Cross-correlating the Forest

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Outline

- Why cross-correlations?
- DLA - LyaF cross-correlation
- QSO - LyaF cross-correlation
- BAO in cross-correlation

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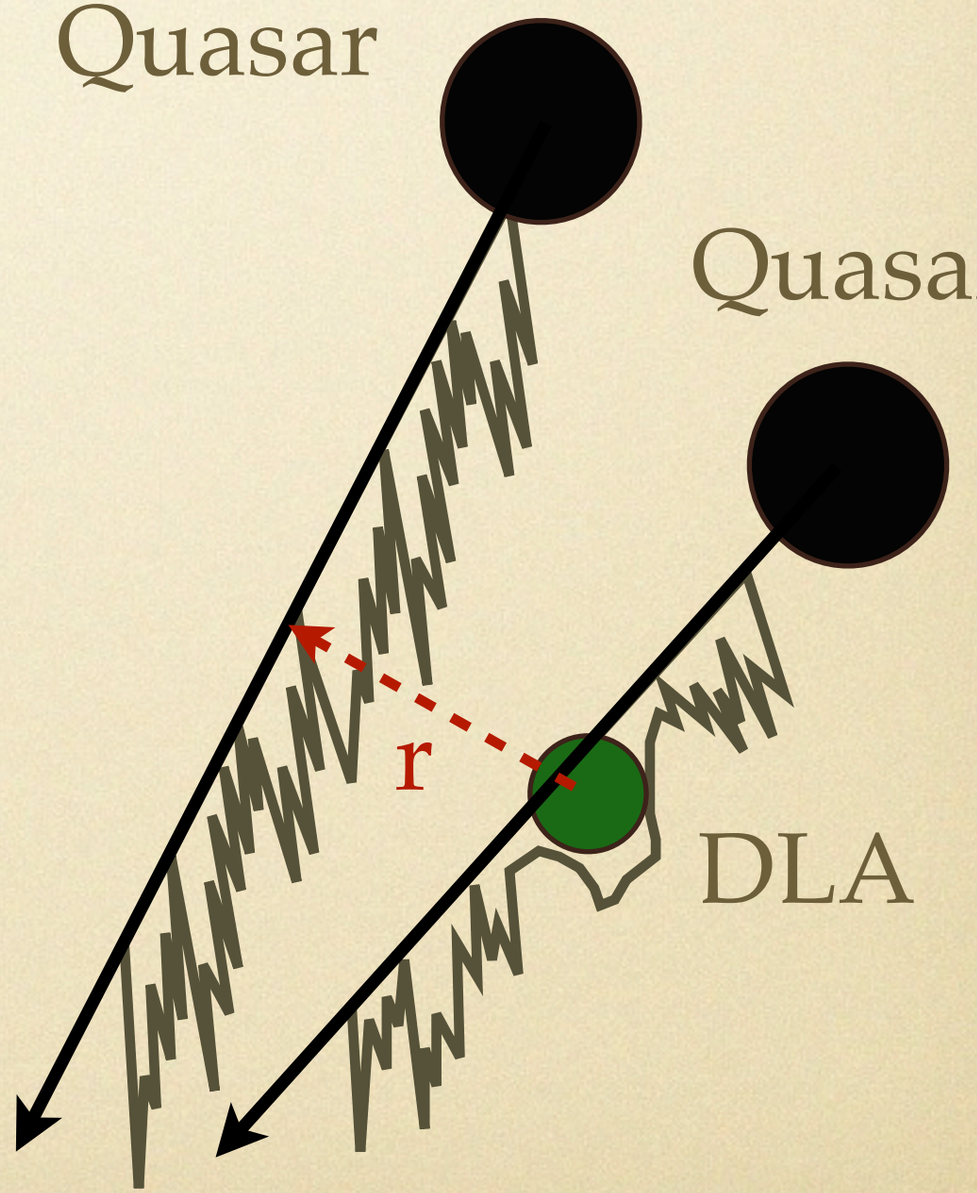
- **Why cross-correlations?**
- DLA - LyaF cross-correlation
- QSO - LyaF cross-correlation
- BAO in cross-correlation

Why cross-correlations?

- Study clustering of sparse systems (DLAs, metal absorbers, anything you give me...)
- Quasar radiation models
- Cosmology!

Clustering of sparse systems



Clustering of sparse systems

On large scales :

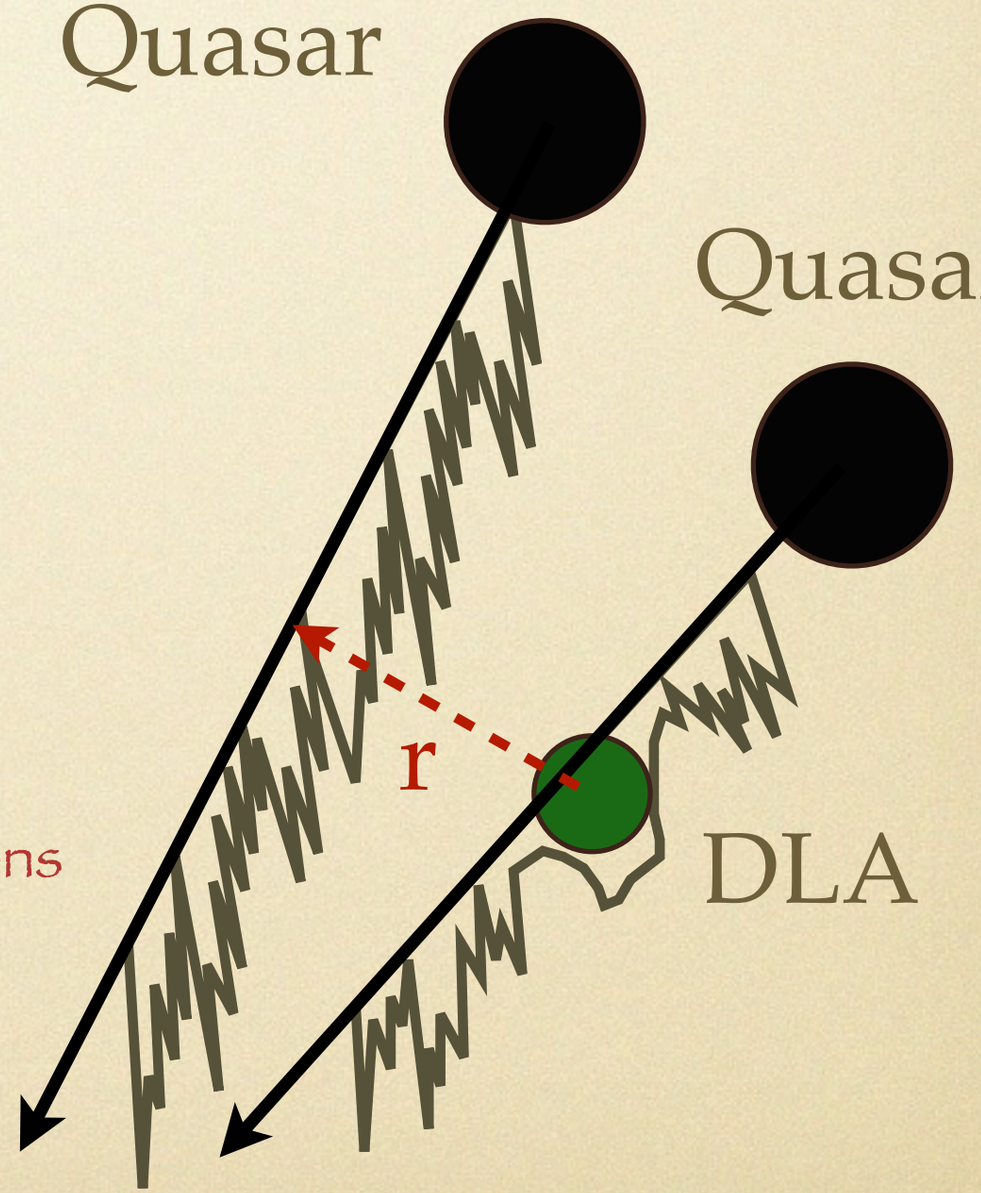
Cross-correlation (measurement)

Ly α Forest bias (known)

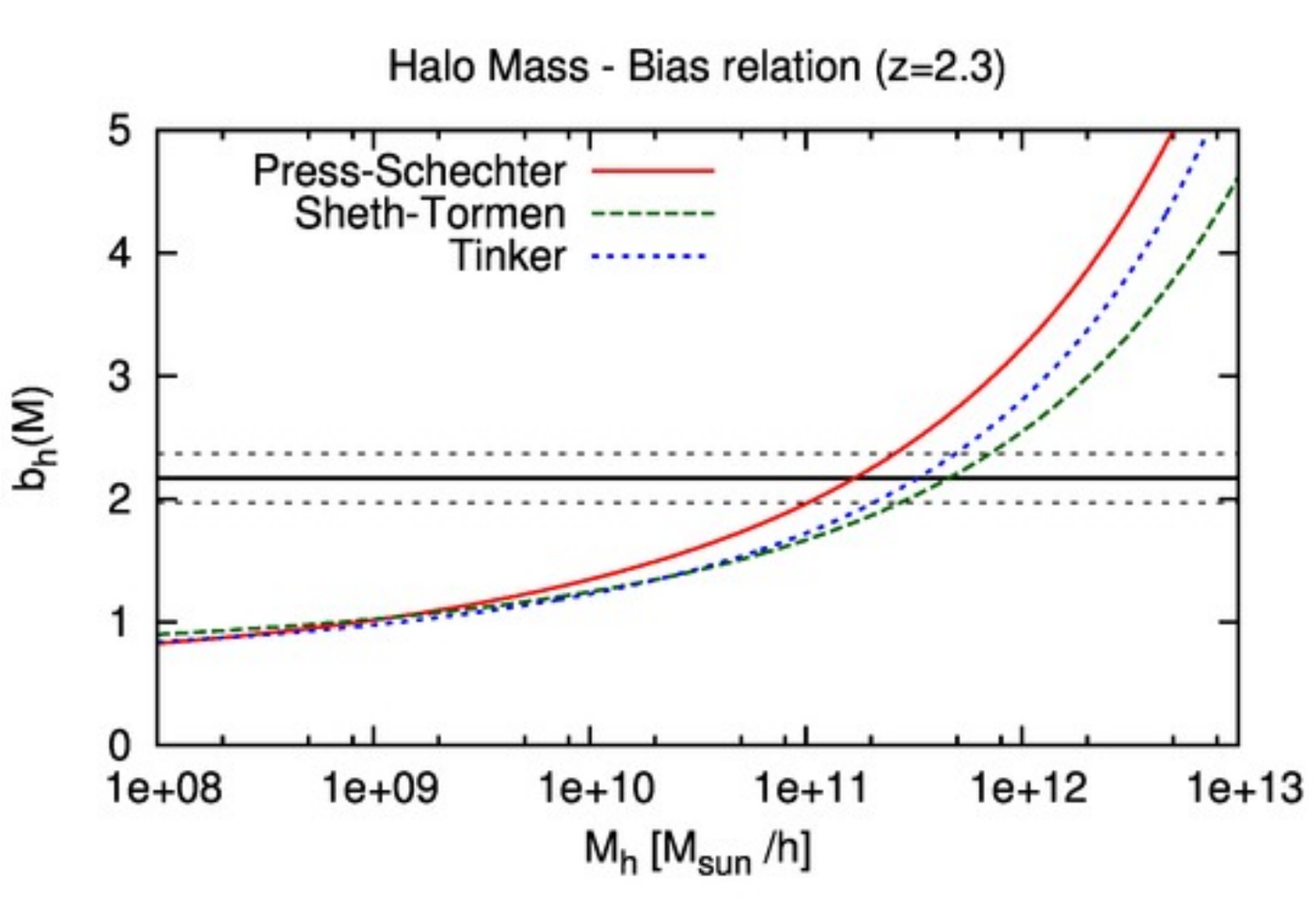
$$\xi_{DF}(r) = b_D \, b_F \, \xi_m(r)$$

DLA bias (main result)

Density correlations (known)



Clustering of sparse systems



Linear bias ---> Host halo mass

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- QSO - LyaF cross-correlation
- BAO in cross-correlation

DLA x LyaF

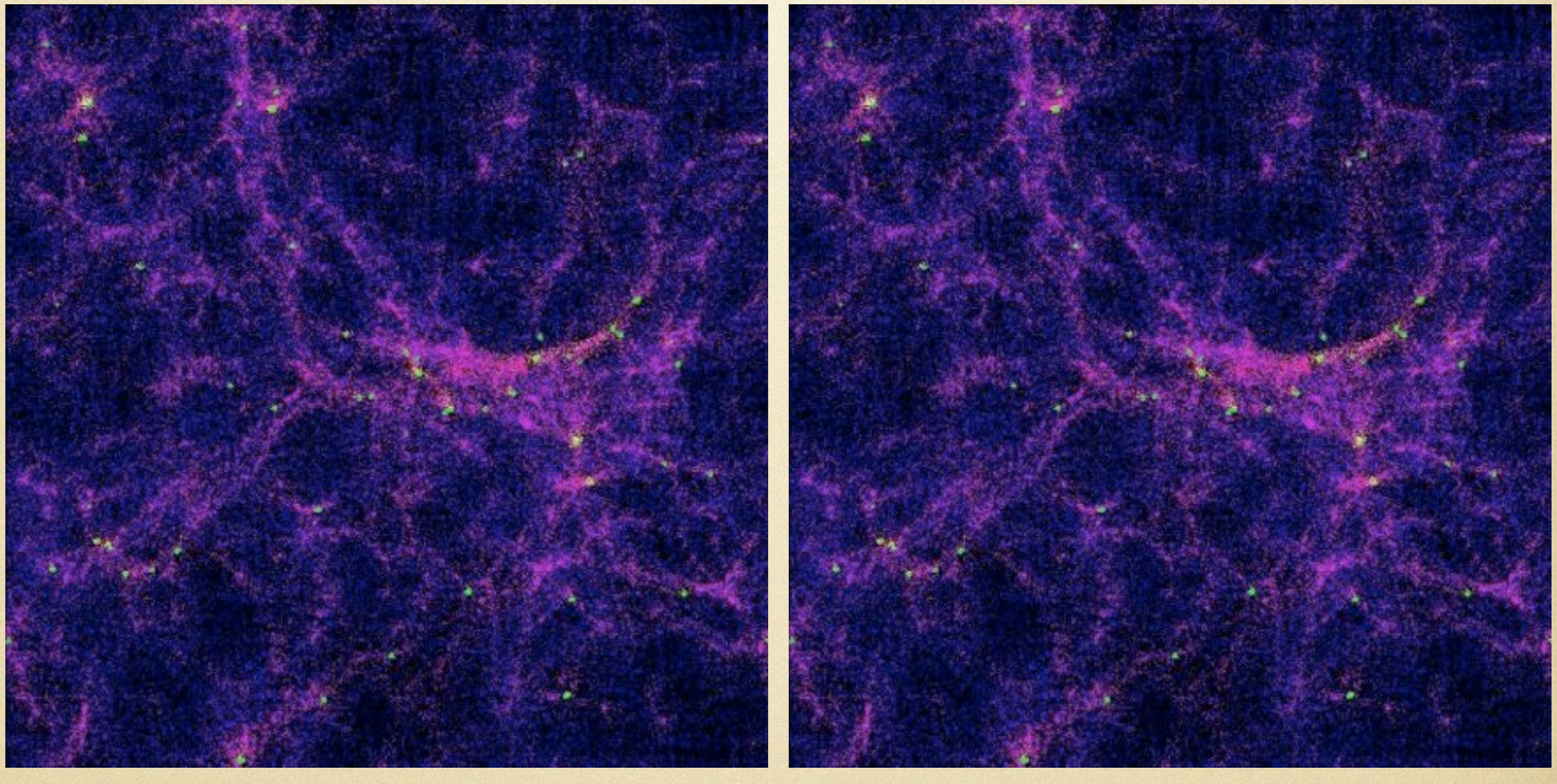
The large-scale cross-correlation of Damped Lyman alpha systems with the Lyman alpha forest: first measurements from BOSS

Andreu Font-Ribera,[a,b] **Jordi Miralda-Escudé,**[c,d] **Eduard Arnau,**[d] **Bill Carithers,**[b] **Khee-Gan Lee,**[e] **Pasquier Noterdaeme,**[f] **Isabelle Pâris,**[f,g] **Patrick Petitjean,**[f] **James Rich,**[h] **Emmanuel Rollinde,**[f] **Nicholas P. Ross,**[b] **Donald P. Schneider,**[i,j] **Martin White**[b,k] **and Donald G. York**[l]

ArXiv : 1209.4596 (published in JCAP)

DLA x LyaF

~ 10% of BOSS spectra have a DLA



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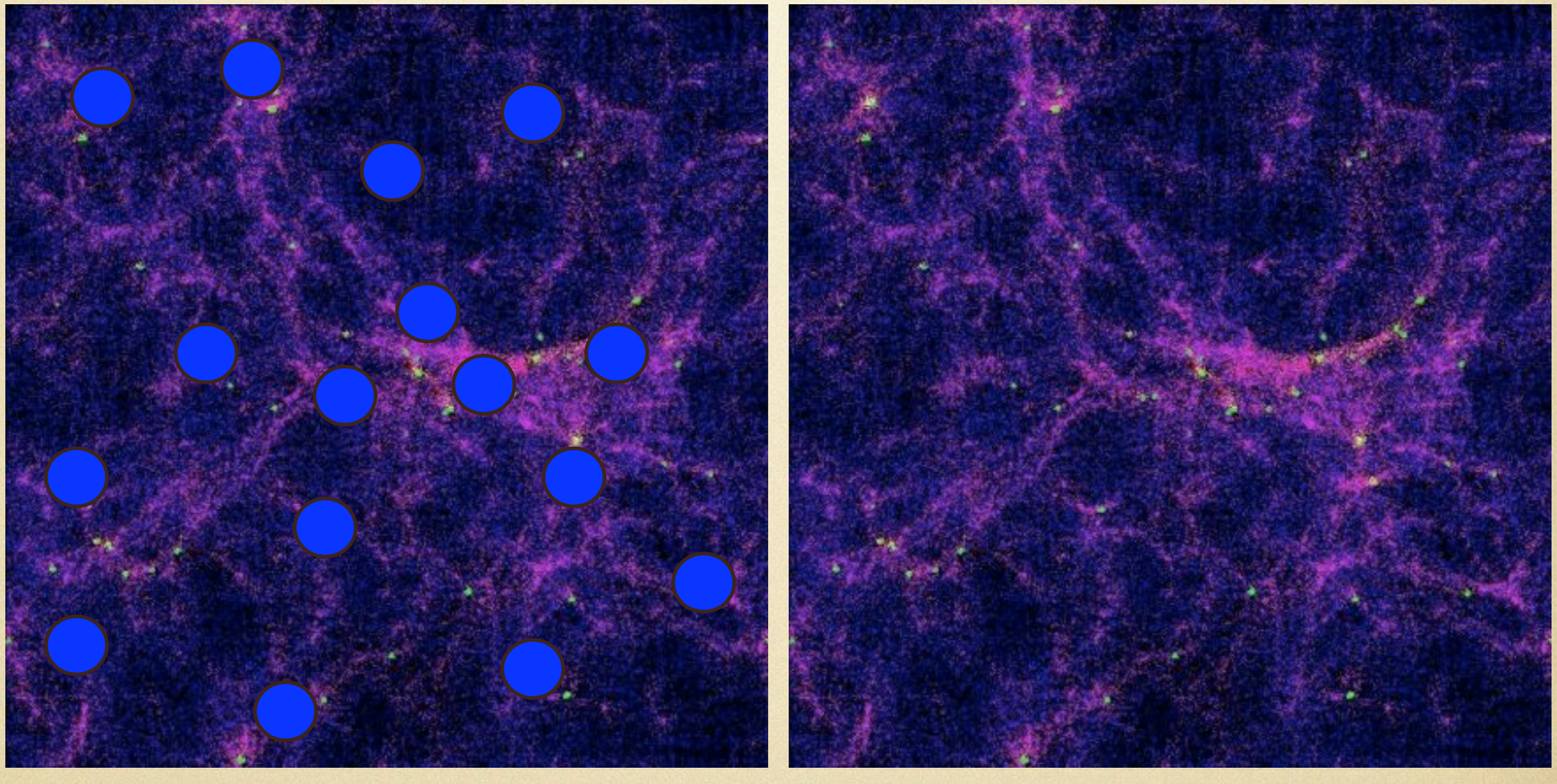

Lots of small DLAs ?

DLA x LyaF

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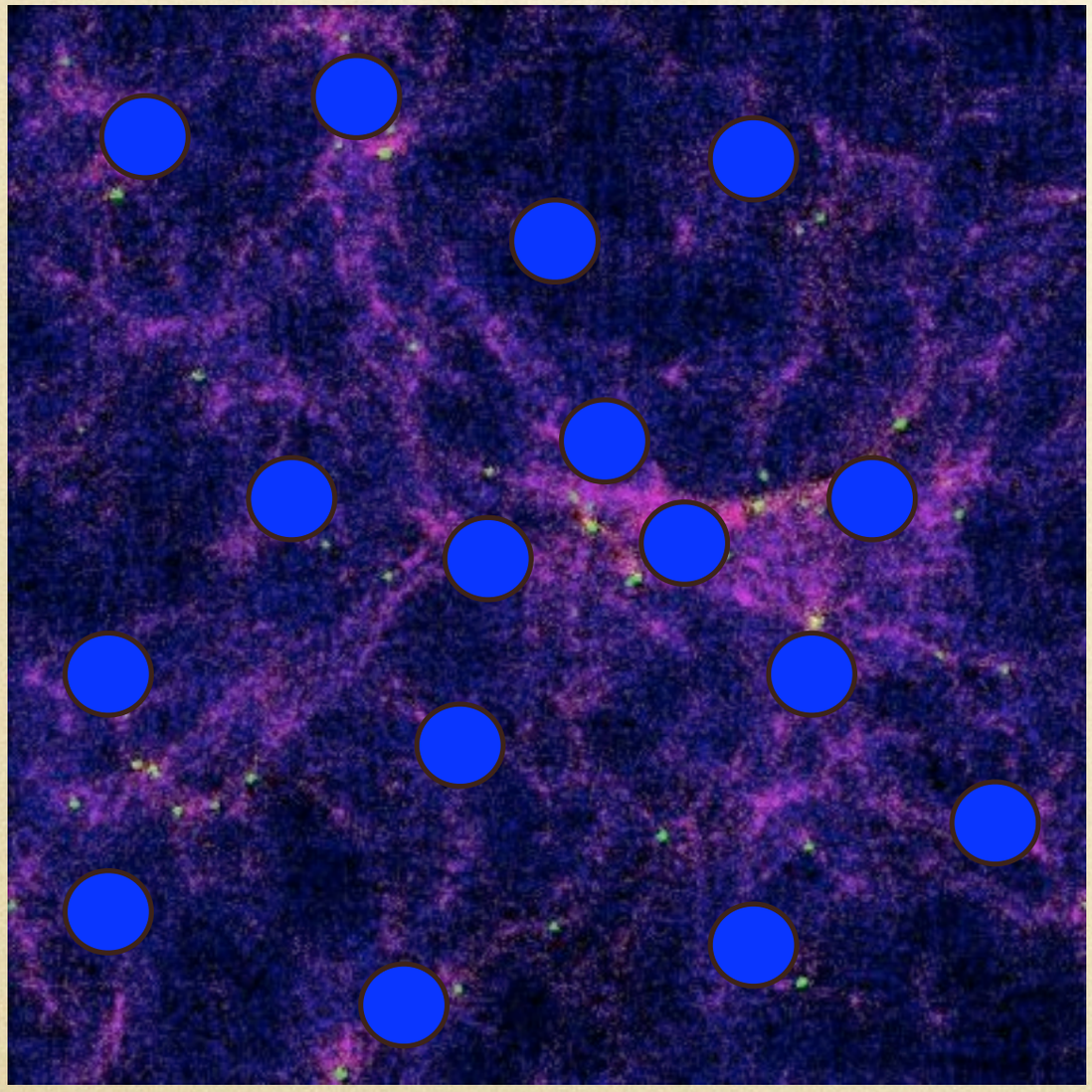

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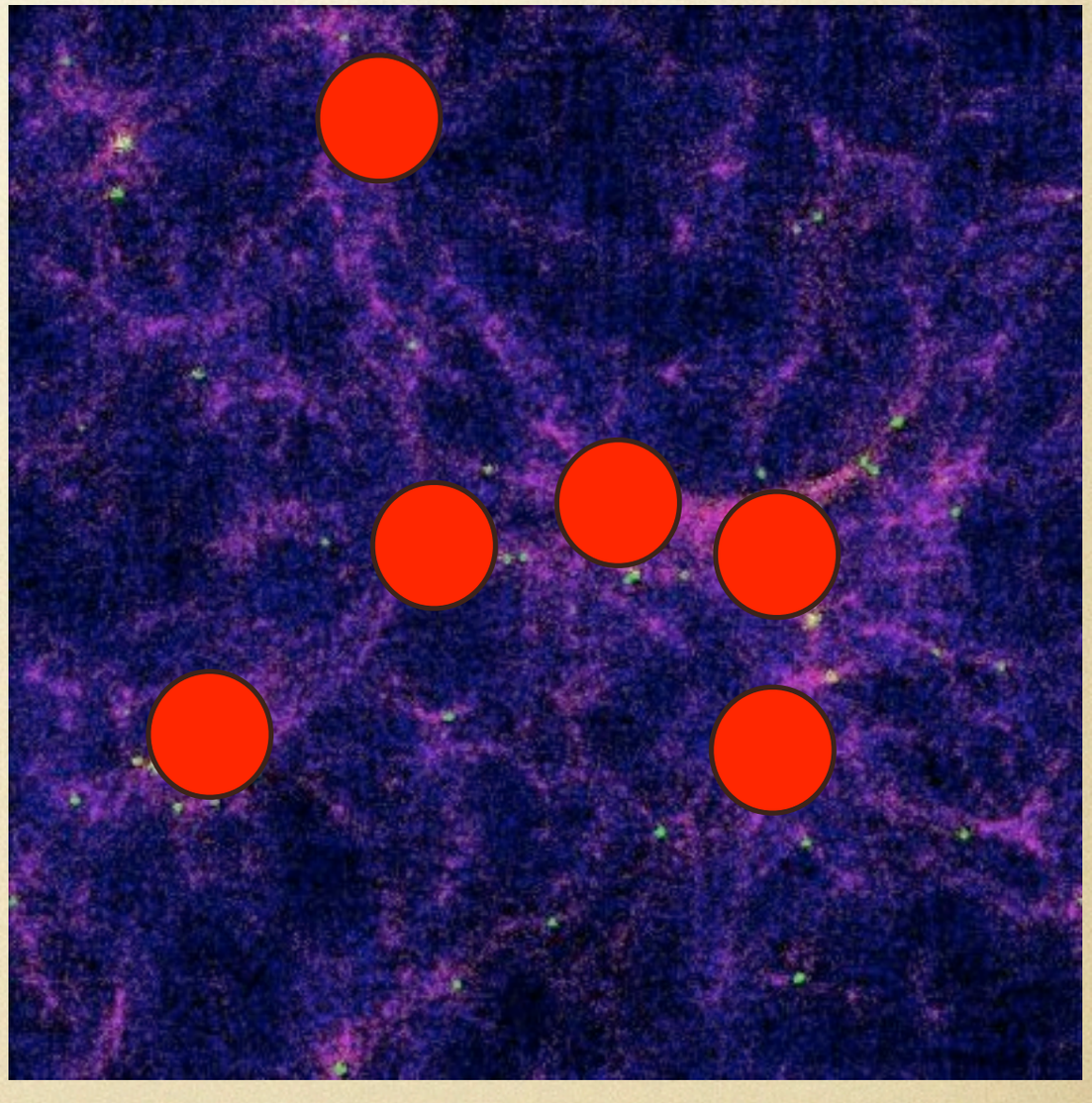
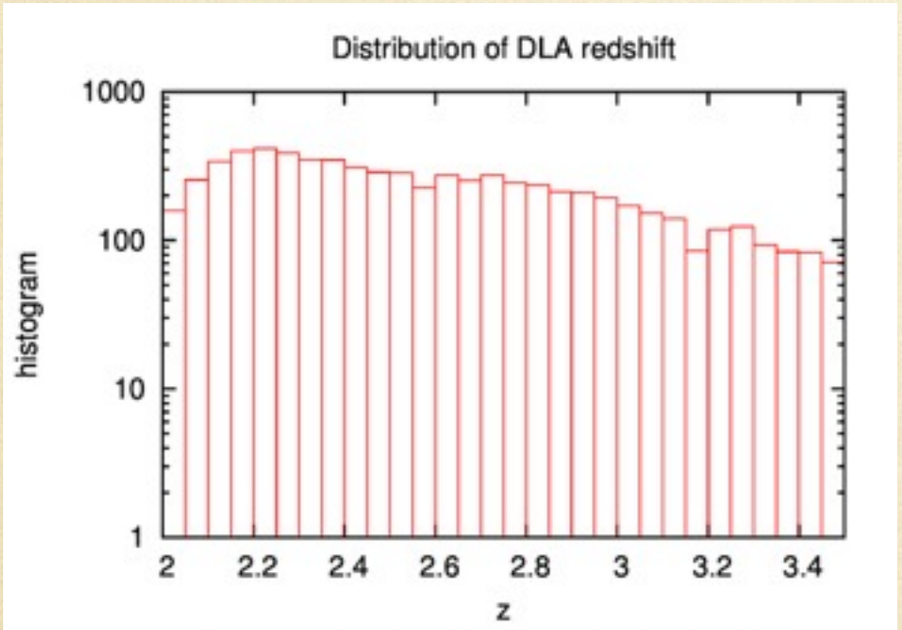
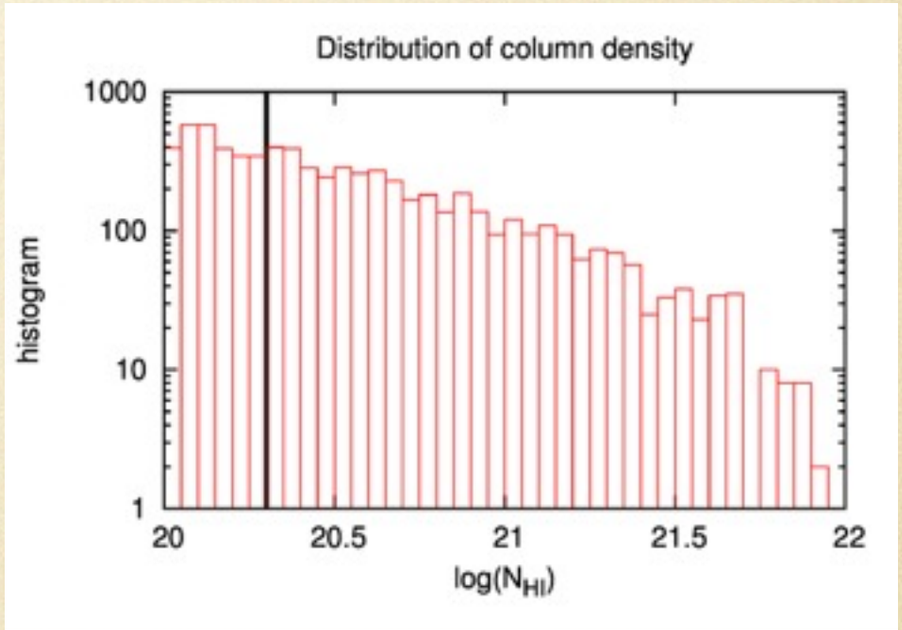


Few huge DLAs ?

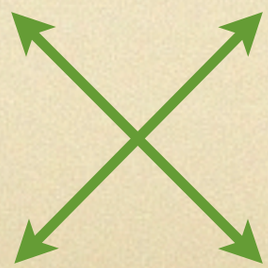
DLA x LyaF

DR9 DLA Catalogue (Noterdaeme++ 2012)





DR9 DLA Catalog :
> 8000 systems
20 < log(N) < 22
CNR > 4

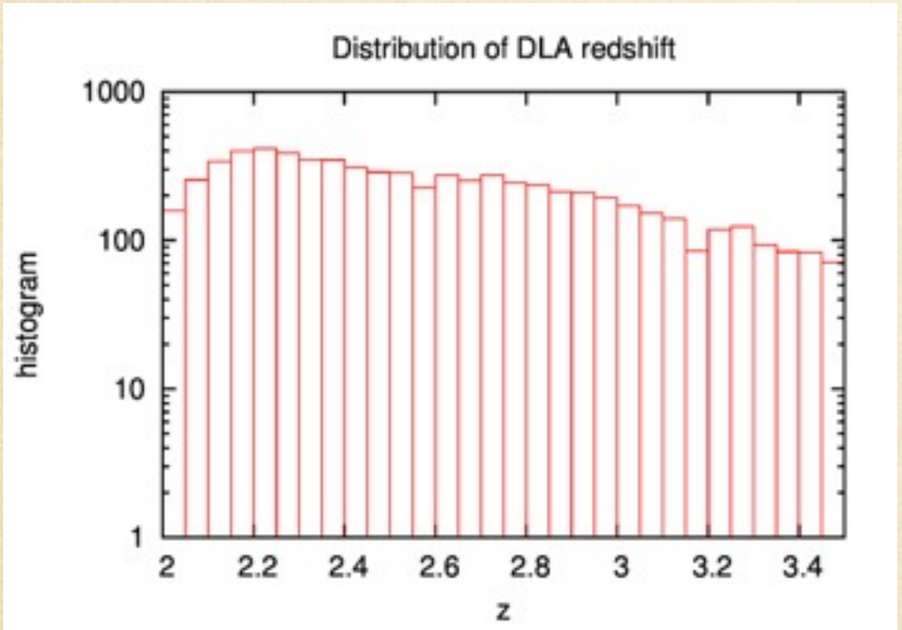


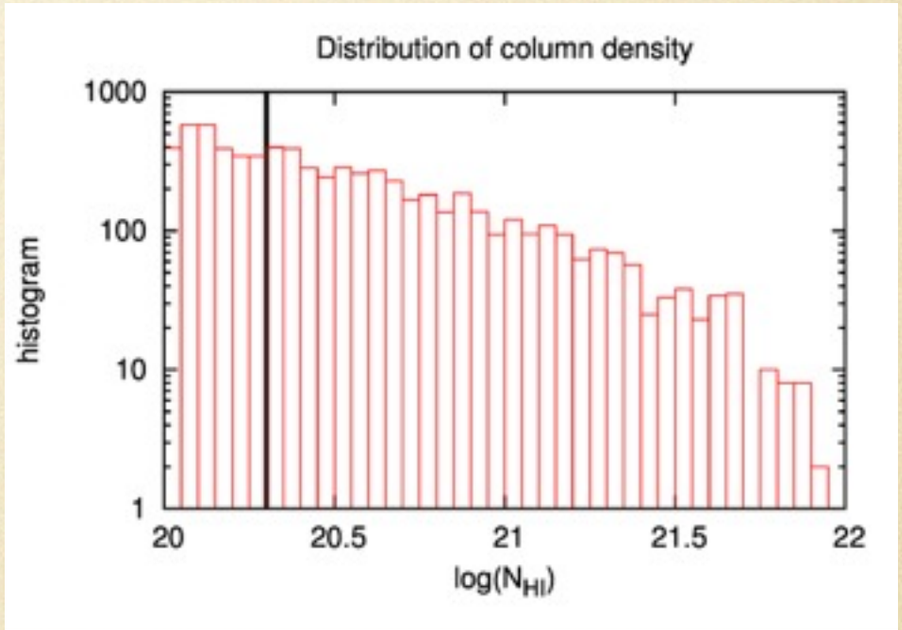
DR9 LyaF Catalog :
> 60000 “good” spectra
2.1 < z < 3.5

Cross-Correlate

DLA x LyaF

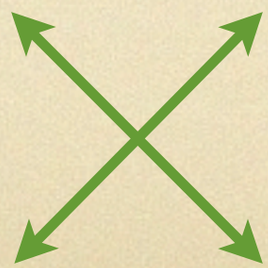
DR9 DLA Catalogue (Noterdaeme++ 2012)





Yes, we include sub-DLAs

DR9 DLA Catalog :
> 8000 systems
20 < log(N) < 22
CNR > 4



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Cross-Correlate

DLA x LyaF

The crosscorrelation of the Lyα absorption field $F(\mathbf{x}) = \bar{F}\left[1 + \delta_F(\mathbf{x})\right]$ with any field of objects (galaxies, quasars, DLAs, etc.) $g(\mathbf{x}) = \bar{g}\left[1 + \delta_g(\mathbf{x})\right]$.

We define the crosscorrelation function as

$$\xi_{Fg}(\mathbf{r}) = \left\langle \delta_g(\mathbf{x})\, \delta_F(\mathbf{x}+\mathbf{r}) \right\rangle \ , \tag{5.3.1}$$

or equivalently,

$$\left\langle F(\mathbf{x})\, g(\mathbf{x}+\mathbf{r}) \right\rangle = \bar{F}\, \bar{g}\left[1 + \xi_{Fg}(\mathbf{r})\right] \ . \tag{5.3.2}$$

Because the galaxy field $g(\mathbf{x})$ can only take the values 0 or 1, the crosscorrelation of this field with any other field will be

$$\left\langle g(\mathbf{x})\, F(\mathbf{x}+\mathbf{r}) \right\rangle = \bar{g}\ \left\langle F(\mathbf{r}) \right\rangle_g \ , \tag{5.3.3}$$

and

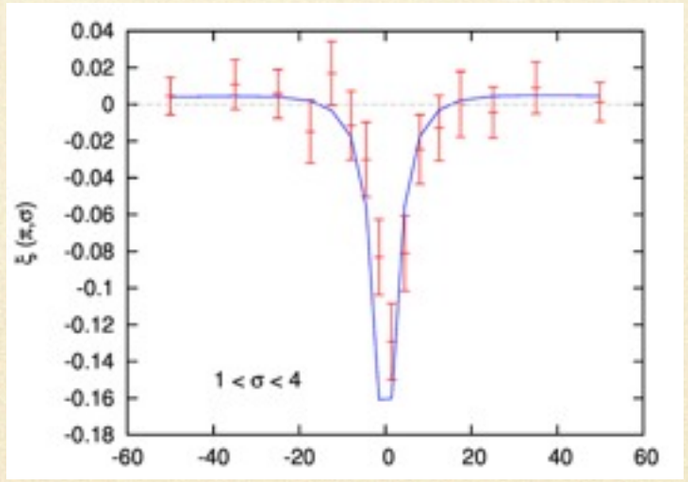
$$\xi_{gF}(\mathbf{r}) = \left\langle \delta_g(\mathbf{x})\, \delta_F(\mathbf{x}+\mathbf{r}) \right\rangle = \left\langle \delta_F(\mathbf{r}) \right\rangle_g \ , \tag{5.3.4}$$

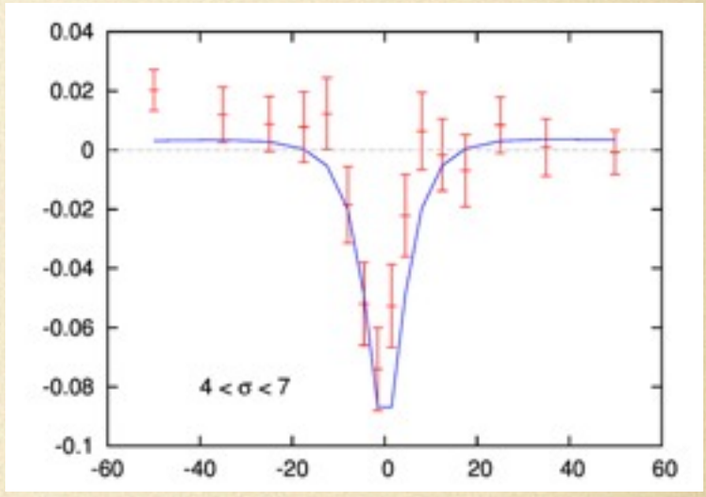
where $\left\langle X(\mathbf{r}) \right\rangle_g$ is the average of any field X over pixels at a distance $\mathbf{r}$ from a galaxy.

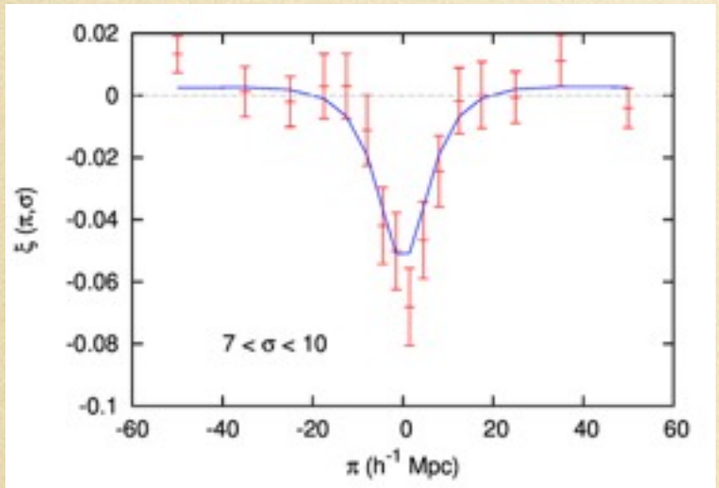
DLA x LyaF

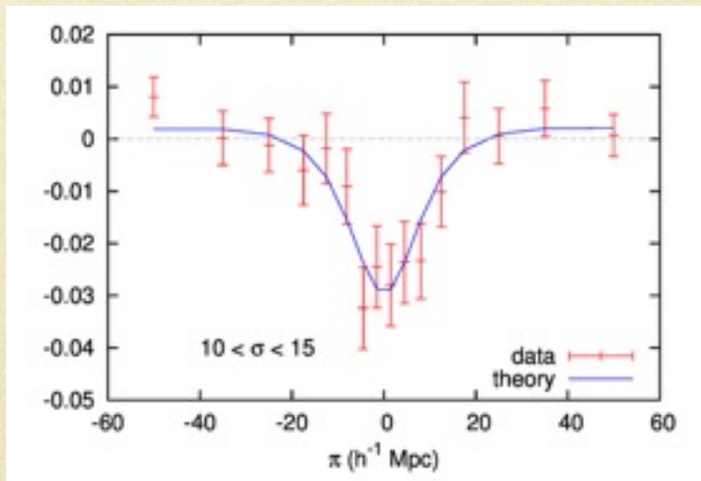
128 correlated bins

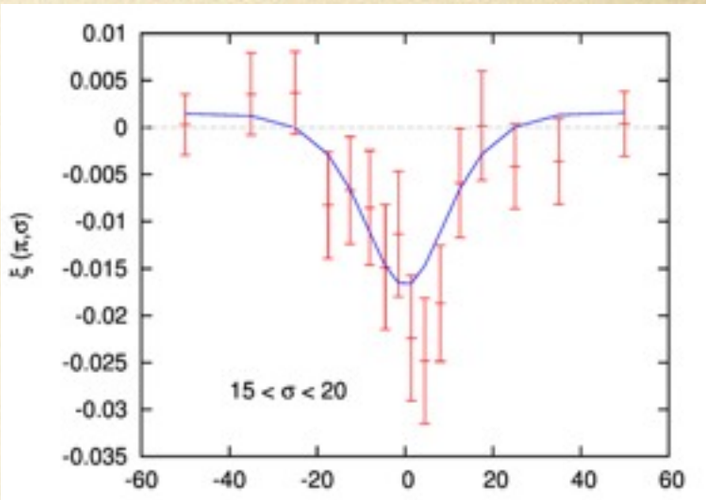
up to 60 Mpc/h

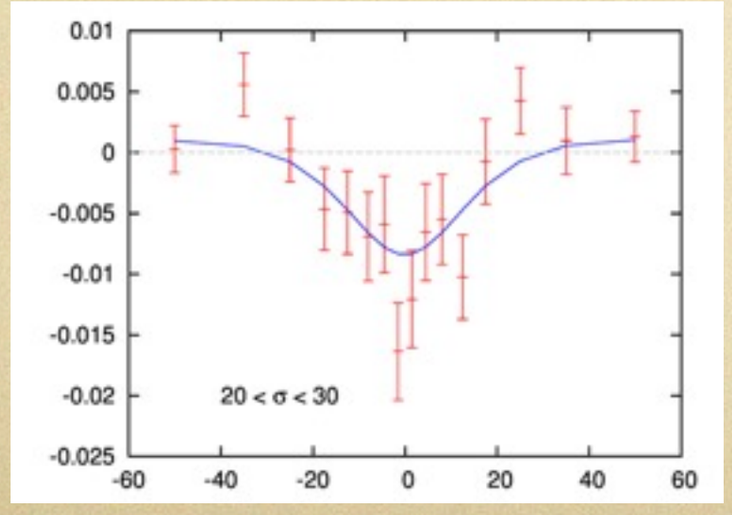


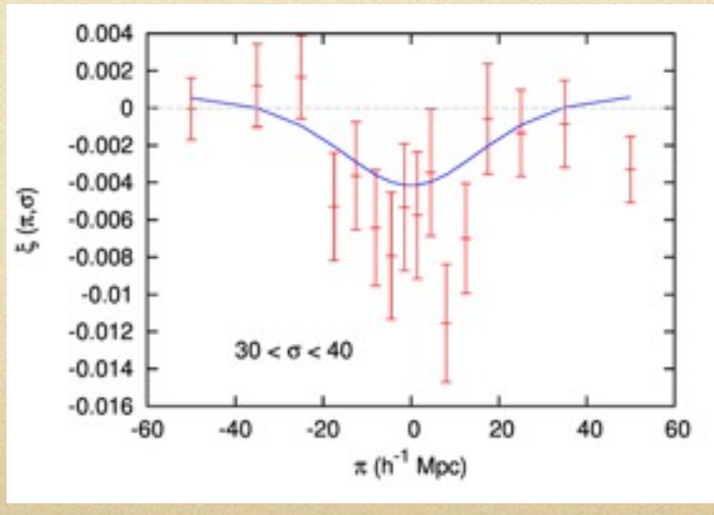


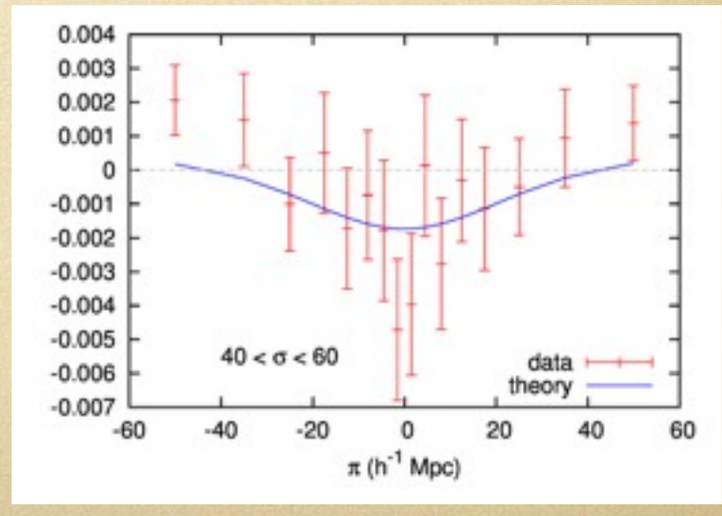








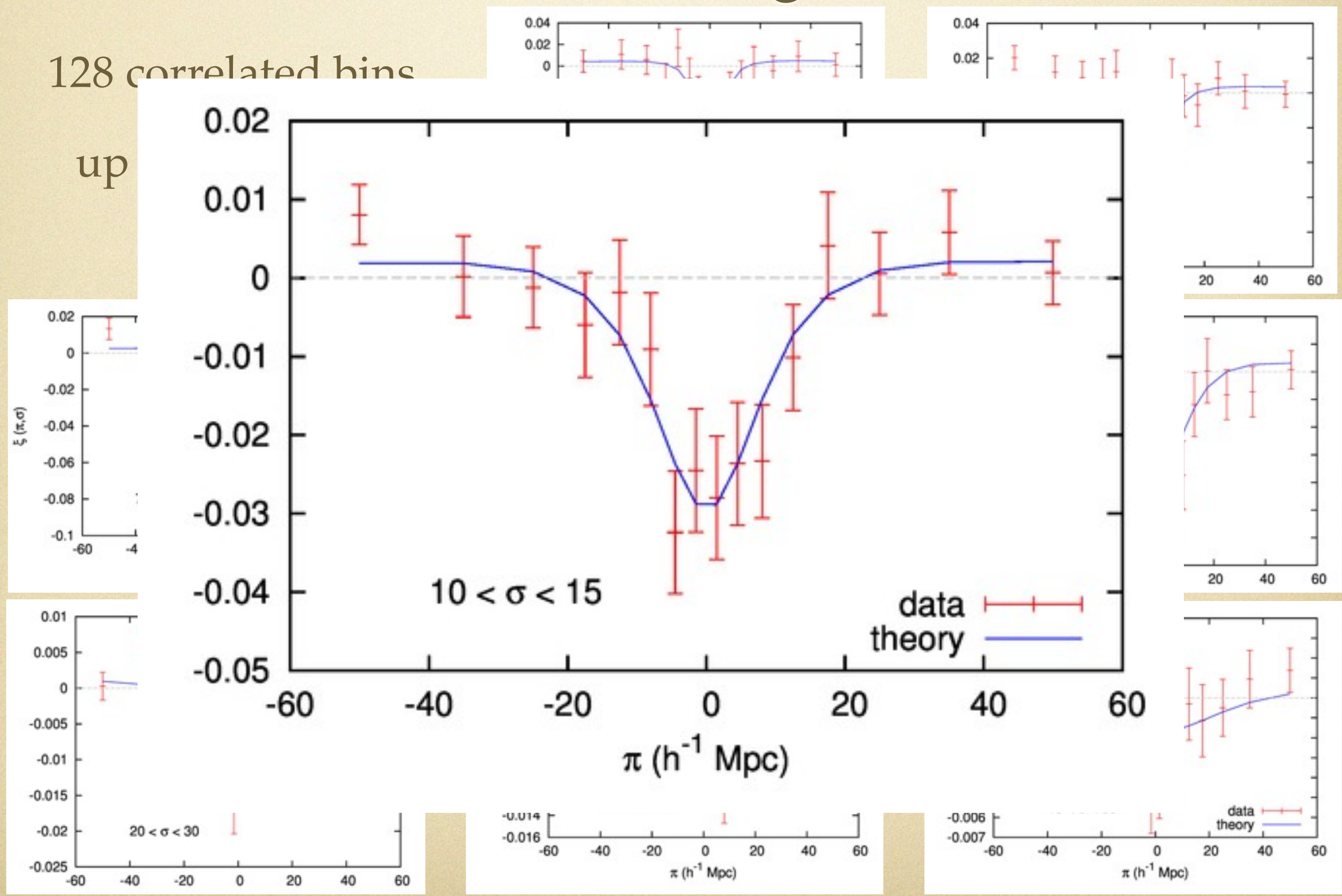




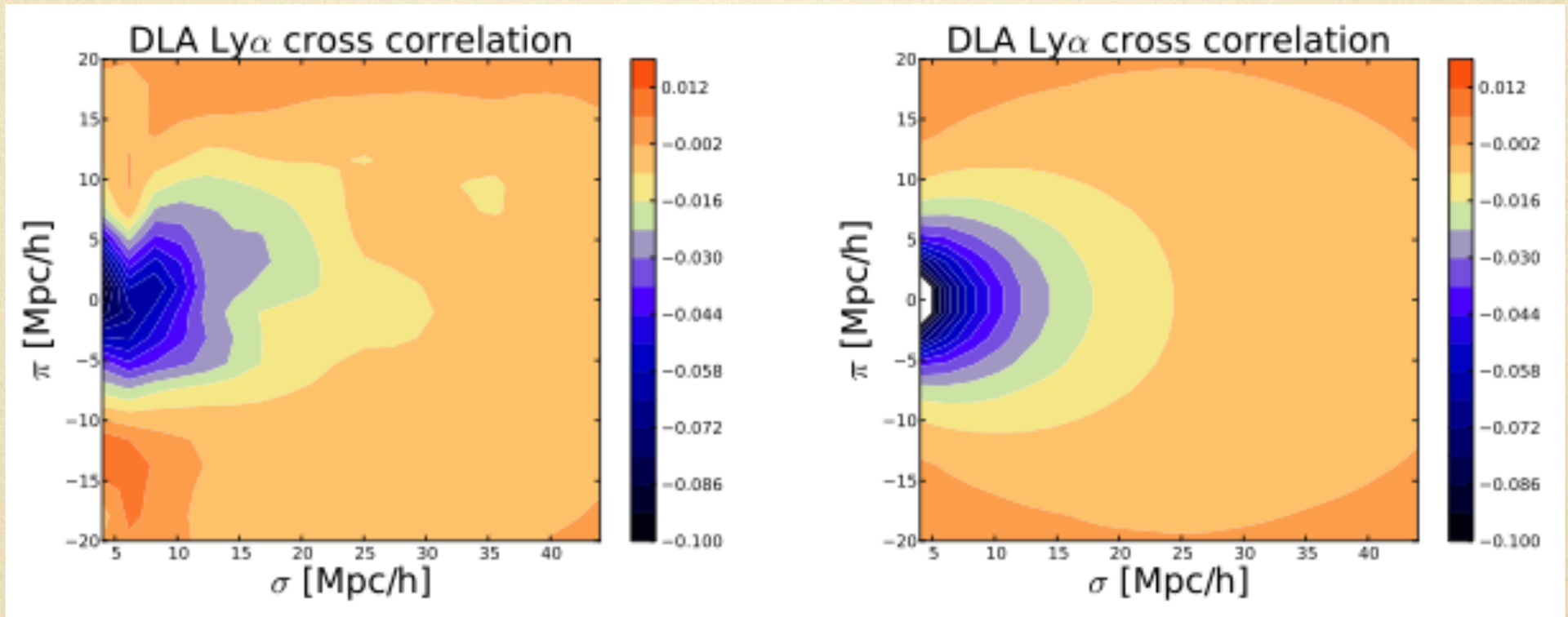
DLA x LyaF

128 correlated bins

up



DLA x LyaF



Well described by linear theory + Kaiser RSD

DLA linear bias measured $b_D = 2.17 \pm 0.20$

DLA x LyaF

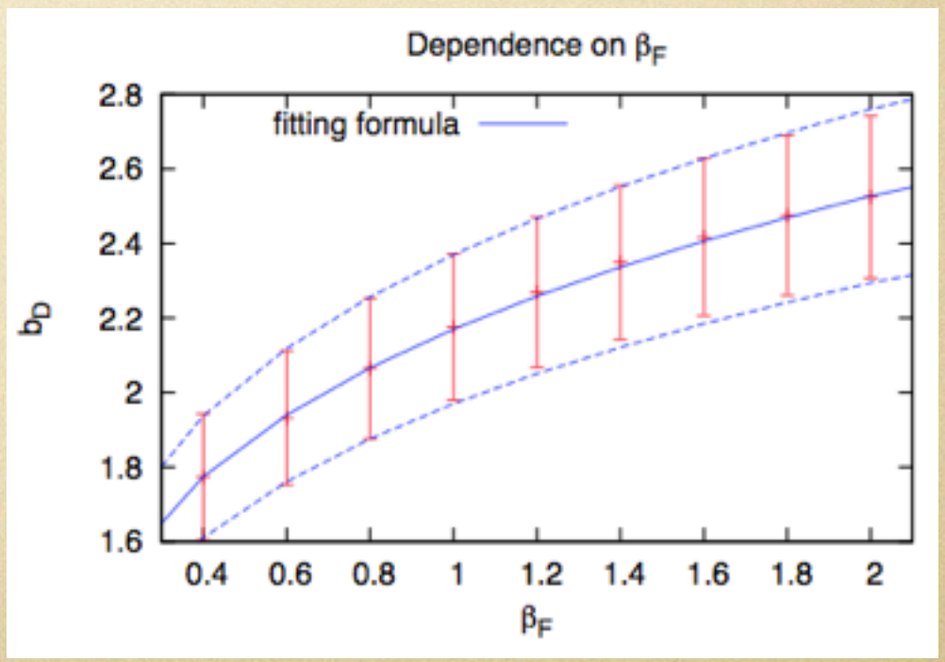
	b_D	BS errors	MCMC errors	χ^2 (d.o.f)
FIDUCIAL	2.17	0.20	0.20	106 (125)
NOMTC	2.11	0.21	0.22	109 (125)
NOCOR	2.00	0.19	0.20	111 (125)
NODLA	2.25	0.22	0.21	109 (125)
LOWZ ($2 < z < 2.25$)	2.18	0.41	0.33	116 (125)
MIDZ ($2.25 < z < 2.5$)	2.16	0.32	0.34	109 (125)
HIGHZ ($2.5 < z < 3.5$)	1.88	0.57	0.37	92 (125)
LOWNHI ($\log(N_{HI}) < 20.4$)	2.27	0.30	0.29	133 (125)
HIGHNHI ($\log(N_{HI}) > 20.4$)	1.89	0.26	0.30	110 (125)

Table 2. Best fit value of the DLA bias with its bootstrap errors, MCMC errors and χ^2 value of the fit, for various analyses: FIDUCIAL (with the MTC and the theory corrected with the expression derived in appendix A), NOMTC (PCA-only continuum fitting, uncorrected theory), NOCOR (MTC, uncorrected theory), NODLA (spectra containing DLAs are rejected), data split in redshift bins (LOWZ, MIDZ, HIGHZ) and finally the DLA sample split in two bins of column density (LOWNHI, HIGHNHI).

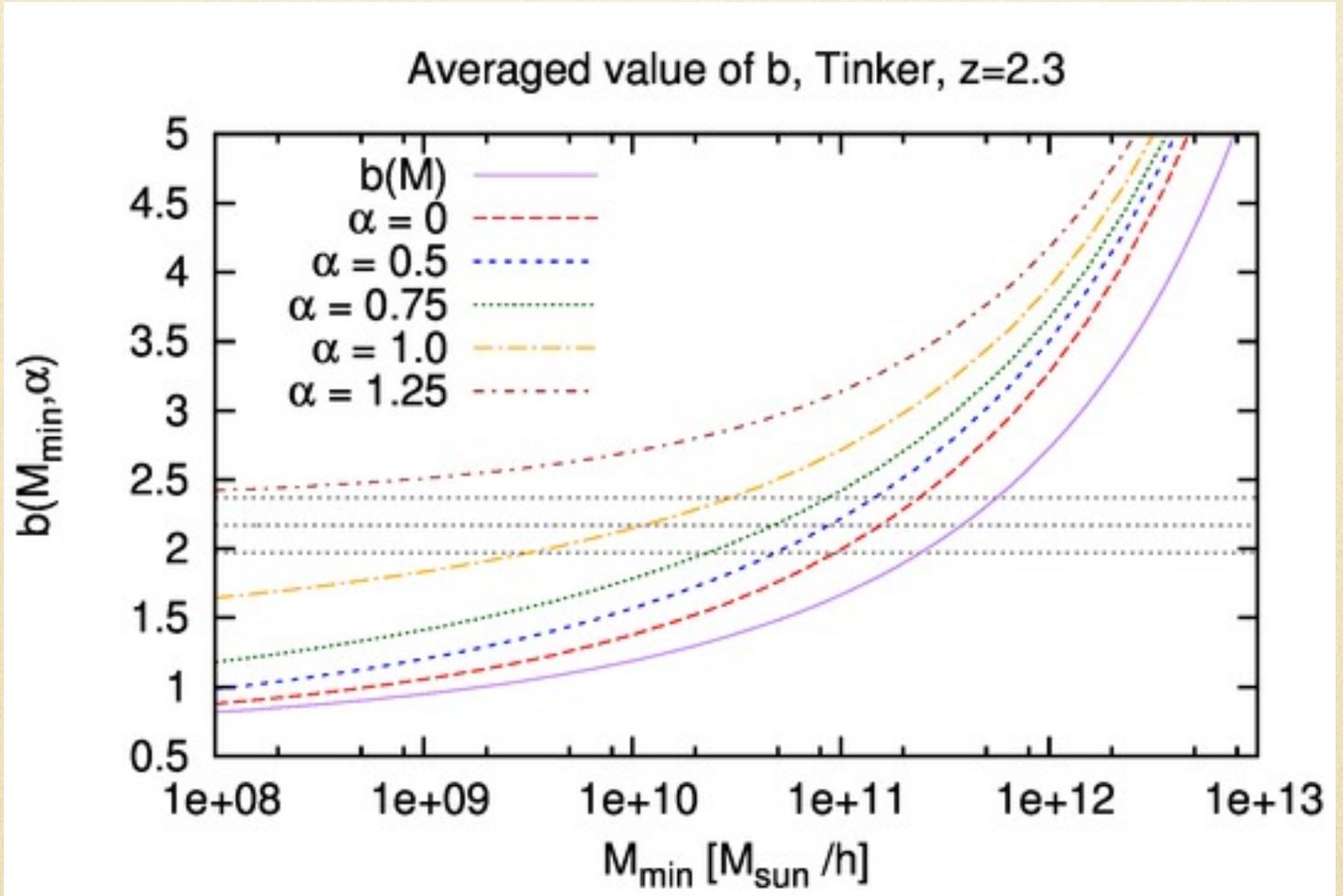
Bias measurement is robust

Small dependence on β_F

If the purity of the catalogue was low, the true bias would be even higher



DLA x LyaF



$$b_D(z) = \frac{\int_0^\infty dM\, n(M,z)\Sigma(M,z)b_h(M,z)}{\int_0^\infty dM\, n(M,z)\Sigma(M,z)}$$

$$b_D = 2.17 \pm 0.20$$

$$\Sigma(M = 10^{12}\, M_\odot) = 1400\,\mathrm{kpc}^2$$

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- DLA - LyaF cross-correlation
- **QSO - LyaF cross-correlation**
- BAO in cross-correlation

QSO x LyaF

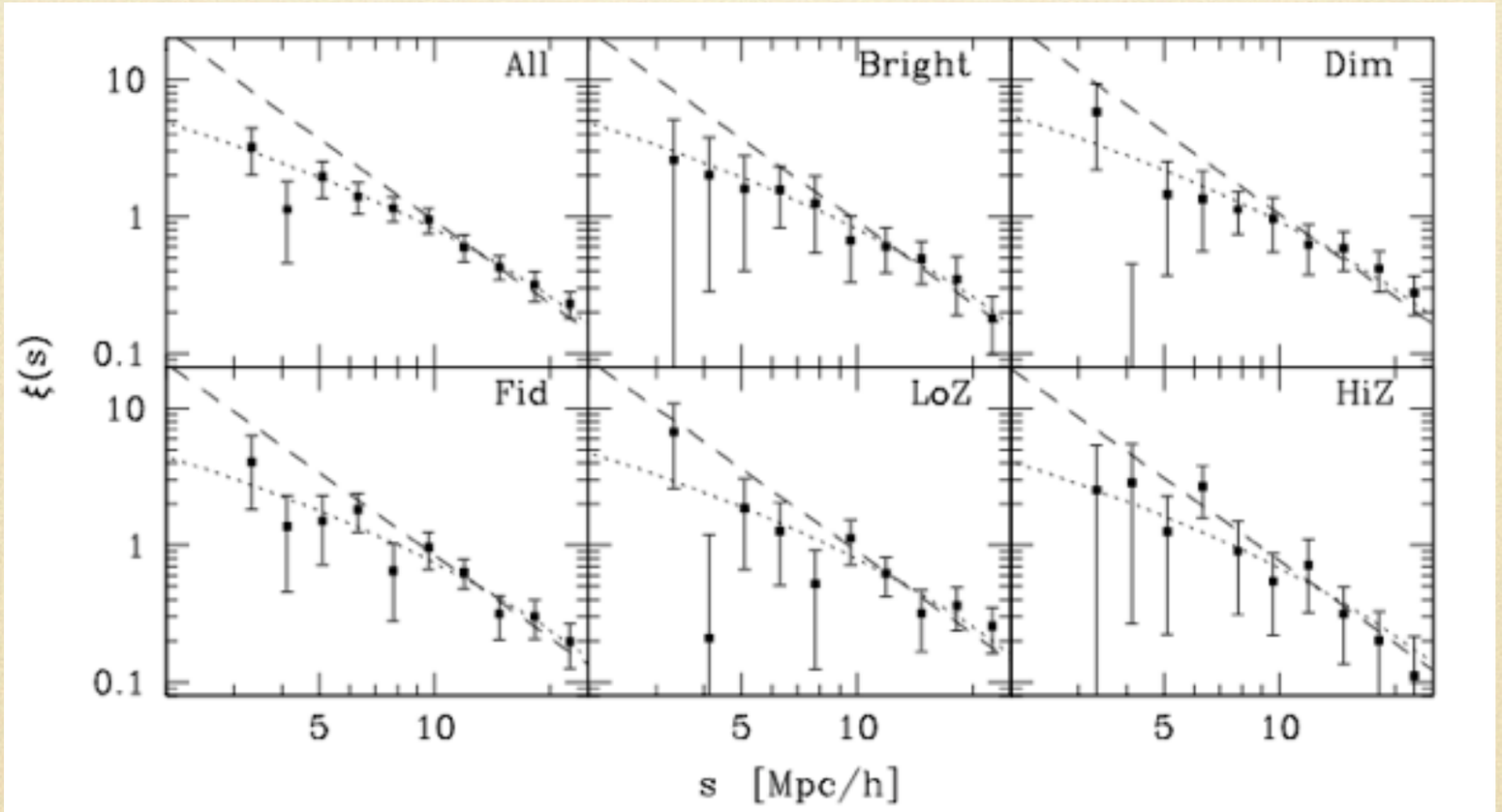
The large-scale Quasar-Lyman α Forest Cross-Correlation from BOSS

Andreu Font-Ribera[a,b] , **Eduard Arnau**[c] , **Jordi Miralda-Escudé**[d,c] , **Emmanuel Rollinde**[e] , **J. Brinkmann**[f] , **Joel R. Brownstein**[g] , **Khee-Gan Lee**[h] , **Adam D. Myers**[i] , **Nathalie Palanque-Delabrouille**[j] , **Isabelle Pâris**[k] , **Patrick Petitjean**[e] , **James Rich**[j] , **Nicholas P. Ross**[b] , **Donald P. Schneider**[l,m] **and Martin White**[b,n]

ArXiv : 1303.1937 (published in JCAP)

QSO x LyaF

Quasar auto-correlation already measured (White++ 2012)



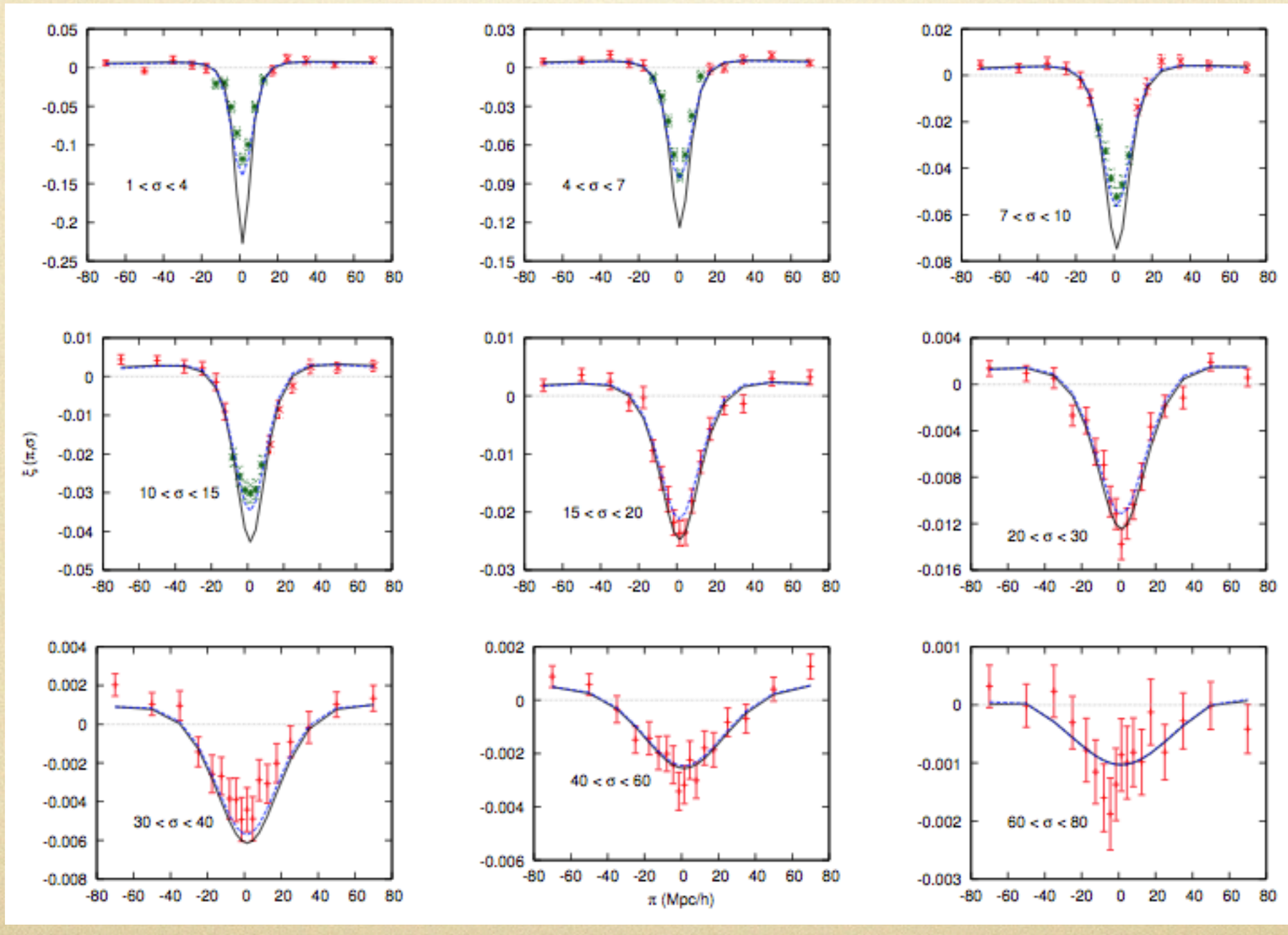
b_q = 3.5

M > 10^12 M_sun

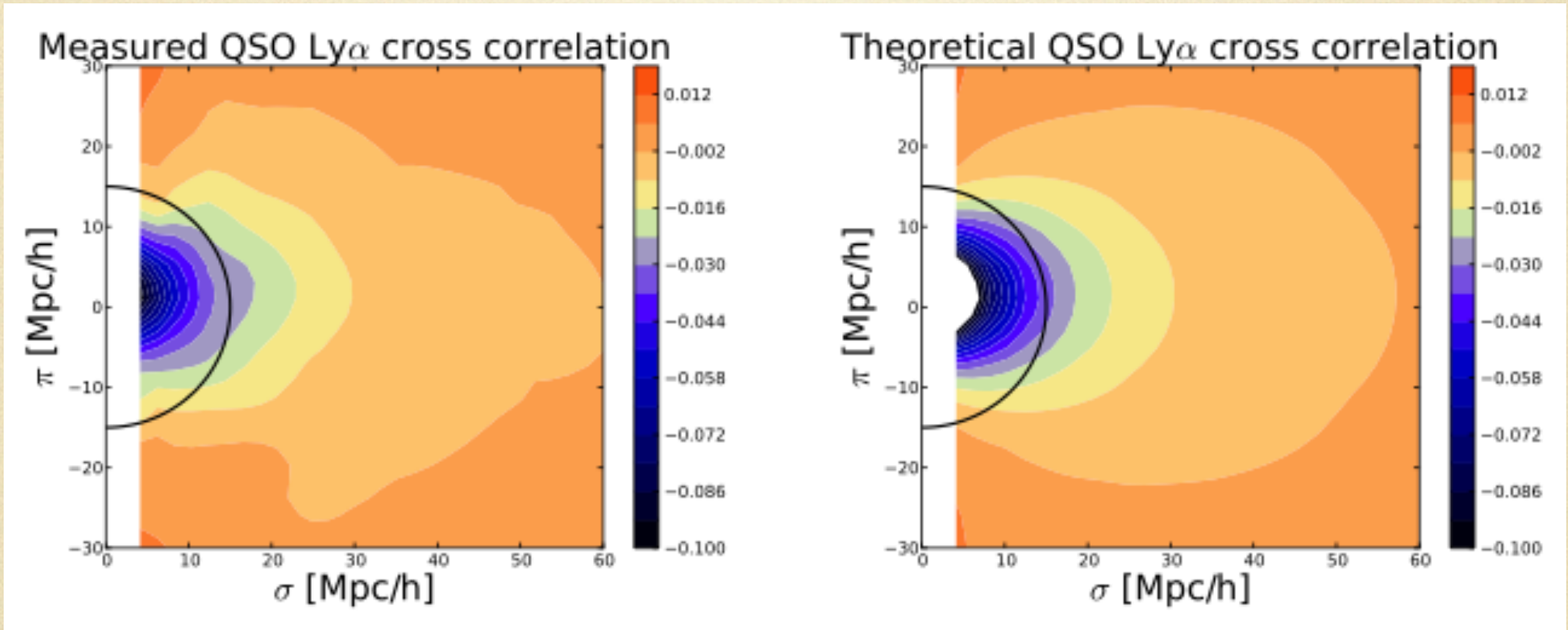
QSO x LyaF

- Better measurement of quasar bias
- Redshift quasar errors
- Quasar radiation models

QSO x LyaF



QSO x LyaF



Linear theory beautifully fitted on large scales (r > 15 Mpc/h)

Bias parameter consistent with quasar clustering

Systematic offset in quasar redshift (~ 150 km/s too low)

QSO x LyaF

All quasar redshift estimators are biased !!!

	β_F	b_q	$\epsilon_z(\mathrm{km\,s^{-1}})$	$\Delta_z(\mathrm{km\,s^{-1}})$	χ^2 (d.o.f)
FIDUCIAL	$1.1^{+0.17}_{-0.15}$	$3.64^{+0.13}_{-0.15}$	< 370	-157^{+38}_{-36}	116 (130)
Z_VISUAL	$1.2^{+0.23}_{-0.16}$	$3.65^{+0.14}_{-0.16}$	399^{+110}_{-99}	-231^{+28}_{-38}	142 (130)
Z_PIPELINE	$1.13^{+0.21}_{-0.21}$	$3.4^{+0.15}_{-0.16}$	546^{+86}_{-100}	-154^{+43}_{-24}	114 (130)
Z_CIV	$1.34^{+0.19}_{-0.17}$	$3.66^{+0.13}_{-0.15}$	503^{+72}_{-79}	-412^{+28}_{-36}	137 (130)
Z_CIII	$1.44^{+0.26}_{-0.21}$	$3.5^{+0.2}_{-0.17}$	648^{+87}_{-67}	-436^{+48}_{-34}	137 (130)
Z_MgII	$1.73^{+0.44}_{-0.39}$	$3.55^{+0.26}_{-0.19}$	636^{+110}_{-150}	-79^{+38}_{-56}	126 (130)

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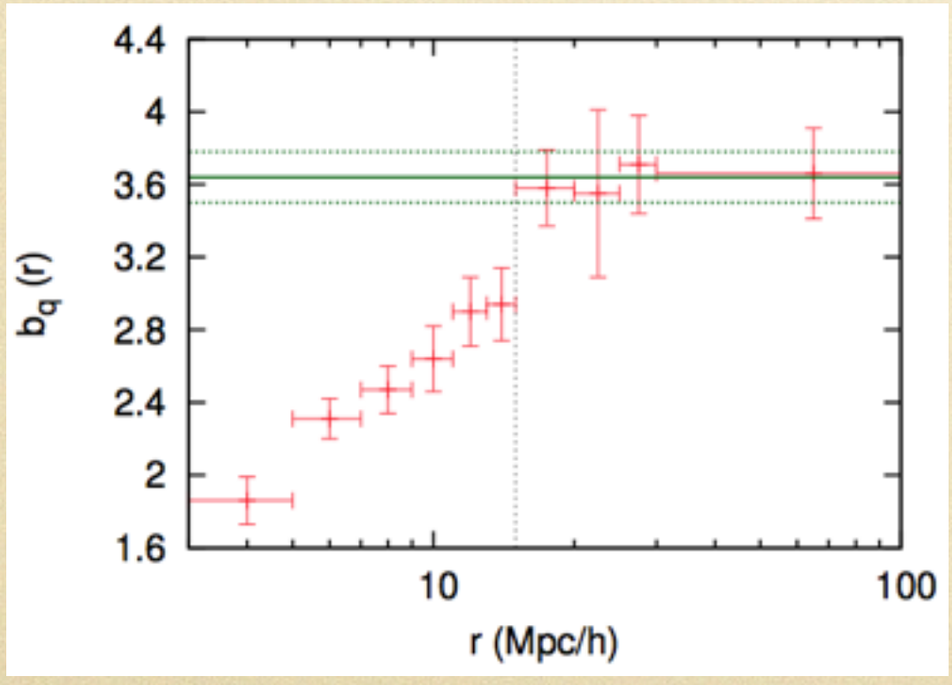
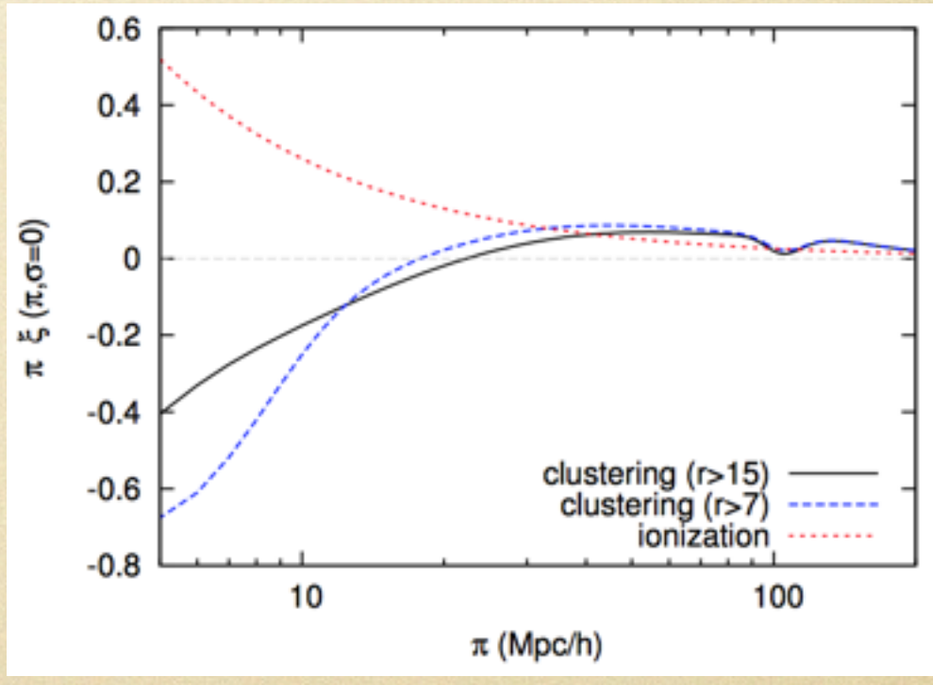
However: might be correlated with quasar radiation models

QSO x LyaF

Once we have a good handle on clustering,
we can look at quasar radiation effects



3D cross-correlation

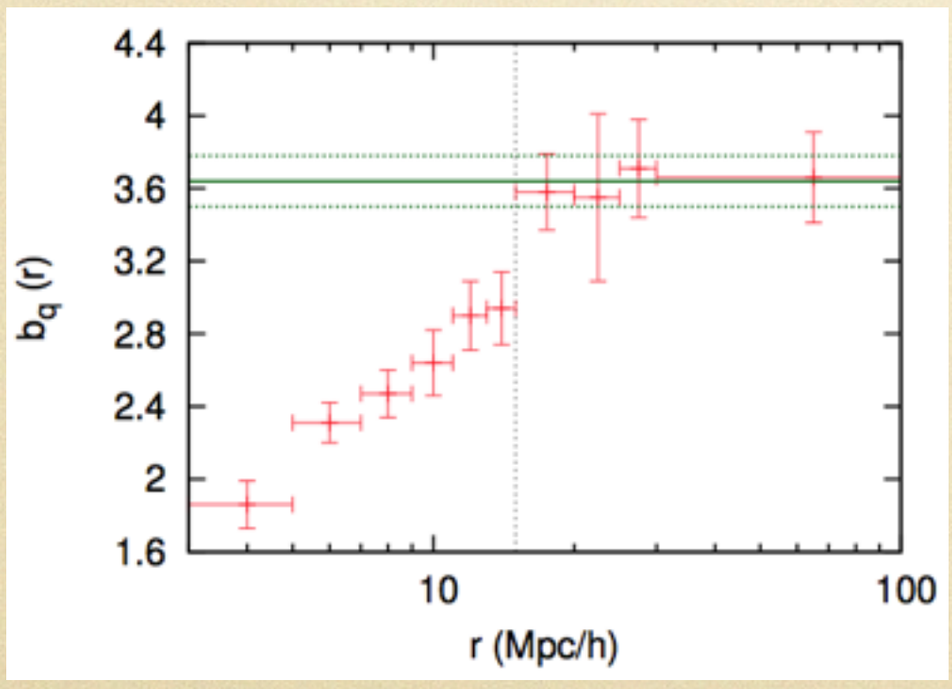


1D proximity effect

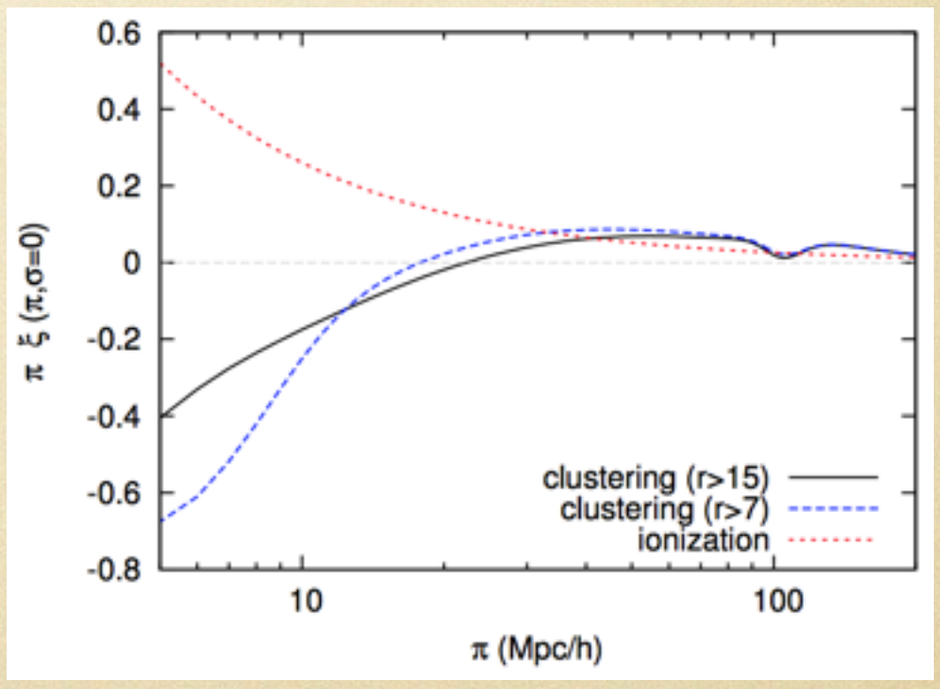
QSO x LyaF

Once we have a good handle on clustering,
we can look at quasar radiation effects

However: redshift errors, non-linear clustering...



3D cross-correlation



1D proximity effect

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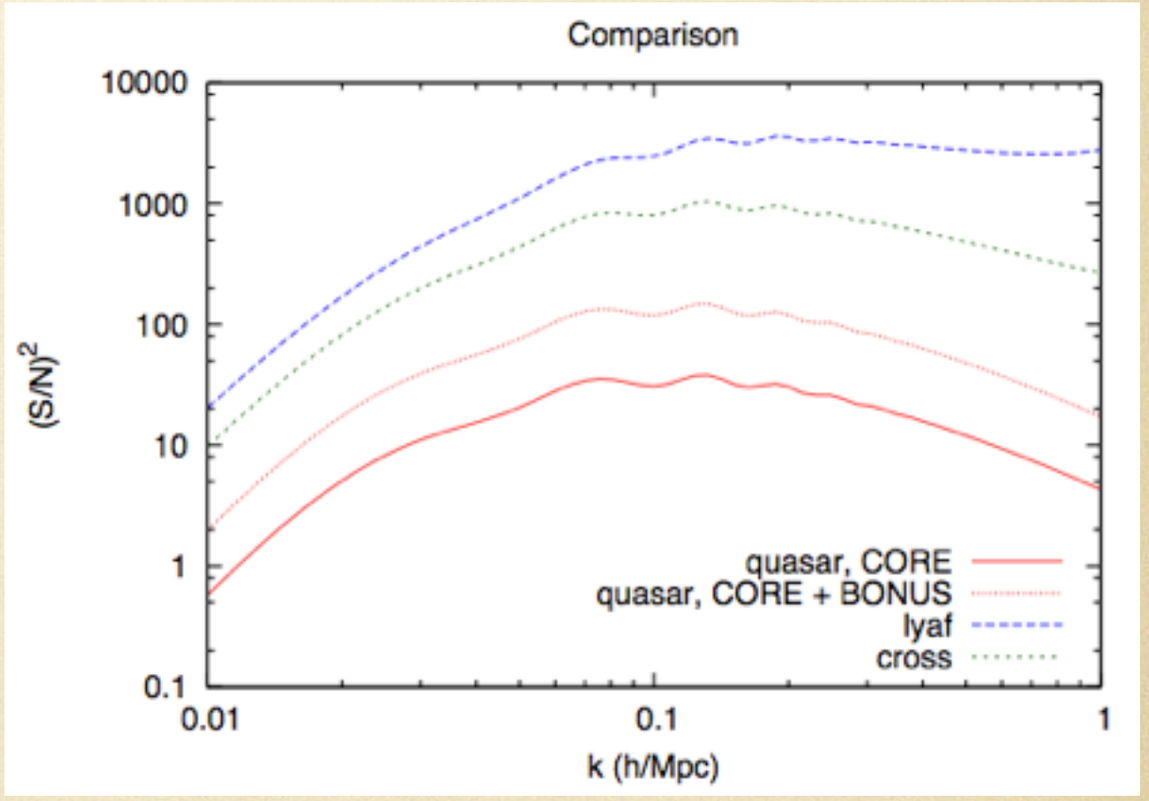
- **BAO in cross-correlation**

BAO in cross-correlation

Fisher forecast for BOSS

Cross-correlation only a factor ~ 2 worst than LyaF auto-correlation

More sensitive to transverse clustering



$$P_{gF}(\mathbf{k}) = b_g \left[1 + \beta_g \mu_k^2\right] \; b_F \left[1 + \beta_F \mu_k^2\right] P_L(k)$$

McQuinn & White (2011)

$$\left(\frac{S}{N}\right)^2_{Fg} = N_k \frac{P_{gF}^2(k,\mu_k)}{P_{gF}(k,\mu_k)^2 + \left(P_g(k,\mu_k) + n_g^{-1}\right)\left(P_F(k,\mu_k) + P^{1D}(k\mu_k)\, n_{eff}^{-1}\right)}$$

BAO in cross-correlation

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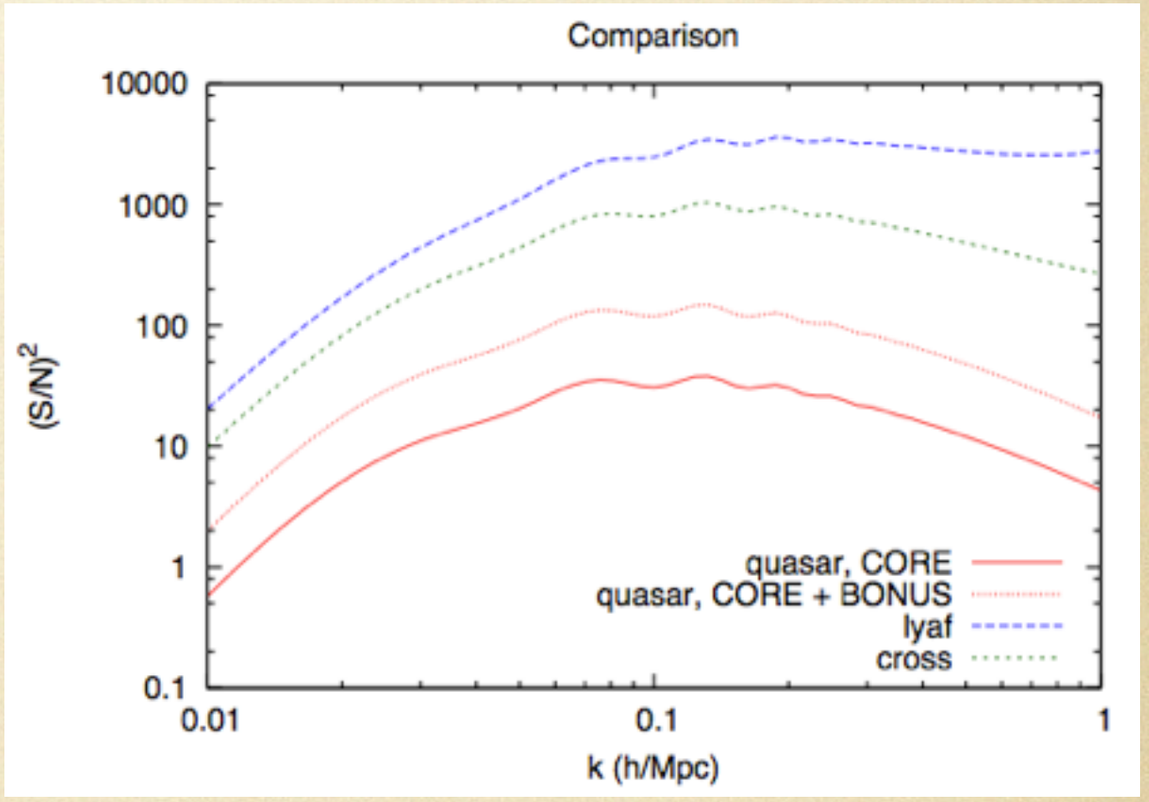

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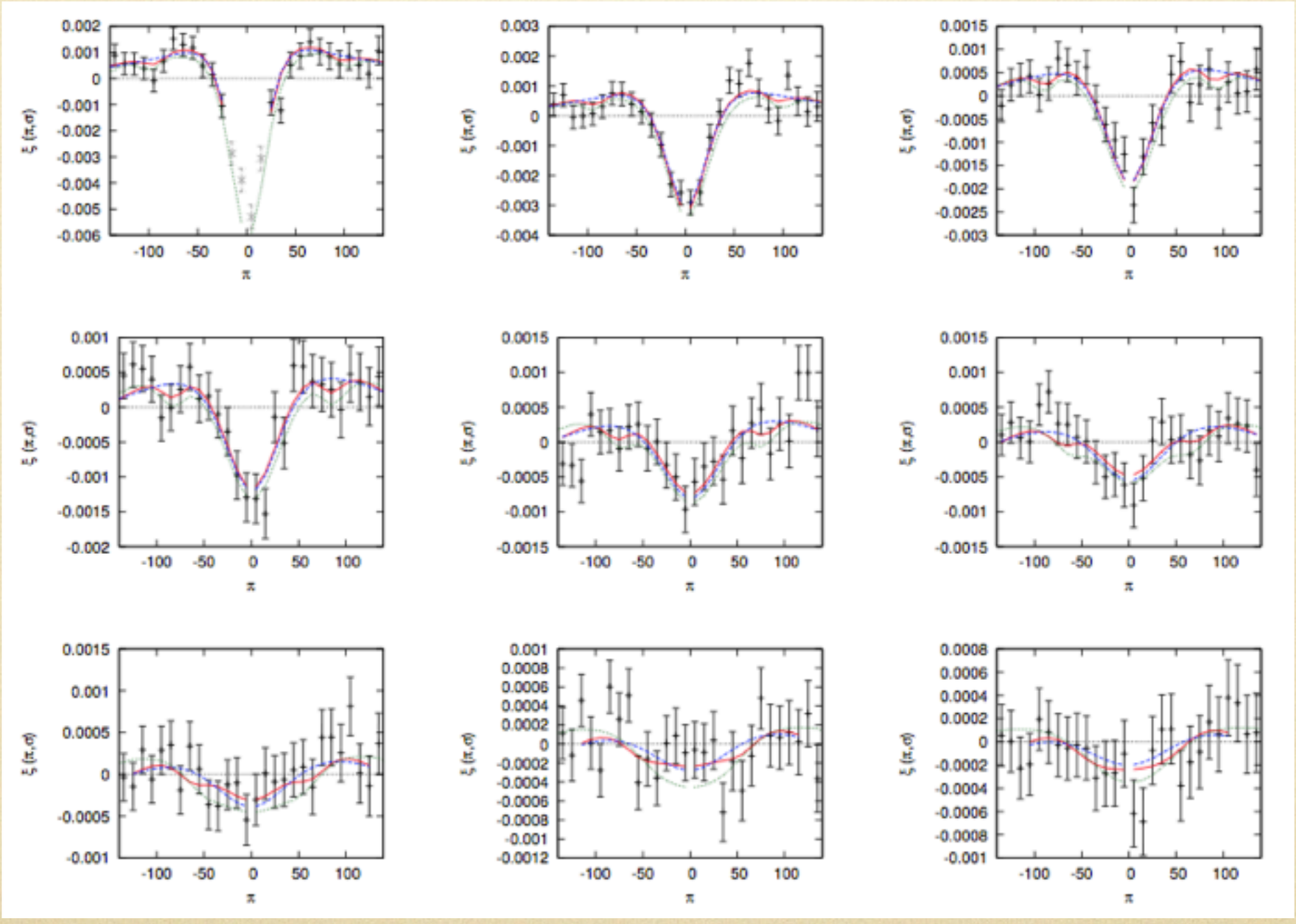
BAO in cross-correlation

$\sigma = 35$ Mpc/h

512 strongly correlated points

$\sigma = 55$ Mpc/h



$\sigma = 95$ Mpc/h

$\sigma = 115$ Mpc/h

BAO in cross-correlation

$$\xi(\pi,\sigma) = \xi_{\rm cosmo}(\pi,\sigma,\alpha_{\parallel},\alpha_{\perp}) + \xi_{\rm bb}(\pi,\sigma)$$

$$\xi_{\rm cosmo}(\pi,\sigma) = \xi_{\text{no peak}}(\pi,\sigma) + a_{\rm peak}\cdot\xi_{\rm peak}(\pi\alpha_{\parallel},\sigma\alpha_{\perp})$$

$$\xi_{bb}(\pi,\sigma) = \sum_{i=i_{min}}^{i_{max}} \sum_{j=j_{min}}^{j_{max}} b_{i,j}\ \pi^i\ \sigma^j$$

$$\alpha_{\parallel} = \frac{\left[(r_s H(z))^{-1}\right]}{\left[(r_s H(z))^{-1}\right]_{\rm fid}}$$

$$\alpha_{\perp} = \frac{\left[D_a/r_s(z)\right]}{\left[D_a/r_s\right]_{\rm fid}}$$

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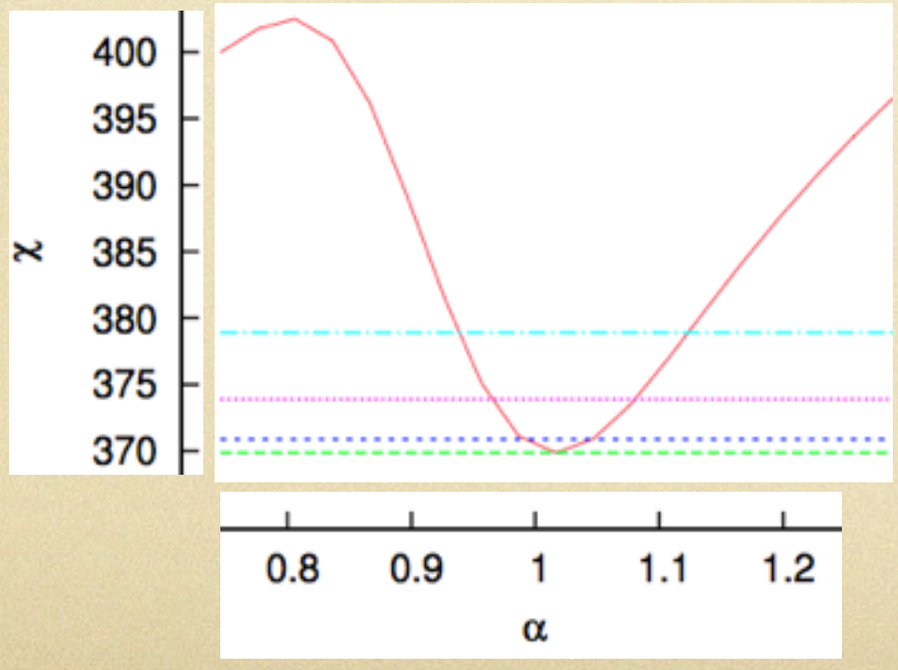

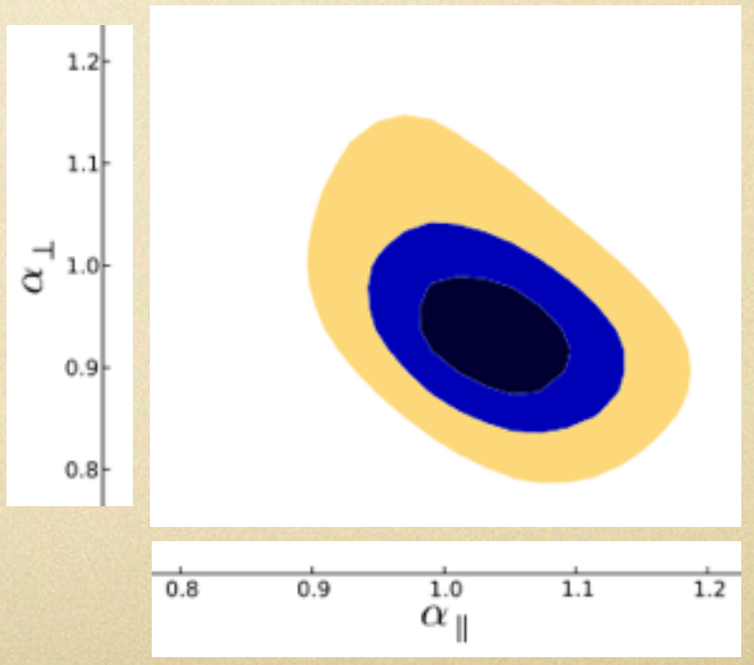

BAO in cross-correlation

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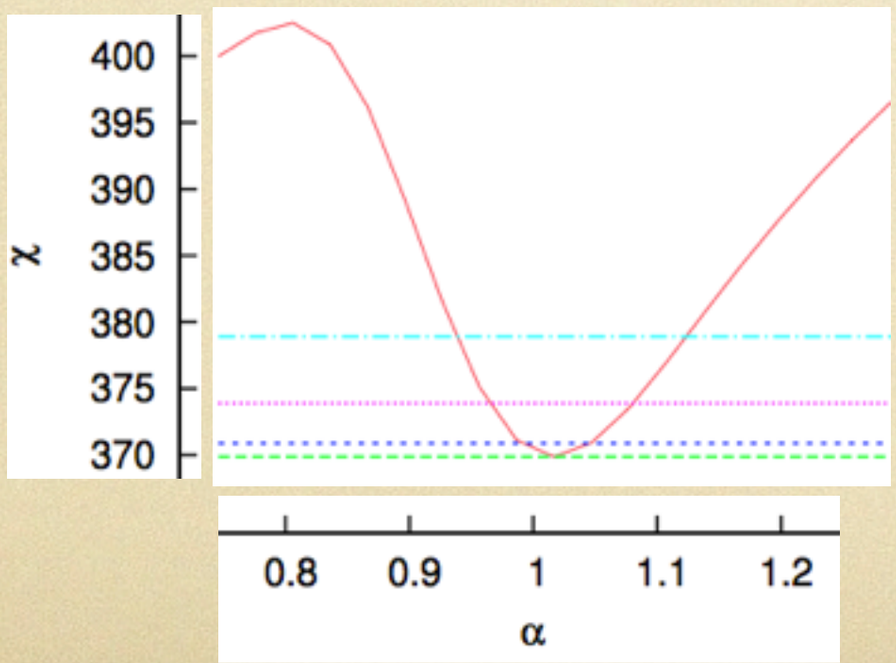
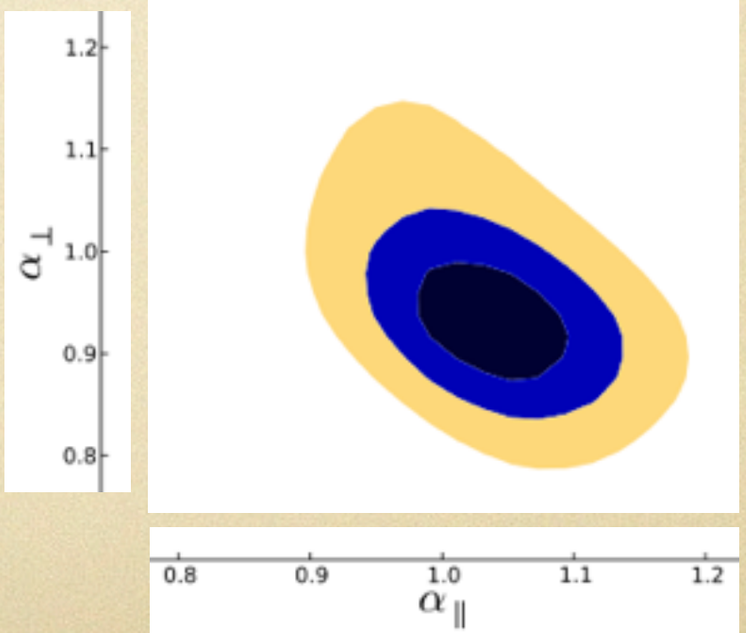
$$\alpha_{\parallel} = \frac{\left[(r_s H(z))^{-1}\right]}{\left[(r_s H(z))^{-1}\right]_{\rm fid}} \frac{\left[D_a/r_s(z)\right]}{\left[\quad s\right]_{\rm fid}}$$

PRELIMINARY





BAO in cross-correlation

4% uncertainties on both BAO scales

	β_F	b_q	α	$\alpha_\parallel$	$\alpha_\perp$	χ^2 (d.o.f)
FID	1.74 ± 0.53	3.45 ± 0.25	-	± 0.038	± 0.037	363.2 (363)
ISO	1.93 ± 0.65	3.34 ± 0.25	± 0.028	-	-	369.5 (364)
NW	2.47 ± 0.86	3.04 ± 0.23	-	-	-	386.3 (365)

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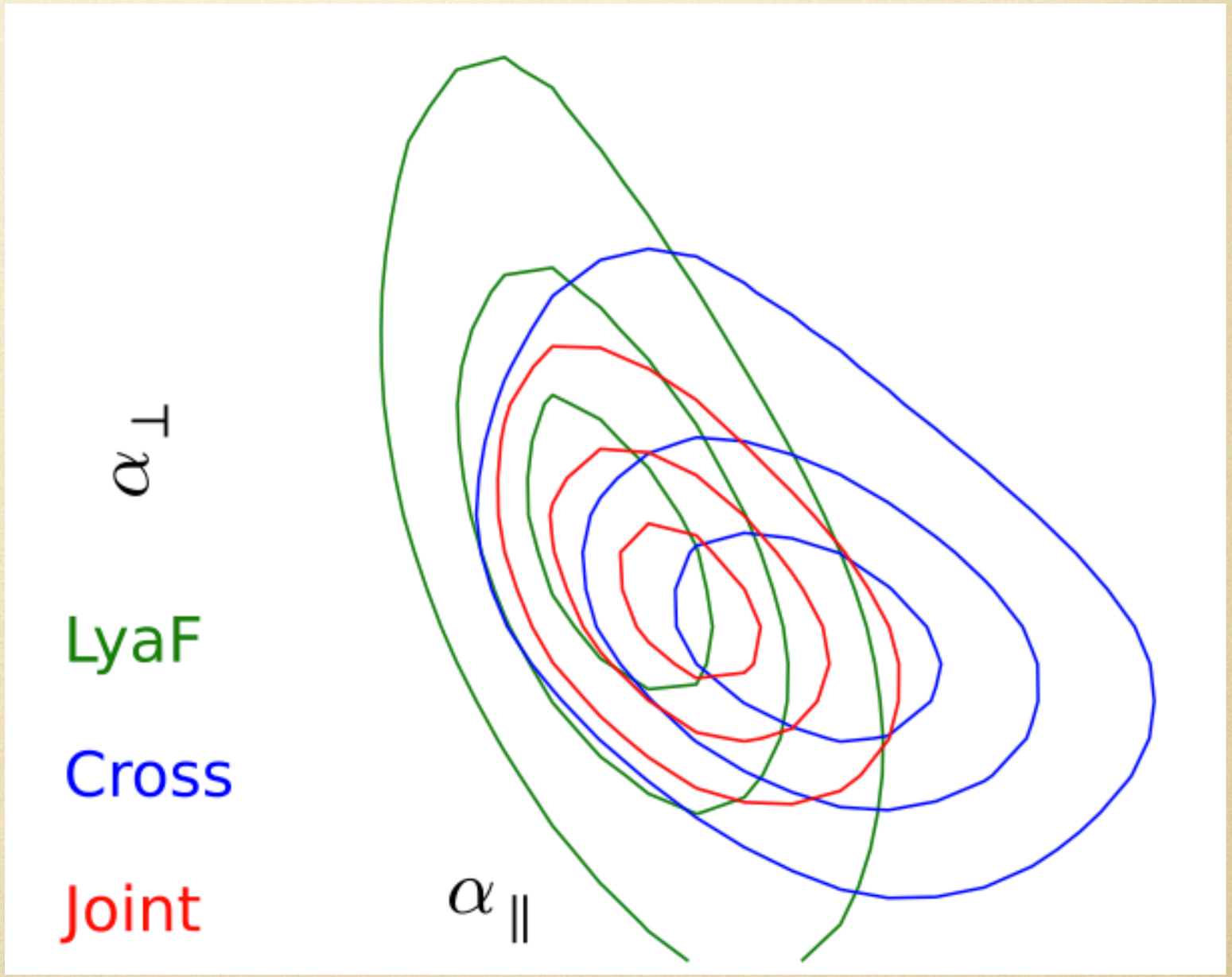
Results robust under changes of:

- Broad band distortion models
- Continuum fitting method
- Red / Blue forest (lr < > 1140 A)
- Error estimate (bootstrap errors)
- Separation fitting range
- mu > 0 , mu < 0

BAO in cross-correlation

LyaF BAO from DR9
(Slosar++ 2013)

LyaF BAO from DR11
(Font-Ribera++, in prep)



BAO in cross-correlation

LyaF BAO from DR9
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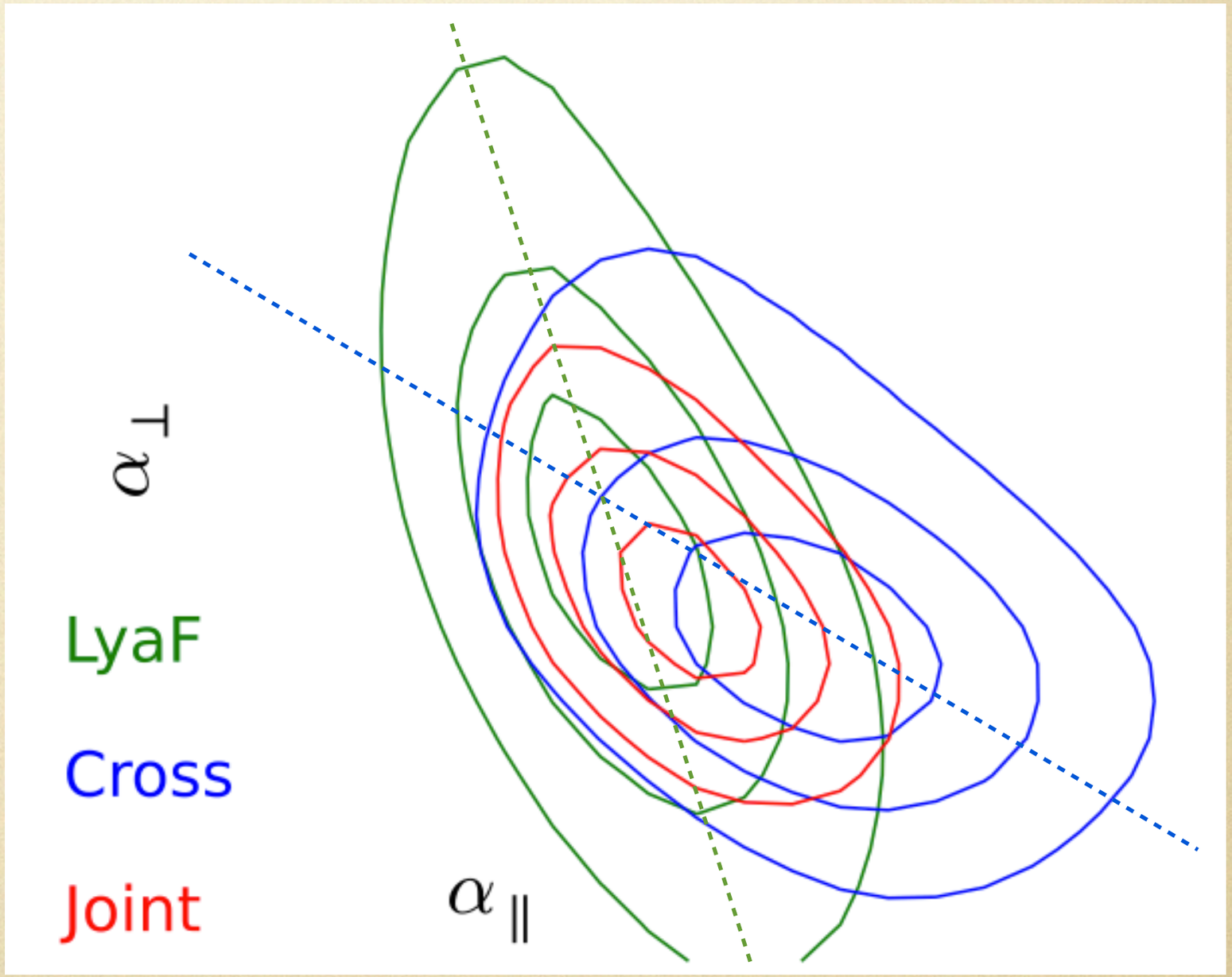
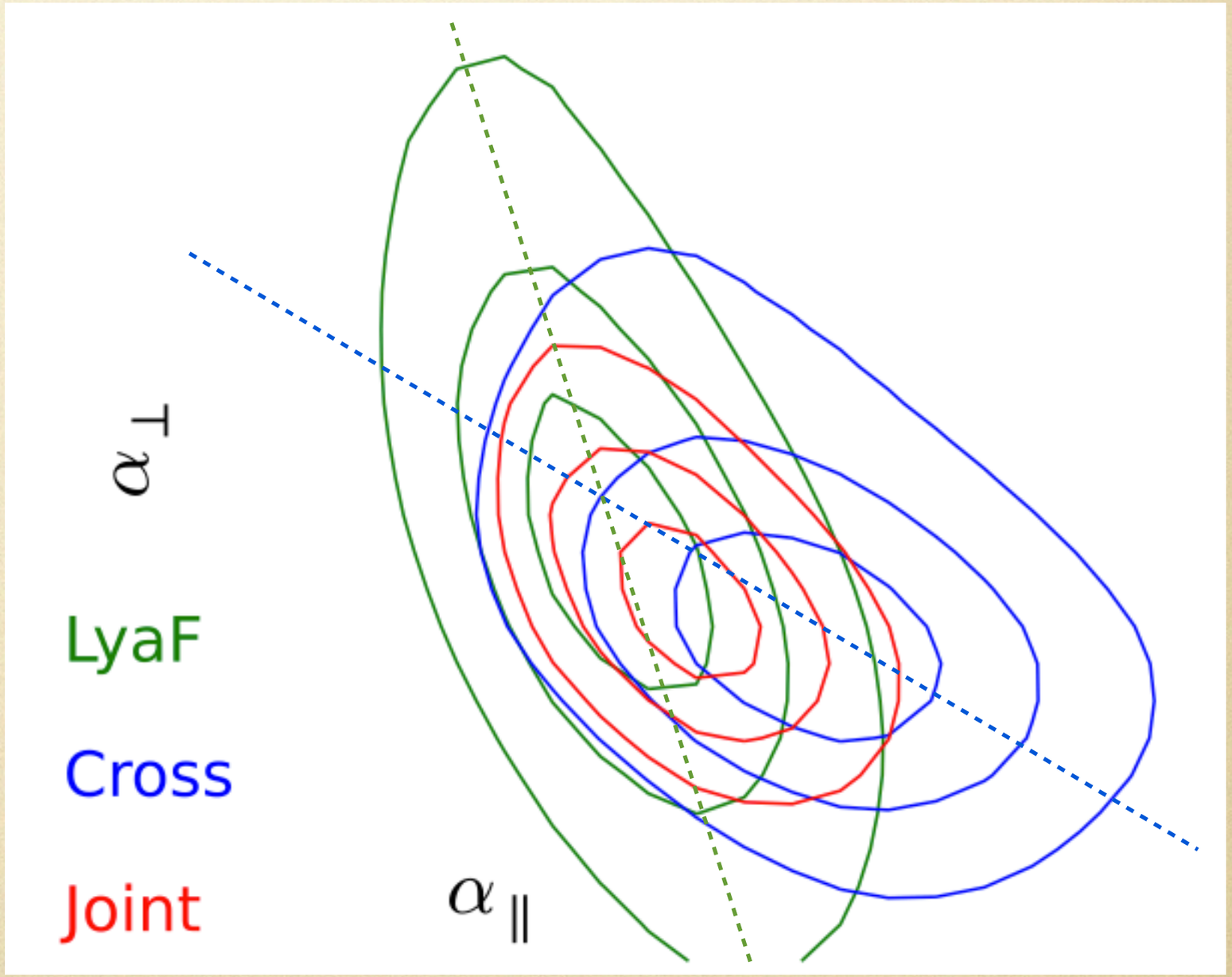


BAO in cross-correlation

We are NOT dominated by cosmic variance, but it is a good question and we are looking at it

LyaF BAO from DR9 (Slosar++ 2013)

LyaF BAO from DR11 (Font-Ribera++, in prep)



BAO in cross-correlation

We do not use multipoles
at any stage of our analysis

But people want to “see” the peak...

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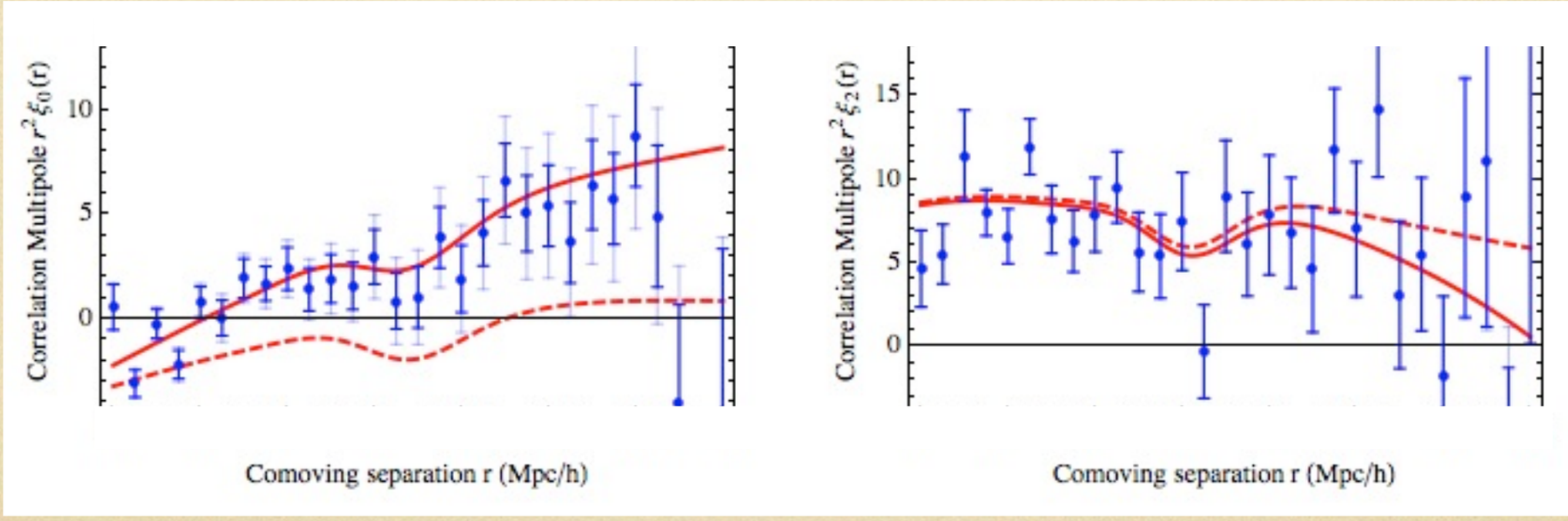

Summary

- b_D = 2 ---> models / sims should look at it !
- Room for improving QSO redshift
- QSO radiation models can be constrained
- Cosmology from QSO-LyaF cross-correlation