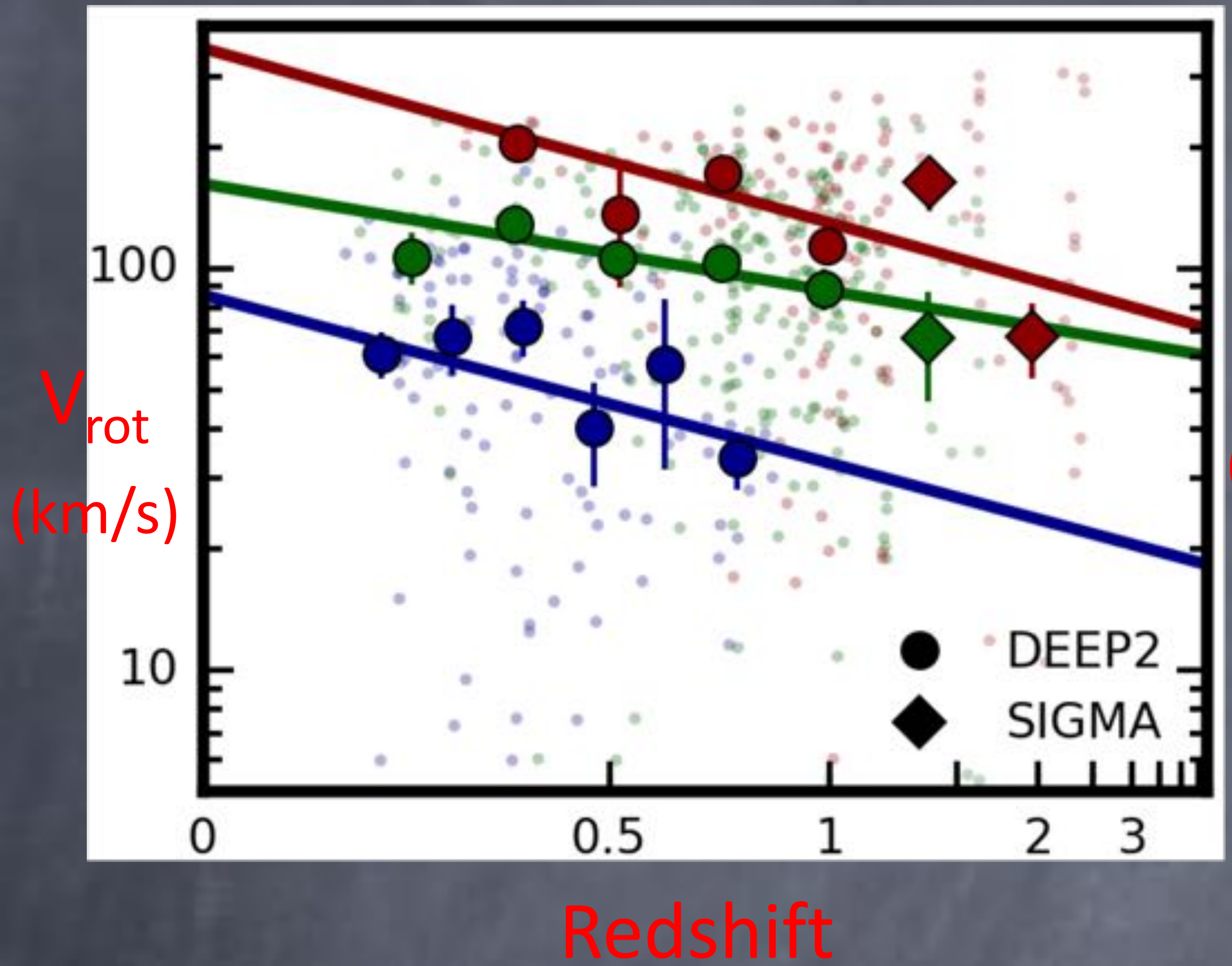
$$G = \frac{1}{2\,n(n-1)\,\rho} \sum_{i,j} |\rho_i - \rho_j|$$

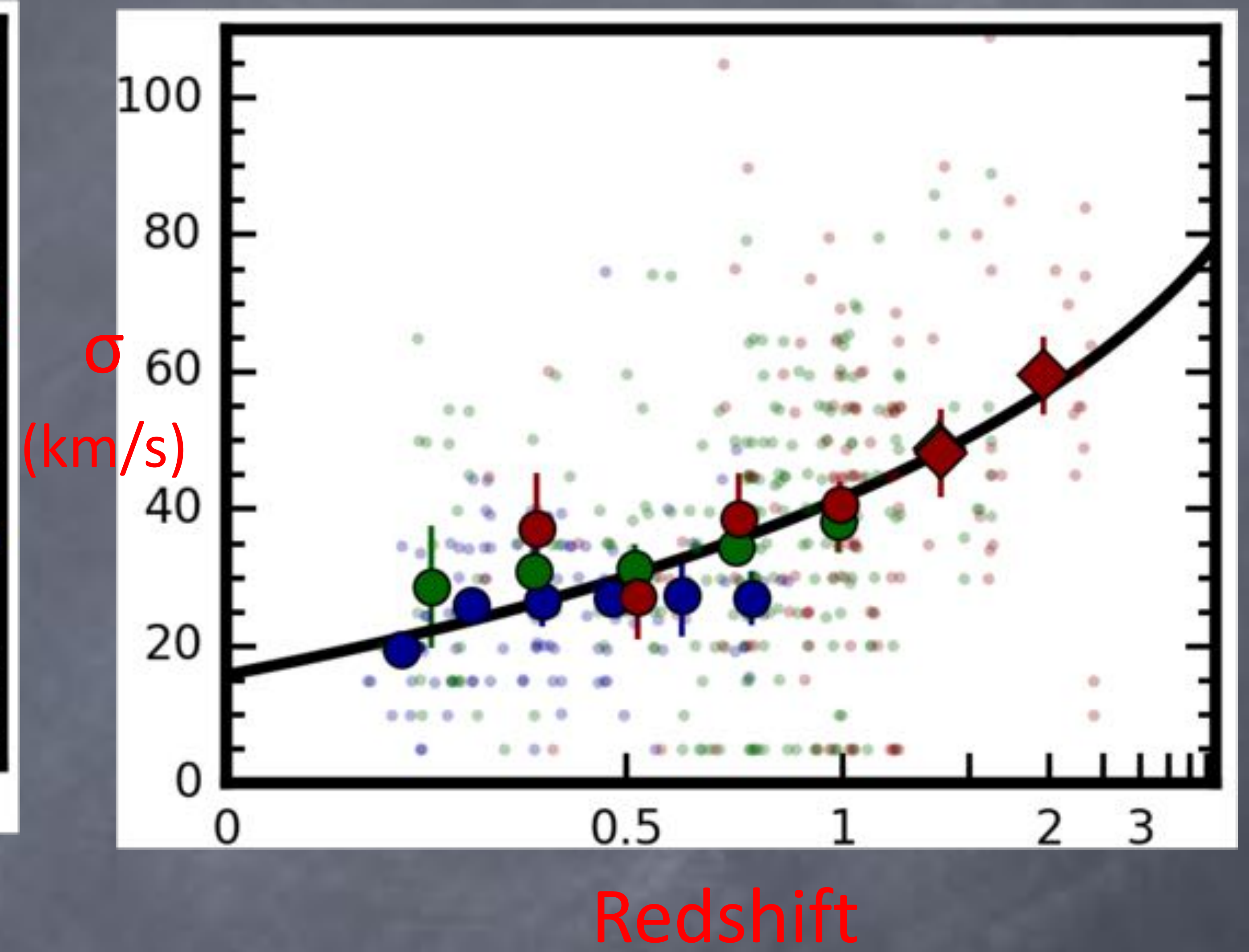
$$\frac{dG}{dt} \propto \nabla^2\left(\frac{d\phi_G}{dt}\right) \propto \frac{dT}{dt}$$

$$\boxed{\frac{\partial u}{\partial t} - \alpha \nabla^2 u = 0}$$

Heat equation

Dynamical evidence of structural transformations: disk evolution





"Disk Settling" or new disks?

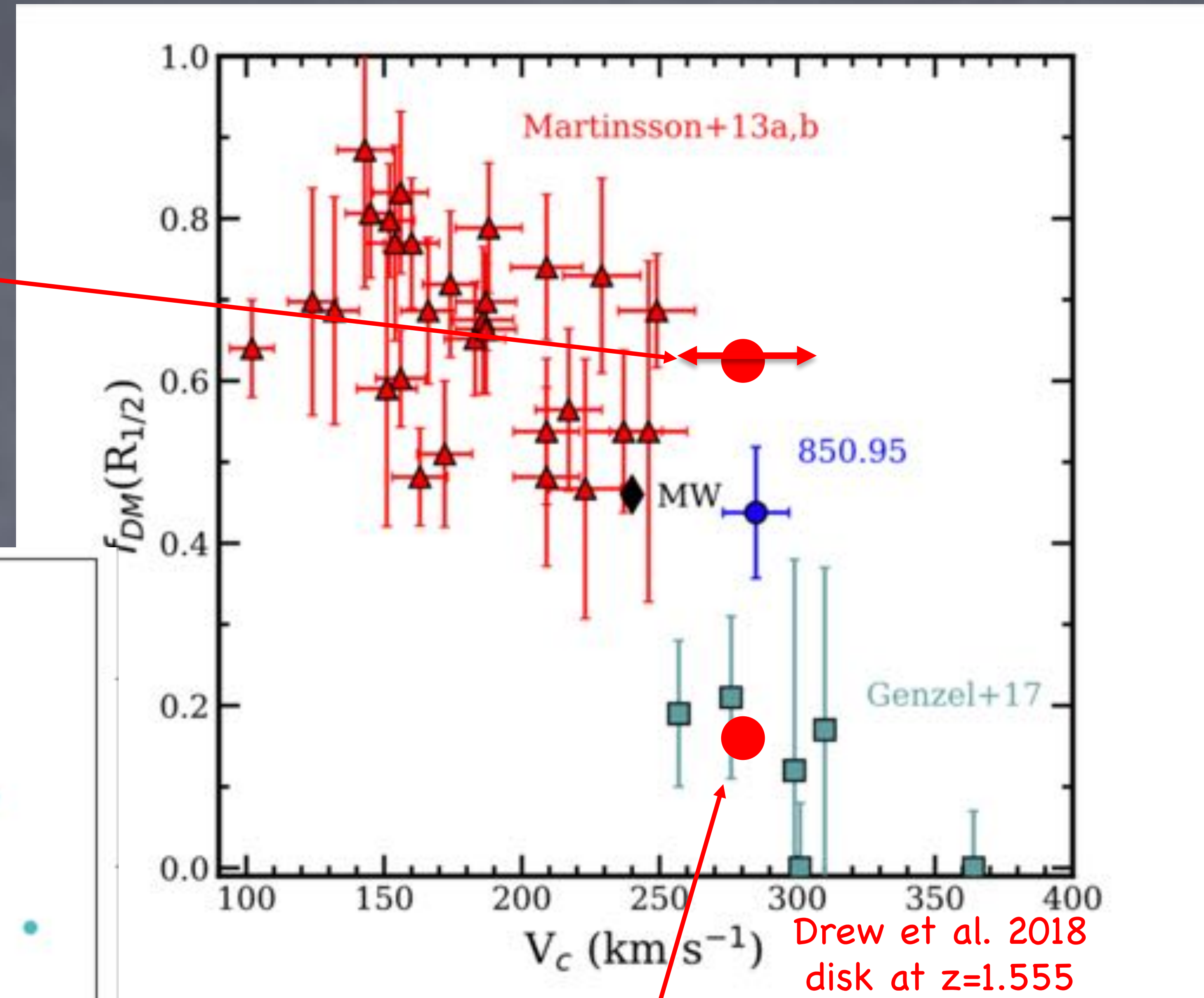
Secular "compactification" of mass distribution? But why σ decreases?

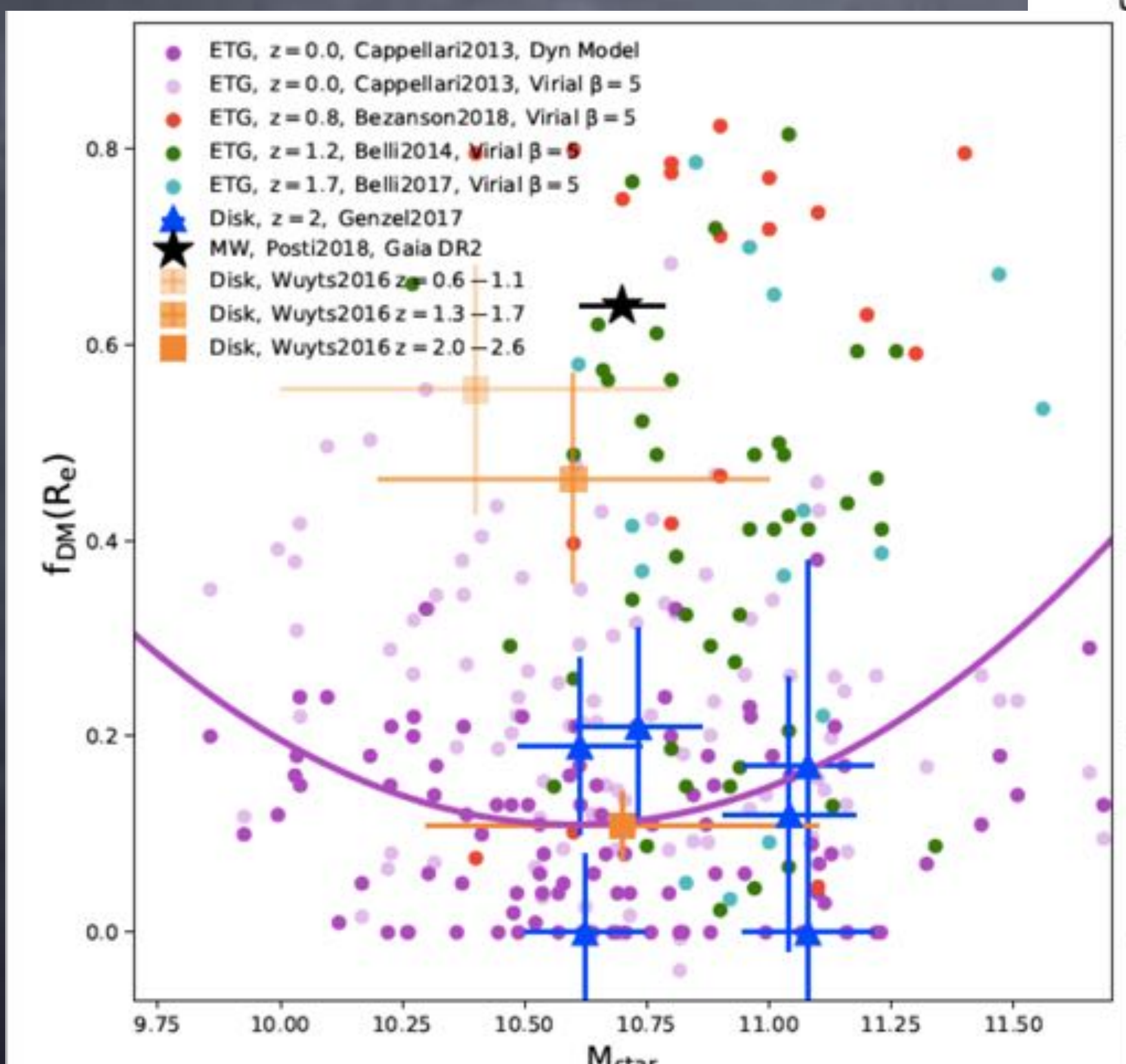
Abundance matched galaxy populations (Moster et al. 2013)

Kassin et al. 2012

Simons, Kassin et al. 2017

Tiley et al. 2018:
$f_{DM} \approx 0.6$ if I do
normalize it
differently…





Disk at z=1.4, from CO and Hα
f_{DM}=0.18-/+0.05
V_{rot}=296 km/s
Übler et al. 2018

Ji et al. 2019

Conclusions

1. **Galaxies transform their structure (and dynamics) OVER LARGE SCALES as they evolve and go through quenching:**
    1. They develop a high-density central structure, r≈1 kpc
    2. they re-adjust their structure, regardless of the density of the central region, over large scales, r ≈ 10 kpc, by increasing mass inequality:
        1. more mass in volume elements where there is already more mass than average or by increasing the number of those with less mass than average, or both
    3. Effect is mass dependent: more massive galaxies evolve more
2. **The mass-inequality growth continue? after quenching?**
    1. Different "dissipation" time scales of gas and of DM+stars: gas dynamics vs. dynamical friction?
3. **Quenching happens as mass inequality grows. The formation of a compact core also happens at the same time:**
    1. <u>Quenching is likely due to a combination of causes: AGN, stars, gravity</u>
        1. Gravitational heating a mechanism to help or even cause quenching (heats gas to 10^5 K: soft X-ray emission likely to destroy coolants, see Cantalupo+ 2010)
    2. Spheroidal morphology might help keep galaxies quenched
4. Lower-mass galaxies are also be found quenched, but larger dispersion of Σ_1, Gini and M_{20} distributions suggest that their evolution and quenching are different (mass vs. environmental)