UNIVERSIDAD DE ANTIOQUIA
1803

Sterrewacht Leiden

The large-scale structure of the Universe

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AstroTwinCoLo (Virtual) School 2020

Previous class: The dependence of clustering on galaxy properties

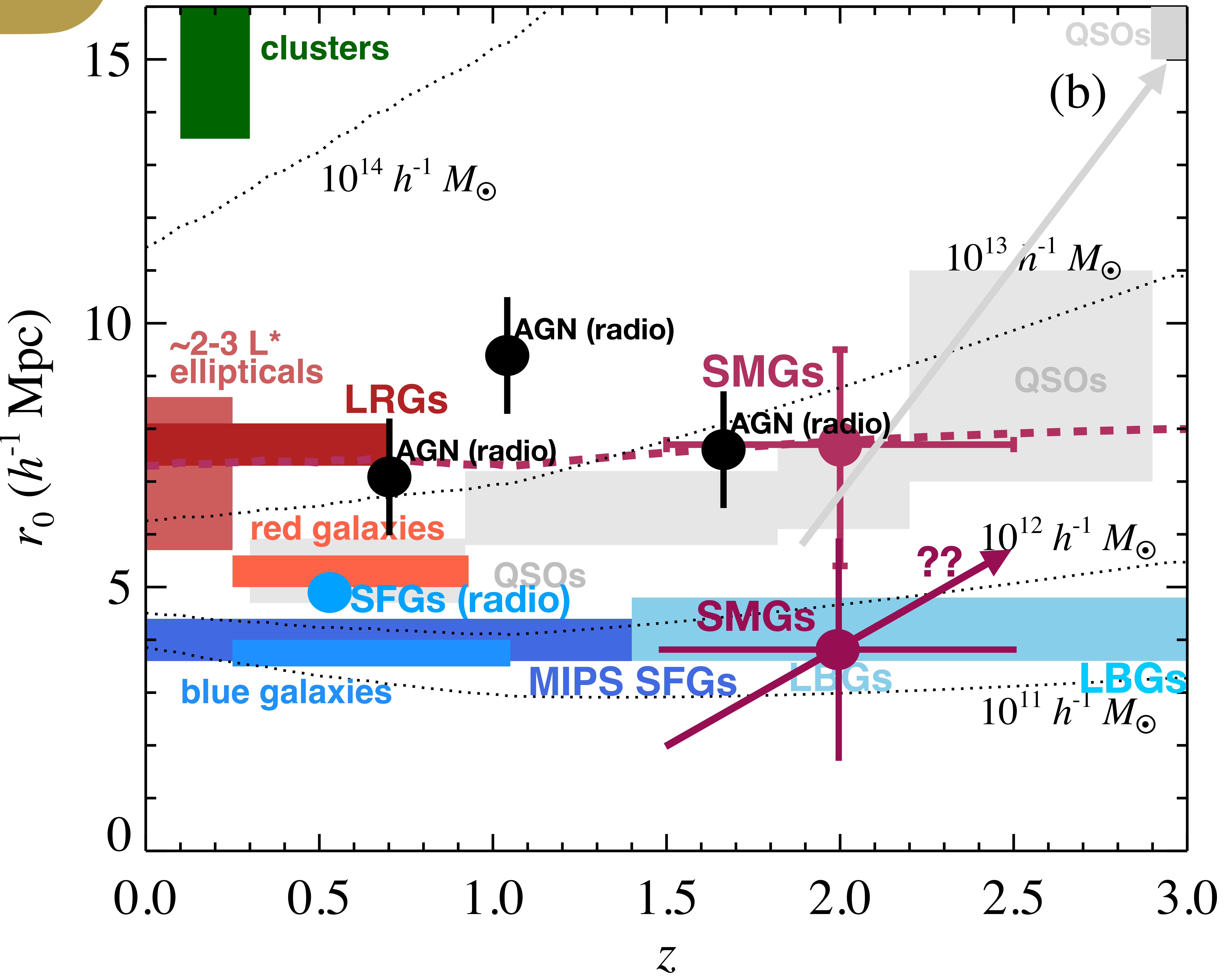
The two-point correlation function depends on galaxy properties.

More luminous		less luminous	
Optically red		optically blue	
Early-type	…galaxies are more clustered than the…	late-type	galaxies
Bulge-dominated		disk-dominated	
Higher stellar mass		lower stellar mass	
Low sSFR		higher sSFR	

(at a fixed redshift)

Previous class: The dependence of clustering on galaxy properties

(Adapted from Hickox et al. 2012)



- Against of the intuitive expectation in which the clustering of a population would increase with time, we observe that some population are equally clustered over long times and some of them decrease their clustering with time.

This class: Interpreting clustering measurements

- How can we interpret the different r_0 values for different populations?
- How can we interpret the evolution of r_0 with redshift for the different populations?
- How can we translate r_0 measurement to dark matter halos estimations?
- Can we build a coherent evolutionary scenario using clustering measurements?

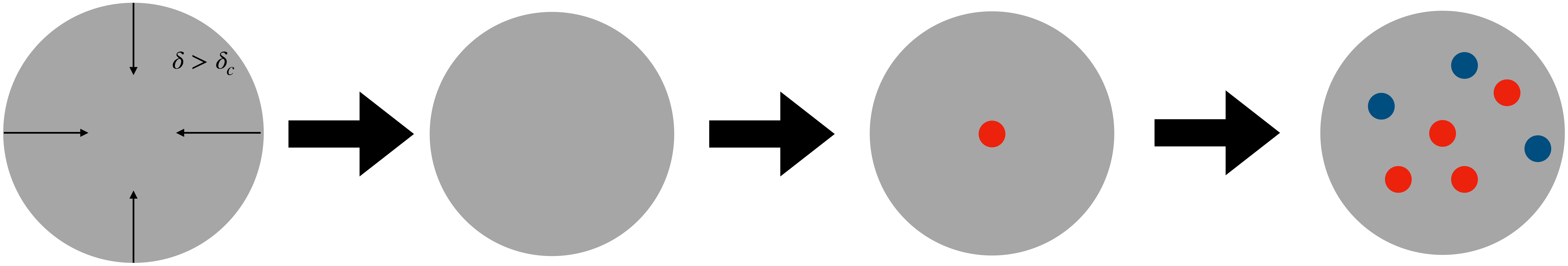
How can we interpret all these r_0 measurements?

To understand this, we need to review the basics of the growth of structure in the universe.

Let's remember lecture 1: Dark matter distribution at three different epochs.

▶ Matter overdensities grow over time and become more and more overdense.

How can we interpret all these r_0 measurements?



- At some point material start to collapse to form dark matter halos.
- Galaxies form in these dark matter halos

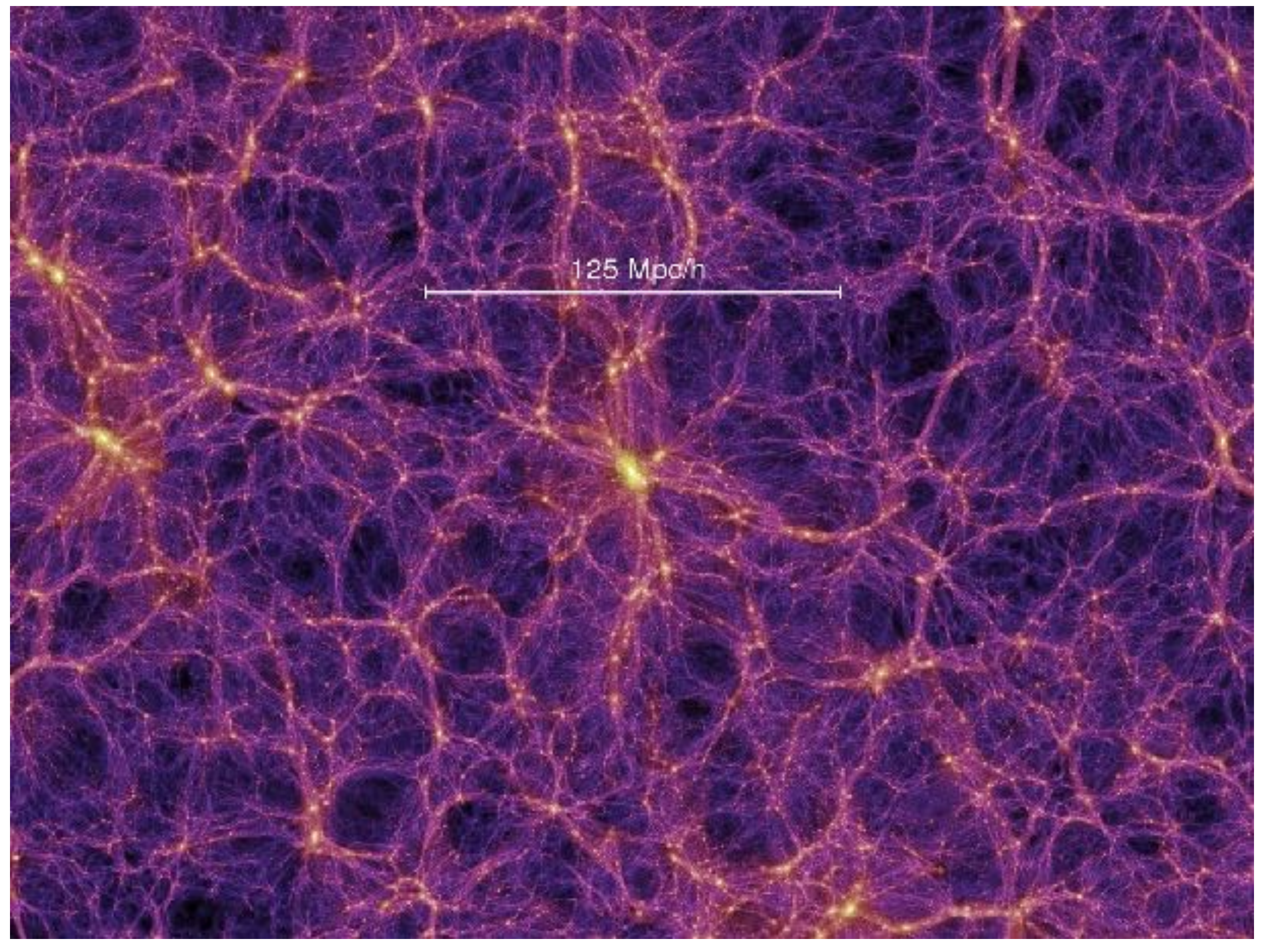
How to relate clustering of galaxies with the distribution of matter in the universe?

Matter is composed by baryonic and dark matter, with dark being dominant. But, we only can directly observe baryonic (luminous) matter and therefore only measure clustering for it.

Does the total matter have the same distribution of luminous matter?

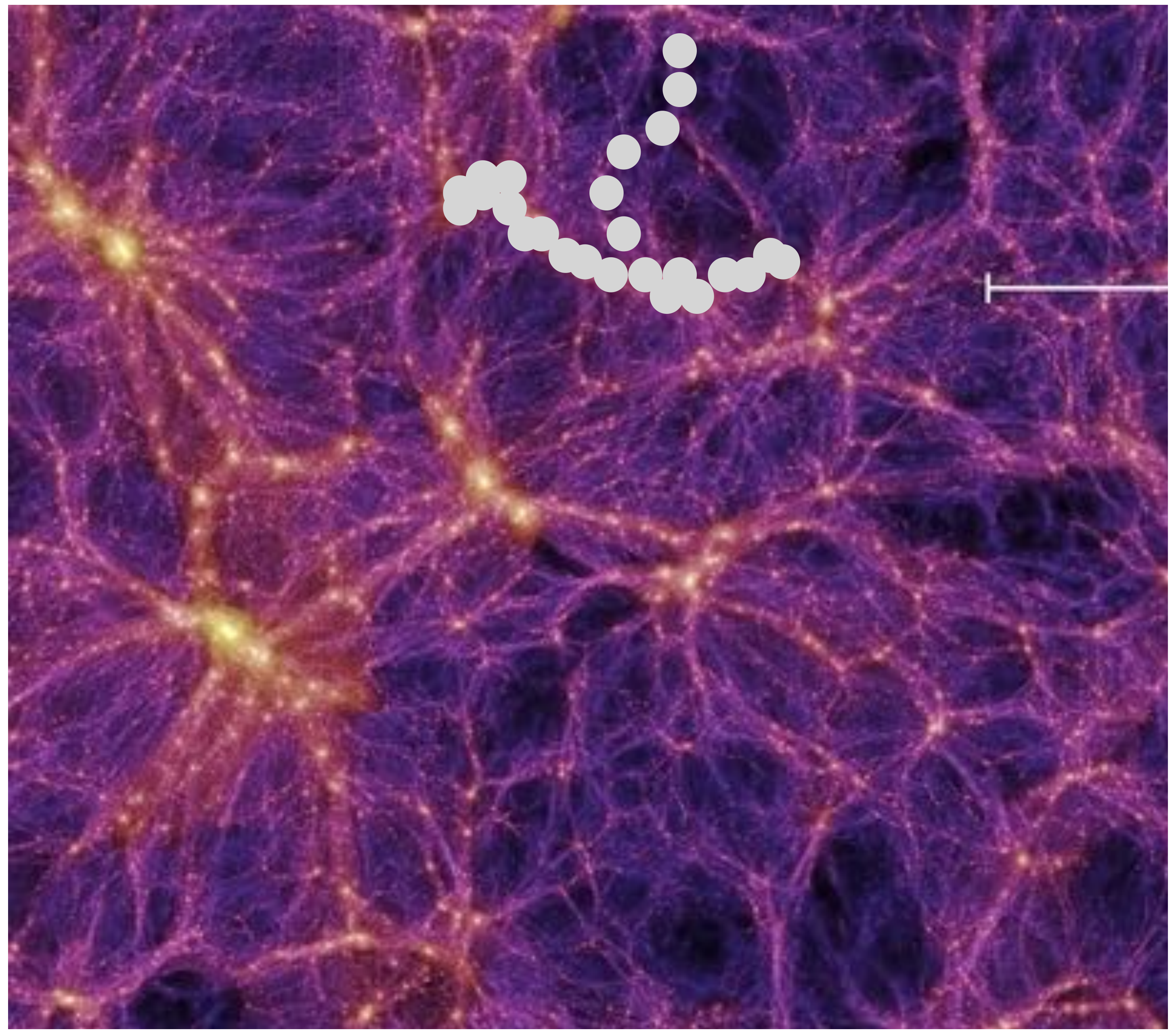
If the answer is yes: nice! we can just measure the clustering of galaxies, and then we can learn about dark matter distribution.

However the answer is: more or less but not completely.



Why the distribution of galaxies is not the same as the distribution of dark matter?

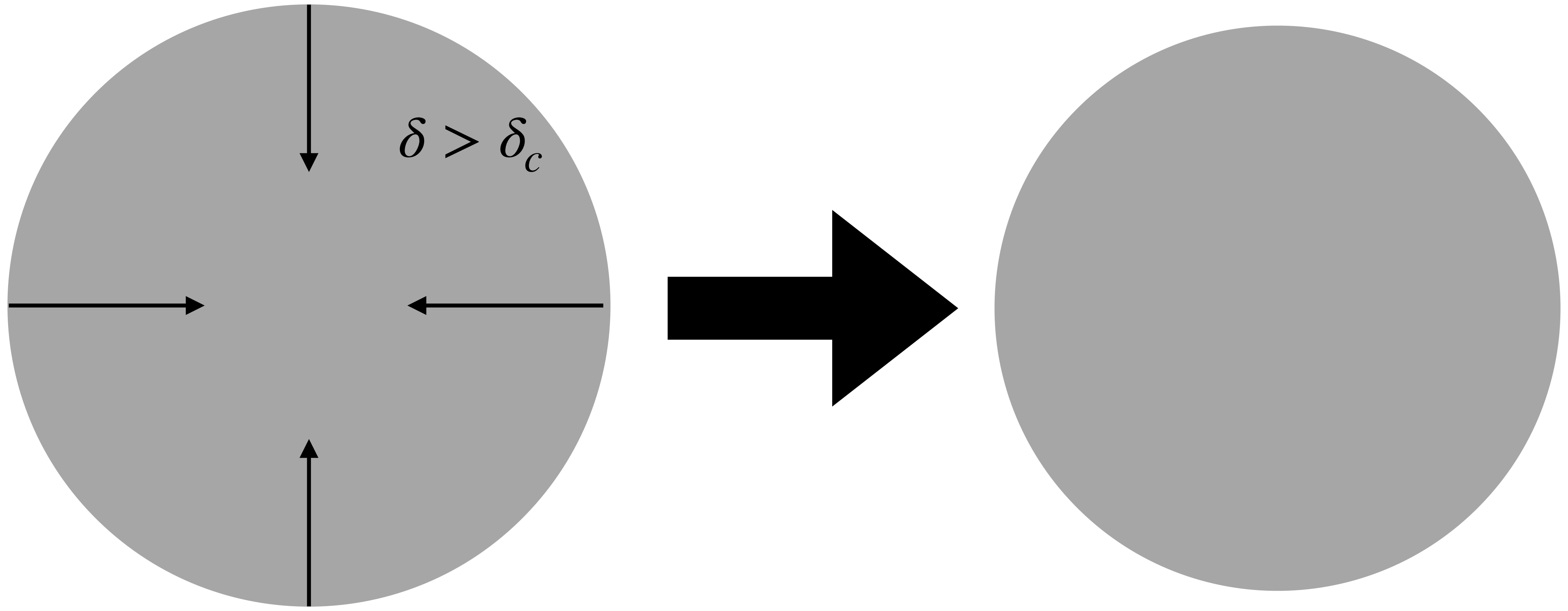
Since dark matter halos are made of dark matter, intuitively we could think that the number density of dark matter halos is proportional to the matter density, and then we could think that the distribution of dark matter halos is the same as the distribution of dark matter.



In this case we could say that **dark matter halos are unbiased tracers of dark matter**, and given that galaxies form in dark matter halos, then we could say that **the number density of galaxies and their distribution are unbiased tracers of dark matter**, i.e light traces matter.

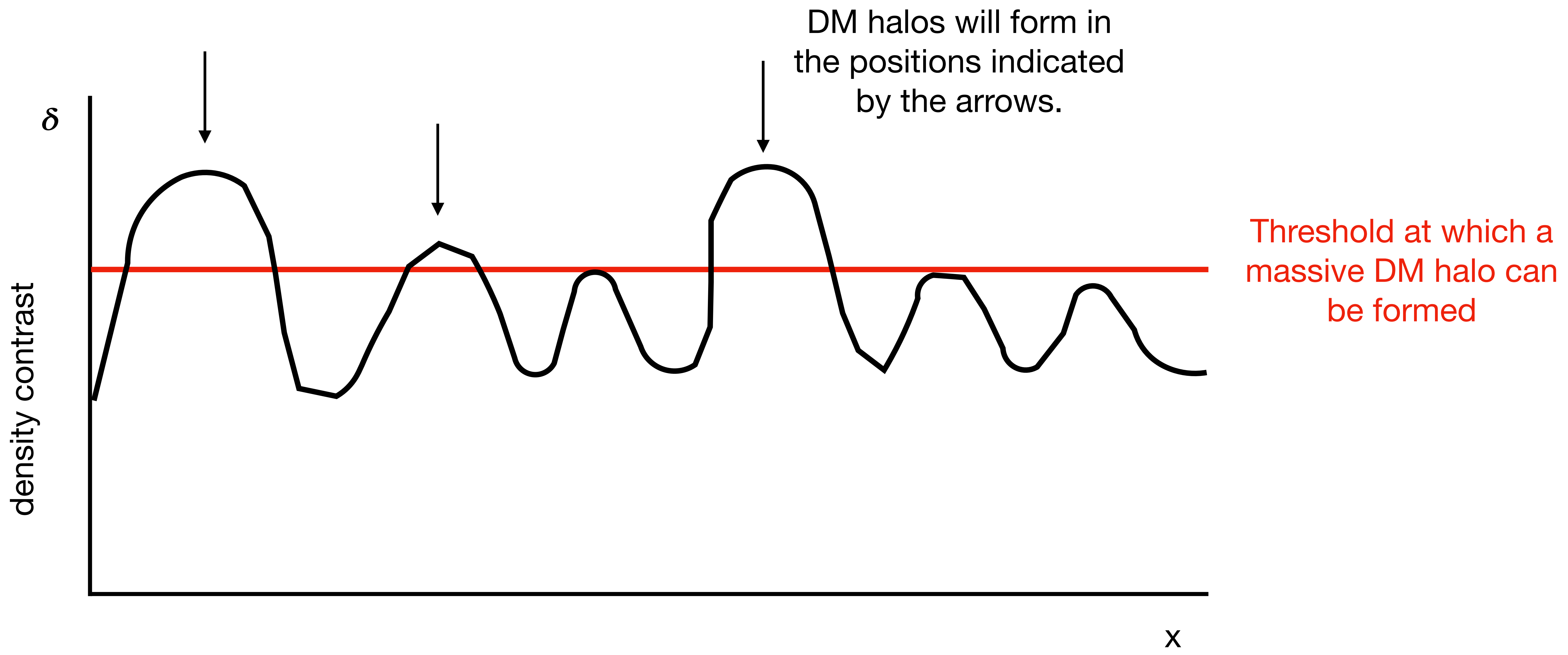
Why the distribution of galaxies is not the same as the distribution of dark matter?

- However, **not even dark matter halos are unbiased tracers of dark matter**, because a dark matter halo of certain mass only can be formed under certain conditions, that are not fulfilled in all the overdensities of dark matter.
- Dark matter halos of certain mass form when the density contrast δ reach a certain threshold, such that gravity is high enough in that region.



Why the distribution of galaxies is not the same as the distribution of dark matter?

If we imagine that dark matter distribution (represented by the solid line) only have small-scale fluctuations in the density field, we would have this situation:



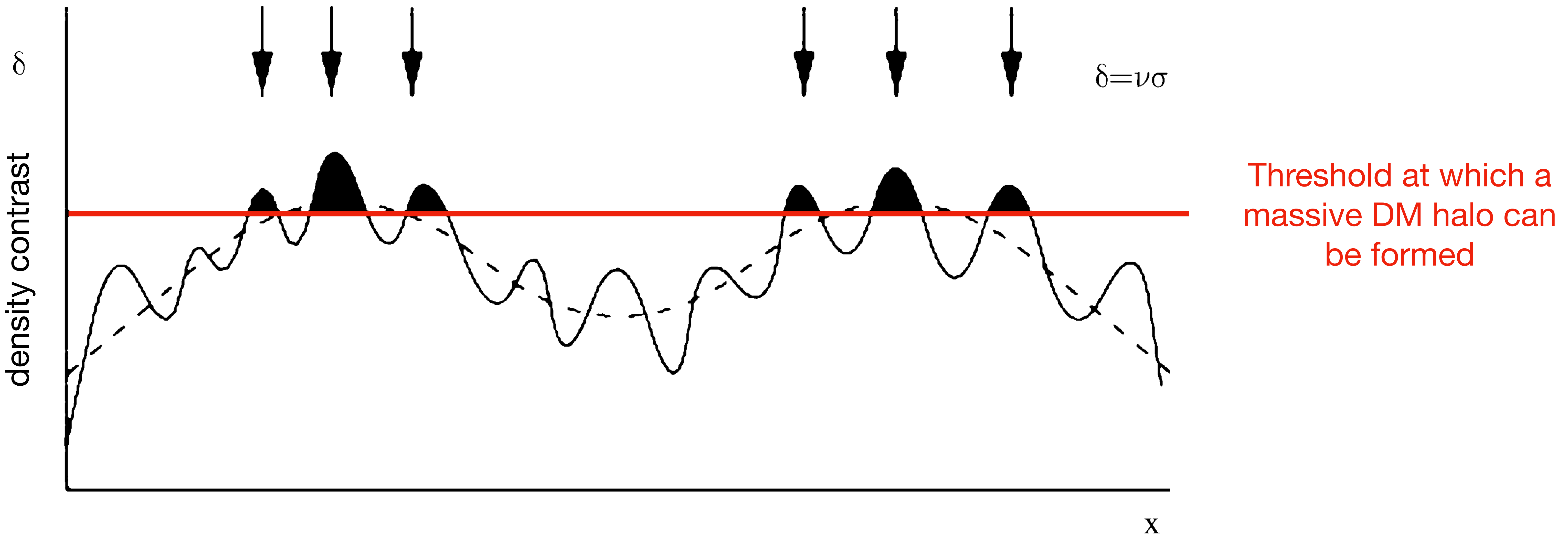
Massive DM halos can be formed on the position where small-scale fluctuations of matter are large. If the fluctuation is small, massive DM halos cannot be formed.

If this were the case, then dark matter halos would trace dark matter distribution: Halos form in locations where there is more dark matter.

Distribution of dark matter halos (which are the locations where a galaxy can be formed) is not the same as the distribution of dark matter.

However, there are also large-scale fluctuations in the density field (represented as a dashed line):

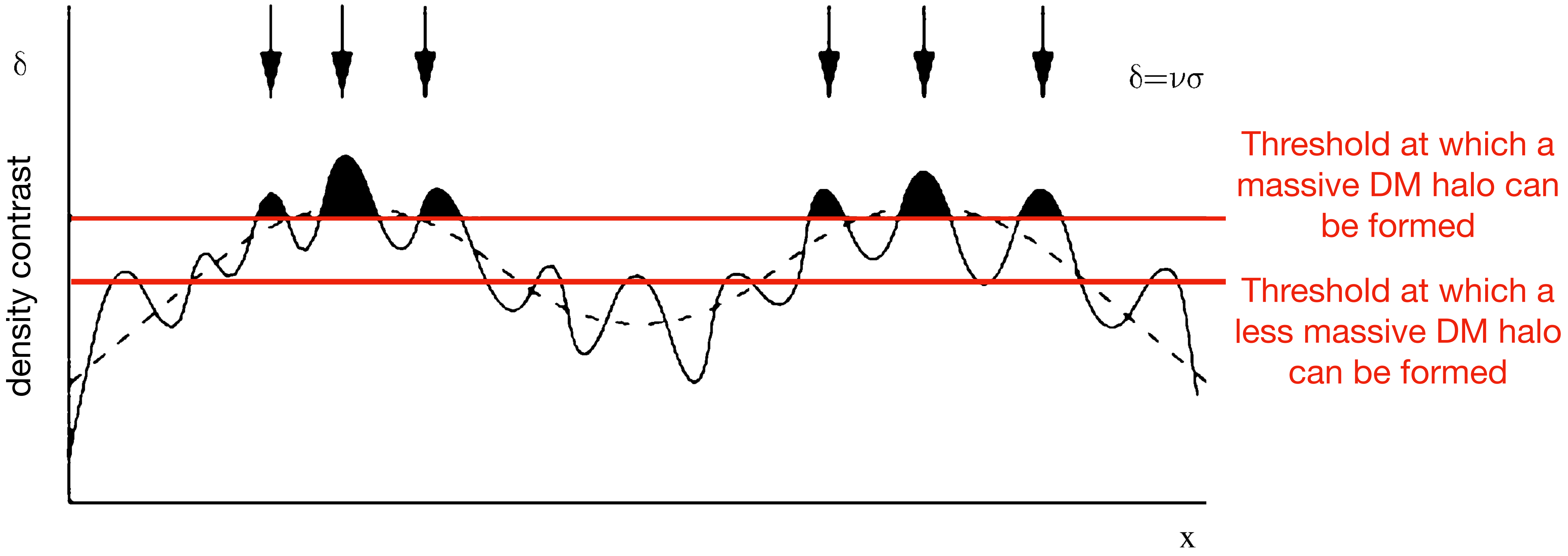
Large-scale fluctuations can push small fluctuation over the threshold needed to form a halo.



Massive DM halos can be formed even on the positions of small dark matter fluctuations. On the position of large matter fluctuation massive DM halos will not necessarily be formed.

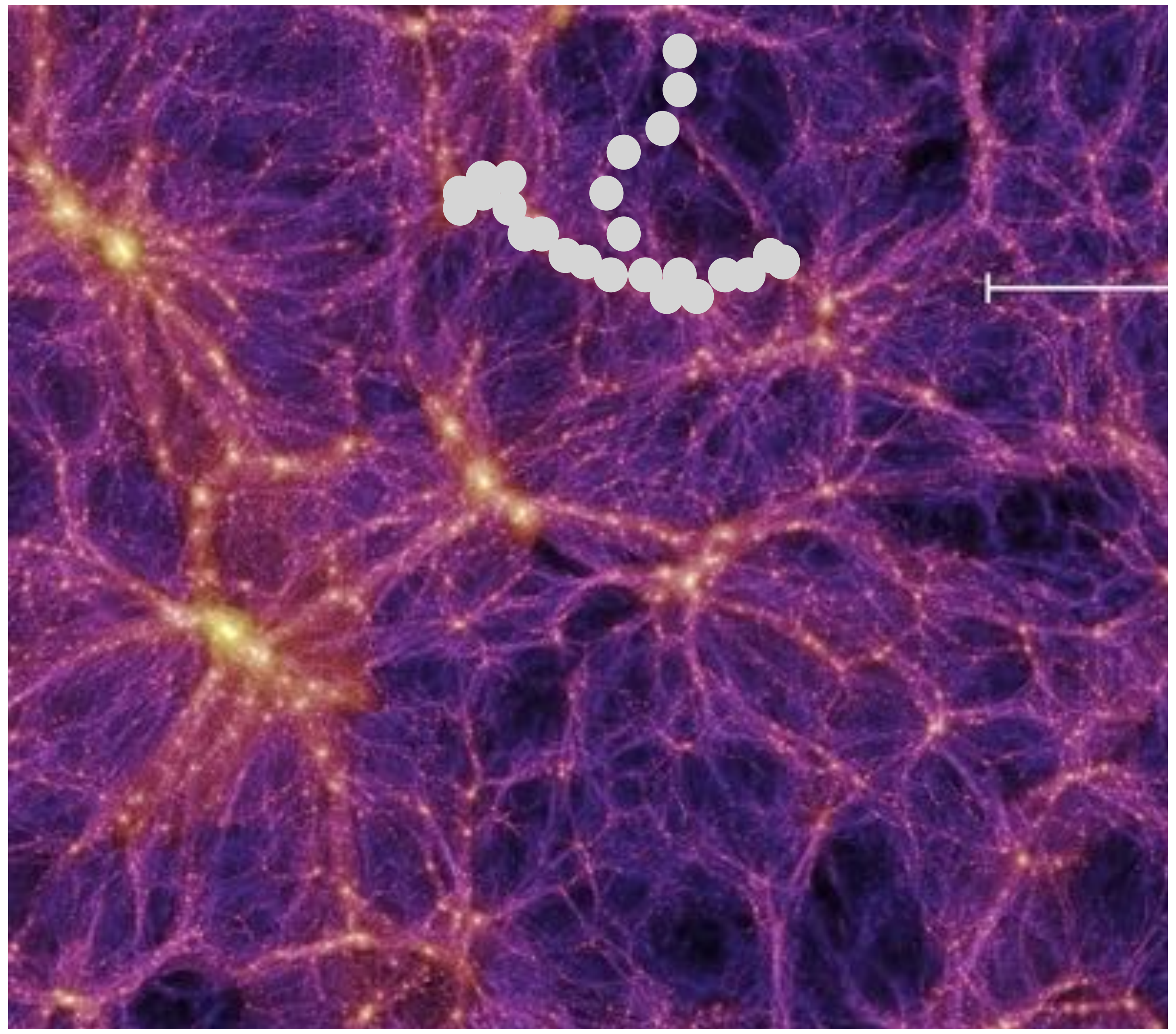
Distribution of dark matter halos (which are the locations where a galaxy can be formed) is not the same as the distribution of dark matter.

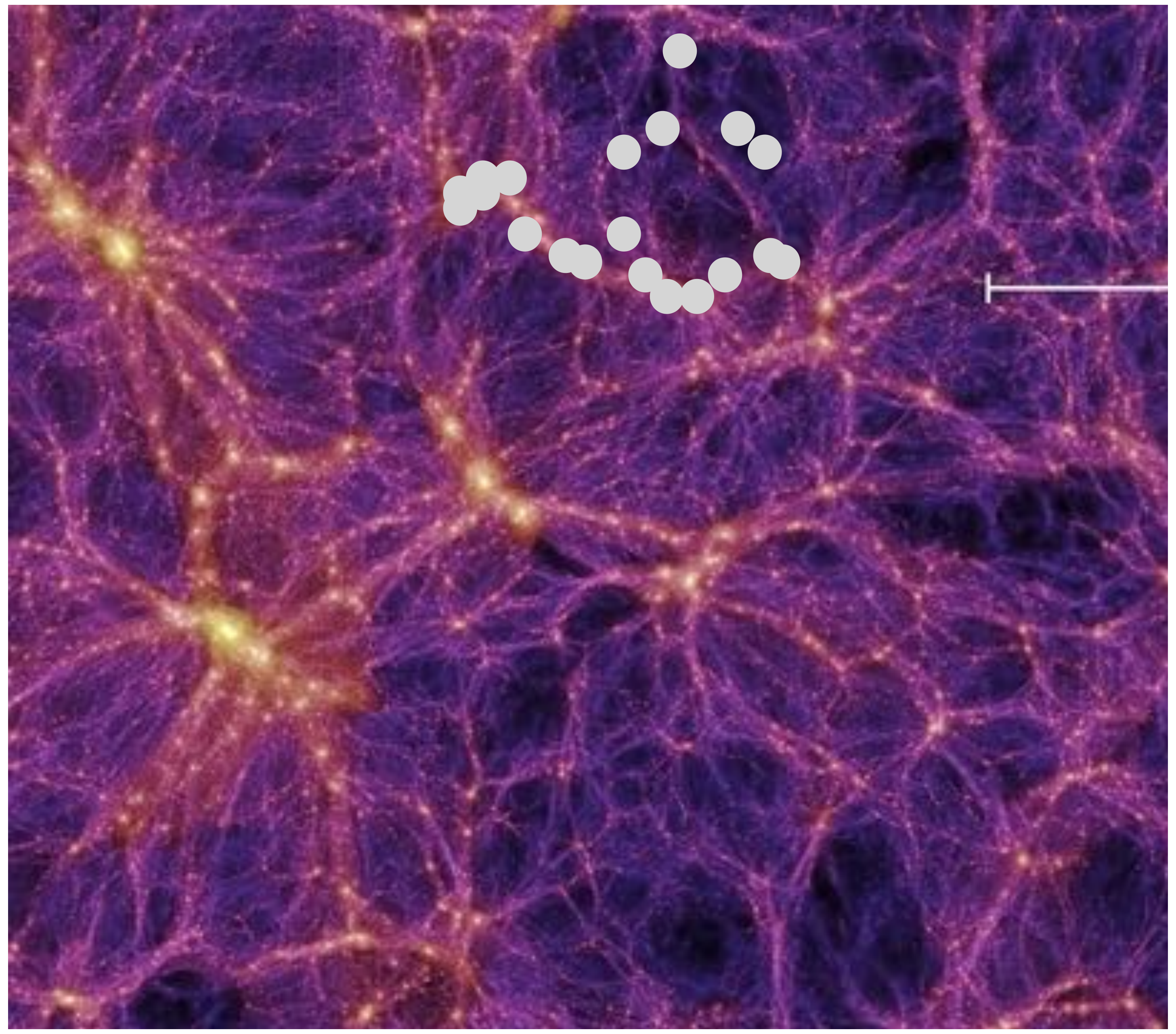
Dark matter halo distribution (and therefore the galaxy distribution) do not follow exactly the distribution of dark matter. Dark matter halos are said to be biased tracers of the underlying dark matter distribution.



The most massive dark matter halos are expected to trace worst the dark matter density distribution (because they only form where large scale fluctuations are high) and be the most biased. Less massive halos will trace better the dark matter distribution, and they are less biased.

Distribution of dark matter halos (which are the locations where a galaxy can be formed) is not the same as the distribution of dark matter.





- In the example shown before, this means that massive halos will not be formed in all the massive matter overdensitites, and that some massive halos can be formed even in not so massive dark matter regions (if they are just located over a large scale dark matter fluctuation).

As a result, dark matter halos do not follow exactly dark matter distribution, but they more or less follow it: **dark matter halos are biased tracers of dark matter.**

The most prominent peaks in the density field at the early universe will be the location of the most massive protoclusters that will evolve into massive clusters at z=0

- Also remember: Not all the halos will be formed at the same time. If in some regions the critical density condition is reached at earlier times, then that halo will start forming first.

- These halos will be the location of the most massive galaxy clusters in the local universe.

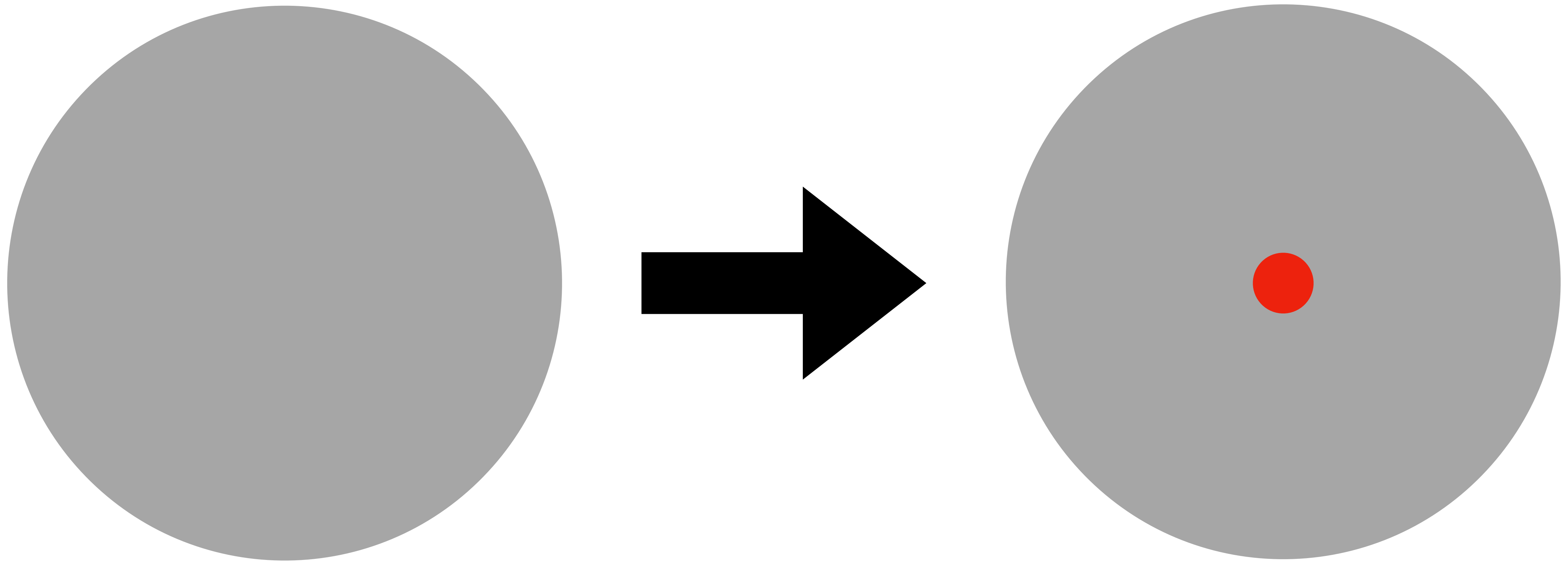
- How can we identify these locations in the universe where the first halos formed? (tracers of matter overdensities) ⟶ See Lecture 5

Is the distribution of galaxies the same as the distribution of dark matter halos?

Since dark matter halo do not exactly trace the dark matter distribution, this implies that galaxies do not exactly trace the dark matter distribution.

But now, Does galaxies trace the dark matter halo distribution? In general yes since galaxies only can be formed in collapsed dark matter halos. This would imply that the clustering of galaxies should reflect the clustering of dark matter halos.

$$\xi_{gal}(r) \sim \xi_{DMhalo}(r)$$



*galaxy bias ~ dark matter halo bias

Distribution of galaxies is not equal to the distribution of matter but it is biased to it

Galaxy bias (b_g): the relationship between the spatial distribution of galaxies and the underlying dark matter density field.

$$\delta_g = b_g \delta_{DM}$$

Galaxies are biased tracers of the underlying total mass field

Remember from Lecture 1 the definition of correlation function in terms of overdensity:

$$\xi(r) = \langle \delta_x \delta_y \rangle$$

Therefore we can write the bias of galaxies as a function of the dark matter and galaxy correlation function:

$$b_g = \sqrt{\xi_g / \xi_{DM}}$$

If a population is less biased than other (have a lower bias value), this will follow more exactly the the dark matter distribution. If the population is more biased this will be a worst tracer of the dark matter distribution

How do we measure the bias?

- The only measurable quantity from observations is the correlation function of galaxies, parametrized by r_0 and γ.

- The only way to determine the correlation function of DM is using cosmological N-body simulations. They provide the clustering amplitude of DM halos as a function of their mass.

- The computed bias depend on the cosmological model assumed in the simulation.

$$b_g = \sqrt{\xi_g / \xi_{DM}}$$

ξ_{DM}: Determined from simulations

ξ_g: Measured from observations, given by the r0 and γ parameters

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

How do we measure the halo mass?

- The clustering amplitude of dark matter halos as a function of halo mass is well determined in N-body simulations. We can therefore know what is the mass of a halo given their clustering.

- If we assume that the clustering of dark matter halos is the same as the clustering of galaxies (which is the measurable quantity) then we can obtain the mass of these halos using simulations.

- There are analytical fitting formula to compute the dark matter mass using bias (e.g. Mo & White 1996, Sheth et al. 2001)

$$b_g = \sqrt{\xi_g / \xi_{DM}}$$

ξ_g: from observations ξ_{DM}: from simulations

$$b_g \longrightarrow M_{DMhalo}$$

from simulations (or the analytical fitted form)

Clustering measurements allow us to know the halo mass of the dark matter halos where the objects live.

Particularly, a population with higher bias means that the population live in more massive dark matter halos

Relative bias

If the goal is only to study dependence of clustering with different properties of galaxies (at a fixed redshift), we can compute the relative bias between populations:

$$b_1 = \sqrt{\xi_1/\xi_{DM}}$$

$$b_2 = \sqrt{\xi_2/\xi_{DM}}$$

$$\frac{b_1}{b_2} = \sqrt{\frac{\xi_1}{\xi_2}}$$

Independent of simulations

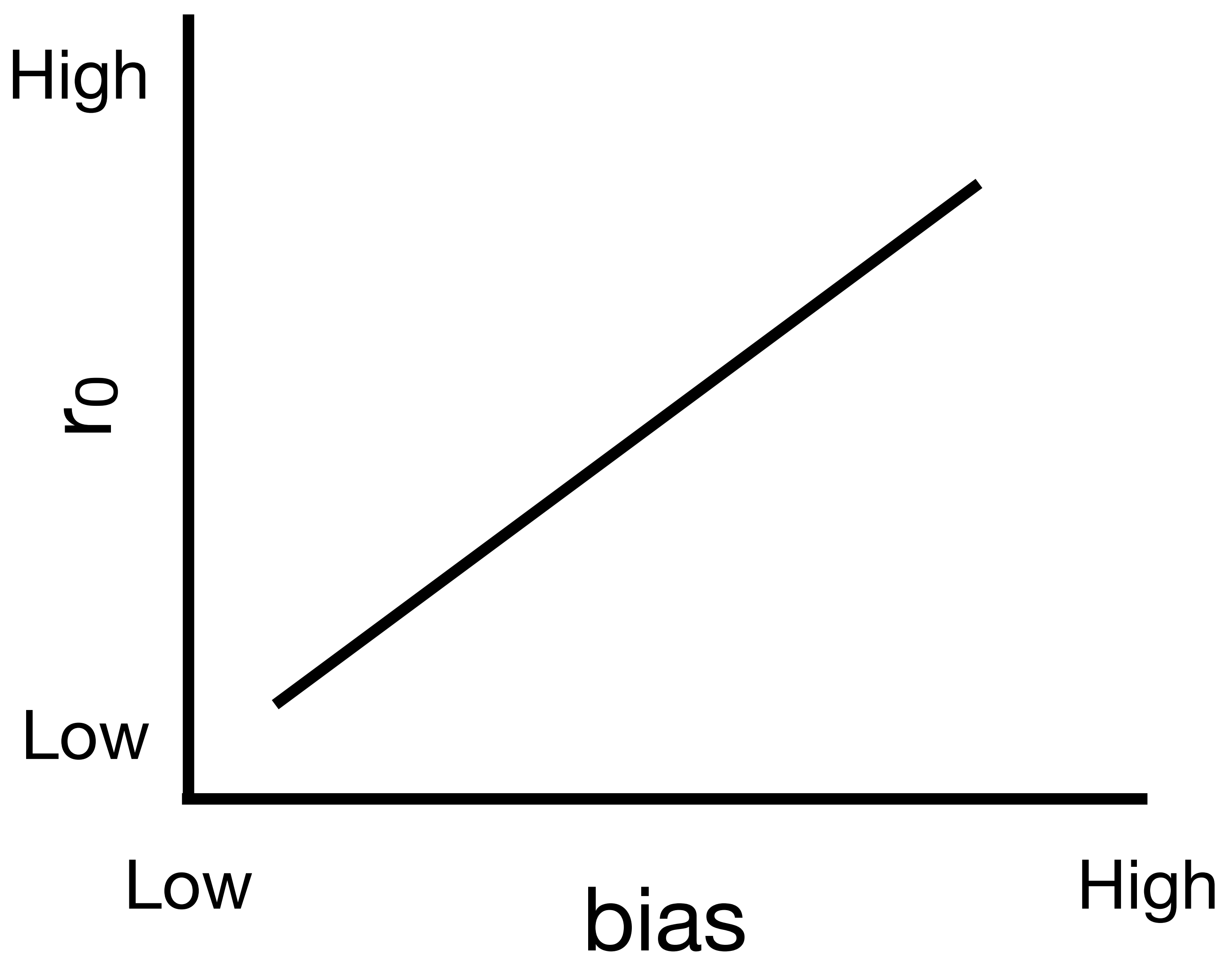
Useful for example to compare the clustering of blue vs red galaxies at the same z

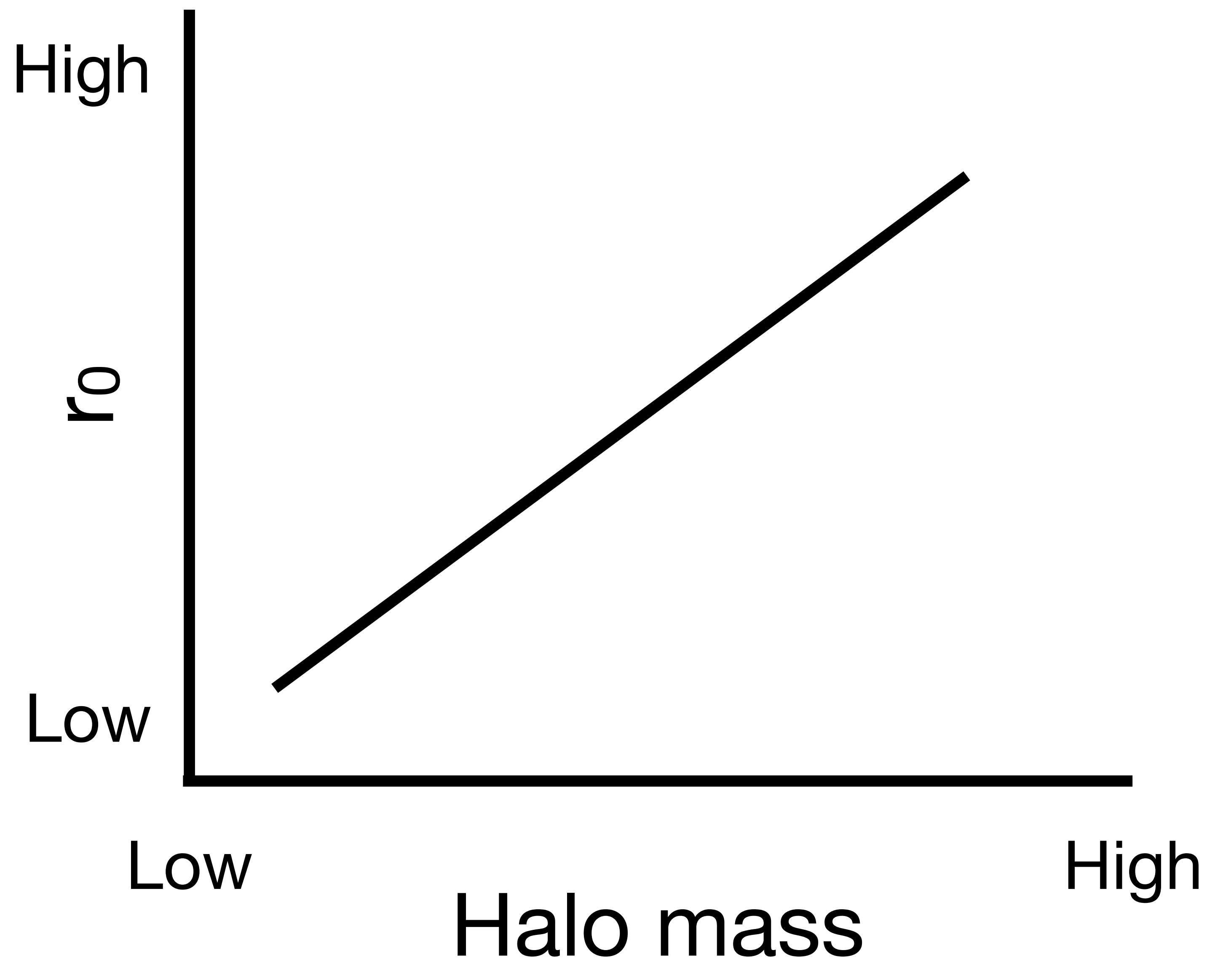
If we just want to compare clustering at a fixed epoch, computing relative r_0 (or relative biases) is enough. If we want to compare populations at different redshifts, computing the absolute bias will be required and more informative.

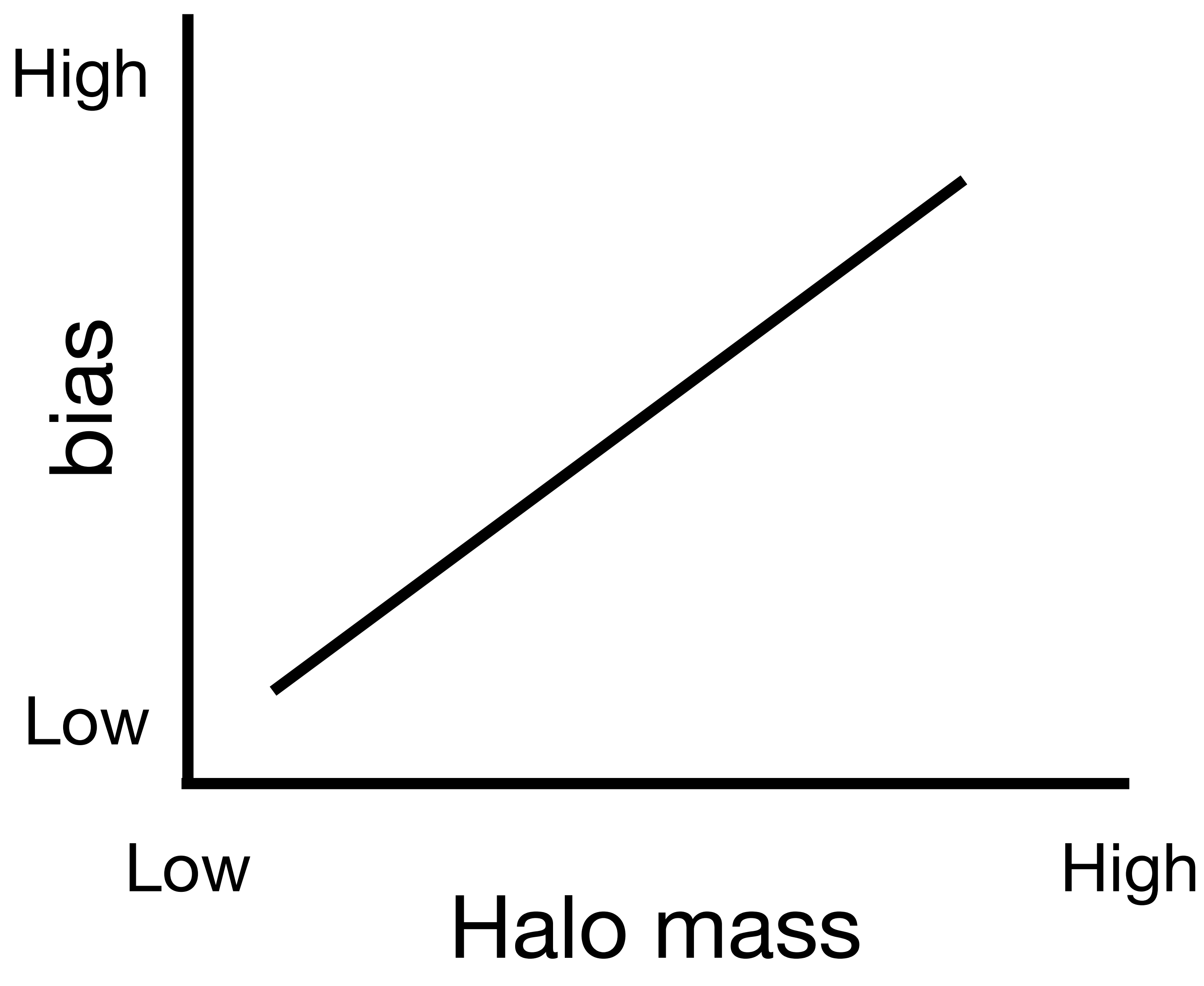
Relation between correlation length, bias and dark matter halo mass

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma} \qquad b_g = \sqrt{\xi_g/\xi_{DM}}$$

- A higher correlation length (r_0) means a more clustered population and a higher correlation function.
- **At a fixed time (redshift)** a higher correlation function implies a higher galaxy bias.
- **At a fixed time (redshift)** a higher galaxy bias implies a higher halo mass (more massive halos are more biased)





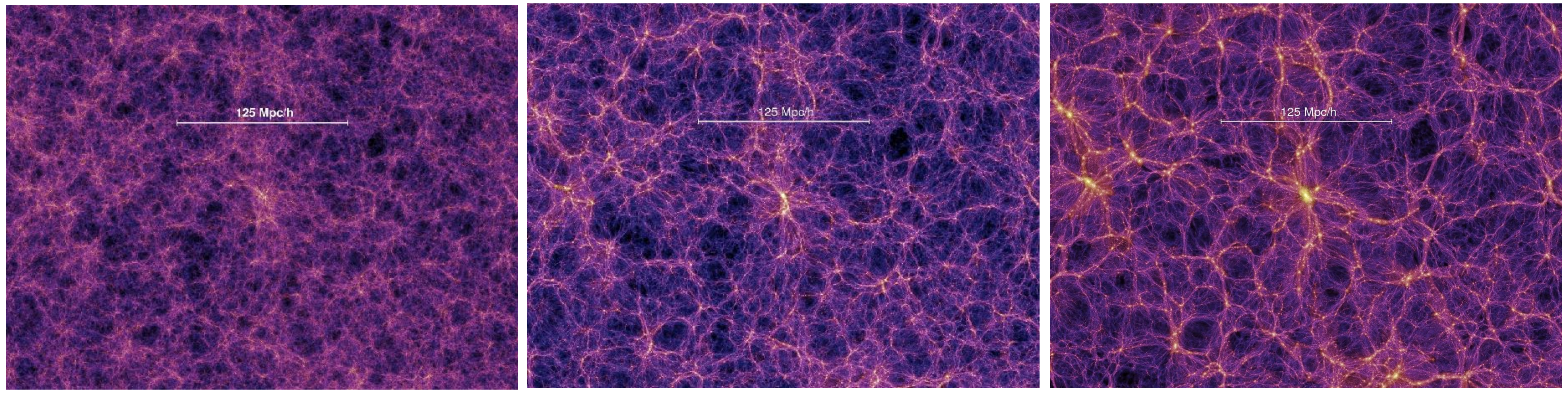


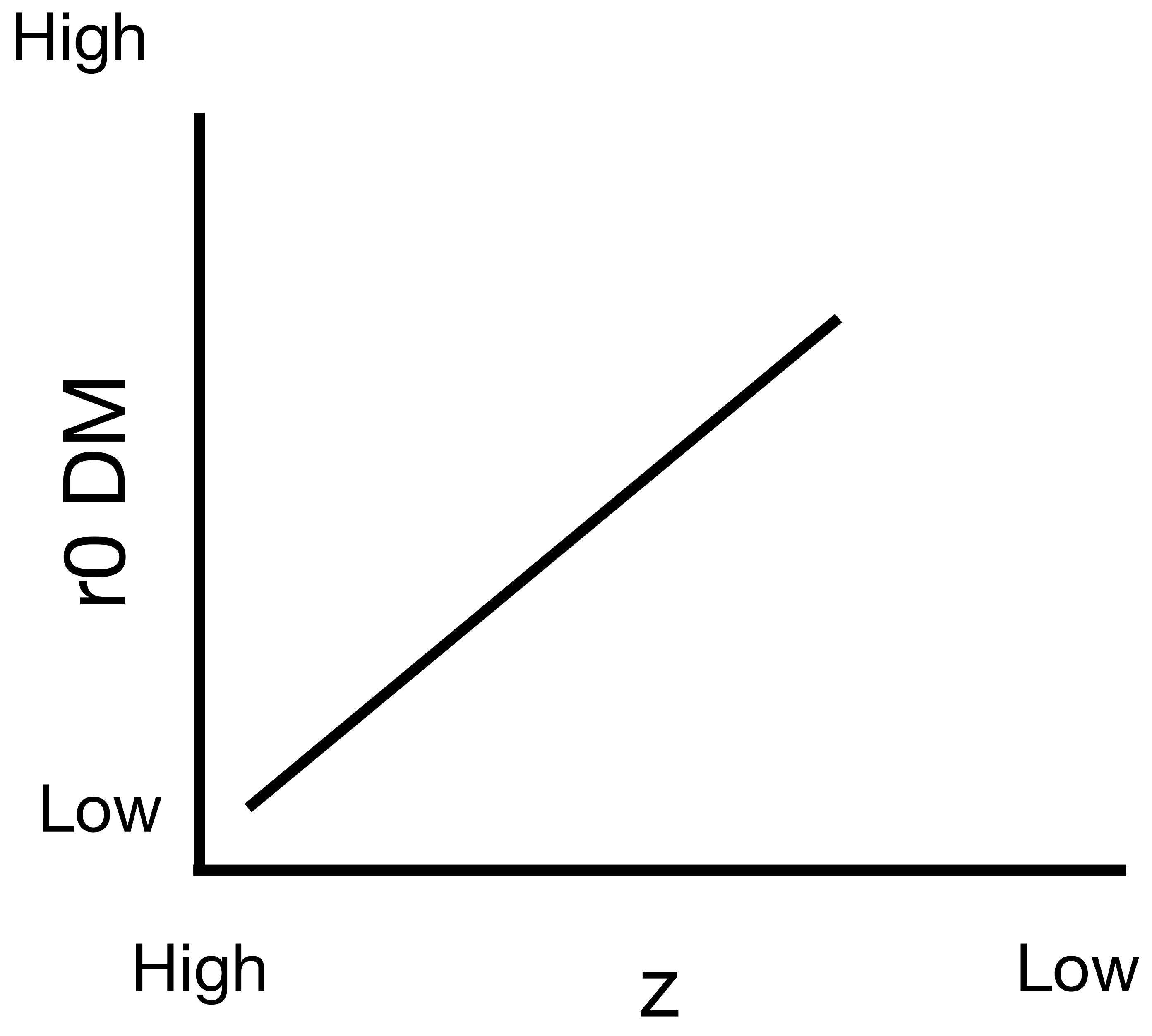
How are these relations at different redshifts? (not trivial)

Evolution of clustering with redshift

$$b_g = \sqrt{\xi_g / \xi_{DM}}$$

Dark matter distribution





- Overdensities of dark matter become more overdense with time, therefore the clustering of dark matter ξ_{DM} also increases over time (It is larger at z=0 compared with their value at z=10).

- If a population of galaxies has a constant correlation length r_0 over time, this means that their bias will decreases over time (the bias will be smaller at lower redshift), this will means that the population live in massive halos at high z, but not so massive halos at low redshift. Then, a constant r_0 do not means constant halo mass, bias is more informative about halo mass.

Interpreting the dependencies of clustering with different properties

More luminous Optically red Early-type Bulge-dominated Higher stellar mass Low sSFR	…galaxies are more clustered than the…	less luminous optically blue late-type disk-dominated lower stellar mass higher sSFR	galaxies

(at a fixed redshift)

Implies that

More luminous Optically red Early-type Bulge-dominated Higher stellar mass Low sSFR	…galaxies live in more massive dark matter halos than the…	less luminous optically blue late-type disk-dominated lower stellar mass higher sSFR	galaxies

Why is it useful to learn about the dark matter halos in which galaxies live?

*More about this type of interpretations in Lecture 5

It provides us a powerful insights about physical processes involved in the formation or evolution of galaxies.

For example, if high-z quasars inhabit massive halos, that means that they live in more massive environments with more galaxies in their neighborhood. In these environments merger are more common, and then we could believe that quasar may be originated, or triggered by mergers.

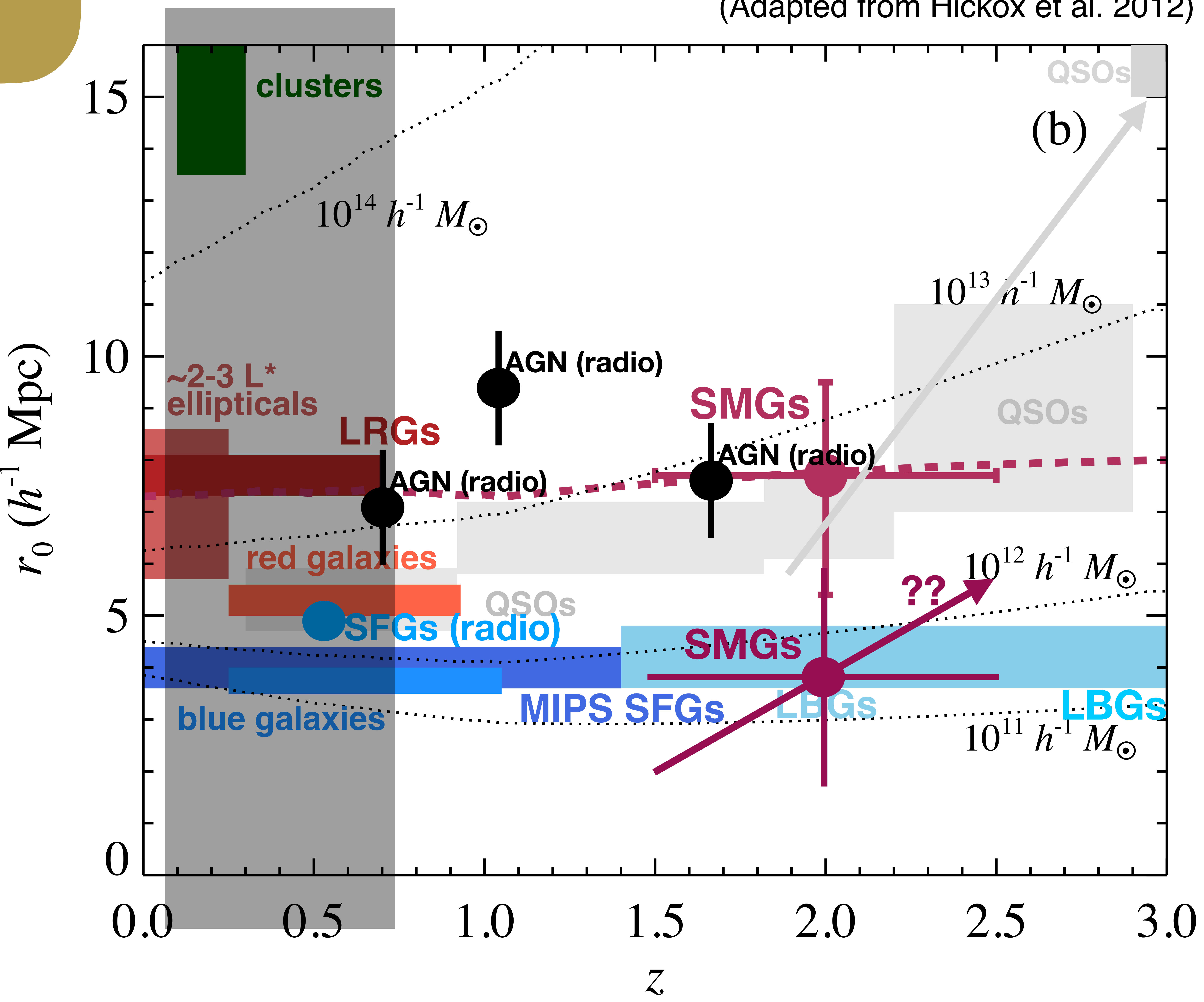
More massive halos
More galaxies
Higher merger rate

Less massive halos
Less galaxies
Less merger rates

Why at high redshift quasars are only found in extremely massive dark matter halos? One (possible) answer: because quasars are originated from mergers

Interpreting the dependencies of clustering with different properties

(Adapted from Hickox et al. 2012)



In the local universe:

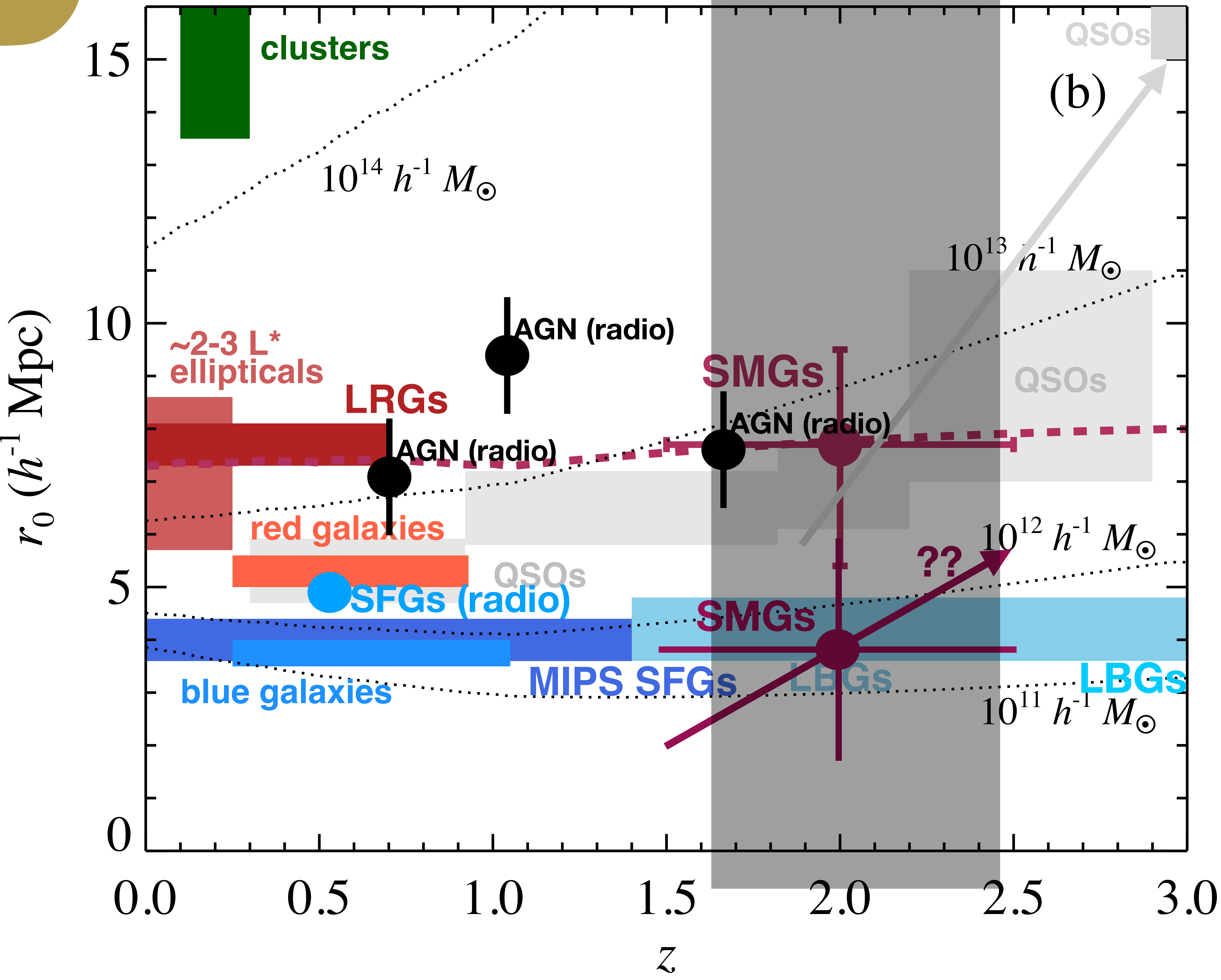
- Galaxy clusters inhabit more massive halos than all the other objects.
- Elliptical galaxies inhabit in more massive halos than red galaxies.
- Red galaxies inhabit in more massive halos than blue galaxies.

Interpreting the dependencies of clustering with different properties

At z~2:

- Quasars lives in more massive halos than LBGs.
- AGNs live in similar halos as quasars.

(Adapted from Hickox et al. 2012)

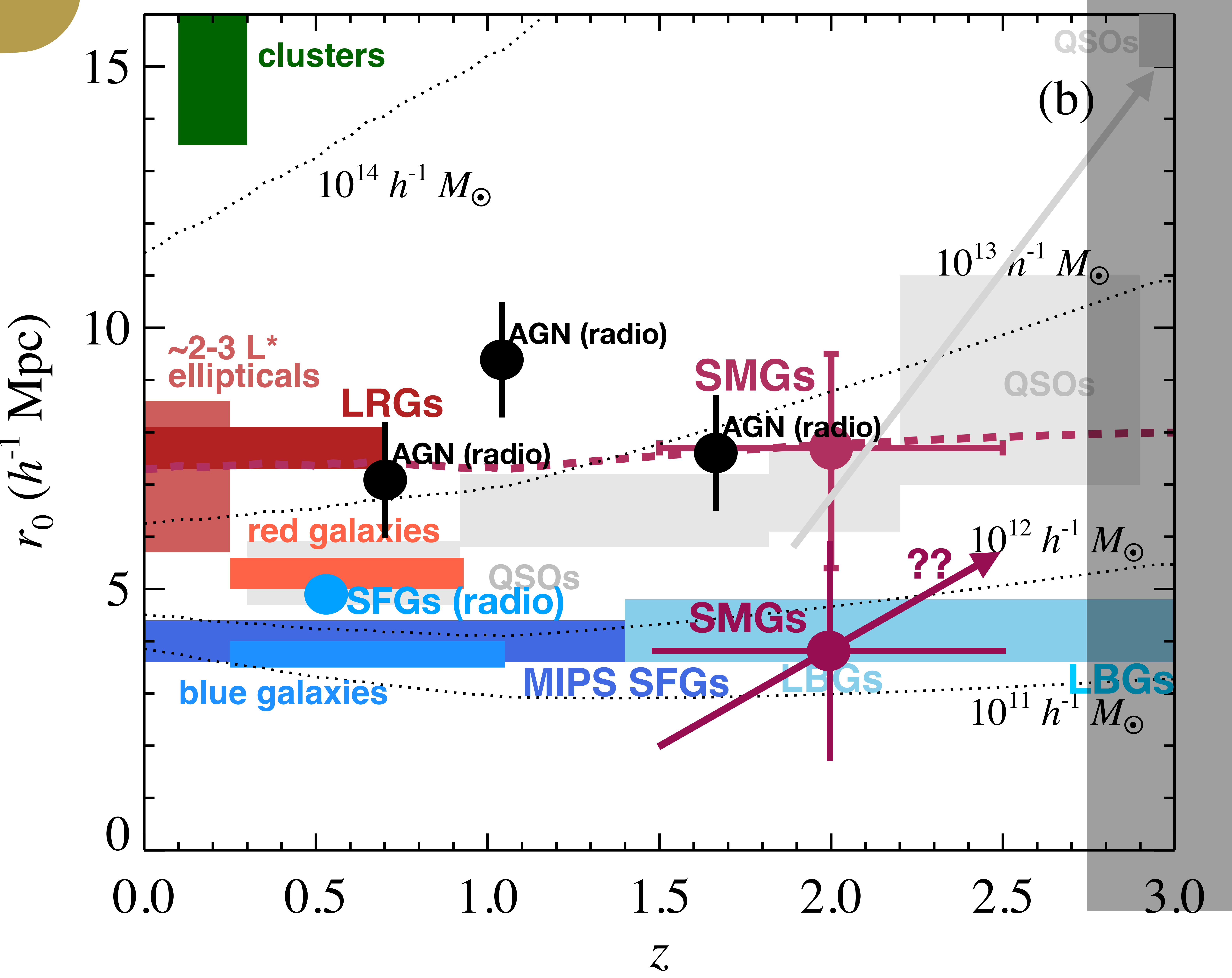


Interpreting the dependencies of clustering with different properties

At z~3-4:

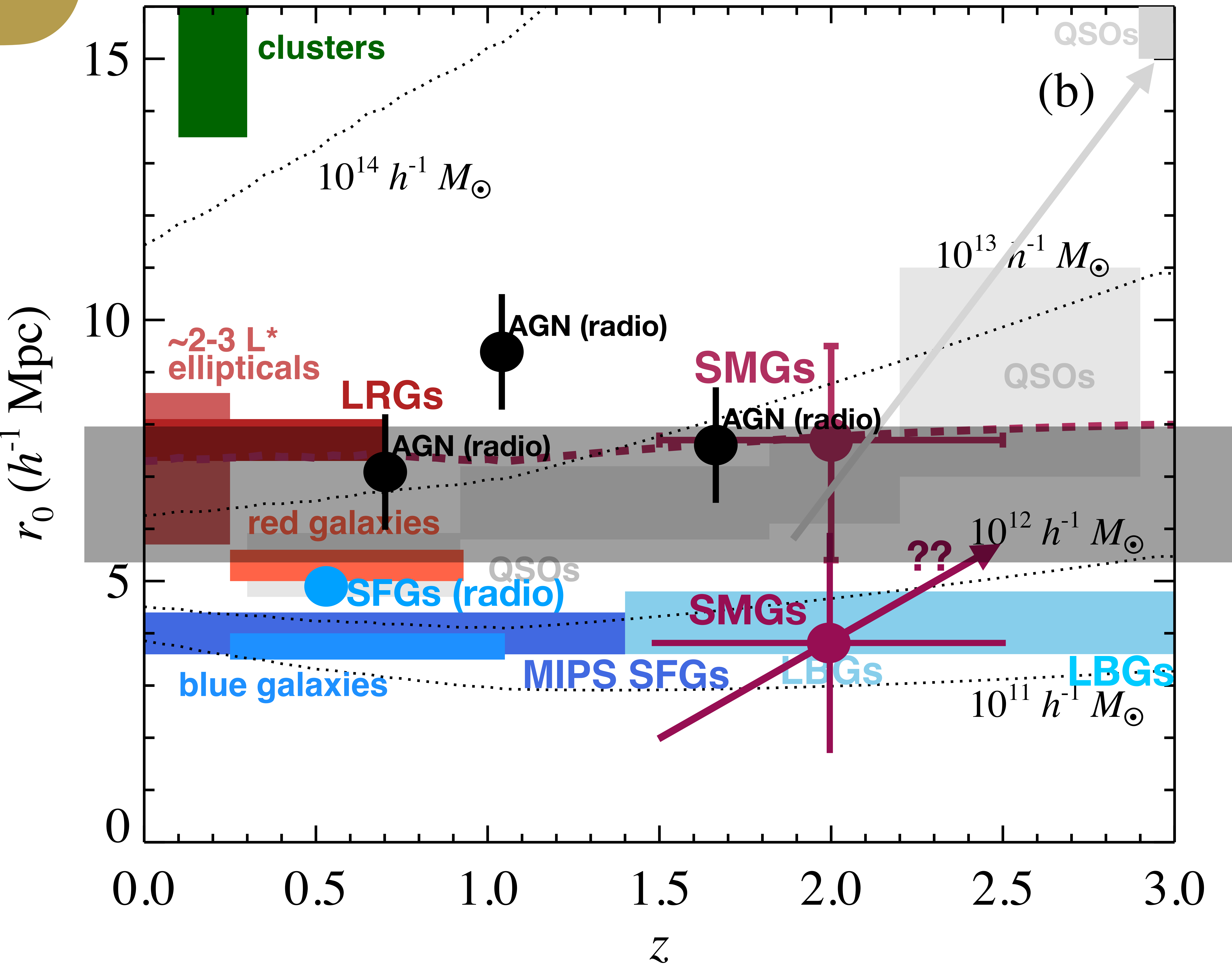
- Quasars lives in the more massive halos.

(Adapted from Hickox et al. 2012)



Interpreting the dependencies of clustering with different properties

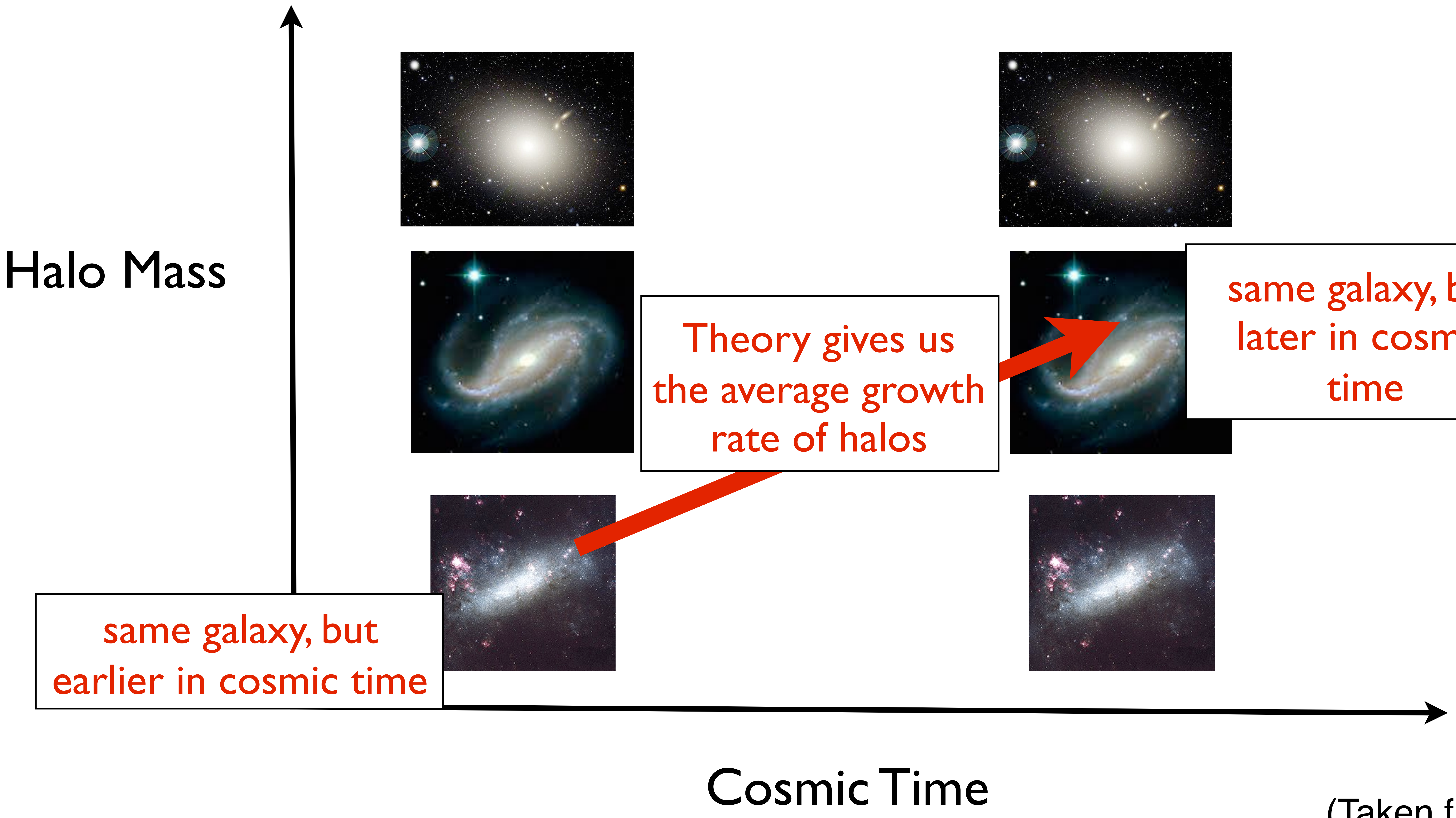
(Adapted from Hickox et al. 2012)



- To interpret this over redshifts, we need to compare halo mas or bias, not r_0 values.
- For example, if r_0 of LBG is constant, their bias is lower at lower redshift, then inhabit less massive halos at lower redshifts.

Why is it useful to learn about the dark matter halos in which galaxies live?

It provides us a powerful tool for tracing the same population of galaxies through cosmic time.

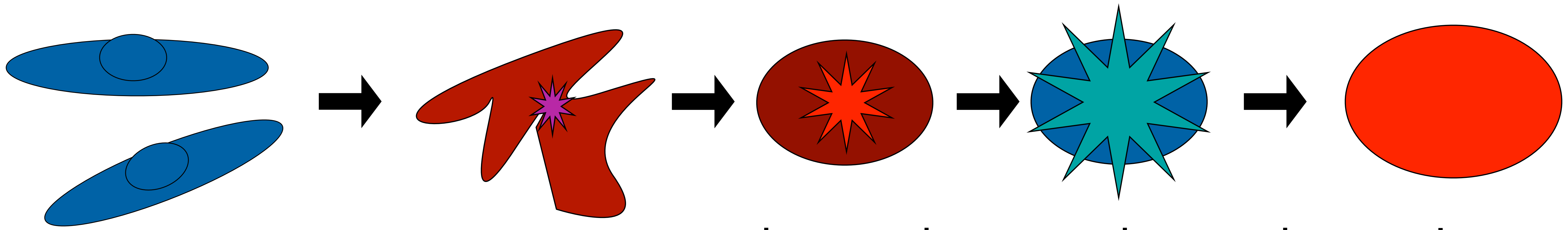


(Taken from R. Bouwens' Lectures)

Example: A possible evolutionary sequence for massive galaxies

High-z Low-z

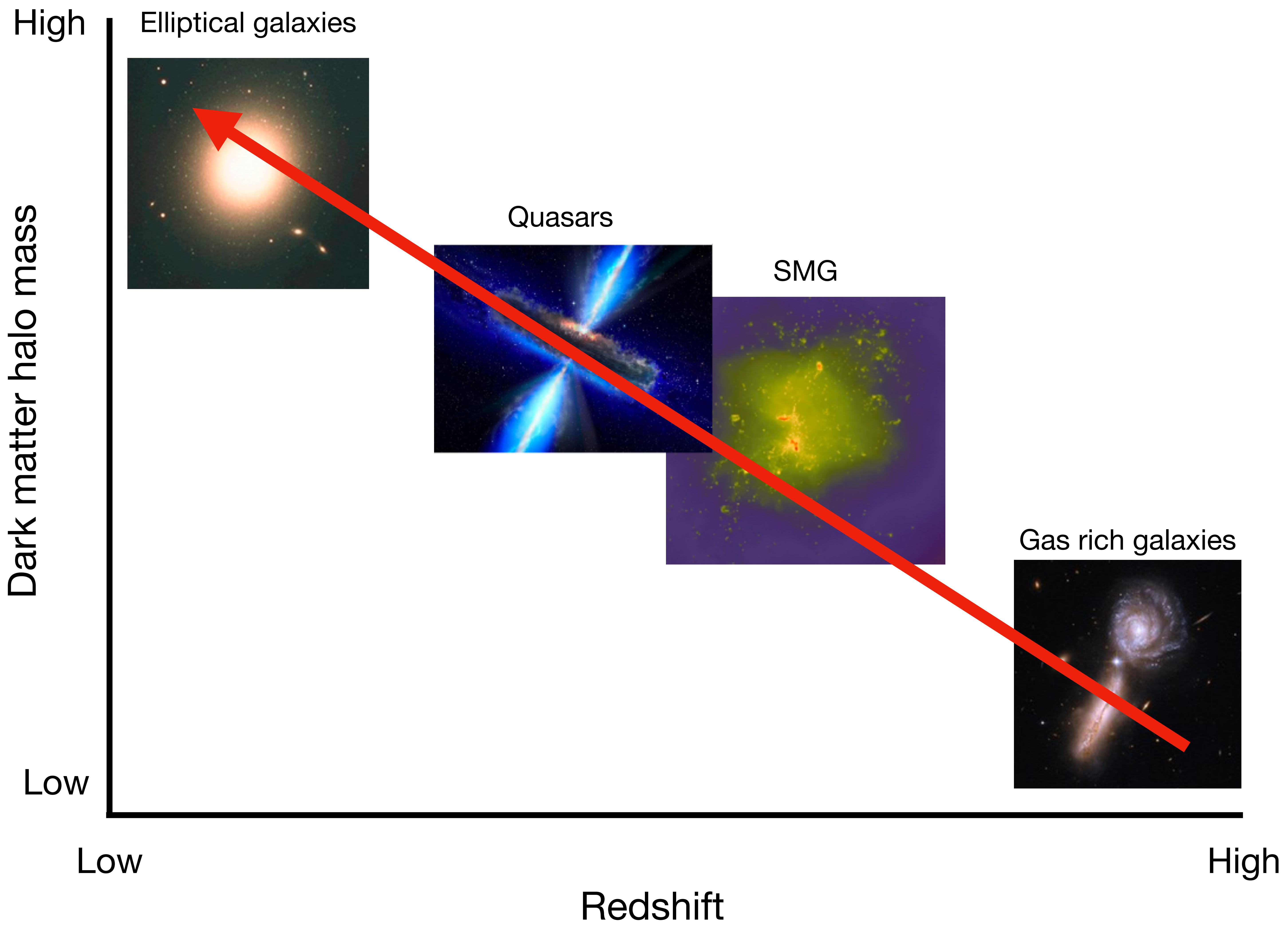
Major Merger evolutionary scenario



Alexander & Hickox (2012)

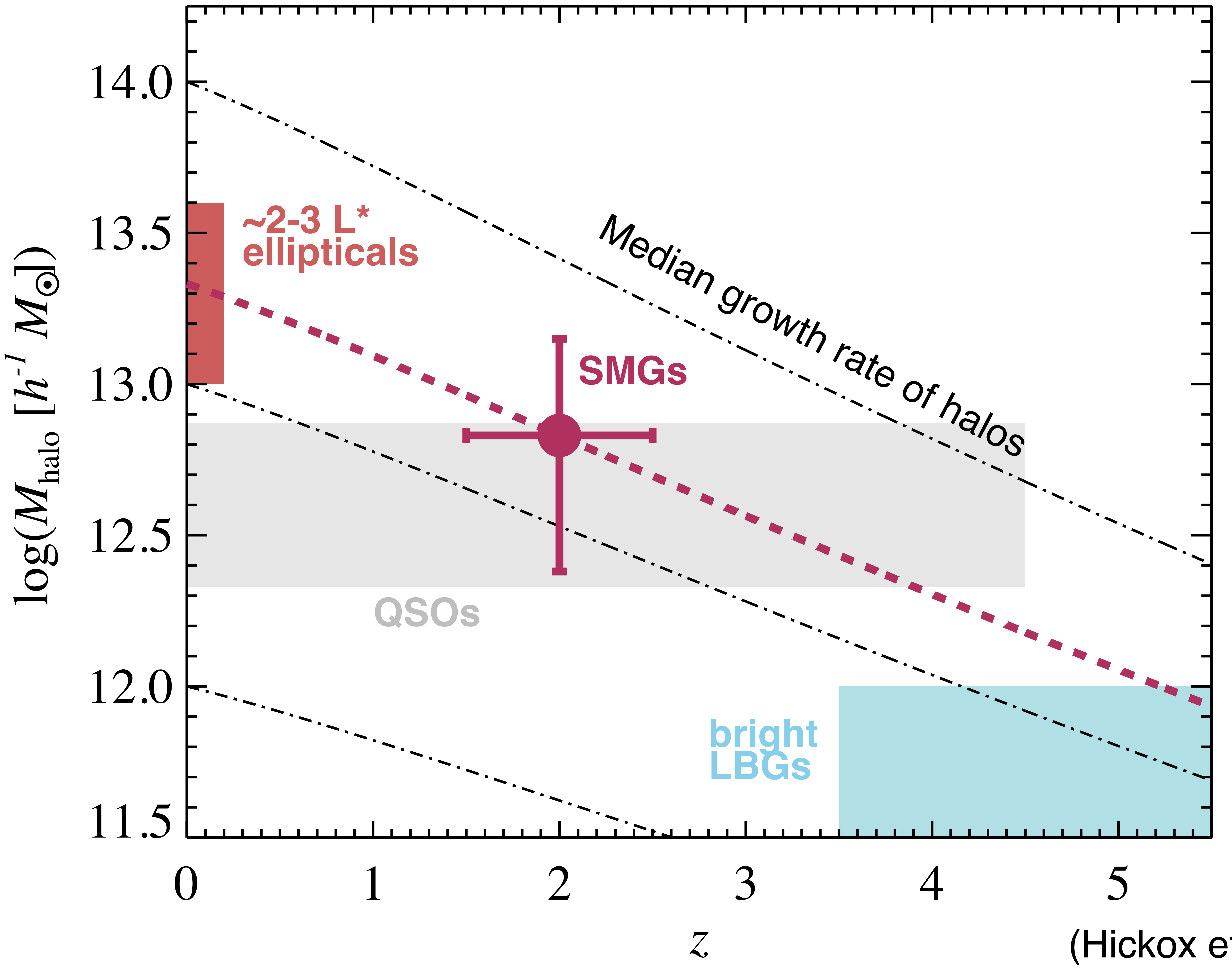
- Tentatively supported by similarities in some physical properties of these populations: $M_\star$, $M_{\rm BH}$, $N(z)$, $R_{\rm eff}$ (but, large systematics)
- An alternative method: $M_{\rm halo}$ (Clustering)

Expectation if they were linked:



Comparing the clustering of the populations at different redshifts

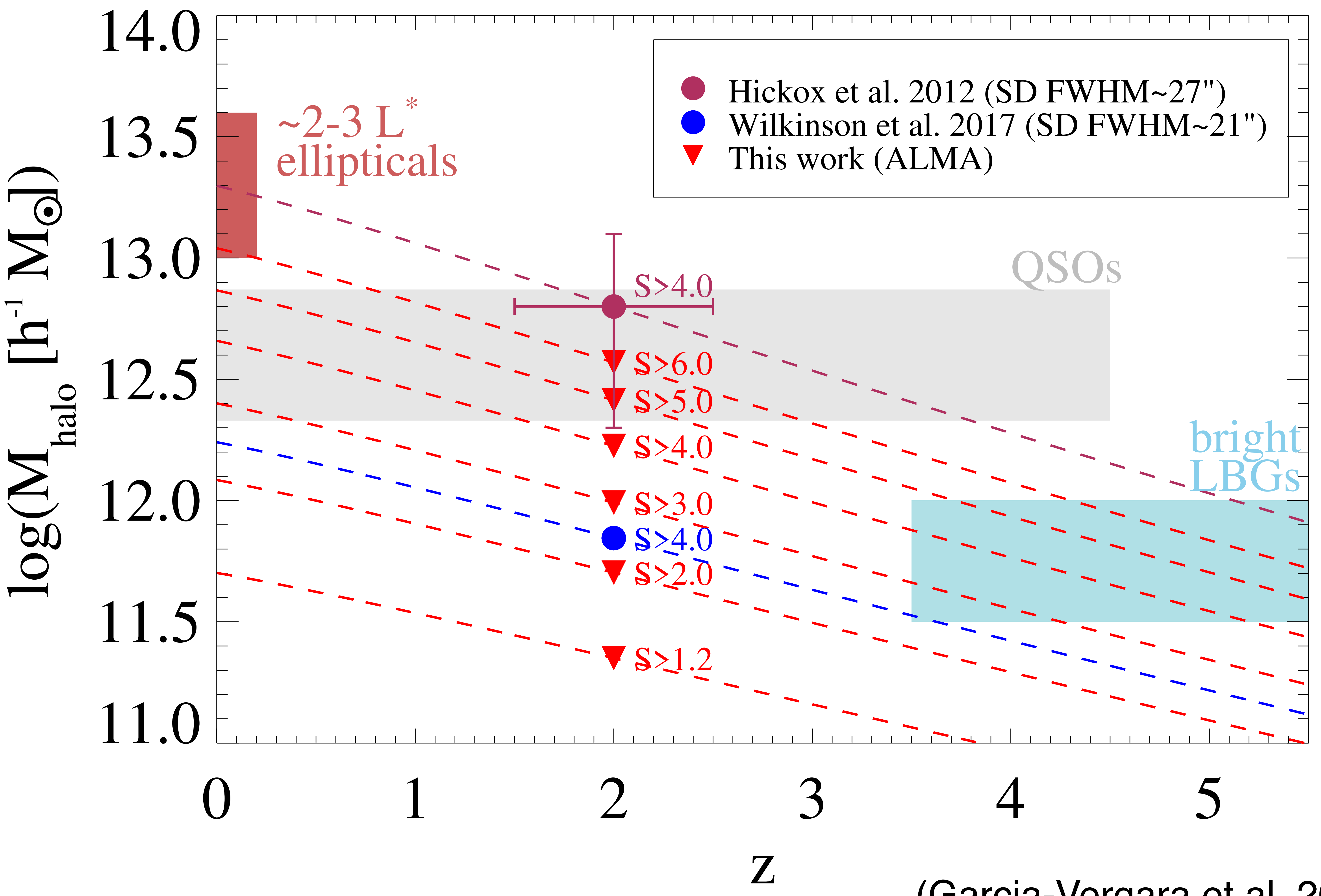
- Measurements of clustering of SMGs implies evidence for the major merger evolutionary scenario.



(Hickox et al. 2012)

Comparing the clustering of the populations at different redshifts

- Recent measurements of clustering of SMGs based on ALMA data implies evidence for the major merger evolutionary scenario **only** for the brightest SMGs.



(Garcia-Vergara et al. 2020)

Take home message

- Dark matter halos do not trace exactly the distribution of dark matter, but they are biased tracers of dark matter, with more massive halos being more biased.

- Distribution of galaxies roughly trace the distribution of dark matter halos, therefore galaxies are also biased tracers of dark matter.

- Comparison of the correlation function for different populations at the same redshift provide insights about physical processes involved in the evolution of each different population.

- The computation of correlation function also allow us to compute the bias of galaxies, and if we know the bias we can know the halo mass in which the population inhabit.

- Knowledge of the halo mass for different populations at different redshifts are useful to study evolutionary scenarios between populations over cosmic time.