# Large-Scale Structure with the Lyα forest: First results and ongoing analysis from BOSS, SDSS-III.


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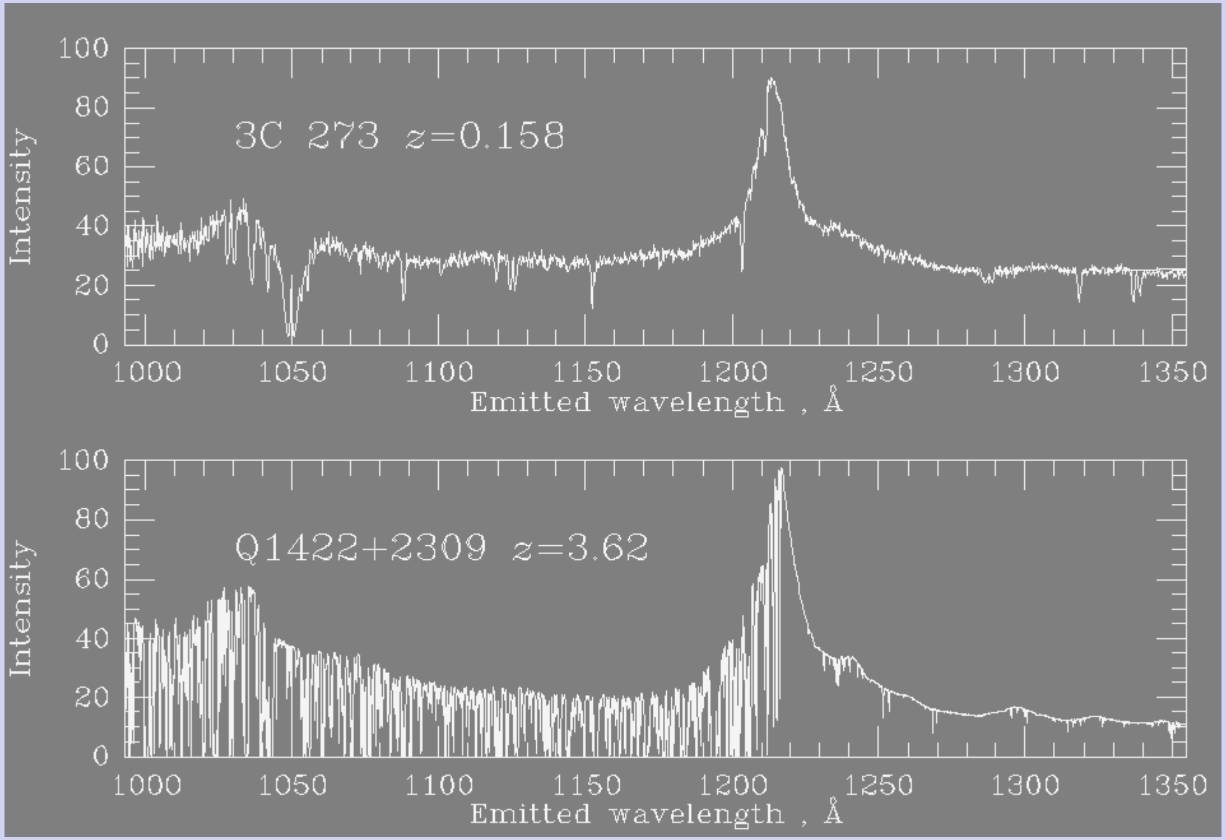
*València, 3-30-2012*

# This work is possible thanks to a very large number of participants in SDSS-III

# Quasar Lyα absorption spectra when the medium is ionized

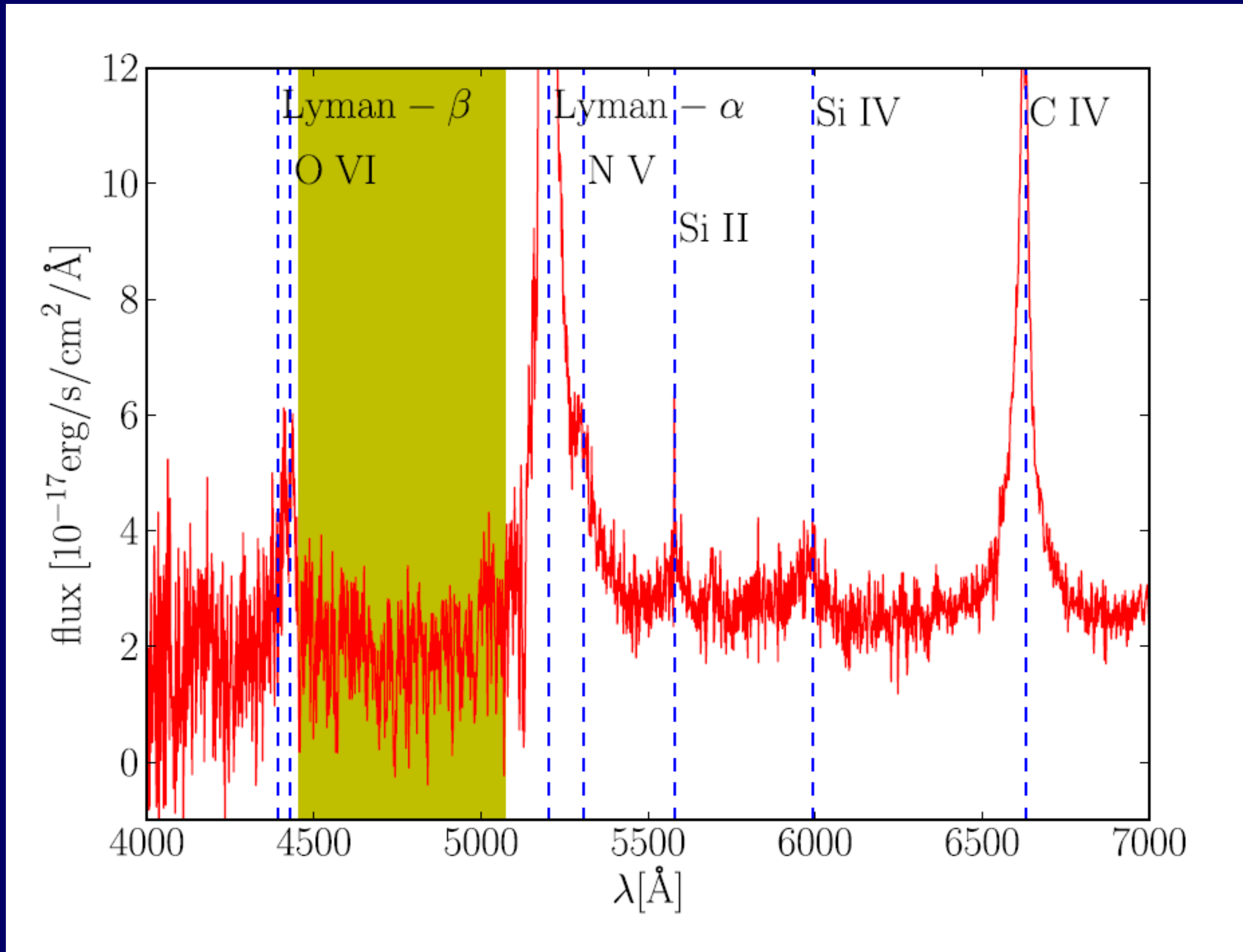



$$F = e^{-\tau}$$

$$\tau = \frac{\tau_0\,(1+\delta)x_{HI}}{1-\eta}$$

$$\eta = -H^{-1}\frac{d\upsilon_{pec}}{dx}$$

Key to SDSS success: large numbers of uniformly observed objects (14000 in first-year analysis, nearly 200000 by the end). Example of quasar spectrum:



# What we measure

- in every quasar spectrum pixel: $\delta_F = F / \bar{F} - 1$

$$\xi_F(r,\mu) = \; < \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r}) >$$

$$\vec{r} = (r_{\parallel}, r_{\perp}) = (r\mu,\, r\sqrt{1-\mu^2}) = [cH^{-1}\Delta z, D_A(1+z)\theta]$$

- The small-scale variations in $\delta_F$ are very large. We need to average over many lines of sight to see the large-scale correlations after the small-scale variance is averaged down.
- Pixel pairs are added with adequate weights in bins in r,μ, to obtain the correlation of Lyα transmitted flux fraction with optimized signal-to-noise.

# What we expect: linear theory

- To first order, the mean value of $\delta_F$ in a large region may depend on the deformation tensor:

$$\partial_i \partial_j \phi \approx \partial_i \upsilon_j$$

  - direction independent:

$$\partial_i \partial_i \phi = \nabla^2 \phi \approx \delta$$

$$n_g = n_{g0}(1 + b_g \delta)$$

  - dependent on direction $n_i$:

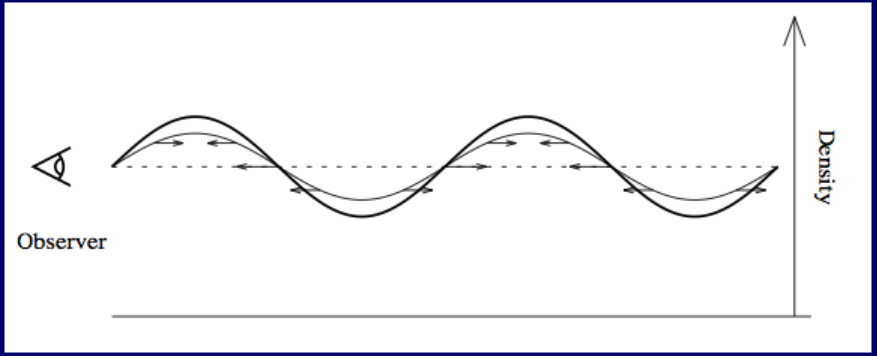
$$n_i n_j \partial_i \partial_j \phi \approx H^{-1} \partial \upsilon_{\|} / \partial x_{\|} = -\eta$$

  - Galaxies in redshift space:

$$n_g / n_{g0} - 1 = (1 + b_g \delta)/(1 - \eta) - 1 \approx b_g \delta + \eta$$

  - Lyα forest:

$$F / \overline{F} - 1 = \delta_F \approx b_\delta \delta + b_\eta \eta$$



# What we expect: linear theory

- Consider a single Fourier mode: $\delta = \delta_0 \, e^{ik\cdot r}$
- Peculiar velocity gradient:

$$\eta = f(\Omega)\frac{k_x^2}{k^2}\delta = f(\Omega)\mu_k^2\delta \qquad f(\Omega) = \frac{d\ln D}{d\ln a}$$

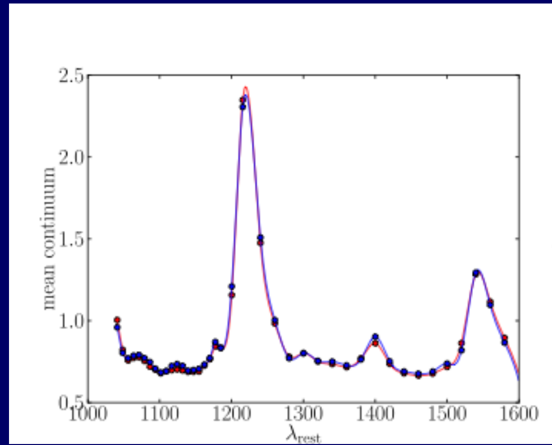
- Galaxies: $n_g = n_{g0}[1+\delta(b_g + f(\Omega)\mu_k^2)]$
- Lyα forest: $\delta_F = \delta(b_\delta + b_\eta f(\Omega)\mu_k^2)$

- Power spectrum in redshift space:

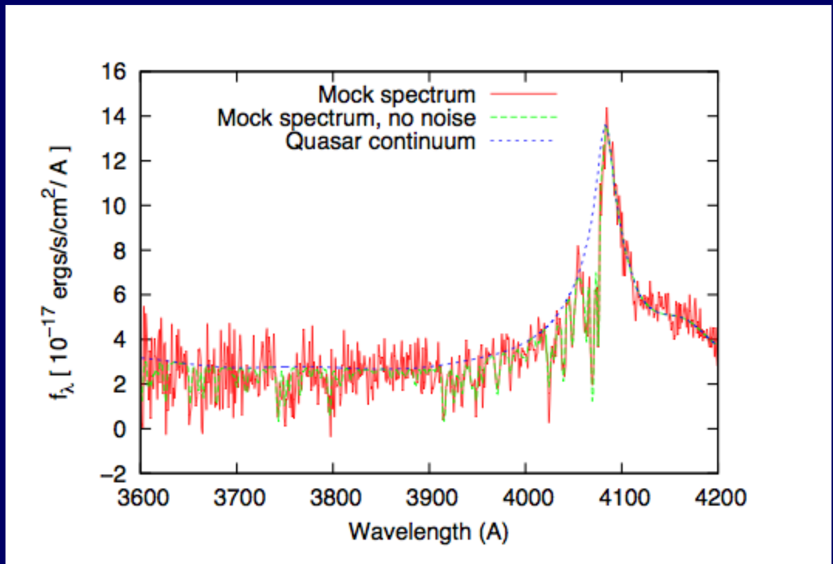
$$P_g(k_\parallel, k_\perp) = P(k) b_\delta^2 (1+\beta\mu_k^2)^2 \;\; ; \;\; \beta = f(\Omega) b_\eta / b_\delta$$

(Kaiser 1987; Hamilton 1998;
McDonald et al. 2000; McDonald 2003

A new technique has been introduced to generate mocks of correlated Lyα spectra, which we use to simulate and correct for any systematics we can identify (e.g. continuum fitting, contamination by DLA and metal lines, testing covariance matrix and measurement errors…)
(Slosar et al., Font-Ribera et al.)

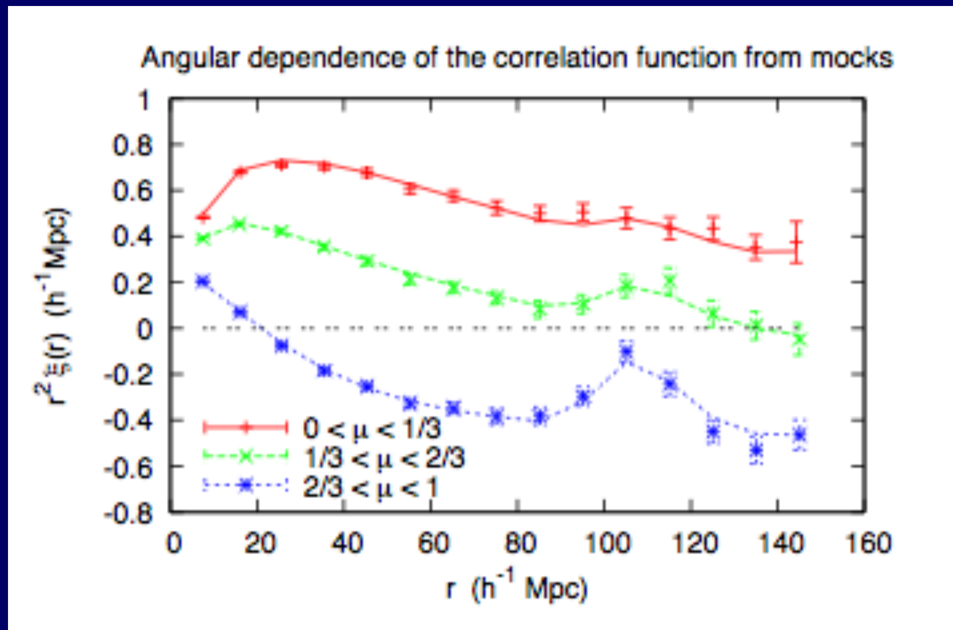



Mean continuum

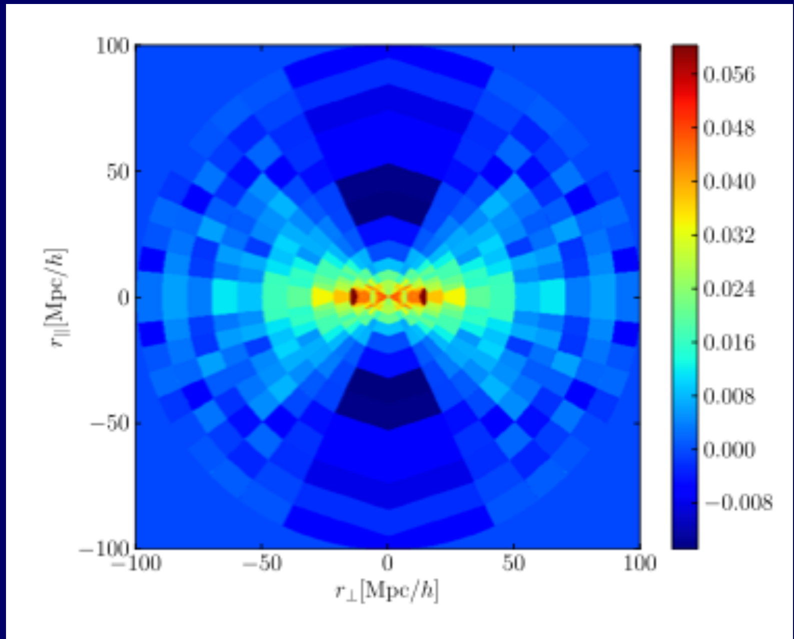


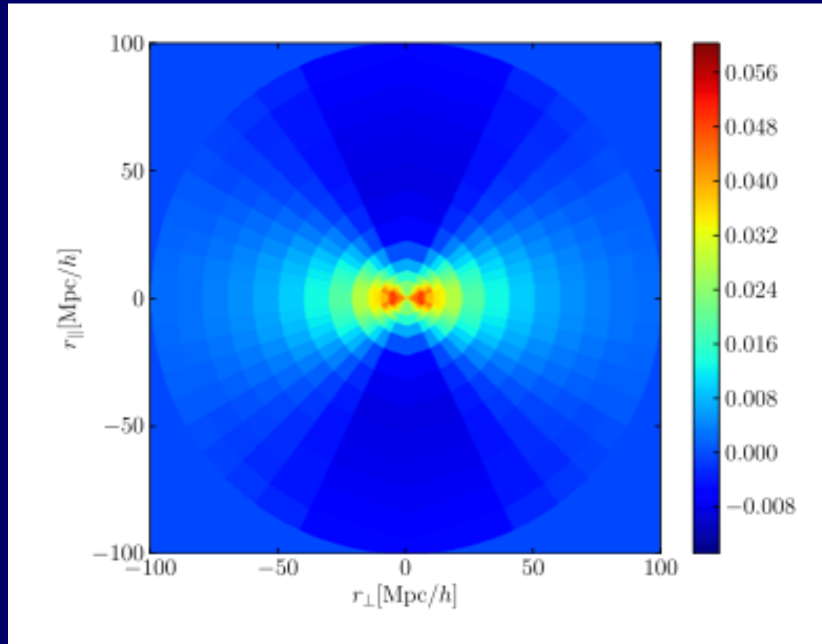

Mock spectrum

Mock correlation function measurement



# Results



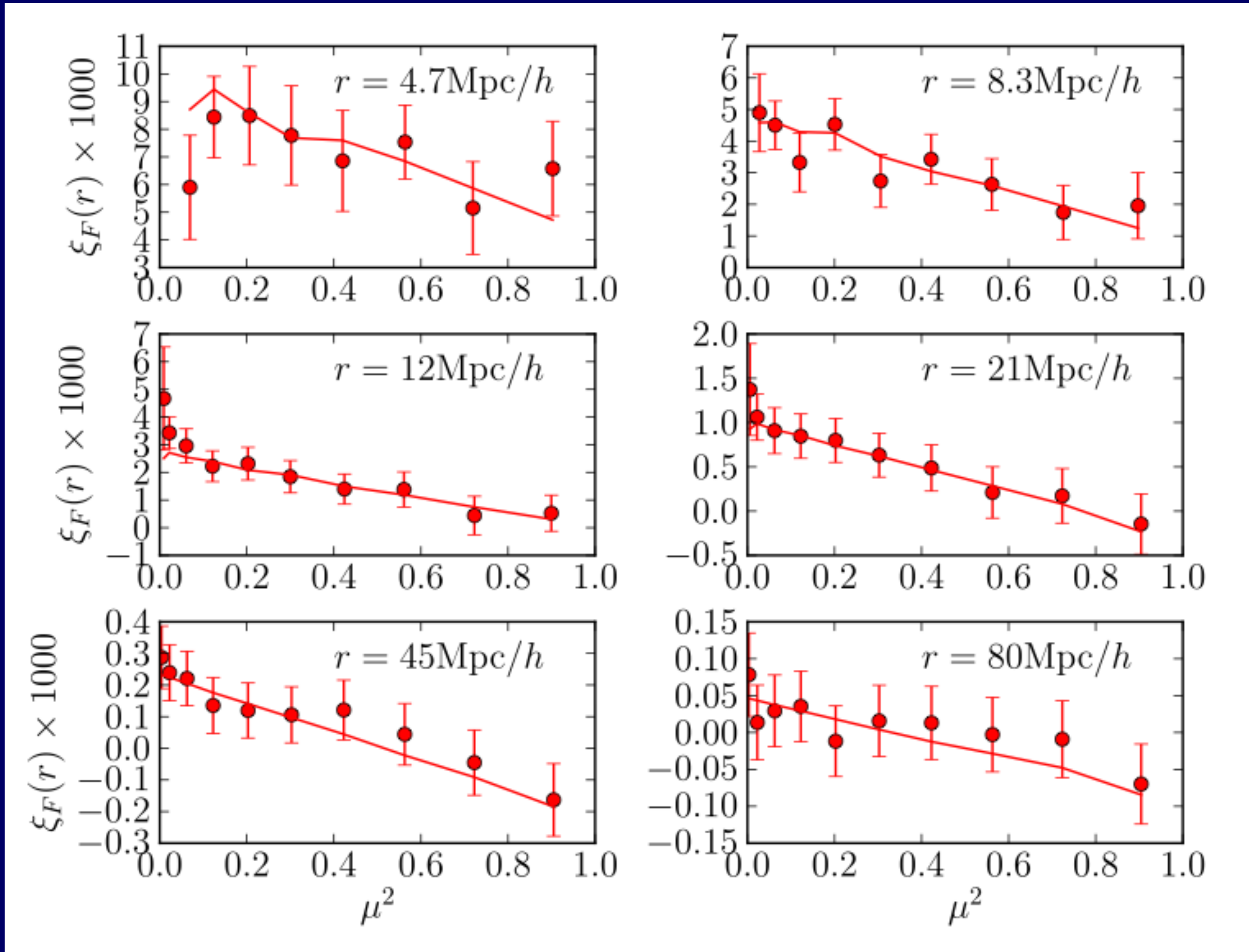




- The anisotropy is clearly detected in the correlation function, consistently with Kaiser's linear formula.

- Fit model:

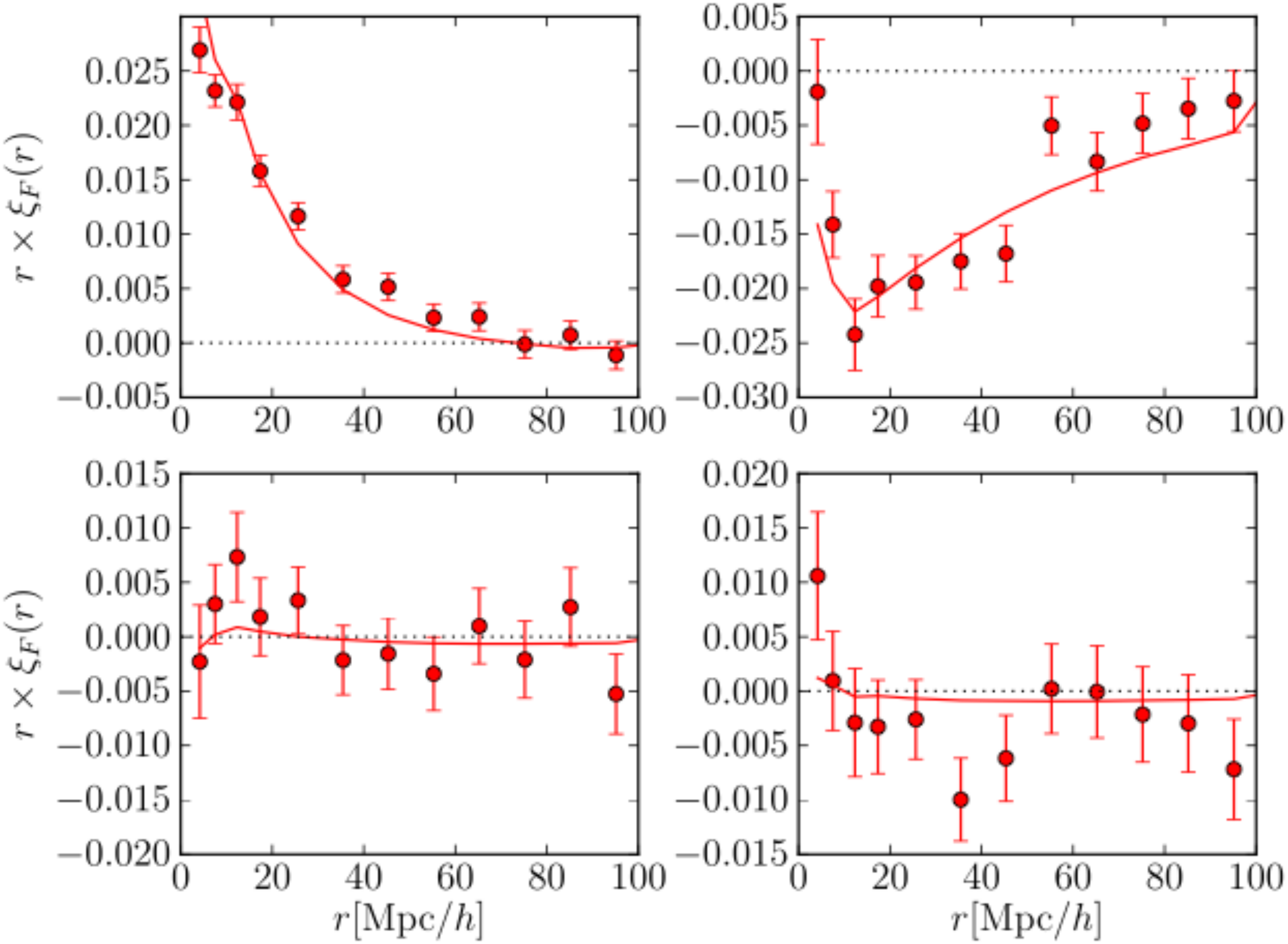
$$P(k_{\|},k_{\perp}) = P_{CDM}(k)b_\delta^2(1+\beta\mu_k^2)^2$$

# Results



$r = 4.7\mathrm{Mpc}/h$
$r = 8.3\mathrm{Mpc}/h$
$r = 12\mathrm{Mpc}/h$
$r = 21\mathrm{Mpc}/h$
$r = 45\mathrm{Mpc}/h$
$r = 80\mathrm{Mpc}/h$
$\xi_F(r) \times 1000$
$\mu^2$

# Results



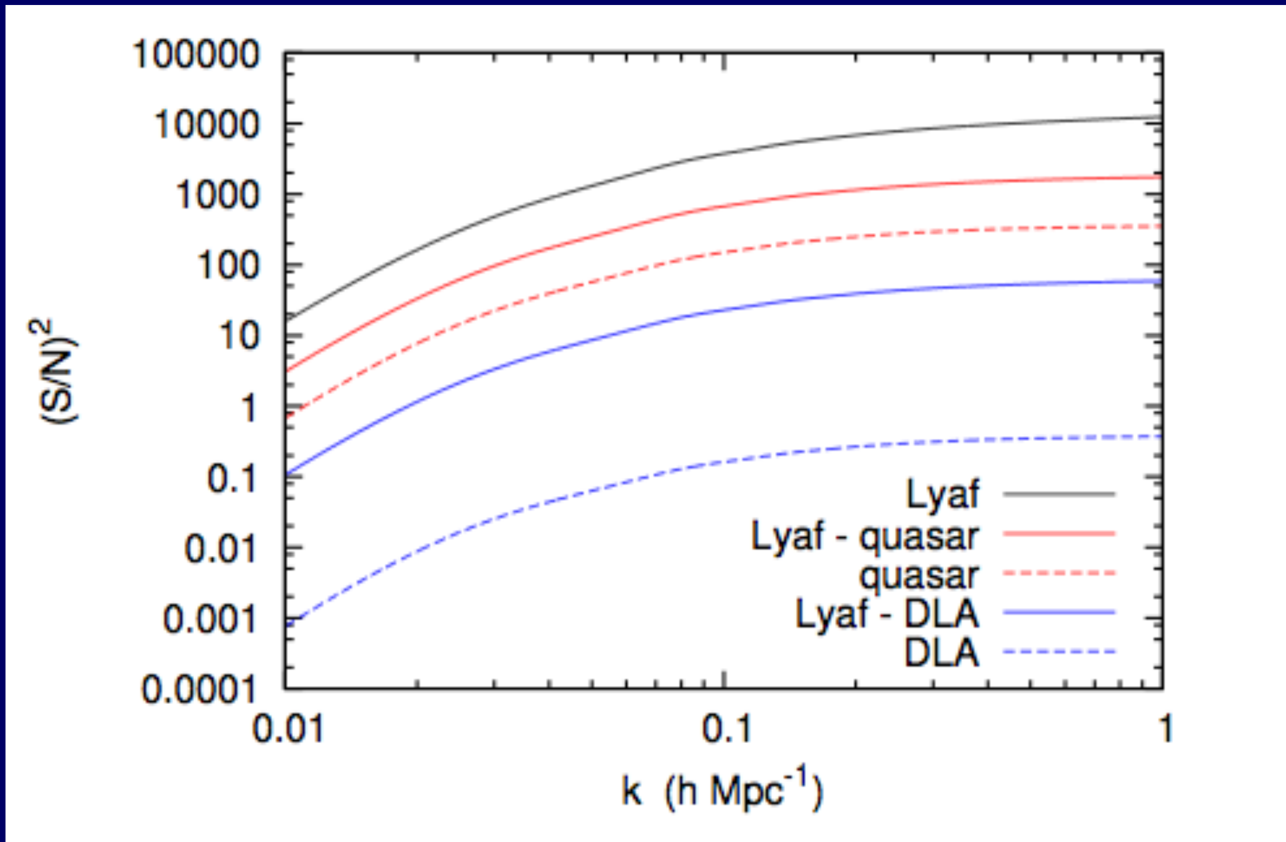
# Results: best fit model

- $\beta = b_\eta / b_\delta f(\Omega) = 0.87 \pm 0.13$
- Most accurately measured: $b_\delta (1+\beta) = -0.34 \pm 0.01$
- More "usual" bias definition: $b'_\delta = b_\delta \overline{F} / (1 - \overline{F}) \approx 0.8$
- Comparison to theory: hydrodynamic simulations suggest $\beta \approx 1.5$ (McDonald 2003), but our tests with mocks have shown that the high column-density and metal-line absorption systems tend to reduce $\beta$.
- The shape is consistent with P(k) from CDM.
- This is a proof-of-concept: the Lyα forest is a useful tool for measuring large-scale structure.

# Cross-correlations in BOSS

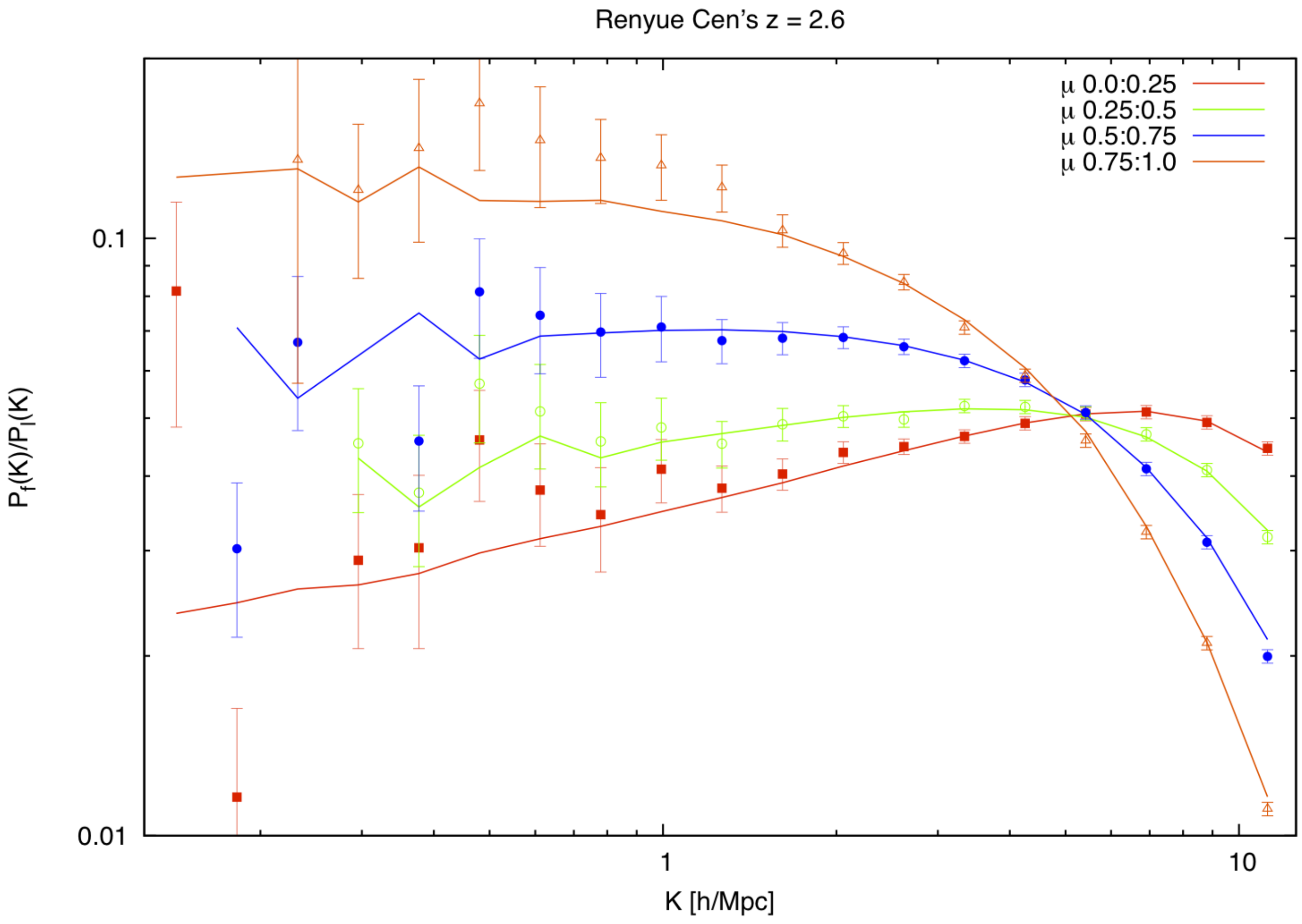
- In addition to the Lyα forest transmission auto-correlation, we can measure cross-correlation with several other things:
  - The quasars themselves
  - Damped Lyα absorption systems
  - Metal lines
  - Lyα-Lyβ
- Each one of this can yield a bias measurement of a new population, which related to host halo masses.
- For quasars, we may see in addition the radiative "proximity effect", through which we can measure physical quasar properties such as emission anisotropy and lifetime.

# Measuring cross-correlations with BOSS




- The relative S/N of the Lyα auto-correlation and the quasar-Lyα cross-correlation is only ~ 2!
- White et al. (2012), quasar auto-correlation: $b_q \sim 4$

# New hydrodynamic simulations for predicting the bias factors (A. Ariño, R. Cen, M. Viel)



# New hydrodynamic simulations for predicting the bias factors

- Values of $\beta$ can be predicted from a hydrodynamic simulation of the Ly$\alpha$ forest, as a function of redshift, mean flux, IGM temperature…
- First results: $\beta$=1.5 ($z$=2.6)

  $\beta$=1.2 ($z$=3)

  $\beta$ decreases for flatter $\rho$-T relation
- In principle these values of $\beta$ can be compared with observations, although effects of DLAs and metal lines need to be properly included.

# For the future

- Next goal: measuring the Baryon Acoustic Oscillation bump, more precise β values, other power spectrum properties.
- Many other things to do: quasar – Lyα cross-correlation, DLA-Lyα and metal-Lyα cross-correlation, for the first time in 3D…