Simulating Galaxy Evolution

Is very hard! The ingredients:

- Cosmological initial conditions
- Gravitational dynamics
- Gas hydrodynamics
- Radiation / Photoionization
- Star formation, supernovae, stellar winds
- AGN triggering, radiation, and outflows
- Stars and Stellar Evolution
- Dust absorption / extinction

Requires “High Performance Computing”

Example: The Illustris Project, international collaboration of astronomers, physicists, and computer scientists..

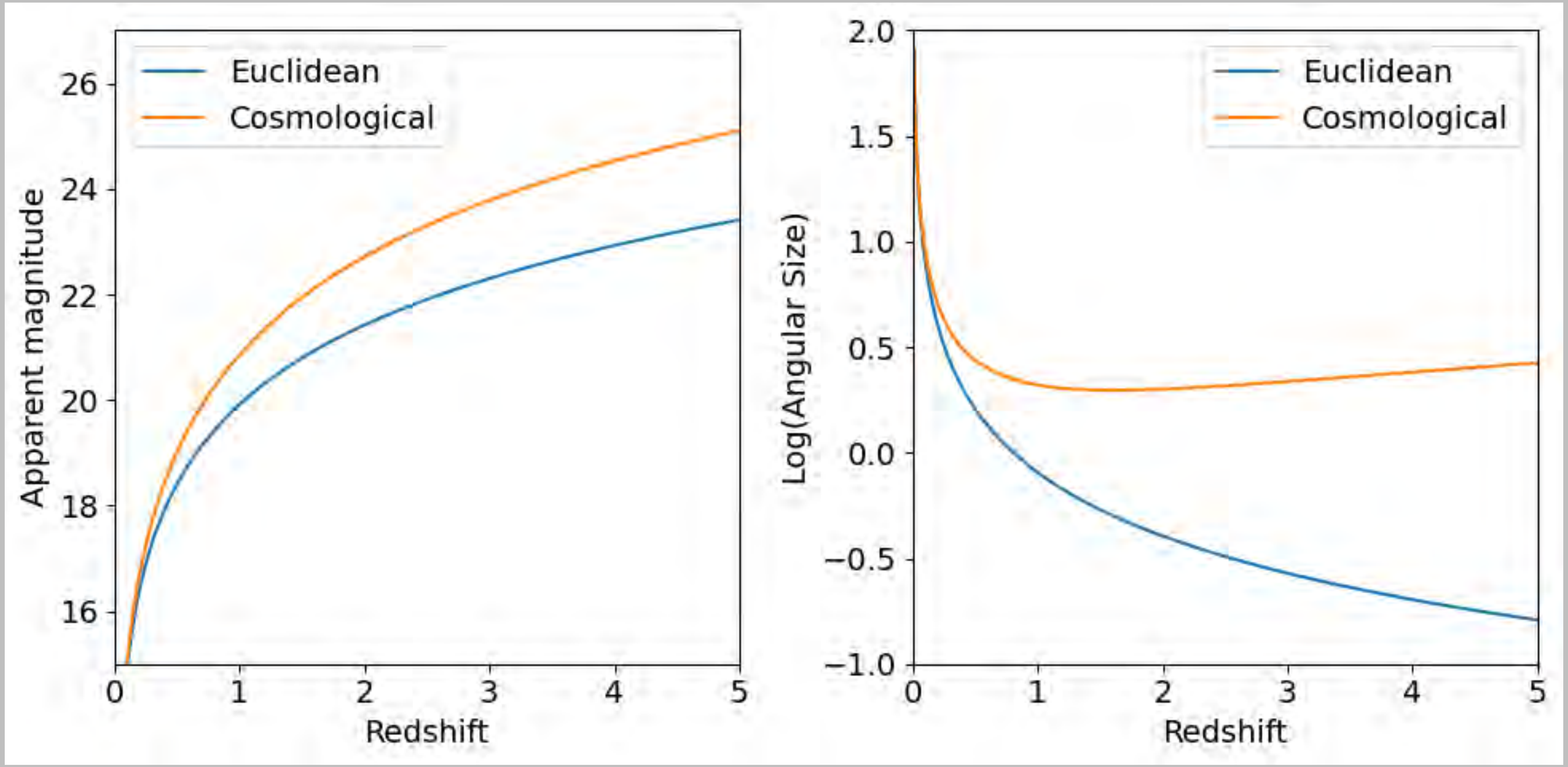
Largest simulations run on 8,192 compute cores, and took 19 million CPU hours (the equivalent of one computer CPU running for 19 million hours, or about 2,000 years

Simulations continue to get bigger and include even more physics, resolveing smaller and smaller scales, and doing so over larger and larger volumes. Some of the most intensive computational tasks in modern science.

Observing Galaxies in the Early Universe

Compared to the local universe "Euclidean expectation", if we think of moving a galaxy to higher and higher redshifts, cosmological effects make it

a) even fainter in apparent magnitude
b) not appreciably smaller beyond z=1.



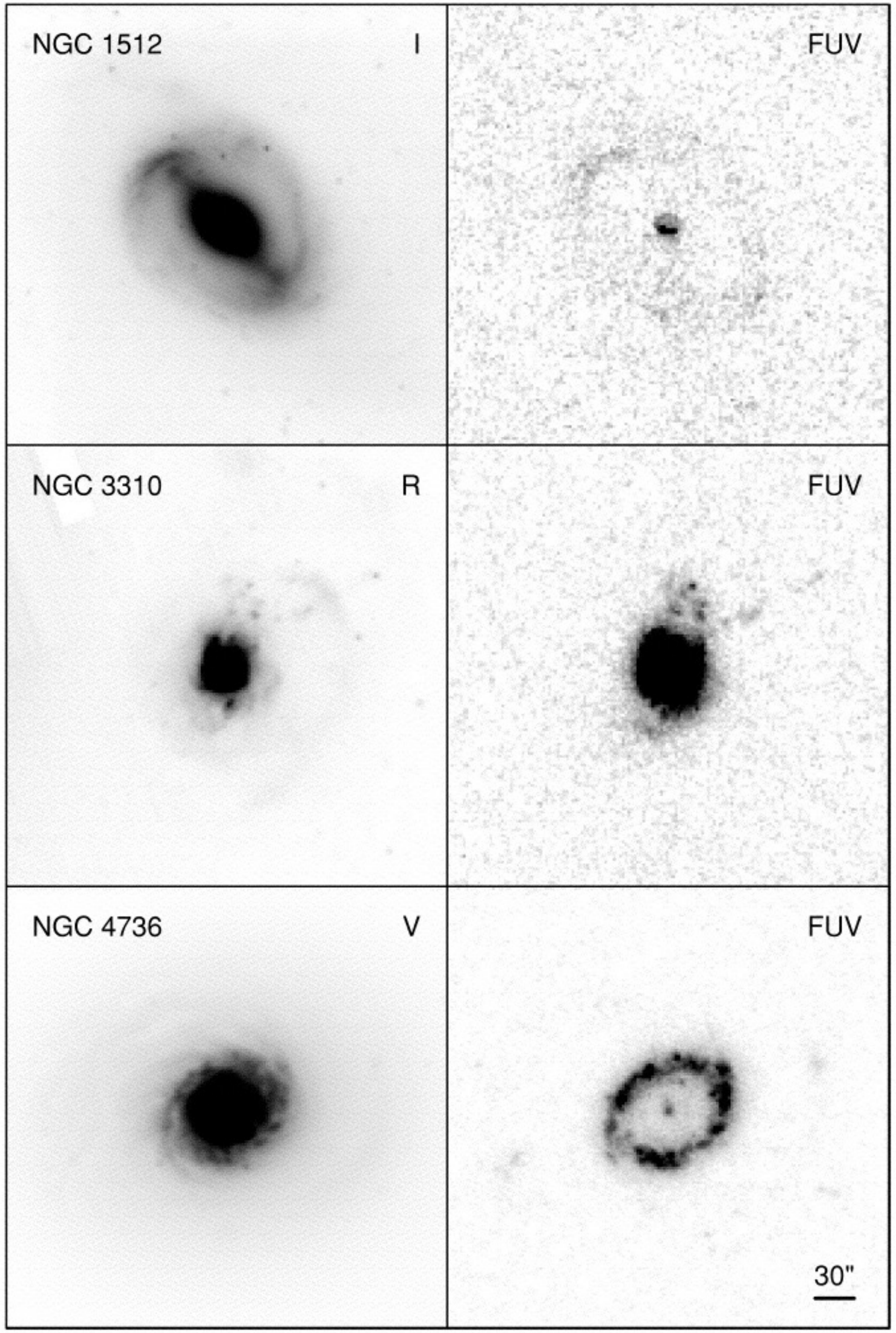
Observing Galaxies in the Early Universe

Also, at high redshift when we observe with optical telescopes, we see redshifted light that was originally emitted by the galaxy in the ultraviolet.

Ultraviolet light:

- dominated by young massive stars, not the general stellar population.
- easily obscured by dust.

Galaxies look very different in the ultraviolet than they do in the visible.



Images of nearby galaxies

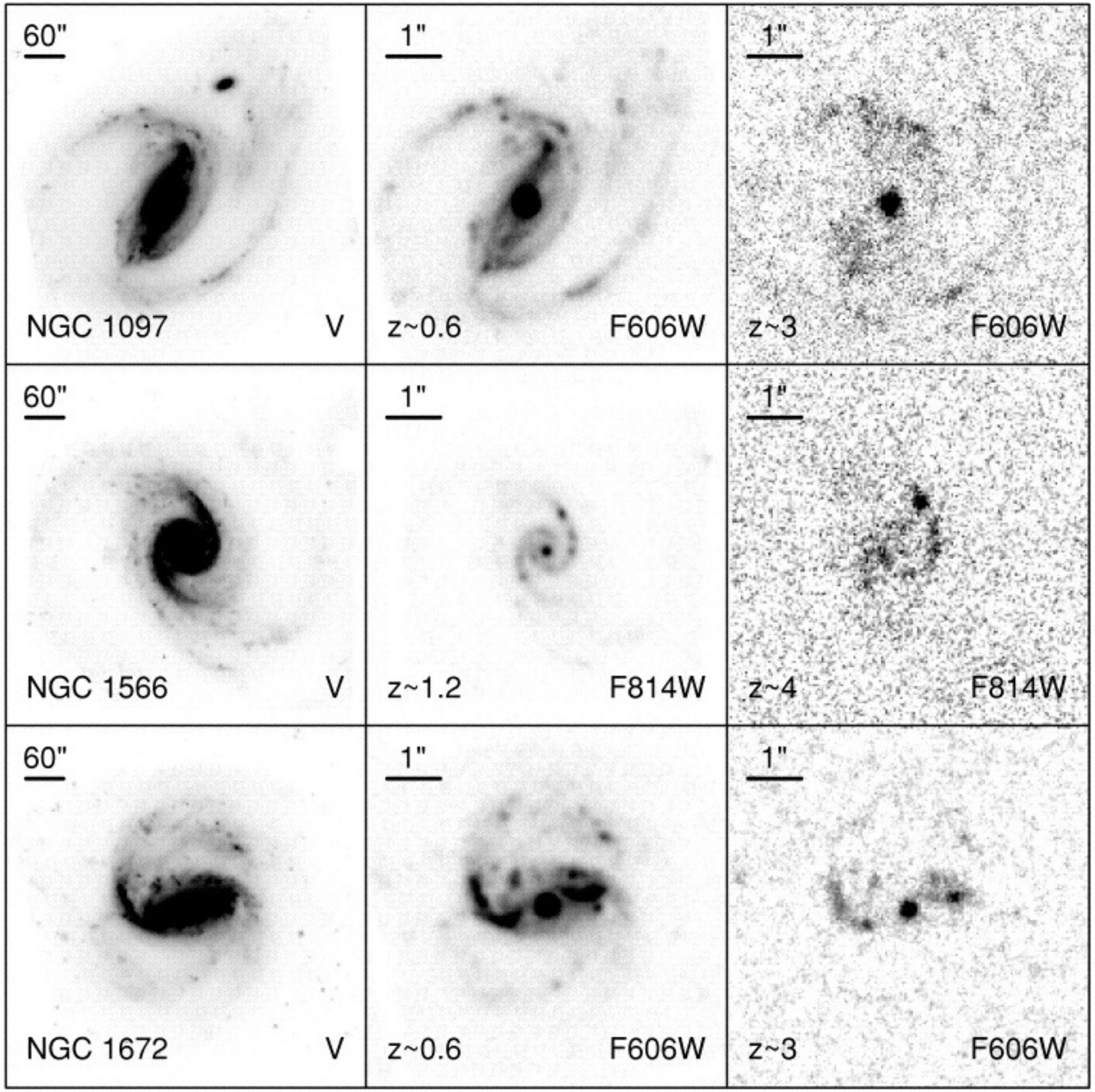
Left column: Optical images
Right column: Ultraviolet images

Kuchinski+01

Observing Galaxies in the Early Universe

So the combination of brightness and size effects, coupled with bandshifting, means that optical images of high-z galaxies can look very different from local galaxies even if they are physically similar!

Tend to only see the highest surface brightness regions and/or the star forming regions of a high redshift galaxy.



“Mock redshifting”

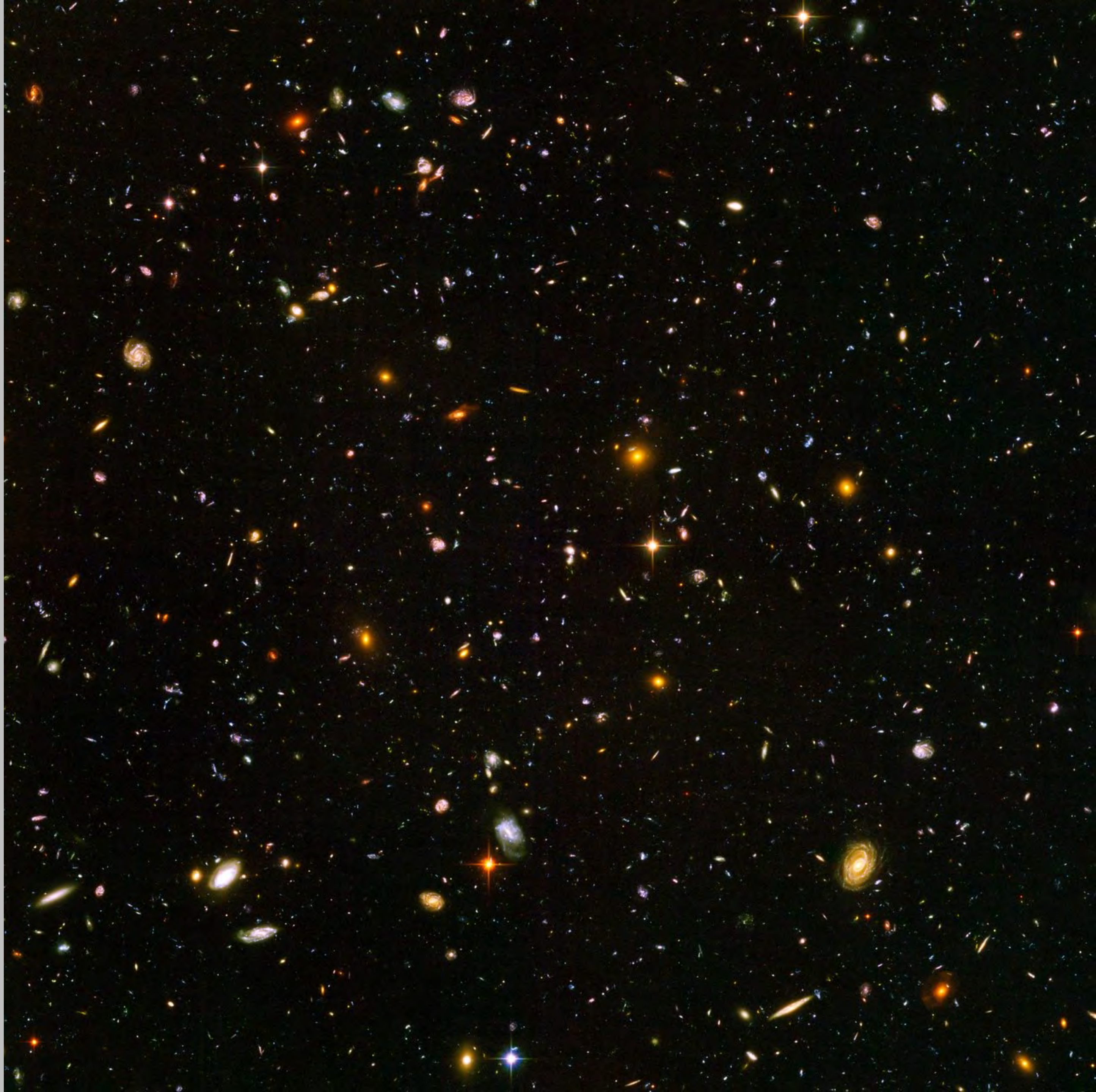
Left: True images of nearby galaxies
Middle: Simulated images at moderately high redshift
Right: Simulated images at high redshift

Kuchinski+01

The Hubble Ultradeep Field

- Observed in 2003-04
- Blank patch of sky 2.5 arcmin across (about 1/10th the size of the full moon)
- ~ 1,000,000 seconds of exposure time across four different optical filters
- Deep enough to detect galaxies to z ~ 6-7.

Remember, the image shows all galaxies along the line of sight, across a range of redshifts.



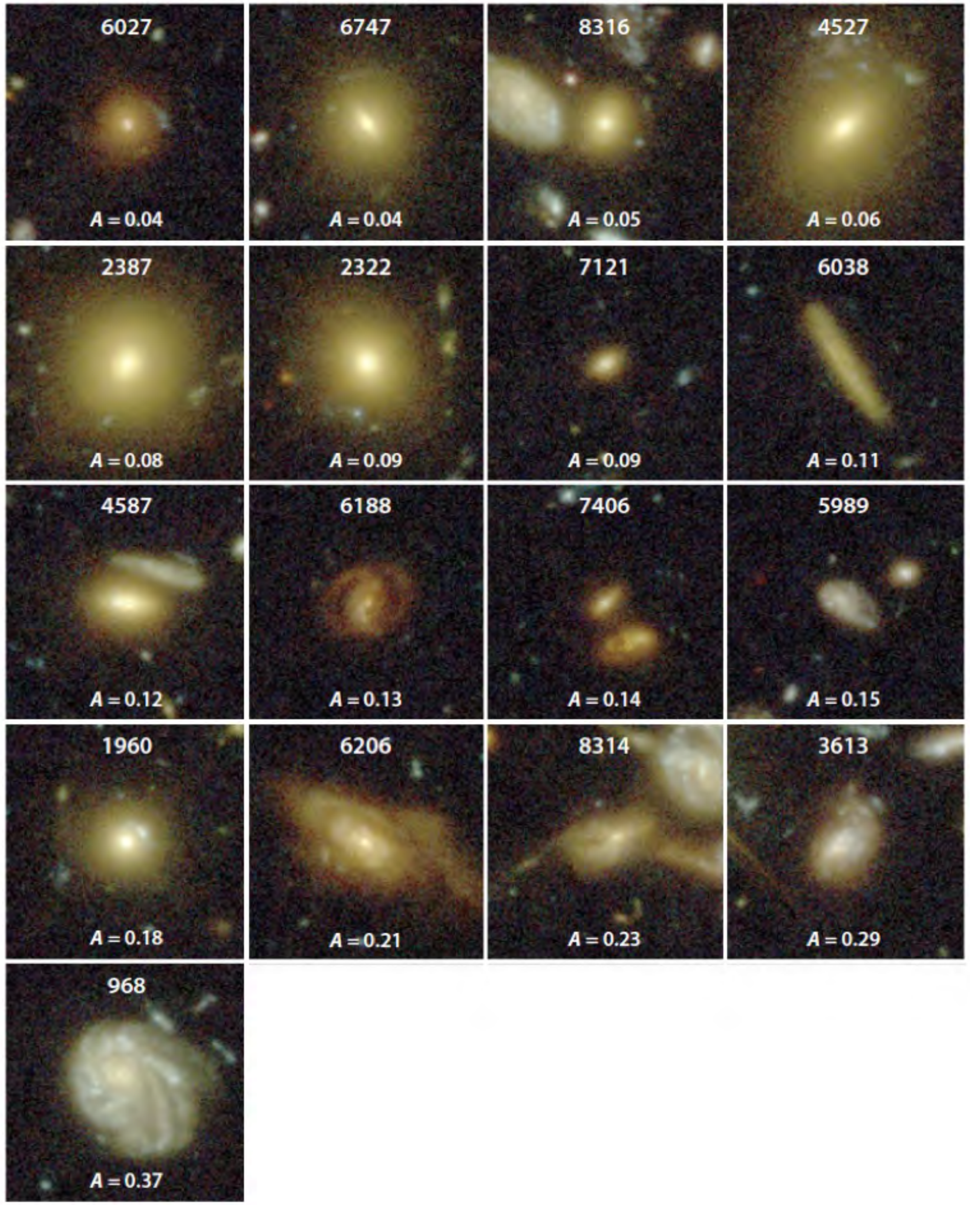


Figure 9

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.

Massive Galaxies in the UDF

Moderate z

$0.5 < z < 1.2$

$\Longleftarrow$

High z

$2.2 < z < 3.0$

$\Longrightarrow$

[Conselice ARAA 2014]

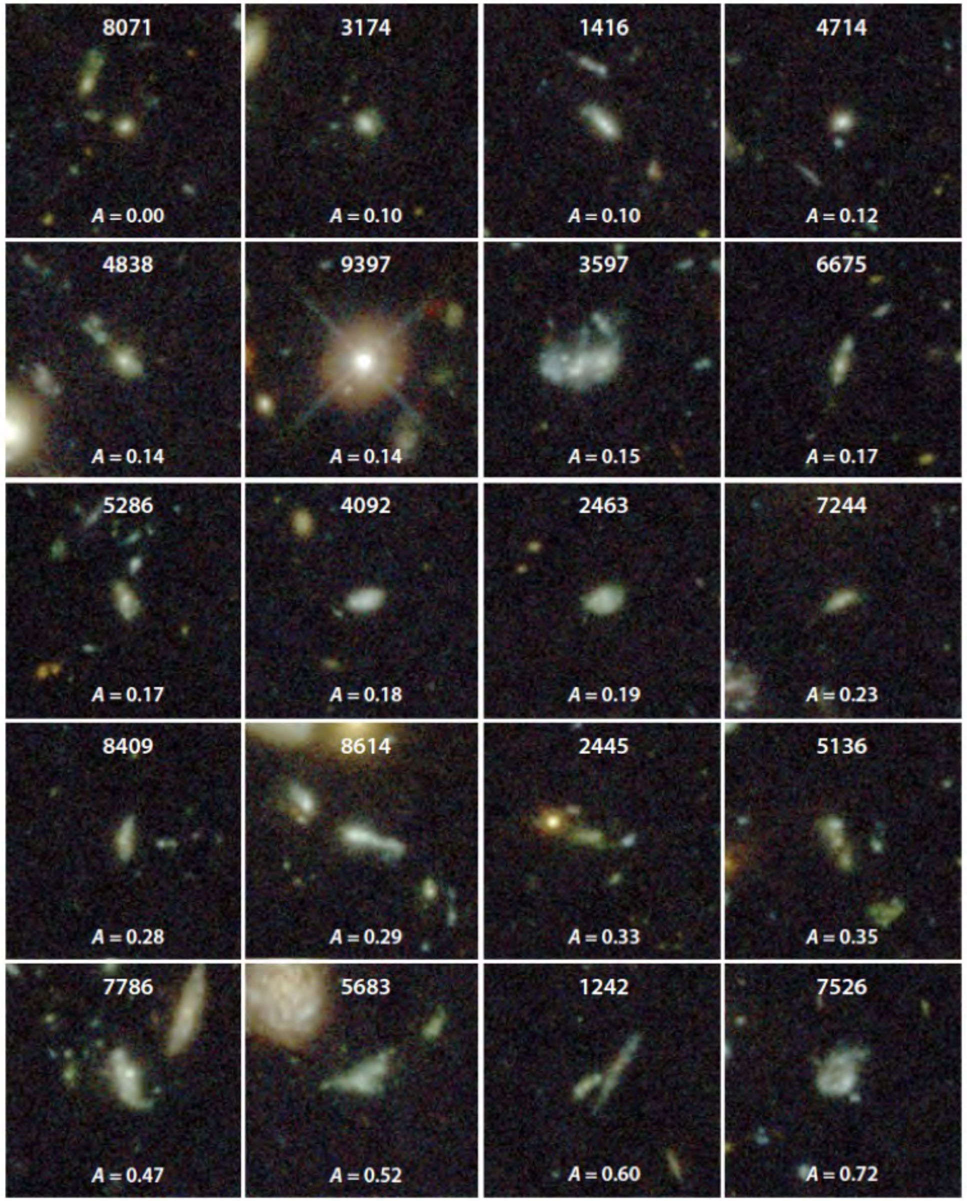


Figure 10

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).

Galaxy populations evolve with time

Late-type galaxies: spirals
Early-type galaxies: E/S0

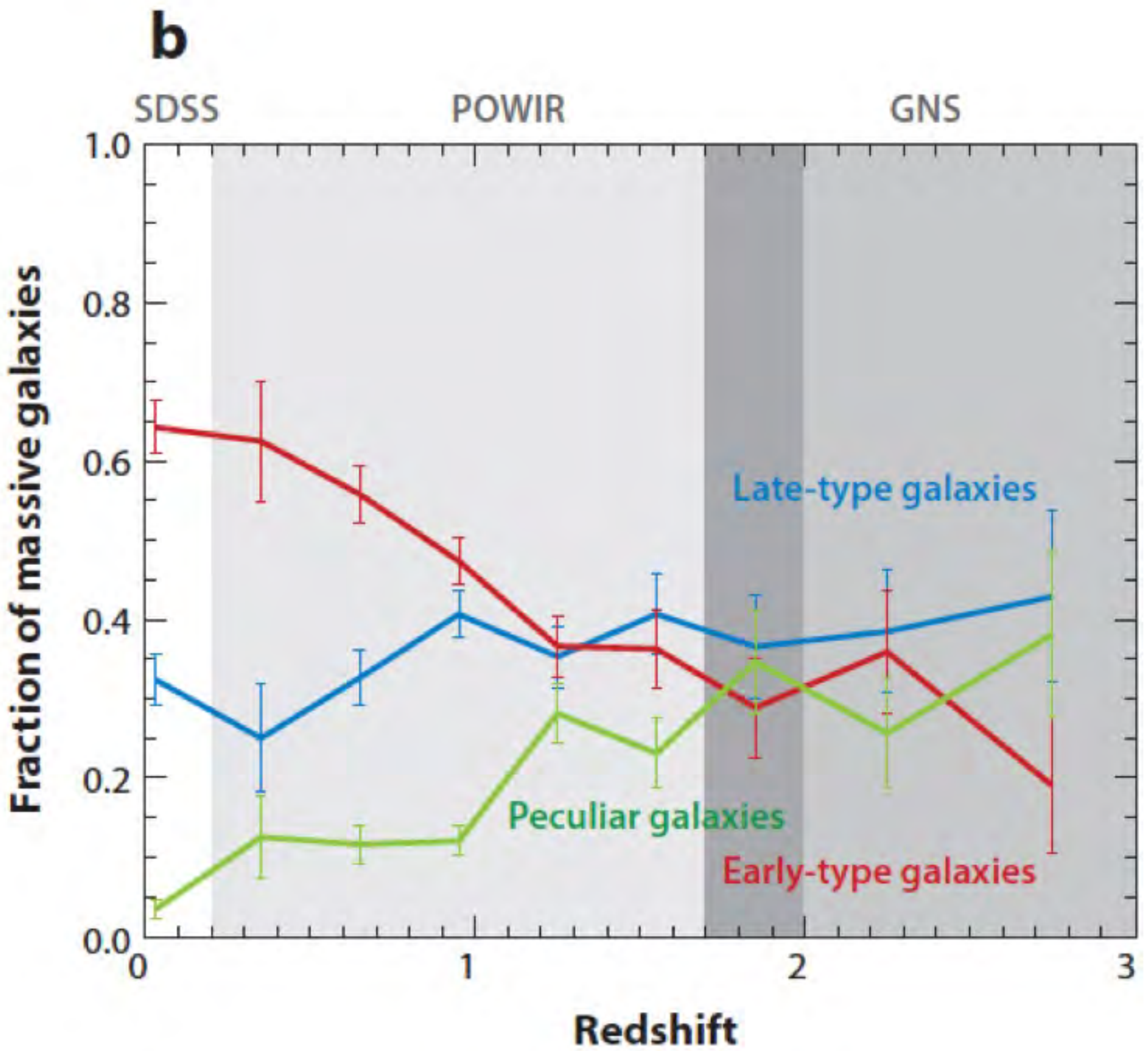
Lots of peculiar galaxies at early times (high redshift), products of interactions, mergers, and starbursts. Density of the Universe was higher, interactions common.

Spirals common across time.

Ellipticals become the dominant type of massive galaxy at late times.

Hierarchical growth shaping the local galaxy population observed today.

[Conselice ARAA 2014]



“Downsizing”

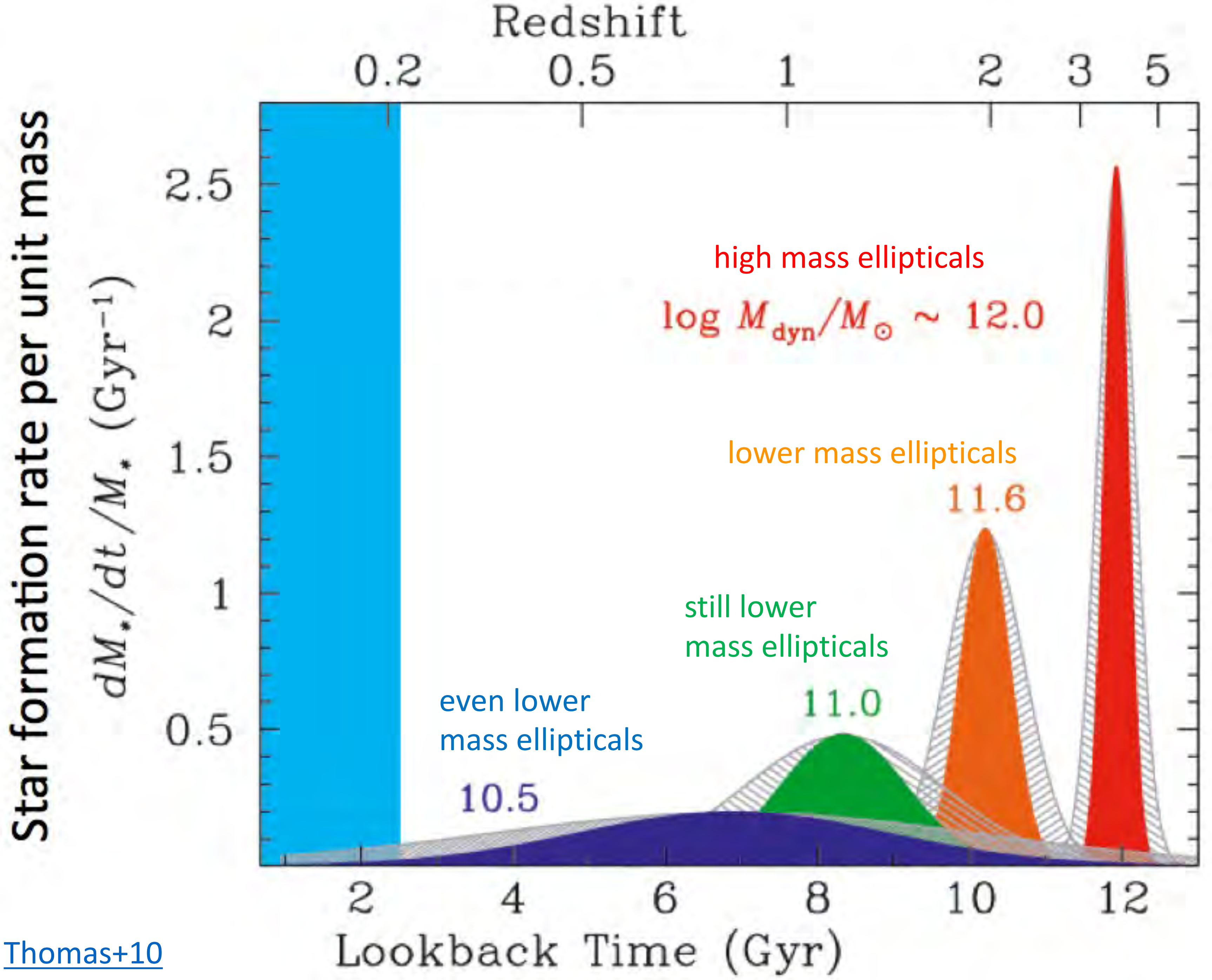
The stellar populations of high mass ellipticals formed very early on.

The stellar populations of lower mass ellipticals formed at later times (but still long ago!)

Remember: the age of the stellar populations is not the same as the age of the galaxy.

The stars in today massive ellipticals formed long ago, in smaller galaxies, that merged together over time to build up the massive ellipticals..

Environmental density important: massive ellipticals are found in dense environments. Their stars formed early, mergers built the ellipticals quickly.



Thomas+10

Inside-out Galaxy Formation

Galaxies are growing in physical size over time.

At high redshift galaxies are more compact than today.

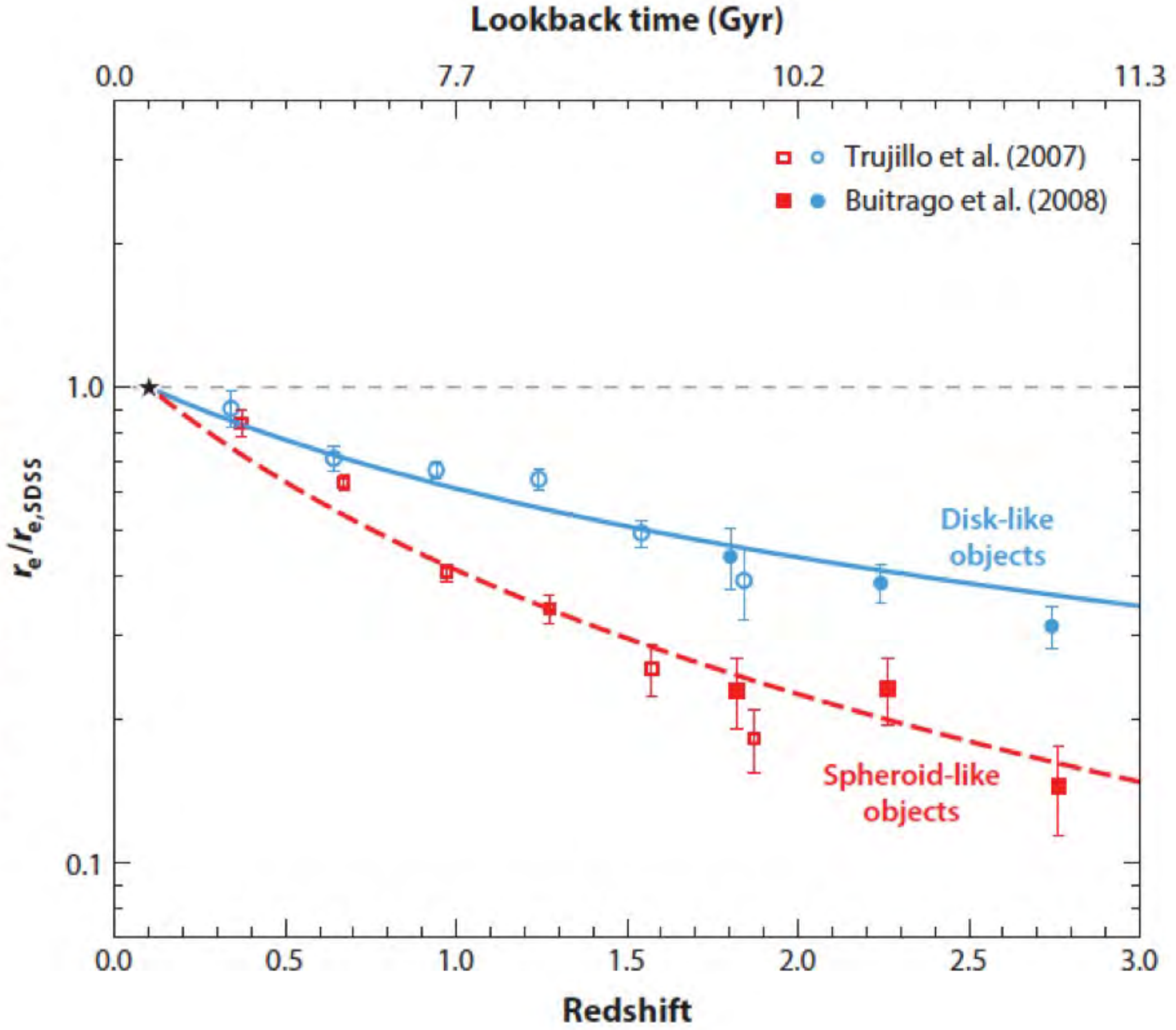
Two likely effects:

- Star formation in outer parts of spirals happens more gradually, builds up the outer disks.
- Low mass galaxies fall in to larger galaxies ("accretion") and their stars are stripped and left in the larger galaxies' halos.

Both processes build the outer parts of galaxies.

[Conselice ARAA 2014]

Effective radius / today's value



Star forming history of the Universe

Cosmic Happy Hour! 🍸🍺🍷

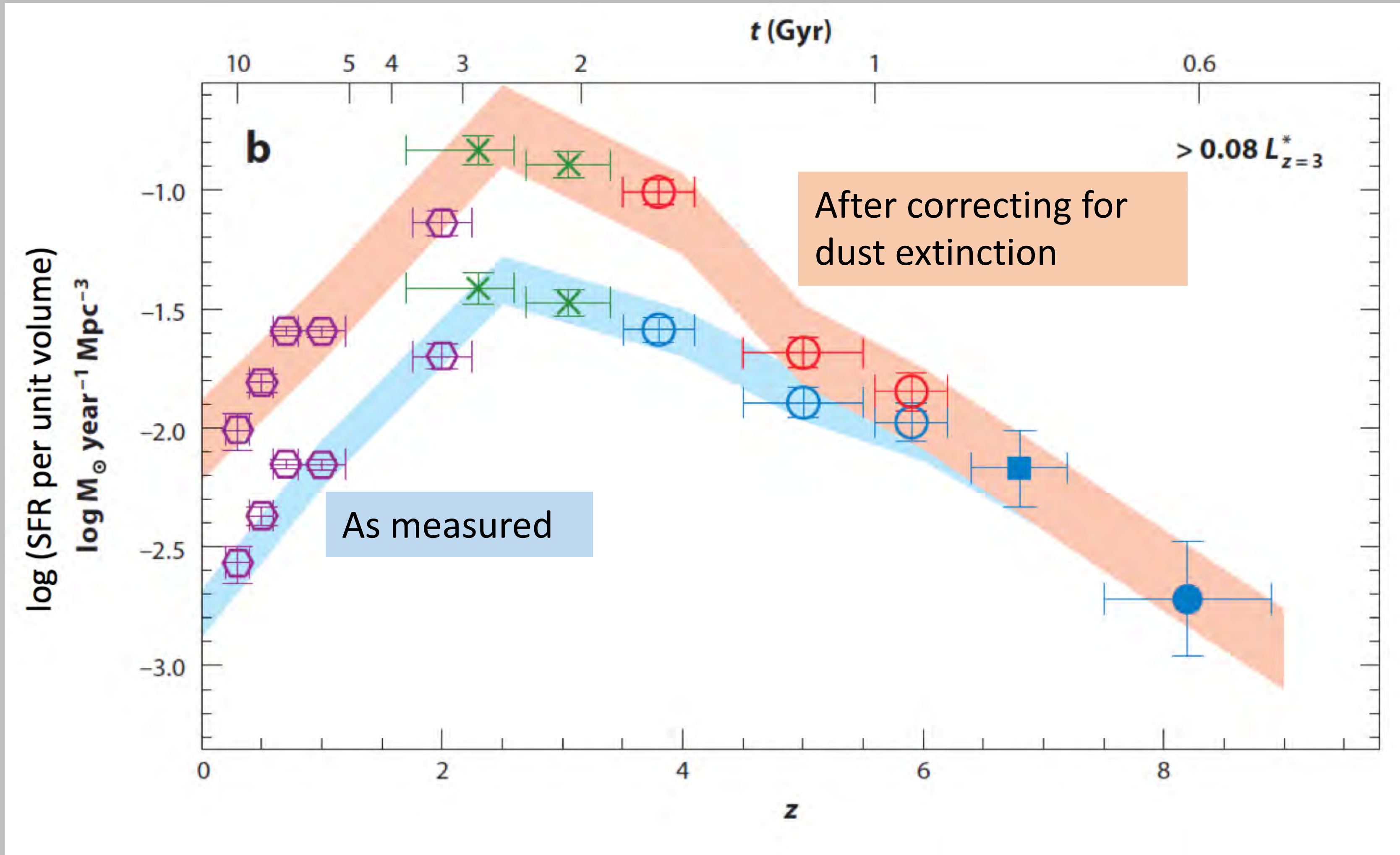
Integrated over all galaxies, we see that the star formation rate of the universe grows quickly and peaks at $z \approx 2 - 4$, or a few billion years after the Big Bang.

Since them star formation has been slowly ramping down.

Individual galaxies may behave differently, of course!

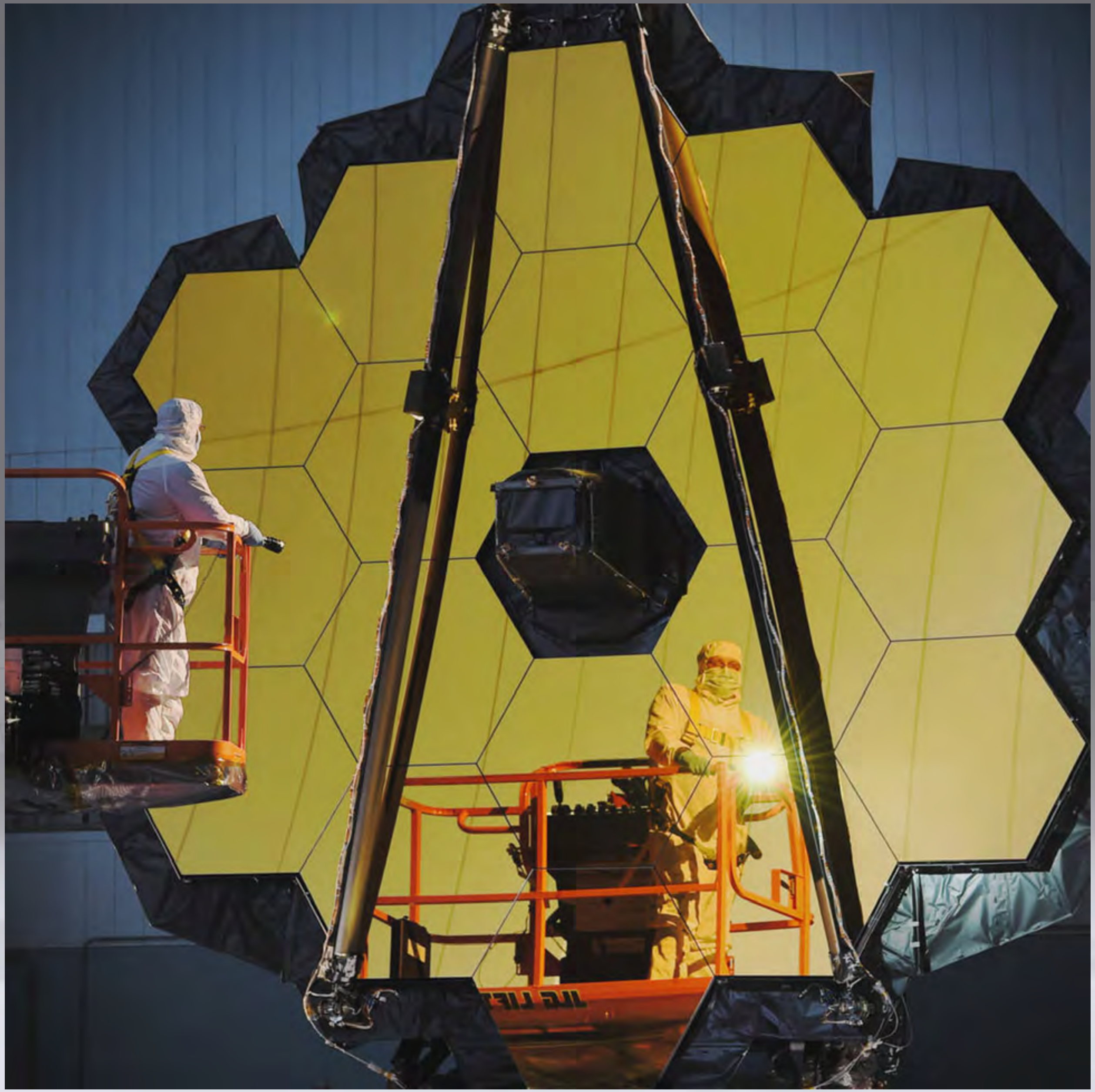
“Cosmic Noon”

“Cosmic Dawn”

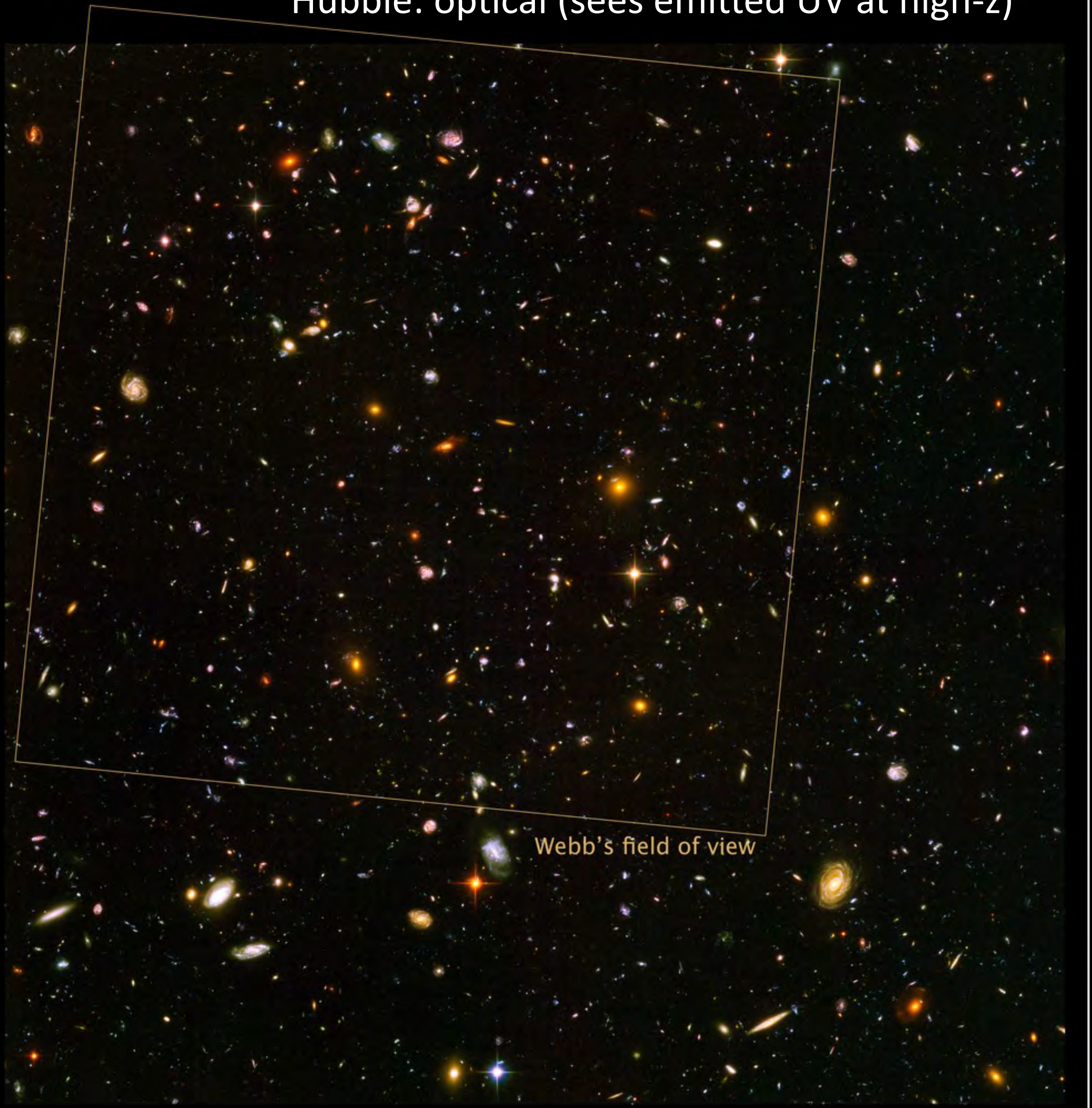


JWST vs Hubble

JWST



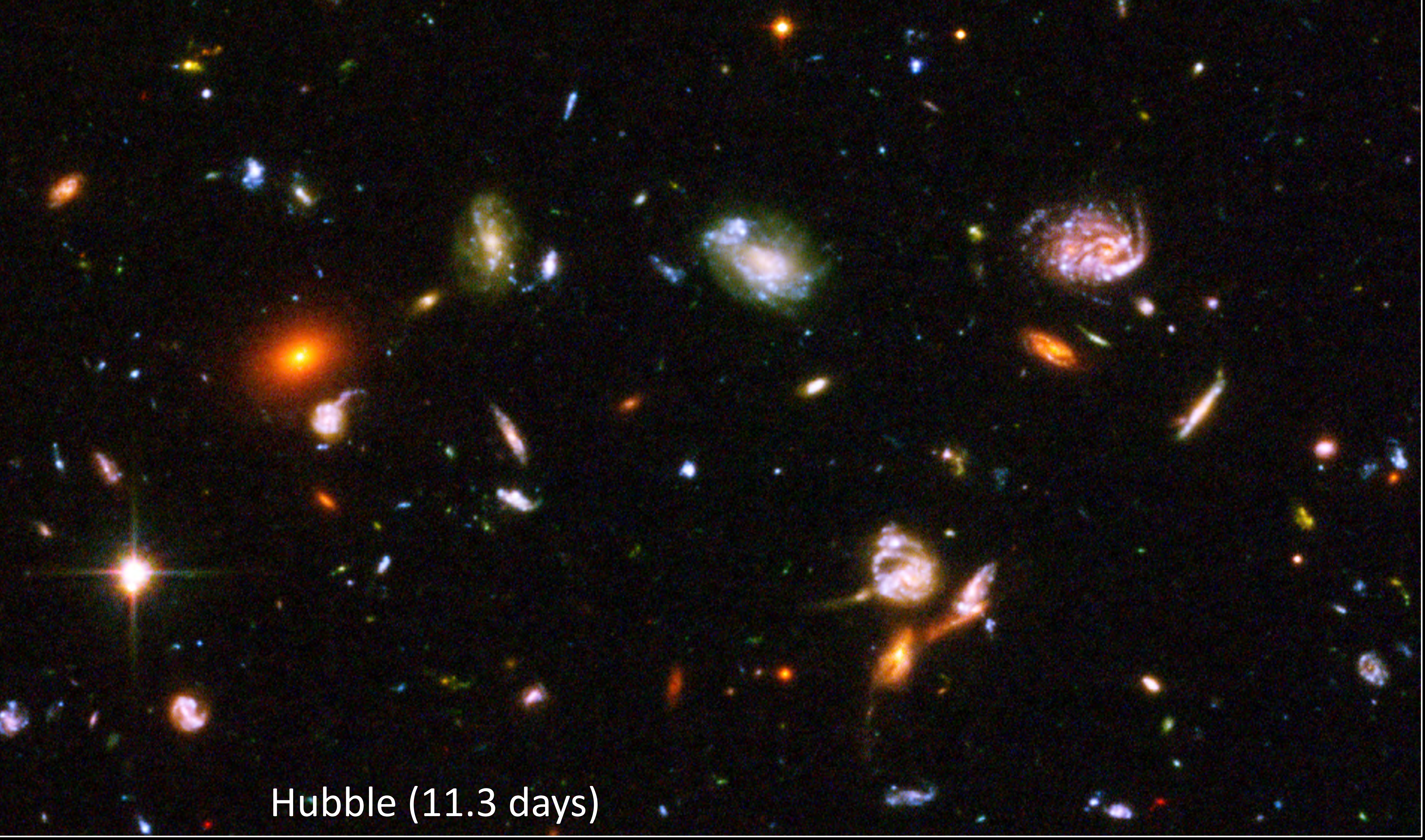
Hubble: optical (sees emitted UV at high-z)



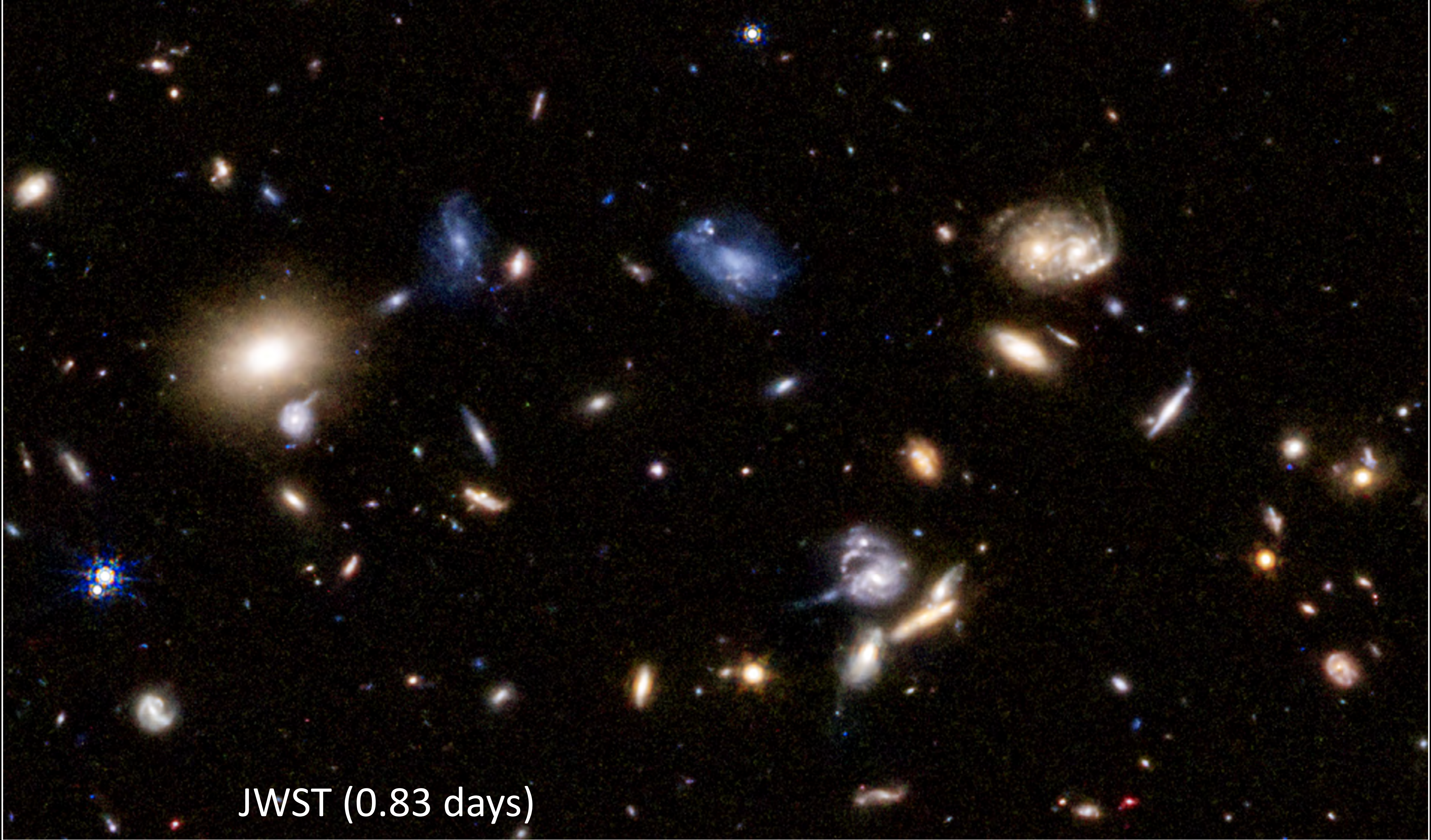
Hubble UDF (exposure time: 11.3 days)

JWST: infrared (sees emitted optical at high-z)

Webb (exposure time: 0.83 days)



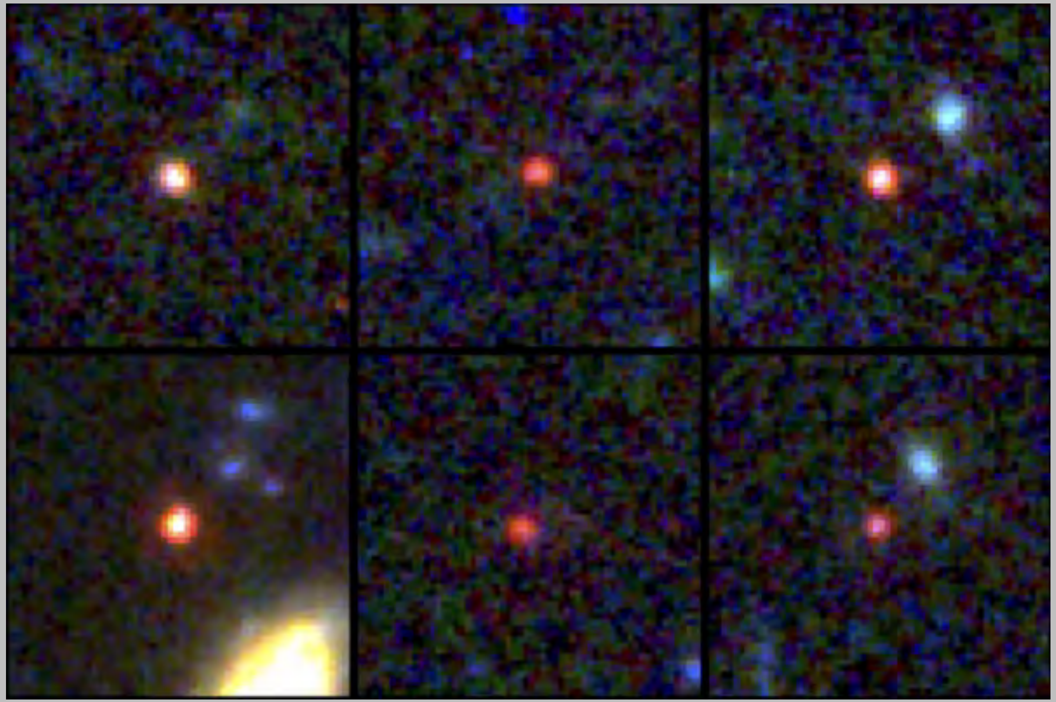
Hubble (11.3 days)

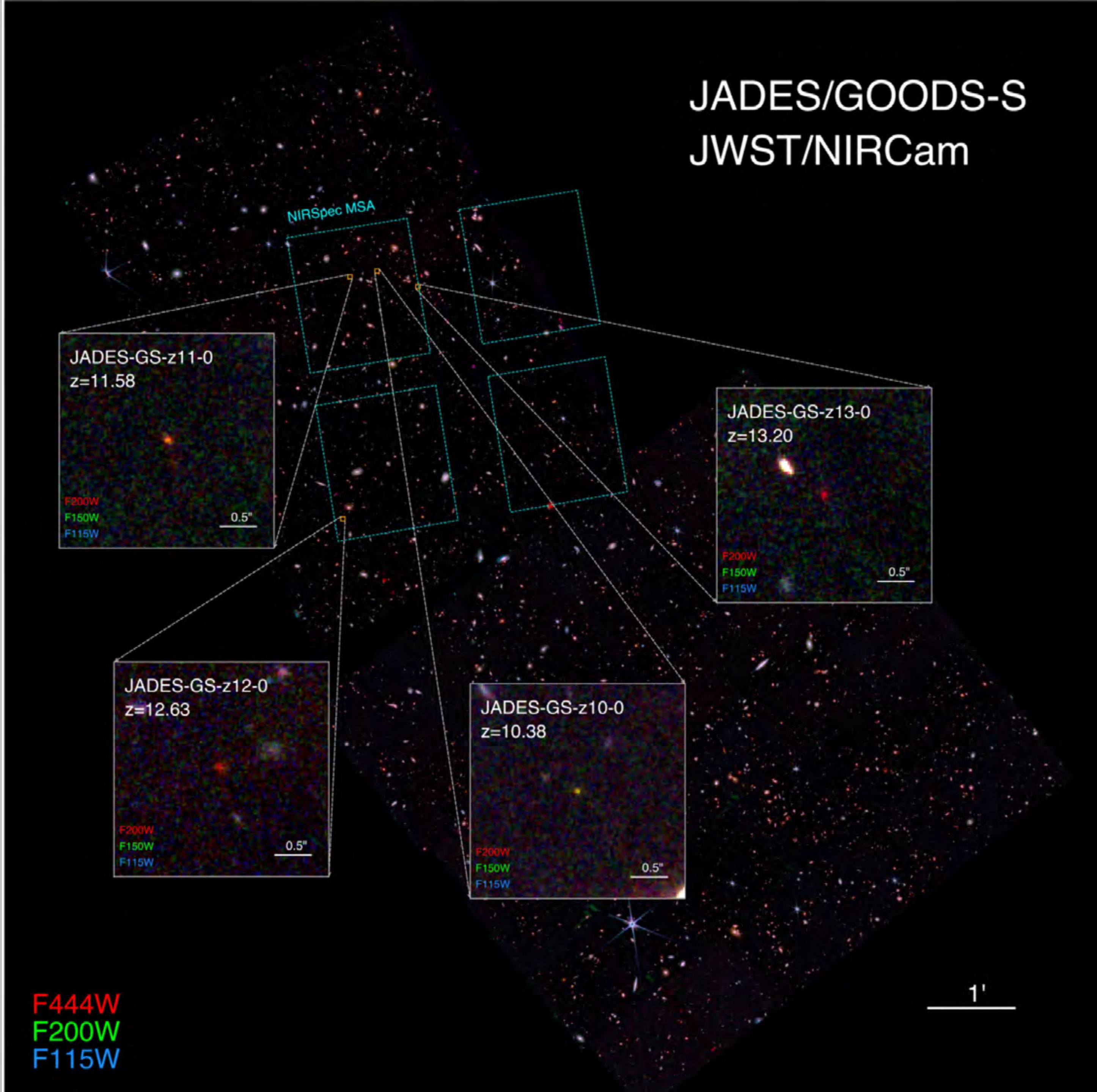

JWST (0.83 days)

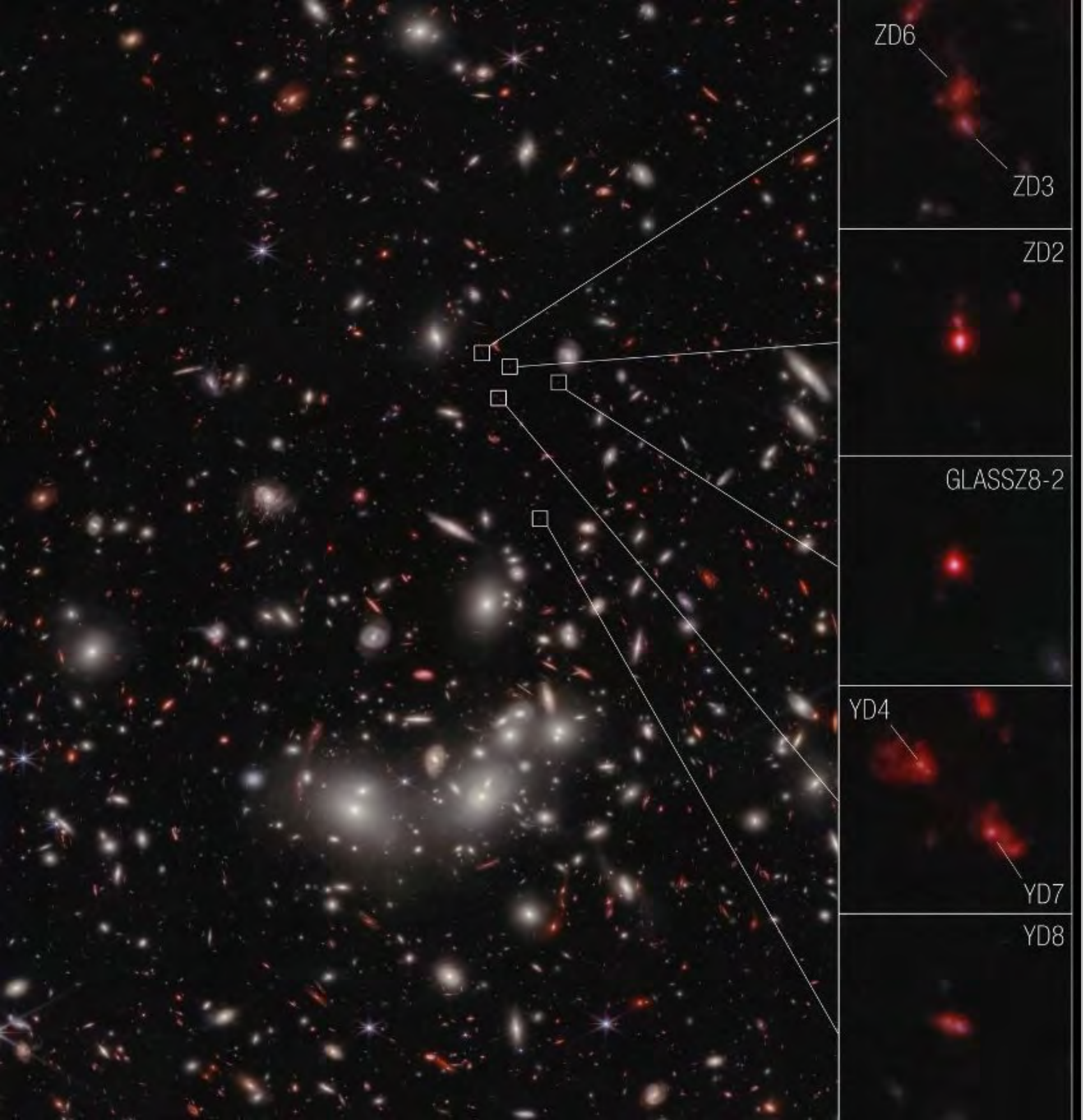
Galaxies at the highest (yet) redshift:

- Redshifts: $z \approx 10 - 13$
- Universe age: $300 - 450$ Myr
- Stellar mass: $\approx 10^8 - 10^9\ M_\odot$
- SFR: $\approx 0.2 - 5\ M_\odot/yr$
- Stellar ages: $\approx 15 - 70$ Myr

Robertson+23







High redshift proto-cluster:

- Proto-cluster behind foreground cluster
- Redshift $z = 7.9$
- Universe age: 650 Myr