Phisics of the Intergalactic Medium: Key questions and Future Perspectives

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Shibukawa Karumi
Star Chart (1677)

What is your favorite list of key questions on the evolution of the IGM?

- What is the impact of galaxy winds, ionizing intensity and T-ρ fluctuations from reionization on the Lyα transmission power spectrum, bispectrum, cross-correlations, and other statistics?
  - We can predict the non-linear Lyα power spectrum with gravitational evolution and photoionization, with no winds, and no Γ and T-ρ fluctuations. Can we measure these effects, which should be there because of HI and HeII reionization, and discrete sources with clustering?
- What is the luminosity function, lifetime, duty cycle and emission anisotropy of ionizing sources during and after HI and HeII reionization?
  - How are these related to the evolution and large-scale fluctuations of the ionizing radiation mean free path and its large-scale fluctuations?
- How were metals injected into the IGM, and how did this perturb the dynamical evolution of the IGM?
- Can we use the IGM to learn about fundamental properties of dark matter and primordial fluctuations?

Observational probes for these key questions

- We need multitracer cross-correlation studies over a wide range of redshifts.
- Galaxy – absorption cross-correlations:
  - Lyman limit galaxies, Lyα emitters, with Lyα, Lyβ, metal absorption.
  - Go around $z>5$ sightlines for HI reionization, with OI absorbers, and $z \sim 3$ HeII sightlines, with SiIV/CIV/OVI absorbers.
  - Predictions for 21-cm observations.

Bias factors of the Lyα forest

- In every quasar spectrum pixel: $$\delta_F = F/\bar{F} - 1$$
- On small scales, the variations in δ_F are large and strongly affected by non-linear evolution and complex physical processes. But the 3-D average over a large scale should behave linearly.
- Galaxy number density fluctuation in redshift space:

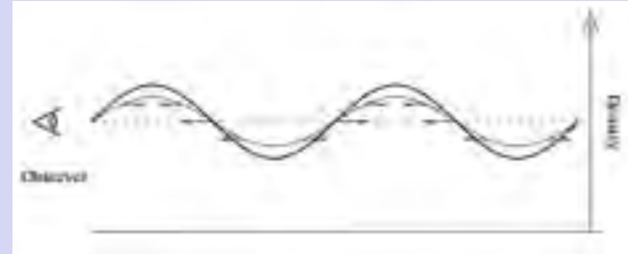
$$\delta_g = n_g / n_{g0} - 1 = (1 + b_g \delta)/(1 - \eta) - 1 \approx b_g \delta + \eta$$

- Same for Lyα forest, except that a peculiar velocity gradient bias factor different from 1 is induced by the non-linear relation :

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

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

What we expect: linear theory



- For a single Fourier mode, peculiar velocity gradient:

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

- Galaxies: $$\delta_g = n_g / n_{g0} - 1 \approx b_g\delta + \eta = \delta[b_g + f(\Omega)\mu^2]$$
- Lyα forest: $$\delta_F = \delta[b_{F\delta} + b_{F\eta} f(\Omega)\mu^2]$$
- Power spectrum in redshift space:

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

- In one dimension: $$P_{1D}(k_\parallel) = \int dk_\perp \, k_\perp /(2\pi) \; P_F(k_\parallel, k_\perp)$$

Kaiser 1987; Hamilton 1998;

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

Physical bias factors

- The transmission bias factors are defined as

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

so that the linear power spectrum is:

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

- But F is not zero when there is no gas. The physical bias factors are related to the variations in the absorption effective optical depth:

$$\tau_e = -\log(\bar{F}) \qquad b_{\tau\delta} = \frac{b_{F\delta}}{\log(\bar{F})} \qquad b_{\tau\eta} = \frac{b_{F\eta}}{\log(\bar{F})}$$

- These bias factors are interpretable as we are used to and reflect the biased distribution of the underlying gas structures in the IGM: a value of 1 means that Lyα absorption varies with the same amplitude as mass density fluctuation.

IGM Simulations in Arinyo-Prats et al. 2015
Gadget-II, CDMΛ.
Ω_m=0.3, σ_8=0.88, n_s=1

- At a given redshift output, choose one axis as the line of sight and compute simulated Lyα spectra of transmission fraction F along all simulation rows.
- Compute 3-D FFT of the F field.
- Compute power spectrum $P_F(k,\mu_k)$, divide by linear power $P_L(k)$
- Fit formula for the non-linear power spectrum (McDonald 2003):

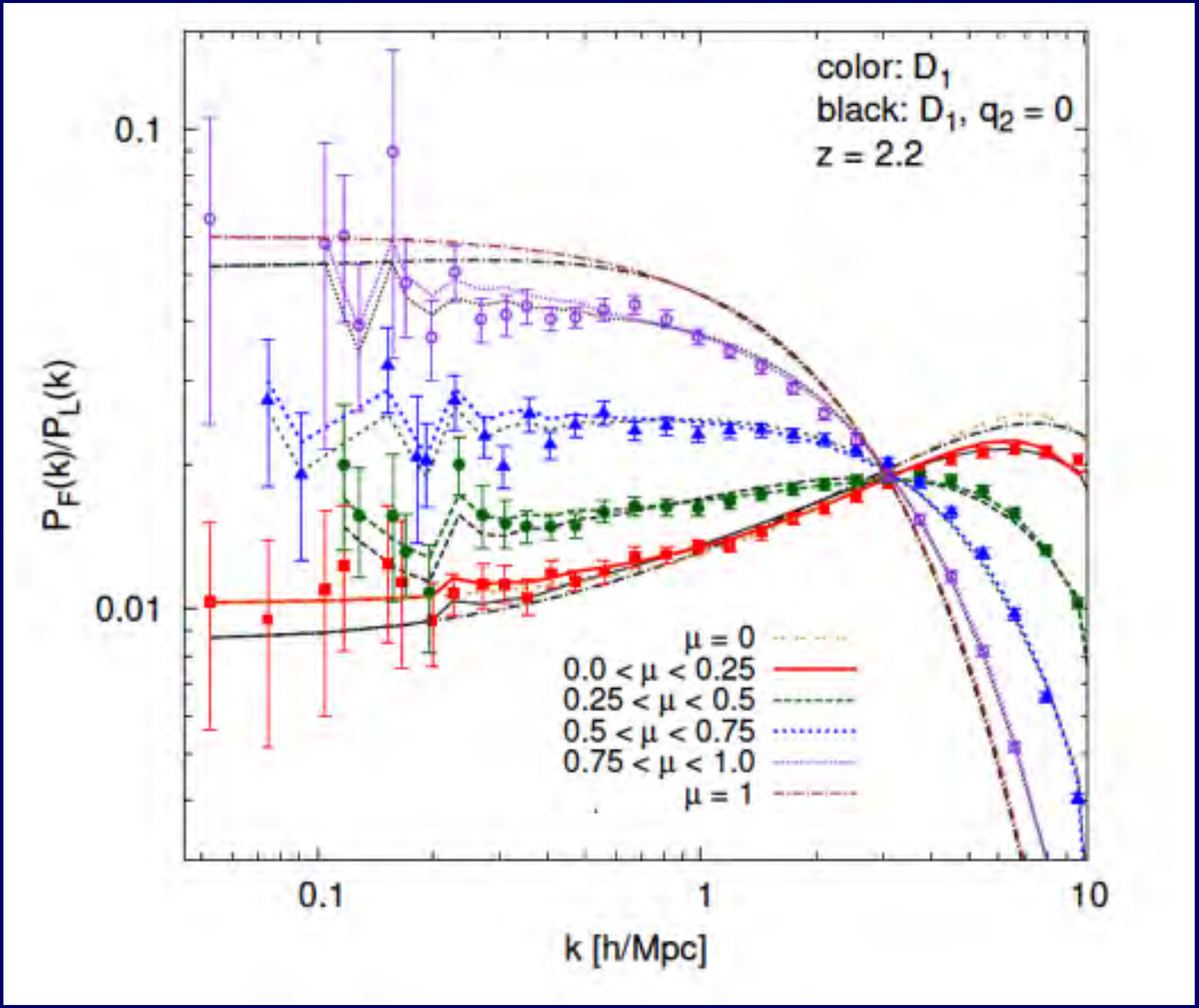
$$P_F(k,\mu) = b_{F\delta}^2 \,(1+\beta\mu^2)^2 \; P_L(k)\, D(k,\mu)$$

Ansatz from perturbation theory:

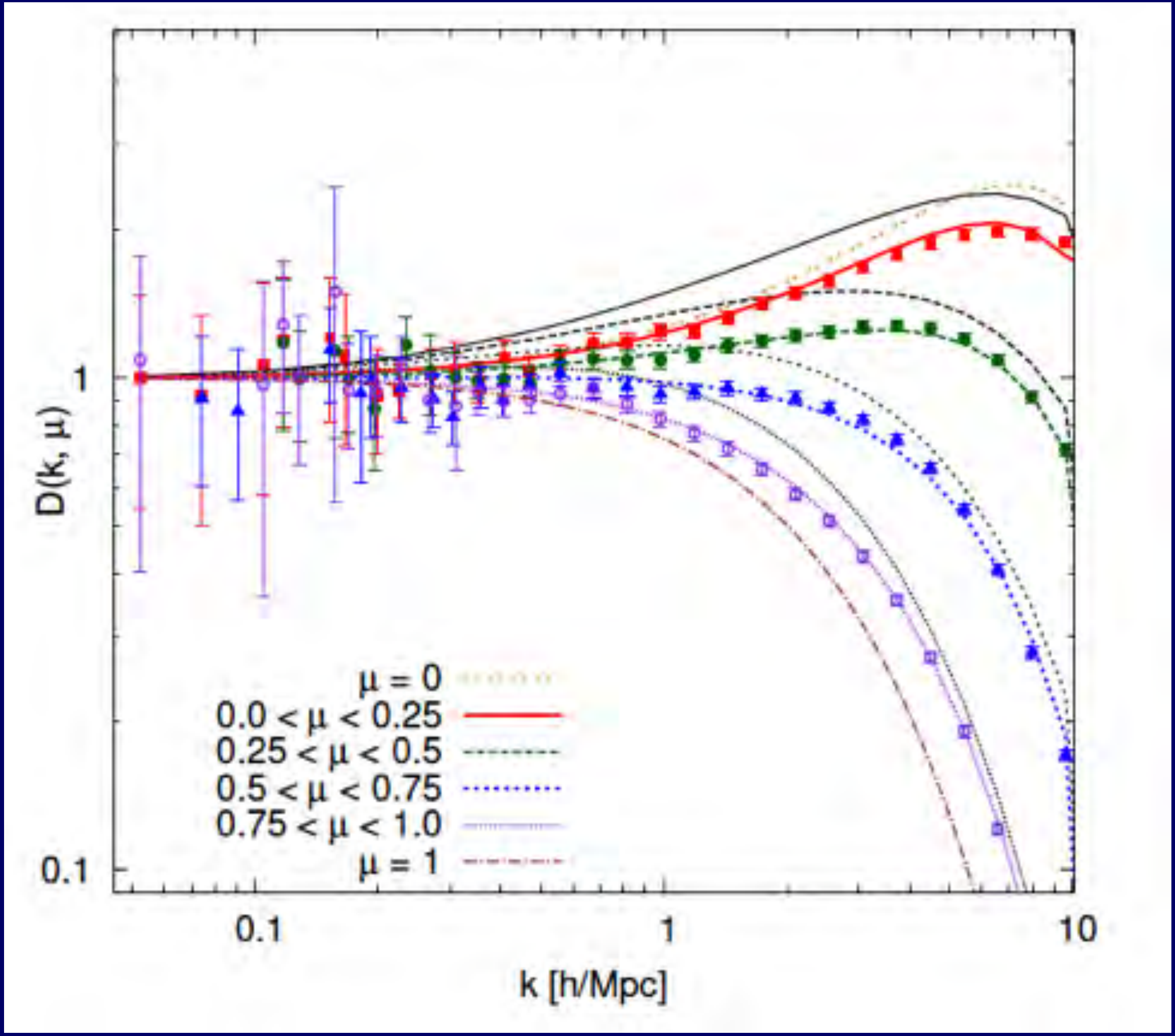
$$\Delta^2(k) = \frac{1}{2\pi^2} k^3 P_L(k)$$

$$D_1(k,\mu) = \exp\left\{ [q_1\Delta^2(k) + q_2\Delta^4(k)] \left[1 - \left(\frac{k}{k_v}\right)^{a_v} \mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2 \right\}.$$

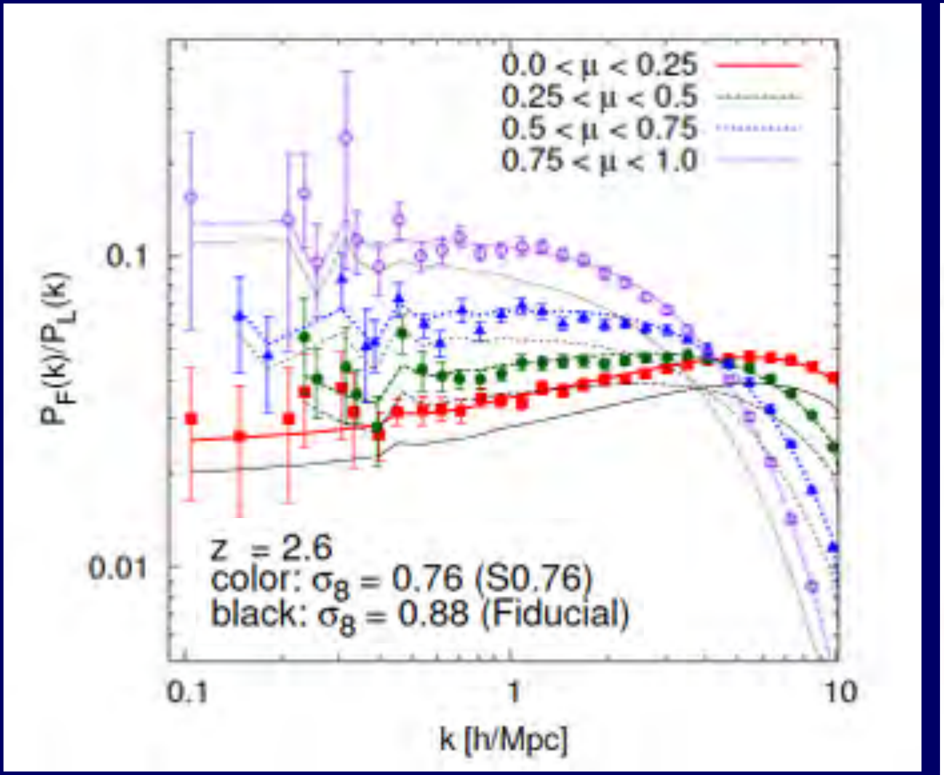
P_F/P_L : 120 Mpc/h box, 768^3 particles

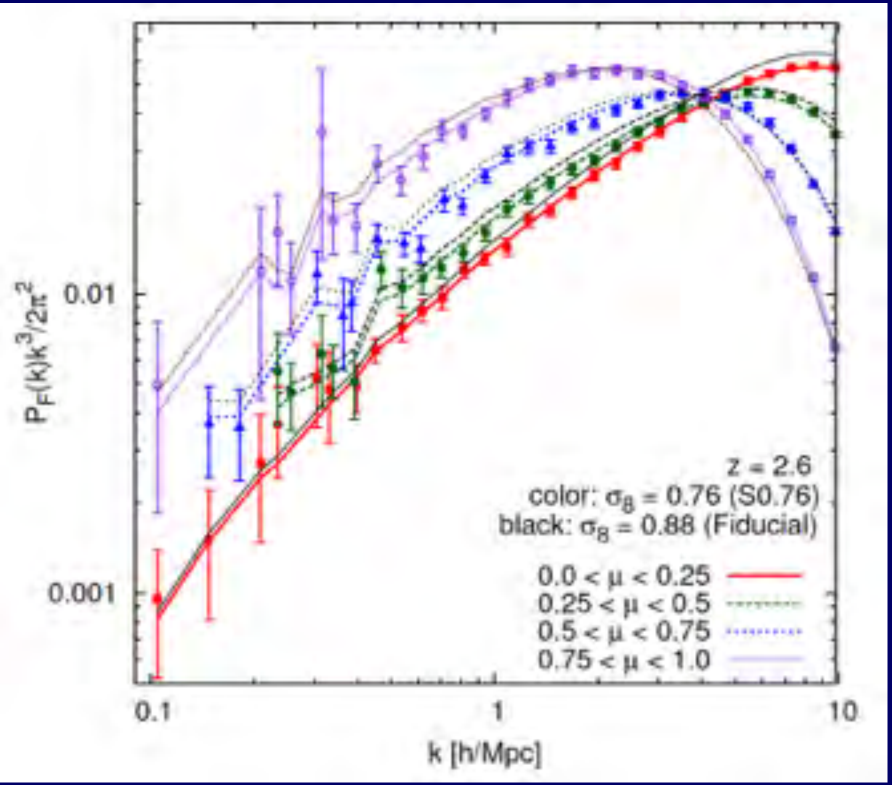


Non-linear correction

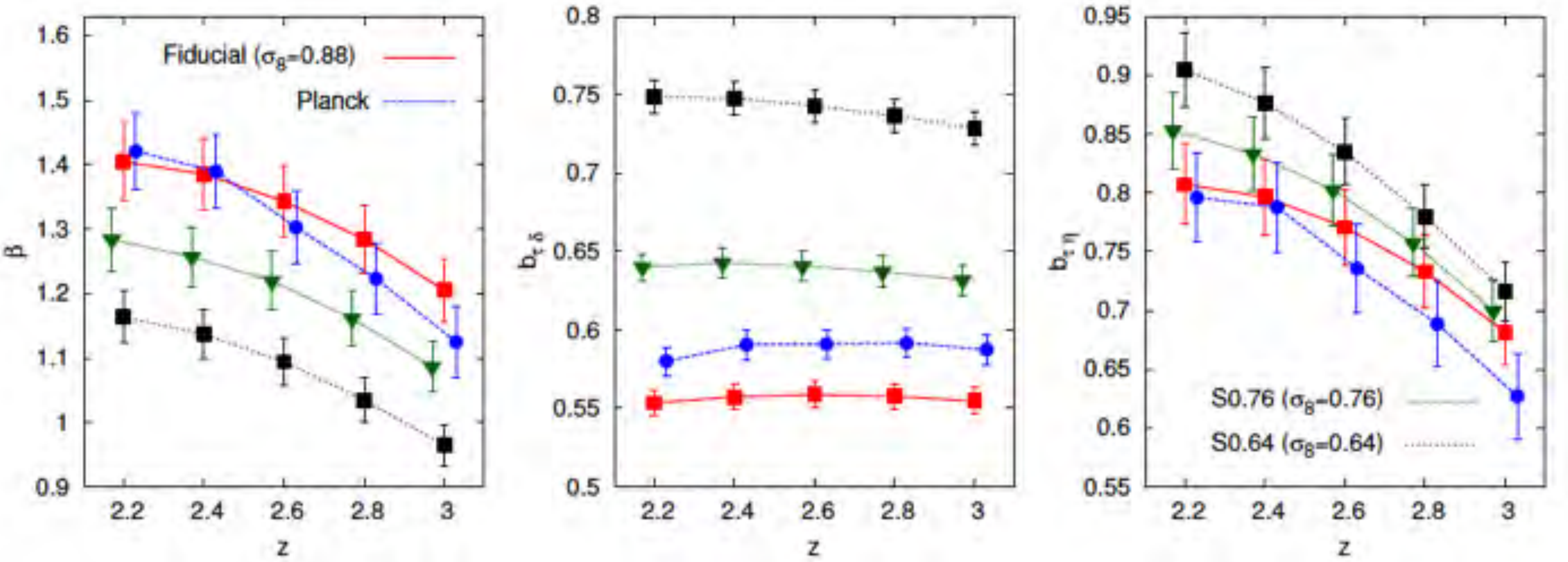


Example of predictions that can be made: dependence on power spectrum amplitude, σ_8





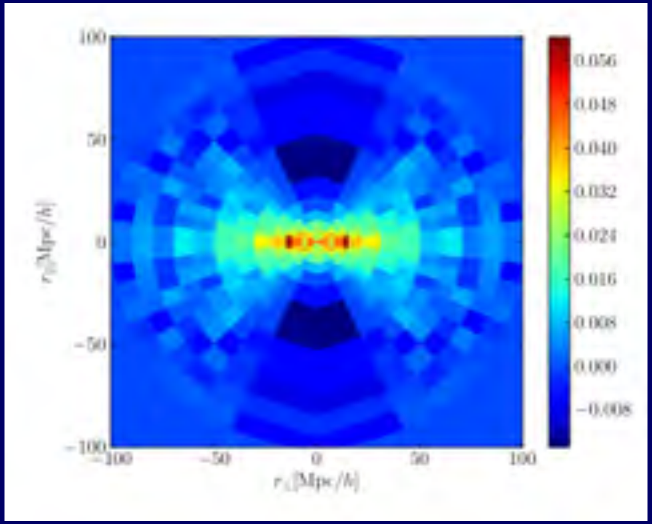
Bias factors for different σ_8

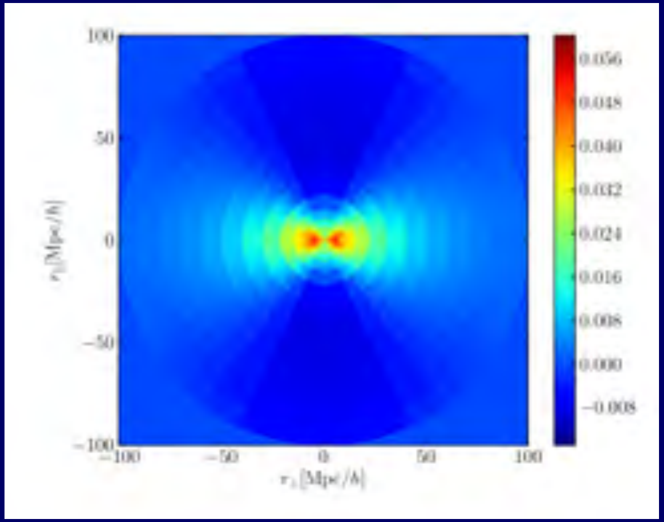


- Transmission power varies weakly with mass power, so density bias factor is nearly inversely proportional to σ_8.
- β increases with σ_8, is greater than 1 and decreases with redshift.
- Physical density bias is around 0.6, nearly flat with redshift.

First year results: redshift distortions
(Slosar et al. 2011)

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





- Fitting model:

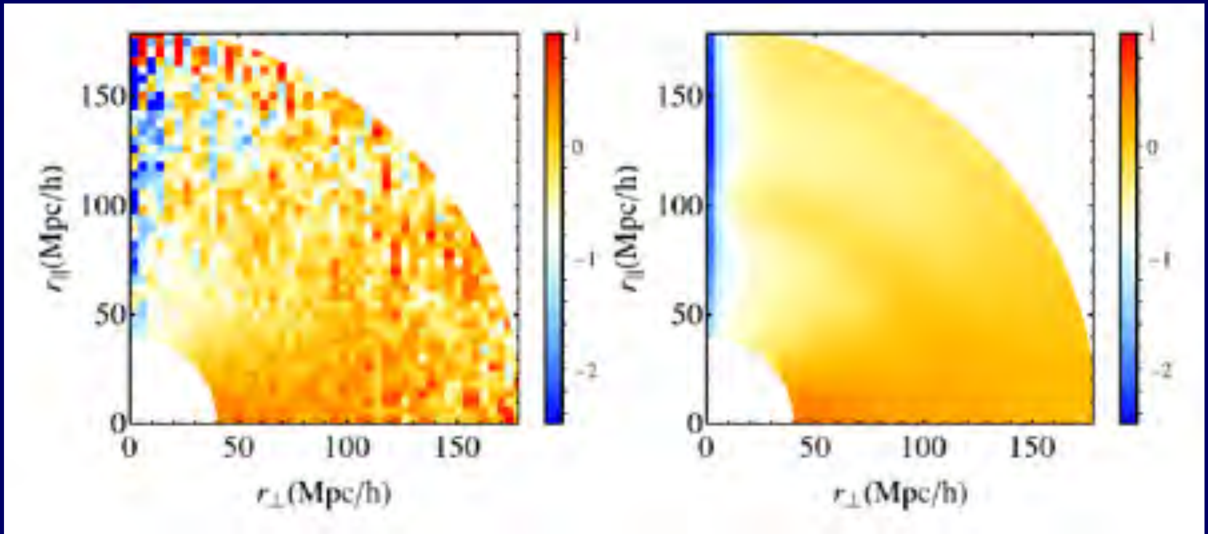
$$P_F(k_\parallel, k_\perp) = P_{CDM}(k) b_\delta^2 (1 + \beta \mu_k^2)^2$$

- Also, from quasar-Lyα cross-correlation, $\beta \approx 1.2$.
- But continuum fitting distortion effects prevented more reliable fits.

$$b_{F\delta}(1+\beta) = -0.35 \pm 0.01$$

$$\beta \approx 1?$$

Blomqvist et al. 2015: DR11 data with an improved method to deal with continuum fitting distortion.

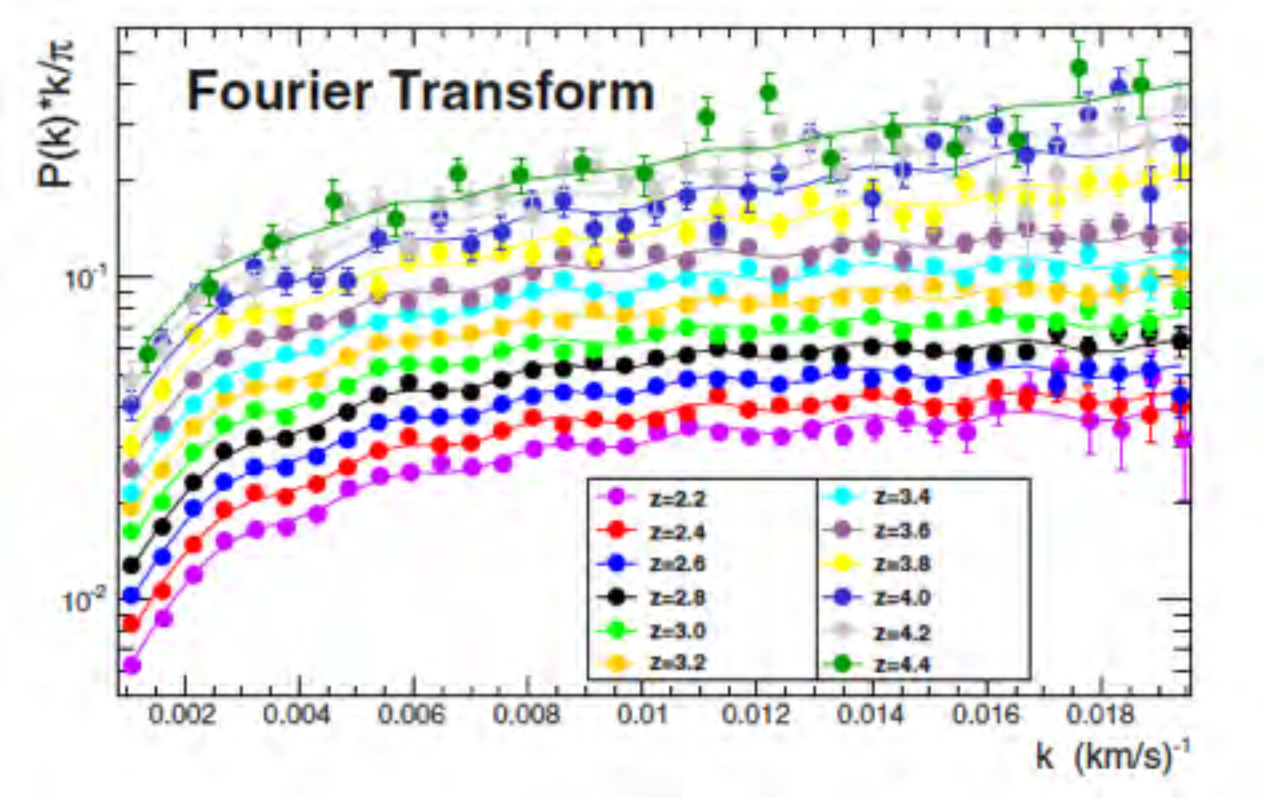


$$b_{F\delta}(1+\beta) = -0.374 \pm 0.007$$
$$\beta = 1.39 \pm 0.11$$

Everything agrees with linear theory so far.

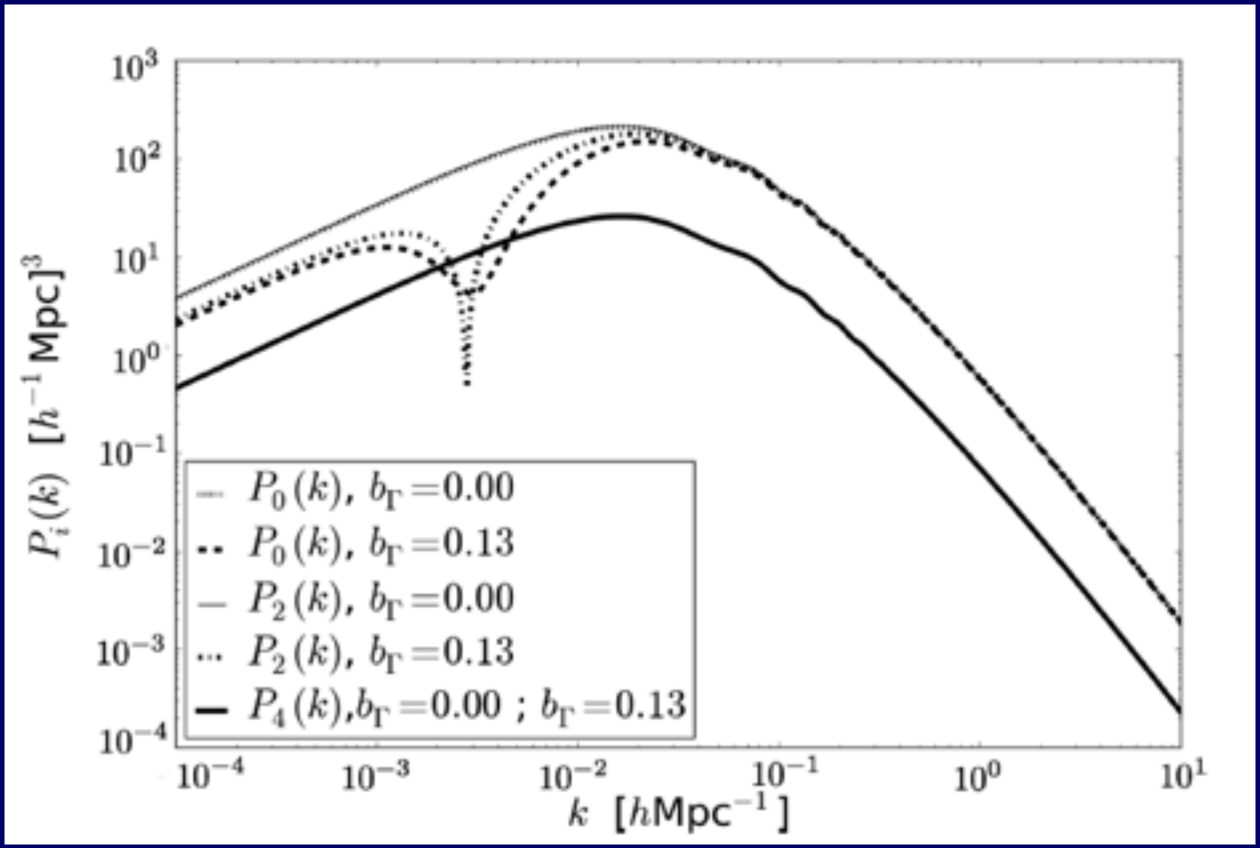
These linear bias factors roughly agree with our results for a model consistent with Planck, although the observed $b_{F\delta}$ is larger than predicted by ~ 20% but there are substantial systematic errors in the prediction and the observational determination.

The non-linear part of the power spectrum has been probed by the 1D power. Full 3D shape should be probed.



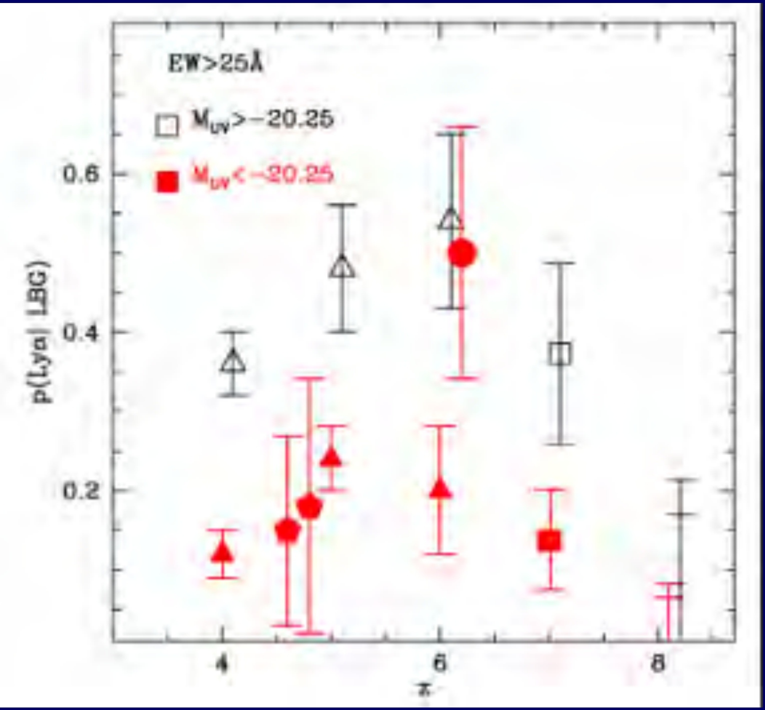
- Palaque-Delabrouille et al. 2013.
- Recent work by Rorai, Waltzer, Hennawi, et al. on using close quasar pairs to probe the Jeans scale.

Example of simple theory modification: large-scale fluctuations in Γ due to source clustering originate a scale-dependent β in the Lyα power spectrum.



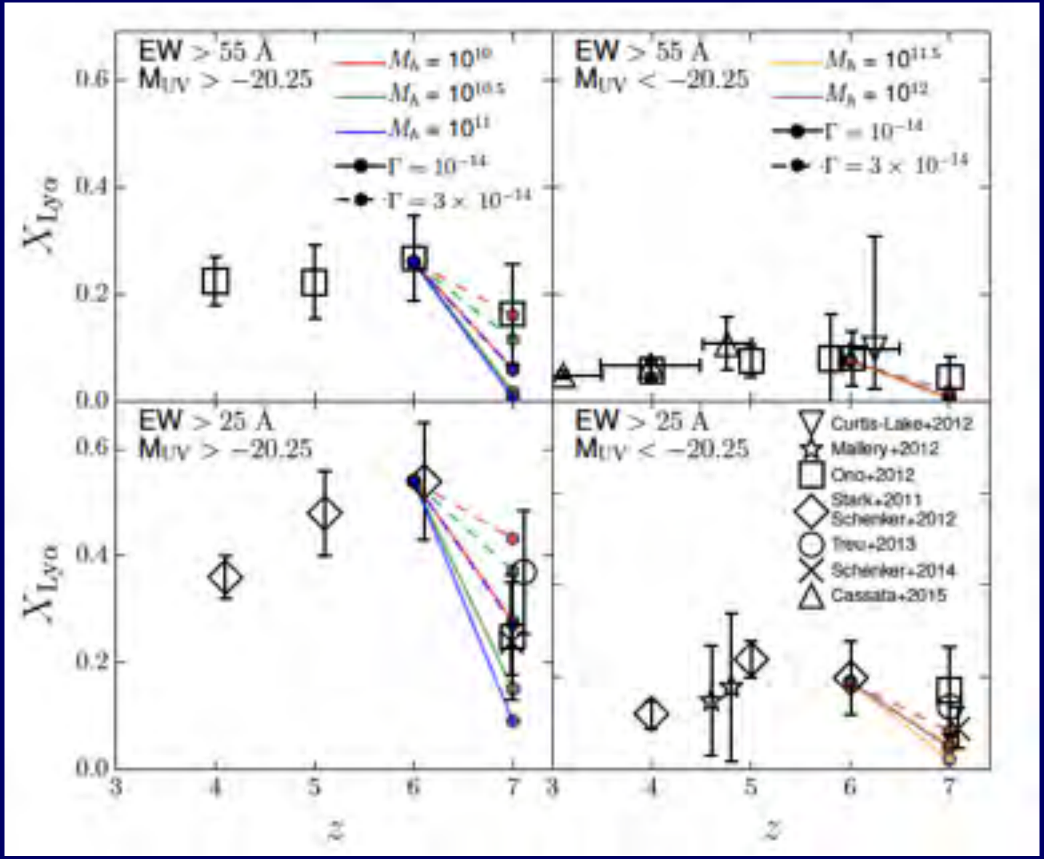
- Gontcho A Gontcho et al. 2014: linear treatment with a simple bias model for the Lyα transmission response to the photoionization rate Γ.

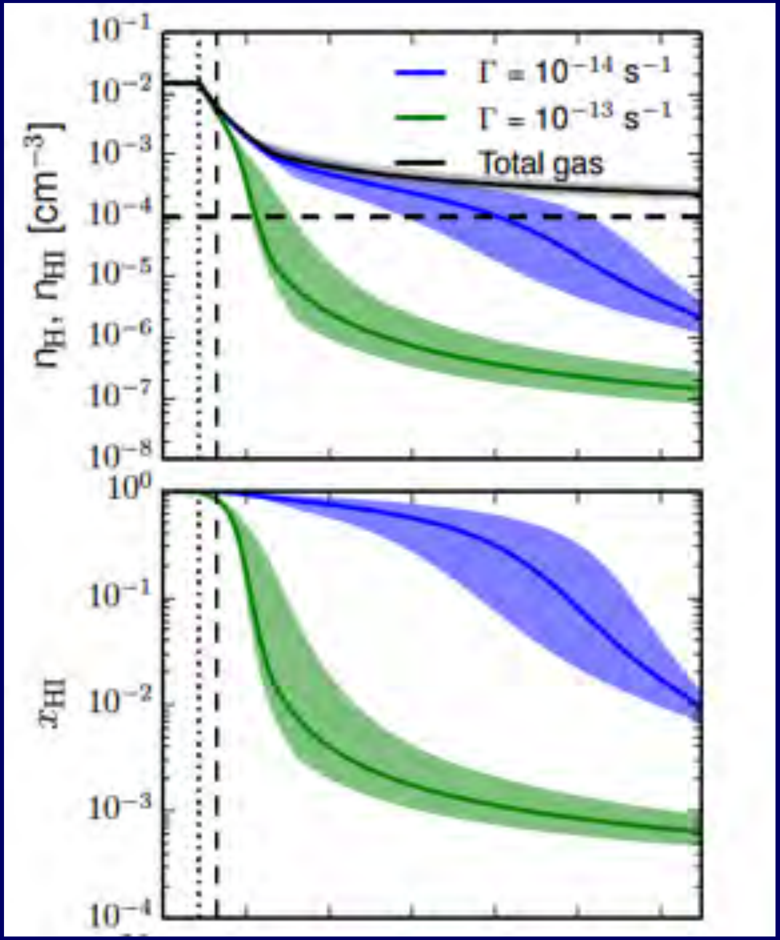
Evolution of Lyα emitters: probe of reionization through the blocking of Lyα emission line by damped absorption from neutral IGM.



- It is difficult to account for the observed drop because neutral regions should not be increasing so abruptly.
- How about if the medium that is increasingly neutral is close to the galaxies? Can it be the infall region, between the virialization radius and turnaround radius?

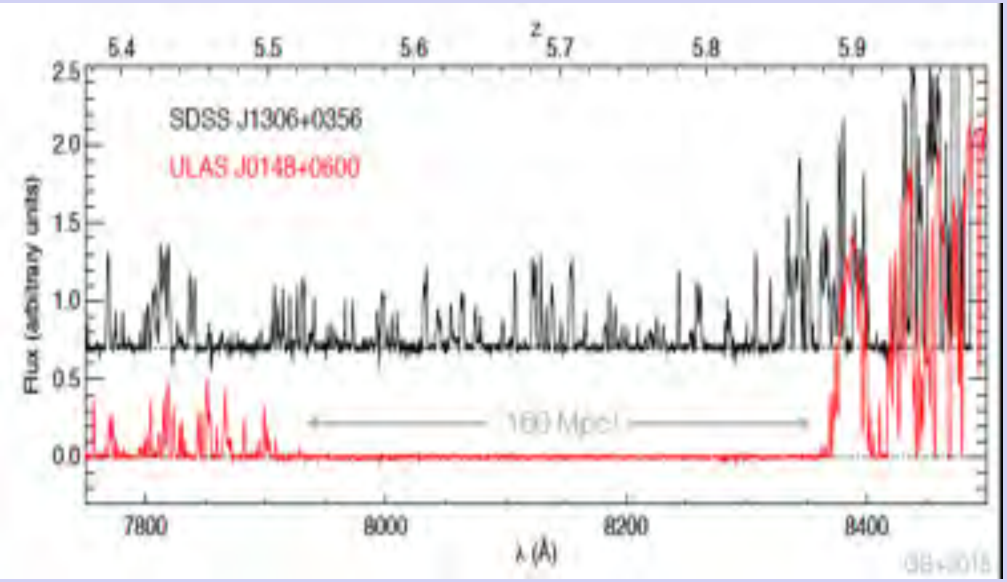
The infall region around galaxies changes from self-shielded to ionized just before reionization (Sadoun+ 16)

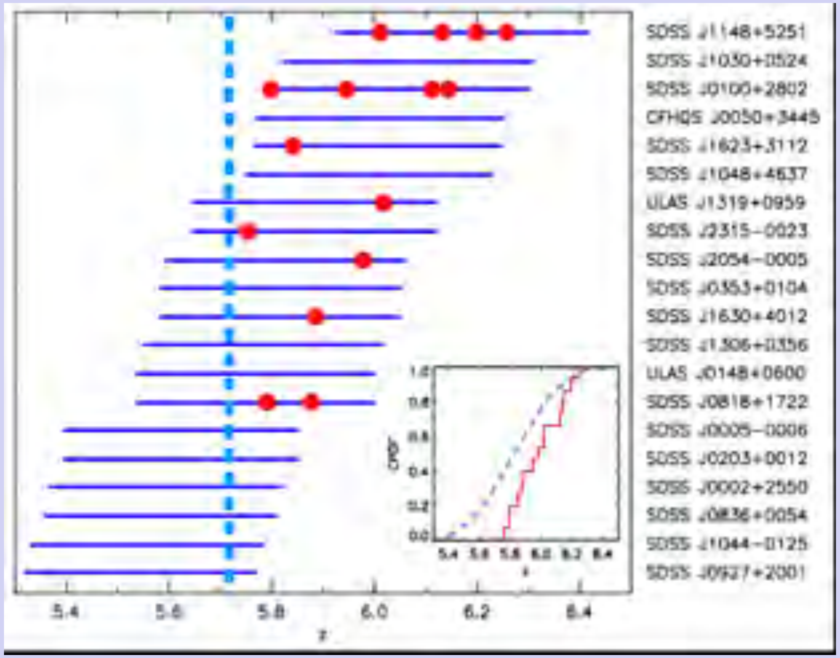




- A moderate factor of 3 change in Γ can account for change in Lyα emitters from z=6 to z=7.

- Fluctuations in mean free path: how do we model them? (Davies & Furlanetto).
- Evolution in OI: can we infer the late stages of reionization from this?





Becker & Pettini