

Galaxies: Structure, Dynamics, and Evolution

Cosmic Star Formation History and Early Galaxy Assembly

Can we construct a picture of how galaxies
form and evolve across cosmic time?

Layout of the Course

Lectures

Feb 2: Course Introduction, Overview, and Galaxy Formation Basics

Feb 9: Disk Galaxies (I)

Feb 12: Disk Galaxies (II)

Feb 16: Disk Galaxies (III) / Collisionless Stellar Dynamics

Feb 23: Collisionless Stellar Dynamics + Vlasov/Jeans Equations

Feb 26: Vlasov/Jeans Equations / Elliptical Galaxies (I)

Mar 9: Elliptical Galaxies (II)

Mar 23: Dark Matter Halos

Mar 30: Connecting Galaxies to Dark Matter Halos

Apr 13: Galaxy Stellar Populations + Lessons from Galaxies at $z < 0.2$

Apr 20: Lessons from Galaxy Samples at $z < 0.2$ + Evolution with Redshift

Apr 23: Evolution of Galaxies with Redshift + Pushing to $z > 1.5$

May 4: Cosmic Star Formation History + Galaxy Evolution at $z > 6$

May 11: Galaxy Evolution with JWST / Review for Final Exam

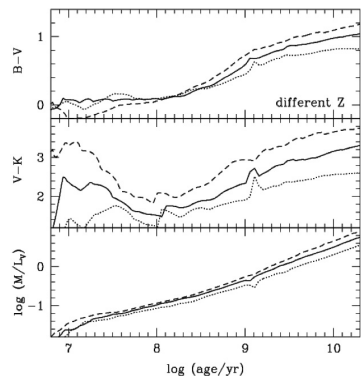
Problem Set 6

Due on May 11

Galaxies: Structure, Dynamics, and Evolution
 Problem Set 6
 Instructor: Dr. Bouwens

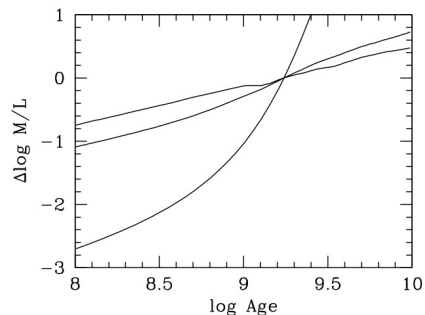
Here is Problem Set 6. The entire problem set will be due before class on Monday, May 11 (email them to Wout and include GSD in the subject line). Be sure to pay extra attention to problem 1, as your solution to that problem will be checked carefully and used in determining your homework grade.

1. Evolution of the mass-to-light ratio. (a) The mass-to-light ratio is roughly a power-law with time. Measure by hand the coefficient α for the mass-to-light ratio $M/L = t^\alpha$ for the V band from the following figure shown in lecture (choose the middle line):



(b) The $B - V$ and $V - K$ color of a SSP (simple stellar population) depend more or less linearly on $\log t$ for ages about 10^8 years. Determine this dependence from the figure shown above (take the middle line again). Use the result to derive the coefficient α for the mass-to-light ratio dependence on time for the B band and the K band.

(c) Use the following figure (also shown in lecture) to derive α for the U -band (the U band curve is the steepest one):



2. (a) Assume that the time dependence of the mass-to-light ratio derived in problem #1 for all t below 10^{10} years. The equations above were derived for single burst stellar populations. Now assume a population with constant star formation. Calculate the evolution of the M/L ratio with time T for the U , B , V and K band. Do this by calculating the light from a populations formed at a time interval $t, t + dt$, and then integrating from $t = 0$ to $t = T$, where T varies from 1 to 10 Gyr. The only thing we care about is the dependence of the M/L ratio with time, not the absolute value of the M/L ratio.

(b) Use the results obtained in (a) to derive the dependence of the $U - B$, $B - V$, and $V - K$ colors with time. Compare these numbers to the time dependence of the same colors for an SSP.

3. An important assumption in the analysis of unresolved stellar population is that of a universal initial mass function. What would be the impact if this assumption were not true? Consider two cases: the first being a Salpeter IMF with cut-offs at $0.1 M_\odot$ and $100 M_\odot$ and the second being a Salpeter IMF with cut-offs at $0.1 M_\odot$ and $1 M_\odot$.

(a) Assume that a galaxy formed stars according to the two IMFs described. Very qualitatively, what would the SEDs of galaxies look like like 10 Myr later and 11 Gyr later? How similar are the SEDs of galaxies in the two cases at the later time?

(b) How do the SEDs of galaxies evolve in the case of the first IMF vs. the second IMF? How accurately could one determine the time since the instan-

taneous burst of star formation in the two cases?

(c) Let's suppose that the true IMF of a galaxy corresponded to the second case, but let's suppose one assumed it was the first case. How might it impact one's estimates of the total mass locked up in stars based on the observed SED? How might it impact one's estimates on the total metals ejected as a result of supernovae in the formed stars? Describe each case.

4. Use a modern stellar population synthesis code to predict galaxy spectra. In this problem you will use the Flexible Stellar Population Synthesis (FSPS) code through its Python interface (`python-fsps`). Start early, as installation and setup may take some time.

(a) Consider a simple stellar population (SSP), in which all stars form instantaneously at $t = 0$. Using FSPS, generate spectra for a population with the following parameters:

- Star formation history: instantaneous burst (SSP)
- Metallicity: $Z \approx 0.004$ (subsolar)
- Initial mass function: Salpeter
- No dust attenuation and no nebular emission

Compute spectra over a range of ages from 10^6 to 10^{10} years, using logarithmically spaced time steps (e.g., ~ 100 steps). Plot the spectrum at approximately 10^7 , 10^8 , 10^9 , and 10^{10} years on the same wavelength range.

Briefly describe how the spectral shape evolves with time.

(b) Using the same model, compute the absolute magnitudes in the V and I bands as a function of time over the range 10^6 to 10^{10} years.

From these results, determine the absolute magnitude in the I band, M_I , either directly or using

$$M_I = M_V - (V - I).$$

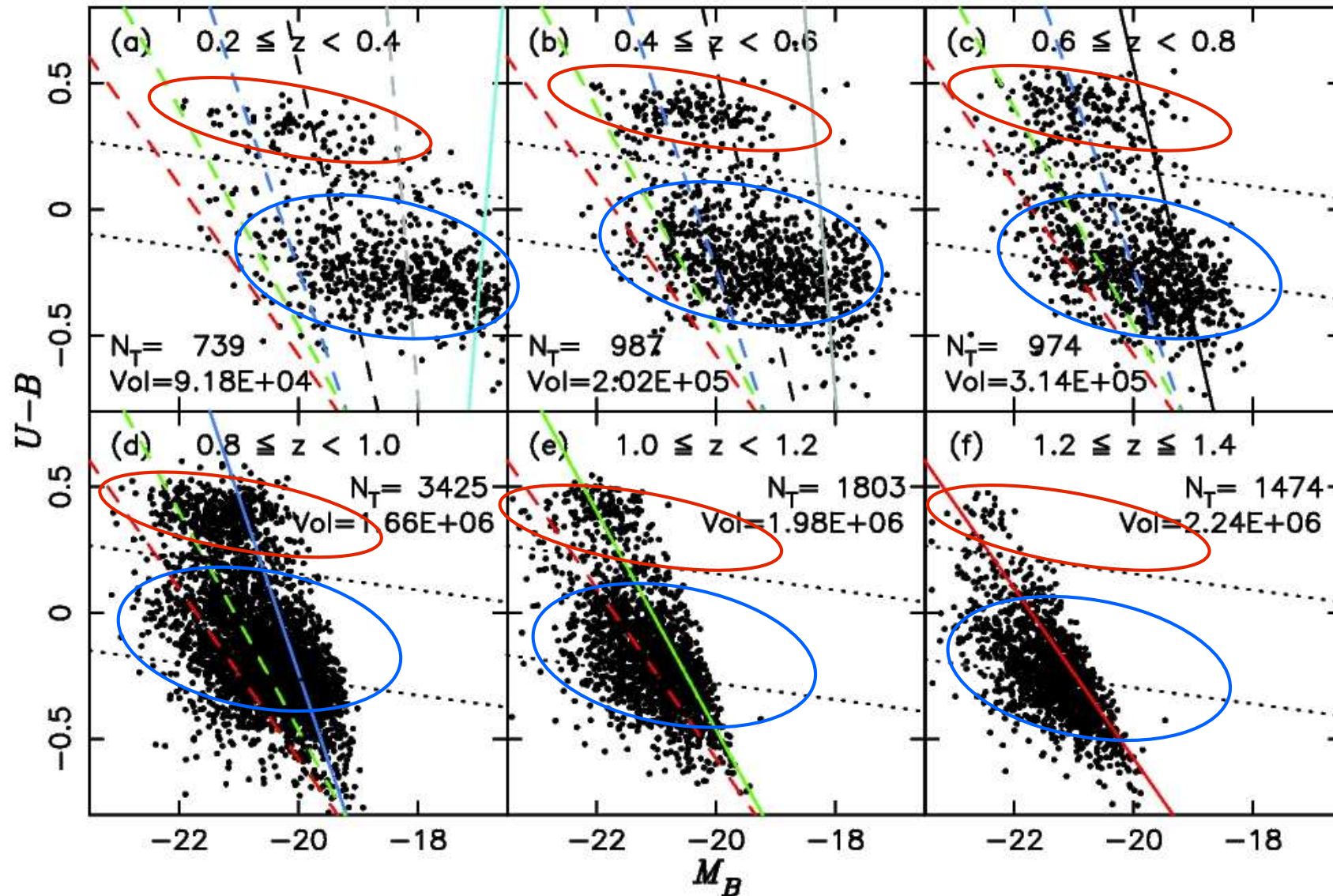
Plot M_I as a function of $\log_{10}(t/\text{yr})$.

Using the stellar mass of the population and the I -band luminosity, determine how the mass-to-light ratio evolves with time. Assume a power-law form

$$\frac{M}{L_I} \propto t^\alpha.$$

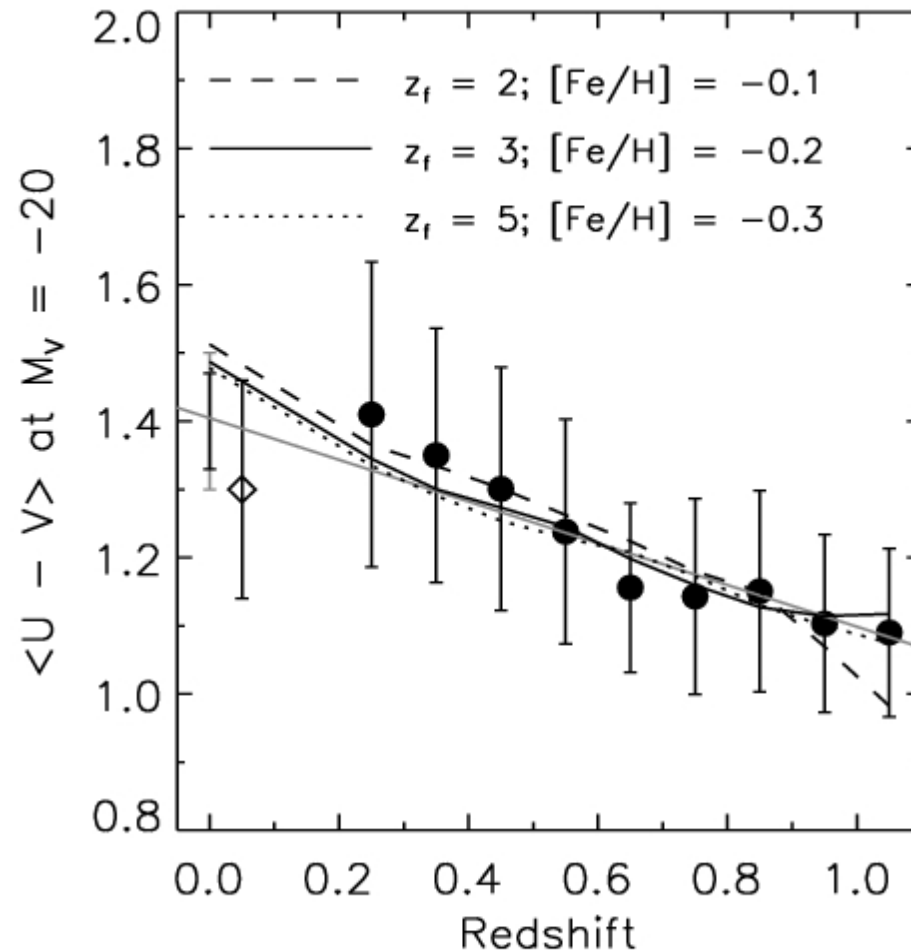
**First, let's review the important
material from last week**

One of the most interesting aspects of the evolution of galaxies with cosmic time are changes to the “red sequence” and “blue cloud”:



One can see the existence of the red-sequence out to $z \sim 1$

How do the colors of galaxies in the red sequence change with redshift?

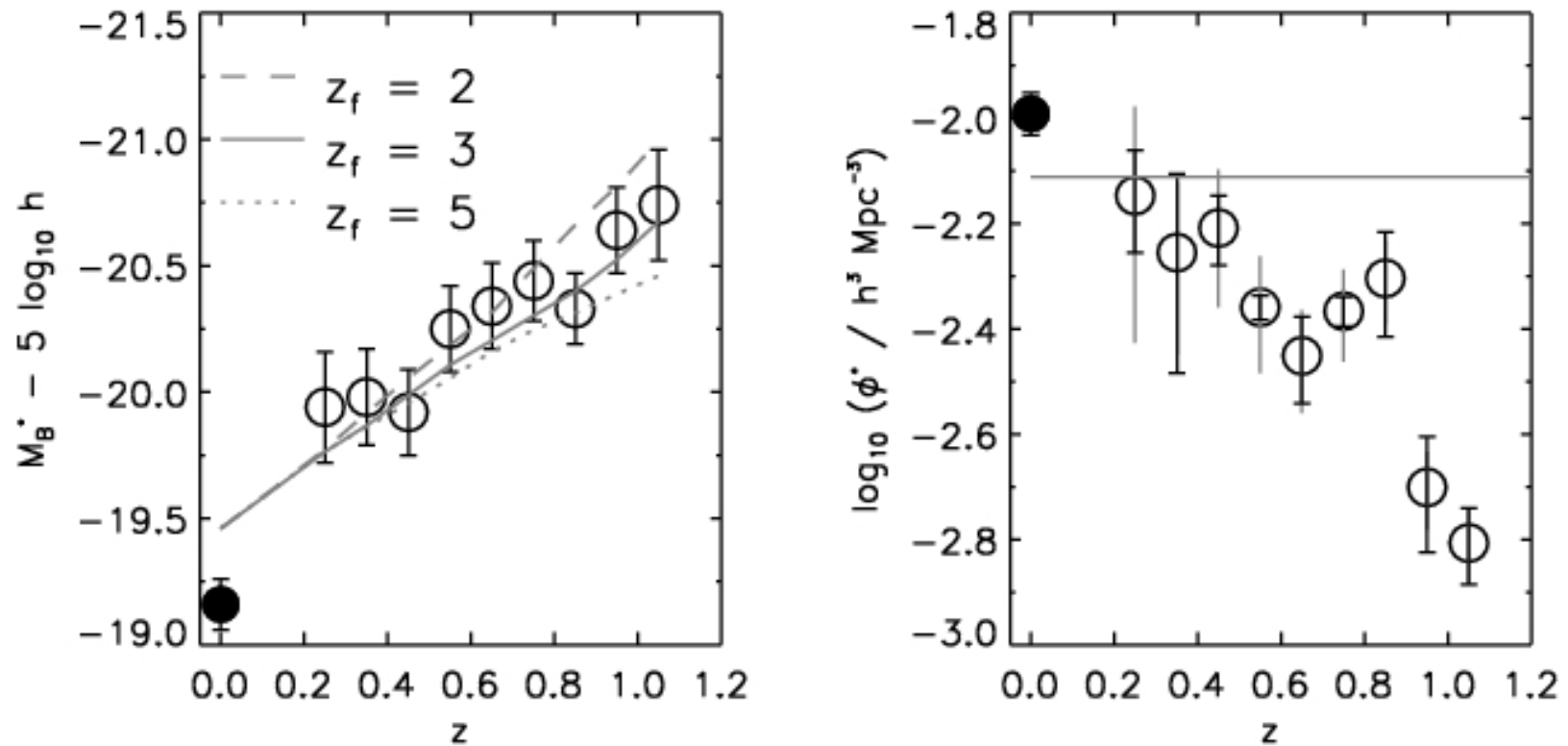


“Red sequence” galaxies are becoming bluer, as one moves to higher redshift. This is what one would expect if they formed almost all of their stars a long time ago. Since the colors of galaxies change as a power law, one can try to use the evolution in color to determine when red sequence galaxies formed their stars.

Parameterizing the evolution of the luminosity function of “red sequence” galaxies using the Schechter function,

$$\phi(L) = \phi^* e^{-L/L^*} (L/L^*)^\alpha$$

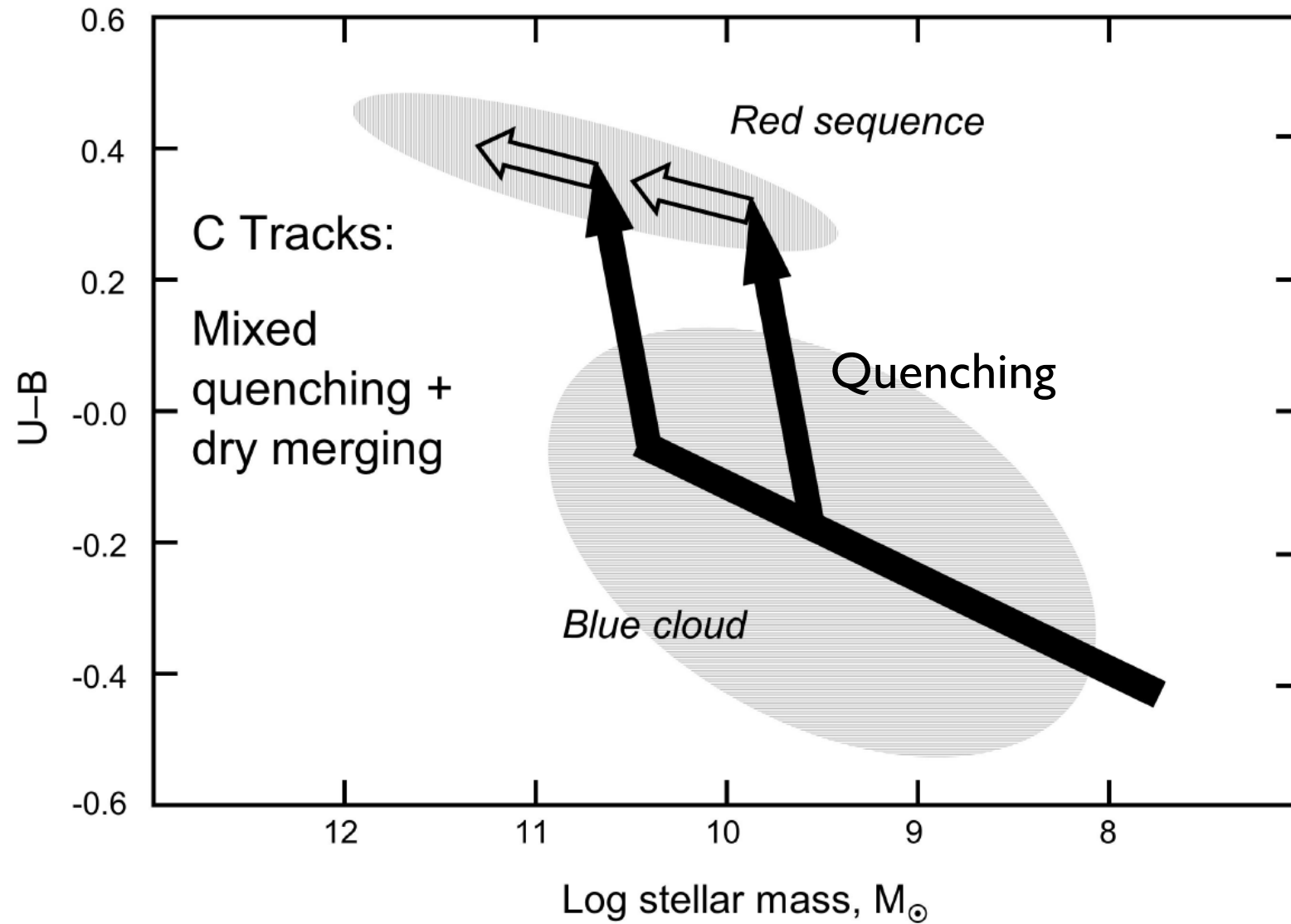
how do the individual parameters evolve?



How would you interpret these trends?

How might galaxies move from the blue cloud to red sequence?

There are many possibilities!



What is quenching?

A galaxy is “quenched” when it stops forming stars. It appears that most quenched galaxies never form stars again.

How does quenching happen?

It is unknown. Maybe due to energy coming from black holes at the center of a galaxy heating up the gas in and around a galaxy.

Observationally, by noting which galaxies are quenched and which are not, we can determine the factors which led to “quenching”:

1) Mass Quenching -- When galaxies become more massive, “quenching” is more likely to happen

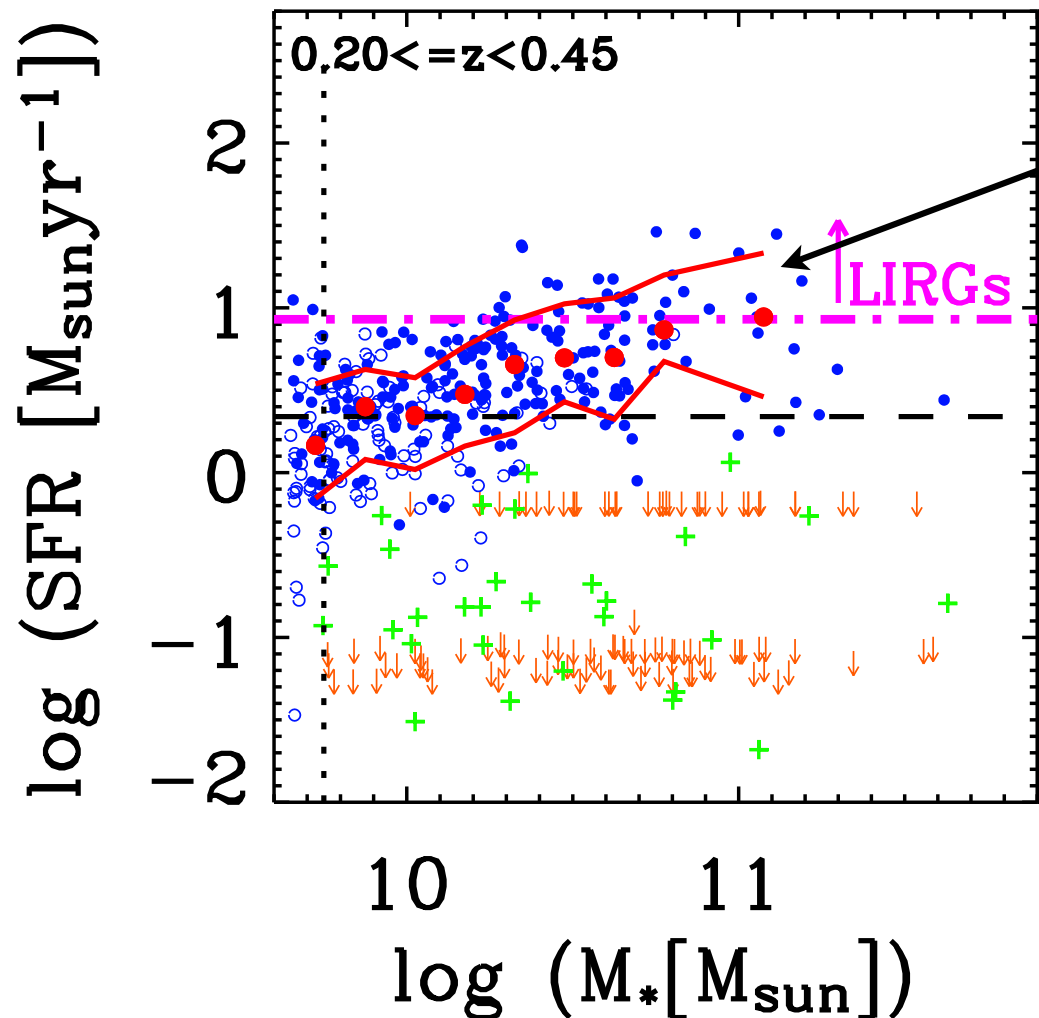
(could be due to increased importance of AGN in the most massive galaxies)

2) Environmental Quenching -- When galaxies are in dense environments (nearby many other galaxies), “quenching” is more likely to happen

(could occur as galaxies become satellites in more massive halos and lose their gas supply)

What about the blue cloud?

Clear relationship between the star formation rate and the stellar mass of a galaxy...



Spread in the relation is only 0.3 dex

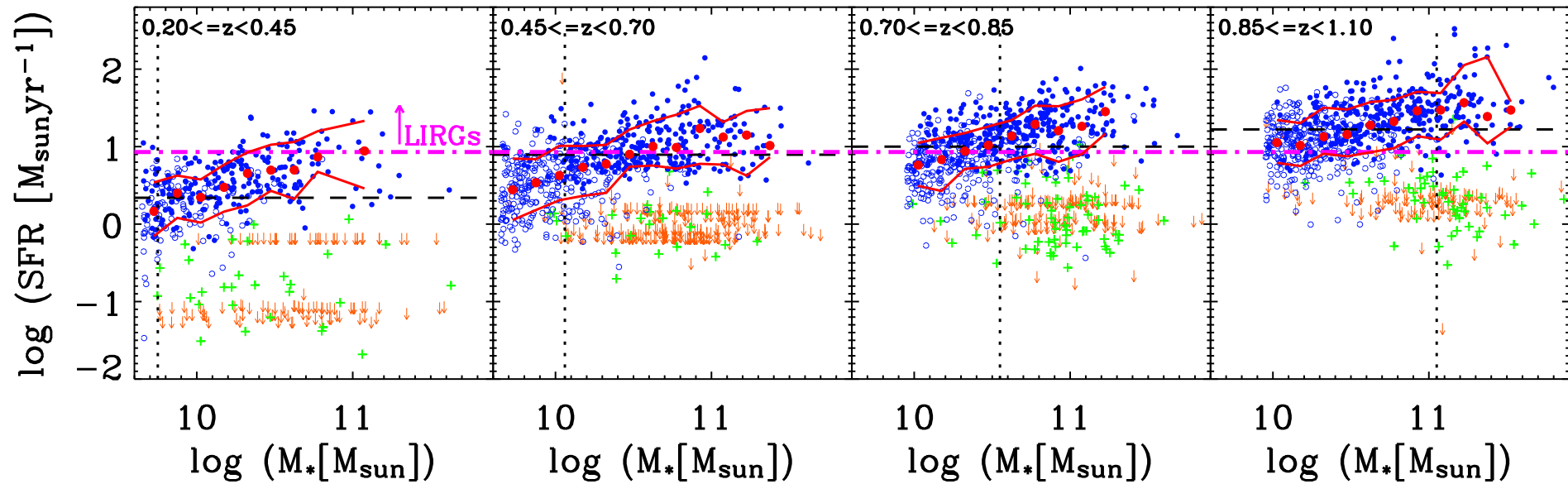
Suggests that SFR is proportion to stellar mass

called “main sequence of star formation” for galaxies

Implies exponential growth of galaxies

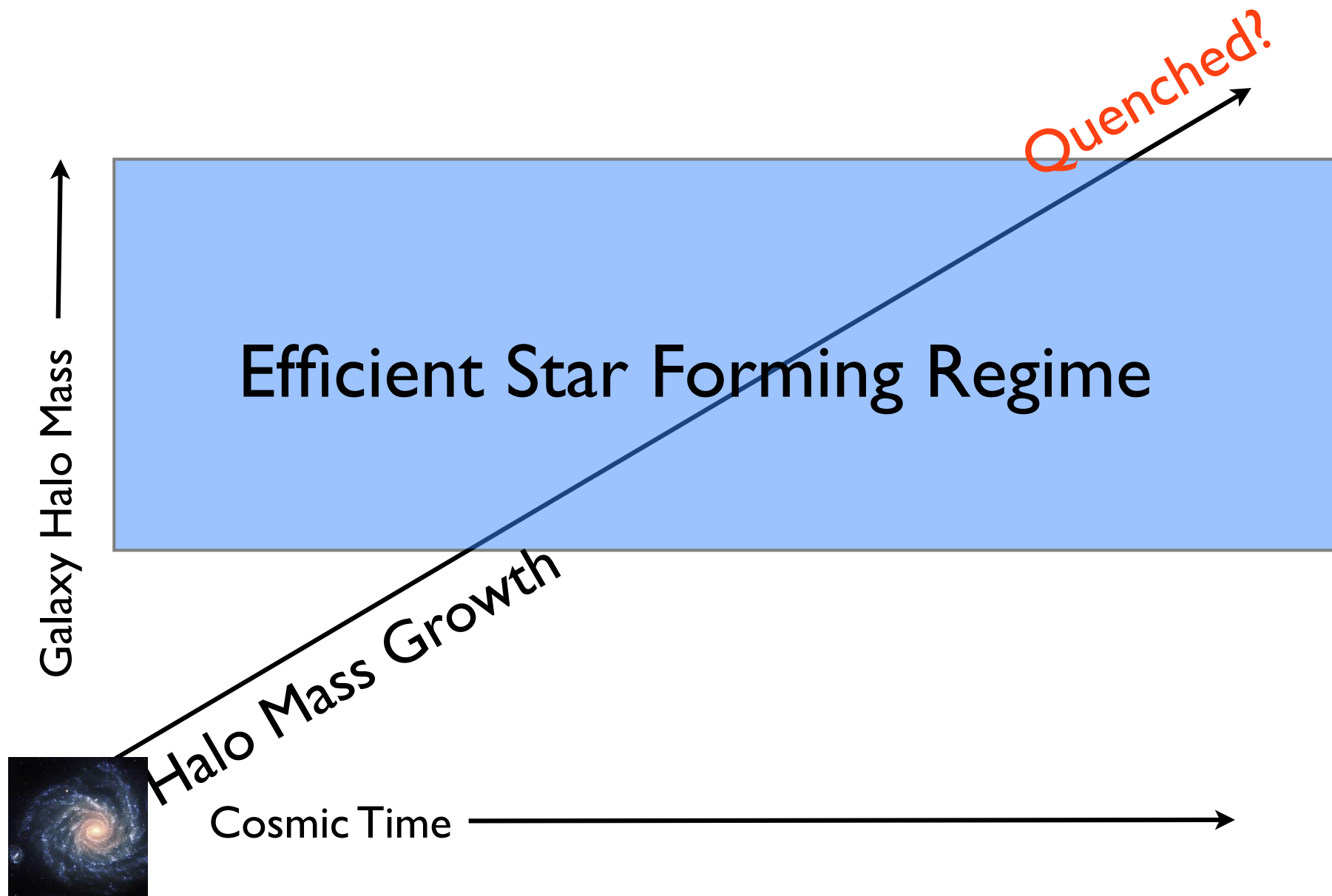
What about evolution on the blue sequence?

Clear relationship between the star formation rate and the stellar mass of a galaxy...



Constant of proportionality
between the star formation rate and
stellar mass evolves with redshift...

Galaxies form stars for a given
stellar mass at high redshift...

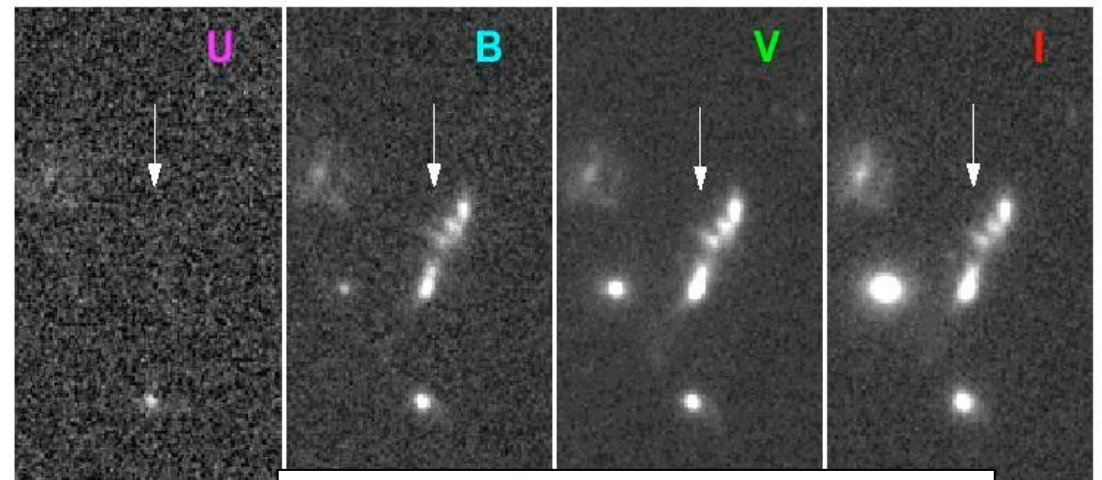
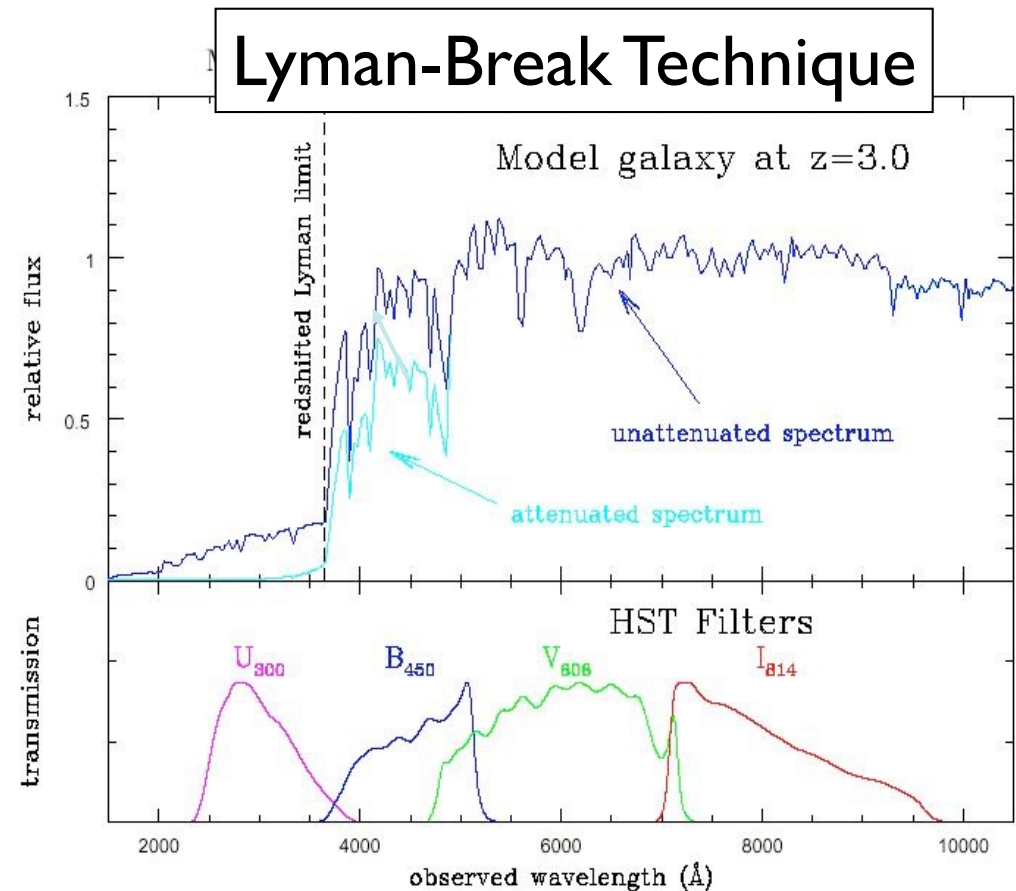


Let's begin by talking about selecting $z > 1.5$ galaxies at optical wavelengths (i.e., in the rest-frame UV)

We can take advantage of neutral hydrogen in the distant universe which absorbs light in galaxies blueward of 1216 Angstroms (Lyman Alpha)

This introduces a very sharp break in the spectrum -- which is a very characteristic feature that is easy to identify in looking at light in broad-band images.

Expect very Red U-B colors and Blue B-V colors

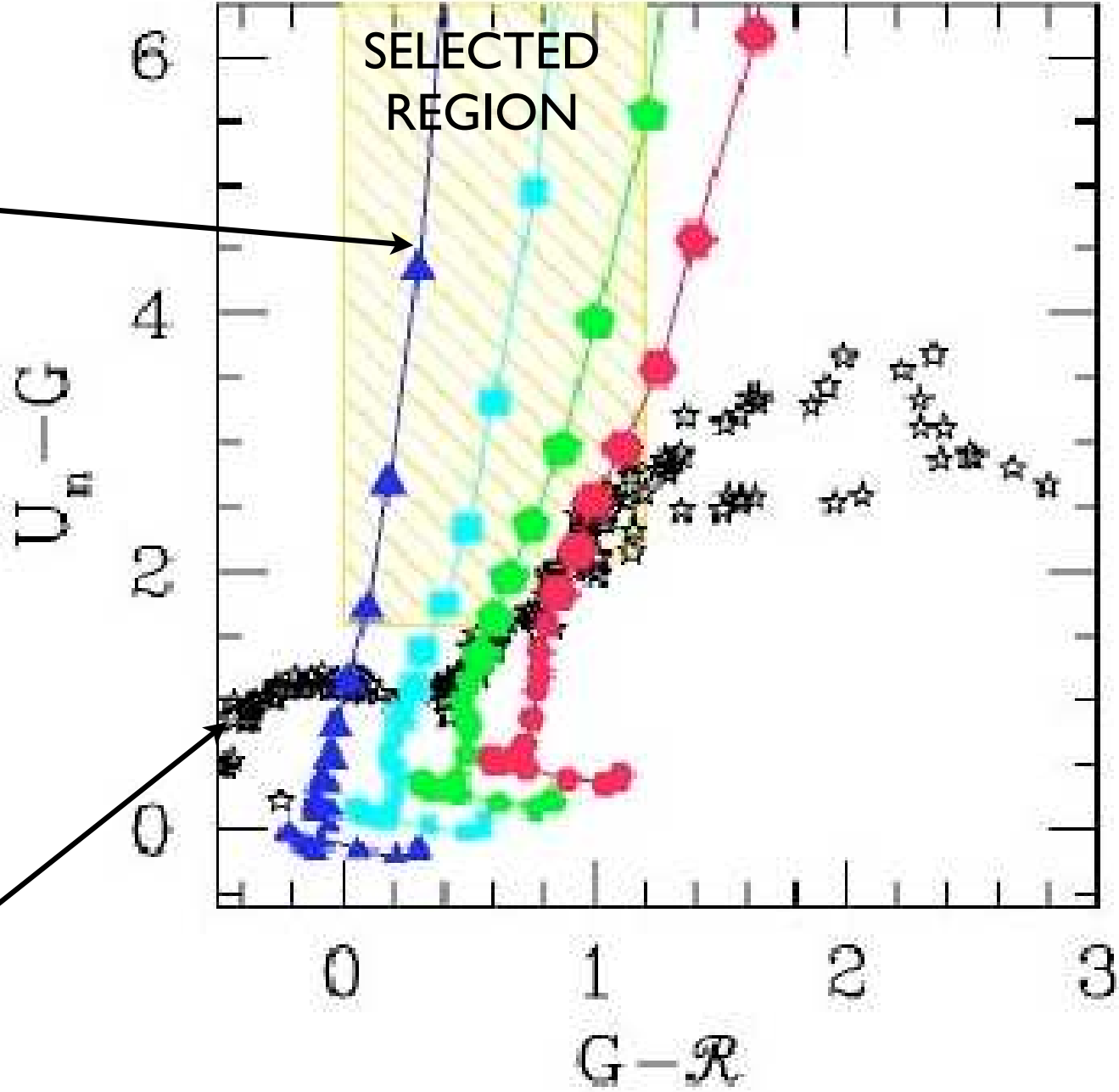


Credit: Dickinson 1999

How does such a selection look like in color-color space?

tracks show the expected colors of star-forming galaxies with a variety of dust reddening

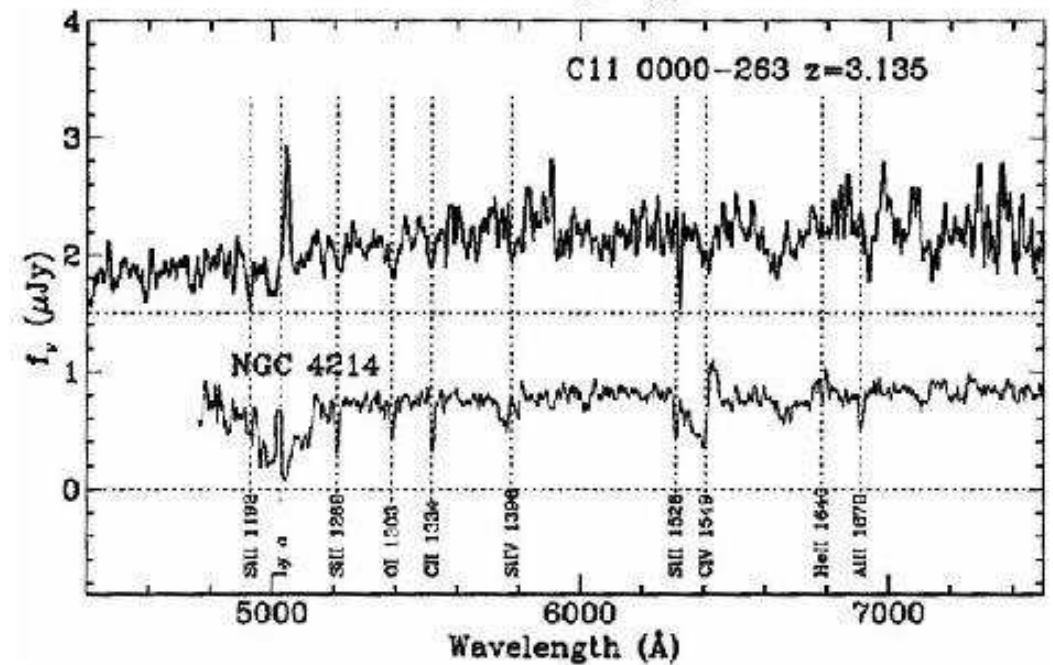
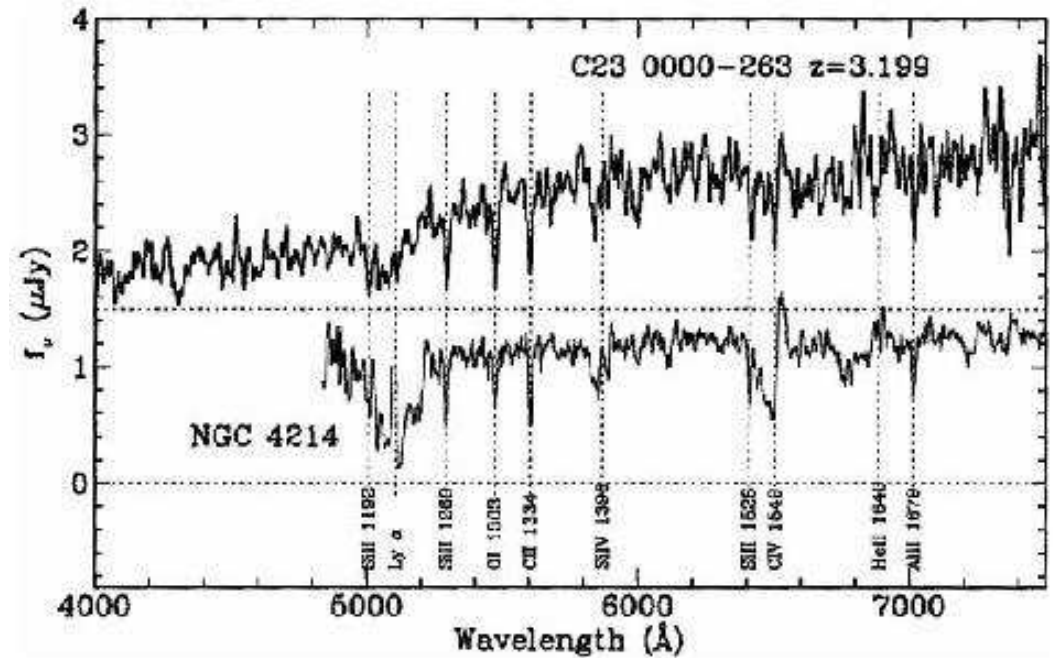
colors of nearby stars



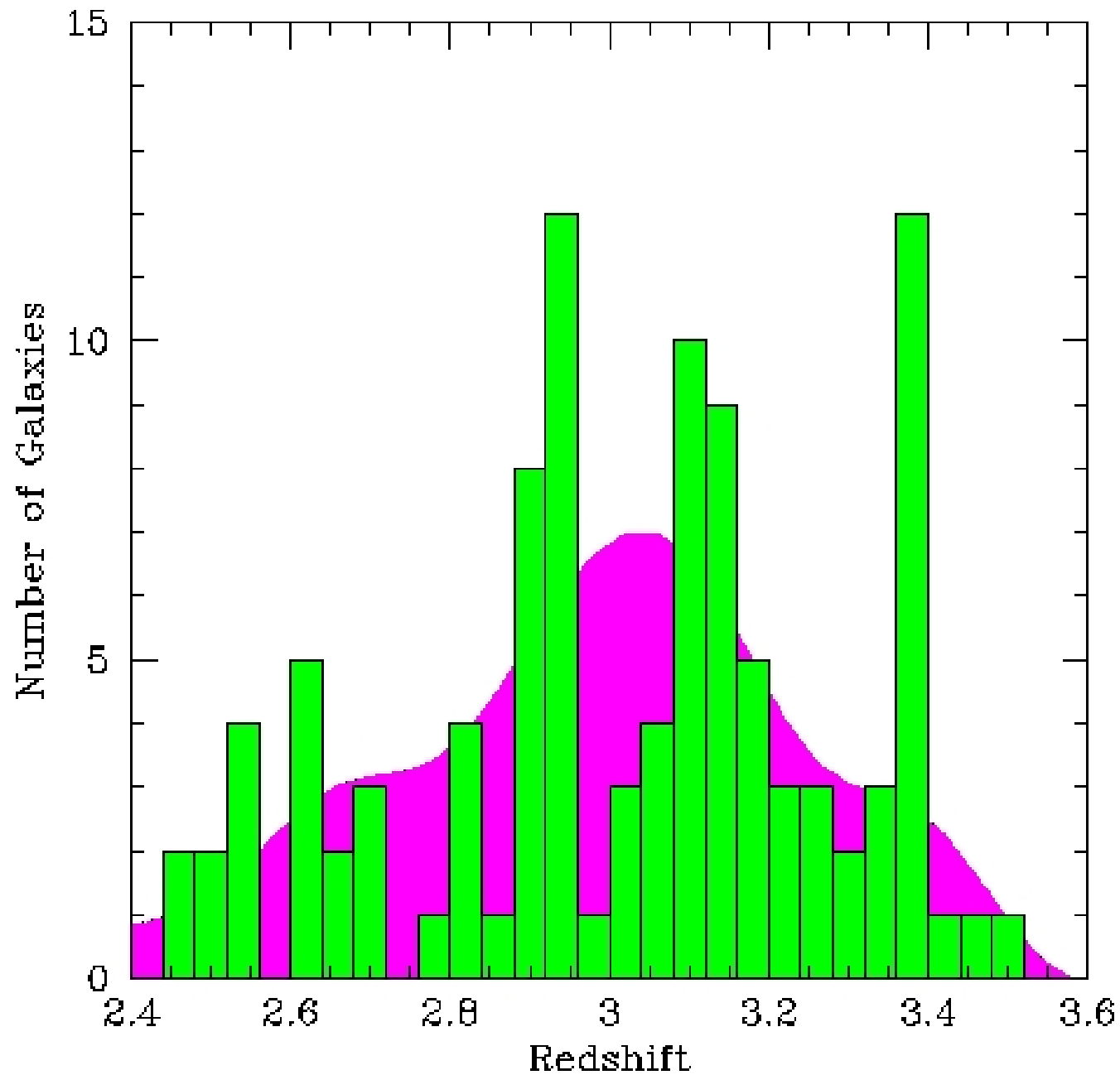
When one takes deep spectra at optical wavelengths of Lyman-Break selected galaxies (“U-Dropouts”), one finds the spectra to the right:

Notice how similar the spectra are to spectra taken of starburst (actively star-forming) galaxies in the nearby universe.

Steidel+1996



What redshift distribution was found for galaxies selected in this way?



The newly discovered $z\sim 3$ population was found to be very different from any galaxy known in the local universe.

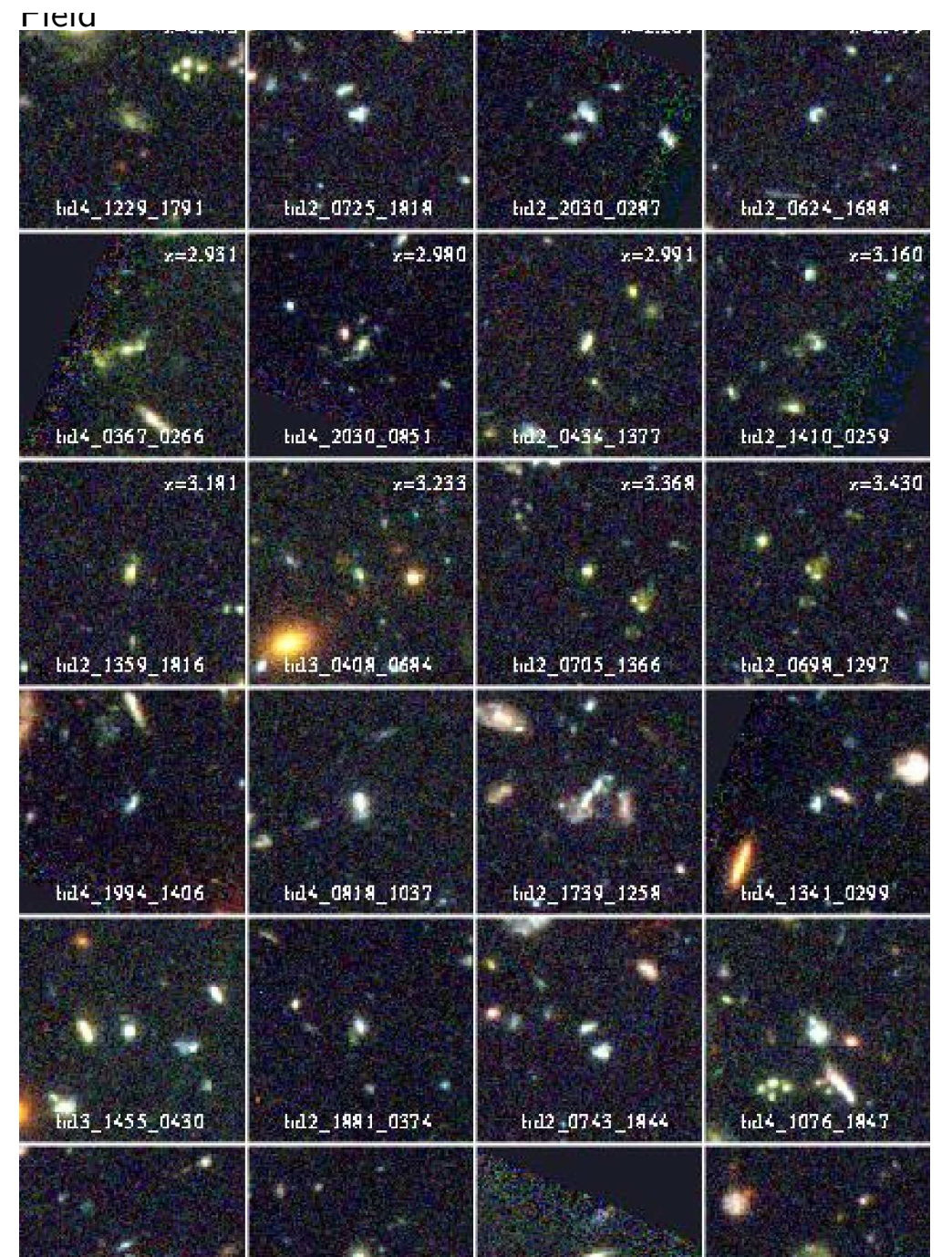
It was a major discovery and revolutionized extragalactic science in 1995-1996.

These galaxies are very irregular, clumpy, and quite small.

Most had sizes of ~ 1 -2 kpc.

This is many times smaller than most bright star-forming galaxies today!

$z\sim 3$ galaxies in the Hubble Deep Field North

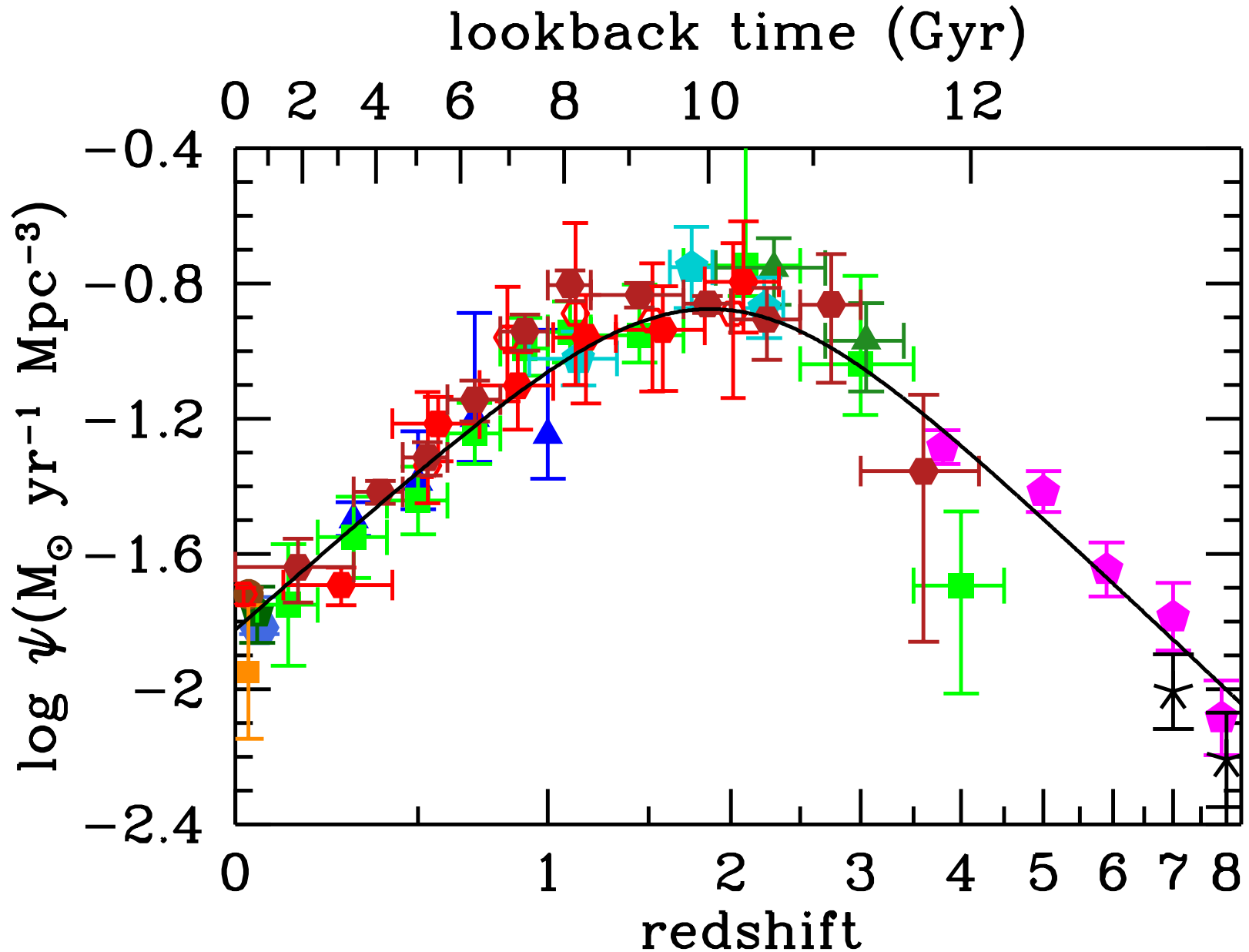


NOW new material for this
week

Can we construct a picture
of how galaxies form and
evolve across cosmic time?

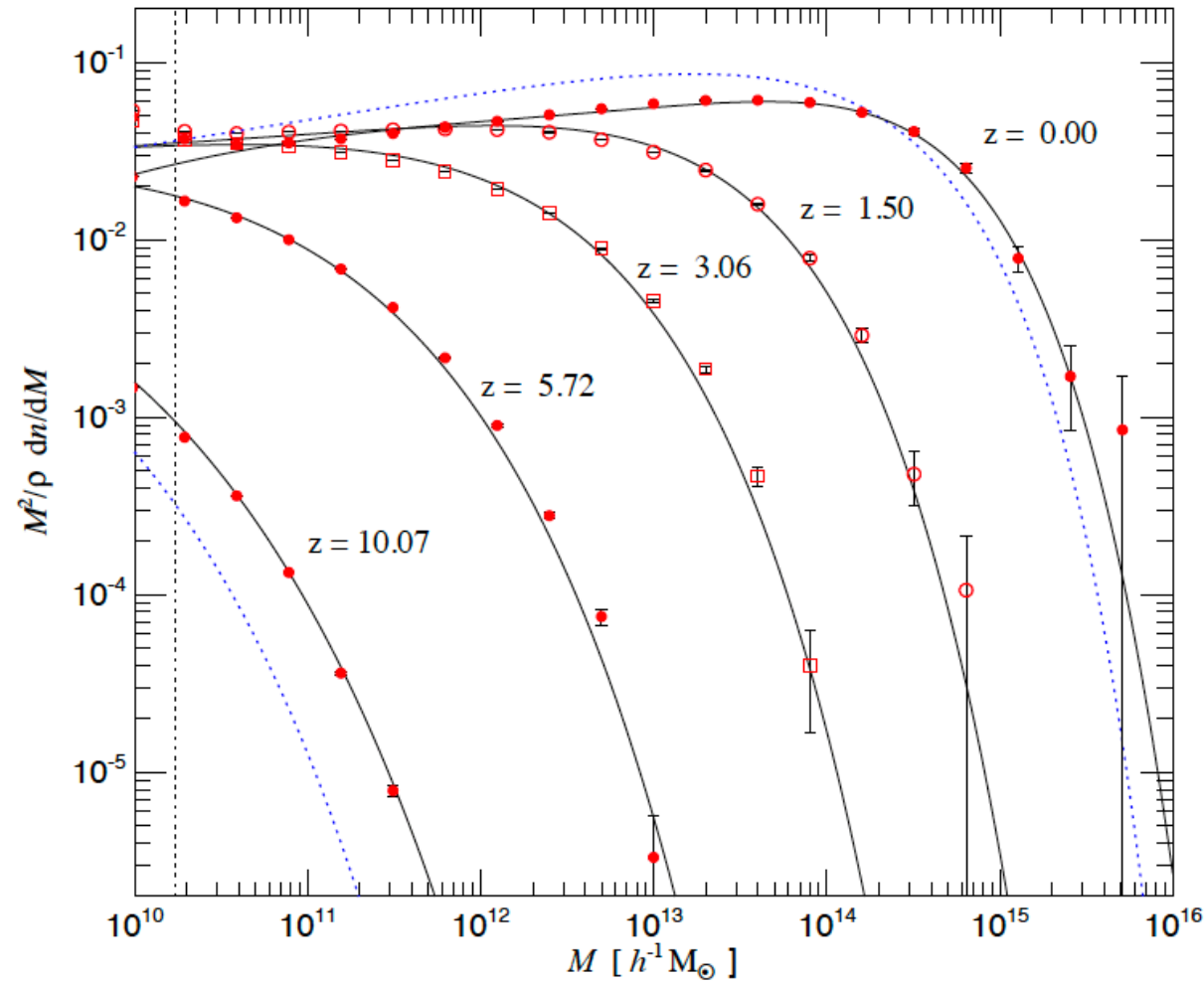
When do galaxies / does the
universe form most of its
stars?

When does universe form most of its stars?



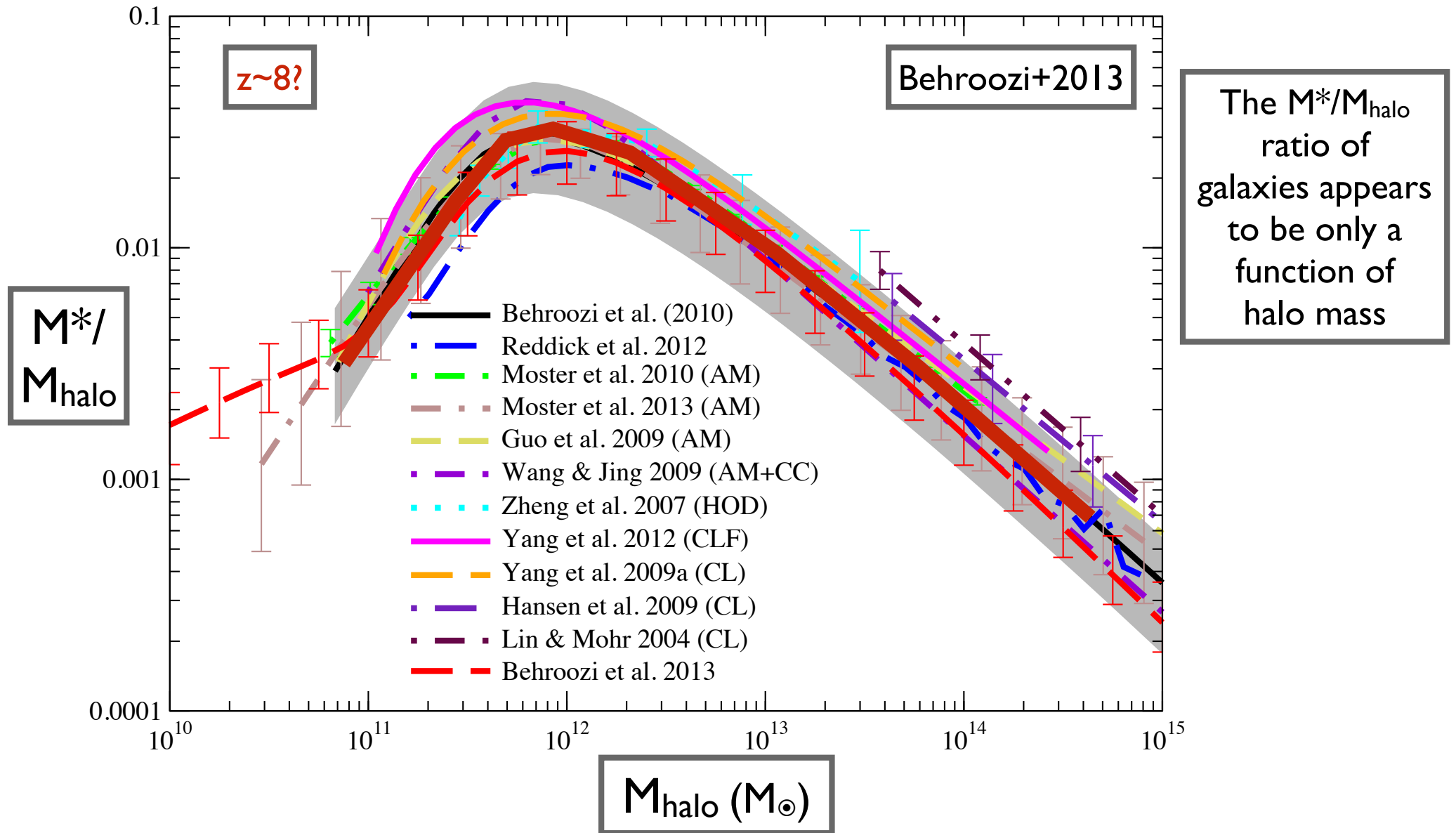
Let's try to understand this in terms of the growth and evolution of dark matter halos

Volume
Density of
Halos

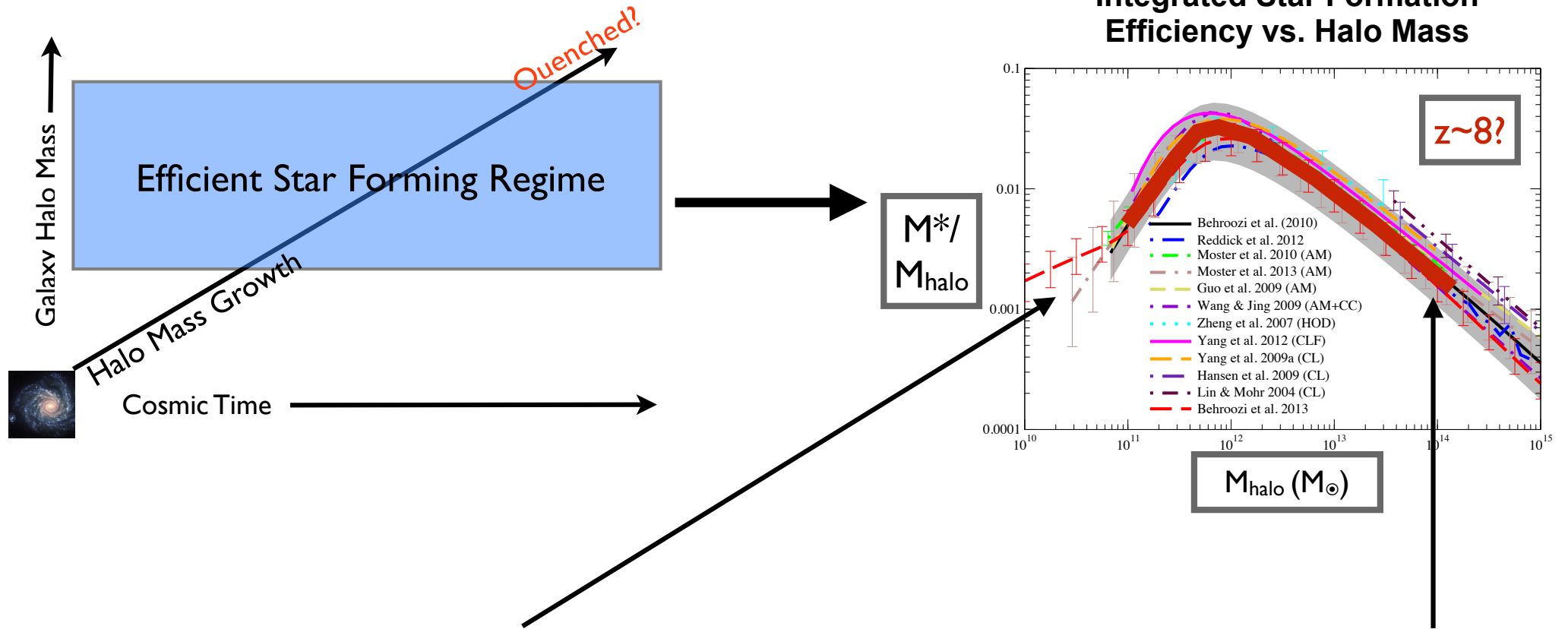


Galaxy Mass

Note \Rightarrow Integrated Star Formation Efficiency vs. Halo Mass



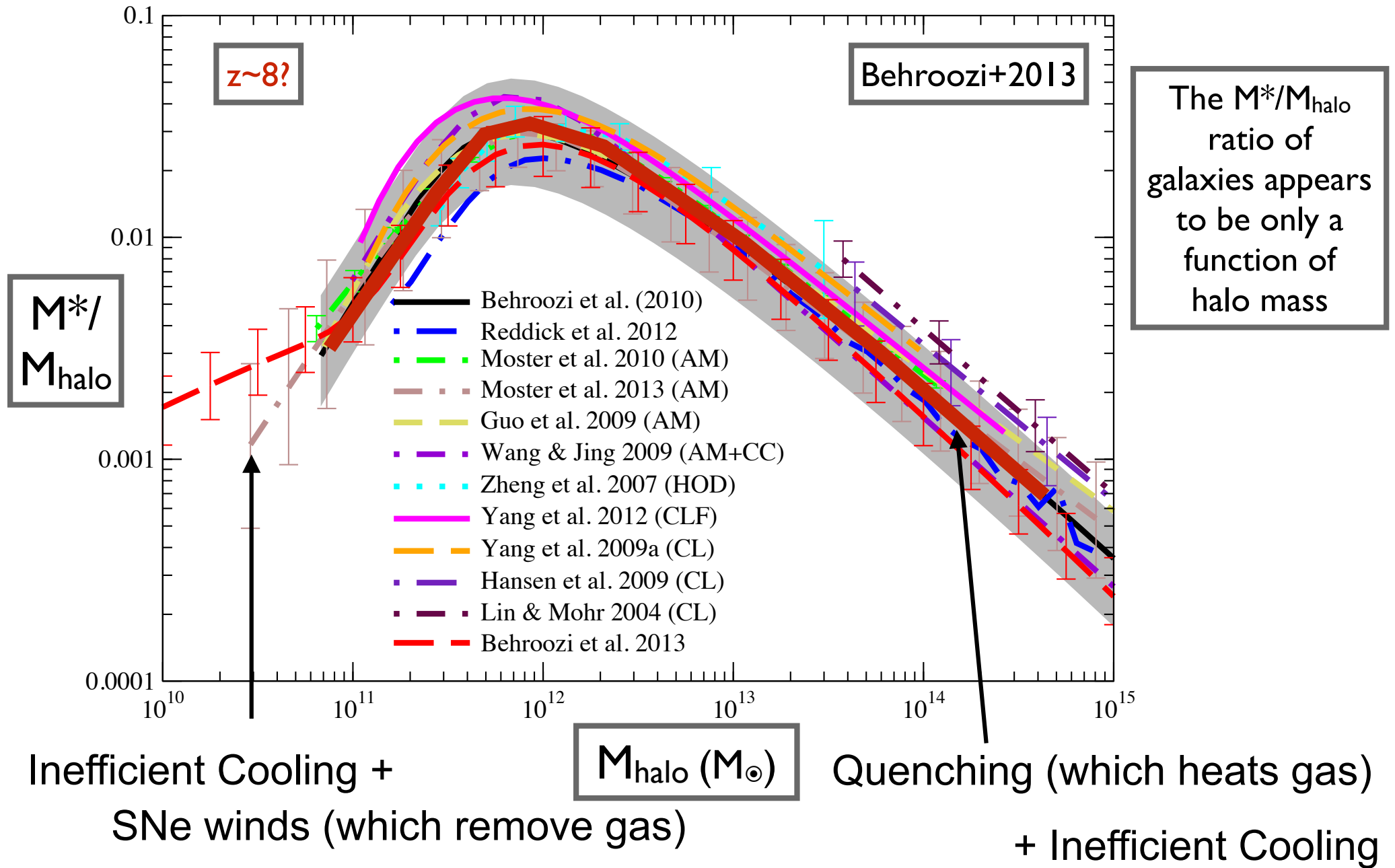
How can we understand the plot to the right?



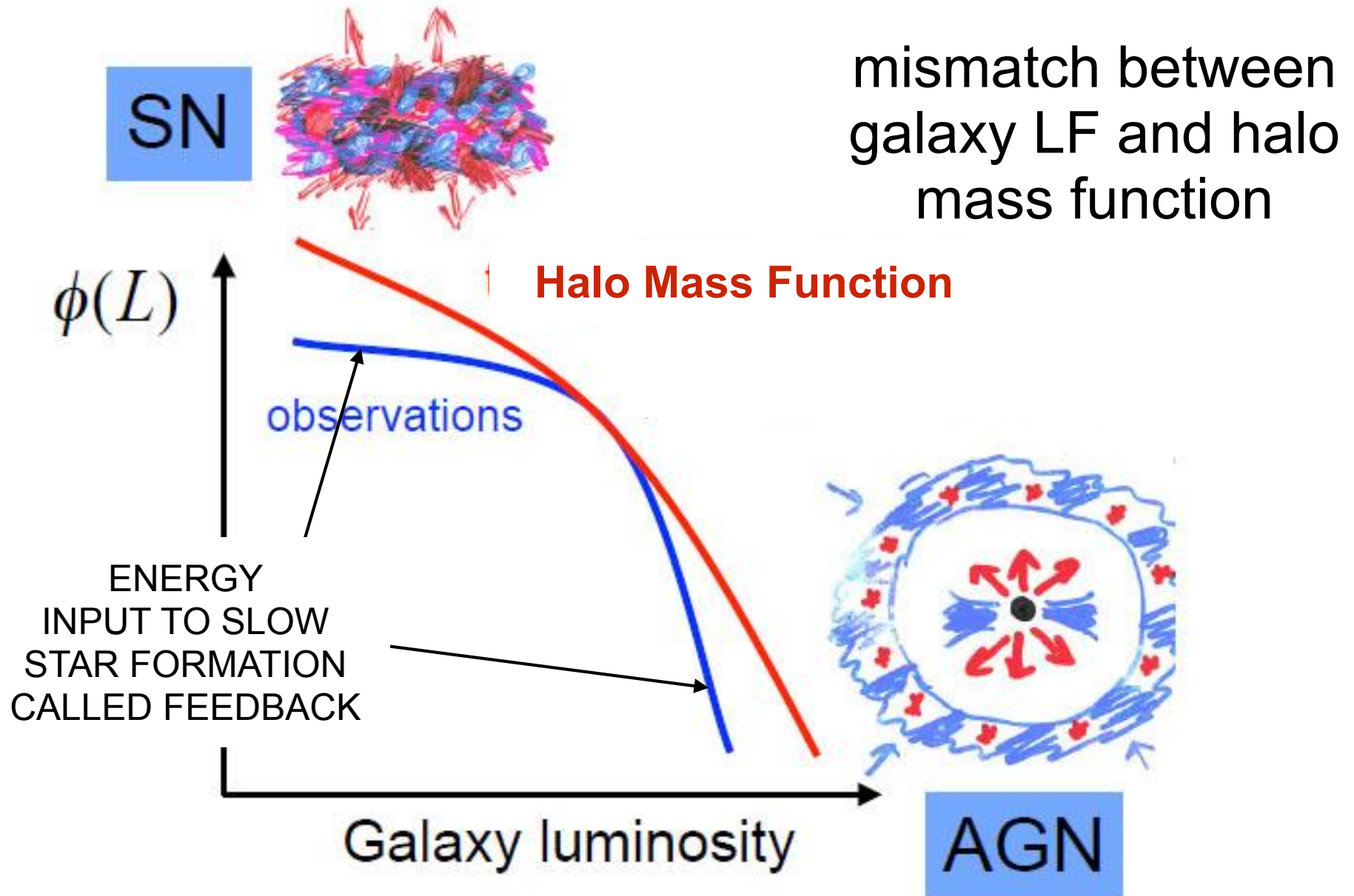
If the halo mass isn't large, galaxy isn't yet in efficient star forming regime

If the halo mass is high, galaxy has moved out of efficient star forming regime.

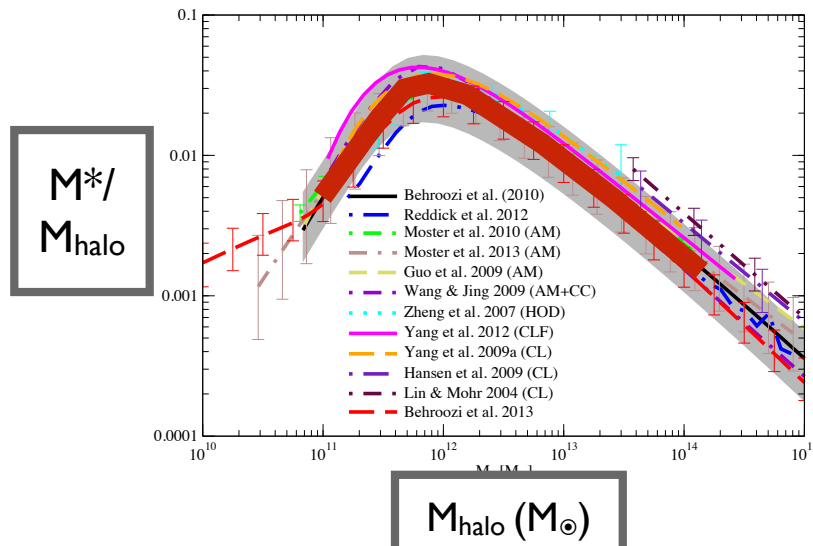
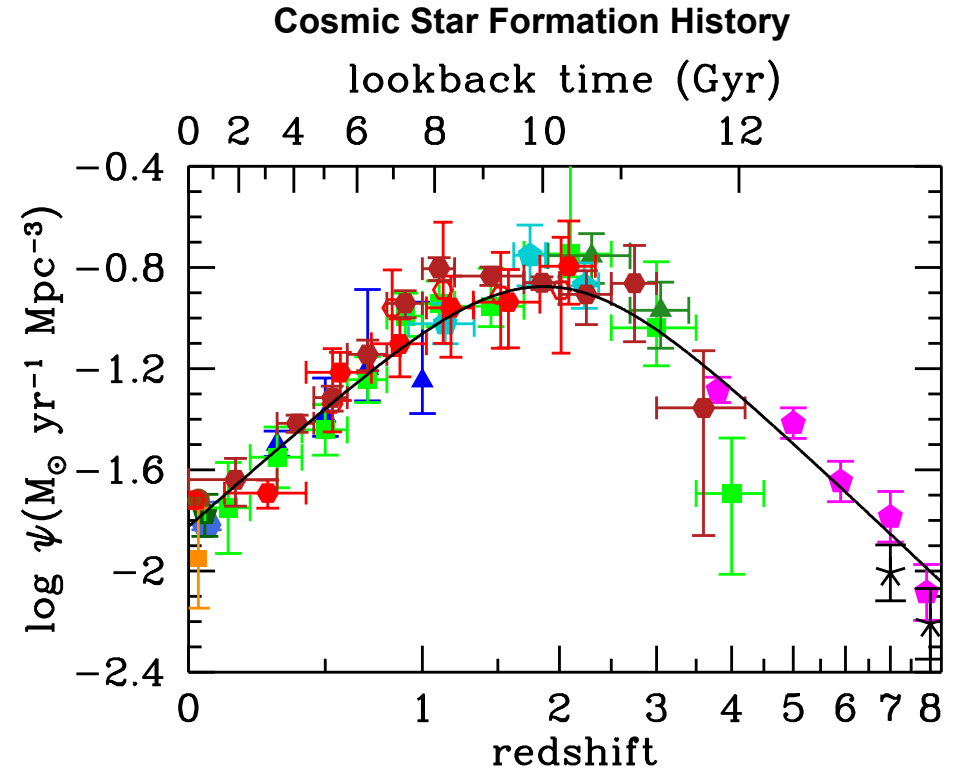
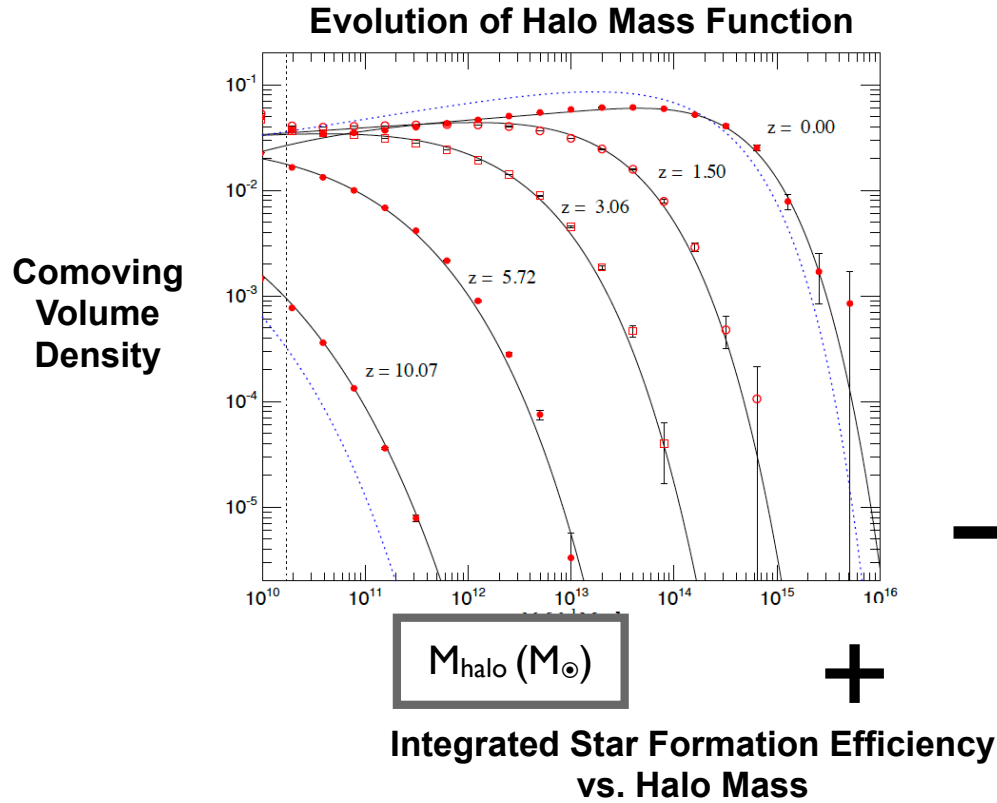
Note \Rightarrow Integrated Star Formation Efficiency vs. Halo Mass



Here is another illustration of the same thing



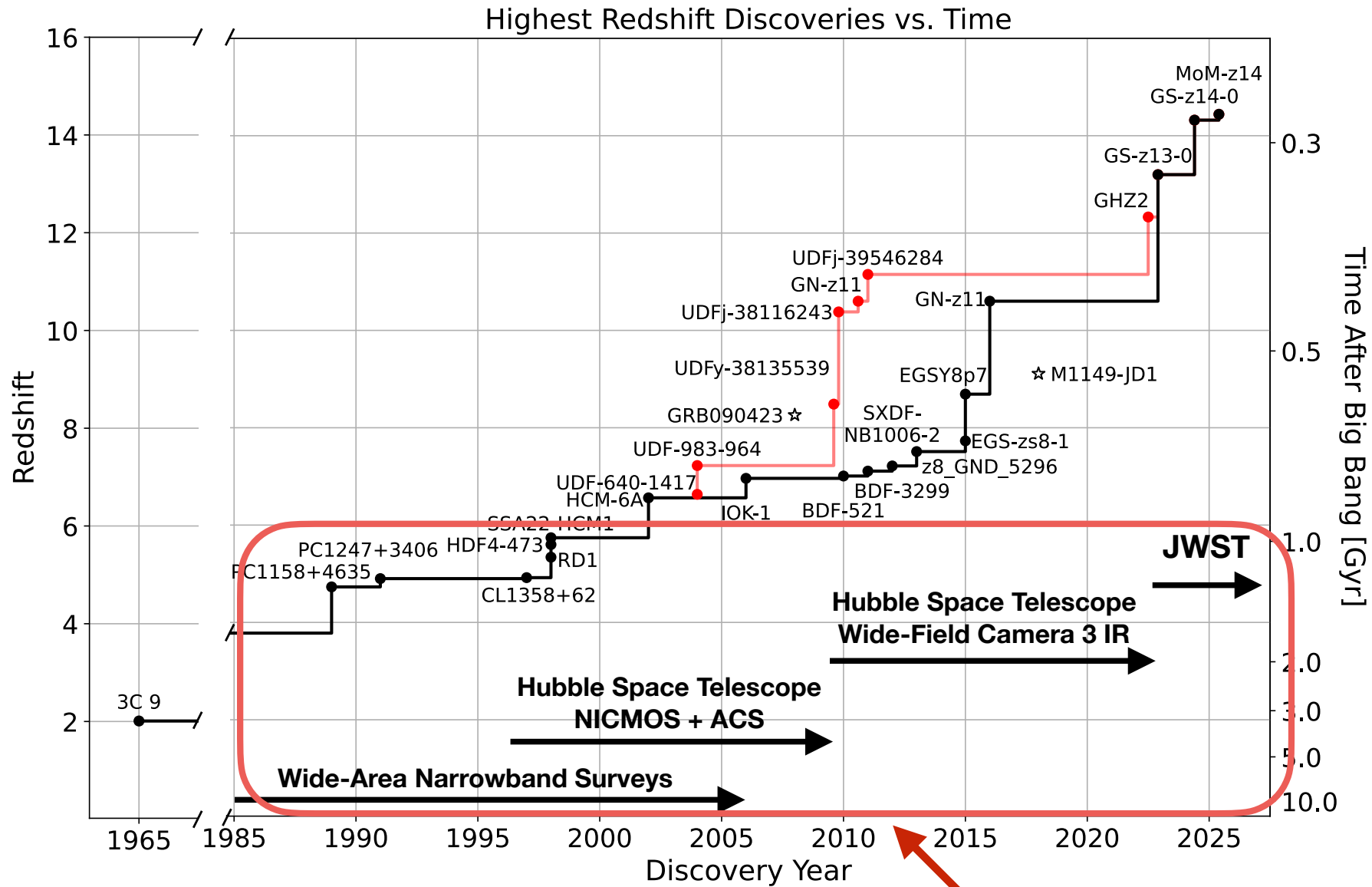
Can we understand the diagram to the right?



But before going into a
detailed look at the cosmic
star formation history +
explaining it

But let's give a bit of history
in terms of exploration of the
early universe

Here is the evolution of the redshift record



Bouwens+2026, in prep

Technology played a major role

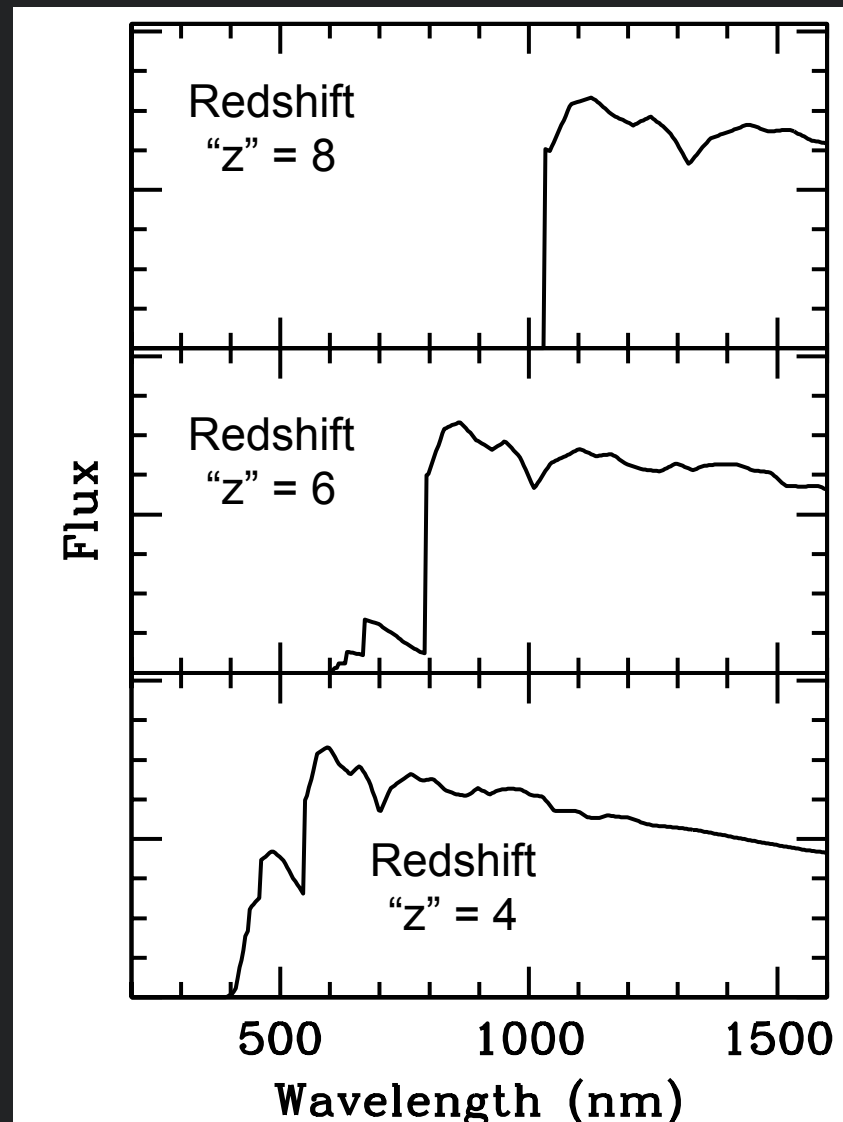
How can we determine which galaxies on deep images come from the most distant galaxies?

There is a sharp break in spectrum of distant galaxies due to neutral hydrogen in the universe.

As the universe expands, this break in the spectrum is shifted to redder wavelengths (“redshifted”)

By looking for sources with breaks at very red wavelengths, we identify the most distant galaxies.

Spectra of Distant Galaxies

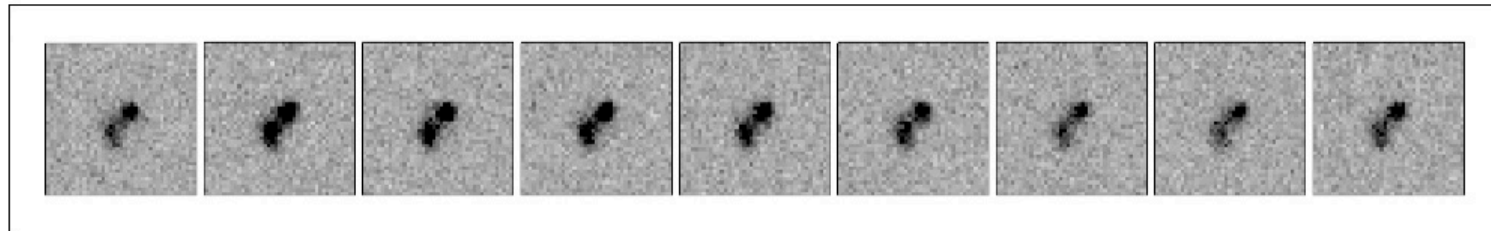
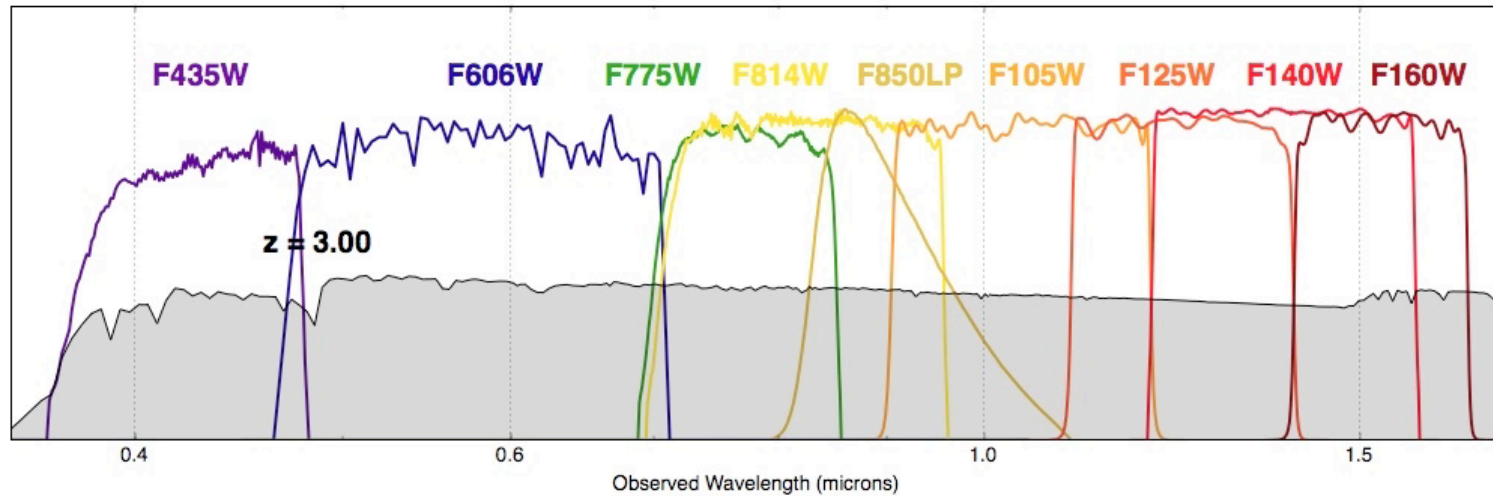


Most Distant
@ 850 Myr
after Big Bang

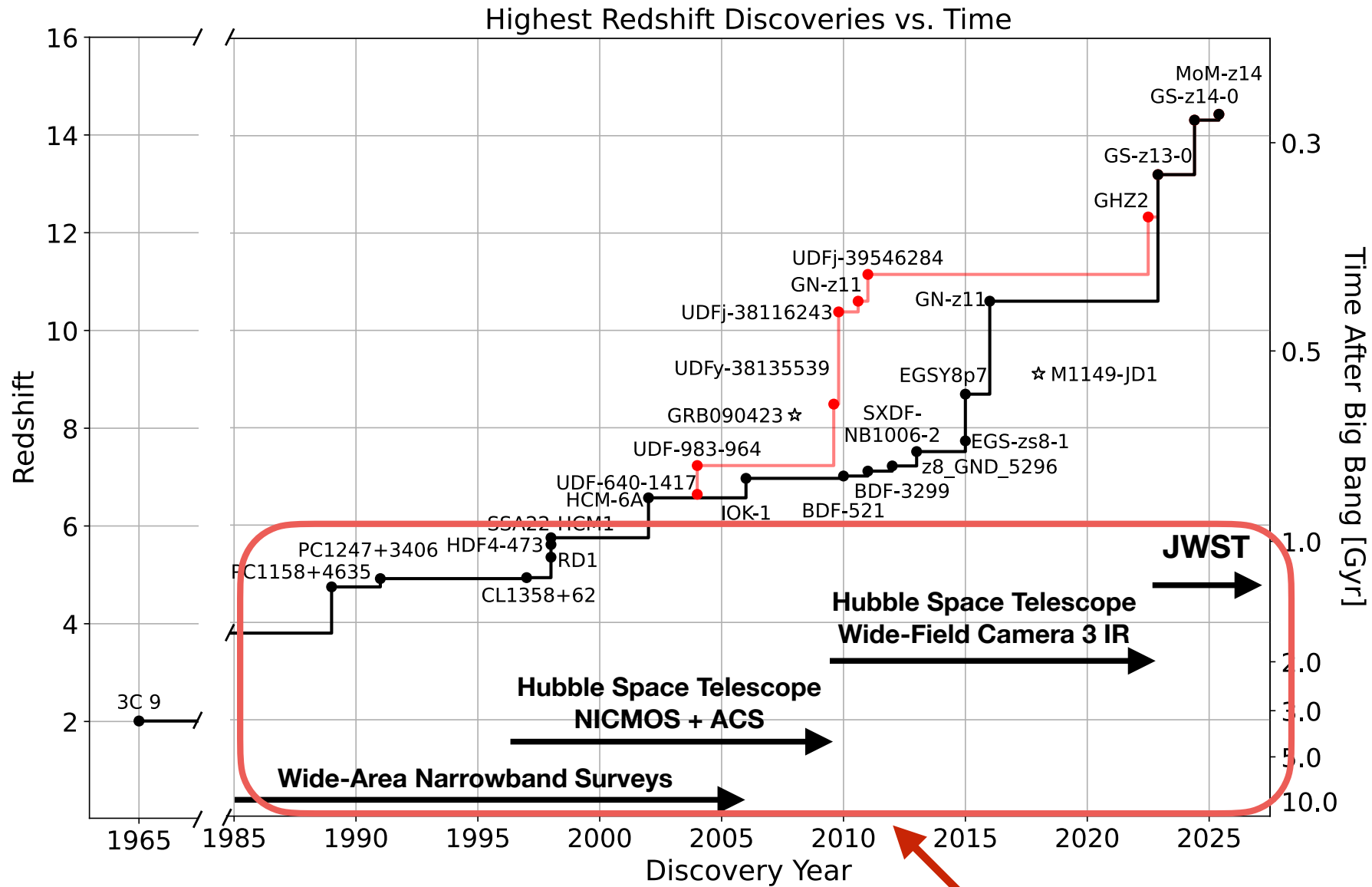
@ 1000 Myr
after Big Bang

Least Distant
@ 1800 Myr
after Big Bang

How can we determine which galaxies on deep images come from the most distant galaxies?



Here is the evolution of the redshift record



Bouwens+2026, in prep

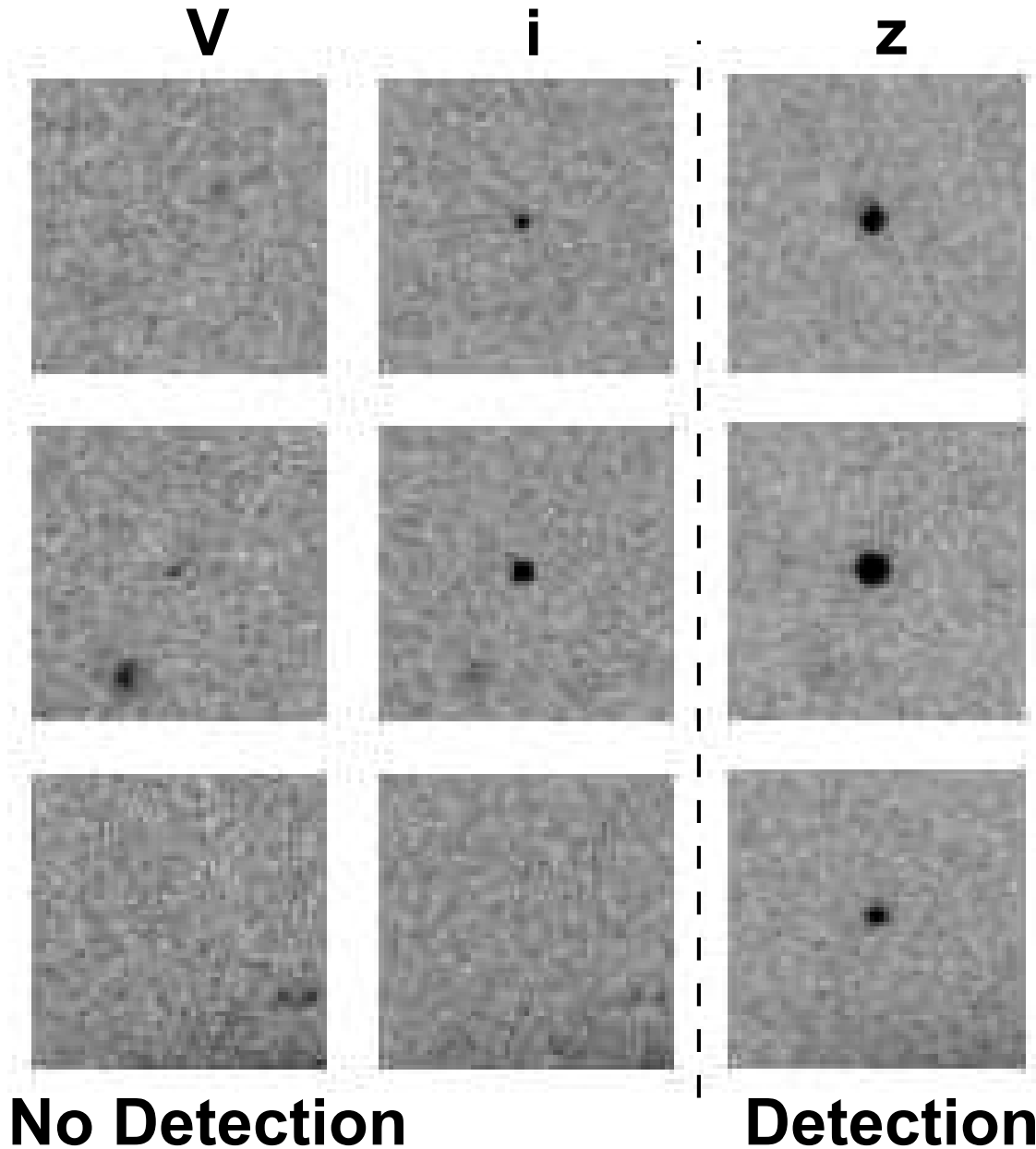
Technology played a major role

Advanced Camera for Surveys Instrument on the Hubble Space Telescope



Installed in 2002 on the Hubble Space Telescope
from shuttle servicing mission 3B

Discovery of $z \sim 6$ Galaxies



Immediately, after the first data from ACS became available, modest samples of $z \sim 6$ galaxies were discovered.

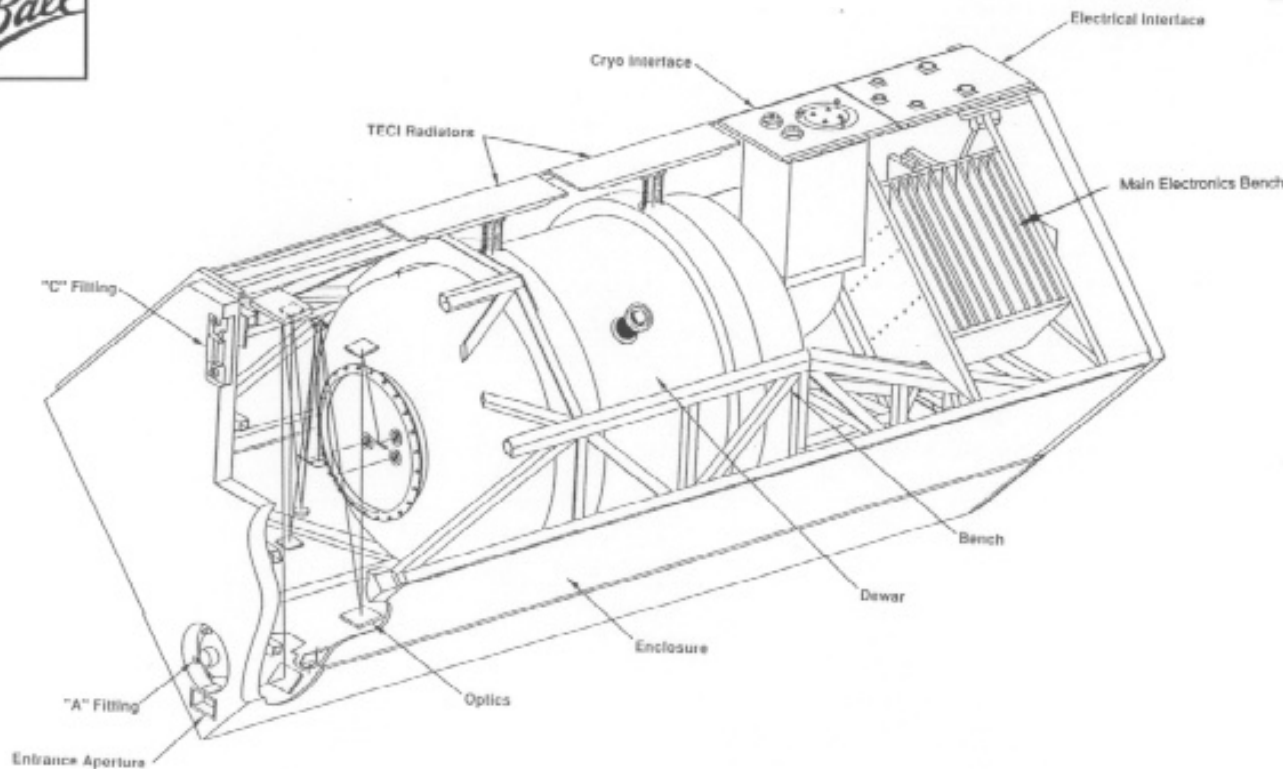
Modest samples were discovered both in the GOODS fields and in the Hubble Ultra Deep Field.

900 million years after the Big Bang

Advent of near-IR imaging capabilities on the Hubble Space Telescope



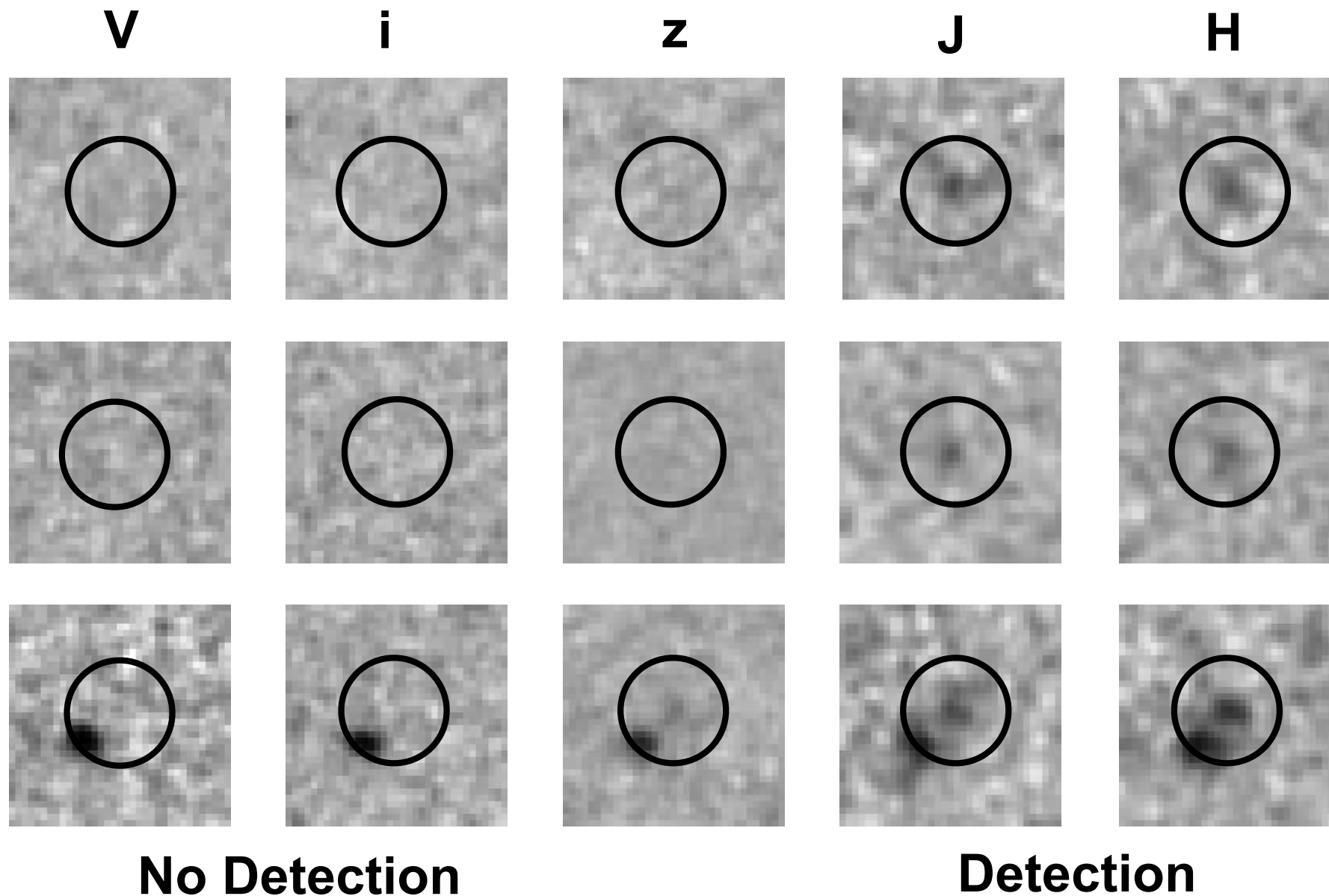
NICMOS



The NICMOS camera was originally installed in 1997. It was given new life during the 2002 servicing mission.

Importantly, NICMOS gave astronomers the ability to obtain sensitive images of the distant universe.

Discovery of $z \sim 7$ Galaxies



The installation of WFC3/IR on the Hubble significantly enhanced our ability to survey the distant universe in the near infrared.

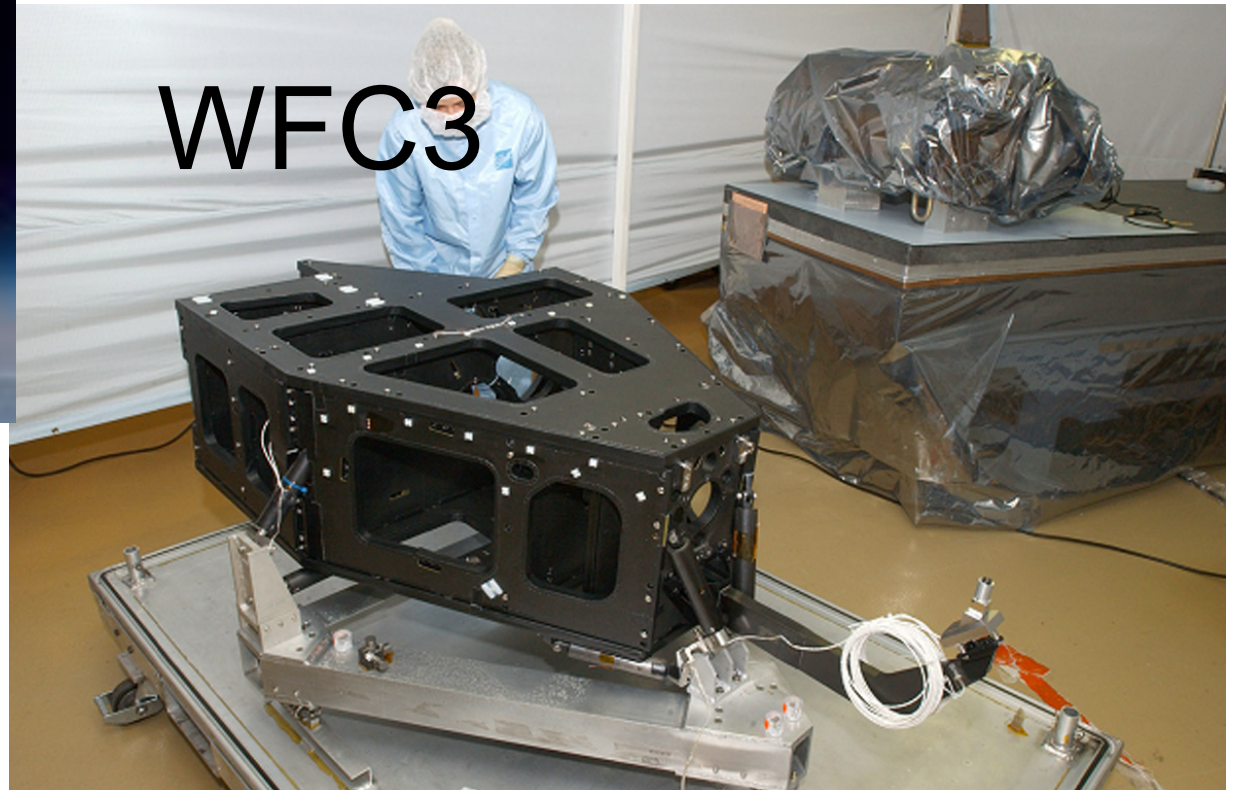
HST



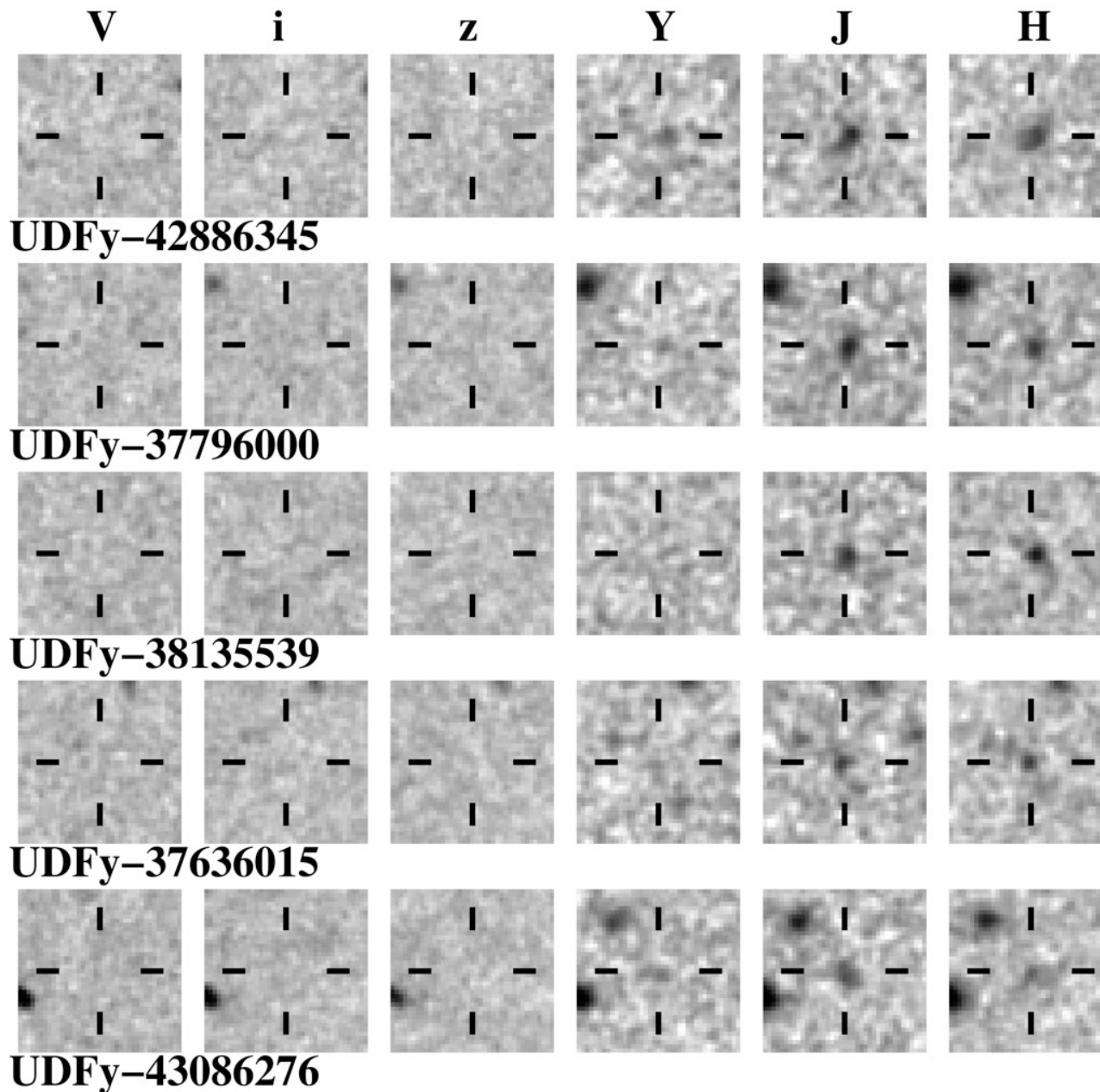
Installed
in 2009

Wide Field Camera 3

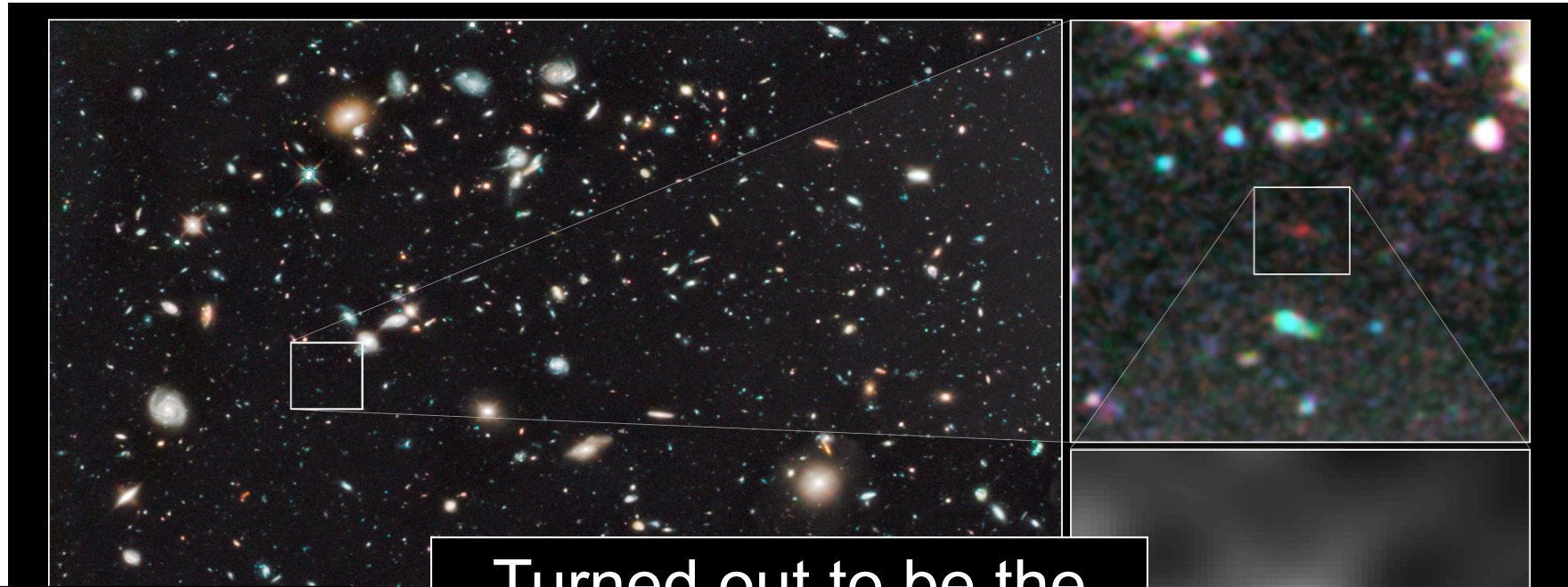
WFC3



Discovery of $z \sim 8$ galaxies



Discovery of a $z \sim 10$ Candidate Galaxy (500 Myr after Big Bang)



Turned out to be the most distant galaxy found with the Hubble Space Telescope.

UDFj-39546284

LETTER

doi:10.1038/nature09717

A candidate redshift $z \approx 10$ galaxy and rapid changes in that population at an age of 500 Myr

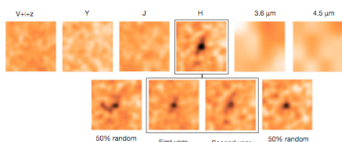
R. J. Bouwens^{1,2}, G. D. Illingworth¹, I. Labbé¹, P. A. Oesch¹, M. Trenti¹, C. M. Carollo¹, P. G. van Dokkum³, M. Franx², M. Staveletti¹, V. González¹, D. Magee¹ & L. Bradley¹

Searches for very-high-redshift galaxies over the past decade have yielded a large sample of more than 6,000 galaxies existing just 200–2,000 million years (Myr) after the Big Bang (redshifts $3 < z < 6$; ref. 1). The Hubble Ultra Deep Field (HUDF09) data^{2,3} have yielded the first reliable detections of $z \approx 8$ galaxies⁴, that, together with reports of a $z \approx 8.2$ (refs 10, 11), constitute the earliest objects reliably reported to date. Observations of $z \approx 7$ –8 galaxies suggest substantial star formation at $z > 9$ –10 (refs 12, 13). Here we use the full two-year HUDF09 data to conduct an ultra-deep search for $z \approx 10$ galaxies in the heart of the reionization epoch, only 500 Myr after the Big Bang. Not only do we find one possible $z \approx 10$ galaxy candidate, but we show that, regardless of source detections, the star formation rate density is much smaller ($\sim 10\%$) at this time than it is just ~ 200 Myr later at $z \approx 8$. This demonstrates how rapid galaxy build-up was at $z \approx 10$, as galaxies increased in both luminosity density and volume density from $z \approx 8$ to $z \approx 10$. The 100–200 Myr before $z \approx 10$ is clearly a crucial phase in the assembly of the earliest galaxies.

The detection of galaxies at very high redshift from deep imaging data depends on the absorption (by intervening neutral hydrogen) of much of the flux in the spectrum at wavelengths below the wavelength of Lyman α (121.6 nm). These 'spectral breaks' shift to longer wavelengths for more distant, redshifted galaxies seen at earlier times. A distinguishing characteristic of $z \approx 10$ galaxies would be, first, a detection in the H_{160} band, and, second, the absence of flux in the J_{125} band, and in all other shorter-wavelength Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3/IR) and Advanced Camera for Surveys (ACS) filters blueward of the J_{125} band (hence they are called ' J_{125} -dropouts'). The new, powerful HST WFC3/IR camera is ~ 40 times more efficient at finding $z \approx 7$ galaxies⁵ than the previous near-infrared NICMOS camera owing to its wider field of view and greater sensitivity in its Y_{105} , J_{125} and H_{160} filters. It provides us with the capability to explore $z \approx 10$.

A thorough search of the deep WFC3/IR HUDF09 data set strong limits at $z \approx 10$, and also resulted in the detection of a candidate $z \approx 10$ dropout galaxy, SDP5-39546284 at $z \approx 8$ in our $0.2''$ -diameter selection aperture (Fig. 1). The signal-to-noise ratio grows to 5.8 σ in a larger $0.35''$ -diameter aperture, is 28.92 ± 0.18 mag in the WFC3/IR H_{160} band ($1.10 \pm 0.18 \times 10^{-17}$ erg s^{-1} cm^{-2} \AA^{-1}), has a likely redshift of $z \approx 10.3$ (Fig. 2), and appears to be slightly extended. Given the importance of the limits that we set, and of the candidate $z \approx 10$ galaxy, we perform extensive tests and simulations. These are

UDFj-39546284 ($z = 28.8$, $J-H = 2.0$)



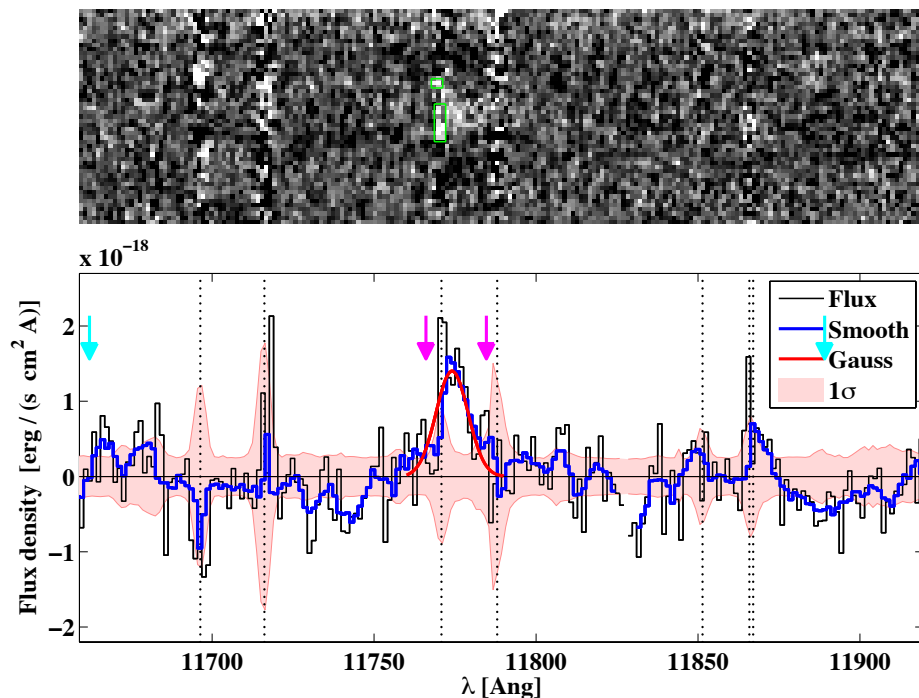
Hubble Ultra Deep Field 2009–2010
Hubble Space Telescope • WFC3/IR

University of California, Santa Cruz),
California, Santa Cruz and Leiden University), and the HUDF09 Team

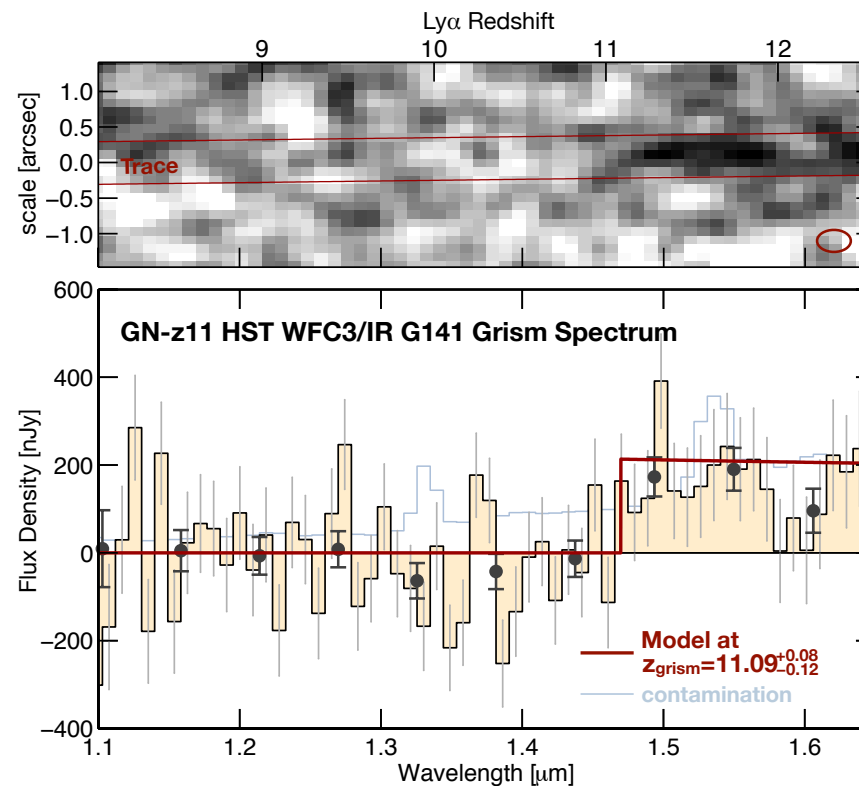
STScI-PRC11-05

Spectroscopic Confirmations of $z > 8$ Galaxies in 2010s

Spectroscopic Redshift:
 $z = 8.683 \pm 0.003$ (Lyman α)



Spectroscopic Redshift:
 $z = 11.1 \pm 0.1$ (continuum break)



Detection of Ly- α with
Keck MOSFIRE

Zitrin+2015

Break in HST WFC3/IR Grism Data
(similar to that present in photometric data)
Requires full day of HST Observations



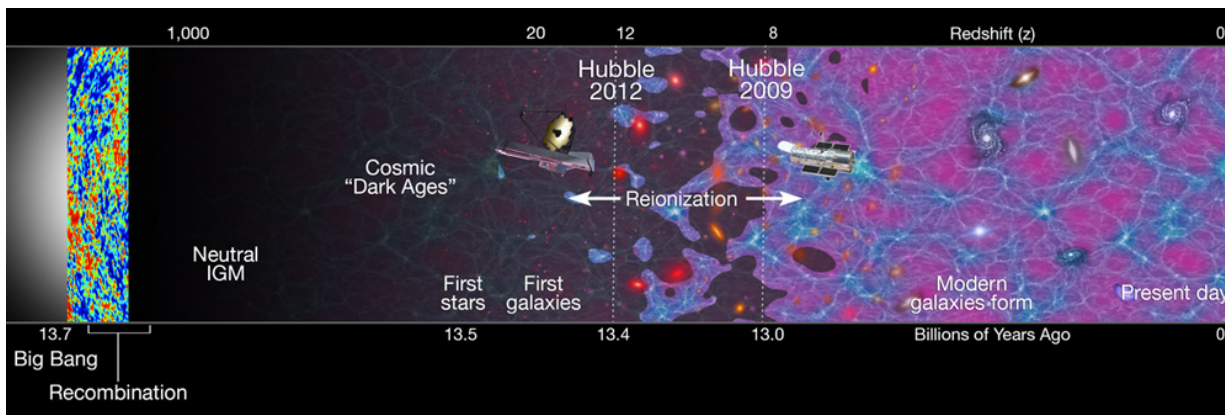
Oesch+2016

Revolutionizing Our Understanding with JWST

Very Exciting Time:
Launch of JWST



Time Line of Universe

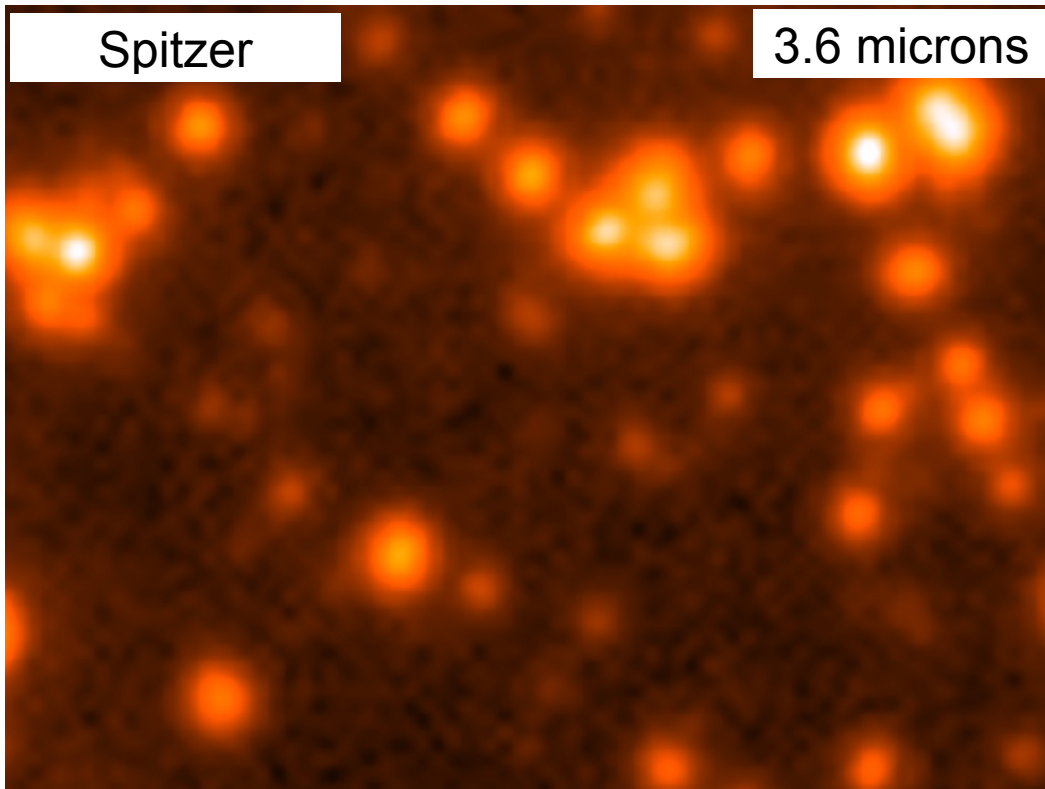


Huge Implications for
Study of Galaxies in
the Early Universe

Revolutionizing Our Understanding with JWST

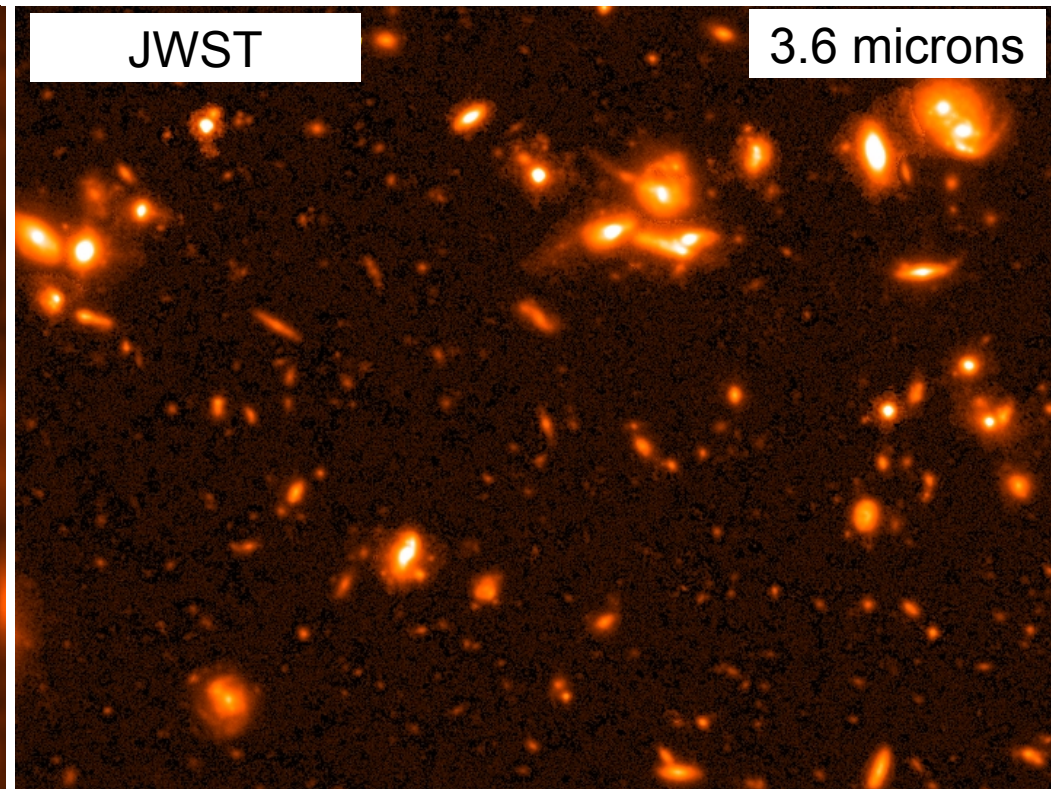
JWST will Revolutionize the Study of Galaxies in the Early Universe

To the Present



With JWST

Much Higher Sensitivity & Resolution

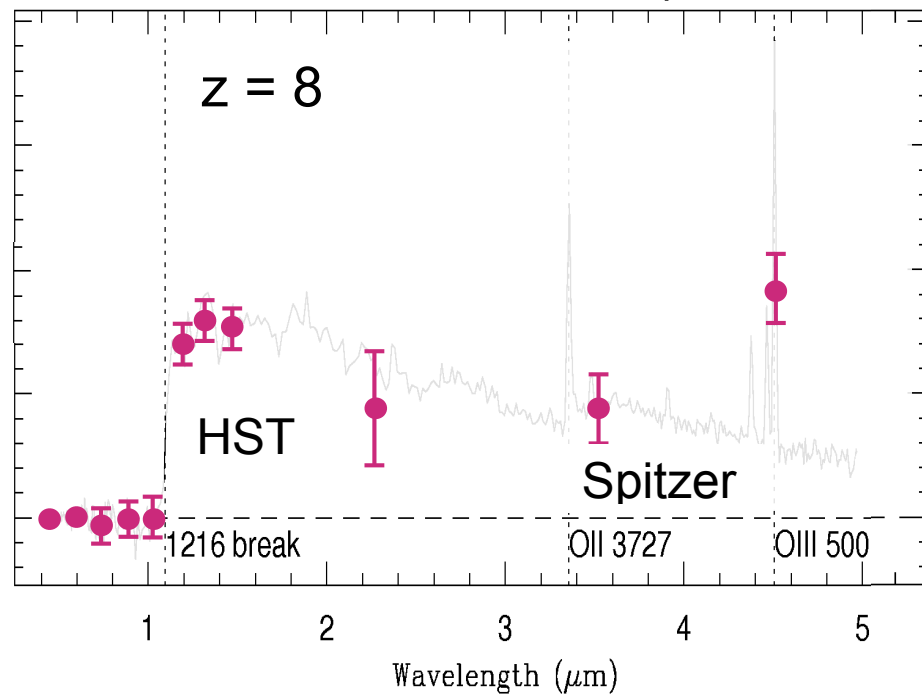


View of Galaxies / Distant Universe

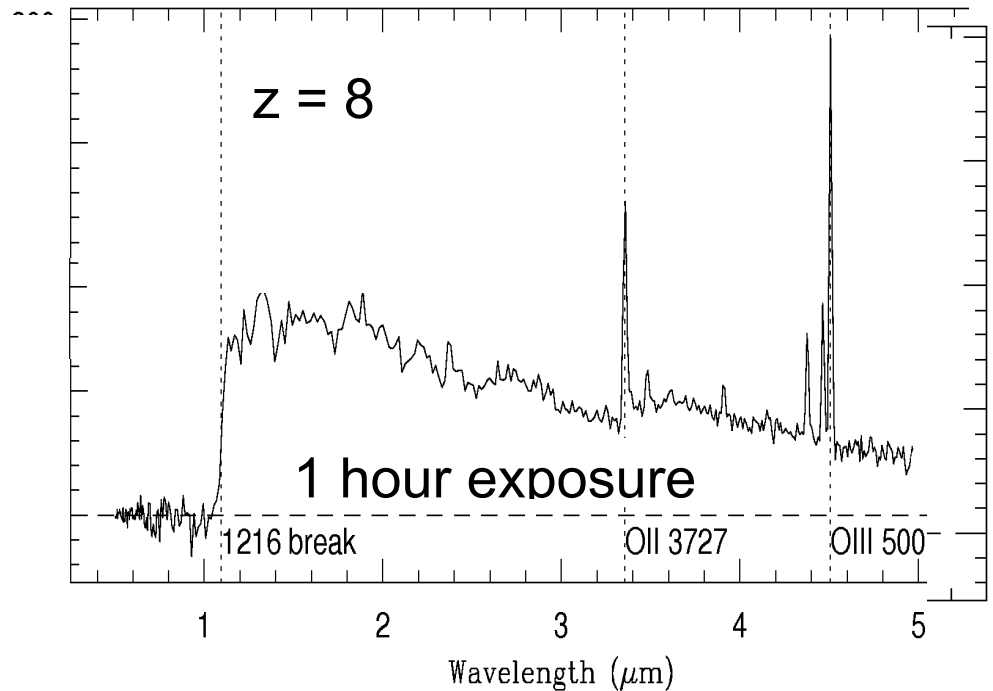
Revolutionizing Our Understanding with JWST

JWST will Revolutionize the Study of Galaxies in the Early Universe

**To the Present
(Only Photometry)**



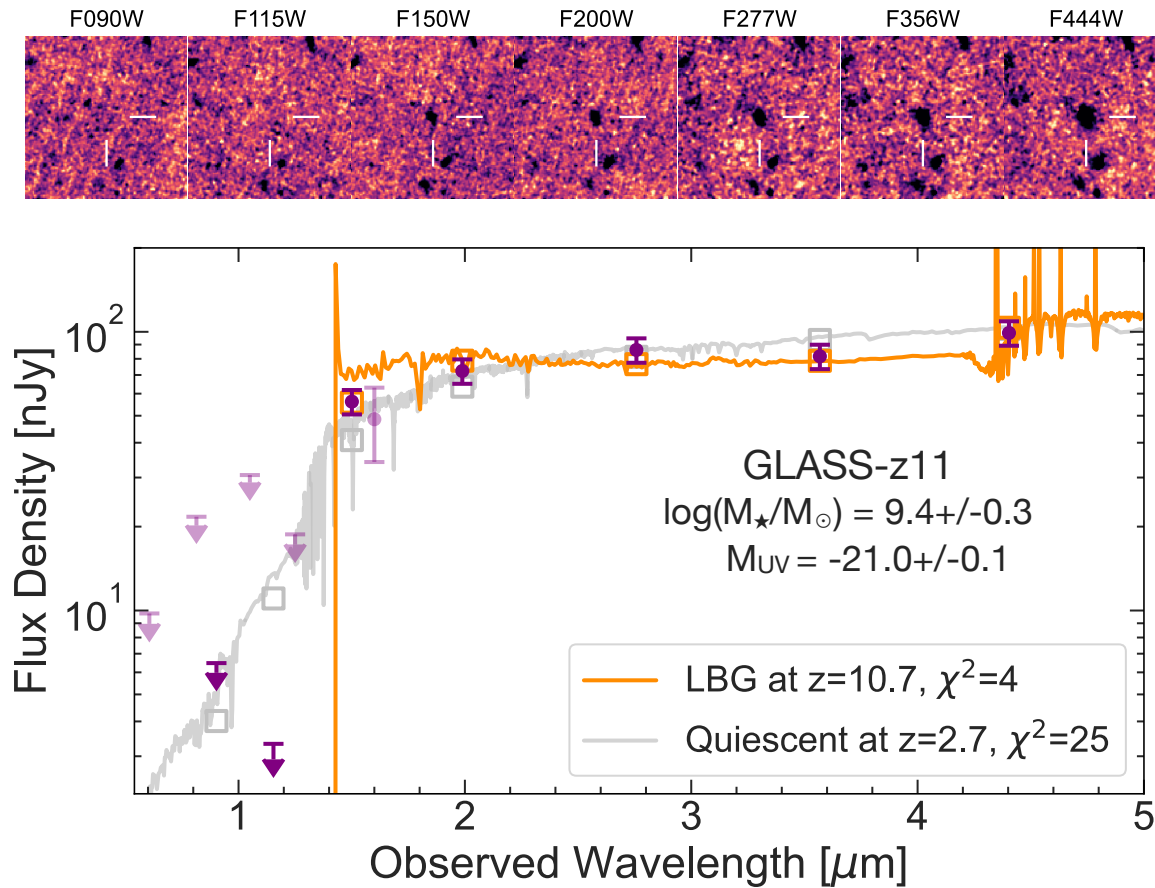
**With JWST
High Sensitivity Spectroscopy**



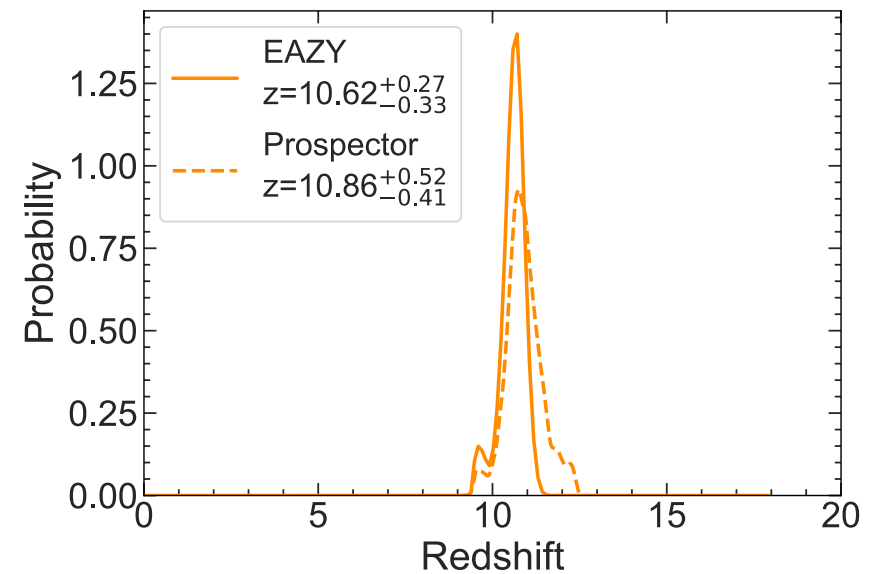
Roberts-Borsani, Bouwens, et al. 2016

View of Galaxies / Distant Universe

High-z Searches Observations from Early JWST Data

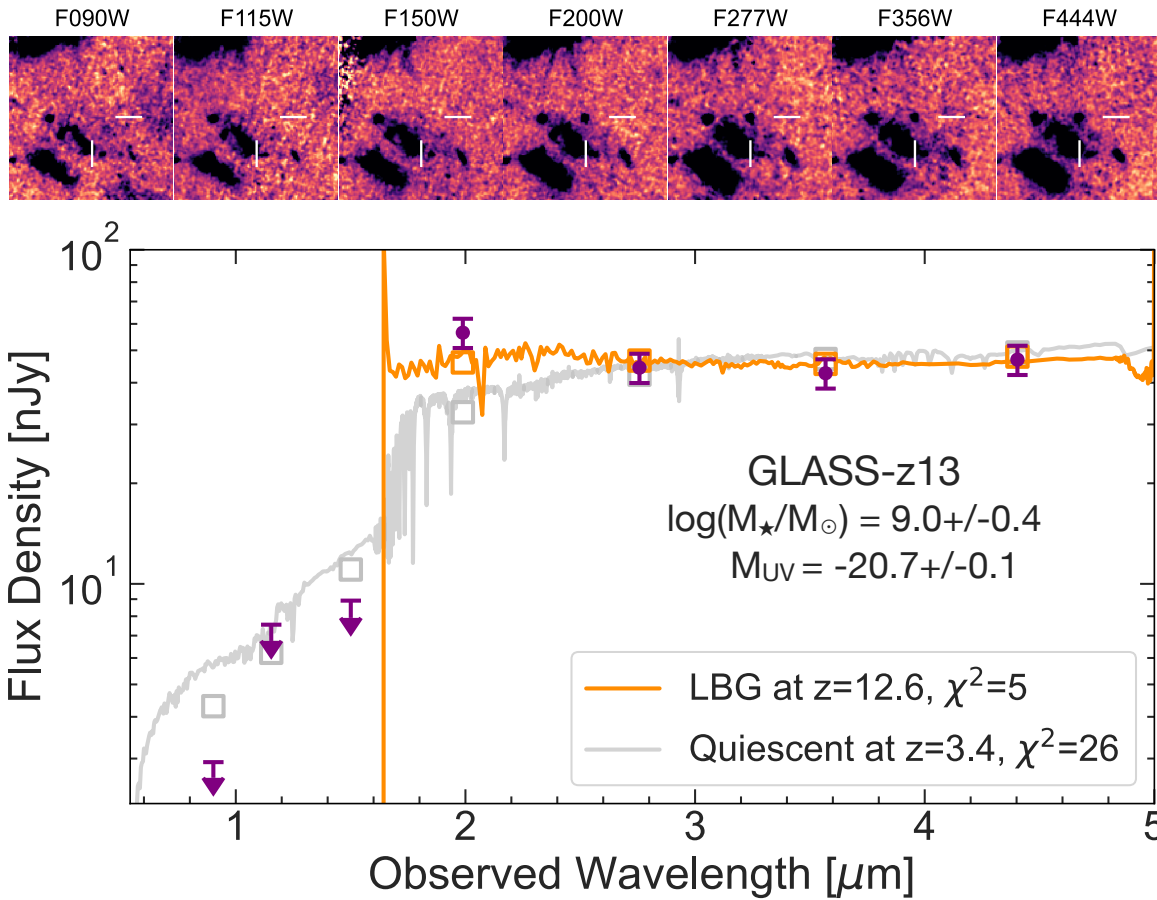


→ $z = 10.7$

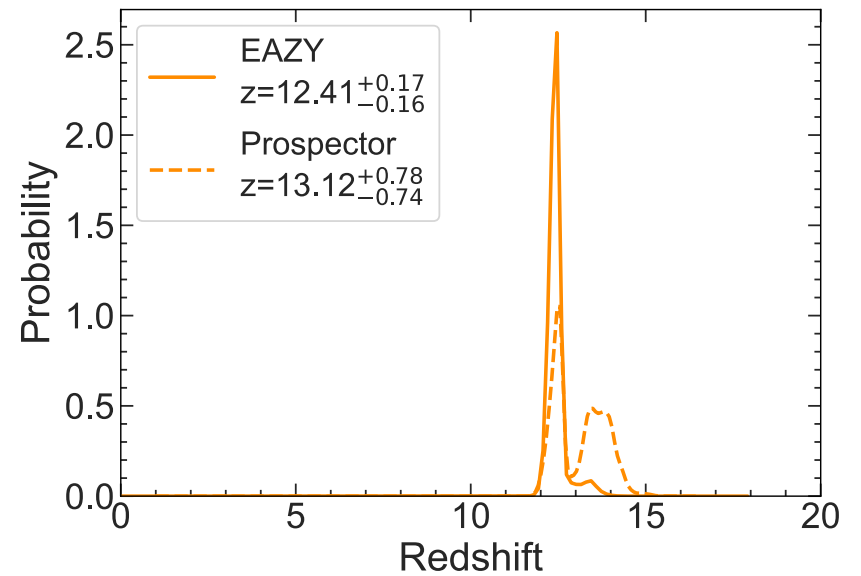


Naidu+2022; but see also Castellano+2022

High-z Searches Observations from Early JWST Data

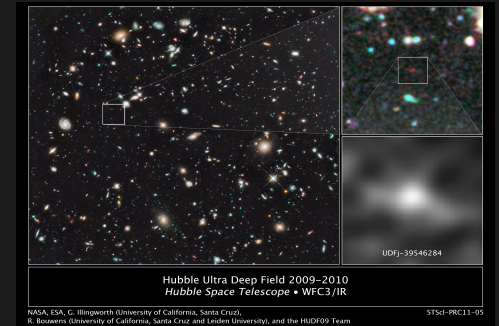
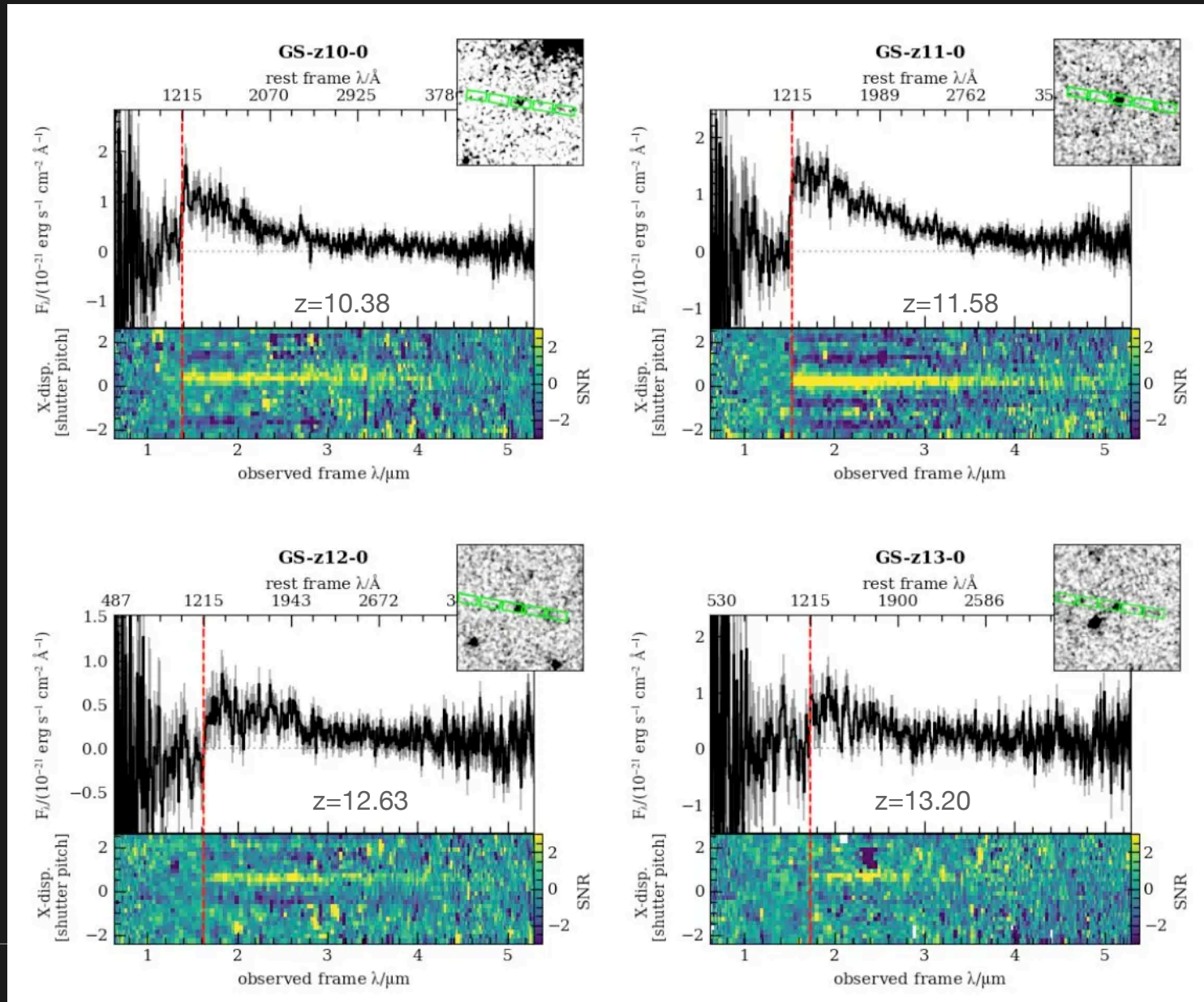


→ $z = 12.5$



Naidu+2022; but see also Castellano+2022

Fortunately spectroscopic confirmation came quickly for some



Bouwens+11

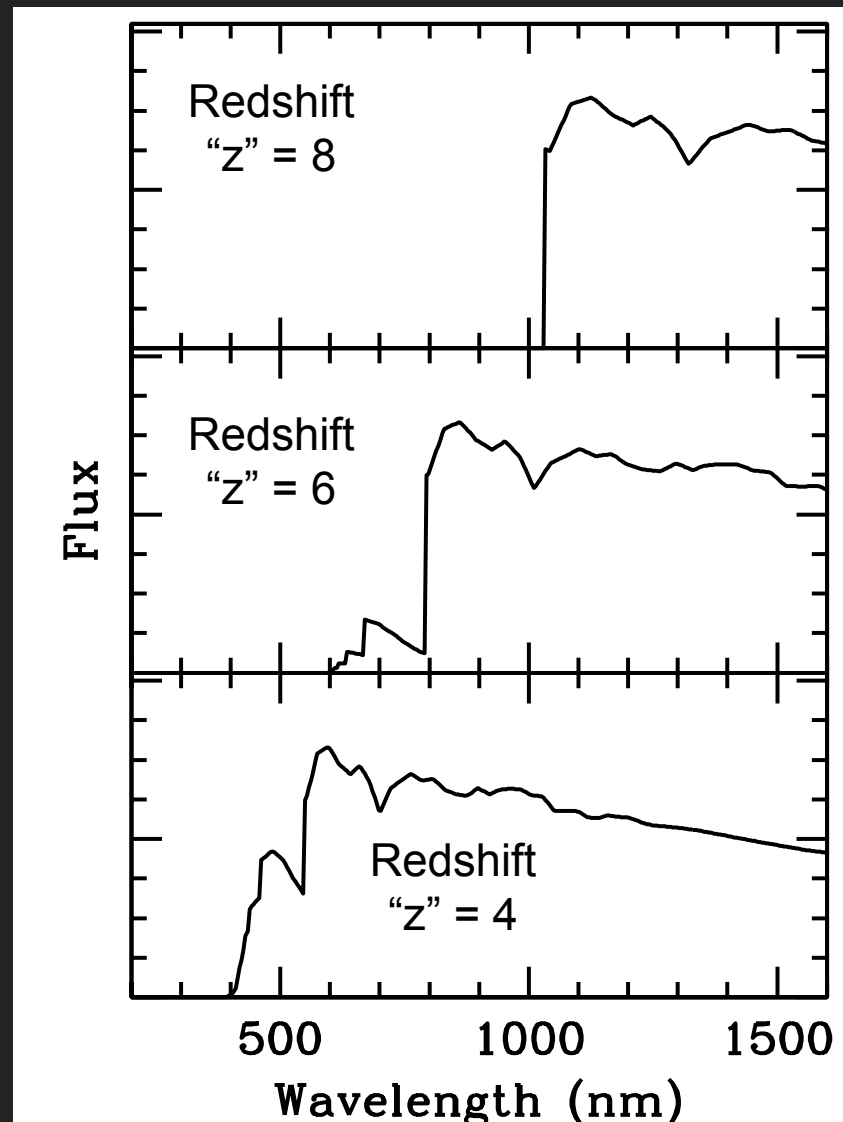
How can we determine which galaxies on deep images come from the most distant galaxies?

There is a sharp break in spectrum of distant galaxies due to neutral hydrogen in the universe.

As the universe expands, this break in the spectrum is shifted to redder wavelengths (“redshifted”)

By looking for sources with breaks at very red wavelengths, we identify the most distant galaxies.

Spectra of Distant Galaxies

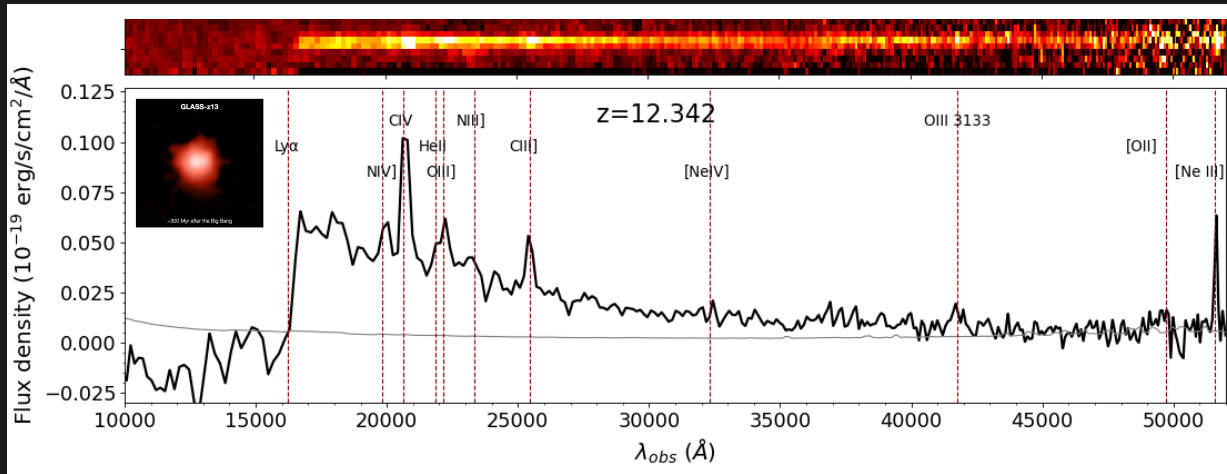


Most Distant
@ 850 Myr
after Big Bang

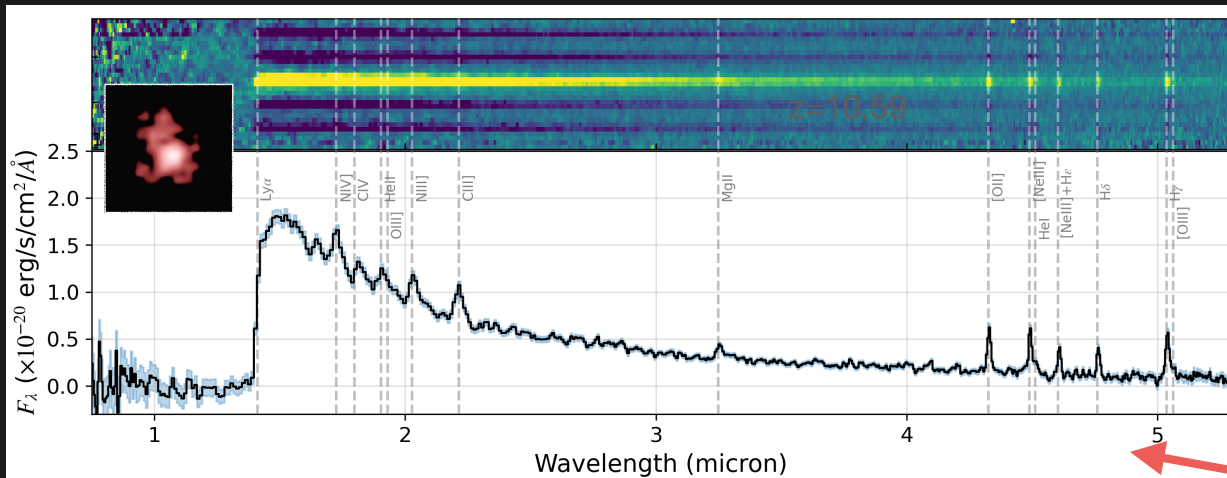
@ 1000 Myr
after Big Bang

Least Distant
@ 1800 Myr
after Big Bang

Treasure troves for understanding physics of early galaxies



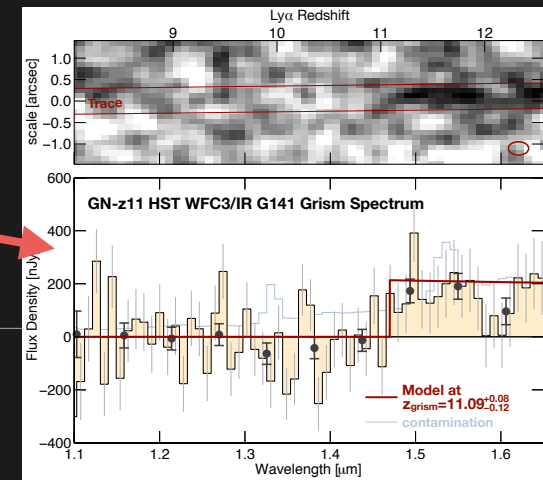
Castellano+24



Bunker+23 & Maiolino+24

- ▶ Fainter galaxies only confirmed through Ly α breaks
- ▶ Luminous sources revealed strong rest-UV emission lines at $z > 10$
- ▶ Enables much more detailed physical insight beyond number densities

HST Grism Spectrum



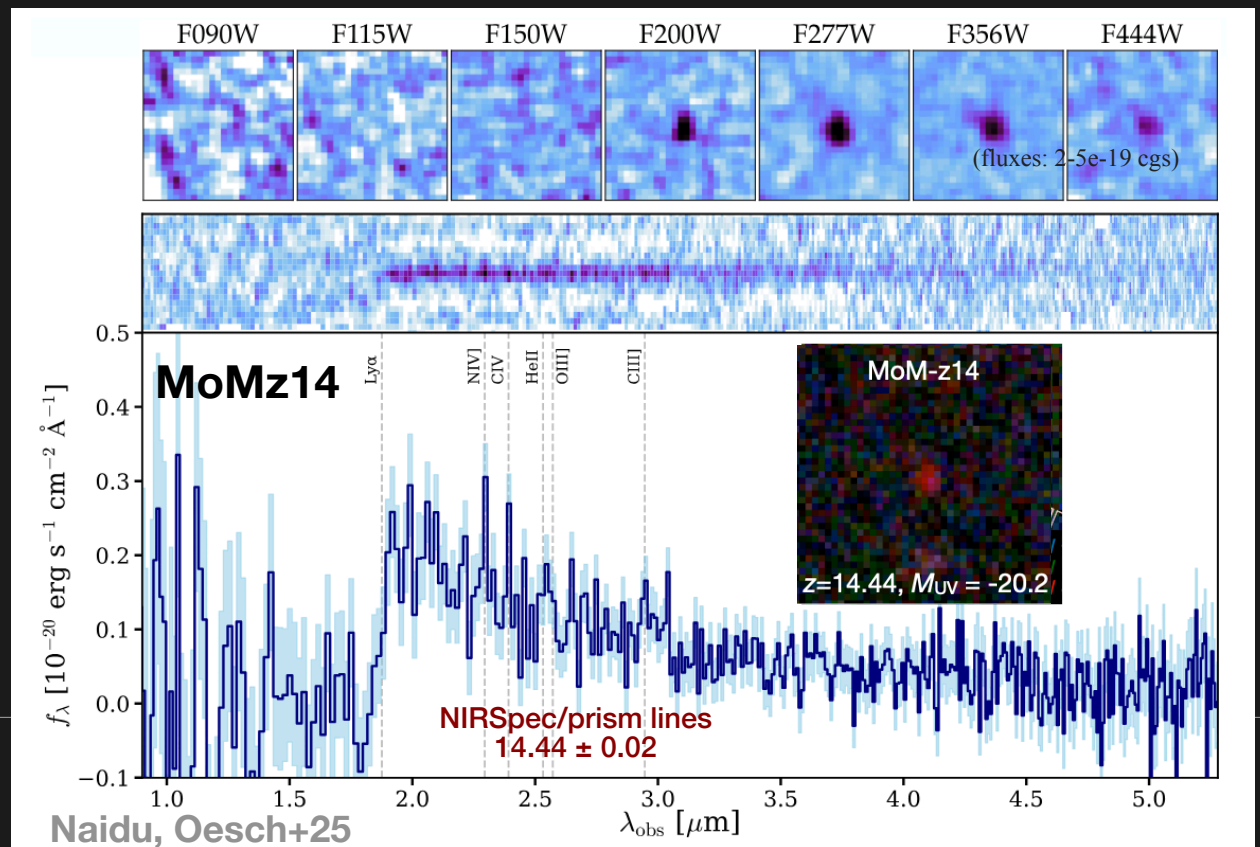
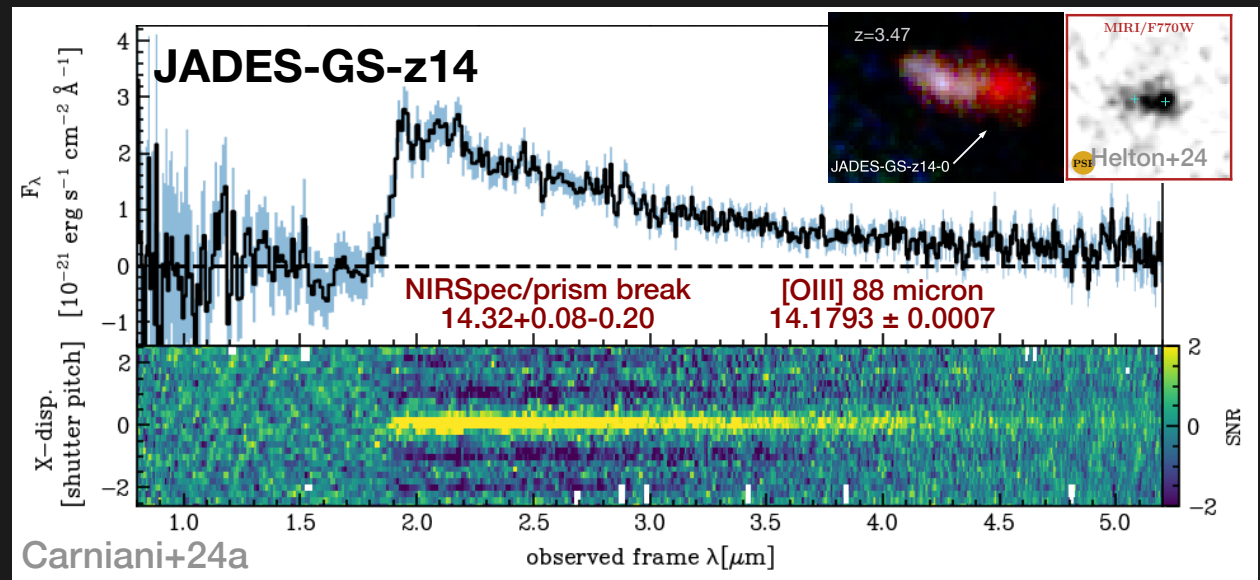
Oesch+16

Same Source

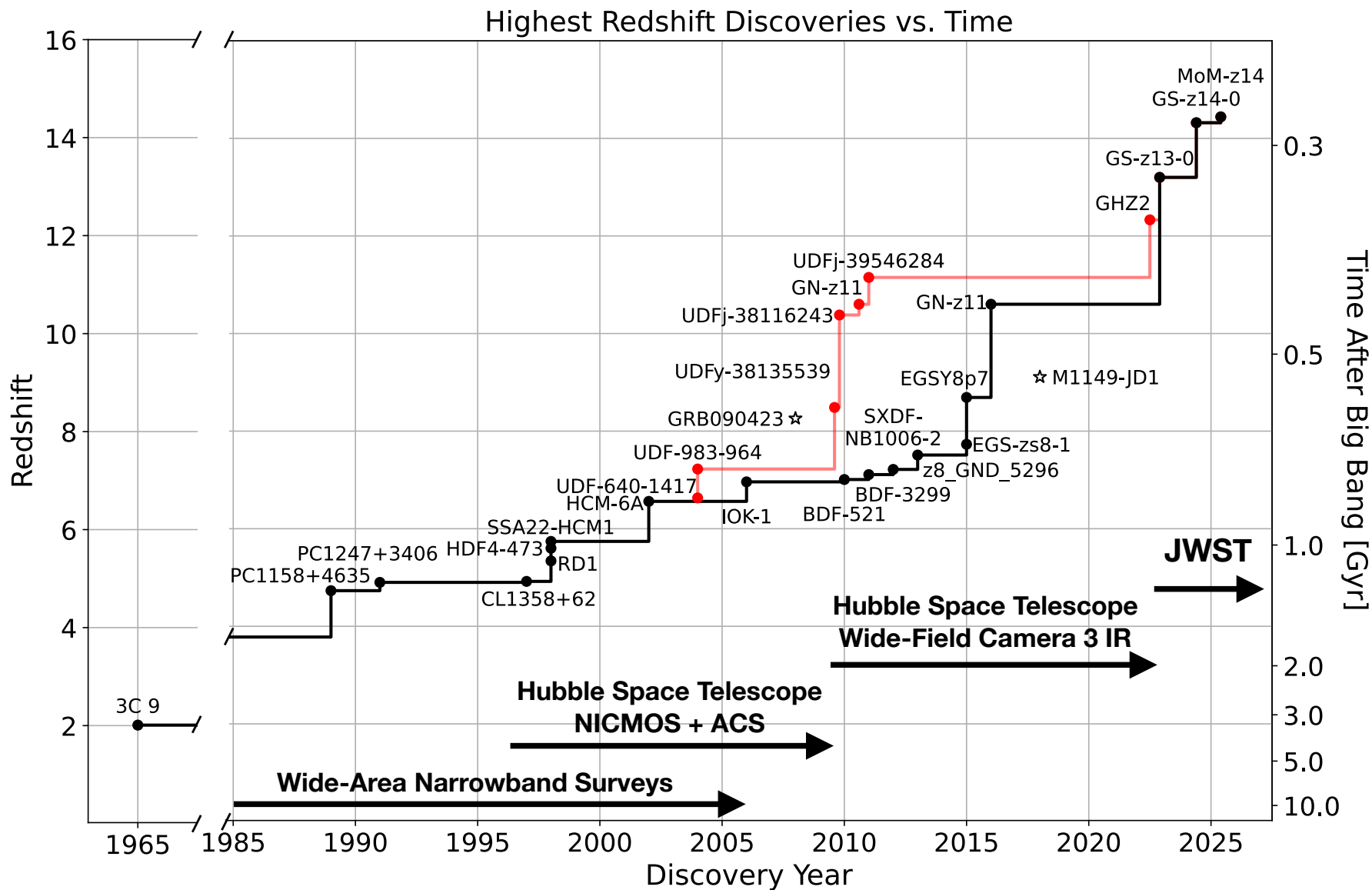
Spectroscopic High-Redshift Frontier

- ▶ Obtaining spectroscopic redshift confirmations is critical
- ▶ The spectroscopic record holder was broken several times over the past three years

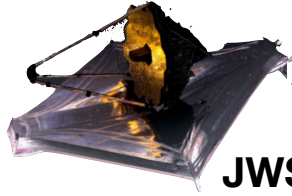
JWST obtained a spectrum of the $z_{\text{spec}}=14.44$ galaxy in only ~ 4.5 hrs



Here is the evolution of the redshift record



Our Multi-Wavelength Census of Early Galaxies



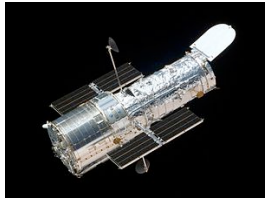
JWST:

rest-frame UV+optical
SFRs, stellar masses,
metallicity, ionized gas



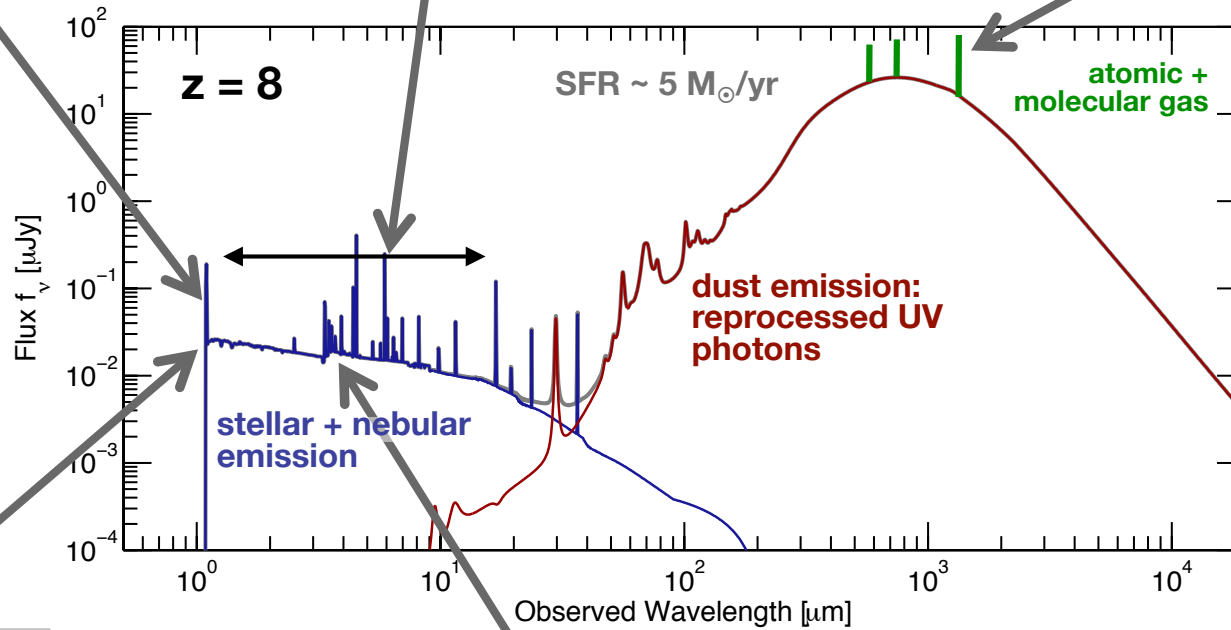
ALMA/NOEMA:

cold gas
dust re-emission
closes energy balance



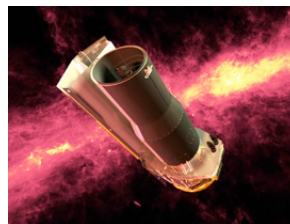
HST:

rest-frame UV
un-obscured SFR



NIR Spectra:

rest-frame UV lines



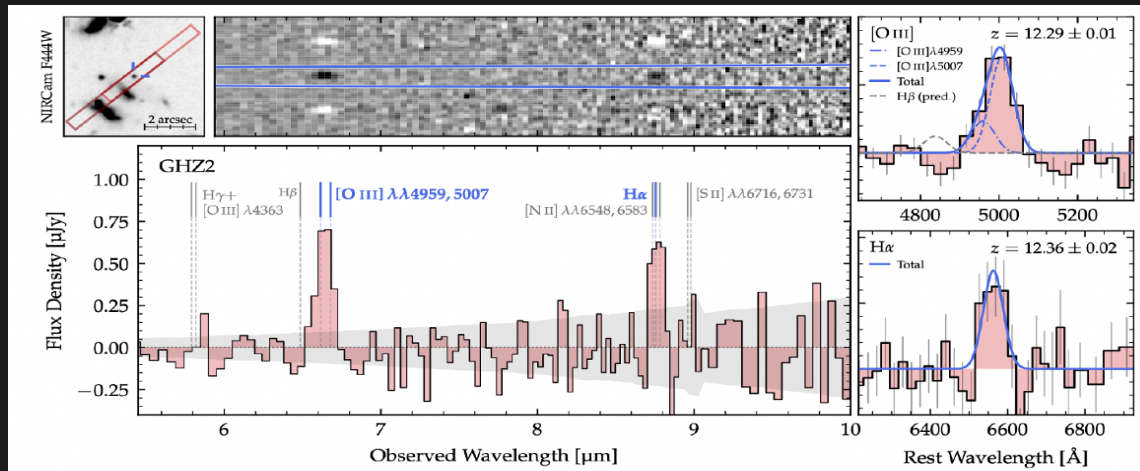
Spitzer:

rest-frame optical imaging
stellar masses
rest-frame optical emission lines

Credit for Illustration: Pascal Oesch

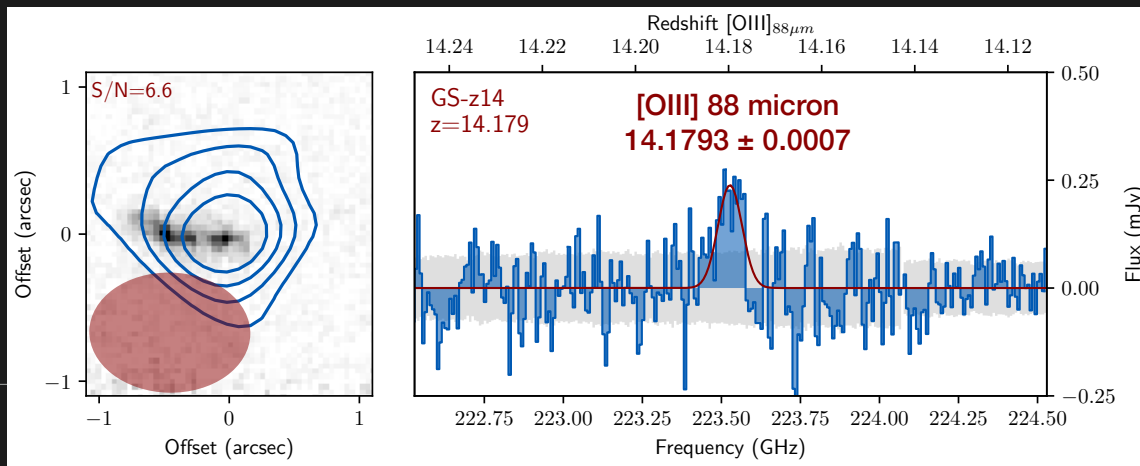
Treasure troves for understanding physics of early galaxies

Spectroscopy with MIRI Instrument on JWST



Zavala+24

- ▶ Fainter galaxies only confirmed through Ly α breaks
- ▶ Luminous sources revealed strong rest-UV emission lines at $z > 10$
- ▶ Follow-up with MIRI and ALMA spectroscopy
- ▶ Enables much more detailed physical insight beyond number densities



ALMA

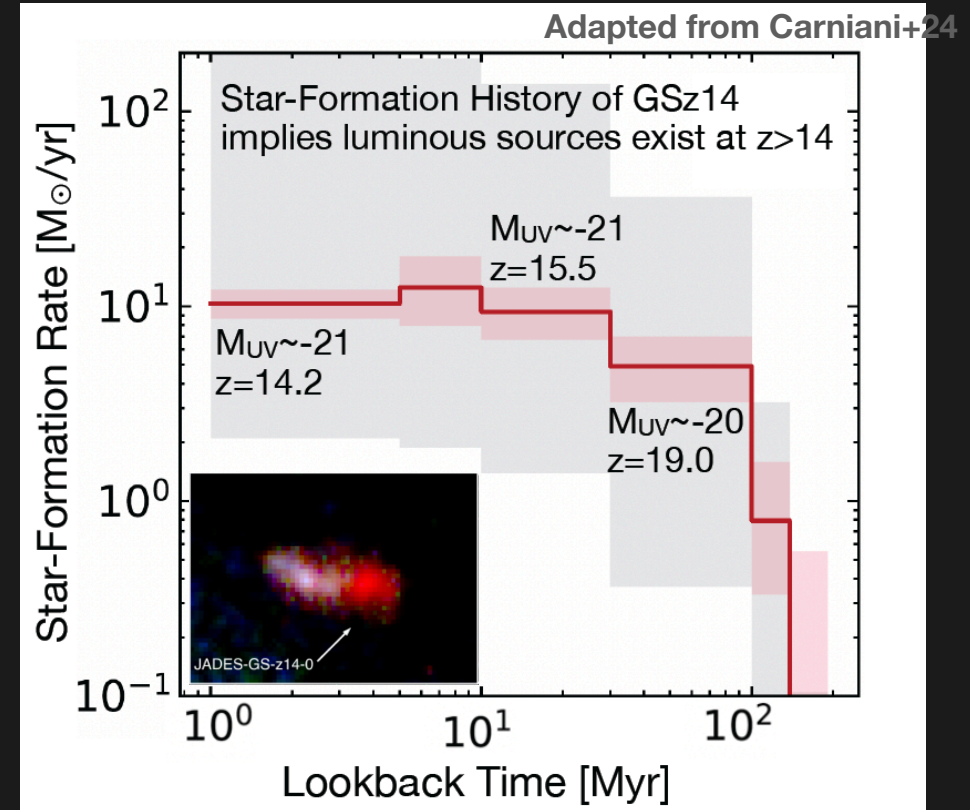


Schouws+24; Carniani+24b

See also Álvarez-Márquez+23, Hsiao+24, Bakx+23, Yoon+23

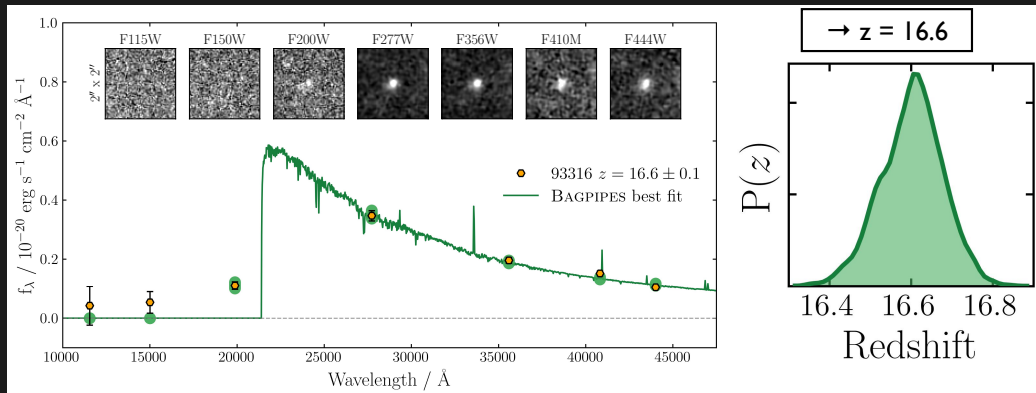
To $z > 15$ and beyond!

- ▶ Pushing the cosmic frontier would allow us to rule out some of the proposed models
- ▶ Remarkable chemical maturity ($\sim 20\%$ solar metallicity) and brightness imply an extended star-formation history in GSz14.
- ▶ Progenitors (at $z \sim 15-20$) should be easily detectable!
- ▶ First photometric samples are reported! (Kokorev+25, Perez-Gonzalez+25, Castellano+25)



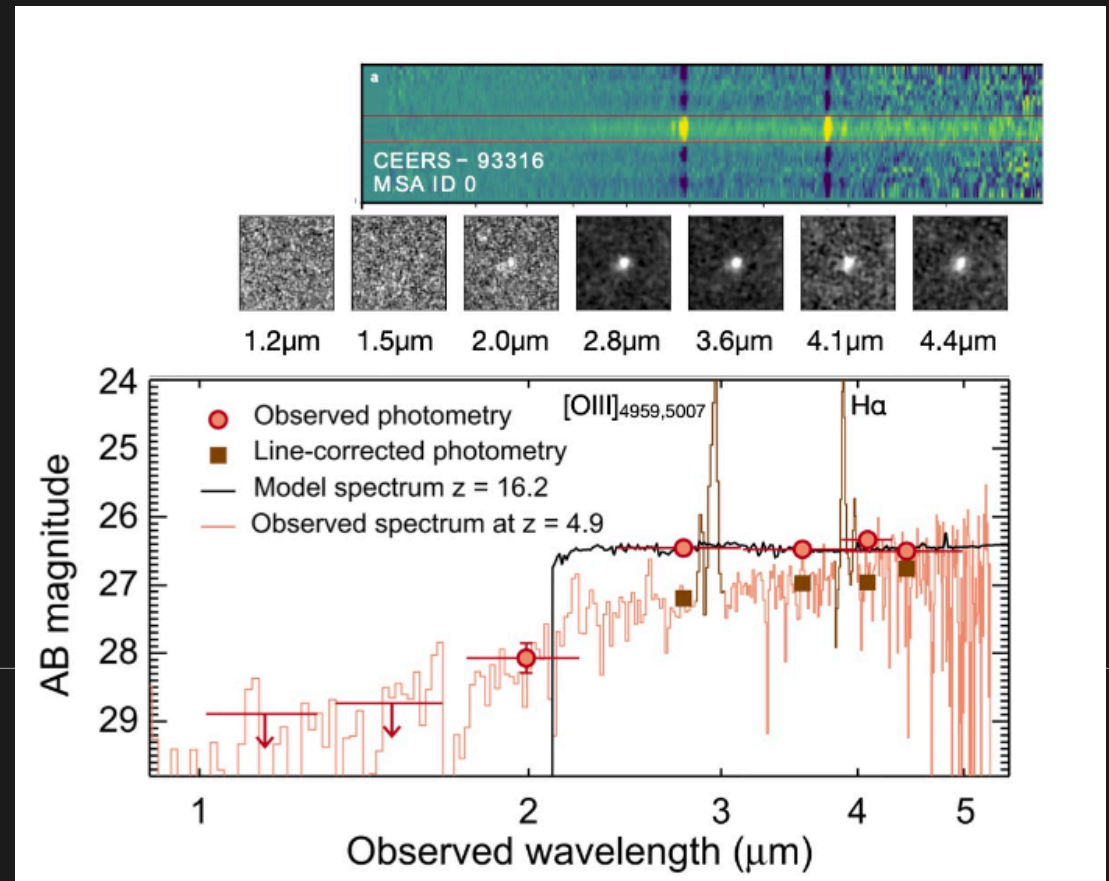
Pushing to $z > 15$ has proven challenging however

Bright $z \sim 16.6$ Identified in Early ERS Data over CEERS



Donnan+23

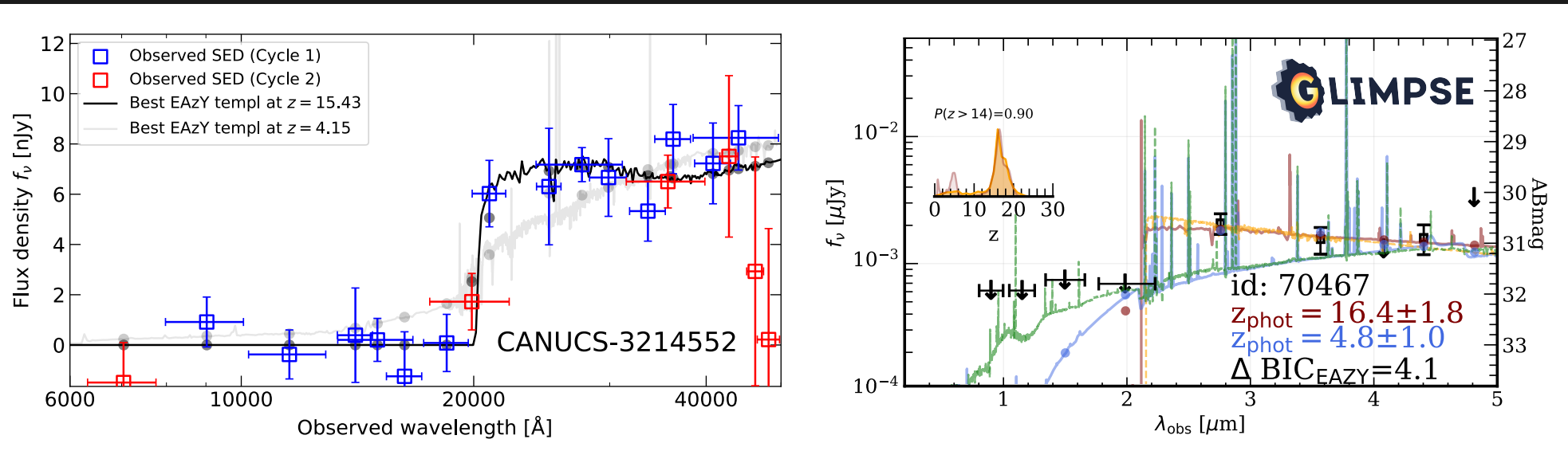
But proved to be an extreme emission line galaxy at $z = 4.91$



Haro-Arrabal+23

What about $z > 15$?

Two examples of possible $z > 15$ candidate galaxies from Asada+25 and Glimpse (Kokorev+25), F200W dropouts (see also Gandolfi+25)

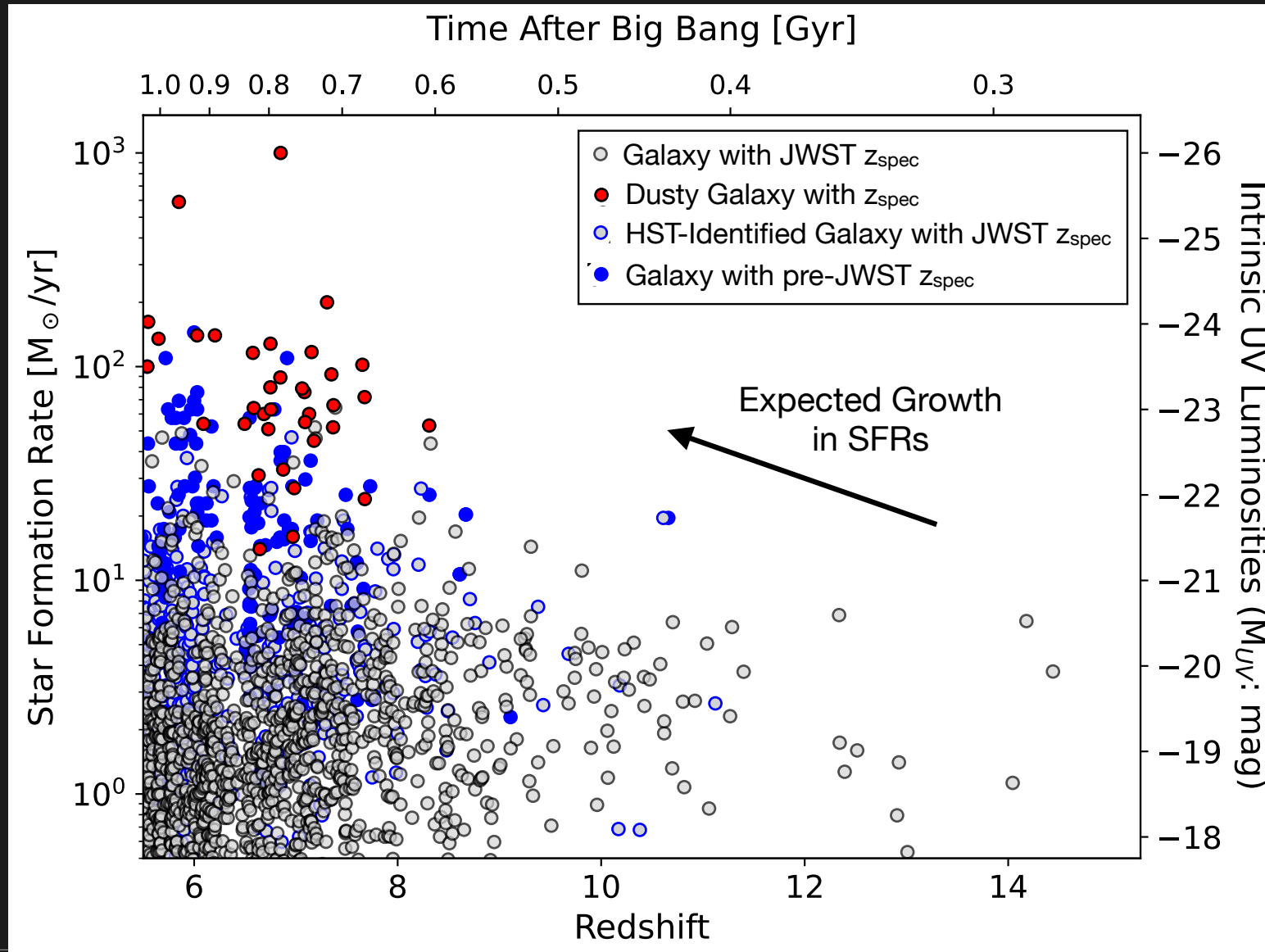


Asada+25

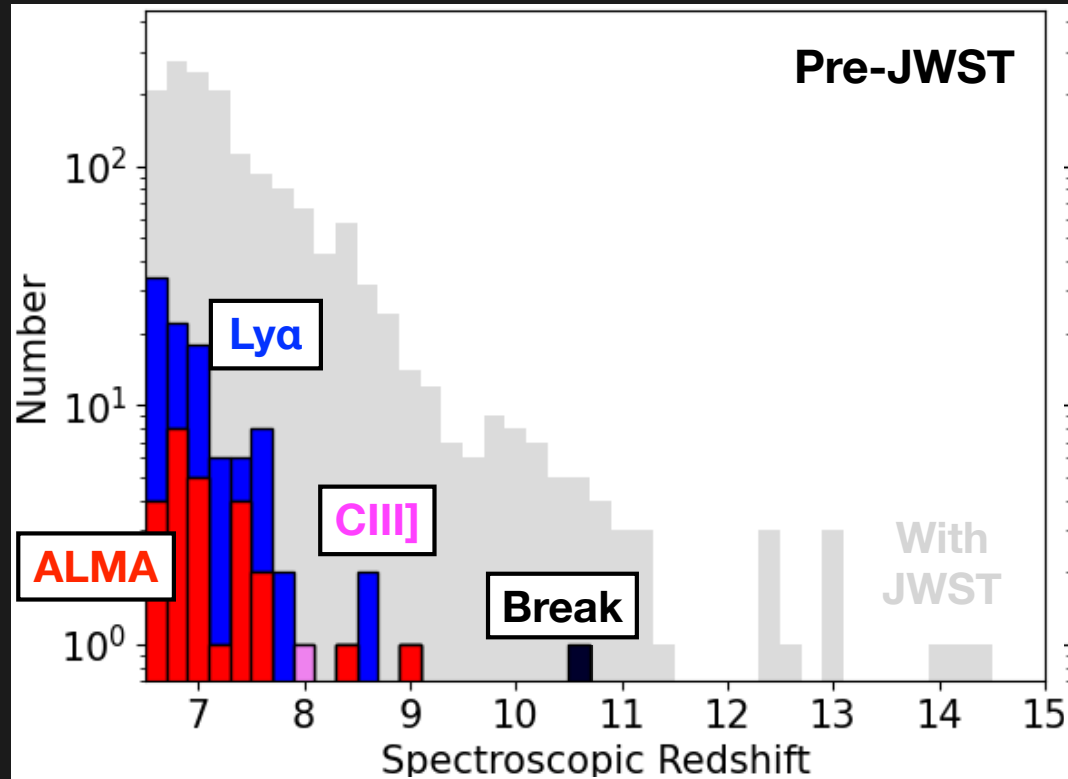
Kokorev+25

See also Perez-Gonzalez+25; Castellano+25

Unprecedented Samples of Galaxies with Spectroscopic Redshifts

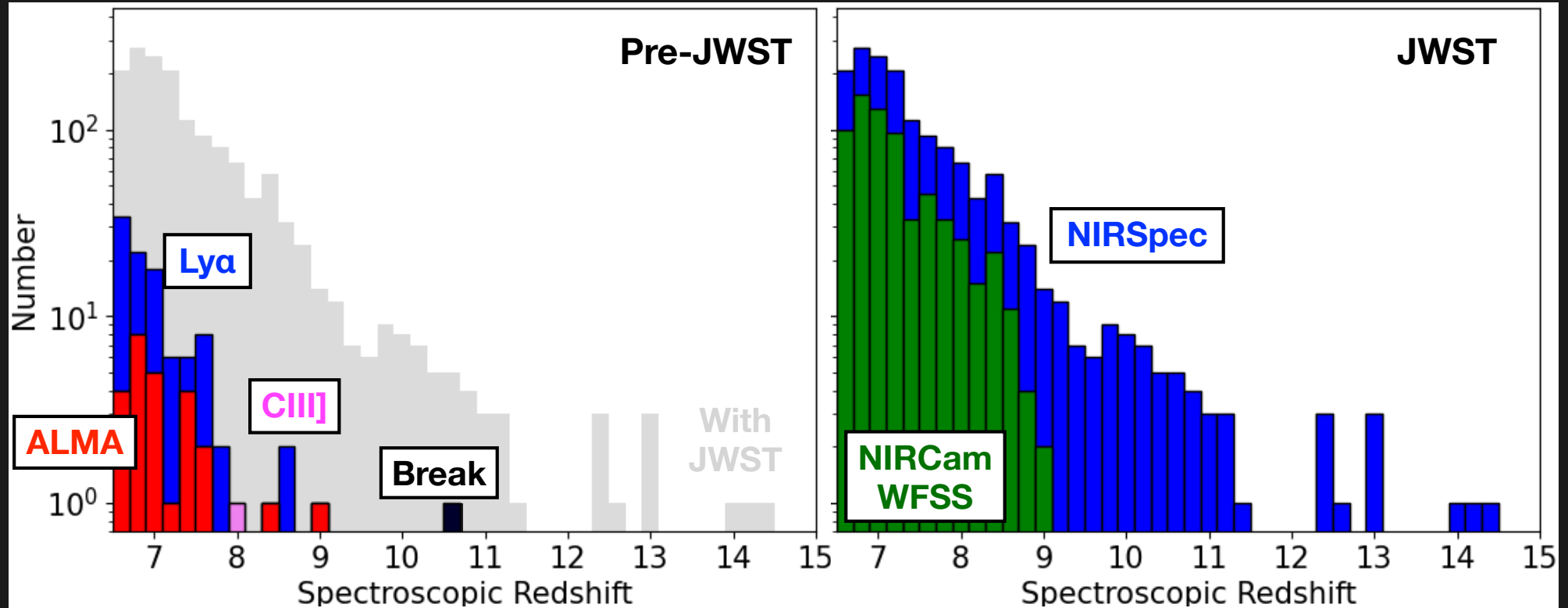


Unprecedented Samples of Galaxies with Spectroscopic Redshifts



Bouwens+26

Unprecedented Samples of Galaxies with Spectroscopic Redshifts



Bouwens+26

Wide-Field Slitless Spectroscopy – FRESCO

(PI: Oesch)

Wavelength \longrightarrow
Dispersed Image

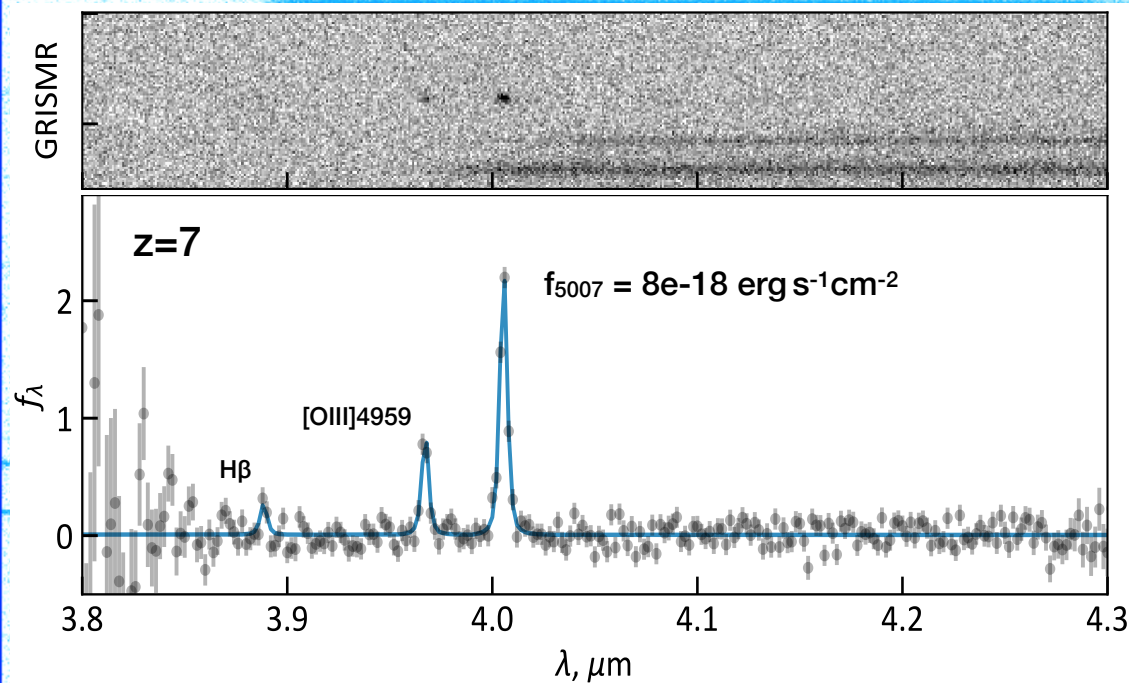
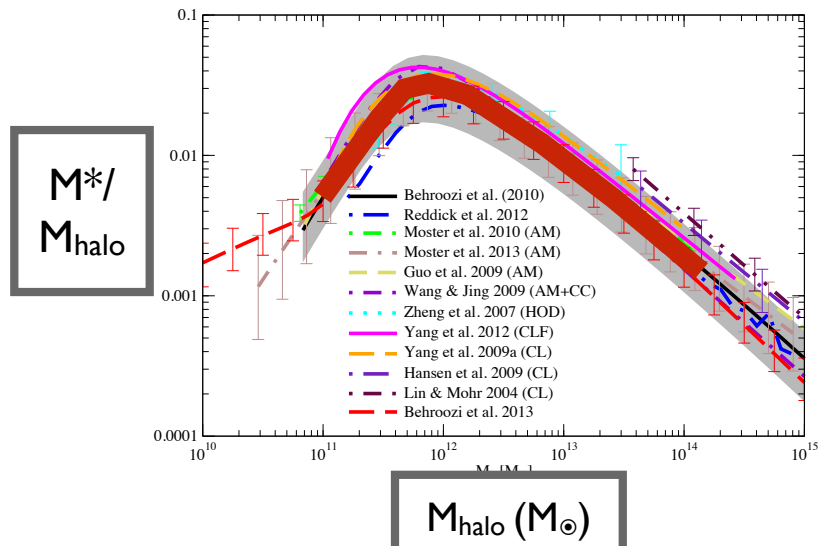
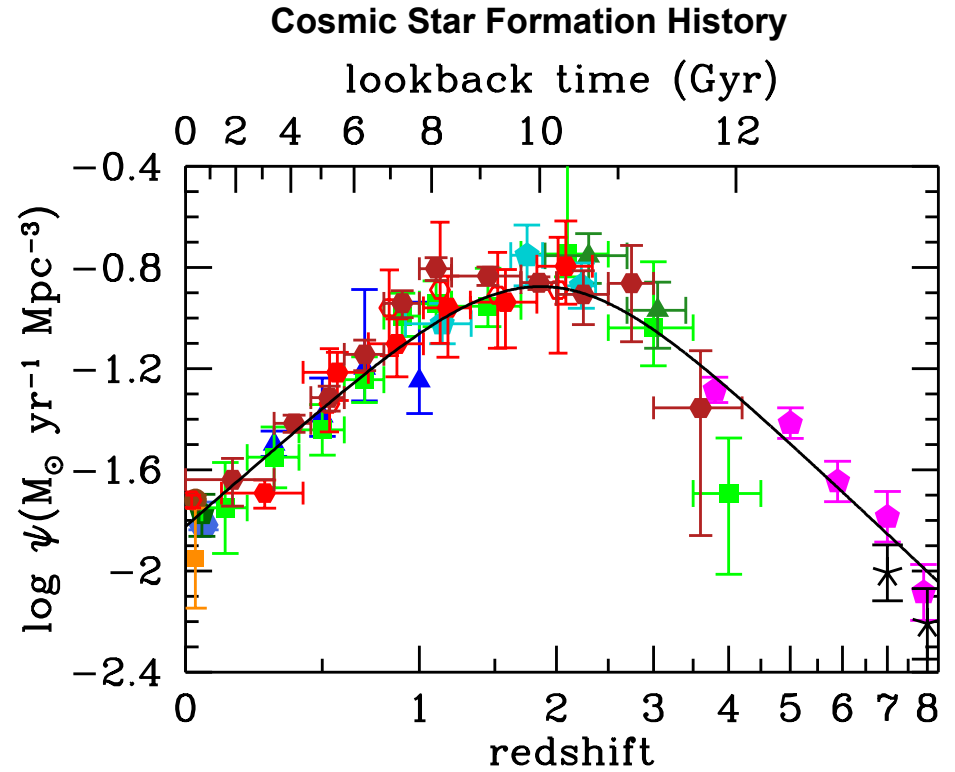
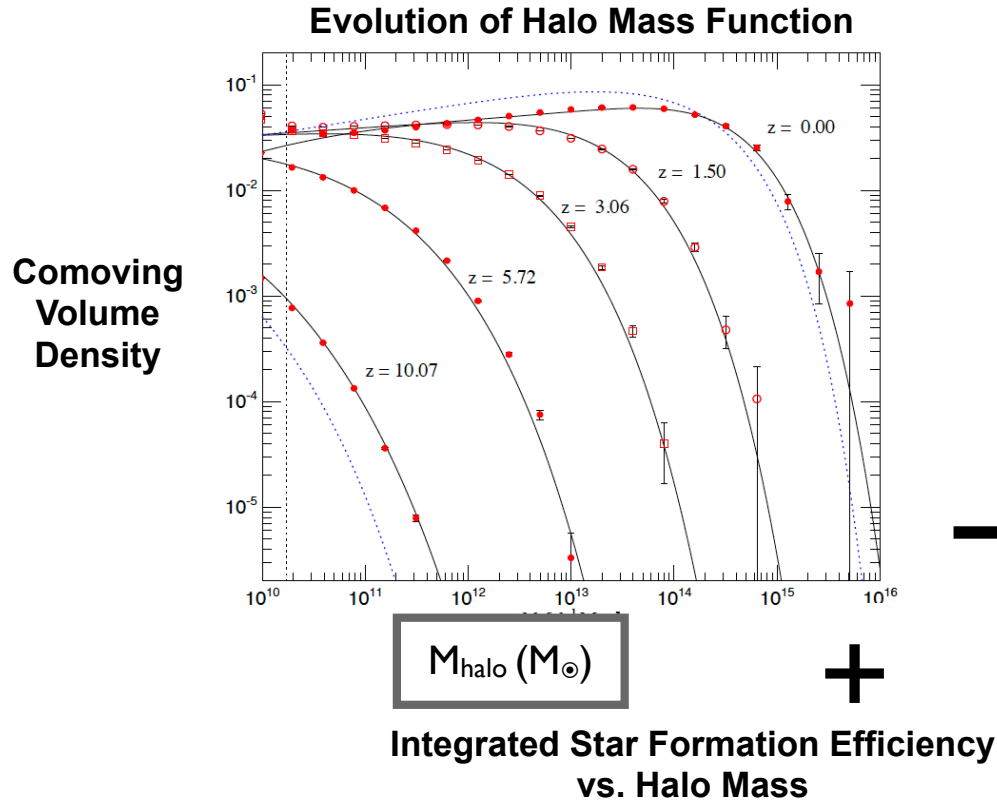


Image Credit: Gabe Brammer

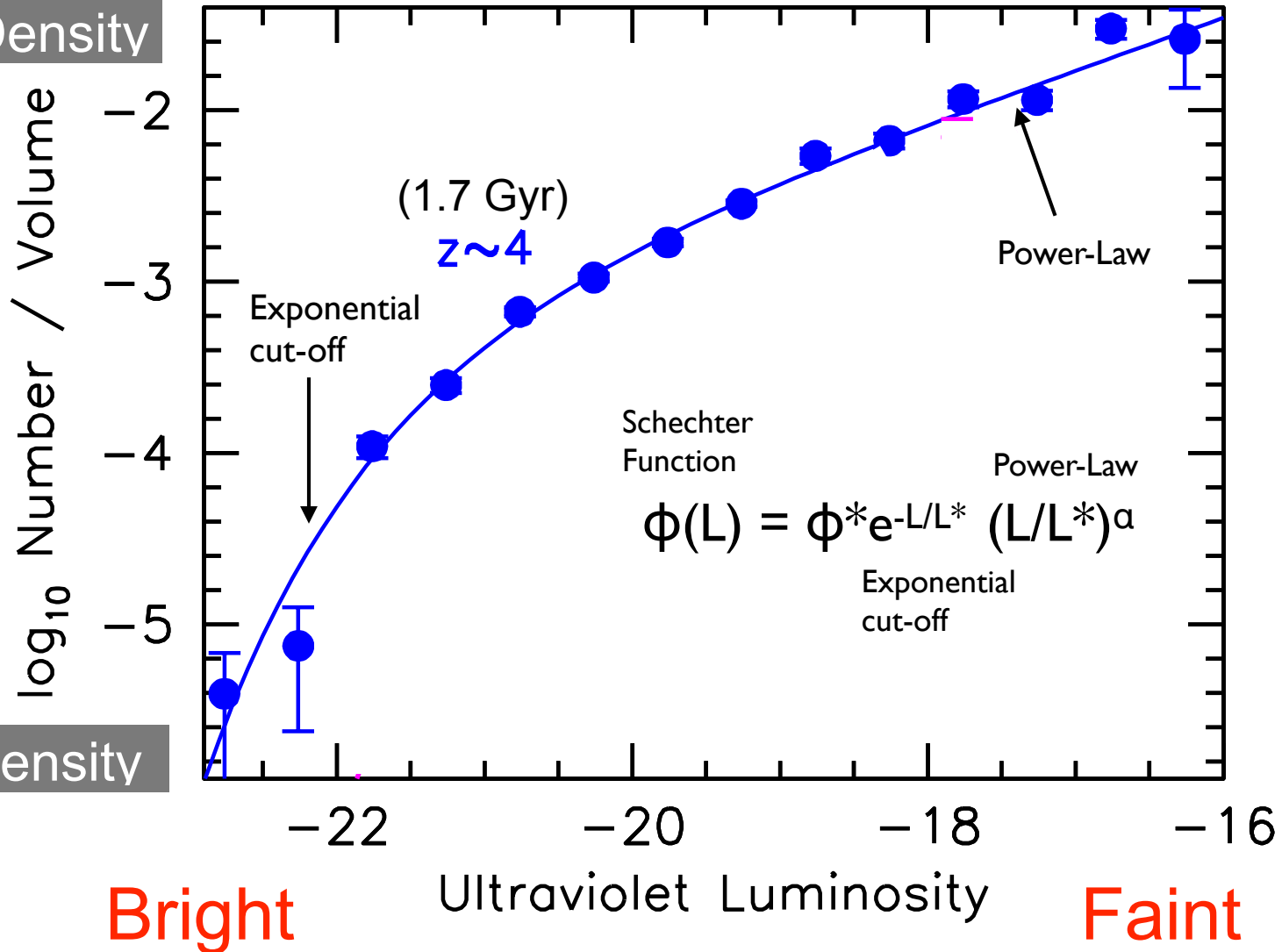
Can we understand the diagram to the right?



**But first let us remind ourselves
about luminosity functions...**

One of the most fundamental measures of galaxy growth is from the Luminosity Function...

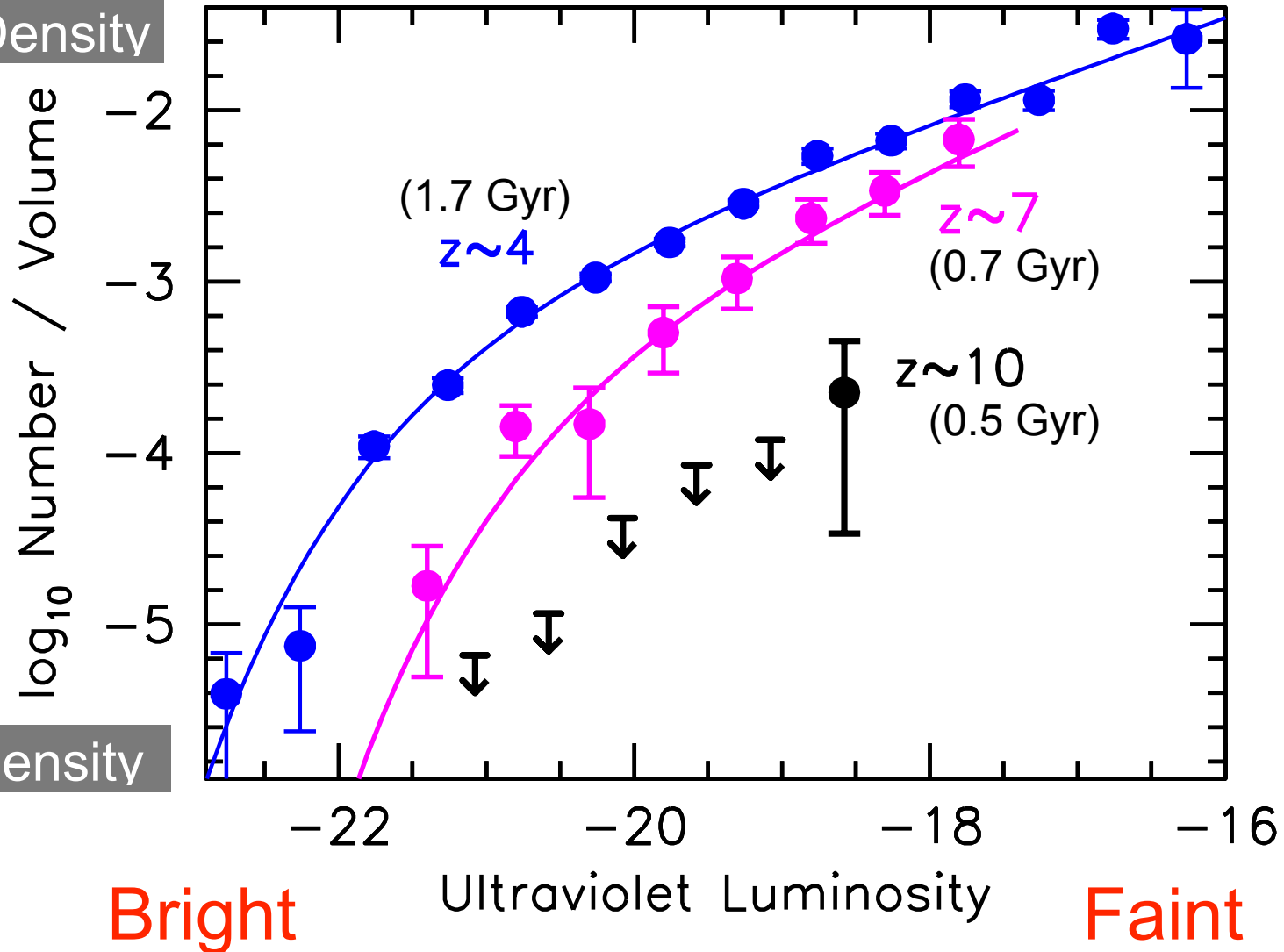
High Density



Low Density

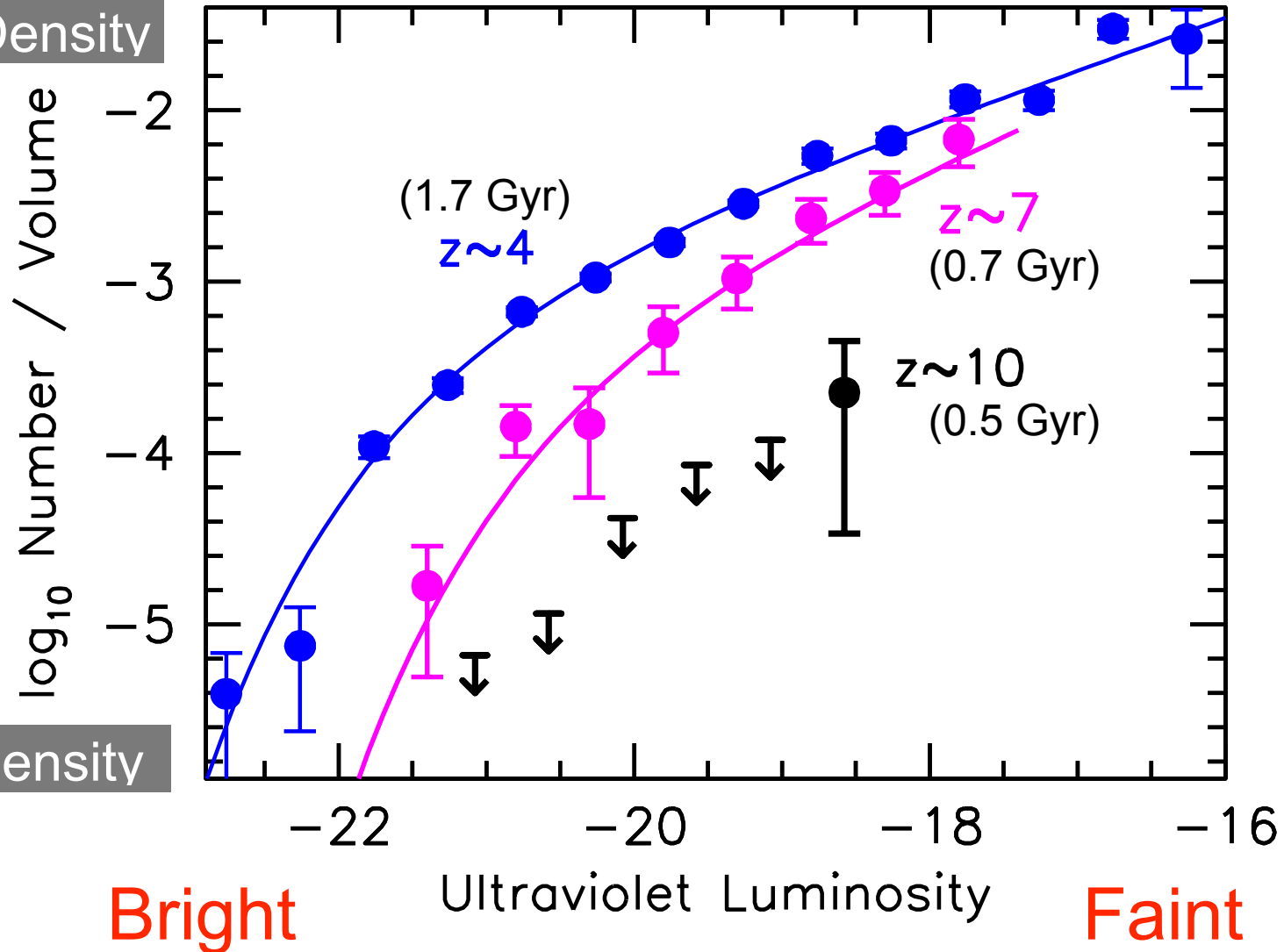
One of the most fundamental measures of this growth is from the Luminosity Function...

High Density



One of the most fundamental measures of this growth is from the Luminosity Function...

High Density

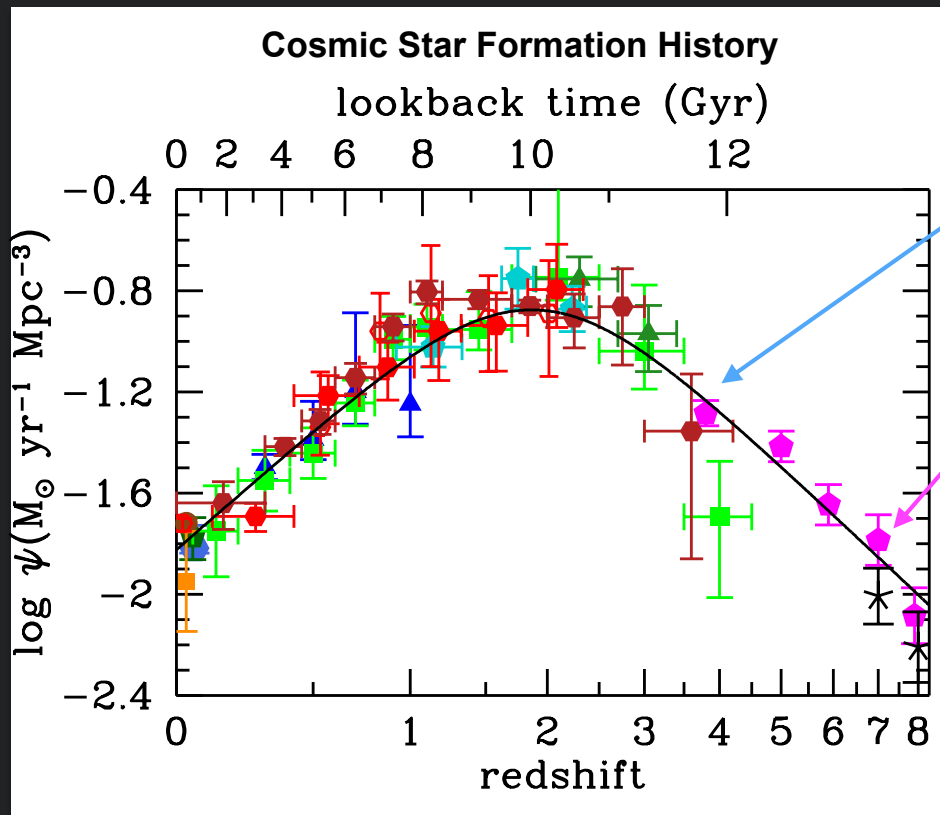
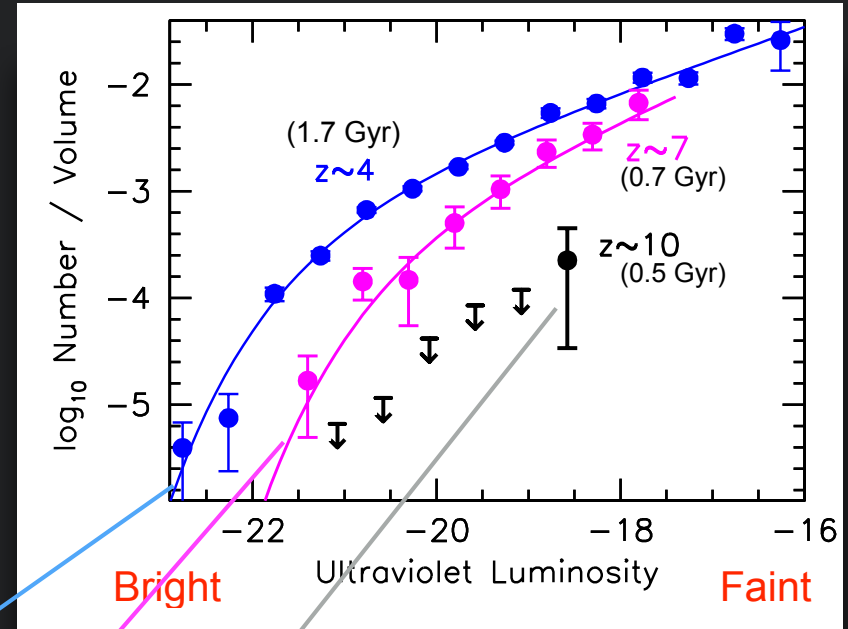


Low Density

Can Calculate SFR Density from UV Luminosity Function

UV Luminosity is from newly formed O+B stars in last 100 Myr

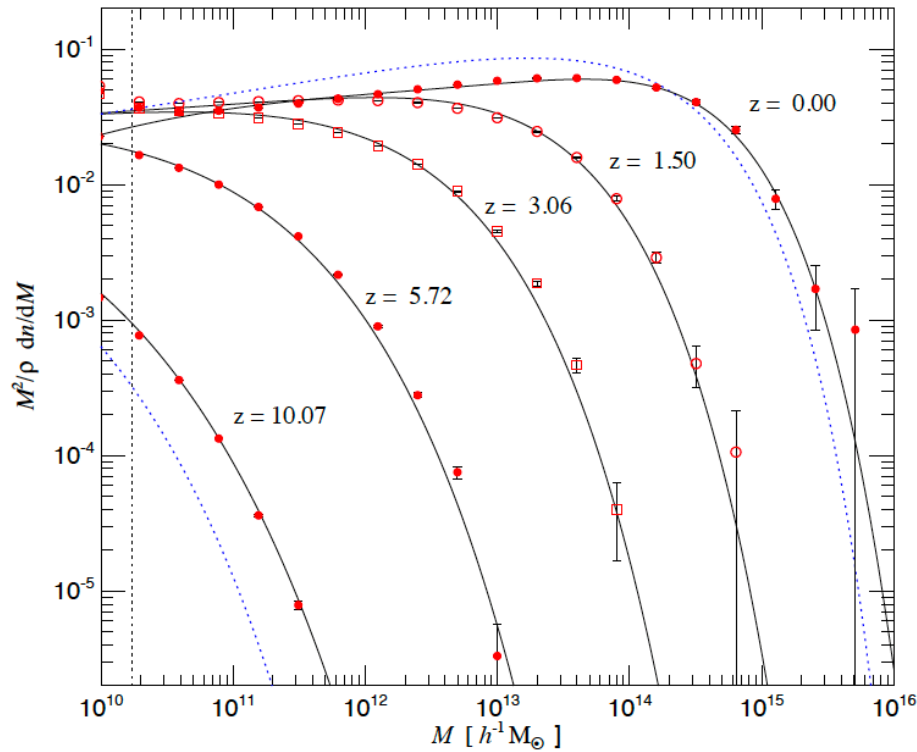
$$\text{SFR} = L_{\text{UV}} \times \text{conversion factor}$$



Integrate
Luminosity
Functions to
Derive SFR
Density

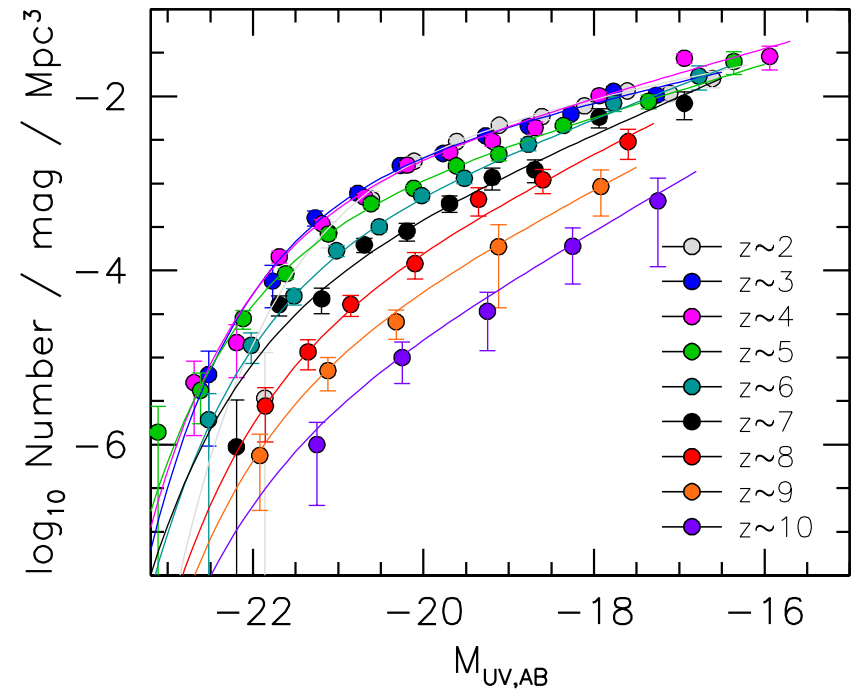
Impact Dark Matter Halo Have on the Density of Galaxies with Various Properties

Evolution of Dark Matter Halo Mass Function



Springel+2005

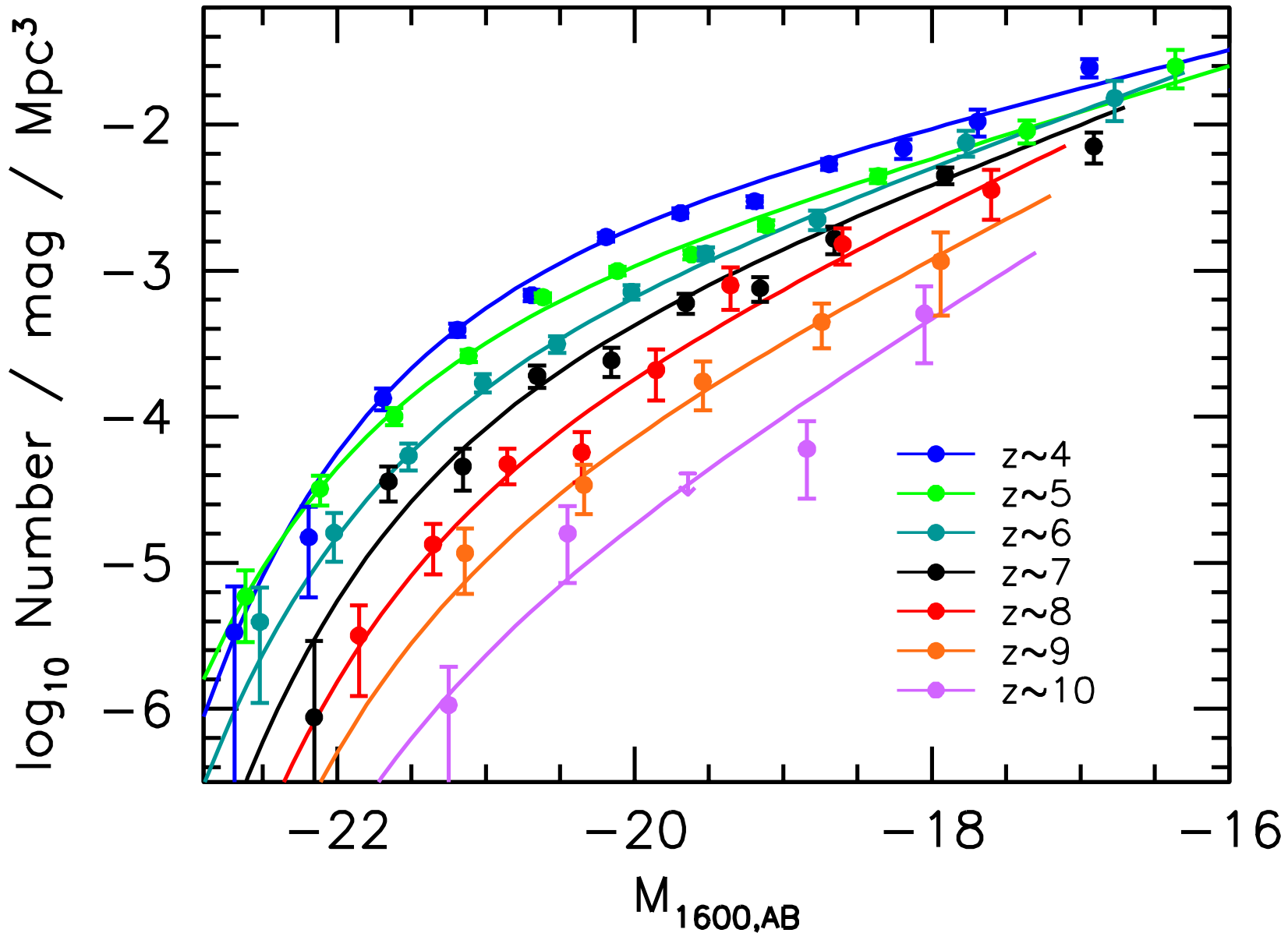
Evolution of Luminosity Function at UV Wavelengths



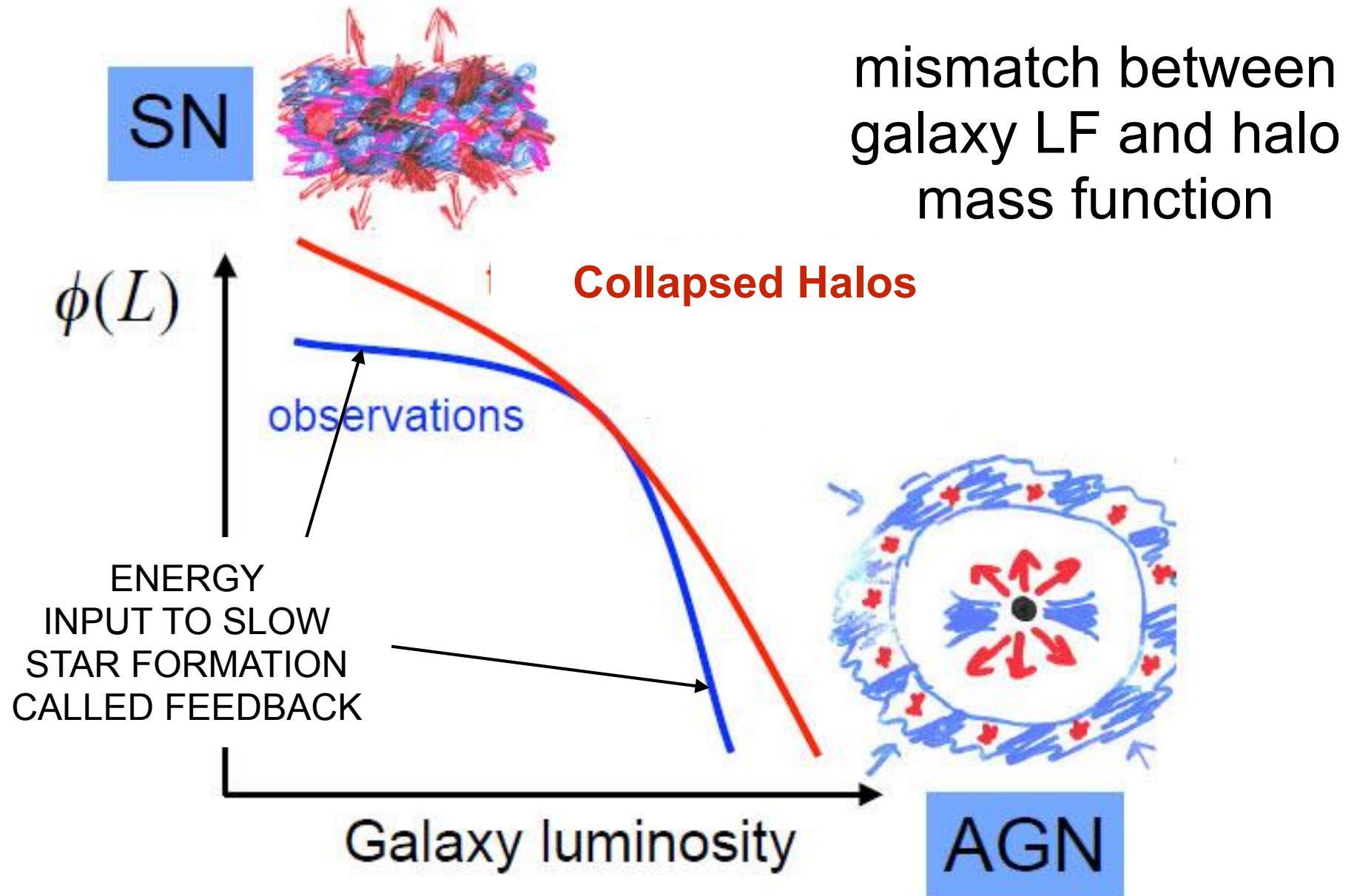
Bouwens+2021

**Perhaps we can match the evolution of the UV LFs
by lighting up dark-matter halos?**

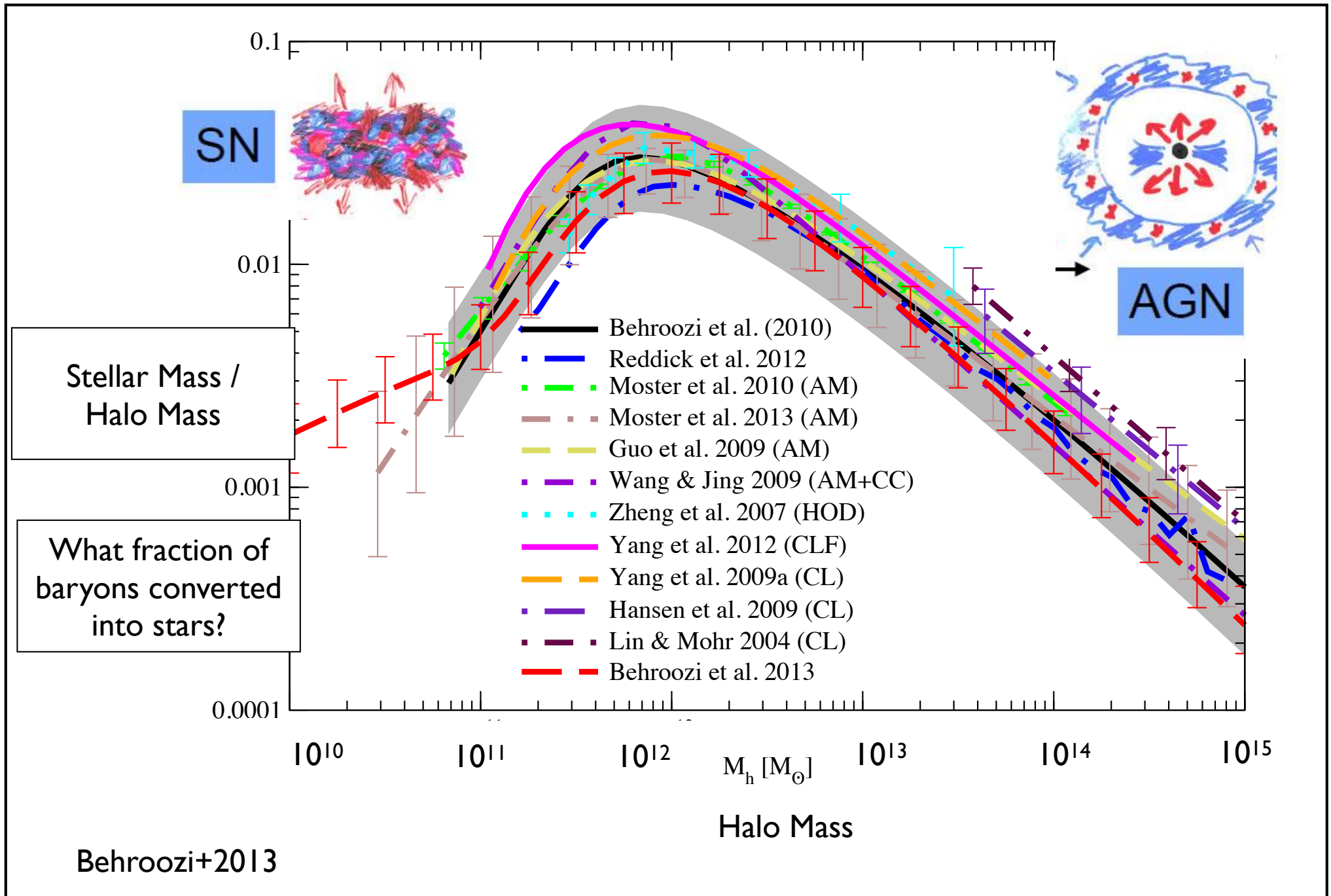
How can we match the evolution of the UV LFs by lighting up dark-matter halos?



In doing so, we will want to take advantage of processes we know are important at $z \sim 0$



Thus we will use the plotted relation

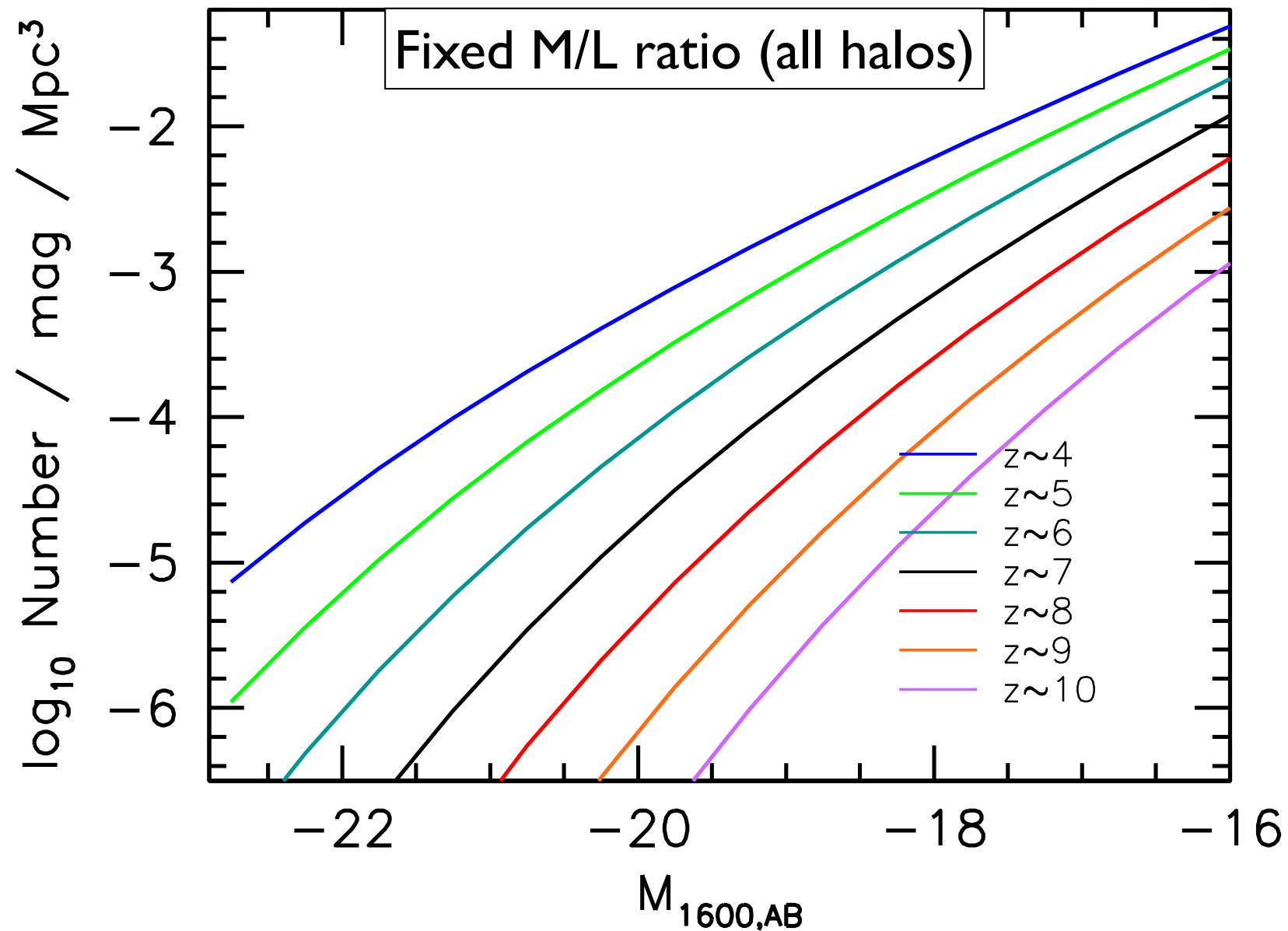


**Perhaps we can match the evolution of the UV LFs
by lighting up dark-matter halos?**

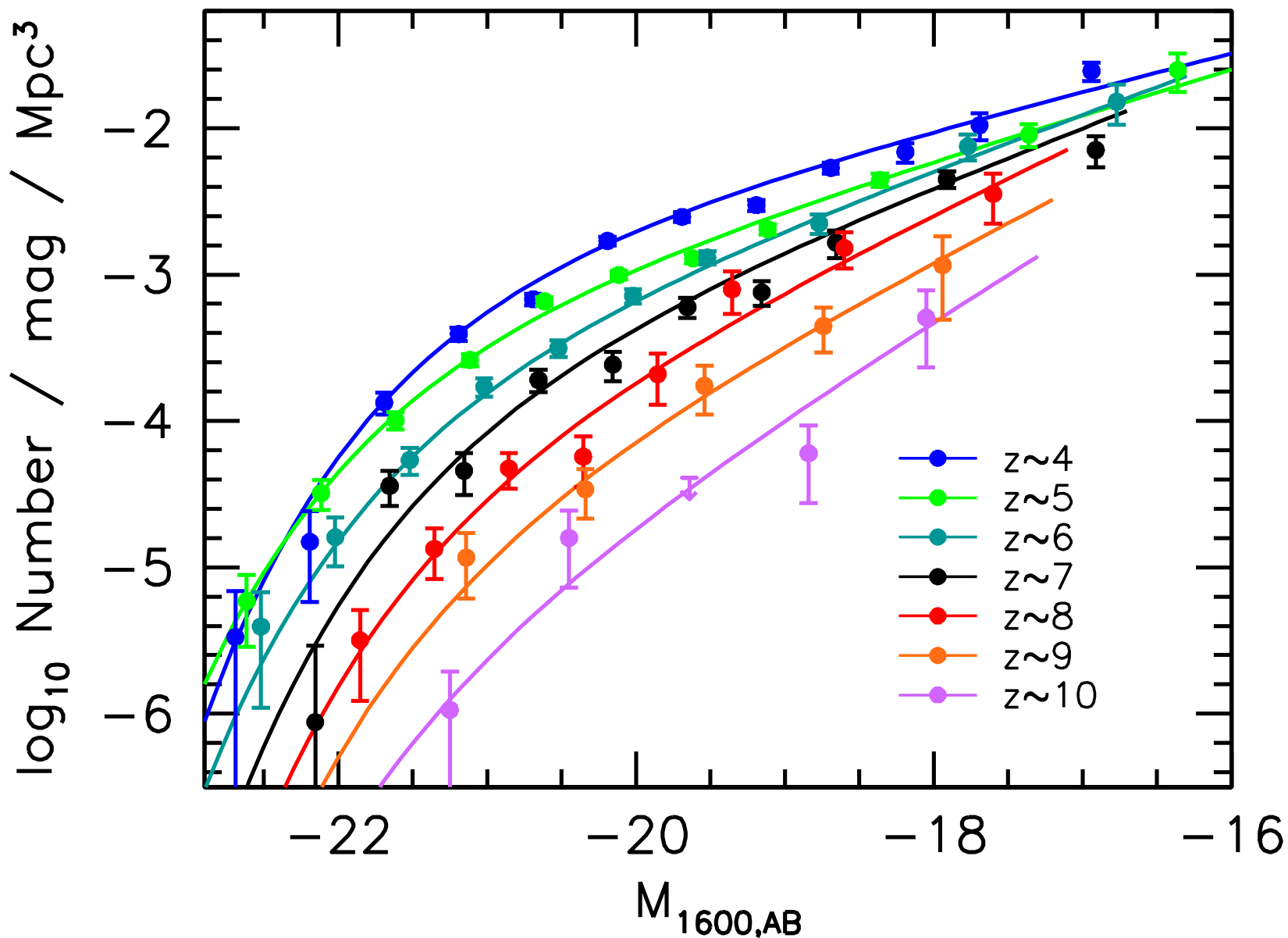
First, the simplest approach:

$$\text{Luminosity}_{(\text{Halo})} \propto \text{Mass}_{(\text{Halo})}$$

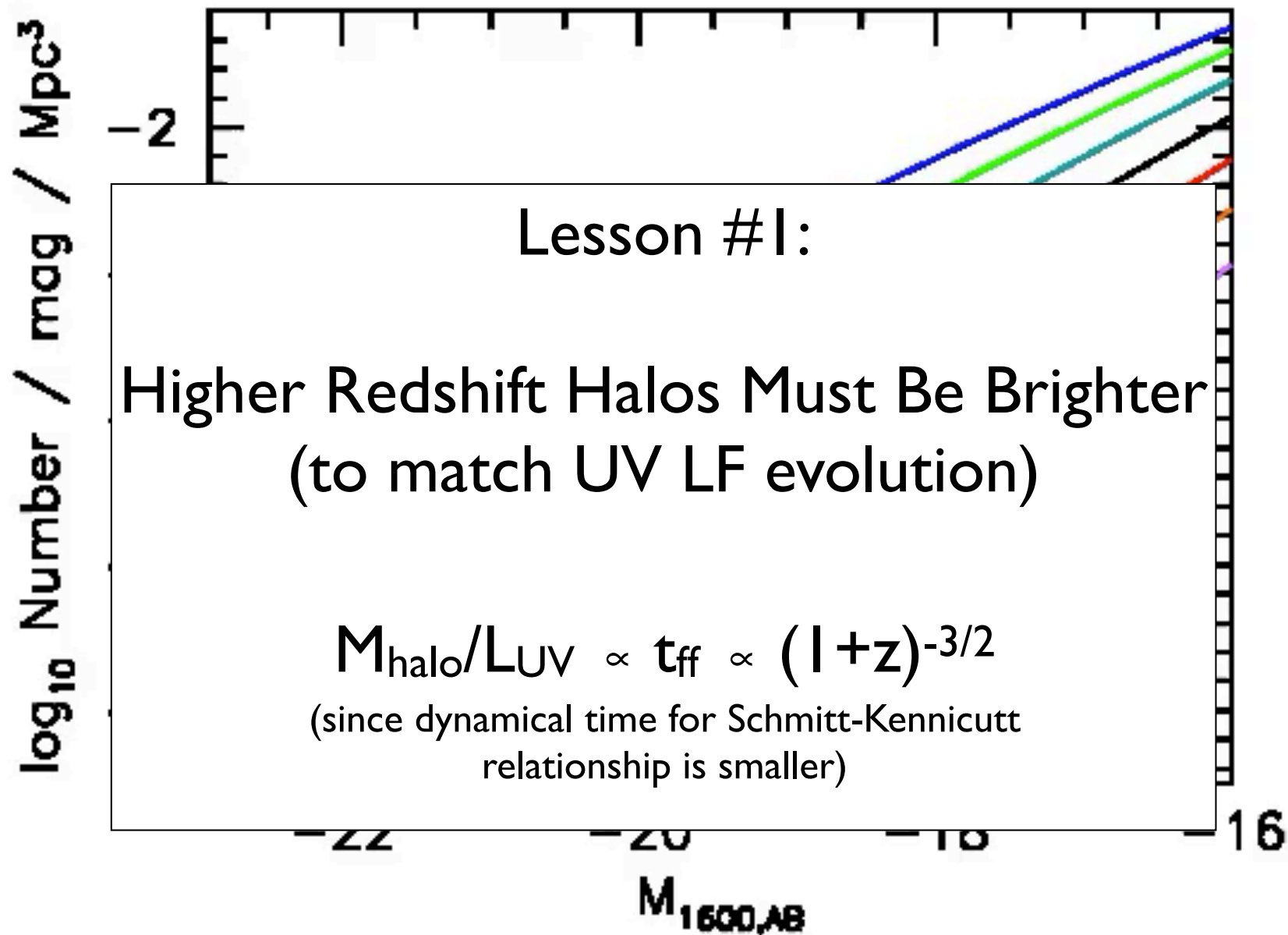
Halo Mass Functions (expressed as UV LFs)



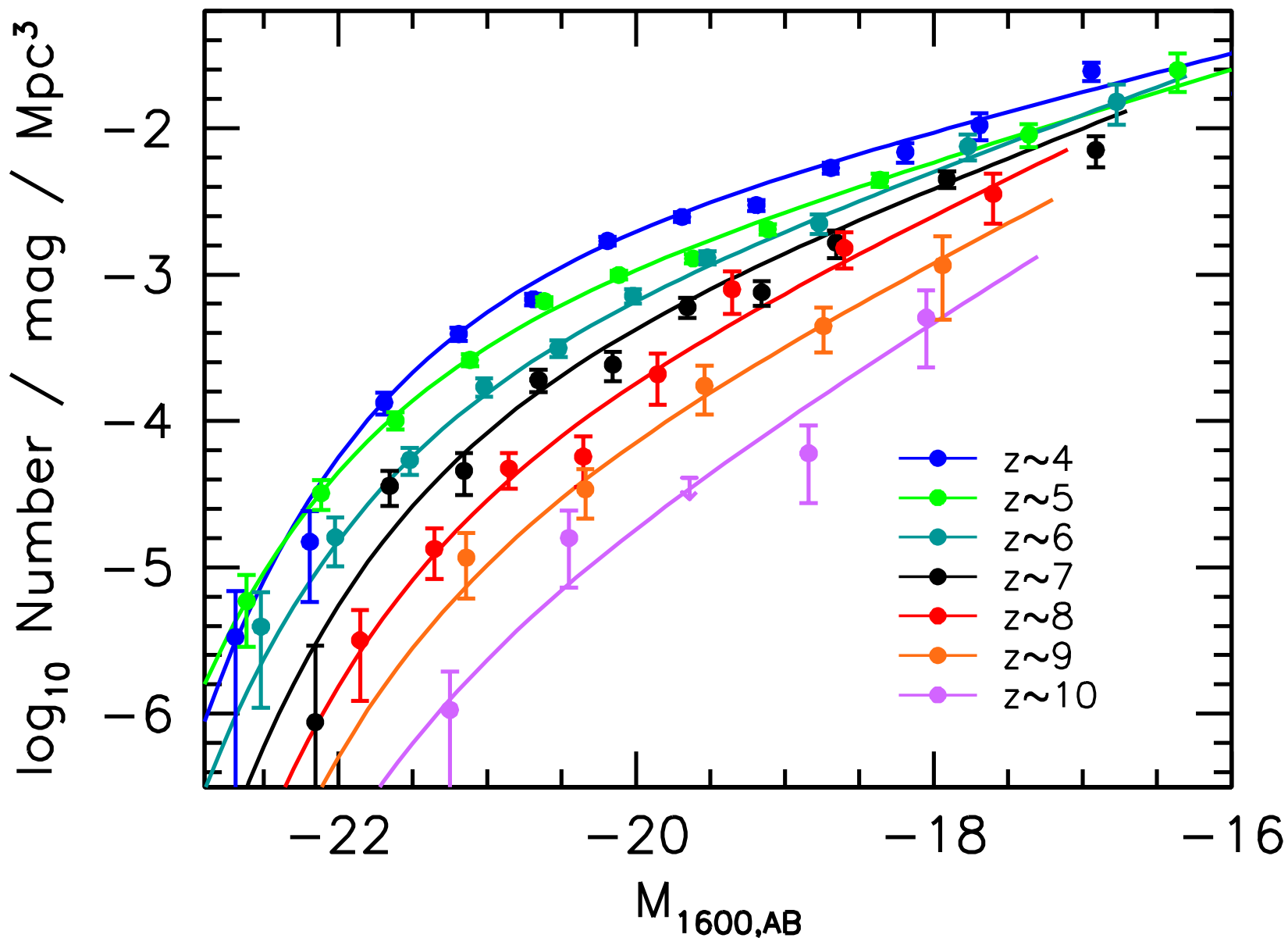
UV Luminosity Functions (to be matched)



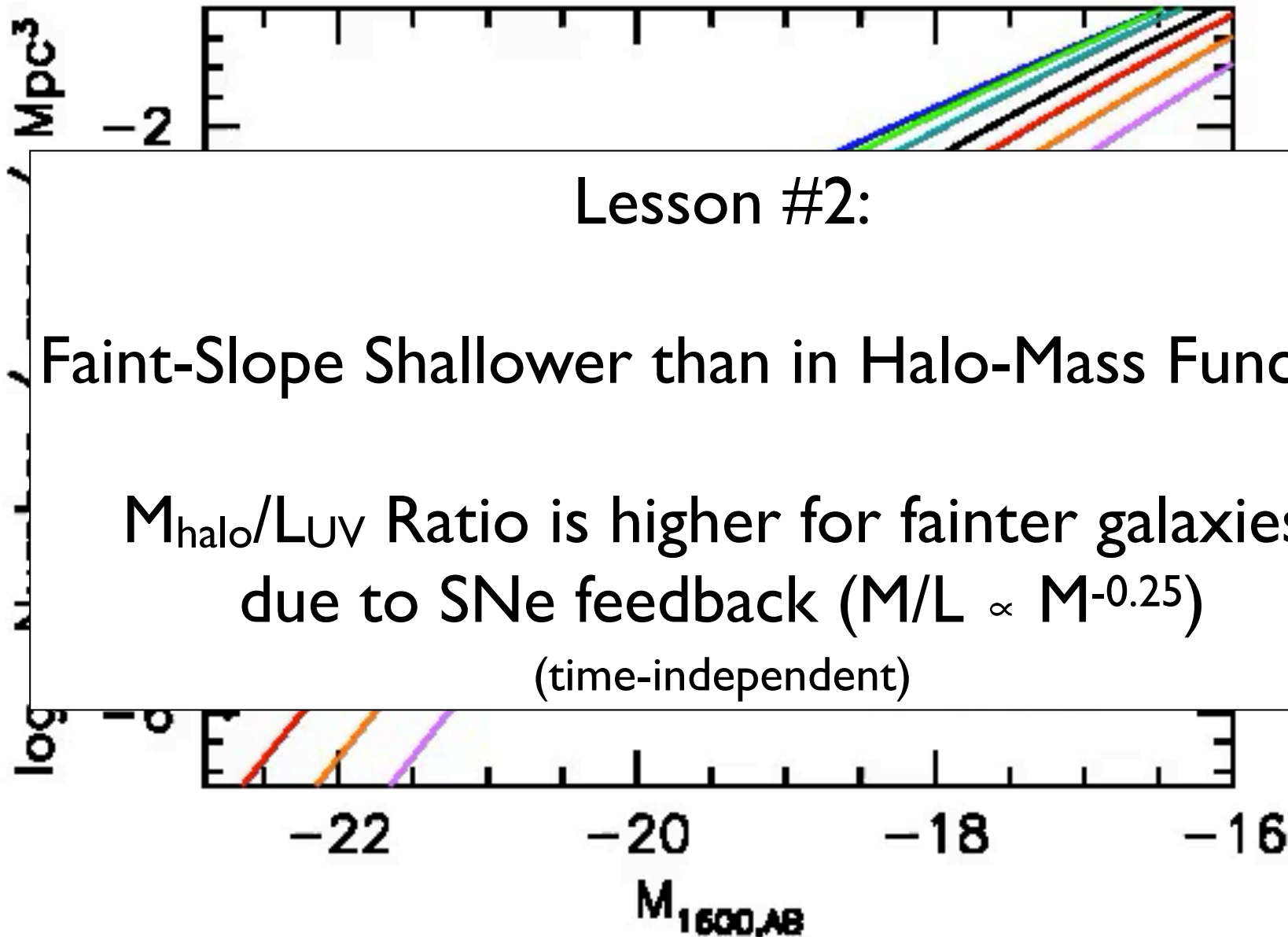
Model z=4-10 UV Luminosity Functions



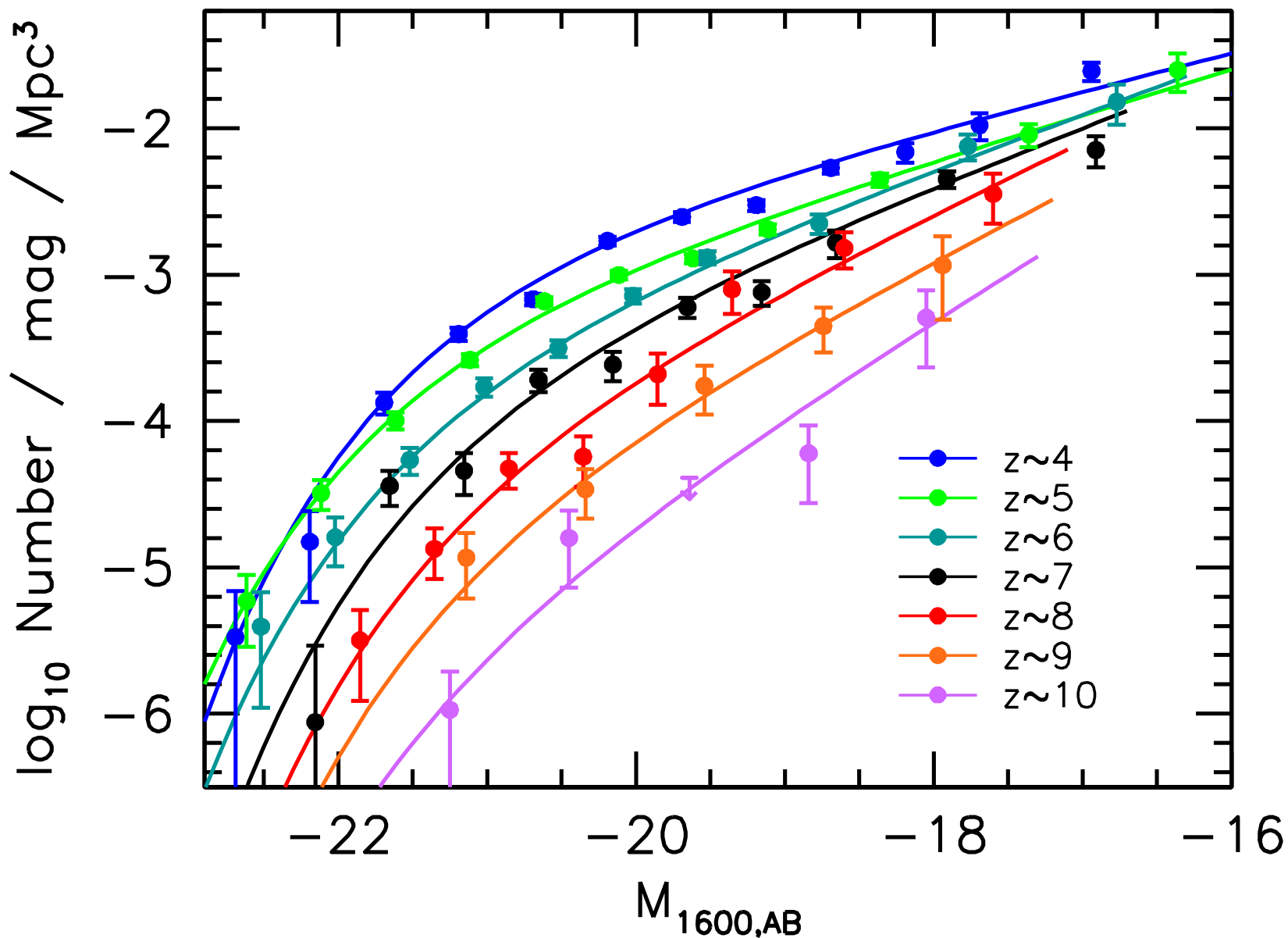
UV Luminosity Functions (to be matched)



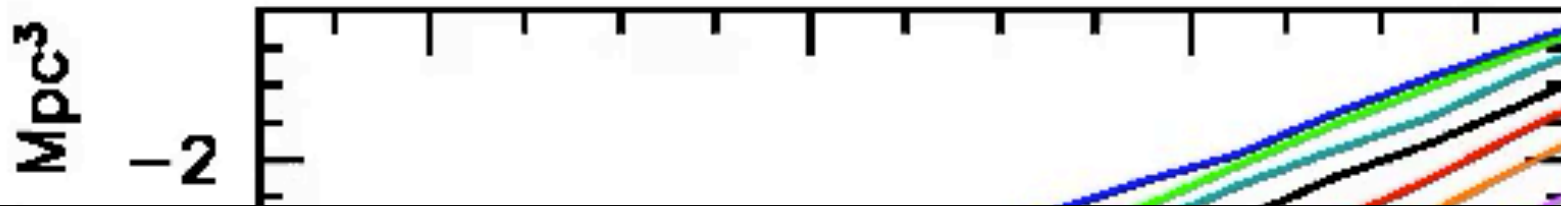
Model z=4-10 UV Luminosity Functions



UV Luminosity Functions (to be matched)



Model z=4-10 UV Luminosity Functions



Lesson #3:

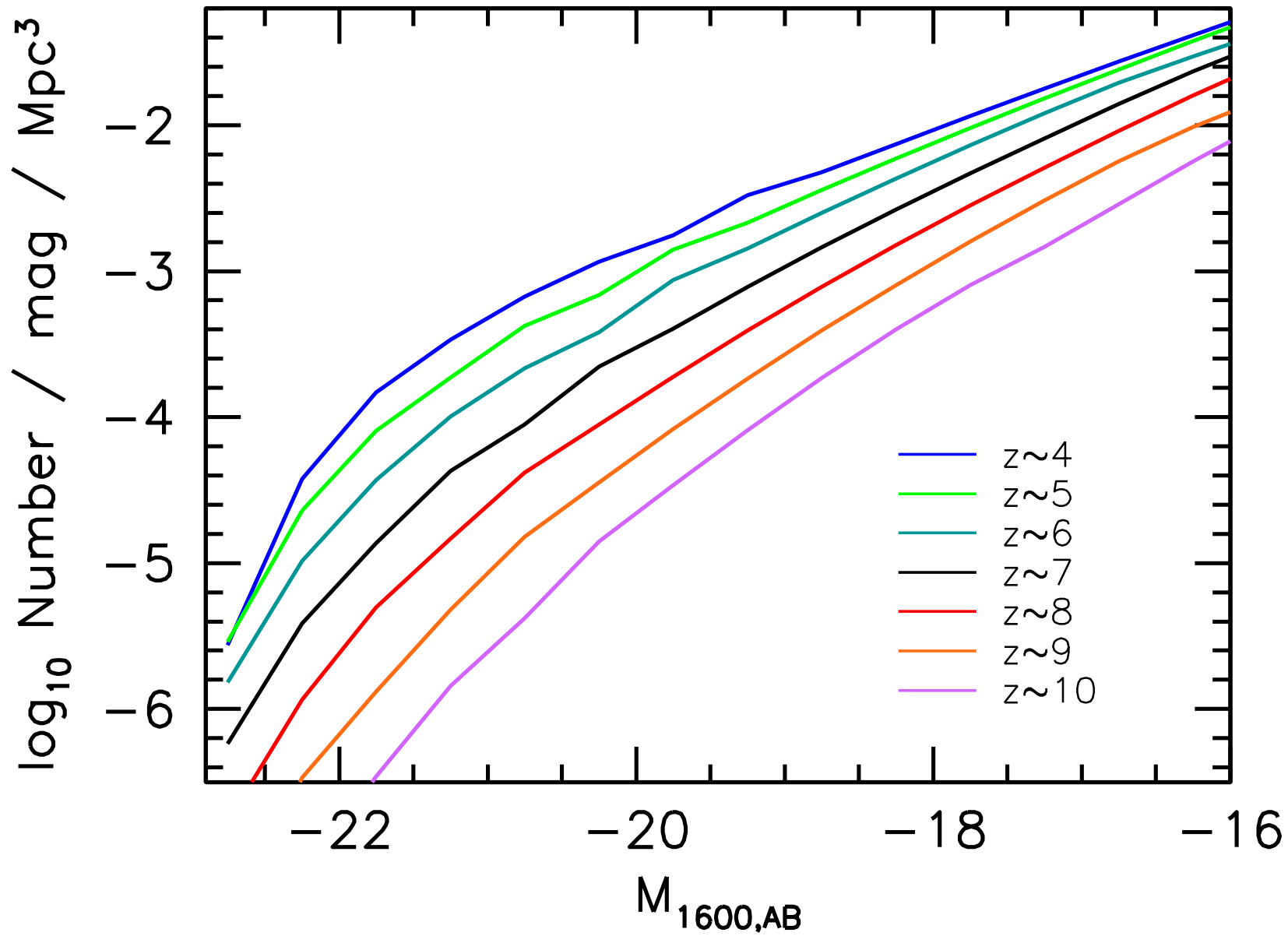
Need to Introduce a Cut-off at the Bright End of the Luminosity Function

Physical Cause: Quenching / Dust Extinction

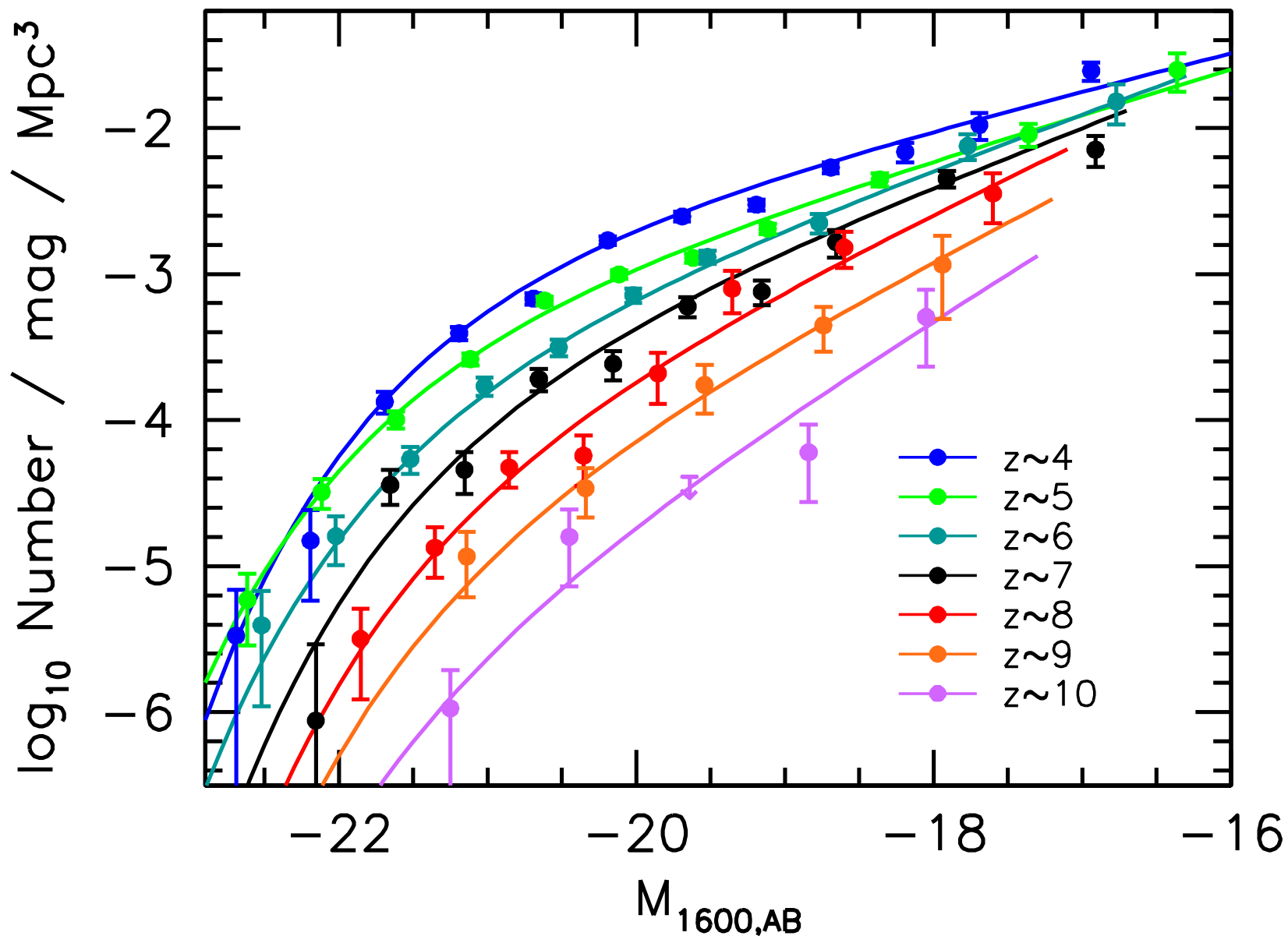
Cut-off Introduced at Fixed Halo Mass
(time-independent)

$M_{1600,AB}$

Model z=4-10 UV Luminosity Functions



UV Luminosity Functions (to be matched)



RJB et al. 2015, in prep; Oesch+2015, in prep

Required Physics

Independent of Halo Mass

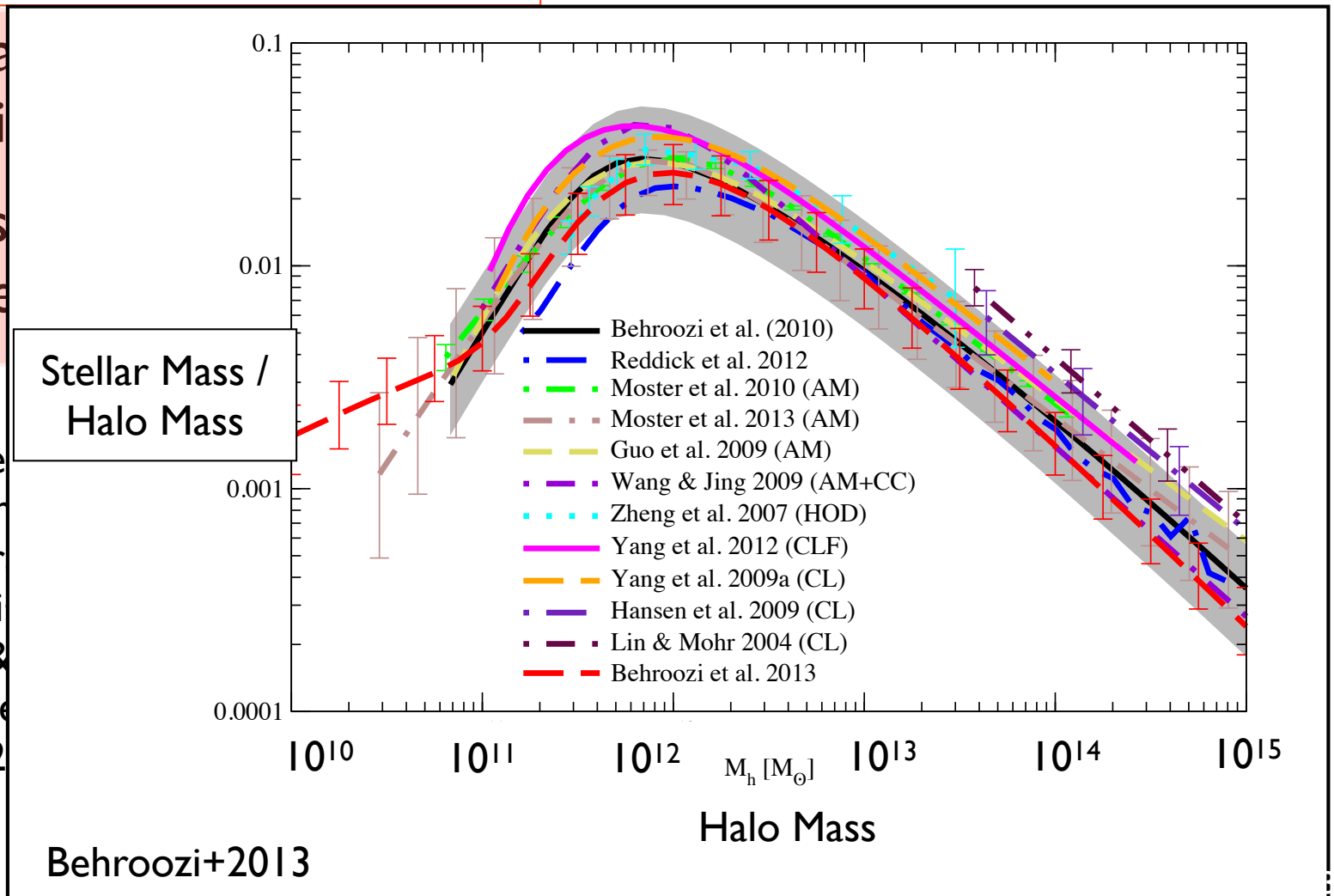
Lesson #1: Higher Redshift Halos Must Be Brighter
(Star Formation More Efficient)

Independent of Redshift / Cosmic Time

Lesson #2: Fa
 $M_{\text{halo}}/L_{\text{UV}}$ hi

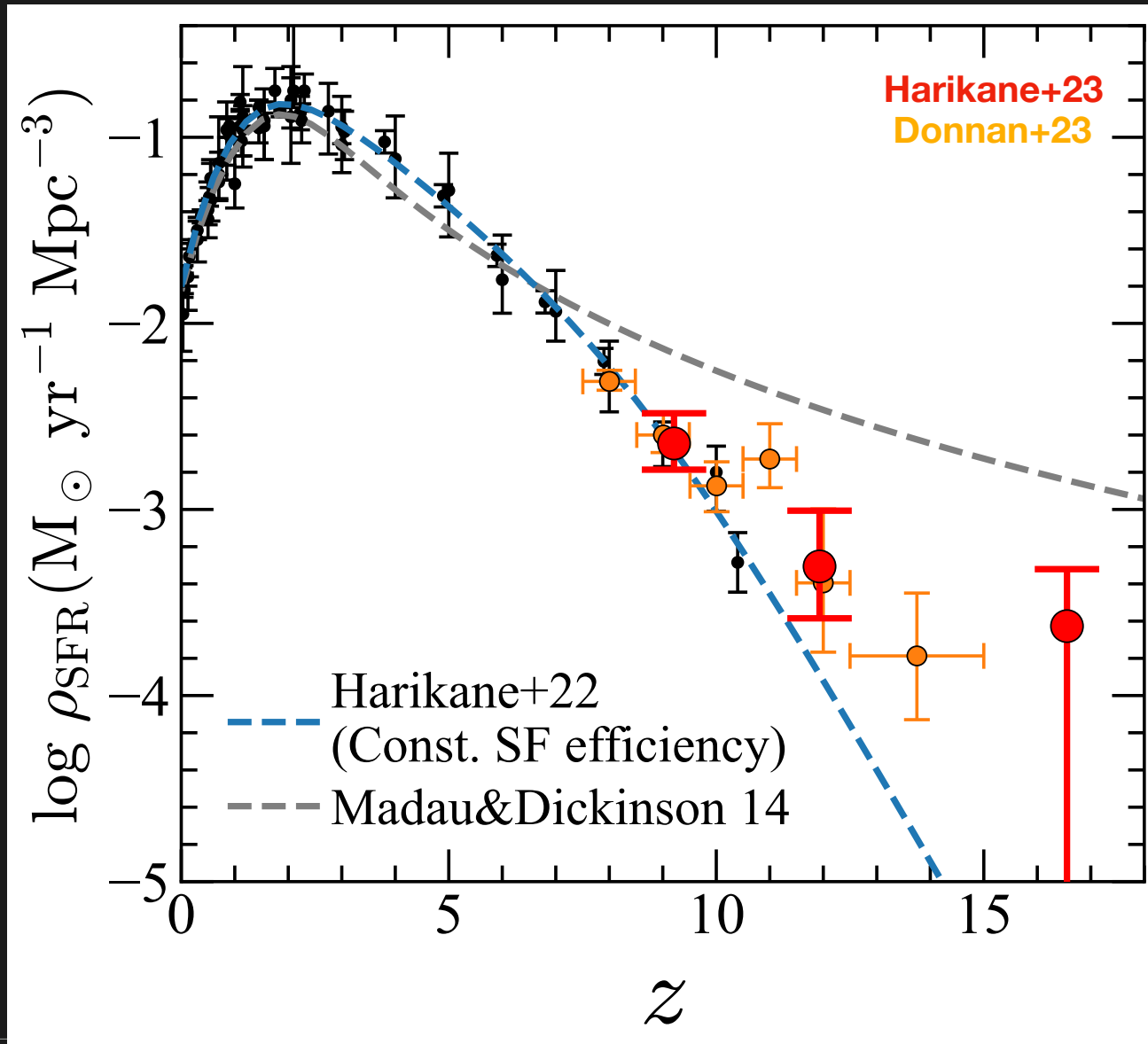
Lesson #3: Mus
Function above

These Physics Impleme
Simple Analytical Th
Models: e.g., Coor
RJB+2008, Trenti
Mashian+2015, Trac &
Mason+2015, Tacche
Cai+2014, Stark+2



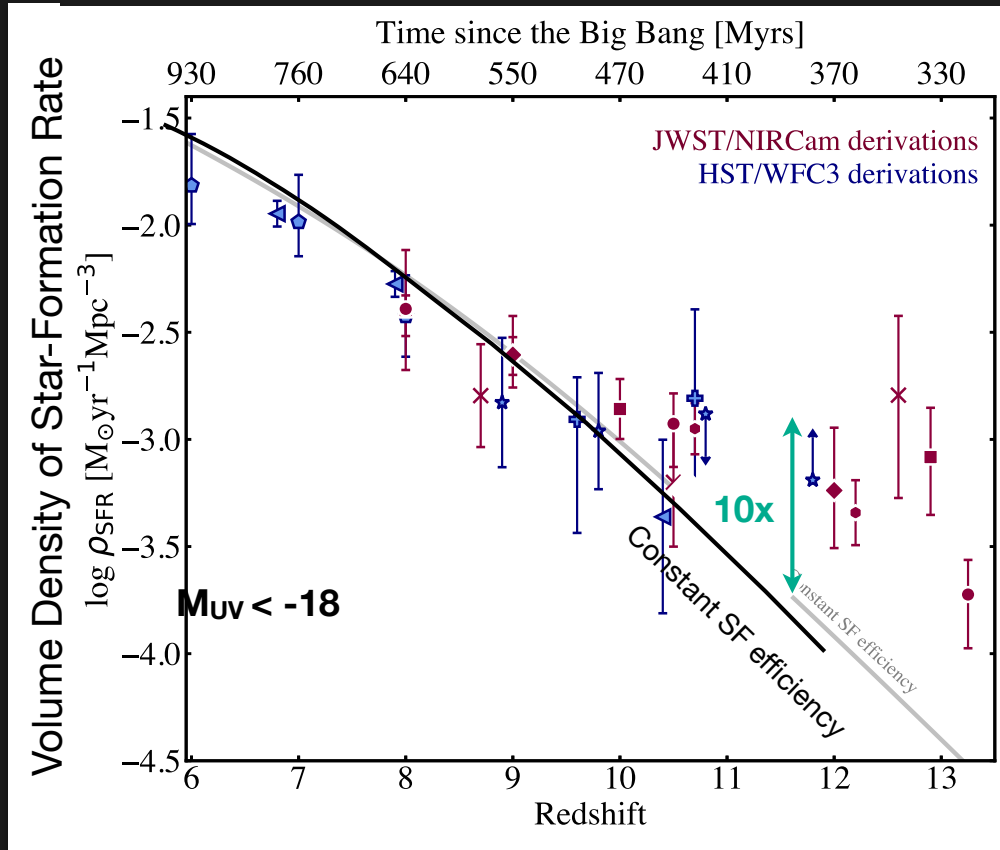
Do such models appear to explain the new galaxies found by JWST at the earliest times?

Significant Excess of UV Luminous Galaxies at $z > 9$ (relative to constant efficiency models)

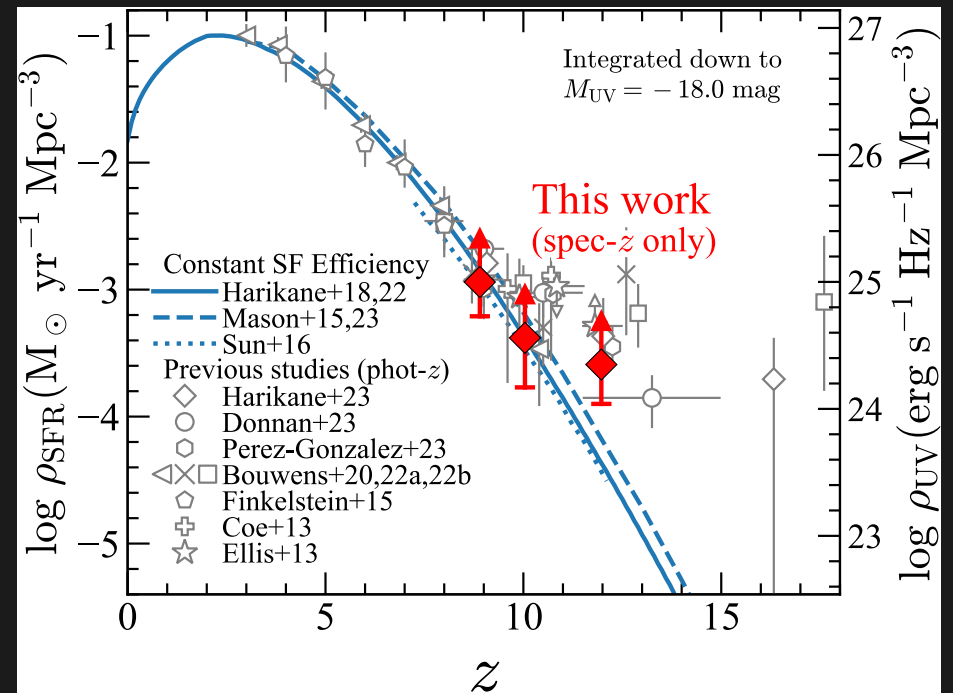


Significant Excess of UV Luminous Galaxies at $z > 9$ (relative to constant efficiency models)

Photo-z Results



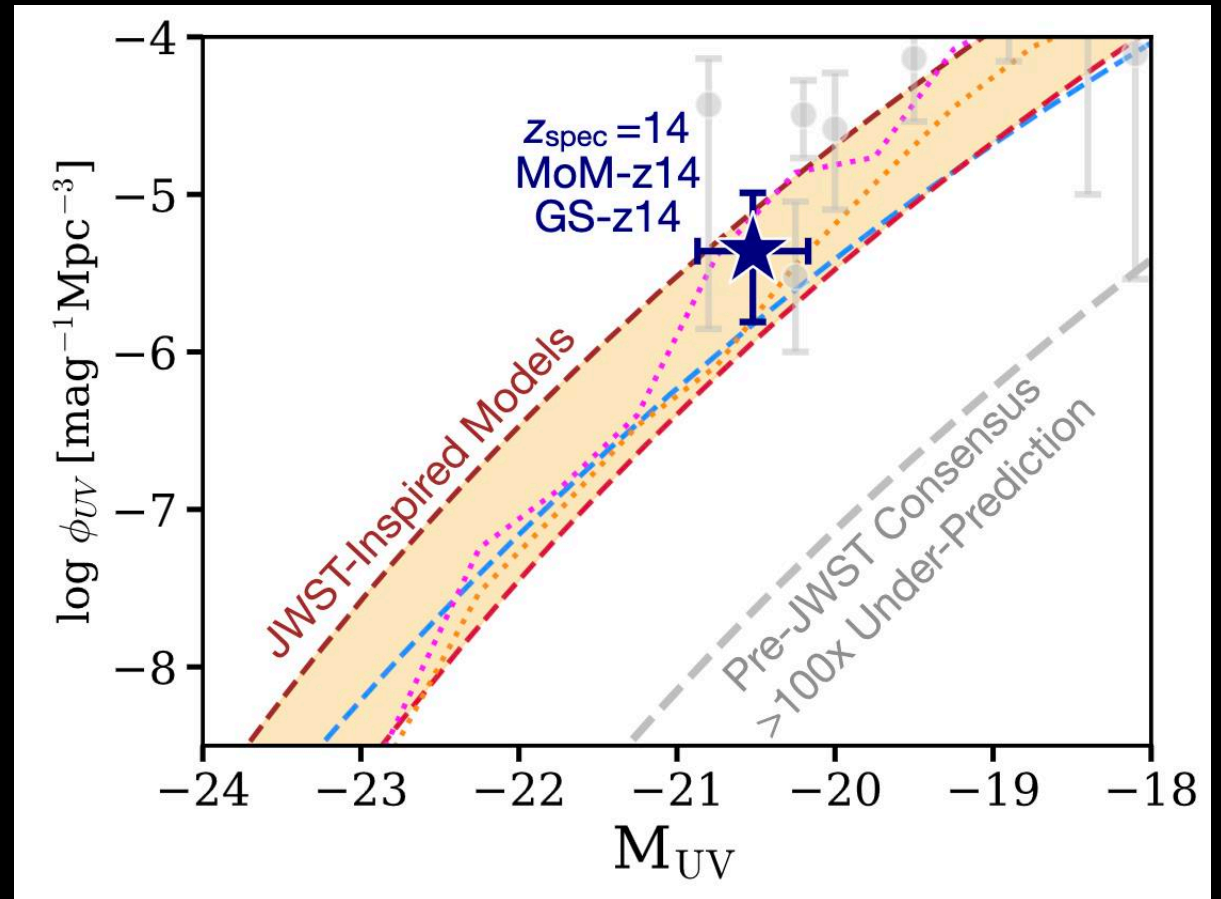
Only Based on Spec-z Redshifts



$M_{\text{UV}} - M_{\text{halo}}$ relation must change at $z > 10$,
and it must evolve significantly with
redshift

The stunning abundance of UV-bright galaxies

- 10-100x more bright galaxies versus (literature-averaged) pre-launch predictions seen in photometric datasets.
- Initial results borne out by ~4 years of imaging e.g., talks by Andrea Weibel & Christian Kragh Jespersen tomorrow
- Now spectroscopically confirmed out to $z \sim 14-15$



Naidu+26

Spectroscopic luminosity function at $z \sim 14-15$

Three Classes of Possible Solutions

▶ **Increased UV luminosity at given stellar mass**

- ▶ Top-heavy IMF (e.g. Schaerer+24, Inayoshi+22; Trinca+24; Yung+24; Mauerhofer+25)
- ▶ Bursty star-formation (e.g, Mason+23; Shen+23; Sun+23; Yung+24; Gelli+24)
- ▶ Younger ages (Donnan+24)
- ▶ Evolution in dust attenuation (e.g, Ziparo+23; Ferrara+23, 24)
- ▶ Contribution/contamination by active galactic nuclei (e.g, Inayoshi+22; Volonteri+23; Trinca+24)

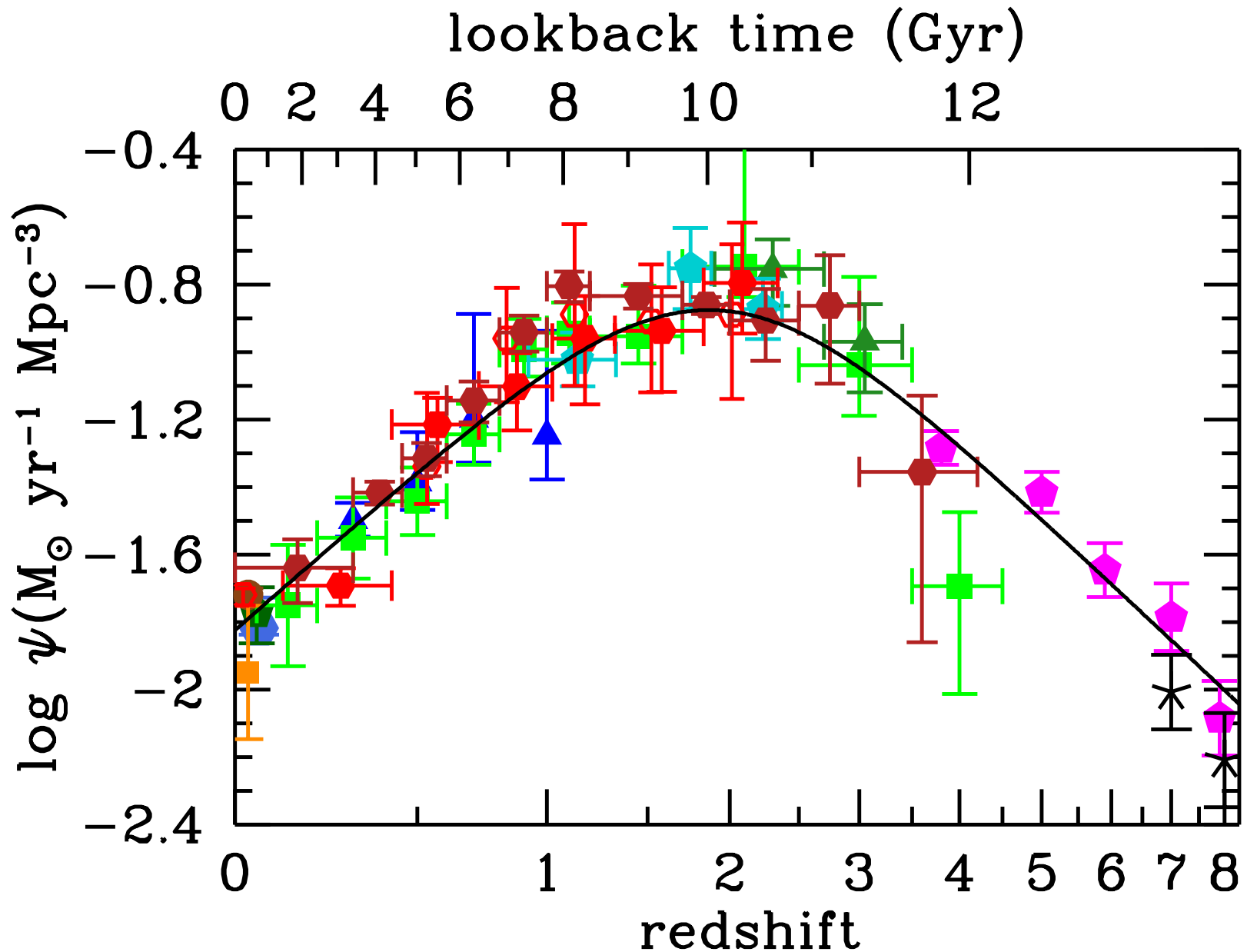
▶ **Increased star-formation efficiency at early times**

- ▶ “Feedback-free” star-bursts due to very short free-fall times (Dekel+23, Li+24)
- ▶ Efficient star-formation due to increased gas densities (e.g. Somerville+25)

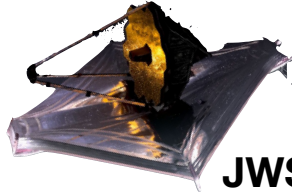
▶ **Change of cosmology?**

- ▶ e.g., early/evolving Dark Energy (Menci+22,24), extra small scale power to the primordial power spectrum (Hirano & Yoshida 2024), primordial black holes (Liu & Bromm 2022; Colazo+24) or cosmic strings (Koehler+24) or ...

When does universe form most of its stars?



Our Multi-Wavelength Census of Early Galaxies



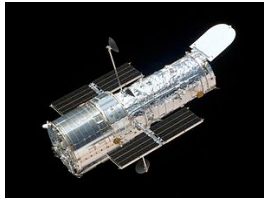
JWST:

rest-frame UV+optical
SFRs, stellar masses,
metallicity, ionized gas



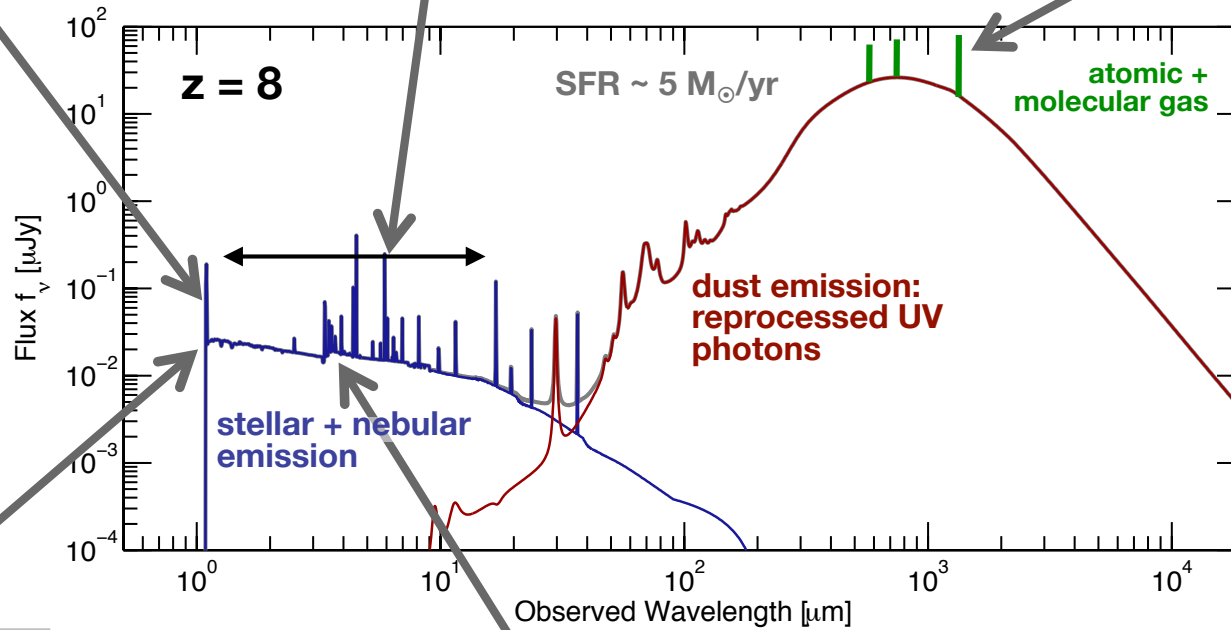
ALMA/NOEMA:

cold gas
dust re-emission
closes energy balance



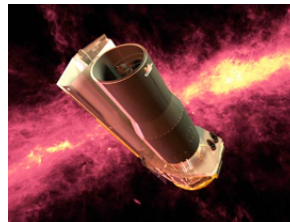
HST:

rest-frame UV
un-obscured SFR



NIR Spectra:

rest-frame UV lines

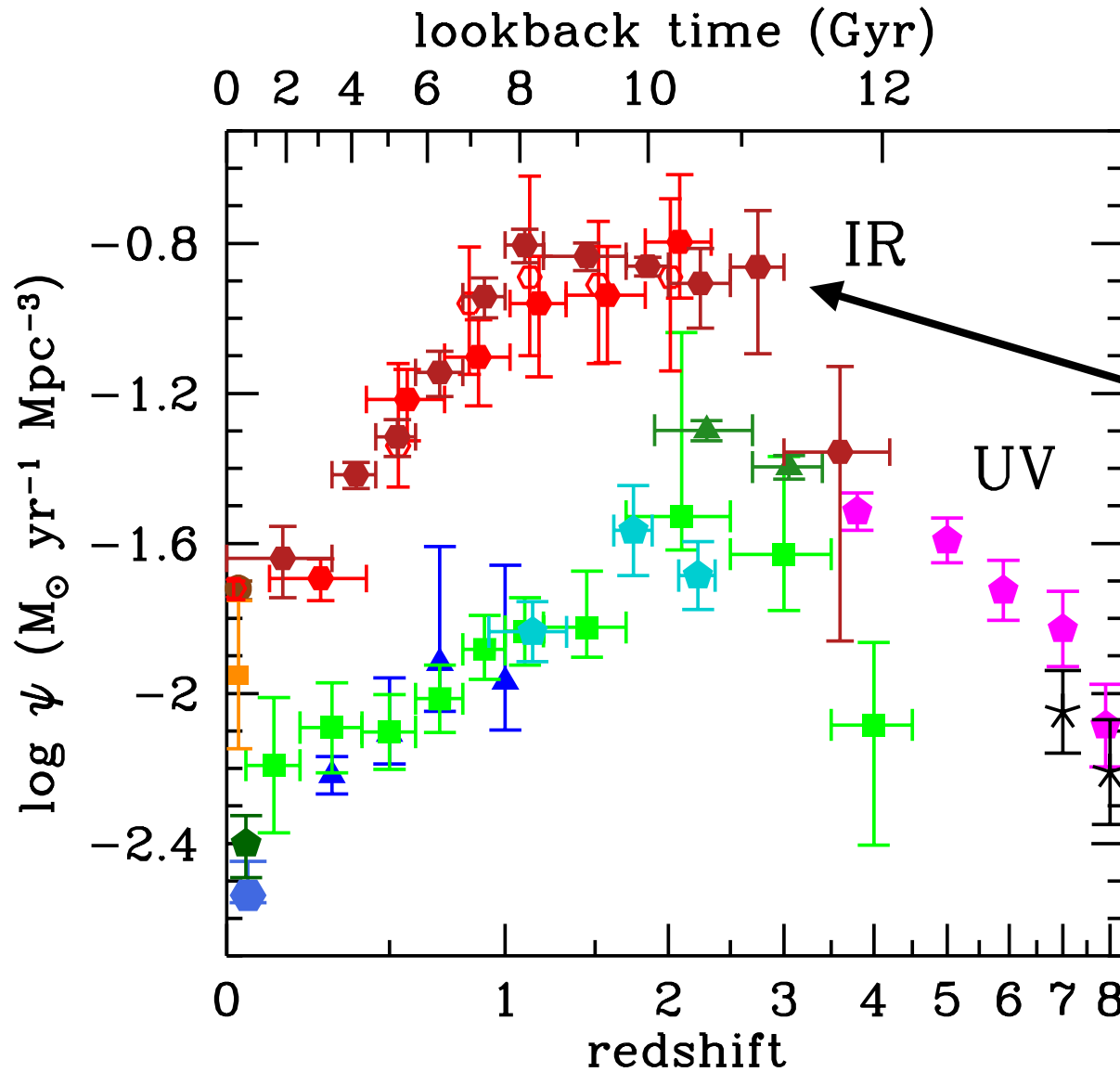


Spitzer:

rest-frame optical imaging
stellar masses
rest-frame optical emission lines

Credit for Illustration: Pascal Oesch

What fraction of SFR is obscured + unobscured?



Most of the energy from hot young stars at $z < 4$ comes out in far-IR

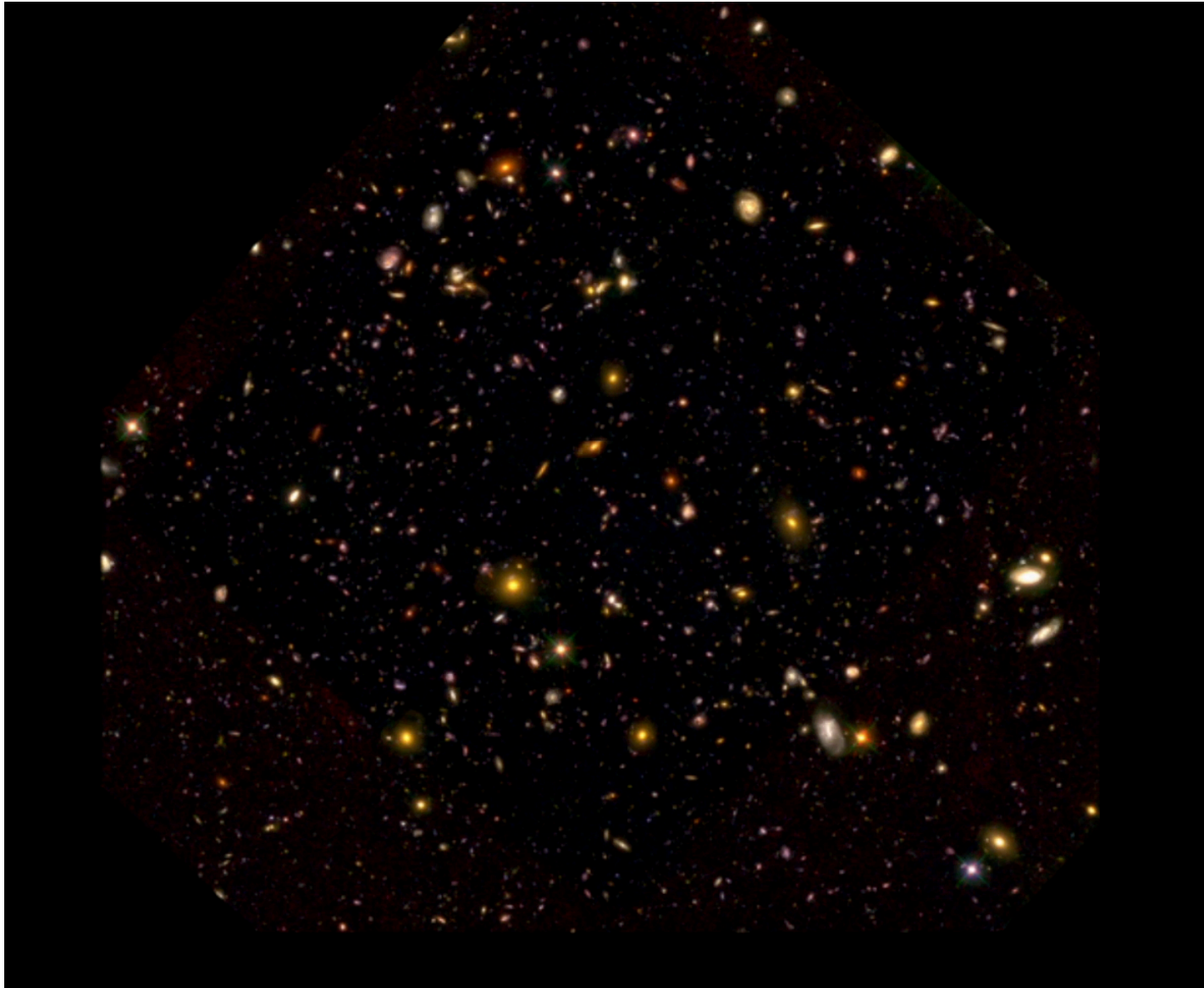
i.e. is dust obscured

Let's look at the Universe with ALMA



*Dust continuum
measurements
(SFR obscured by dust)
~1.3 billion euro facility
~50 12-m antennas
~0.4 - 3 mm observations*

How does the Hubble Ultra Deep Field Look?



Initial Image from
HST

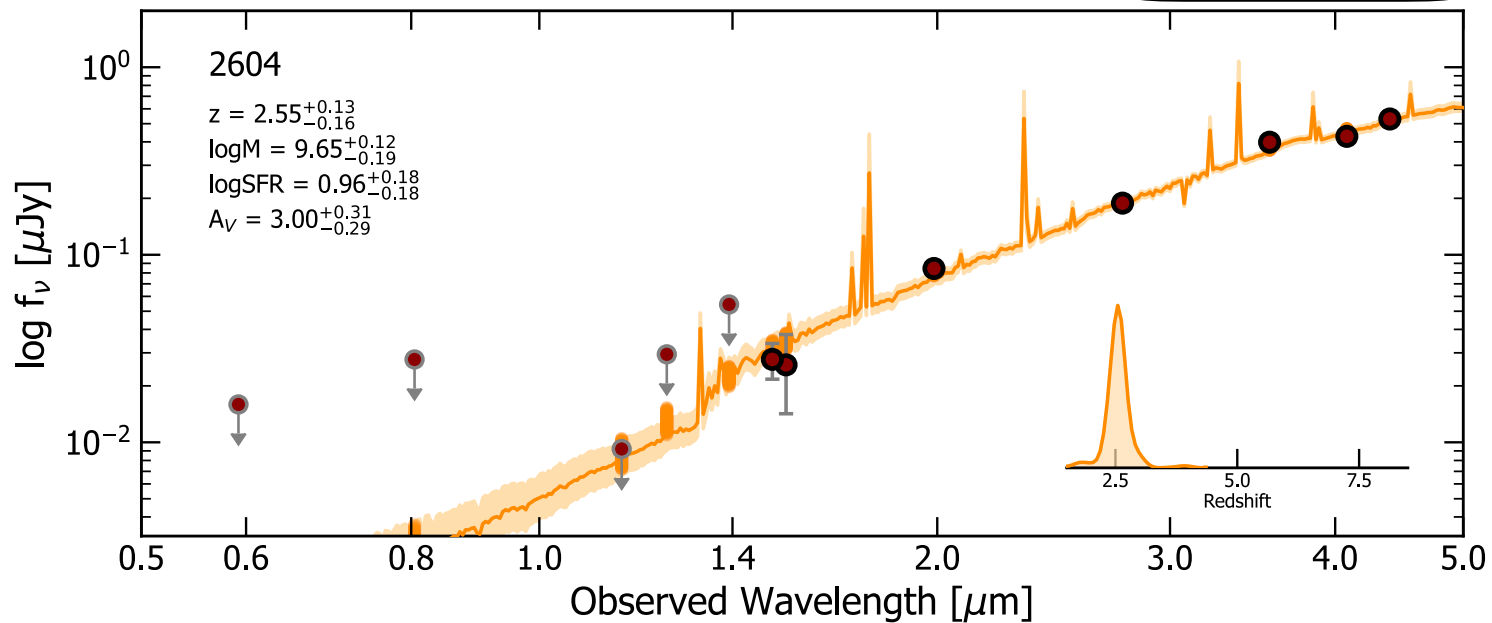
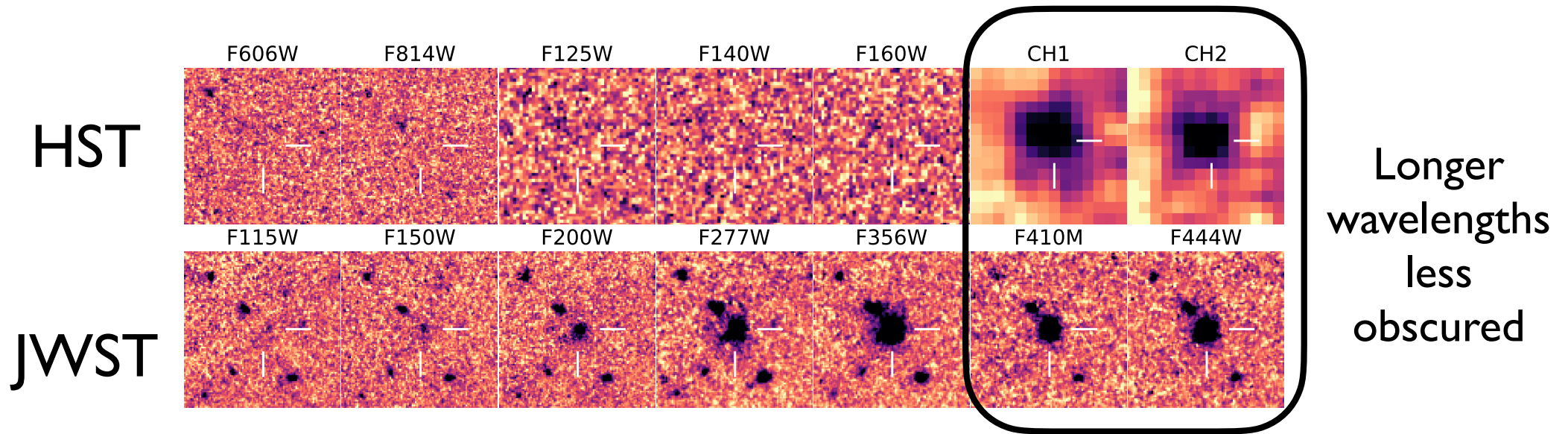
(In rest-UV/
optical/
near-IR)

Later Image from
ALMA

(In far-IR)

Credit: ASPECS team

Loads of Obscured Galaxies are Found



Which galaxies would we expect to contain the most dust?

i.e. those with the most metals (i.e., the mass ones):

From lecture 11:

Relationship between the Gas-Phase Metallicity in a Galaxy and Its Mass

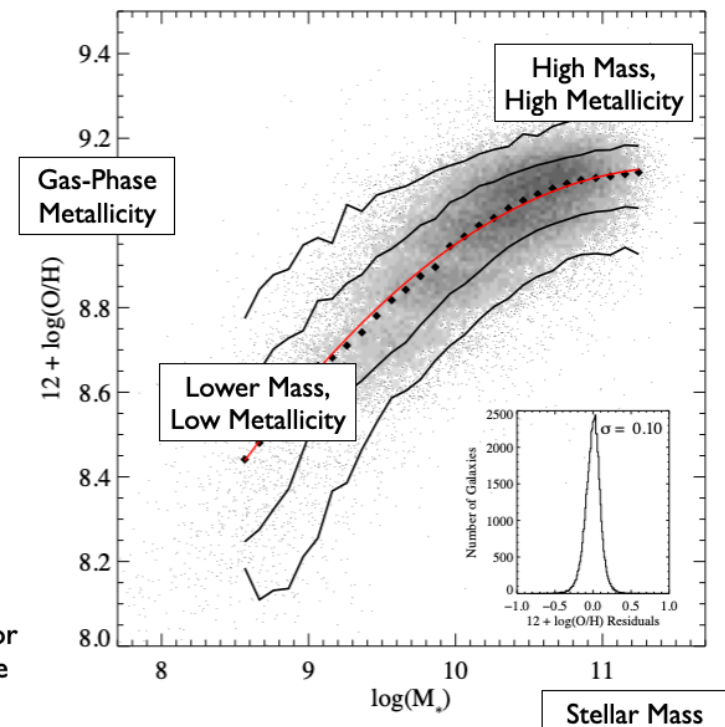
Two primary explanations for this:

1) Low Mass Galaxies Form Stars Less Efficiently

As such, only a small percentage of the gas turns into SNe (which adds more metals to the mix)

2) Metals can escape more easily from low-mass galaxies due to SNe winds

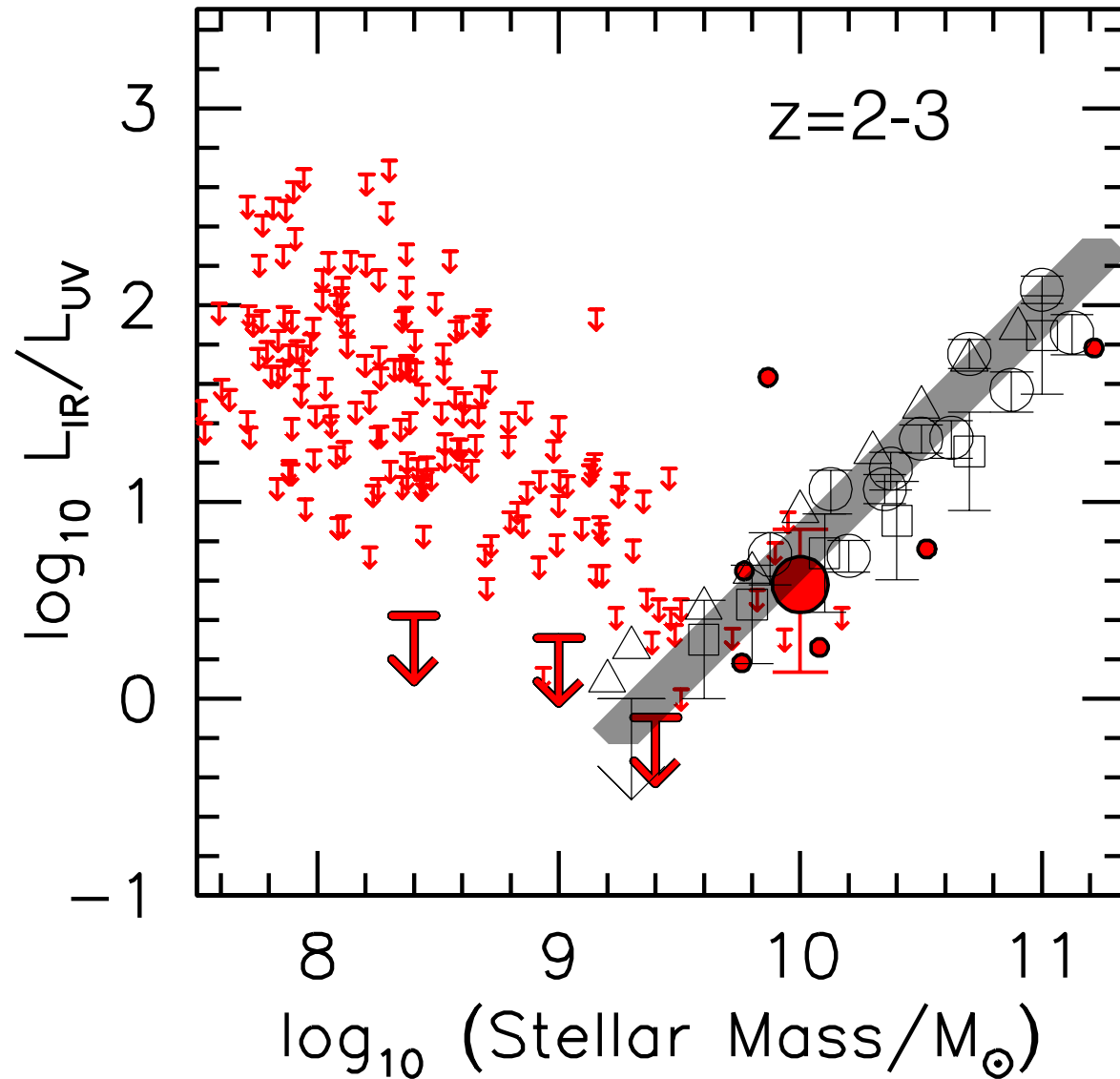
The escape velocity for lower mass galaxies is lower and hence it is easier for metals to escape from such galaxies due to SNe winds



Tremonti+2004

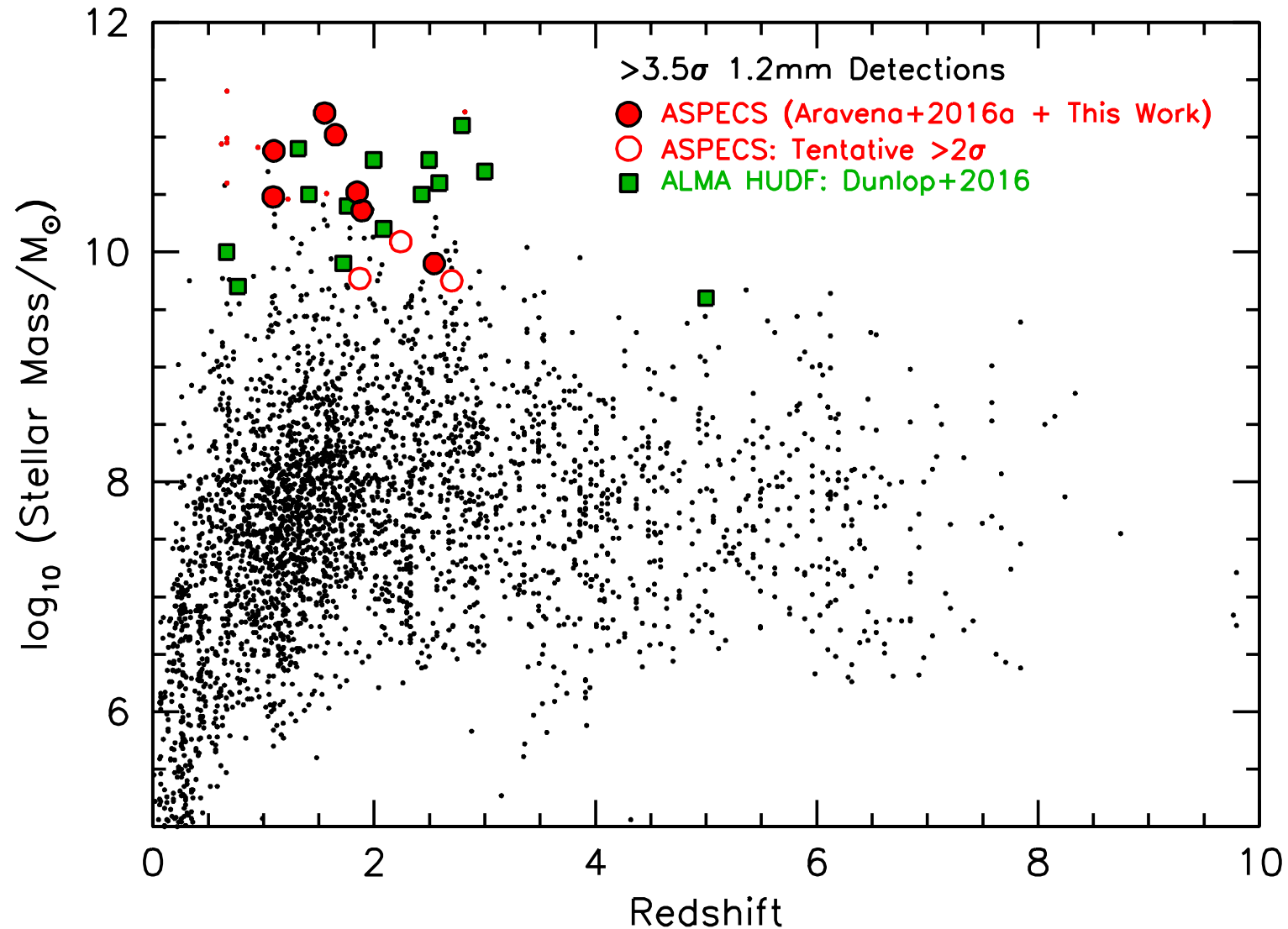
ALMA UDF

Ratio of Obscured SFR to UV SFR vs. Stellar Mass



ALMA UDF

Only the highest-mass sources are individually detected!

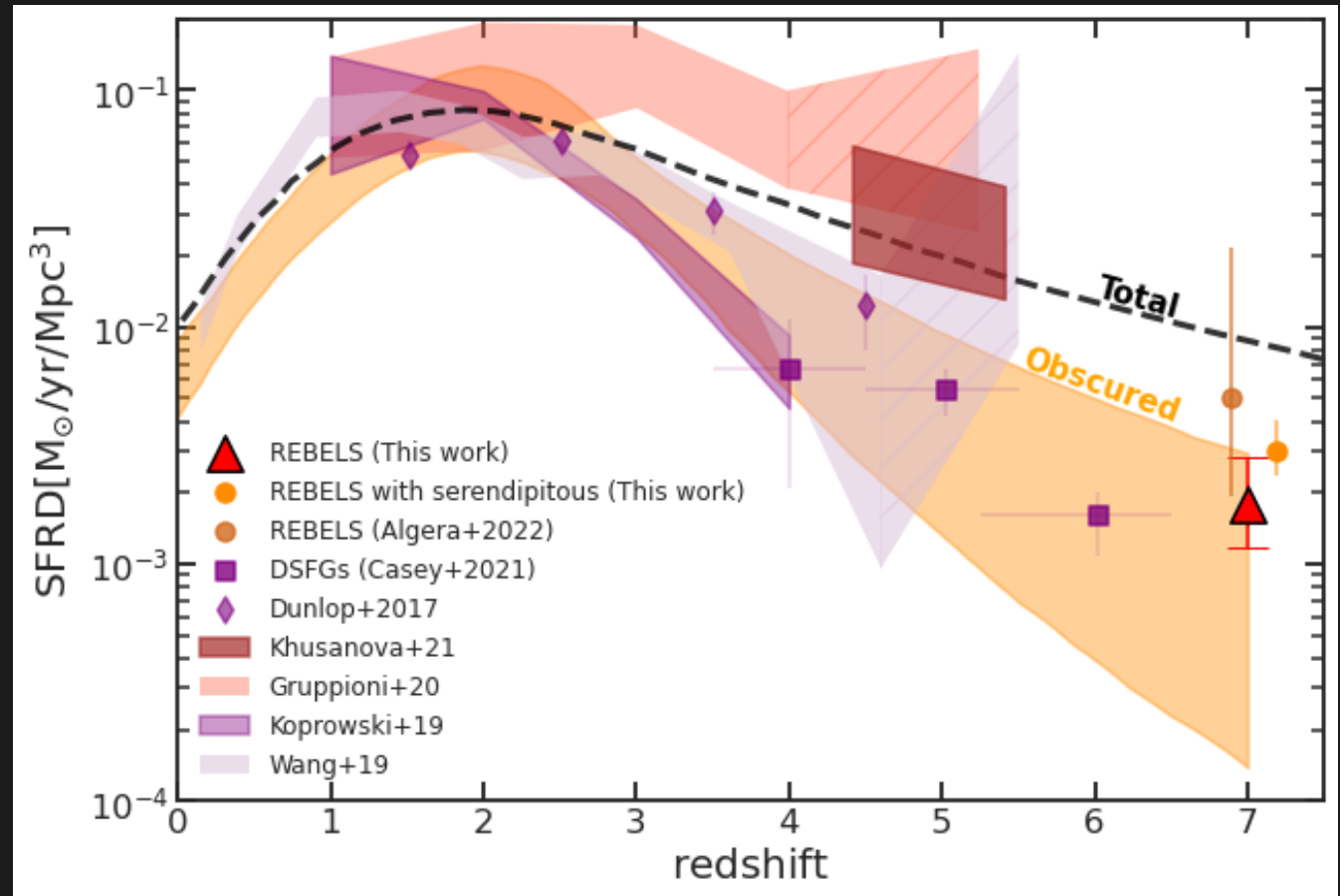


Contribution of Dusty Galaxies to Star Formation Rate Density

Given the abundance of massive galaxies at $z \sim 3-5$ — galaxies must have grown very fast at early times.

Implies there are many sources in $z > 6$ universe with high SFRs and potentially high obscuration fractions.

There has thus been loads of interest in measure the star formation rate density at $z > 5$, especially from potentially high mass obscured galaxies.



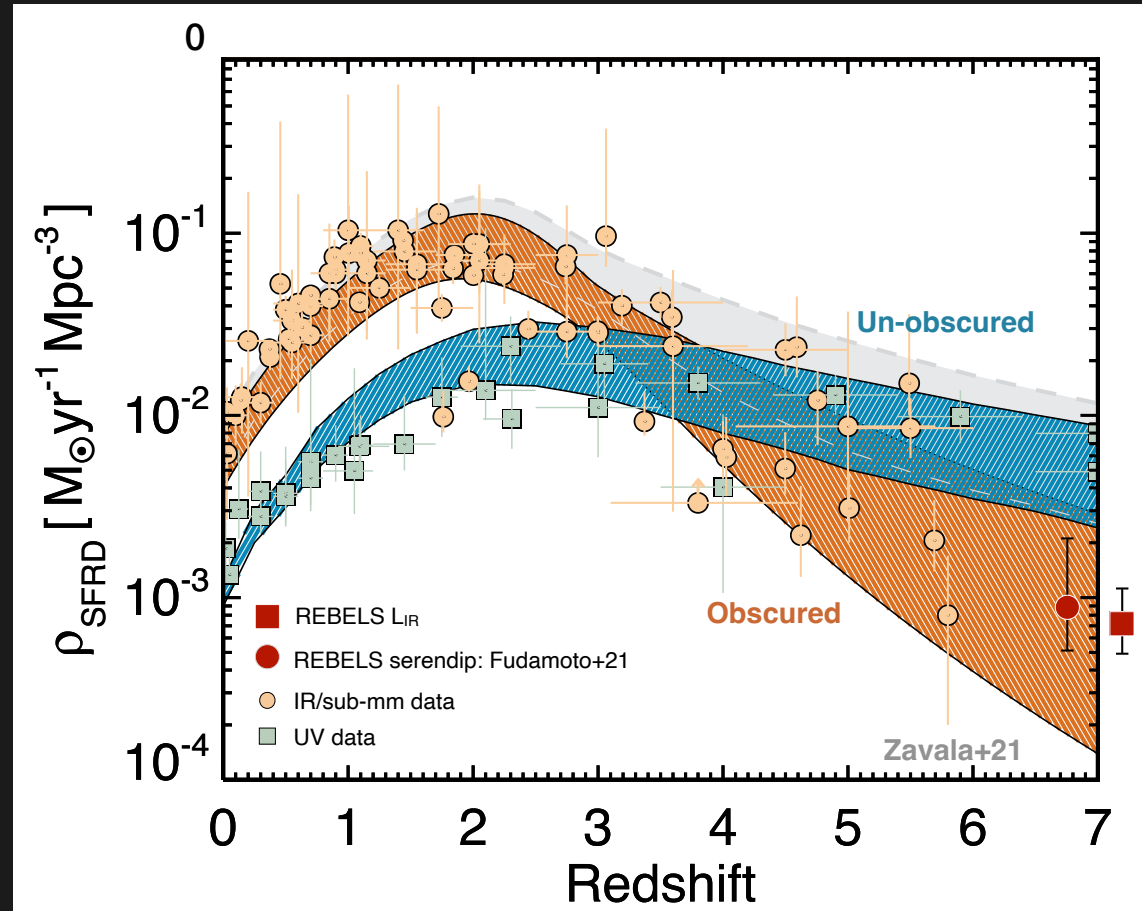
Barrufet+24

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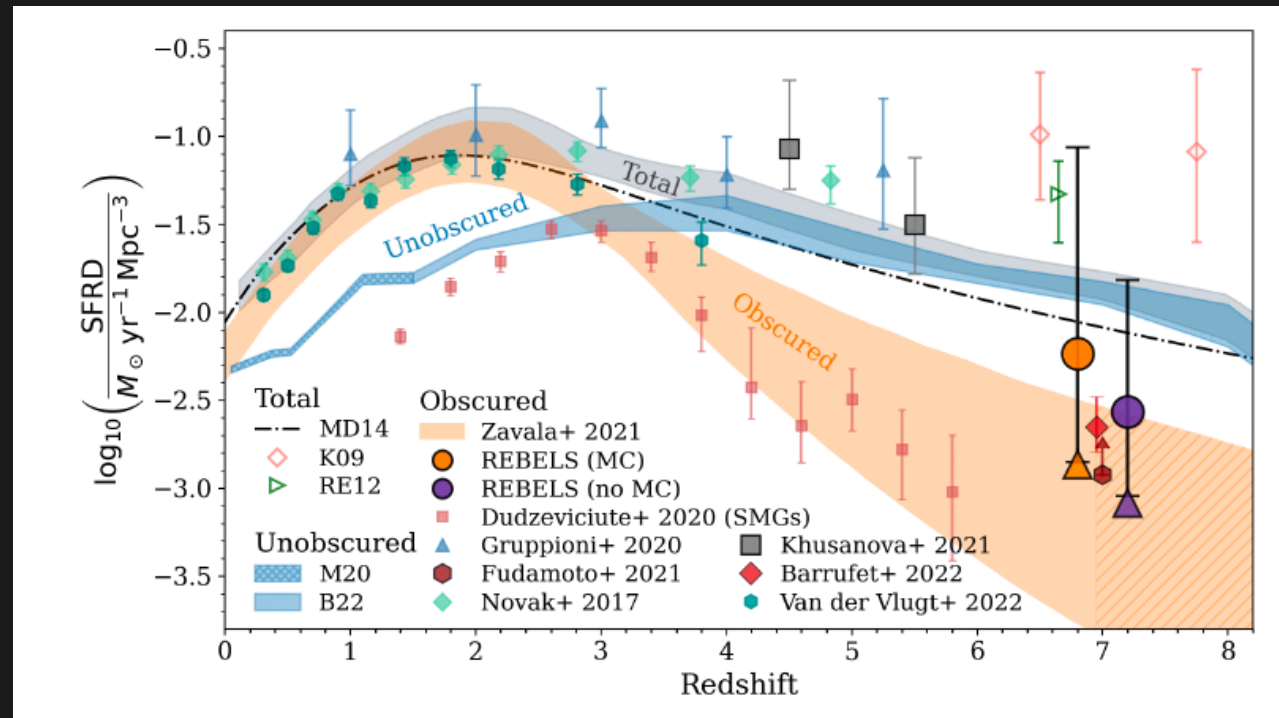
Zavala+21

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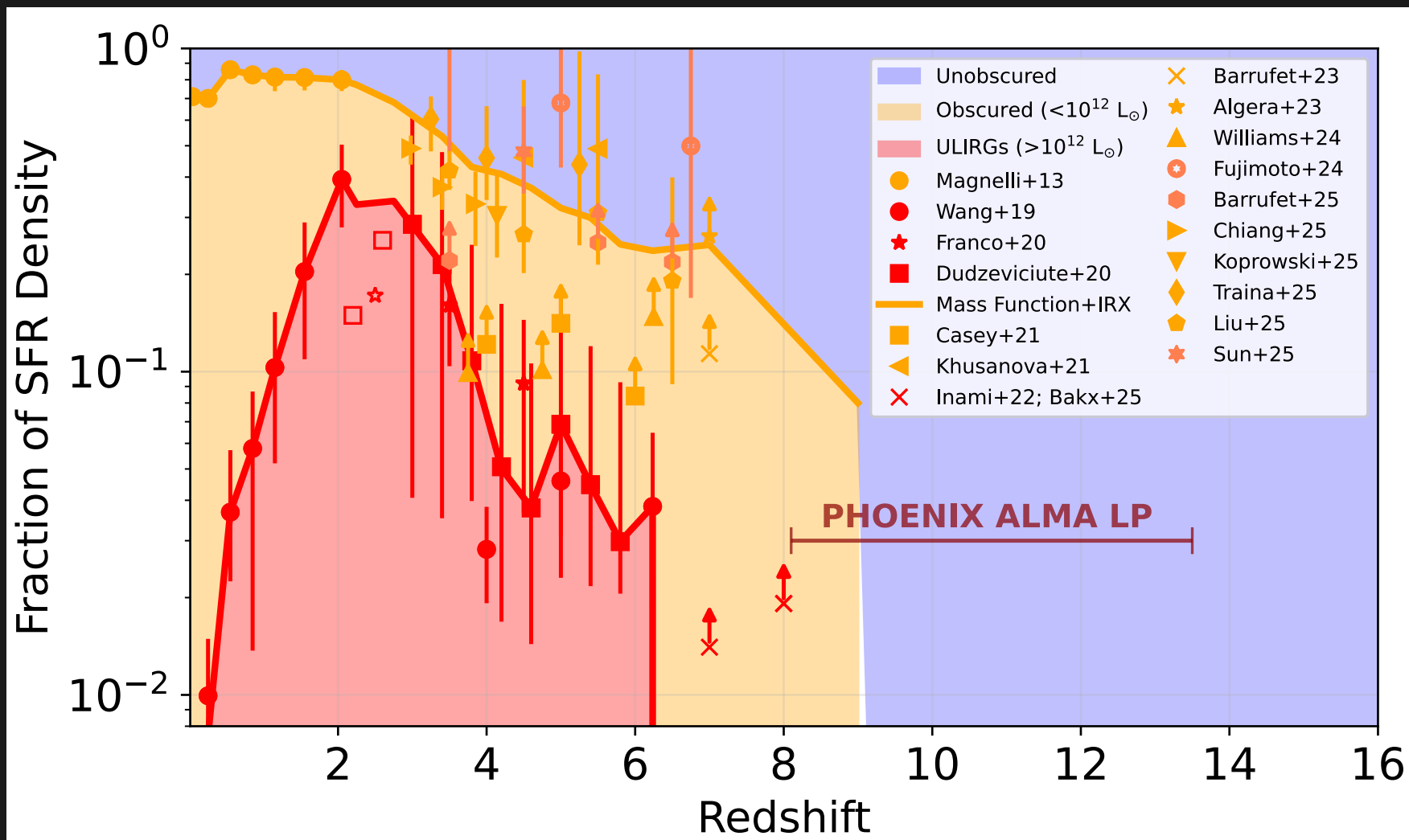
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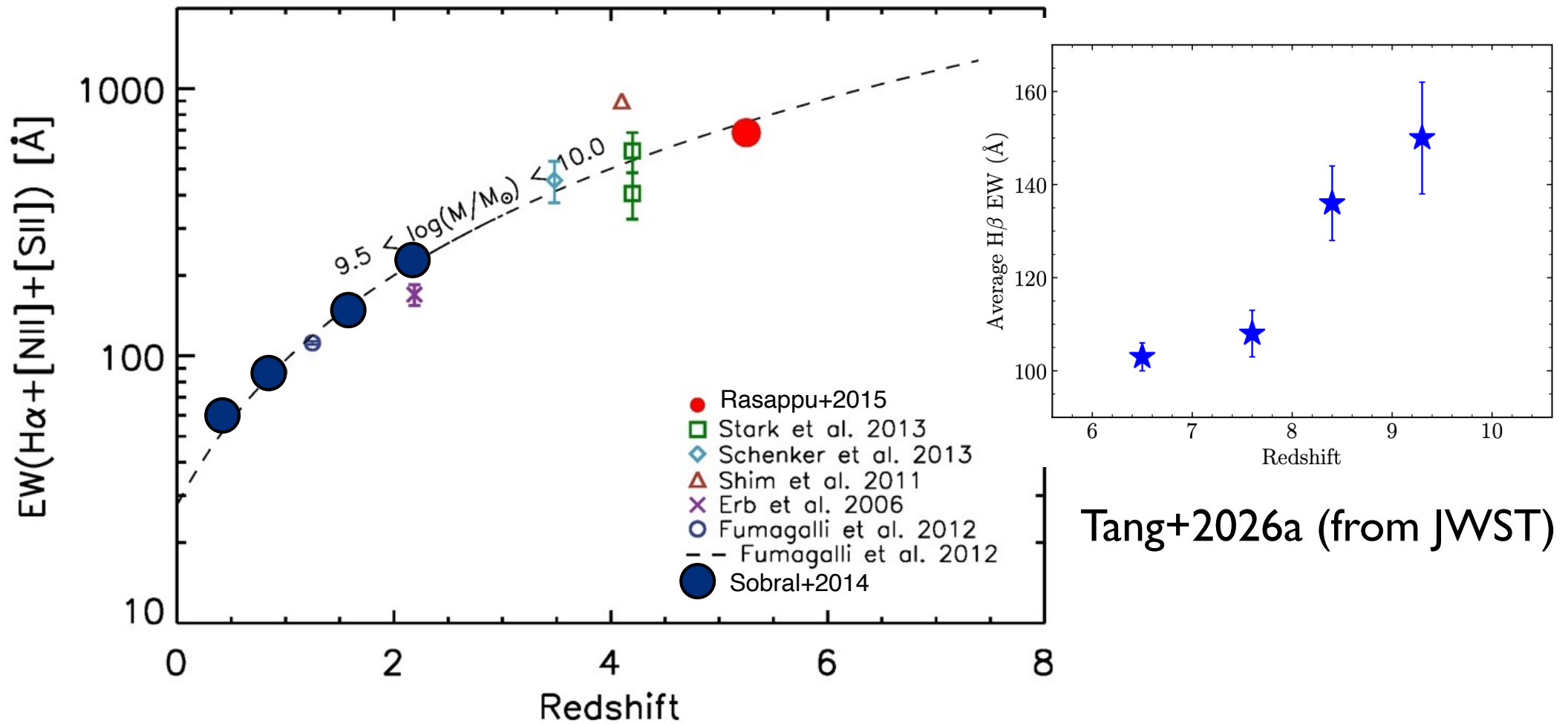
Algera+23

Contribution of Obscured Star Formation to SFR Density



Compilation of
Many Exciting
Independent
Efforts

The rest-frame EW of various nebular emission lines (e.g. H α) increases dramatically towards earlier times

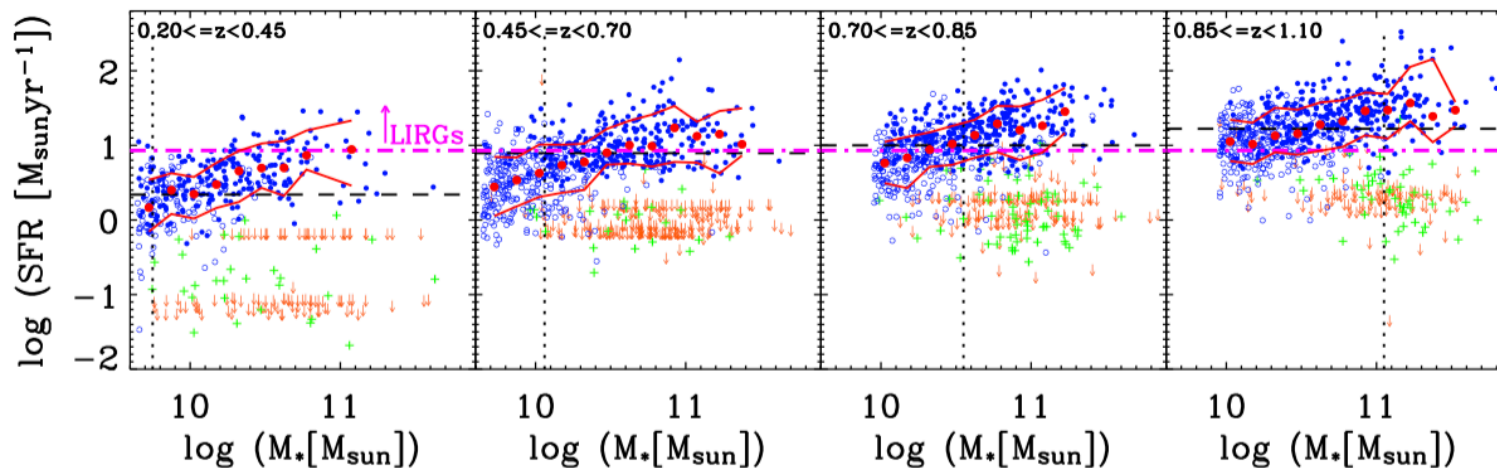


This is due to the evolution of $\text{SFR} / M^* =$ specific star formation rate

Recall from Lecture 12:

What about evolution on the blue sequence?

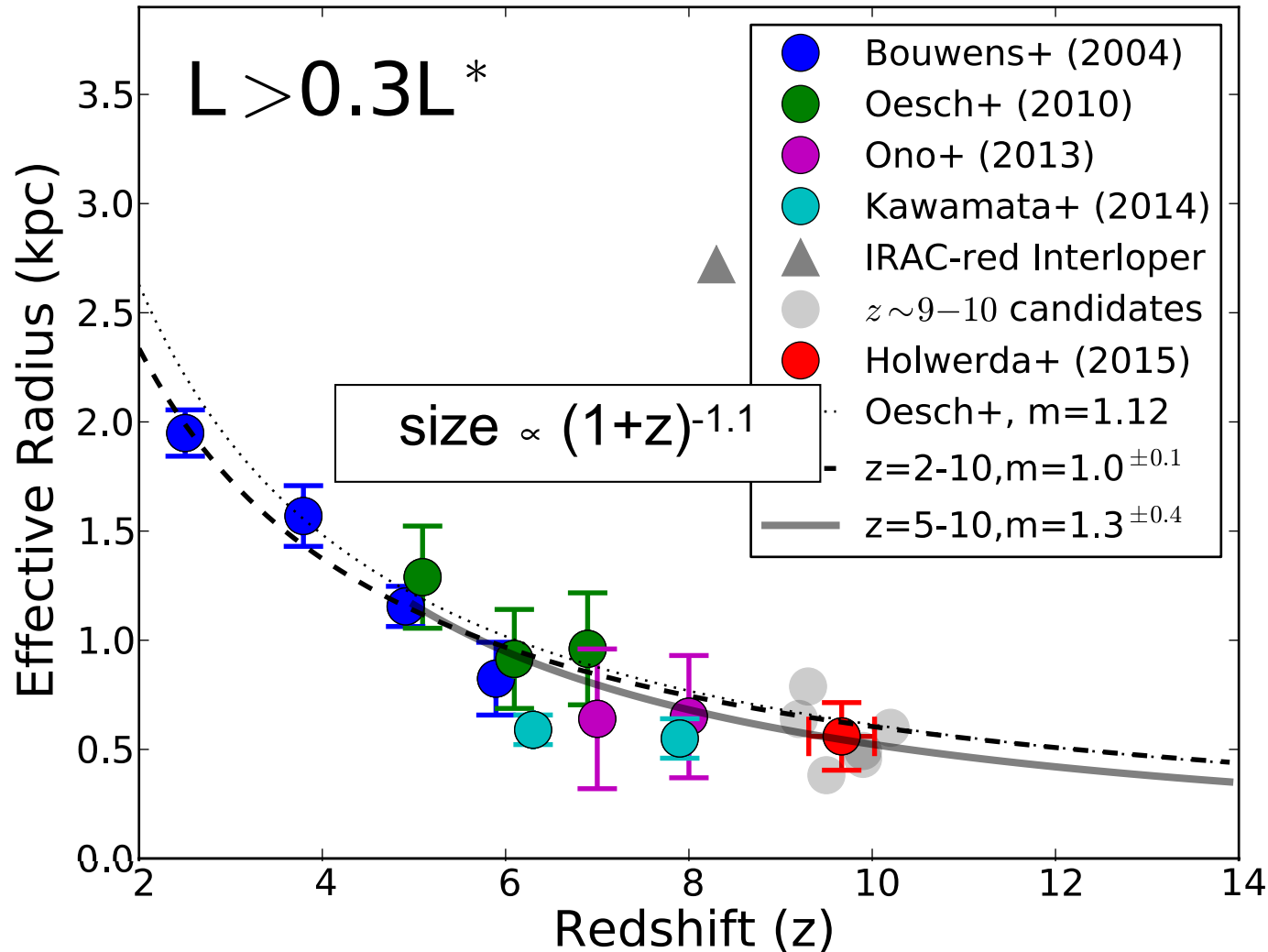
Clear relationship between the star formation rate and the stellar mass of a galaxy...



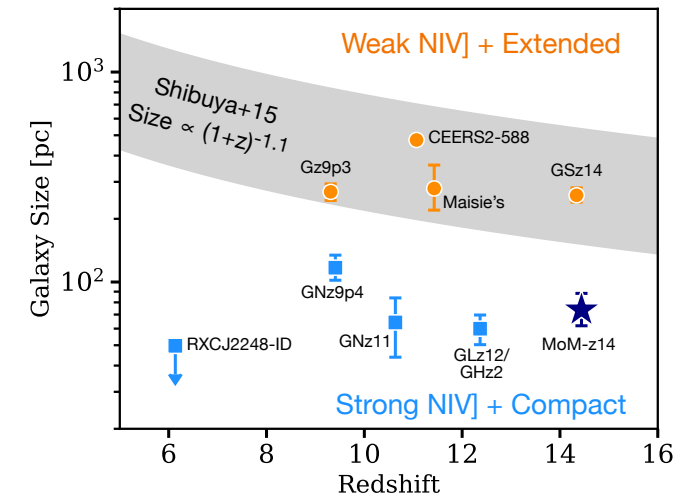
Constant of proportionality
between the star formation rate and
stellar mass evolves with redshift...

Galaxies form stars for a given
stellar mass at high redshift...

How do the Sizes of the Star-Forming Regions in Galaxies Evolve?



Mirrors the evolution of the halo sizes



How do the Sizes of the Star-Forming Regions in Galaxies Evolve?

Observations:
size $\propto (1+z)^{-1.1}$

Consistent with expectations from
lecture 8:

Theory of Dark Matter Halos

From the virial relationship:

$$(V_{200})^2 = GM/r_{200}$$

One can write expressions for the mass and radius of the halo in terms of the circular velocity and the Hubble constant:

$$M = (V_{200})^3 / 10GH(z)$$

$$r_{200} = V_{200} / 10H(z)$$

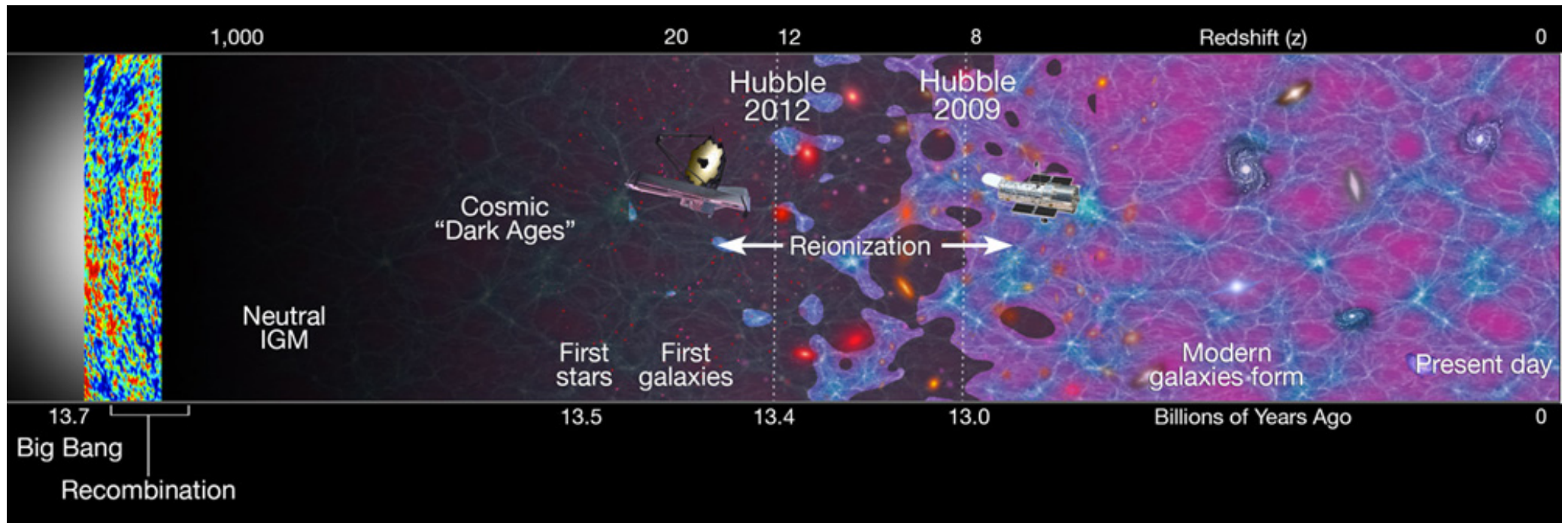
The Hubble “constant” $H(z)$ increases towards higher redshifts, effectively scaling as $(1+z)^{3/2}$ at very high redshifts.

Halos of a given mass are more compact at high redshift.

From lecture 2:

$$r_{\text{disk}} = \lambda R_{200} / 2^{1/2}$$

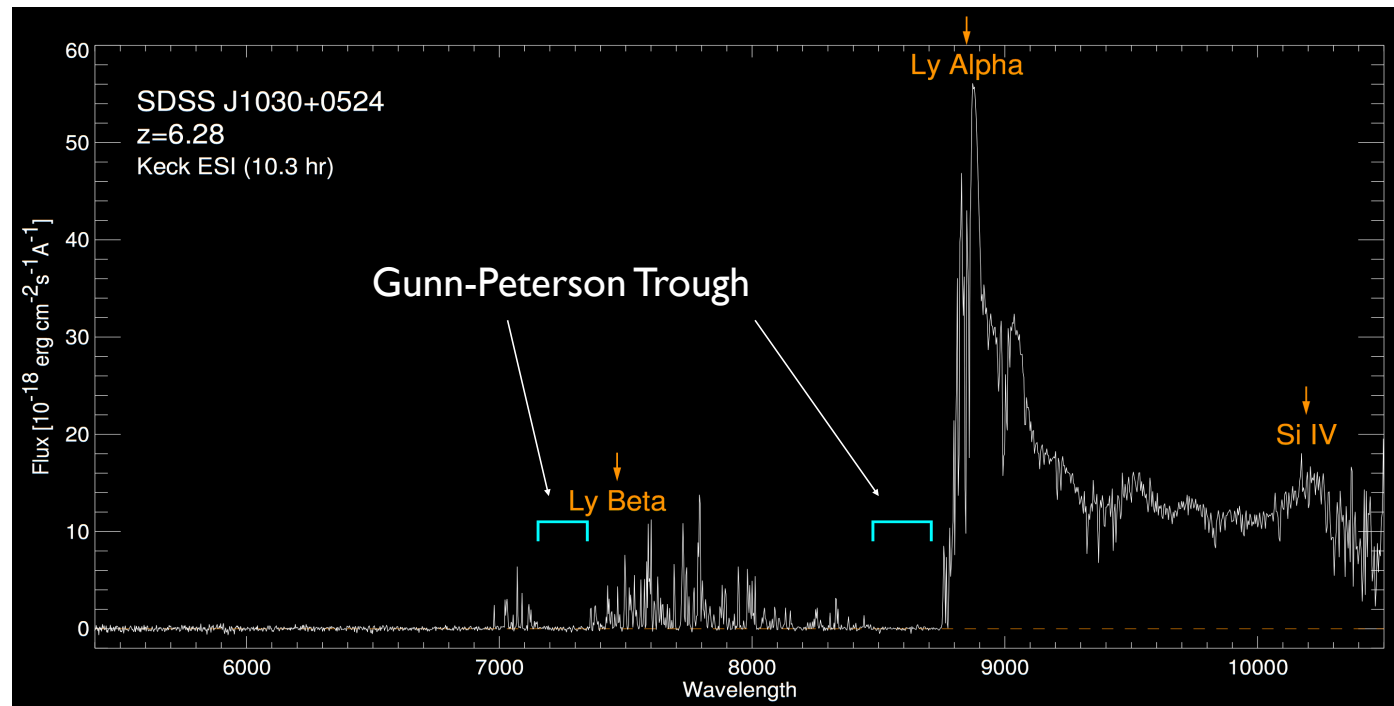
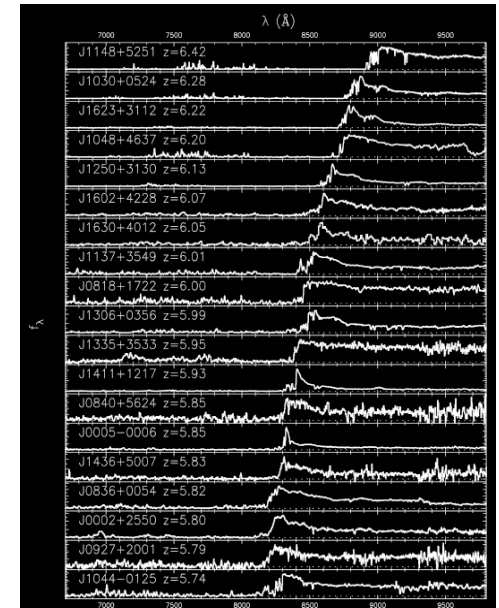
Do Galaxies Drive Cosmic Reionization?



Cosmic Reionization: Evidence

Absorption studies of bright $z > 5.9$ quasars: Reionization is likely completed around $z \sim 6$

Fraction of Neutral Hydrogen $> 0.1\%$ at $z > 6$



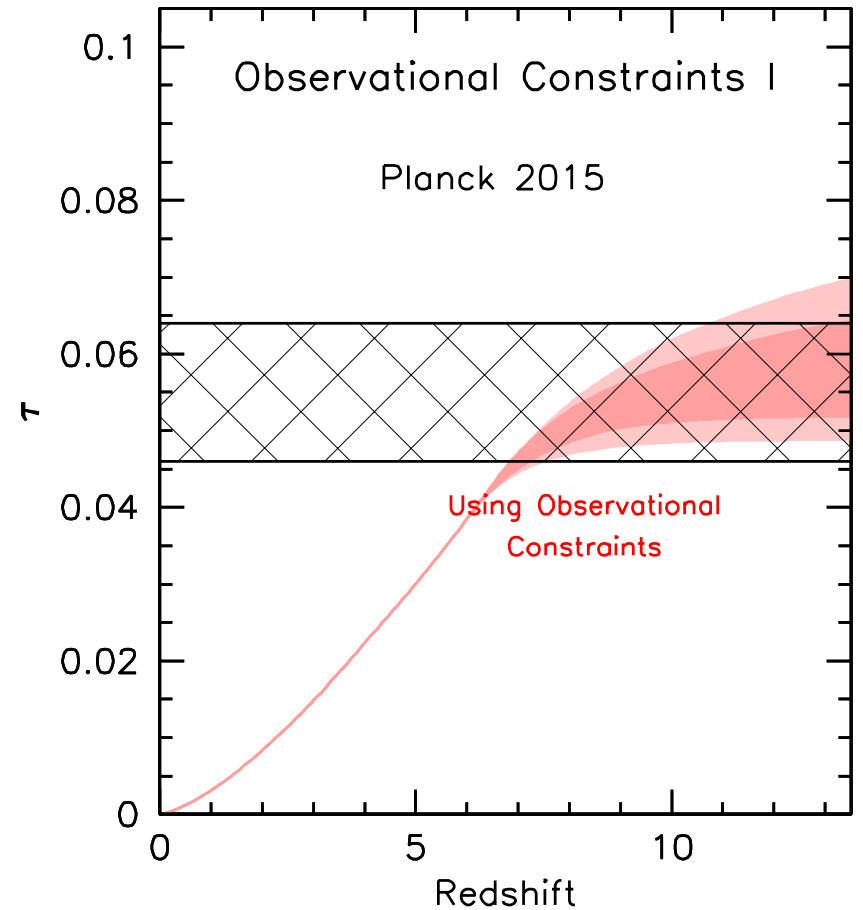
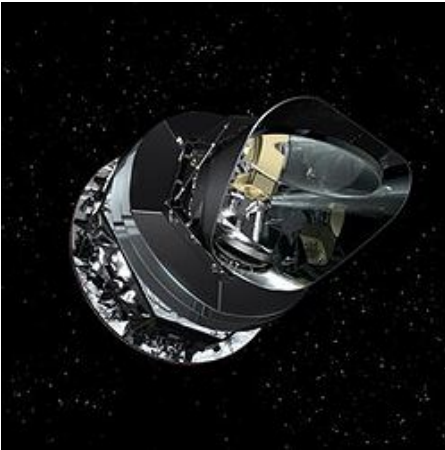
Cosmic Reionization: Evidence

Planck Thomson optical depth τ measurements: 0.055 ± 0.009

(Integral Constraint on electron column density “ionized material” from
 $z \sim 1000$ to $z \sim 0$)

Cosmic Reionization History:

Beginning: $z > 10$,
Mid-point: $z \sim 8$,
Completion: $z \sim 6$

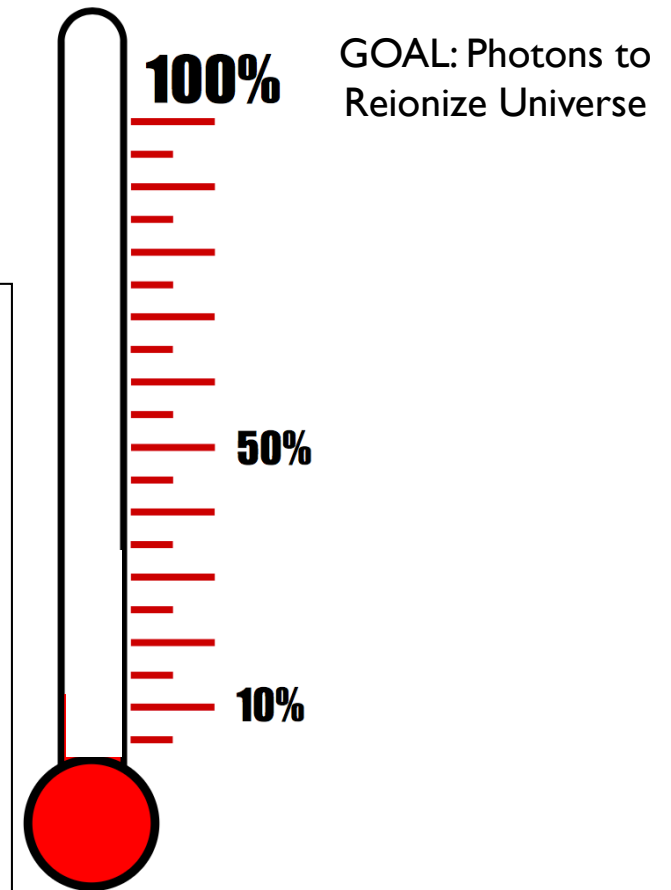


Do galaxies produce enough UV / ionizing photons to reionize the universe?

Ionizing Emissivity from Galaxies: Product of 3 Factors

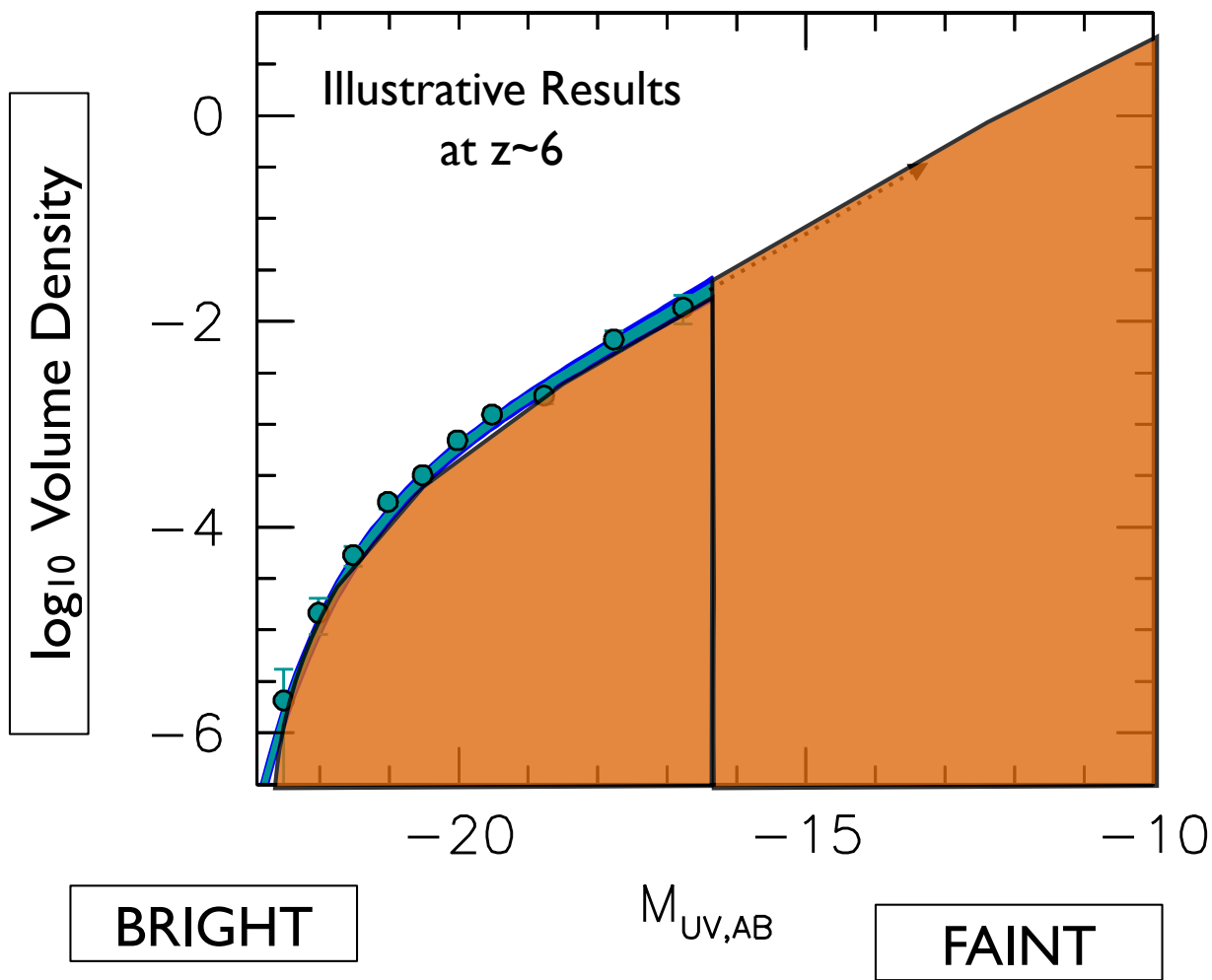
1. ρ_{UV} (UV luminosity density)
2. ξ_{ion} (conversion factor from UV to ionizing photons)
3. f_{esc} (fraction of ionizing photons that escape into the IGM)

Uncertain, but let's assume 10%

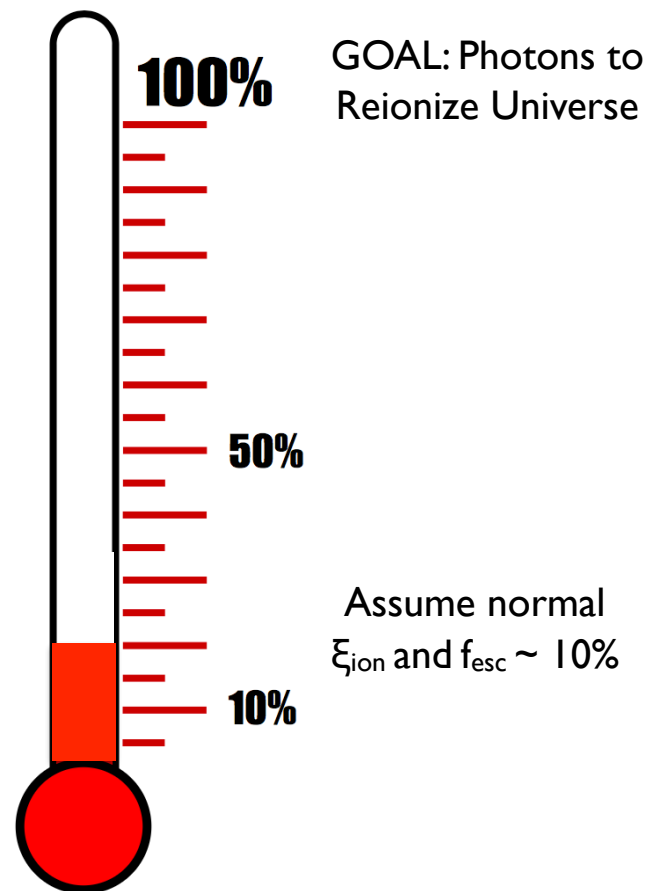


Do galaxies produce enough UV / ionizing photons to reionize the universe?

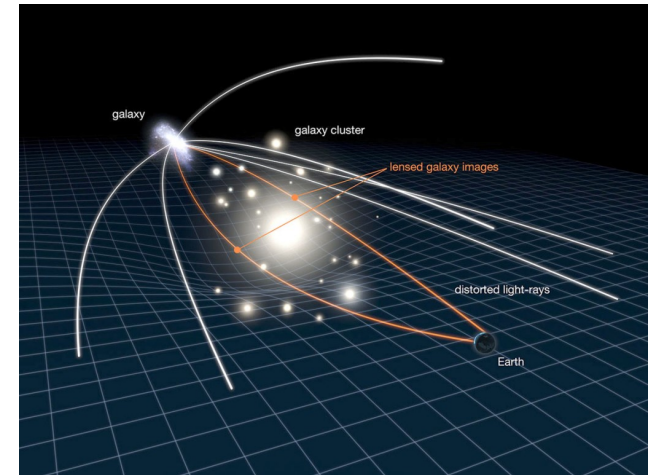
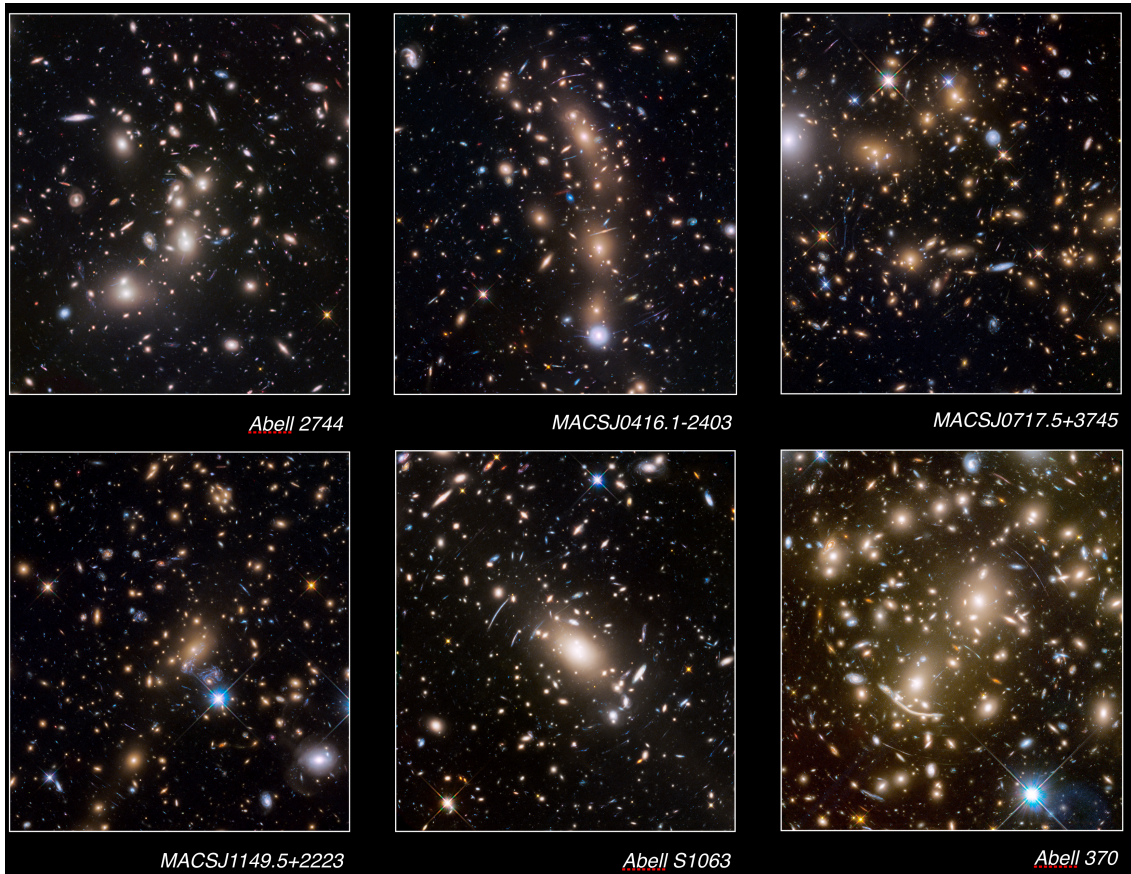
I. ρ_{UV} (UV luminosity density)



Integrate the UV Luminosity Function to calculate the total emissivity in UV photons from galaxies vs. redshift



Do galaxies produce enough UV / ionizing photons to reionize the universe?



Leverage observations from the Hubble Frontier Fields Program

combine power of gravitational lensing with long exposures with HST

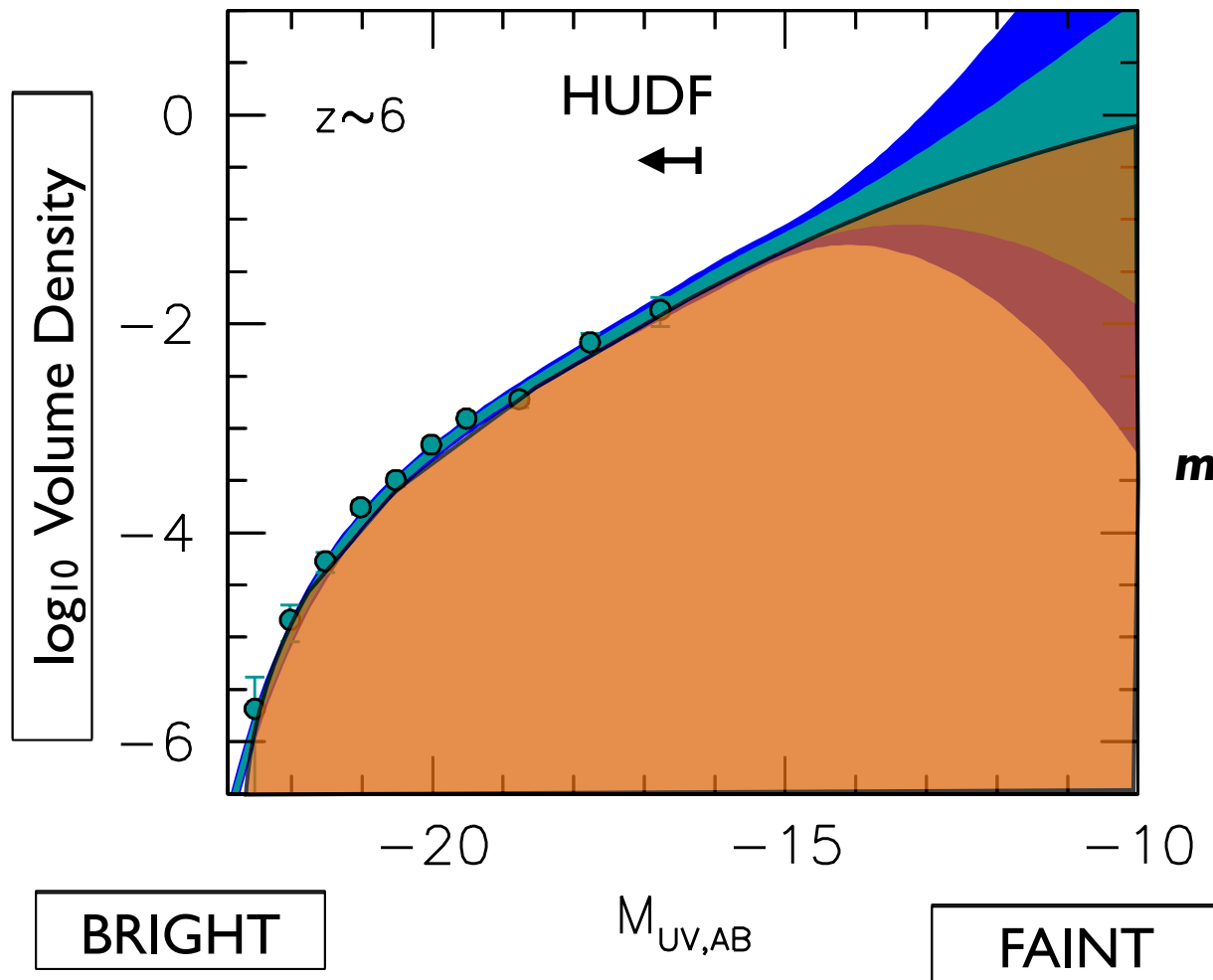
Identify some ~ 300 $z \sim 6$ galaxies behind the HFF clusters

RJB+2017; Lotz+2017; Coe+2015



Do galaxies produce enough UV / ionizing photons to reionize the universe?

I. ρ_{UV} (UV luminosity density)



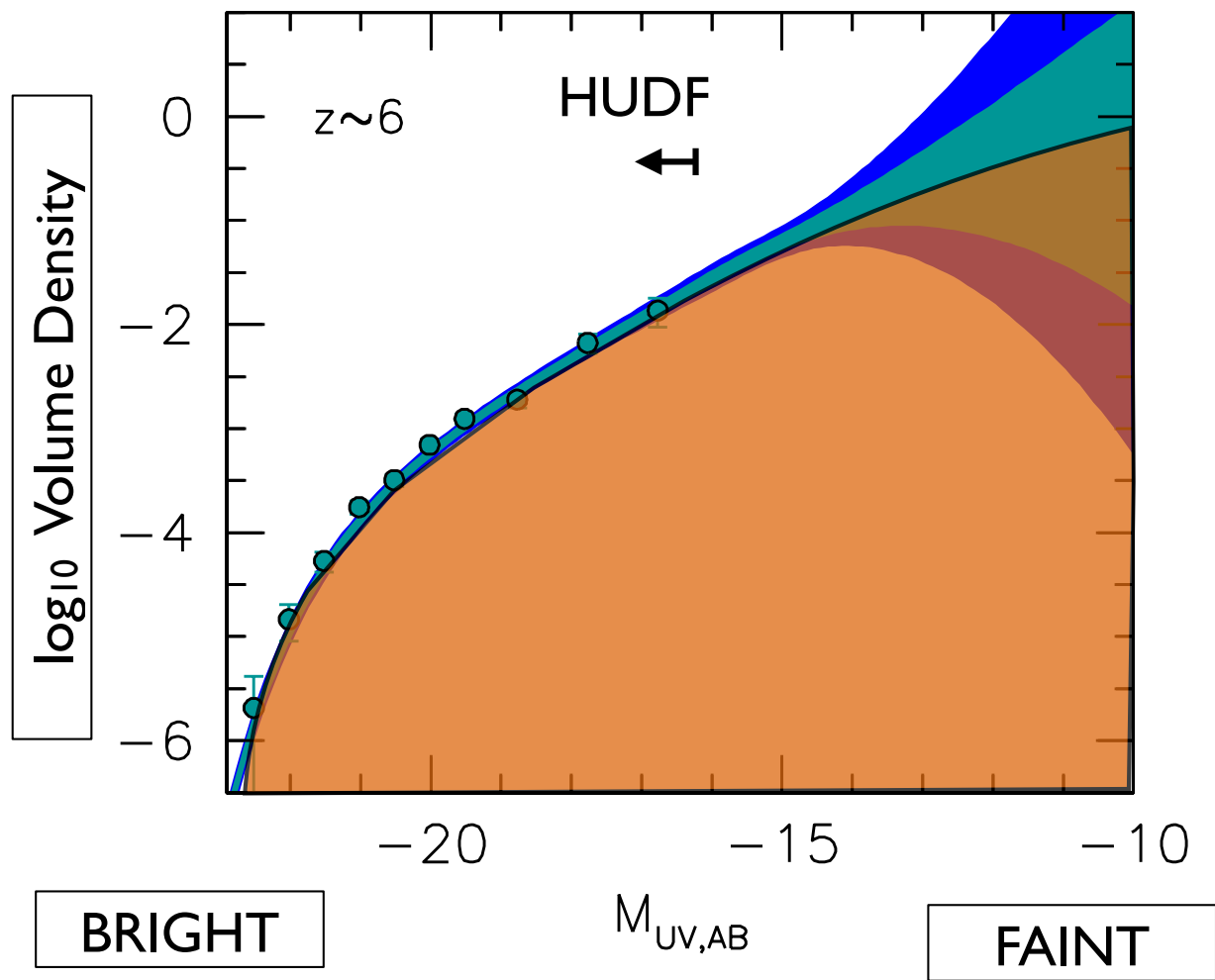
In deriving constraints on the LF, we give special attention to the impact that uncertainties in the **source size** distribution have on the result.

Introducing a curvature parameter and **forward-modeling lensing errors** (important for coping with **magnification uncertainties**) we derive 68-95% confidence intervals.

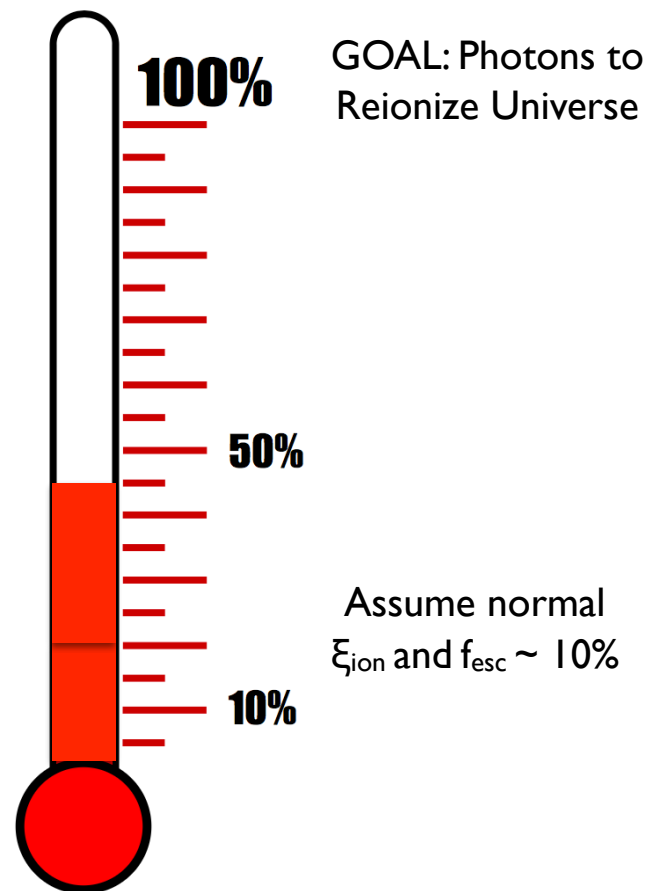


Do galaxies produce enough UV / ionizing photons to reionize the universe?

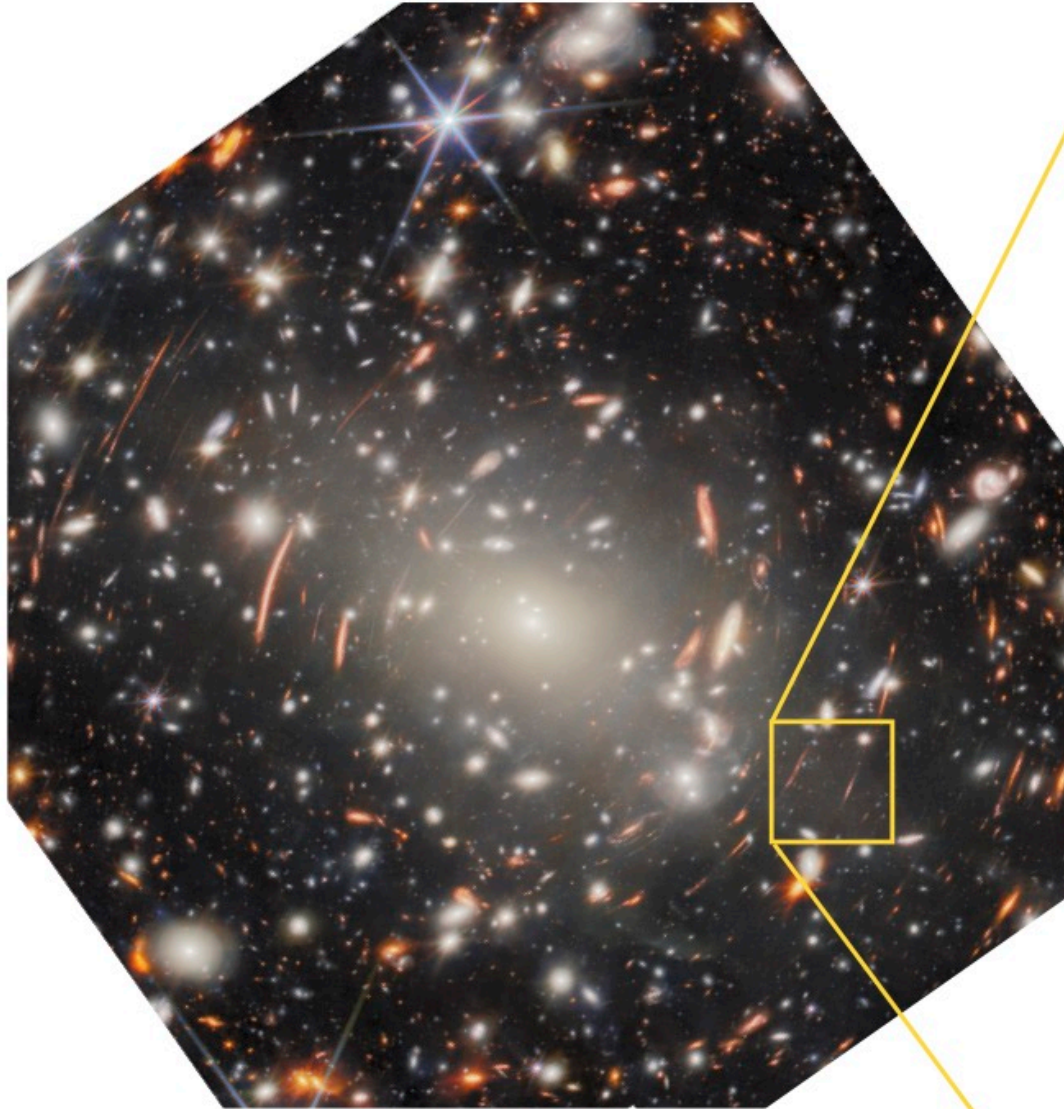
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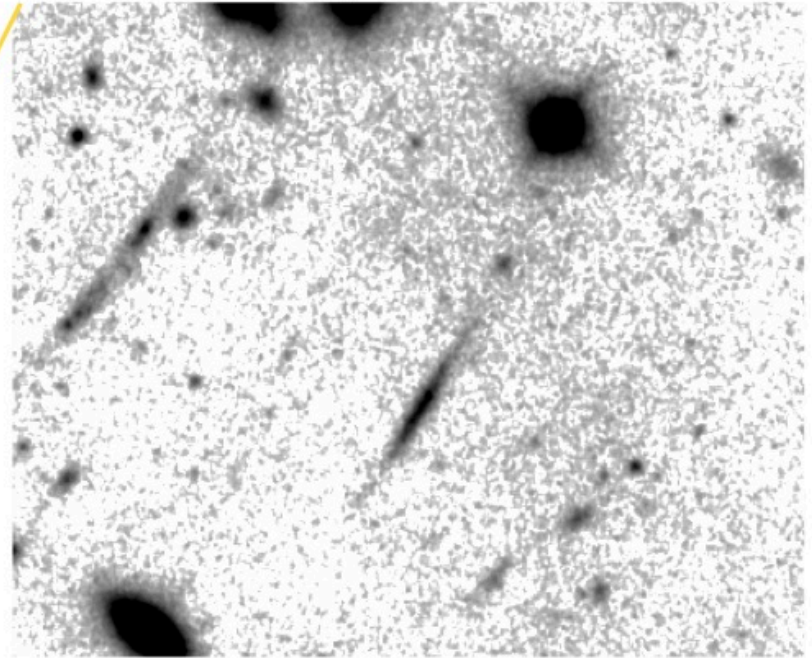
Integrate the UV Luminosity Function to calculate the total



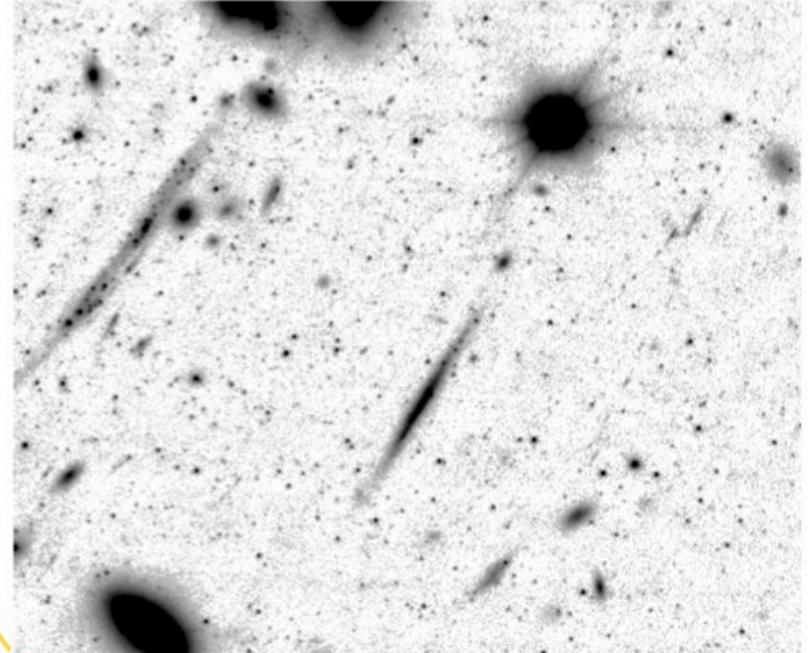
JWST NIRCам Image of Abell S1063



Hubble Space Telescope

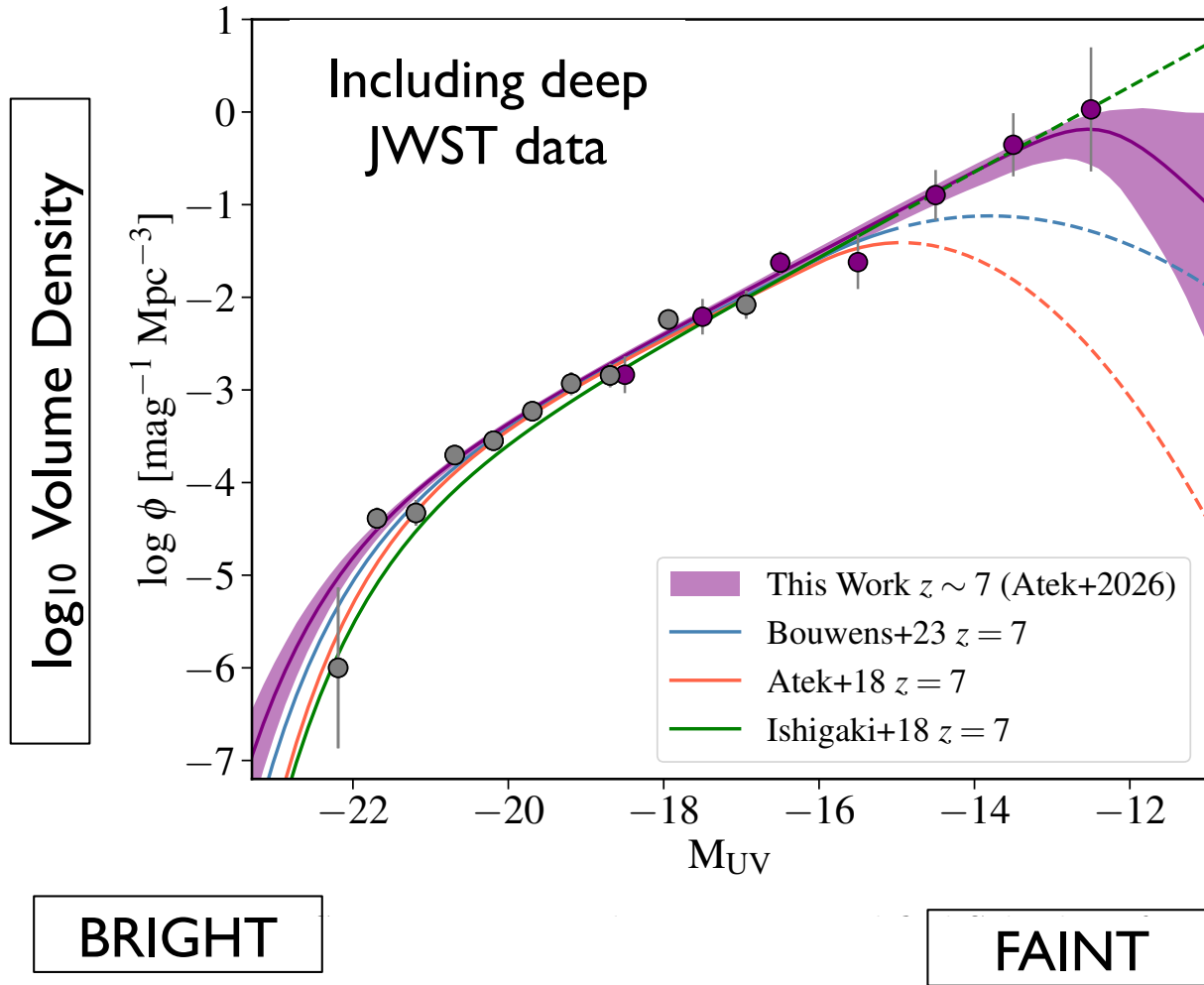


James Webb Space Telescope



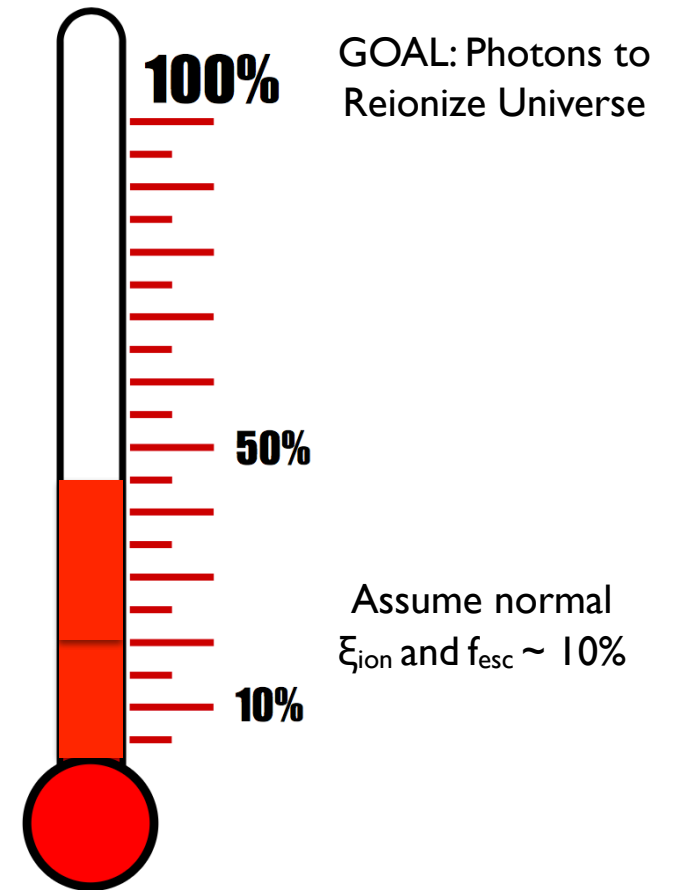
Do galaxies produce enough UV / ionizing photons to reionize the universe?

I. ρ_{UV} (UV luminosity density)



Atek+2026

Integrate the UV Luminosity Function to calculate the total

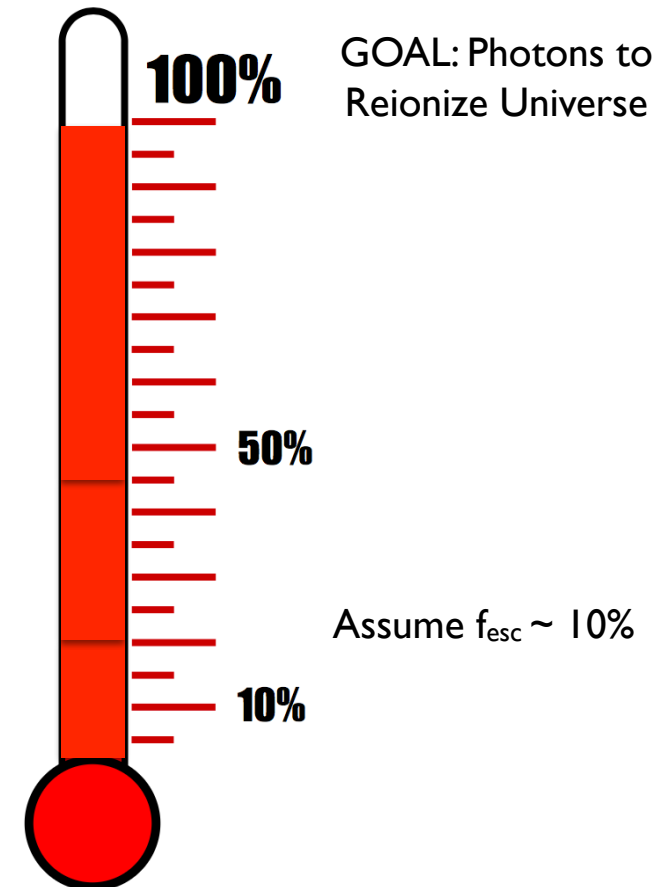
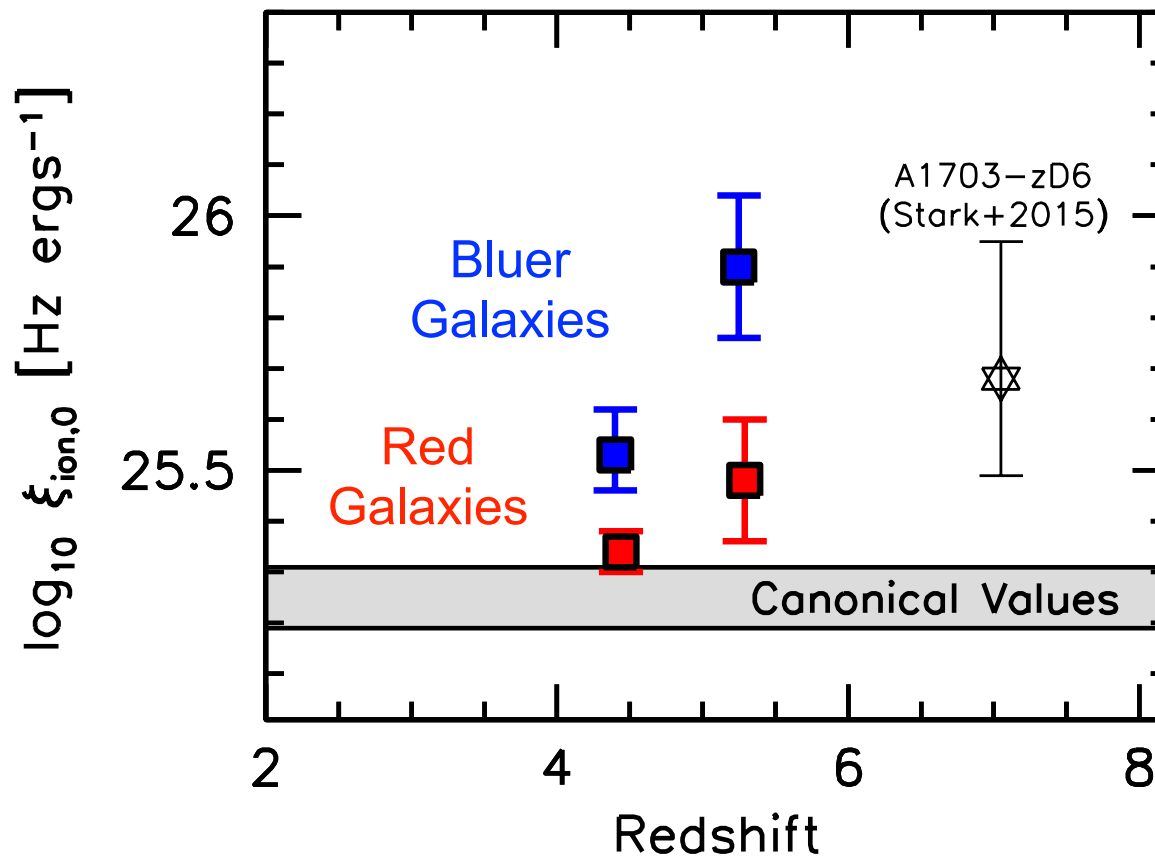


Do galaxies produce enough UV / ionizing photons to reionize the universe?

2. ξ_{ion} (conversion factor from UV to ionizing photons)

Incorporate Impact of Stronger than Expected Line Emission in $z \geq 2$ Galaxies

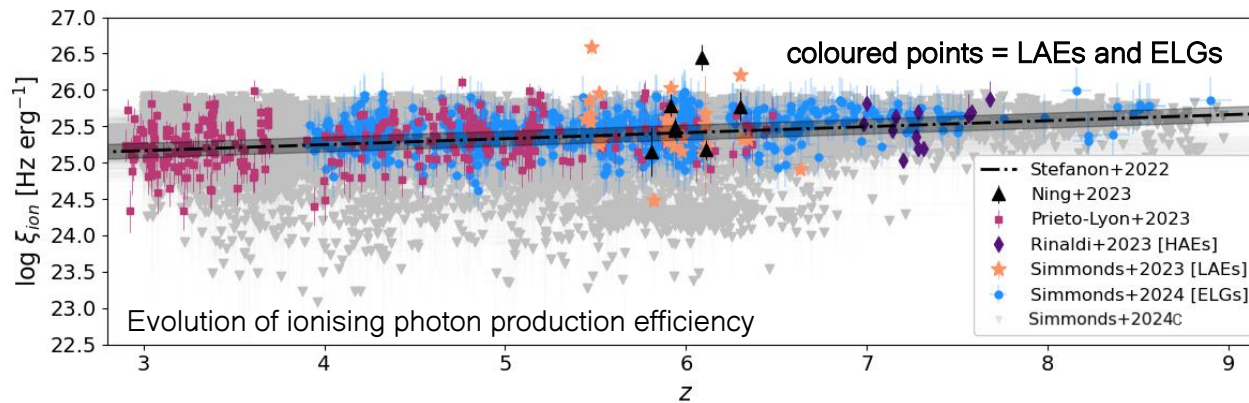
Ionizing Photons per UV-continuum Photons



Do galaxies produce enough UV / ionizing photons to reionize the universe?

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Ionizing Photons per UV-continuum Photons



Stefanon+2022 includes measurements from Stark+2015,2017, Marmol-Queralto+2016, Nakajima+2016, Bouwens+2016, Matthee+2017, Harikane+2018, Shivaiei+2018, DeBarros+2019, Lam+2019, Faisst+2019, Tang+2019, Nanayakkara+2020, Emami+2020, Endsley+2021, Atek+2022, Naidu+2022

Now including new JWST results
(From Simmonds+2026 talk)

Incorporate Impact of Stronger than Expected Line Emission in $z \geq 2$ Galaxies

