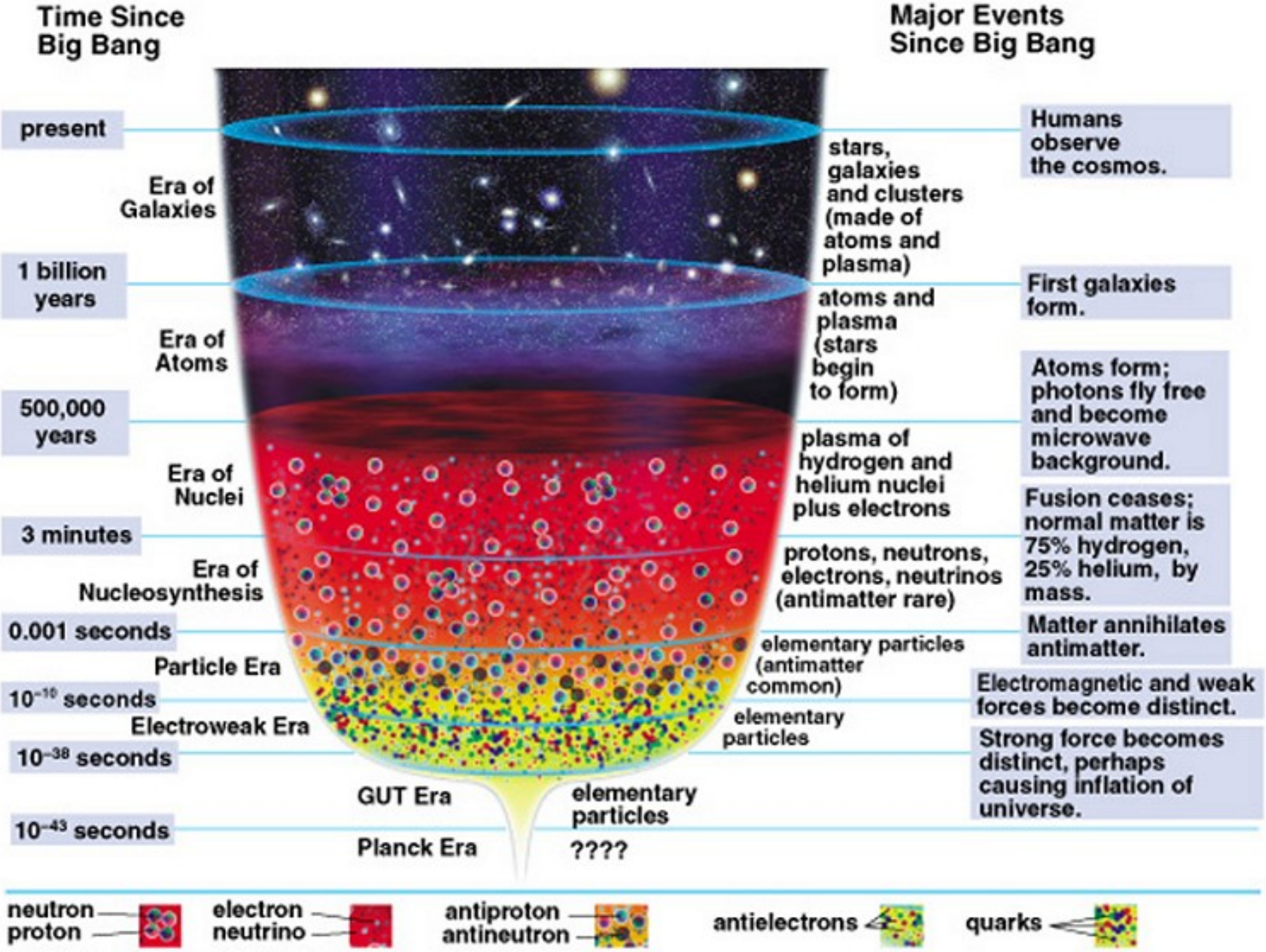
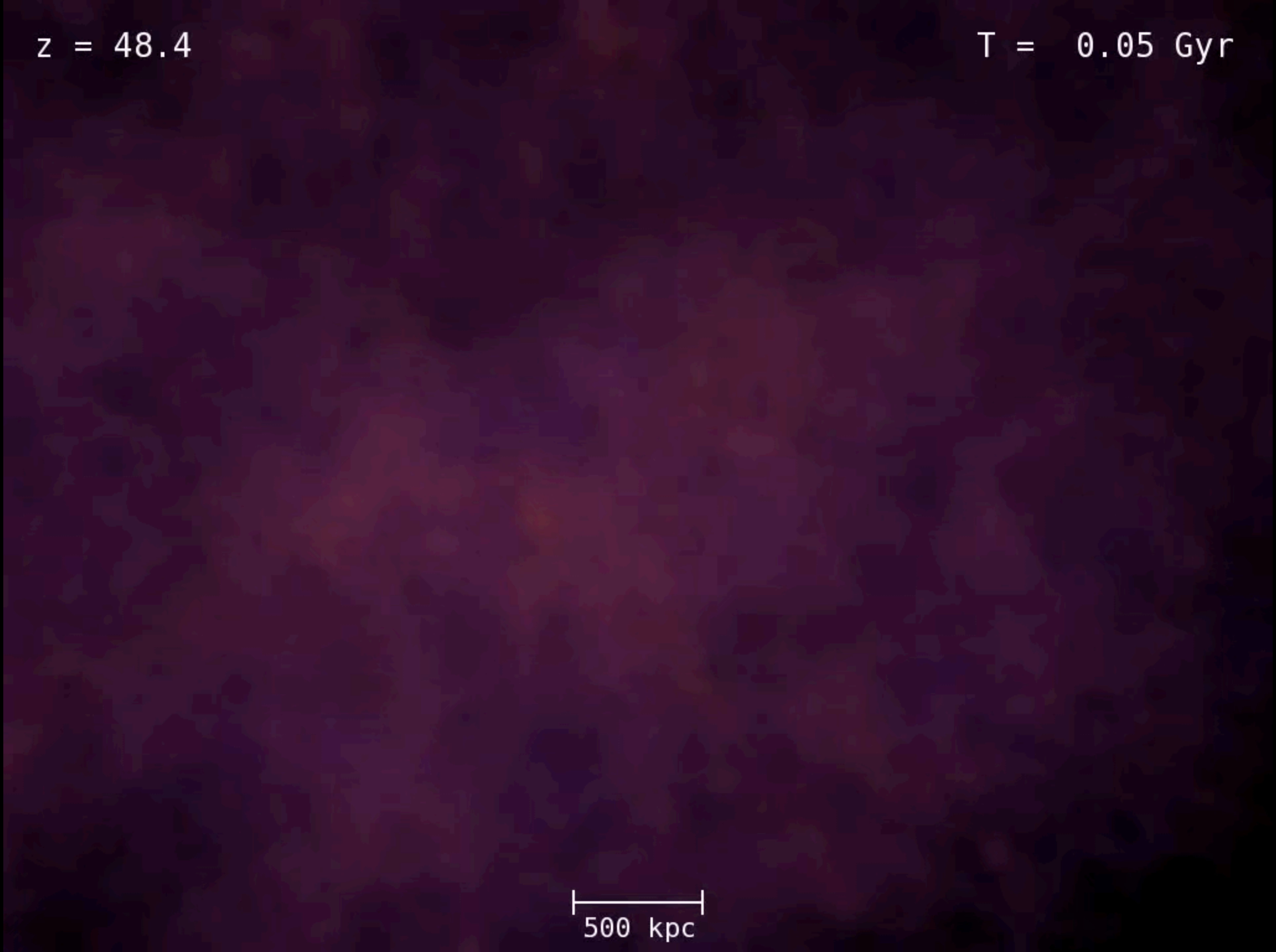
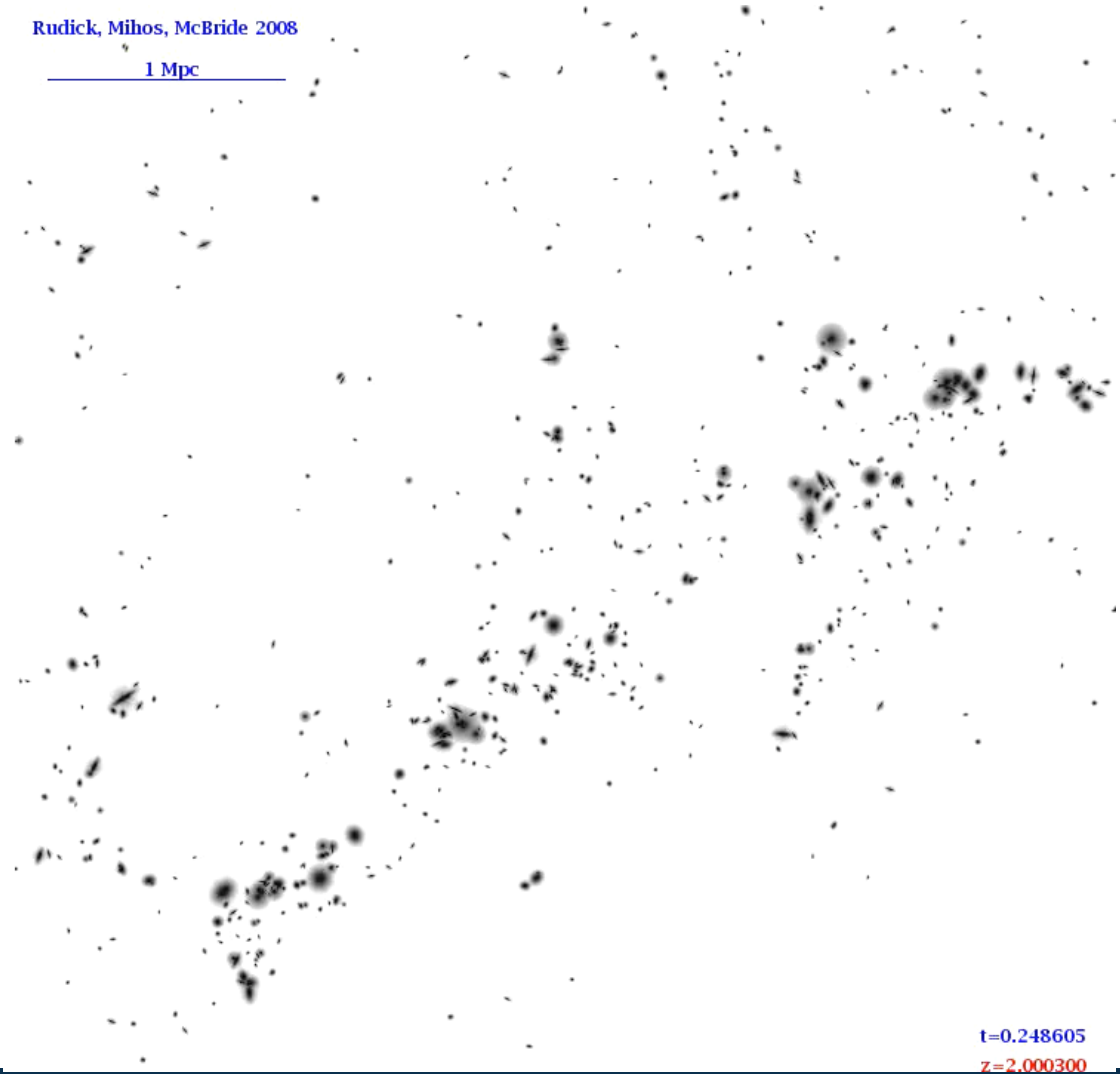

Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10^{-10} seconds
Electroweak Era
10^{-38} seconds
GUT Era
10^{-43} seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

Before recombination, baryons and photons were coupled, and **the photons kept the baryons from collapsing** under their own gravity. Structure can't start growing until the photons and baryons decouple at recombination. **But if we postulate some sort of matter that doesn't interact with radiation the way baryons do, it can start growing much earlier — dark matter!**

When we look at the CMB, the fluctuations in baryons that we see are sitting on top of much stronger fluctuations in the dark matter. Once recombination occurs, the baryons are free to collapse under gravity, and they quickly fall into the dark matter concentrations to form into galaxies.


z = 48.4
T = 0.05 Gyr
500 kpc


Rudick, Mihos, McBride 2008

Since high density things collapse fastest (short free-fall times), this leads to hierarchical growth of structure as small things form first and then are drawn together by gravity to make bigger things. Schematically, we think of galaxy growth looking like this:

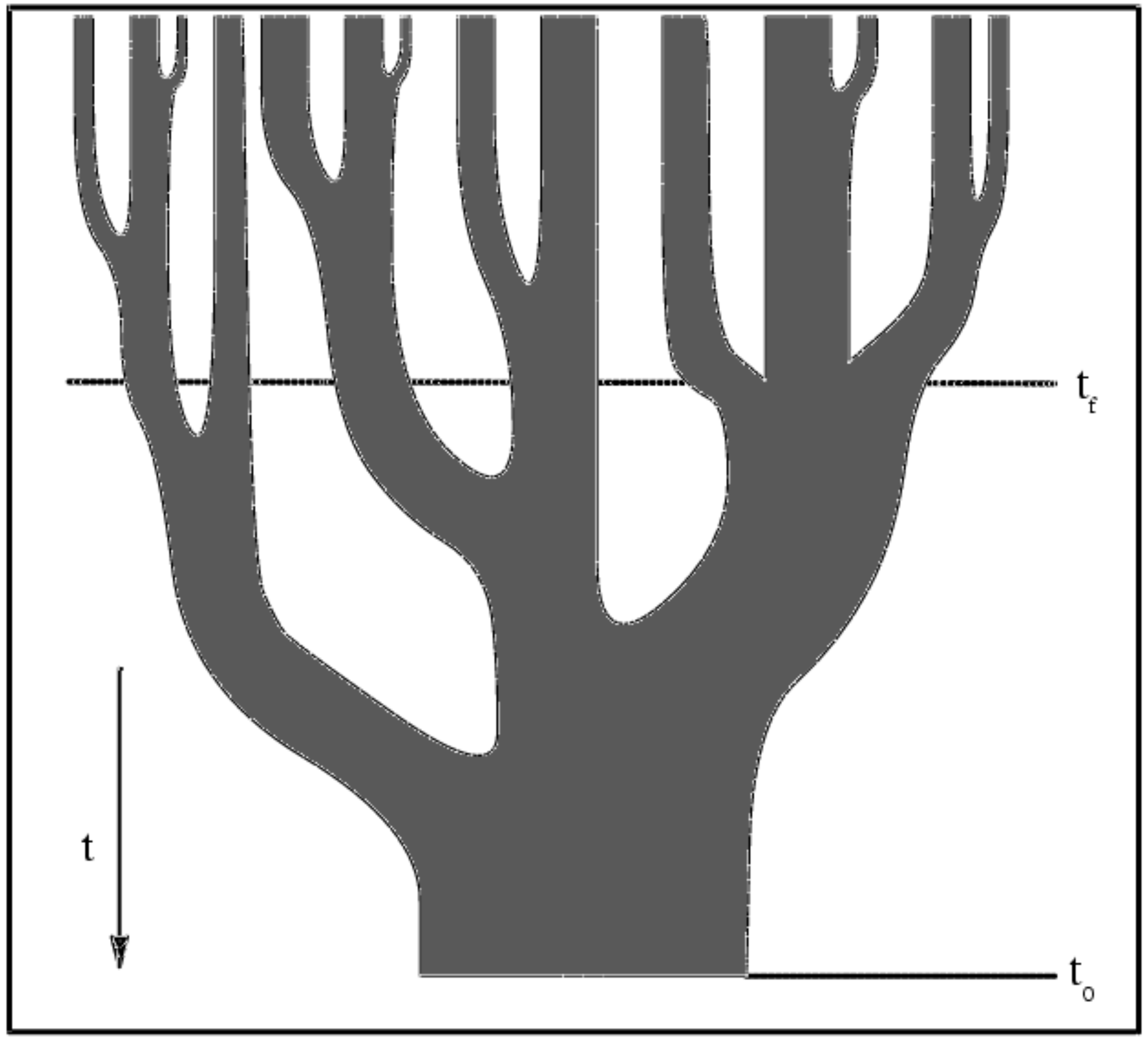


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Note that this has a number of important meanings:

- The concept of a "formation time" for a galaxy is ill-defined. In the example above, the formation time (t_f) is simply the time at which the galaxy had half of its final total mass in a single object.
- Defined this way, a galaxy's stars can be older than the galaxy itself. Stars form early, in small proto-galaxies, but only later do these protogalaxies merge together to form the main galaxy.

Galaxy dark matter halo masses as a function of redshift (remember, we think our galaxy has a halo mass of ~ 10^{12} M_{sun}):

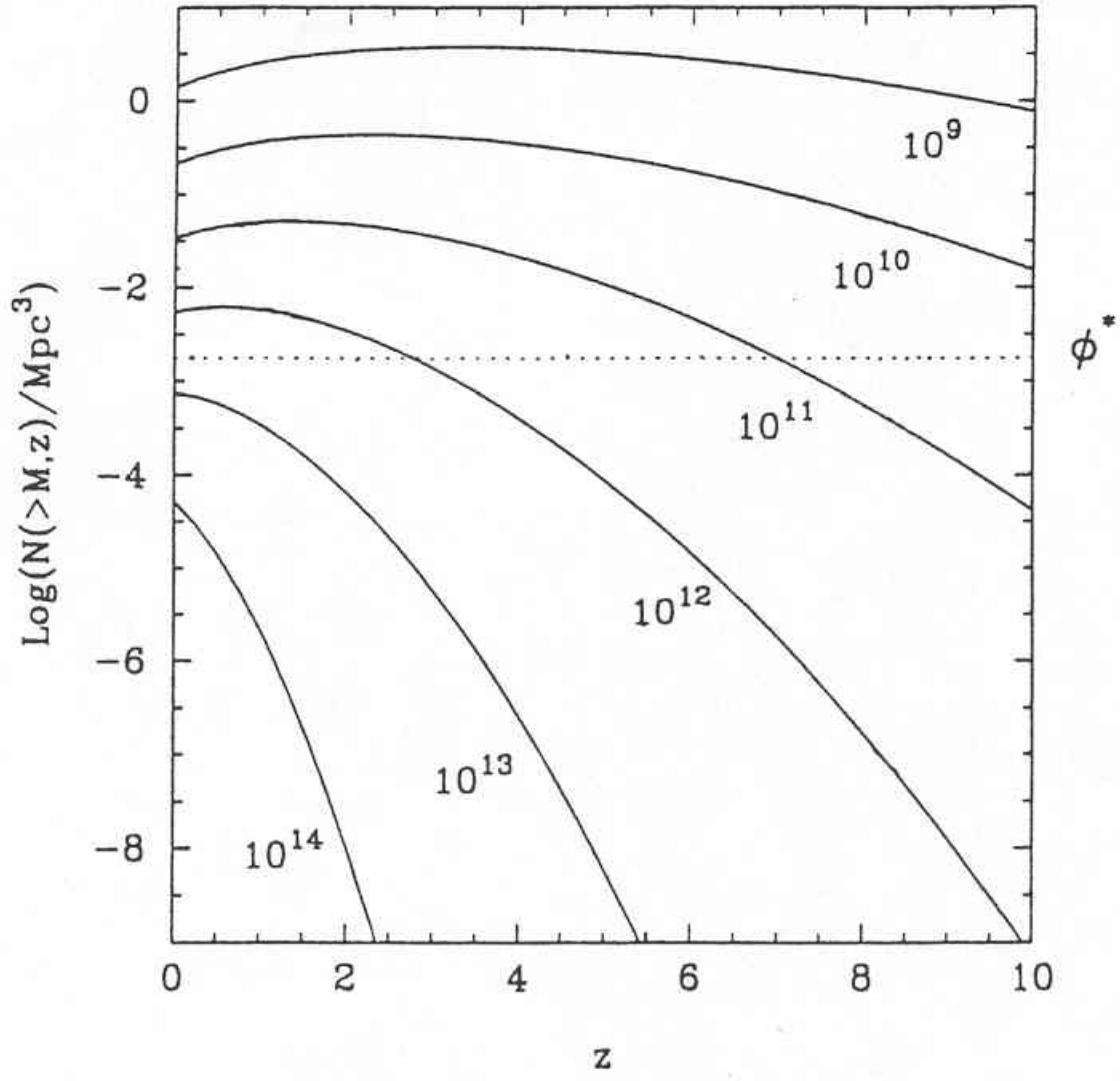


Fig. 16.5 The evolution of the comoving number density of dark matter haloes wit masses greater than M as a function of redshift for a standard Cold Dark Matte model with $\Omega_0 = 1$. The curves have been derived using the Press-Schechter for

So dark matter can grow early. It is important to distinguish now between different flavors of dark matter:

- **baryonic dark matter: *doesn't help.* we want nonbaryonic dark matter!**
- **nonbaryonic dark matter: we characterize dark matter by the random velocities of the particles**
  - **hot dark matter: relativistic velocity, like neutrinos**
  - **cold dark matter: moving more slowly, no known particles (hypothetic axions, WIMPS, etc)**

Different types of dark matter result in different evolutionary histories for the Universe.

Hot Dark Matter

Because HDM particles are moving so fast, they can escape from small mass density fluctuations. Since it is their mass that makes the density fluctuation, these small fluctuations will essentially dissolve. Calculations for neutrinos suggest that any density fluctuation smaller than about 10^{15} M_{sun} will dissolve away before recombination, so the baryons won't collapse into small lumps. Instead, only the big surviving lumps will collapse. The scale of these lumps is like that of big clusters of galaxies, which have relatively low overdensities, so the collapse occurs slowly. Then after the big things collapse, fragmentation can occur (like individual stars form out of a bigger collapsing gas cloud). So,

- **structure forms slowly**
- **structure forms "top down"**
- **galaxies form very late in the Universe's history**

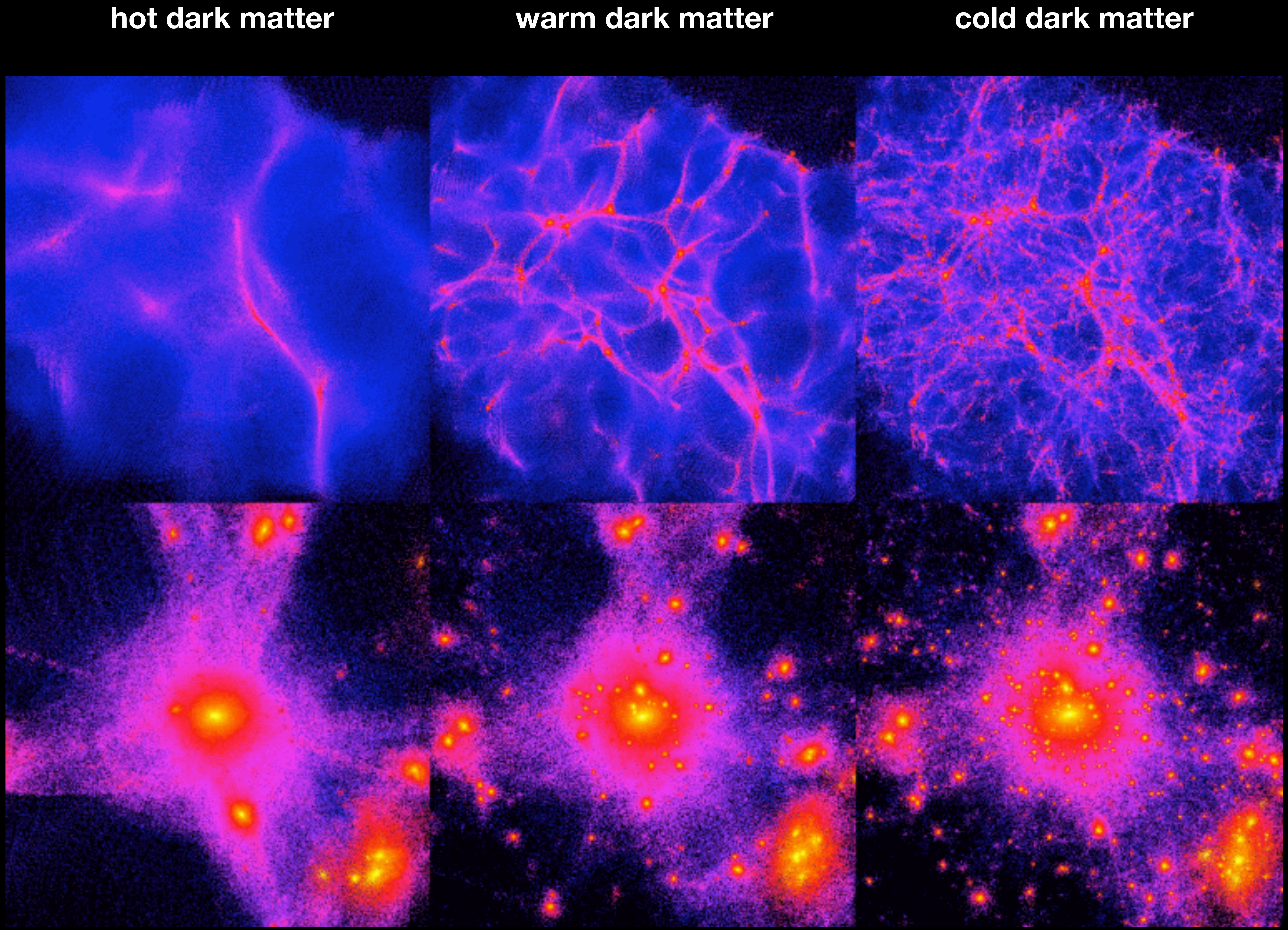
Not like what we see! Hot dark matter doesn't work!

Cold Dark Matter

CDM particles do not diffuse out of small lumps. So lumps exist on all scales -- small and large. The little things collapse first, and the big things collapse later, incorporating the little things in as they collapse.

- **structure begins to form early**
- **structure forms "bottom up"**
- **galaxies form before galaxy clusters.**

This gives a much better description of what we see in the universe, and leads to a picture for structure formation called hierarchical structure formation.


hot dark matter
warm dark matter
cold dark matter
z = early
z = now

Observations of the high redshift universe
Complications:

Cosmological effects distort our view of high redshift galaxies:

- **High redshift galaxies are faint and small**
- **Their light has been redshifted**
- **At cosmological distances, their surface brightnesses are systematically fainter**

We use imperfect clocks to judge evolution:

- **The formation of stars is not the same thing as the formation of galaxies. Galaxies can have old stars but assemble late.**
- **Evolution proceeds faster in dense environments: $t_{dyn} \sim 1/\sqrt{\rho}$. Things that might take time in the field environment can happen faster in dense environments.**
- **Metallicity is a poor clock for measuring time -- metallicity can build up quickly in regions of high star formation, much more slowly in regions of low star formation.**

High redshift galaxies are intrinsically different from those around us today -- they are younger. Think of comparing a massive galaxy nearby to a massive galaxy in the early universe:

- **Different stellar ages, so different star formation histories**
- **Different assembly histories**

High redshift galaxies often look smaller, lumpier, and bluer than galaxies at intermediate and low redshift.

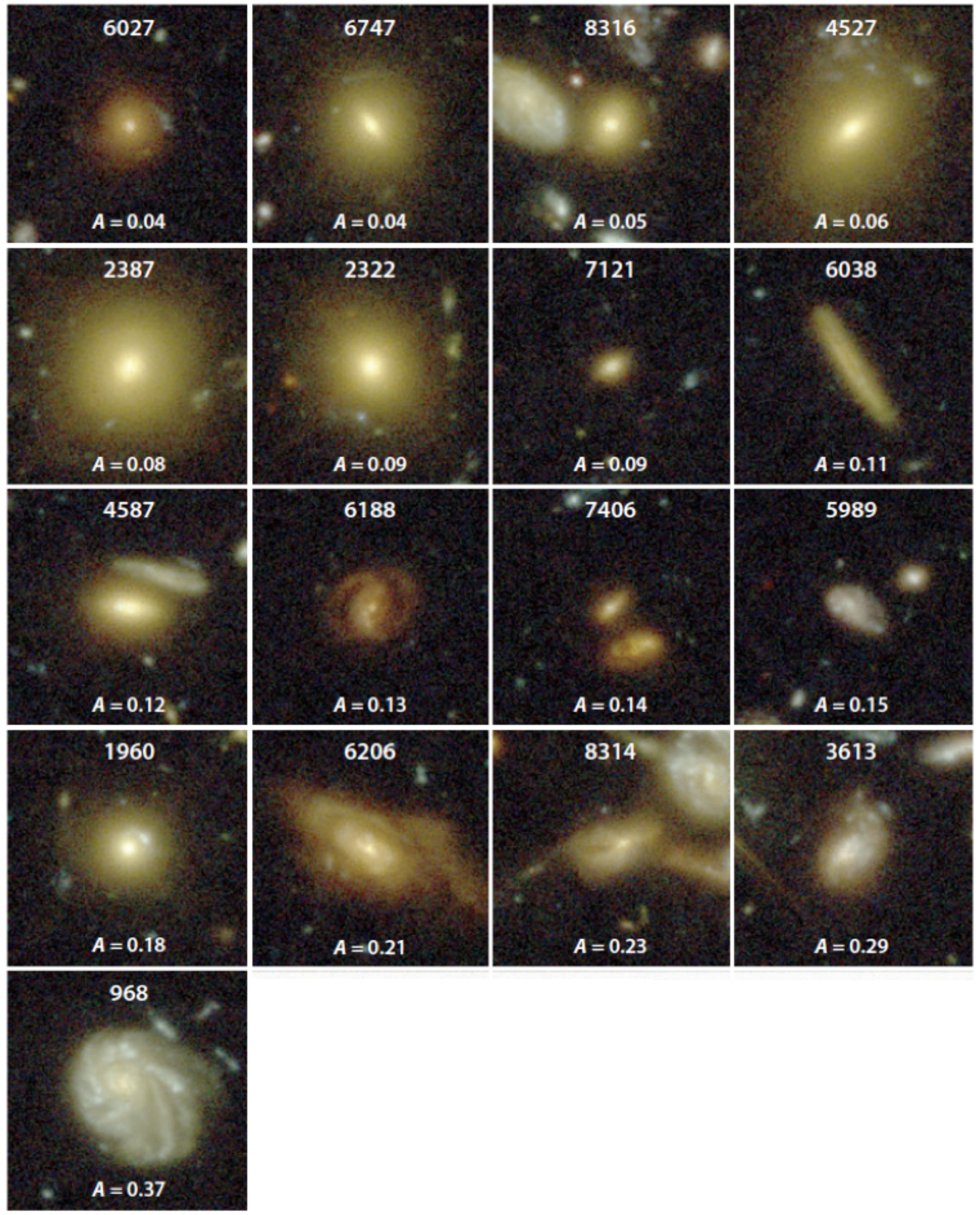


Figure 9

Galaxies in the Hubble Ultra Deep Field as imaged through the ACS camera and ordered by how asymmetric they are. These are all galaxies with redshifts $0.5 < z < 1.2$ and stellar masses $M_* > 10^{10}\,M_\odot$. The ID is the number used by Conselice et al. (2008), and the A value is the value of the asymmetry. At these redshifts most of the massive galaxies can still be classified as being on the Hubble sequence.

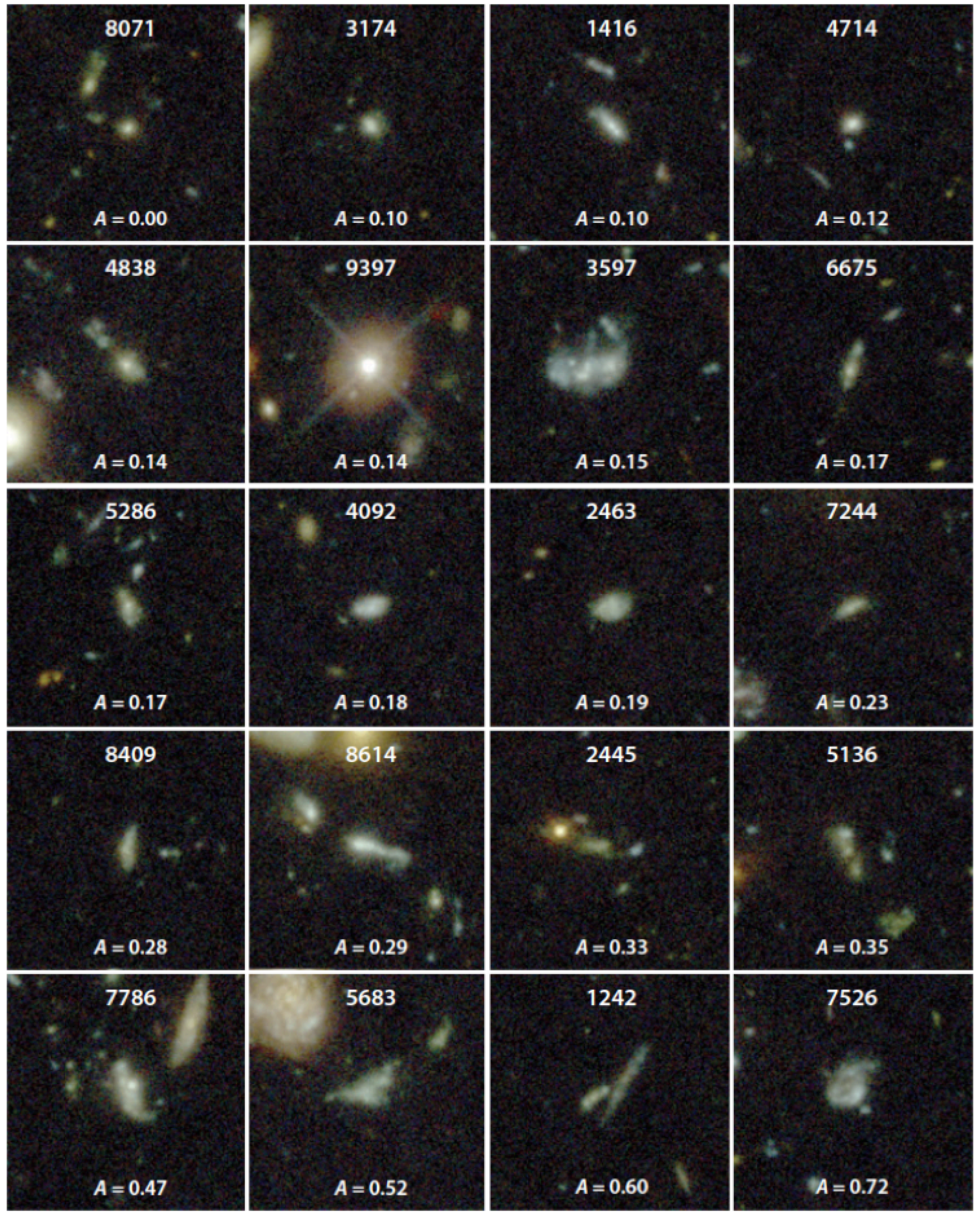
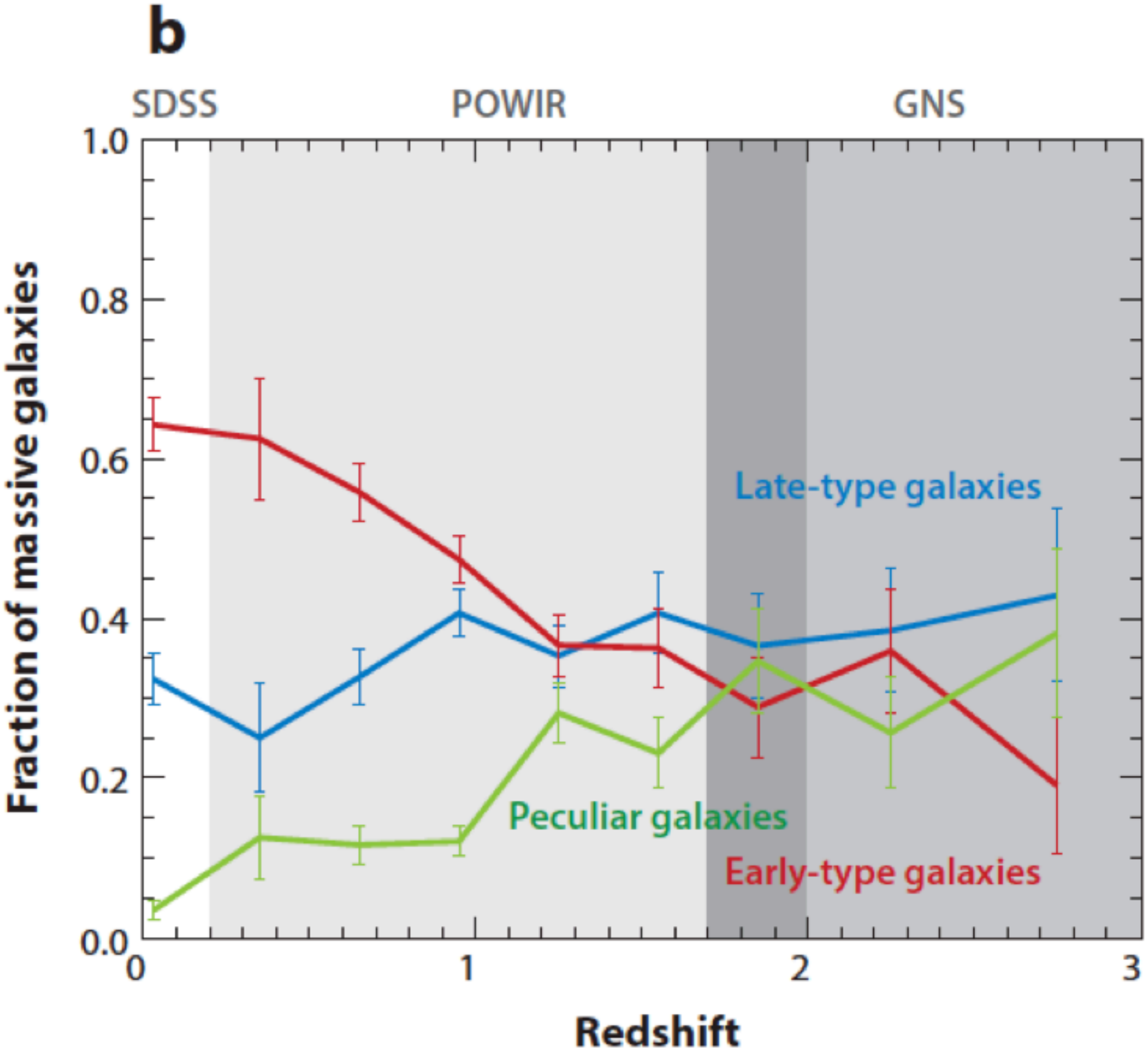


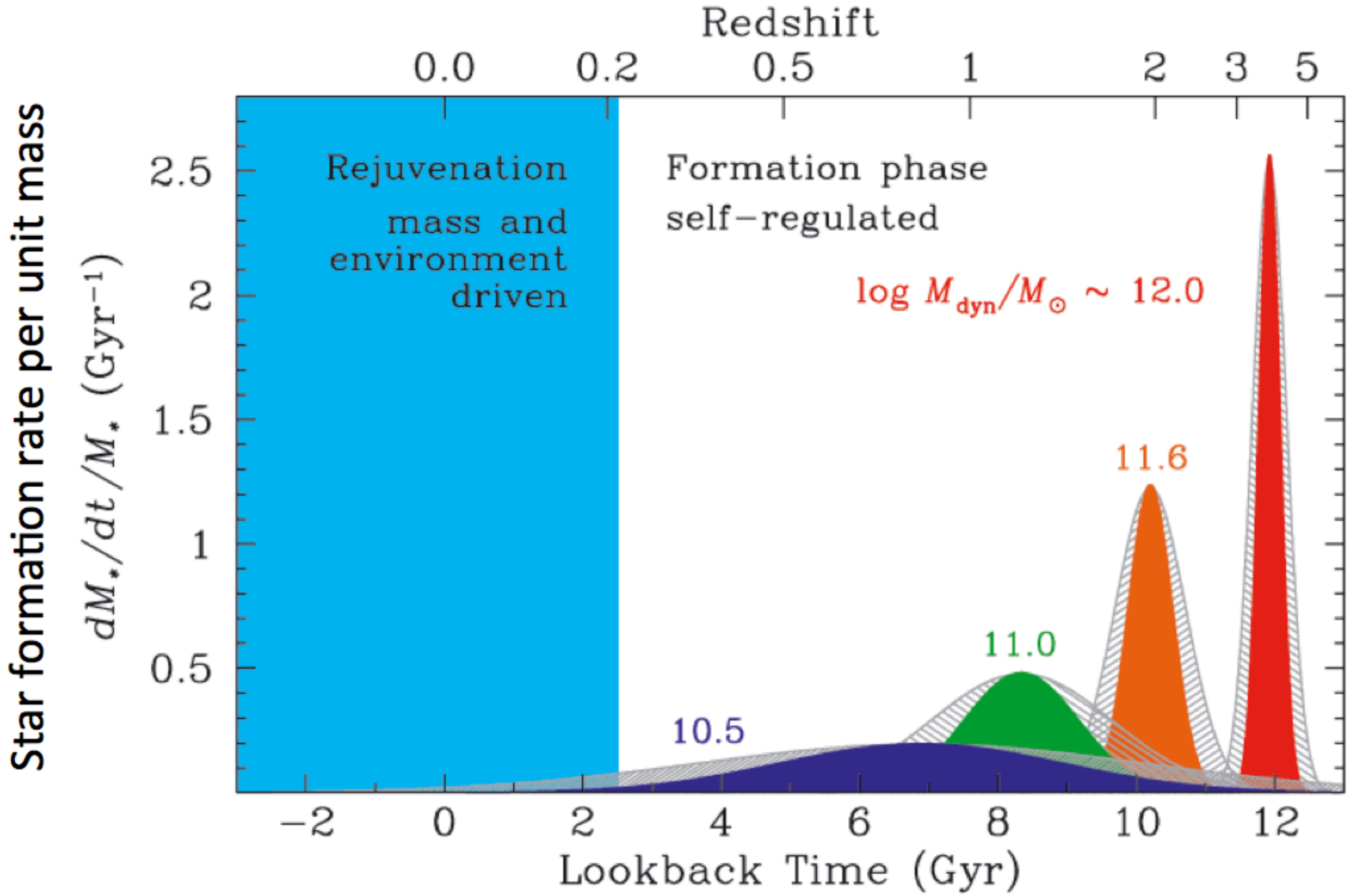
Figure 10

Massive galaxies in the Hubble Ultra Deep Field as imaged through the ACS camera and ordered by the value of their asymmetries from most symmetric to most asymmetric. Shown in this figure are systems with stellar masses $M_* > 10^{10}\,M_\odot$ at redshifts $2.2 < z < 3$. These galaxies are typically much smaller and bluer and have a higher asymmetry and inferred merger fraction than galaxies of comparable mass today (Conselice et al. 2008).

What about morphology? Look at massive galaxies see at a range of redshifts (again from Conselice, ARAA, 2014). The mix of types appears to change with redshift -- Peculiar objects and disky things first, spheroidal types later. But this is almost certainly very dependent on environment and galaxy mass!



What about if we look at the stars in nearby galaxies and ask when they formed? Population synthesis studies of nearby elliptical galaxies by Thomas et al (2010) show downsizing. Plot inferred star formation rate (y-axis) against time/redshift (x-axis) for elliptical galaxies of different masses (red: most massive, blue: less massive).

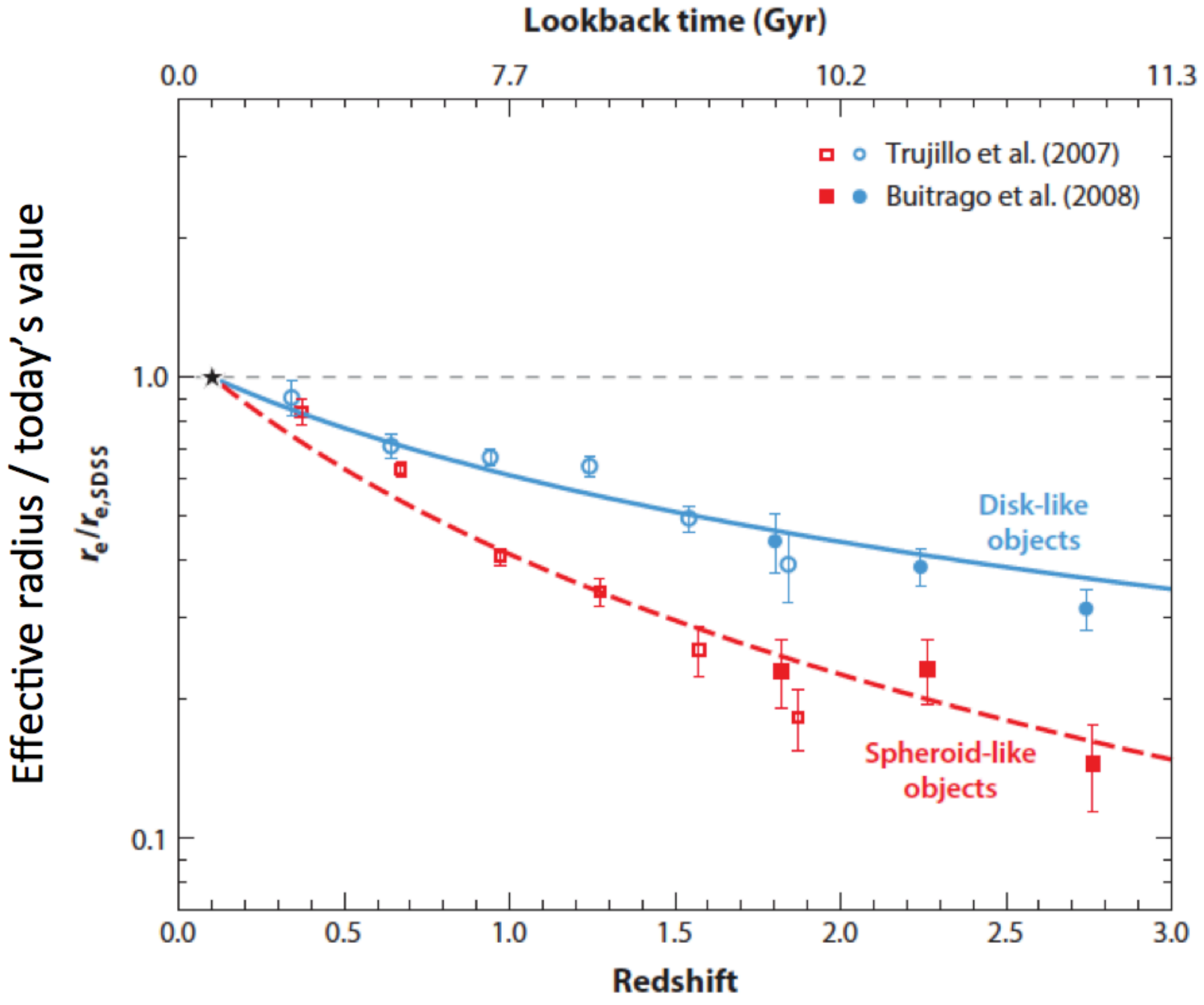


So wait. Observations of the high redshift universe suggest it takes time for massive ellipticals to grow, but studies of massive ellipticals in the local universe suggest these things formed very early. What's wrong with this picture?

It actually holds together. The stars that are in massive galaxies today formed long ago when they were in smaller clumps. Over time, these smaller lumps then merged together to assemble themselves into the massive objects we see today. Lower mass galaxies we see today formed their stars later and/or over longer timescales, on average.

So what about the idea of inside out galaxy formation? Do galaxies grow their outskirts later than their inner regions? Look at the changing sizes of massive galaxies, as measured by their effective radius (Conselice 2014 ARAA):

Also, we know that disk galaxies in the local universe show [color gradients](): they get bluer (younger?) as you go outwards in the disk.



The Cosmological Evolution of Star Formation

Remember that galaxy growth and star formation can be very different things. Let's forget about galaxies specifically and just ask how quickly did the *universe* form its stars?

(from Shapley 2011 ARAA)
Blue band shows star formation rate as observed; red band shows the rate inferred after correcting for dust obscuration.

Star formation in the universe peaked around z ~ 2-3, when the universe was only a few billion years old. So most of the stars in the universe are ~ 10 billion years old. But...

- **Star formation rates inside individual galaxies look very different**
- **Galaxies show stellar populations with a wide range of ages**
- **Many low mass galaxies today show preferentially young stars**

So again, we are seeing differences between when stars formed, where stars formed, and how galaxies assemble. There are significant variations due to differences in mass and environment.