The intergalactic medium as a biased tracer of large-scale mass density fluctuations: the transmission and absorber bias factors.

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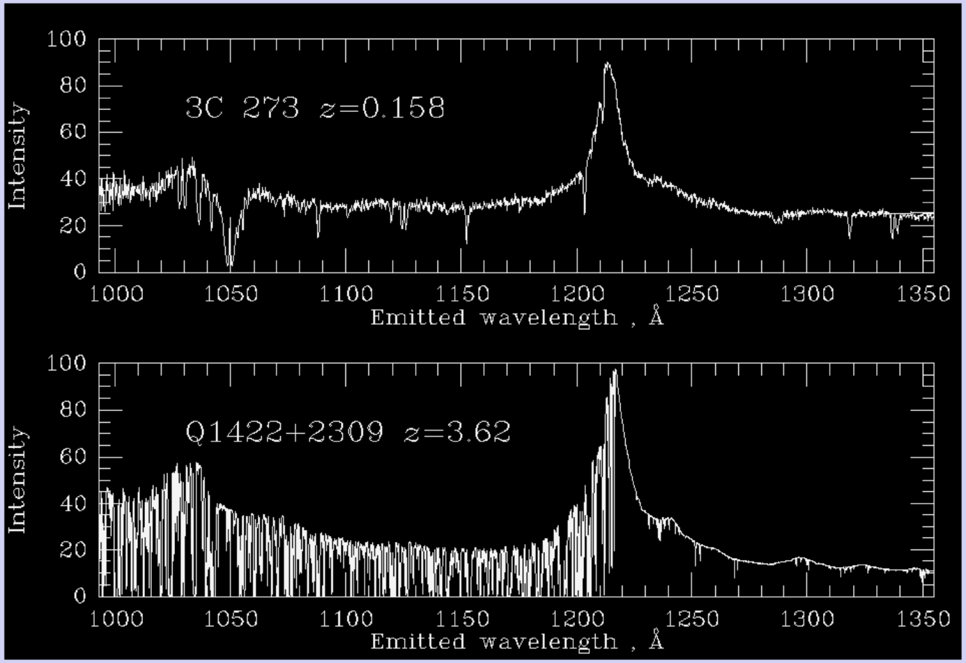
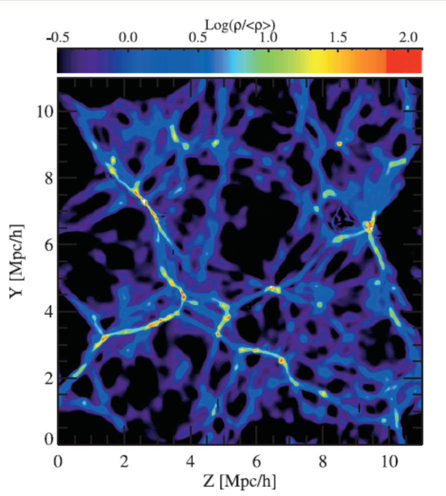
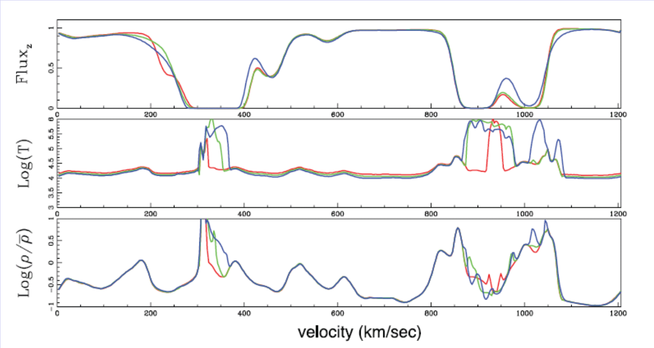
Bias factors of Lyα forest: what are they and why are they interesting?

- Similar to bias factors of galaxies: what is the relative fluctuation amplitude of the density of the tracer compared to that of mass density fluctuations?
- The Lyα forest has two bias factors: one for density, the other for peculiar velocity gradient. For galaxies, the peculiar velocity gradient bias factor is (very close to) one.
- As opposed to galaxies, bias factors of Lyα forest can in principle be predicted from theory. And they should be compared to observations!
- For large scales (linear theory) and Gaussian fluctuations, bias factors are constant (no dependence on scale), but are a function of redshift. Ionizing background intensity fluctuations can introduce scale-dependence.

Lyα absorption spectra in photoionized medium: fluctuating Gunn-Peterson optical depth







Kollmeier et al. 2006

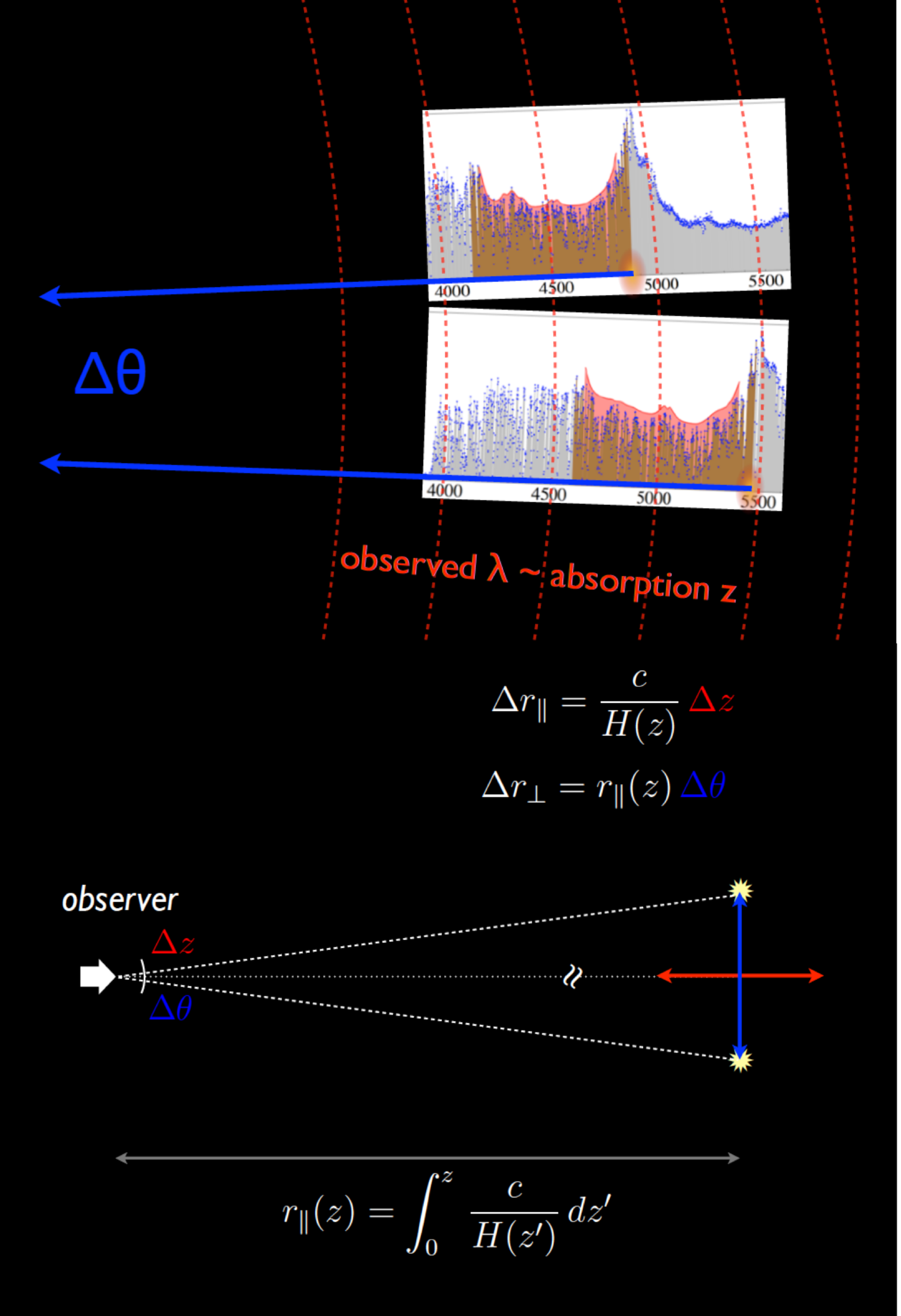
Without thermal broadening:

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

$$\tau = \frac{\tau_0\,(1+\delta)x_{HI}}{1-\eta} \approx \frac{\tau_{GP}(1+\delta)^{2-0.7\gamma}}{1-\eta}$$

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

The Lyα forest is a tool to do large-scale structure at high redshift when we can cross-correlate many lines of sight.



Measuring large-scale correlations with the Lyα forest

- After fitting a continuum model, the absorption at each redshift is a tracer of density fluctuations that we can correlate. The transmission fraction fluctuation is:

$$\delta_F = F / \overline{F(z)} - 1$$

- Just like for galaxies, we can measure correlation functions along and across the line of sight.
- Spectroscopic surveys allow large-scale correlation measurements, with hundreds of thousands of quasars.

Image credit: David Kirkby

Transmission and absorber bias factors:

The Lyα forest bias factors are usually defined in terms of the fluctuation in transmission fraction:

$$\delta_F = \frac{F}{\overline{F}} - 1 \simeq b_{F\delta}\delta + b_{F\eta}\eta.$$

These bias factors, however, do not represent a physical property of the IGM: they are negative and depend on the mean transmission. When mass density is zero, F=1. Instead, we want something like an absorber bias factor: relative fluctuation of absorbers compared to mass fluctuation.

Effective optical depth from a biased population of absorbers:

$$\tau_{\rm eff} = \int_0^\infty dW\, f(W) W (1 + b_{\tau\delta}\delta + \eta)$$

Fluctuations :

$$\overline{F} = \exp\left[-\tau_{eff,0}\left(1 + b_{\tau\delta}\delta + \eta\right)\right] = \overline{F_0}\left[1 + \log(\overline{F}_0)(b_{\tau\delta}\delta + \eta)\right]$$

Absorber bias factors :

$$b_{F\delta} = \log(\overline{F}_0) b_{\tau\delta}$$

$$b_{F\eta} = \log(\overline{F}_0) b_{\tau\eta} = \log(\overline{F}_0)$$

What we measure:
Lyα correlation function

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

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

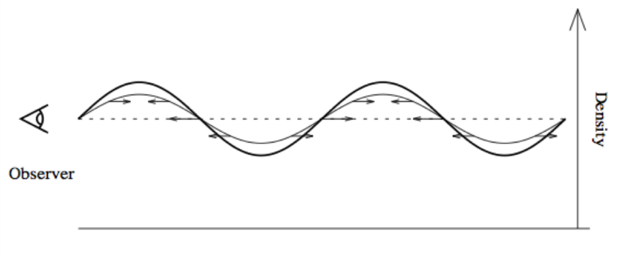
What we expect: linear theory

- For a single Fourier mode, peculiar velocity gradient:

$$\eta = f(\Omega)\frac{k_{\parallel}^2}{k^2}\delta = f(\Omega)\mu_k^2\delta$$

$$f(\Omega) = \frac{d\ln D}{d\ln a}$$

- Galaxies: $\delta n_g / n_{g0} = \delta(b_g + f(\Omega)\mu_k^2)$



- Lyα forest: $\delta_F = \delta(b_\delta + b_\eta f(\Omega)\mu_k^2)$
- Power spectrum in redshift space:

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

Kaiser 1987; Hamilton 1998;

Croft et al. 1998, 1999, McDonald et al. 2000; McDonald 2003

Advantages of Lyα forest over galaxies for measuring large-scale structure:

Linear redshift space distortions are more obvious in the Lyα forest power spectrum than for galaxies, because of the higher redshift and because high-density regions are suppressed by absorption line saturation. However, damped wings of absorbers cause a "fingers-of-God" contaminating effect.

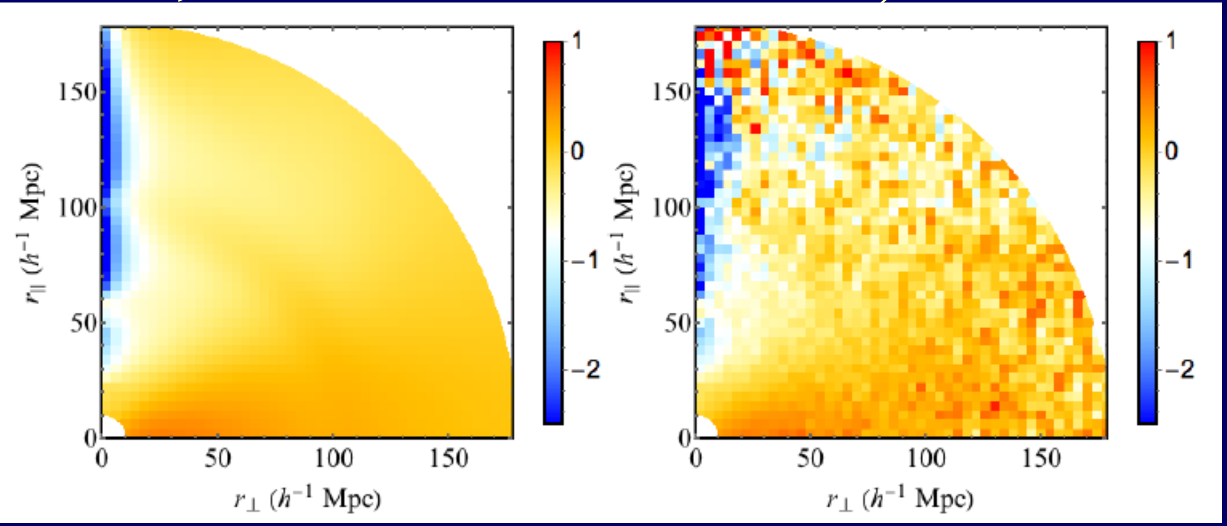
One-dimensional power spectrum: obtained from the one-dimensional correlation on a single line of sight.

$$P_{1D}(k_{\parallel}) = \int_0^\infty \frac{k_\perp \, dk_\perp}{2\pi^2} P(k_{\parallel}, k_\perp)$$

The 1D power spectrum, based only on correlations along single lines of sight, is simply a projection of the full 3D power and is affected by non-linearities on all scales, and by similar systematic effects.

Results for the Lyman alpha autocorrelation (DR12, Bautista et al. 2017)

Clearly detected anisotropy, consistent with Kaiser's linear formula.



Basic fitting model:

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

Measured bias and redshift distortion factors with DR12 at z=2.3 (Bautista et al. 2017).

Various systematics (continuum fitting, contamination by HCDs, metals, ionizing background…)

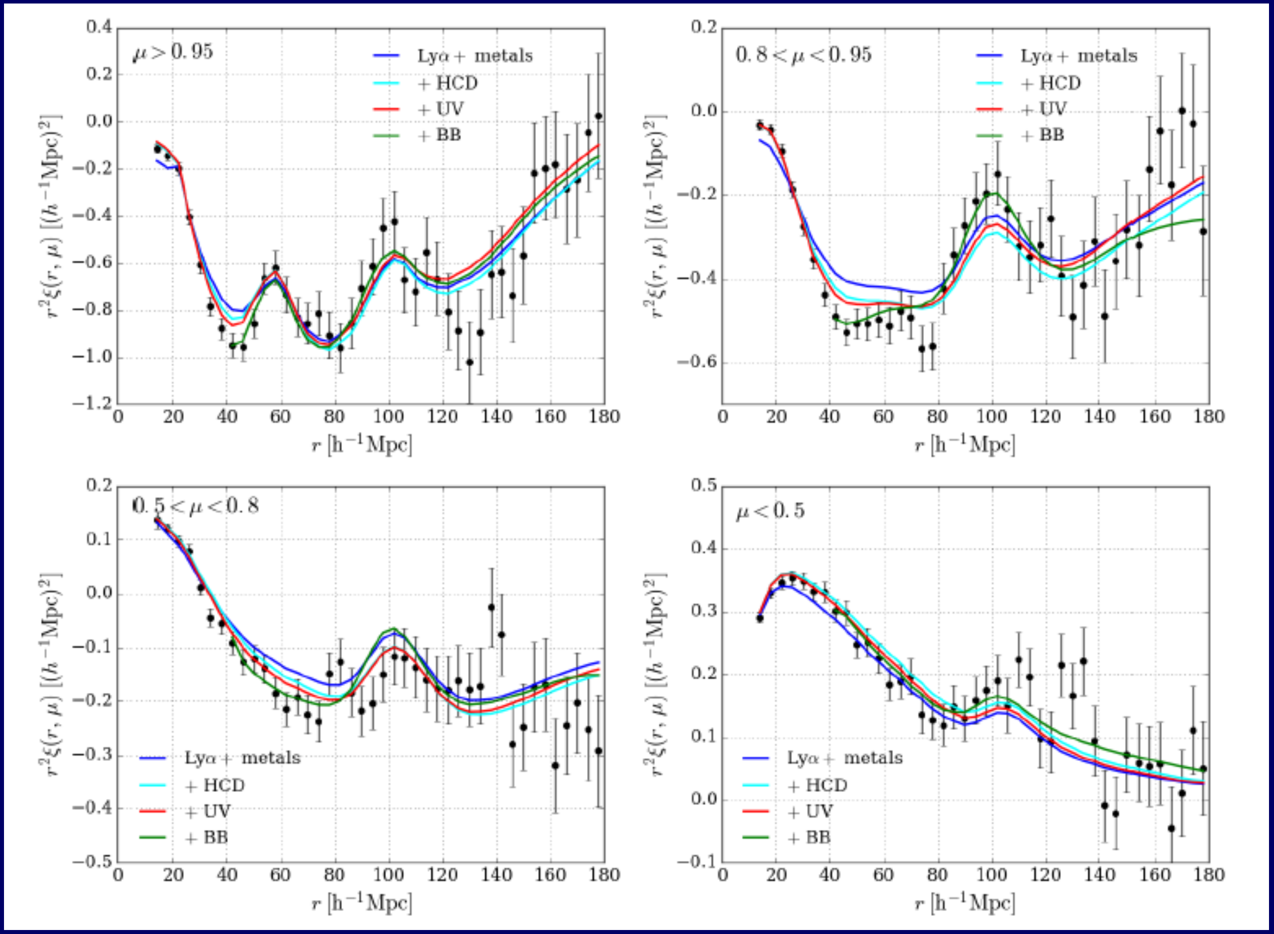
$$b_{F\delta}(1+\beta) = -0.326 \pm 0.002 \,,$$

$$\beta = 1.25 \pm 0.05 \qquad \text{(no HCD correction)} \,,$$

$$b_{F\delta}(1+\beta) = -0.321 \pm 0.003 \,,$$

$$\beta = 1.66 \pm 0.09 \qquad \text{(HCD correction)} \,.$$

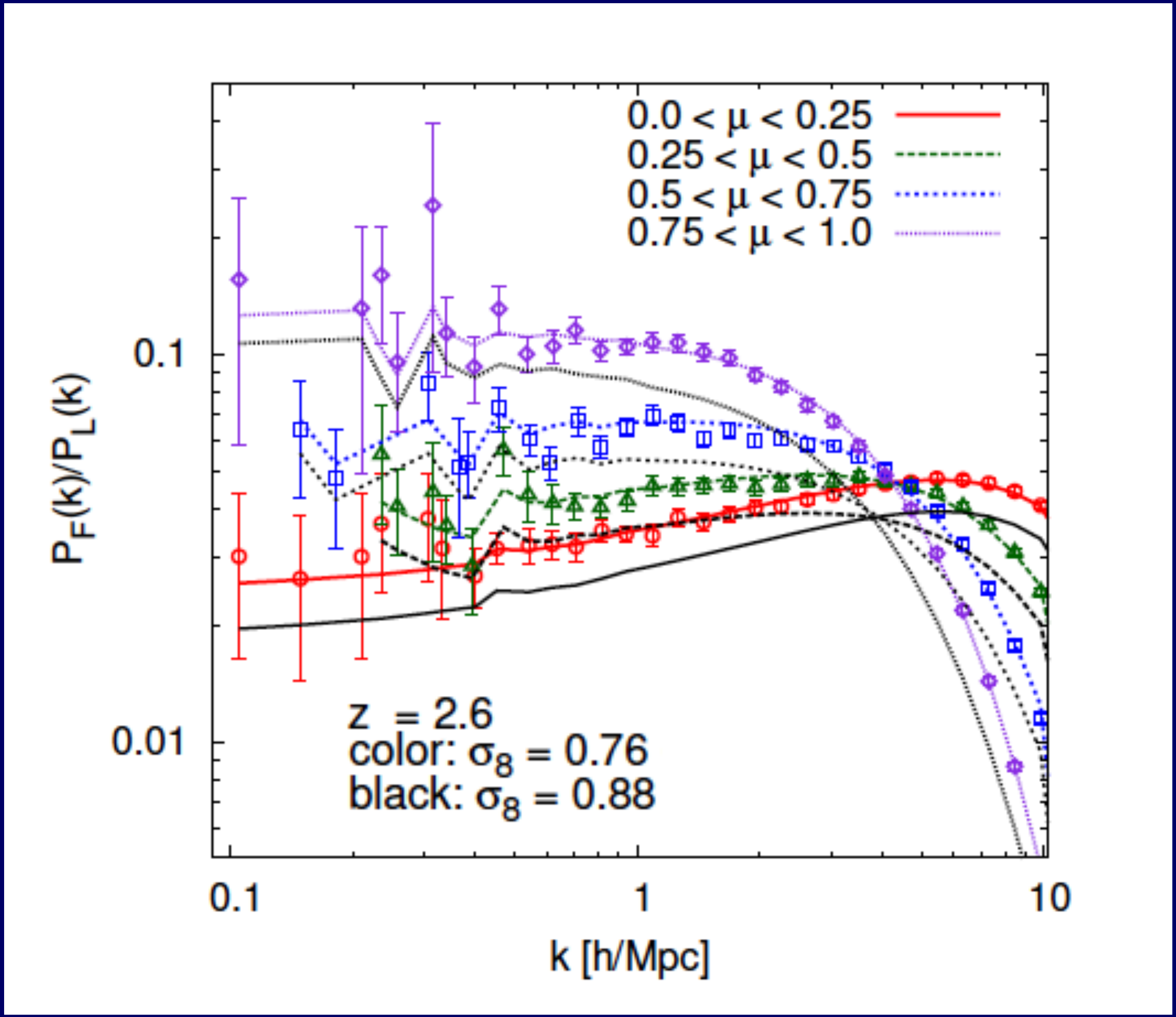
BAO measured in the Lyα autocorrelation (Bautista et al. 2017, DR12)



The Baryon Acoustic Oscillation peak is well measured and not much affected by broadband errors. Other parameters depending on the broadband shape are more strongly affected, but the CDMΛ prediction is successful.

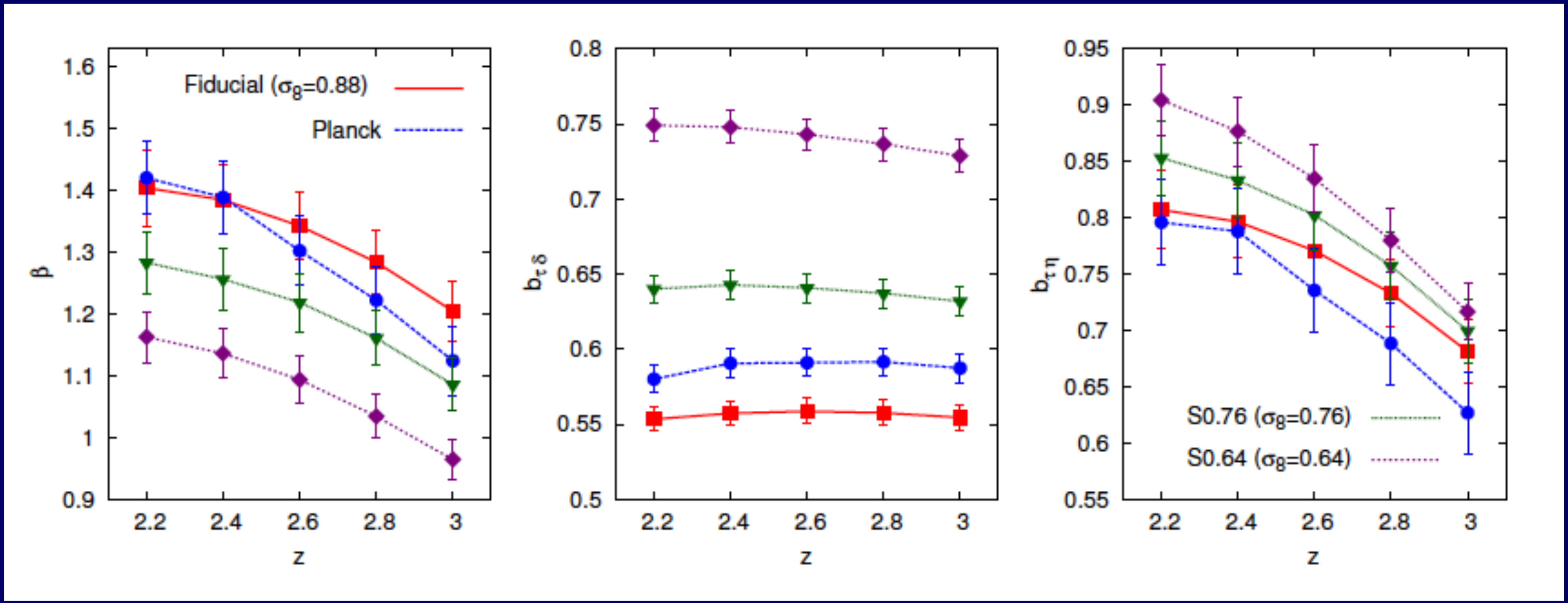
Non-linear power spectrum predictions: use hydrodynamic simulations of the IGM.

- Small k: linear limit.
- k ~ 3 h/Mpc: cross-over.
- Large k: Jeans length and thermal, peculiar velocity broadenings.



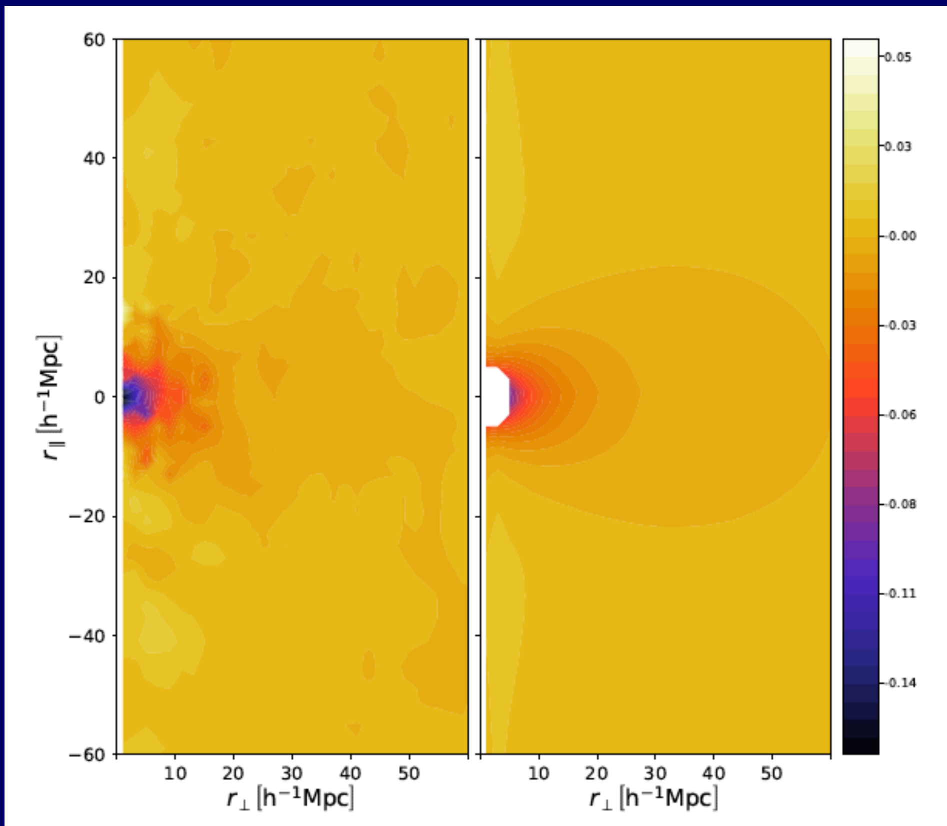
Arinyo-i-Prats et al. (2015)

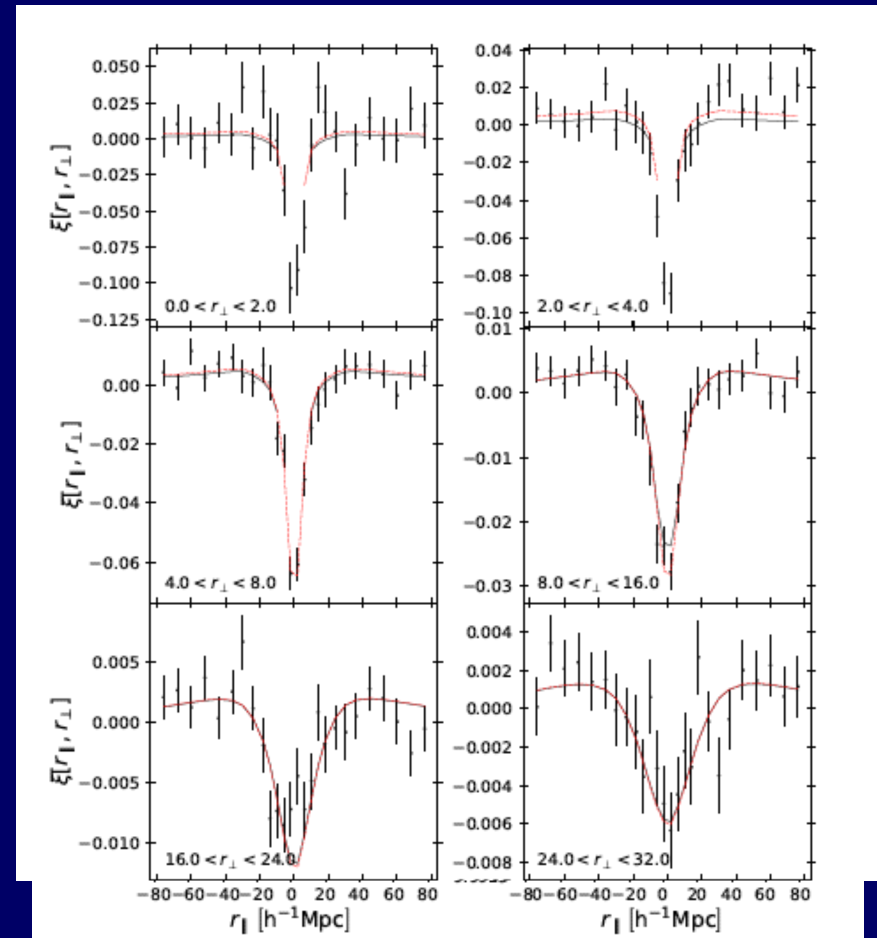
The Lyα forest bias factors can be predicted (they depend on thermal history, winds…) (Arinyo-Prats et al. 2015)



These are consistent with the observed values in Bautista et al. (2017), but there are still large systematic errors from continuum fitting, ionizing background fluctuations, DLAs, metal lines.

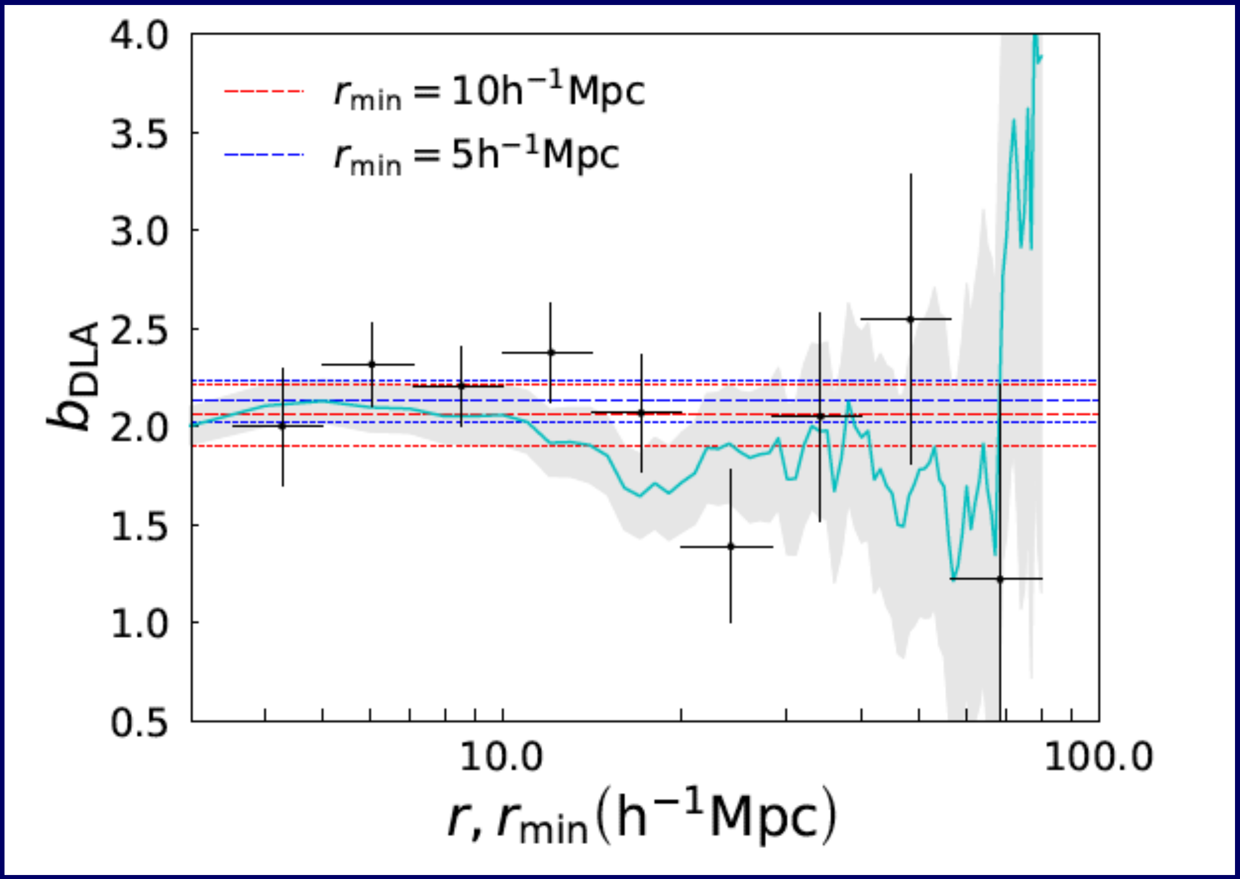
Damped Lyman Alpha – Lyα forest cross-correlations (Font-Ribera et al. 2012, Pérez-Ràfols et al. 2018)





The cross-correlation is well-fitted by the simple linear model, with a value of $\beta_{Ly\alpha}$ that was obtained from the autocorrelation of the forest.

DLA bias fitted at different radial intervals (Pérez-Ràfols et al. 2018)



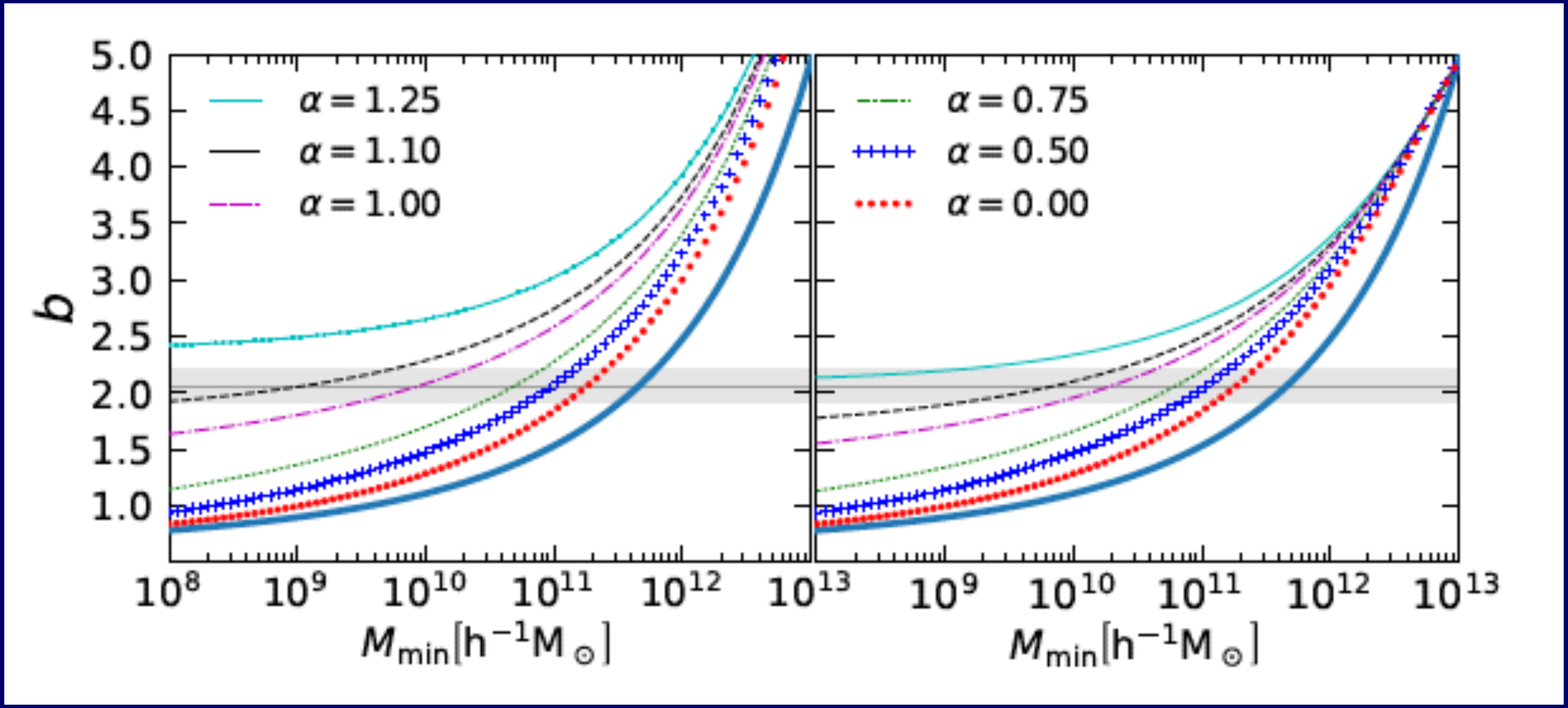
b_{DLA}=2.01 ± 0.10
($\beta_{Ly\alpha}$ = 1.65)

b_{DLA}=2.08 ± 0.10
($\beta_{Ly\alpha}$ = 1.25)

Some systematic errors: uncertainty on $\beta_{Ly\alpha}$, catalog impurities and selection.

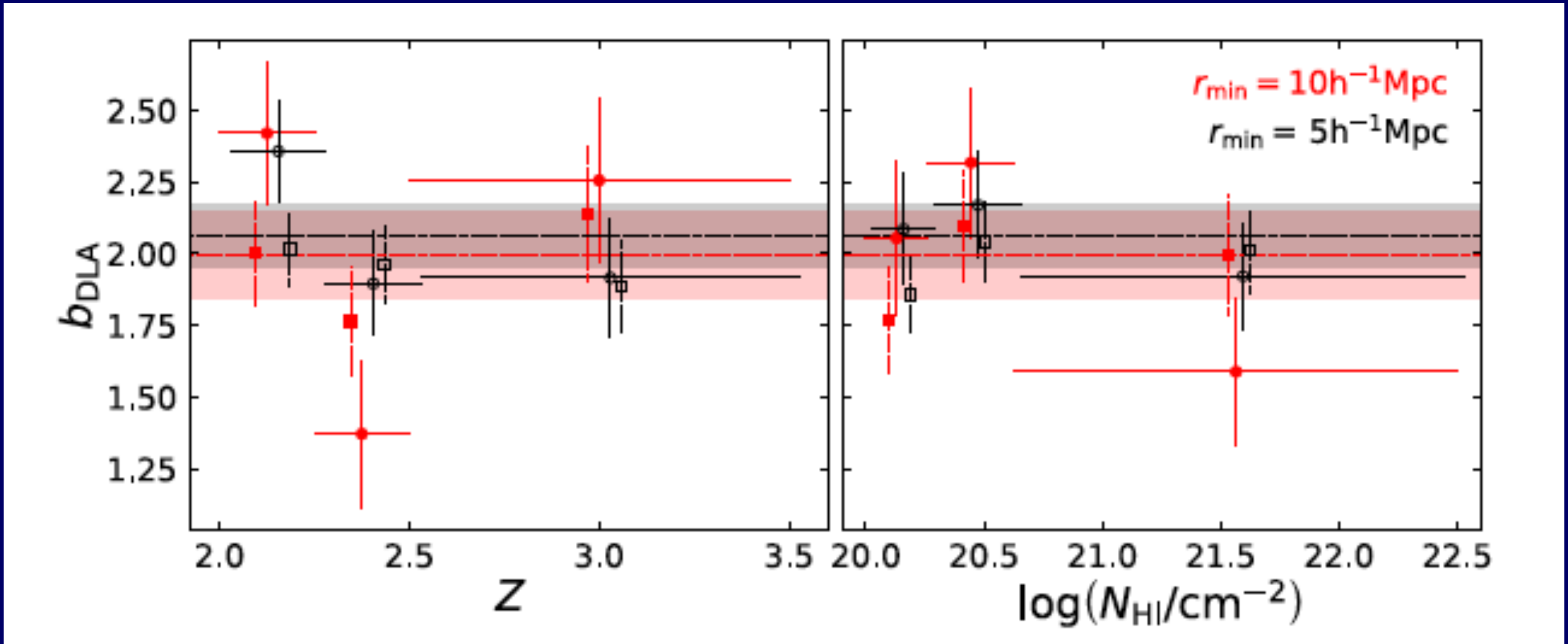
- The agreement with constant bias shows the cross-correlation agrees well with CDM prediction. We find the bias to be independent of the DLA column density and redshift.

Simple model for DLA bias in host halos of mass M: Cross section: $\Sigma(M) \sim M^{\alpha}$ ($M>M_{min}$)



- Implications for median DLA host halos: $M \sim 10^{11}$ -10^{12} $M_{\odot}$.
- Realistic model with a broad halo mass distribution: $M_{min} \sim 10^9$ $M_{\odot}$, $\alpha>1$
- Models of galaxy formation (e.g. Pontzen et al. 2008, Bird et al. 2014) have predicted lower DLA host halo masses, and so lower bias. Strong winds are needed to deplete low-mass halos of gas and spread out gas in high-mass halos.

Dependence on N_{HI} and redshift.



Conclusions

- The Lyα forest can now be used to study the large-scale structure of the Universe at z>2. In addition to the parallel and perpendicular BAO scales, BOSS measured the bias and redshift distortion factors of the Lyα forest, and the bias factors of DLA systems and other tracers, using the autocorrelation of the Lyα transmission and cross-correlations. The Lyα forest bias factors provide a test of our theories of the structure of the photoionized intergalactic medium.
- The measured DLA bias factor is a powerful constraint for the host halo mass distribution of DLAs, connecting to our models of galaxy formation. The high value of the DLA bias requires strong winds in galaxies to suppress gas in low-mass halos and spread around the gas in high-mass halos. It is good news for 21-cm intensity mapping.