The probability distribution of the flux in the Lyα forest

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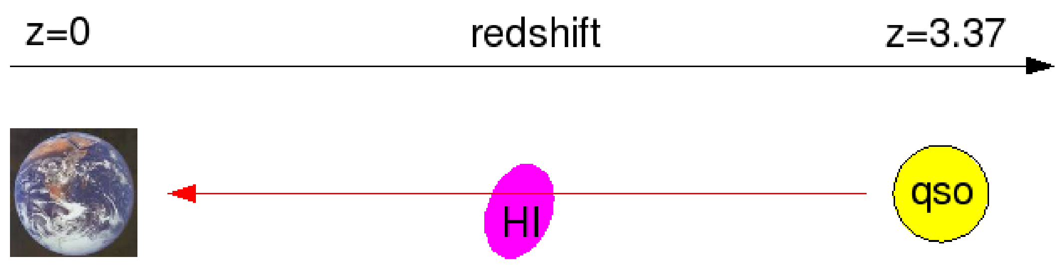
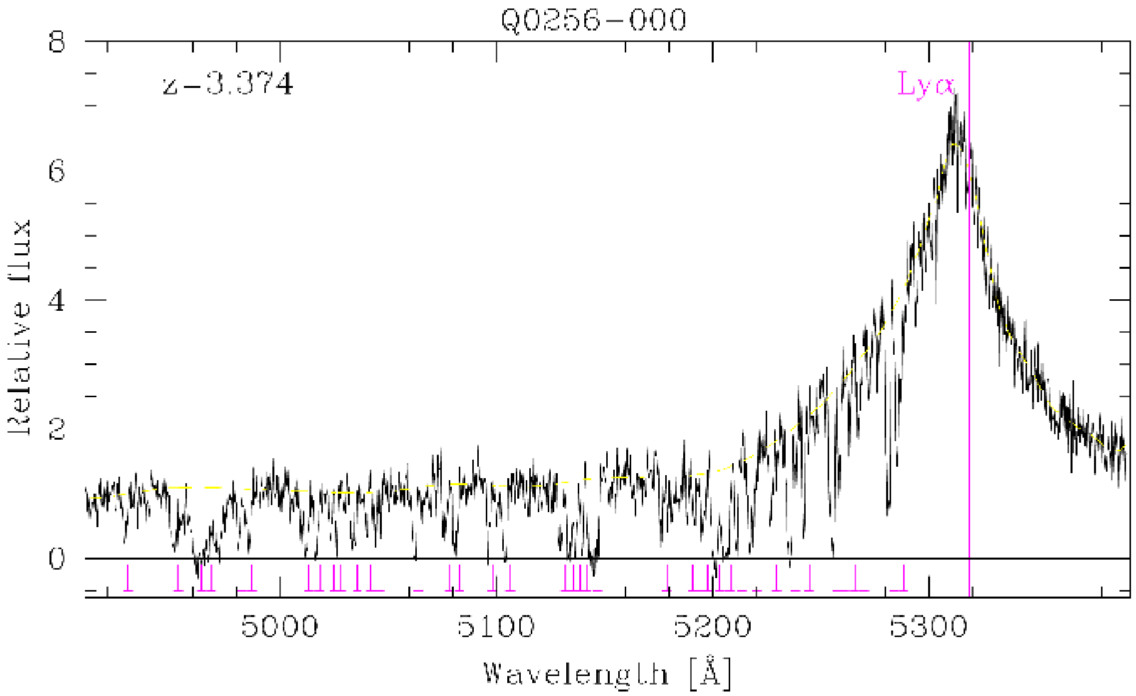
Outline

- The Lyα forest in quasar spectra
- Probing structure formation with the forest
- The probability distribution of the Lyα flux

The Lyα forest in quasar spectra

(resonant) absorption phenomenon in the foreground of quasars, $\lambda_\alpha = 1216\,\AA$

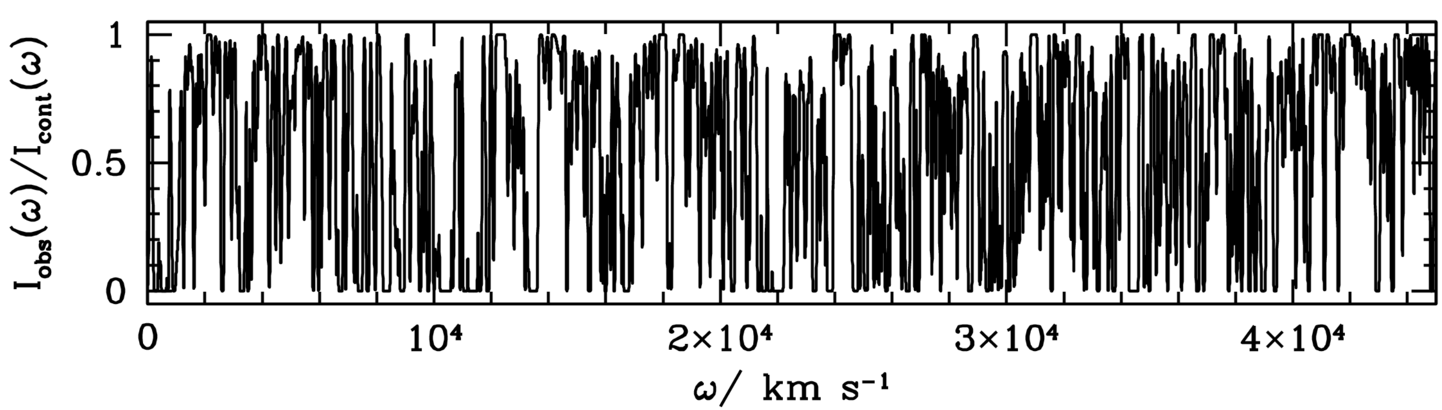




Basic observables

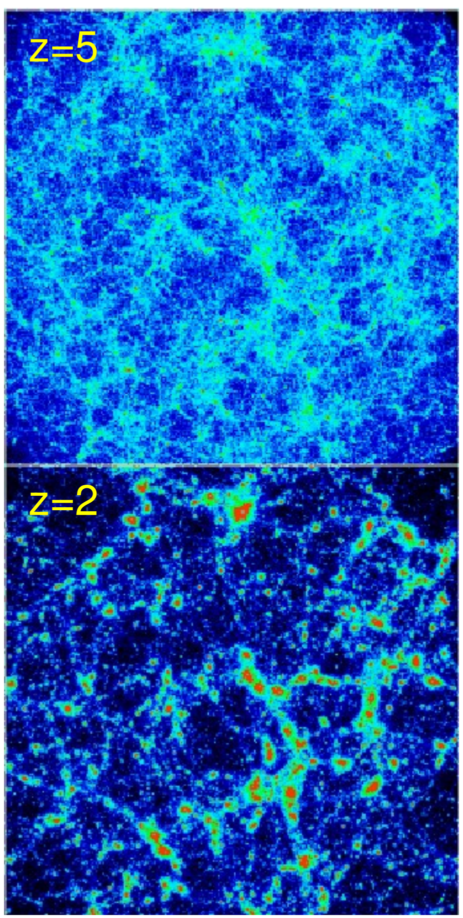
Beside the discrete **absorption lines**, the basic observable of the Lyα forest is the **transmitted flux**,

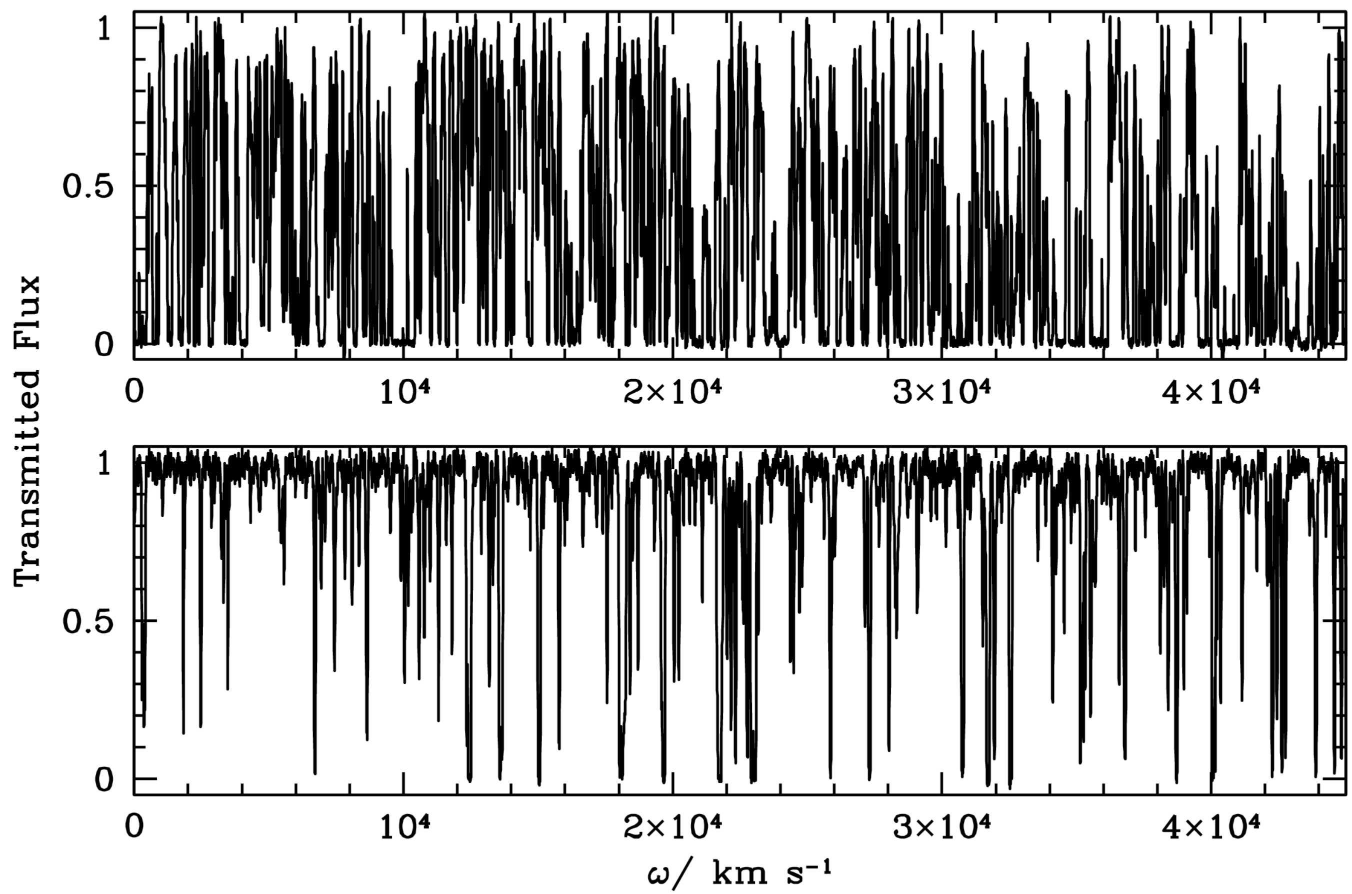
$$F(\omega) = I_{\rm obs}(\omega)/I_{\rm cont}(\omega) = \exp\left[-\tau(\omega)\right]$$



The Lyα forest in CDM cosmologies

The Lyα forest smoothly traces a cosmic web of dark matter sheets and filaments.





The Physical state of the absorbing gas

Gunn & Peterson (1965), Bahcall & Salpeter (1965)

The optical depth for Lya scattering in the resonance at redshift z

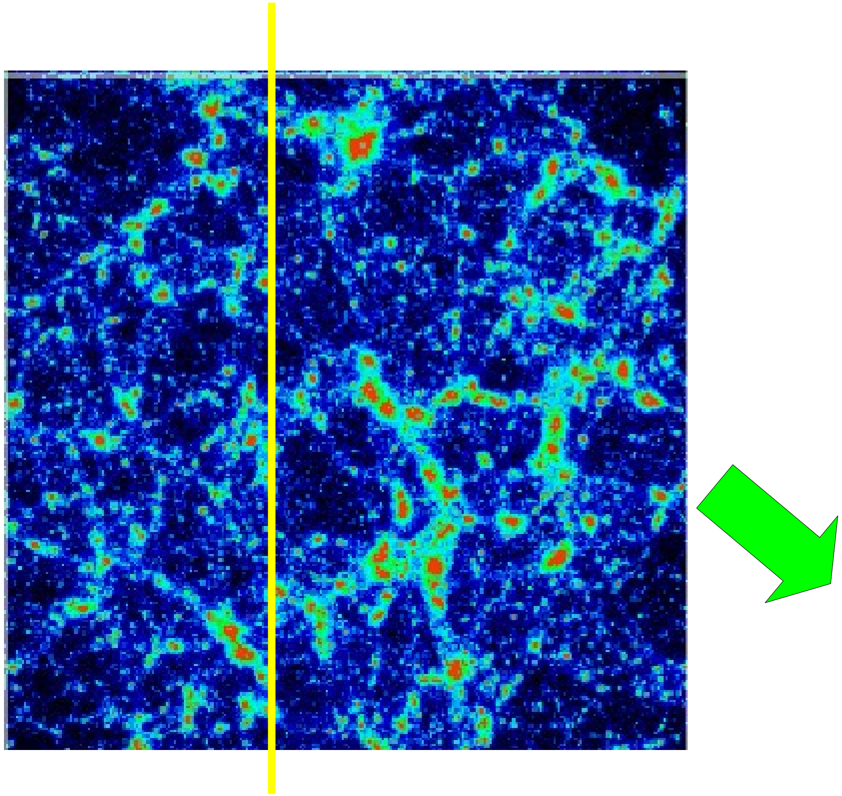
$$\tau(z) \simeq 4.15 \times 10^8 \left(\frac{n_{HI}}{n_H}\right) \left(\Omega h^2\right)^{-1/2} (1+z)^{-3/2} \left(\frac{n_H(z)}{1cm^{-3}}\right)$$

In the spectra of quasars: $\tau \sim 1 \rightarrow n_{HI}/n_H \ll 1$

The gas responsible for the Lya forest is **highly ionized**

$$z_{\rm reion} = ?$$

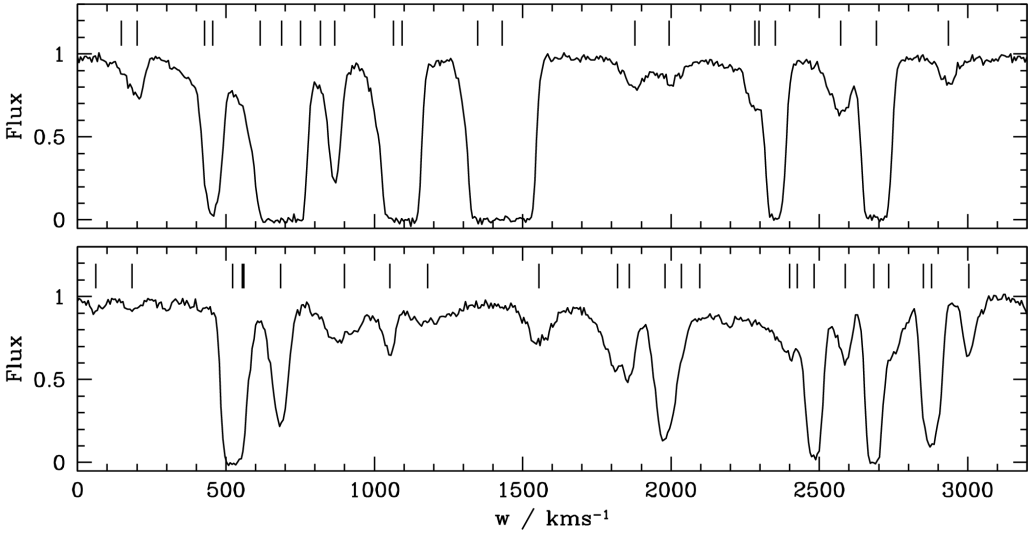
Modelling the Lyα forest



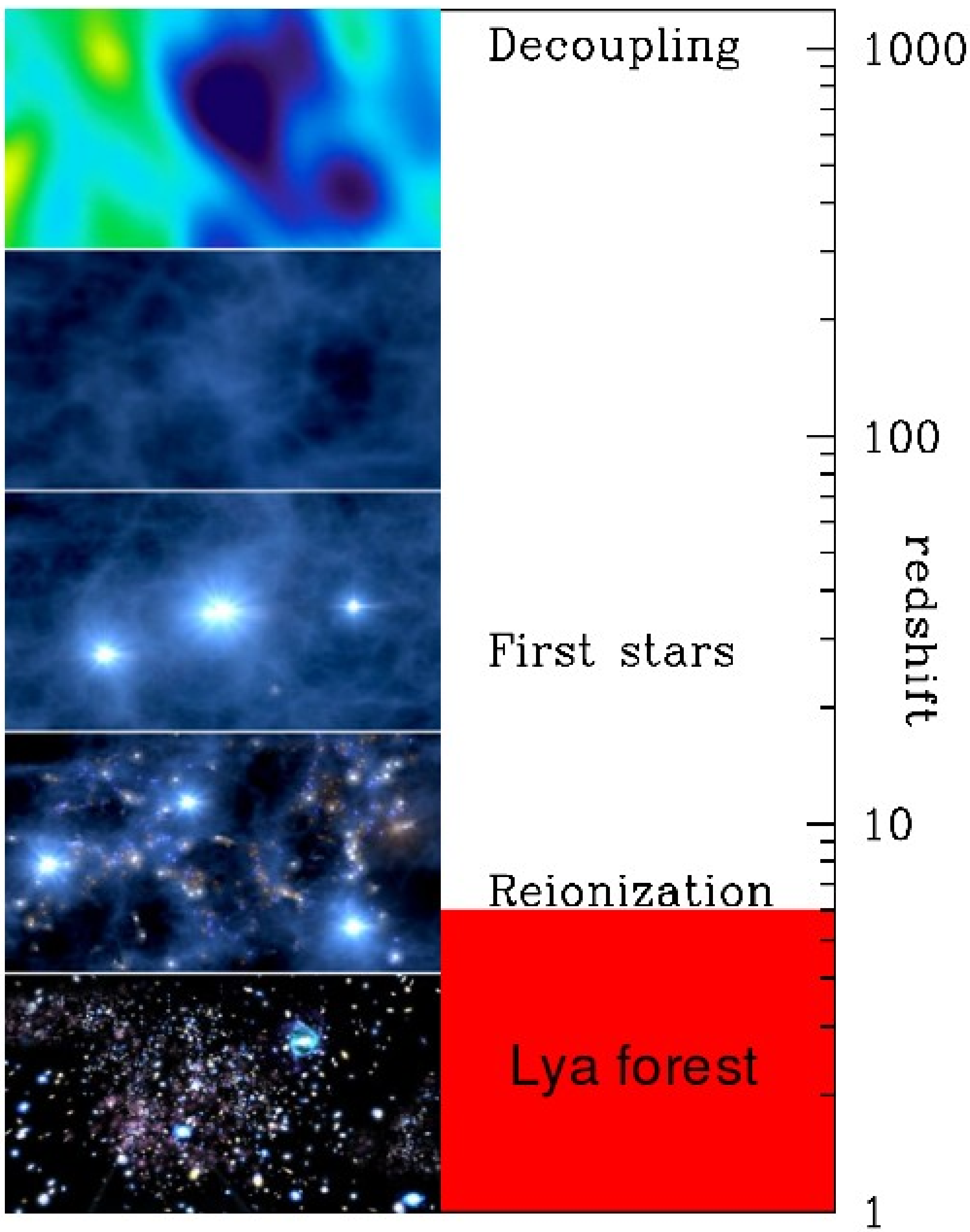
Fluctuating Gunn-Peterson Approximation:

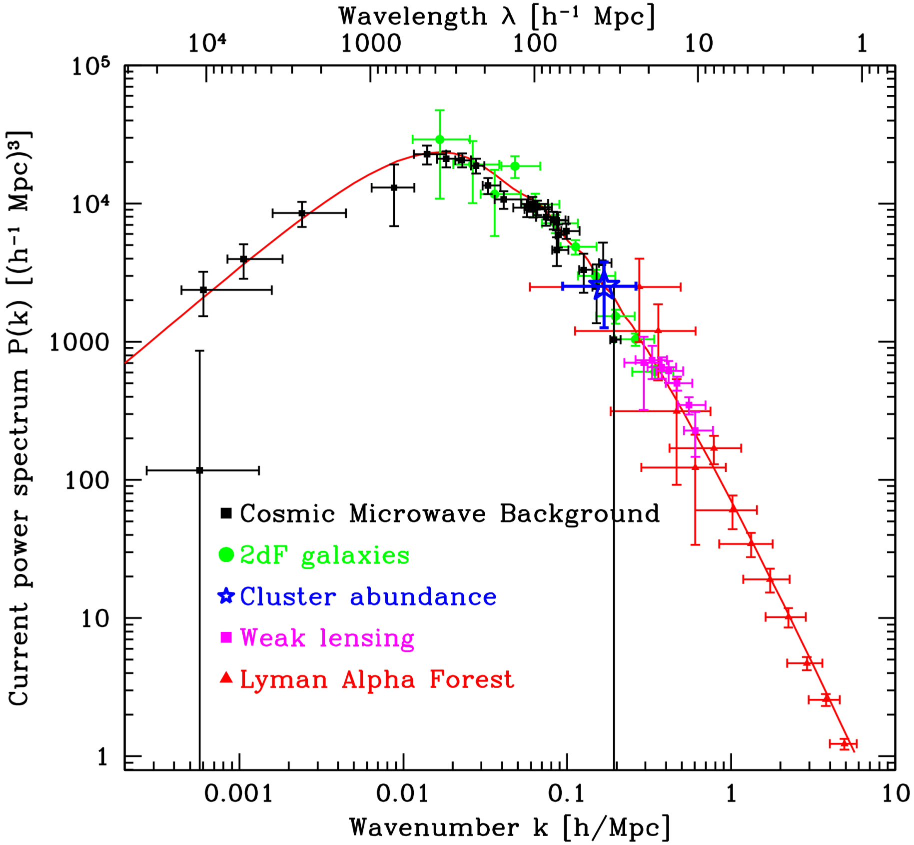
$$\tau(\omega) = \frac{c\sigma_0}{H(z)} \int_{-\infty}^{+\infty} \frac{dx}{\sqrt{\pi} b(x)} n_{HI}(x) \exp\left[-\frac{\left(\omega - x - v_{\parallel}(x)\right)^2}{b(x)^2} \right]$$

Mimic observed spectra by taking into account the noise and the instrumental resolution



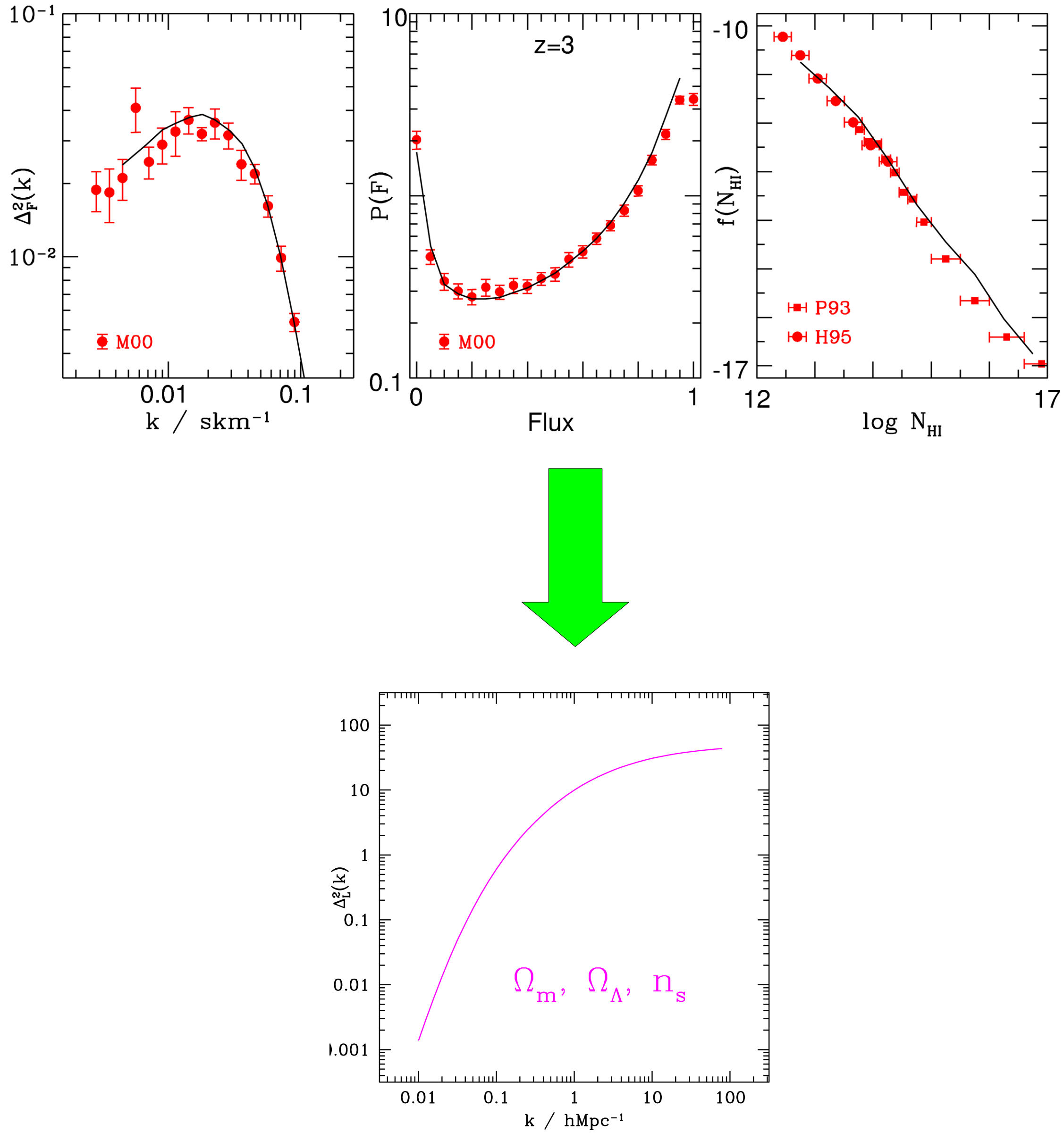
What makes the Lyα forest interesting ?





Tegmark & Zaldarriaga (2002)

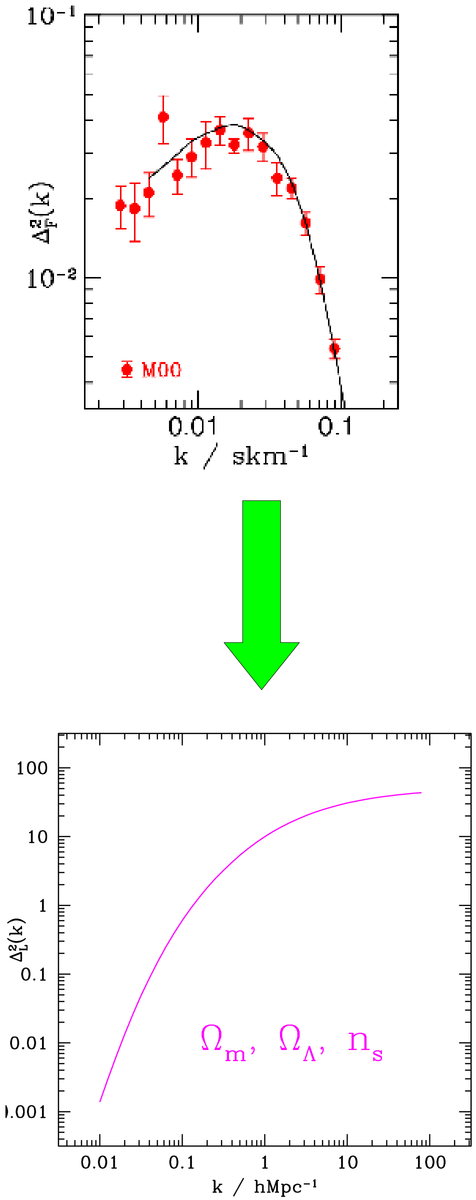
Measuring matter clustering with the Lyα forest



+ other statistics
(bispectrum etc.)

Constraints from the Lyα flux power spectrum

Croft et al. (1998, 2002), McDonald et al. (2000, 2004), Viel et al. (2004)

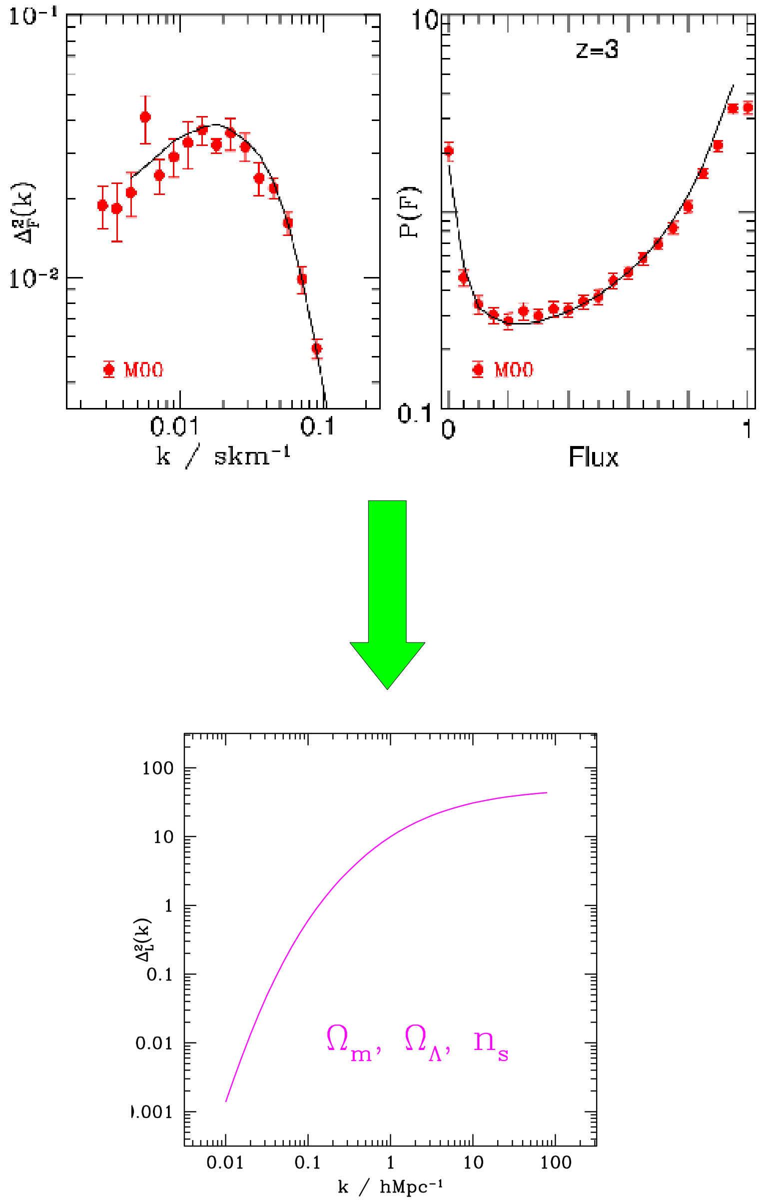


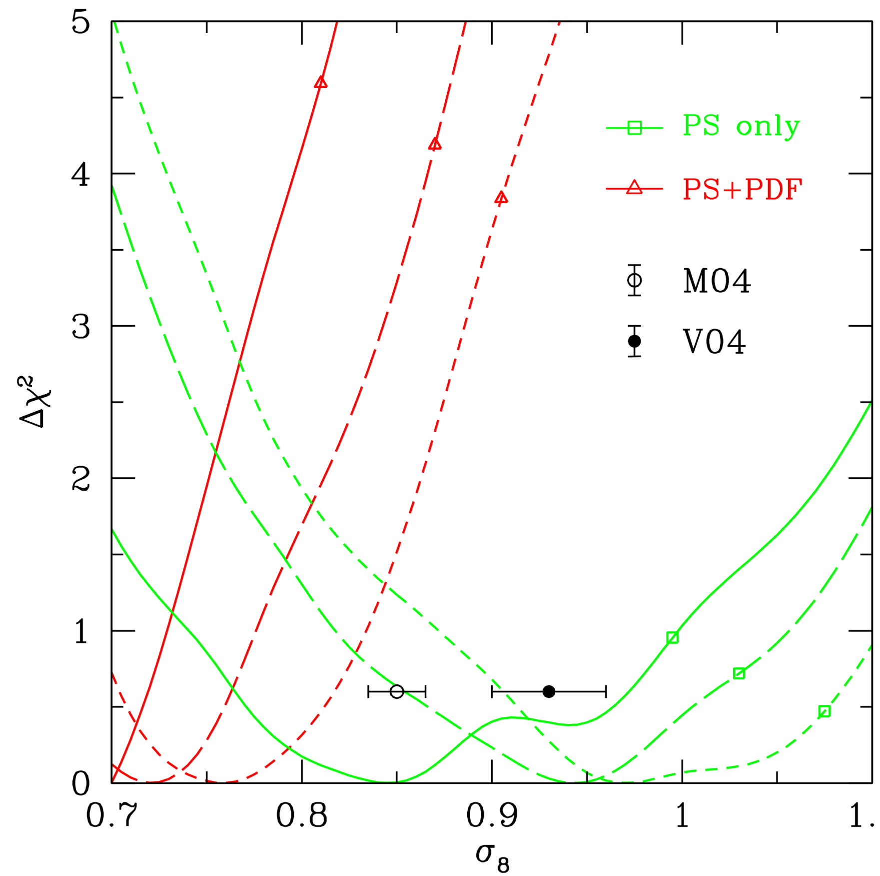
σ_8 = present-day, rms fluctuation amplitude of the density in spheres of 8 Mpc/h

$$\sigma_8 \approx 0.85 - 0.95 \pm 0.03 \pm 0.15$$

Constraints from the Lyα flux PS and PDF

Desjacques & Nusser (2005)



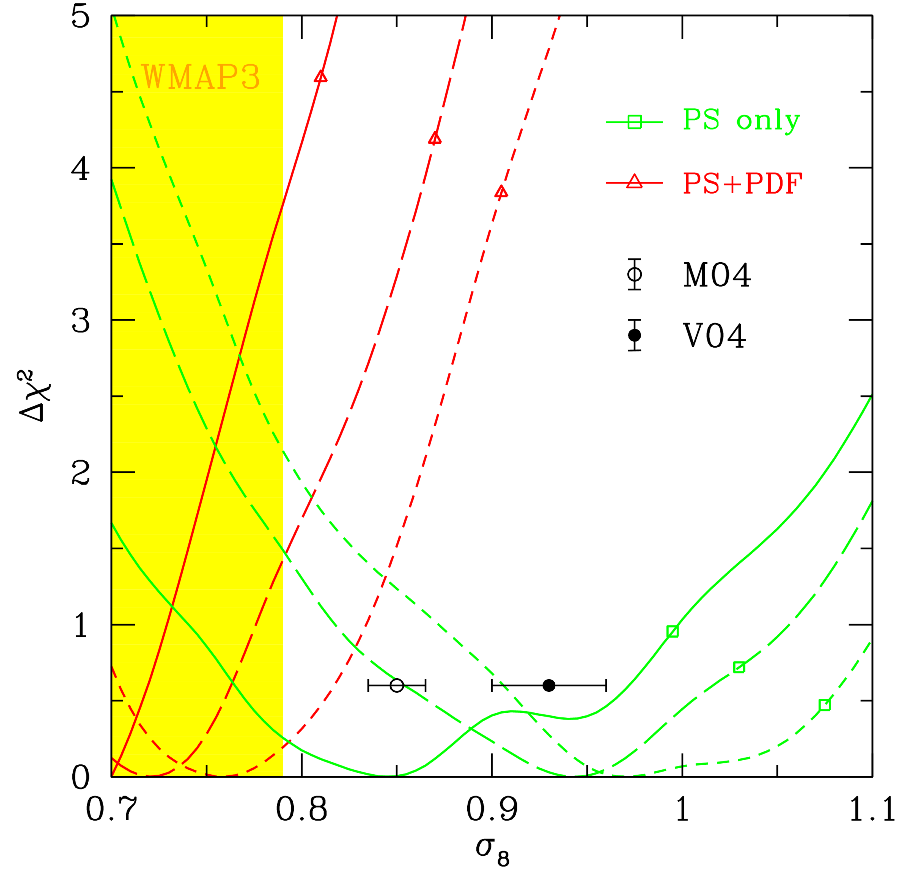


Including the PDF in the analysis has a large impact on the inferred value of the clustering amplitude

Lyα forest and WMAP 3-year data

WMAP Cosmological Parameters Model: lcdm Data: wmap		
$10^2\Omega_b h^2$	=	$2.23^{+0.07}_{-0.09}$
A	=	$0.68^{+0.04}_{-0.06}$
$A_{0.002}$	=	$0.80^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10}{}^{+1\times 10^{-10}}_{-2\times 10^{-10}}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24 \times 10^{-10}{}^{+1\times 10^{-10}}_{-2\times 10^{-10}}) \times 10^{-10}$
h	=	$0.73^{+0.03}_{-0.04}$
H_0	=	73^{+3}_{-4} km/s/Mpc
ℓ_A	=	$302.6^{+0.9}_{-1.4}$
n_s	=	$0.951^{+0.015}_{-0.019}$
$n_s(0.002)$	=	$0.951^{+0.015}_{-0.025}$
Ω_b	=	$0.042^{+0.003}_{-0.005}$
$\Omega_b h^2$	=	$0.0223^{+0.0007}_{-0.0009}$
Ω_c	=	$0.20^{+0.02}_{-0.04}$
Ω_Λ	=	$0.76^{+0.04}_{-0.03}$
Ω_m	=	$0.24^{+0.03}_{-0.04}$
$\Omega_m h^2$	=	$0.127^{+0.007}_{-0.009}$
σ_8	=	$0.74^{+0.05}_{-0.06}$
$\sigma_8\Omega_m^{0.6}$	=	$0.31^{+0.04}_{-0.05}$
A_{SZ}	=	$0.99^{+0.92}_{-0.99}$
t_0	=	$13.7^{+0.1}_{-0.2}$ Gyr
τ	=	$0.088^{+0.028}_{-0.034}$
θ_A	=	0.595 ± 0.002 °
z_{eq}	=	3036^{+168}_{-250}
z_r	=	$10.9^{+2.7}_{-2.3}$

Spergel et al. (2006)



Systematics errors

Incorporate other statistics of the Lyα forest, e.g.

- Probability distribution (PDF)
- Bispectrum
- Line statistics

Understand

- Systematics in the measurements
  - continuum fitting
  - metal contamination
- Systematics in the theoretical models
  - reionisation history
  - feedback from galaxies/quasars
  - numerical modelling

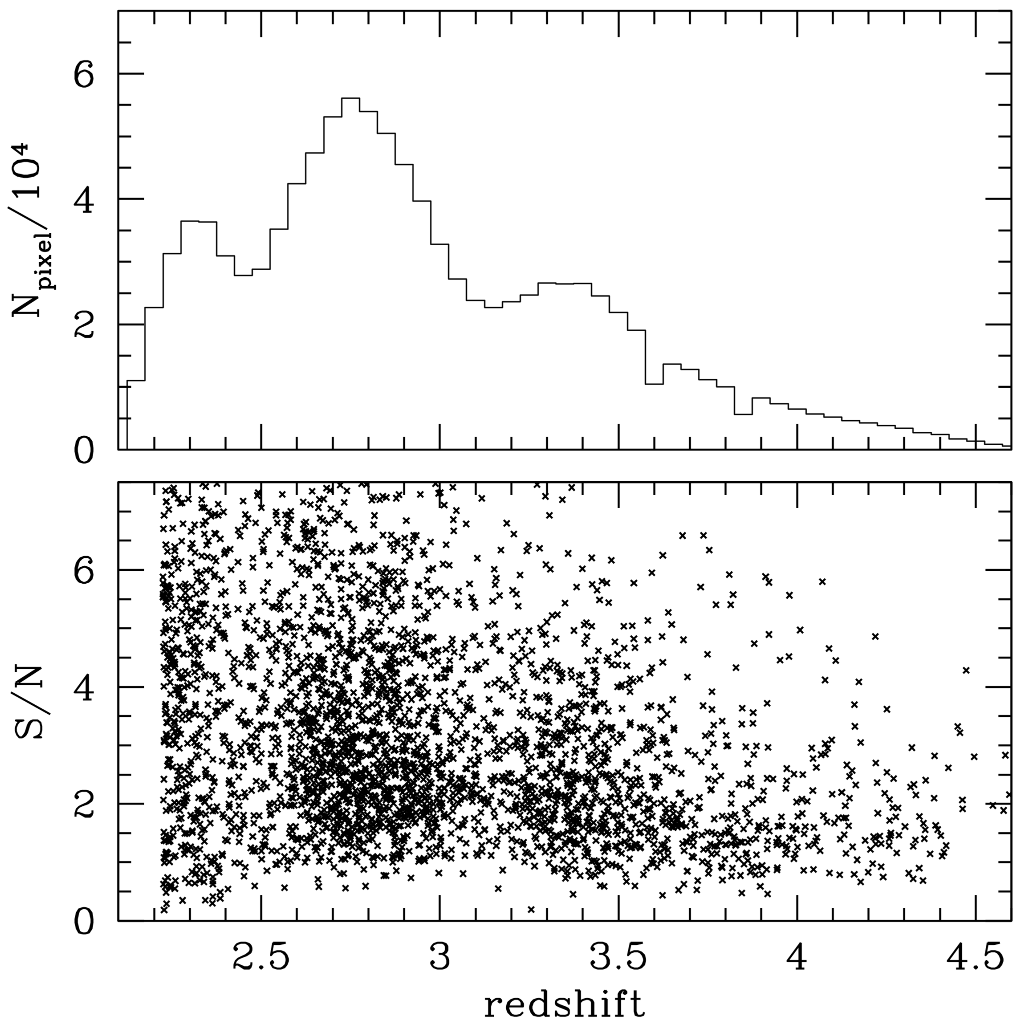
The PDF of the Lyα flux from a sample of SDSS quasars

Use the probability distribution (PDF) of the Lya transmitted flux to understand better the systematics associated with (large) sample of low resolution quasar spectra such as SDSS

The data

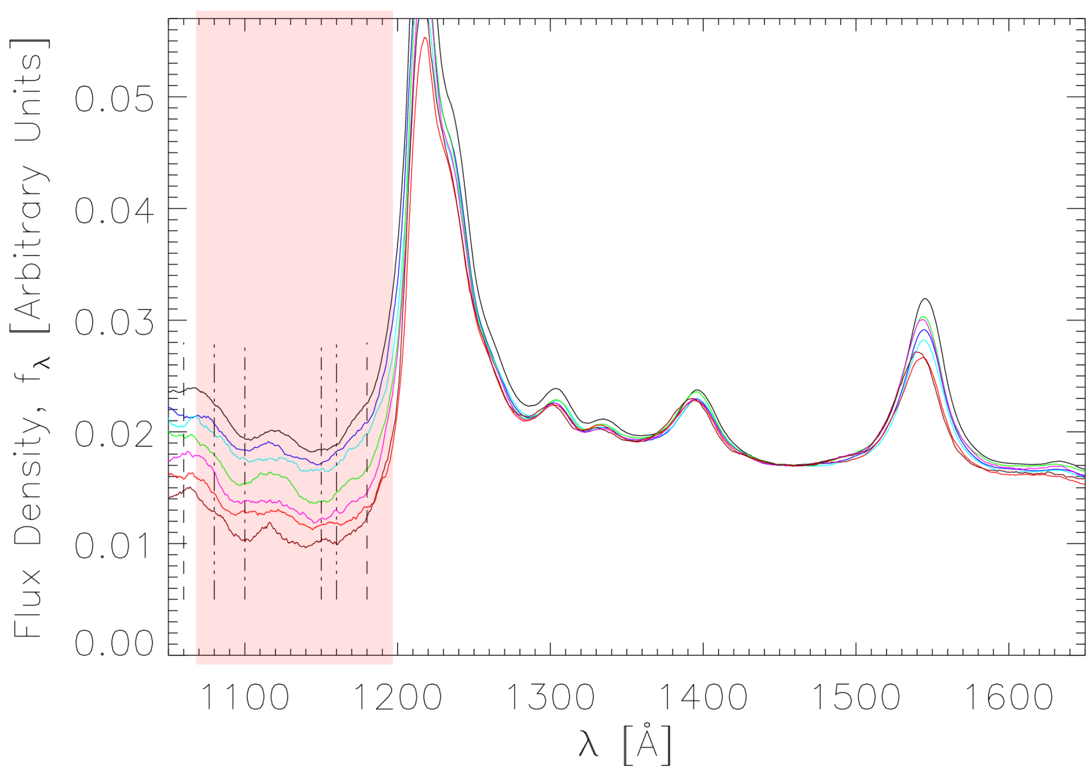
A sample of 3492 quasars included in the SDSS DR3 data release

Lyα forest : 1080 – 1160Å



Continuum fitting: hint from composite spectra

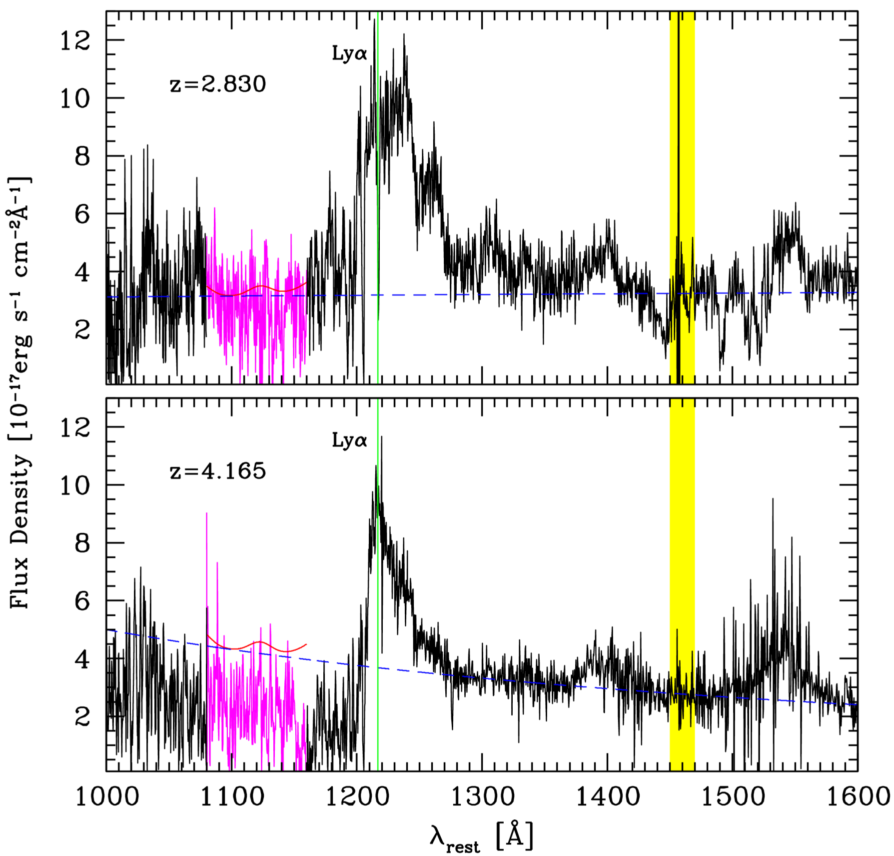
Composite spectra: quasar continuum ≈ powerlaw + emission lines



Bernardi et al. (2003)

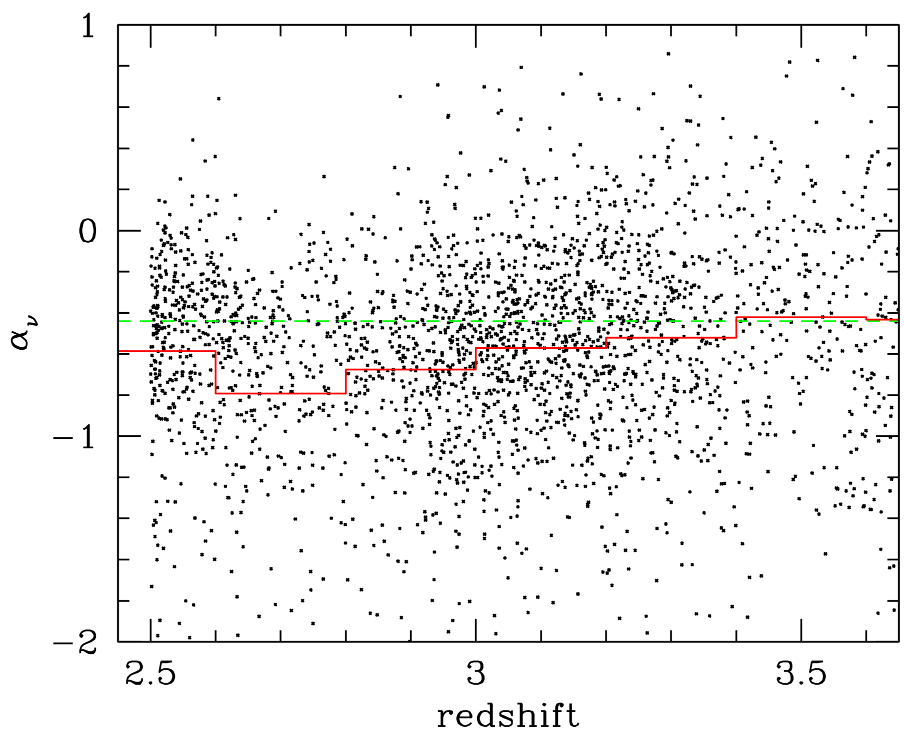
The distribution of spectral indices

Perform a continuum fitting on a spectrum-by-spectrum basis



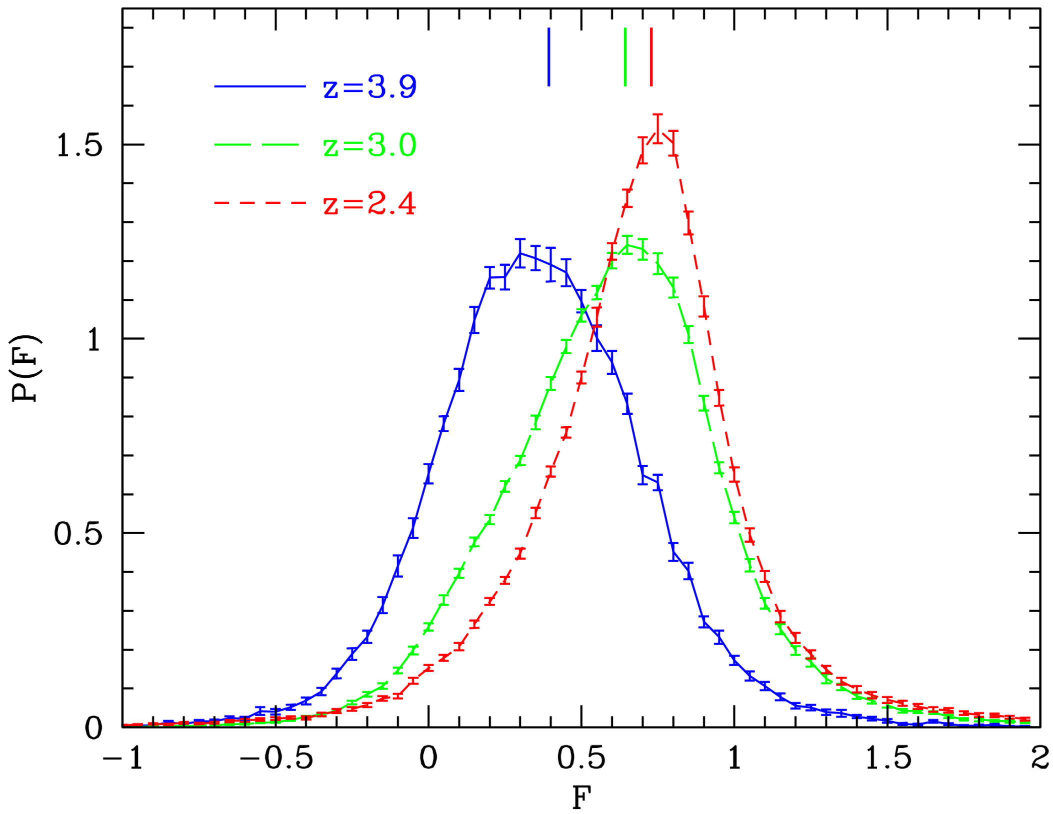
$$I_{\rm cont}(\nu) = I_0\,\nu^{\alpha_\nu} + \text{em. lines}$$

$$\langle \alpha_\nu \rangle = -0.59 \pm 0.36$$



The probability distribution of the Lyα flux

The large noise creates pixels with $F \ll 0$ and $F \gg 1$



A lognormal model for the Lyα forest

Bi et al. (1993)

The gas density and velocity are obtained from a local mapping of the linear density and velocity fields

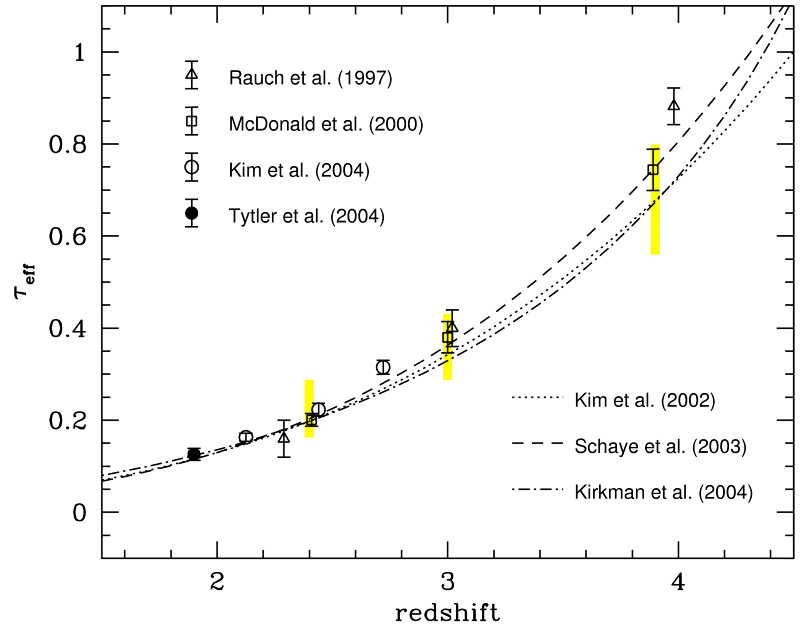
$$\delta_{\rm IGM}(x,z) = \exp\left(\delta_{\rm L}(x,z) - \sigma^2_{\rm L}(z)\right) - 1$$

$$v_{\rm IGM}(x,z) = v_{\rm L}(x,z)$$

Assume photoionization equilibrium + equation of state → HI density

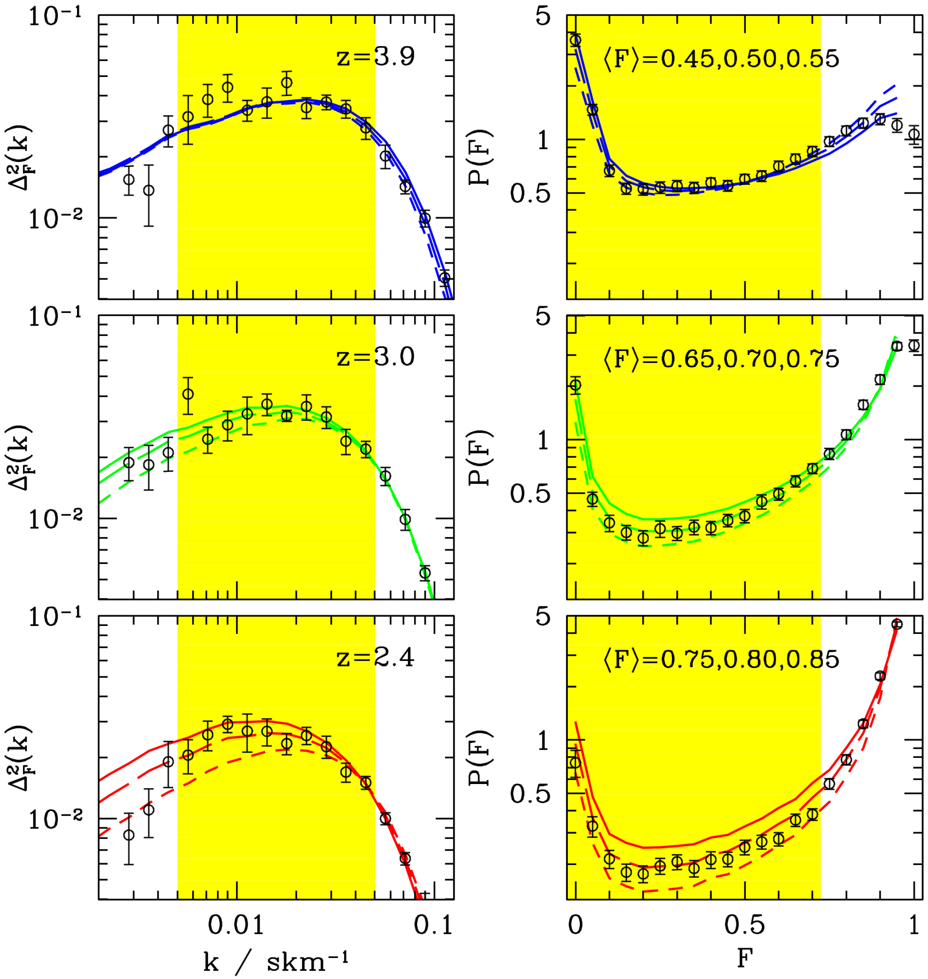
Model parameters:

- IGM filtering length *k*
- Adiabatic index γ
- Mean temperature *T*
- Mean flux $\langle F\rangle = \exp\left(-\tau_{\rm eff}\right)$



Constraining the model parameters

match the observed Lyα flux PS and PDF of Keck (high resolution) spectra



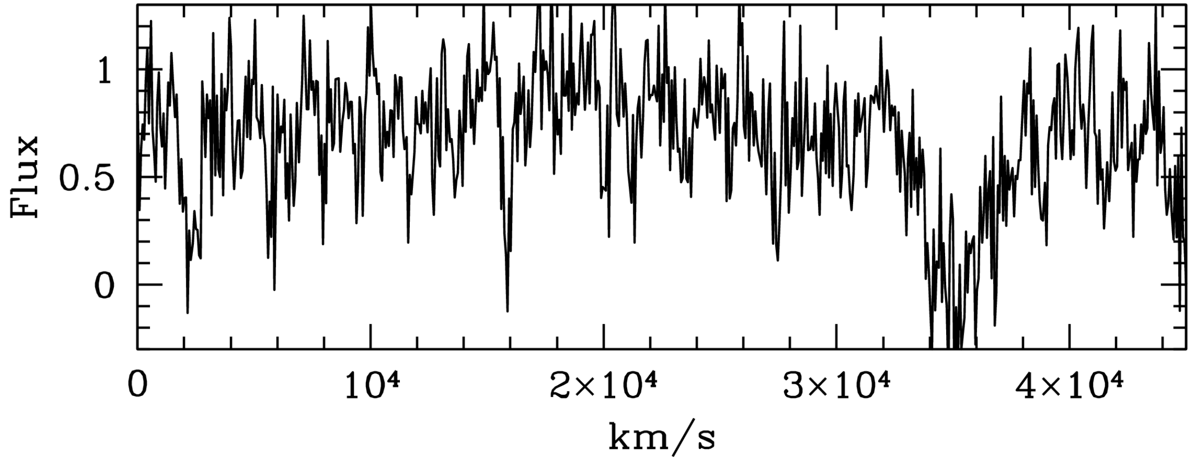
Lognormal model:

- Good fit at redshift z>3
- Best-fitting value of γ=1
  at all redshift

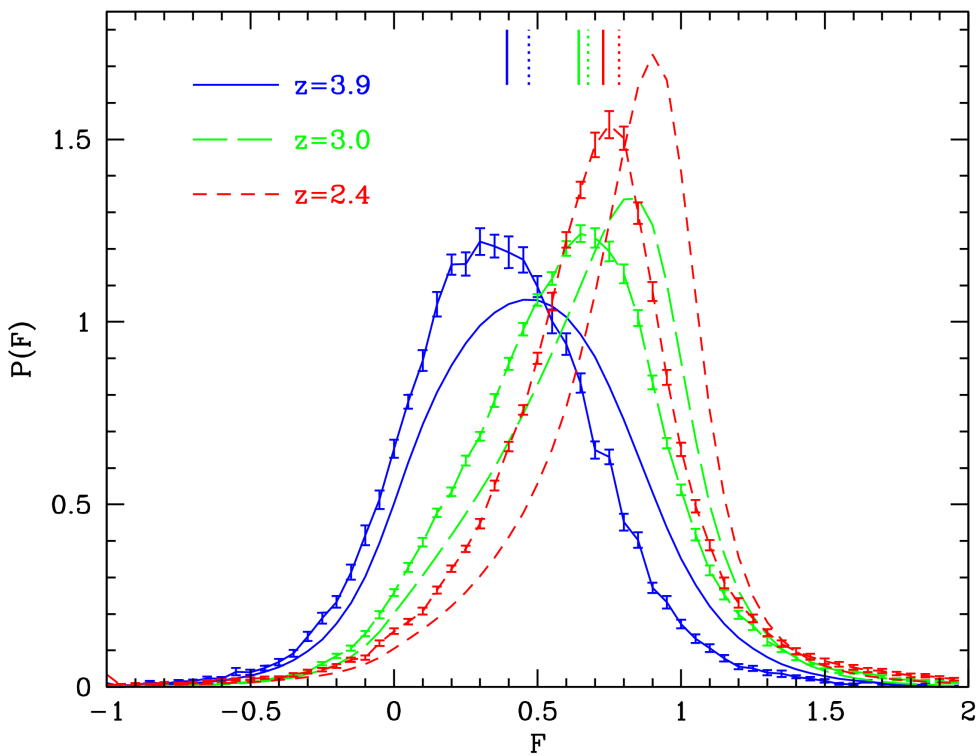
SDSS mock spectra

Account for :

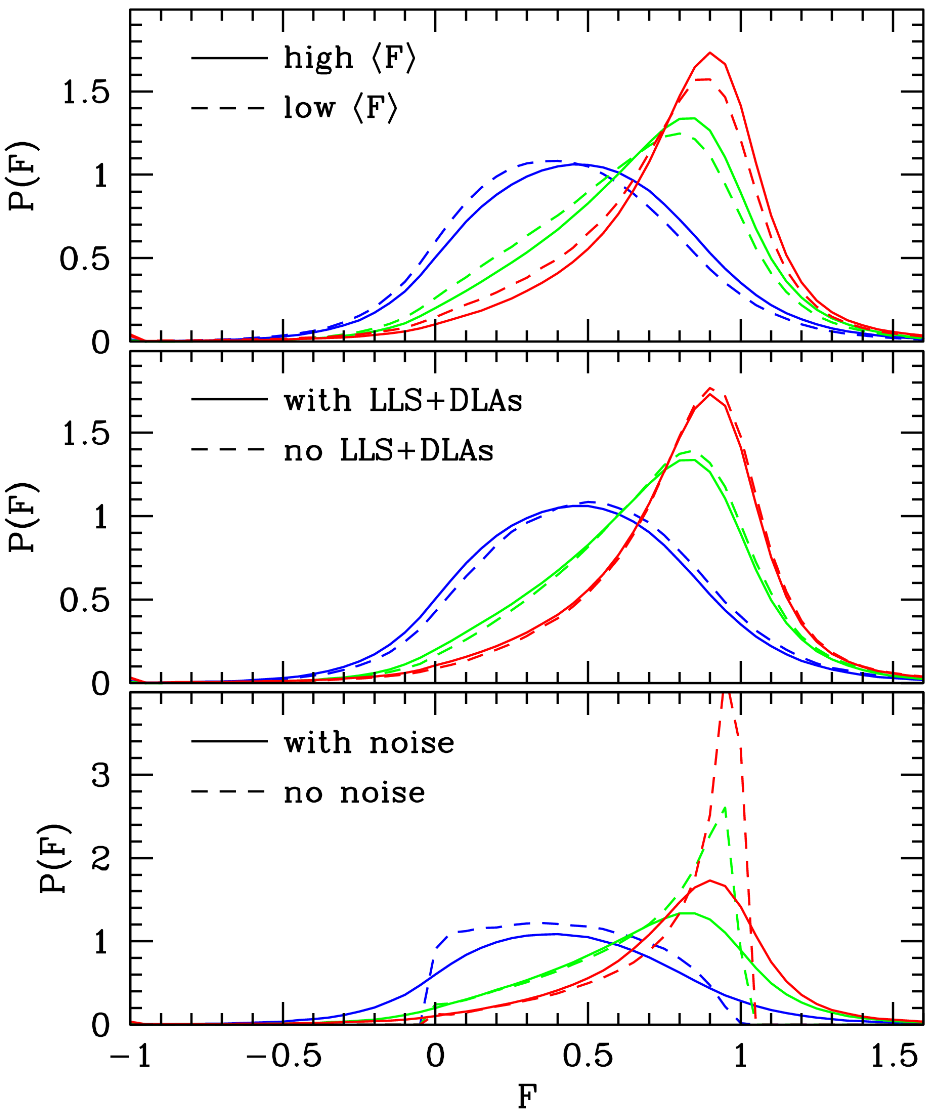
- Instrumental resolution $\sim$150 km/s
- Noise (S/N $\sim$ 3)
- Strong absorption systems



Comparison with the data



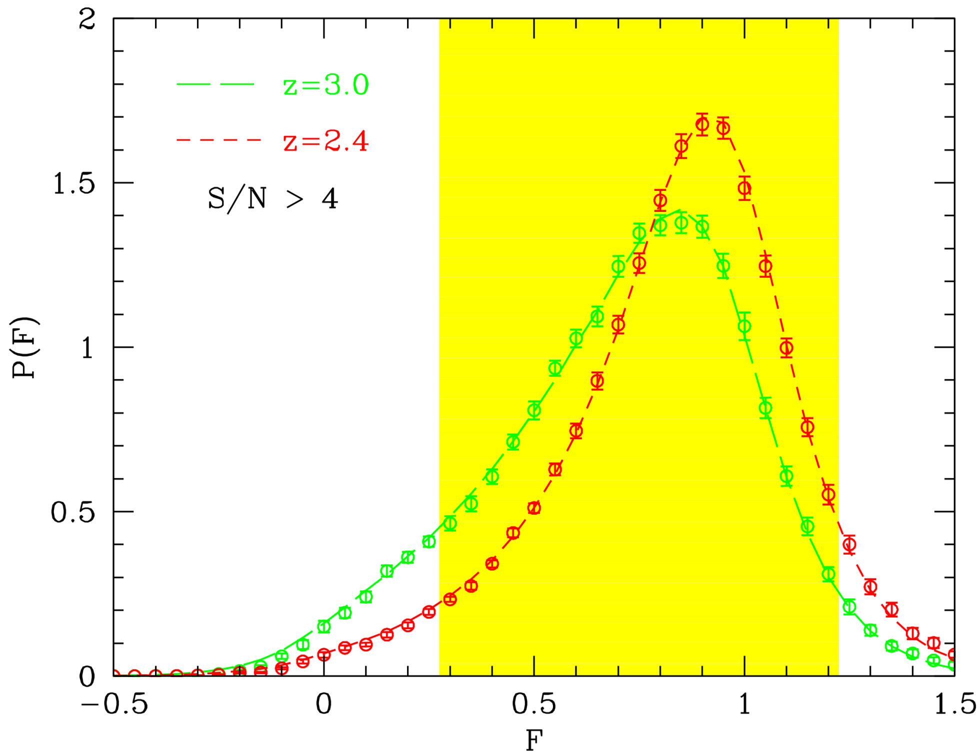
The lognormal model poorly fits the SDSS data at all redshift



Changing the continuum

Add some freedom to the continuum:

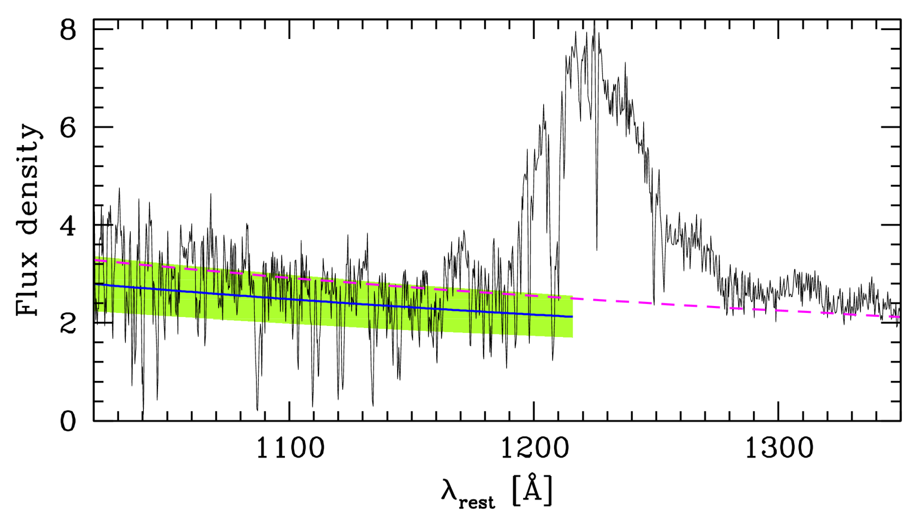
$$I_{\rm cont}(\nu) = y\, I_0\, \nu^{\alpha_\nu} + \text{em. lines}$$



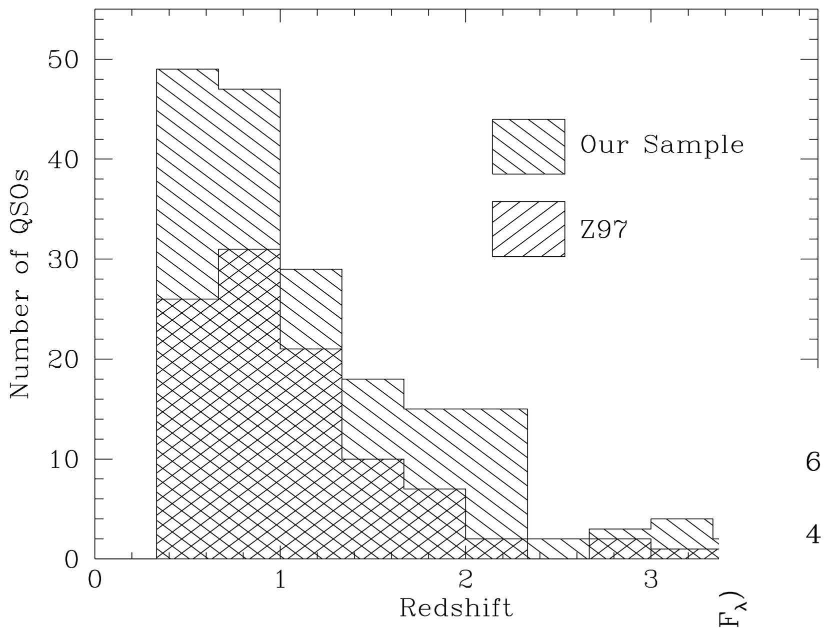
$$P(y) = \exp\left[-(y-\bar{y})^2/2\Delta y^2\right]$$

$$\bar{y} \simeq 0.86$$

$$\Delta y \simeq 0.18$$

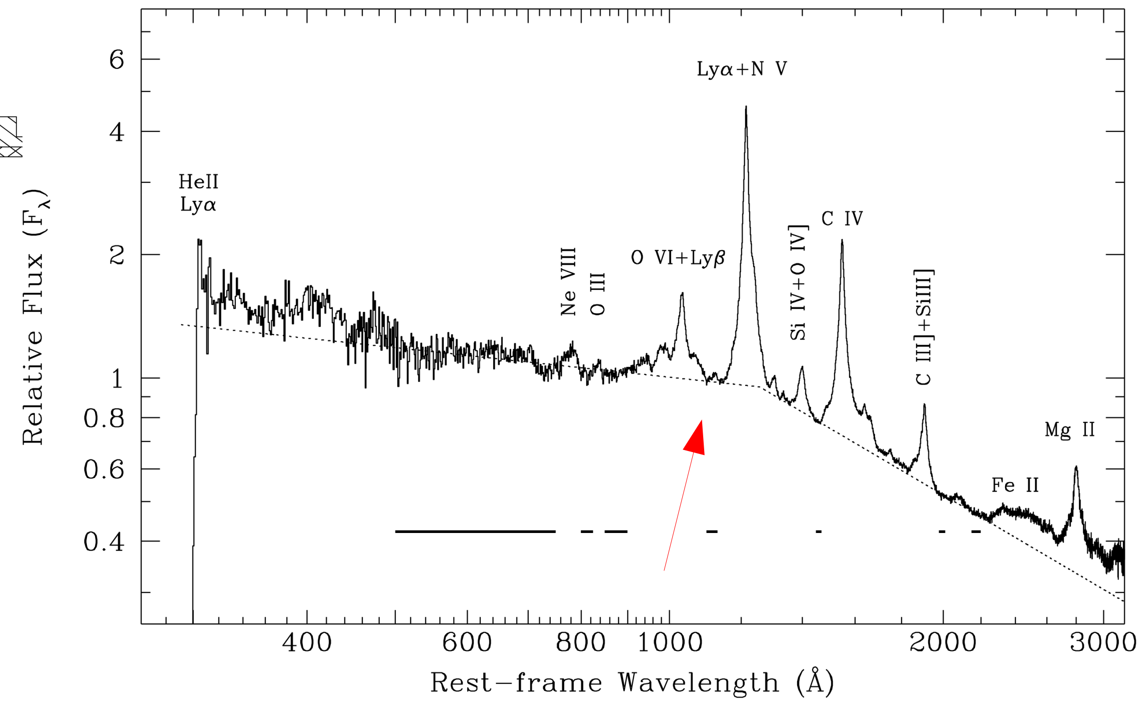


A unseen break around 1200Å ?



composite from low redshift surveys (z<2):
break around the Lyα emission line

Zheng et al. (1997)
Telfer et al. (2002)



Conclusion

- The lognormal model of the Lyα forest provides a good fit to the data at redshift $z \geq 3$
- Evidence for a break in the spectral slope of high-redshift quasars near the Lyα emission line
- Need large residual variations in the continuum normalisation (20 per cent) to account for the smooth shape of the observed PDF

Thank you for your attention