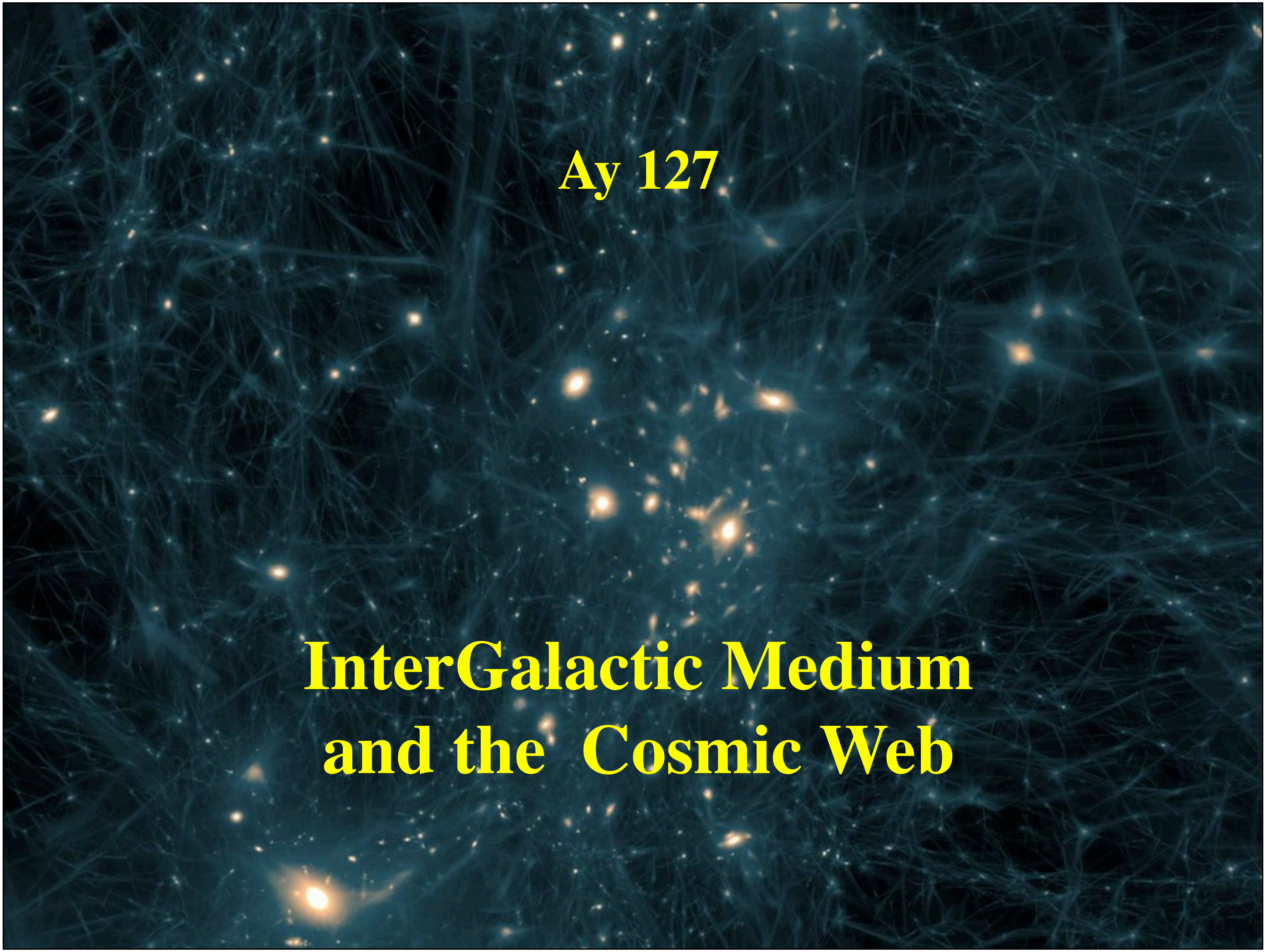
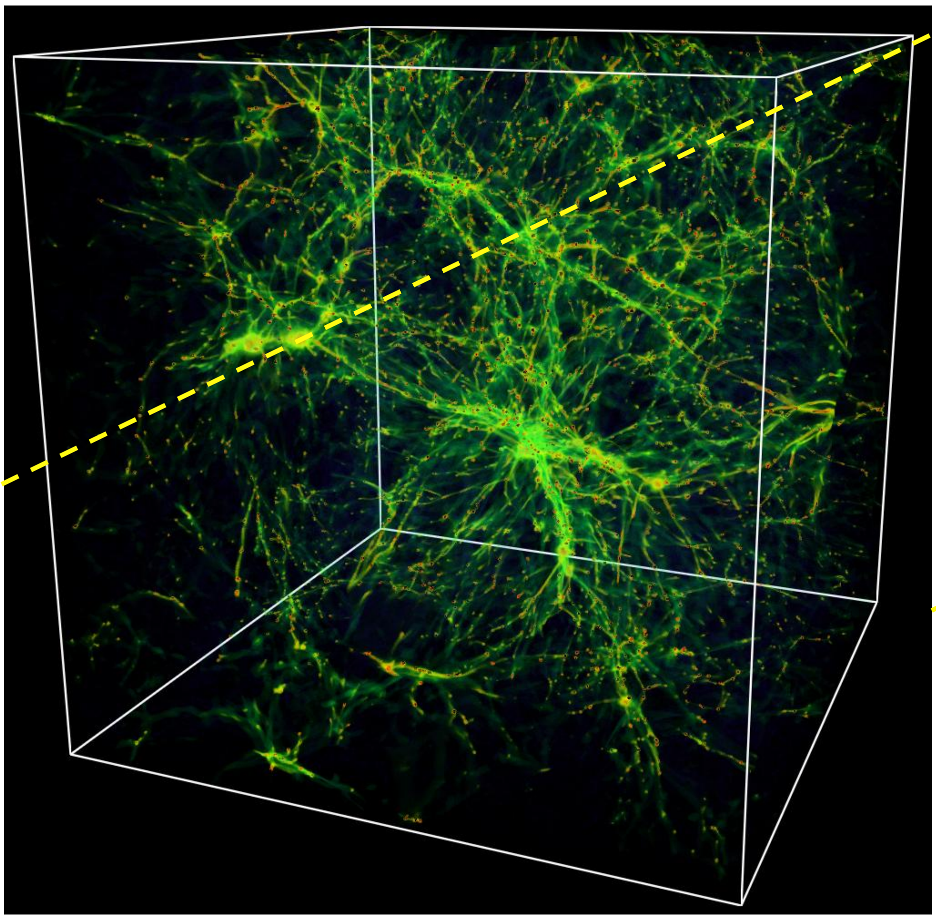

Ay 127
InterGalactic Medium
and the Cosmic Web

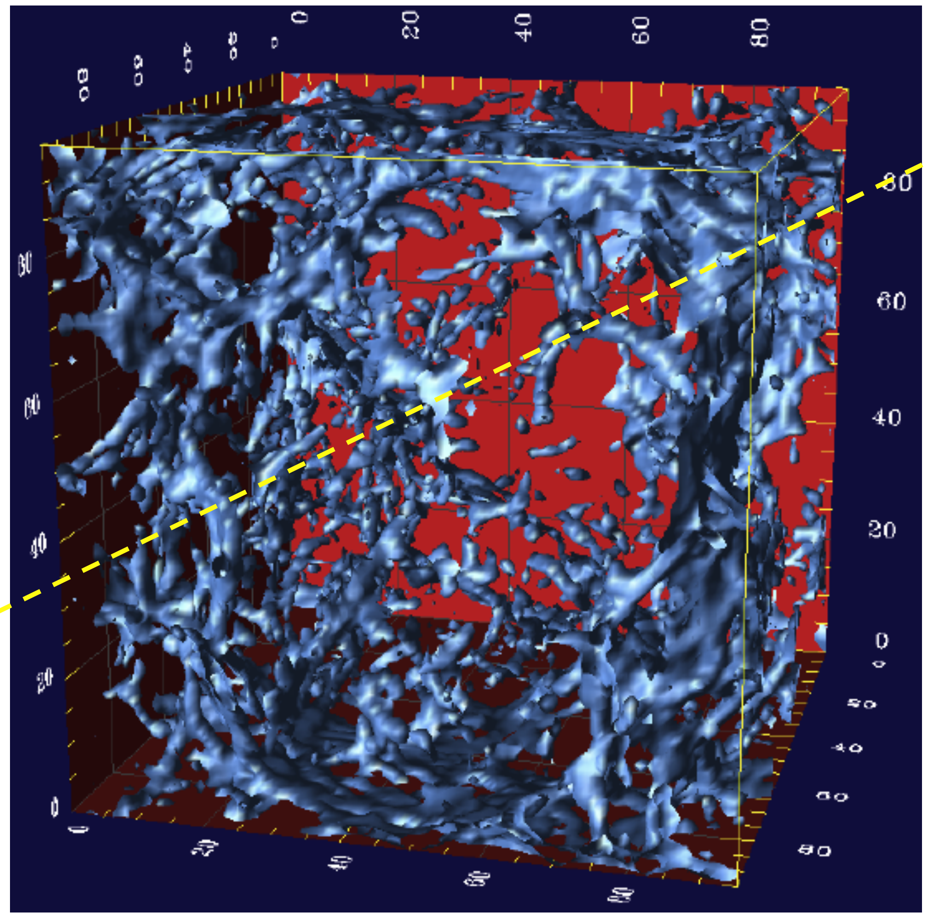
Intergalactic Medium (IGM)

- 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 radiatively 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

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

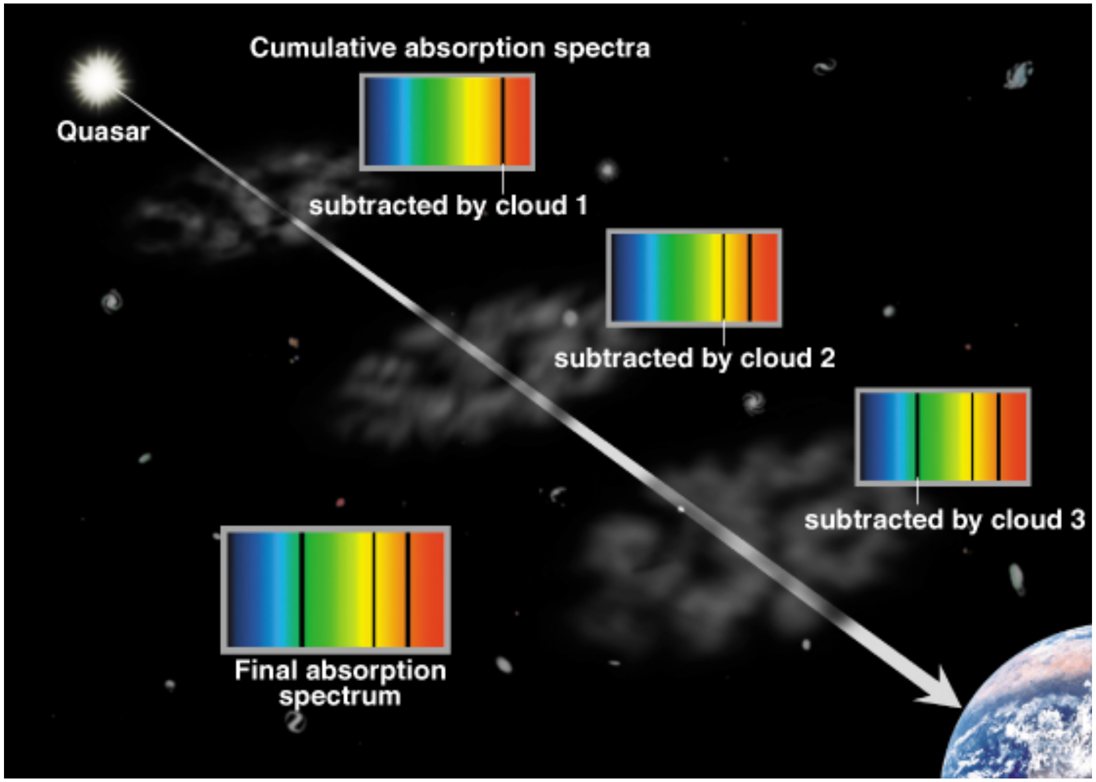




(from R. Cen)

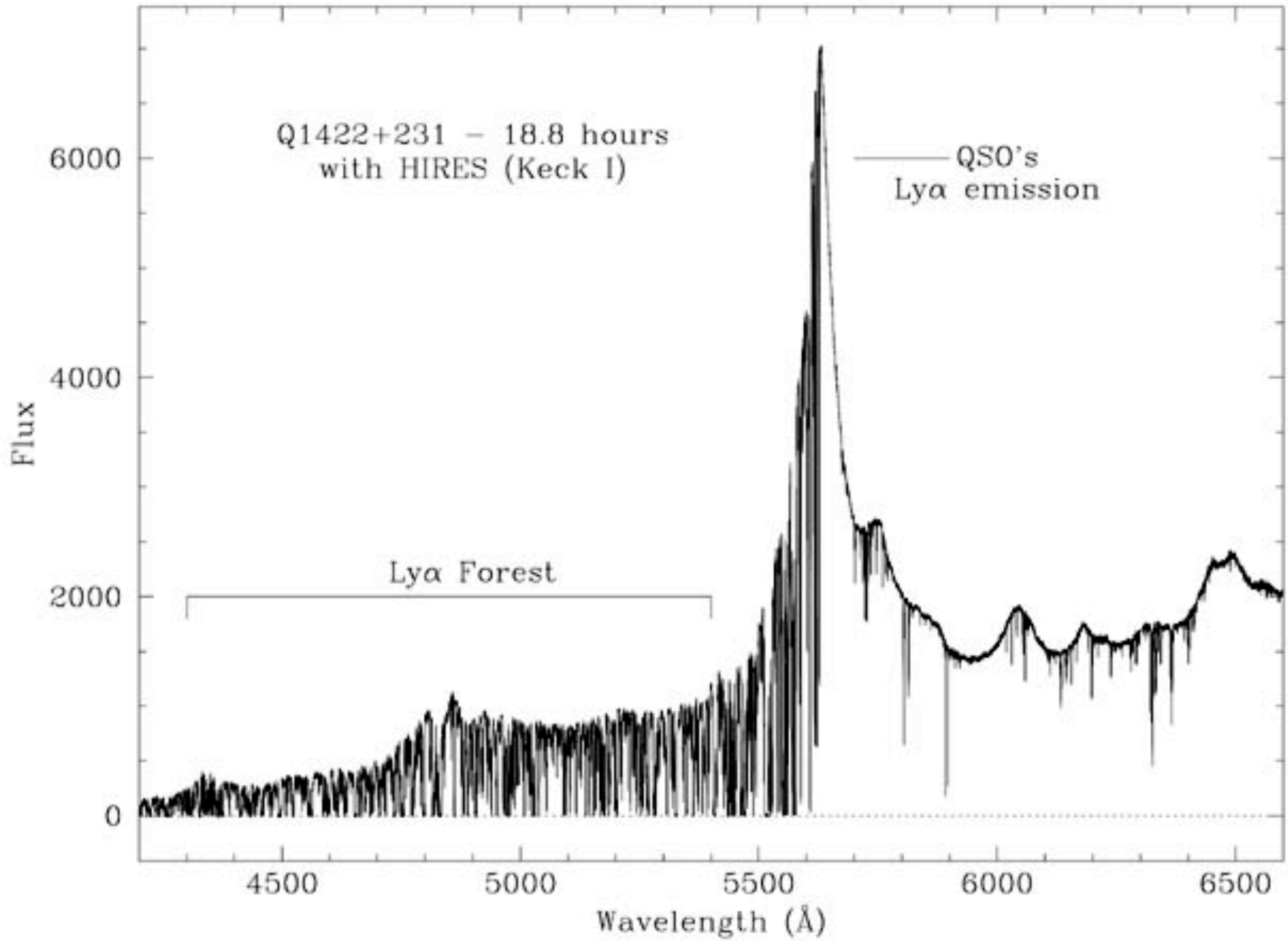
QSO Absorption Line Systems

- 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 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


Q1422+231 – 18.8 hours
with HIRES (Keck I)
QSO's
Lyα emission
Lyα Forest
Flux
Wavelength (Å)
0
2000
4000
6000
4500
5000
5500
6000
6500

Types of QSO Absorption Systems

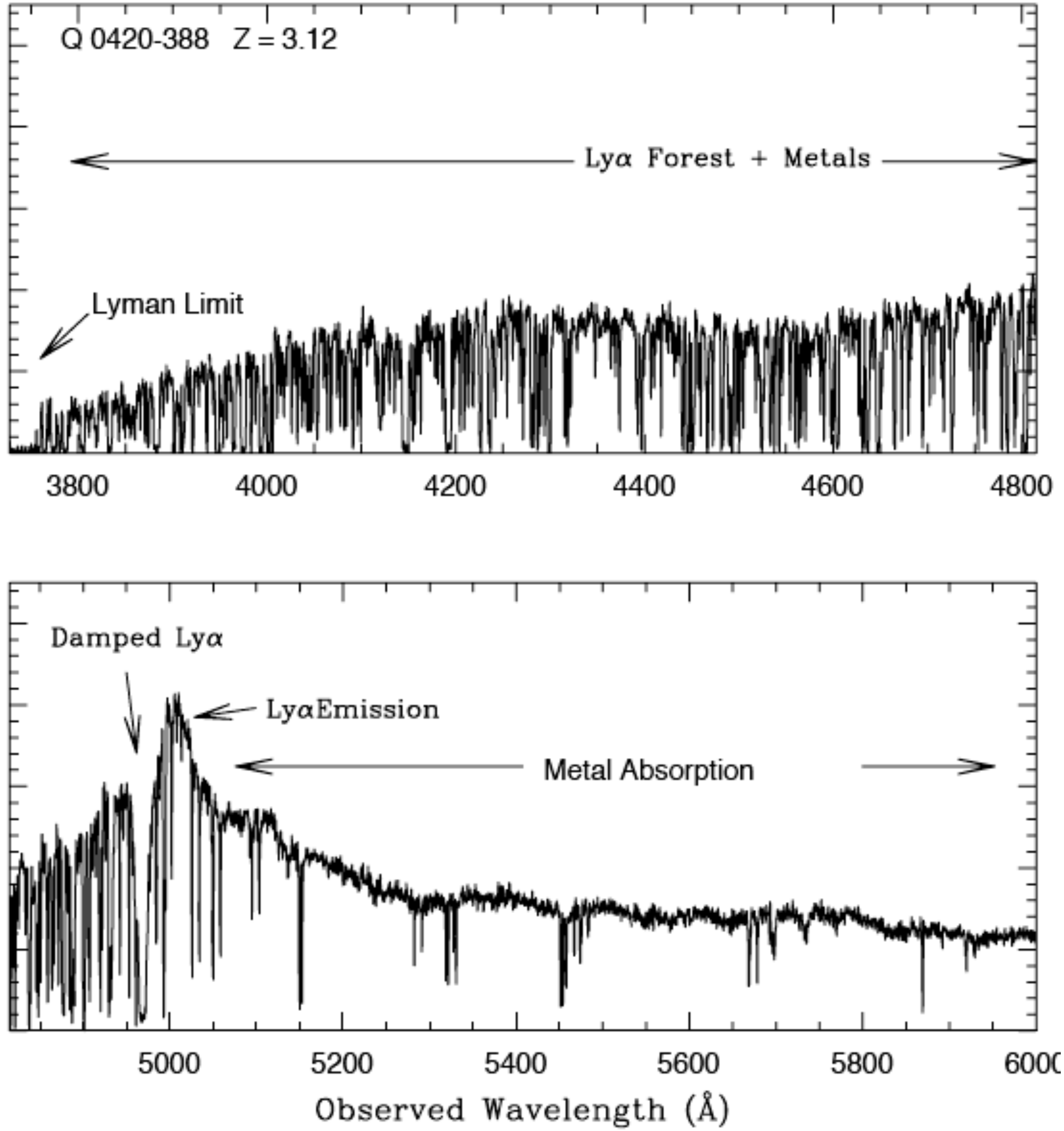


Table 1. A few strong atomic transitions

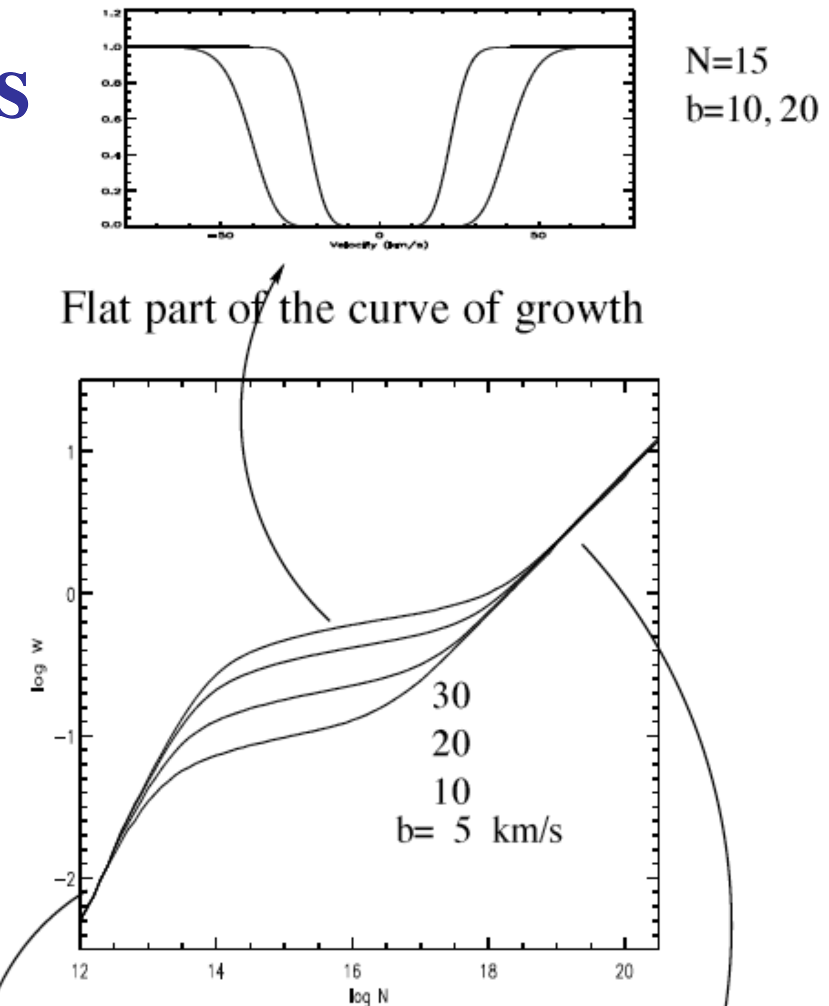
Ion	λ_o (Å)	f	$\log(\lambda_o f)$	$\log(\lambda_o^2 f)$
O VI	1031.927	0.130	2.128	5.141
O VI	1037.616	0.0648	1.828	4.844
H I	1215.670	0.4162	2.704	5.789
O I	1302.169	0.0486	1.801	4.916
C II	1334.532	0.118	2.197	5.323
Si IV	1393.755	0.528	2.867	6.011
Si IV	1402.770	0.262	2.565	5.712
C IV	1548.202	0.194	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

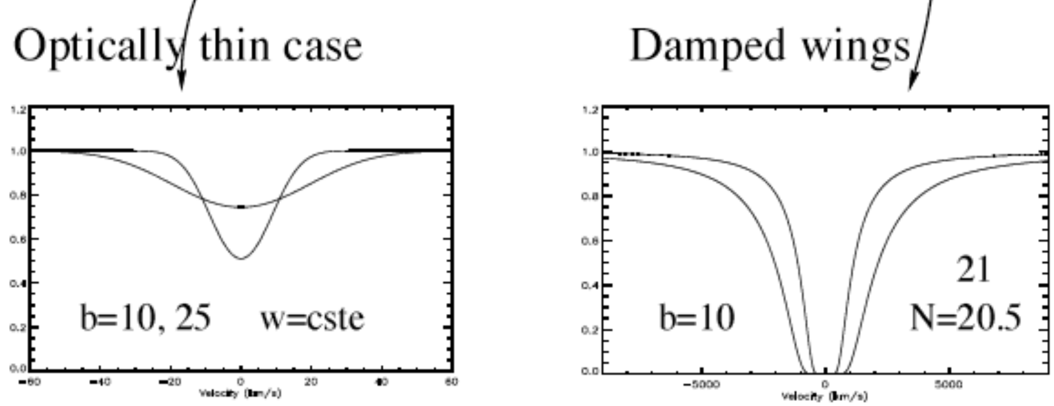
Measuring the Absorbers

We measure equivalent widths of the lines, and in some cases shapes of the line profiles

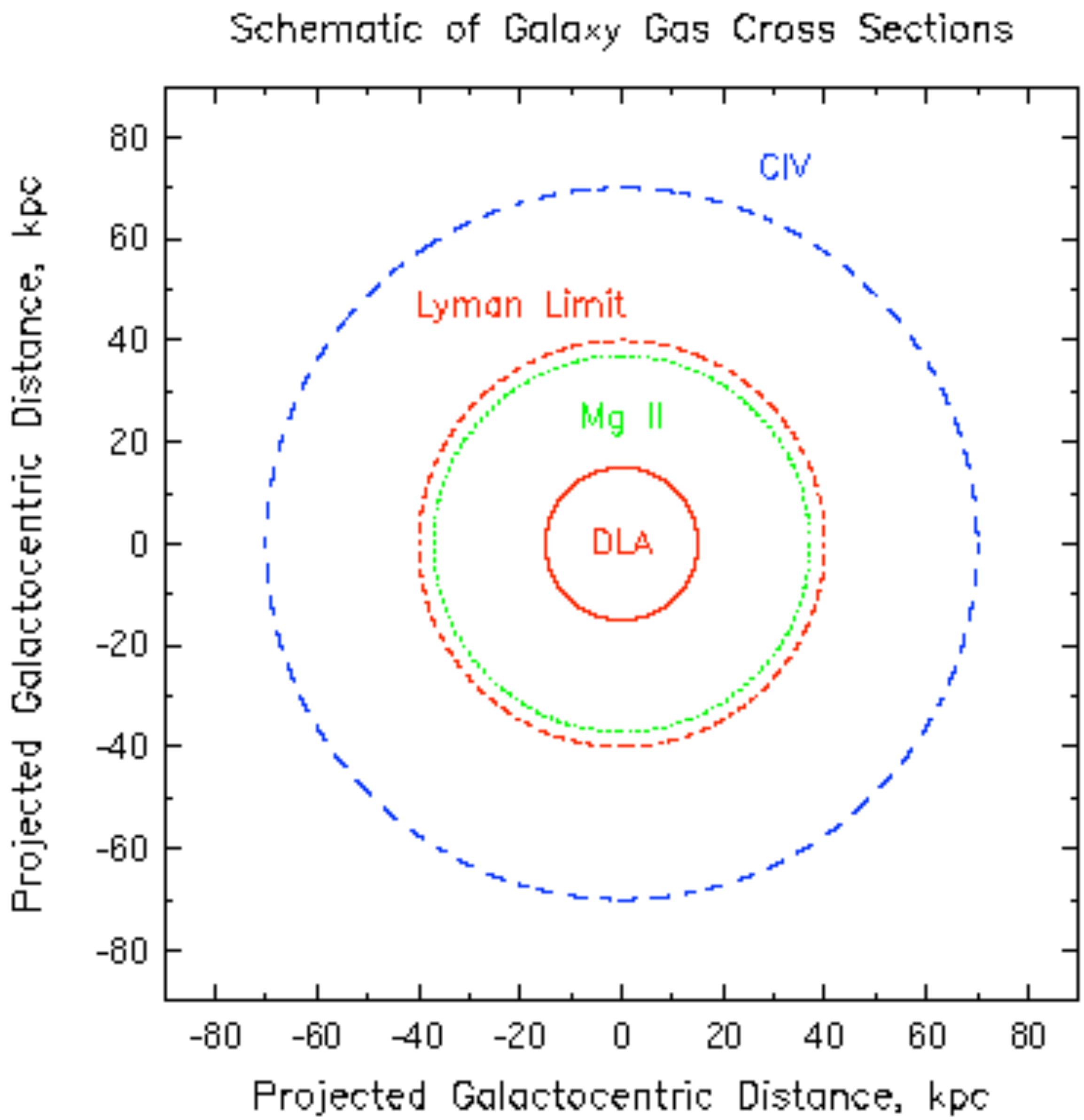
They are connected to the column densities via ***curves of growth*** ➙

The shape of the line profile is also a function of the pressure, which causes a Doppler broadening, and also the global kinematics of the absorbing cloud





Absorber Cross Sections



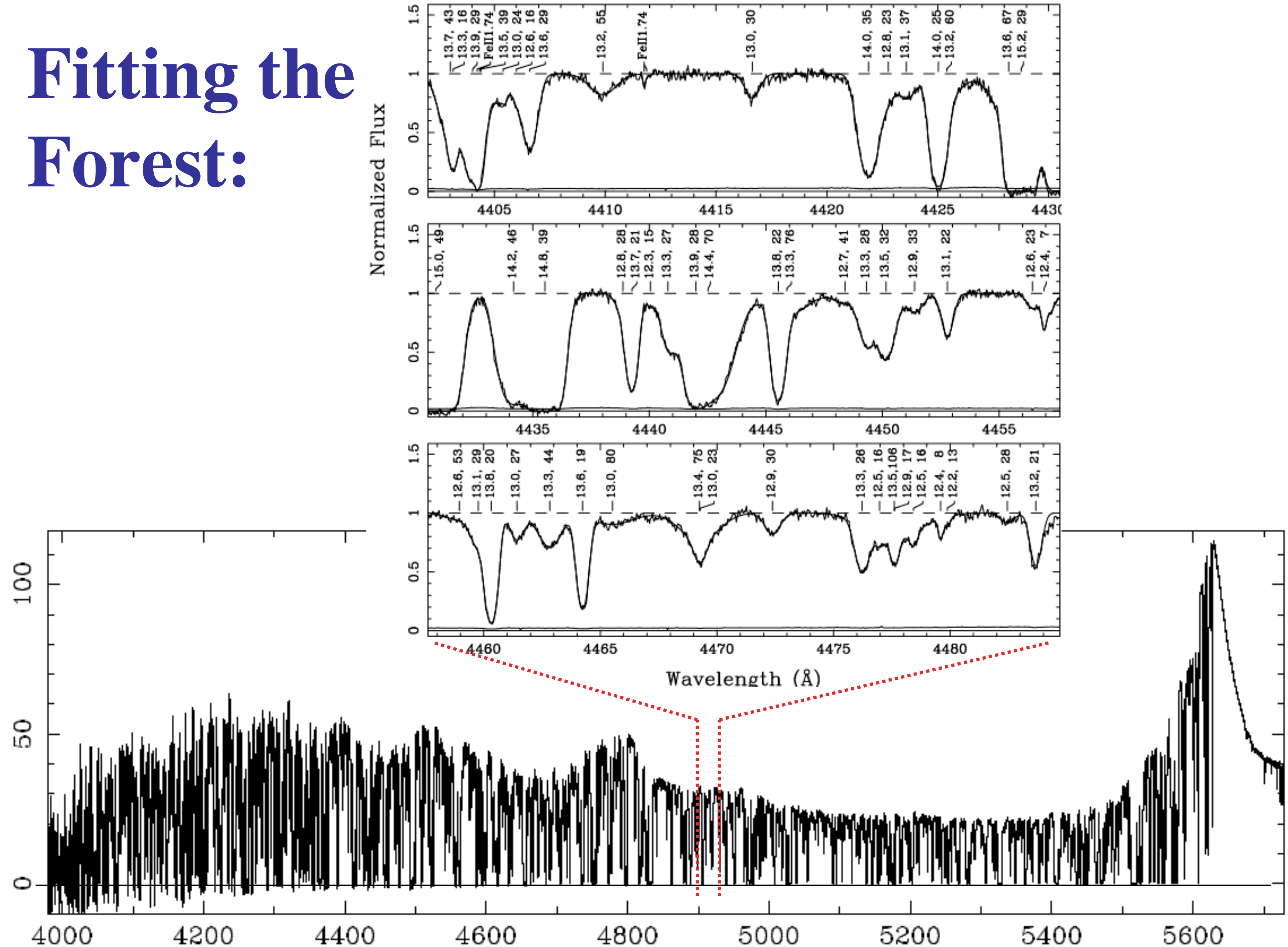
Column density of neutral H is higher at smaller radii, so LLS and DLA absorbers are rare

Metals are ejected out to galactic coronae, and their column densities and ionization states depend on the radius

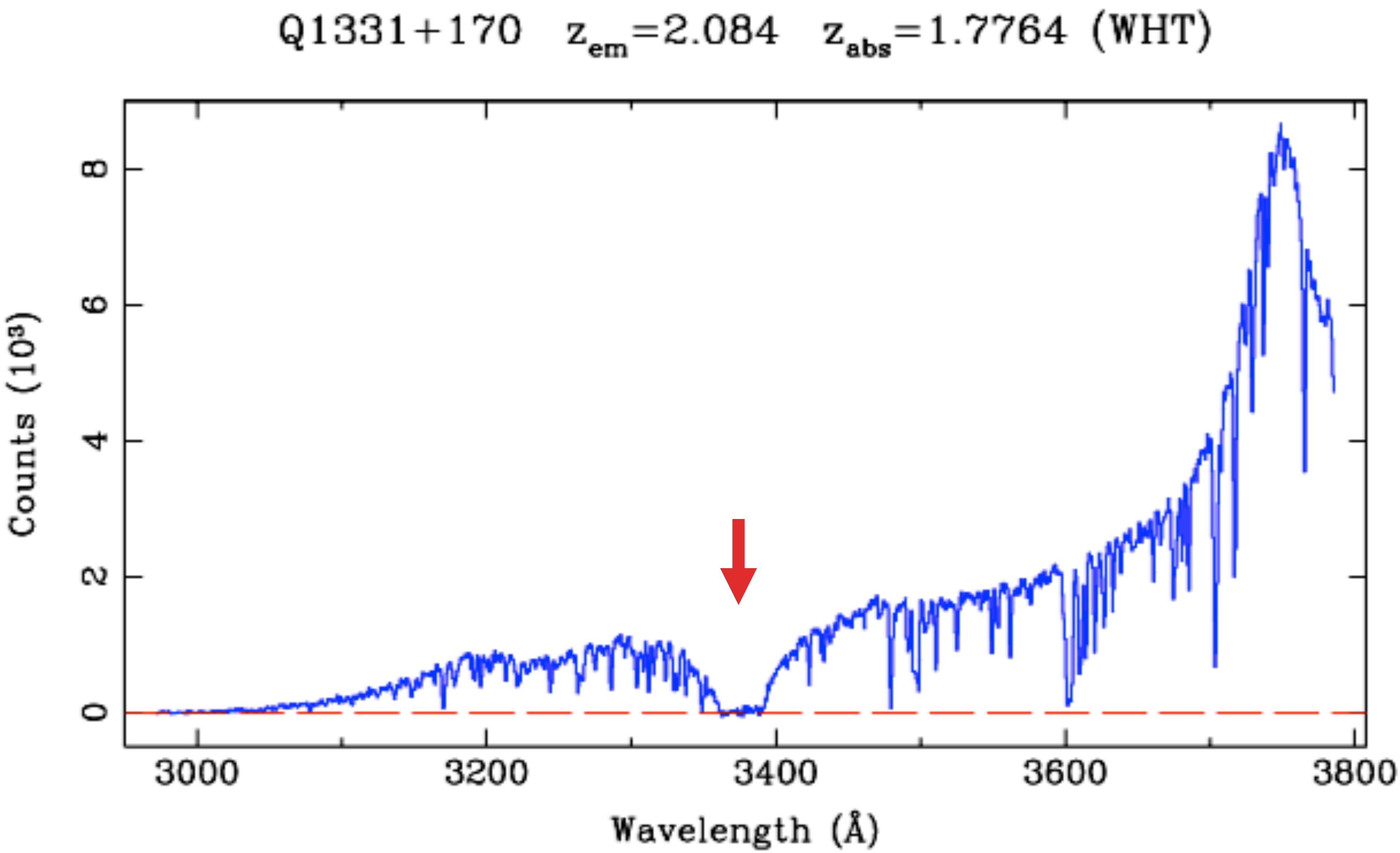
Ly α Absorbers

- **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

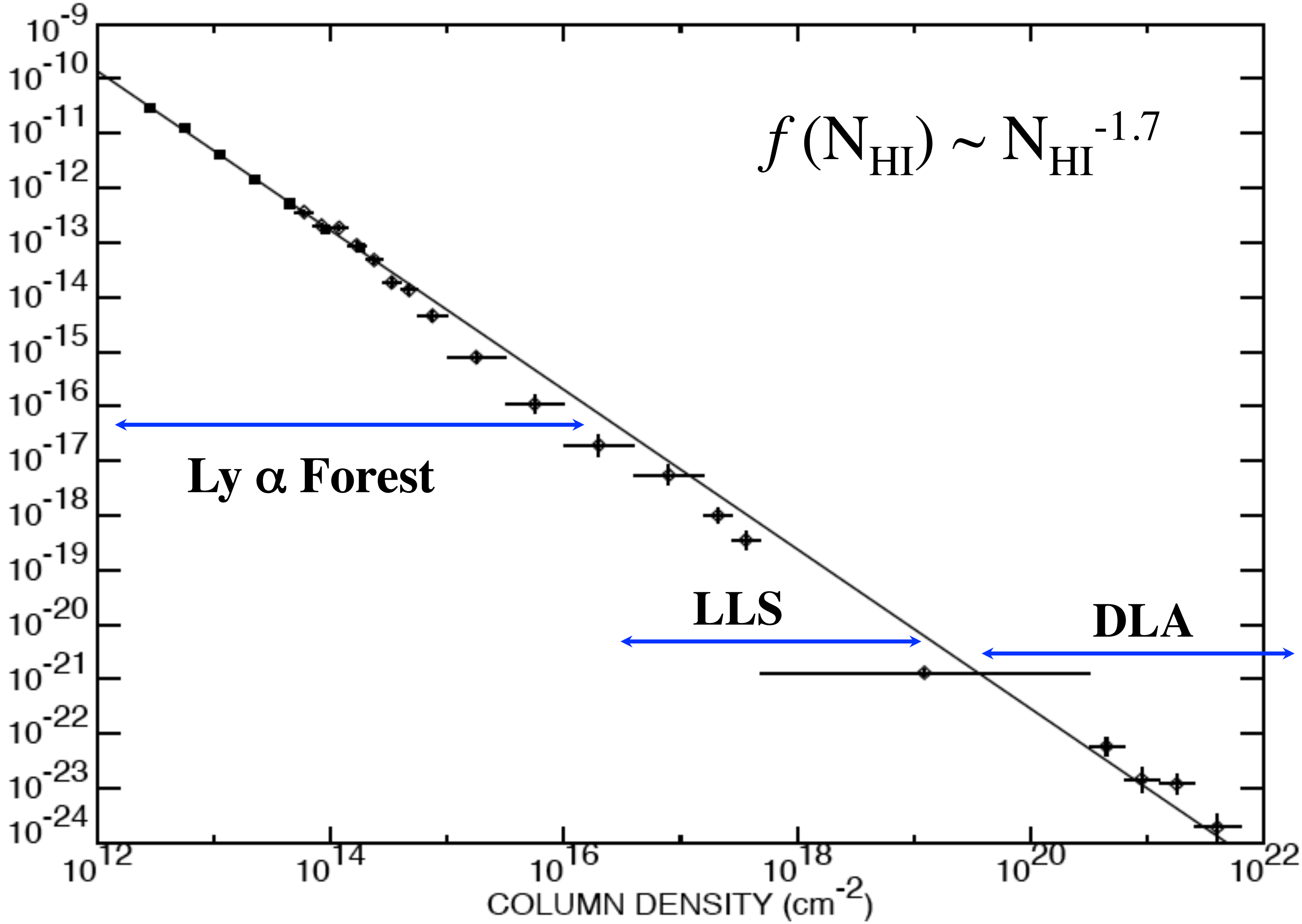
Fitting the Forest:



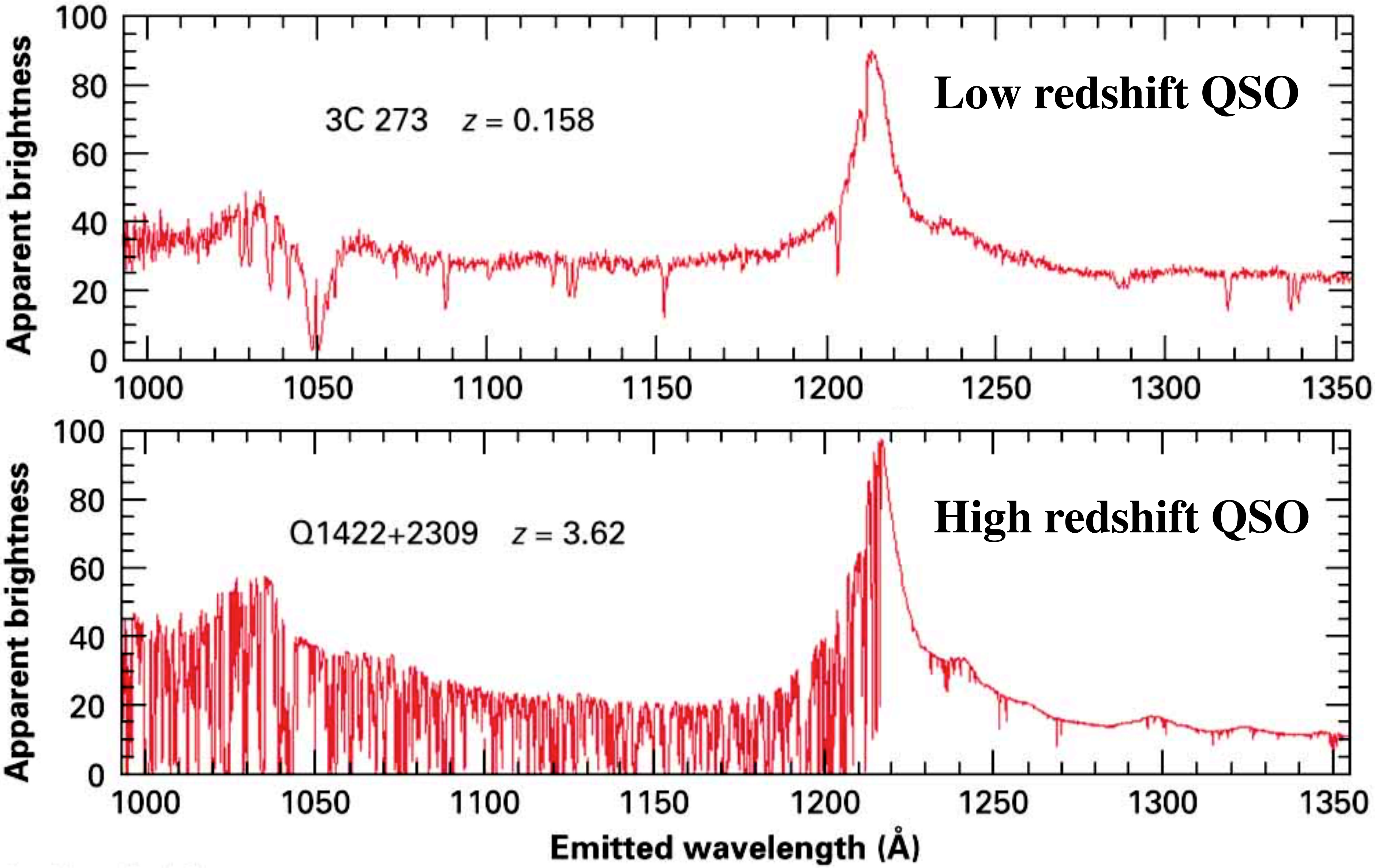
A Damped Lyman α System



Distribution of Column Densities



Evolution of the Hydrogen Absorbers



Evolution of Ly α Absorbers

(from Rauch 1998, ARAA, 36, 267)

EVOLUTION OF THE LINE DENSITY An analytic expression (Wagoner 1967, Bahcall & Peebles 1969) can be given for the number of absorption systems per unit redshift, $d\mathcal{N}/dz$, in terms of the comoving number density $n_0(z)$ of absorbers, the geometric absorption cross section $\sigma(z)$, and the Hubble constant H_0:

$$\frac{d\mathcal{N}}{dz} = \frac{cn_0(z)\sigma(z)}{H_0}\frac{1+z}{(1+q_o z)^{1/2}}. \tag{6}$$

For absorbers with no intrinsic evolution,

$$\frac{d\mathcal{N}}{dz} \propto \begin{cases} 1+z, & q_0 = 0 \\ (1+z)^{1/2}, & q_0 = \frac{1}{2} \end{cases}. \tag{7}$$

(NB: this is for $\Lambda = 0$ cosmology!)

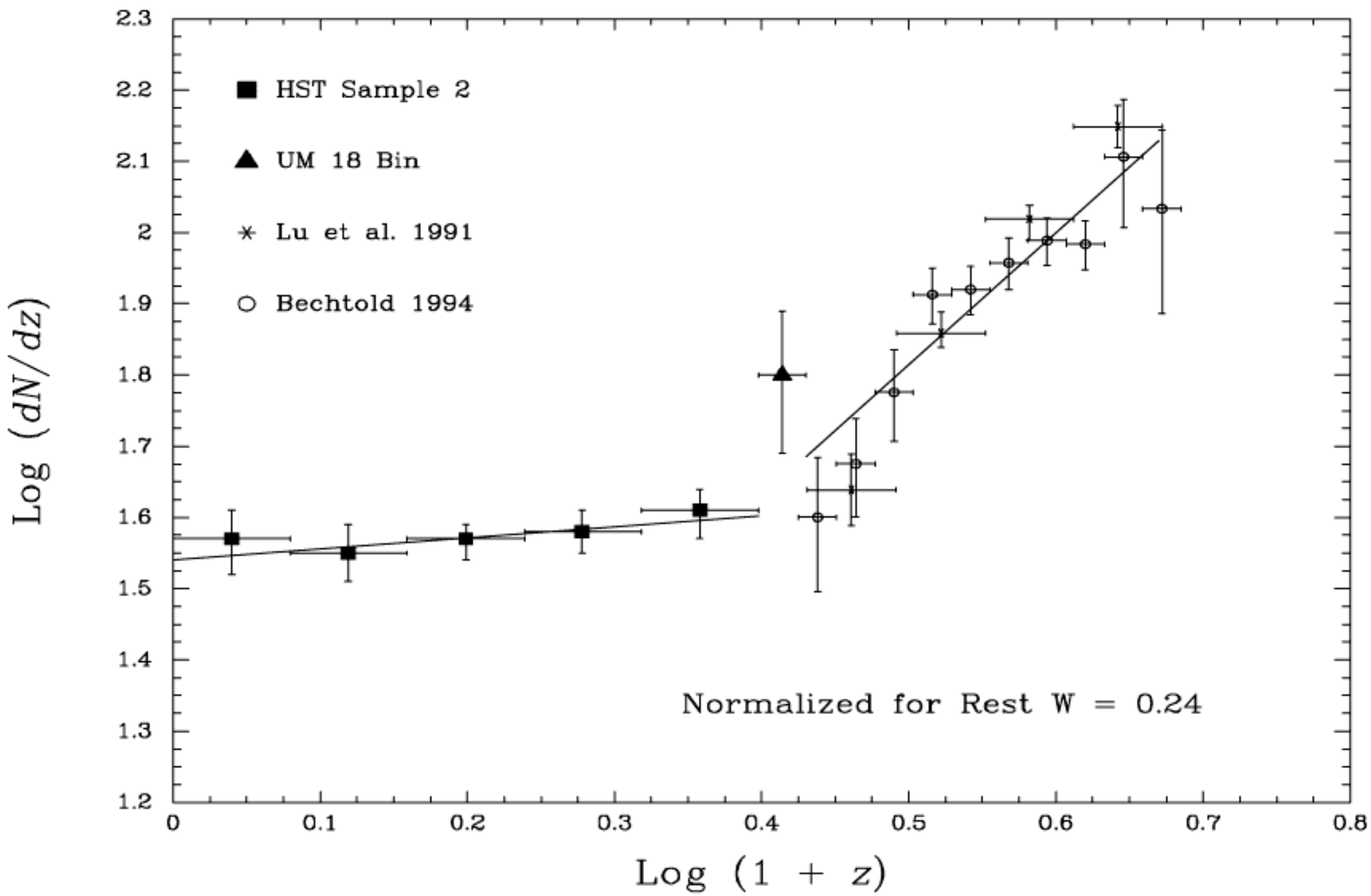
The observationally determined evolution in the number of absorbers above a certain column density threshold is usually expressed in the form

$$\frac{d\mathcal{N}}{dz} = \left(\frac{d\mathcal{N}}{dz}\right)_0 (1+z)^\gamma, \tag{8}$$

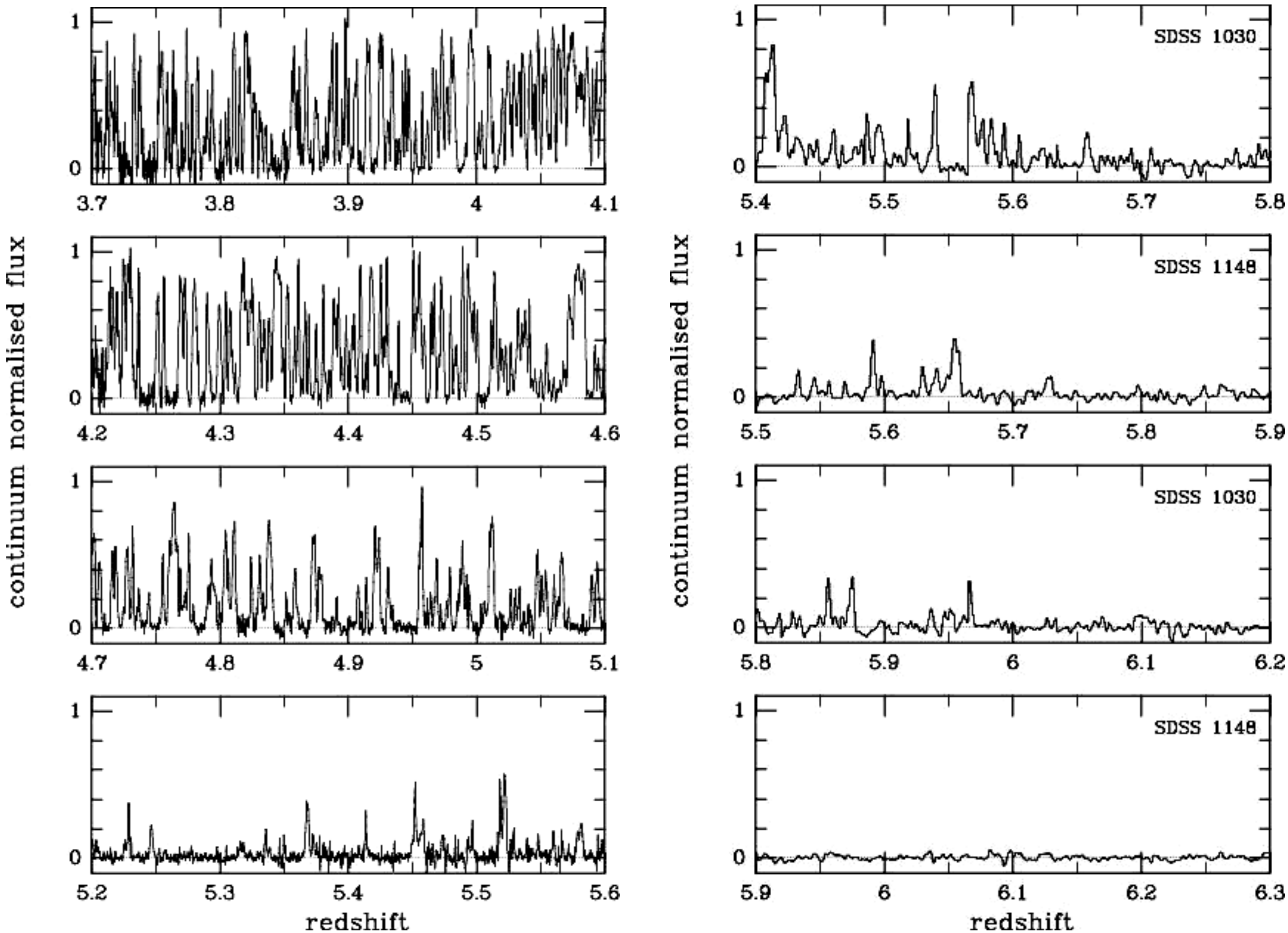
Typical $\gamma \sim 1.8$ (at high z's)

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



Estimating the Evolution of Gas Density

(from Wolfe et al. 2005, ARAA, 43, 861)

To estimate $\Omega_g(z)$ we first derive an expression for the column-density distribution, $f(N, X)$. Let the number of absorbers per sightline with H I column densities and redshifts in the intervals $(N, N + dN)$ and $(z, z + dz)$ be given by

$$d\mathcal{N}(N, z) = n_{co}(N, z)A(N, z)(1 + z)^3|c\,dt/dz|dN\,dz, \quad (1)$$

where $n_{co}(N, z)\,dN$ is the comoving density of absorbers within $(N, N + dN)$ at z and $A(N, z)$ is the absorption cross-section at (N, z). Defining $dX \equiv (H_0/c)(1 + z)^3|c\,dt/dz|dz$ (Bahcall & Peebles 1969) we have

$$\frac{d\mathcal{N}(X)}{dX} = \int_{N_{min}}^{N_{max}} dN f(X, N), \quad (2)$$

$$f(N, X) \equiv (c/H_0)n_{co}(N, X)A(N, X), \quad (3)$$

and N_{min} and N_{max} are minimum and maximum column densities, respectively.[1]

$$\Omega_g = \frac{H_0}{c}\frac{\mu m_H}{\rho_{crit}} \int_{N_{min}}^{N_{max}} dN\,N f(N, X), \quad (4)$$

Evolution of Neutral Gas

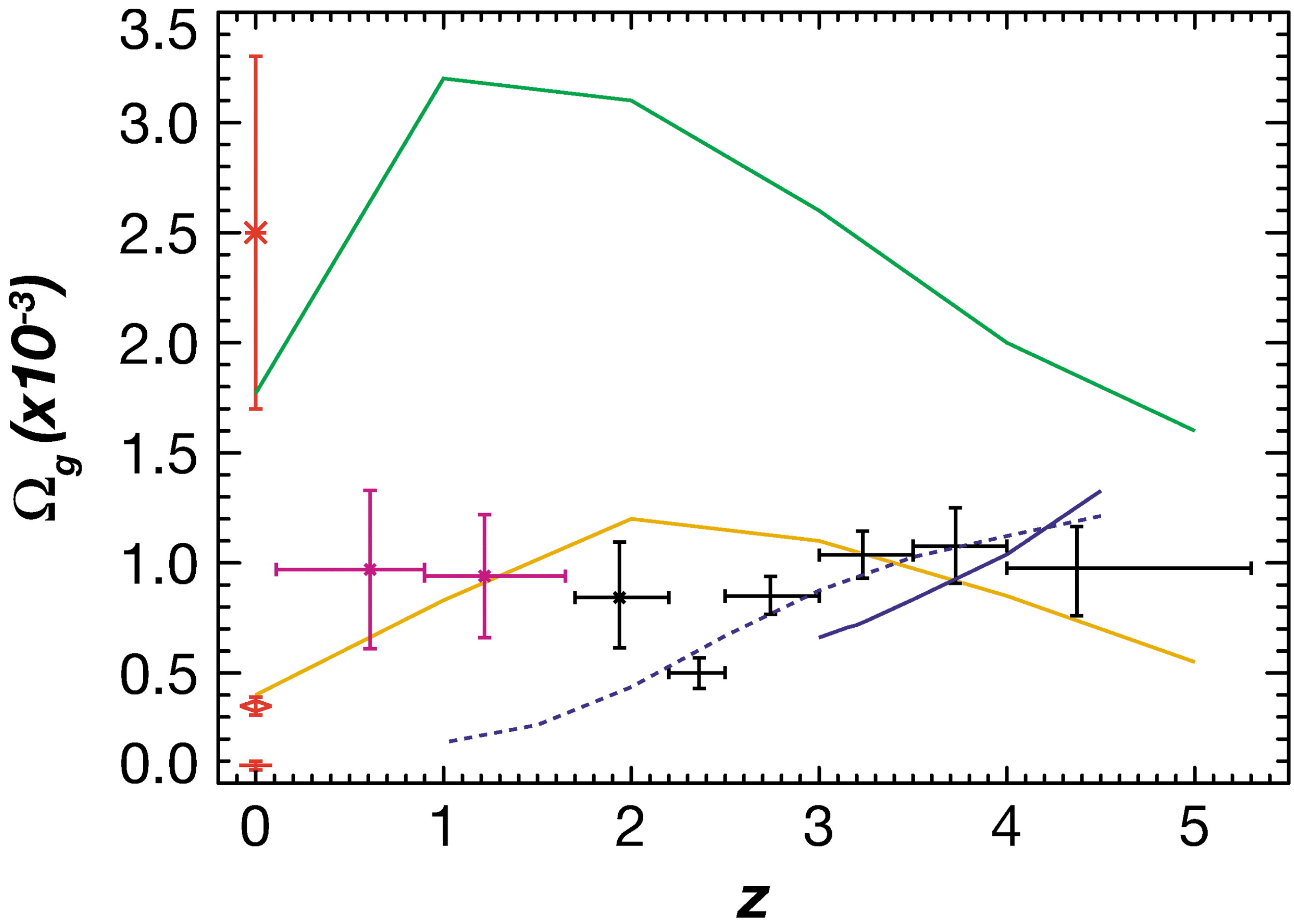


Figure 5 Neutral gas mass density versus *z* from Prochaska et al. (2005). H I data at (*a*) $z \geq 2.2$ from SDSS-DR3_4 survey, (*b*) $0<z<1.6$ from the MgII survey of S.M. Rao, D.A. Turnshek & D.B. Nestor (private communication), and (*c*) at z=0 (*red diamond*) from Fukugita et al. (1998). Stellar mass density at z=0 (*red star*) from Cole et al. (2001) and stellar mass density of Irr galaxies (*red plus sign*) from Fukugita et al. (1998). Theoretical curves from Cen et al. (2003) (*green*), Somerville et al. (2001) (*yellow*), and Nagamine et al. (2004a) (*blue*; *dotted* is D5 model and *solid* is Q5 model).

The Gunn-Peterson Effect

Even a slight amount of neutral hydrogen in the early IGM can completely absorb the flux blueward of Lyα

The Gunn-Peterson (1965) optical depth to Lyα photons is

$$\tau_{\mathrm{GP}} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\mathrm{HI}}, \tag{1}$$

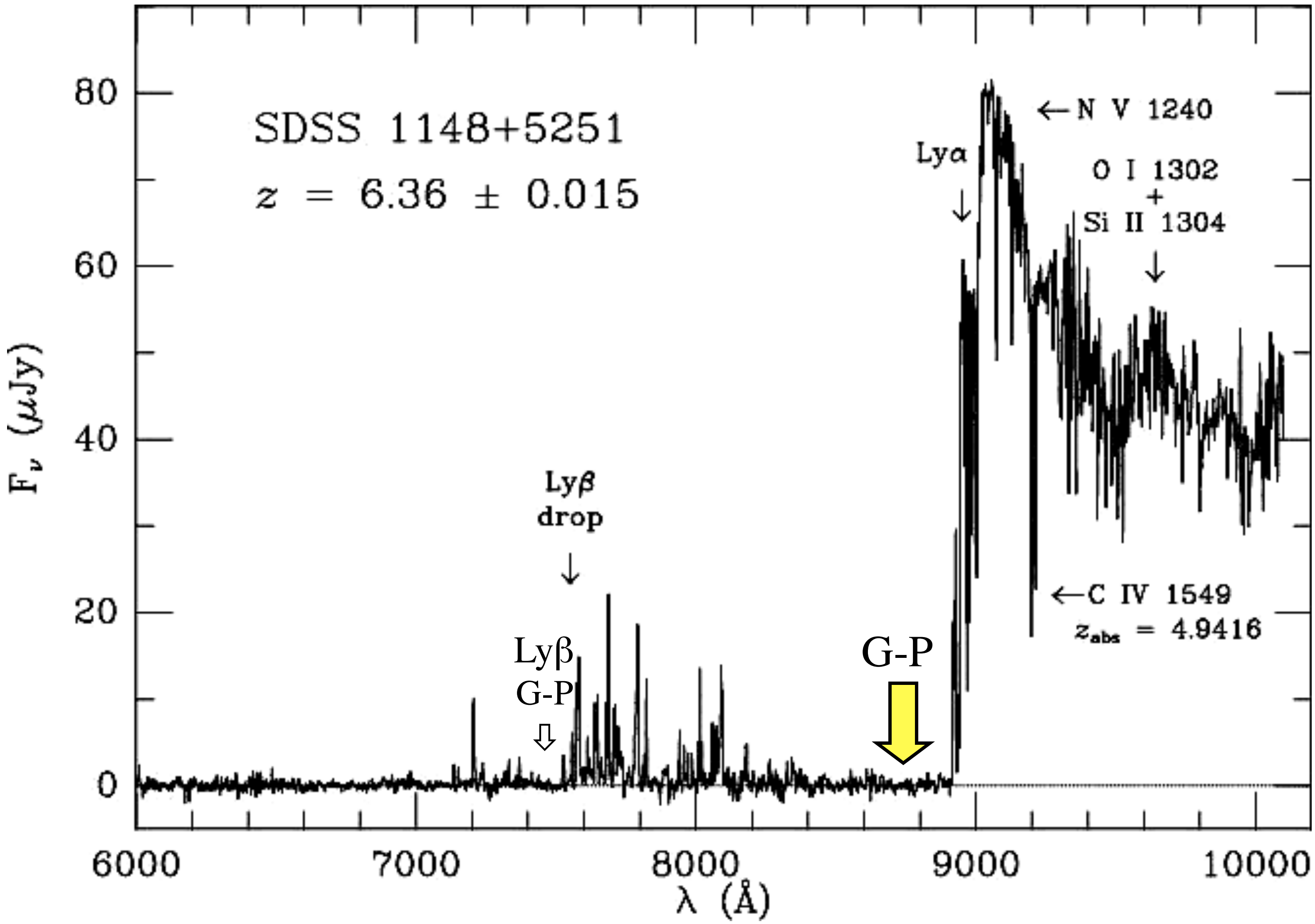
where f_α is the oscillator strength of the Lyα transition, $\lambda_\alpha = 1216$ Å, $H(z)$ is the *Hubble* constant at redshift z, and n_{HI} is the density of neutral hydrogen in the IGM. At high redshifts,

$$\tau_{\mathrm{GP}}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{\mathrm{HI}}}{n_{\mathrm{H}}}\right) \tag{2}$$

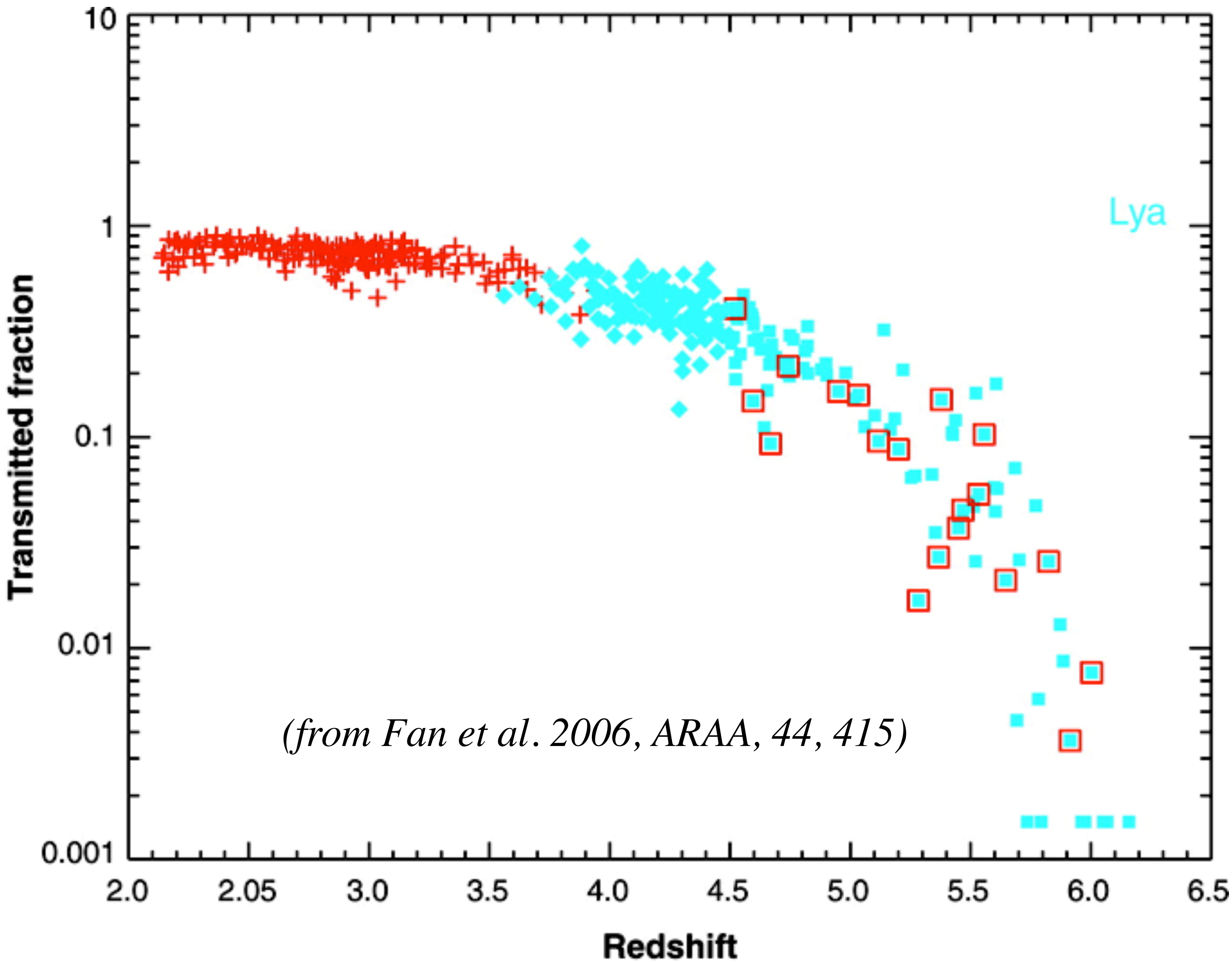
for a uniform IGM. Even a tiny neutral fraction, $x_{\mathrm{HI}} \sim 10^{-4}$, gives rise to complete GP absorption. This test is only sensitive at the end of the reionization when the IGM is already mostly ionized, and the absorption saturates for the higher neutral fraction in the earlier stage.

(from Fan et al. 2006, ARAA, 44, 415)

“Gunn-Peterson like” troughs are now observed along all available lines-of-sight at at $z \sim 6$



Transmitted Lyα Flux vs. Redshift

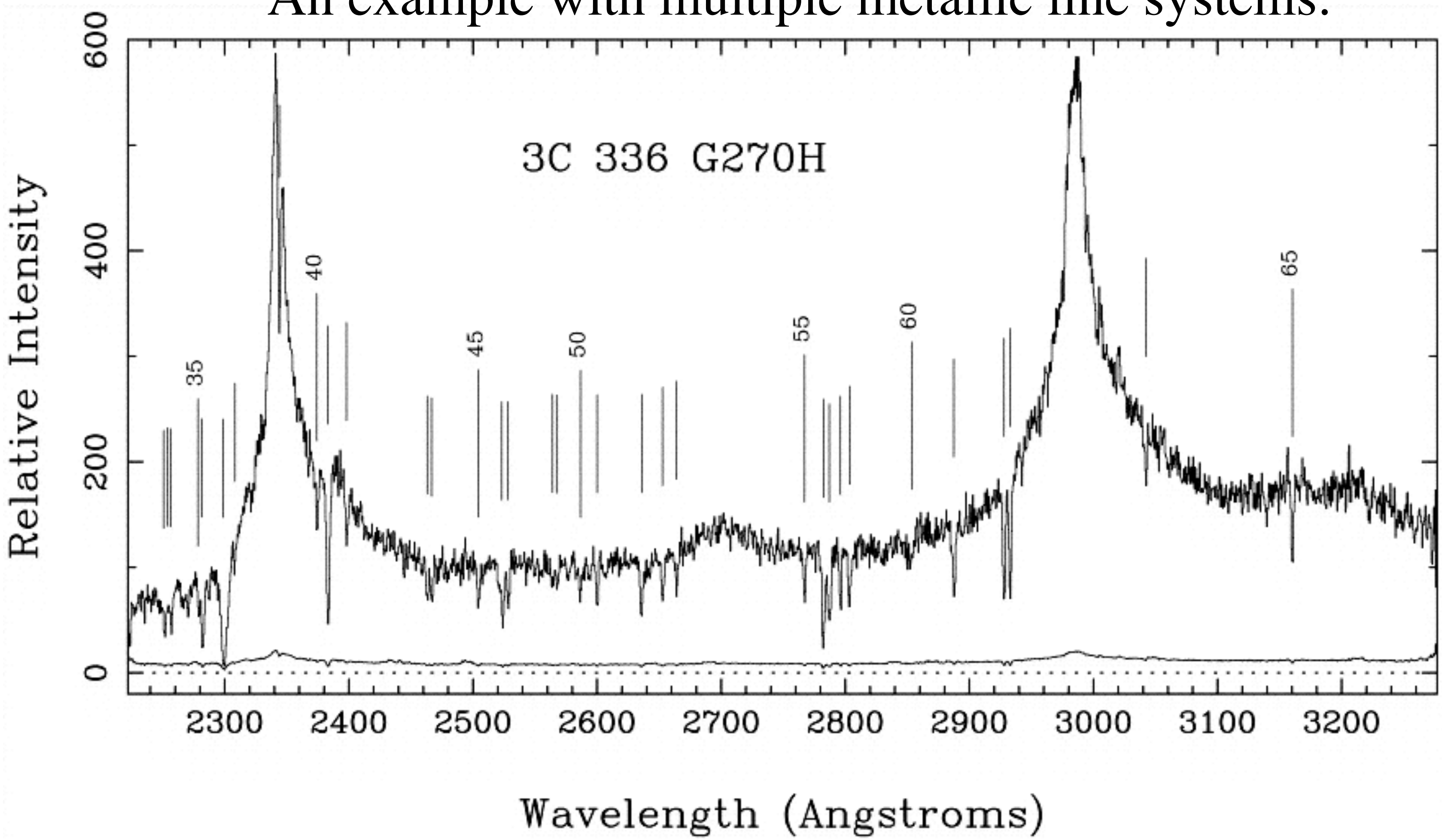


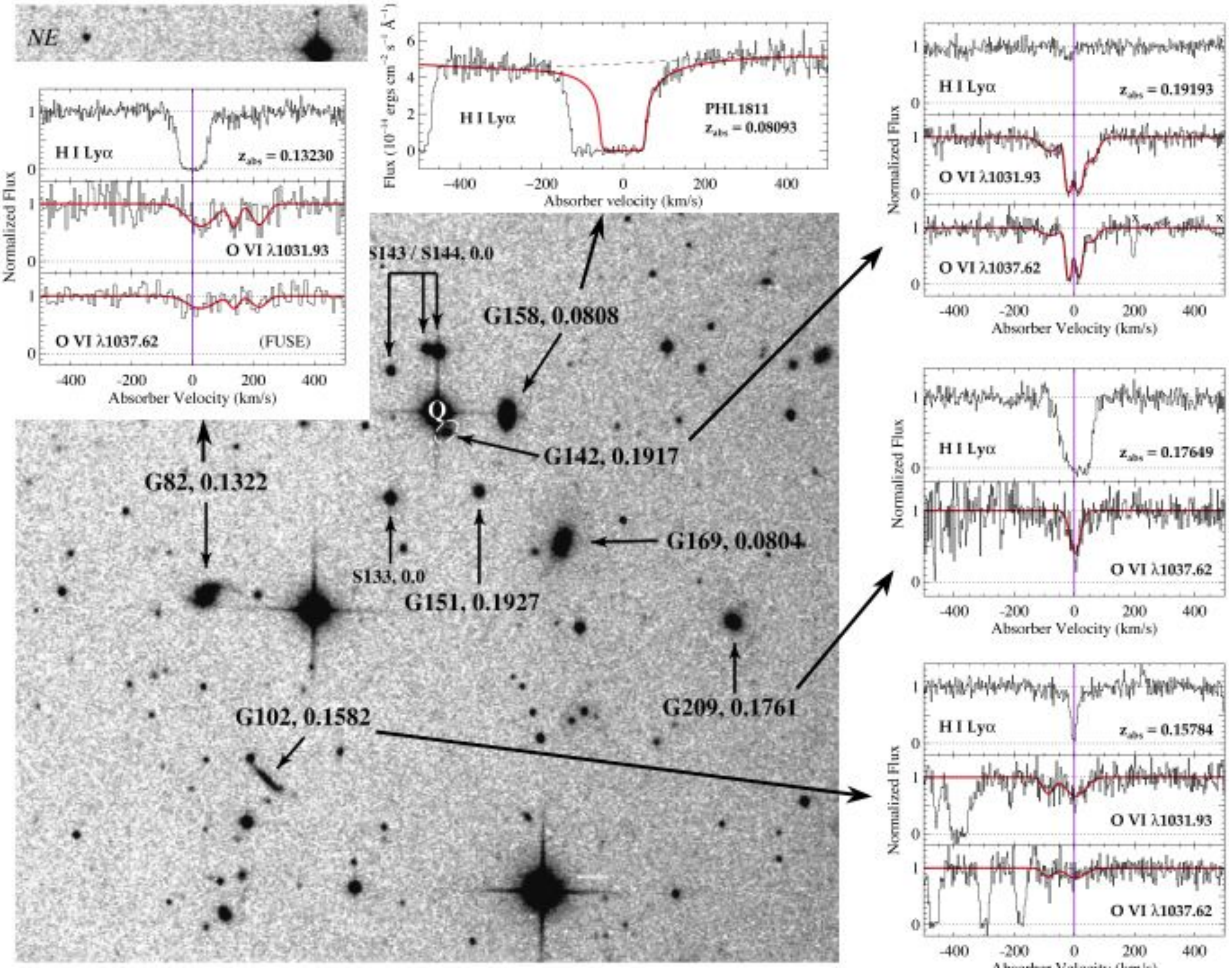
(from Fan et al. 2006, ARAA, 44, 415)

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:

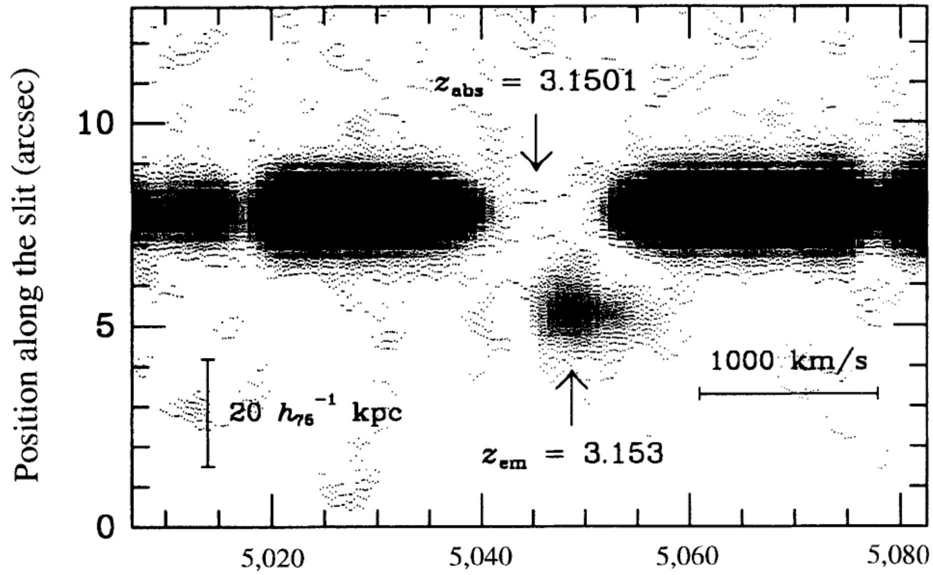


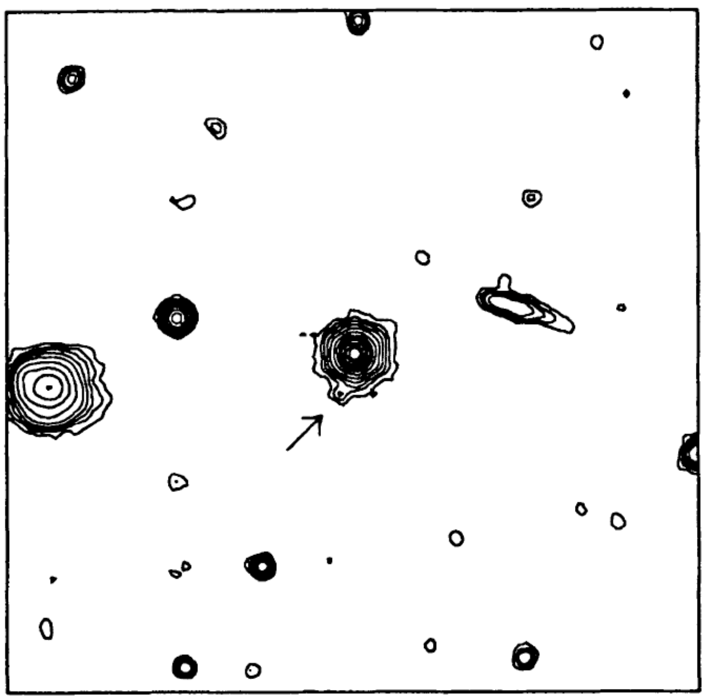


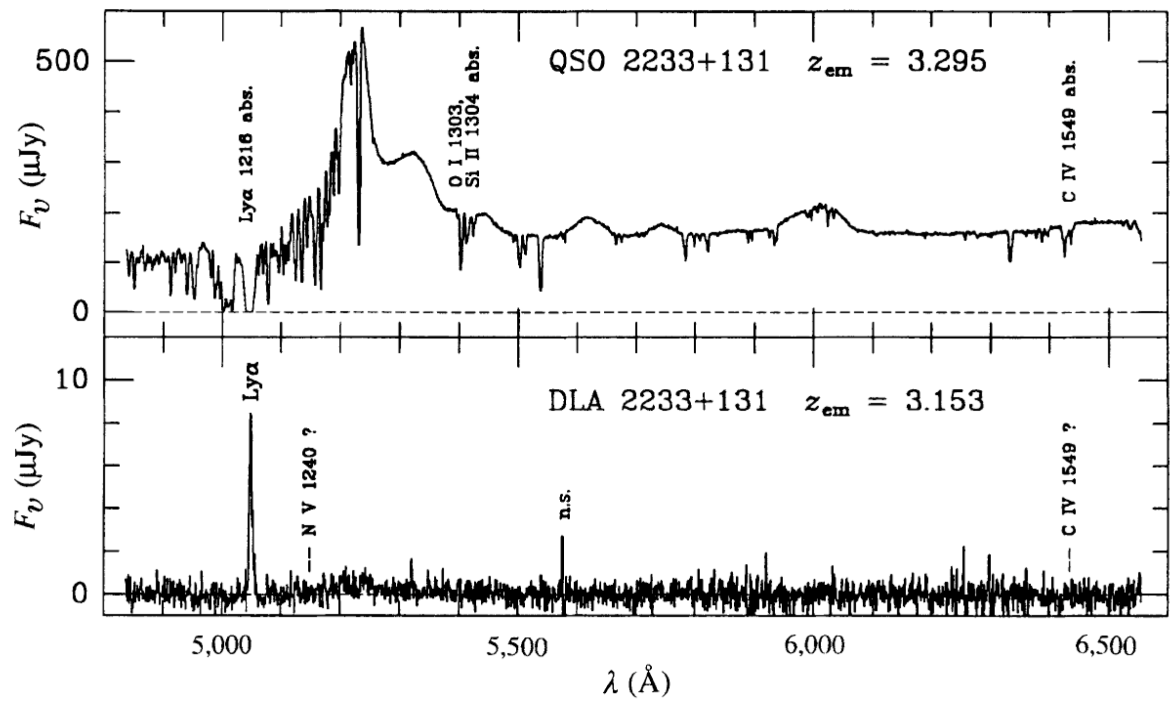
NE
H I Lyα
z_abs = 0.13230
O VI λ1031.93
O VI λ1037.62
(FUSE)
Normalized Flux
Absorber Velocity (km/s)
H I Lyα
PHL1811
z_abs = 0.08093
Flux (10^-14 ergs cm^-2 s^-1 Å^-1)
Absorber velocity (km/s)
S143 / S144, 0.0
G158, 0.0808
G142, 0.1917
G82, 0.1322
S133, 0.0
G151, 0.1927
G169, 0.0804
G209, 0.1761
G102, 0.1582
H I Lyα
z_abs = 0.19193
O VI λ1031.93
O VI λ1037.62
H I Lyα
z_abs = 0.17649
O VI λ1037.62
H I Lyα
z_abs = 0.15784
O VI λ1031.93
O VI λ1037.62

Galaxy Counterparts of DLA Systems

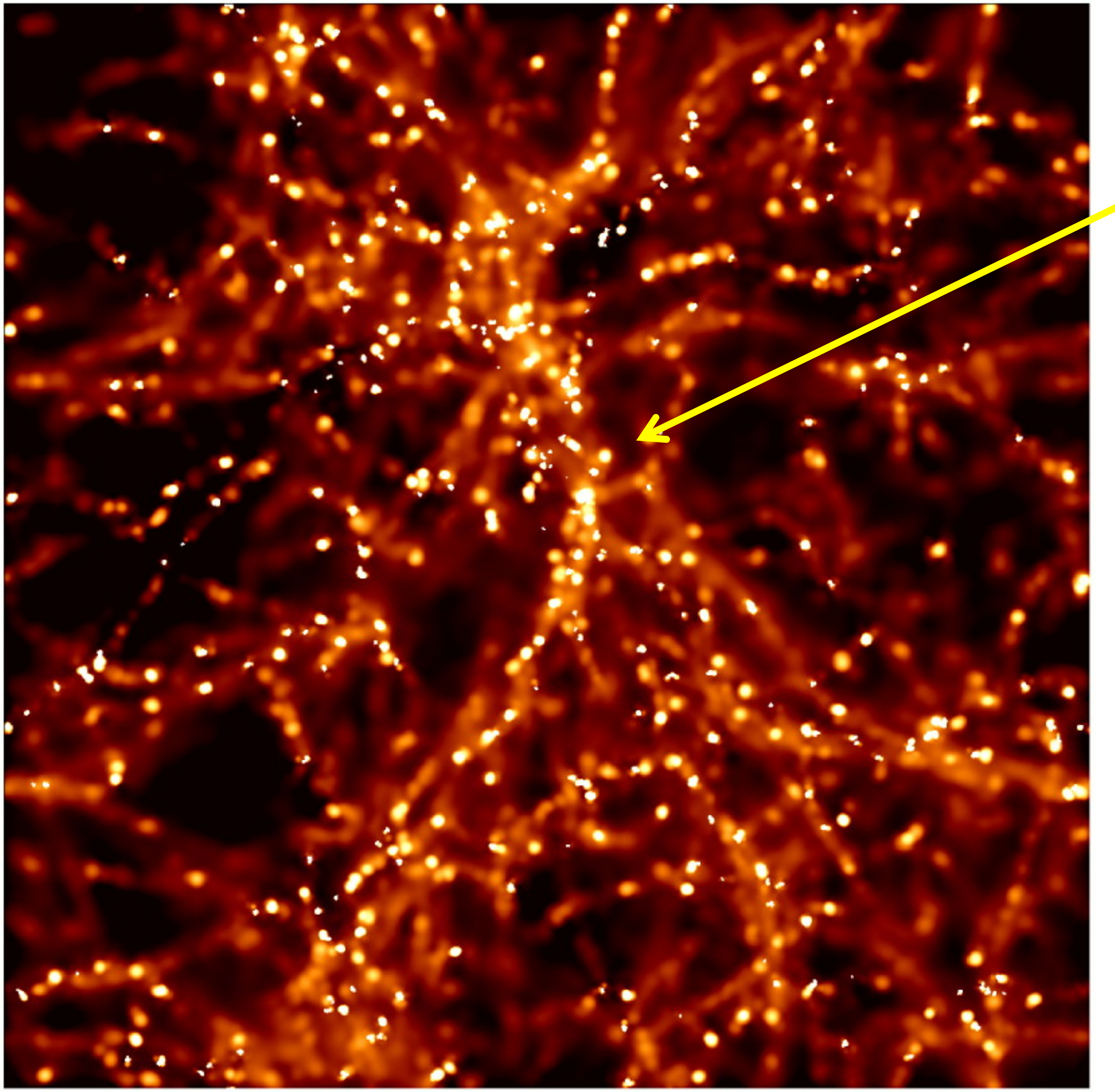
- Several examples are known with Lyα line emission
- Properties (size, luminosity, SFR) are typical of field galaxies at such redshifts, and consistent with being progenitors of $z \sim 0$ disks







Numerical Simulations of IGM



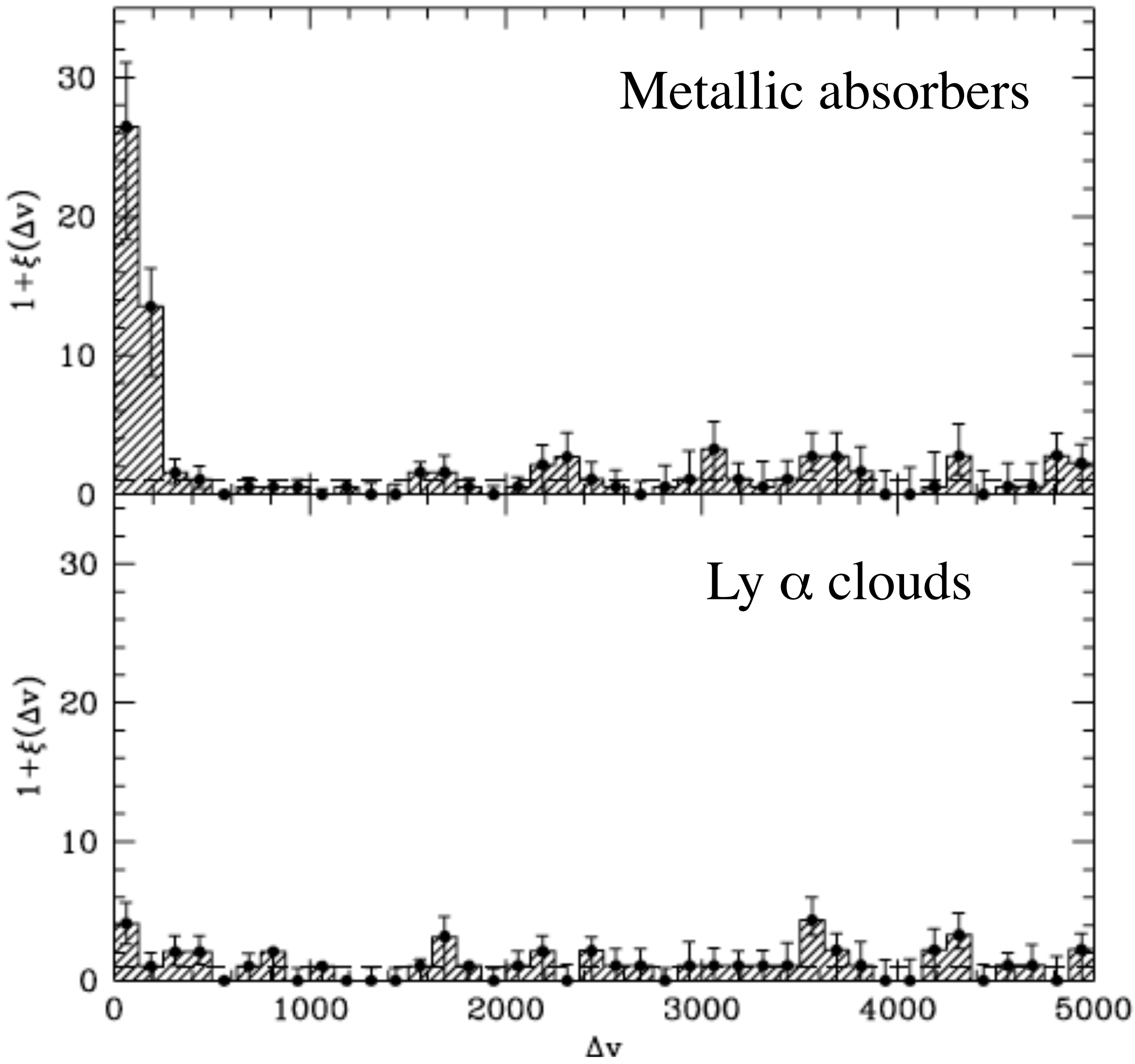
DLA systems as the densest knots in the cosmic web

However, the simulations cannot resolve whether these are rotating (proto)disks

(from Katz et al. 1996)

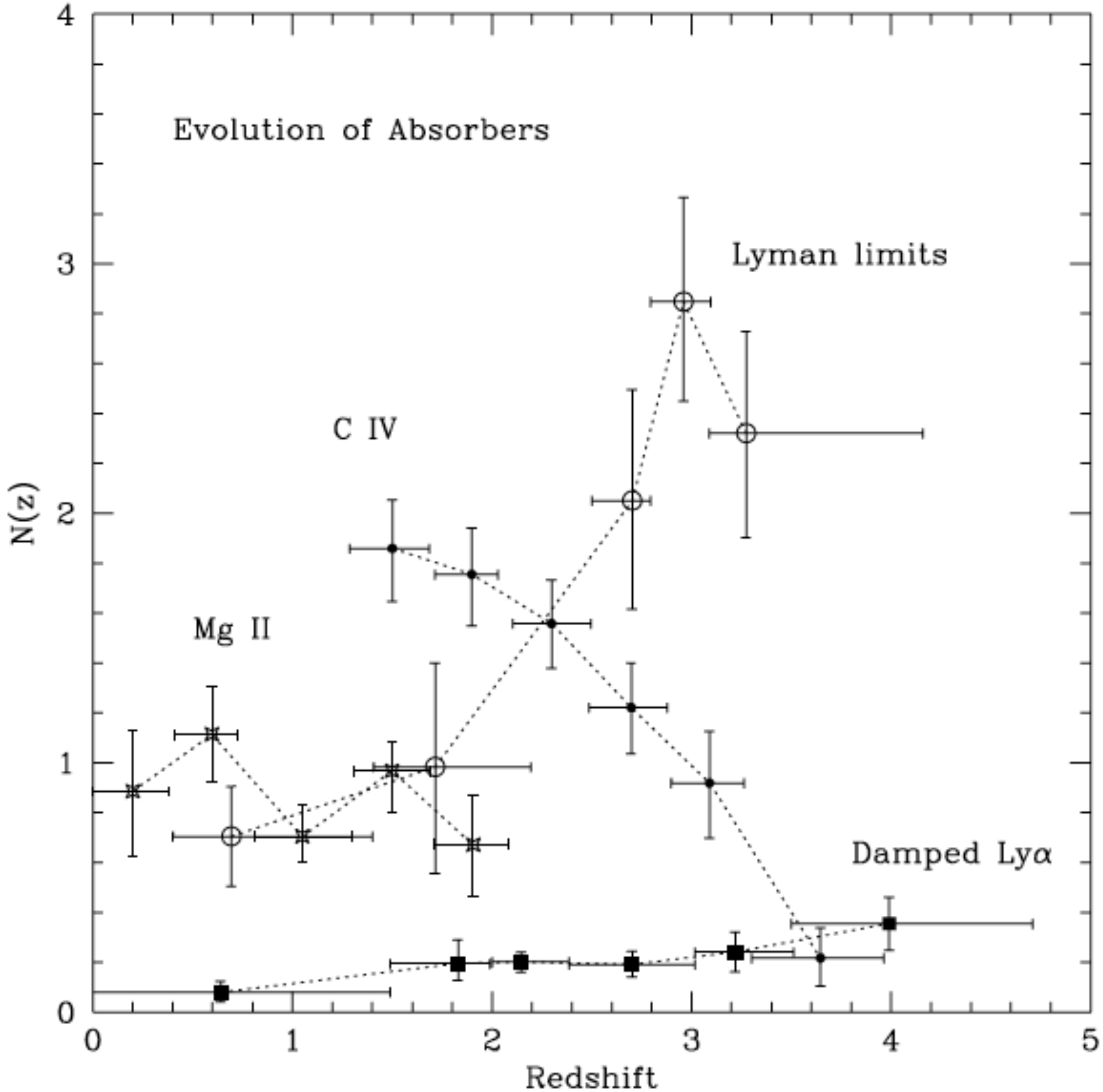
Clustering of Metallic Absorbers

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

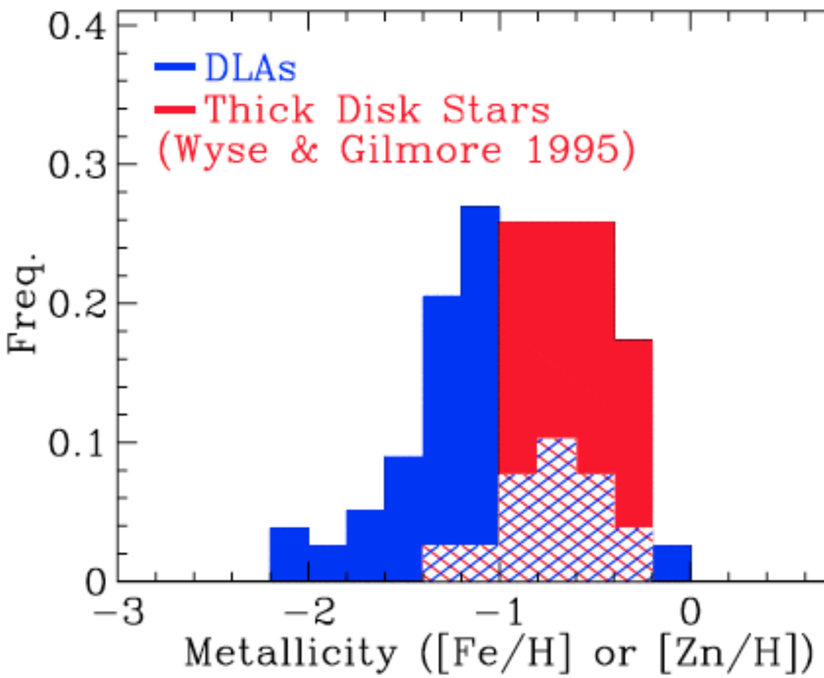


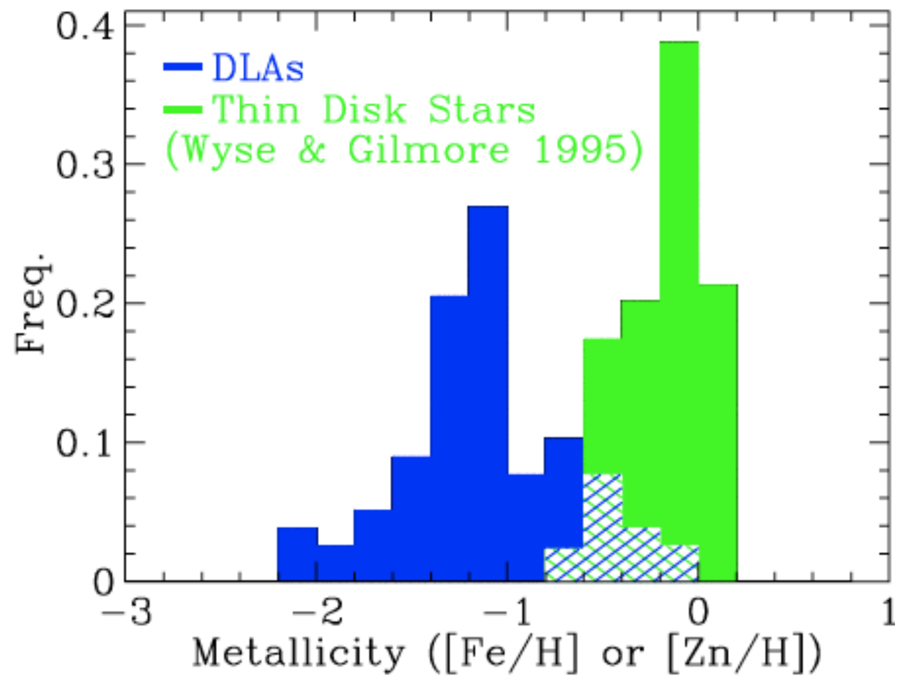
Number Density Evolution of Absorbers

While the H I seems to decline in time (being burned out in stars?), the density of metals seems to be increasing, as one may expect

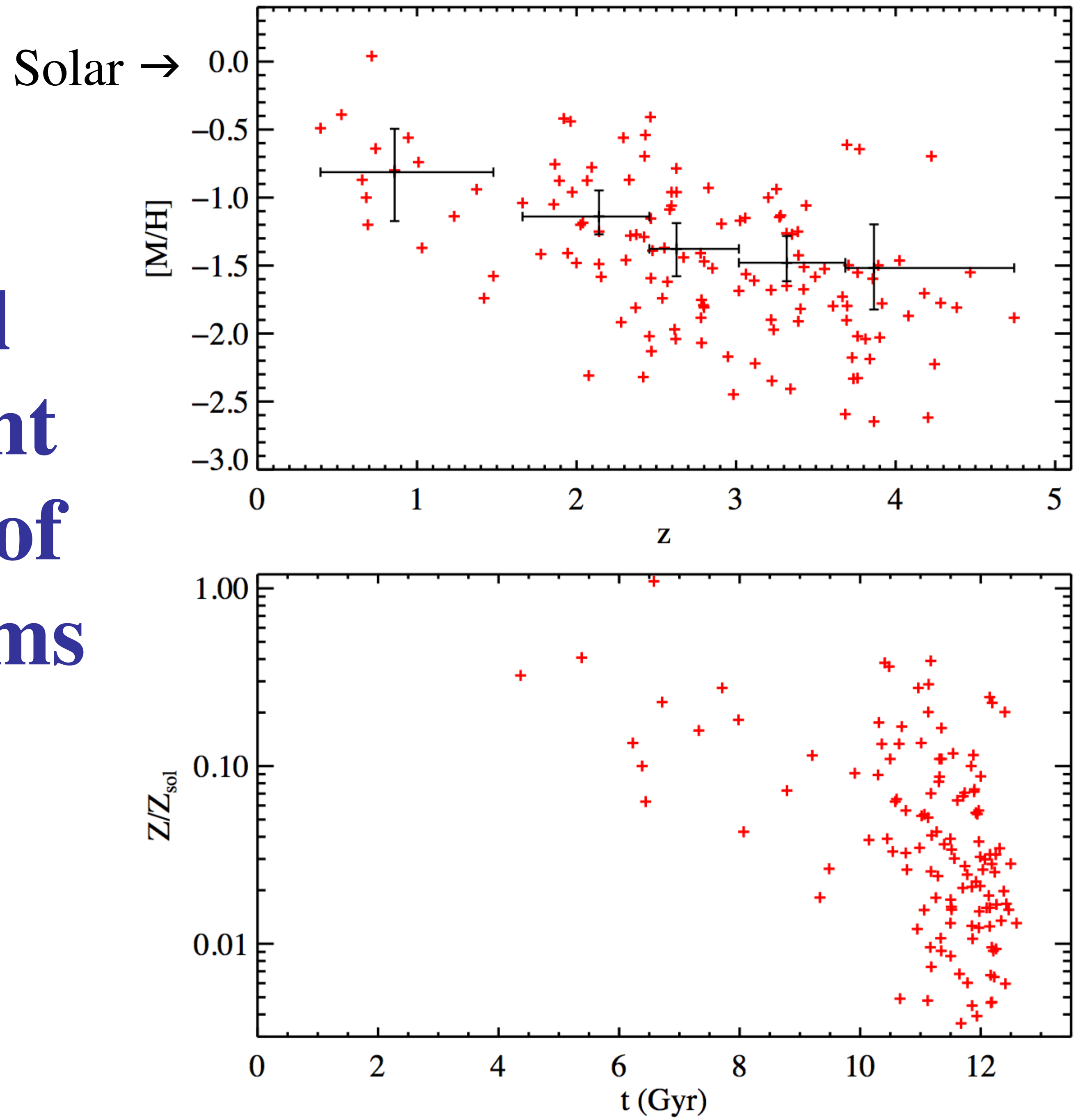


Abundances in DLA Systems and Disks



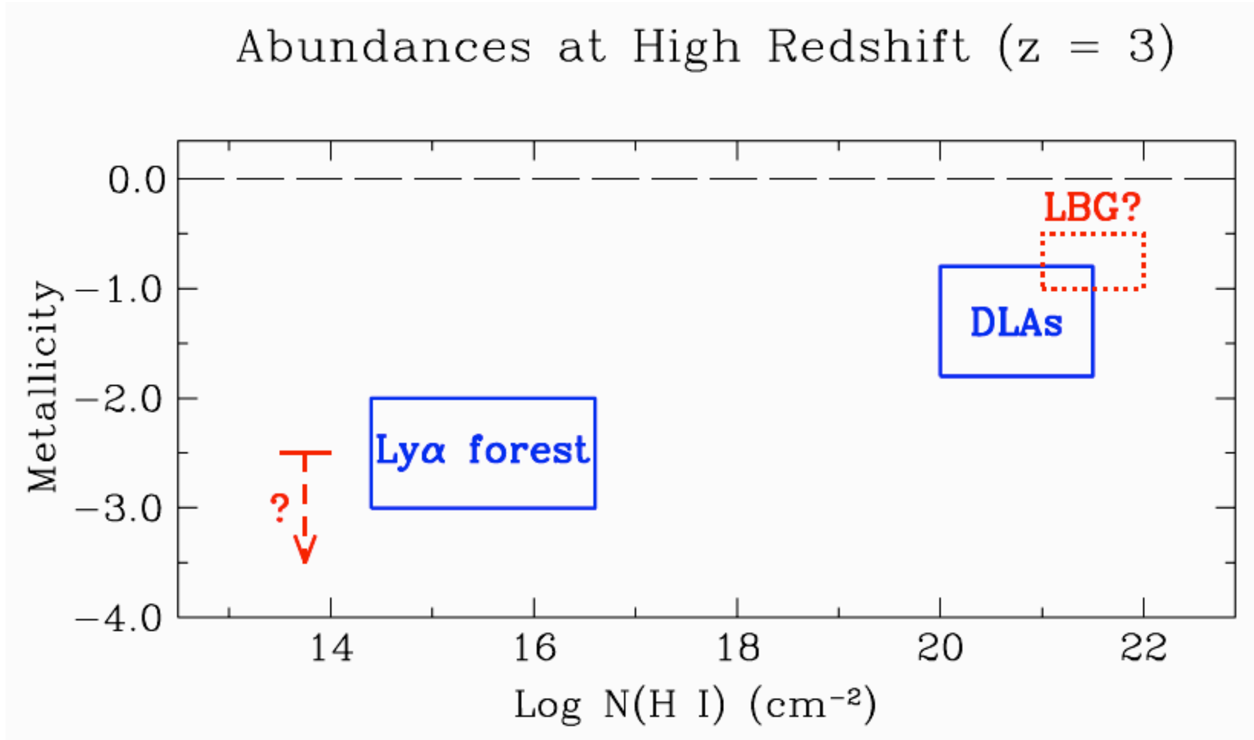


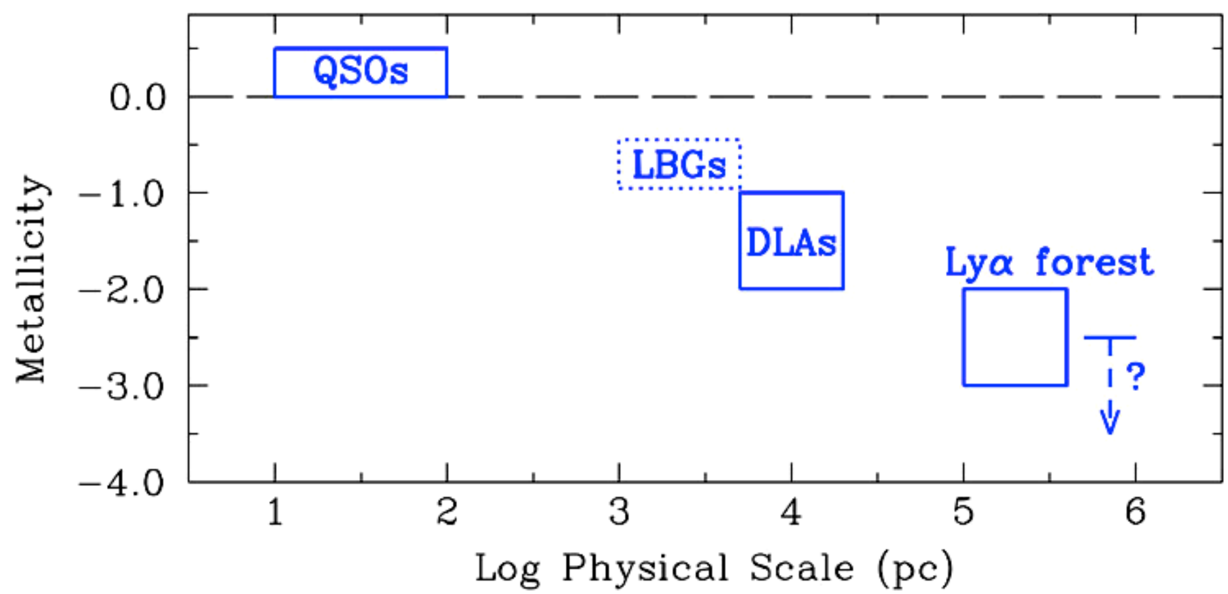
Chemical Enrichment Evolution of DLA Systems



(Wolfe et al.)

But different types of systems may be evolving in different ways …





(from M. Pettini)

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