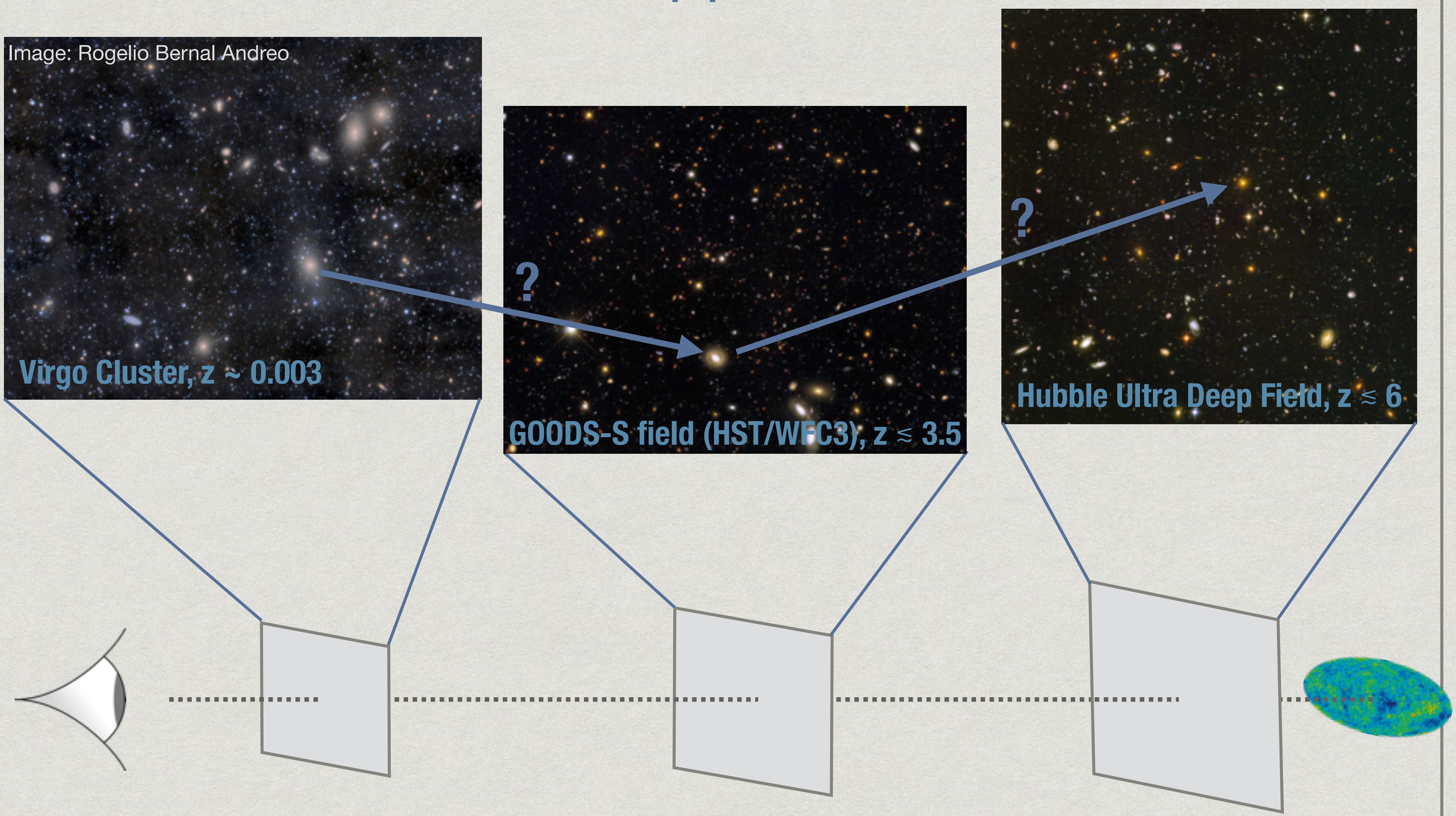
Berkeley TAC seminar
September 2016

The diverse progenitors and descendants of (compact elliptical) galaxies in cosmological simulations

Sarah Wellons
Harvard/CfA

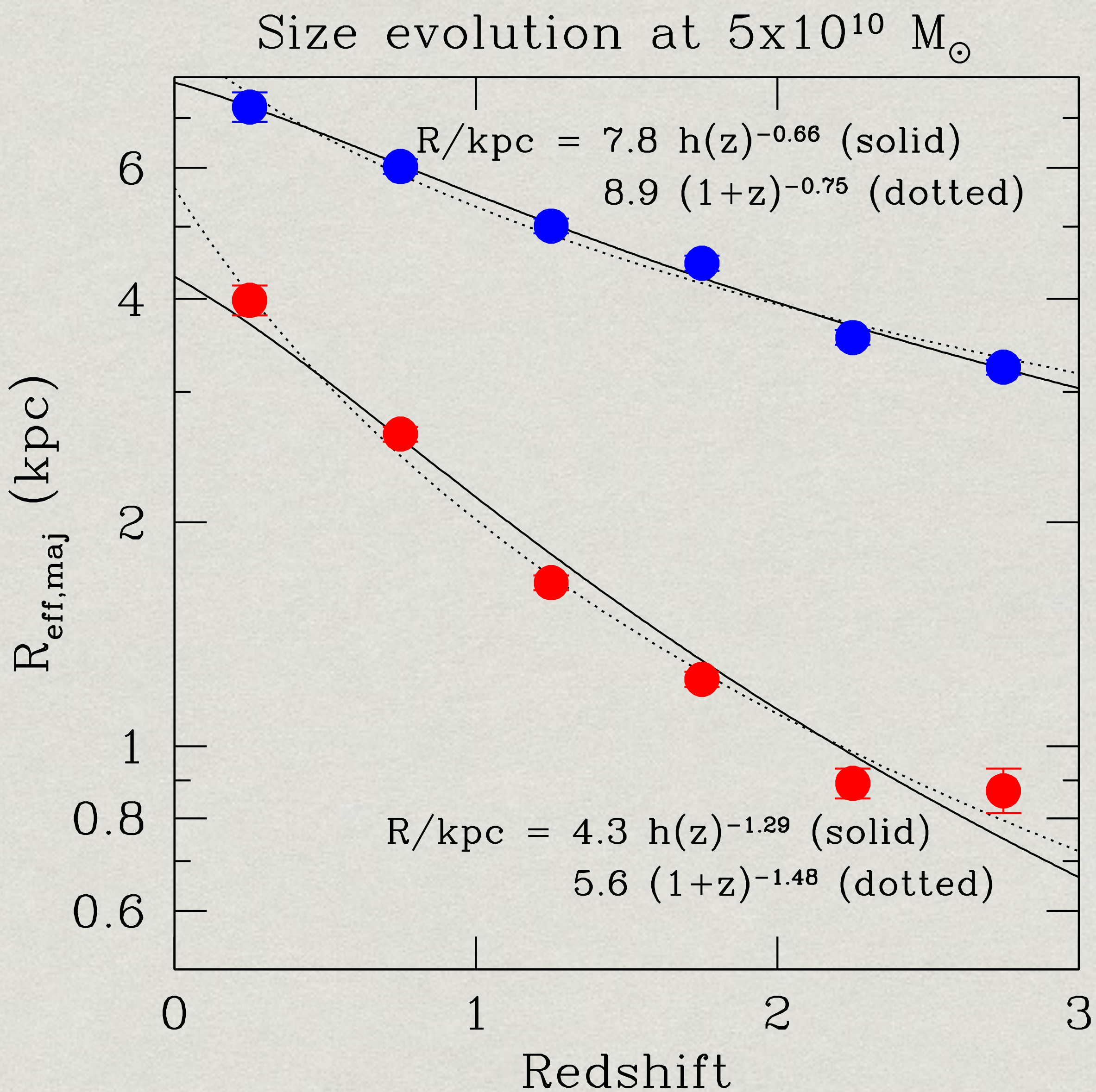
Fundamental challenge in studying galaxy evolution: as an observer, you can't watch it happen

Instead, we have snapshots of galaxy populations at different moments in time, and we have to try to draw connecting/causative lines

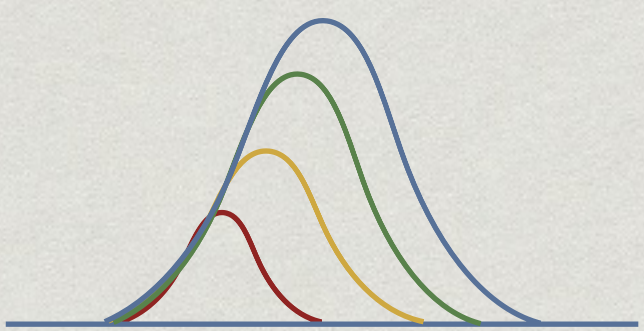


Example: strong evolution in galaxy size with time

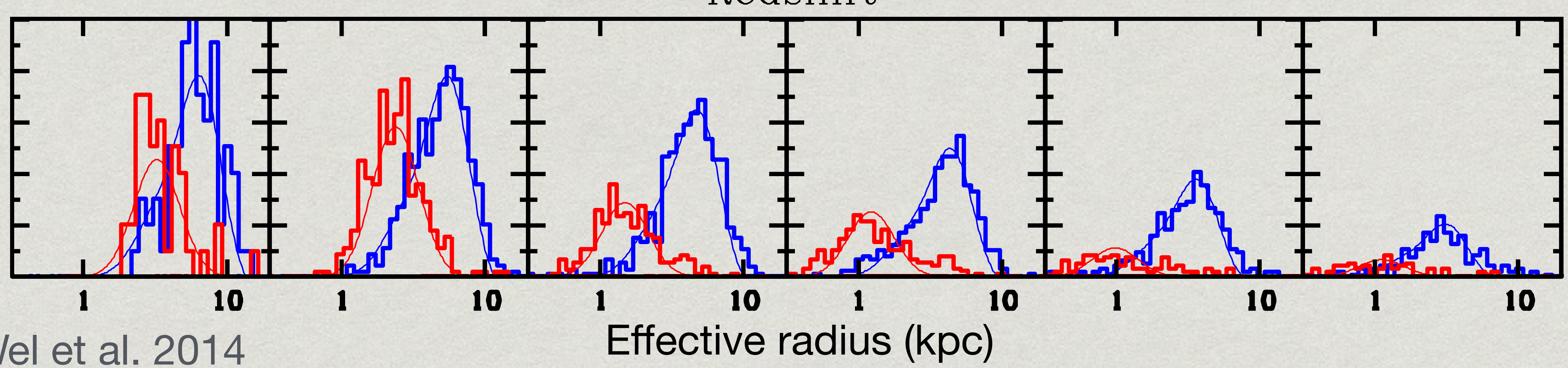
Individual size growth?



Progenitor bias?



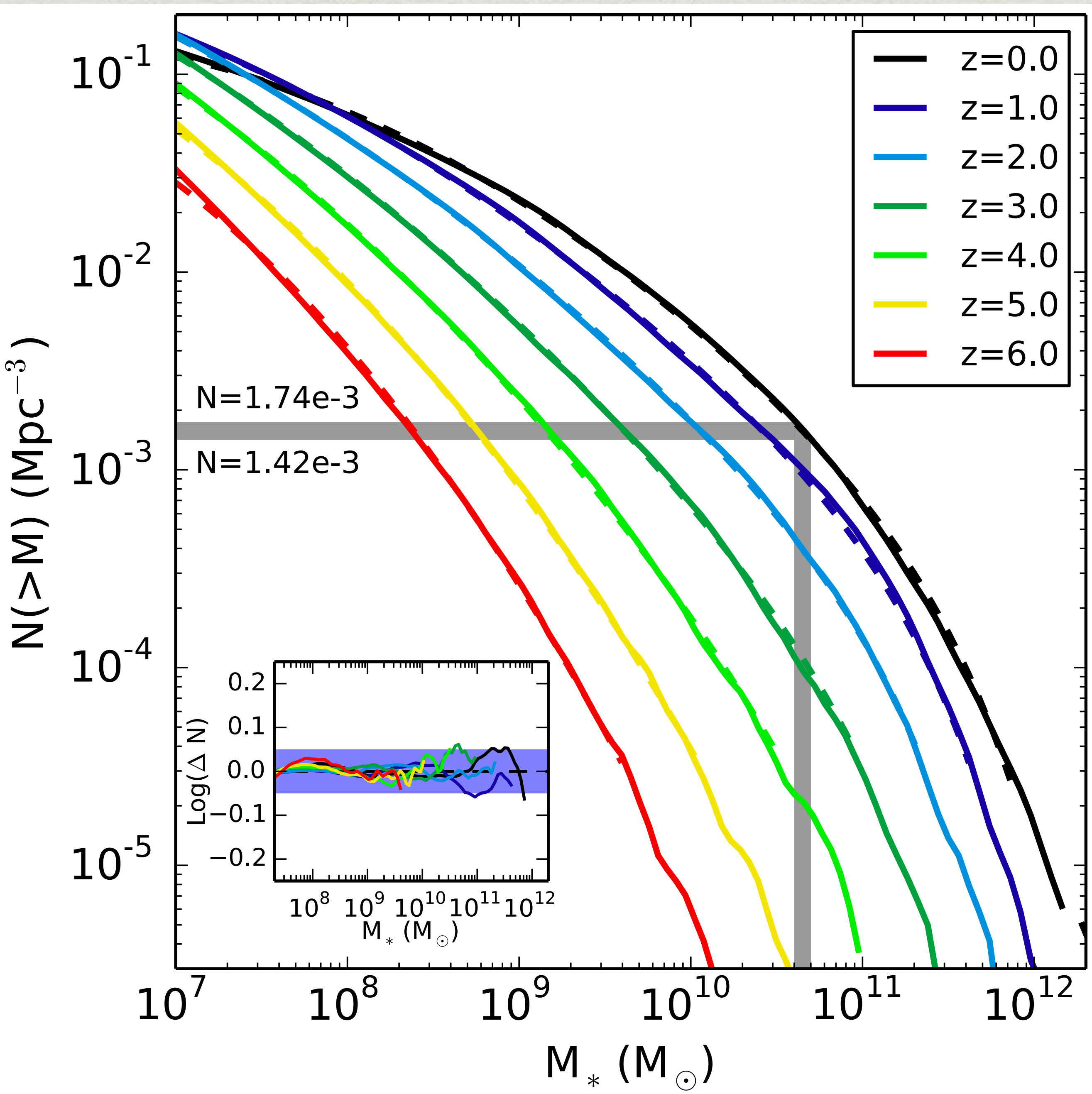
z = 0



z = 3

van der Wel et al. 2014

One common observational approach is the assumption of a constant cumulative comoving number density



Illustris cumulative stellar mass function
(Torrey et al. 2015)

Assuming that

i) Galaxies preserve their relative rank order in time, and

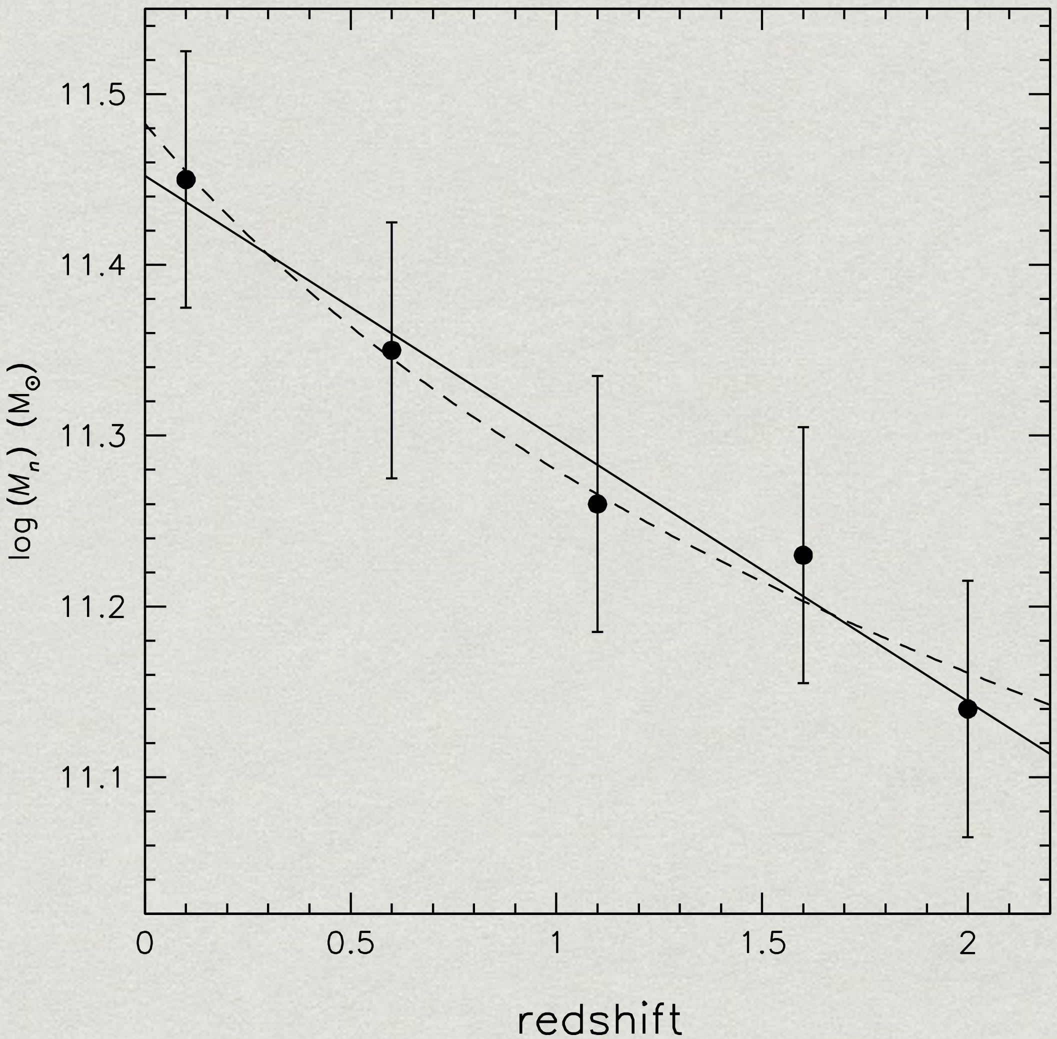
ii) Mergers are negligible,

the cumulative comoving number density of any given galaxy will remain constant

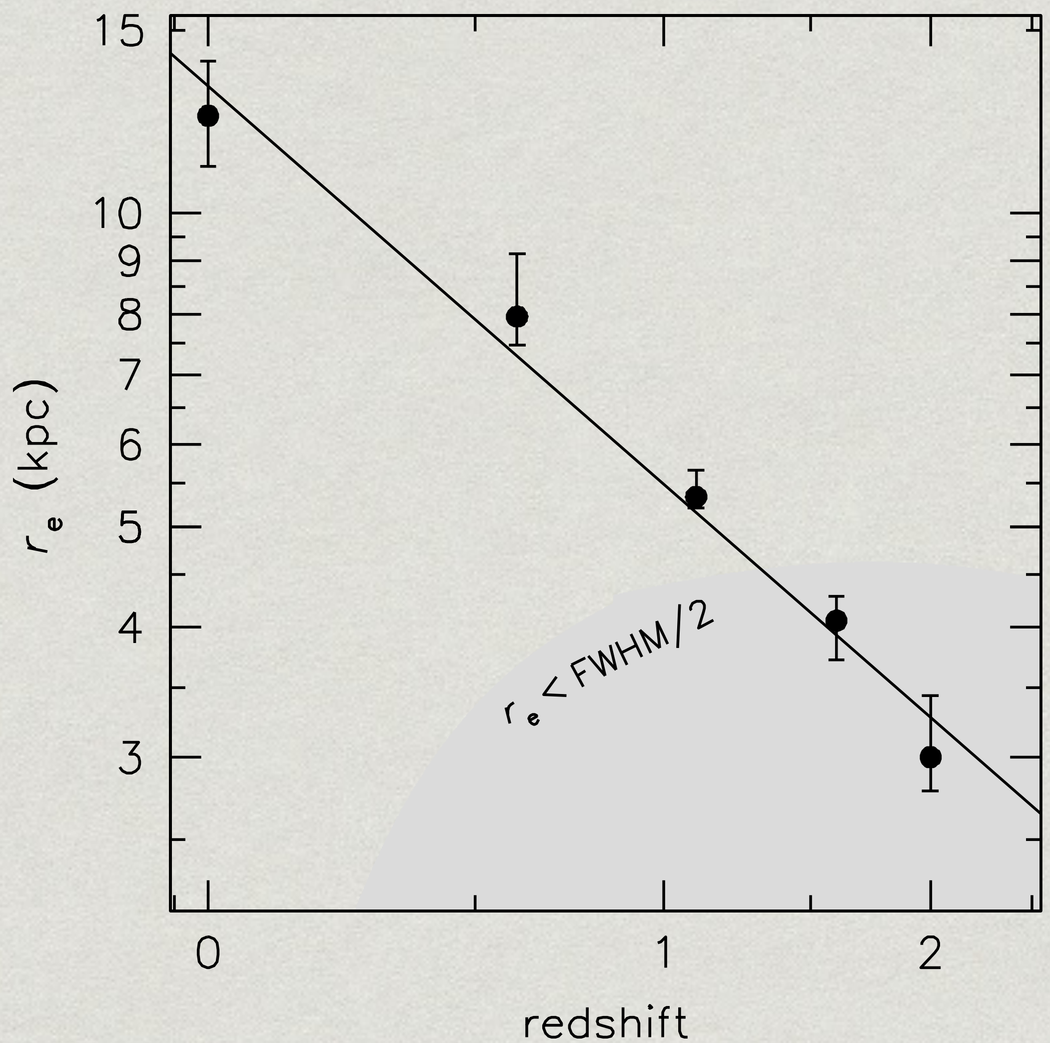
Predicted mass evolution given a set of mass functions

From the mass evolution prediction, the evolution of other quantities can be inferred

Progenitor masses predicted for a 2.5×10^{11} solar mass galaxy at z=0

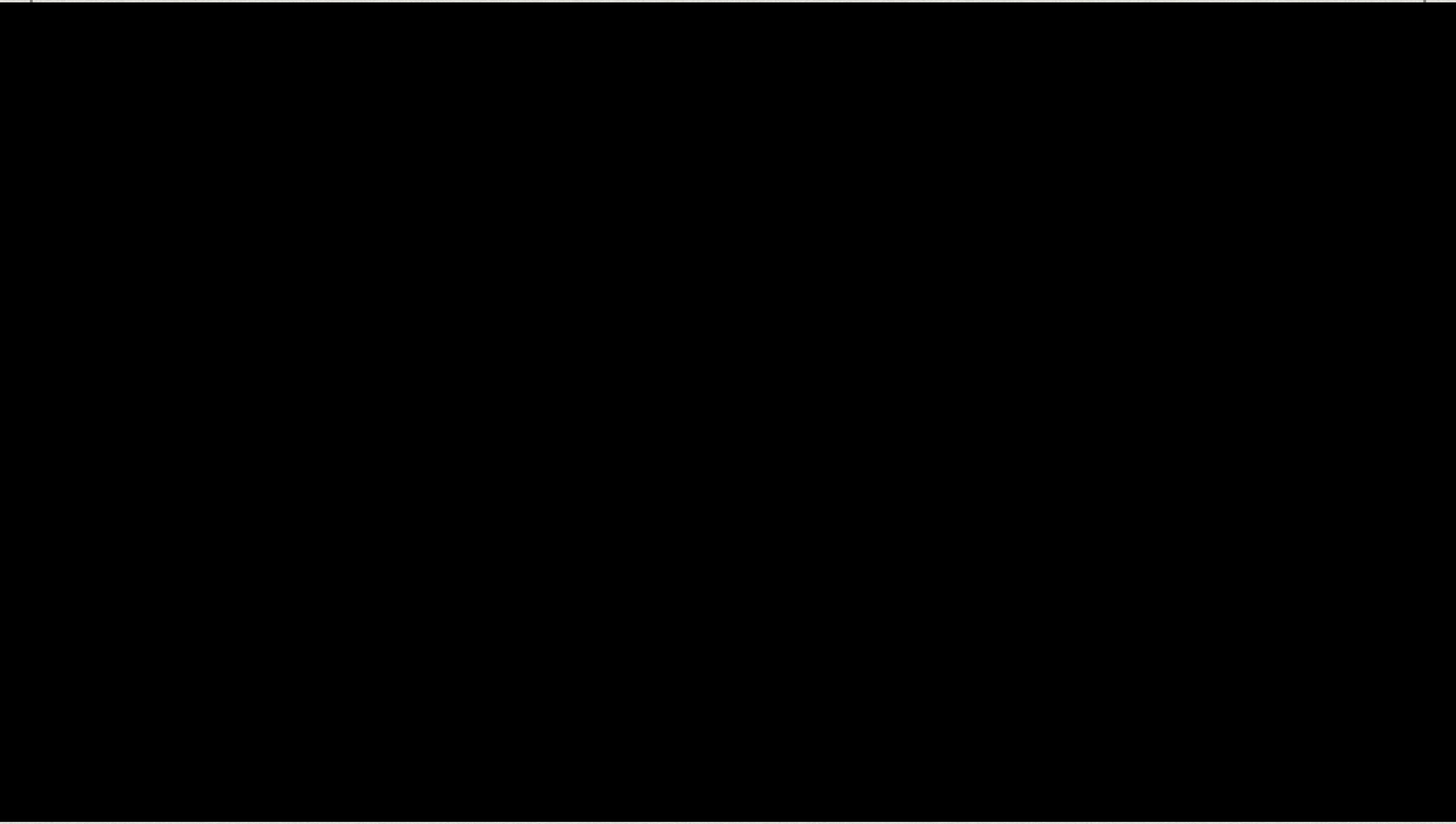


Size evolution inferred from those masses and redshifts



van Dokkum et al 2010

Simulations **do** allow us to follow individual systems through time, so we can see how galaxy populations behave and test these observational approaches



A case study: compact elliptical galaxies

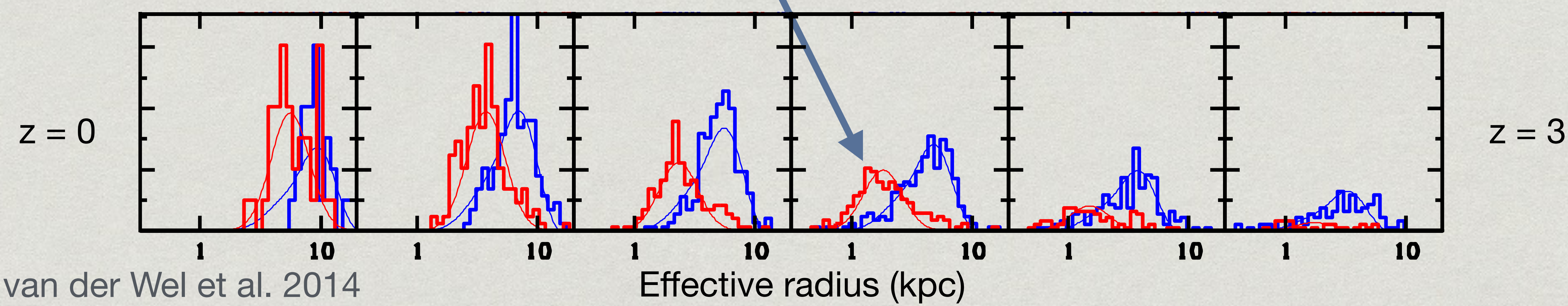
Data: Skelton et al. 2014

High-redshift: $z \sim 2$

Massive: $M_* \sim 10^{11}\ M_\odot$

Small: $R_e \sim 1$ kpc

Quiescent



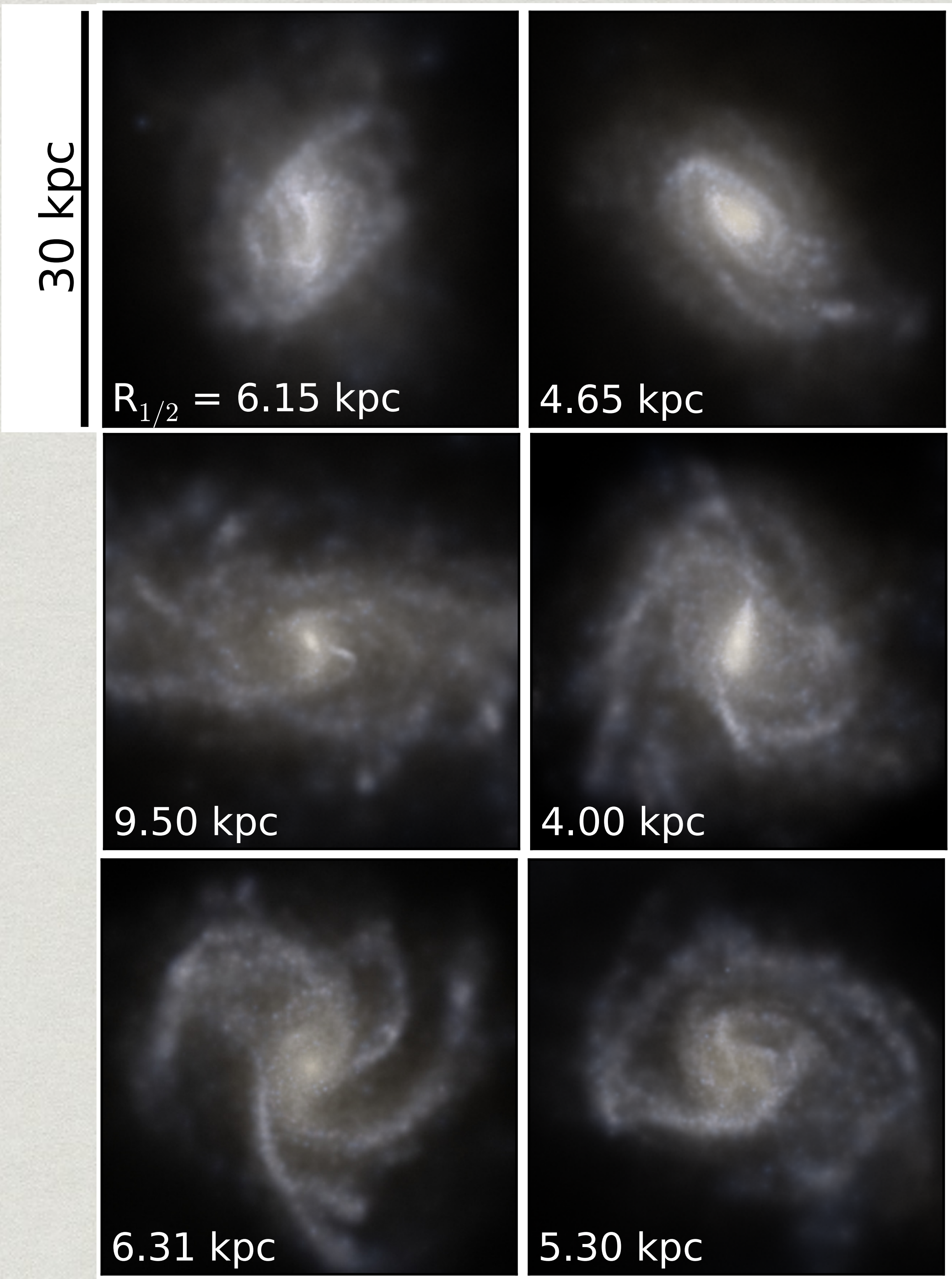
van der Wel et al. 2014

How/why do they form at these masses and sizes?

What has happened to them since?

Massive Galaxies at z=2 in Illustris

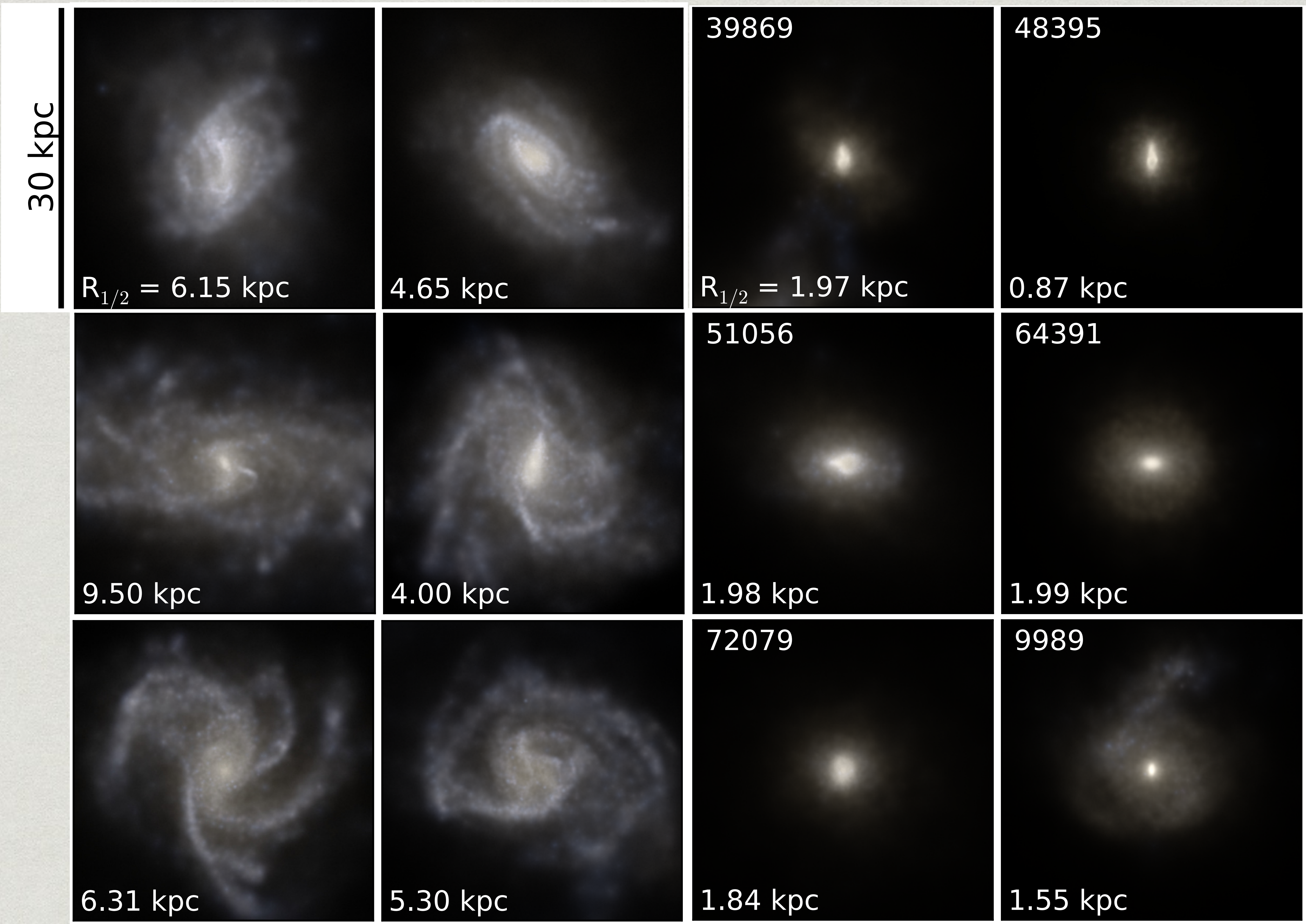
$(1\text{-}3 \times 10^{11}\ M_\odot)$



Visualization: Torrey et al. 2015

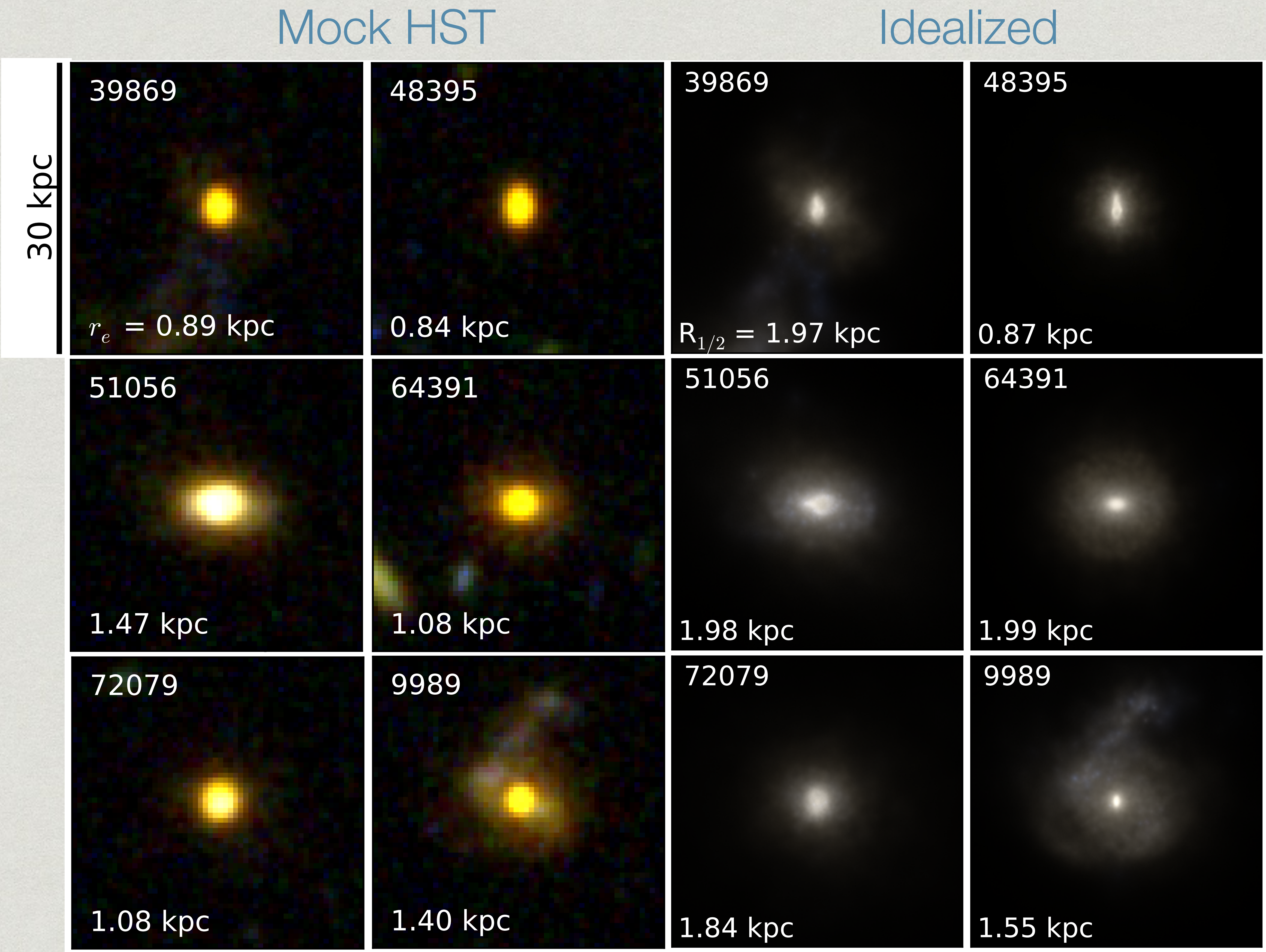
Massive Galaxies at z=2 in Illustris

(1-$3 \times 10^{11}\ M_\odot$)



Visualization: Torrey et al. 2015a

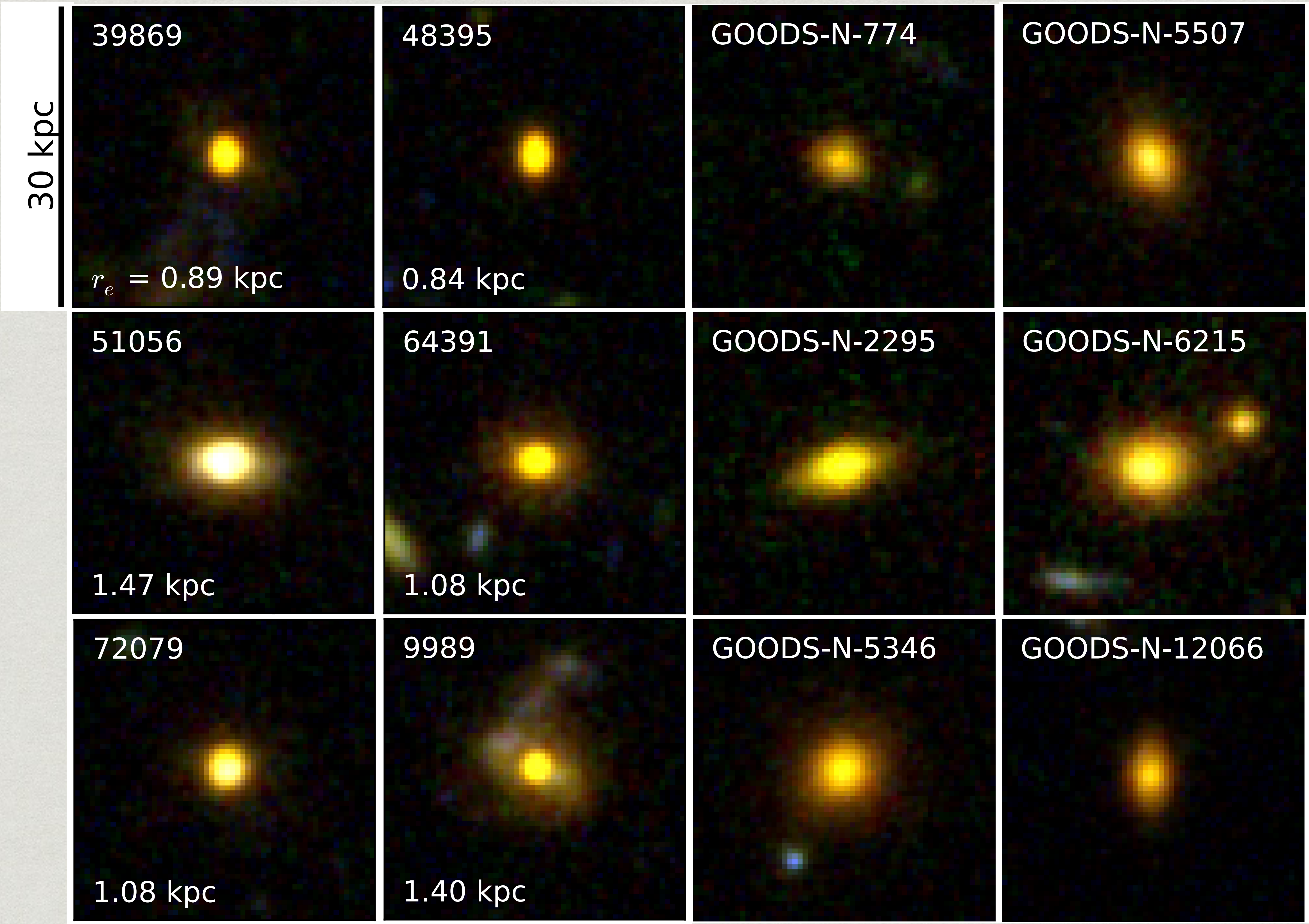
Massive Galaxies at z=2 in Illustris



Visualization: Torrey et al. 2015

Massive Galaxies at z=2

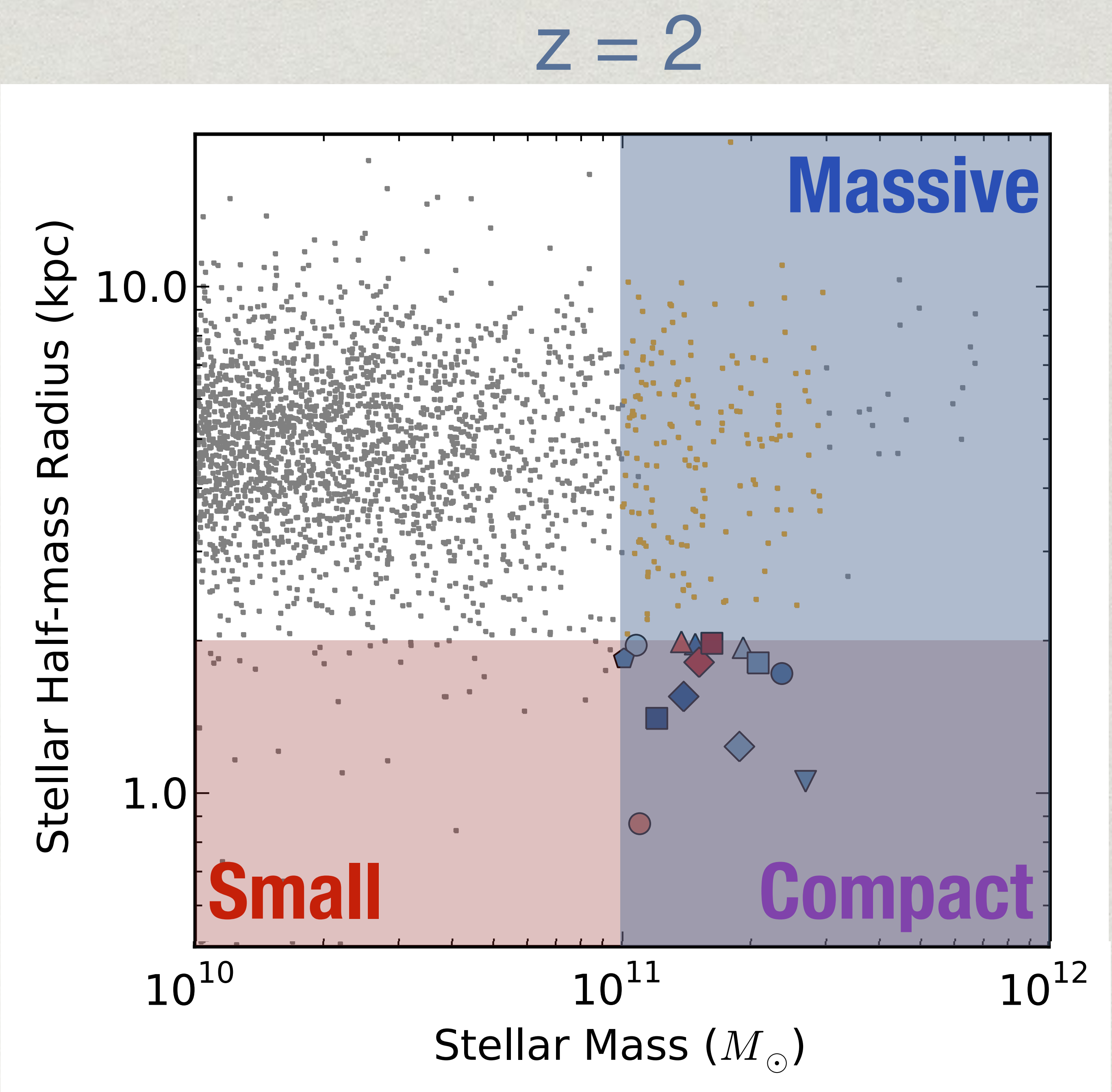
Mock HST — Real HST



Visualization: Torrey et al. 2015 — Data: Skelton et al. 2014

Wellons et al 2015

"Compact" selection criteria



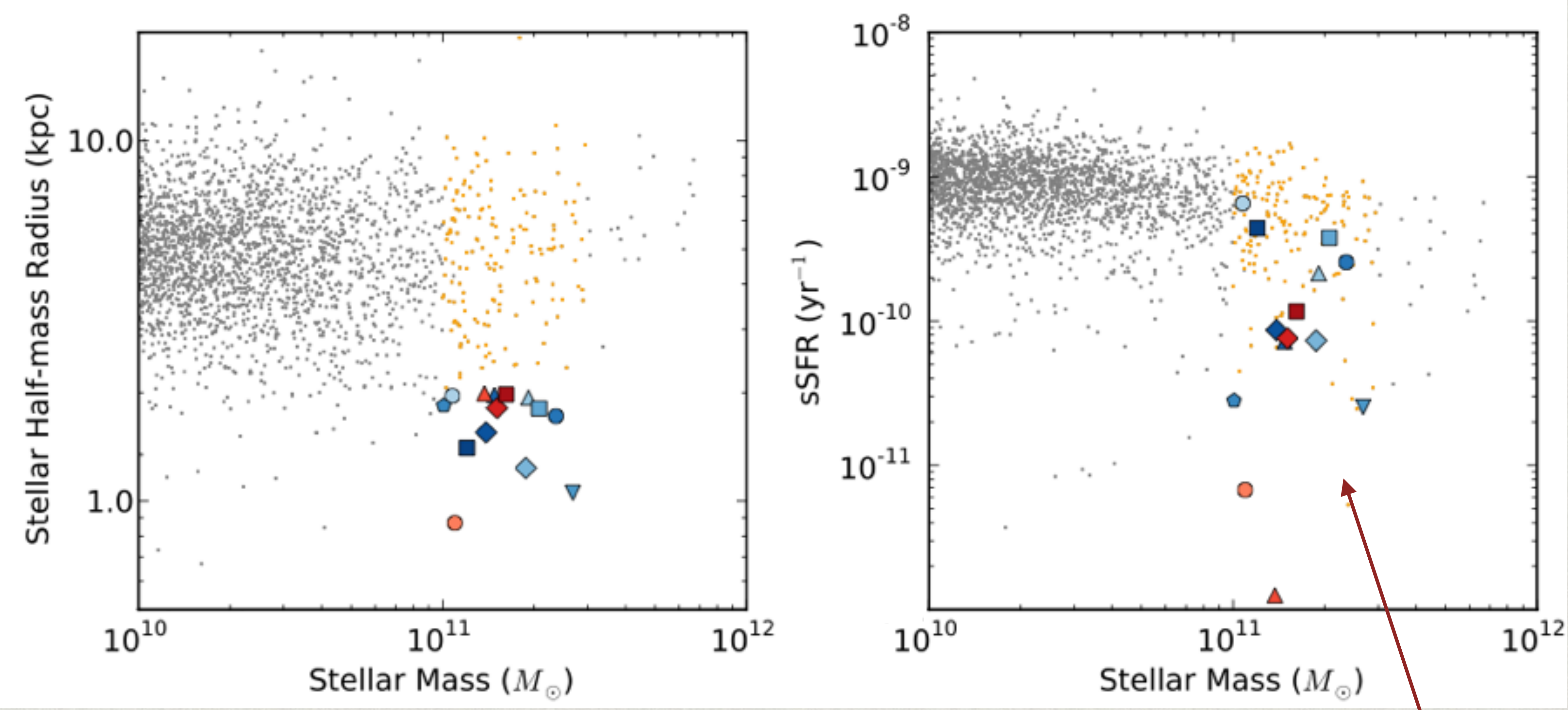
Select for galaxies with:

- stellar mass > 10^{11} $M_\odot$
- half-mass radius < 2 kpc

14 massive, compact galaxies

Wellons et al 2015

Side effect of selection: low sSFR



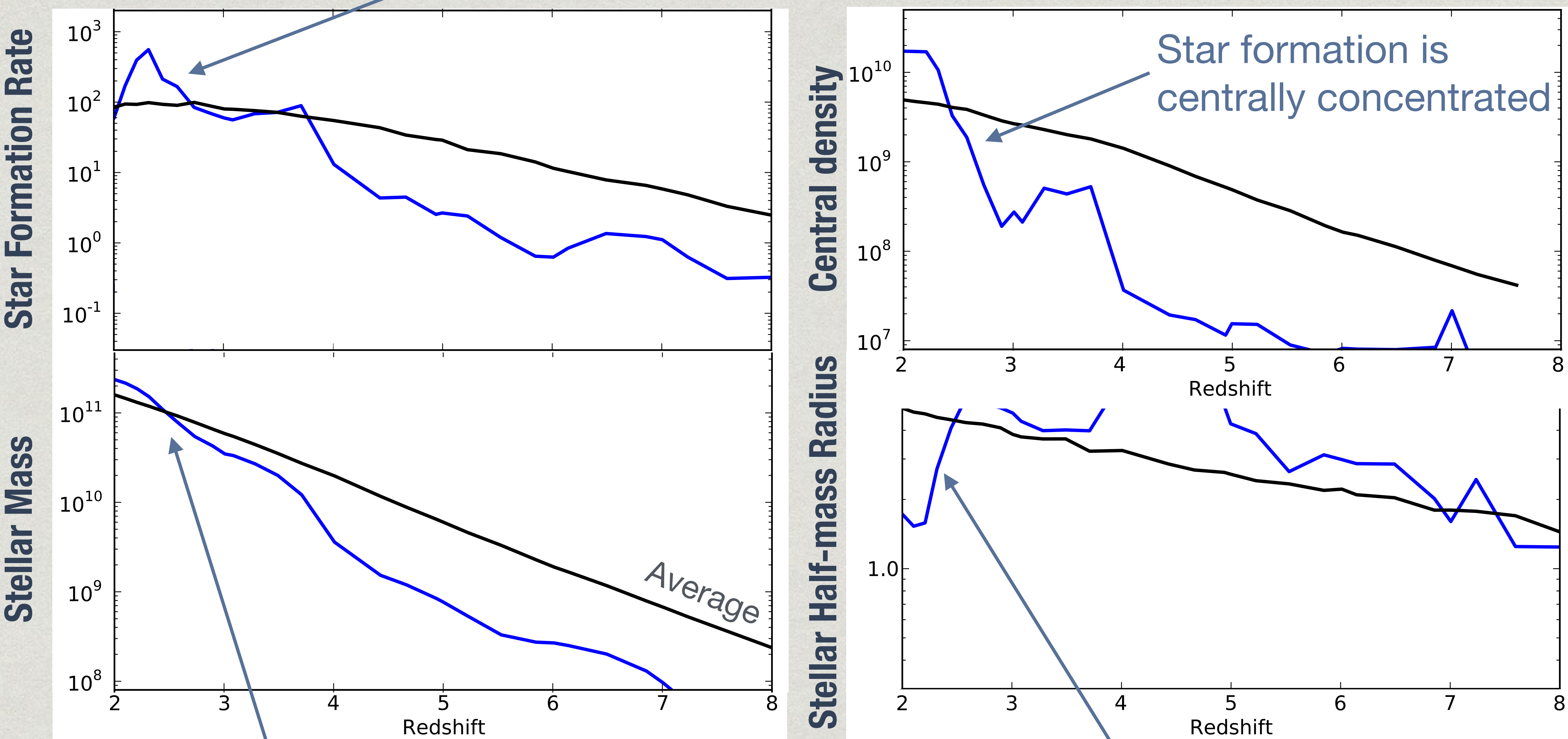
Star formation often quenched

Wellons et al 2015

Formation channels

Example #1:

Major merger is accompanied by burst of star formation



Stellar mass is assembled quickly at z~2.5

Increase in central density drives down half-mass radius

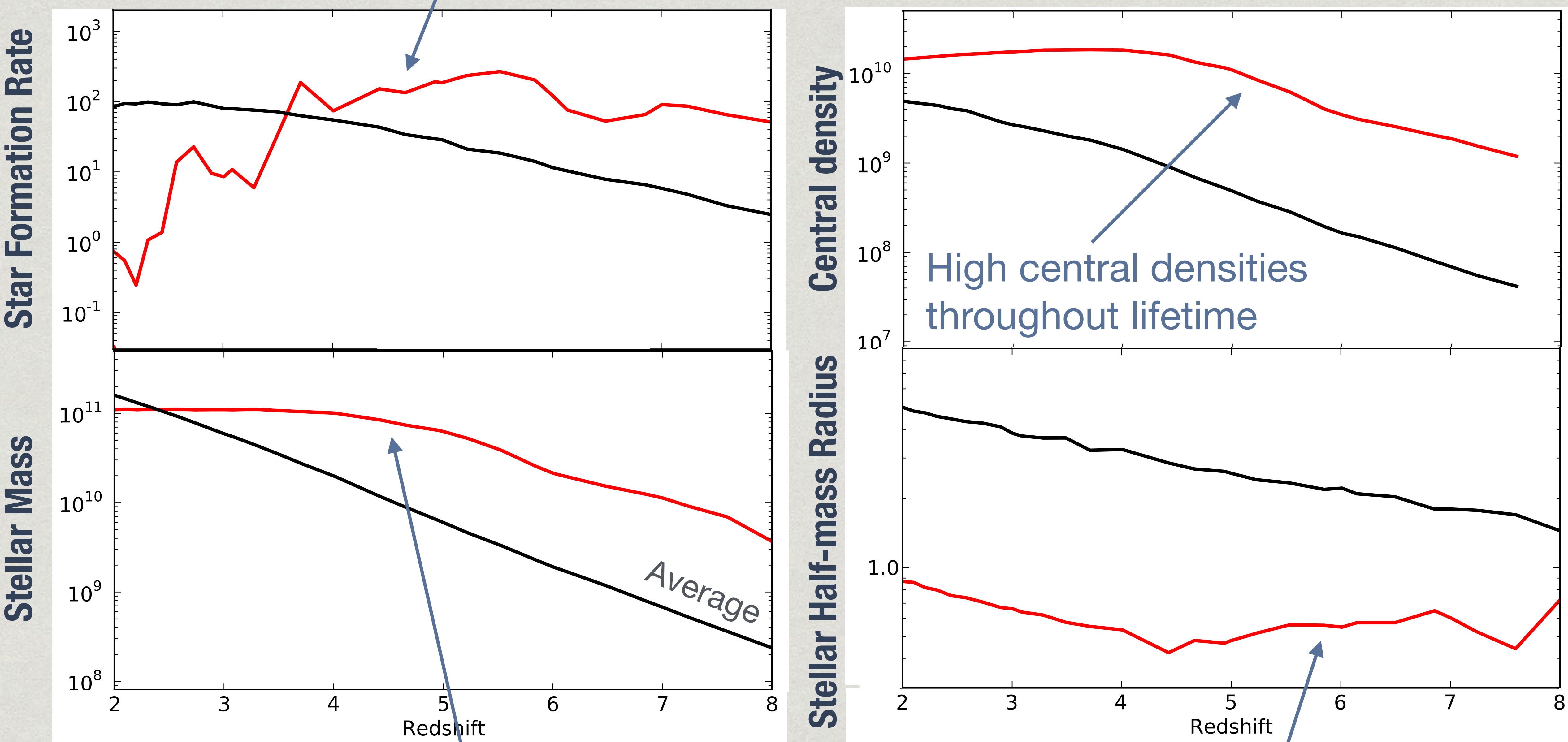
→ **Major gas-rich merger drives intense central starburst**

Wellons et al 2015

Formation channels

Example #2:

SFR an order of magnitude higher at early times, then quenches at z=4



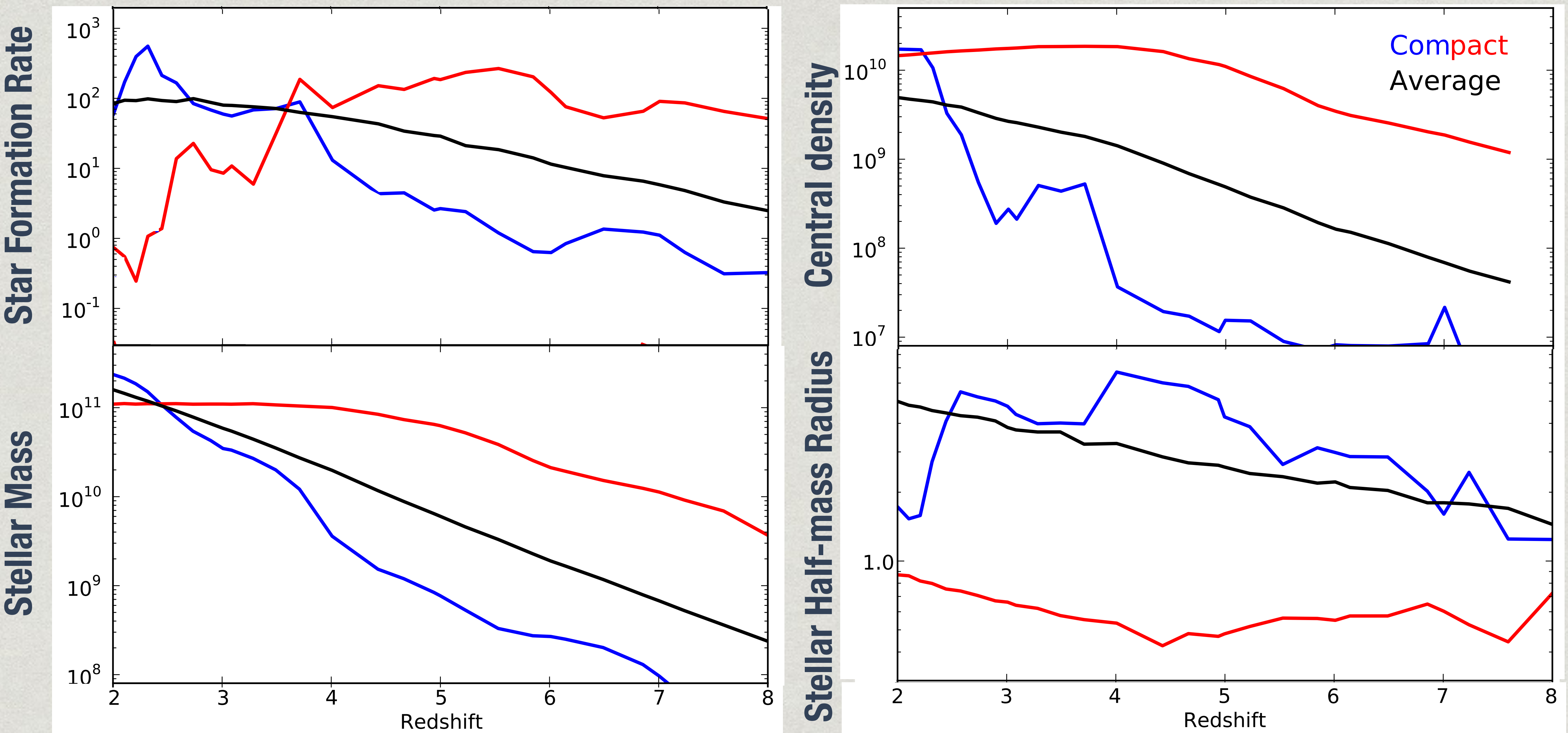
Stellar mass is assembled early and gradually

Forms with, and maintains, small size

Early formation → small size

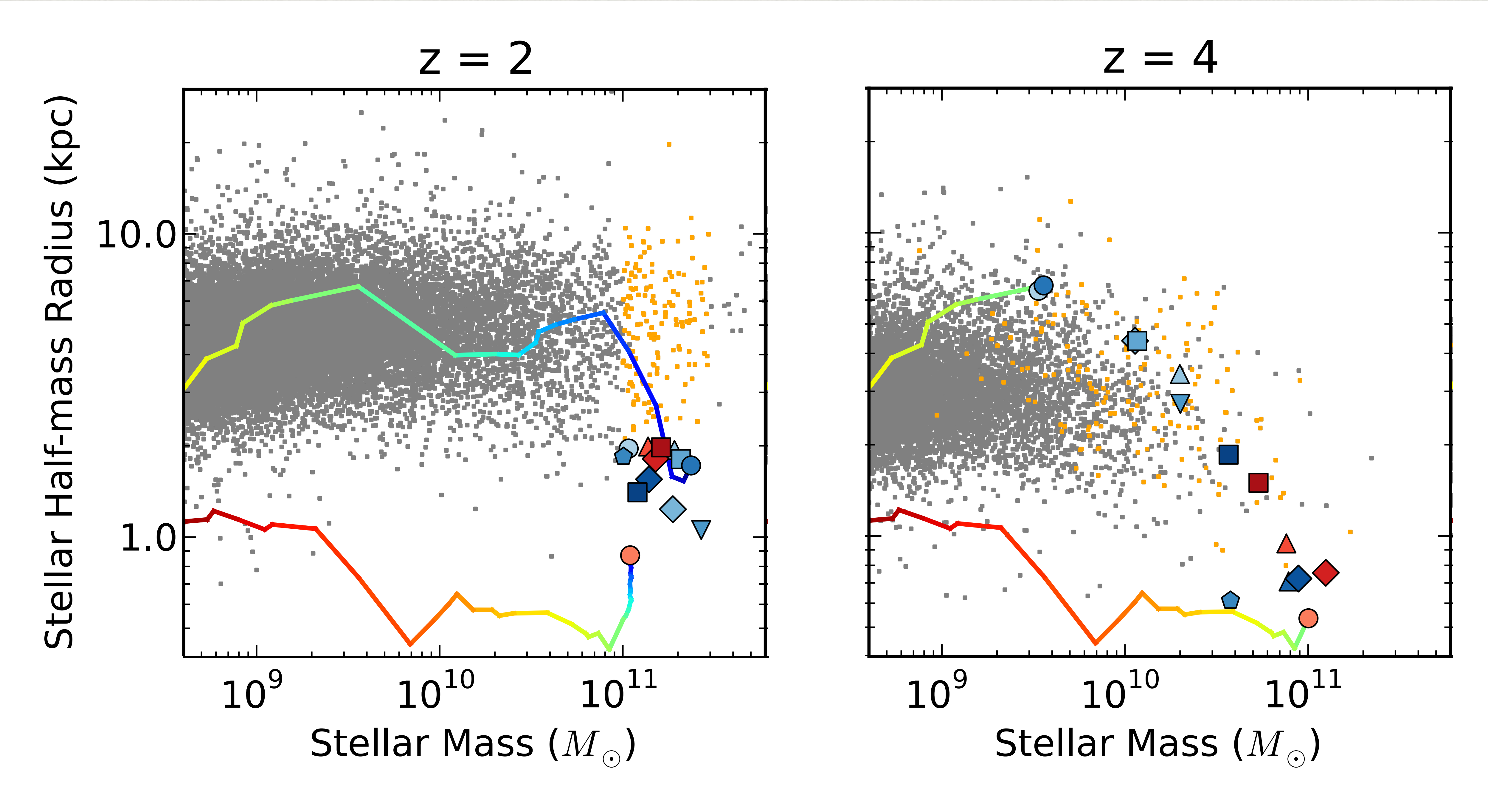
Wellons et al 2015

Two distinct formation mechanisms:
Central starbursts & Early assembly



Wellons et al 2015

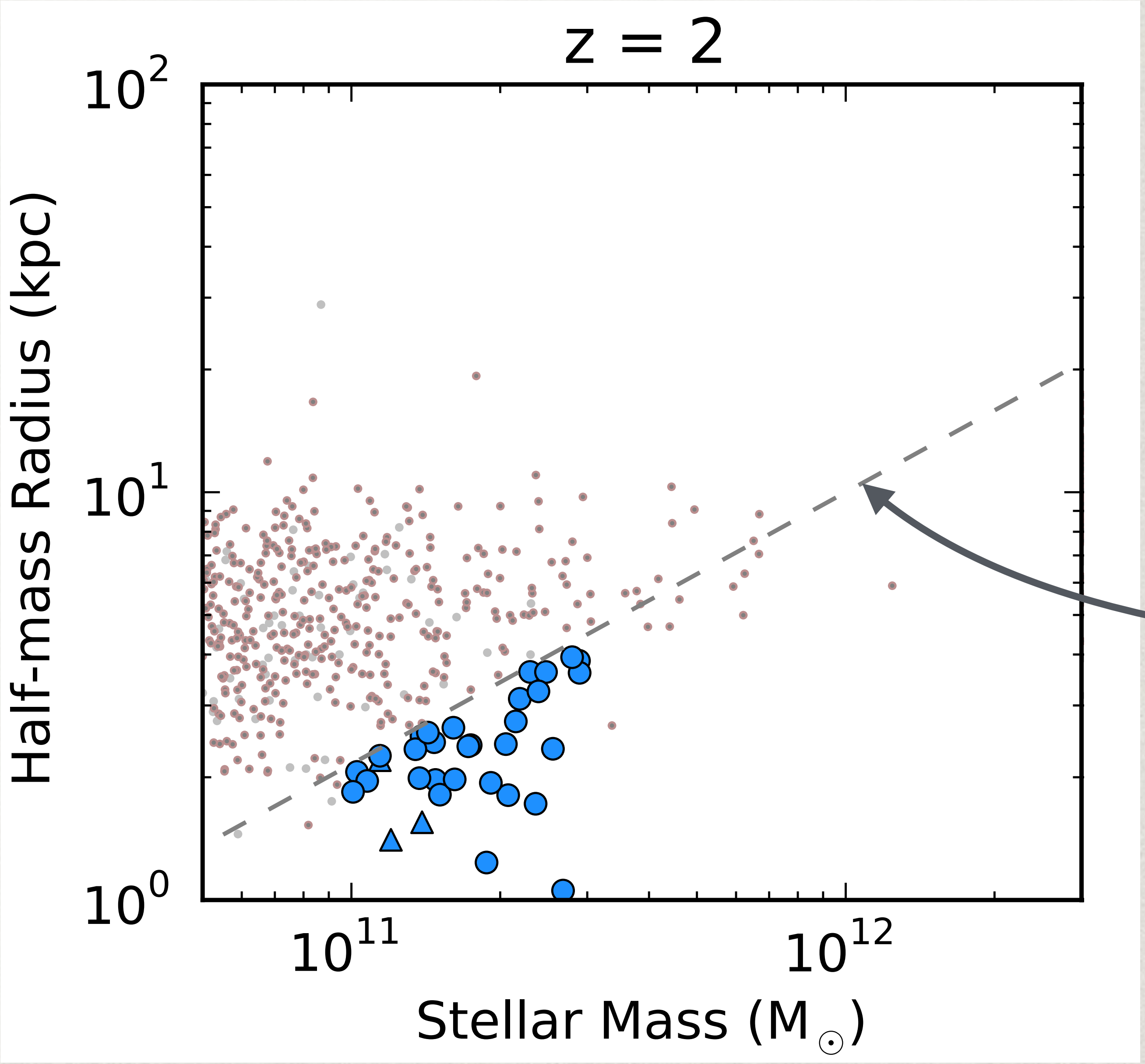
High-z Progenitors



4 early formers, 10 central starbursts

Wellons et al 2016

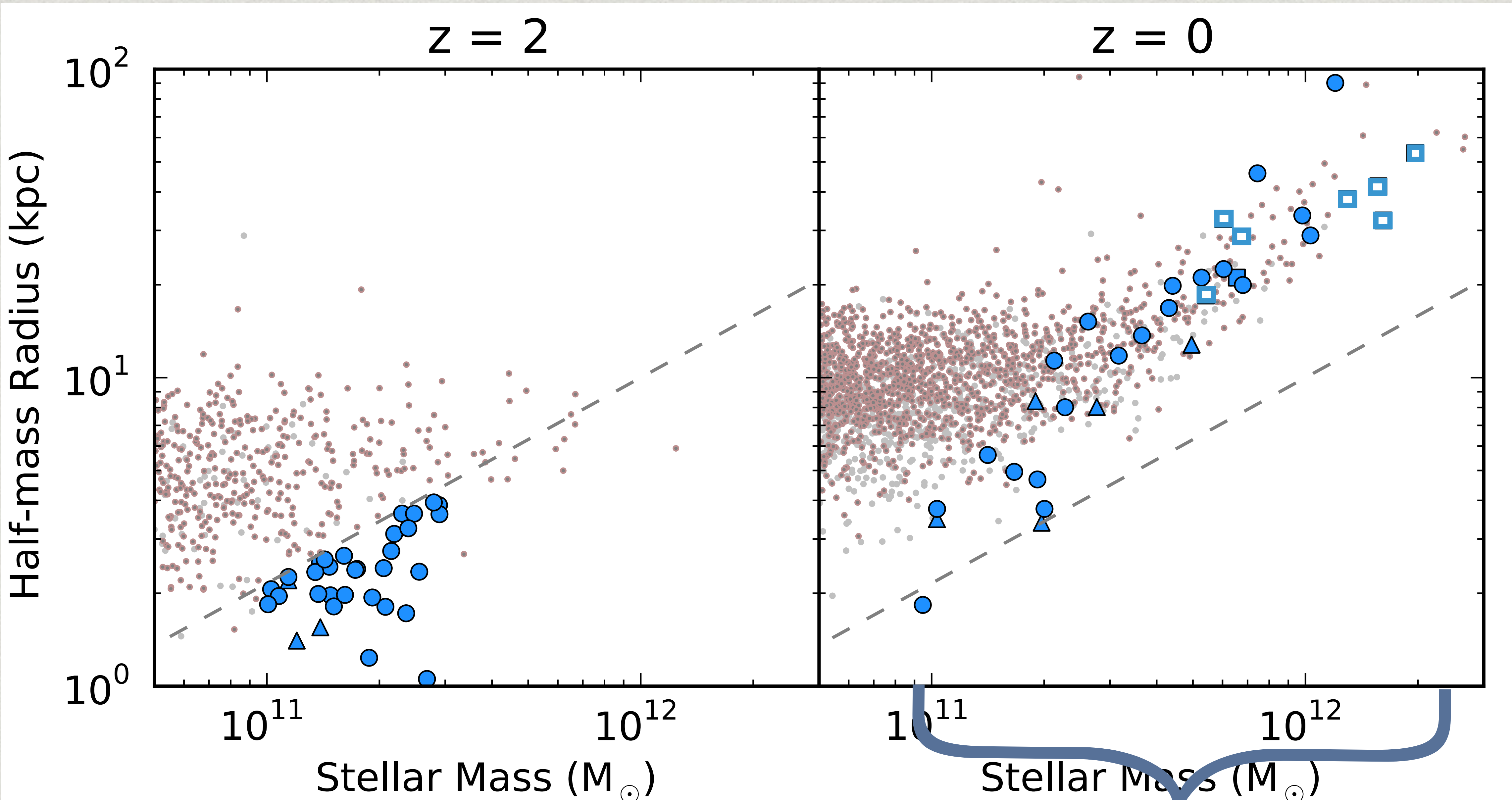
Next: what do they become?



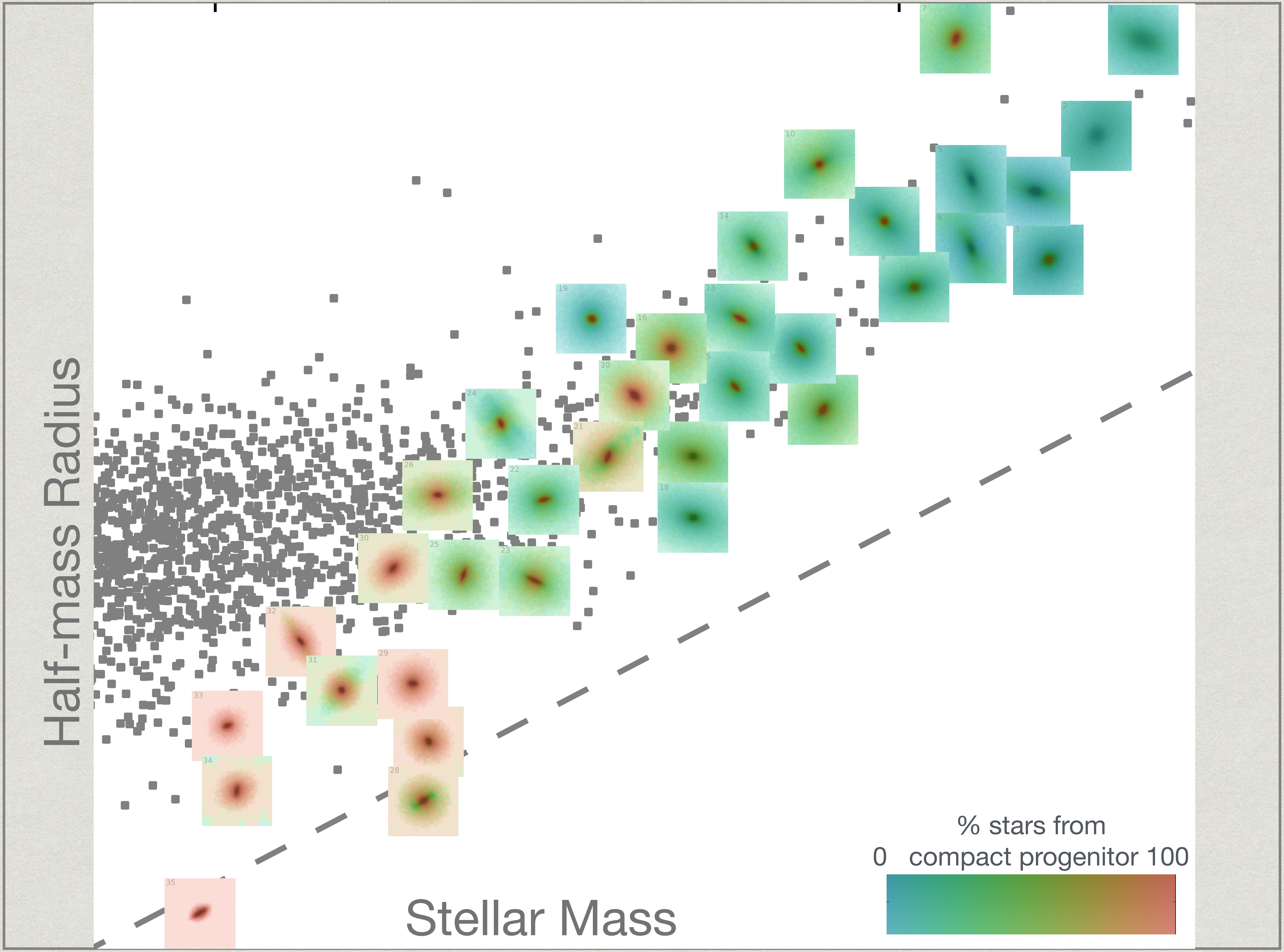
Select for constant $\Sigma_{1.5} \sim M/R^{1.5}$

Wellons et al 2016

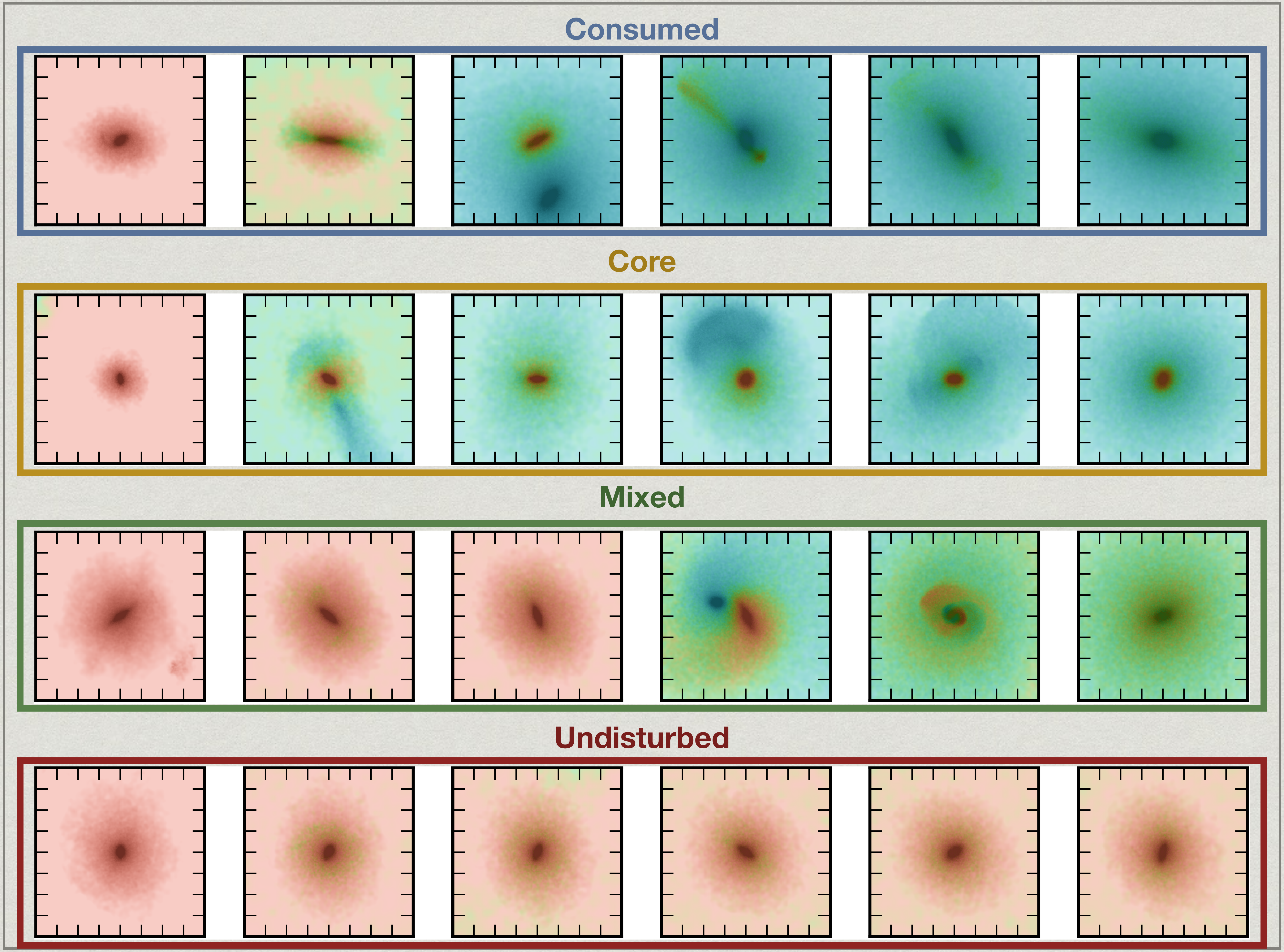
z = 0 Descendants



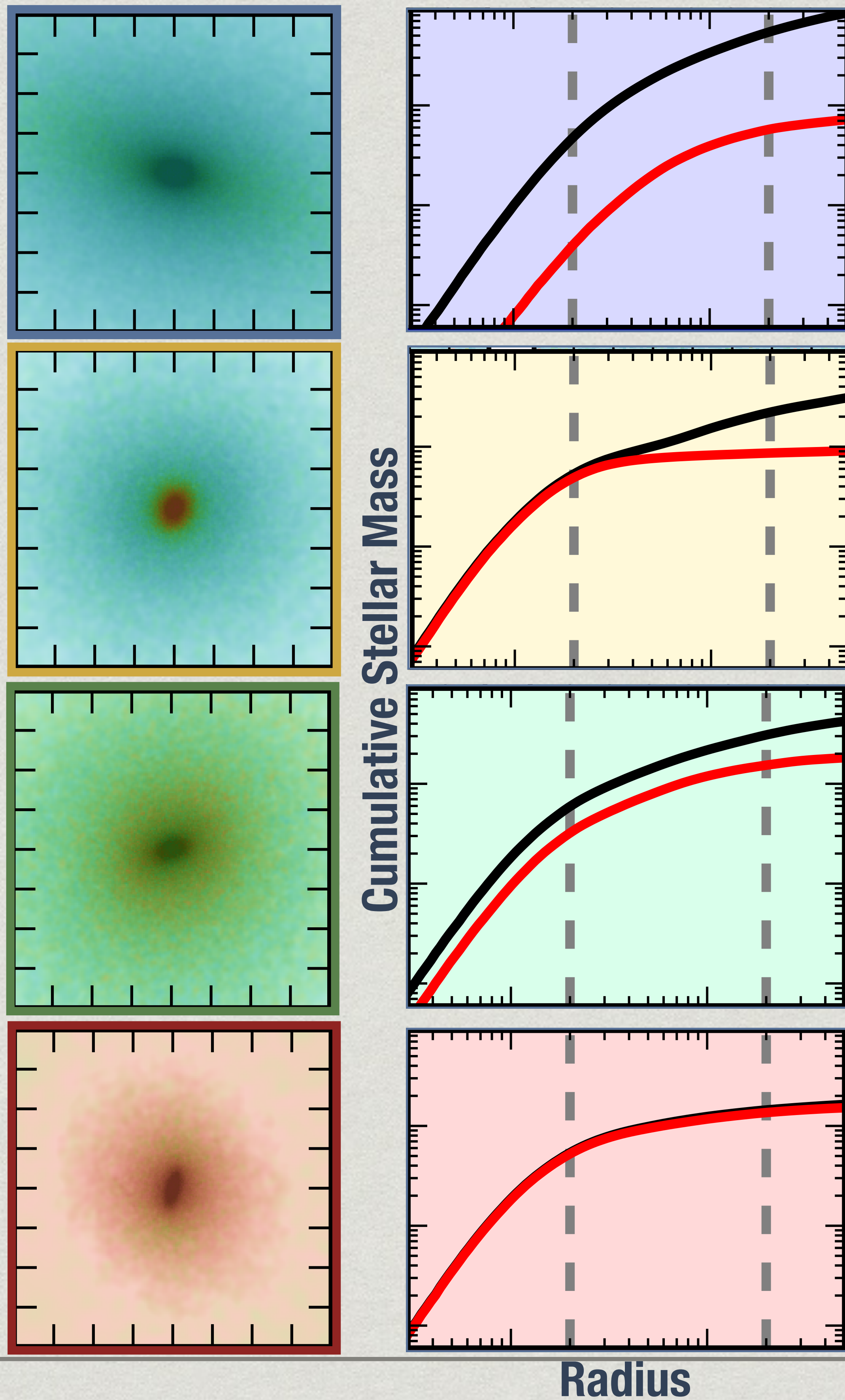
Wide dispersion in stellar mass

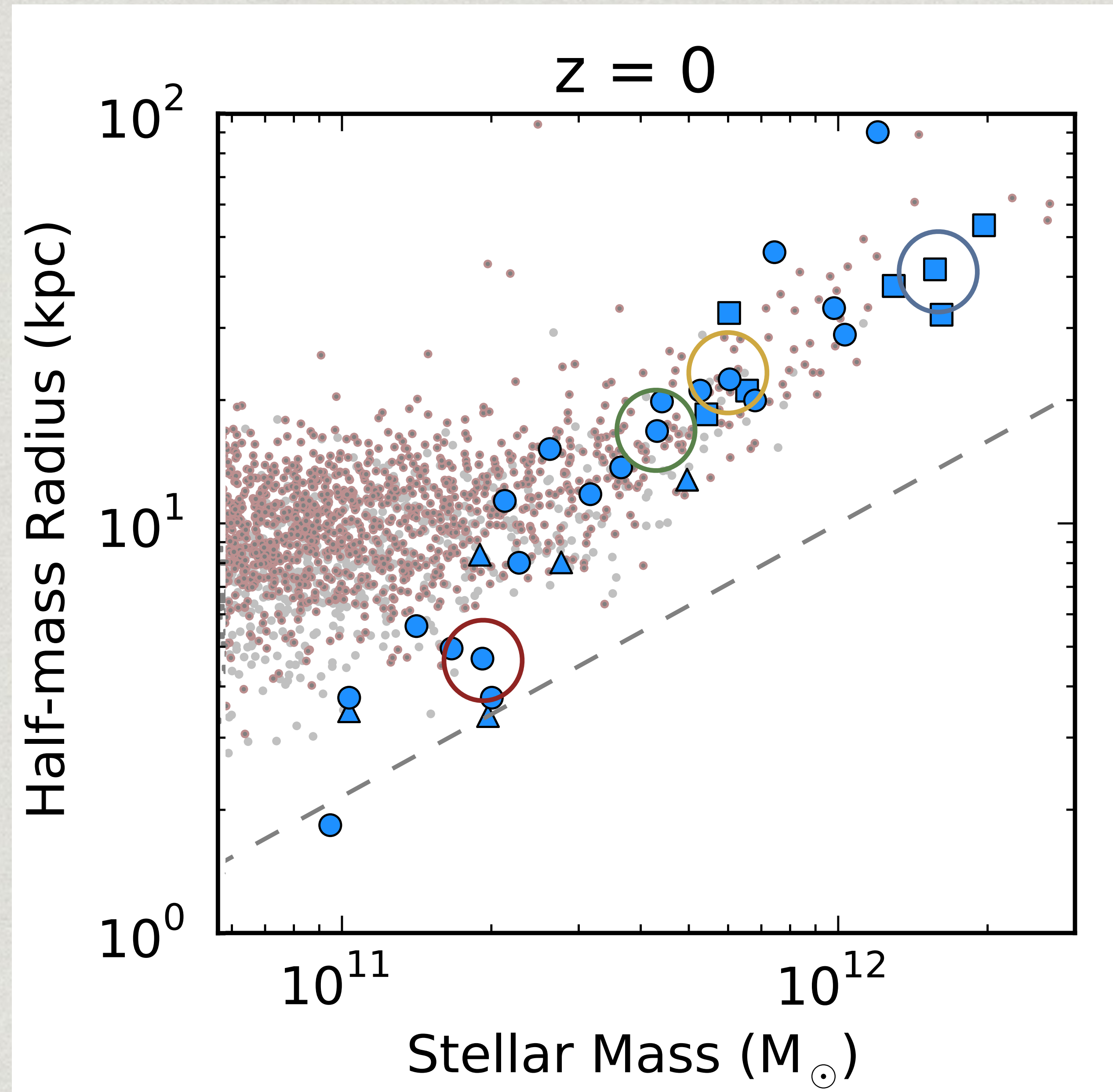


Half-mass Radius
Stellar Mass
% stars from
0 compact progenitor 100

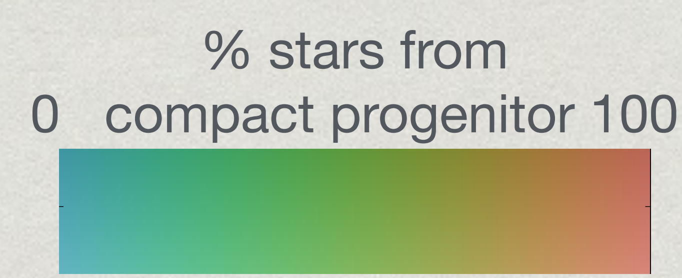

Consumed
Core
Mixed
Undisturbed

Descendant Types

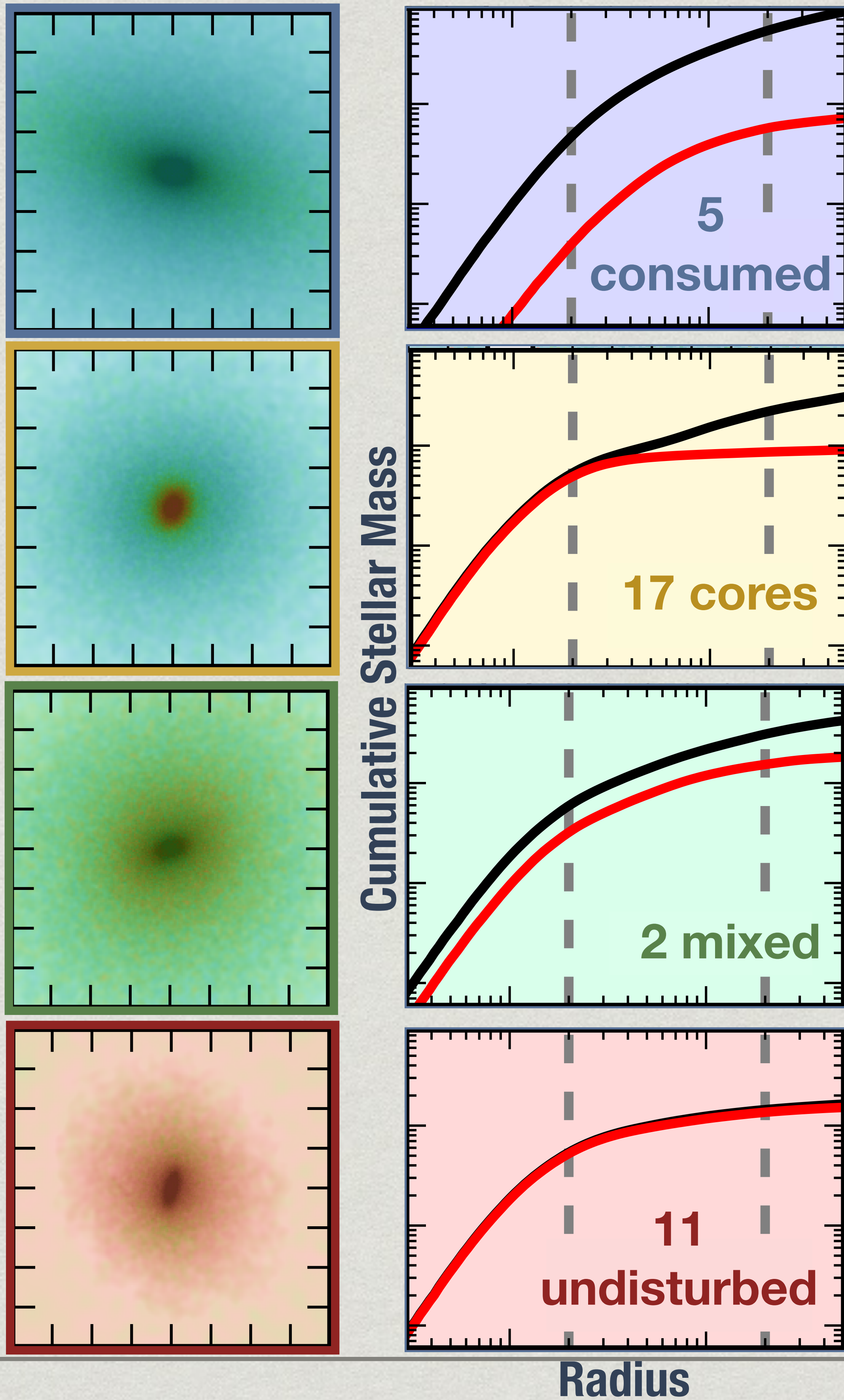


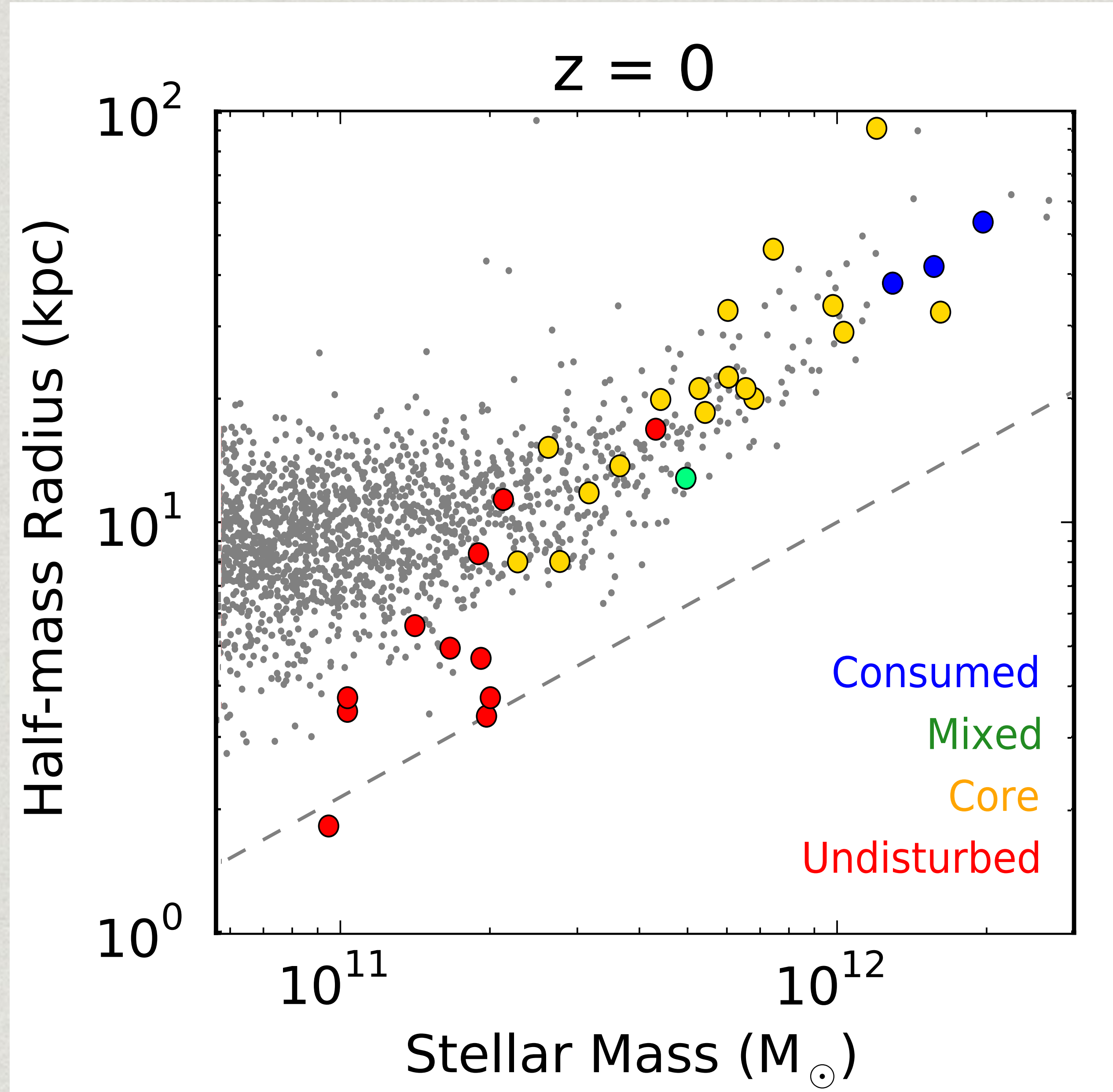


Wellons et al 2016

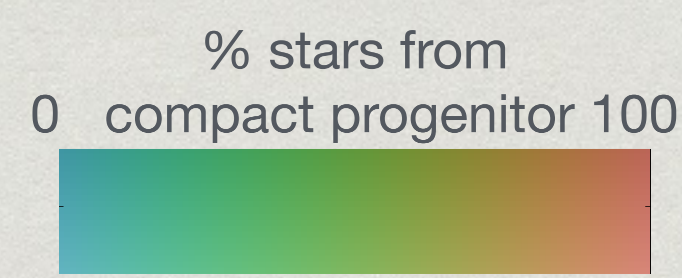


Descendant Types



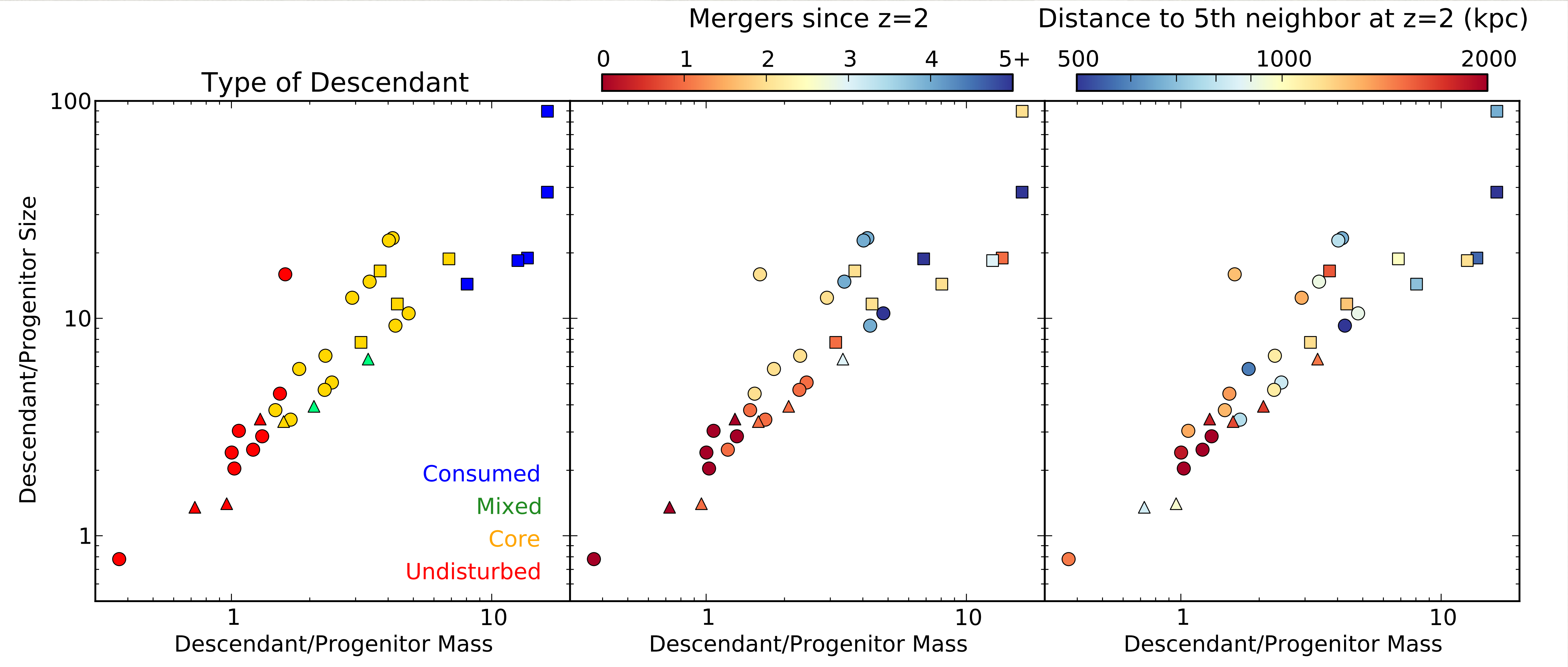


Wellons et al 2016



Wellons et al 2016

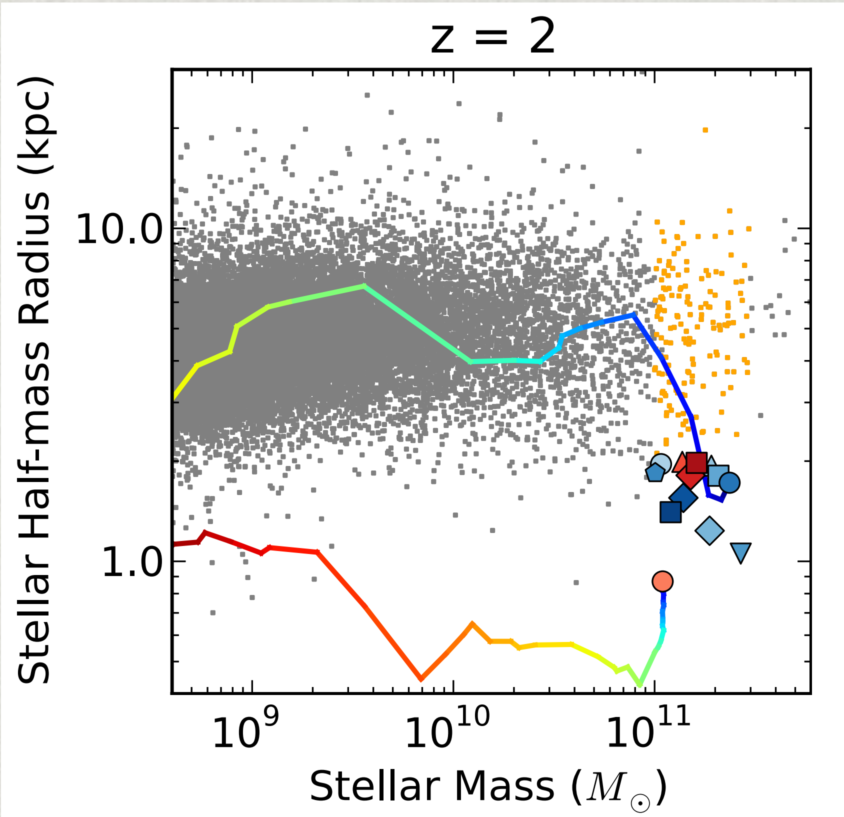
Environmental influence



More mergers -> more mass growth

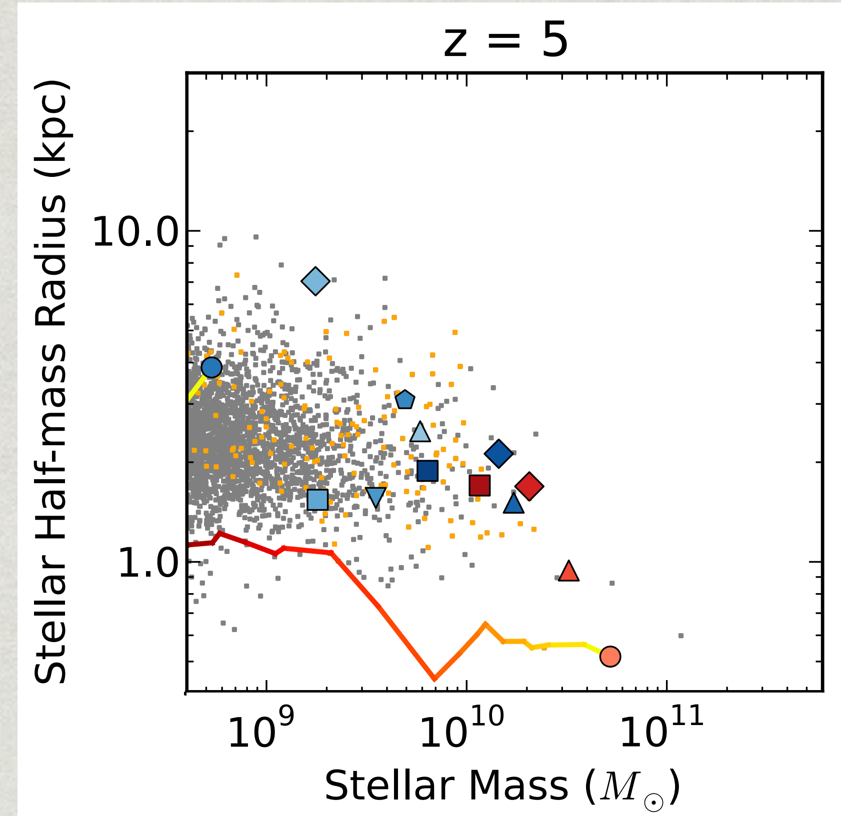
Denser environment -> more mergers

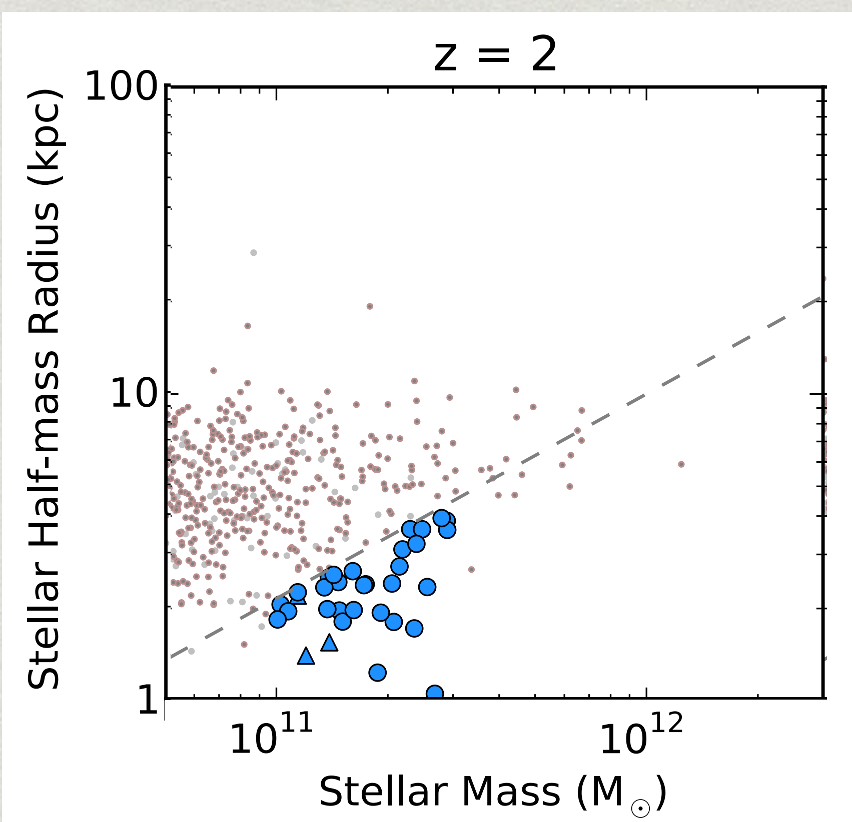
In both directions, the population spreads out!



Progenitors

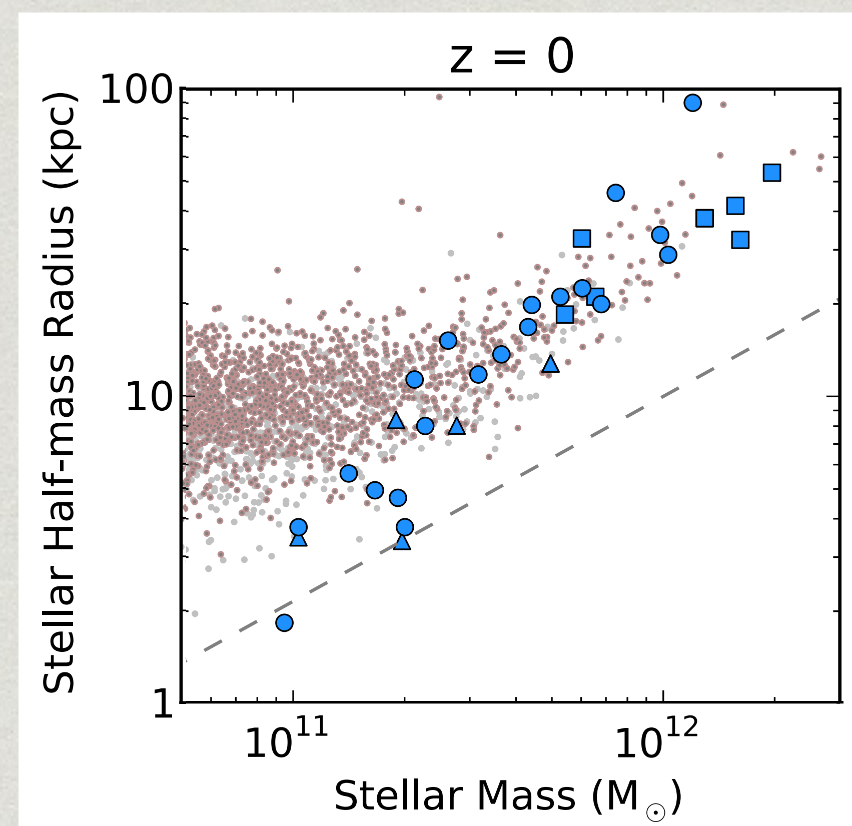
(Wellons et al. 2015)





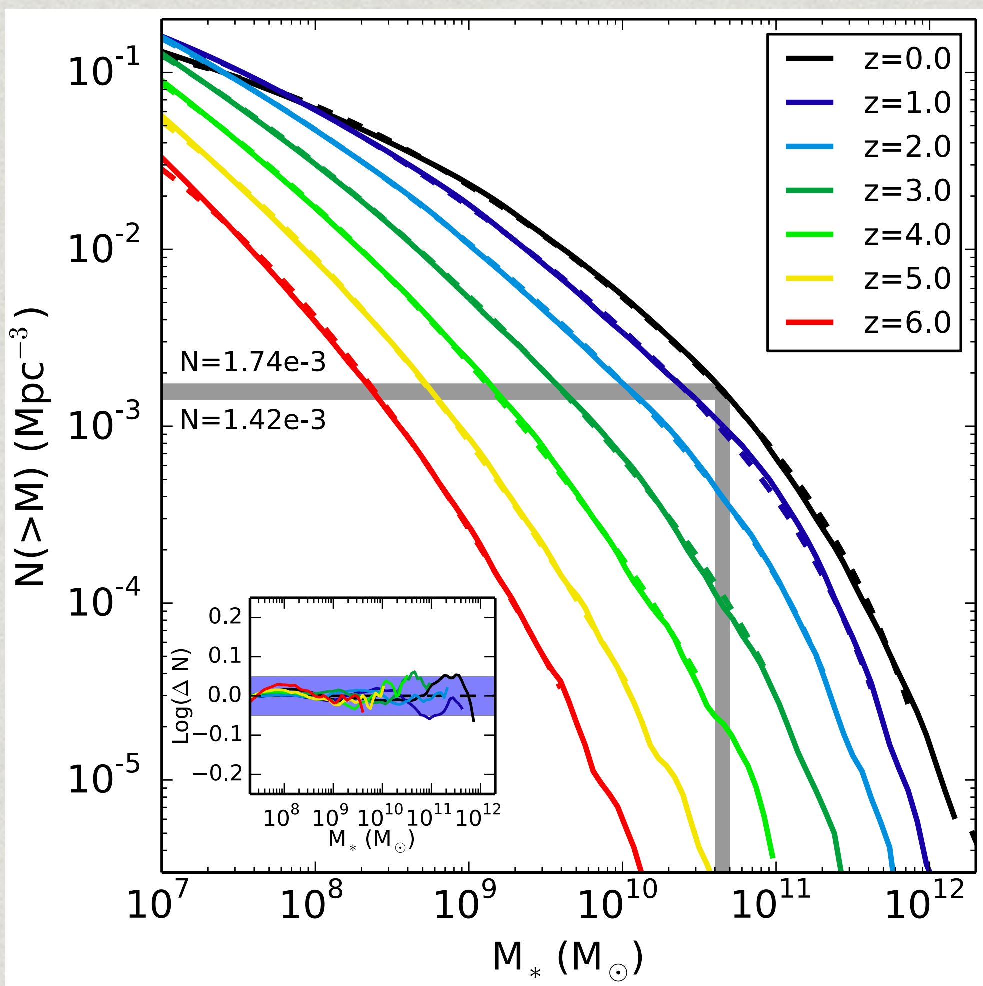
Descendants

(Wellons et al. 2016)



Recall the constant number density method for predicting progenitor/descendant populations that I described earlier:

One common observational approach is the assumption of a constant cumulative comoving number density



Illustris cumulative stellar mass function
(Torrey et al. 2015)

Assuming that

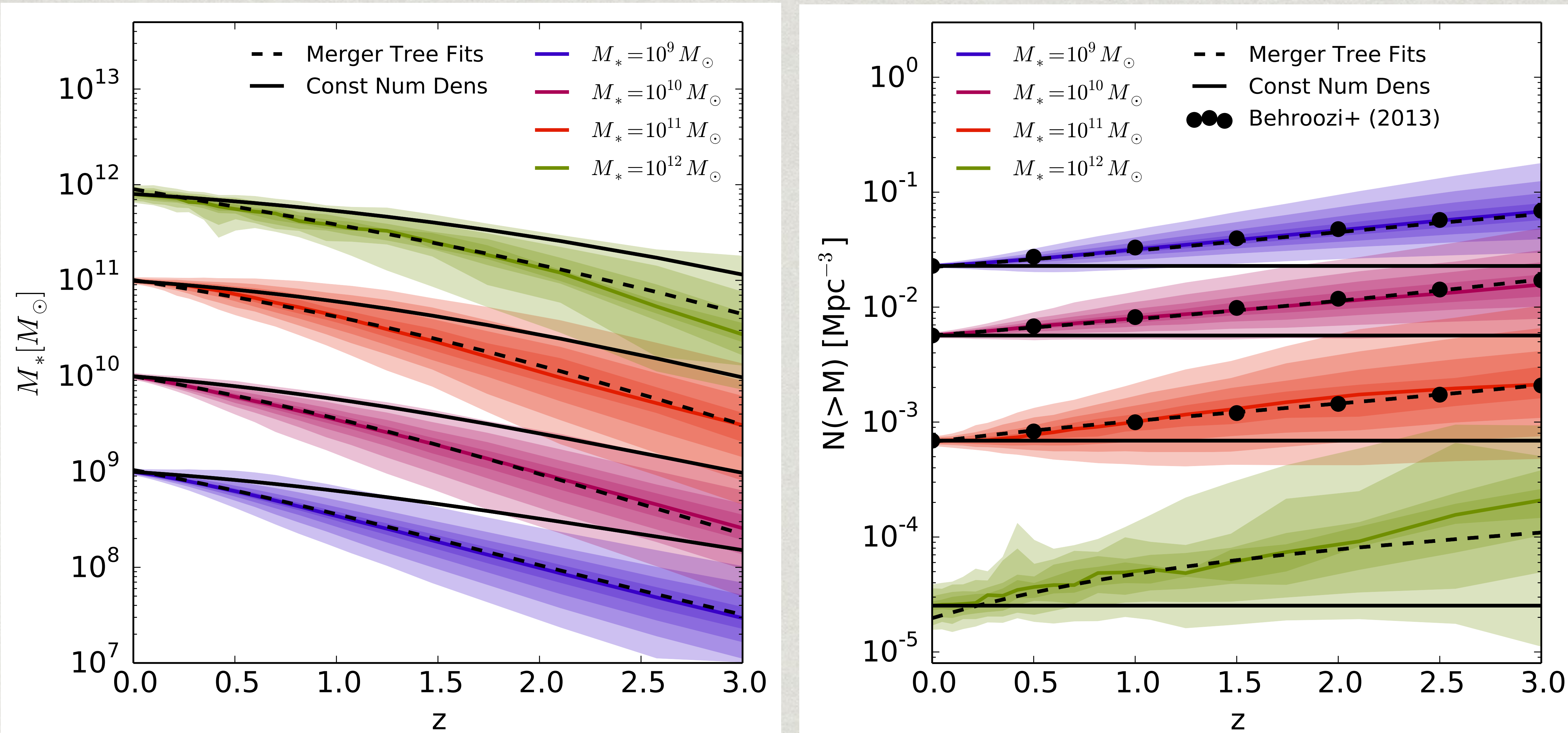
i) ~~Galaxies preserve their relative rank order in time, and~~

ii) ~~Mergers are negligible,~~

the cumulative comoving number density of any given galaxy will remain constant

Predicted mass evolution given a set of mass functions

The spreading-out occurs for any mass-selected sample, not just the compact population.



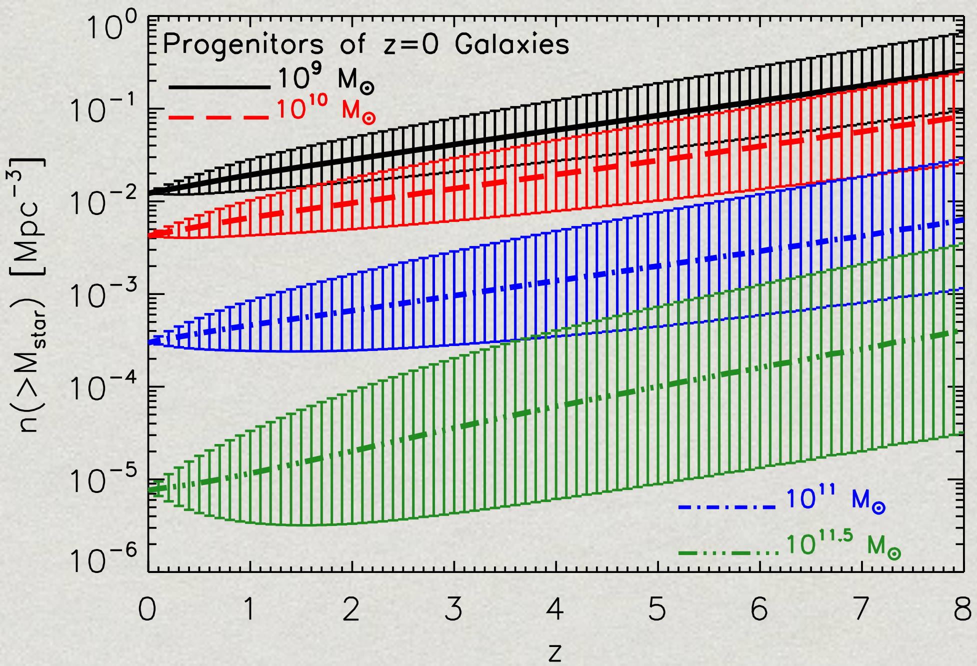
Torrey, Wellons et al. 2015

This presents several problems for the constant number density method of predicting galaxy progenitor/descendant properties.

The predicted evolution in number density is remarkably consistent across theoretical methodologies and ranking quantities

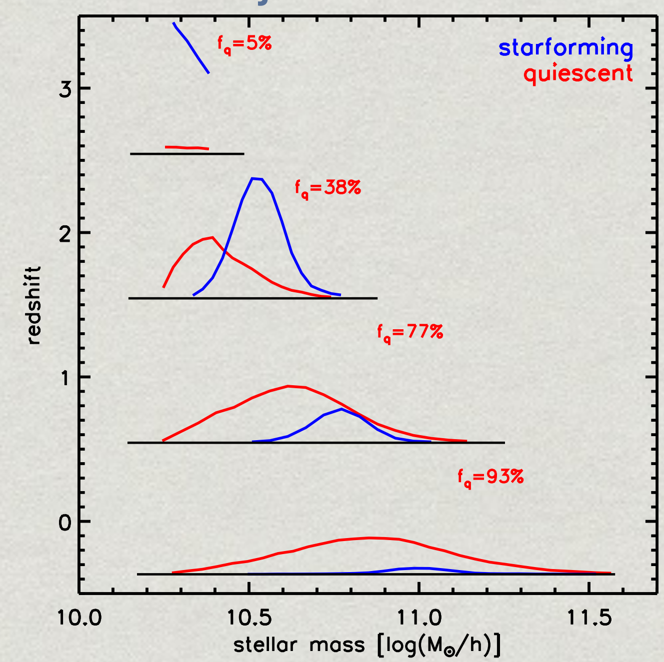
Abundance matching

Behroozi et al 2013

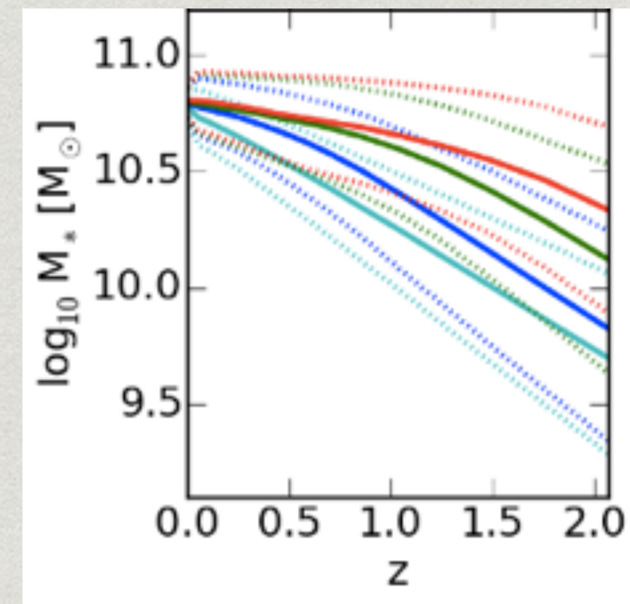


Semi-analytical modeling

Leja et al 2013

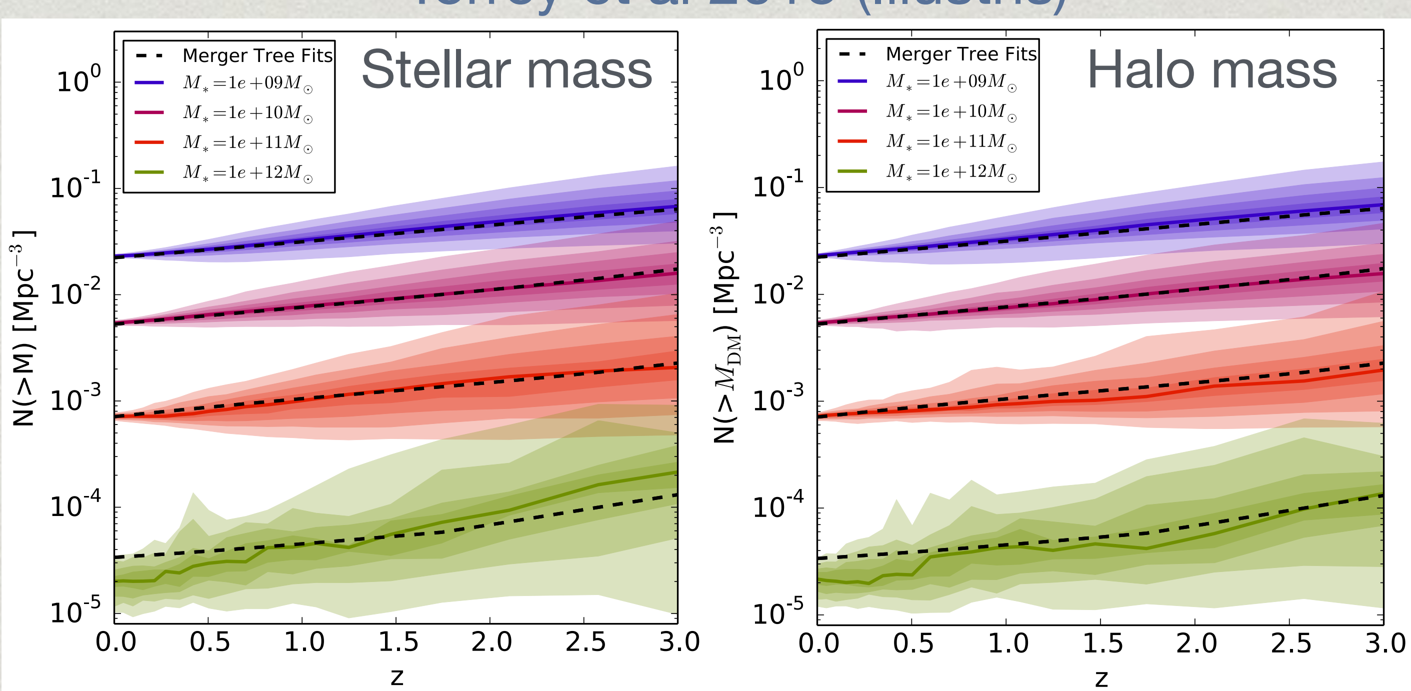


Terrazas et al 2016

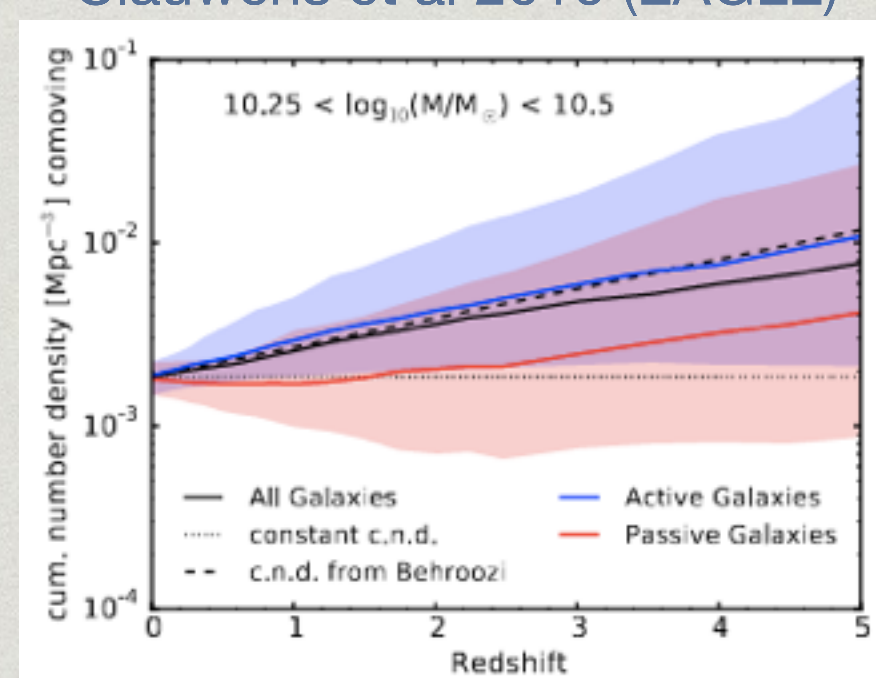


Hydrodynamical simulations

Torrey et al 2015 (Illustris)



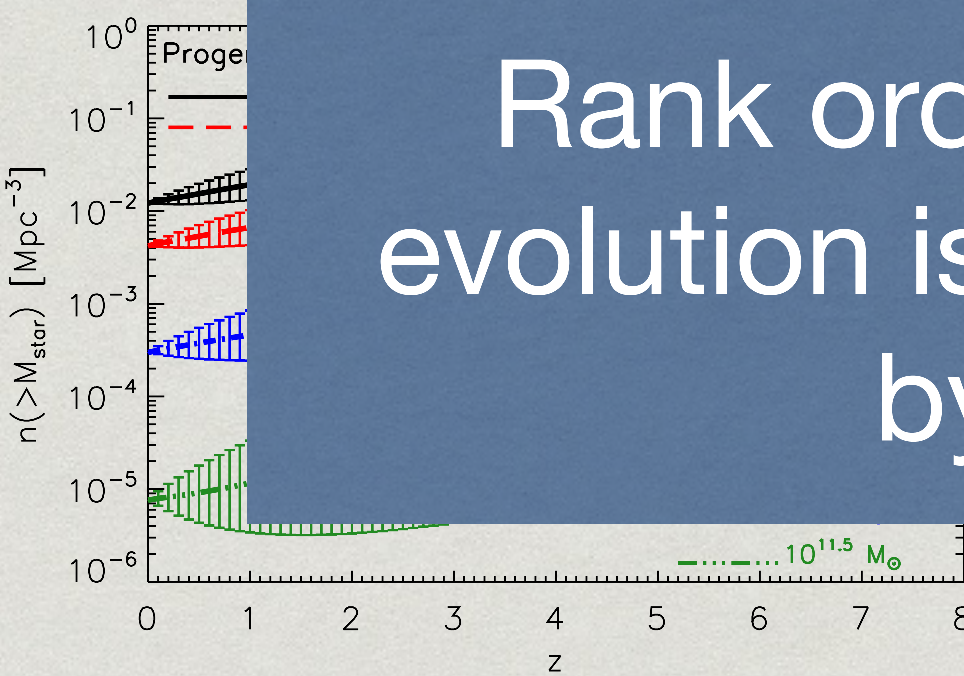
Clauwens et al 2016 (EAGLE)



The predicted evolution in number density is remarkably consistent across theoretical methodologies and ranking quantities

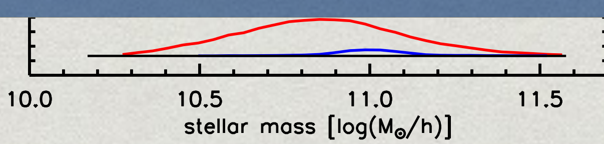
Abundance matching

Behroozi et al 2013

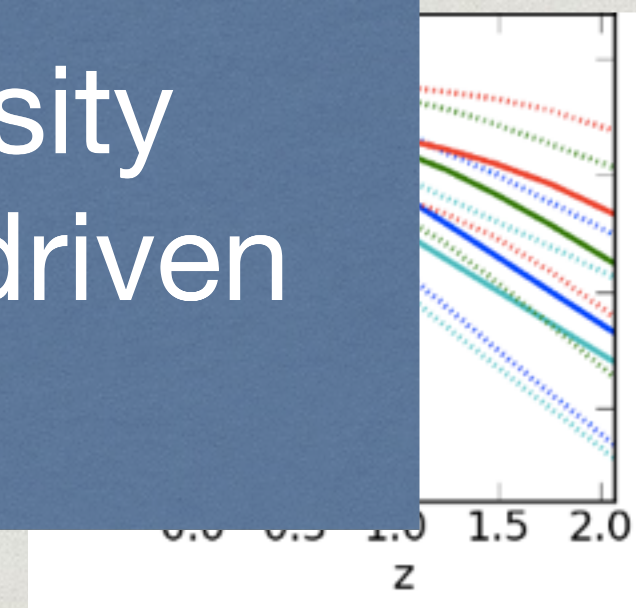


Semi-analytical modeling

Leja et al 2013

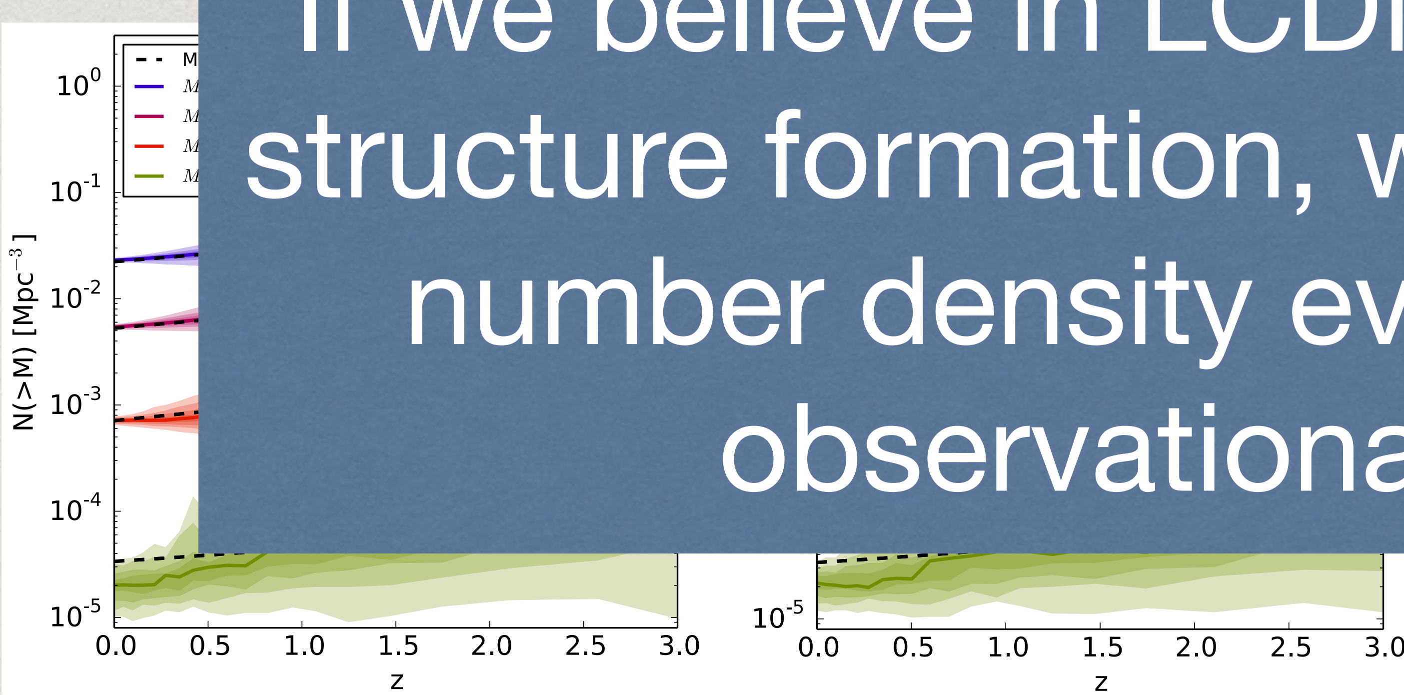


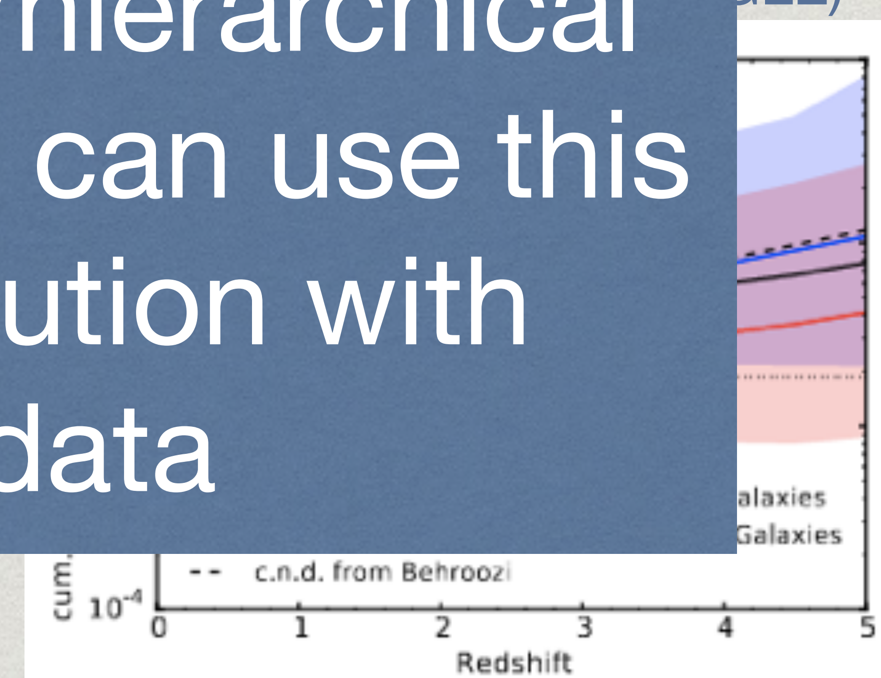
Terrazas et al 2016



Rank order / number density evolution is fundamentally driven by dark matter

GLE)





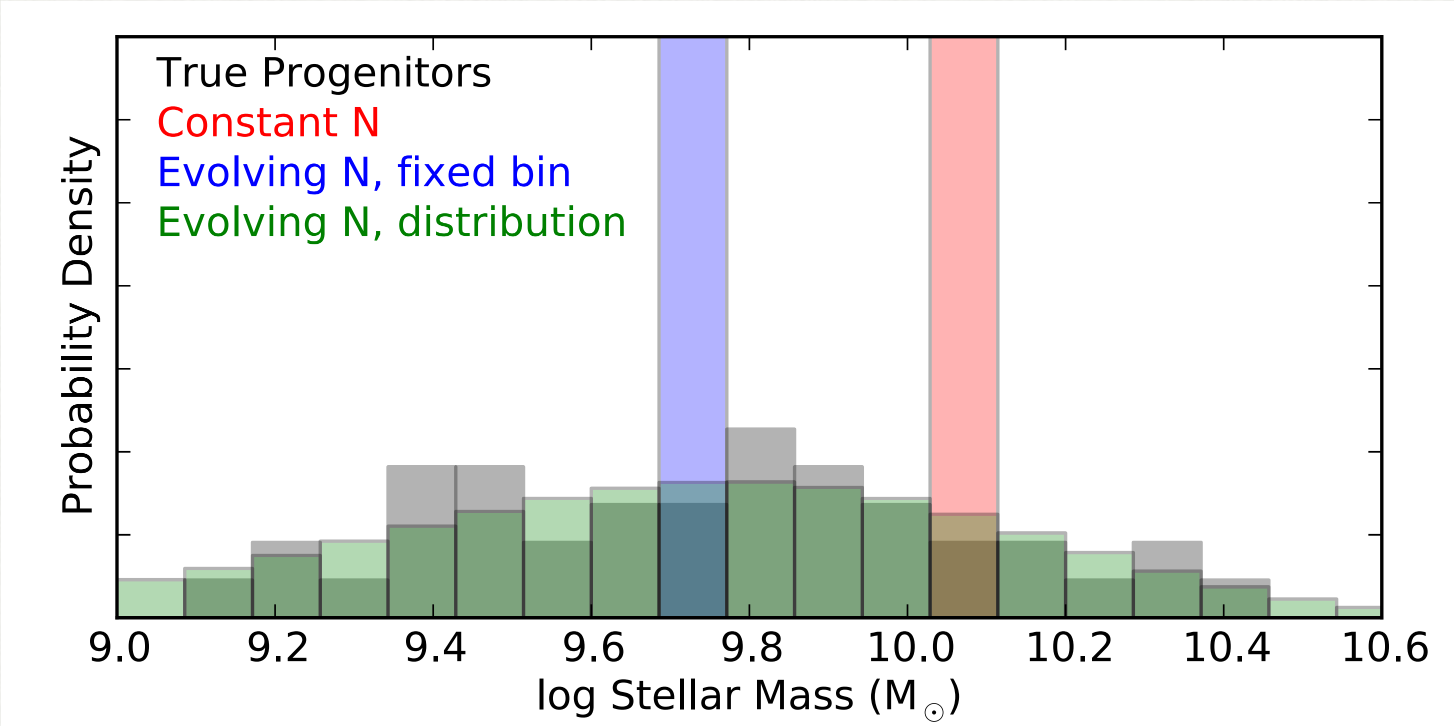
If we believe in LCDM/hierarchical structure formation, we can use this number density evolution with observational data

(Wellons & Torrey, submitted)

How can we do better?

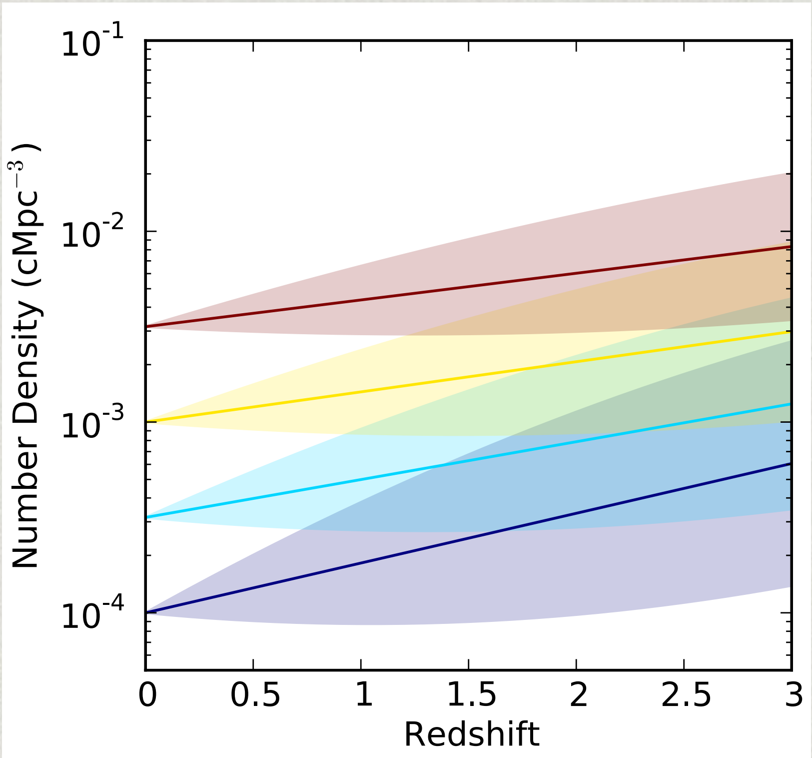
Use an evolving number density as the center of a distribution

Predictions for z=2 progenitors of Milky-Way-mass galaxies:



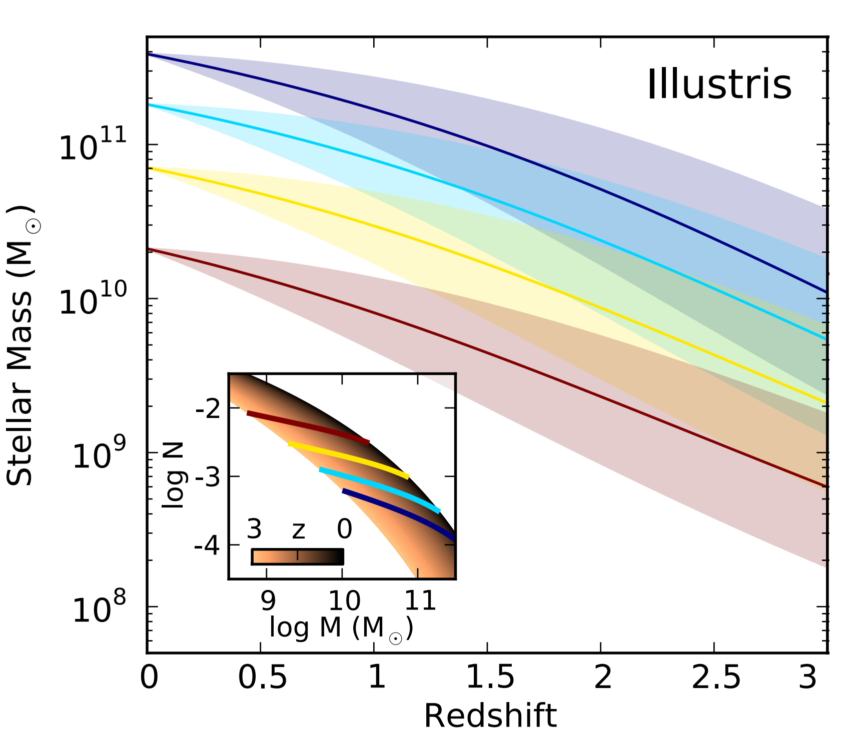
Requires:

Functions for $N(N_0, z_0, z)$ and $\sigma_{\log N}(N_0, z_0, z)$



[Illustris - Torrey, Wellons et al, submitted]

Cumulative mass functions N(M, z)



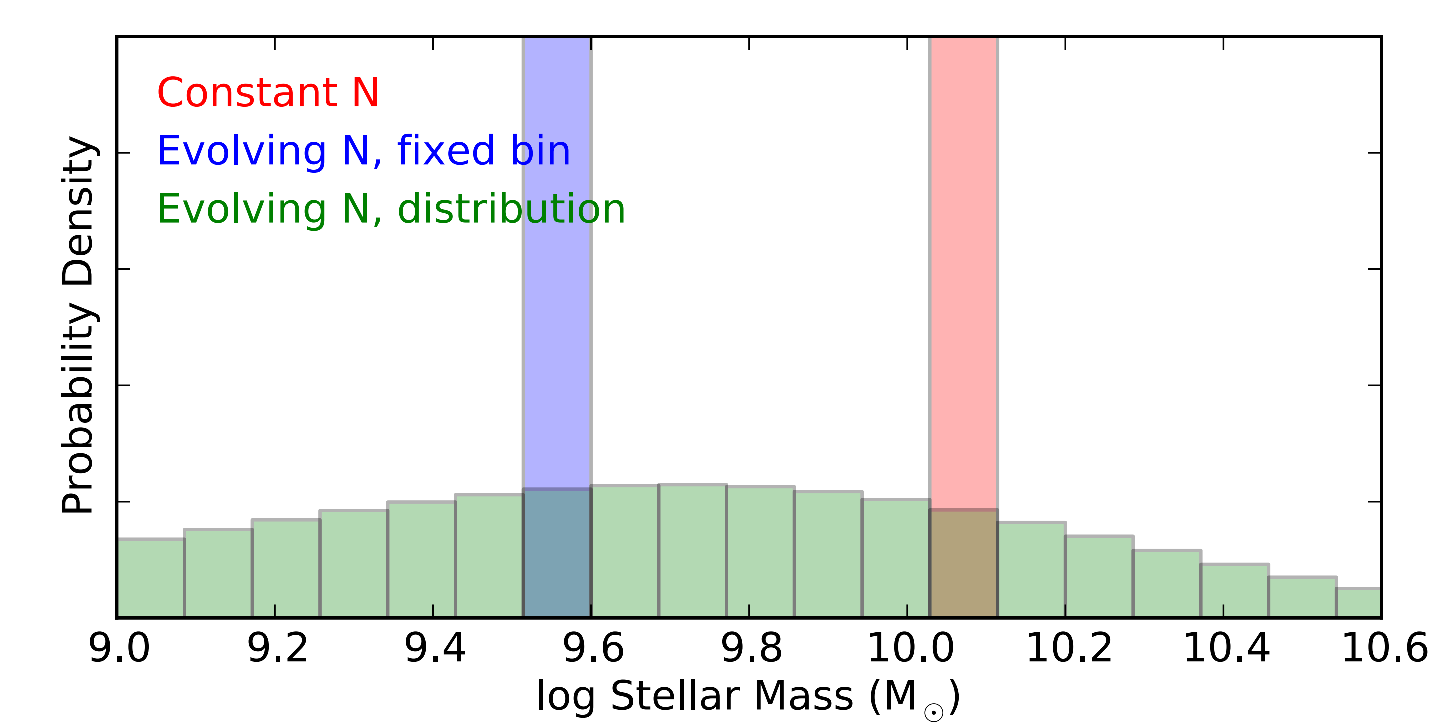
[Illustris - Torrey et al 2015]

(Wellons & Torrey, submitted)

How can we do better?

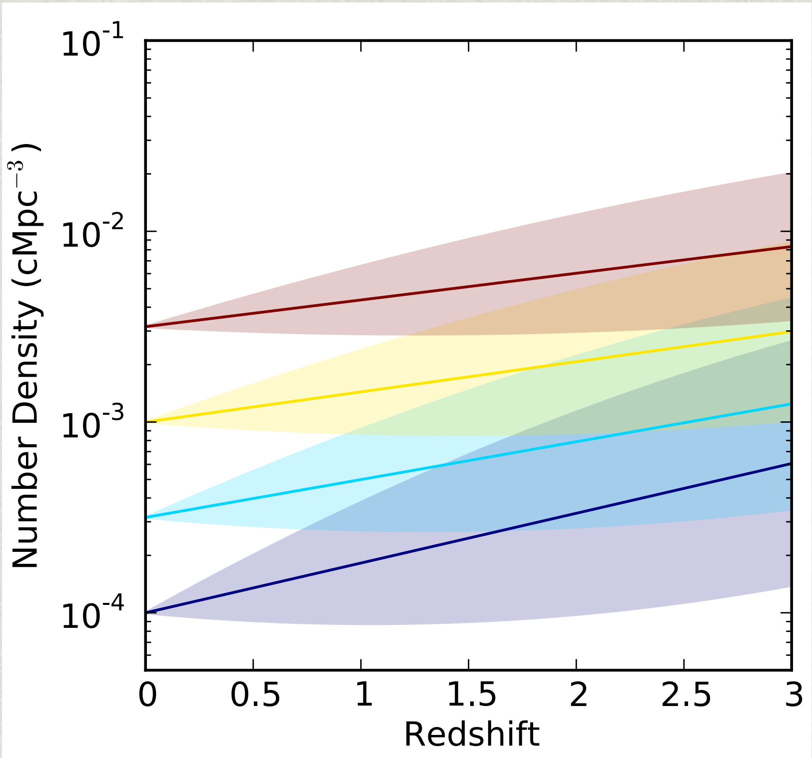
Use an evolving number density as the center of a distribution

Predictions for z=2 progenitors of Milky-Way-mass galaxies:



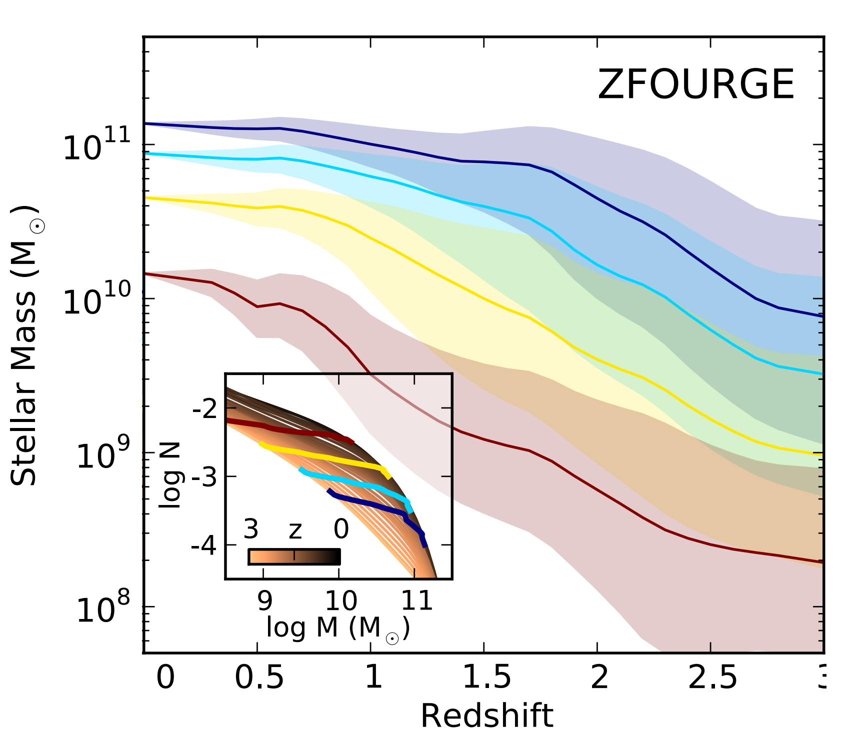
Requires:

Functions for $N(N_0, z_0, z)$ and $\sigma_{\log N}(N_0, z_0, z)$



[Illustris - Torrey, Wellons et al, submitted]

Cumulative mass functions N(M, z)

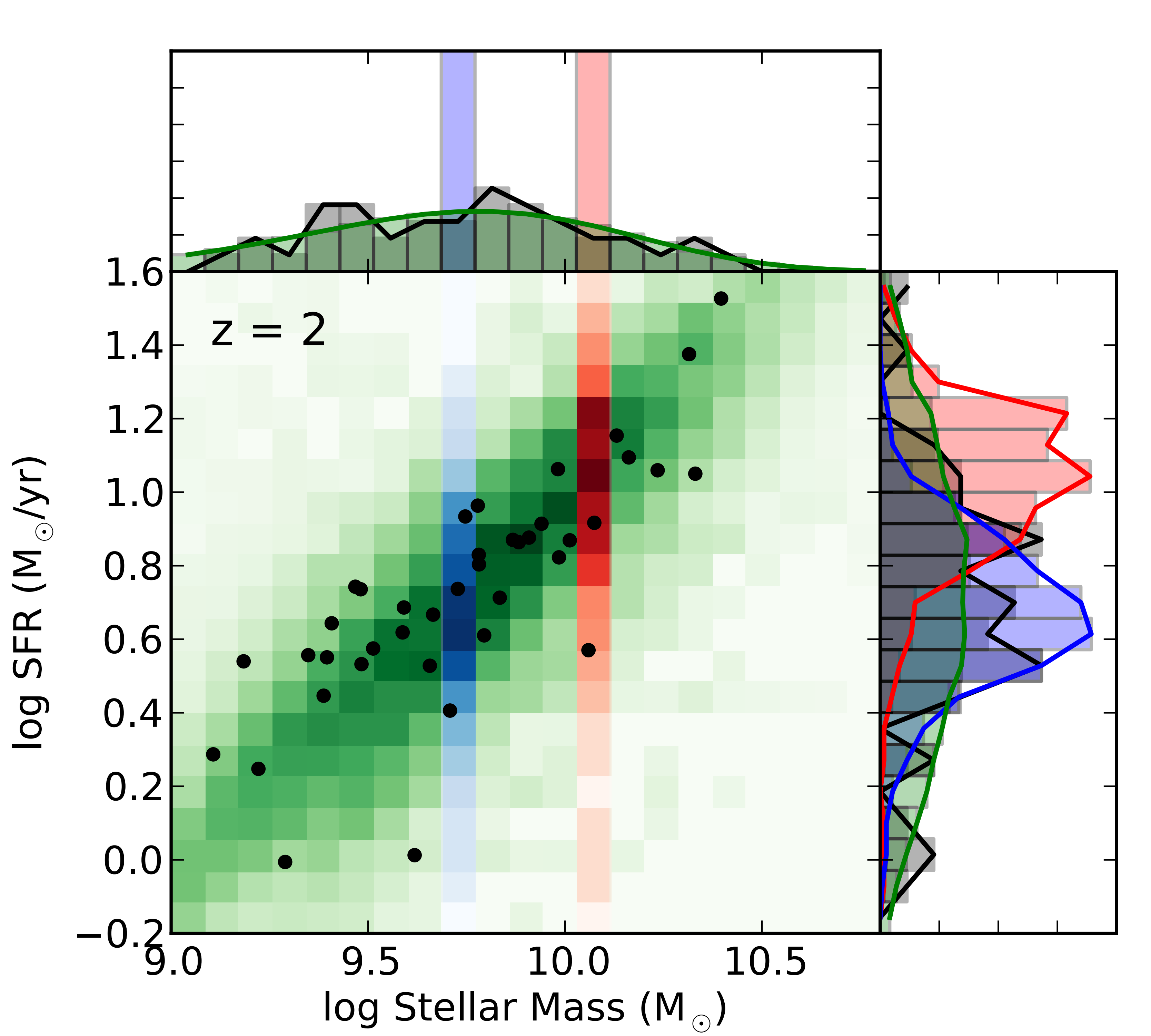


[ZFOURGE - Tomczak et al 2014]

How can we do better?

(Wellons & Torrey, submitted)

Distribution in mass -> distribution in other quantities

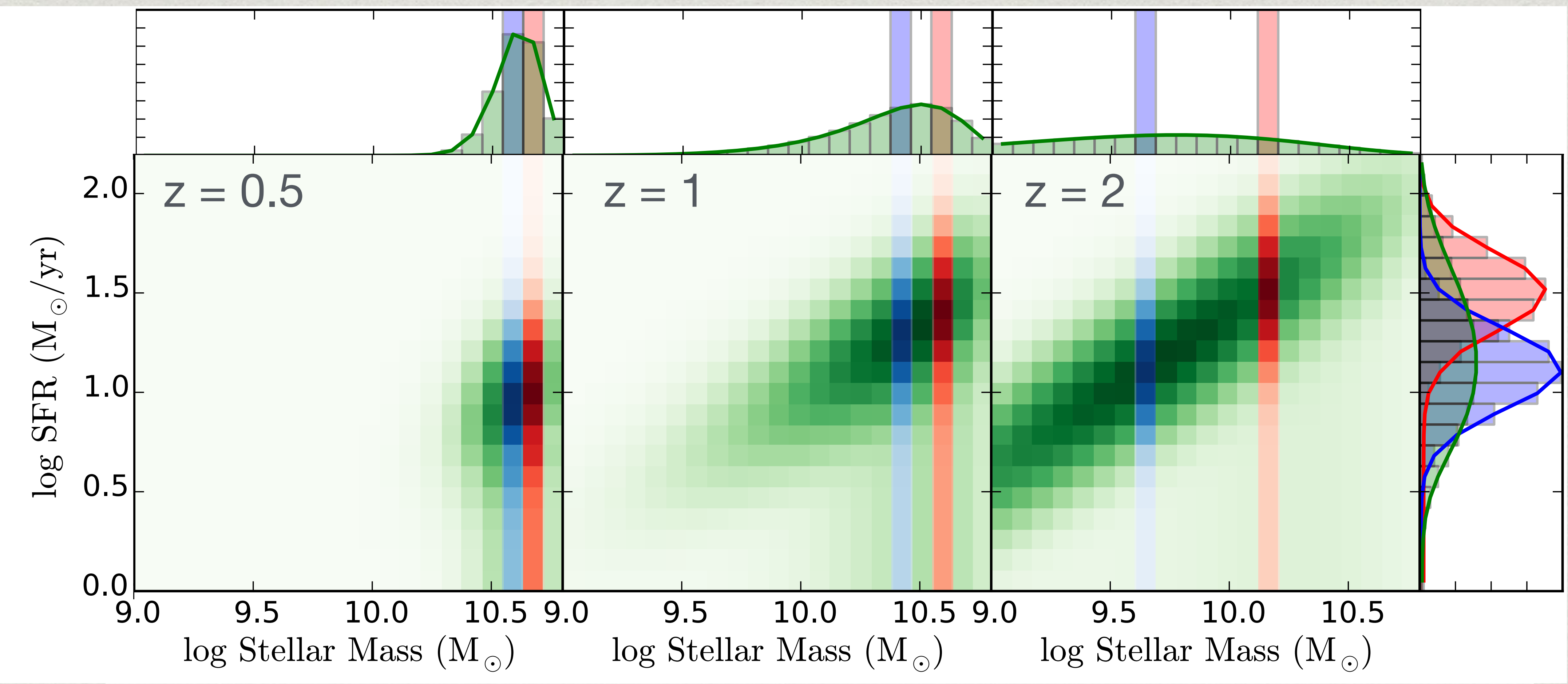


(Wellons & Torrey, submitted)

How can we do better?

The same prediction can be generated from observational data (using my Python package at https://github.com/sawellons/NDpredict) given:

- Measurements of galaxy stellar masses and star formation rates at several redshifts
- A set of observational mass functions at those redshifts



Recap

Wellons et al 2015

- We found a sample of compact galaxies at z=2 in Illustris which are reasonable analogs to observed compact ellipticals.
- The compactness at z=2 is driven by centralized bursts of star formation and/or an early formation time.

Wellons et al 2016

- About half of the compact galaxies exist as the core of their more massive descendant at z=0, a quarter are essentially undisturbed, and a few are mixed or consumed in major mergers.
- Both the progenitors and descendants are widely dispersed in stellar mass and experienced a variety of evolutionary paths, implying that galaxy rank order is not conserved.

Wellons & Torrey, submitted

- Connecting galaxy populations between redshifts can be improved with the use of an evolving distribution in number density.