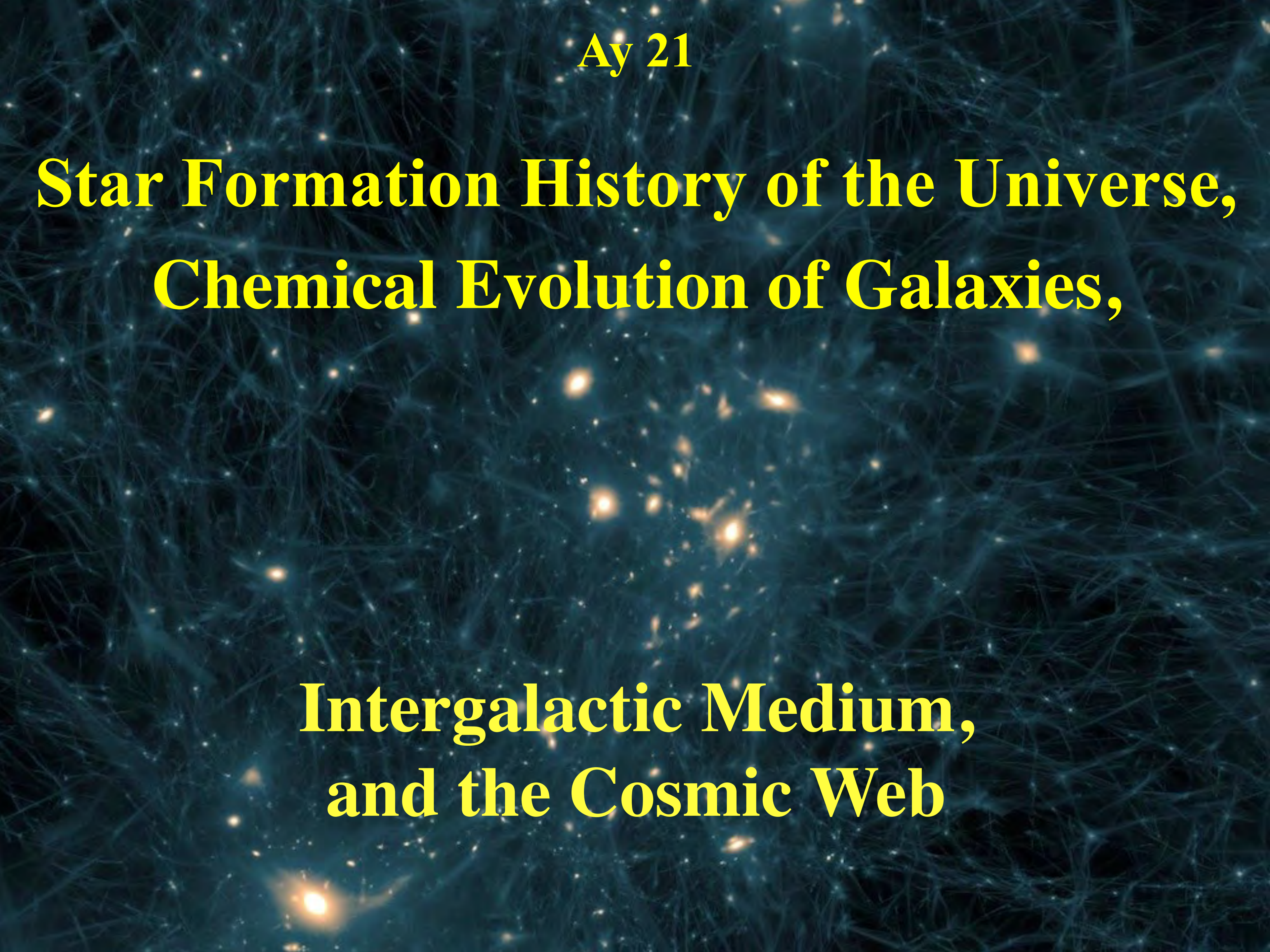


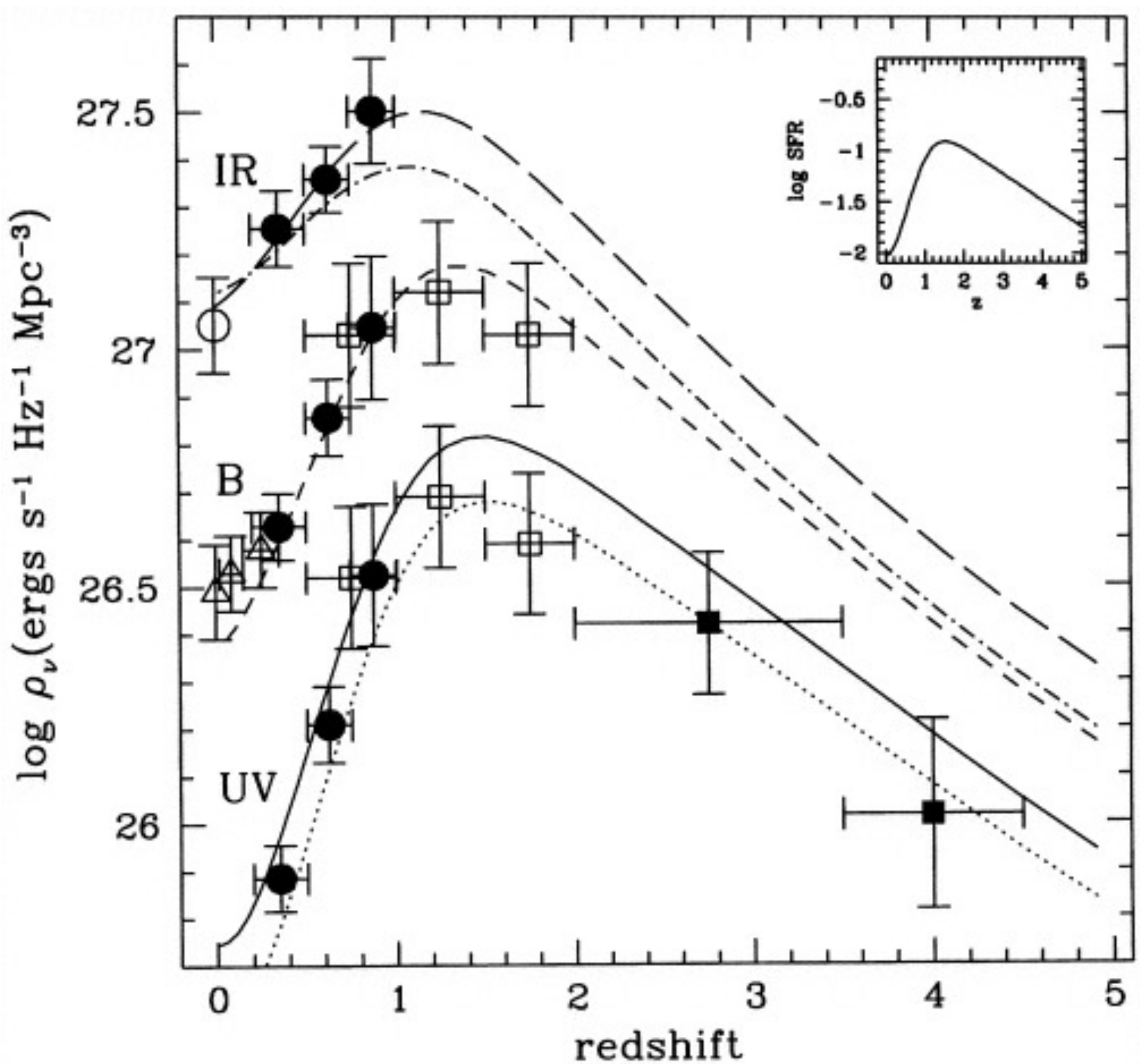
Ay 21

Star Formation History of the Universe, Chemical Evolution of Galaxies,

Intergalactic Medium, and the Cosmic Web

The History of Star Formation

From the various luminosity densities converted to star formation rates, we can construct a possible history of the comoving SFR density



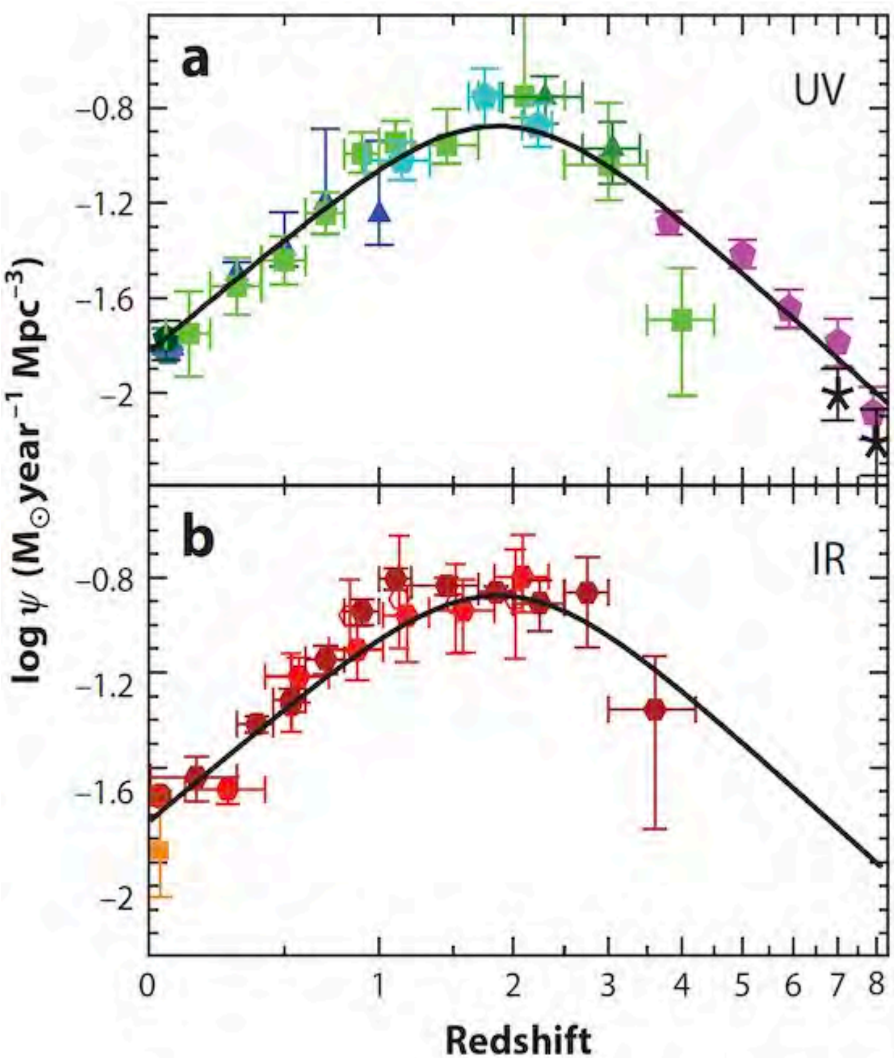
This is the original ("Madau") diagram, based on the deep galaxy counts in the Hubble Deep Field(s)

These data and models are ***not*** corrected for the extinction

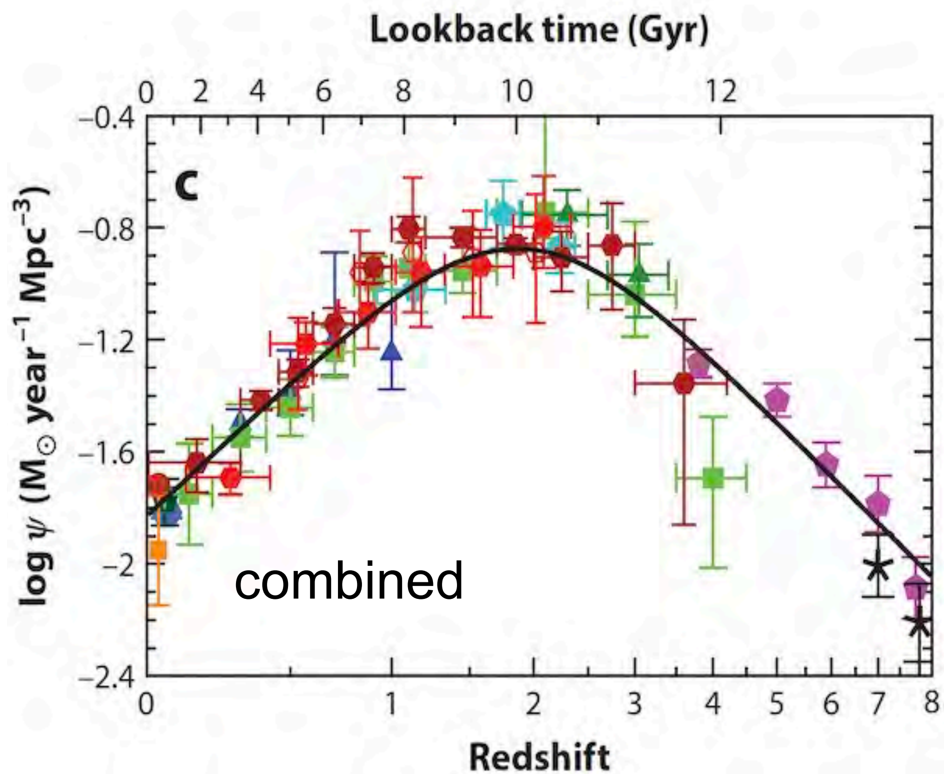
We must also add the dust obscured start formation component

Cosmic Star Formation History

Observations in UV/optical give us the unobscured star formation rate, and in Far-IR/sub-mm the obscured component



The average star formation peaks around z ~ 2 (the "cosmic noon")

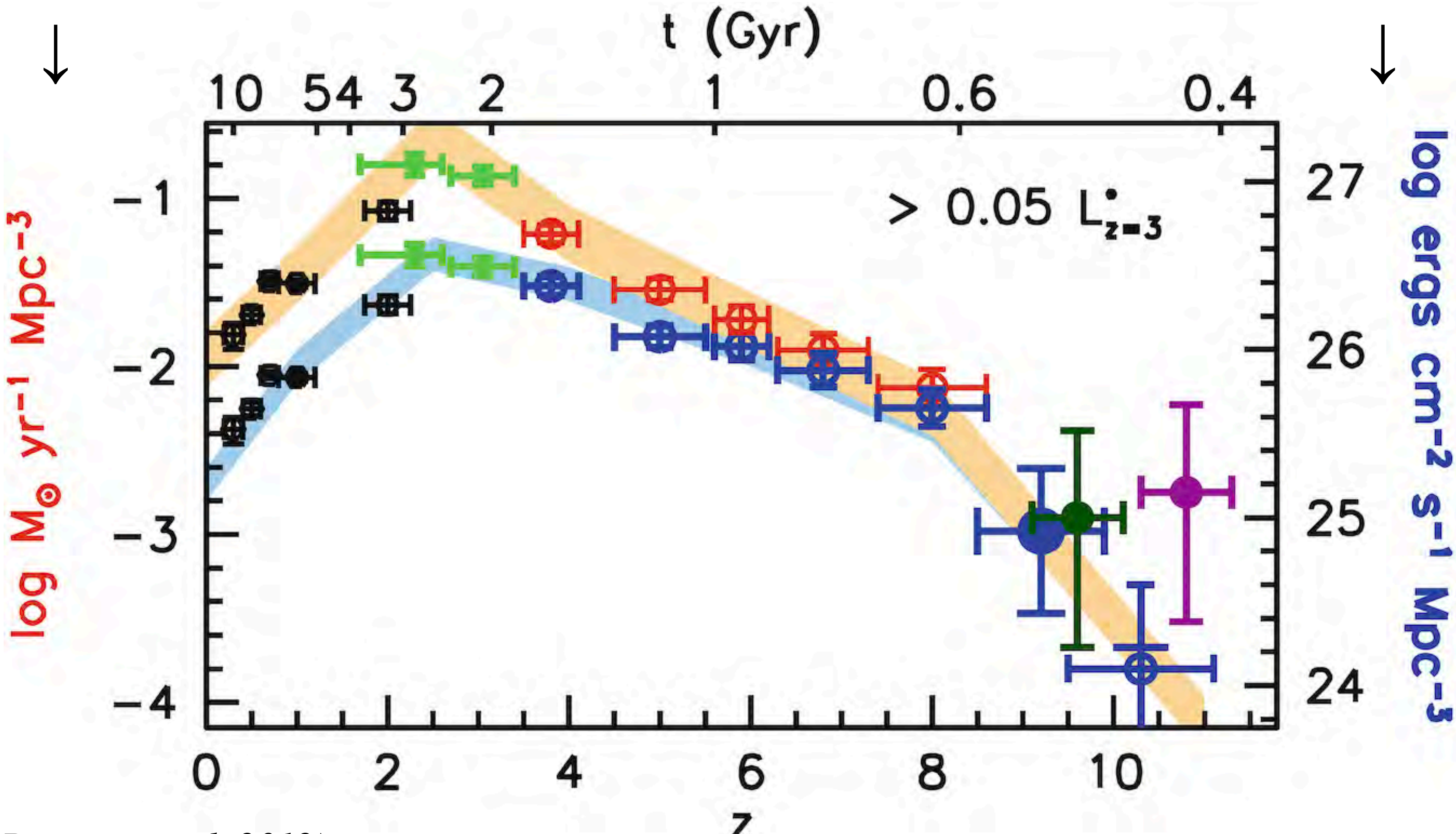


(Madau & Dickinson 2014)

Cosmic Star Formation History

Star formation rate density ↓

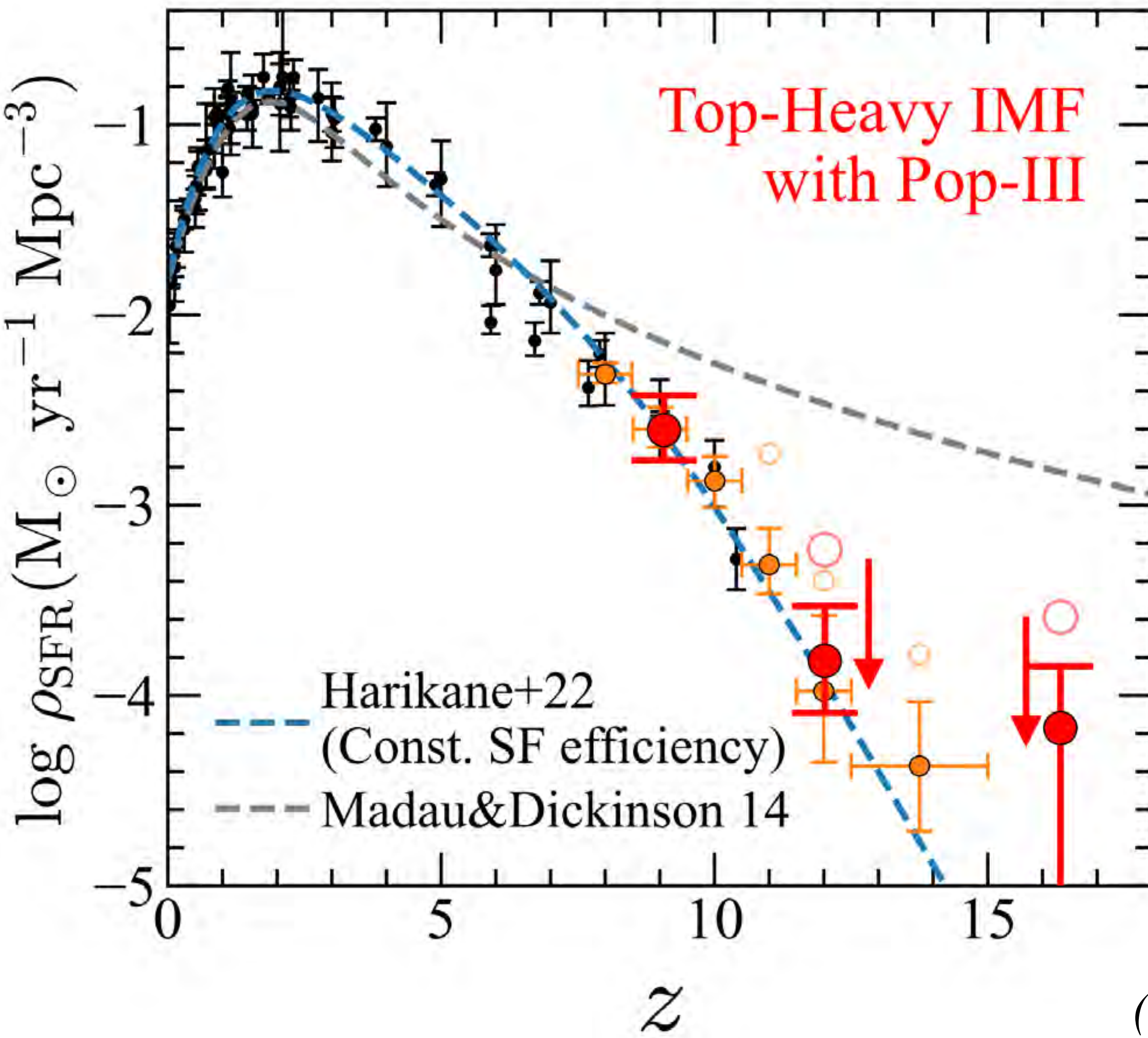
Restframe UV luminosity density ↓



(Bouwens et al. 2012)

Early Star Formation History from JWST

The trend continues out to $z \sim 15$, suggests a *top-heavy stellar IMF*

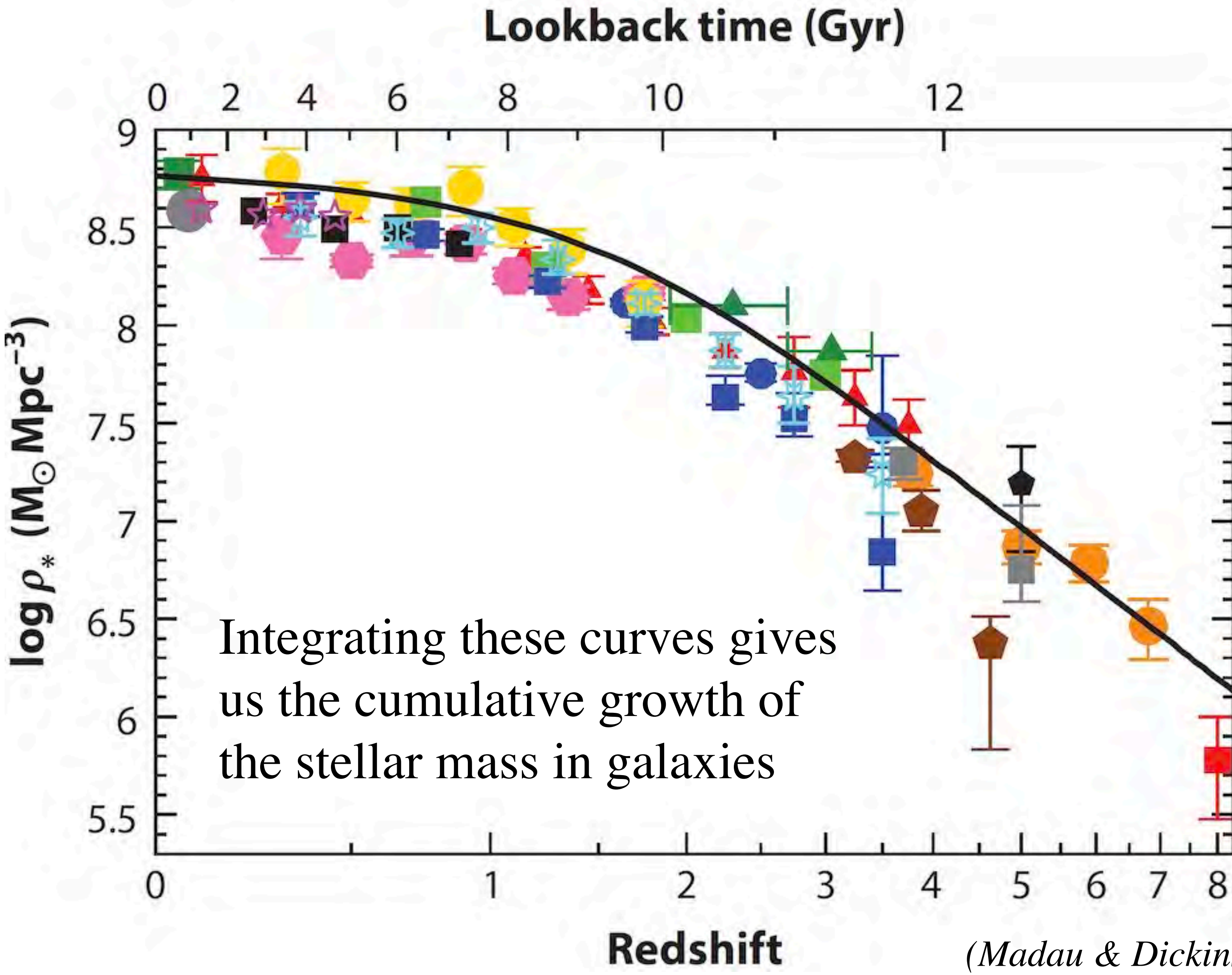


● = new data

Old extrapolation from lower z's assuming no evolution of the stellar IMF

(Harikane et al. 2022)

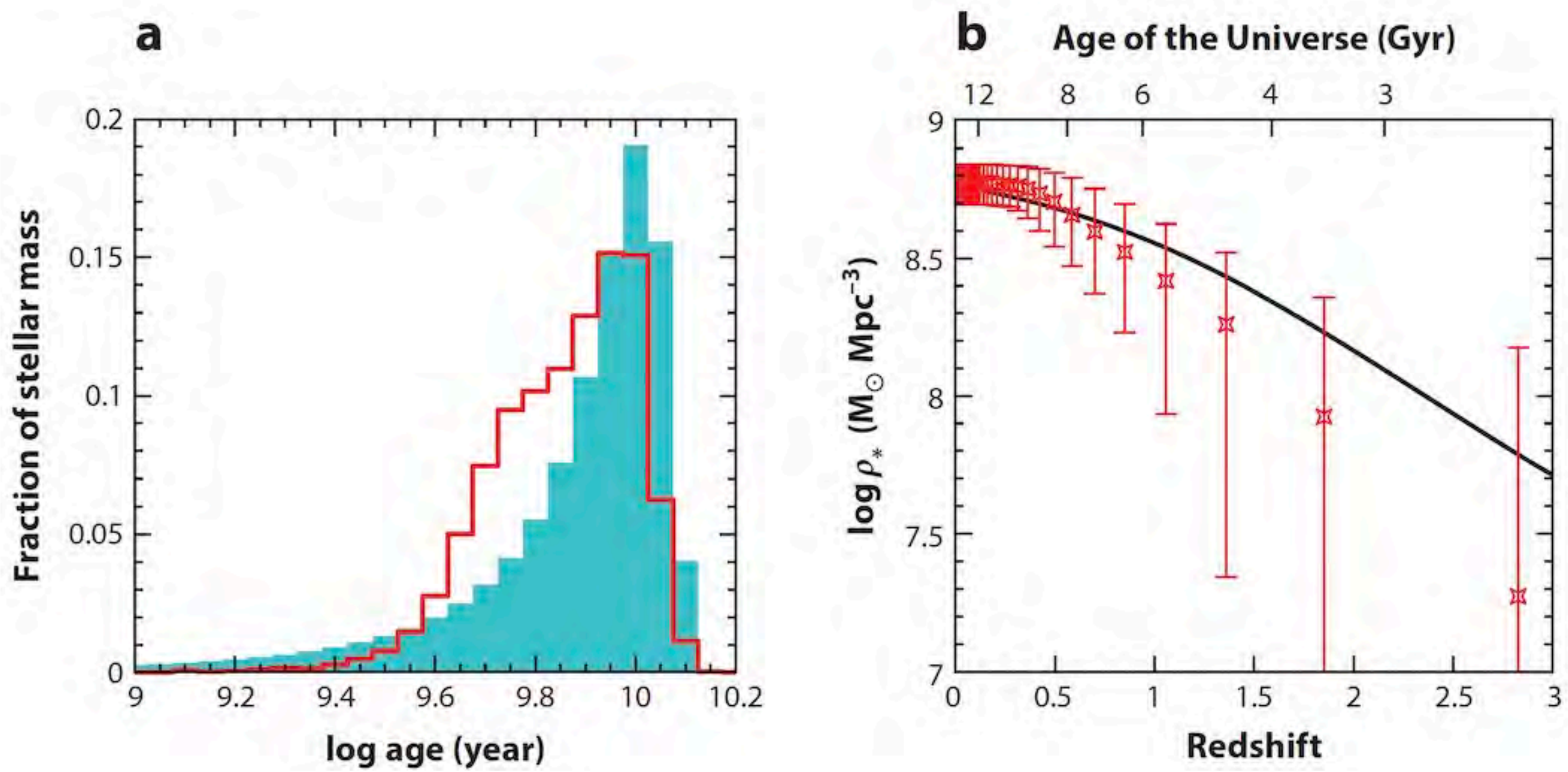
Build-up of the Stellar Mass Density



(Madau & Dickinson 2014)

Build-up of the Stellar Mass Density

We can obtain an independent estimate from the “galactic archeology” at low redshifts: estimate the mean stellar ages in the nearby galaxies detected by SDSS, then convert these ages to the mean formation redshifts:

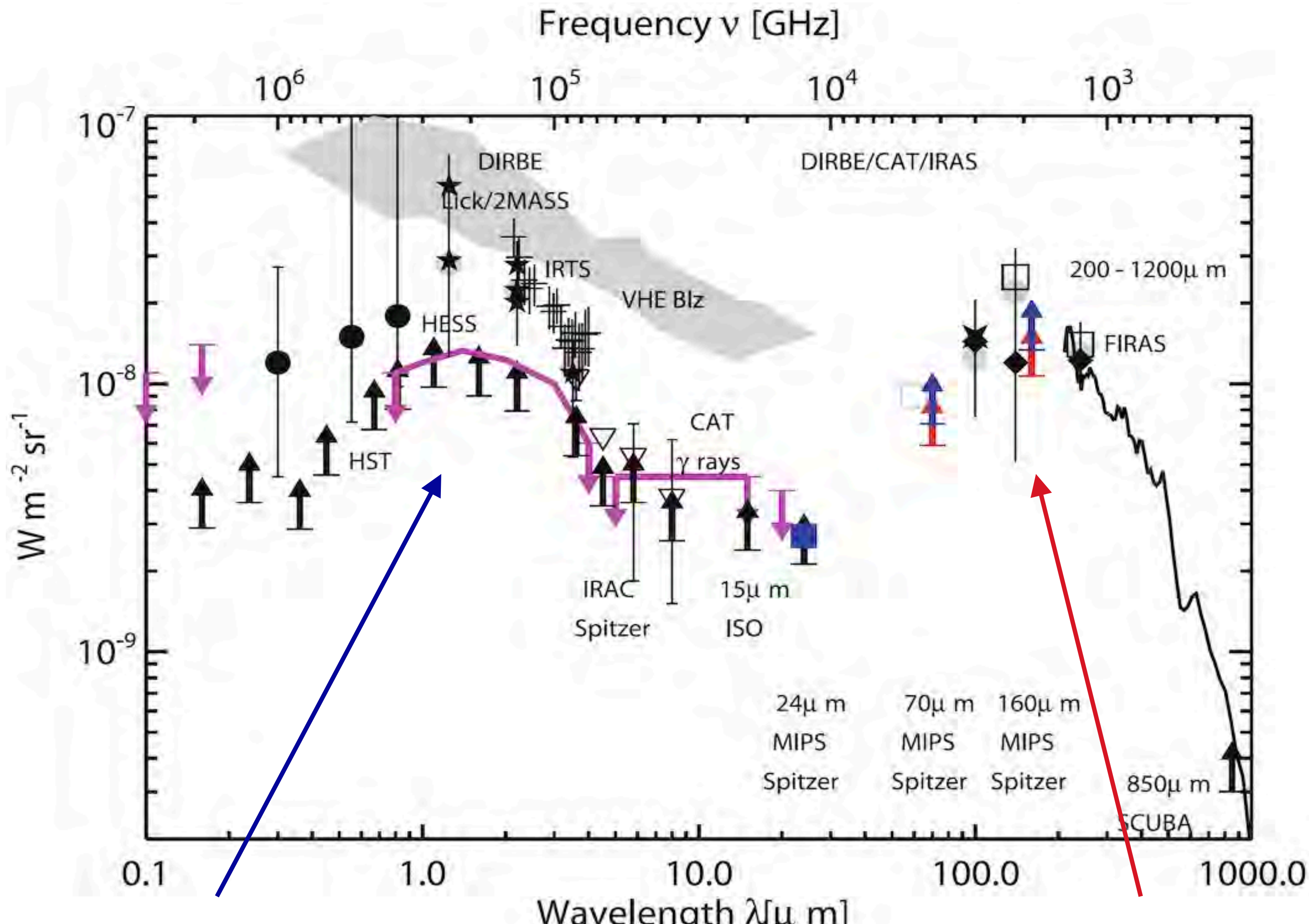


(Madau & Dickinson 2014)

All Starlight in the Universe

- Any deep survey is limited in flux and surface brightness: some fainter and/or more diffuse sources are likely missed; thus, our source counts give us only a lower limit to the total energy emitted by evolving galaxies
- An alternative approach is to measure ***integrated diffuse backgrounds, due to all sources***
  - This is really hard to do, for many reasons
  - Redshifts are lost, but at least the energy census is complete
- The total energy in the diffuse extragalactic backgrounds from UV to sub-mm is ~ 20 nW m^{-2} sr^{-1} (±50% or so)
  - This is distributed roughly equally between the UV/Opt (unobscured SF) and FIR/sub-mm (obscured SF)
  - A few percent of the total is contributed by AGN
  - This is only a few percent of the CMB

Diffuse Optical and IR Backgrounds



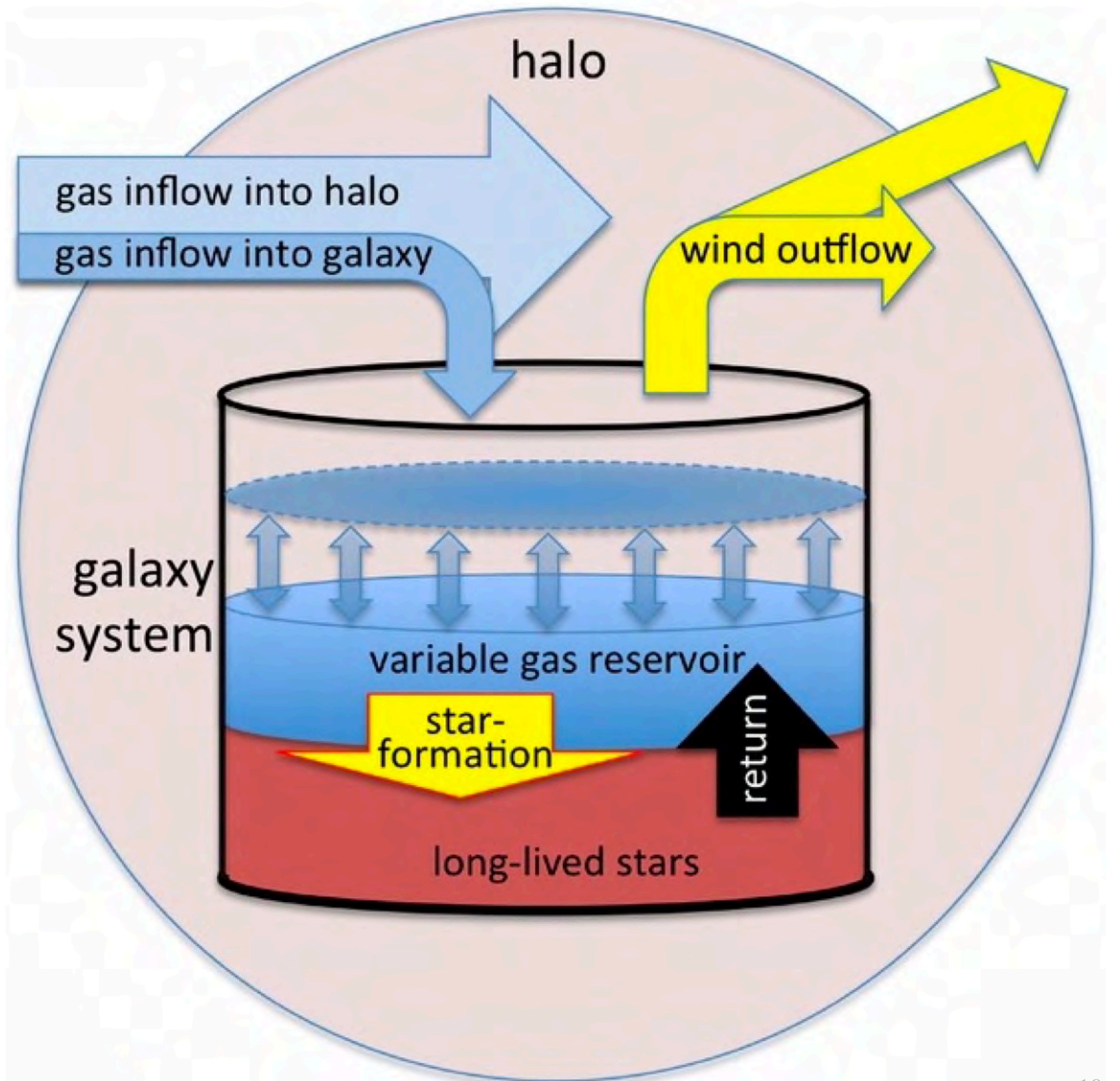
Unobscured component
(restframe UV, obs. Optical/NIR)

Obscured component
(restframe FIR, obs. FIR/sub-mm)

The Cosmic Chemical Evolution

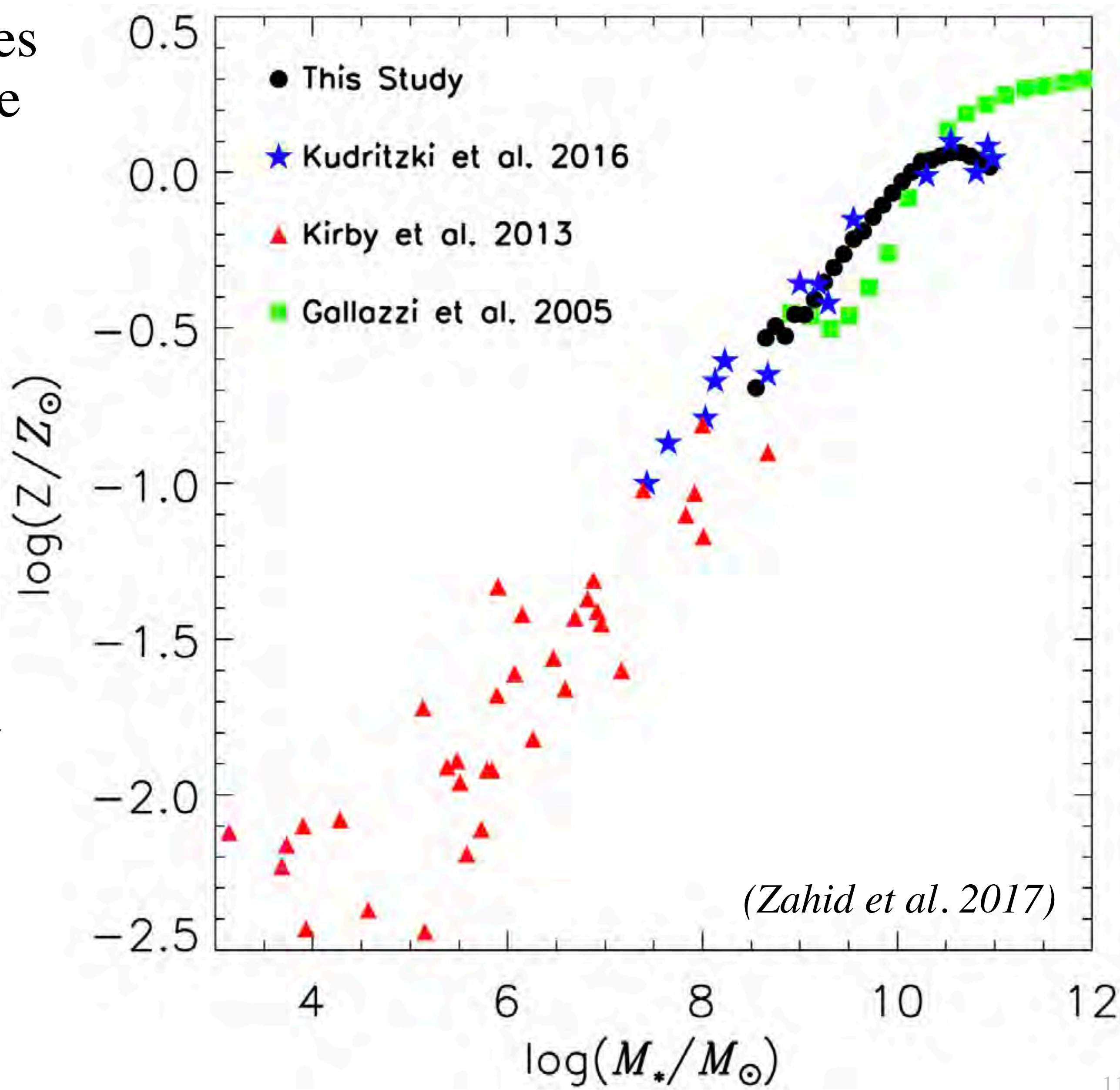
A schematic view:

Details of these processes are very messy and hard to model or simulate. So, simplified (semi)analytical models and assumptions are often used, e.g., the "closed box" model, or the "instanteneous recycling" approximation



Galaxy Mass and Chemical Evolution

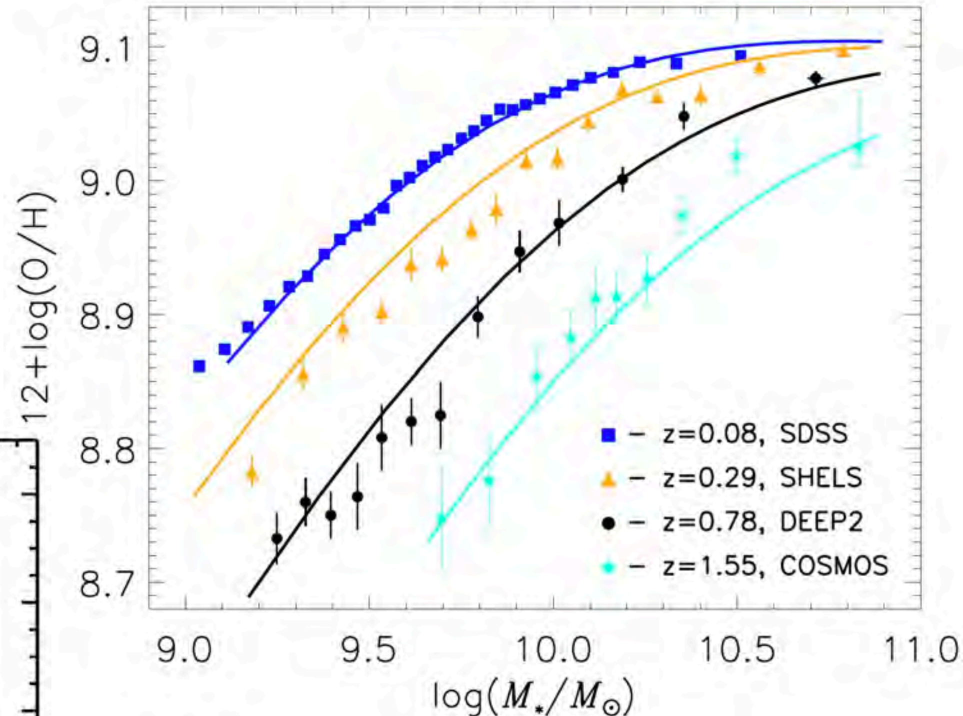
More massive galaxies in the nearby universe are more metal-rich

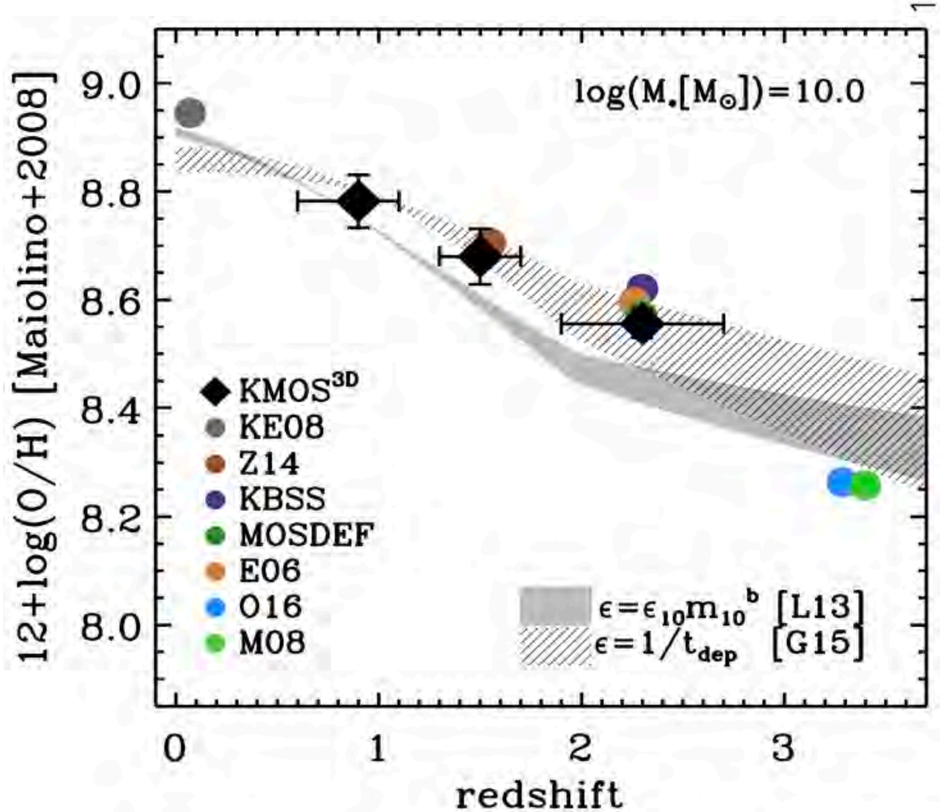


They can retain more effectively the chemically enriched material from the supernova ejecta

Chemical Evolution in Redshift

Similar mass-metallicity trends exist at any given redshift →

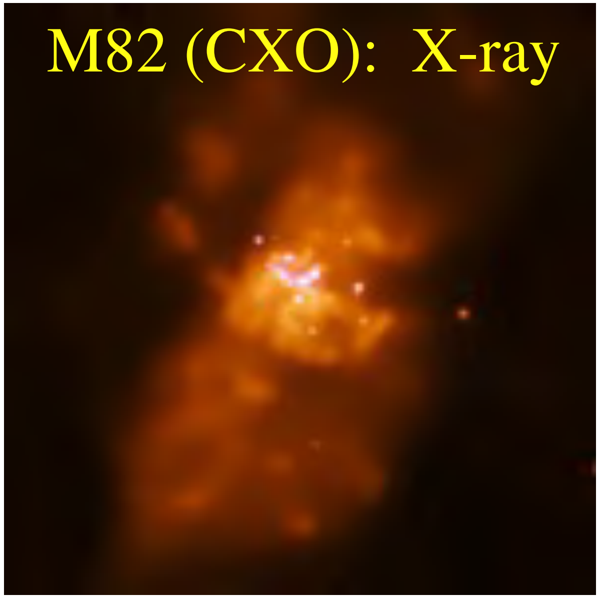


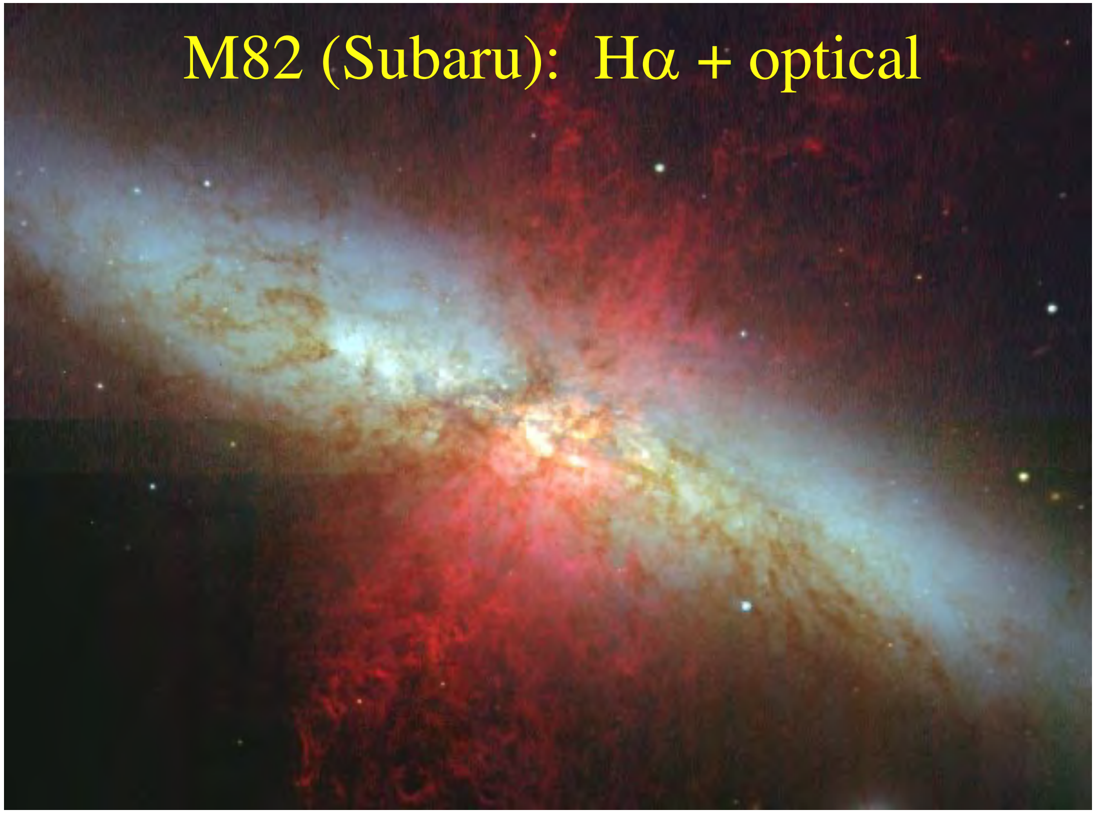


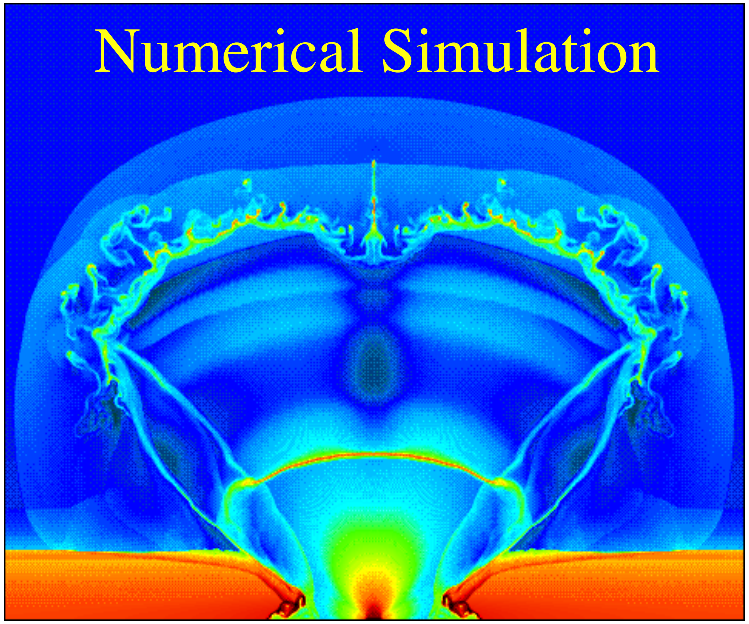
← But the overall metallicity of galaxies increases in time

Galactic Winds

Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows







Star Formation History Summary

- Integrated star formation rate in galaxies increases from the high redshifts (the initial galaxy growth), has a broad peak at $z \sim 2$, and declines after $z \sim 1$
- Contributions from the unobscured and obscured star formation are about equal
- This is reflected in the diffuse optical and infrared backgrounds

Galaxy Chemical Evolution Summary

- Successive generations of stars increase the mean metallicity of galaxies, as some of the enriched material is recycled
- Some of the enriched gas is ejected by the supernova-driven galactic winds, where it enriches the intergalactic medium
- This depends of the galaxy mass, as the more massive galaxies retain more of the enriched material

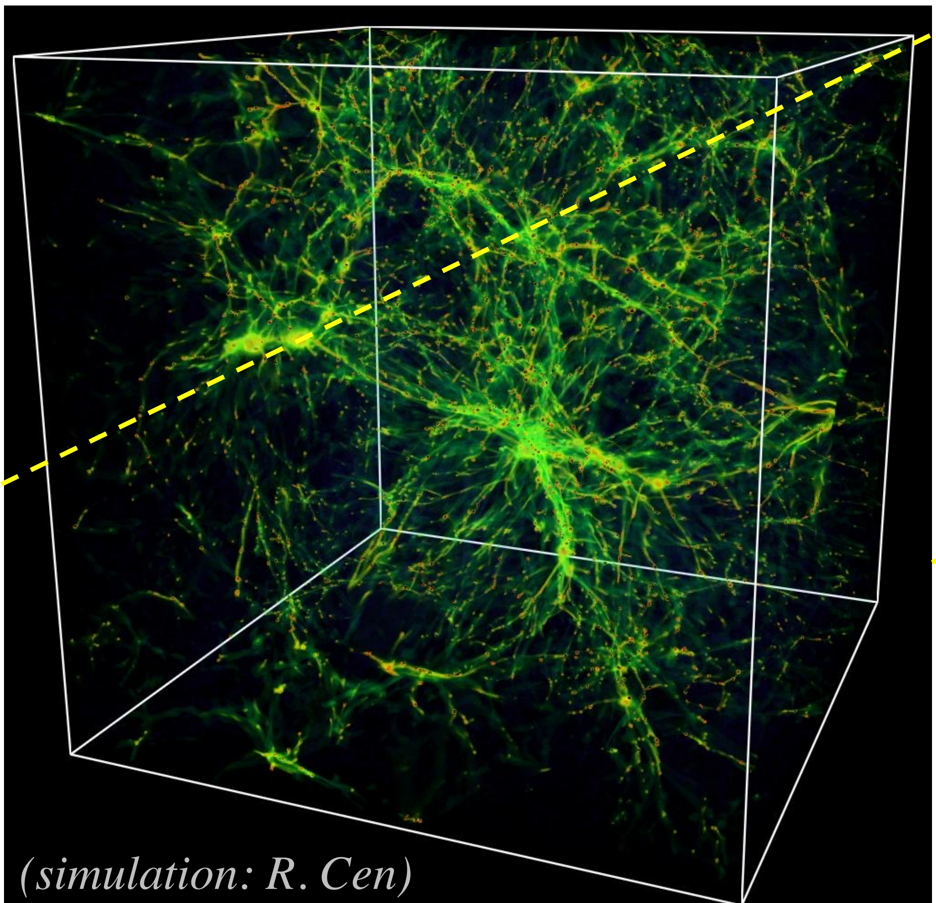
Intergalactic Medium (IGM)

- Essentially, baryons between galaxies
- Its density evolution follows the LSS formation, and the potential wells defined by the DM, forming a web of filaments, the co-called "**Cosmic Web**"
- An important distinction is that this gas unaffiliated with galaxies samples the low-density regions, which are still in a linear regime
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation
- Likewise, enriched gas is driven from galaxies through the radiativly and SN powered **galactic winds**, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other
- Star formation and AGN provide **ionizing flux** for the IGM

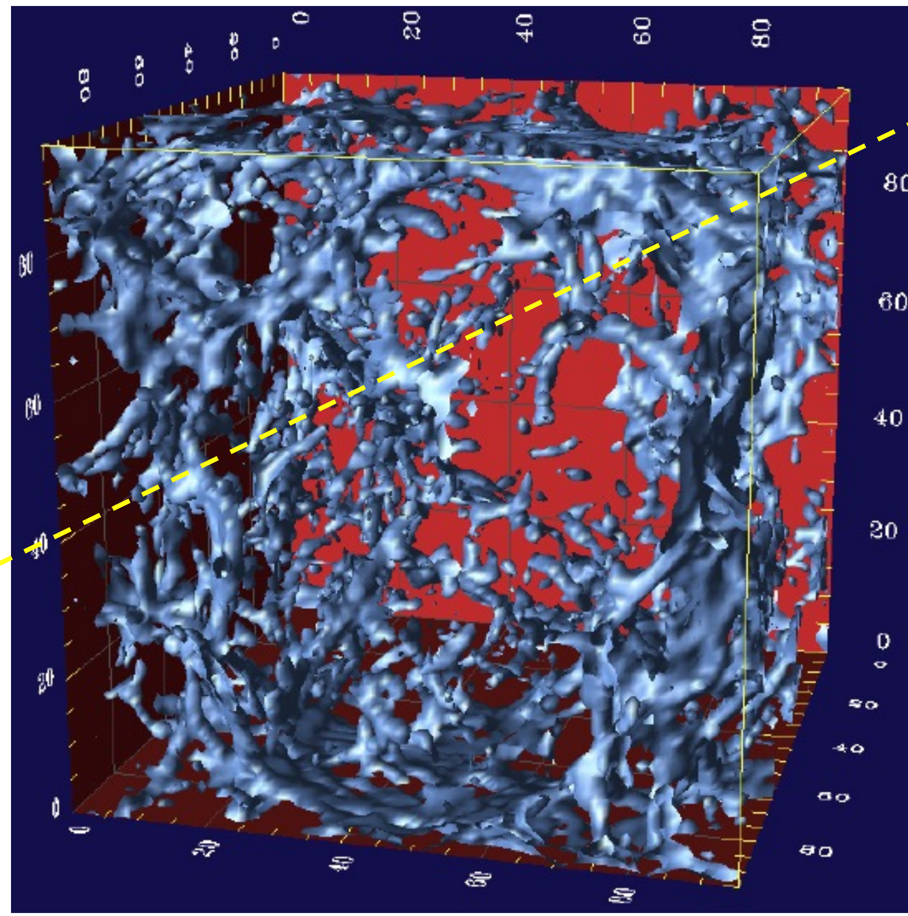
Cosmic Web: Numerical Simulations

The ISM roughly follows the large scale distribution of the DM and its topology (filaments, voids, etc.)

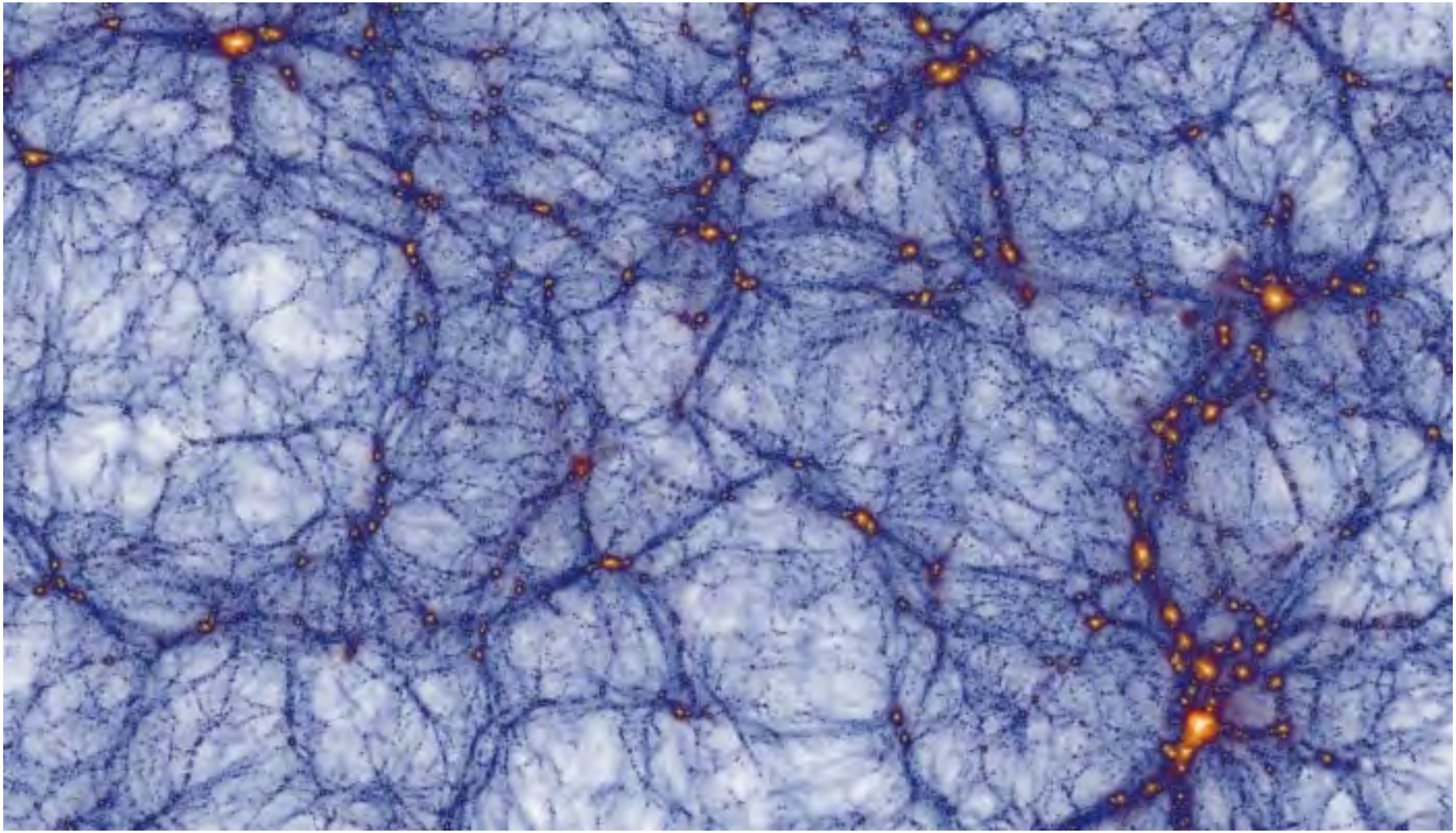
Our lines of sight towards some luminous background sources intersect a range of gas densities, condensed clouds, galaxies …



(simulation: R. Cen)



Cosmic Web Millennium XXL Simulation

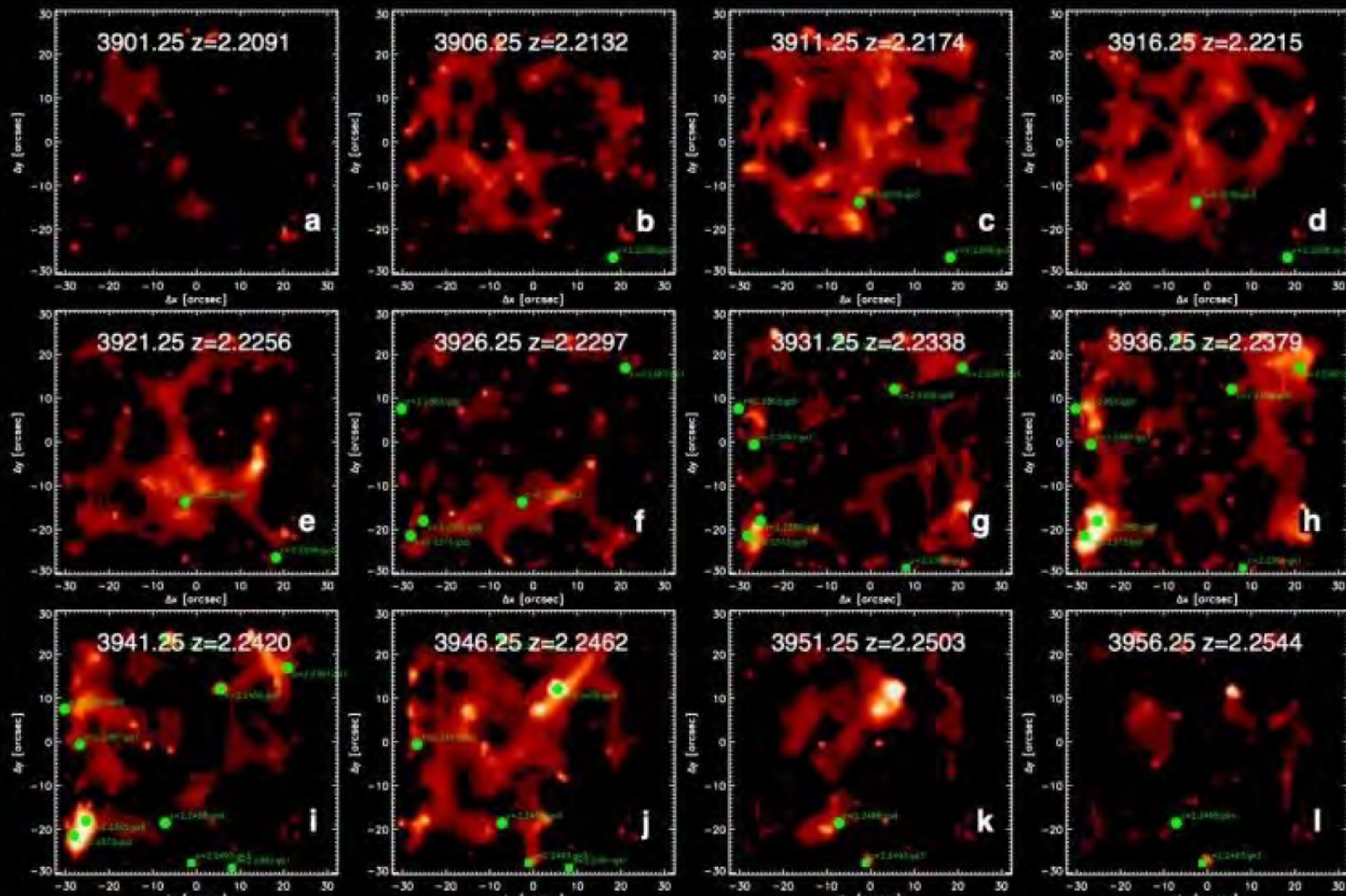


Hydrogen follows the dark matter structure of filaments and voids

Galaxies form at the intersection of filaments, and IGM flows into them

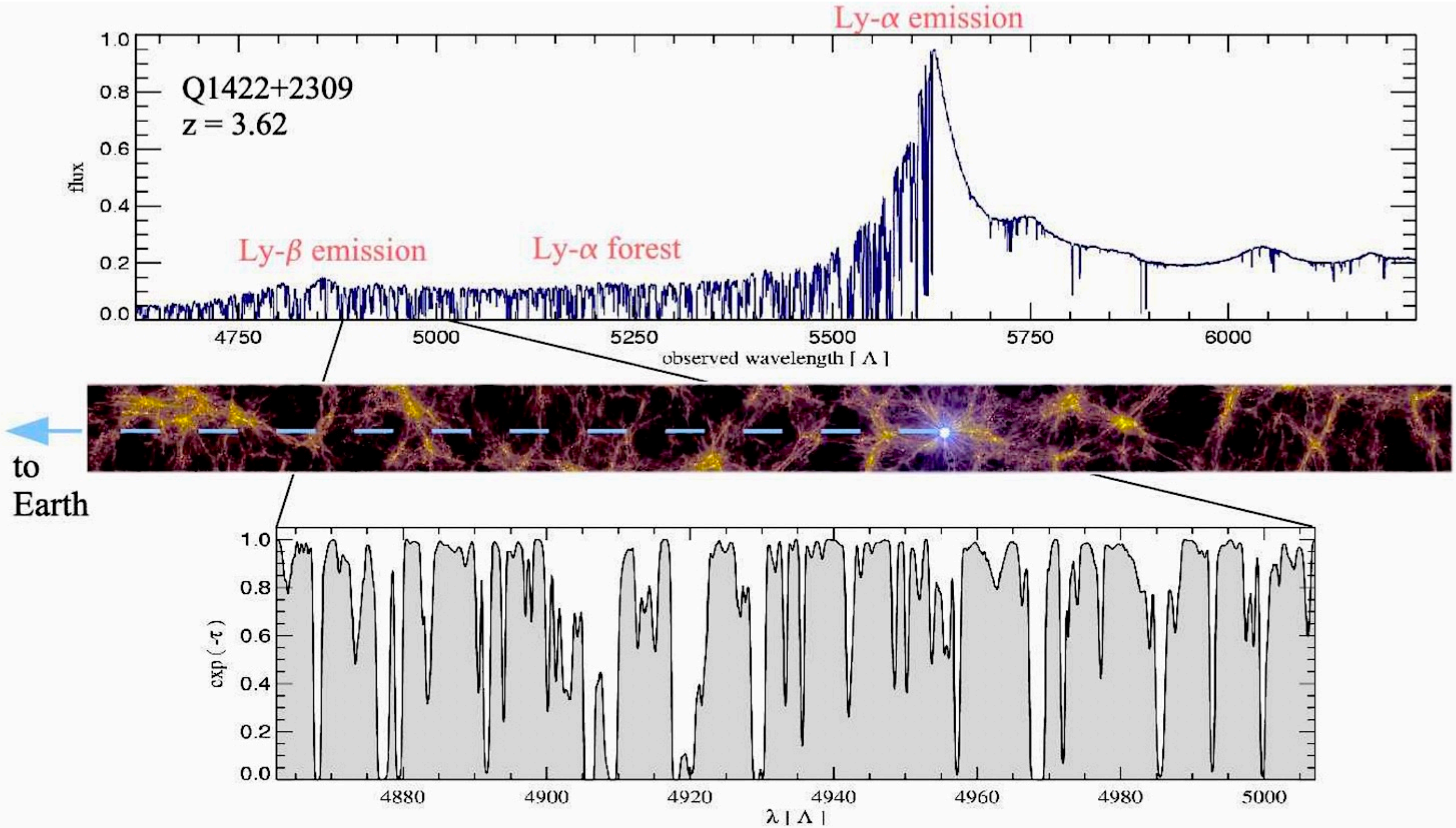
Imaging the Cosmic Web

Images in narrow band Lyman α using KCWI imager at the Keck telescope by C. Martin et al.



Cosmic Web: Numerical Simulations

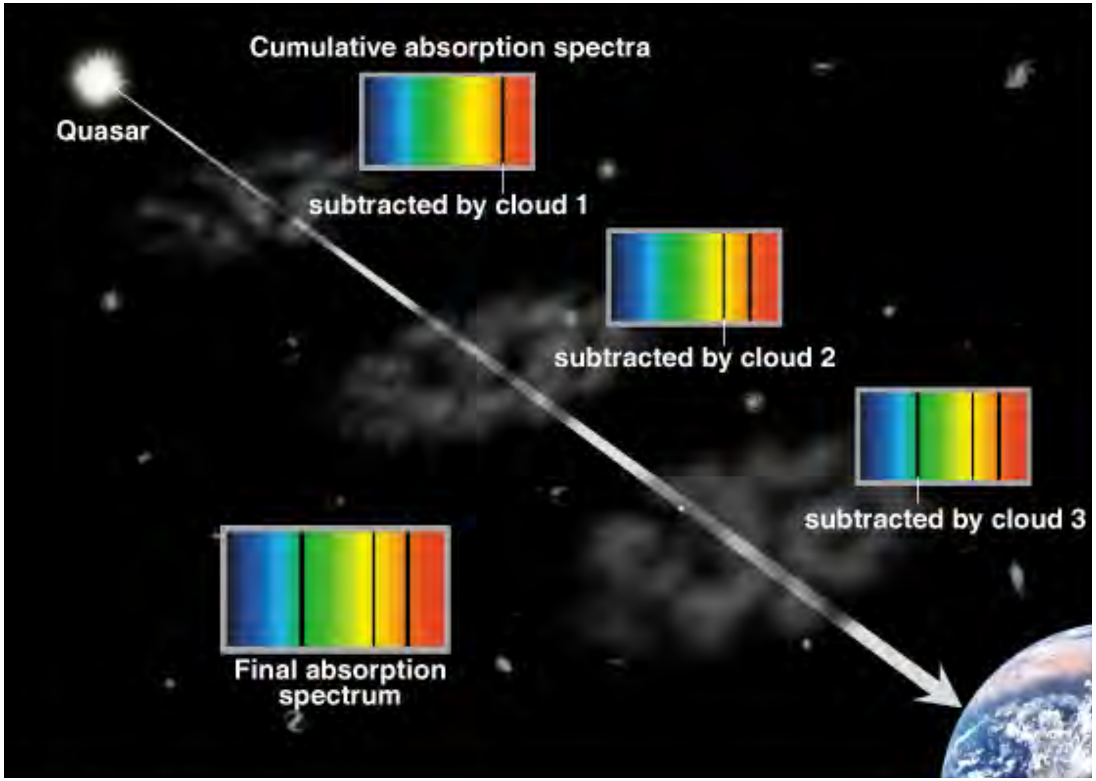
Numerical simulations reproduce well what is observed in the spectra of distant quasars



(simulation: Springel et al.)

QSO Absorption Line Systems

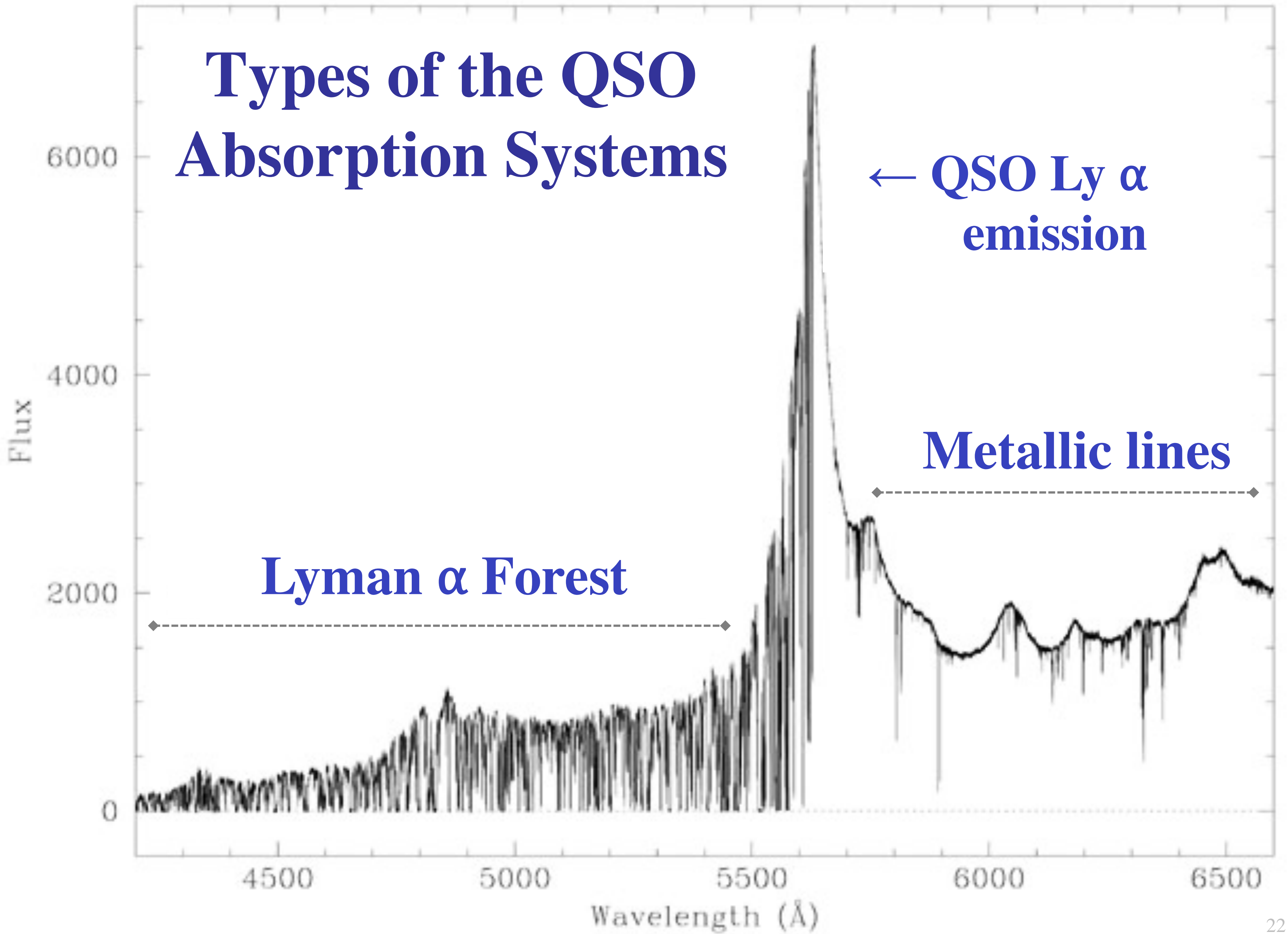
- An alternative to searching for galaxies by their ***emission*** properties is to search for them by their ***absorption***
- Quasars are very luminous objects and have very blue colours which make them relatively easy to detect at high redshifts
- Nowadays, GRB afterglows provide a useful alternative
- Note that this has ***different selection effects*** than the traditional imaging surveys: not by luminosity or surface brightness, but by the cross section (size) and column density



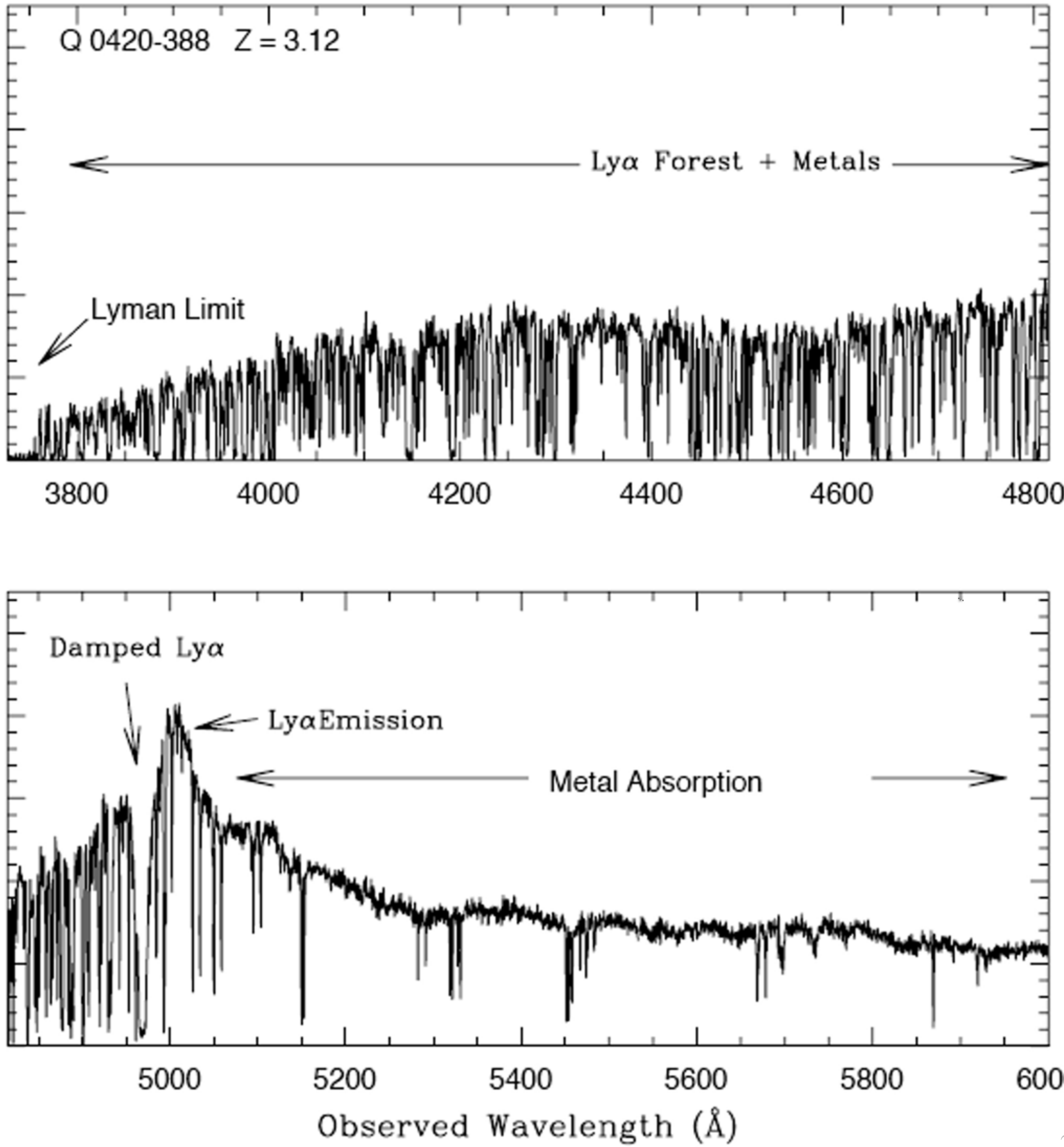
Types of the QSO Absorption Lines

- **Lyman alpha forest:**
  - Numerous, weak lines from low-density hydrogen clouds
  - Lyman alpha clouds are proto-galactic clouds, with low density, they are not galaxies (but some may be proto-dwarfs)
- **Lyman Limit Systems (LLS) and "Damped" Lyman alpha (DLA)** absorption lines:
  - Rare, strong hydrogen absorption, high column densities
  - Coming from intervening galaxies
  - An intervening galaxies often produce both metal and damped Lyman alpha absorptions
- **Helium equivalents** are seen in the far UV part of the spectrum
- **"Metal" absorption lines**
  - Absorption lines from heavy elements, e.g., C, Si, Mg, Al, Fe
  - Most are from intervening galaxies

Types of the QSO Absorption Systems



Types of the QSO Absorption Systems



The strongest Metallic Absorption Lines

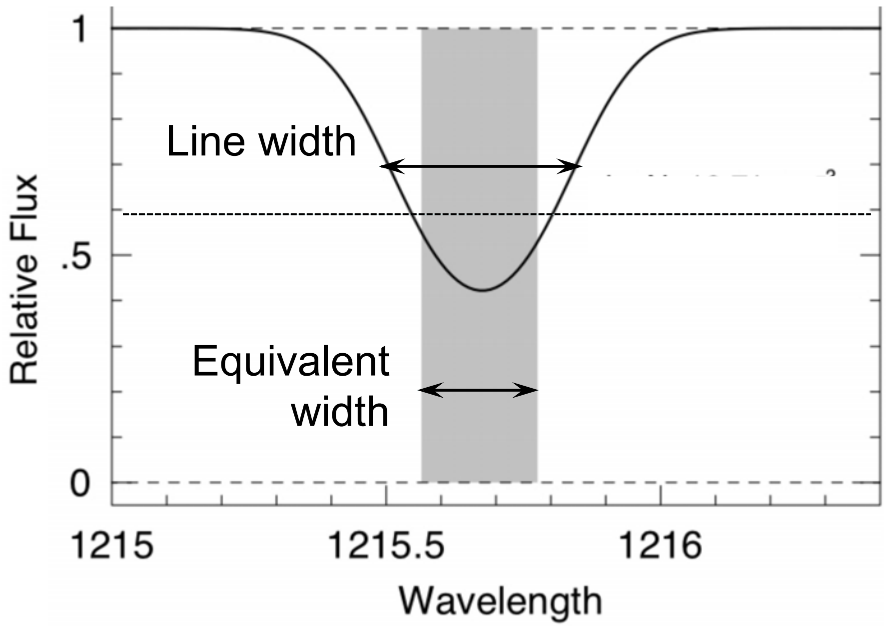
Ion	λ_o (Å)	f Oscillator strength	$\log(\lambda_o f)$	$\log(\lambda_o^2 f)$
O VI	1031.927	0.130	2.128	5.141
O VI	1037.616	0.0648	1.828	4.844
H I	1215.670	0.4162	2.704	5.789
O I	1302.169	0.0486	1.801	4.916
C II	1334.532	0.118	2.197	5.323
Si IV	1393.755	0.528	2.867	6.011
Si IV	1402.770	0.262	2.565	5.712
C IV	1548.202	0.194	2.448	5.667
C IV	1550.774	0.097	2.177	5.368
Mg II	2796.352	0.592	3.219	6.666
Mg II	2803.531	0.295	2.918	6.365

They are products of the stellar chemical evolution in galaxies

Measuring the Absorbers

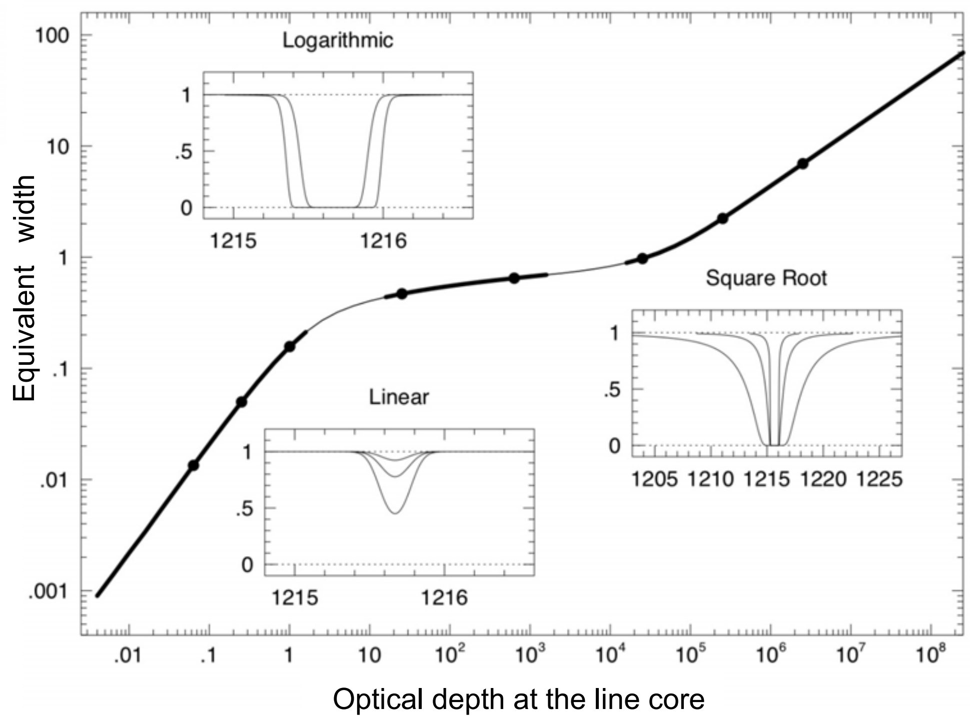
We measure equivalent widths of the lines, and shapes of their profiles

Line width reflects the *thermal broadening* and/or the velocity field

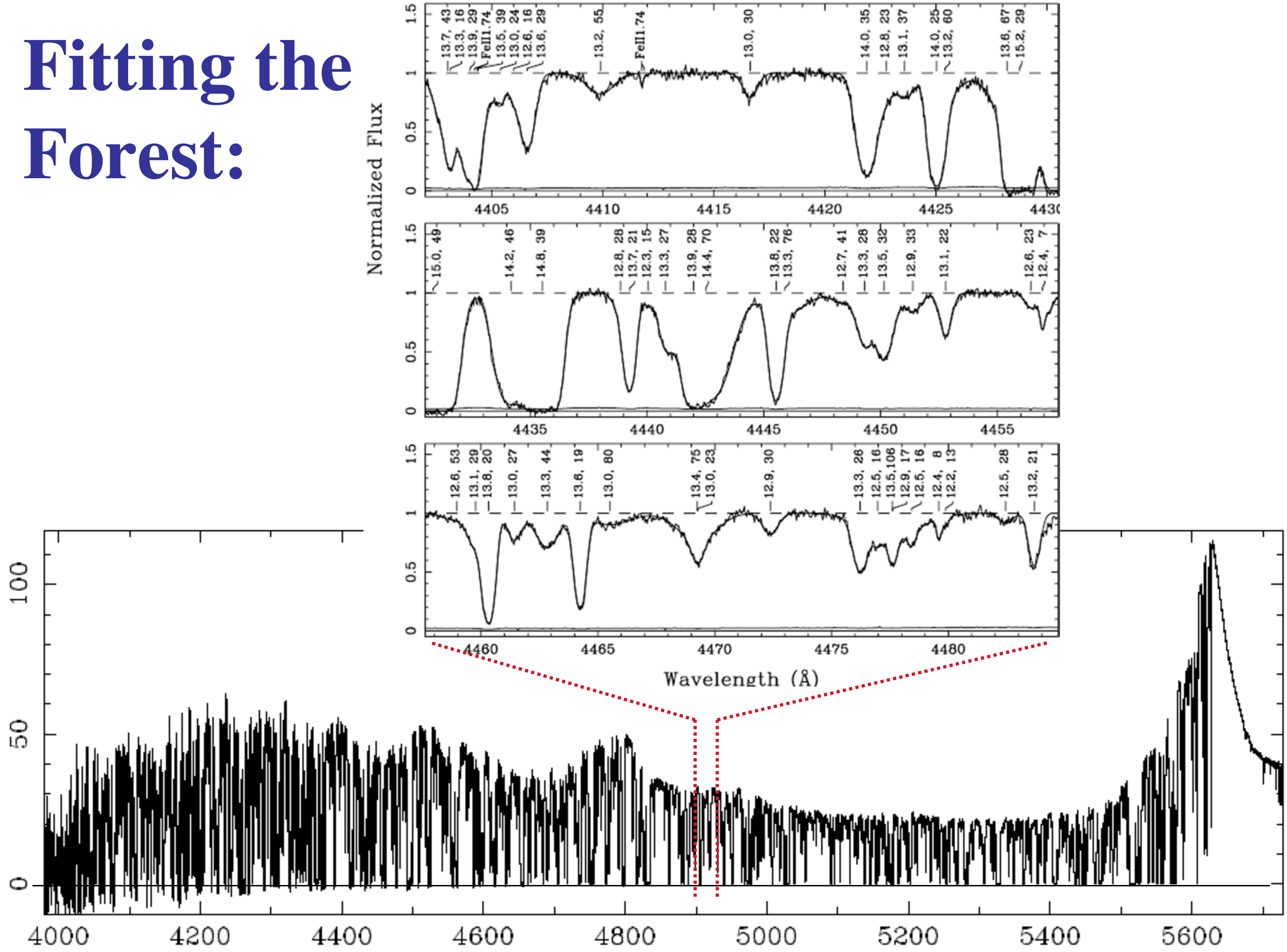


Equivalent width is the width of an unabsorbed continuum with the *same area* as the absorbed flux

Equivalent width is connected to the *column density* and thus the *abundance* via the ***curve of growth*** →



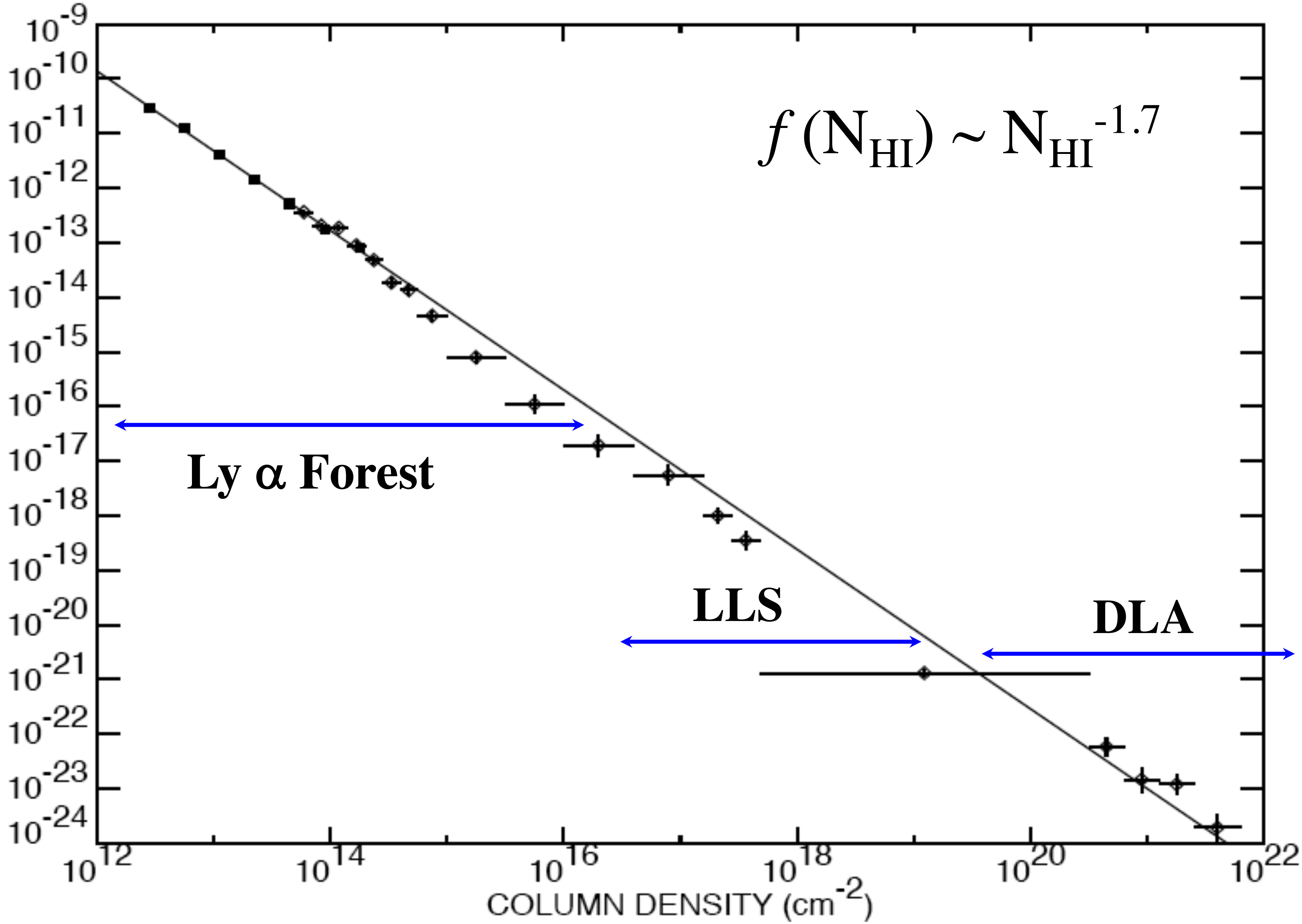
Fitting the Forest:



Ly α Absorbers

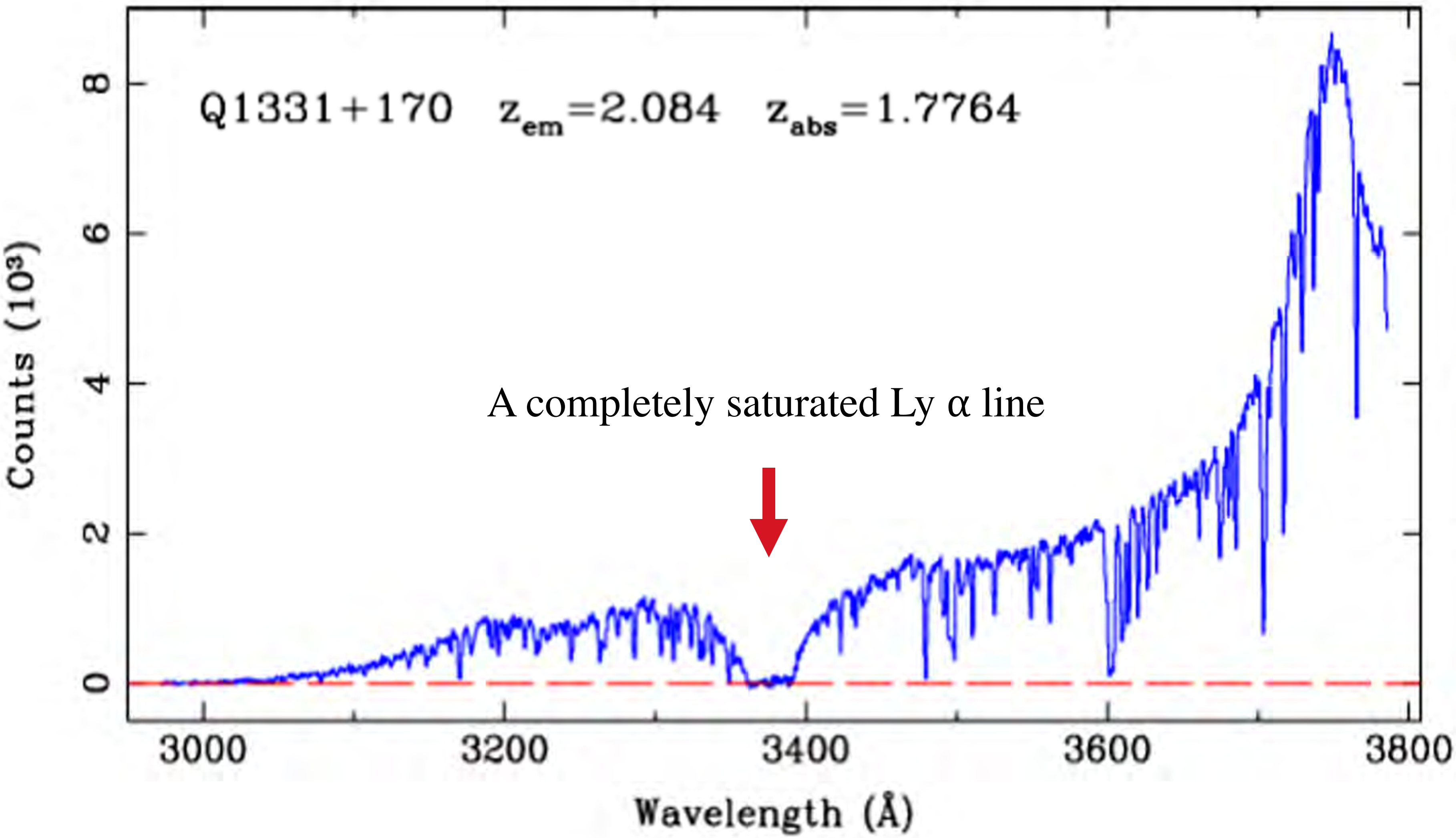
- **Ly α Forest:** $10^{14} \leq N_{HI} \leq 10^{16}$ cm^{-2}
  - Lines are unsaturated
  - Primordial metalicity < solar
  - Sizes are > galaxies
- **Ly Limit Systems (LLS):** $N_{HI} \geq 10^{17}$ cm^{-2}
  - Ly α Lines are saturated
  - N_{HI} is ufficient to absorb *all* ionising photons shortward of the Ly limit at 912Å in the restframe (i.e., like the UV-drop out or Lyman-break galaxies)
- **Damped Ly α (DLA) Systems:** $N_{HI} \geq 10^{20}$ cm^{-2}
  - Line heavily saturated
  - Profile dominated by "damped" Lorentzian wings
  - Almost surely proto-disks or their building blocks

Distribution of Column Densities



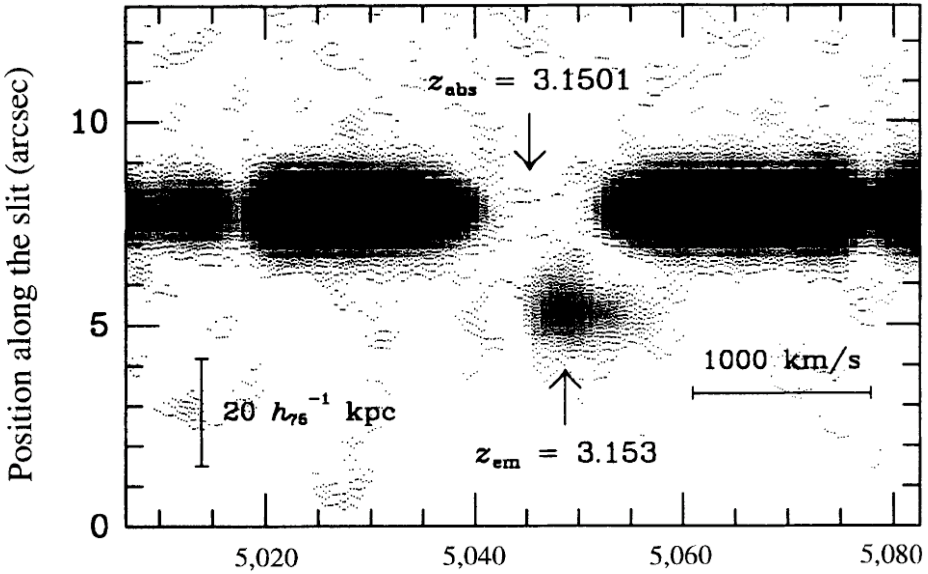
Damped Lyman α Systems

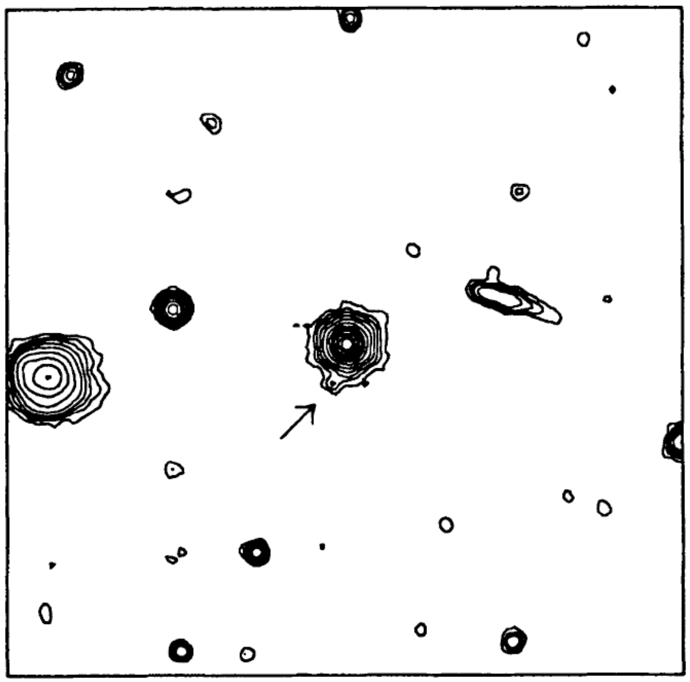
Likely progenitors of the galactic disks: they have a similar column density of the H I

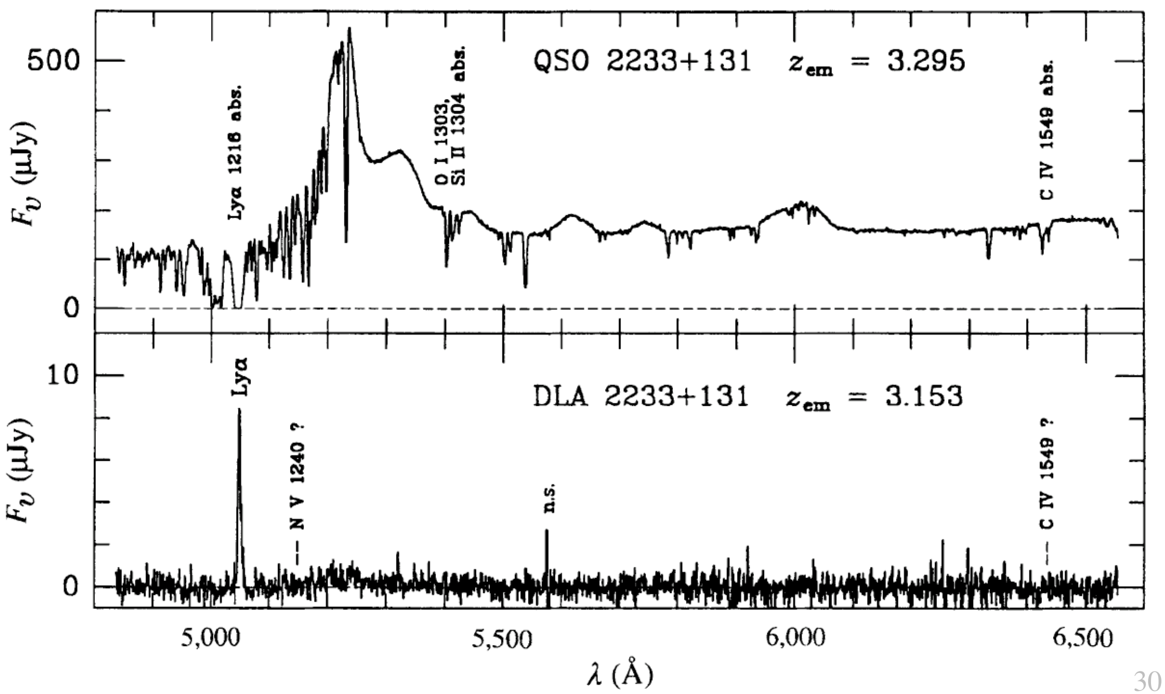


Galaxy Counterparts of DLA Systems

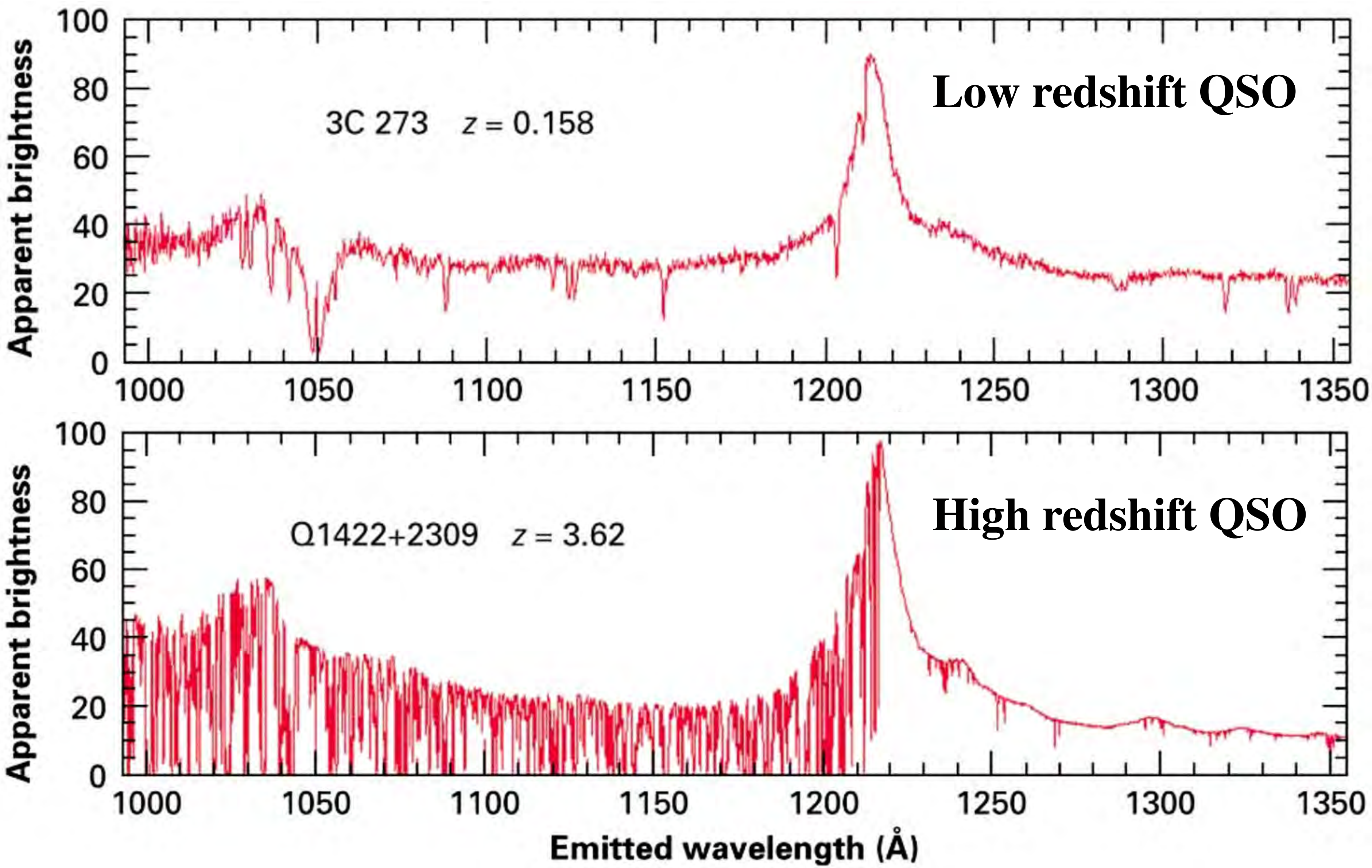
- Several examples are known with Lyα line emission
- Properties (size, luminosity, SFR) are typical of field galaxies at such redshifts, and consistent with being progenitors of $z \sim 0$ disks





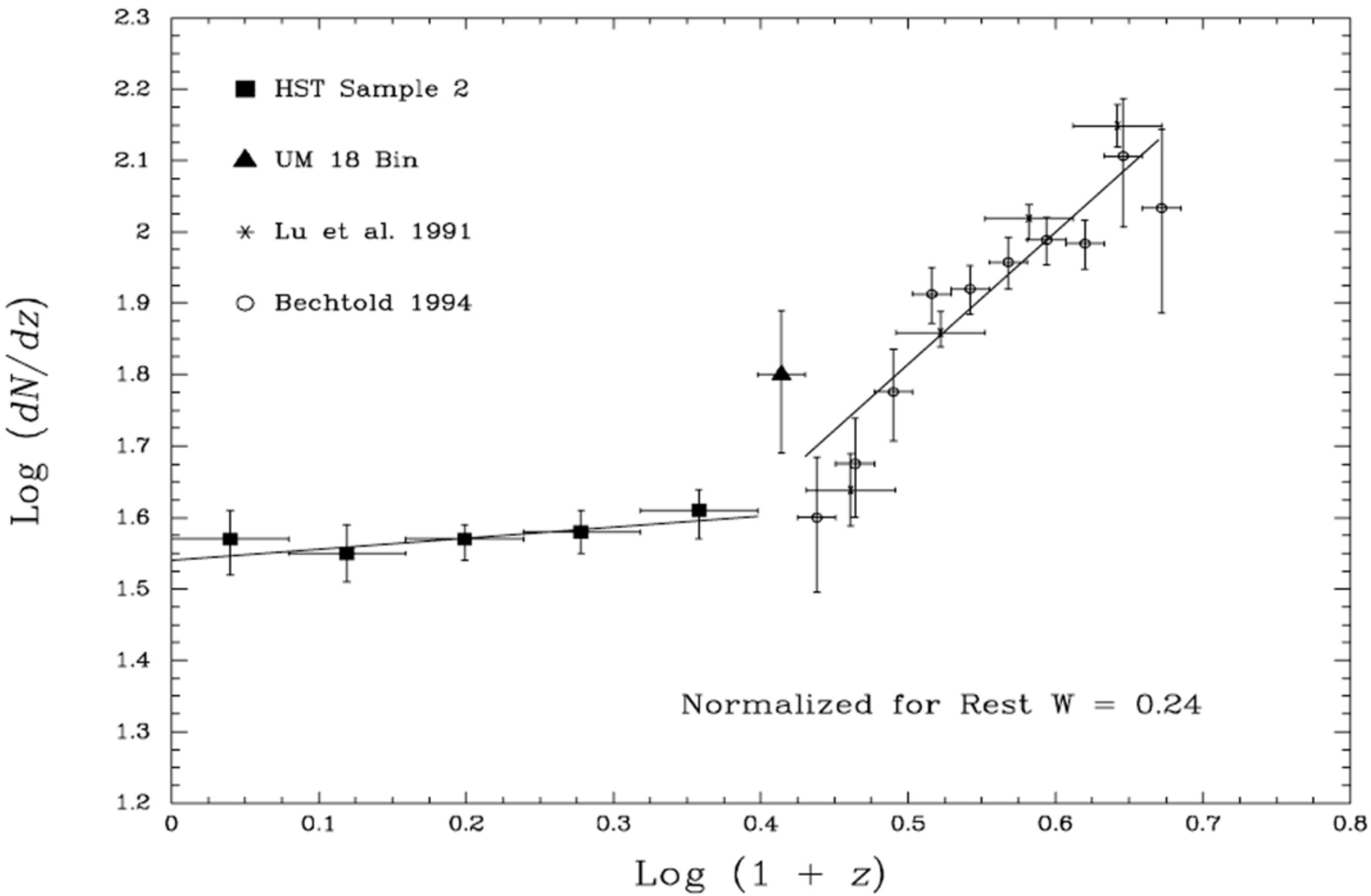


Evolution of the Hydrogen Absorbers

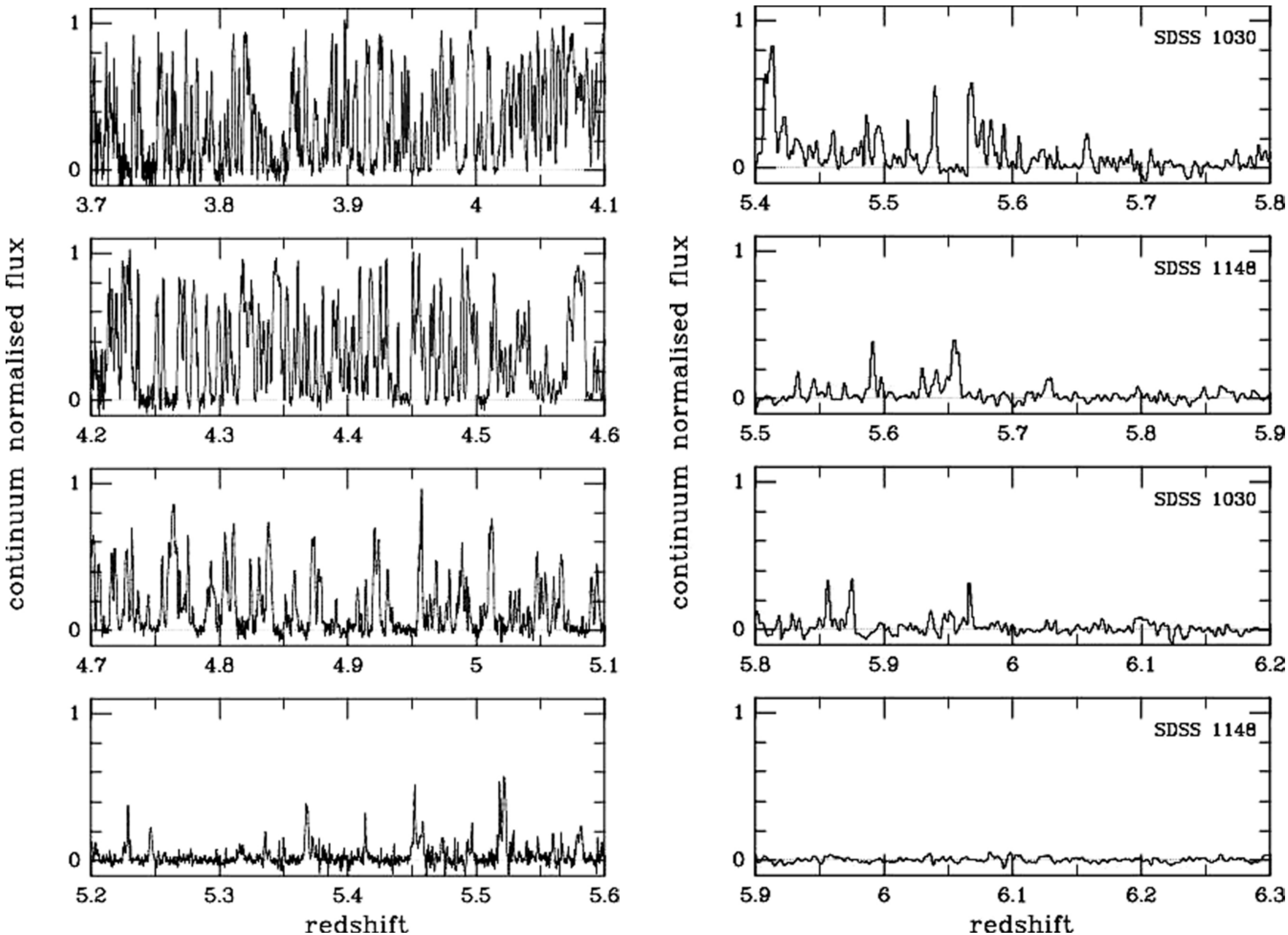


Evolution of Ly α Absorbers

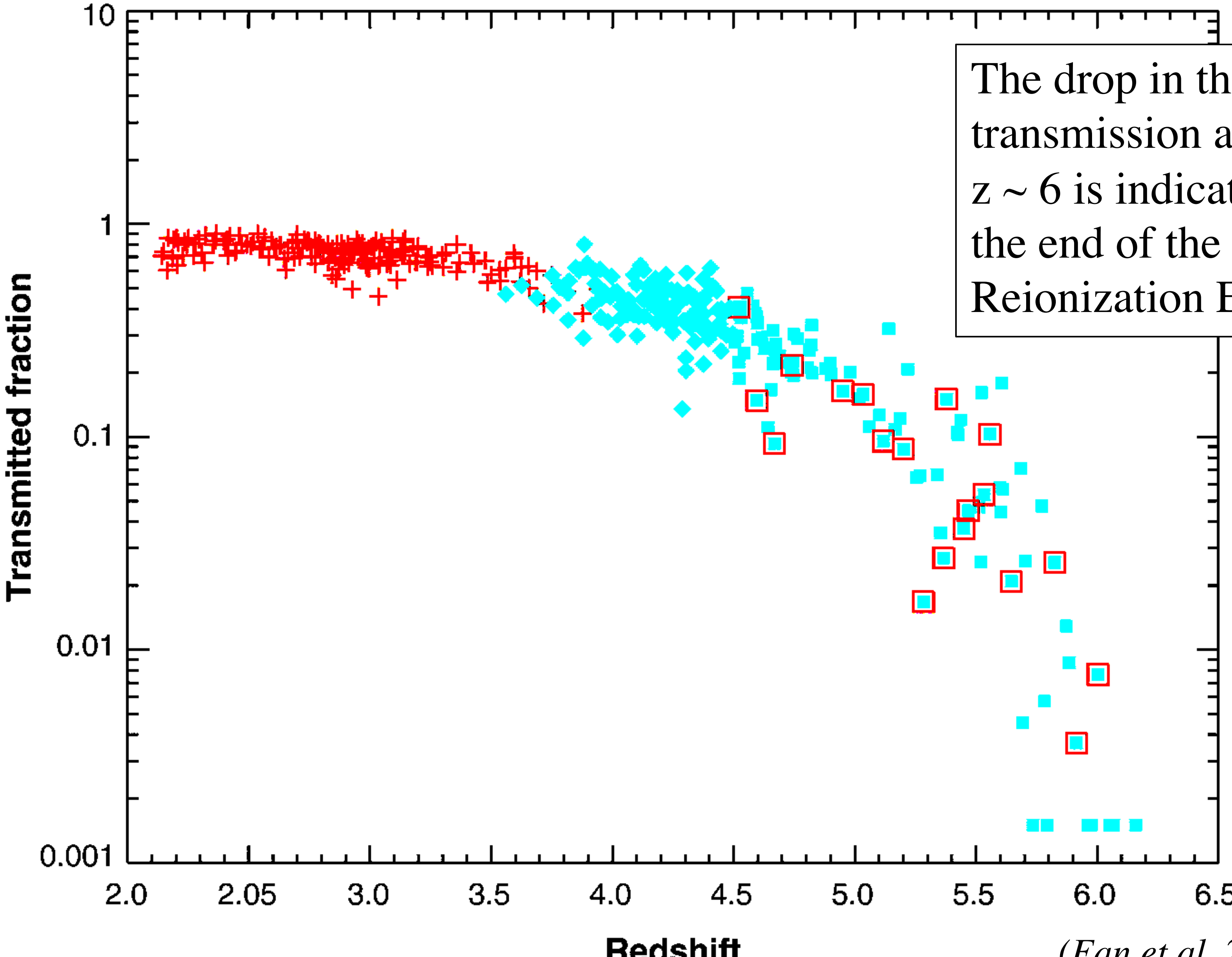
The numbers are higher at higher z's, but it is not yet clear how much of the effect is due to the number density evolution, and how much to a possible cross section evoluton - nor why is there a break at $z \sim 1.5$



The Forest Thickens at Higher Redshifts



Transmitted Lyα Flux vs. Redshift

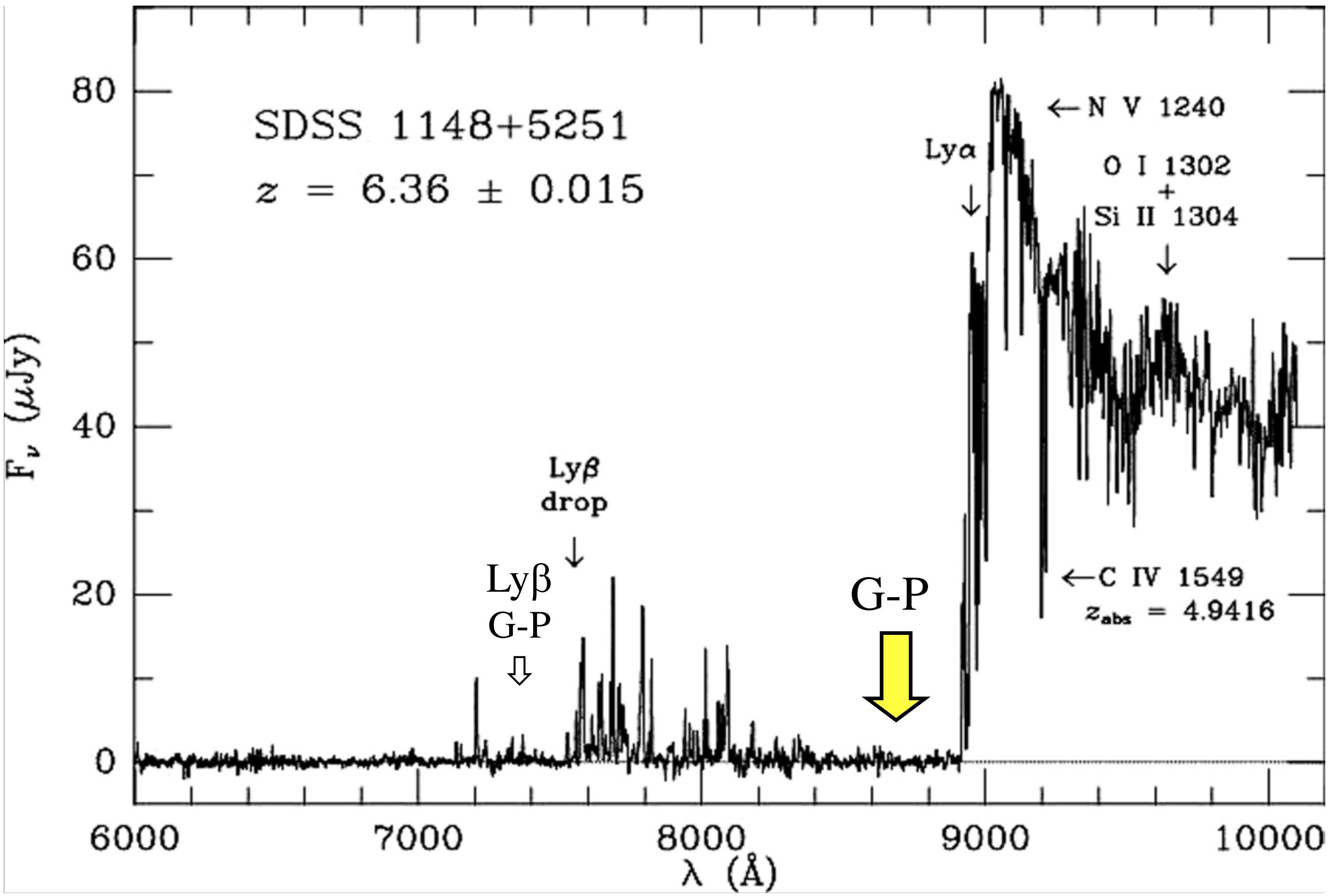


The drop in the transmission around z ~ 6 is indicative of the end of the Reionization Era

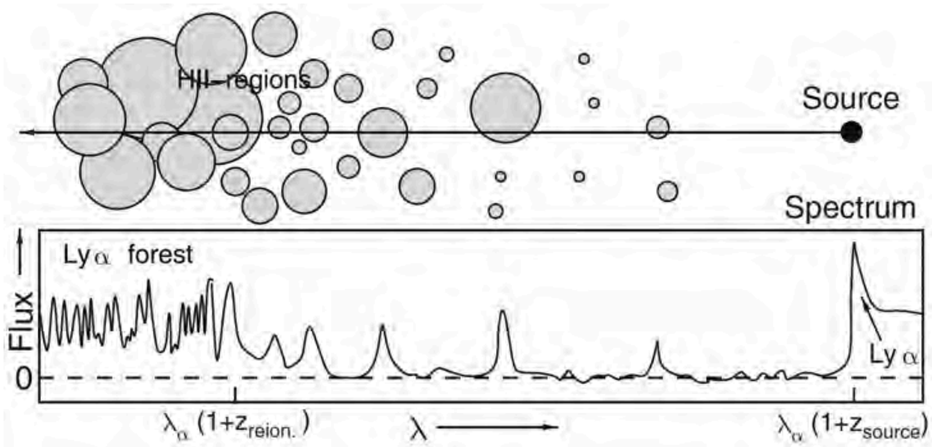
(Fan et al. 2006)

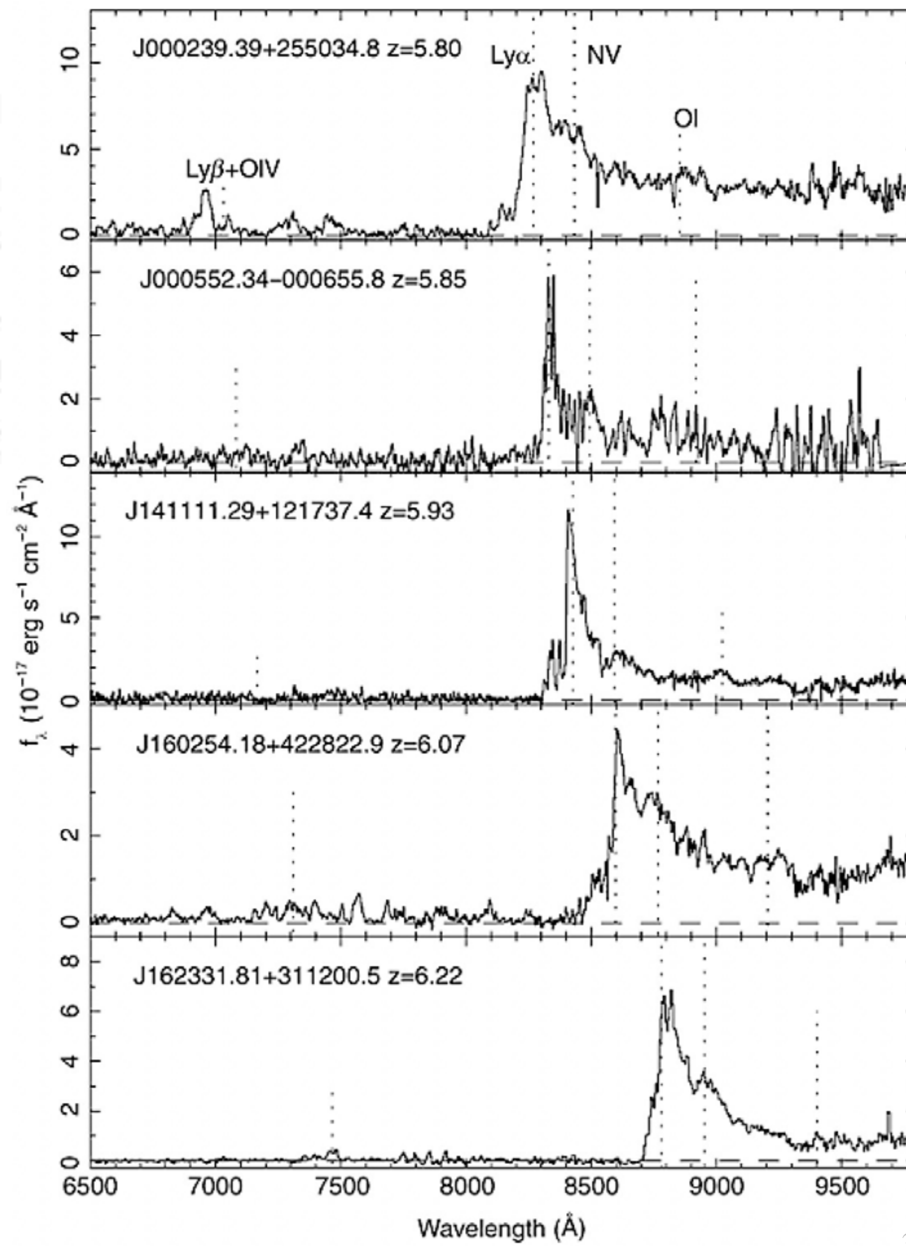
The Approach to the Reionization Era

Looking back towards the higher redshifts, as the density fraction of the neutral hydrogen exceeds ~ 10^{-4}, essentially all light shortward of Ly α line is fully absorbed (the Gunn-Peterson effect)



The Approach to the Reionization Era

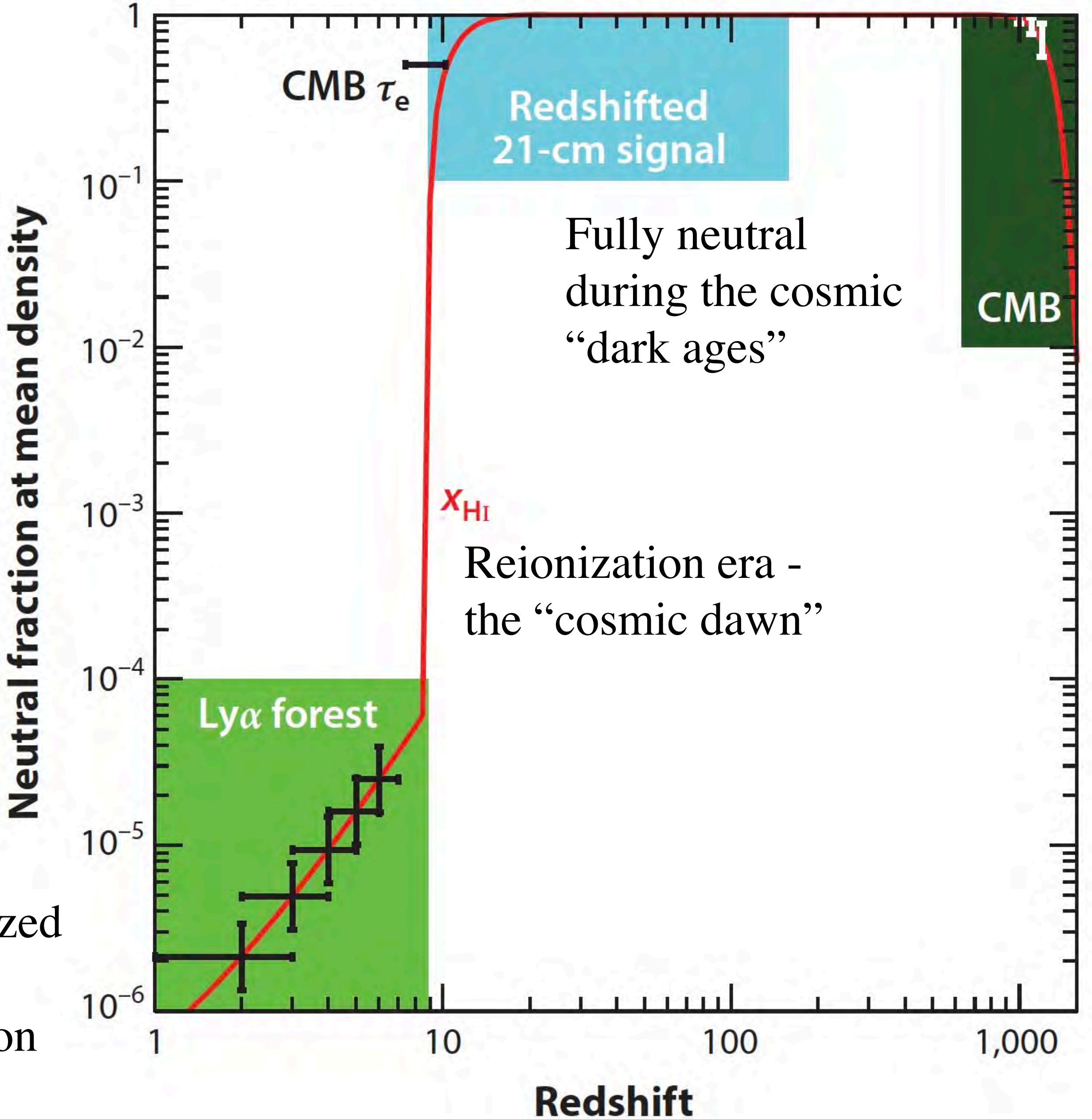




Gunn-Peterson absorption troughs are now observed along all quasar lines of sight at at z ~ 6, signaling the end of the reionization era

(Fan et al.)

Evolution of the IGM Hydrogen



Fully ionized before the recombination

Fully neutral during the cosmic "dark ages"

Reionization era - the "cosmic dawn"

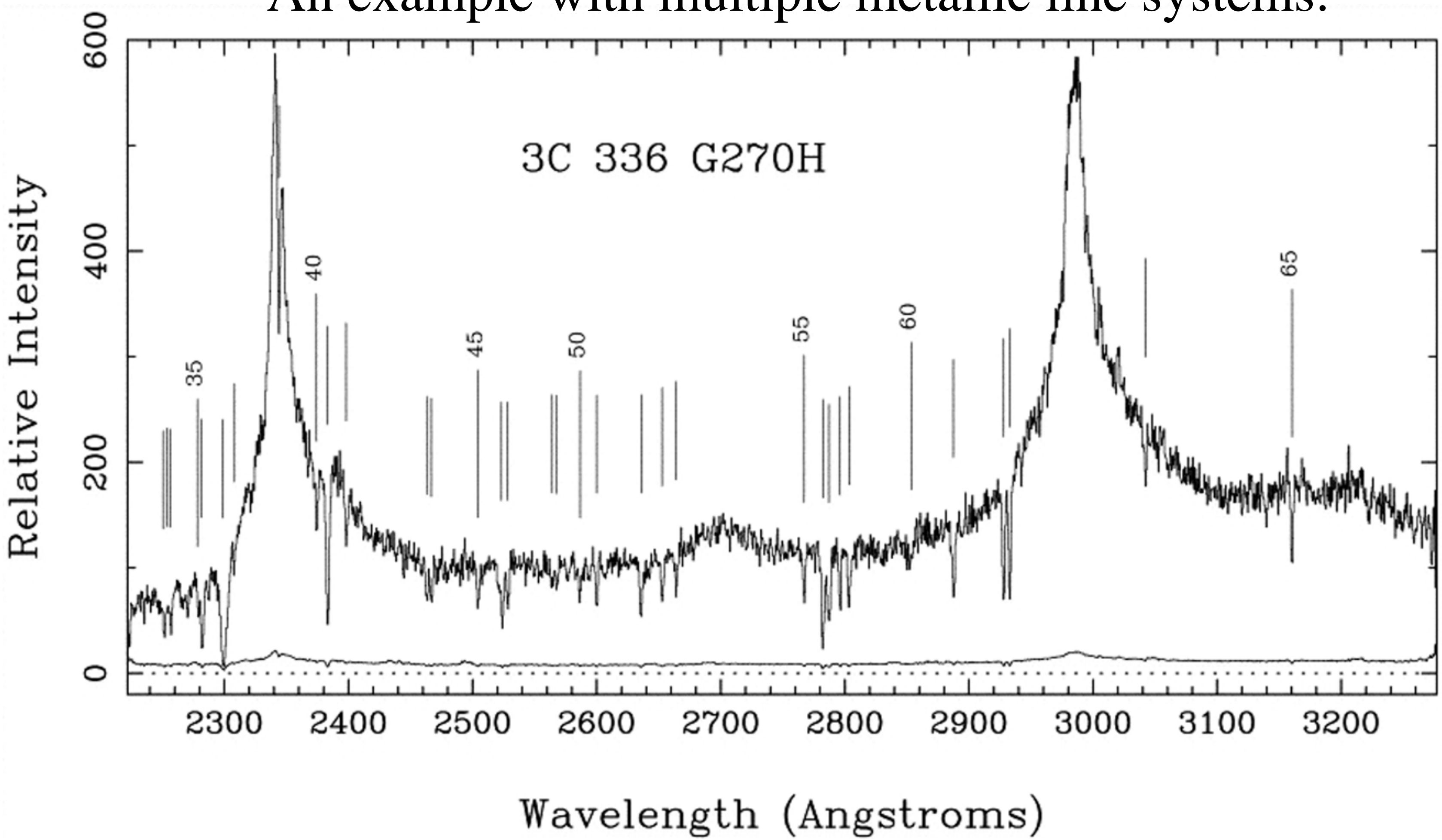
Fully ionized after the reionization

(McQuinn 2016)

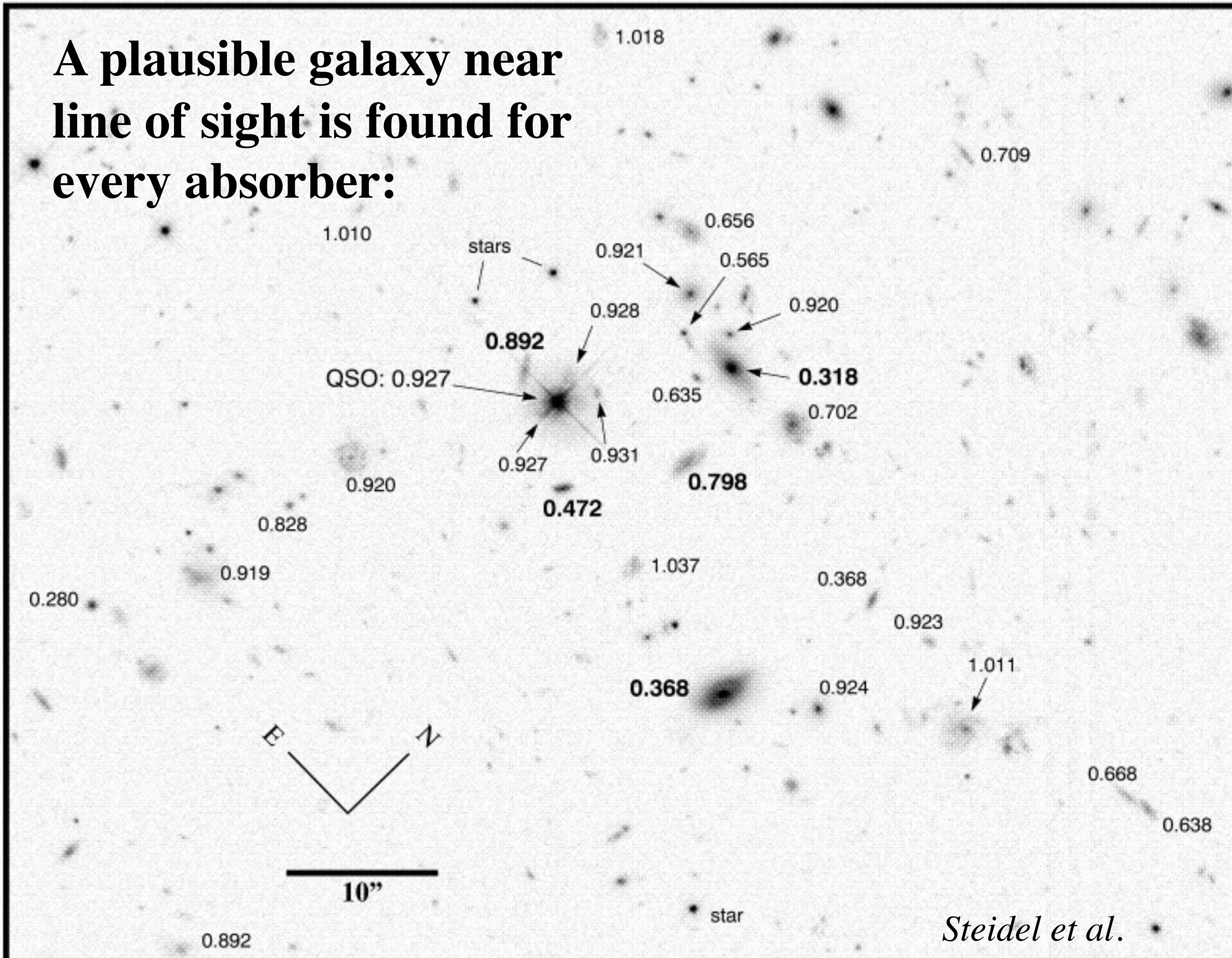
The Absorber - Galaxy Connection

Metallic line absorbers are generally believed to be associated with galaxies (after all, stars must have made the metals)

An example with multiple metallic line systems:



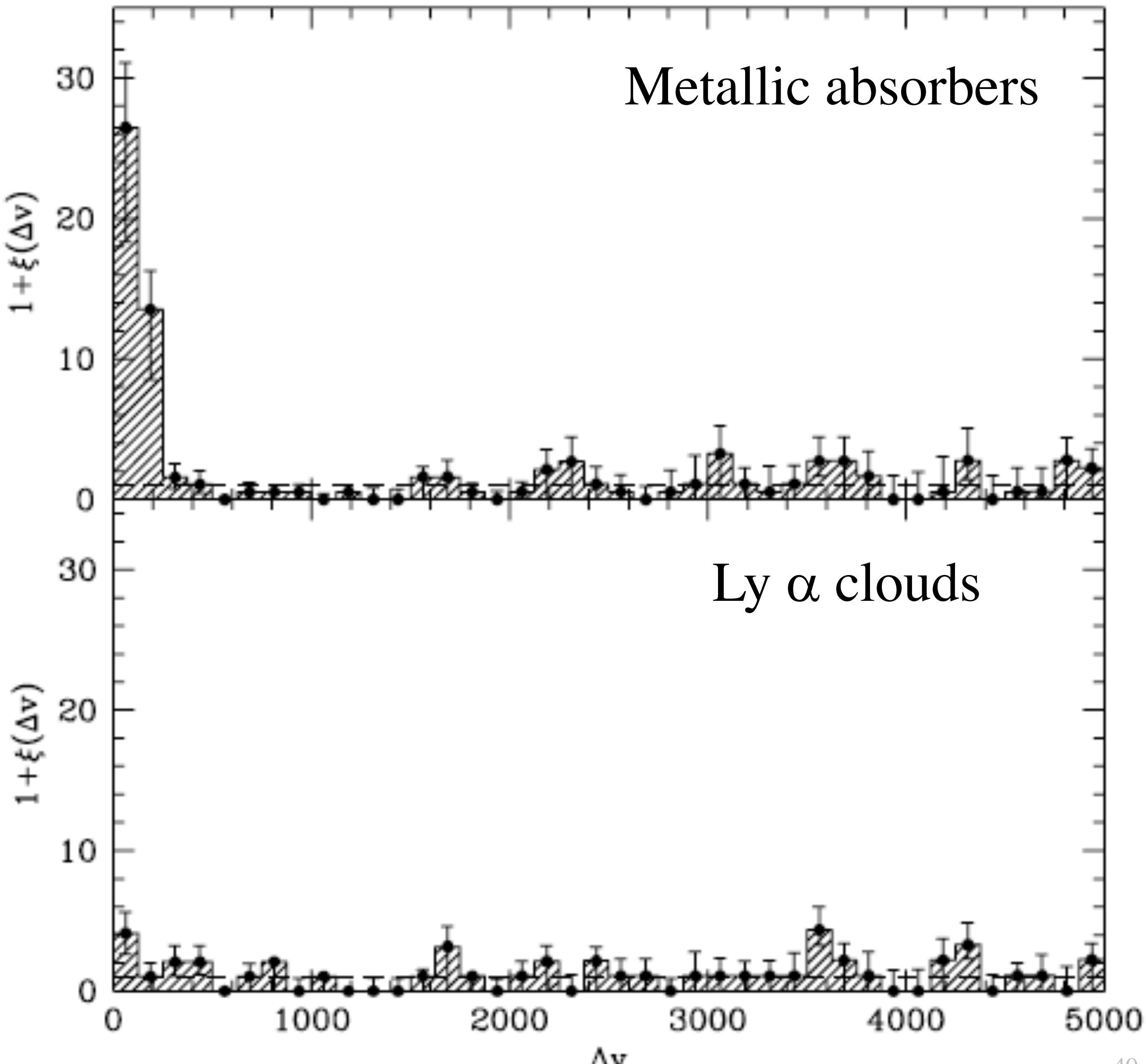
A plausible galaxy near line of sight is found for every absorber:



Steidel et al.

Clustering of Metallic Absorbers

Metallic absorbers are found to cluster in redshift space, even at high z's, while Ly α clouds do not. This further strengthens their association with galaxies



IGM Summary

- Intergalactic medium (IGM) is the gas associated with the large scale structure, rather than galaxies themselves; e.g., along the still collapsing filaments, thus the "cosmic web"
  - However, large column density hydrogen systems, and strong metallic absorbers are always associated with galaxies
- It is condensed into clouds, the smallest of which form the "Ly α forest"
- It is ionized by the UV radiation from star forming galaxies and quasars
- It is metal-enriched by the galactic winds, which expel the gas already processed through stars; thus, it tracks the chemical evolution of galaxies
- Studied through absorption spectra against background continuum sources, e.g., quasars or GRB afterglows