Reionization and High Redshift Galaxies

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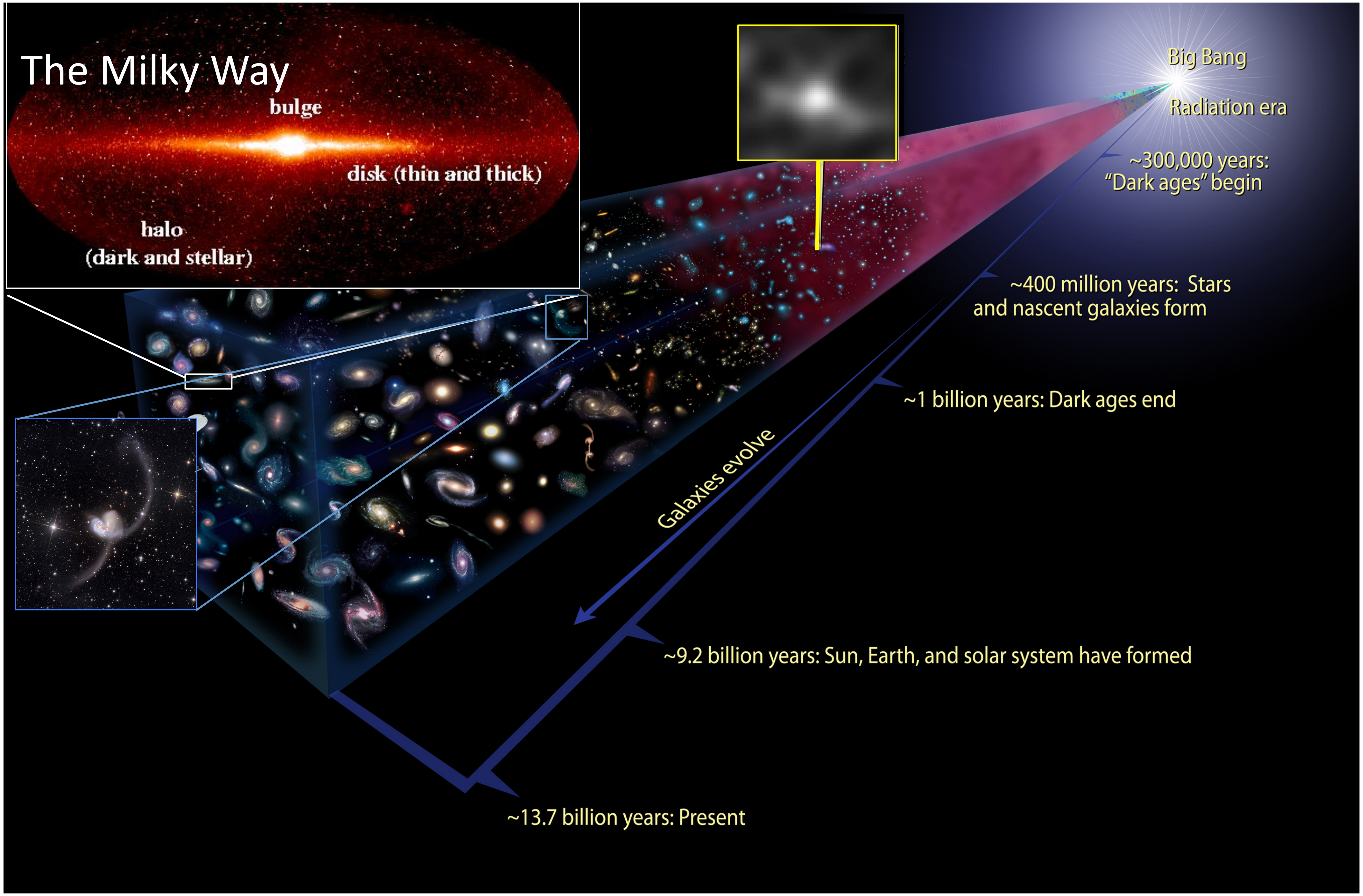
Formation and Evolution of Galaxies 2023-2024 Q1
Rijksuniversiteit Groningen



We can study galaxies at different epochs, and with different levels of detail. All approaches are complementary and constrain in different ways the models.

Reionization and First Galaxies

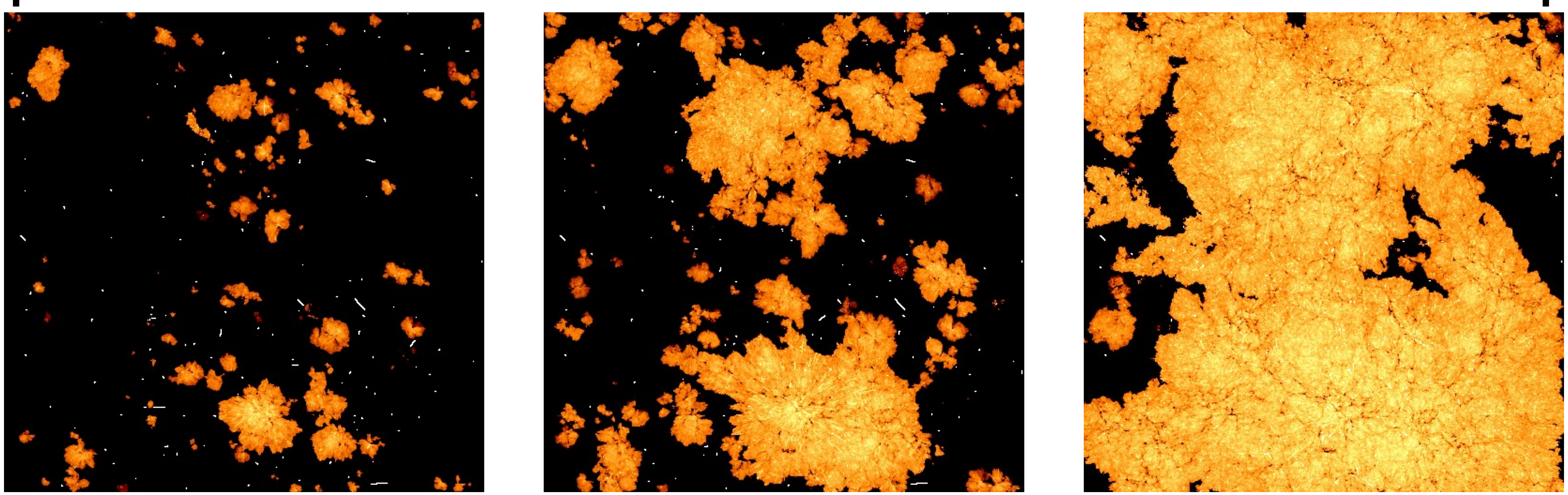
Hydrogen reionization

PRE OVERLAP PHASE
Each galaxy builds a region of ionized hydrogen around itself, the Strömgren sphere

OVERLAP PHASE
Ionized spheres grow and start merging

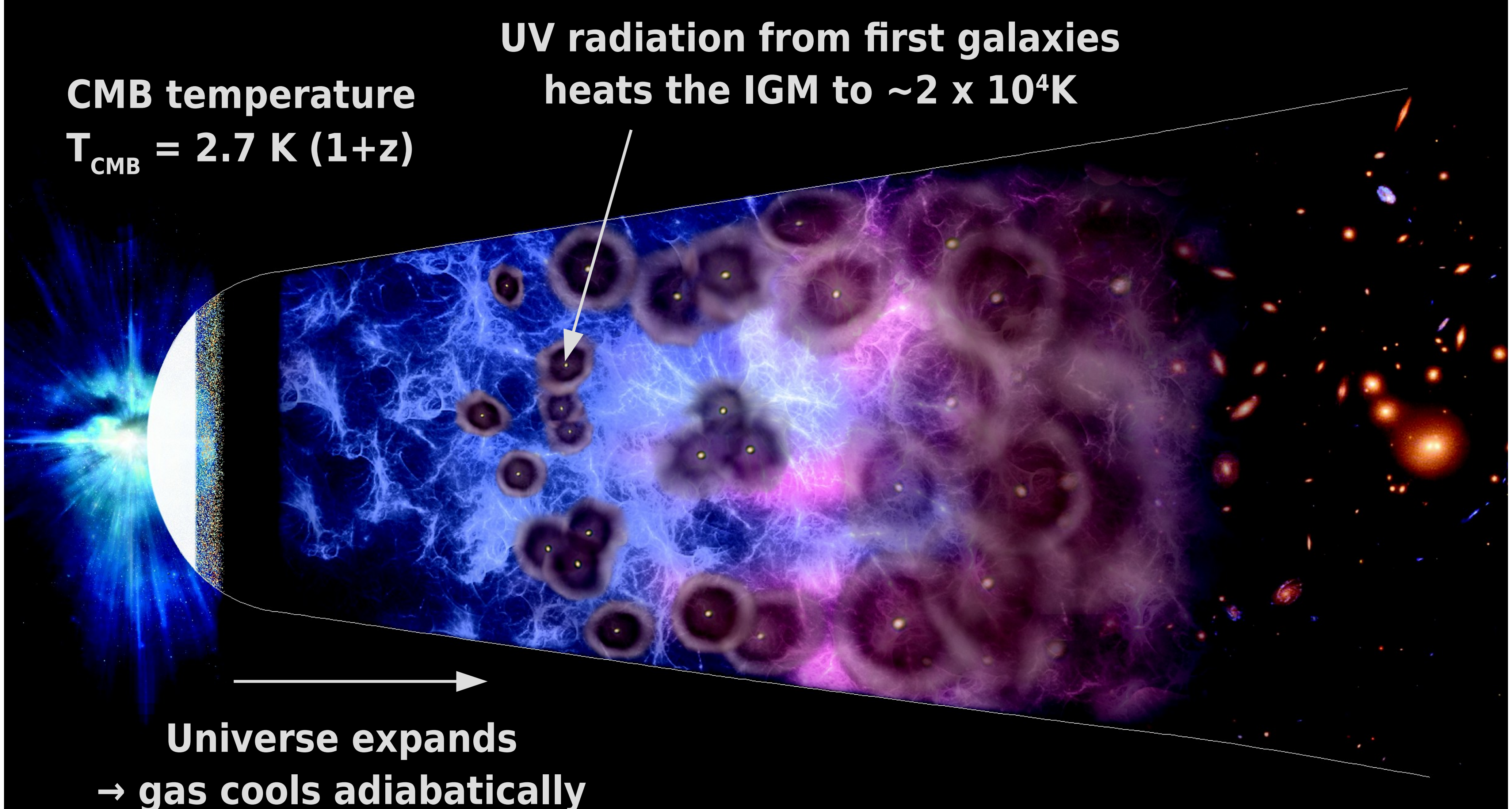
POST OVERLAP PHASE
Large ionized regions start to merge and reionize the left-over neutral islands

START *Reionization continues* ***END***



Reionization is inhomogeneous and extended.

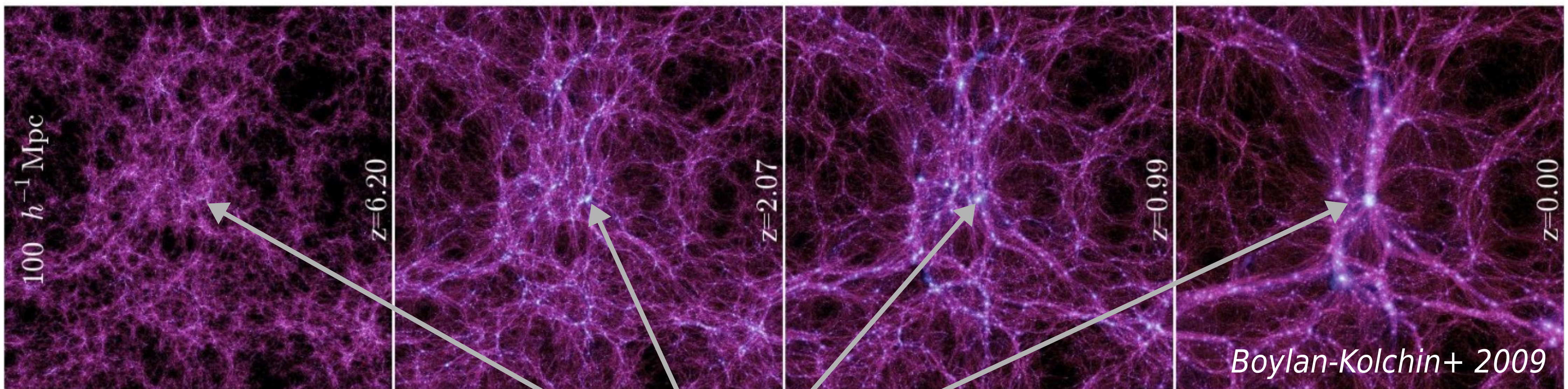
Thermal evolution of the IGM



Credits: ERC and EU Research SPR19/P53

Sources of reionization

earlier **time** later



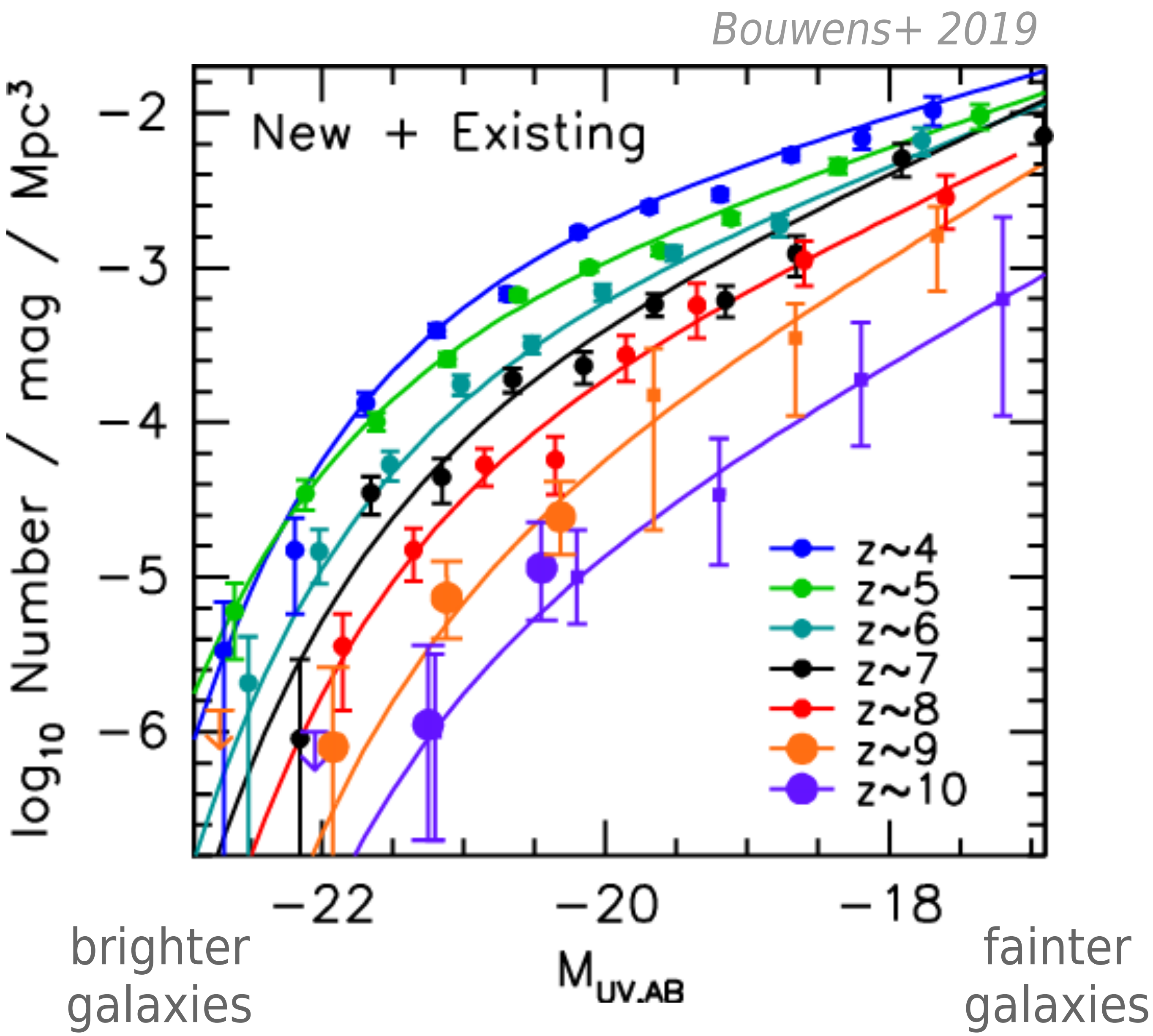
most massive galaxies form earlier
& have more time to grow

Gravity causes the initial fluctuations in the density field to grow over time, i.e. slightly over-dense regions increase their density and become more confined, while slightly under-dense regions become more under-dense.

Galaxies form in the density peaks. The most massive galaxies have formed in the very first density peaks, while less massive galaxies have formed later.

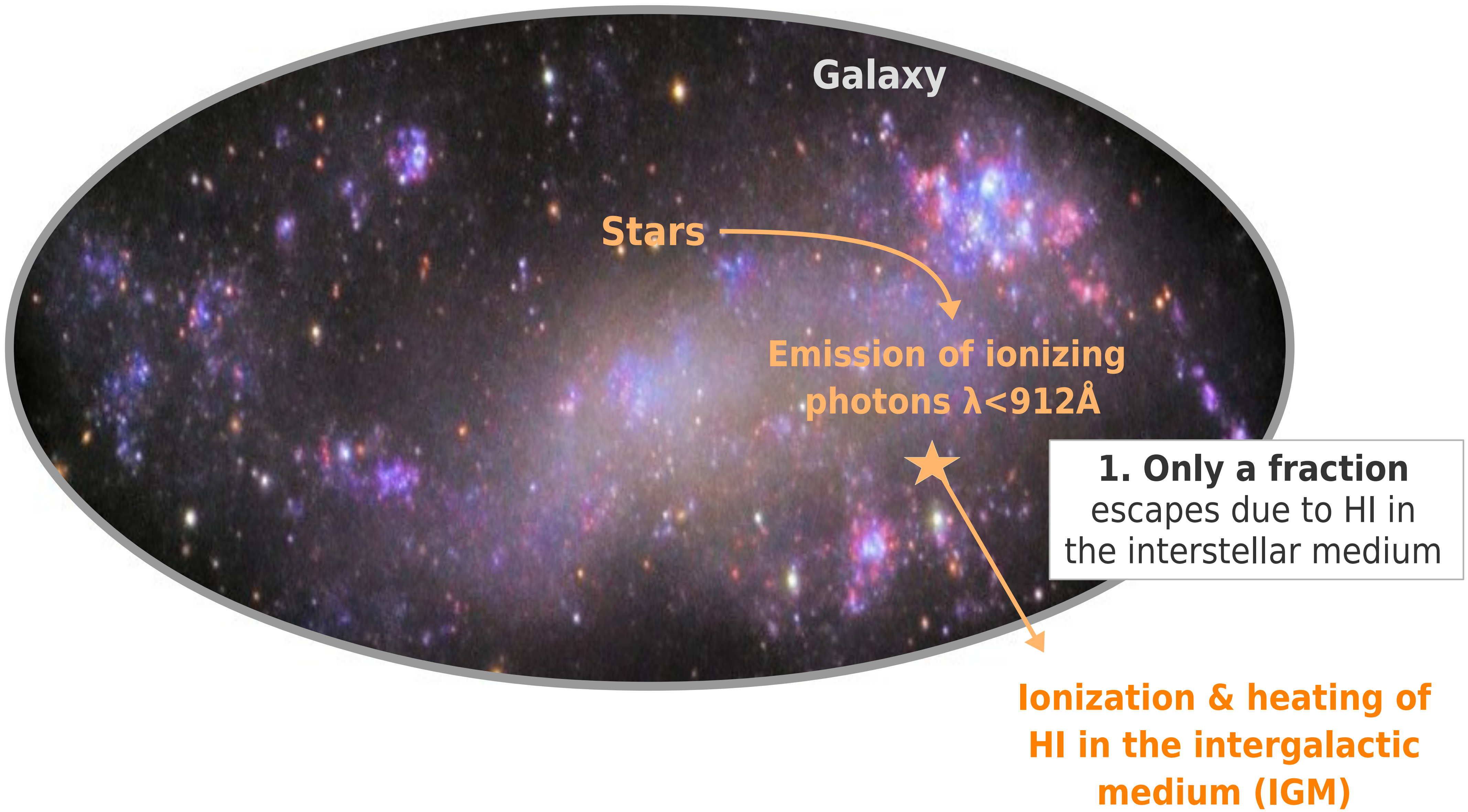
At each time there are far more low massive galaxies than very massive galaxies.

Sources of reionization



Observations of the luminosities of the first galaxies have confirmed:

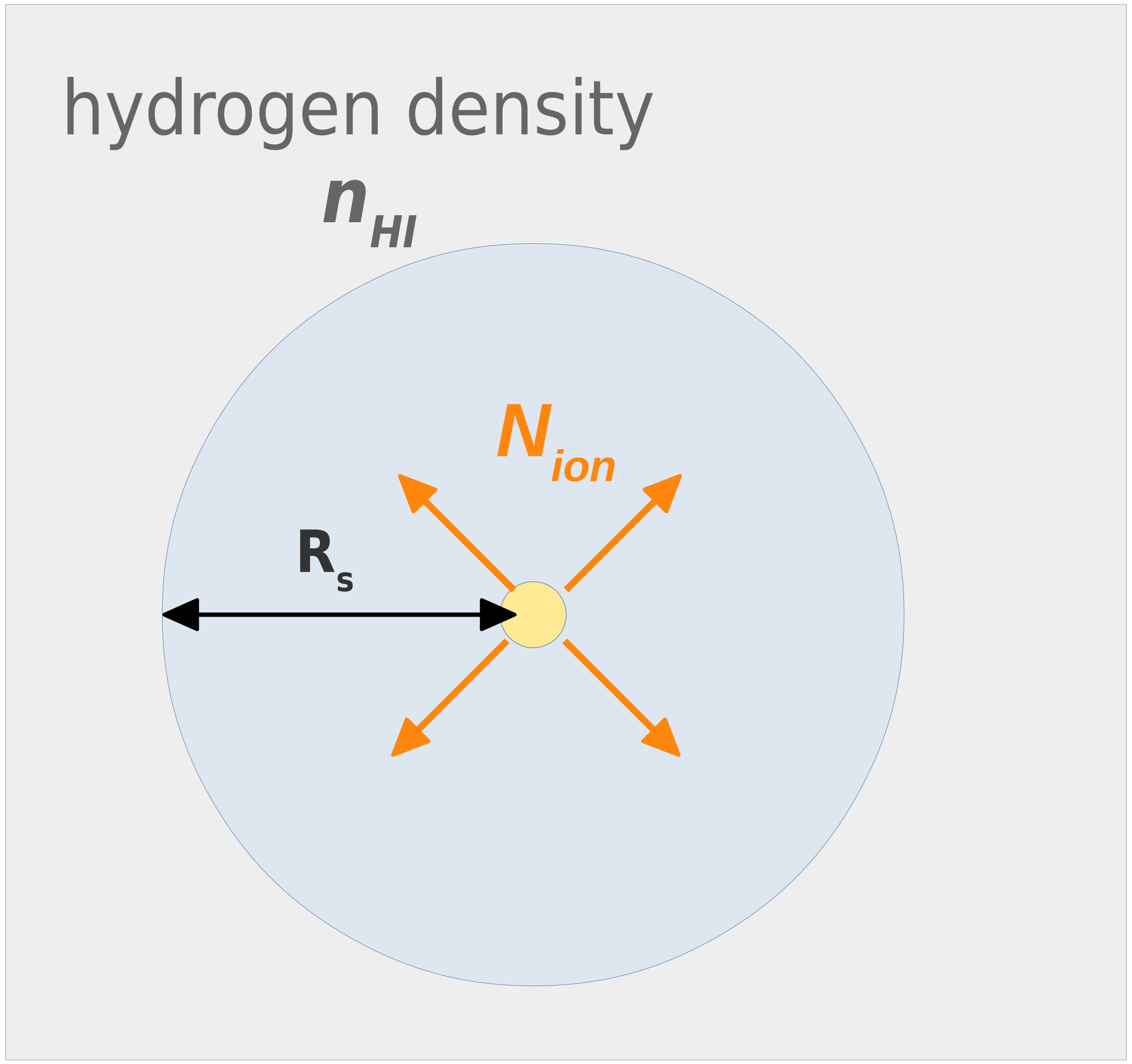
What physical processes affect the contribution of galaxies to reionization?



Strömgren sphere

Galaxy emits hydrogen ionizing photons (λ < 912Å) at a rate $\boldsymbol{N_{ion}}$ [number/sec]

The intergalactic medium around the galaxy has a number density $\boldsymbol{n_{HI}}$ [cm^{-3}]



What is the size of the ionized sphere around the galaxy?

rate of ionizations = rate of recombinations

$$N_{ion} = \alpha\, n_e n_p\, V$$

$$V = 4\pi\, R_s^3 / 3$$

Radius of the Strömgren sphere:

$$R_s = (3N_{ion} / 4\pi\, \alpha\, n_e n_p)^{1/3}$$

Key physics - Reionization

The reionization history is expressed through the evolution of the ionization fraction Q_{HII} of hydrogen:

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{\bar{t}_{rec}}$$

ionization rate recombination rate

The "ionization rate" describes the growth of the ionized regions due to sources of ionizing photons, while the "recombination rate" describes the decrease in the ionized regions due to recombinations (p + e → H). Sources of ionizing photons are stellar populations in galaxies; only a fraction (f_{esc}) of the ionizing photons produced in within the galaxy (n_{ion}^{ISM}) can escape into the intergalactic medium (IGM) and contribute to reionization.

$$\dot{n}_{ion} = f_{esc}\,\dot{n}_{ion}^{ISM}$$

The recombination time scale decreases as more ionized atoms and free electrons are present.

$$\bar{t}_{rec} = \left[\chi_e \bar{n}_H \alpha_B C\right]^{-1}$$

clumping factor of the IGM

$$C = \frac{\langle n^2 \rangle}{\langle n \rangle^2}$$

factor to account for excess in free electrons due to ionized helium

hydrogen density

Case-B recombination coefficient

Example: Deriving the reionization history

$$\frac{dQ_{HII}}{dt} = \frac{\dot{n}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{\bar{t}_{rec}}$$

$$\bar{t}_{rec} = \left[\chi_e \bar{n}_H \alpha_B C\right]^{-1}$$

number of ionizing photons per hydrogen atom and time

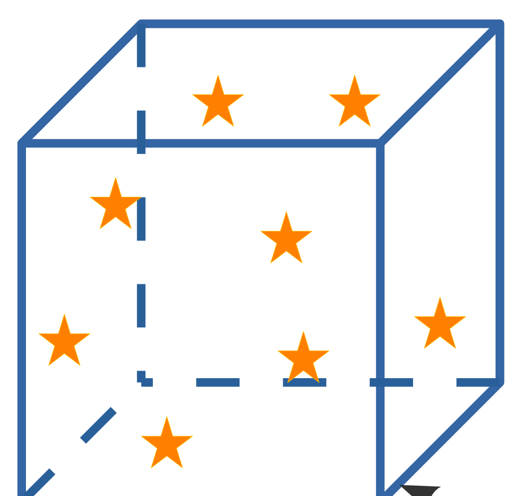
number of recombinations per hydrogen atom and time

Assumptions:

1) gas density is homogeneous: C = 1

2) ionizing emissivity is constant in time: $\dot{n}_{ion}(t) = \dot{n}_{ion}$

3) gas only consists of hydrogen: $\chi_e = 1$



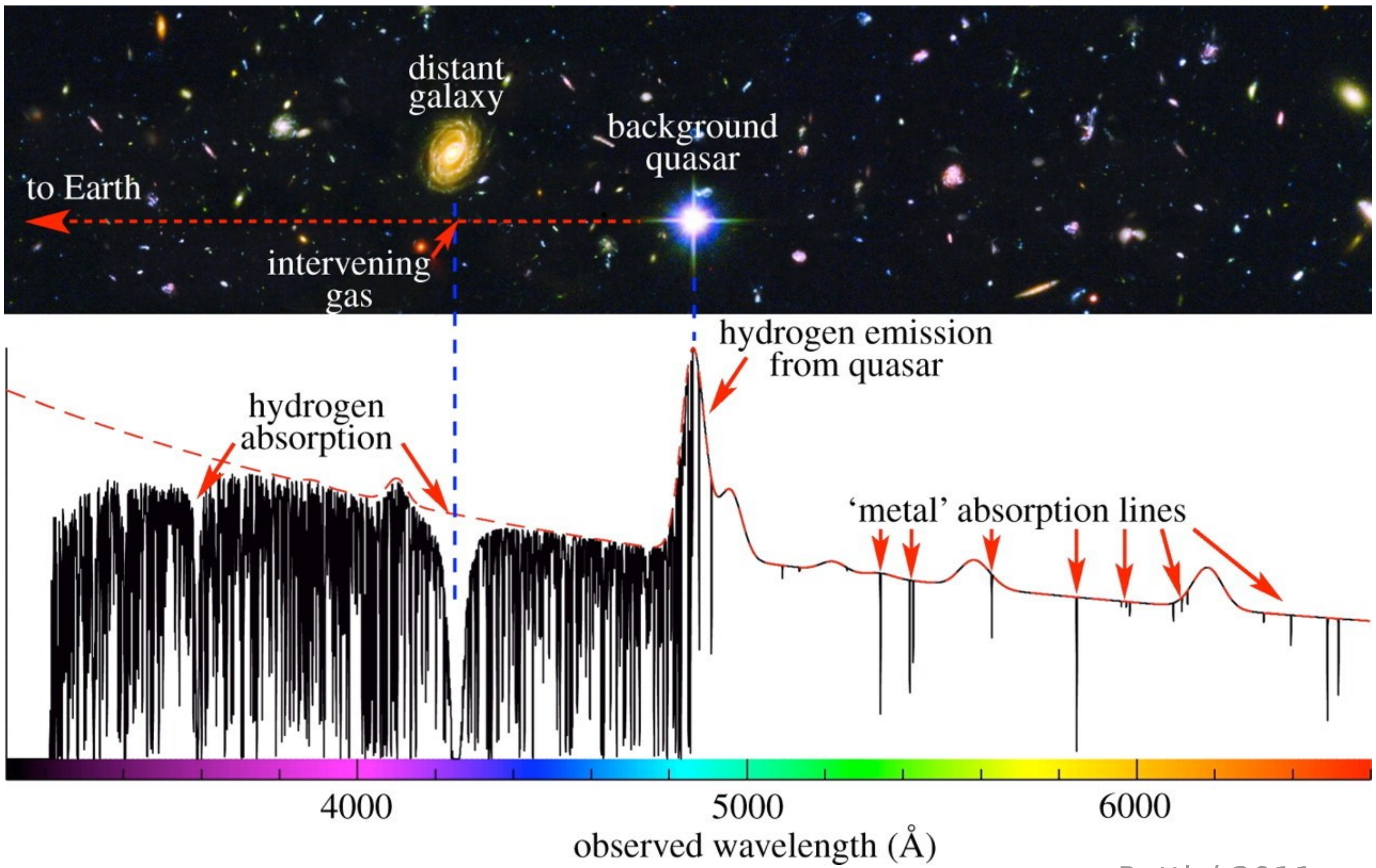
Volume V with $\bar{n}_H$

[# / sec]

$$\dot{n}_{ion} = \frac{\sum_i^{N_{sources}} \dot{N}_{ion,i}}{V}$$

[# / (cm^3 sec)]

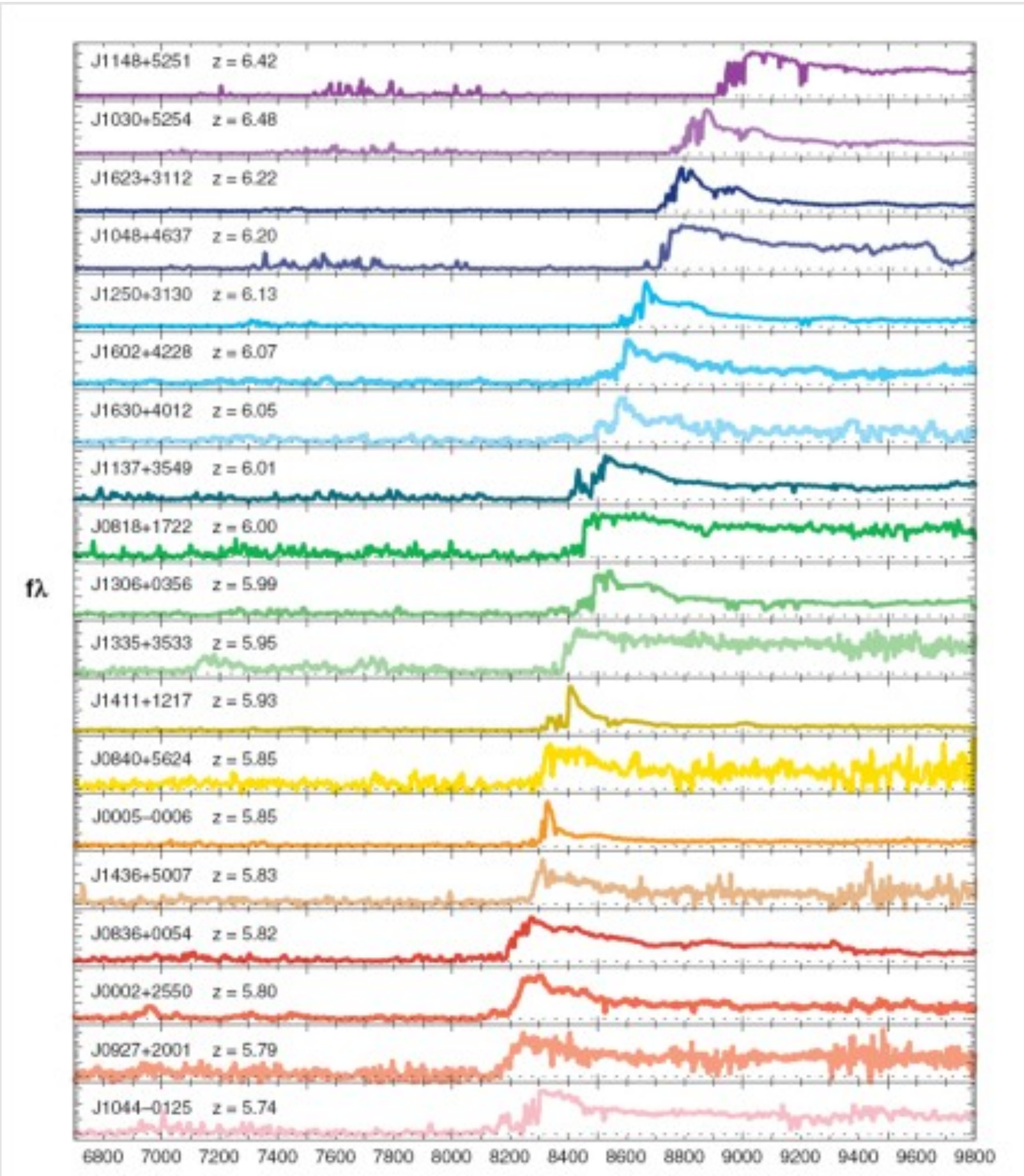
Evidence for reionisation: Gunn-Peterson trough



Pettini 2011

Quasar emits radiation → Radiation travels as Universe expands & is redshifted → Neutral hydrogen in the IGM absorbs Lyman-α always at 1216 Å → Quasar spectra shows absorption at wavelengths shorter than 1216 Å

Evidence for reionisation: Gunn-Peterson trough



Fan+ 2006

If the photons of the quasar spectra passes the neutral gas in the IGM during reionization, they are nearly completely absorbed at wavelengths shorter than 1206Å (in the rest frame of the quasar!)

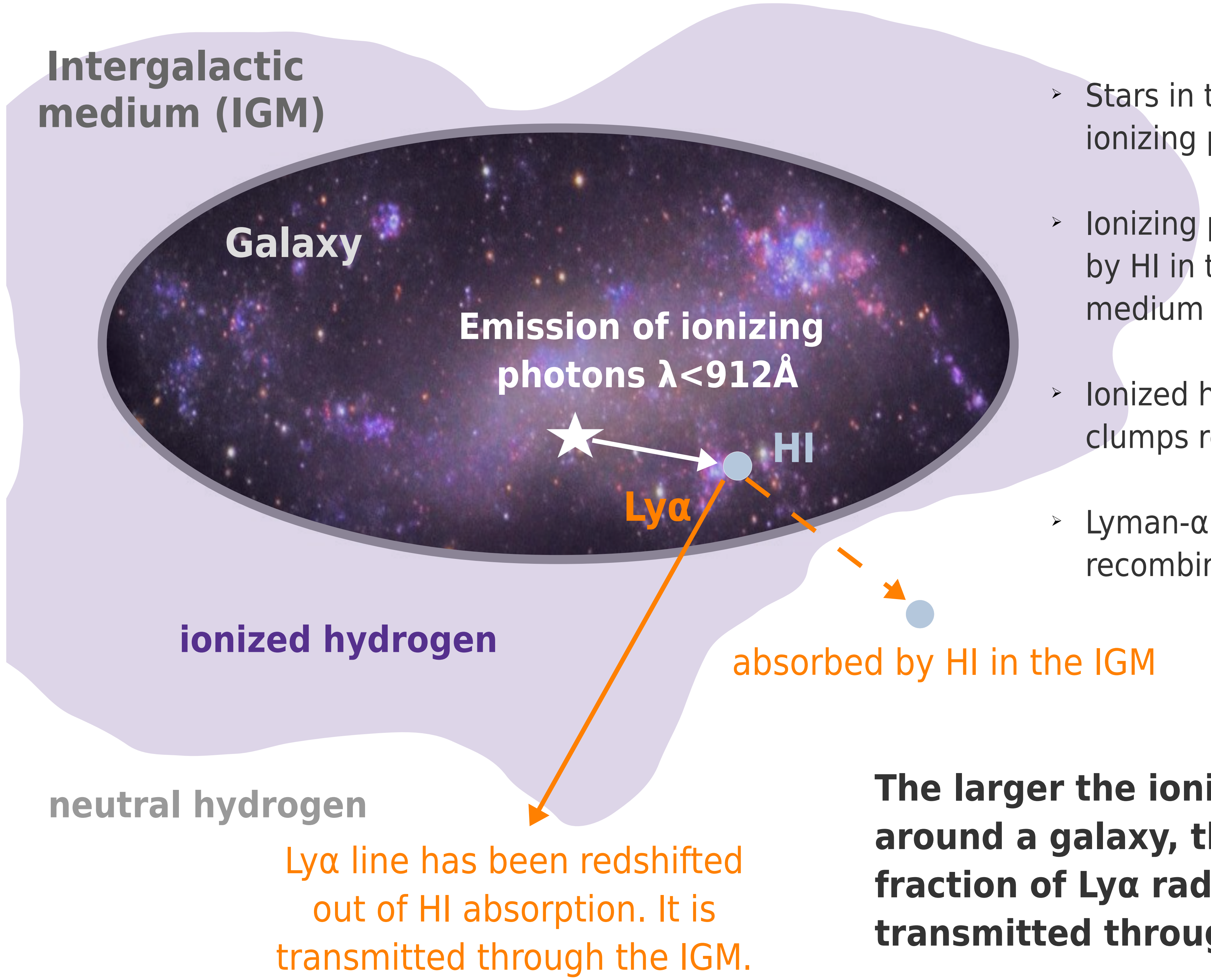
$$\tau_{GP}(z) = \tau_0 \frac{n_{HI}}{\bar{n}_{HI}}$$

$$\tau_0(z) \equiv \frac{\pi e^2 f \lambda_\alpha}{m_e c H(z)}$$

$$\simeq 1.5 * 10^{-5} h^{-1} \Omega_m^{-1/2} \frac{\Omega_b h^2}{0.019} \left(\frac{1+z}{8} \right)^{3/2}$$

One neutral hydrogen atom out of 10^5 can cause complete absorption blue-ward of Lyman-α

Evidence for reionisation: Lya emission

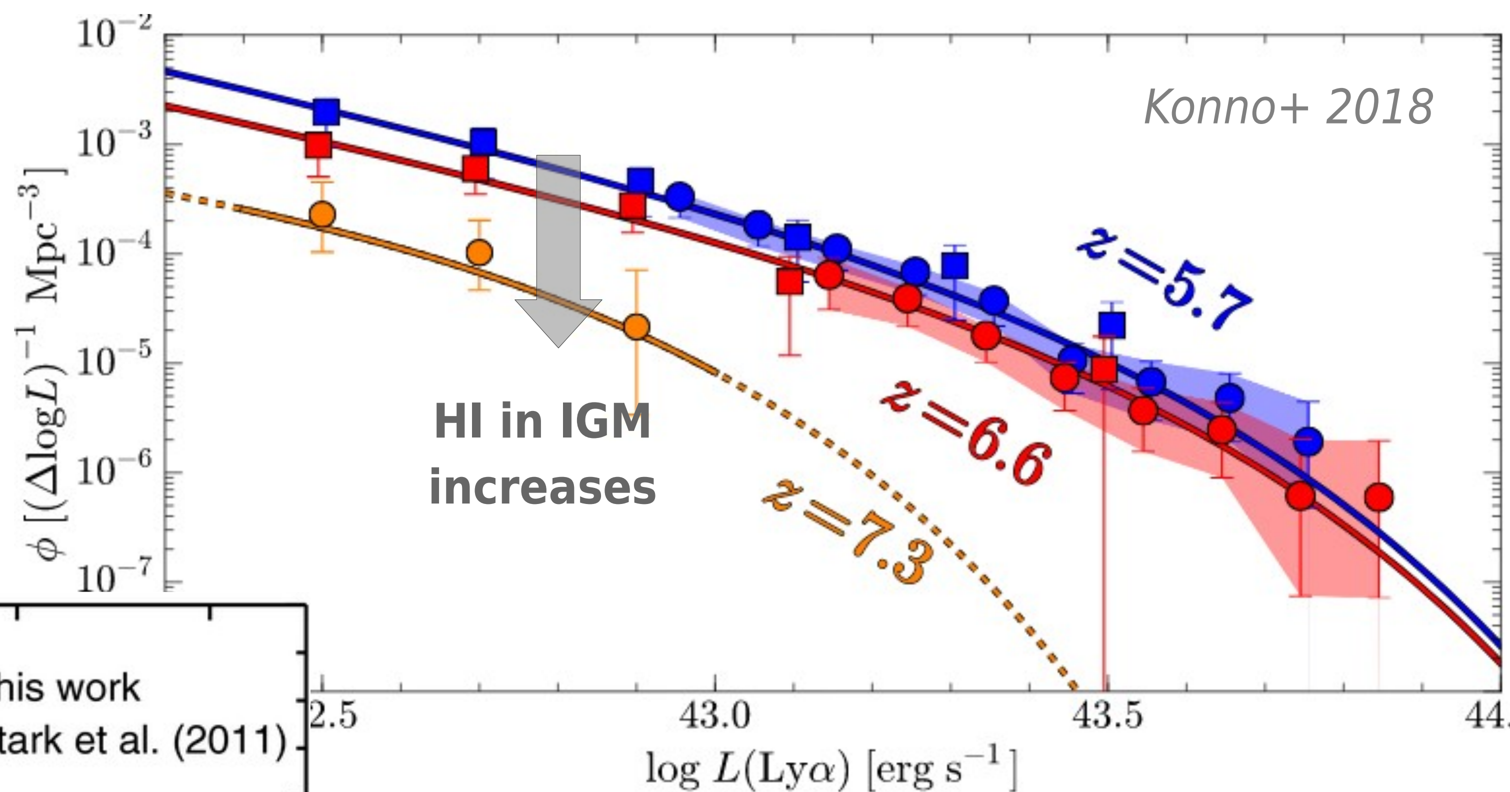


- Stars in the galaxy emit HI ionizing photons
- Ionizing photons are absorbed by HI in the interstellar medium (ISM)
- Ionized hydrogen in dense clumps recombines quickly
- Lyman-α is emitted as part of recombination radiation

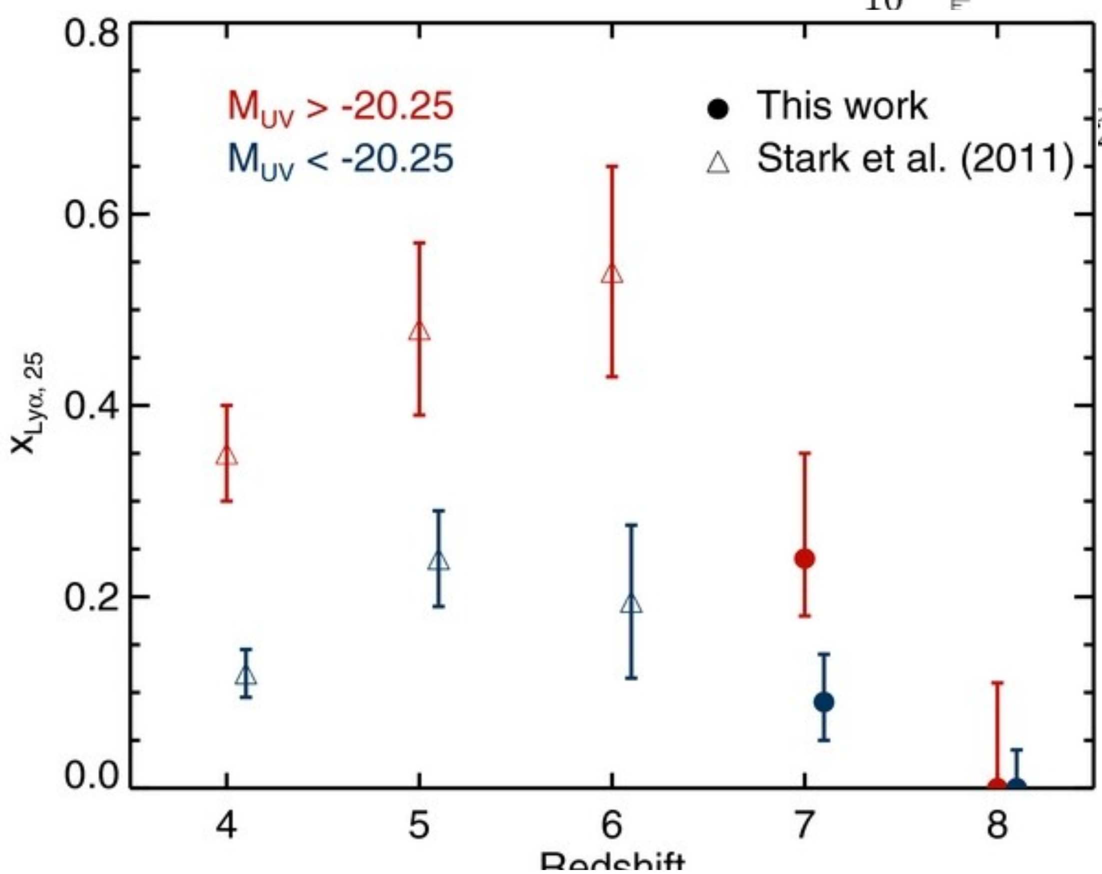
The larger the ionized regions around a galaxy, the higher is its fraction of Lyα radiation that is transmitted through the IGM.

Evidence for reionisation: Lya emission

The decrease of galaxies with a detected Lyα line could be due to a higher HI fraction.



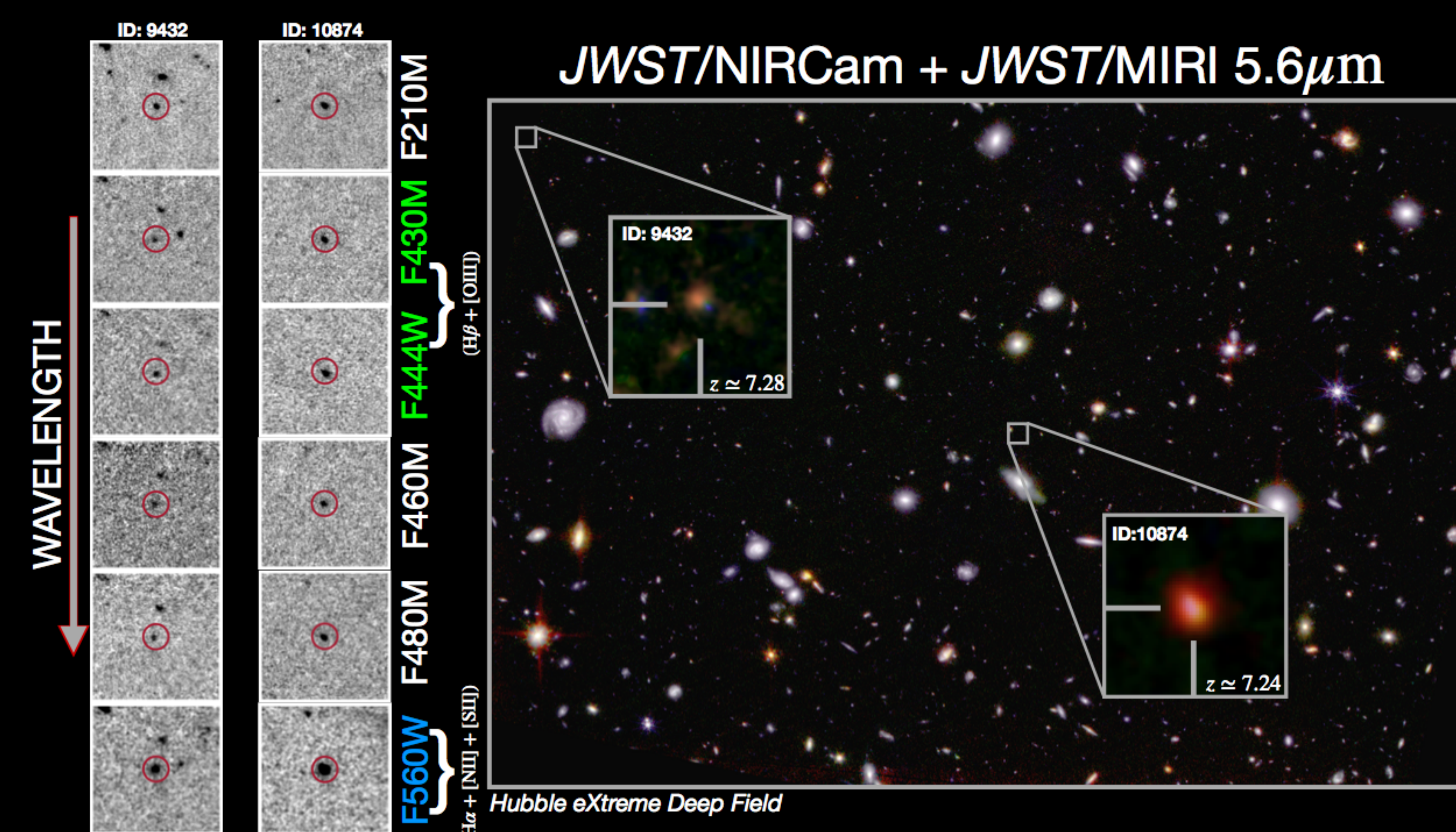
Schenker+ 2014



The fraction of galaxies showing a Lyα line decreases rapidly at z>6. Effects of reionization kick in between z~6 and 7, and reionization is over by z~6.

Search for other emission lines

JWST MIRI detects H-alpha emission at the Epoch of Reionization for the first time



Rinaldi, Caputi et al 2023, ApJ 952, 143

Outstanding questions in reionization

1. Sources of reionization: Main contribution probably from star-forming galaxies but how much do quasars contribute?

2. Ionizing escape fraction from galaxies f_{esc}: What are the f_{esc} values? And how does f_{esc} depend on the physical processes in the galaxies?

3. How many small mass galaxies are there during reionization? What is the “minimum galaxy mass”?

4. How strong is the feedback of reionization on galaxies? How strongly is subsequent star formation suppressed?

High-redshift Galaxies

A bit of perspective…

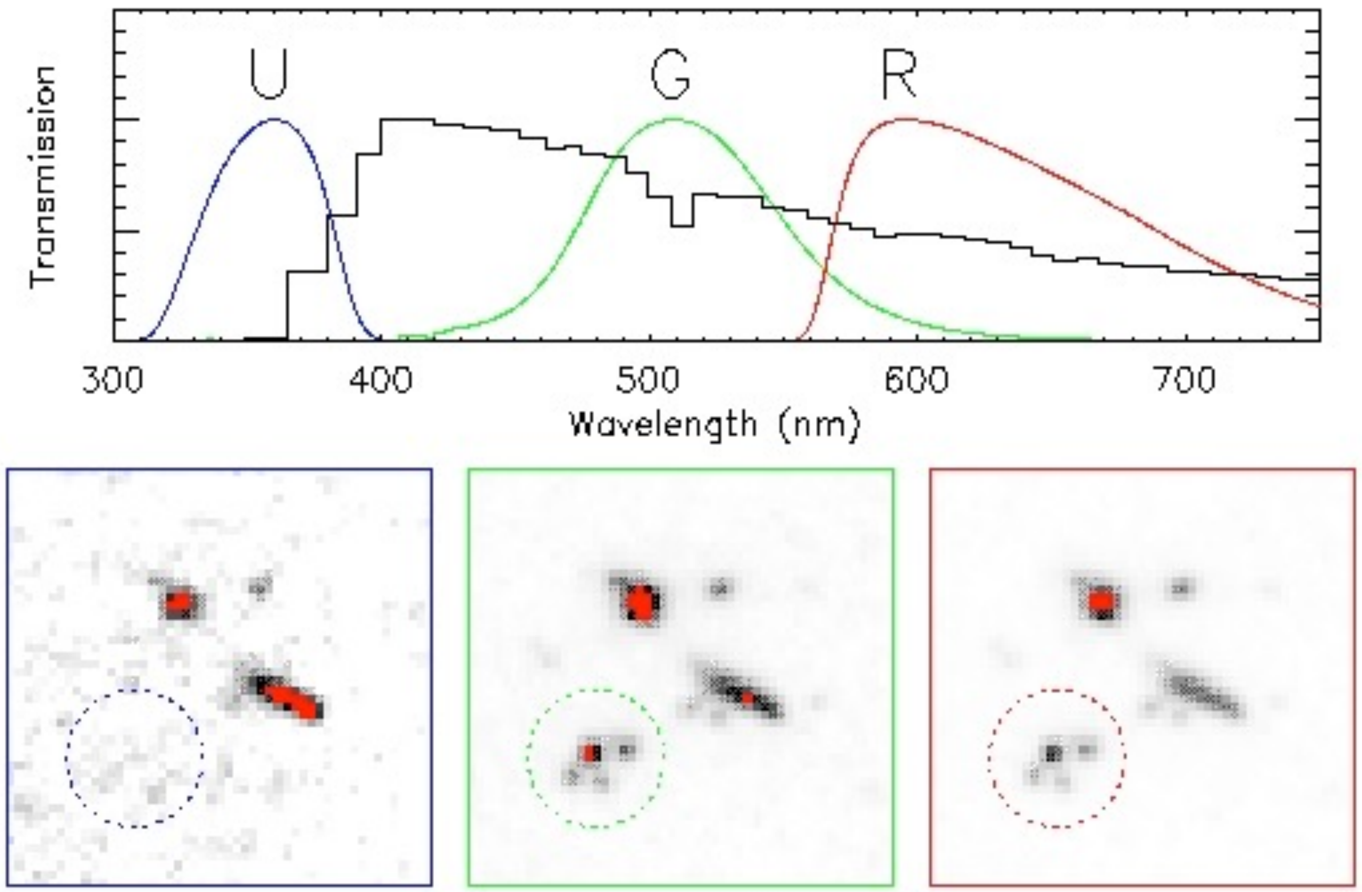
The concept of ‘high redshift’ has changed over time

At the end of 20th century, not much was known about galaxies at z>2-3

(The highest redshifts were proven by radio surveys - most massive galaxies and QSOs)

The advent of HST and large (8m-class) ground based telescopes enabled systematic study of high-z Universe

Selection of SF galaxies at z~2-3



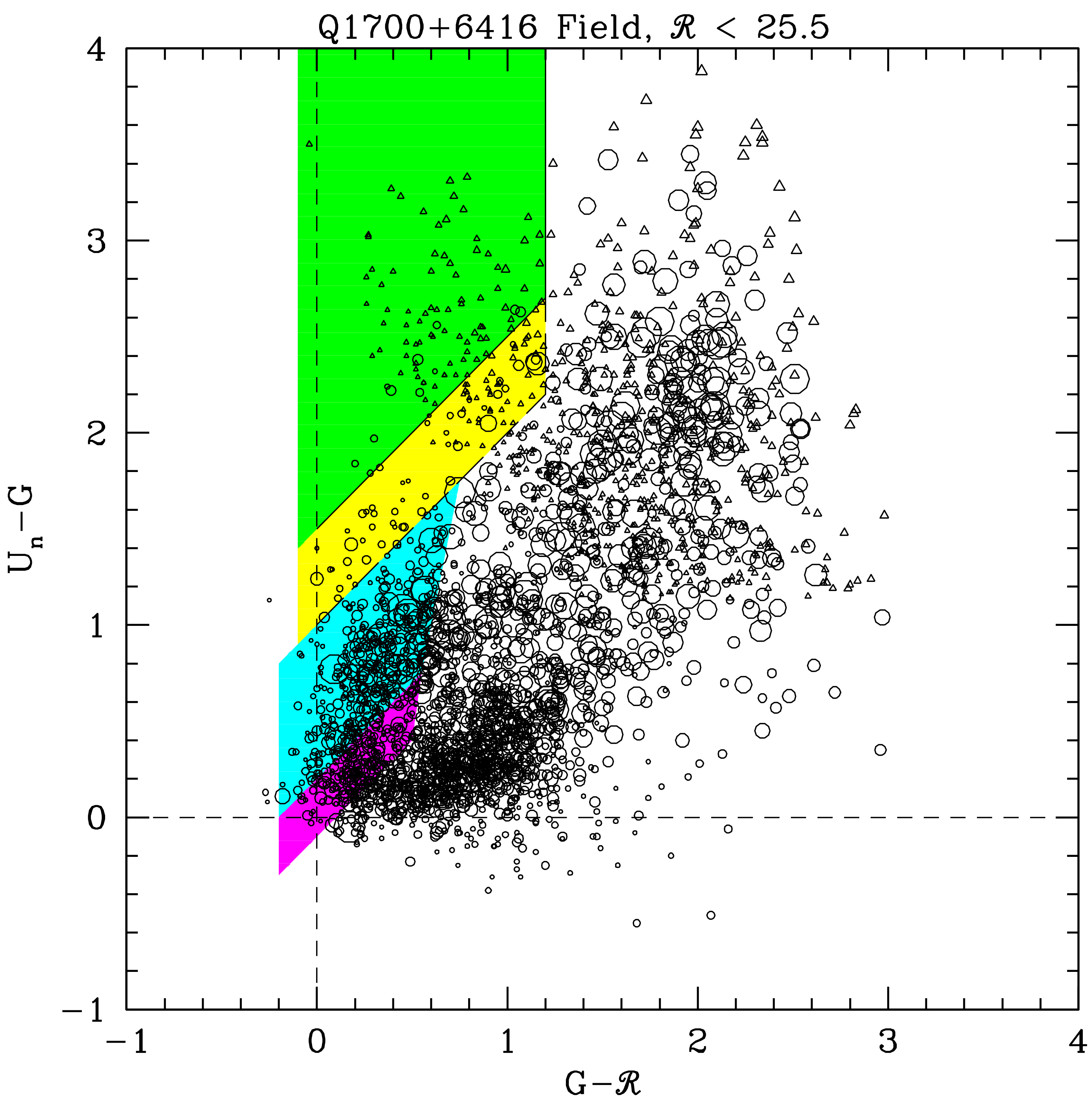
Lyman-break selection technique

Introduced by Steidel et al. (1996) to select star-forming galaxies at z~3

Picture Credit: http://www.astro.ku.dk/~jfynbo/LBG.html

Note: low-z contaminants can be 20-30% of sample

Selection of SF galaxies at z~2-3

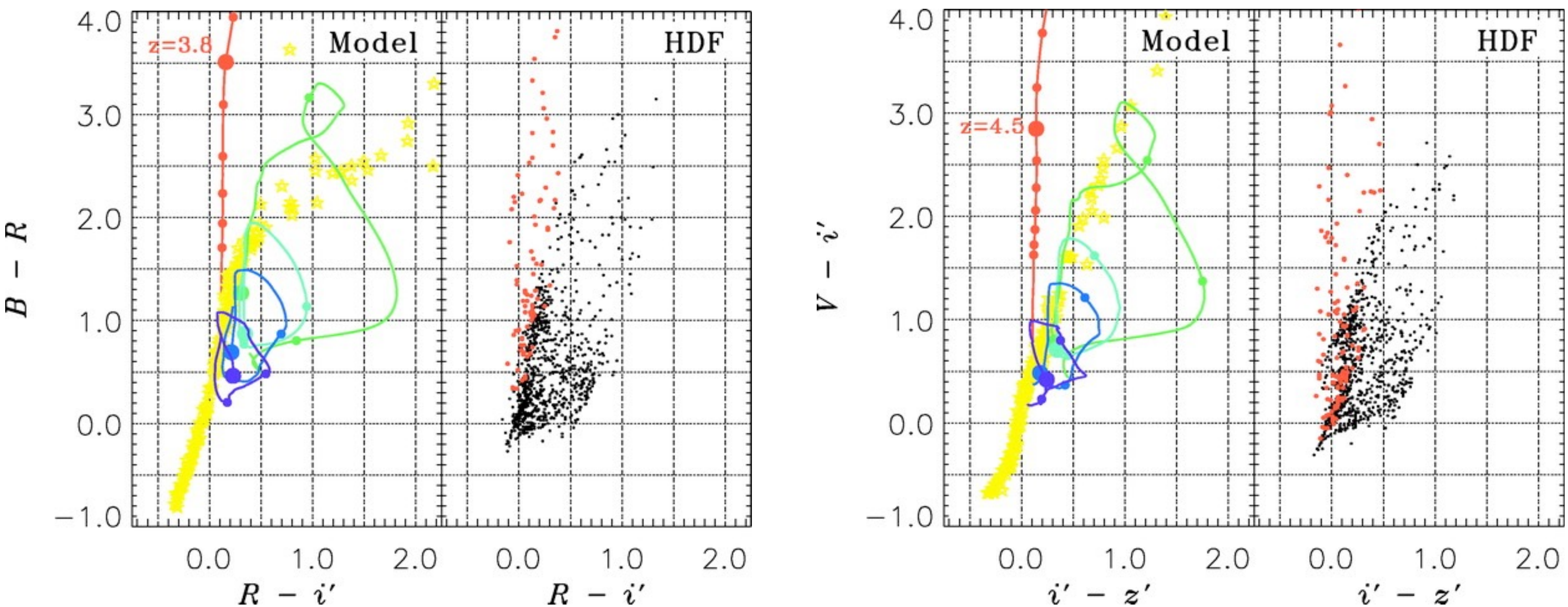


Lyman-break selection technique

Shapley (2011), based on Steidel et al. (2004)

Selection of SF galaxies at z~4-5

changing the set of filters, the technique can be extended to select higher-z galaxies

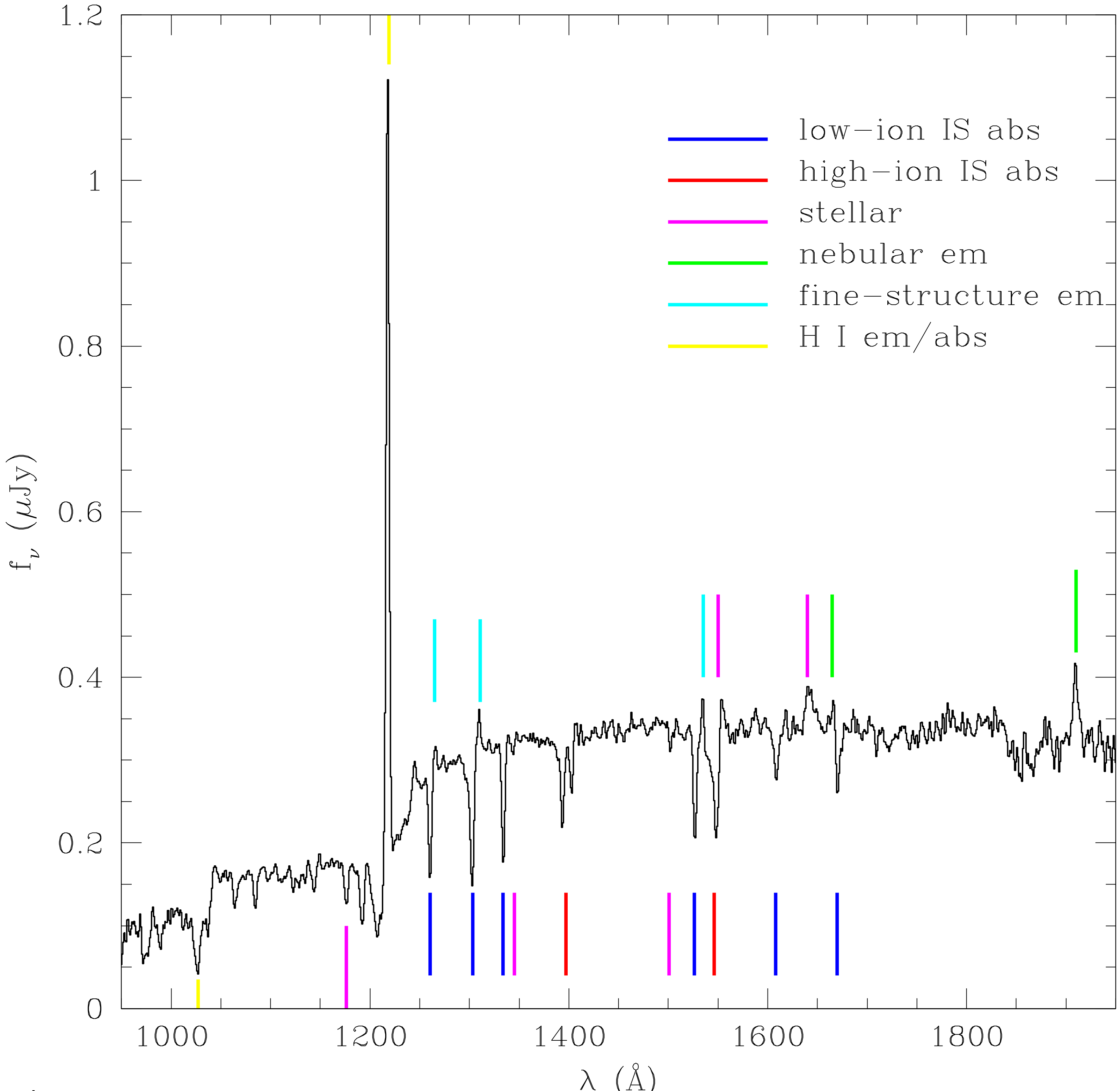


Ouchi et al. (2004)

<u>Caveat of this technique:</u> biased against dusty galaxies!

The spectroscopic confirmation

stacked spectra of ~800 Lyman-break-selected galaxies



Shapley et al. (2003)

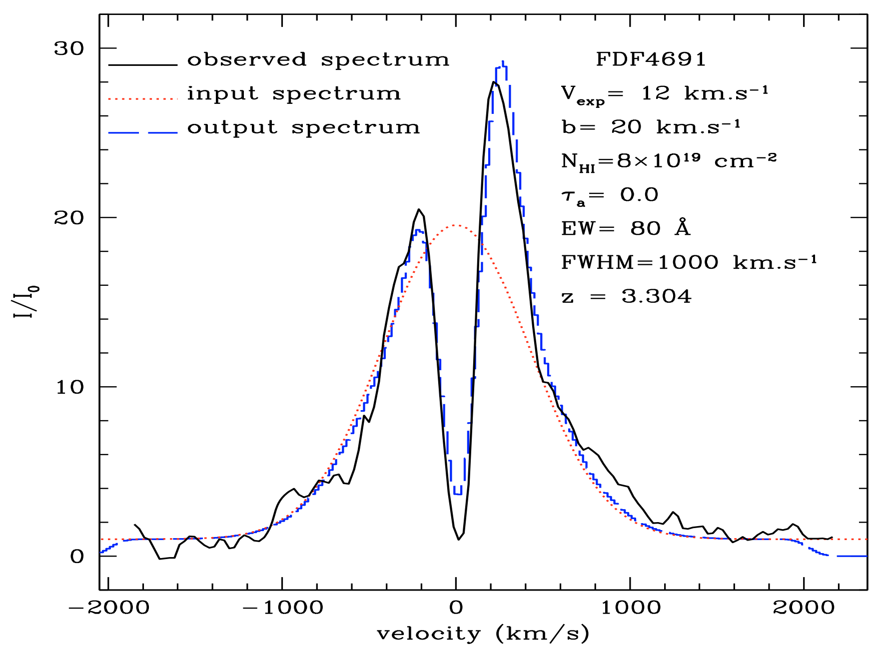
Ly-break galaxies vs. Ly-alpha emitters

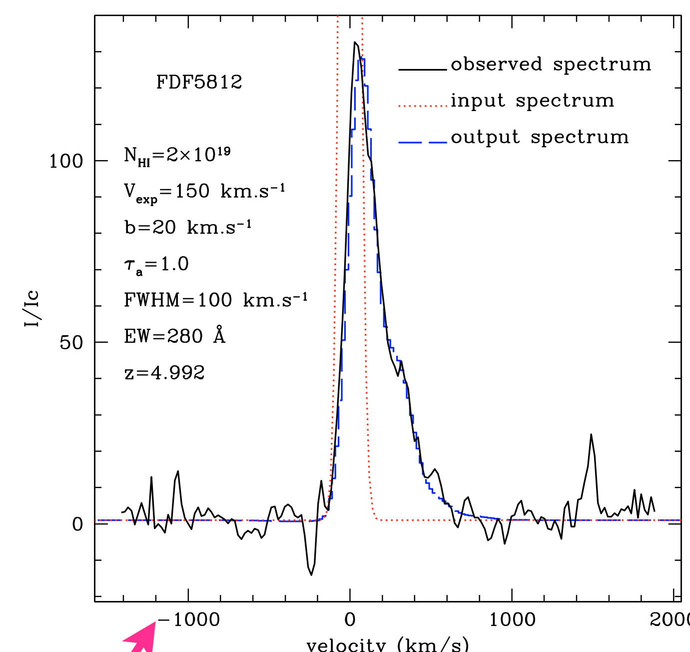
Lyman-break galaxies are not necessarily Lyman-alpha emitters

The Lyman-alpha line profile depends on the ability of Lya photons to escape dusty/clumpy interstellar medium

<u>problem:</u> *resonant scattering of photons with HI*

<u>note:</u> if Lya EW > 100 A, then age < 50 Myr





most common profile in high-z galaxies

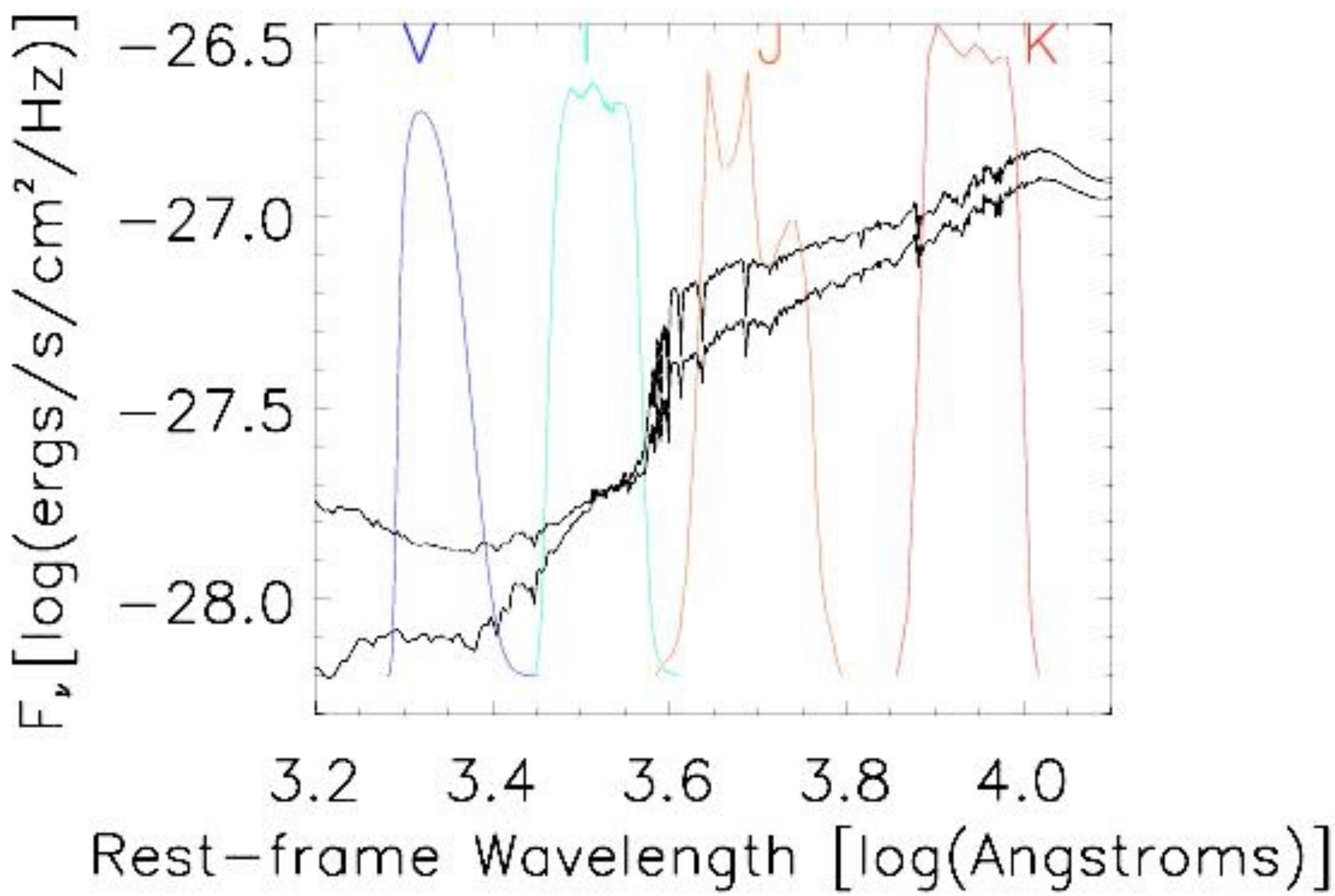
Pictures Credit: Verhamme et al. (2008); see also Neufeld (1990)

Optical vs Near-IR Galaxy Surveys

for many years, the search of z>1.5 galaxies has been performed on optical images

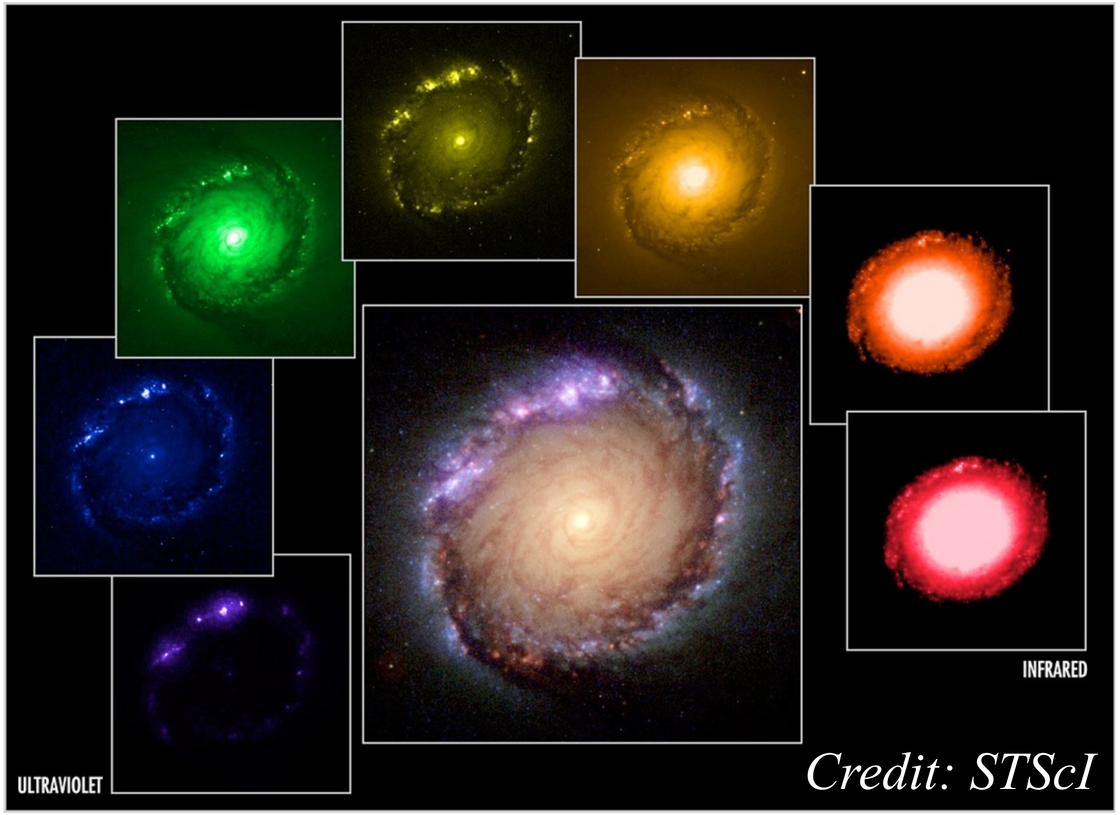
but the advent of near-IR surveys showed that optical surveys miss a significant fraction of high-z galaxies

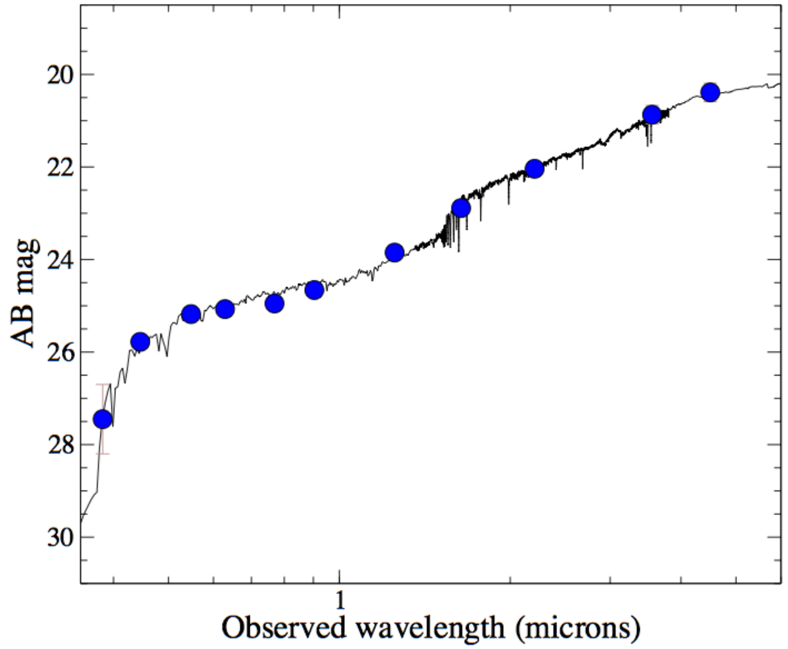
Why?



Picture Credit: http://ned.ipac.caltech.edu/level5/Sept01/Malkan/Malkan2.html

Galaxy selection through photometric redshifts





Photometric redshift

'cheap' alternative to spectroscopic redshifts

Age

Dust Extinction

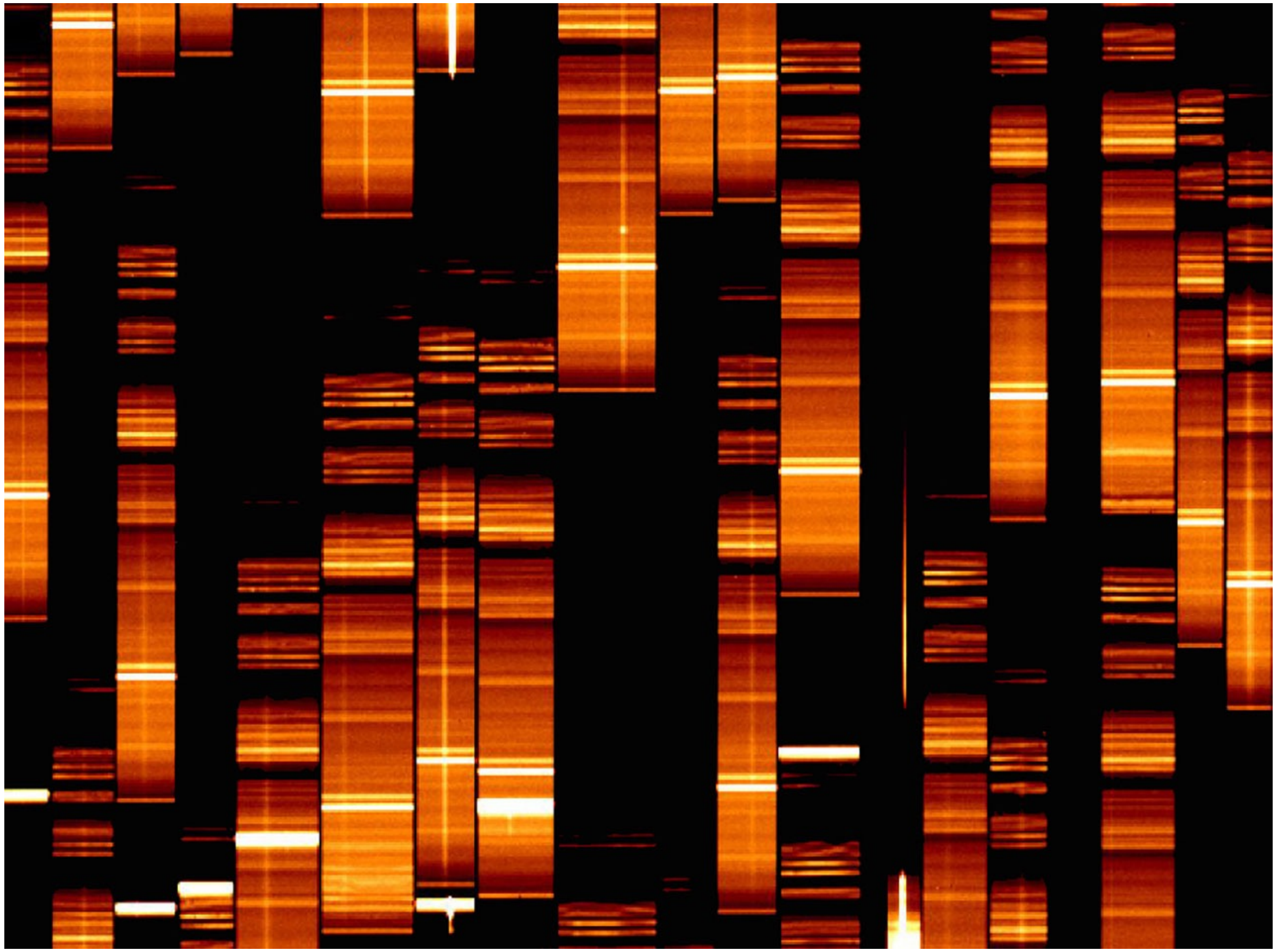
Stellar Mass

Spectroscopic galaxy surveys

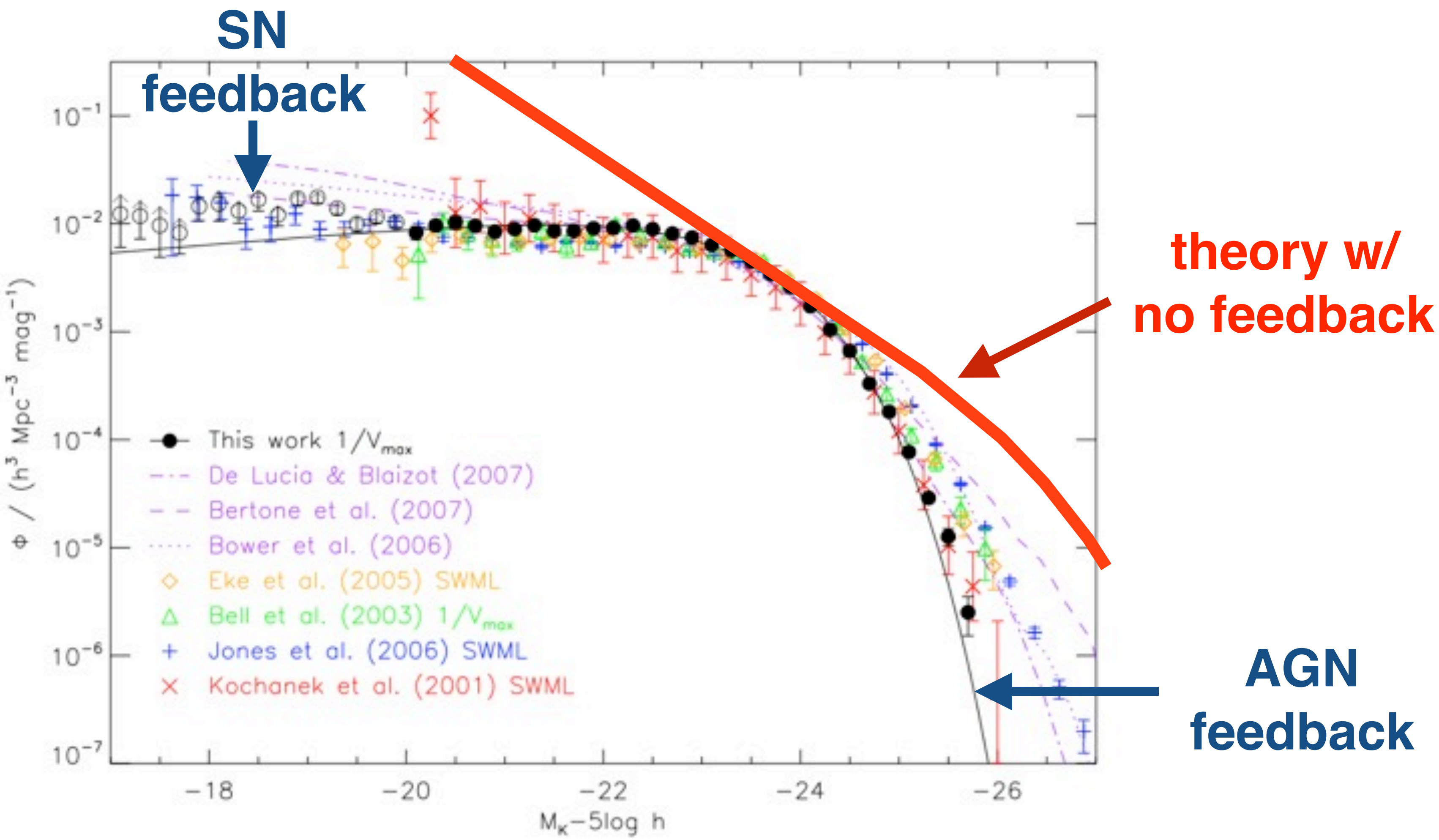
Large and relatively deep spectroscopic surveys have been possible over the past decade

Although biased towards optically-bright galaxies, they are very important to:

- calibrate zphot
- outline large-scale structure at high z
- study ISM properties



Galaxy luminosities: theory vs. observations

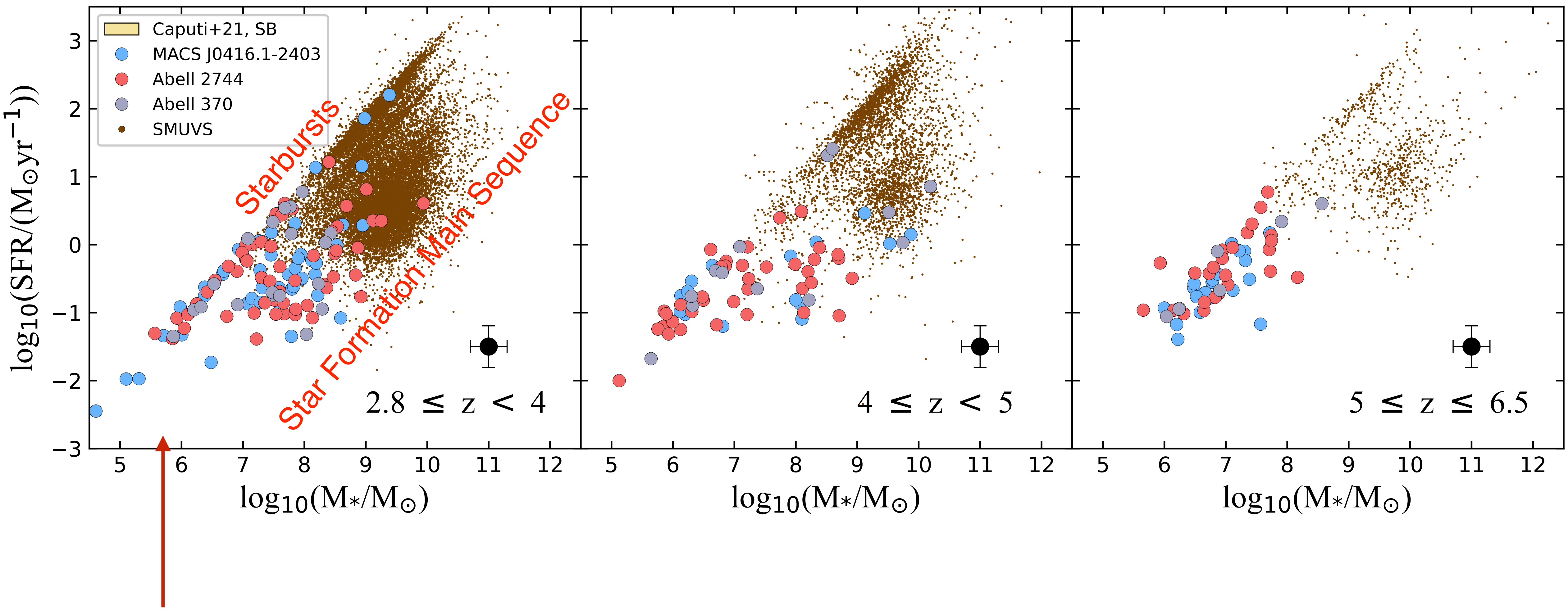


under the assumption that dark matter halos host gas: need to find mechanisms why conversion to stars is less efficient in low and high mass systems

either gas can never cool or gas gets reheated/removed

e.g. Springel et al. (2005); Somerville et al. (2008)

Observational constraints - the SFR-M* plane

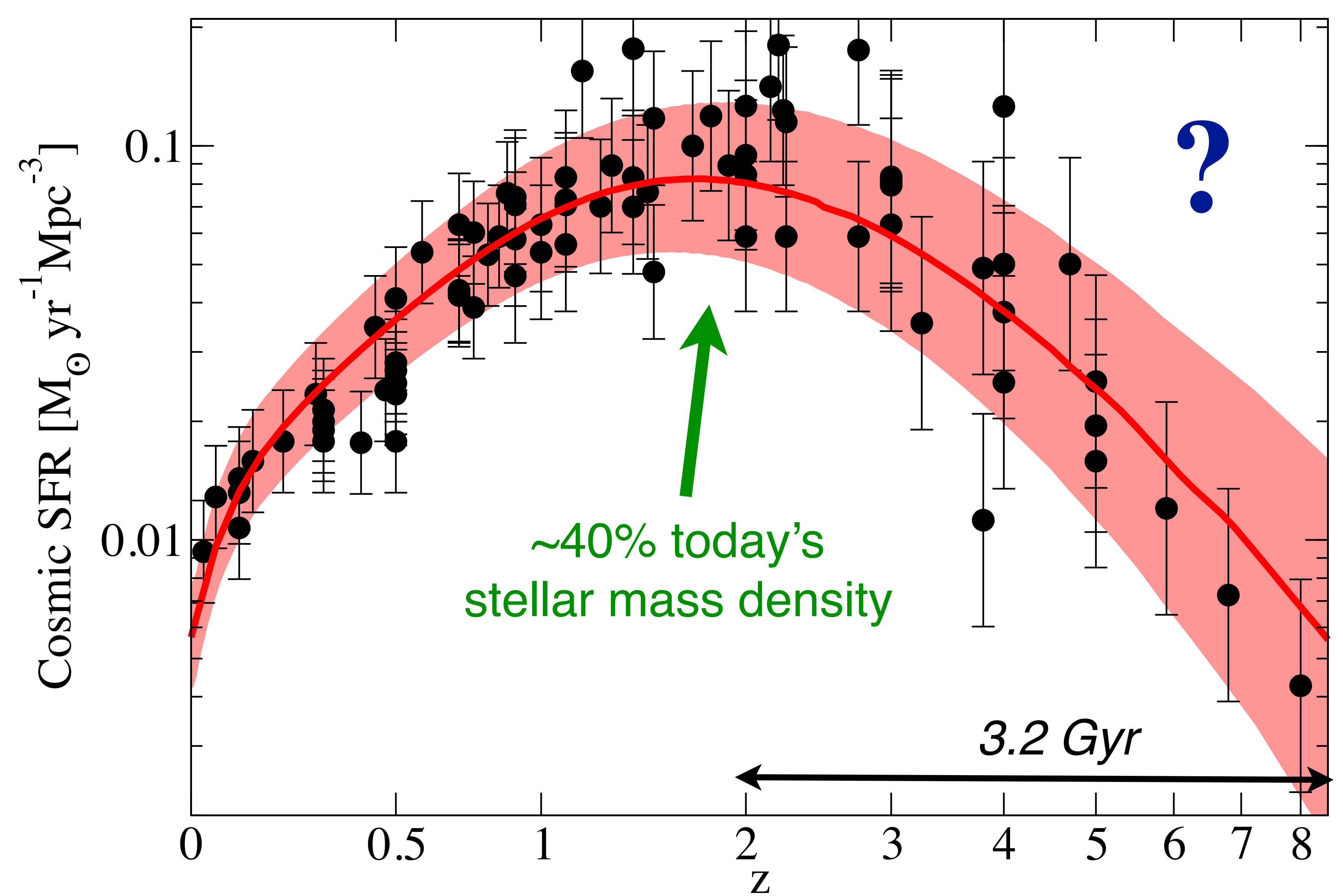


If SFR << 0.01 Msun/yr - quiescent galaxies

Rinaldi et al. (2022)

The cosmic SFR density

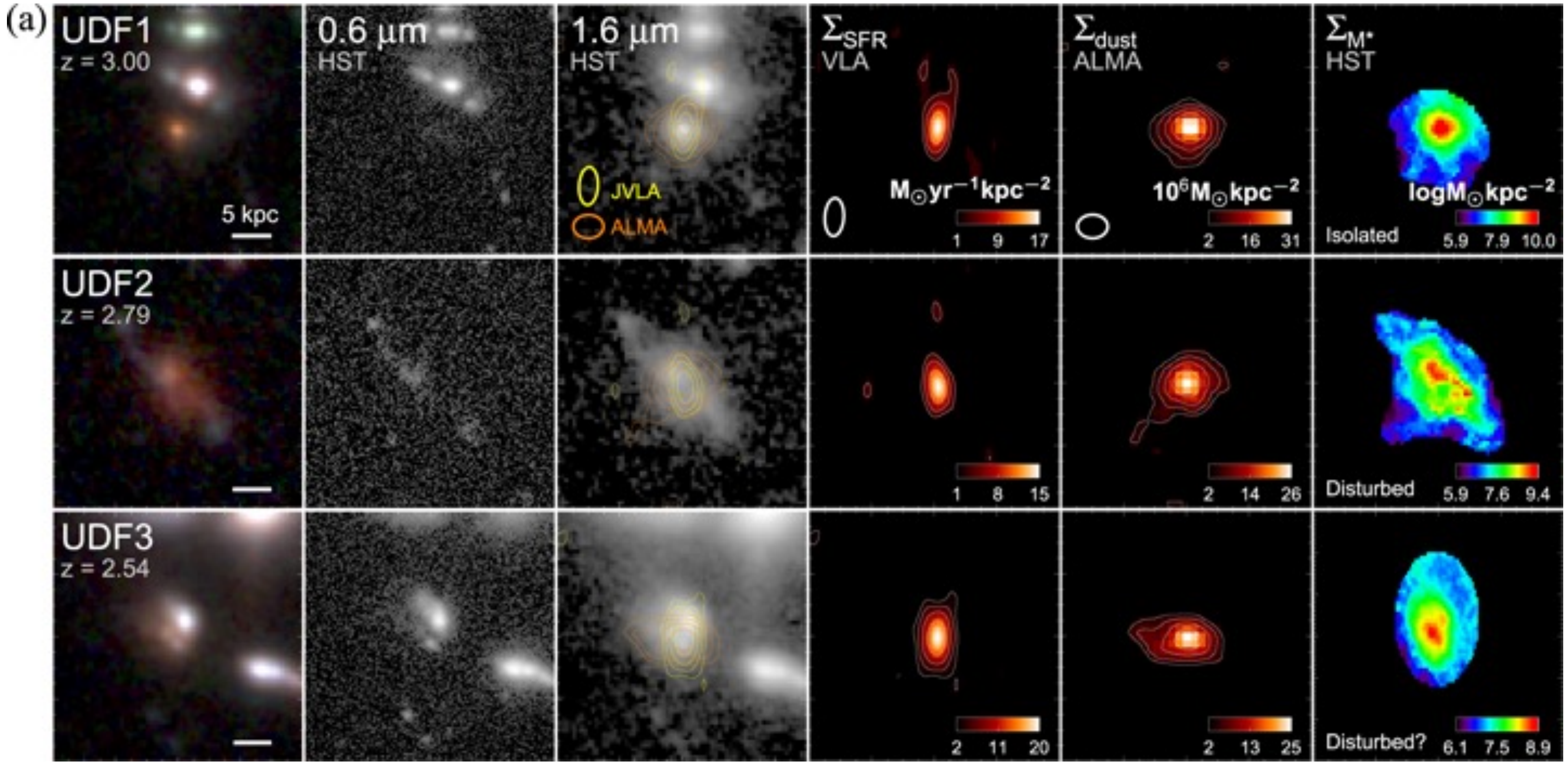
Galaxy formation and growth was much more efficient in the past



Behroozi et al. (2013); Madau & Dickinson (2014)

Dust in the young Universe

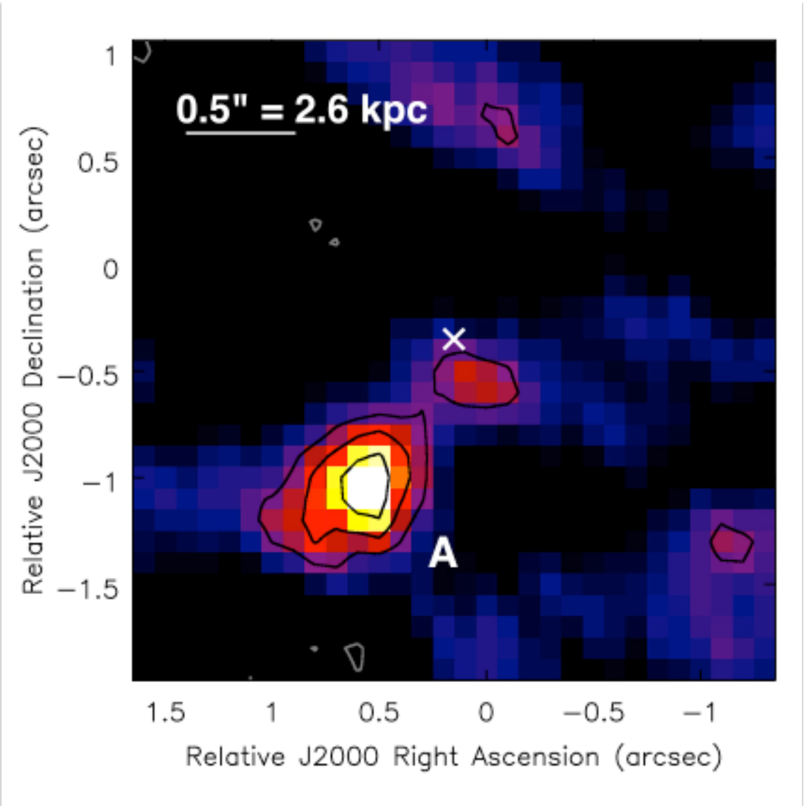
z~2



Rujopakarn et al. (2016)

Dust was very common in galaxies at z~2-4 (Universe was 1.5-3.5 Gyr old)

z~7



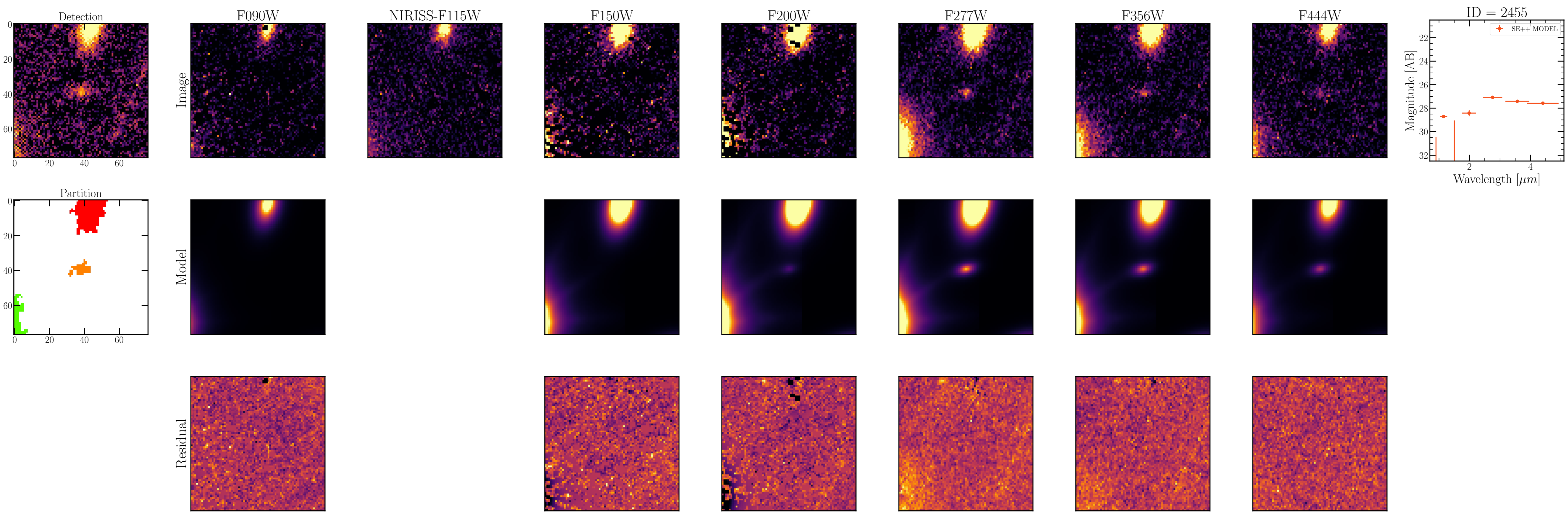
Maiolino et al. (2015)

Dust is rare in the first billion years, but evidence of dust has been found in galaxies up to z~7-8.

Some First JWST Highlights

Galaxy candidates to z~16 (!) behind SMACS 0723

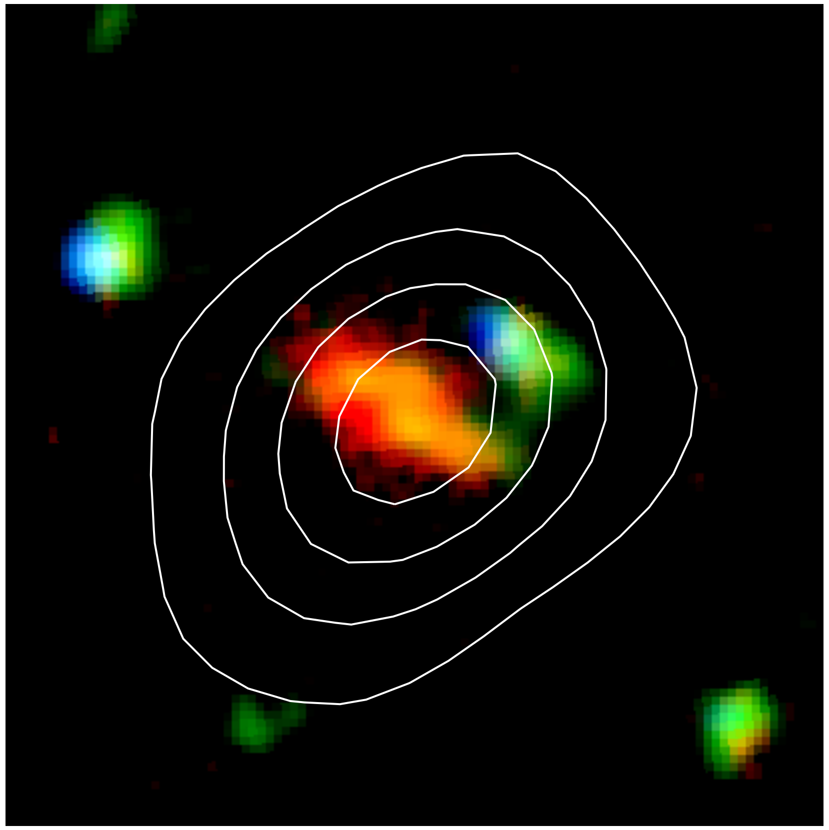
Consider with caution! — JWST photometric calibration still under review

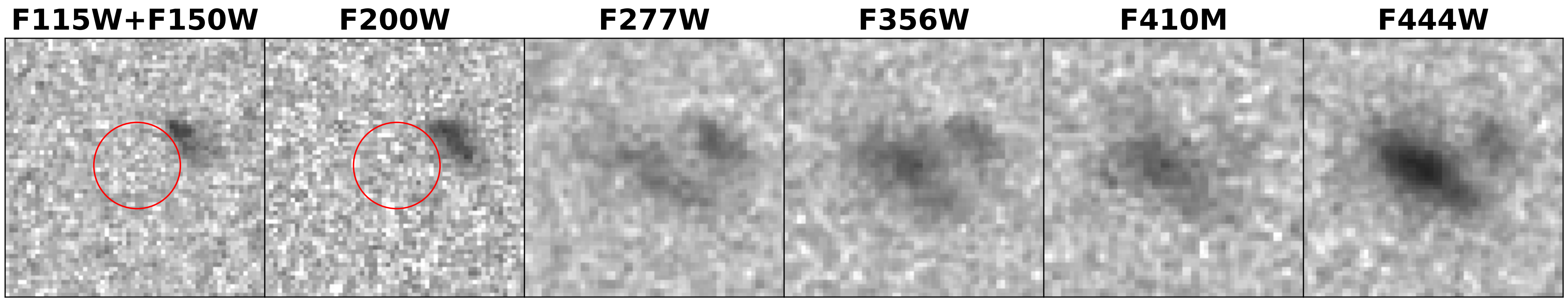


Atek et al. (2022)

There may be degeneracies not properly taken into account, e.g. very dusty galaxies at lower redshifts

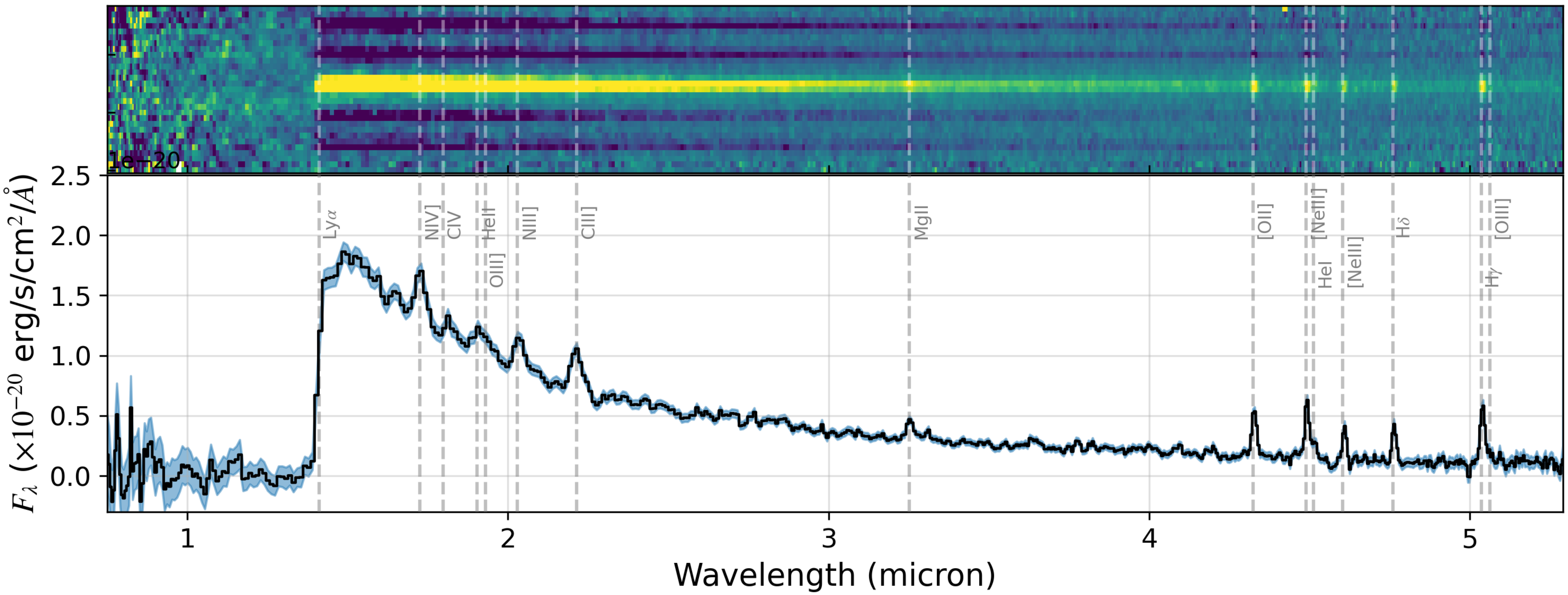
Very dusty galaxy at z~5 confused for z~18 galaxy





Zavala et al. (2022)

Galaxy spec confirmed at z=10.6



Bunker et al. (2023)