Ay 21

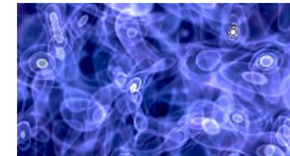
Young and Forming Galaxies

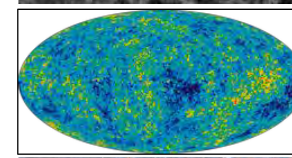
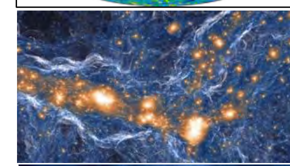
Galaxy Formation

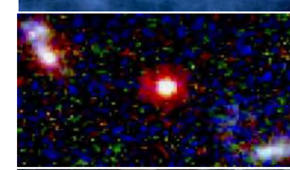
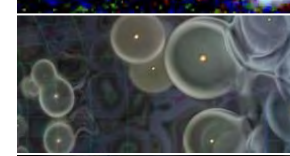
- The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars
- Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes - it is a very messy process, much more complicated than LSS formation and growth
- Probably closely related to the formation of the massive central black holes as well
- Generally, we think of massive galaxy formation at high redshifts ($z \sim 10^{\pm 2}$, say); dwarfs may be still forming now
- Observations have found populations of what must be young galaxies (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at $z \sim 6 - 12$ or so, in the so-called Reionization Era
- The frontier is moving to $z > 20$, before the first galaxies

A Timeline of Galaxy Formation

z	age	
?	?	Quantum fluctuations in the early universe become the seeds of density fluctuations
10^4	10^4	Radiation → matter dominance; DM fluctuations begin to grow
	10^5	
10^3		Recombination; universe becomes neutral and opaque to UV light; CMB released
	10^6	Baryons start falling into DM halos, cooling makes them more concentrated than DM
	10^7	
10^2	10^8	The first (Pop. III) stars; reionization starts
		The earliest observed galaxies (JWST)
10^1		Universe reionized by young stars and AGN
6	10^9	Reionization ends; galaxy evolution begins



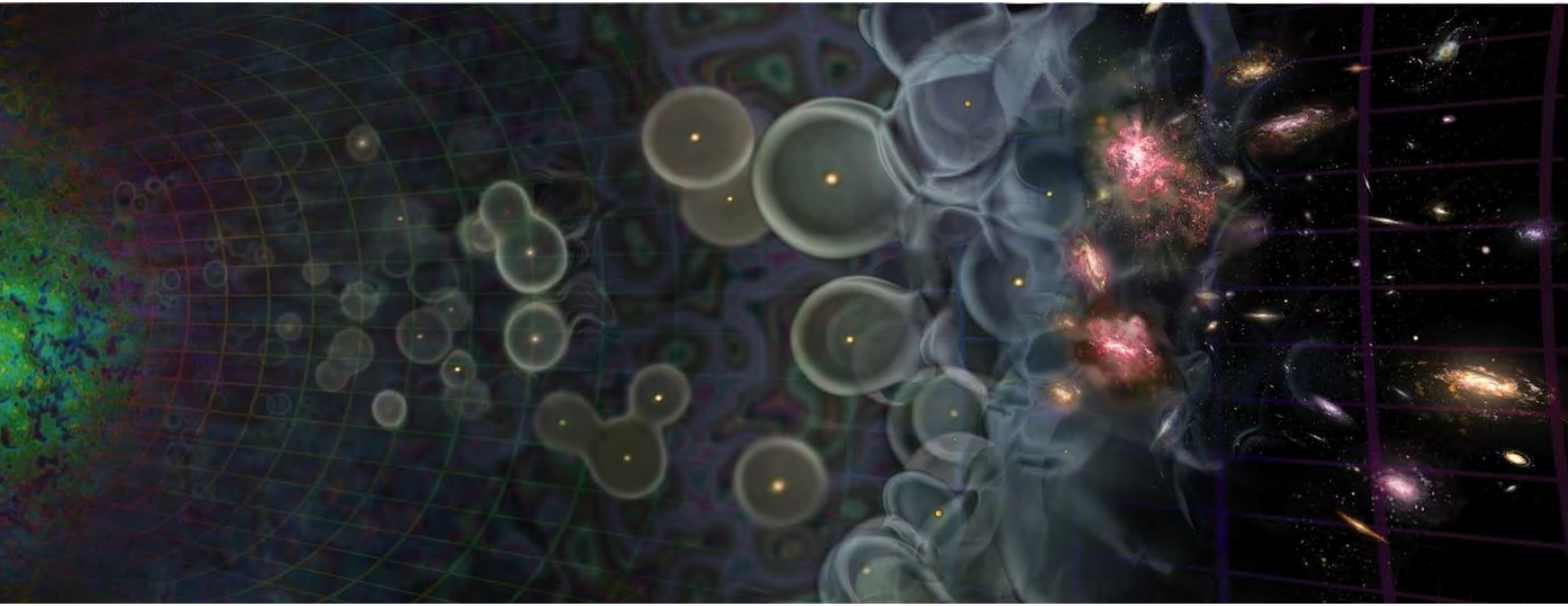




A General Outline

- The smallest scale density fluctuations keep collapsing, with baryons falling into the potential wells dominated by the dark matter, achieving high densties through cooling
  - This process starts right after the recombination at $z \sim 1100$
- Once the gas densities are high enough, star formation ignites
  - This probably happens around $z \sim 20$ - 30
  - By $z \sim 6$, UV radiation from young galaxies reionizes the unverse
- These protogalactic fragments keep merging, forming larger objects in a hierarchical fashion ever since then
- Star formation enriches the gas, and some of it is expelled in the intergalactic medium, while more gas keeps falling in
- If a central massive black hole forms, the energy release from accretion can also create a considerable feedback on the young host galaxy

An Outline of the Early Cosmic History

(illustration from Avi Loeb)



Recombination: Release of the CMBR

Dark Ages: Collapse of Density Fluctuations

Reionization Era: The Cosmic Renaissance

Galaxy evolution begins

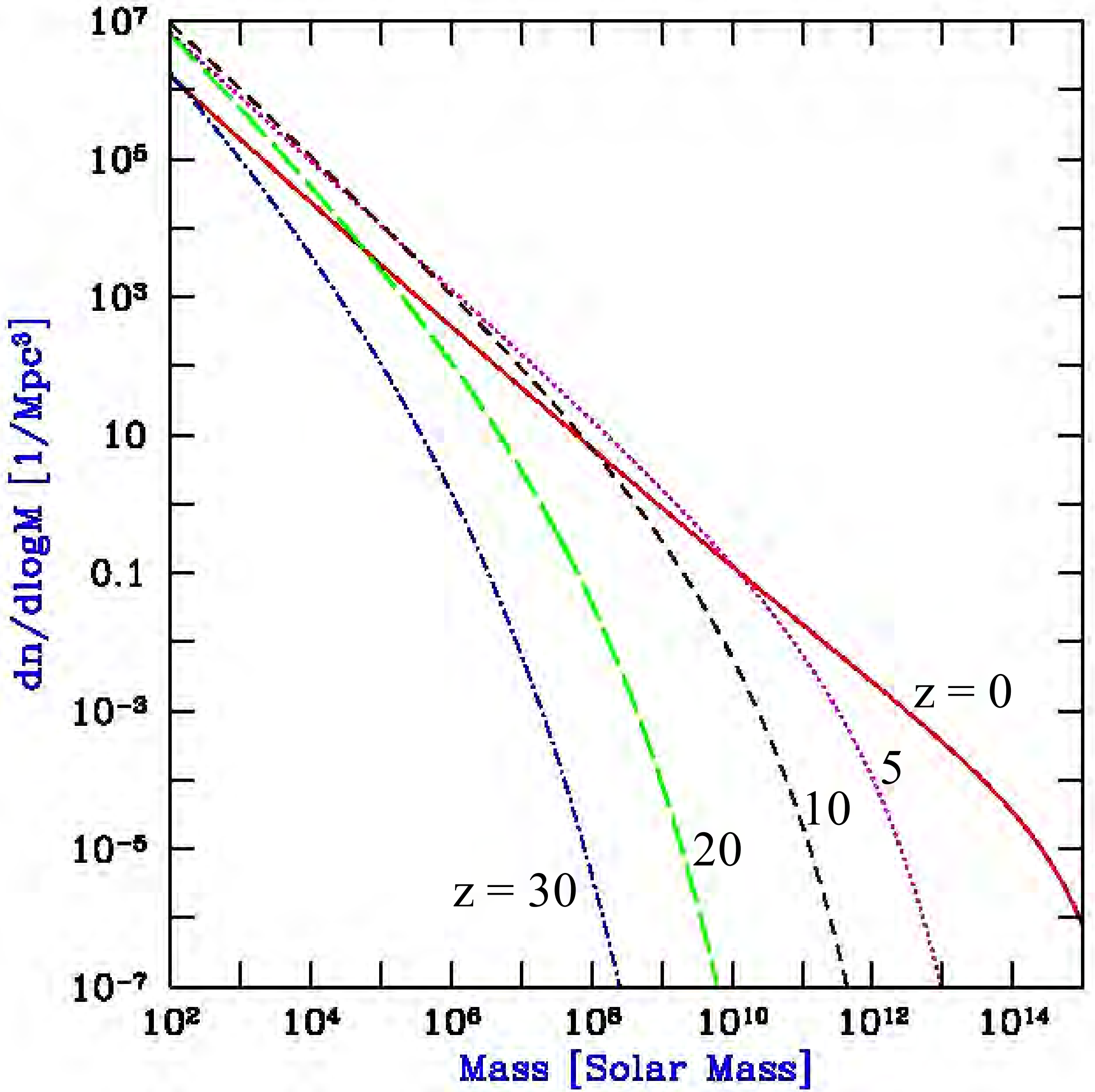
Physical Processes of Galaxy Formation

Galaxy formation is ***a much messier problem than structure formation.*** In addition to gravity and build-up of host dark halos (fairly well understood) we need to add:

- Shock heating of gas
- Cooling of gas into dark halos
- Formation of stars (also not a well understood process!) from the cold gas
- The evolution of the resulting stellar population
- Feedback processes generated by the ejection of mass and energy from evolving stars
- Production and mixing of heavy elements (chemical evolution)
- Effects of dust obscuration
- Formation of black holes at galaxy centers and effects of AGN emission, jets, etc.

… etc., etc., etc.

The Evolving Dark Halo Mass Function (Press-Schechter)

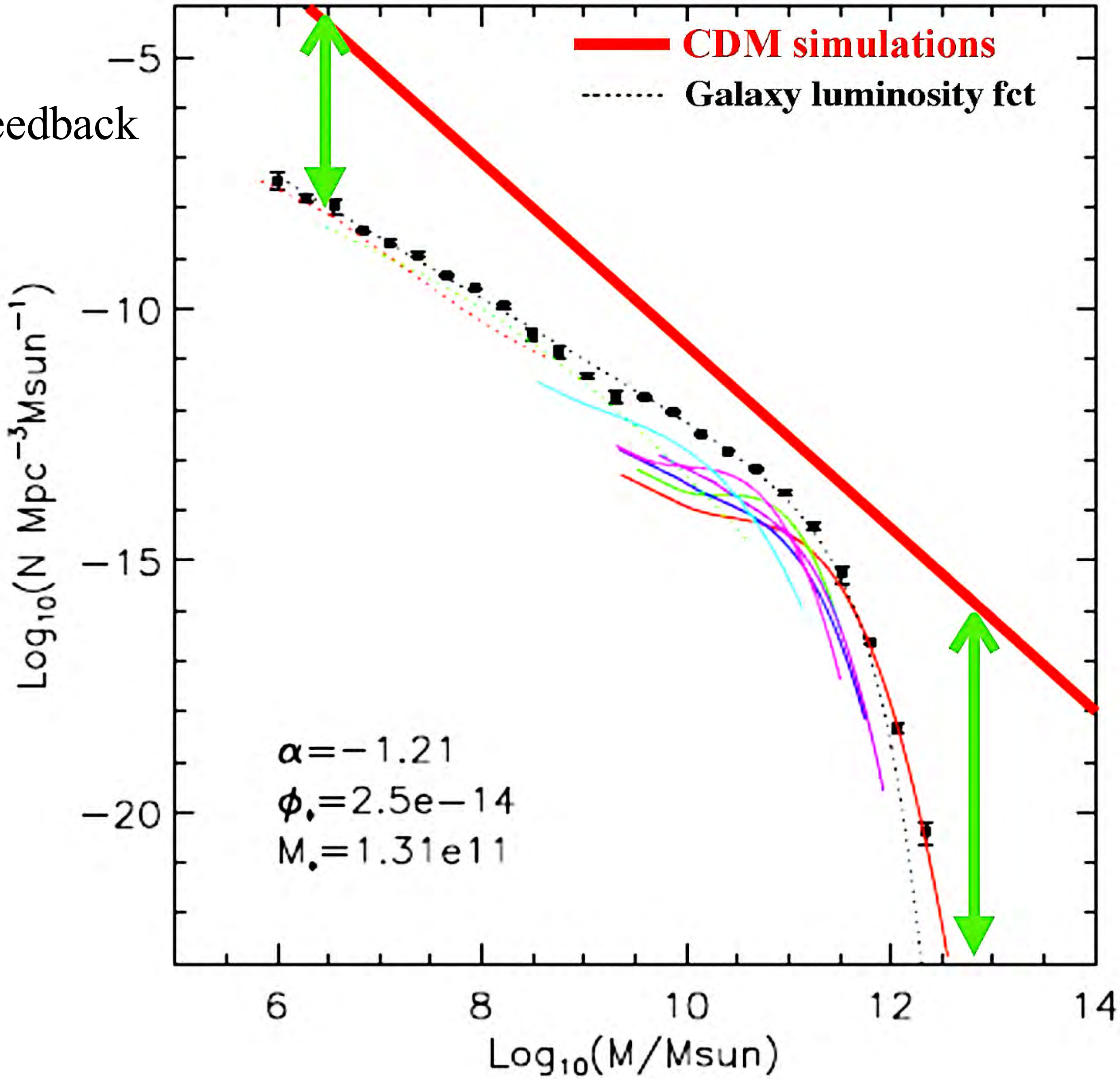


Hierarchical merging produces ever more massive halos as the time goes on

Barkana & Loeb

Predicted vs. Observed

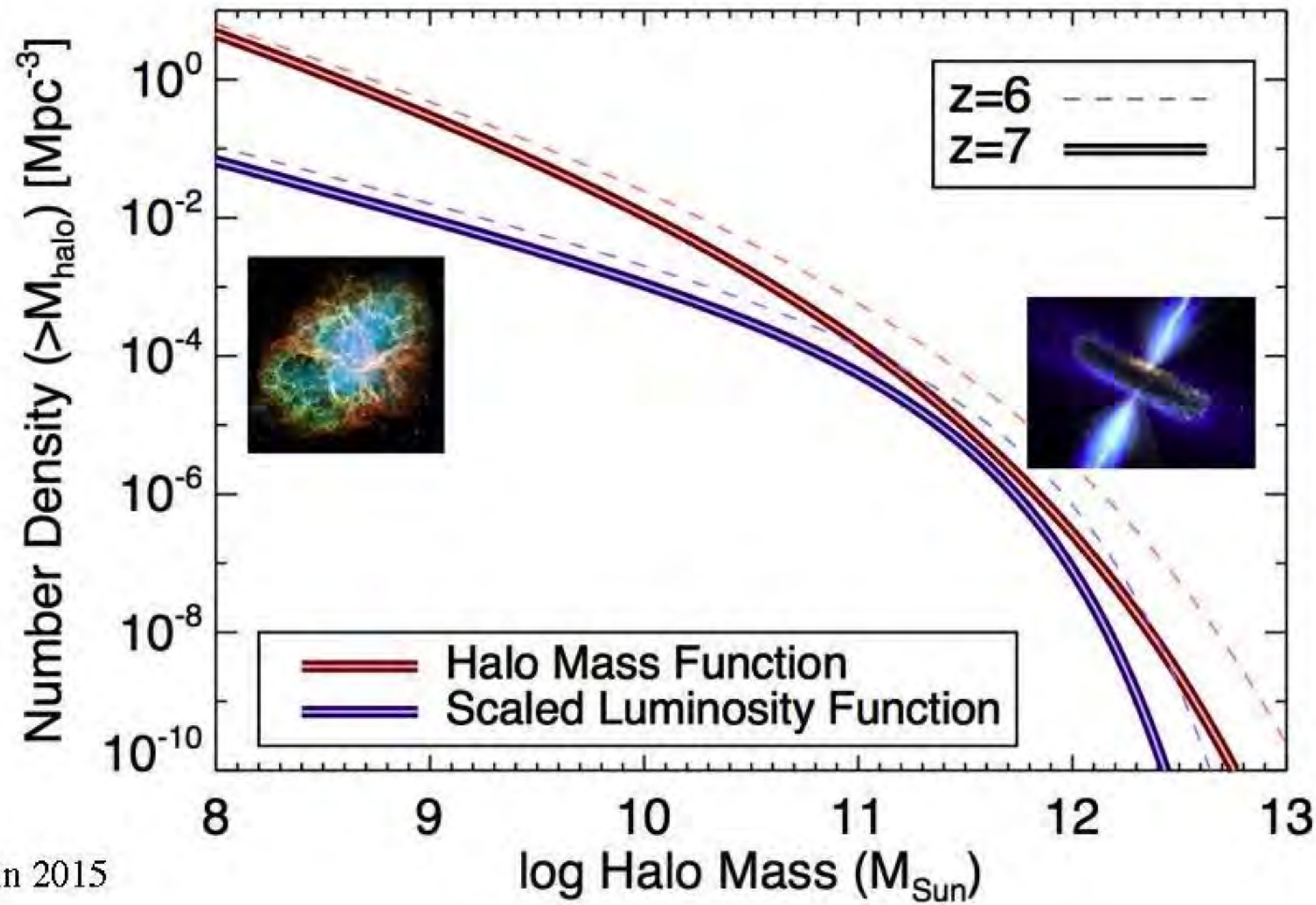
SNe Feedback



Dissipative processes (feedback) modify the galaxy mass function

Cooling and AGN Feedback

SN and AGN Feedback Modified the Halo Mass Function



Finkelstein 2015

Energy Release From Forming Galaxies

Galaxies collapse and cool. The release of the binding energy is:

$$|E_{bind,gal}| \simeq M_{cool} \langle V_{3d}^2 \rangle \simeq$$

$$\simeq 1.2 \times 10^{59} \text{erg} \times (M_{cool}/10^{11} M_\odot) \, (V_{3d}/250 \text{km s}^{-1})^2$$

where M_{cool} is the total mass which can cool radiatively

Binding energy of collapsing protostars is of a comparable value:

$$|E_{bind,\star}| \simeq G \, M_{\Sigma\star} \langle M_\star \rangle / \langle R_\star \rangle \simeq$$

$$\simeq 4 \times 10^{58} \text{erg} \times (M_{\Sigma\star}/10^{10} M_\odot) \, (\langle M_\star \rangle / M_\odot) \, (R_\odot / \langle R_\star \rangle)$$

where $M_{\Sigma\star}$ is the total mass converted to stars
$\langle M_\star \rangle$ is tl average star mass,
and $\langle R_\star \rangle$ is the average star radius

Energy Release From Forming Galaxies

Probably the most important energy source in PGs was the nuclear burning in initial starbursts:

$$E_{nuc} \simeq \epsilon \, M_{\Sigma\star} \, c^2 \, \Delta X \simeq 10^{60} \mathrm{erg} \, (\epsilon/0.001) \, (M_{\Sigma\star}/10^{10} M_{\odot}) \, (\Delta X/0.05)$$

where $M_{\Sigma\star}$ is the total mass burned in stars in the PG phase, $\epsilon \simeq 1$ Mev$/m_p c^2 \simeq 0.001$ is the average net efficiency of nuclear reactions in stars, and $\Delta X \simeq \Delta Z + \Delta Y \simeq 0.05$ is the fraction of the hydrogen converted to helium and metals.

Note: the mean metallicity of old stellar populations is ~ Solar, i.e., about 1.7% by mass; and you get ~ 3-5 g of He (ΔY) for each 1 g of metals (ΔZ) produced in stellar burning

Finally, early active galactic nuclei may have been important contributors to the energy budget in at least some, and possibly all PGs. Their energy release could have rivaled other mechanisms. Taking a rough guess for the average luminosity $\langle L_{bol} \rangle$ and the duration of the active episode Δt:

$$E_{AGN} \sim \langle L_{bol} \rangle \, \Delta t \simeq 1.2 \times 10^{60} \mathrm{erg} \, (\langle L_{bol} \rangle / 10^{10} L_{\odot}) \, (\Delta t / 10^{8} \mathrm{yr})$$

Expected Observable Properties of FGs

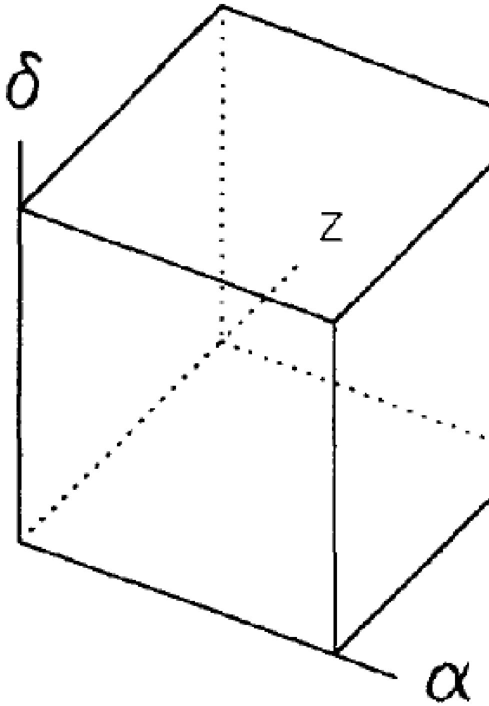
- We expect a release of $\Delta E \sim 10^{60}$ ergs from a typical proto-elliptical (or a large bulge); but over what time scale?
  - The starburst time scale of ~ 10^7 - 10^8 yrs
  - The free-fall time scale of ~ 10^8 yrs
  - The merging time scale of ~ 10^9 yrs
- Since luminosity is $L \sim \Delta E/\Delta t$, we estimate typical

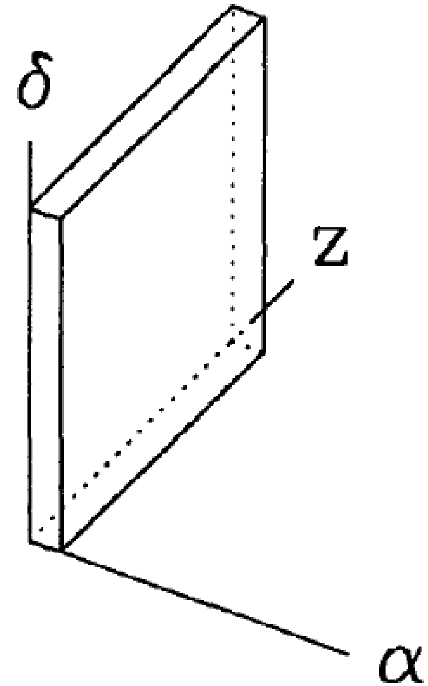
$$L_{PG} \sim 10^{11} - 10^{12}\ L_\odot,$$

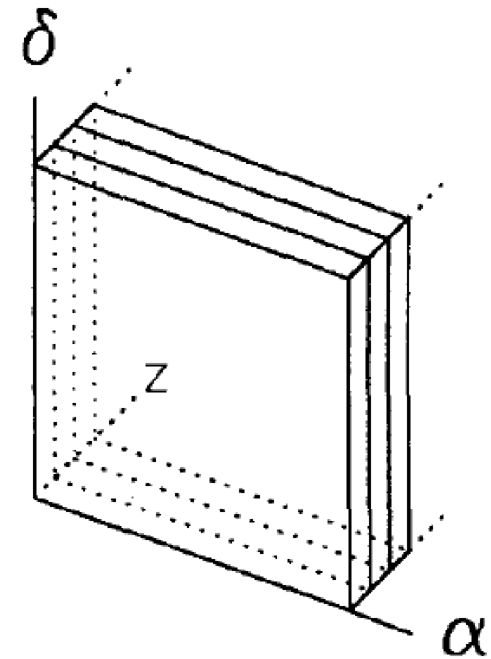
or absolute magnitudes $M \sim -22$ to -25 mag

- Given the luminosity distances to z ~ 6 - 12, the expected apparent magnitudes are in the range ~ 26 to 30 mag
- A few % of the total energy is in recombination lines, e.g., Lyα
- But the **Big Question** is: ***is this luminosity obscured by dust?***
  - No: optical/NIR surveys; look for Ly α emitters
  - Yes: sub-mm/FIR surveys; use molecular lines, e.g., CO

Emission Line Search Methodologies







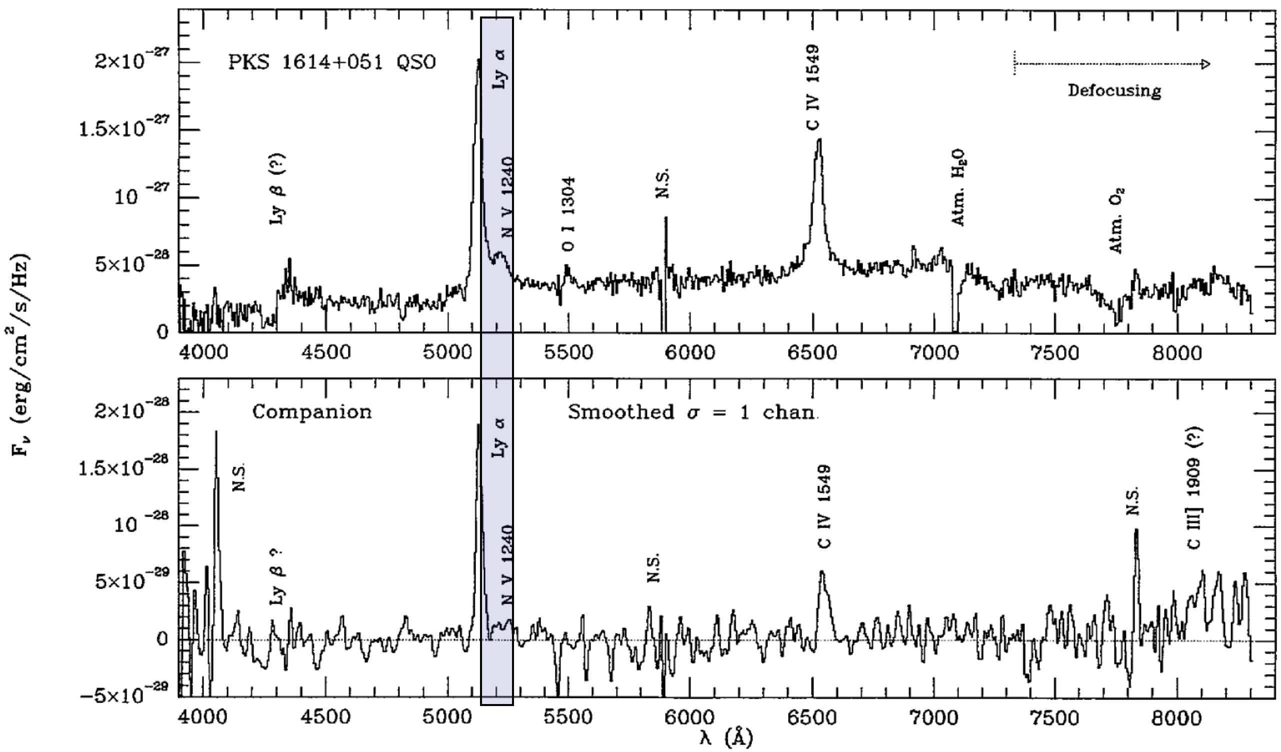
Slitless spectroscopy:
Large volume, but low S/N (~ depth)

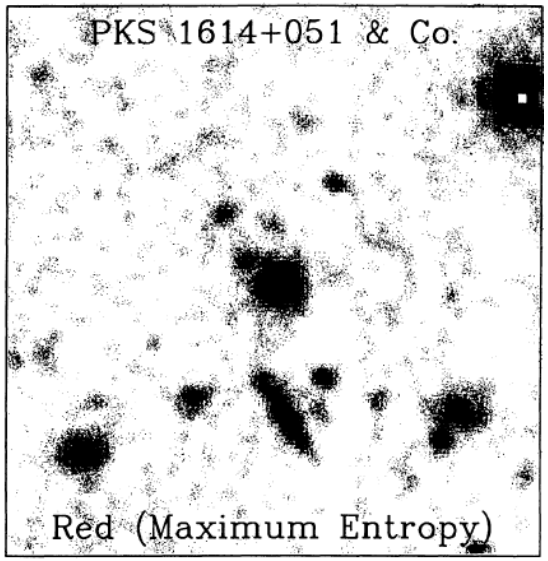
Long-slit spectroscopy:
Small volume,
large redshift range,
good depth

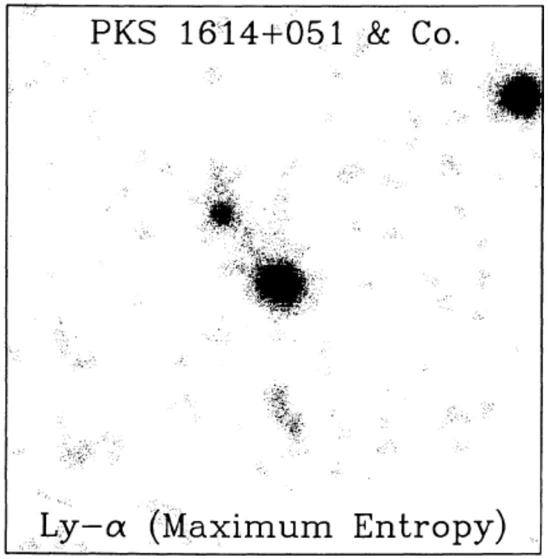
Narrow band imaging:
Moderate volume,
small redshift range,
good depth

Narrow-Band Imaging

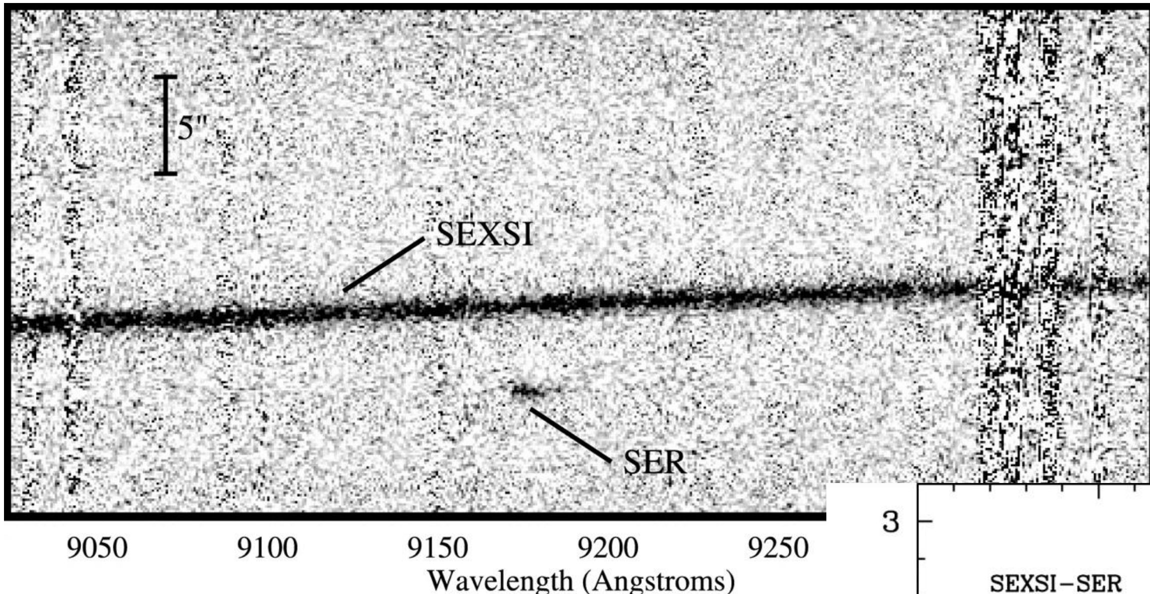
A greatly increased contrast for an object with a strong line emission

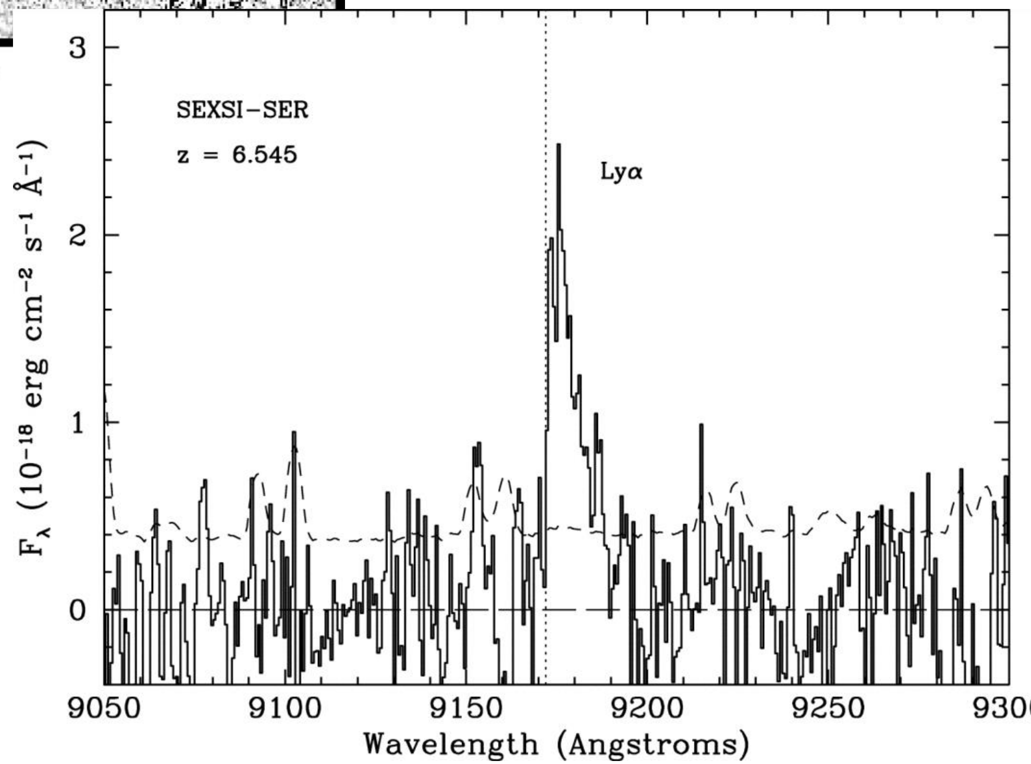






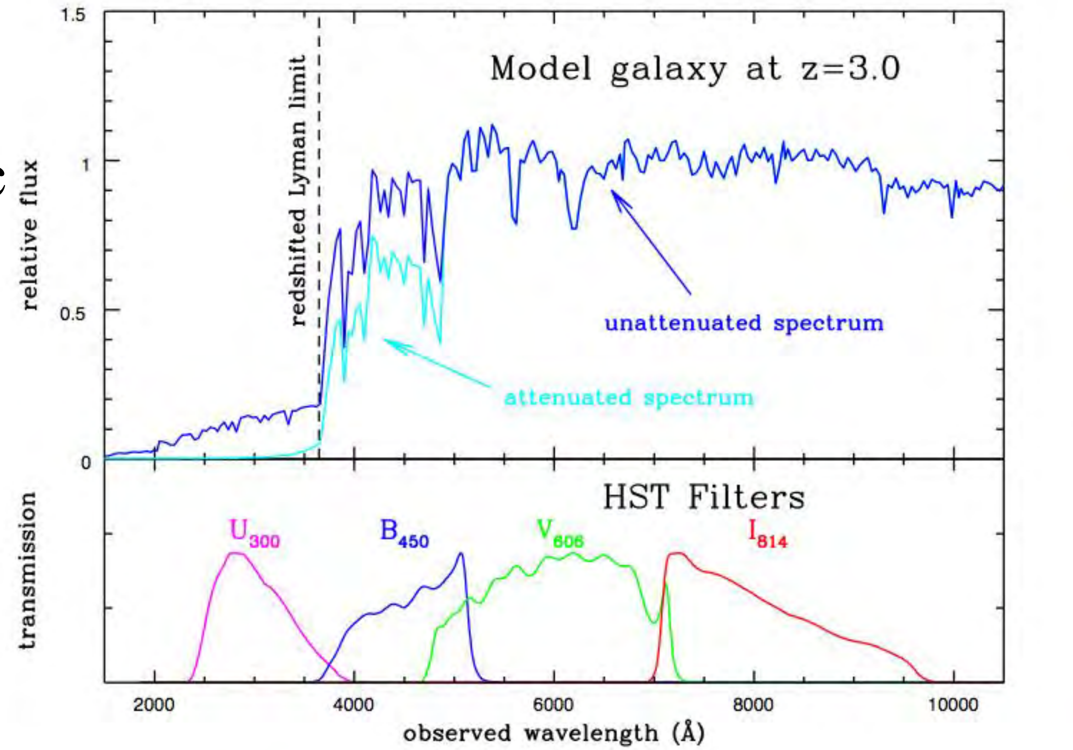
Long-Slit Spectroscopy + Serendipity

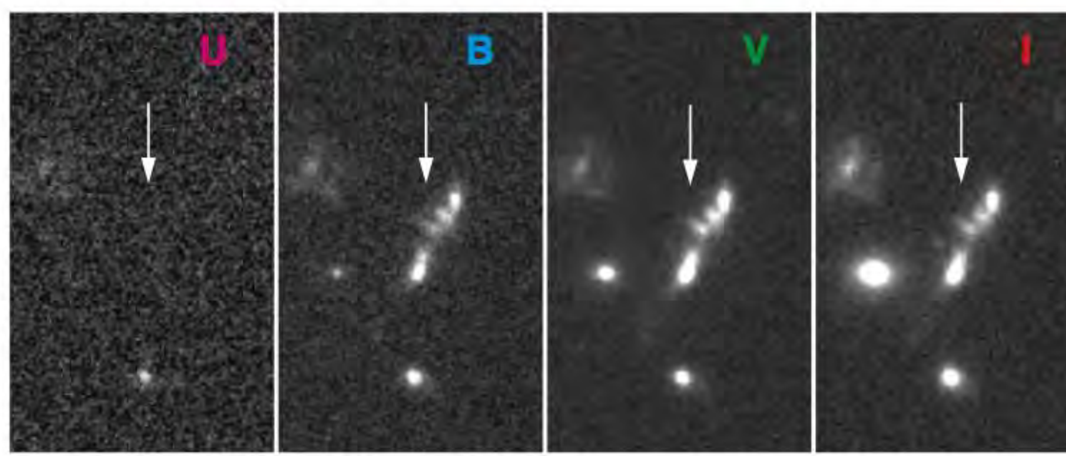




The Lyman-Break Method

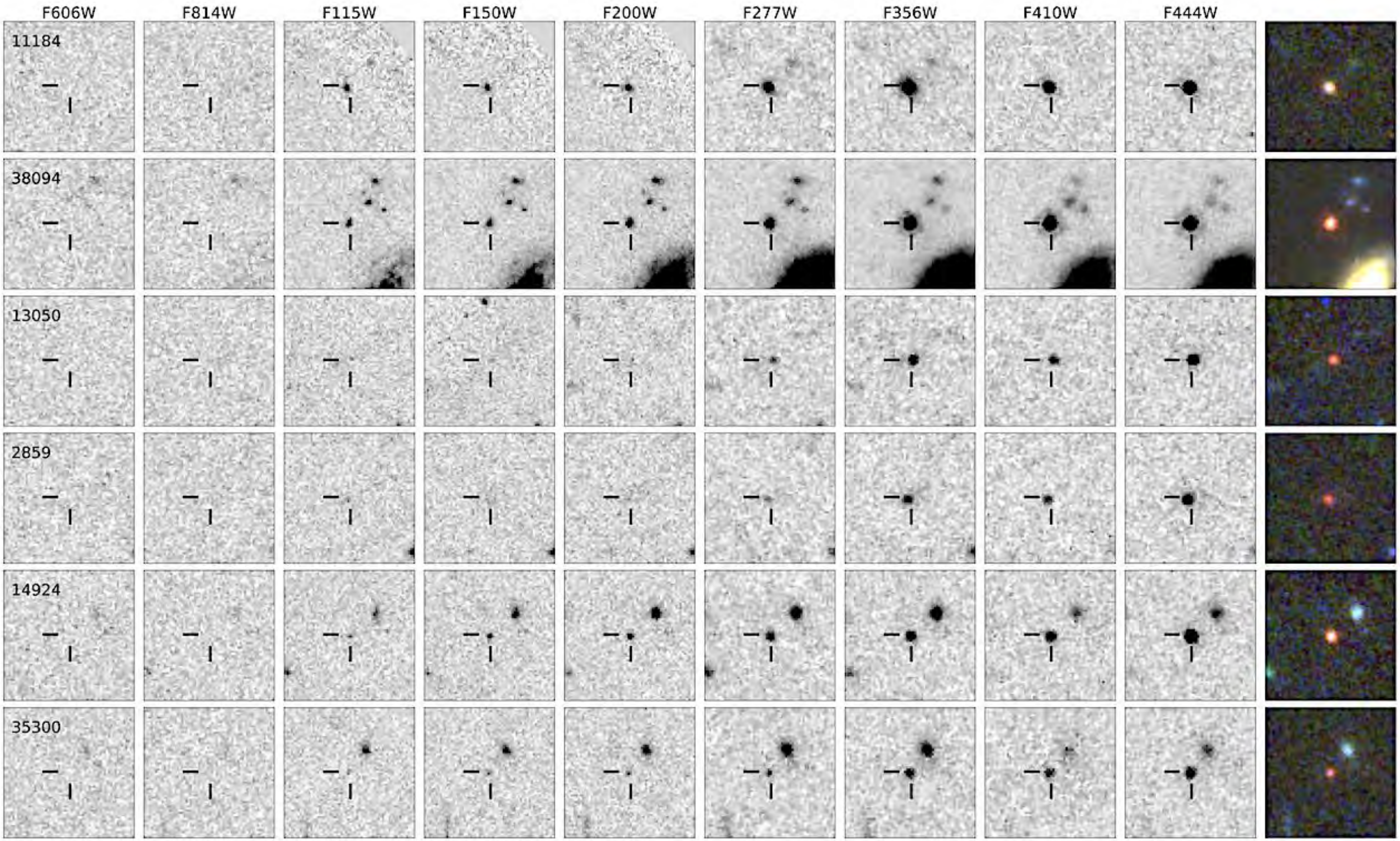
Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging





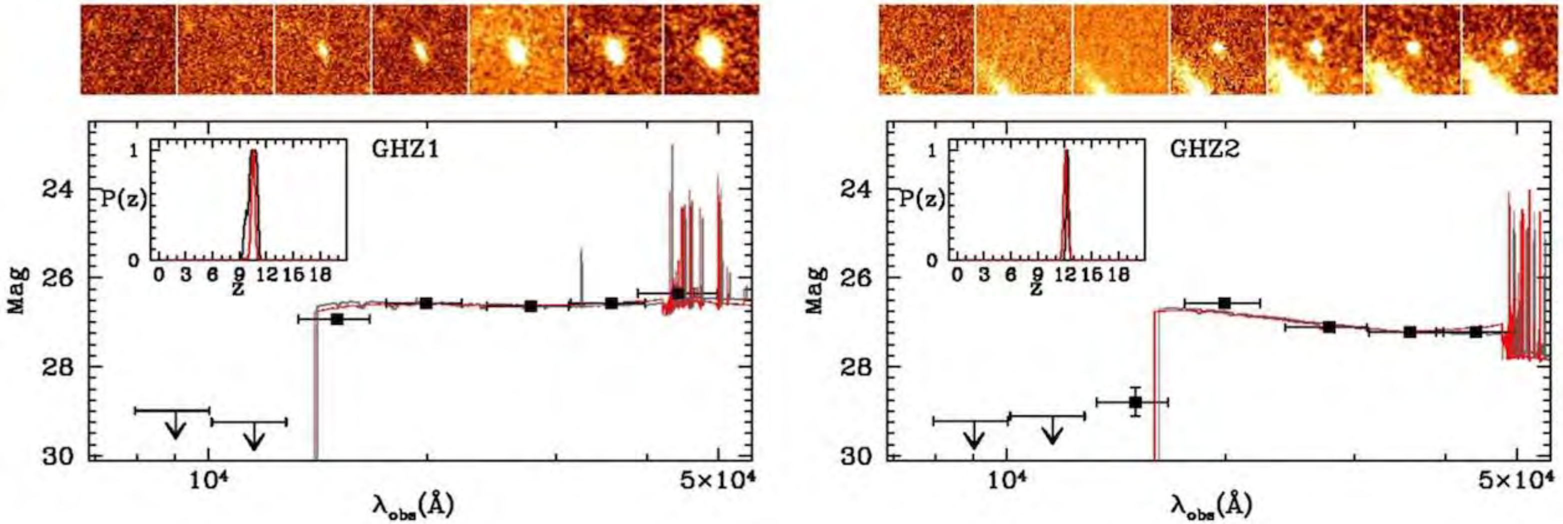
Examples of JWST Color Selection

Images in different filters, from 0.6 μm to 4.44 μm

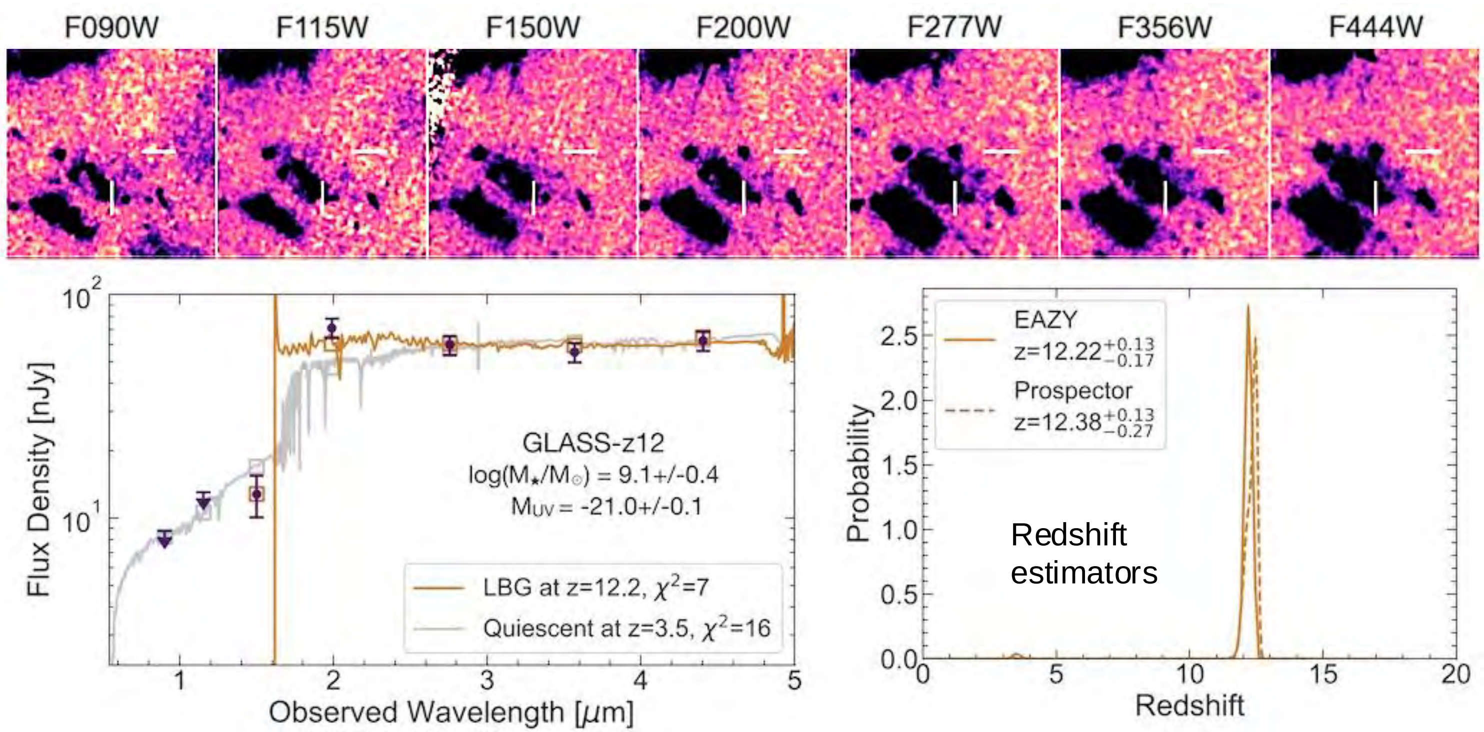


Labbe et al. 2022

Photo-z Redshift Estimators



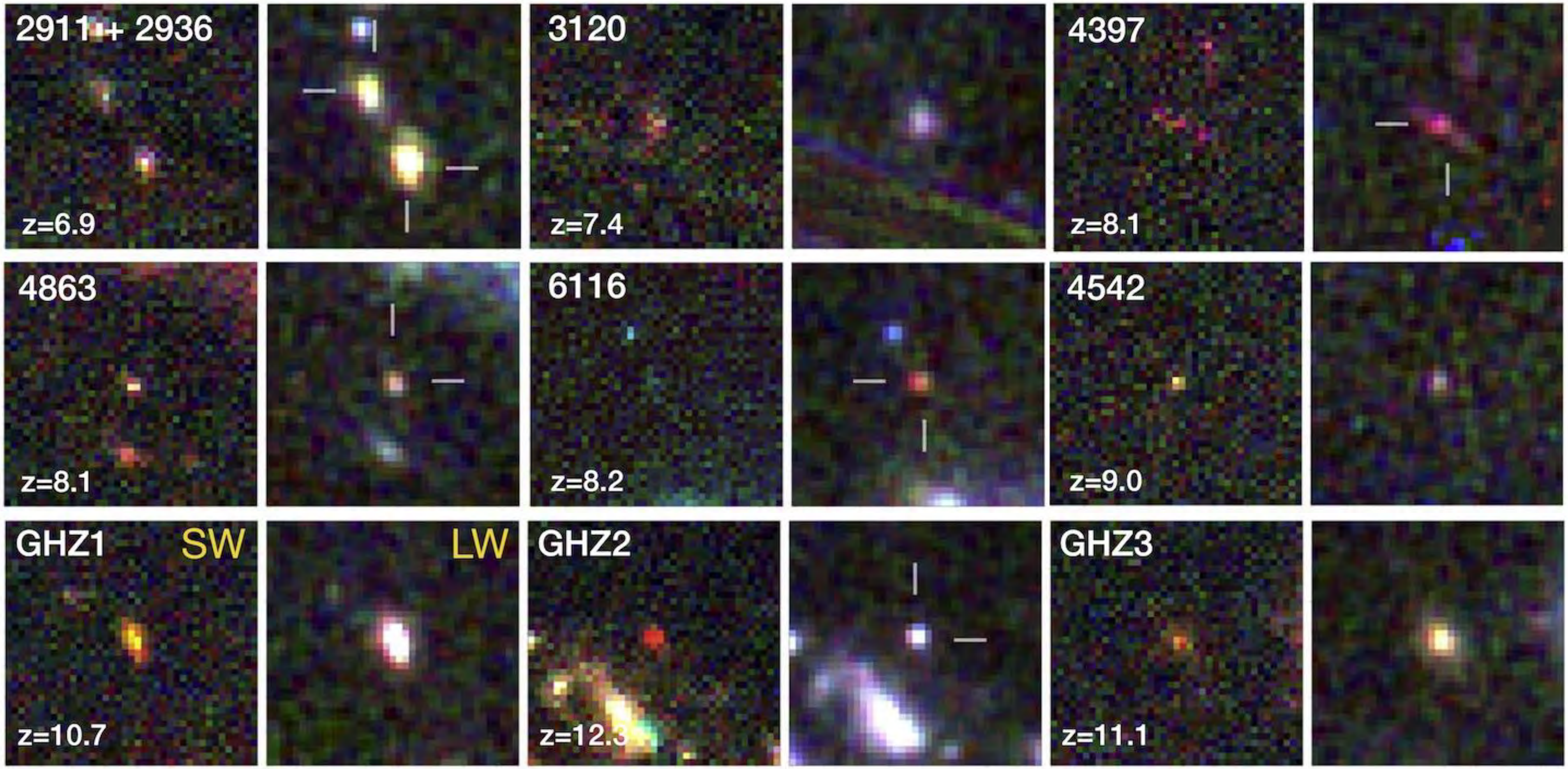
Castellano et al. 2022



Naidu et al. 2022

Examples of JWST Galaxies at z ~ 7 – 12

(Treu et al. 2023)

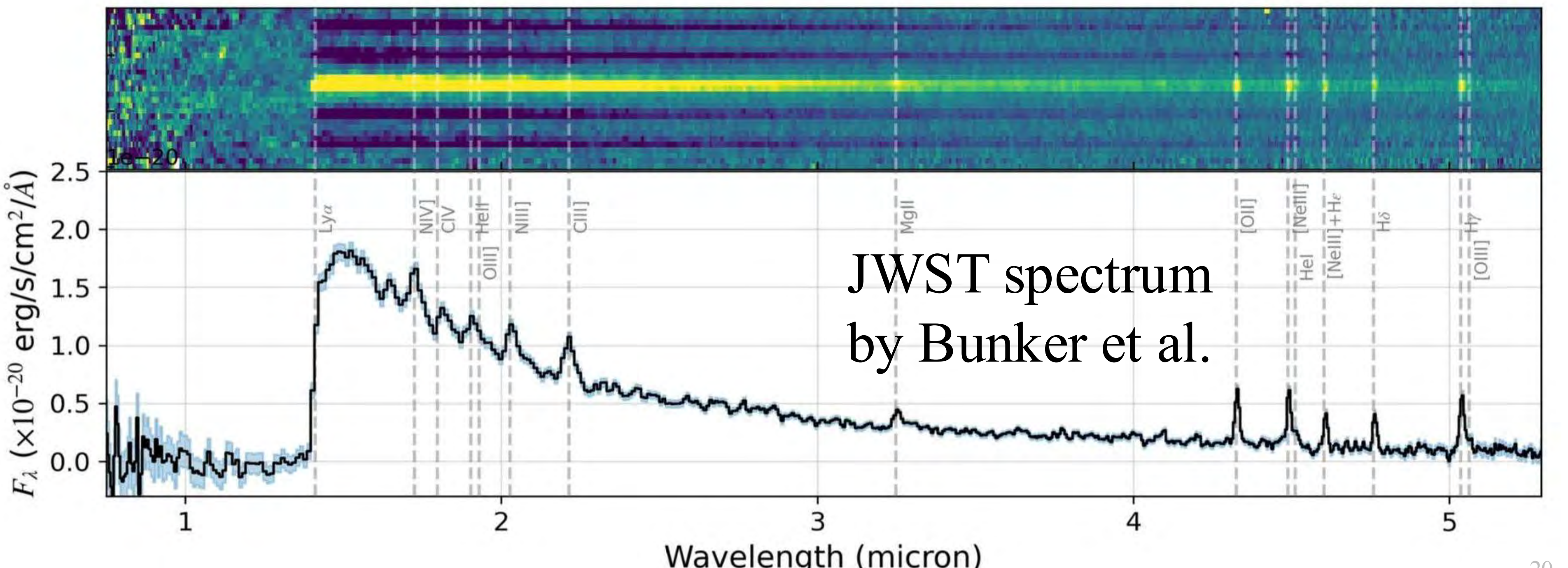


SW = 1.15, 1.45, 2.00 μm filters
LW = 2.77, 3.56, 4.44 μm filters
Images are 2.4 arcsec wide

Mostly compact, but sometimes extended morphologies

GN-z11: A Galaxy at z ~ 11

Originally found in deep HST images by Oesch et al.

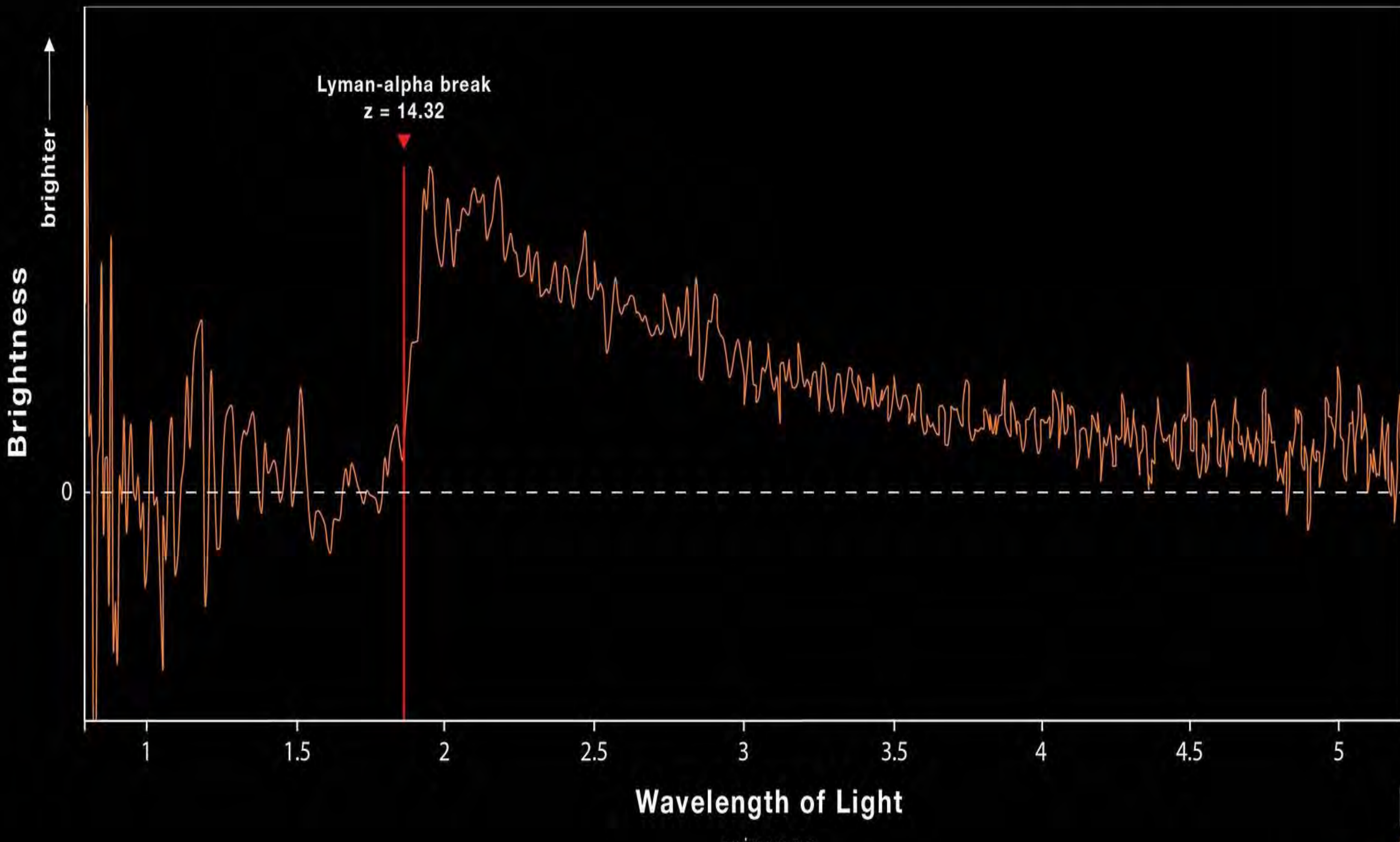


JWST spectrum by Bunker et al.

GALAXY JADES-GS-Z14-0

GALAXY EXISTED 300 MILLION YEARS AFTER BIG BANG

NIRSpec Microshutter Array Spect

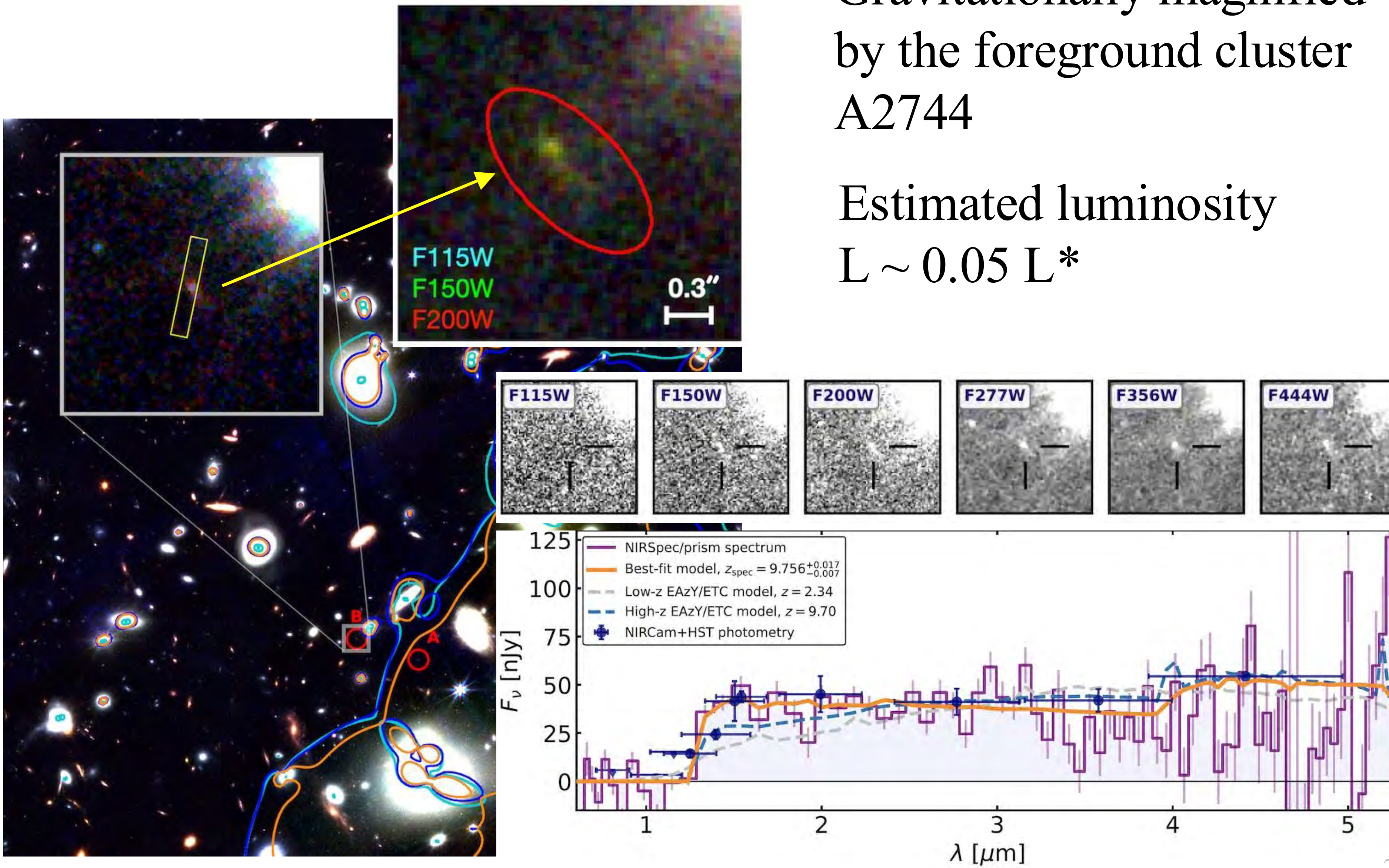


A Dwarf Galaxy at $z = 9.76$

Roberts-Borsani et al. 2023

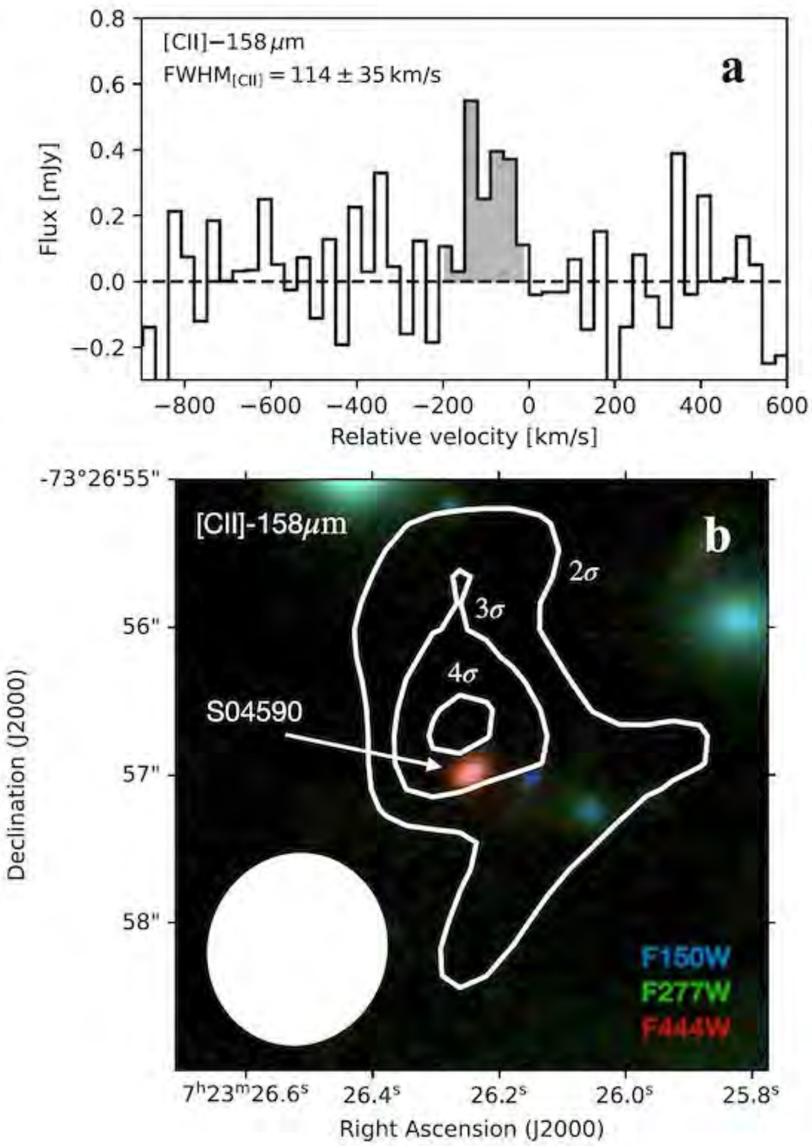
Gravitationally magnified by the foreground cluster A2744

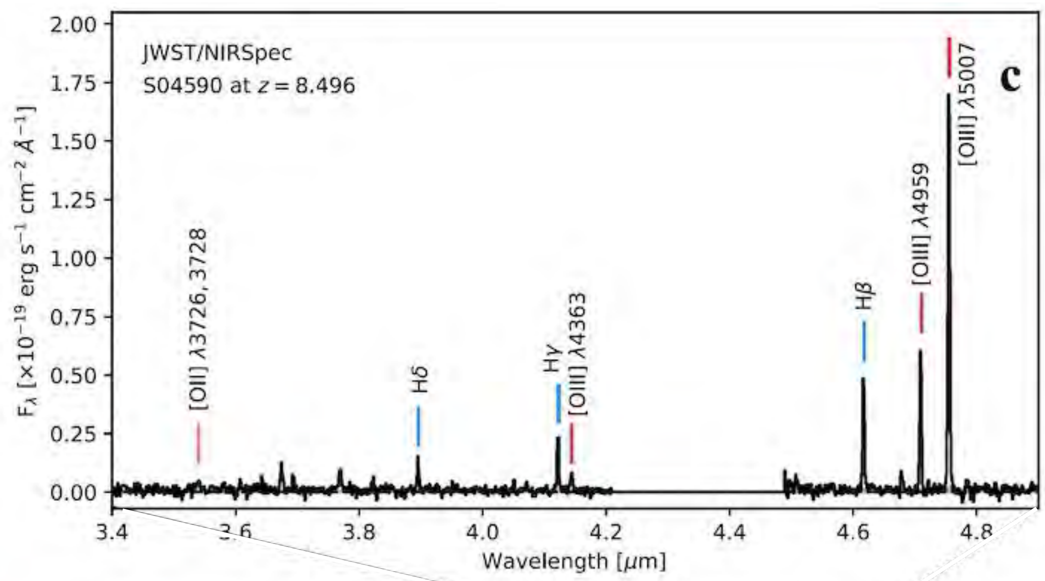
Estimated luminosity L ~ 0.05 L*



Early Chemical Enrichment by z ~ 8.5

A galaxy at z = 8.496 detected by both JWST and ALMA



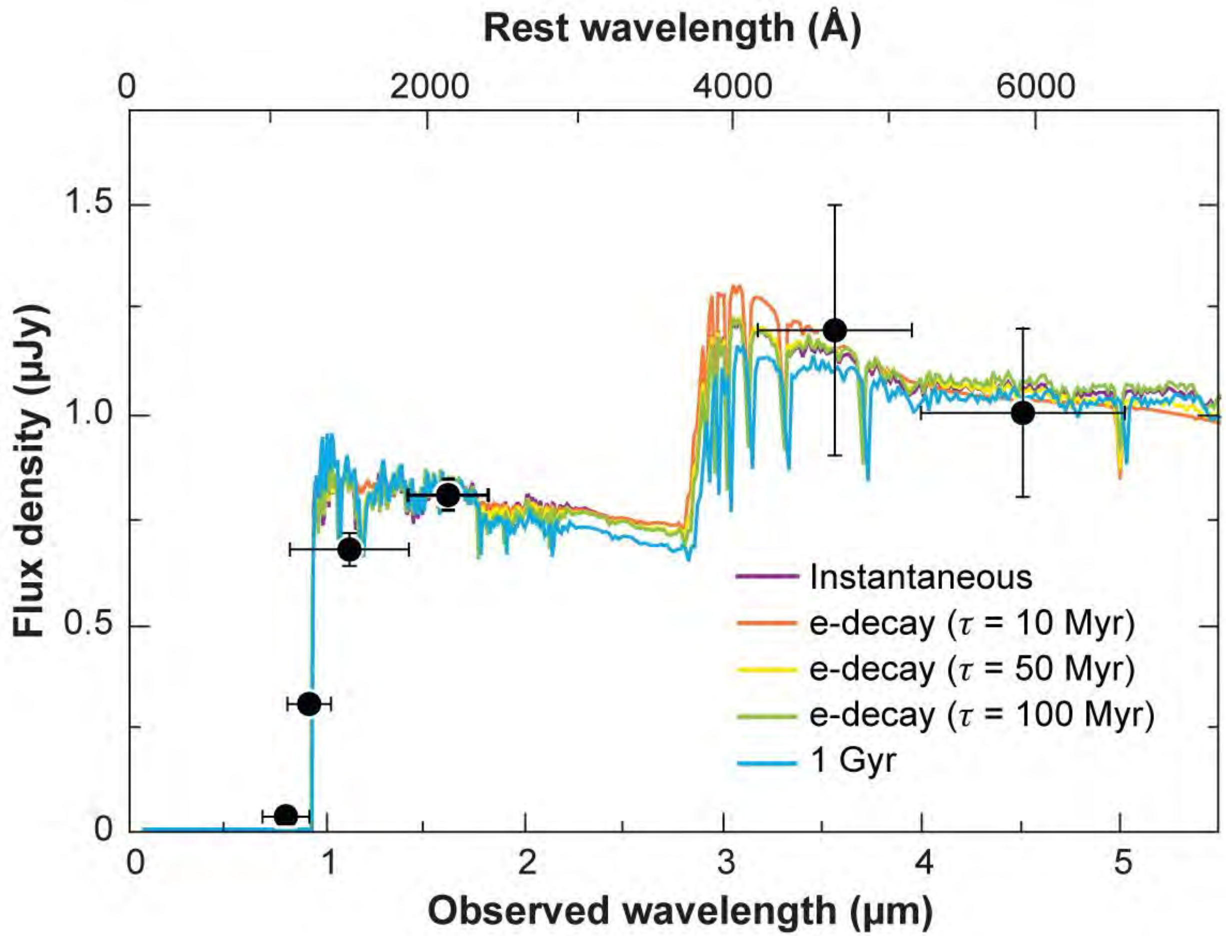


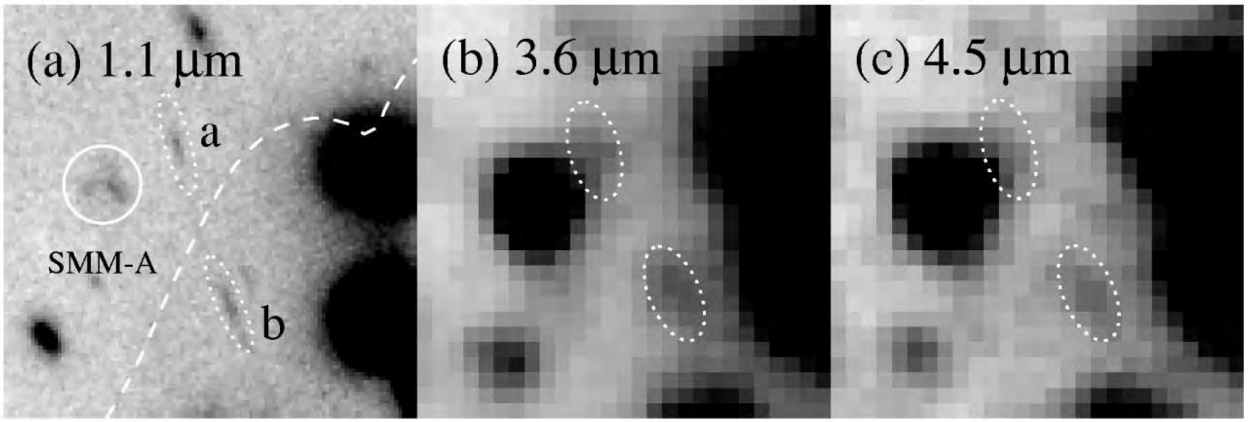
← Image: JWST, contours: ALMA

An early chemical enrichment, requiring multiple generations of massive stars < 600 Myr after the Big Bang

(Heintz et al. 2023)

However, even some galaxies at $z > 6$ seem to have been forming stars for a while, indicating a very early onset of galaxy formation





Lensed arc galaxy at $z \sim 6.7$ (?) behind A2218

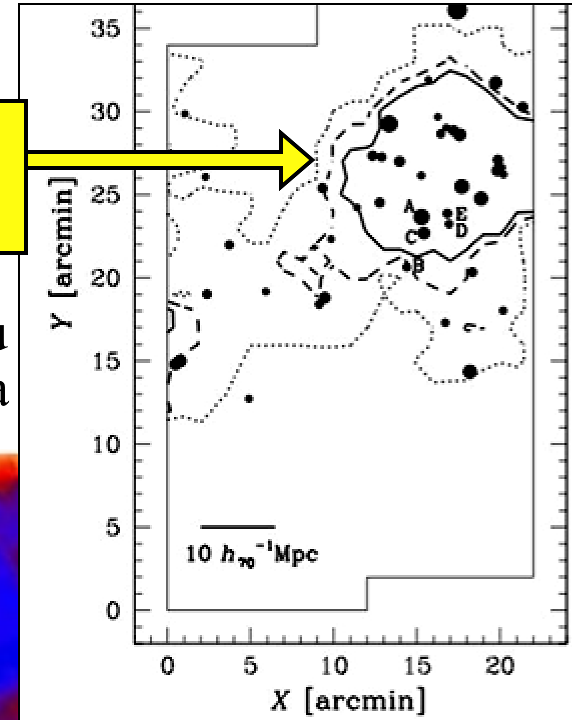
(Egami et al. 2005)

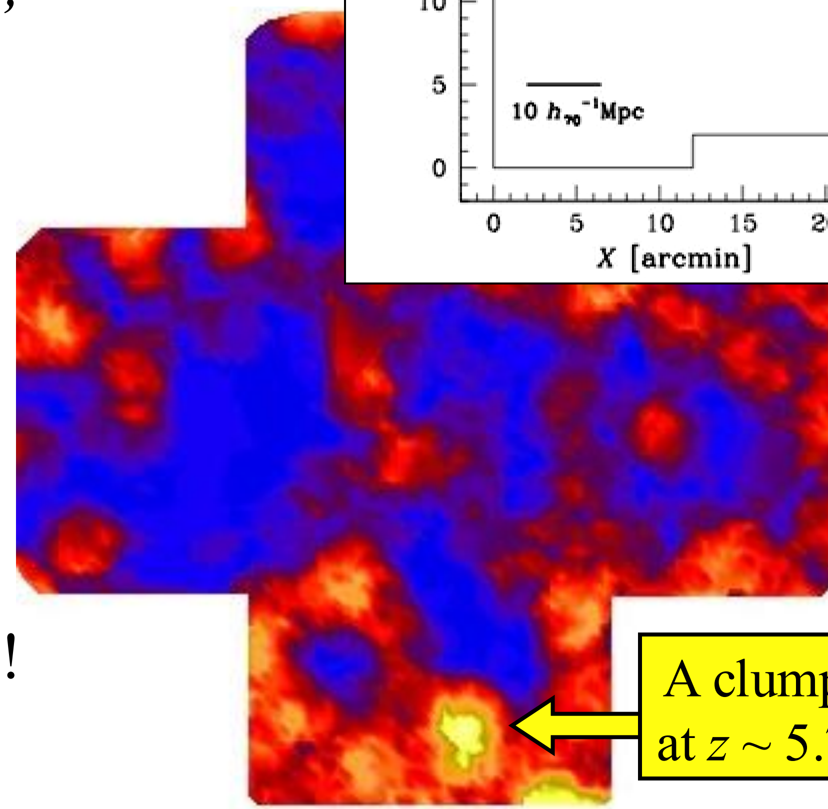
Biasing and Early Structure Formation

- ***Strong, bias-driven clustering*** of the first luminous sources is generally expected in most models
- There is a lot of evidence that this does occur at $z \sim 4 - 6$, from clustering of Lyα galaxies, to clustering of Ly-break galaxies around high-z QSOs
- This may lead to a ***clumpy reionization***, which among other things would produce a rise in the cosmic variance of the IGM transmission in the approach to reionization
- There is some evidence that this indeed does occur, from the spectra of z ~ 6 QSOs - and this may help improve our understanding of the final phases of reionization

Evidence for a Strong Biasing at High *z*' s

- LBGs at $z \geq 3$, ~ Mpc scales *(Steidel, Adelberger, et al.)*
- Clustered QSO companions at $z \sim 4$ - 6, scales ~ 0.1 - 1 Mpc *(Djorgovski et al., Stiavelli et al., etc.)* ; and also radio galaxies at similar *z*' s *(Venemans et al.)*
- Clustered Lyα and LB galaxies at z ~ 4.9 - 5.7, scales ~ a few Mpc *(Shimasaku et al., Ouchi et al., Hu et al., etc.)*
- Estimated **bias factors *b* ~ 3 - 6**, but could be as high as ~ 10 - 30!

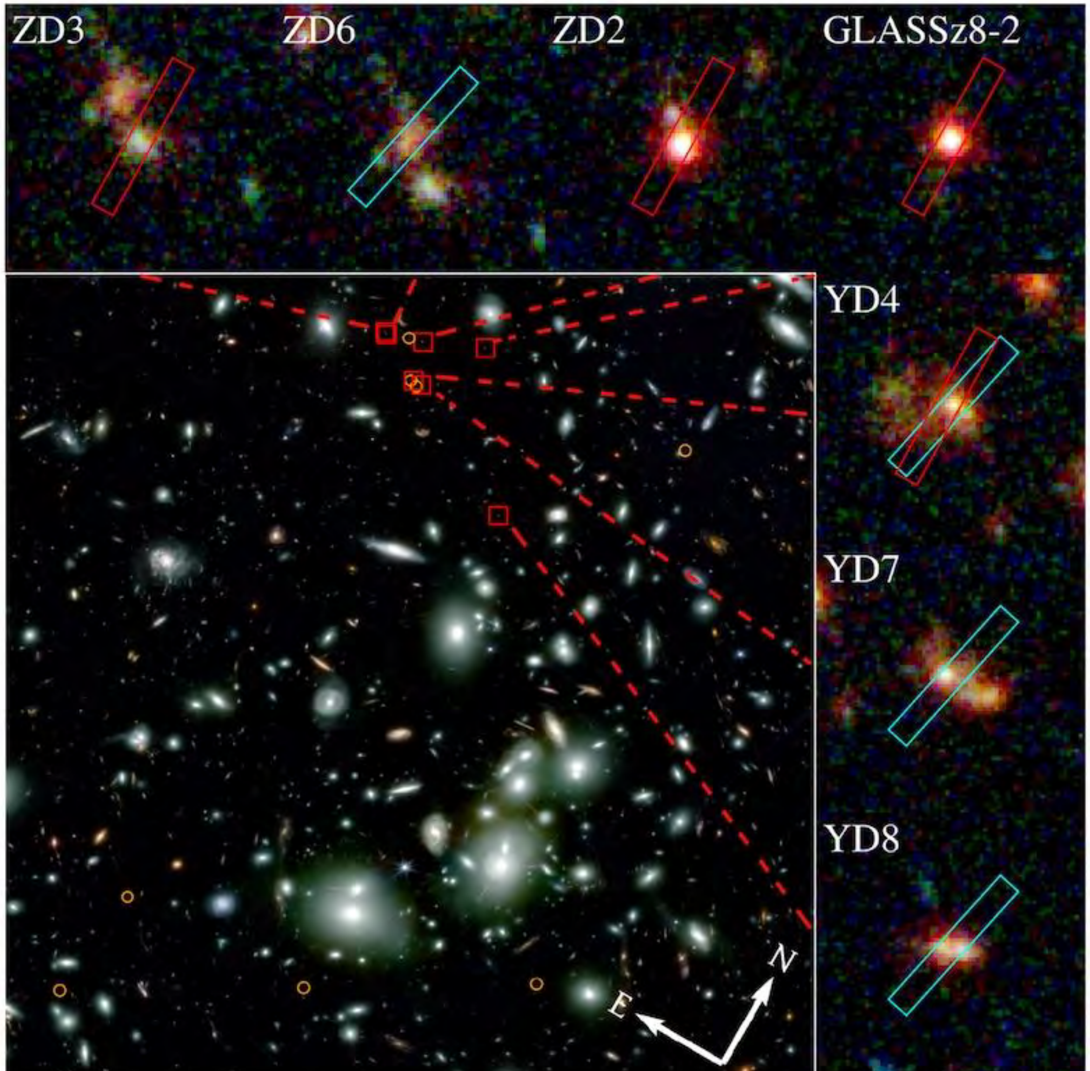


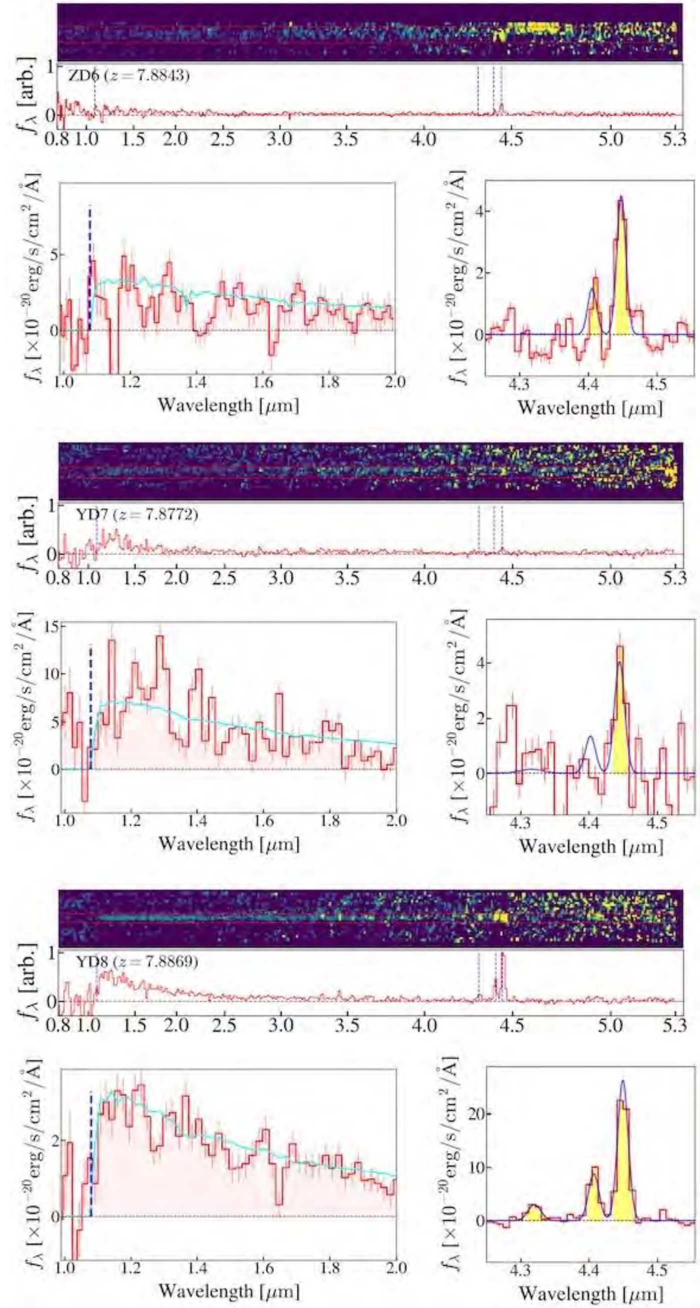


A Protocluster at $z = 7.88$

Morishita et al. 2023, JWST

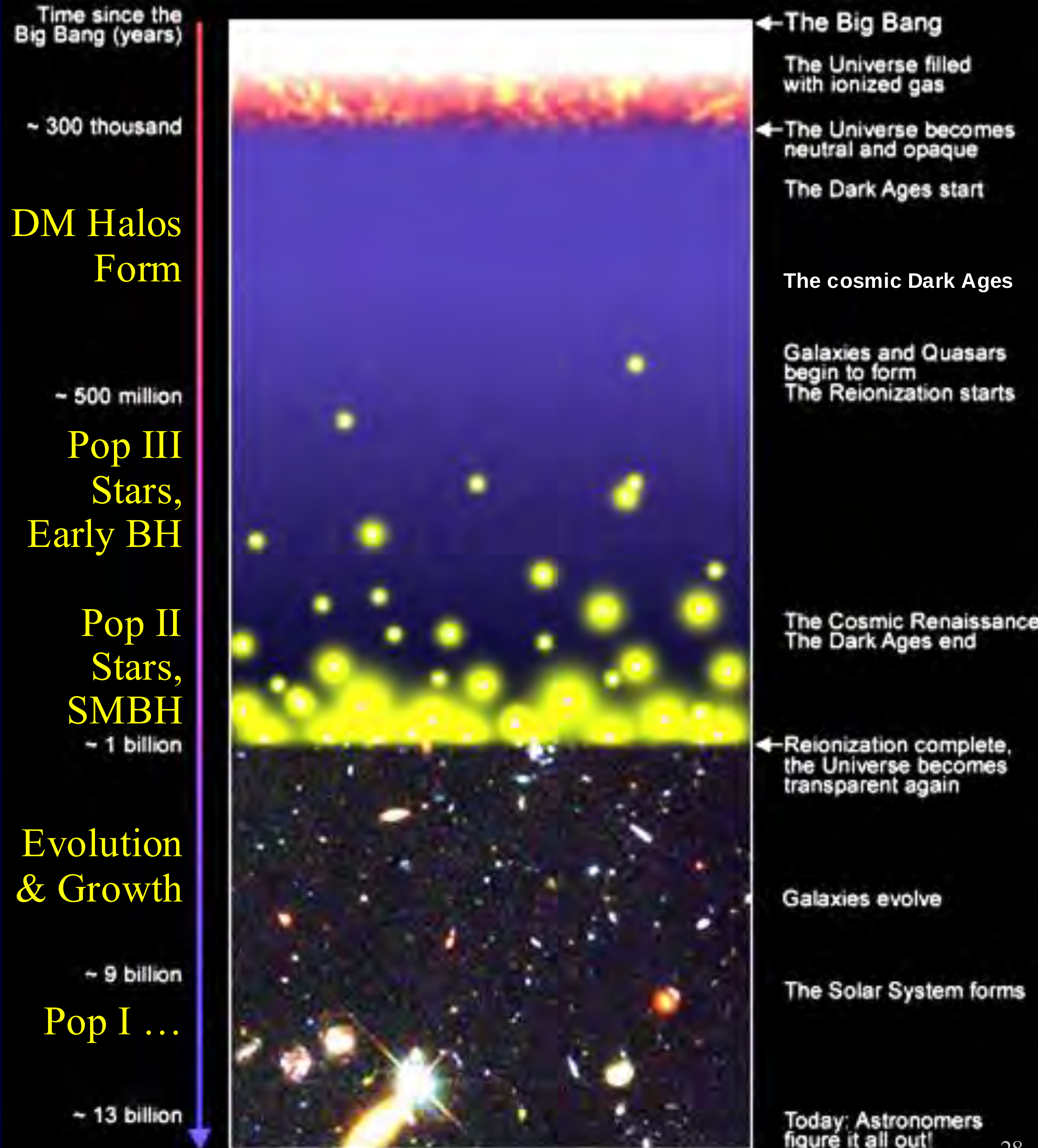
Emission lines of Hβ and [O III] 5007 →





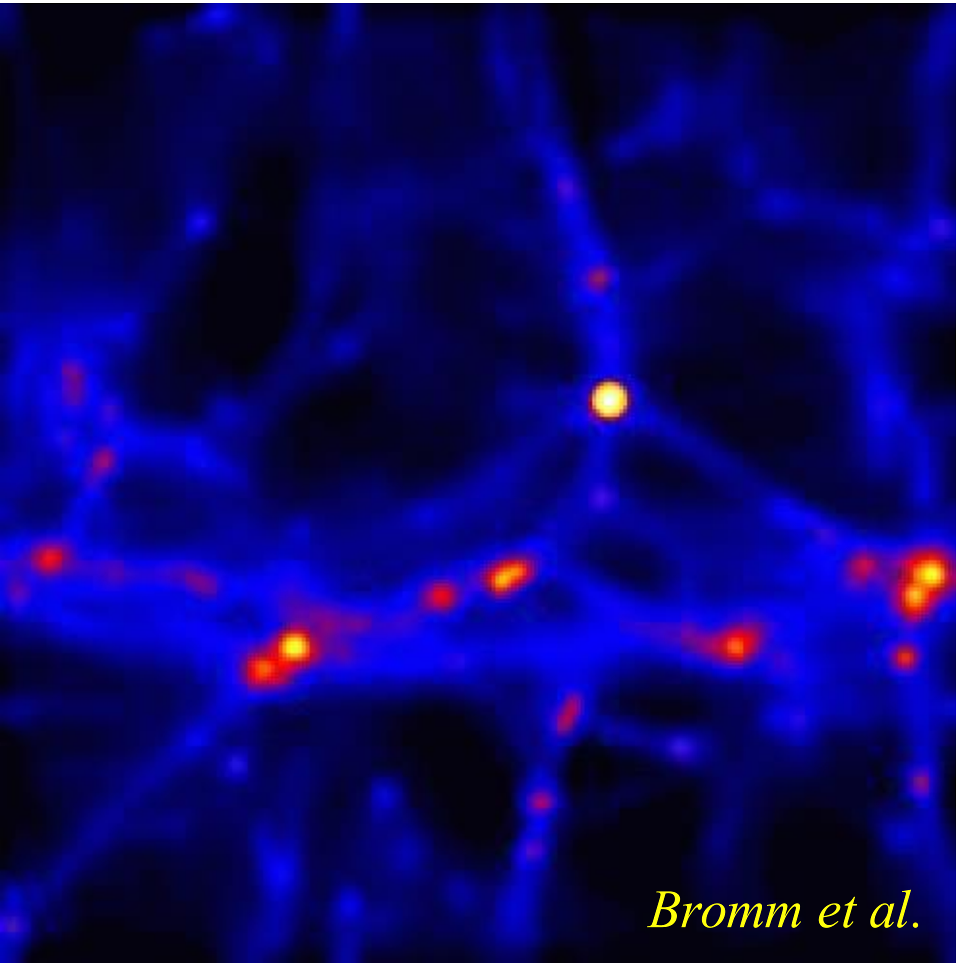
The Cosmic Reionization Era

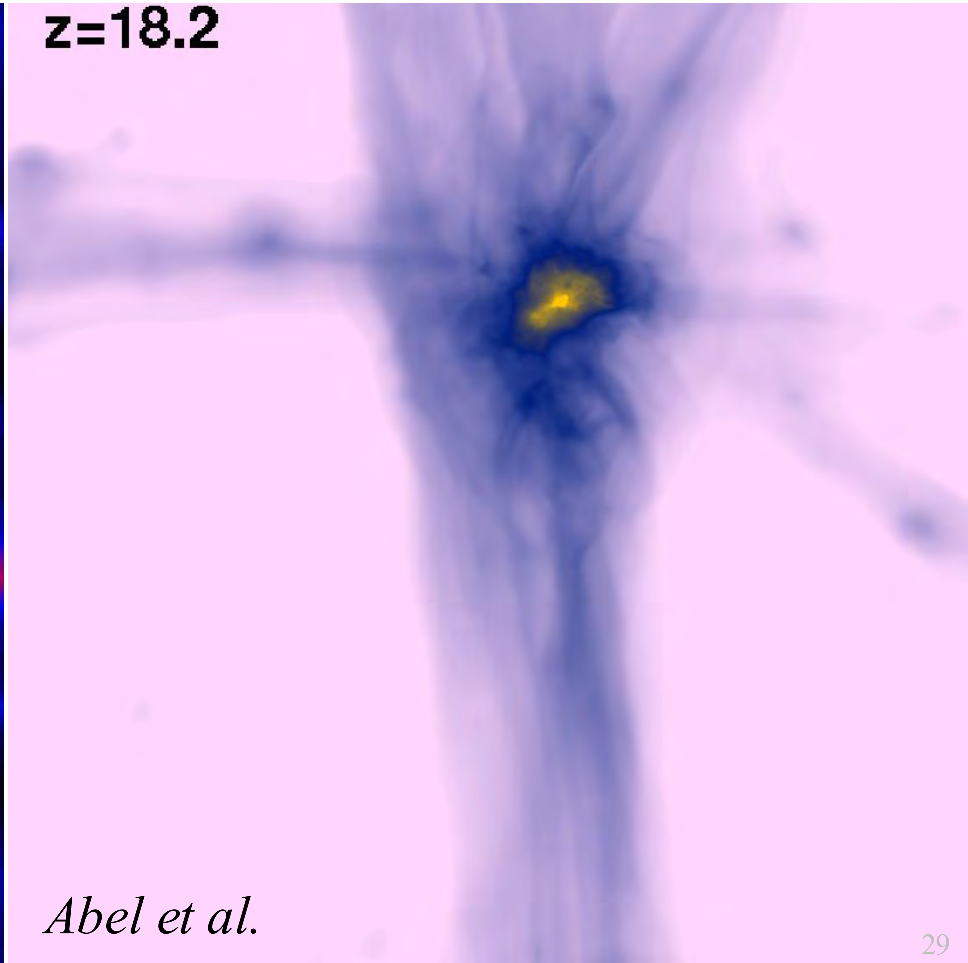
(The Cosmic Renaissance)



The First (Population III) Stars

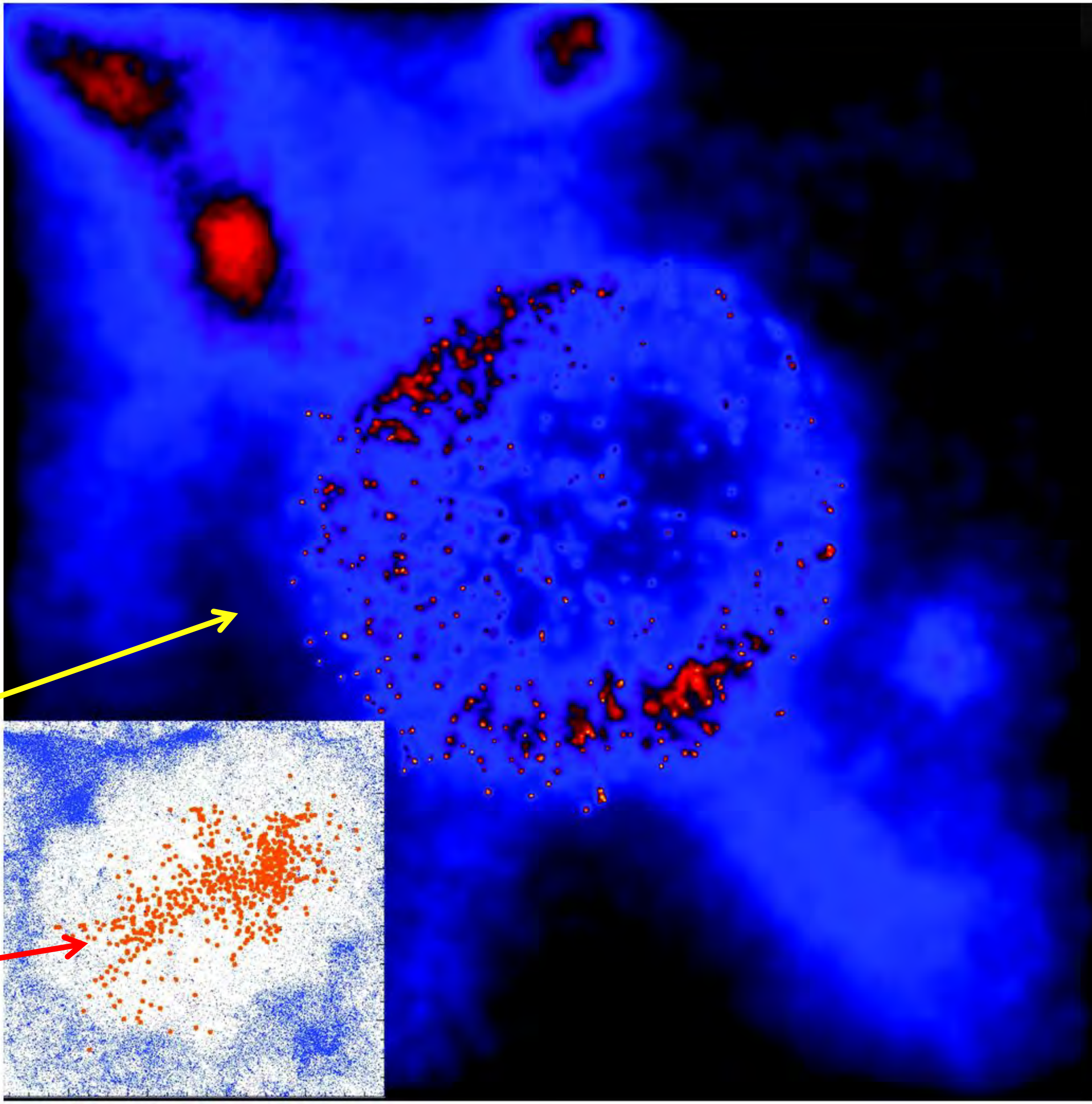
The first protostellar clouds can only cool through the H_2 molecular lines, which leads to a high Jeans mass, resulting in a **top-heavy stellar IMF**, $M \sim 10^2$ - 10^4 $M_{\odot}$. Thus, the first stars are expected to be very **massive, hot, and luminous - they can reionize the universe**





Population III Supernovae

- Early enrichment of the protogalactic gas
- Transition to the "normal" Pop II star formation and IMF when the metallicity reaches a critical value $Z_{crit} \sim 10^{-3.5}\, Z_{\odot}$



Simulated Pop III SN shell after $\sim 10^6$ yr

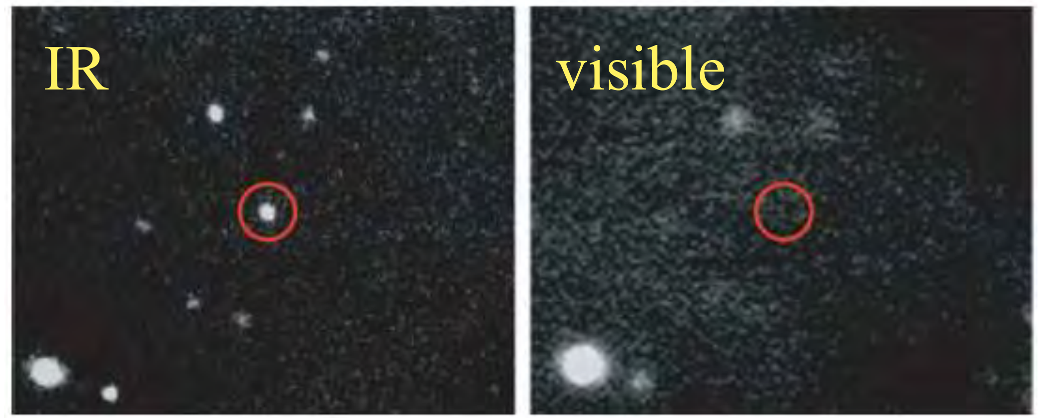
Distrib. of metals (red)

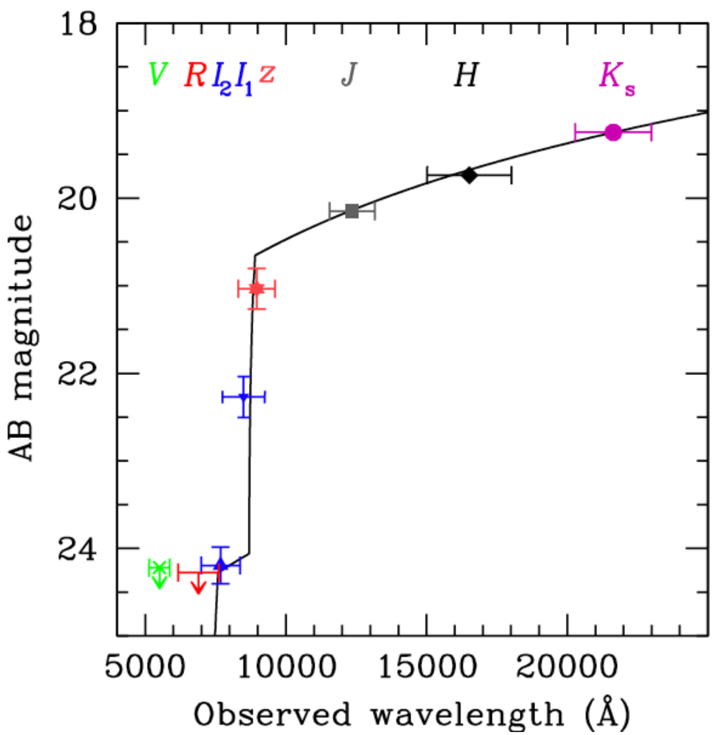
(from Bromm et al. 2003)

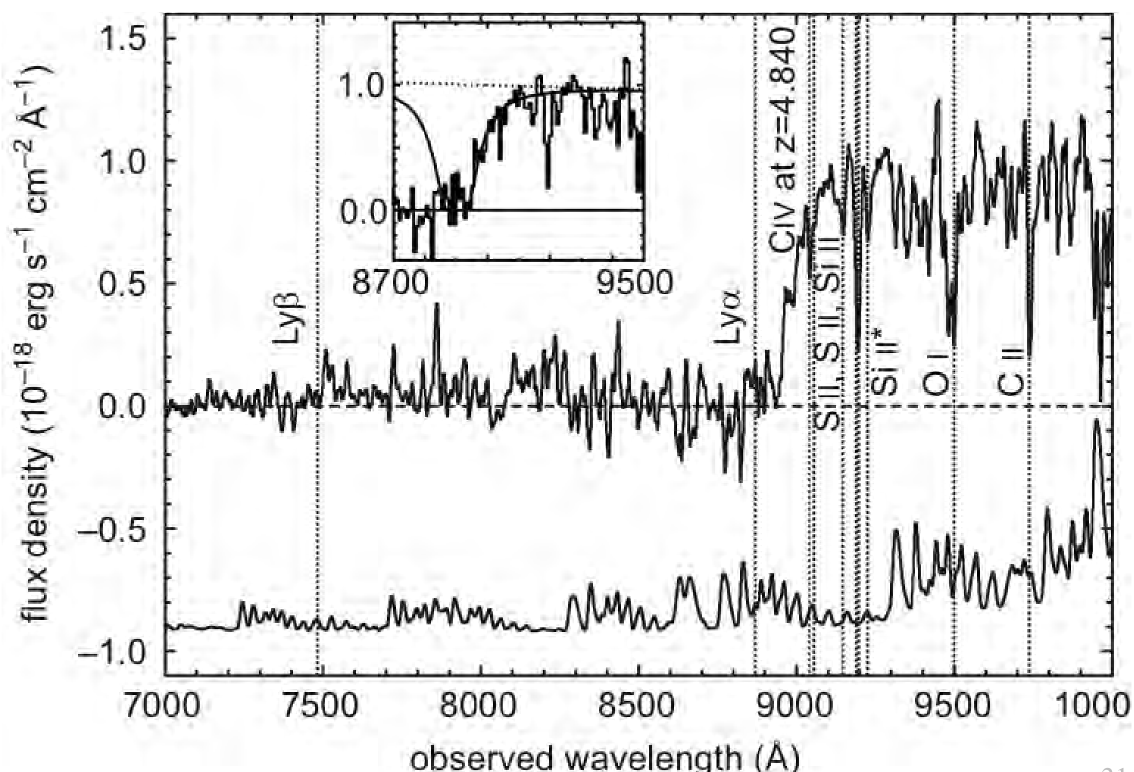
GRB 050904 at z = 6.295

Signaling a death of a massive star – a preview of the more distant, Pop. II flashes to come!

(Kawai et al. 2006, Haislip et al. 2006, Tagliaferri et al. 2006, etc.)



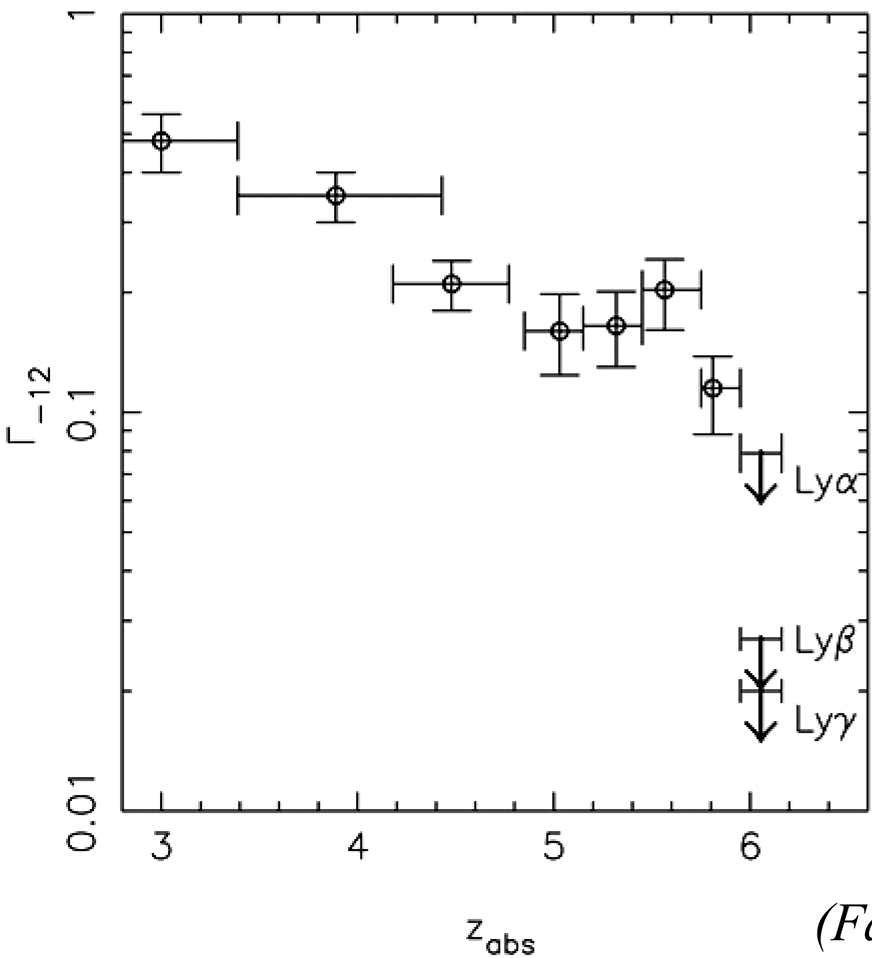




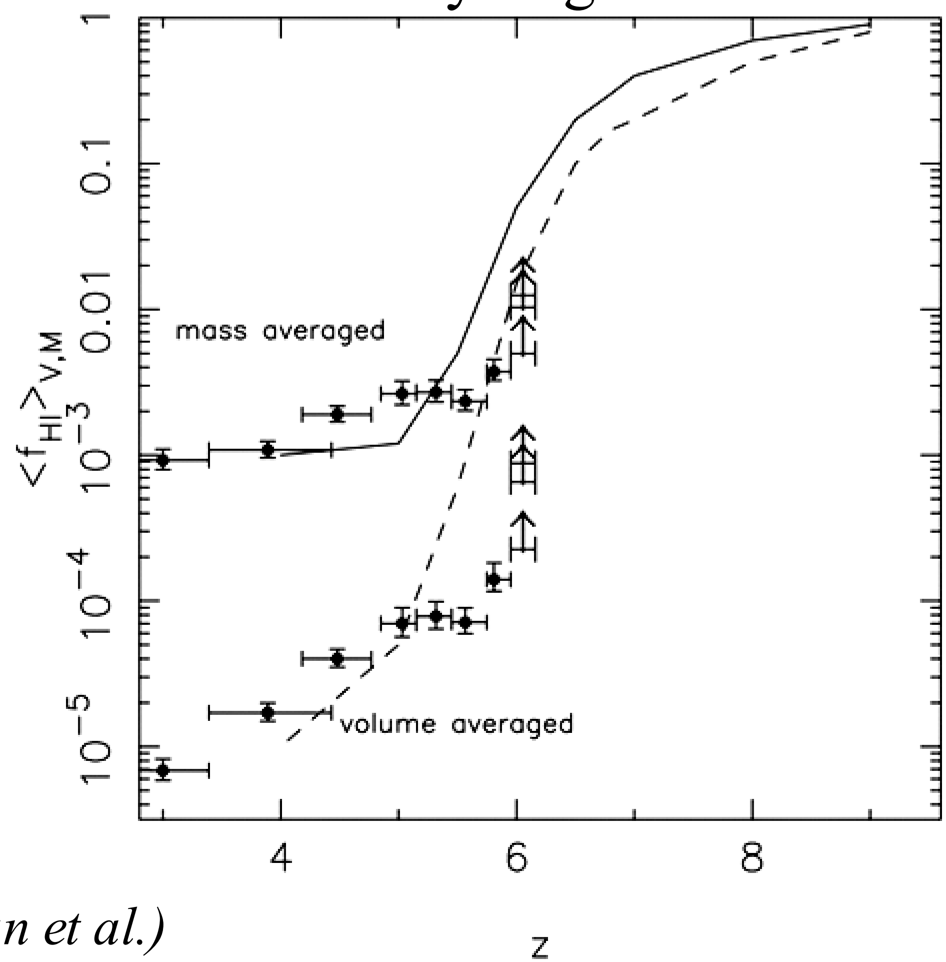
QSO Observations Suggest the End of the Reionization at z ~ 6

A sudden change in the UV opacity of the intergalactic medium

Photoionization Rate



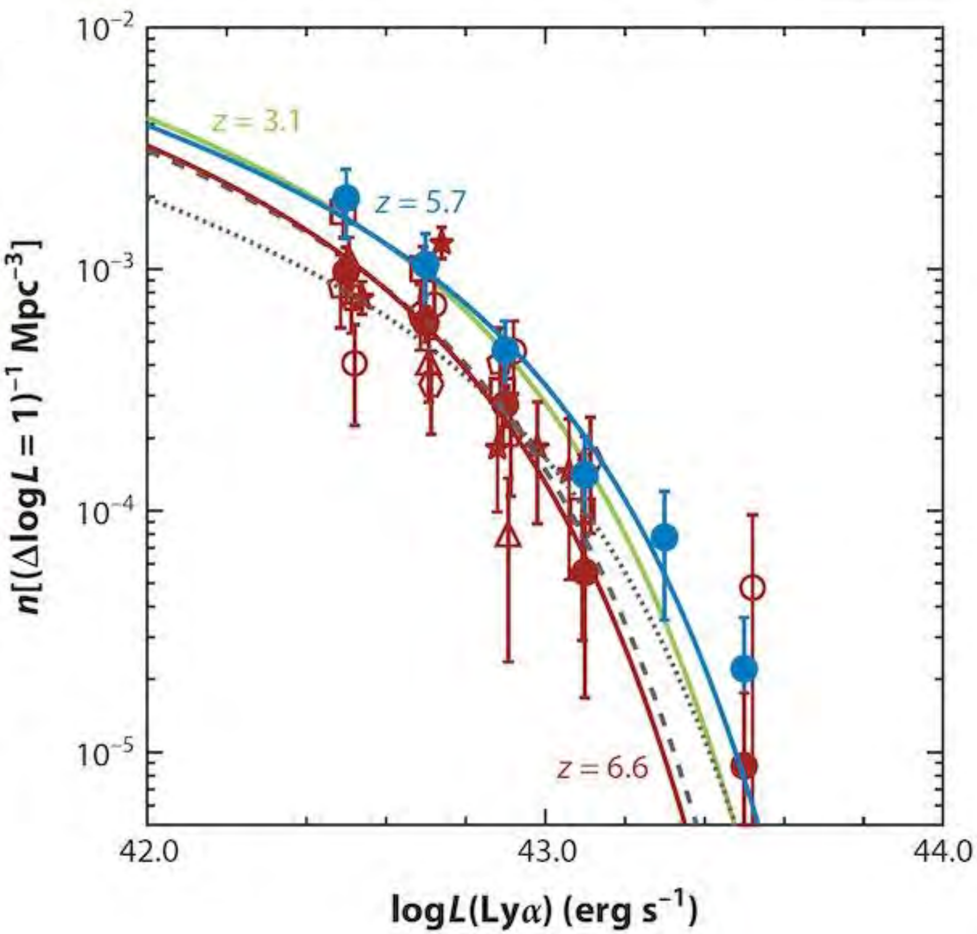
Neutral Hydrogen Fraction



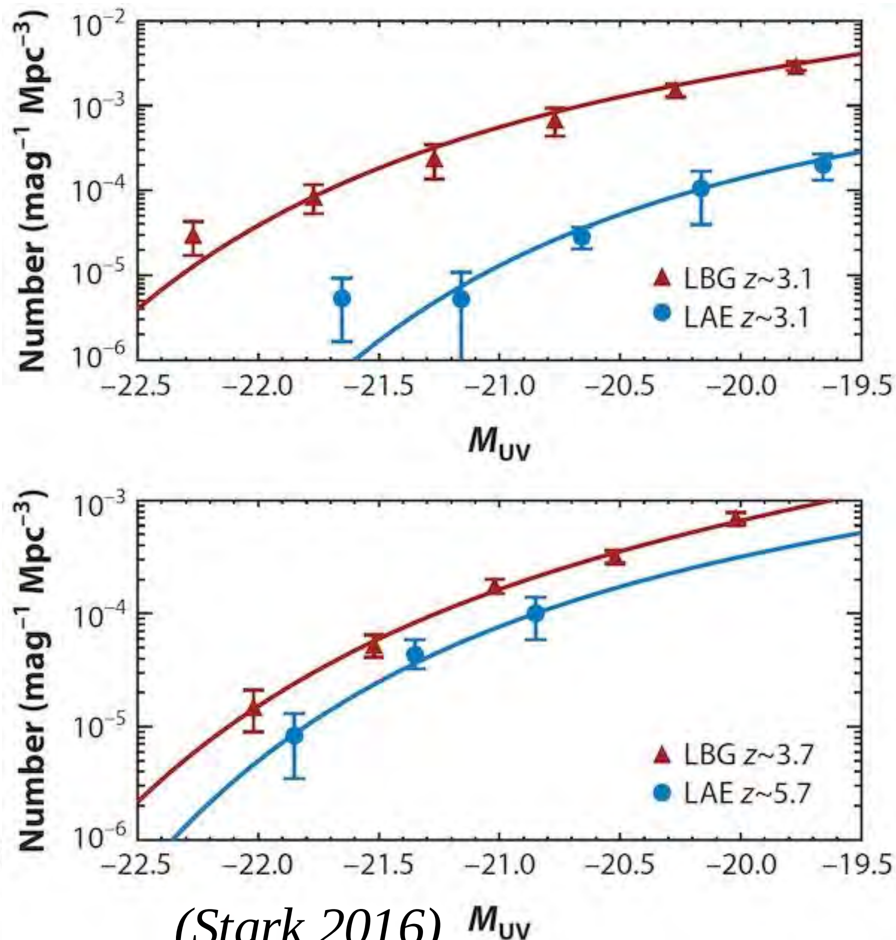
(Fan et al.)

The Rise of Galaxies

The evolving luminosity function of Lyα emitters shows a gradual decline at larger redshifts

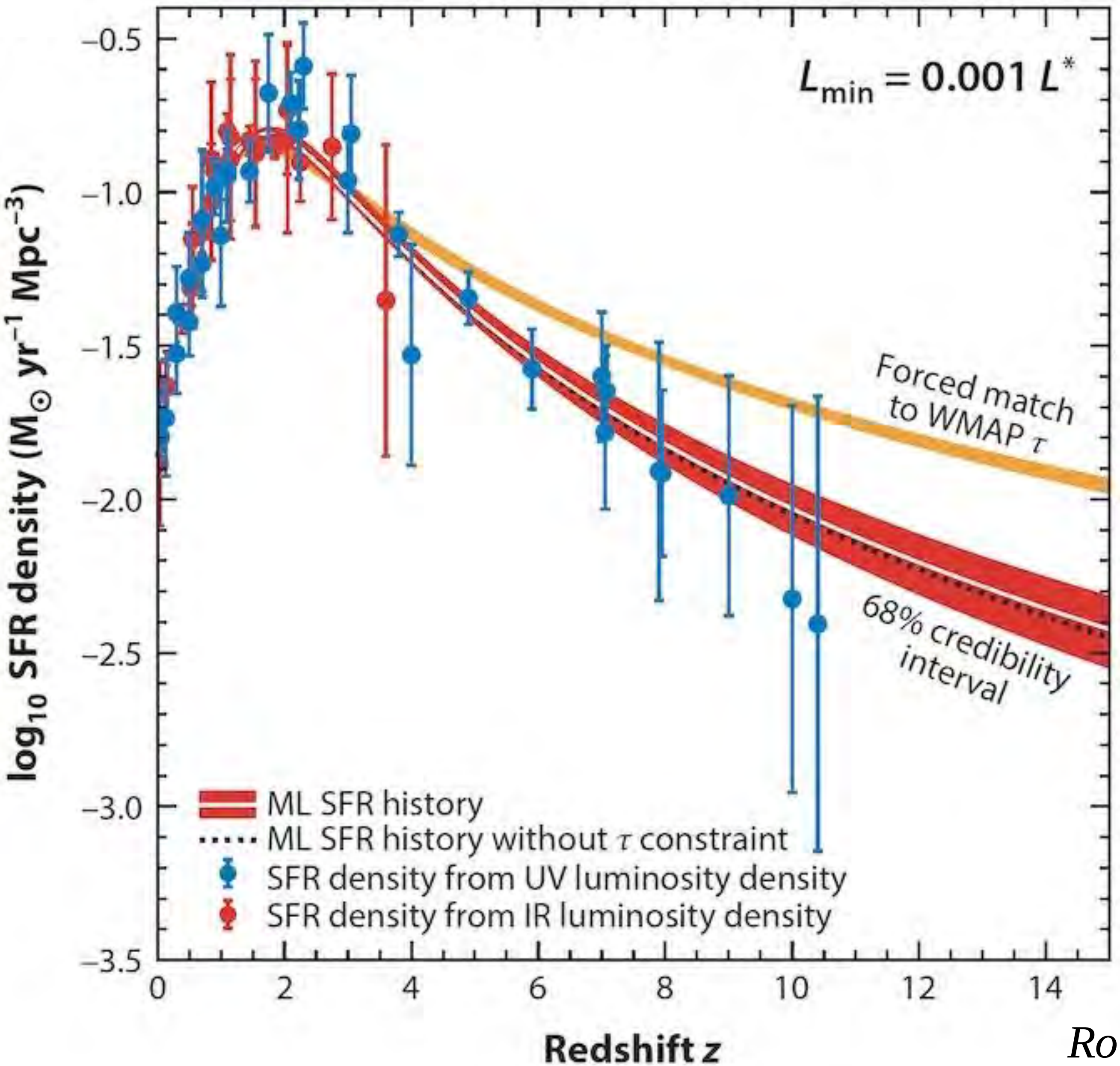


The same applies to the Lyman break galaxies



(Stark 2016)

Reionization by Young Galaxies



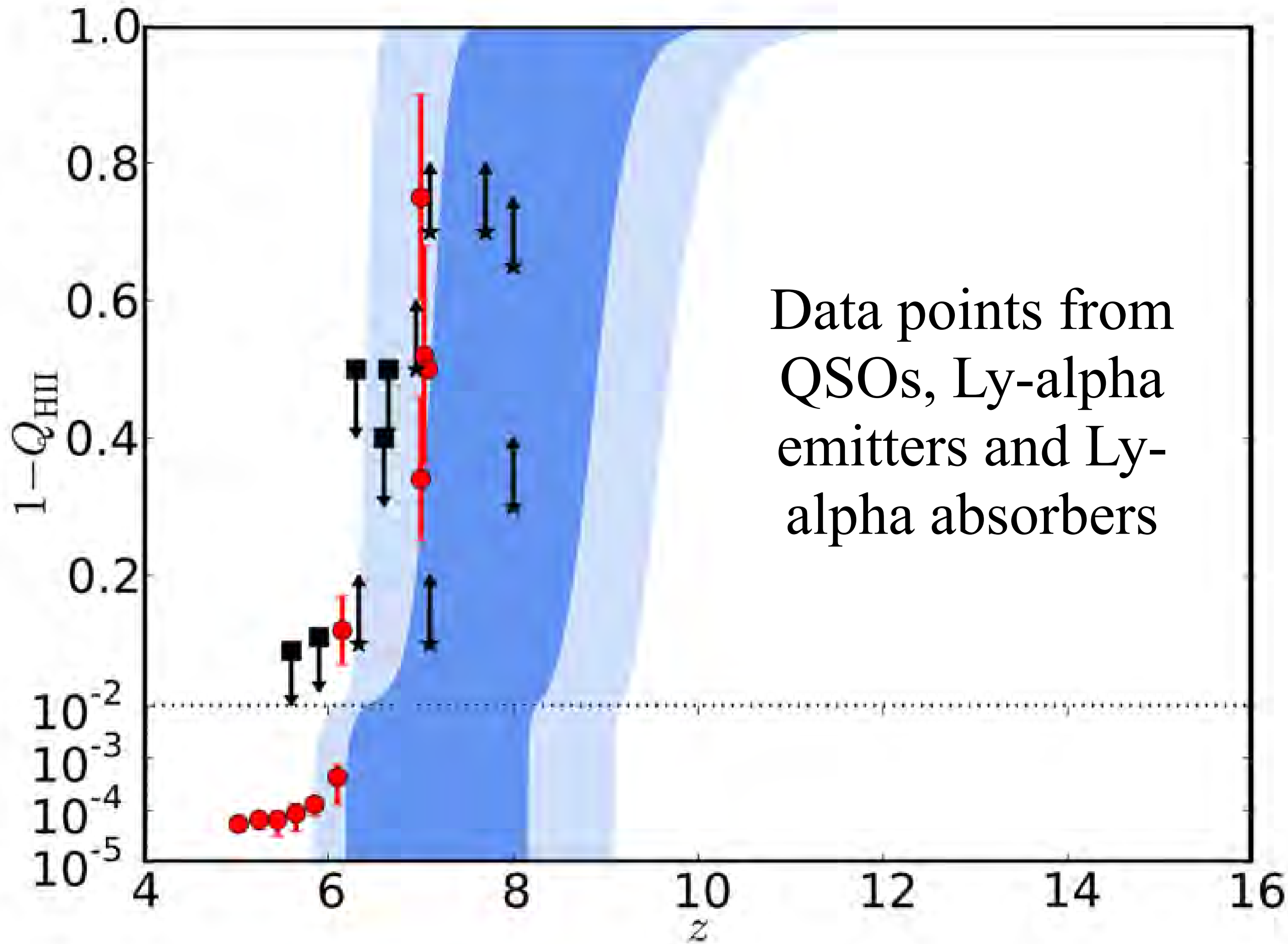
The observed abundance of the unobscured Lyα emitters or Lyman break galaxies is sufficient to reionize the universe

Robertson et al. 2015

CMB Constraints on Reionization

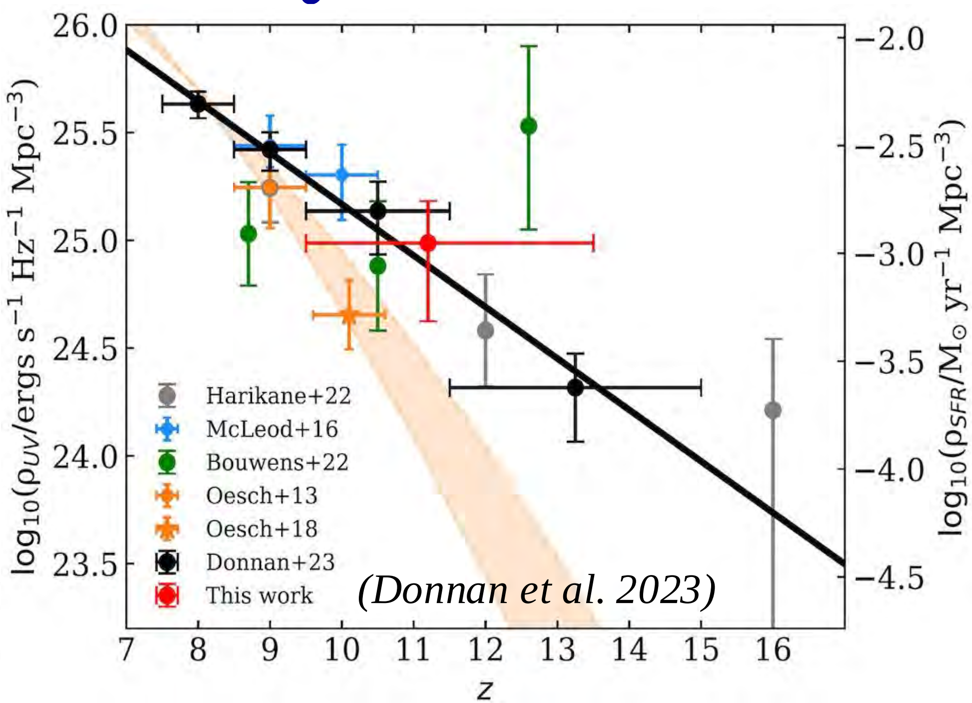
Planck Collaboration 2016: $\tau = 0.058 \pm 0.012$ for instantaneous reionization model, $z = 8.2 \pm 1.1$ favored

Upper limit to the width of reionization period: $\Delta z < 2.8$

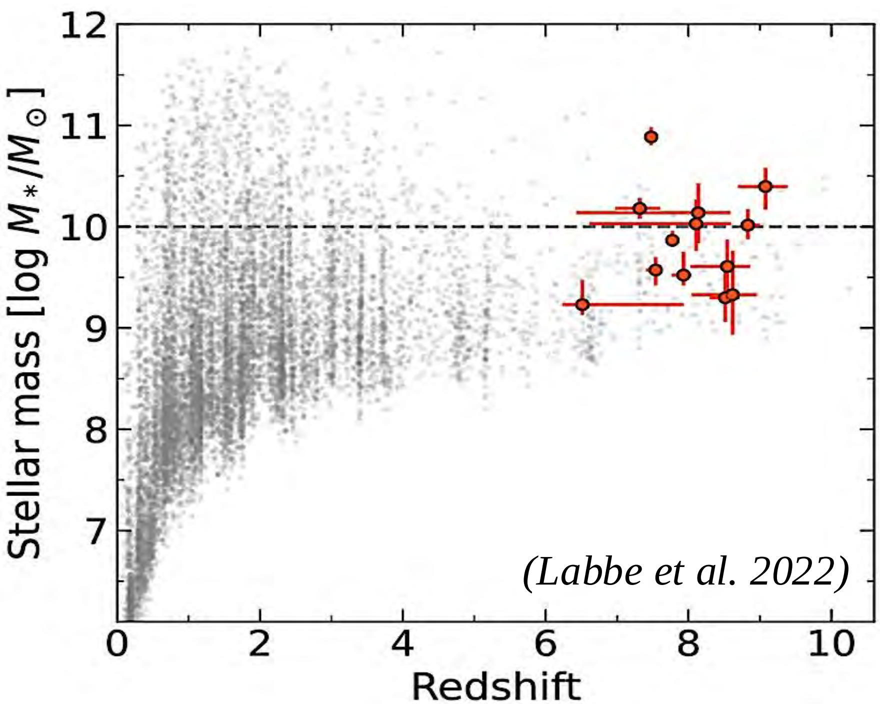


Surprisingly Early Galaxy Formation?

Unexpectedly high UV luminosity density (~ SFR) at $z \geq 12$, when the universe was ~ 370 Myr old, and inferred stellar masses $M \sim 10^9\ M_\odot$



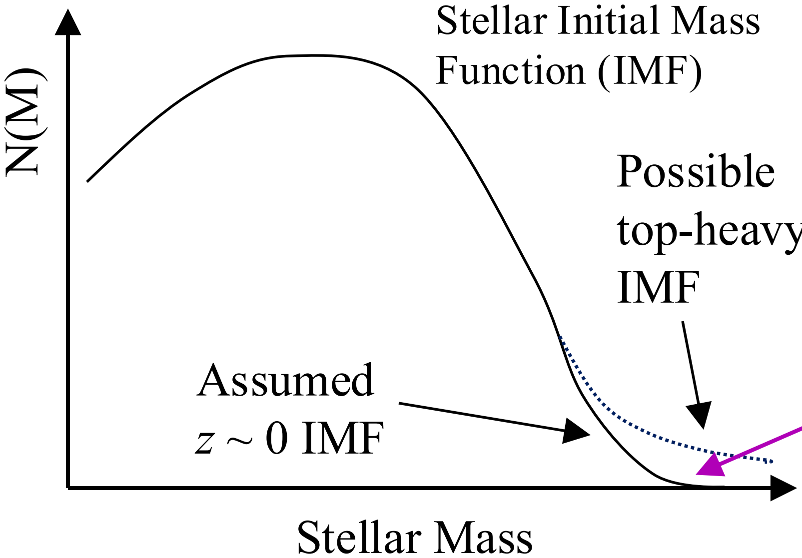
(Donnan et al. 2023)



(Labbe et al. 2022)

It would be hard to start forming stars before the universe age of ~ 100 Myr, because CMB was too hot for the protostars to cool

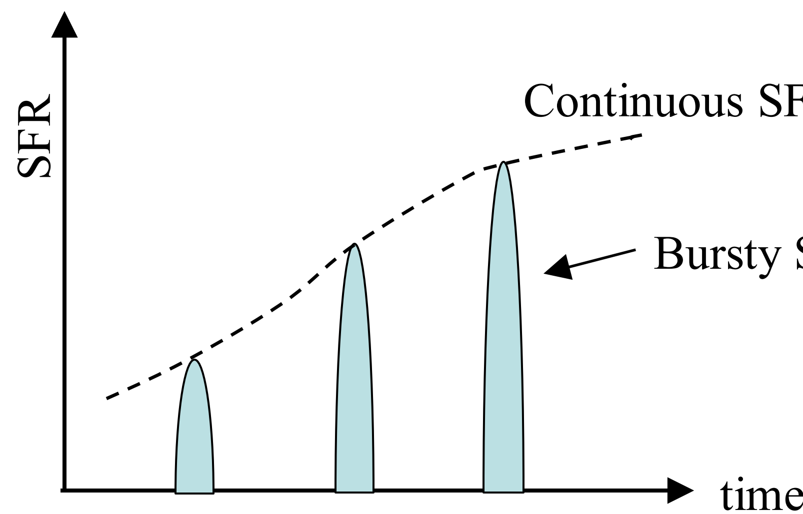
Are These Young Galaxies Really So Massive?



What is observed is the restframe **UV luminosity**. To convert it into the star formation rate (SFR) we must assume the stellar IMF

The most massive stars account for a small fraction of the total mass, but produce most of the UV light

The UV luminosity gives the *instantaneous* SFR. To convert it into the total stellar mass we must assume the *SFR history*



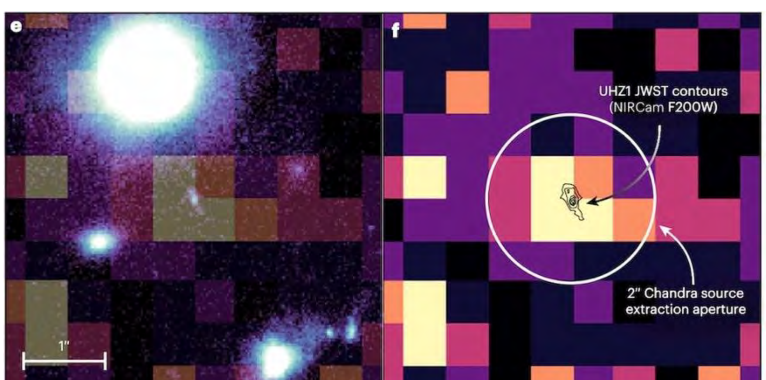
If SFR occurs in bursts, we catch these galaxies at the peaks of SFR

Assuming a continuous SFR overestimates the total stellar mass

The Birth of Quasars

Assembling supermassive black holes with $M_\bullet \sim 10^6 - 10^{10}\ M_\odot$ is not easy in a few $\times\ 10^8$ yrs

JWST images of a galaxy at z H 10.3 (age ~ 460 Myr):



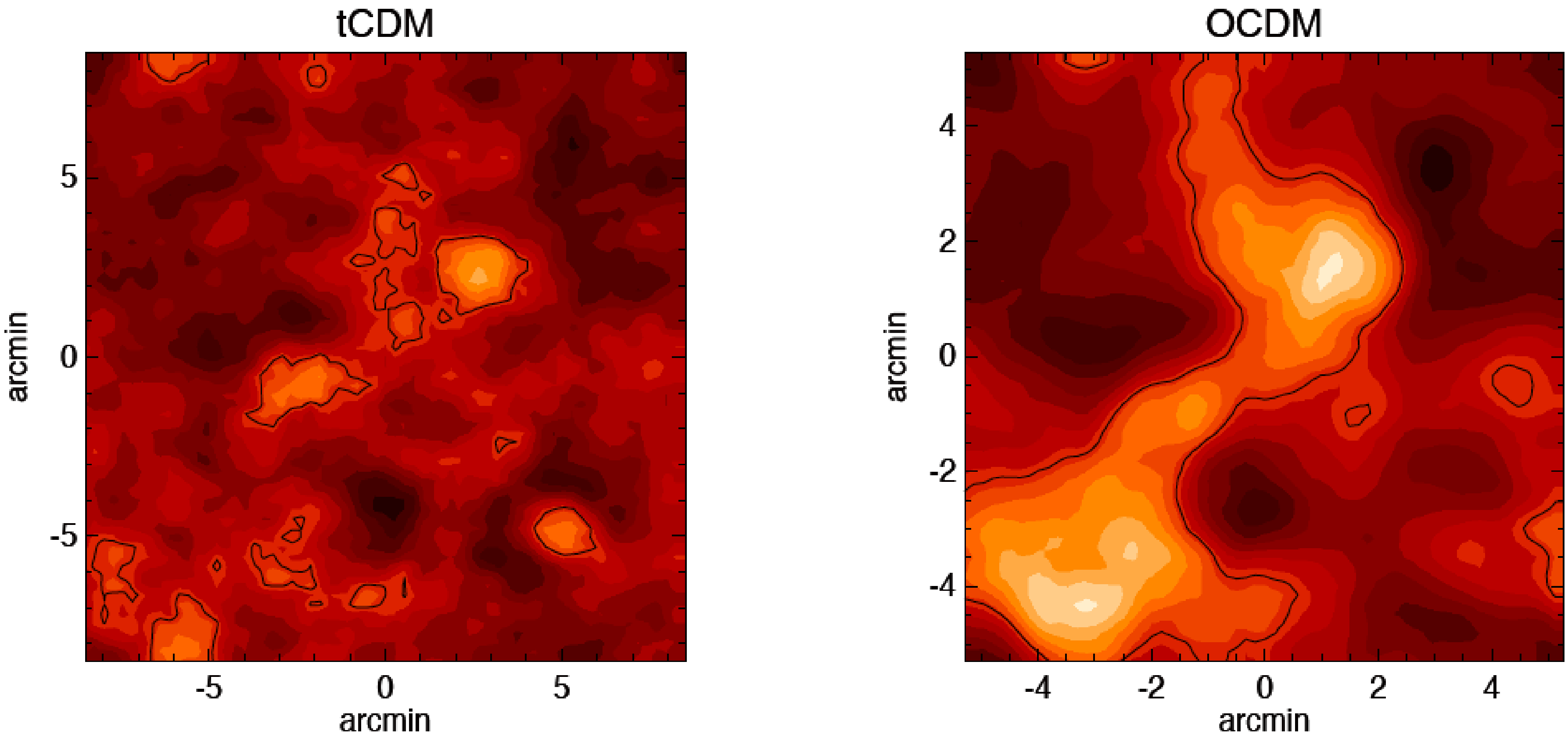
X-ray image

Chandra satellite detected an X-ray source in this galaxy. This can be explained as a young quasar, powered by a SMBH with $M_\bullet \sim 4 \times 10^7\ M_\odot$

(Bogdan et al. 2024)

Looking Even Deeper: The 21cm Line

We can in principle image H I condensations in the still neutral, pre-reionization universe using the 21cm line. Several experiments are now being constructed or planned to do this, in the US (including OVRO), Canada, Australia, Europe, etc.



(Simulations of z = 8.5 H I, from P. Madau)

Young and Forming Galaxies: Summary

- Following the recombination, baryons flow into the DM halos. The cosmic "***dark ages***" begin, and the IGM is neutral
- Eventually the gas reaches sufficient densities to ignite the star formation, perhaps around $z \sim 20 - 30$
- The first generation of stars (Pop III) is expected to be very massive, and thus hot and luminous. Their explosions enrich the gas, which then forms the Pop II stars. The ***reionization peaks around z ~ 8 – 10 and is complete by z ~ 6***
- The Lyman drop technique is a powerful way to select high-z galaxy candidates, but spectroscopy is needed to confirm them
- ***Many galaxies are now known out to z ~ 12 or so***, mainly due to the JWST. Their numbers are unexpected, requiring ***a very early start*** of their formation. Even at z ~ 8 – 10, galaxies show ***a substantial chemical enrichment***