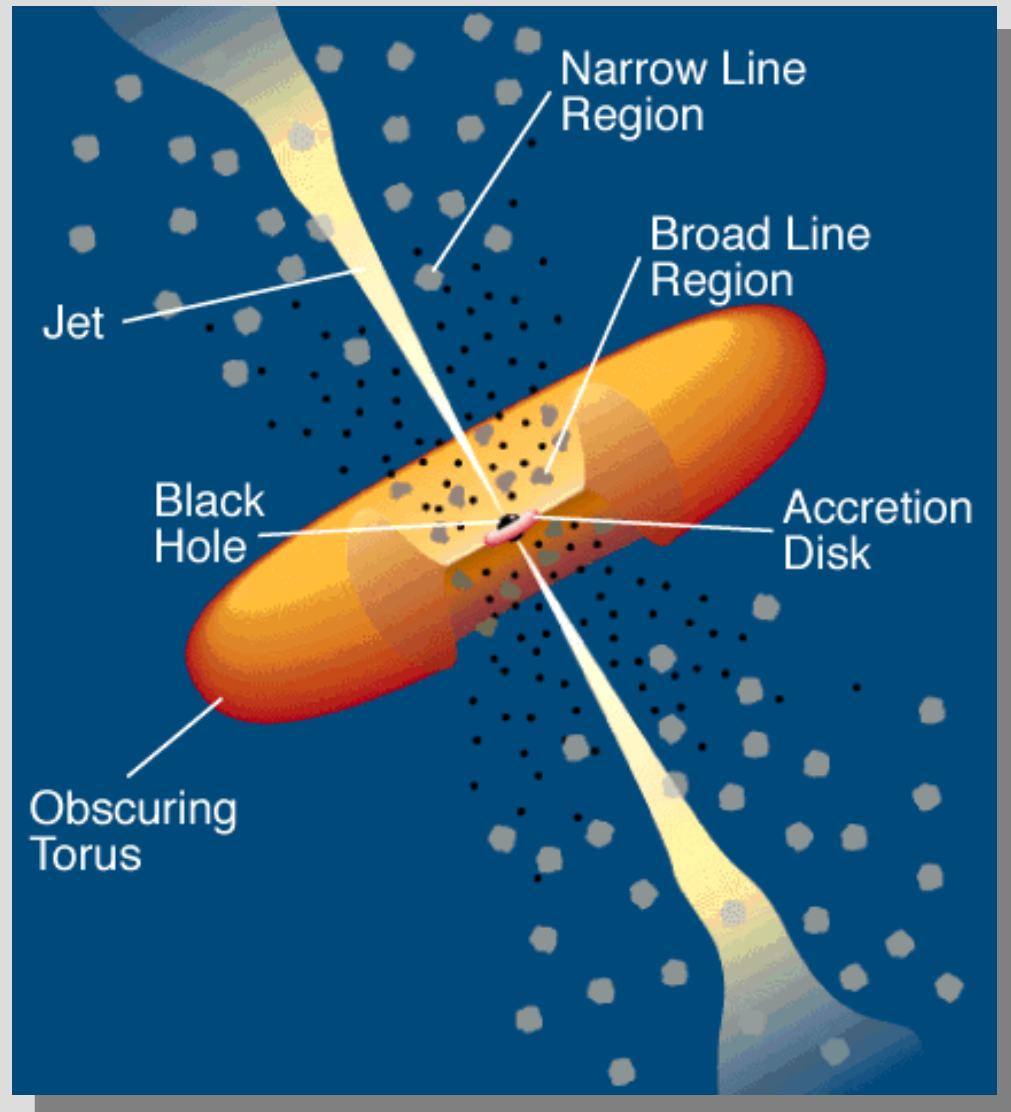


Introduction Active Galactic Nuclei

Lecture -11- Quasars as Cosmological Probes



This Lecture

Give a general overview of quasar absorption line physics and its use in studying cosmology and the IGM

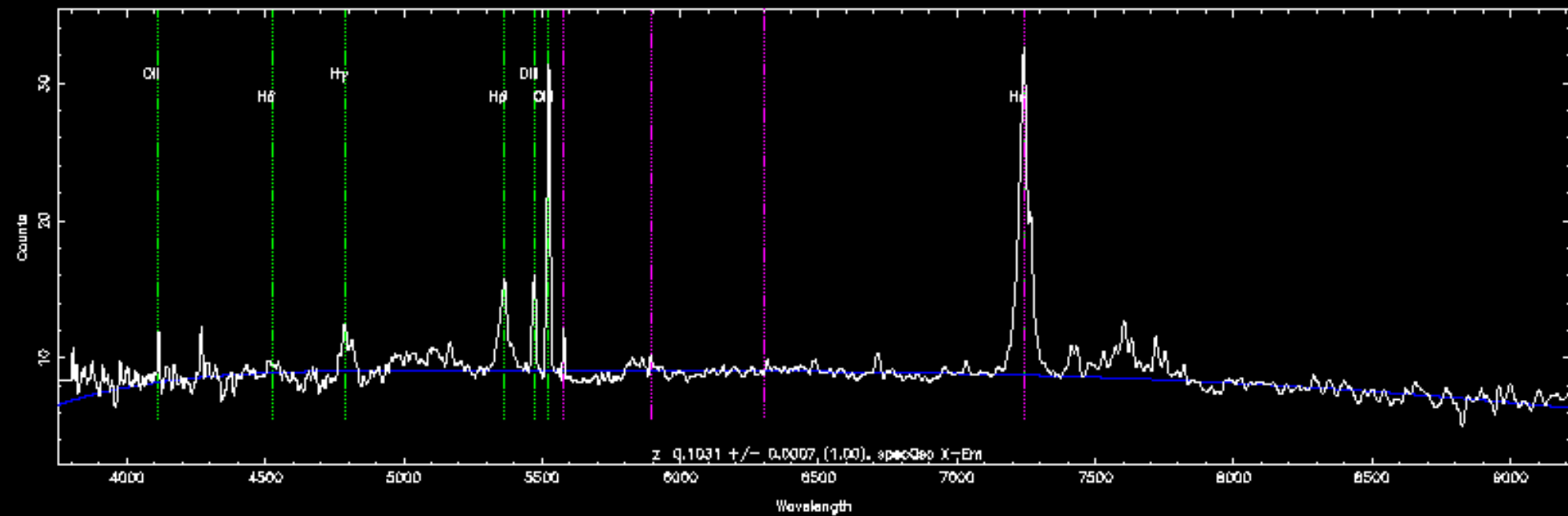
Read Chapt.12 of Peterson
(again somewhat out of date, but read anyway)

Quasars span a wide range in redshift

Quasars are "beacons of light" that can be seen from $z=0$ to $z>6.5$ and thus are probes of the LSS and the IGM between the observer and the quasar



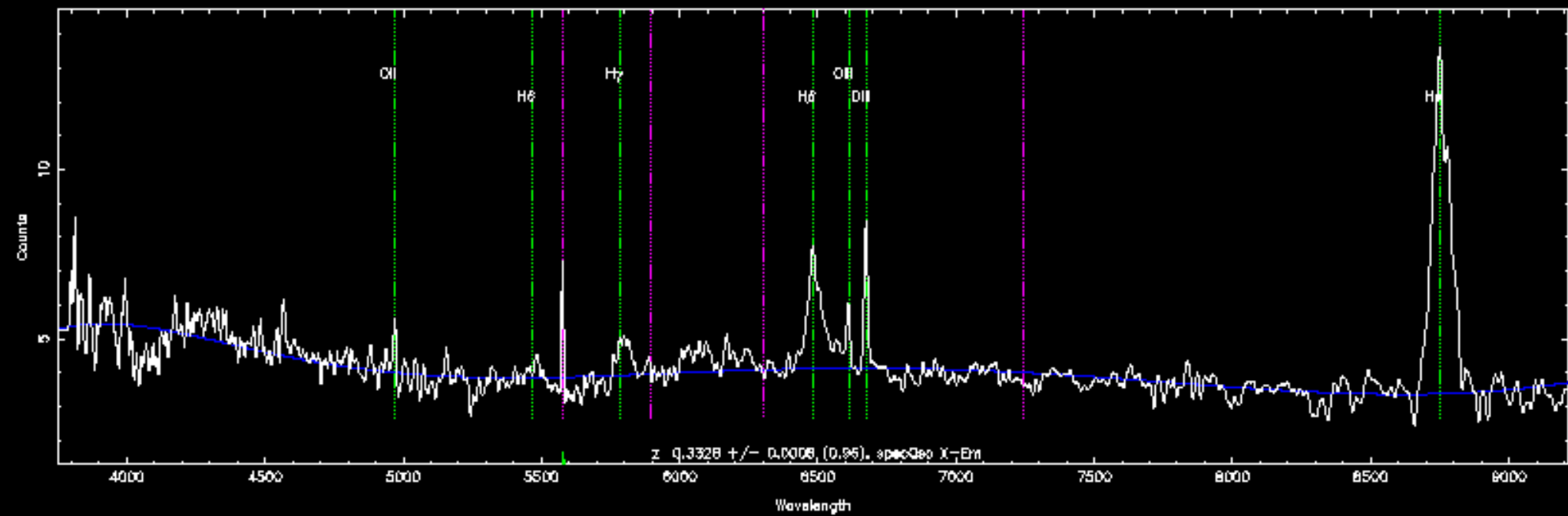
$z=0.1$



From Phil Outram

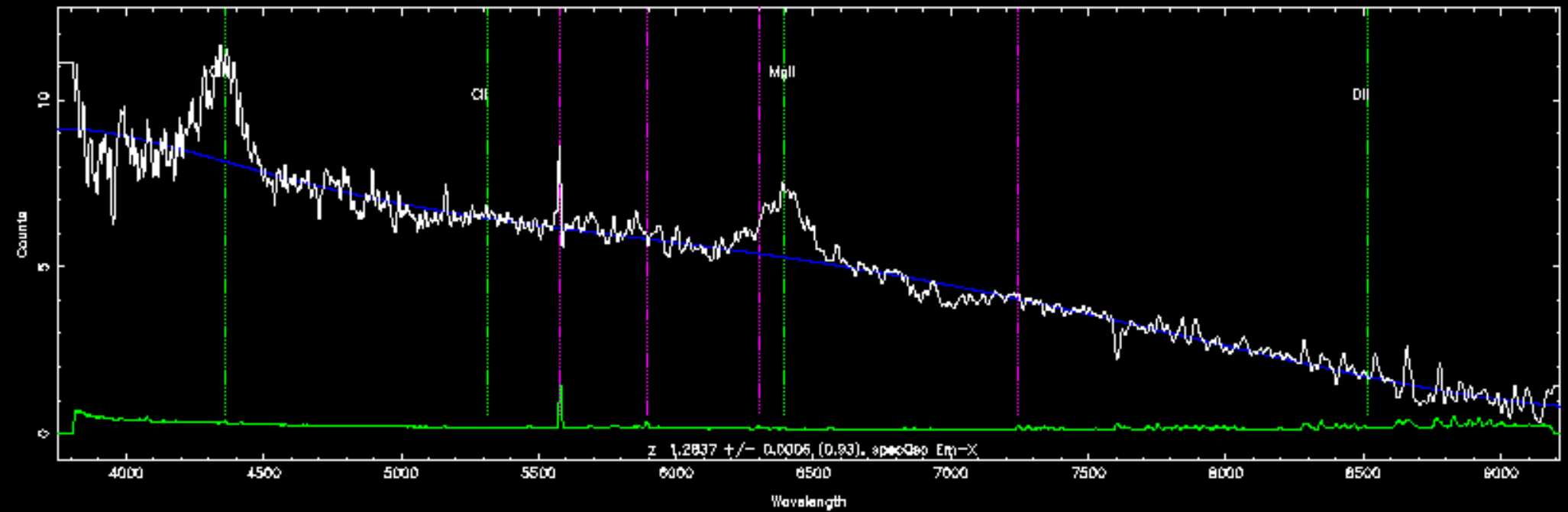


$z=0.3$



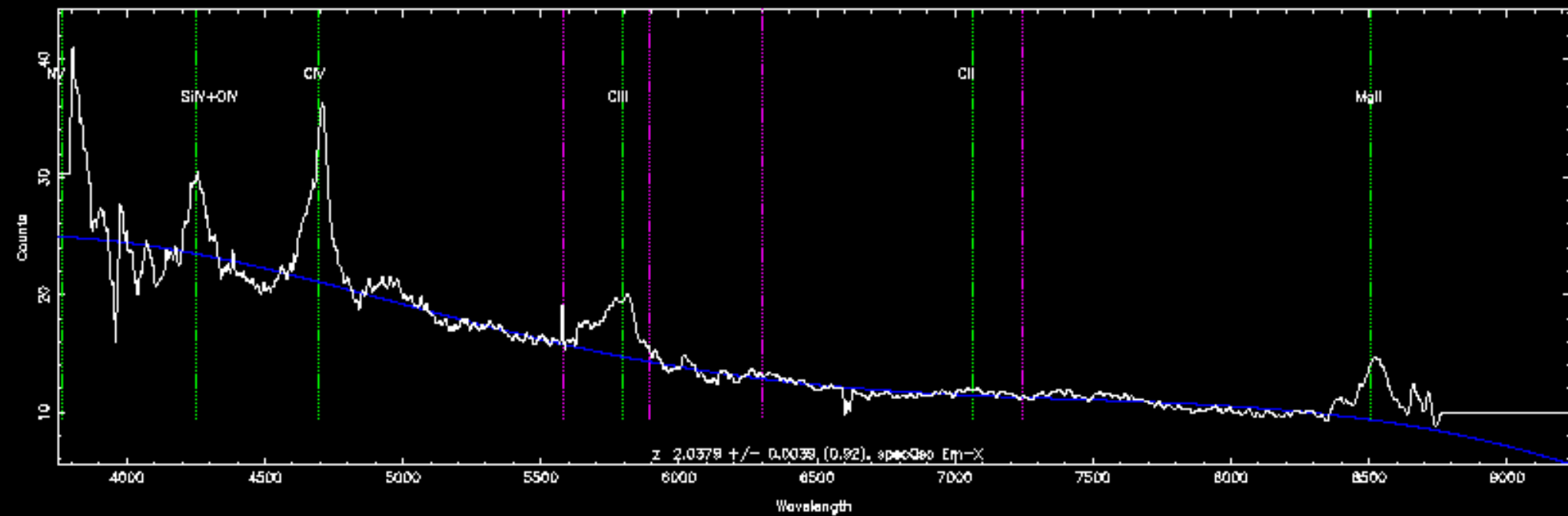


$z=1.3$



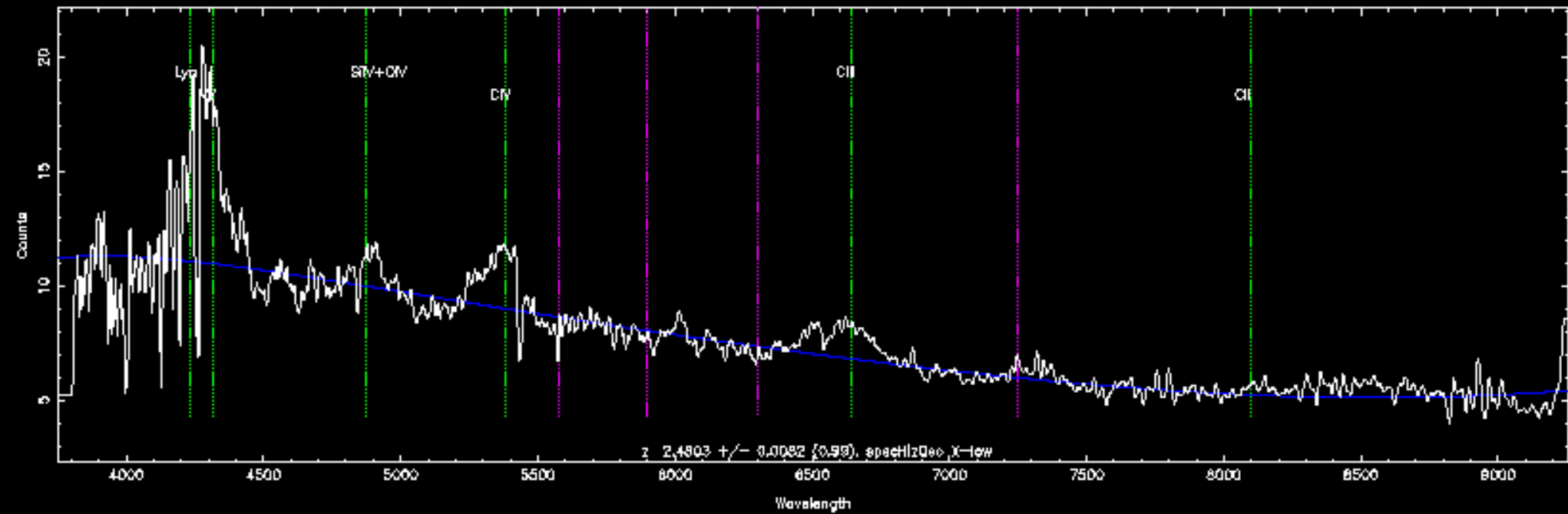


$z=2.0$



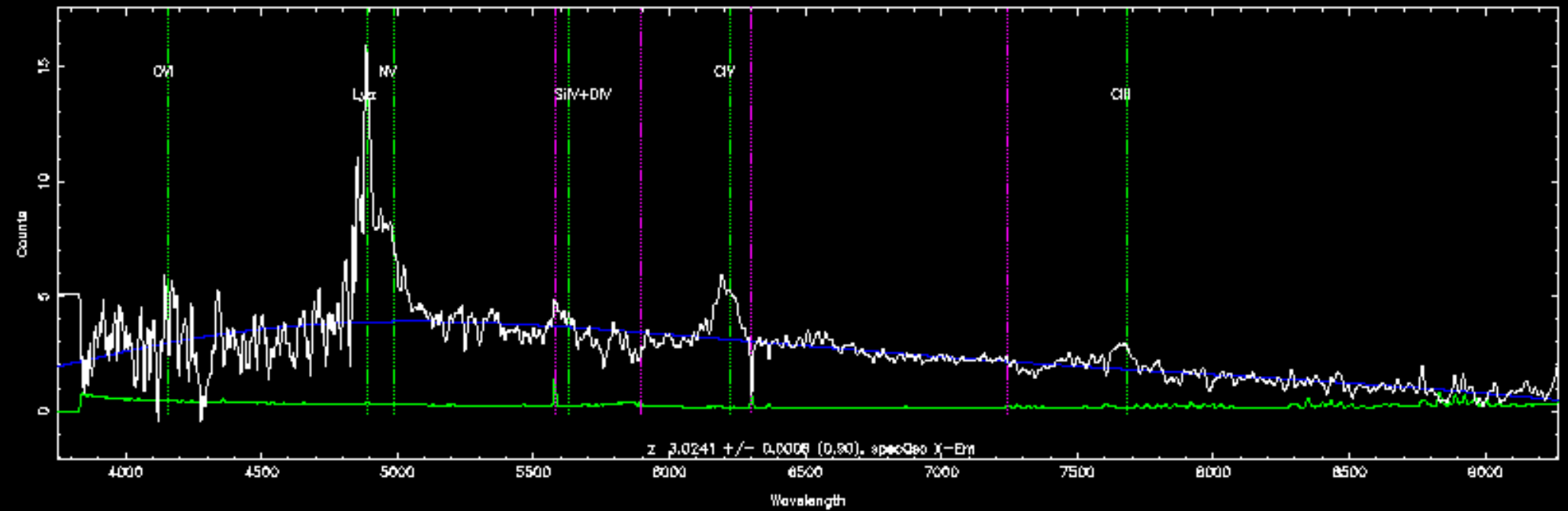


$z=2.5$



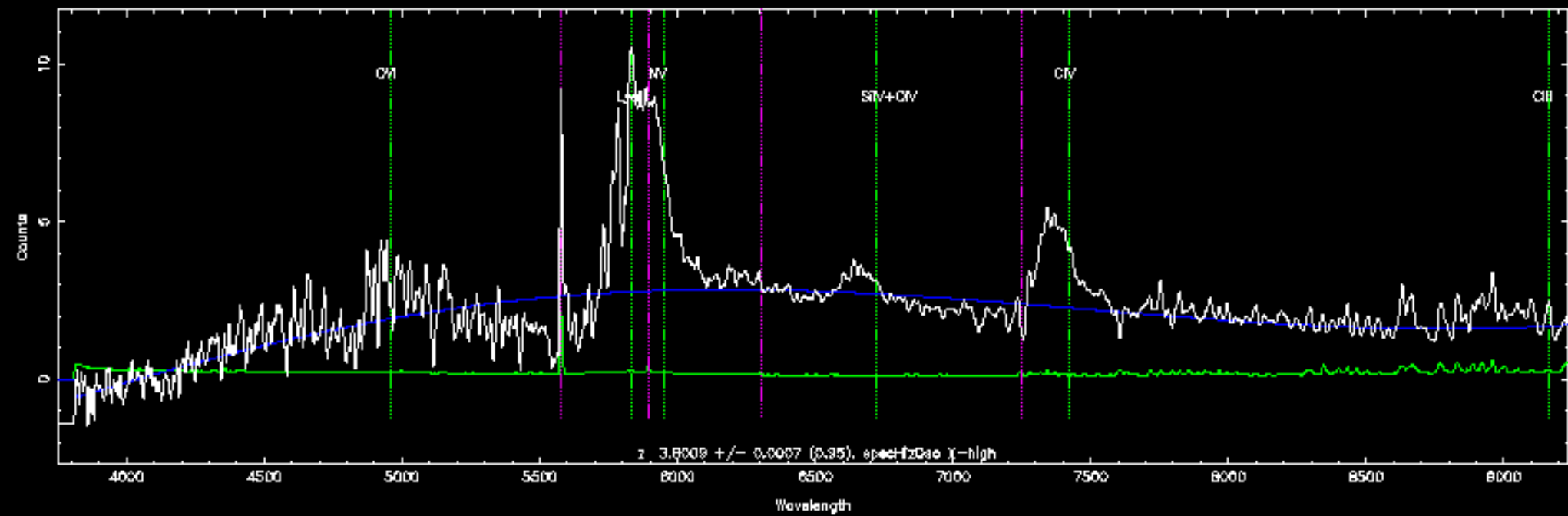


$z=3.0$



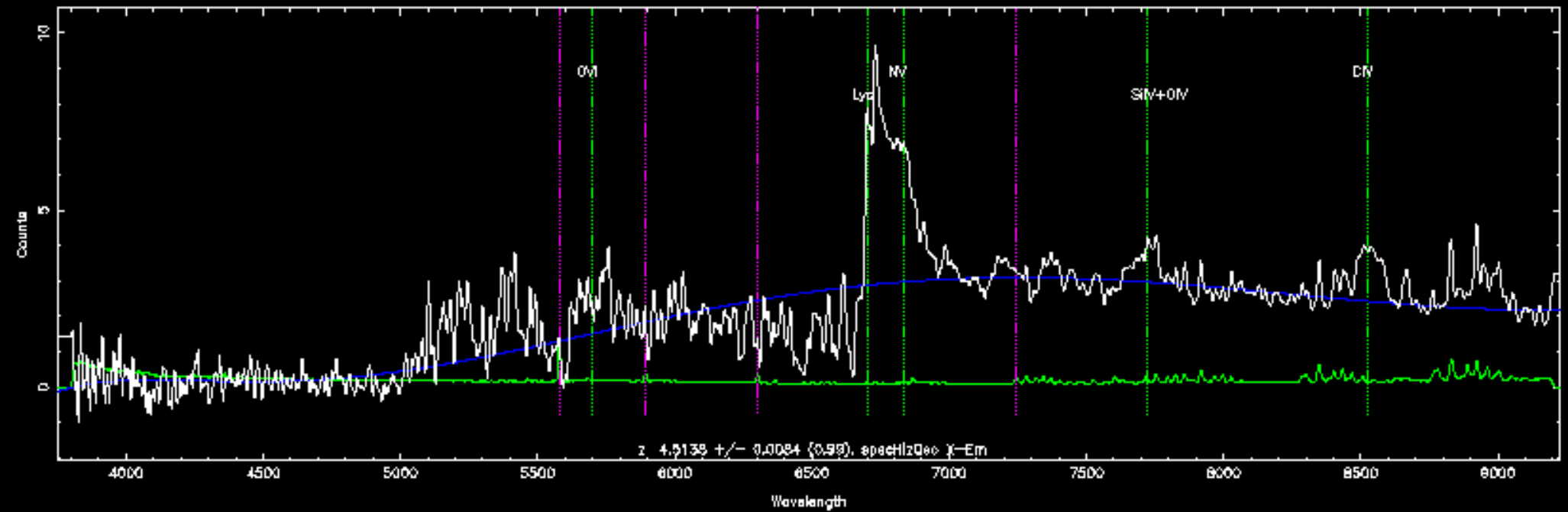


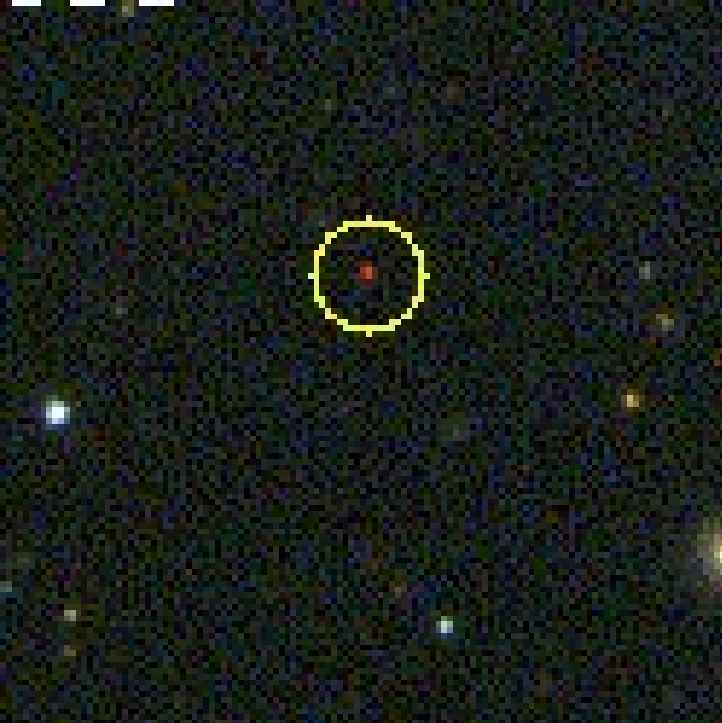
$z=3.8$



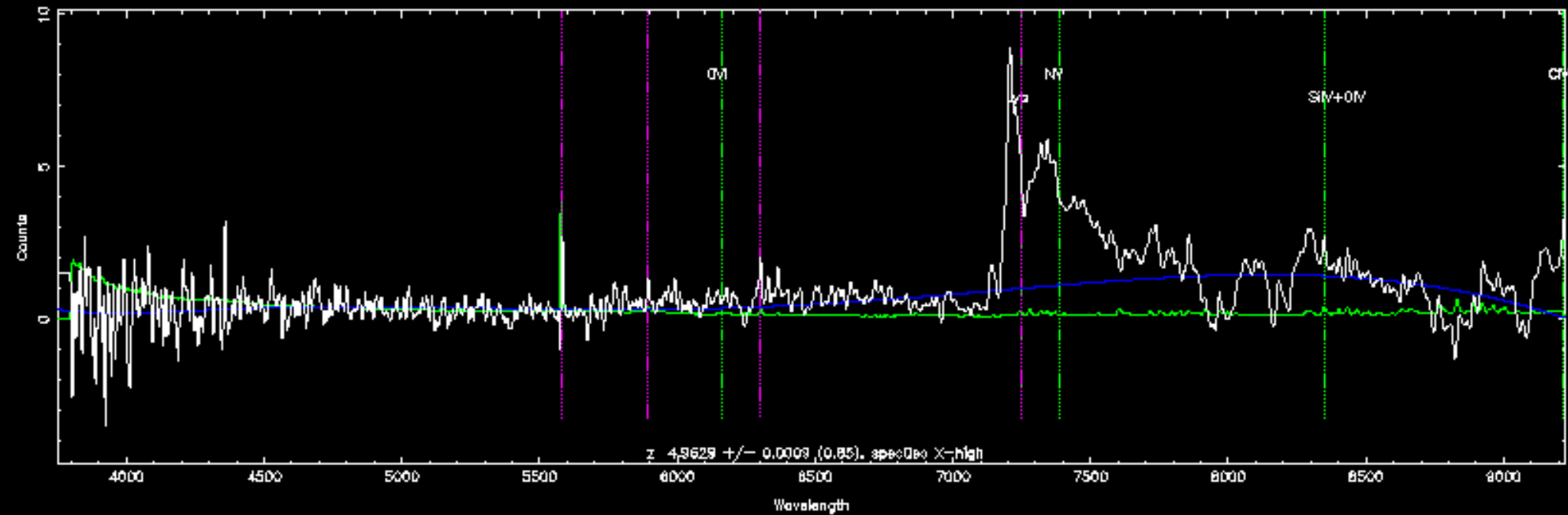


$z=4.5$





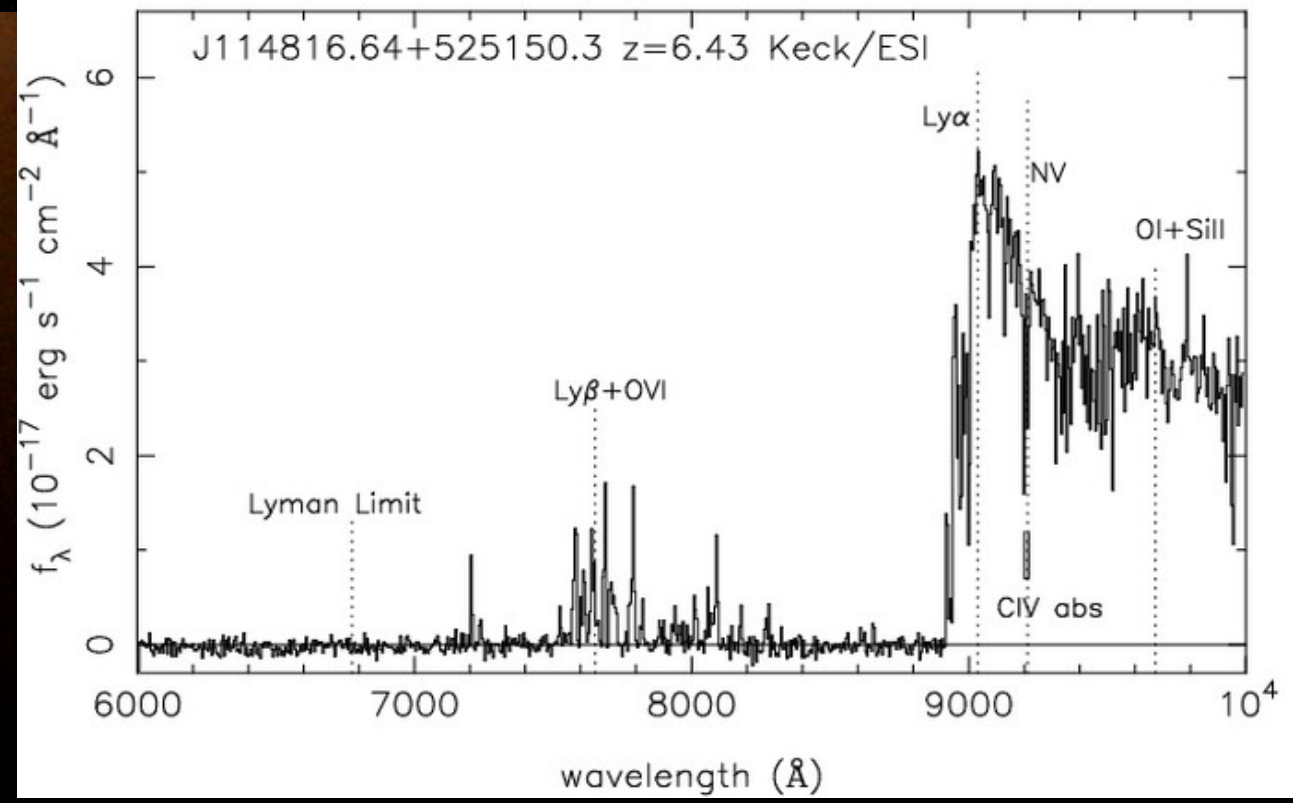
$z=5.0$



$z=6.4$



$z=6.43$



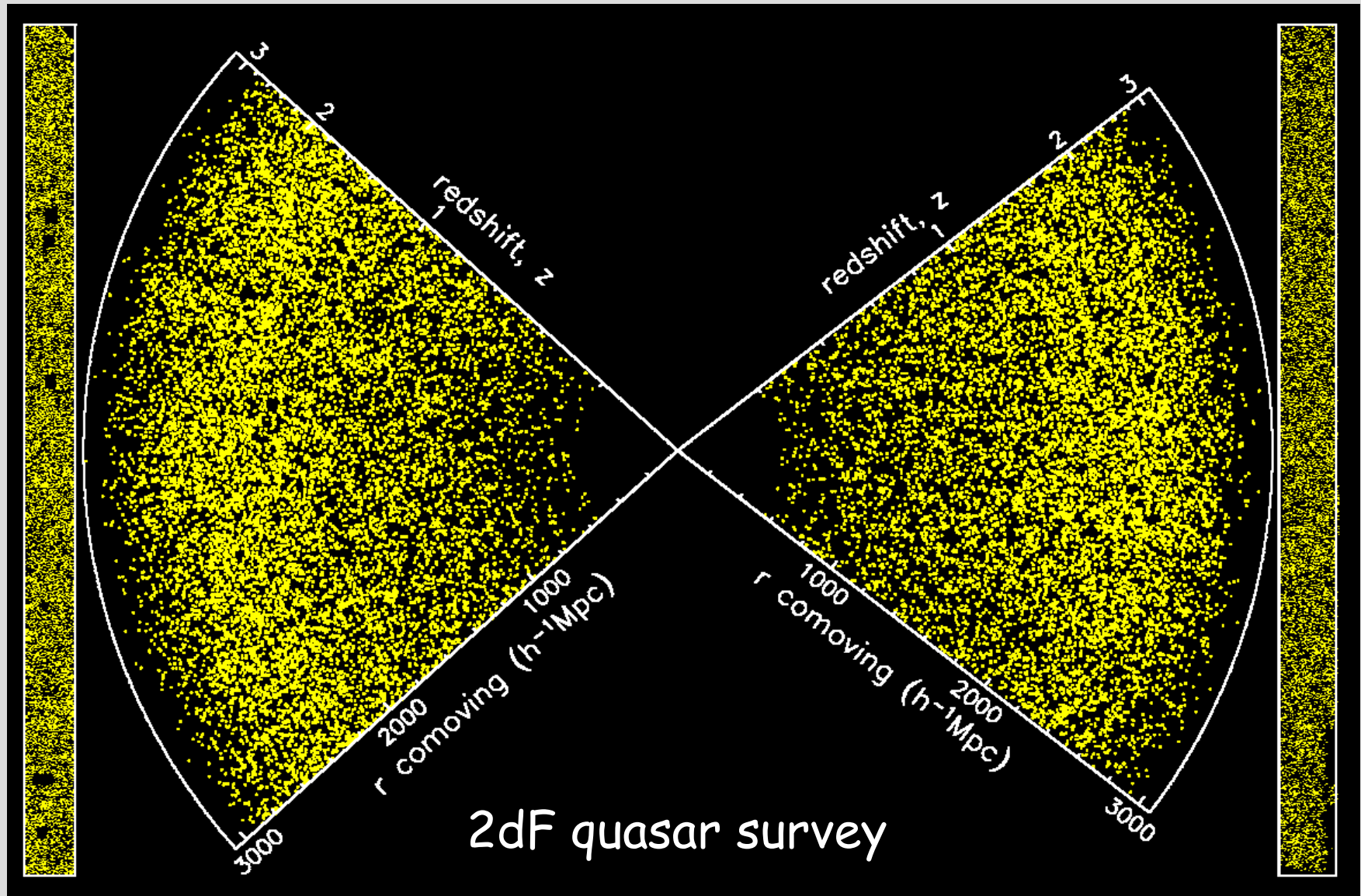
Fundamental questions

- QSO (SMBH) formation & evolution:
 - How?
 - When?
- Cosmology:
 - Ω, Λ, H_0 - DONE?
 - $W(z)$, "dark energy", equation of state...
 - Large Scale Structure (evolution?)
 - Evolution of the IGM and the formation of galaxies.

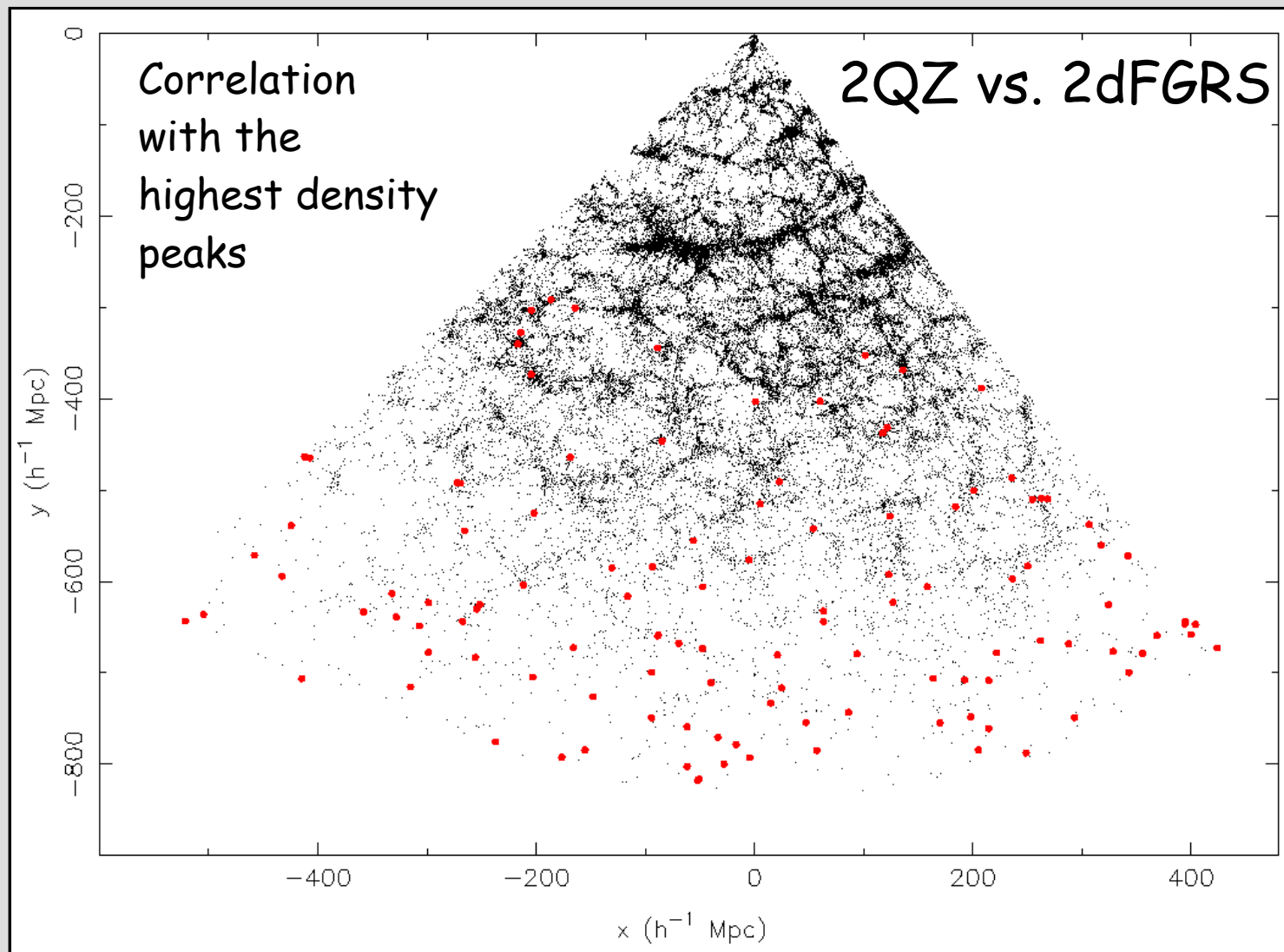
Many studies have only become possible with the advent of large surveys

- Large homogeneous optically selected samples:
2dF, SDSS
- Smaller deep X-ray surveys:
Chandra, XMM
- Follow-up with 8-10m class telescopes (!!)
(see previous lectures)

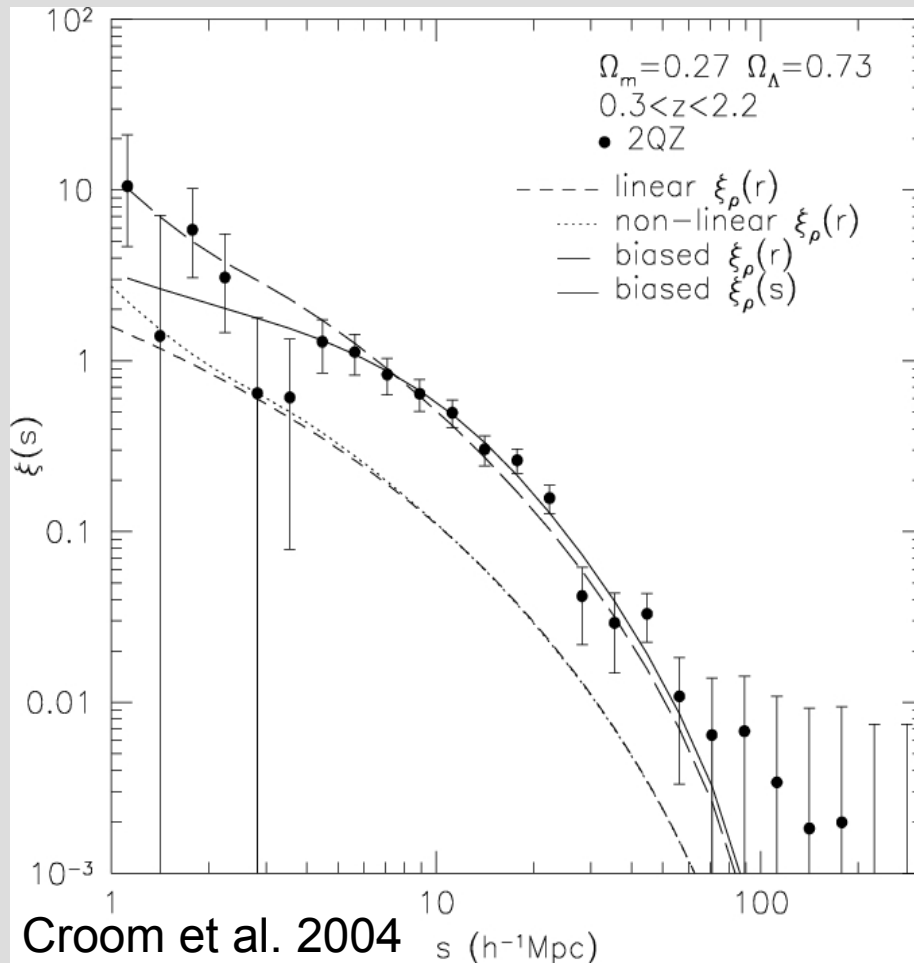
Study Large Scale Structure



Study Large Scale Structure: Galaxies versus Quasars



Study Large Scale Structure

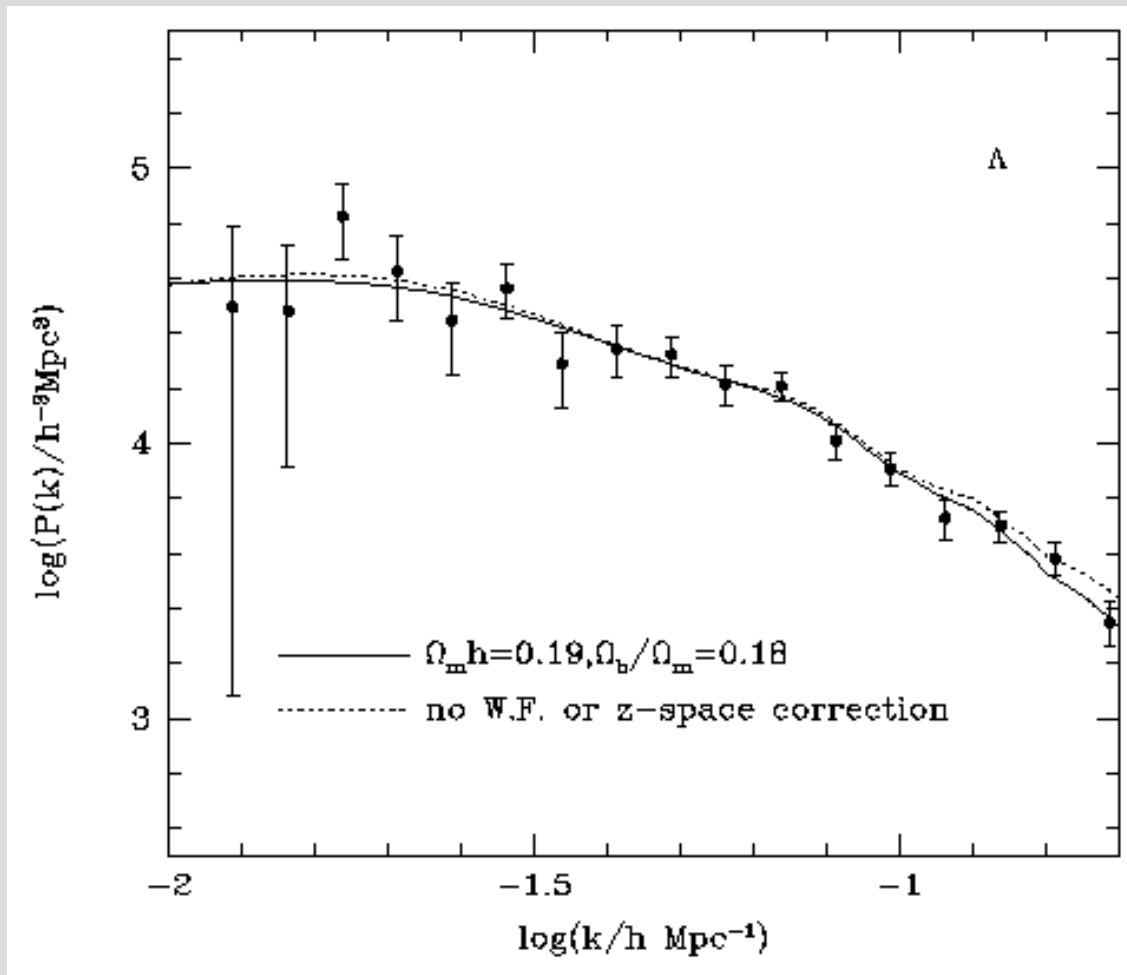


Do QSOs trace:

- the large scale structure of dark matter,
- the distribution of normal galaxies, or,
- just the most overdense regions (a highly-*biased* distribution)?

We can answer this question by determining the amplitude of QSO clustering -> The 2-Point Correlation Function (or P.S.)

The QSO power spectrum



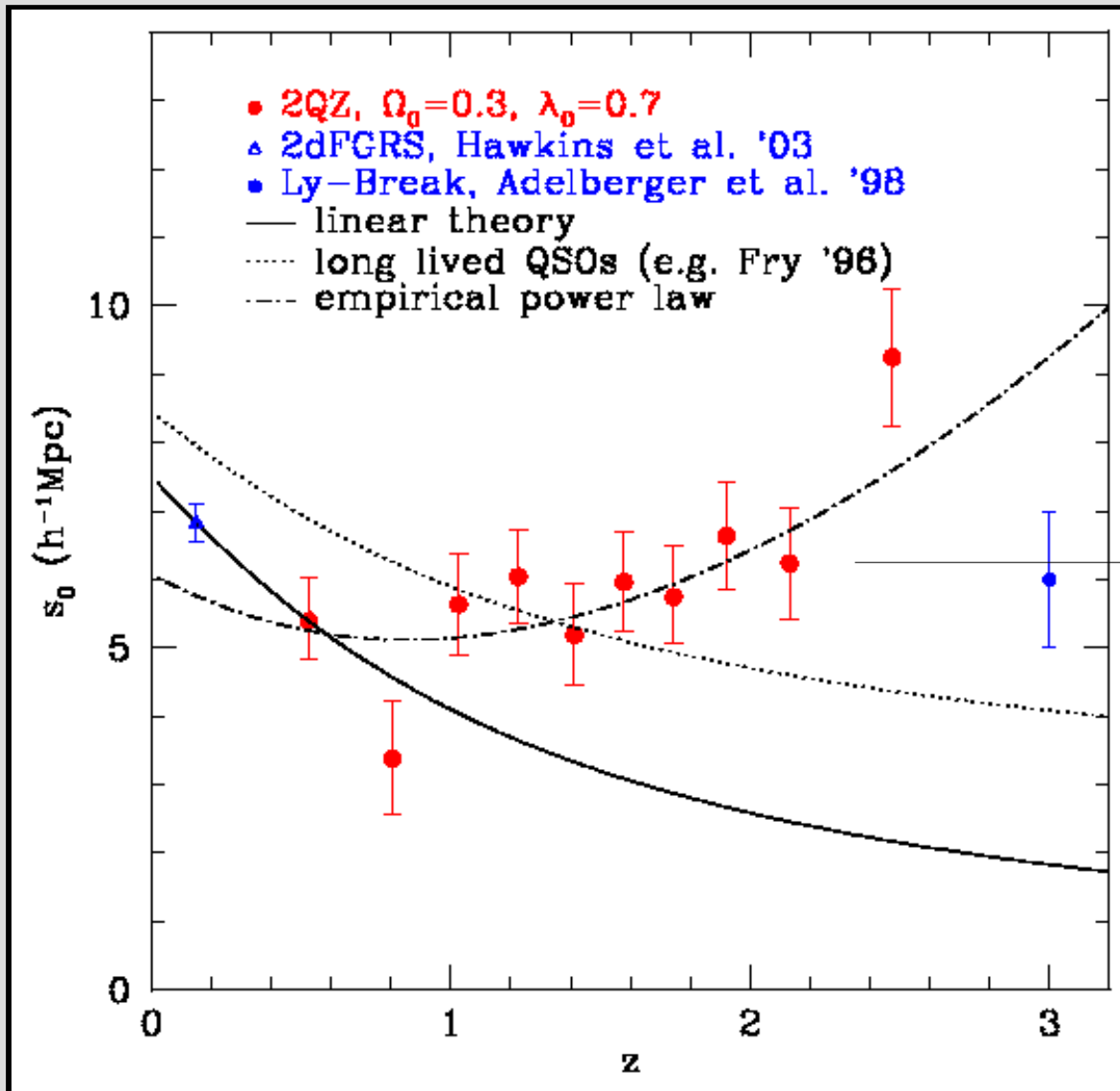
Fitting possible
to $\sim 500 h^{-1}\text{Mpc}$.

$$\Gamma = 0.13 \pm 0.02$$

Γ

Γ (shape parameter of
the power-spectrum)

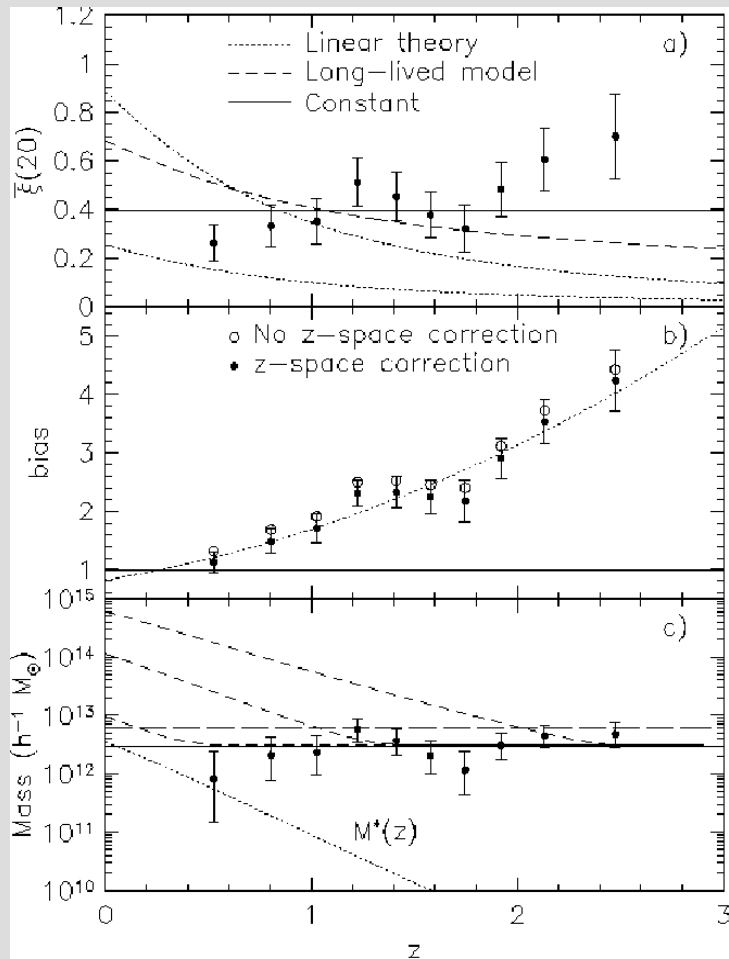
Study Large Scale Structure



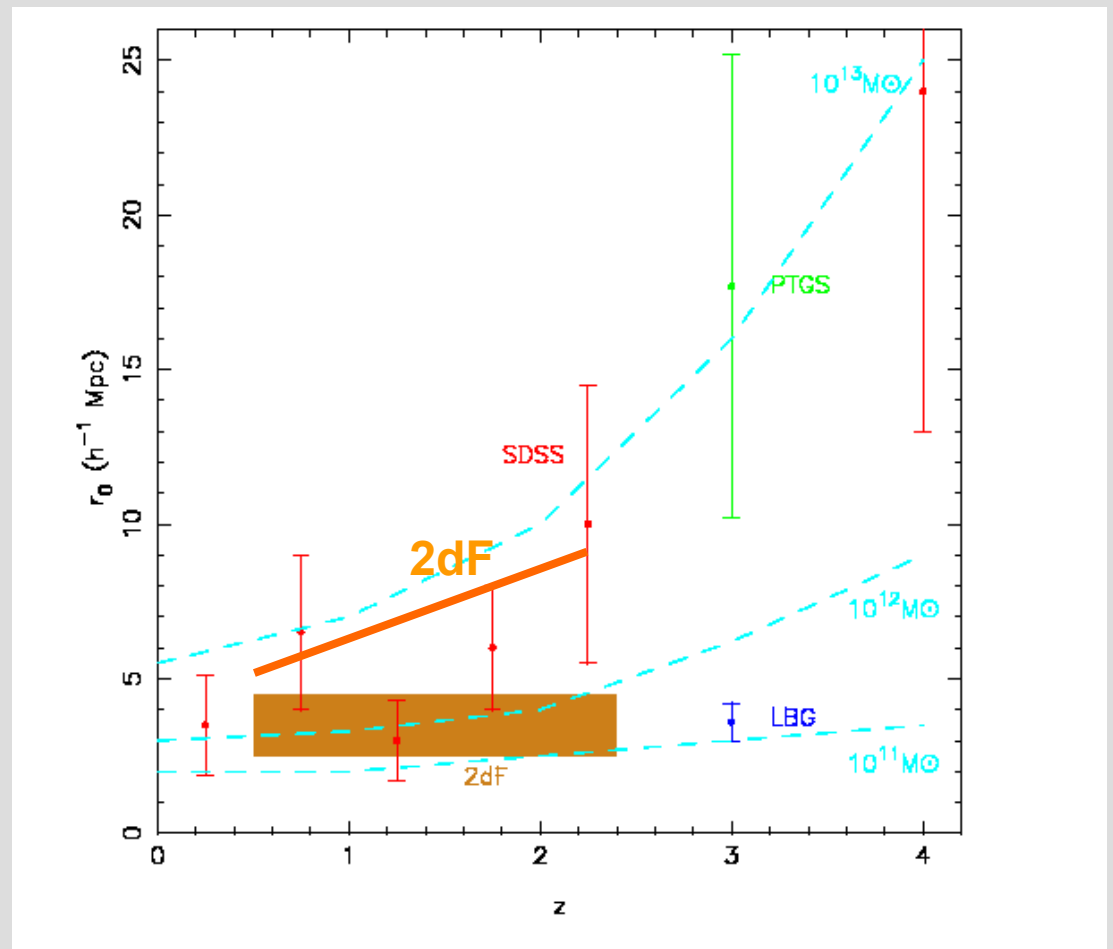
Clustering evolution

Clustering is constant or even decreases?

The QSO power spectrum



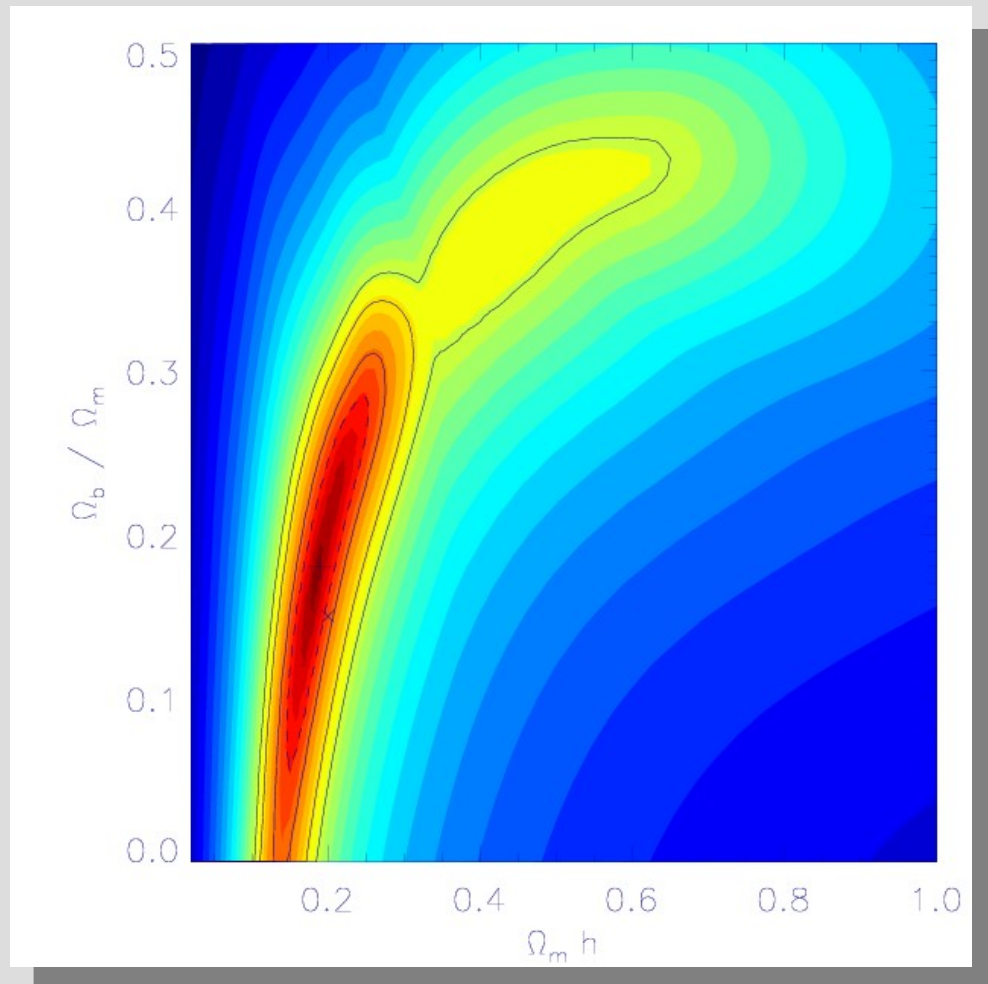
Croom et al. 2004



Fan et al.

Decreasing bias \rightarrow upper limit to lifetime of QSOs 6×10^8 years at $z \sim 2$

Cosmological Parameters



(from z-space distortions)

$$\Omega_b / \Omega_m = 0.18 \pm 0.1$$

$$\Omega_m h = 0.19 \pm 0.05$$

+ 2QZ best fit

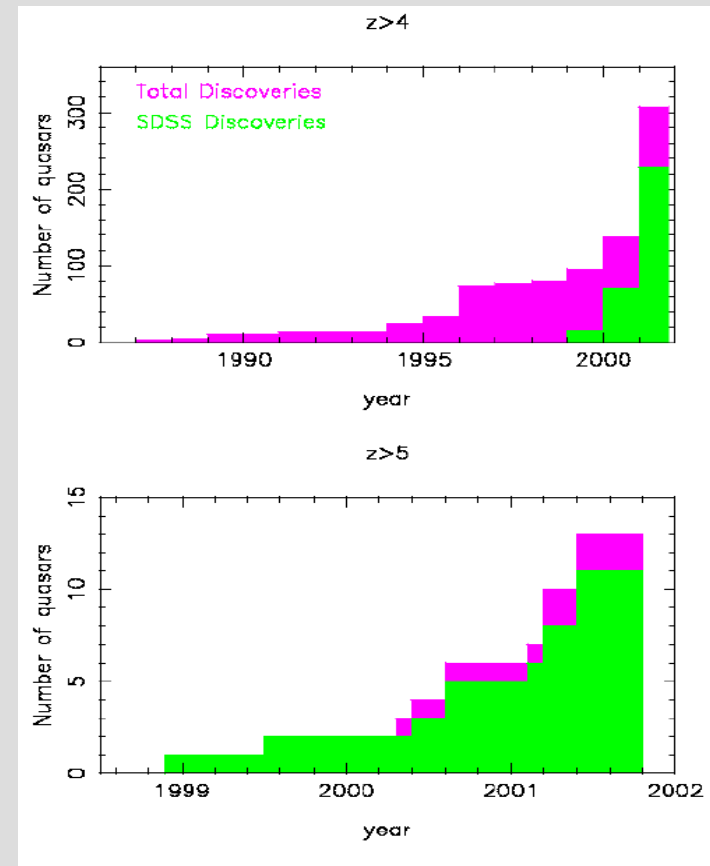
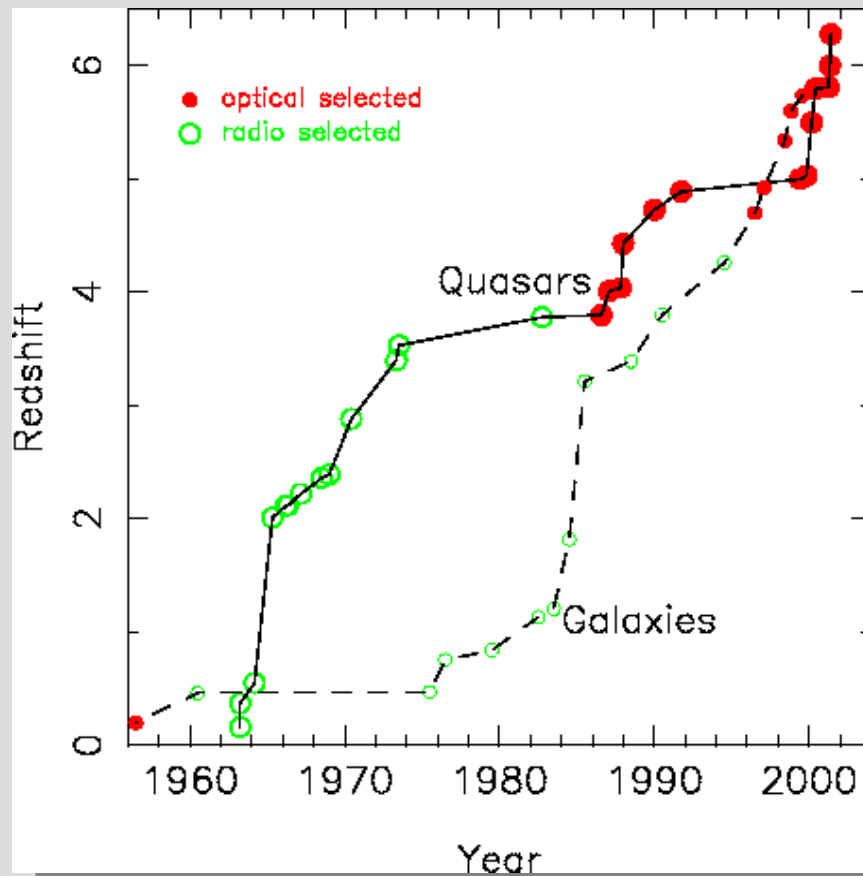
x 2dFGRS best fit

Marginal detection
of baryon wiggles
(non-zero Ω_b).

Moving to even higher redshift
to probe the IGM and the Epoch
of Reionization

New Generation of High-redshift Quasar Surveys

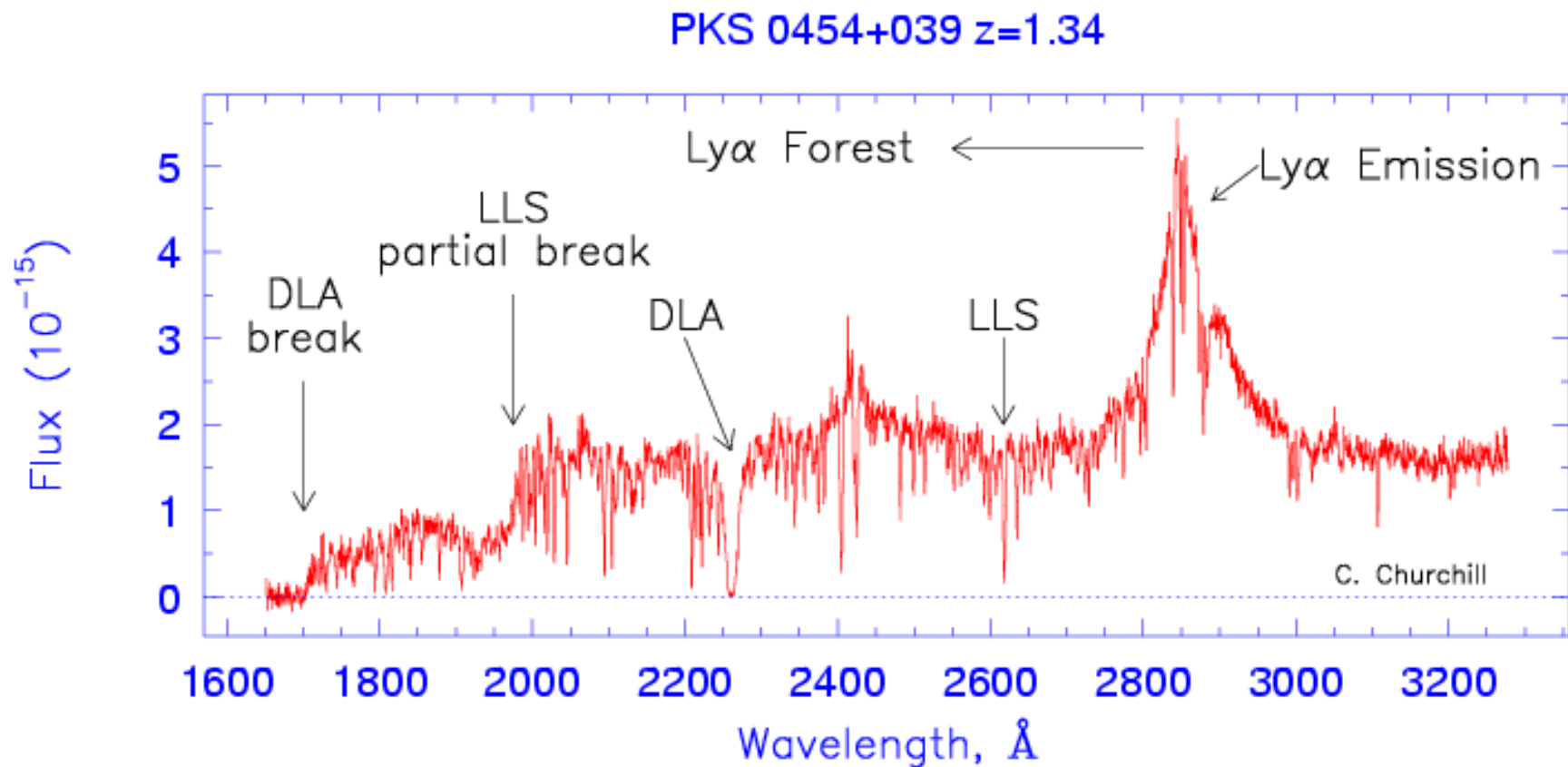
- More than 300 quasars at $z > 4$ discovered
- First detection of quasars at $z > 5$ and $z > 6$



New Generation of High-redshift Quasar Surveys

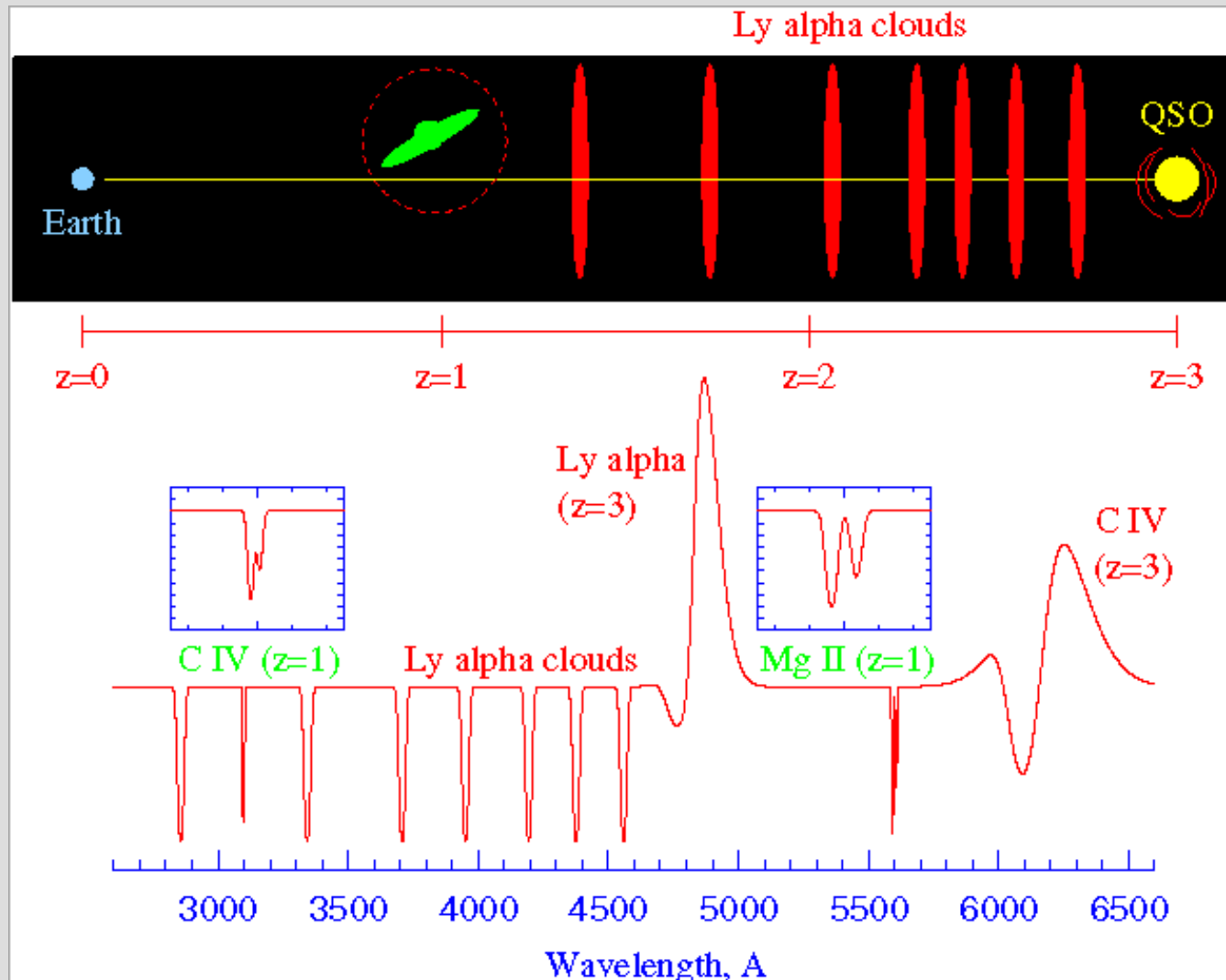
- The Study of Highest-Redshift Quasars Probes:
 - The epoch of first generation of galaxies/quasars
 - Models of black hole formation and quasar evolution
 - State of intergalactic medium
 - Ionizing background at high- z
 - History of reionization

A High Resolution Quasar Spectrum



Thanks to Max Pettini for providing the spectra

Different types of Quasar Absorption Systems



Different types of Quasar Absorption Systems

- “Lyman alpha” forest:
 - Numerous, weak lines from hydrogen clouds
 - Lyman alpha clouds are proto-galactic clouds, with low density, they are not galaxies
- “Metal” absorption lines:
 - Absorption lines from heavy elements, especially C, Si, Mg, O, Fe; others are probably there, but too weak to see.
 - Some are from intervening galaxies, but many are outside of galaxies: What are heavy elements doing there?! (winds)
- “Damped” Lyman alpha absorption lines:
 - Rare, strong hydrogen absorption
 - Coming from intervening galaxies
 - An intervening galaxies often produce both metal and damped Lyman alpha absorptions.

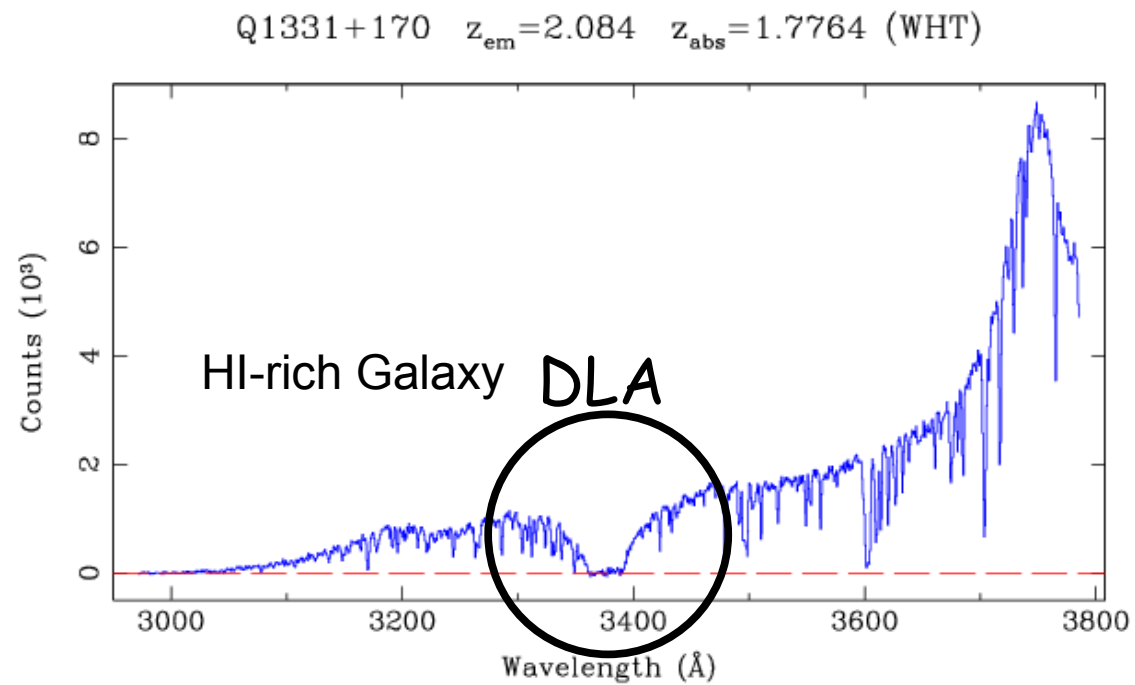
Metal Lines

- Heavy elements are produced in stars that live in galaxies; what are they doing in the IGM?
- They must have been *ejected*.
- Recall that starburst galaxies show winds, gas that is superheated by supernovae flowing out of the galaxies. This gas carries heavy elements!
- So metal lines in the IGM tell us about how many starburst galaxies have been around, and how strong their winds are.
- Remember, heavy elements can only *increase*, so it's like a fossil record of past wind deposition.

Ly- α Absorbers

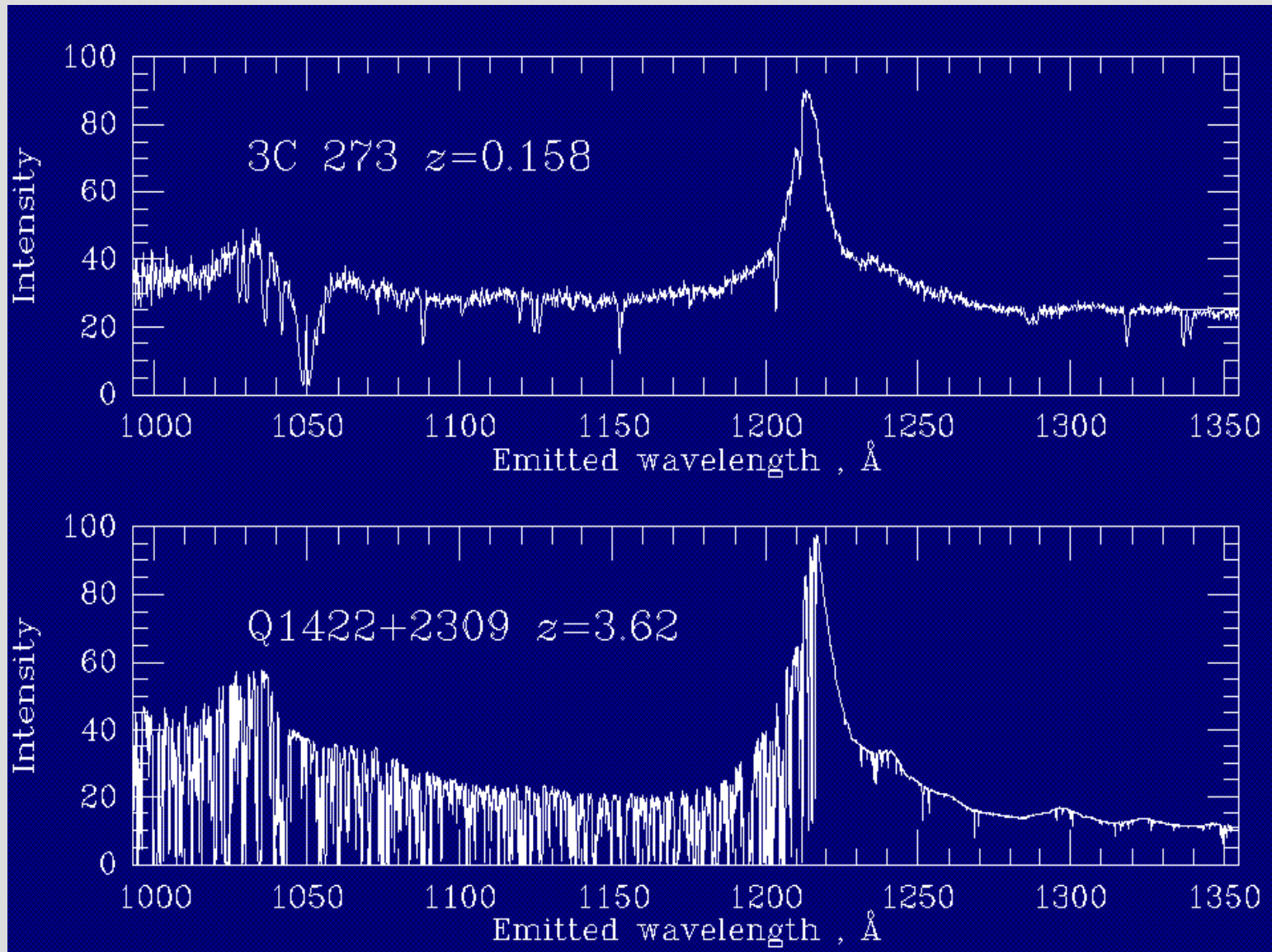
- Ly- α Forest $10^{16} < N_{\text{HI}} < 10^{20} \text{ m}^{-2}$
 - Lines are unsaturated
 - primordial < metallicity < solar
 - sizes are > galaxies
- Ly limit systems $N_{\text{HI}} > 10^{22} \text{ m}^{-2}$
 - Ly α Lines are saturated
 - N_{HI} Sufficient to absorb *all* ionising photons (i.e. like the UV-drop out galaxies)
- Damped Ly- α $N_{\text{HI}} > 10^{24} \text{ m}^{-2}$
 - Line heavily saturated
 - profile dominated by “damped” Lorentzian wings

A Damped Lyman α System



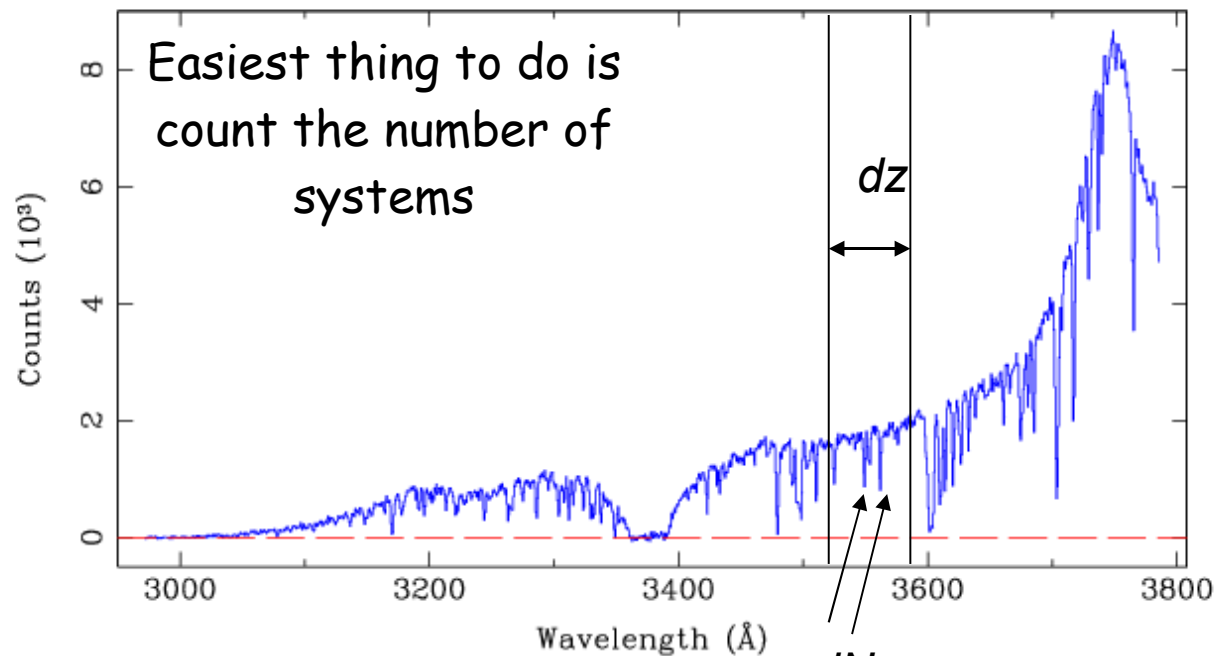
Lyman α Forest: Redshift dependence

Increase in Ly α absorbers



Numbers of Absorbing Systems as a Function of z

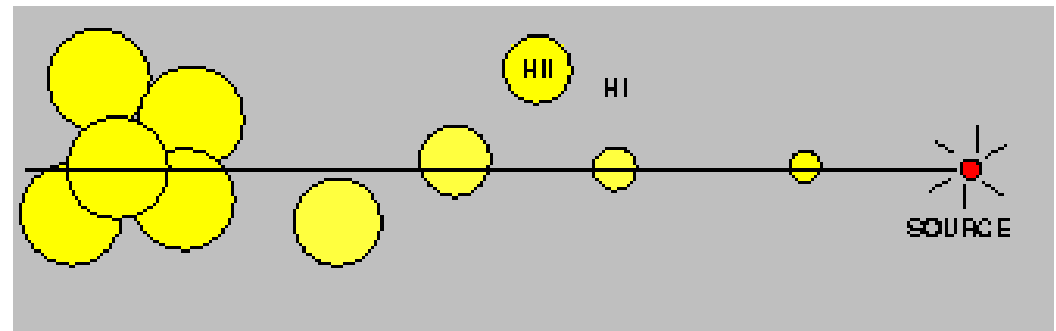
Q1331+170 $z_{\text{em}}=2.084$ $z_{\text{abs}}=1.7764$ (WHT)



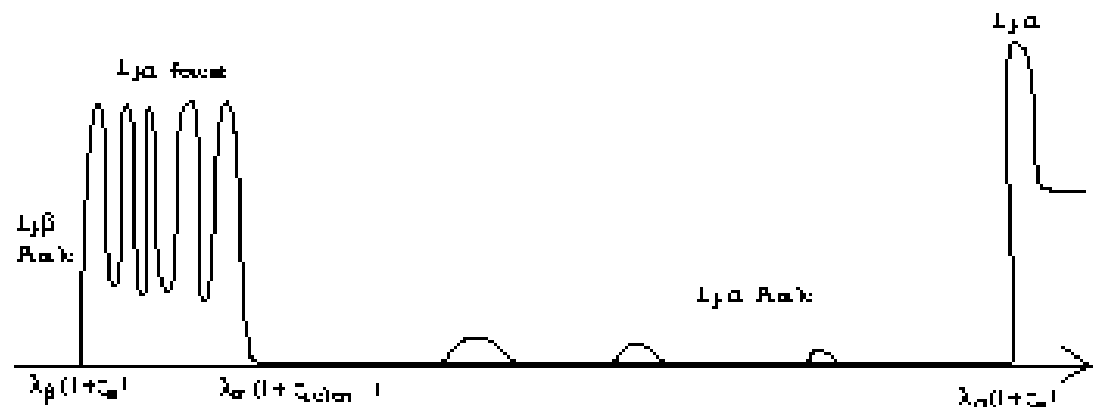
$$\frac{dN}{dz} \propto (1+z)^{2.3 \pm 0.4}$$

Gunn-Peterson effect

Neutral hydrogen regions start overlapping and cause complete ($\tau \gg 1$) Ly- α absorption blueward of the Ly- α emission line



Spectrum



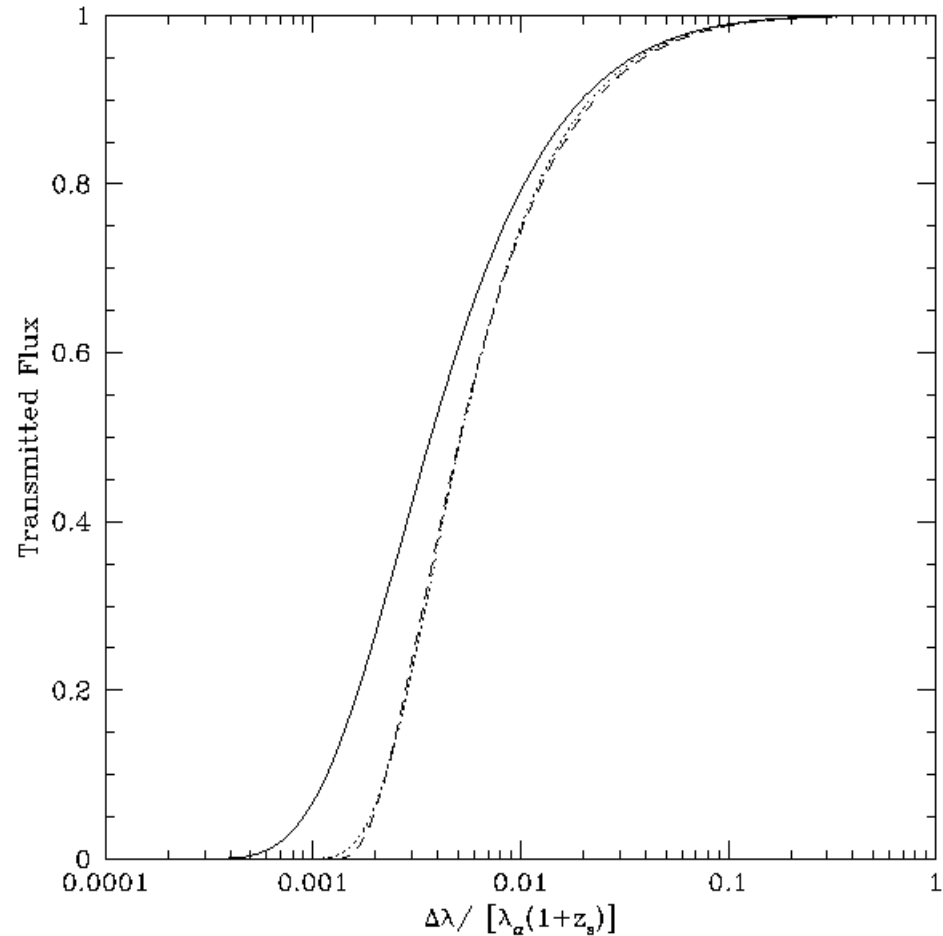
Searching for Gunn-Peterson Trough

- Gunn and Peterson (1965)
 - “It is observed that the continuum of the source continues to the blue of Ly- α (in quasar 3C9, $z=2.01$)”
 - “only about one part of 5×10^6 of the total mass at that time could have been in the form of intergalactic neutral hydrogen ”
- Bahcall and Salpeter (1965)
 - “We propose using the presence or absence of this absorption trough to obtain information on the absorption medium... over a wide range of distances
- Absence of G-P trough -> the universe is still highly ionized

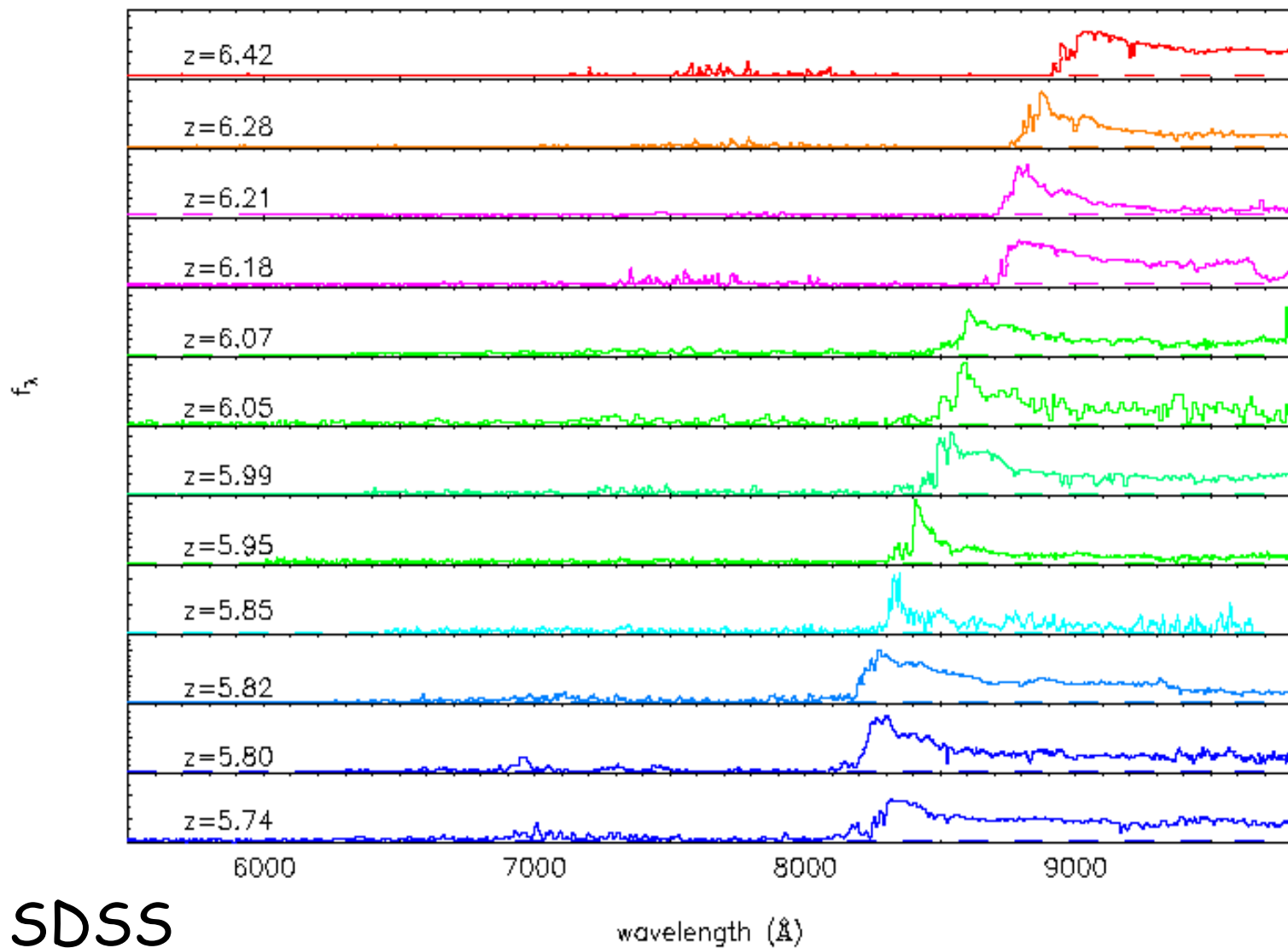
Gunn-Peterson effect

$$\tau_s = \frac{\pi e^2 f_\alpha \lambda_\alpha n_{\text{HI}}(z_s)}{m_e c H(z_s)} \approx 6.45 \times 10^5 z_{\text{HI}} \left(\frac{\Omega_b h^2}{0.03} \right) \left(\frac{\Omega_m}{0.3} \right)^{-1/2} \left(\frac{1+z_s}{10} \right)^{3/2}$$

The damping wing of the Lyman- α transition of neutral hydrogen

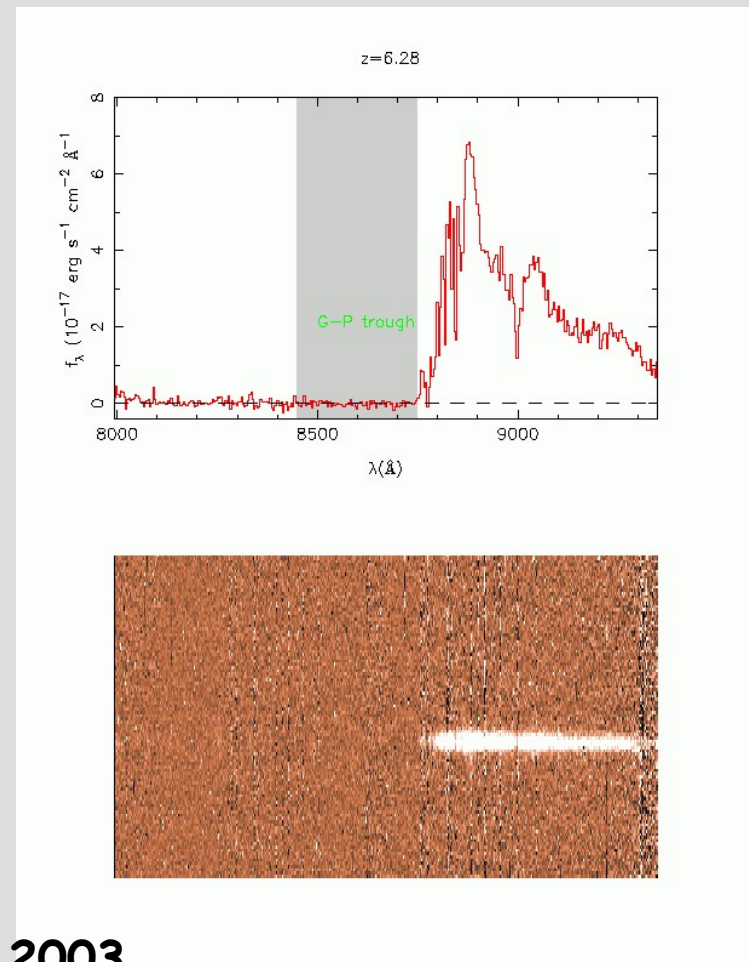
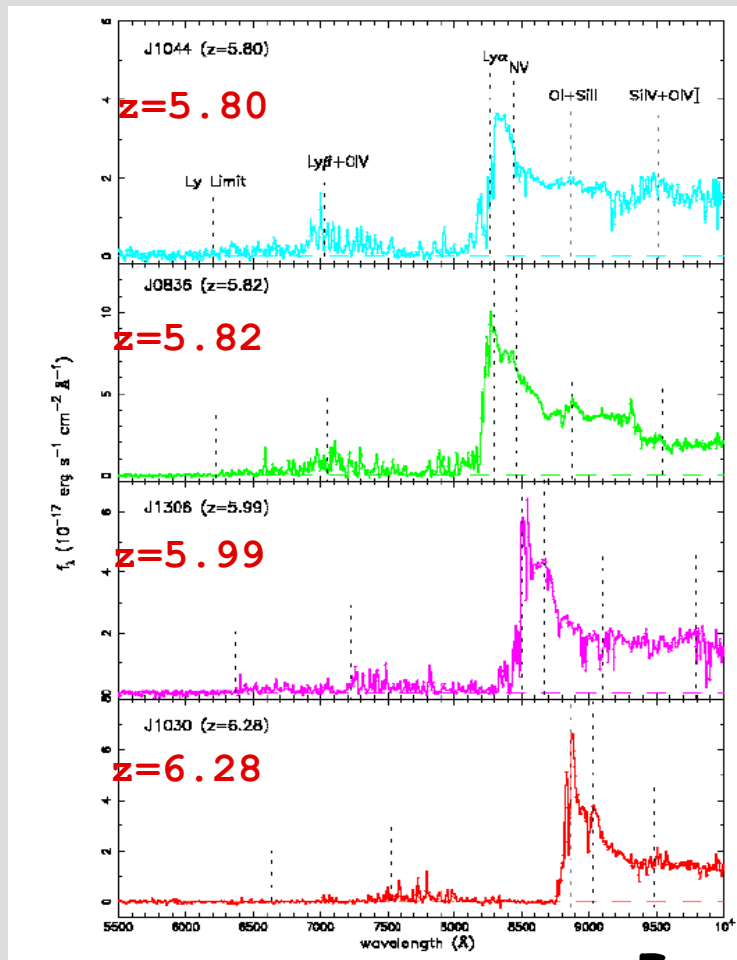


Gunn-Peterson effect: change with z

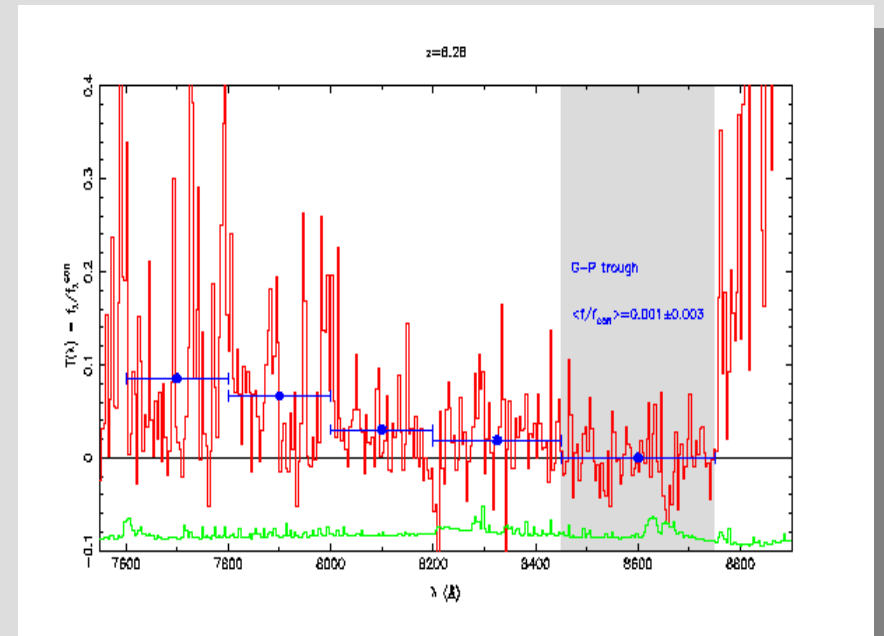
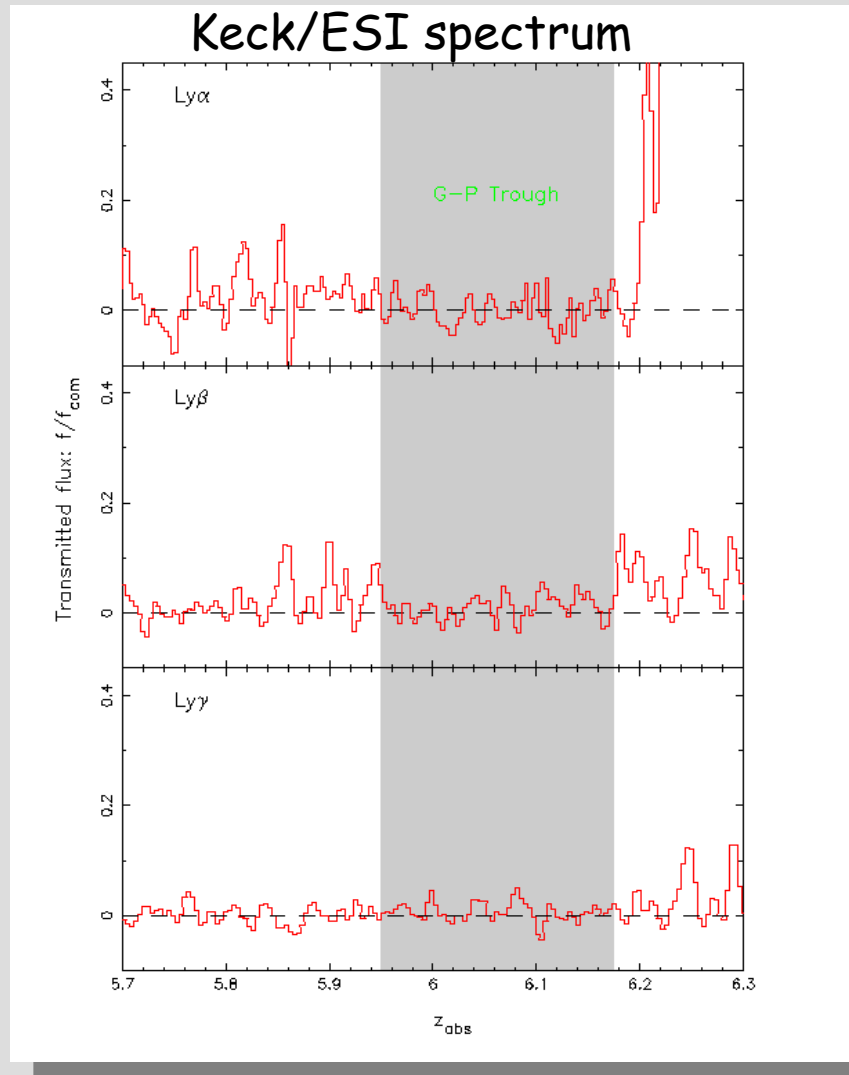


Gunn-Peterson effect: change with z

Fast reionization at $z=6.3$ \rightarrow opaque at $\lambda_{\text{obs}} < 0.9\mu\text{m}$
 $f(\text{HI}) > 0.001$ at $z = 6.3$

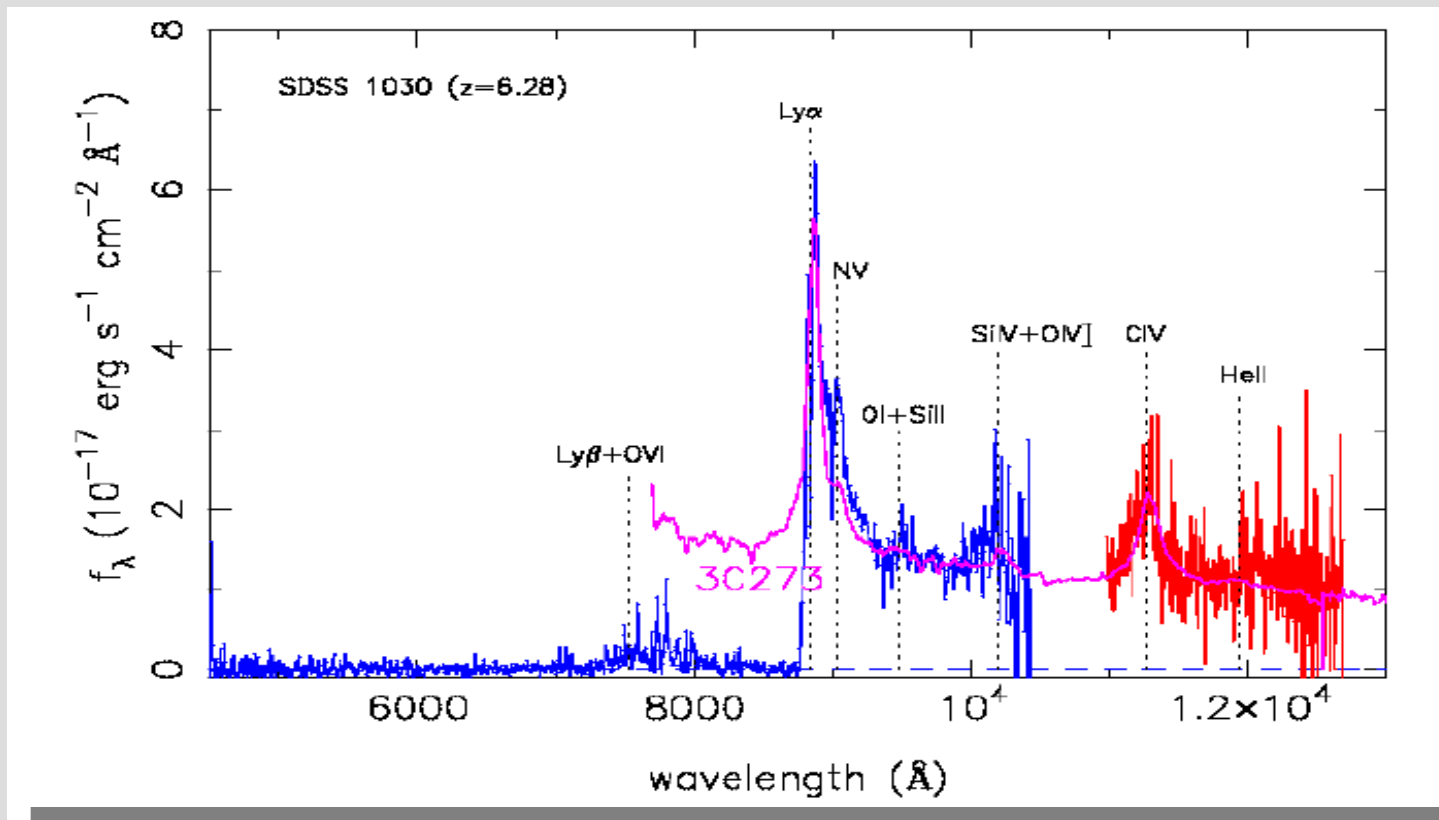


Gunn-Peterson effect: change with z



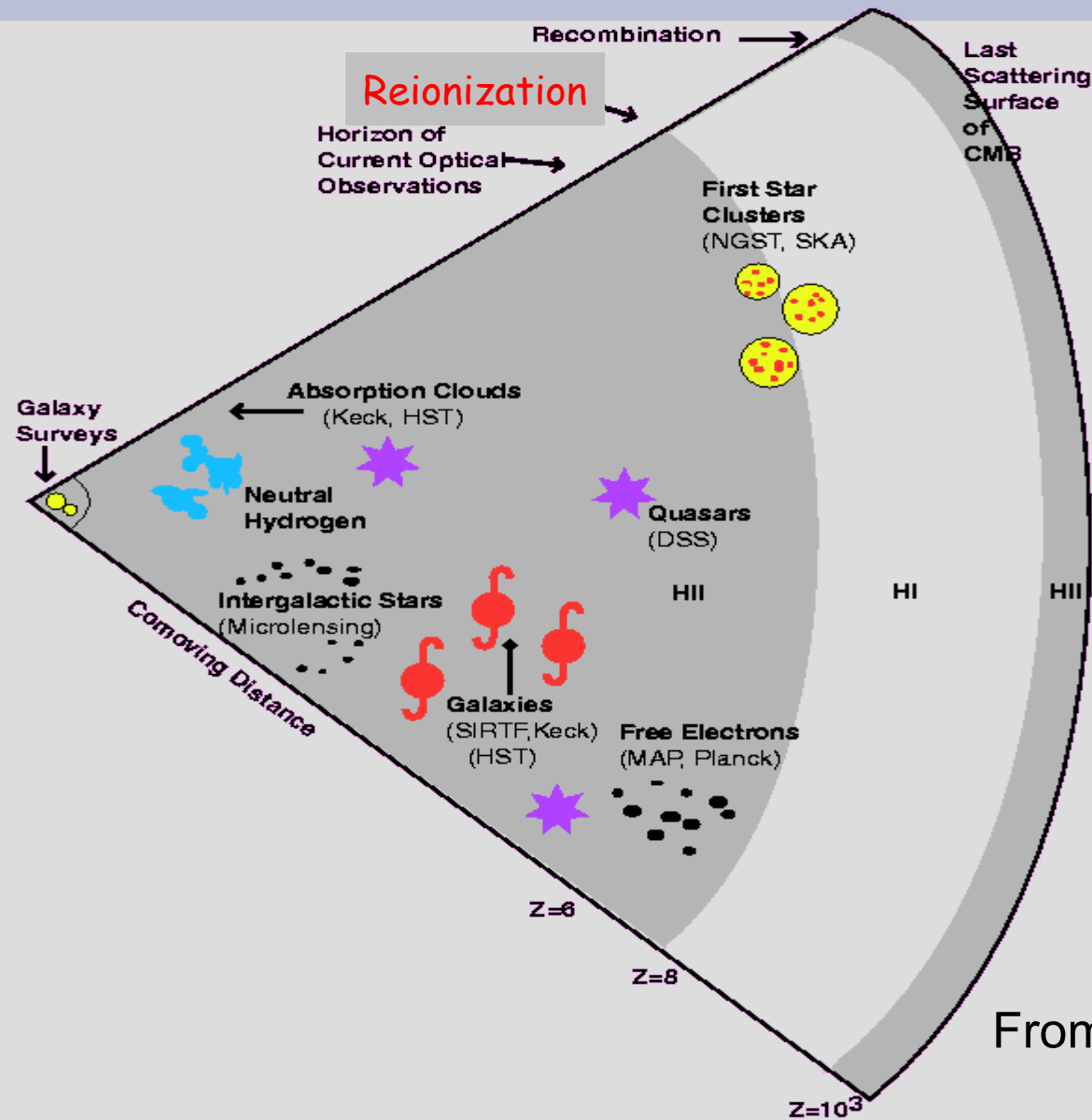
- No flux in 300 \AA region
- Flux decrement > 300
(Keck + VLT)
- G-P troughs for Ly β , γ

Gunn-Peterson effect: change with z



Fan, Narayanan, Lupton, Strauss et al.

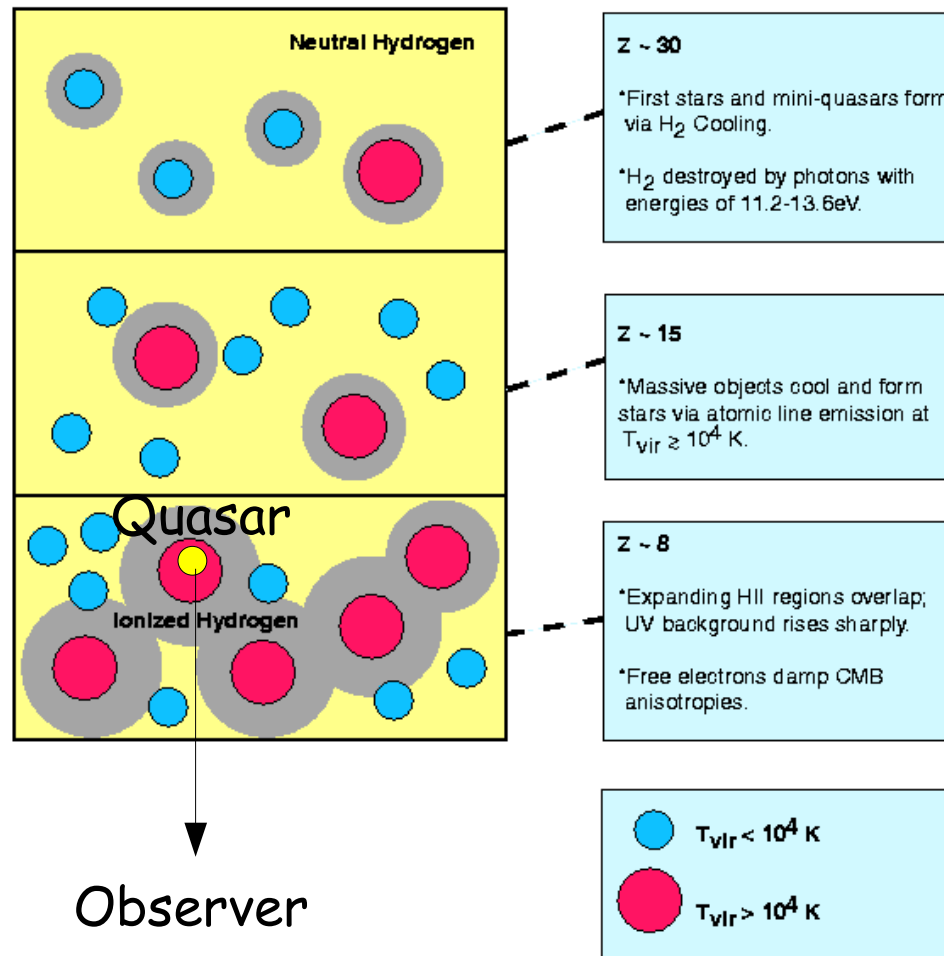
Constraining the Reionization Epoch



From Avi Loeb

Constraining the Reionization Epoch

REIONIZATION OF THE UNIVERSE



Three stages

Pre-overlap



Overlap

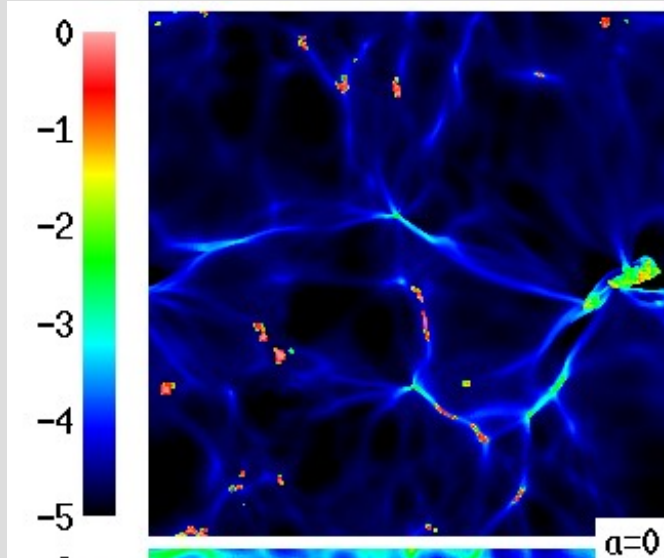


Post-overlap

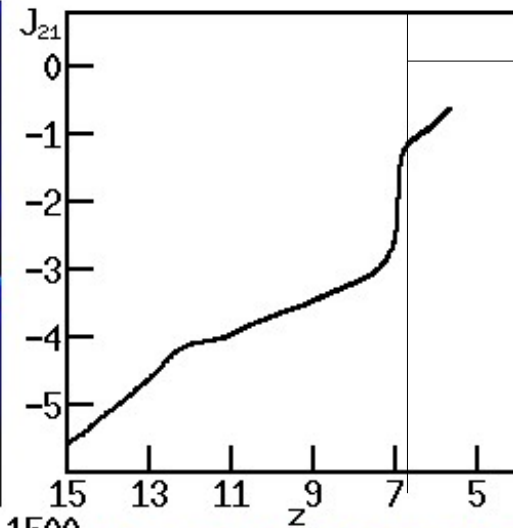
*Currently probed
by QSOs*

Constraining the Reionization Epoch

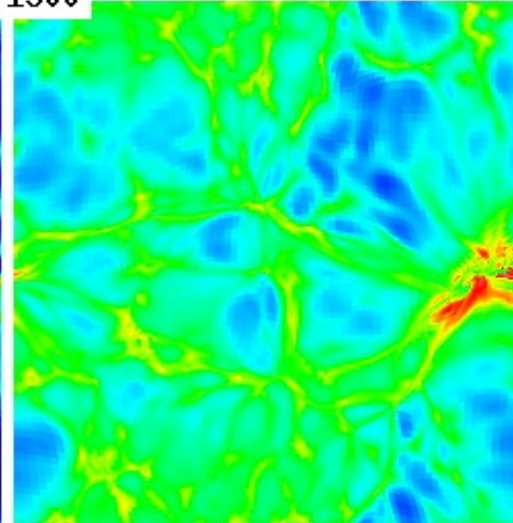
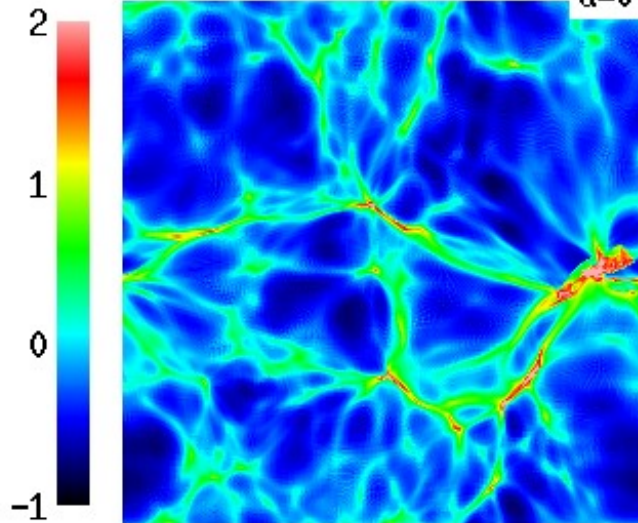
Neutral fraction



Ionizing background



Known
QSOs



Gas density

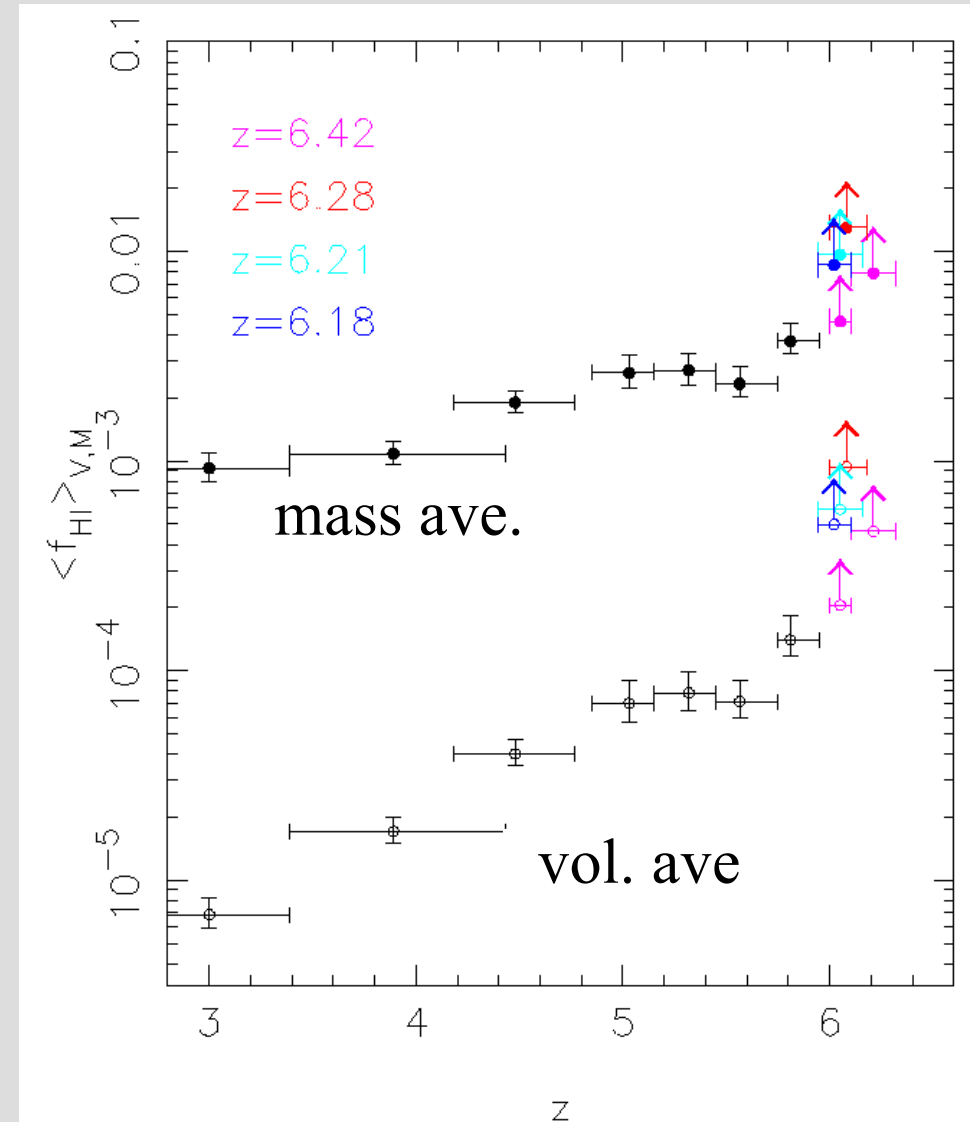
Gas temperature

Gnedin 2000

Constraining the Reionization Epoch

- Neutral hydrogen fraction
 - Volume-averaged HI fraction increased by >100 from $z \sim 3$ to ~ 6
 - Mass-averaged HI fraction $> 1\%$
- At $z \sim 6$:
 - Last remaining neutral regions are being ionized
 - The universe is $>1\%$ neutral

The end of reionization epoch??



General Summary

- Quasars can be used as probes of:
 - The Large Scale Structure
 - The Cosmological Parameters (less import. now)
 - The state of the IGM (metallicity/ionization)
- Quasars now also probe the end of the EoR through the G.P. effect.