The latest on the Lyman-alpha forest

Pat McDonald

Outline

- Introduction to the LyaF
- Recently published BOSS correlation measurement
- Expectation for DR9/full BOSS
- Expectation for BigBOSS
- Theoretical understanding of measurements

What is the Lyman-α forest?

The Lyα absorption by neutral hydrogen in the intergalactic medium (IGM) observed in the spectra of high redshift quasars.

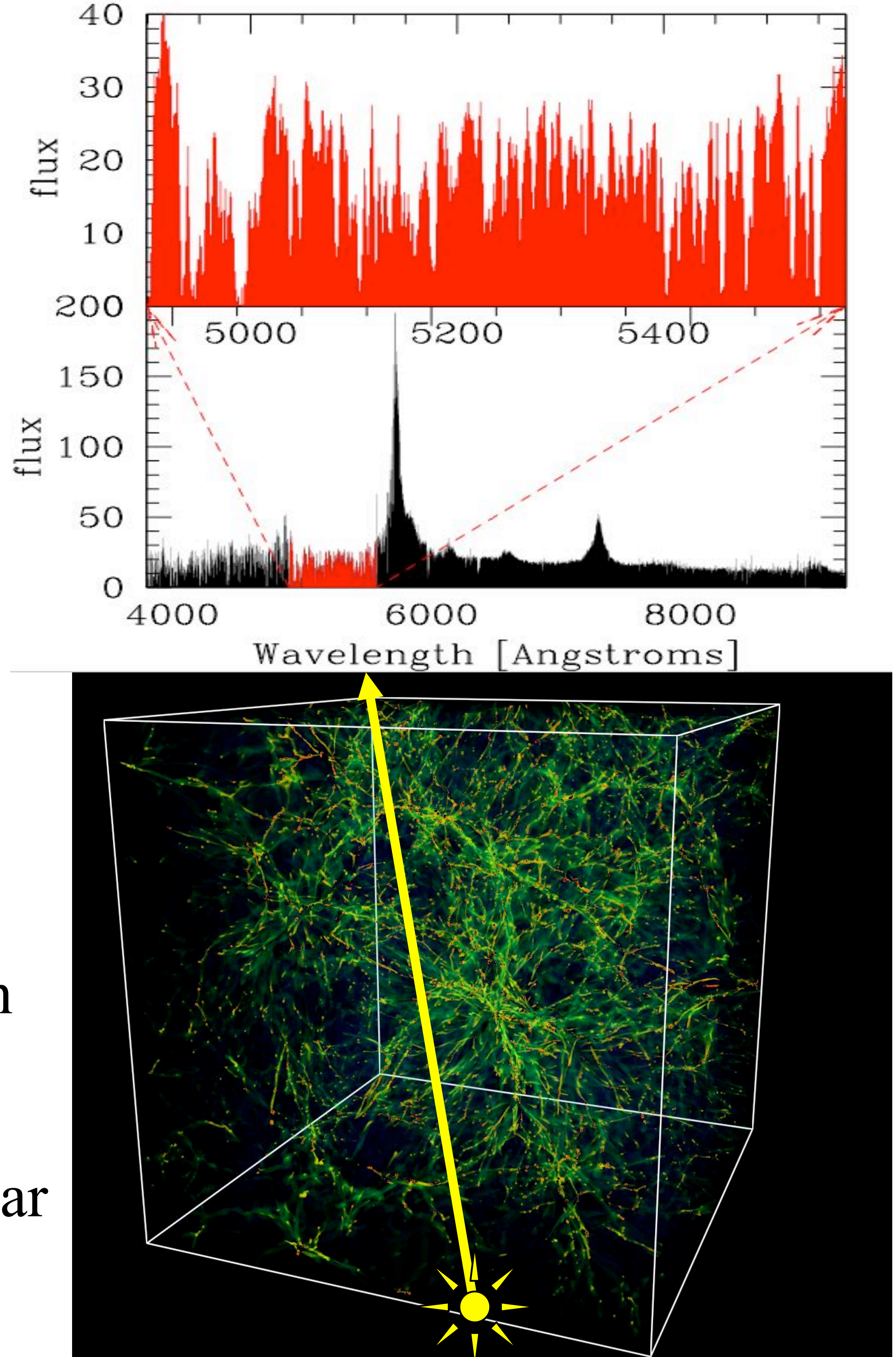
Provides a map of large-scale structure.

Lyα forest

SDSS quasar spectrum

Neutral hydrogen

z = 3.7 quasar

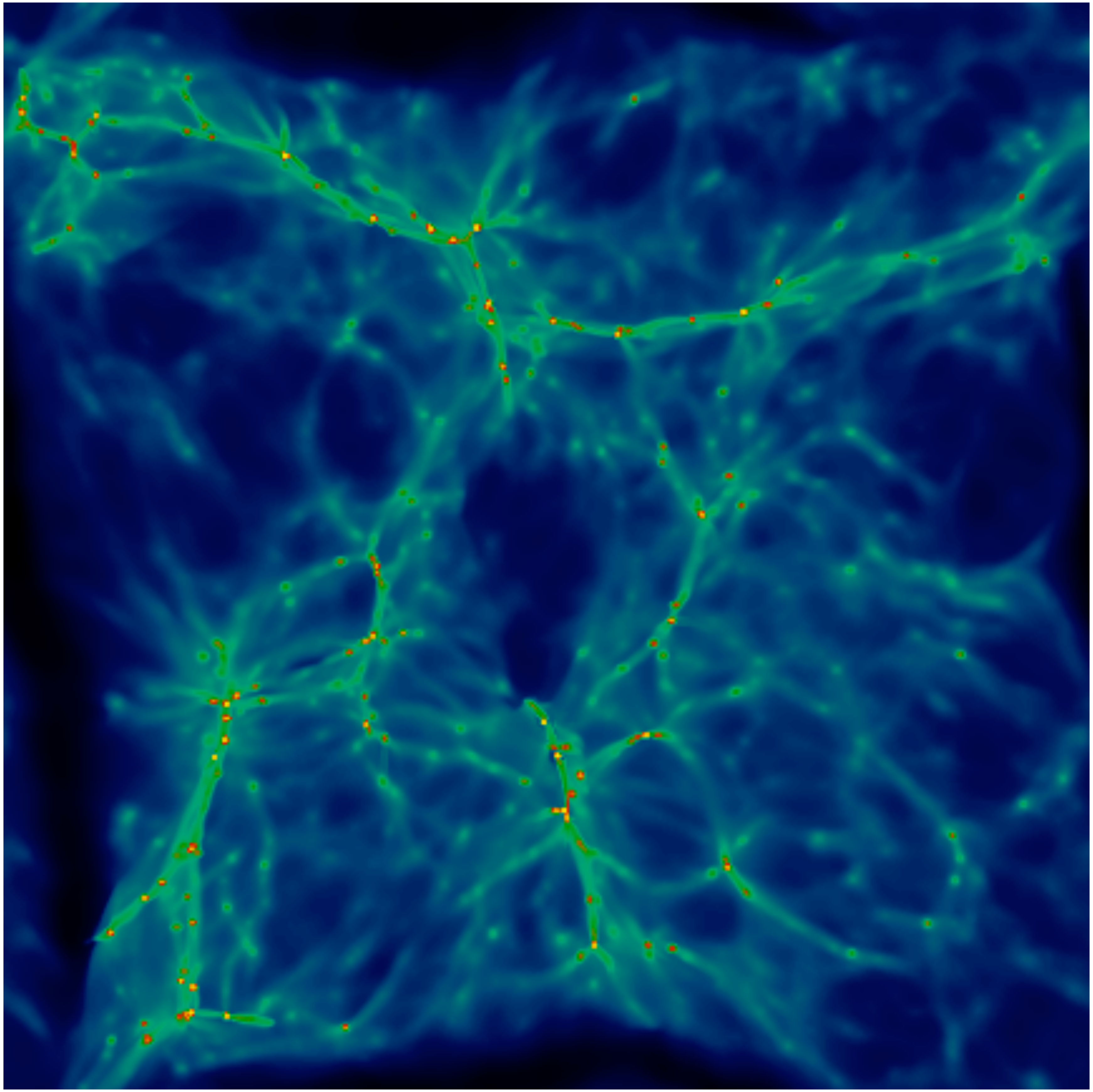


25 Mpc/h cube simulation of the IGM by R. Cen

Numerical simulation of the IGM

(R. Cen)

25 Mpc/h

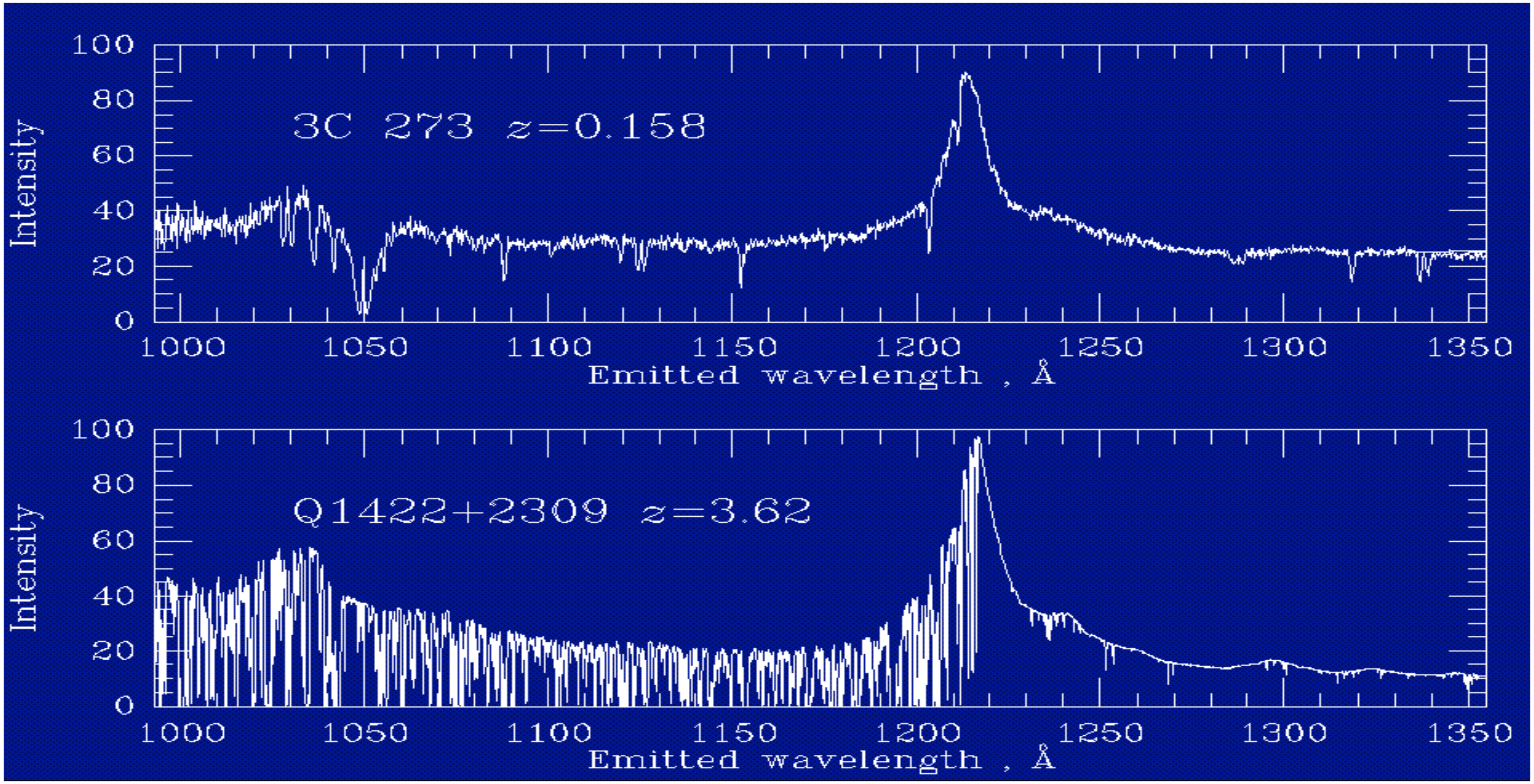


Absorption by gas at redshift z appears in an observed quasar spectrum at wavelength

$$\lambda_{\mathrm{observed}} = \lambda_{\alpha}(1 + z_{\mathrm{gas}})$$

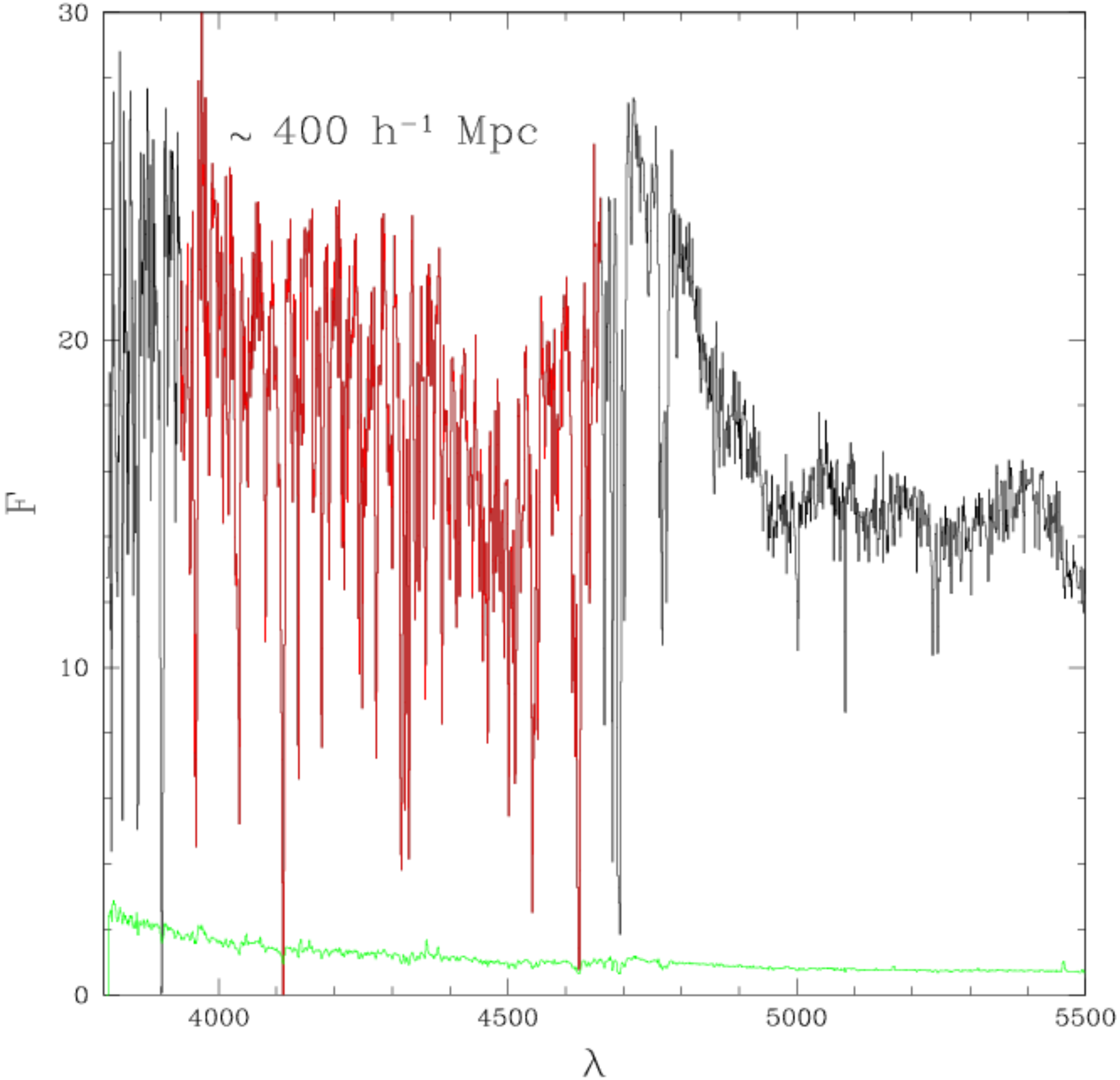
$$\lambda_{\alpha} = 1216\ \text{Å} = 121.6\ \mathrm{nm}$$

z~0 shows a relatively unabsorbed spectrum



Much higher neutral densities at higher z

Each spectrum is a ~400 Mpc/h skewer through the IGM



Typical separation between
BOSS spectra ~20 Mpc/h,
i.e., a small fraction of
their length.

Distances:

$$\Delta v \simeq \frac{c\,\Delta\lambda}{\lambda} \simeq \frac{c\,\Delta z}{1+z} \simeq \frac{H(z)}{1+z}\Delta x$$

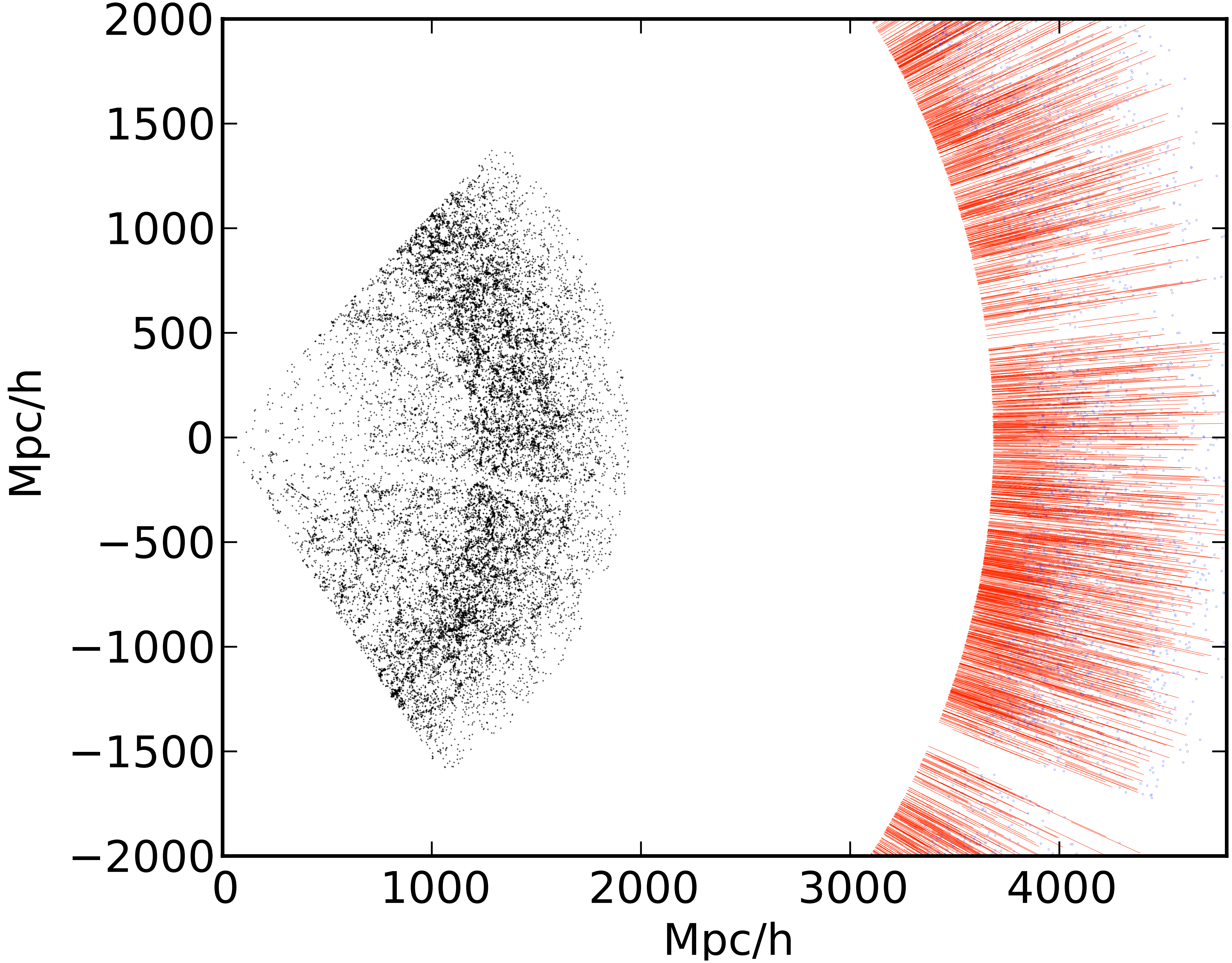
$$1\ h^{-1}\mathrm{Mpc} = 112\ \mathrm{km/s} = 1.8\ \mathrm{\AA}$$

= 0.78 arcmin (BAO scale 1.3 deg)

$$\mathrm{For}\ \Omega_m = 0.3,\ \Omega_\Lambda = 0.7,\ z = 3$$

These relations are qualitatively correct for typical allowed models and the relevant redshift range.

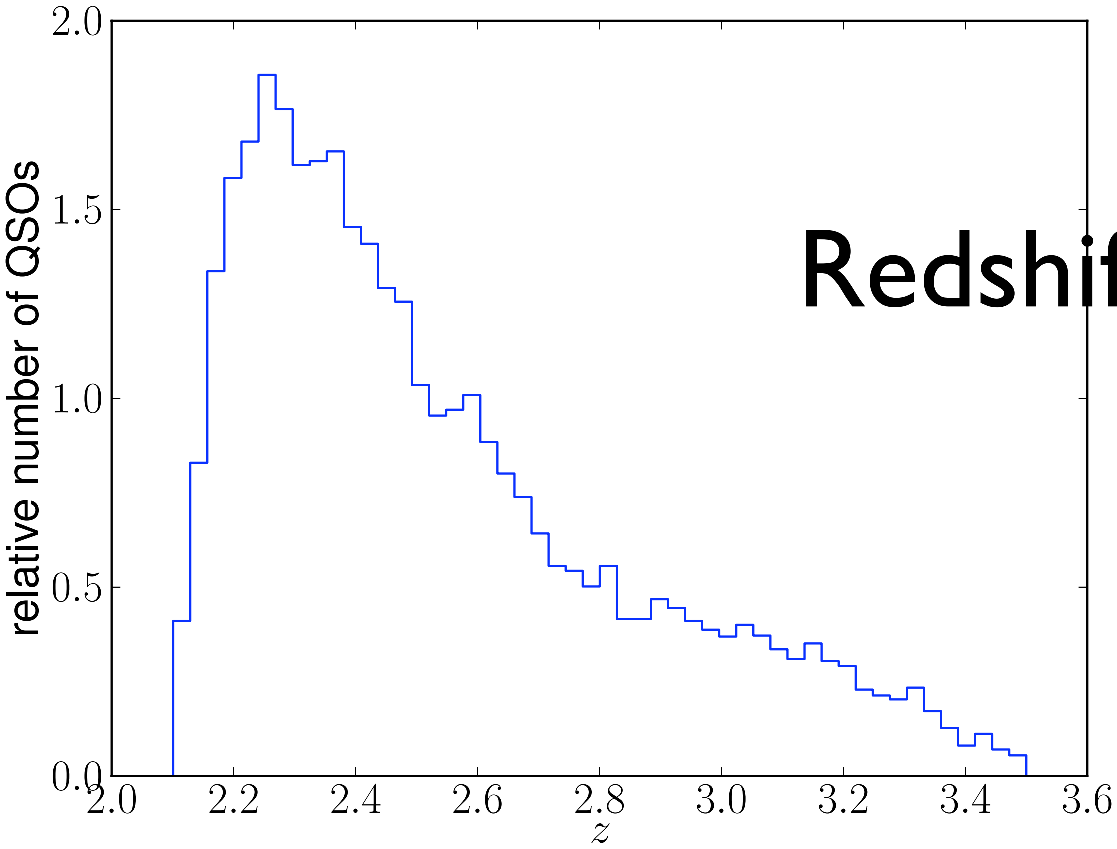
BOSS



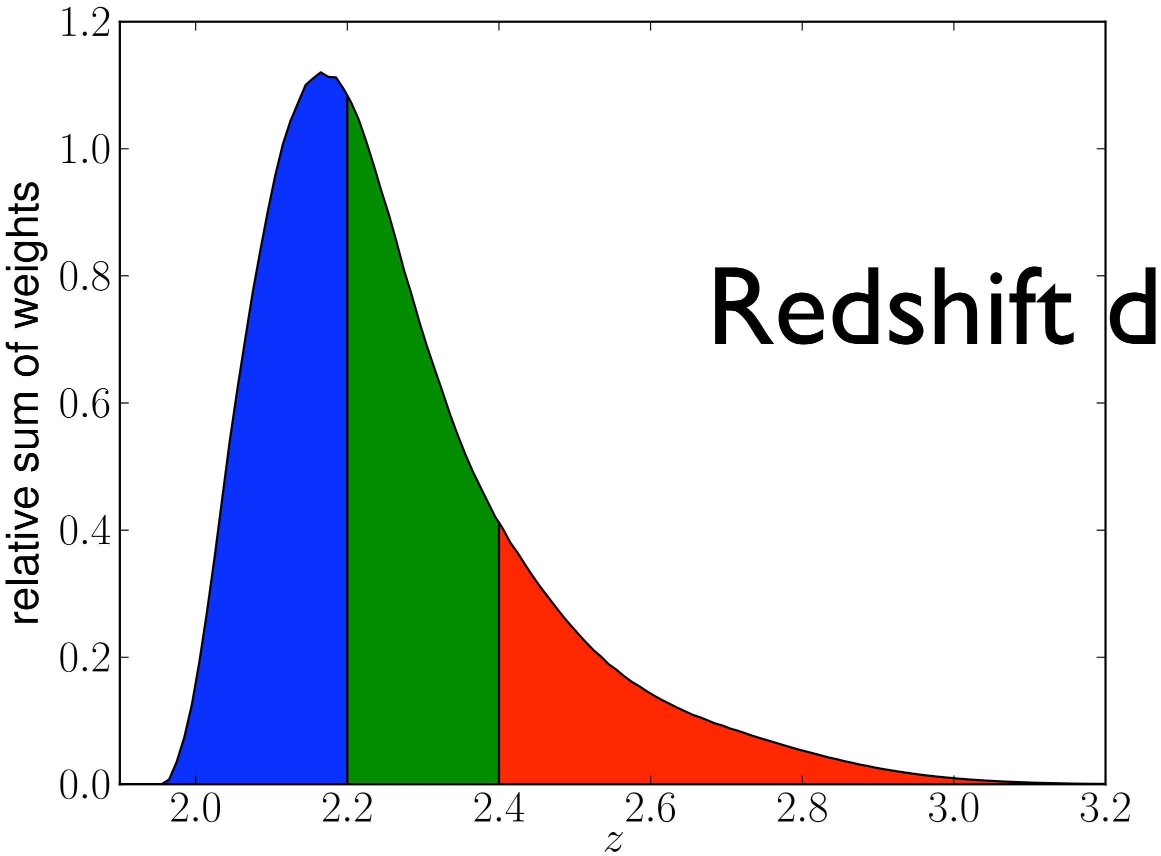
2000
1500
1000
500
0
−500
−1000
−1500
−2000
Mpc/h
0
1000
2000
3000
4000
Mpc/h

"Xi push" arXiv:1104.5244

- "The Lyman-α forest in three dimensions: measurements of large scale flux correlations from BOSS 1st-year data"
- Anze Slosar, Andreu Font-Ribera, et al.
- 14000 BOSS quasars, 880 sq. deg.



Redshift distribution of quasars



Redshift distribution of pair-weights

Measurements of the correlation function of transmitted flux fraction:

$$\delta_F(v) = \frac{F(v)}{\bar{F}} - 1$$

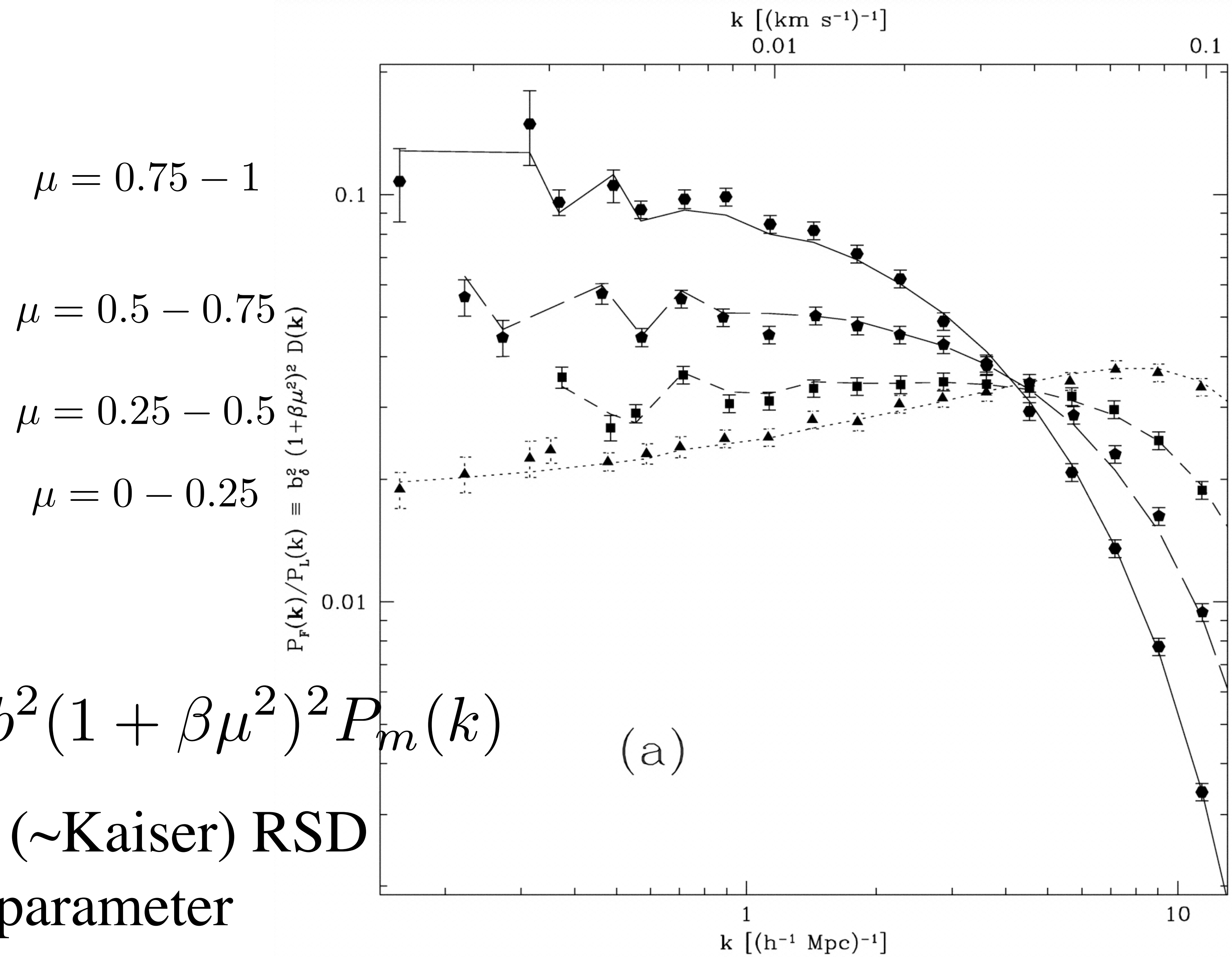
$$\xi(r) = \langle \delta_F(x)\, \delta_F(x+r) \rangle$$

FT of the power spectrum

$$P_F(k) = \left\langle \left| \tilde{\delta}_F(k) \right|^2 \right\rangle$$

Simulated 3D flux power, relative to real-space linear theory (McDonald 2003)

$$\mu = \frac{k_\parallel}{k}$$



$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

Linear theory (~Kaiser) RSD w/beta a free parameter

3D flux power, relative to redshift-space linear theory with fitted beta (McDonald 2003)

Top to bottom on right:

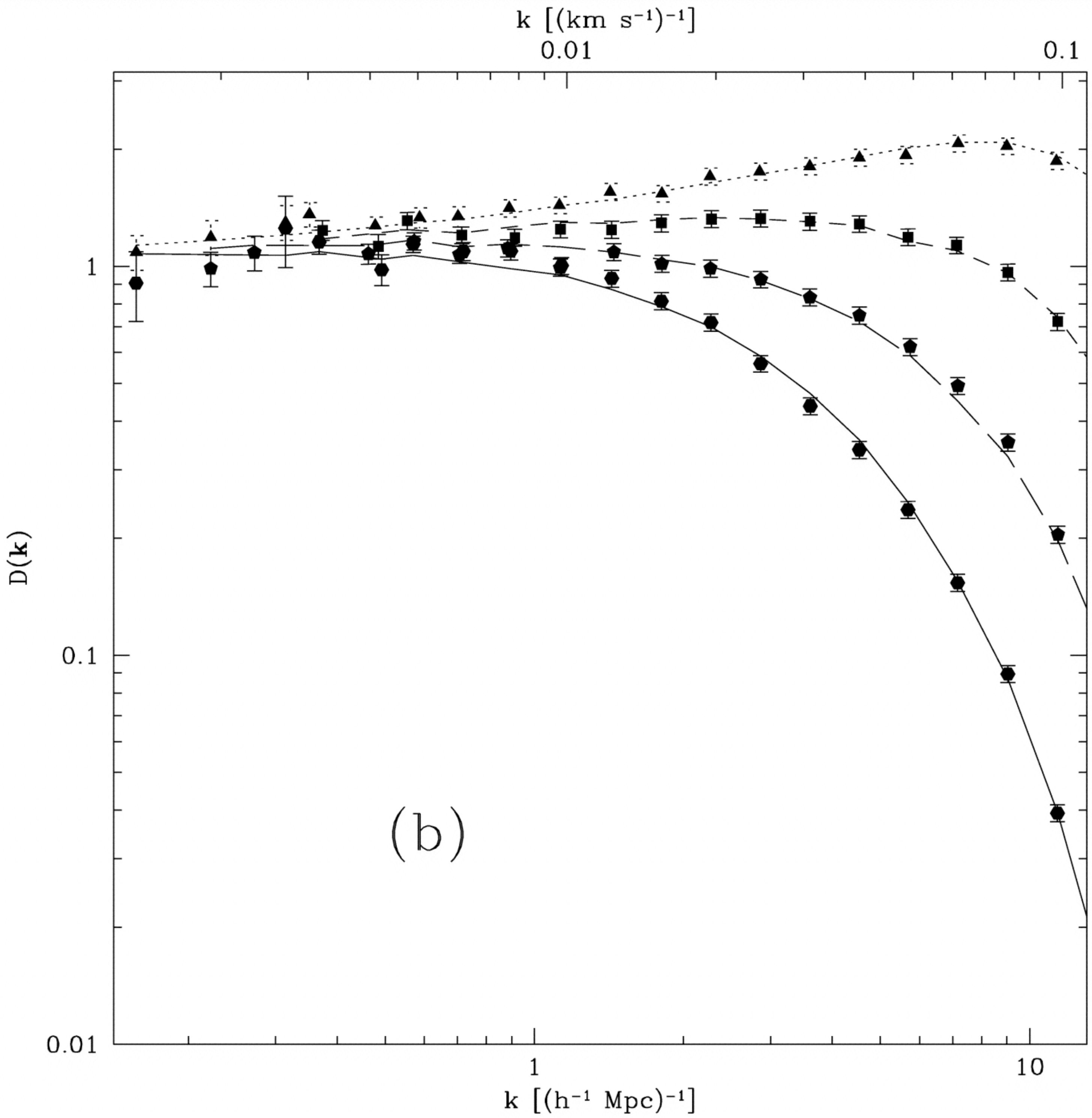
mu=

0-0.25,

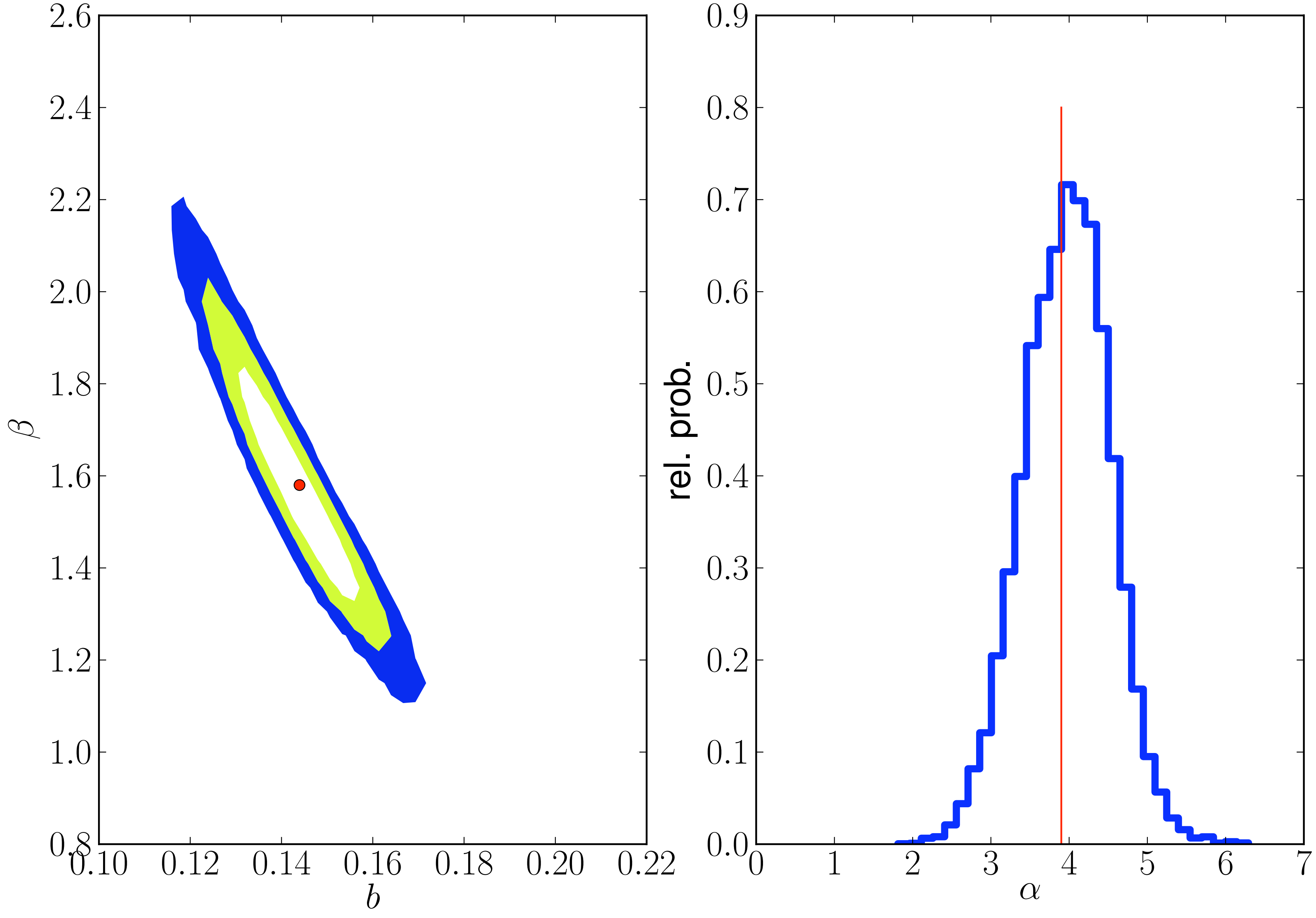
0.25-0.5,

0.5-0.75,

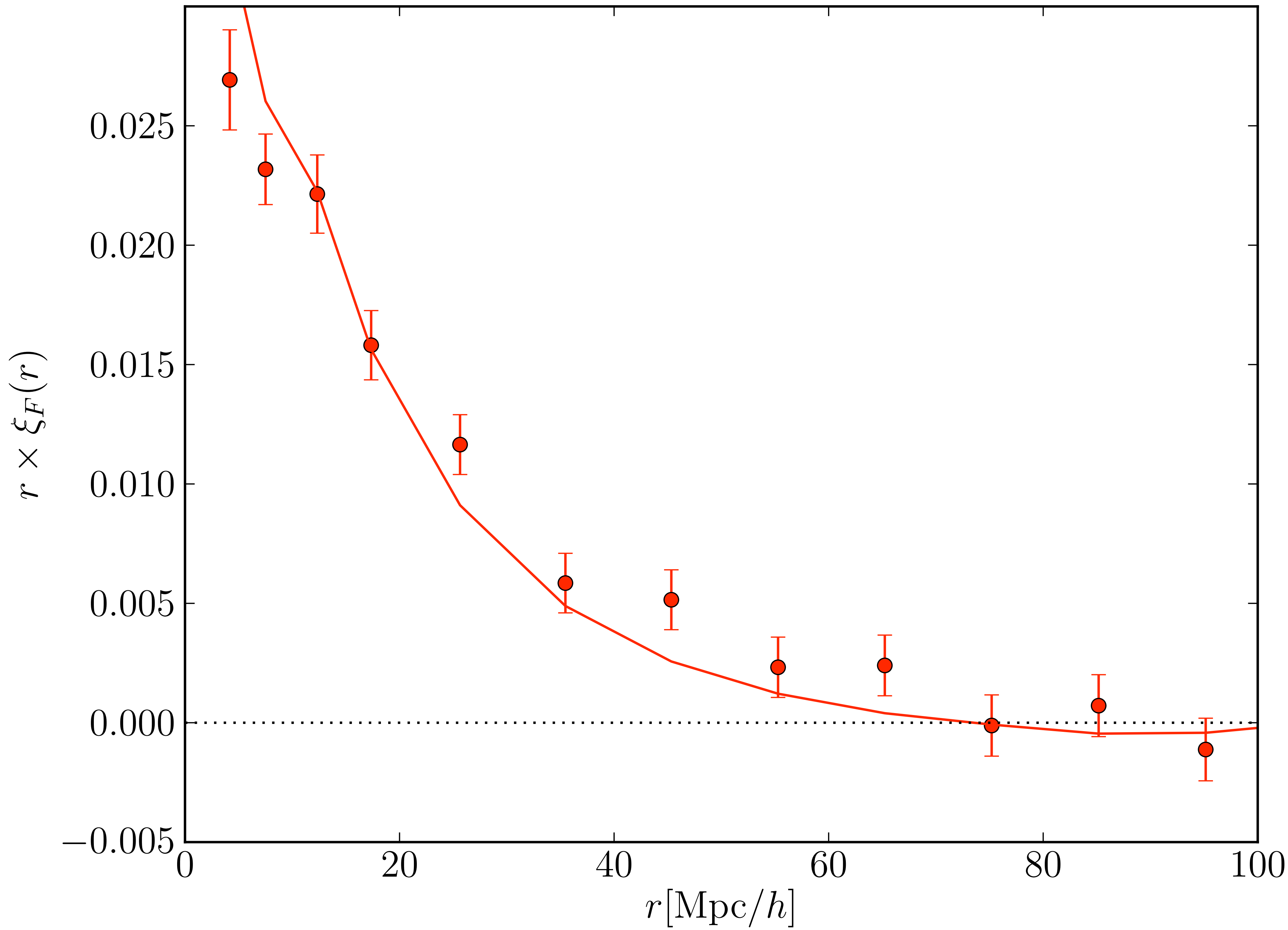
0.75-1.0



Xi push code tested on 30 mocks of the real data set.



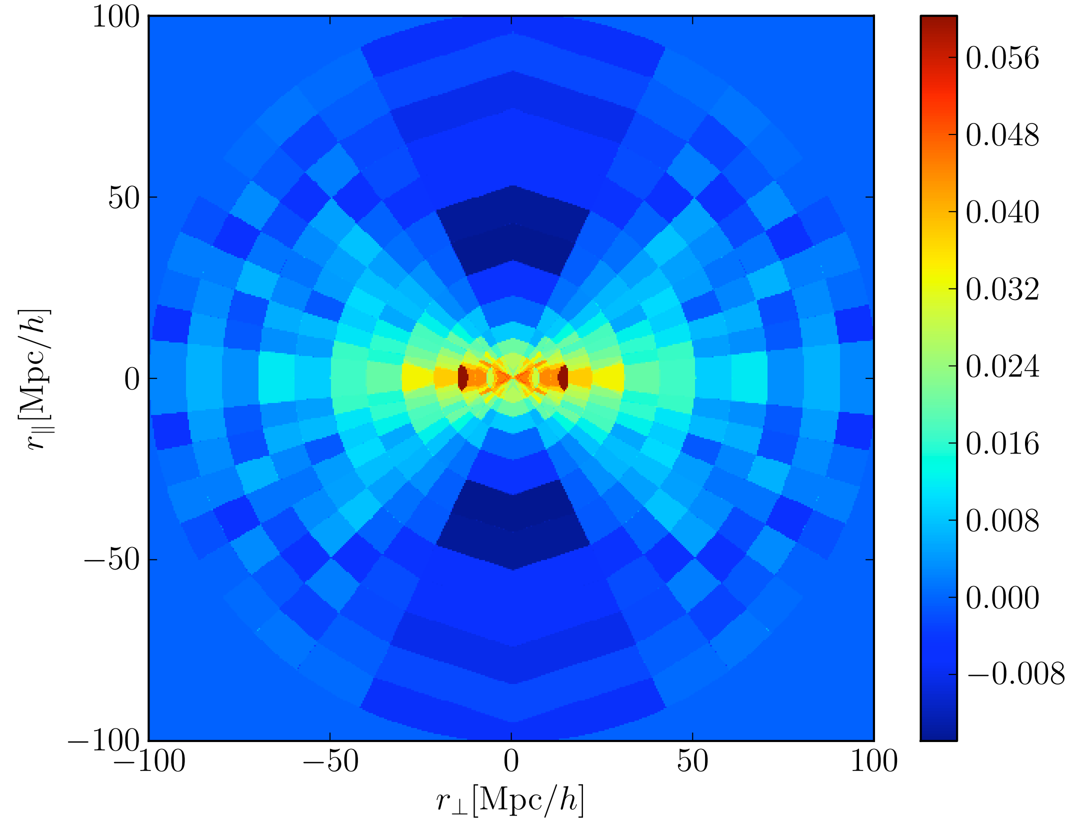
Angle-averaged correlation detected out to ~60 Mpc/h (~as far out as it is expected to be positive). Theoretical LCDM predictions are a good fit.



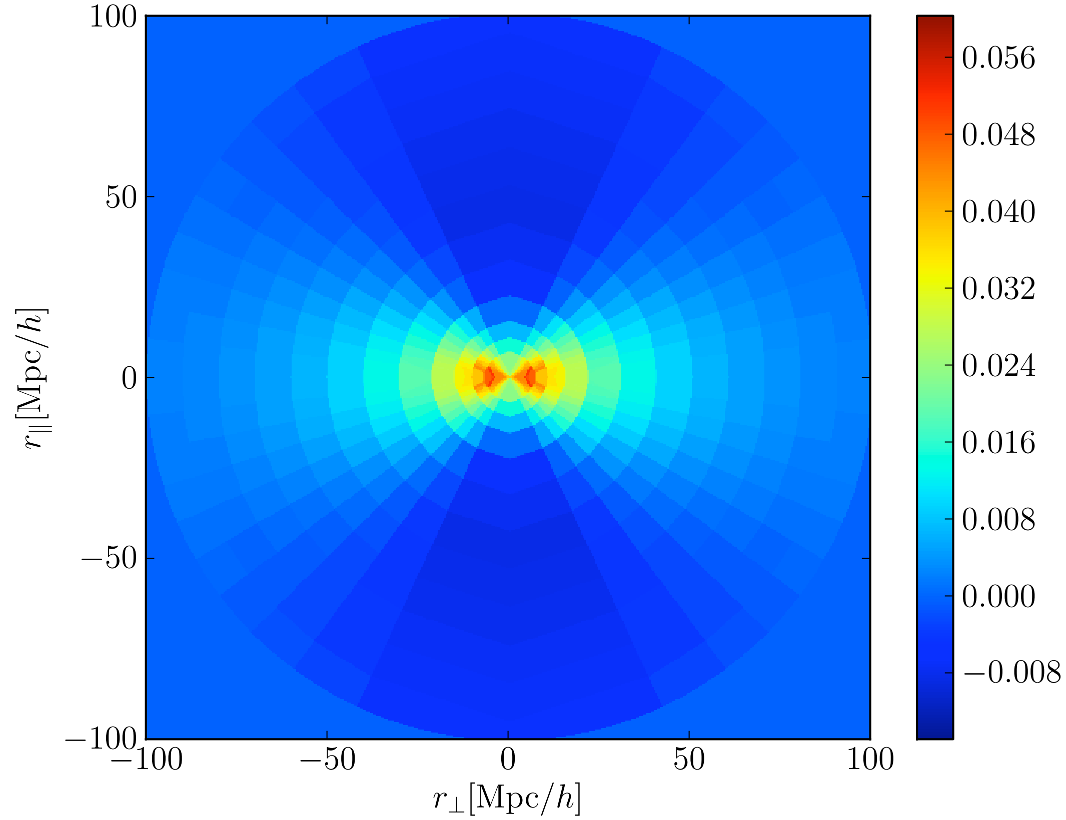
Redshift-space distortions

$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

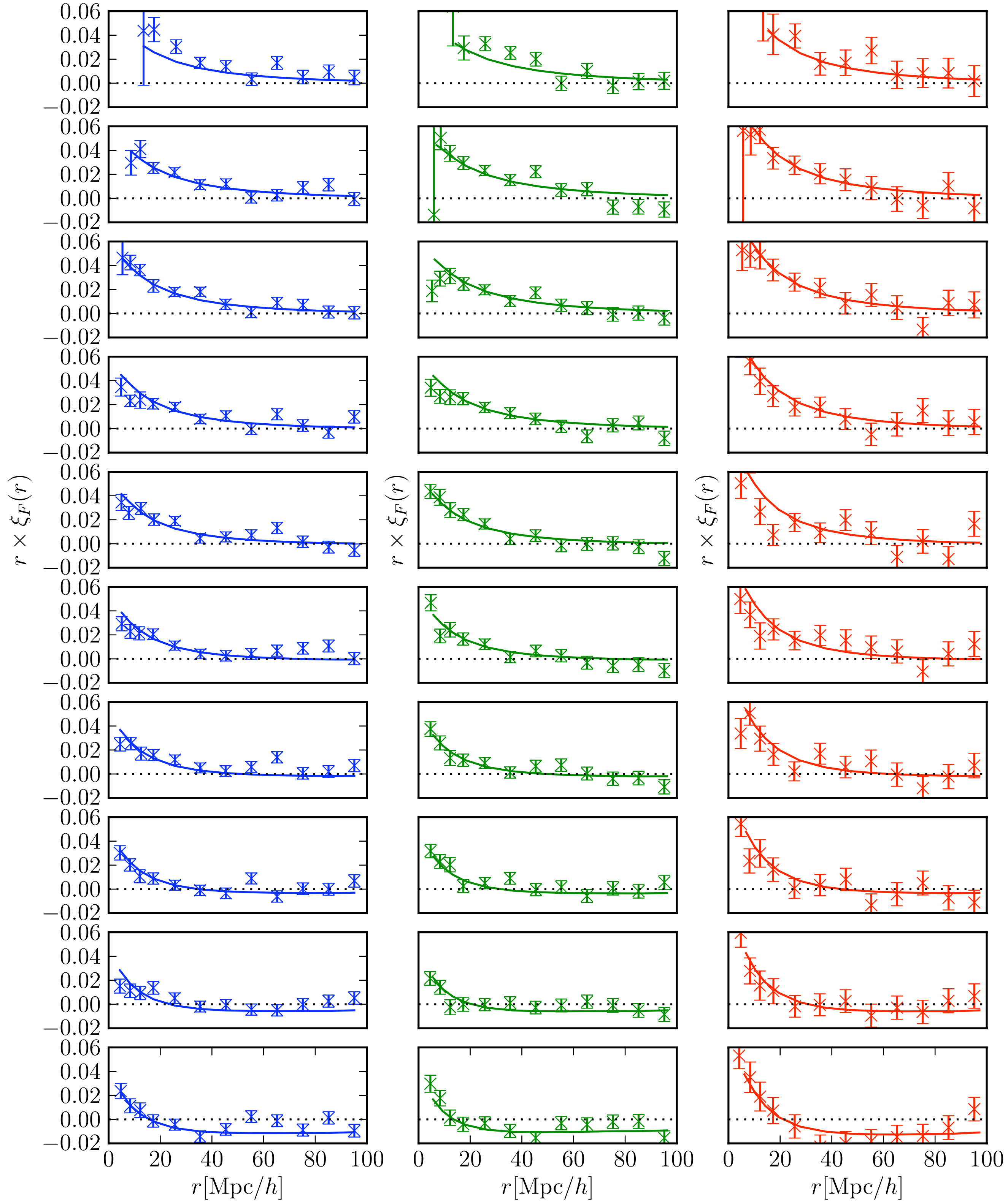
measured anisotropy



predicted anisotropy



z=2.1, 2.3, 2.55

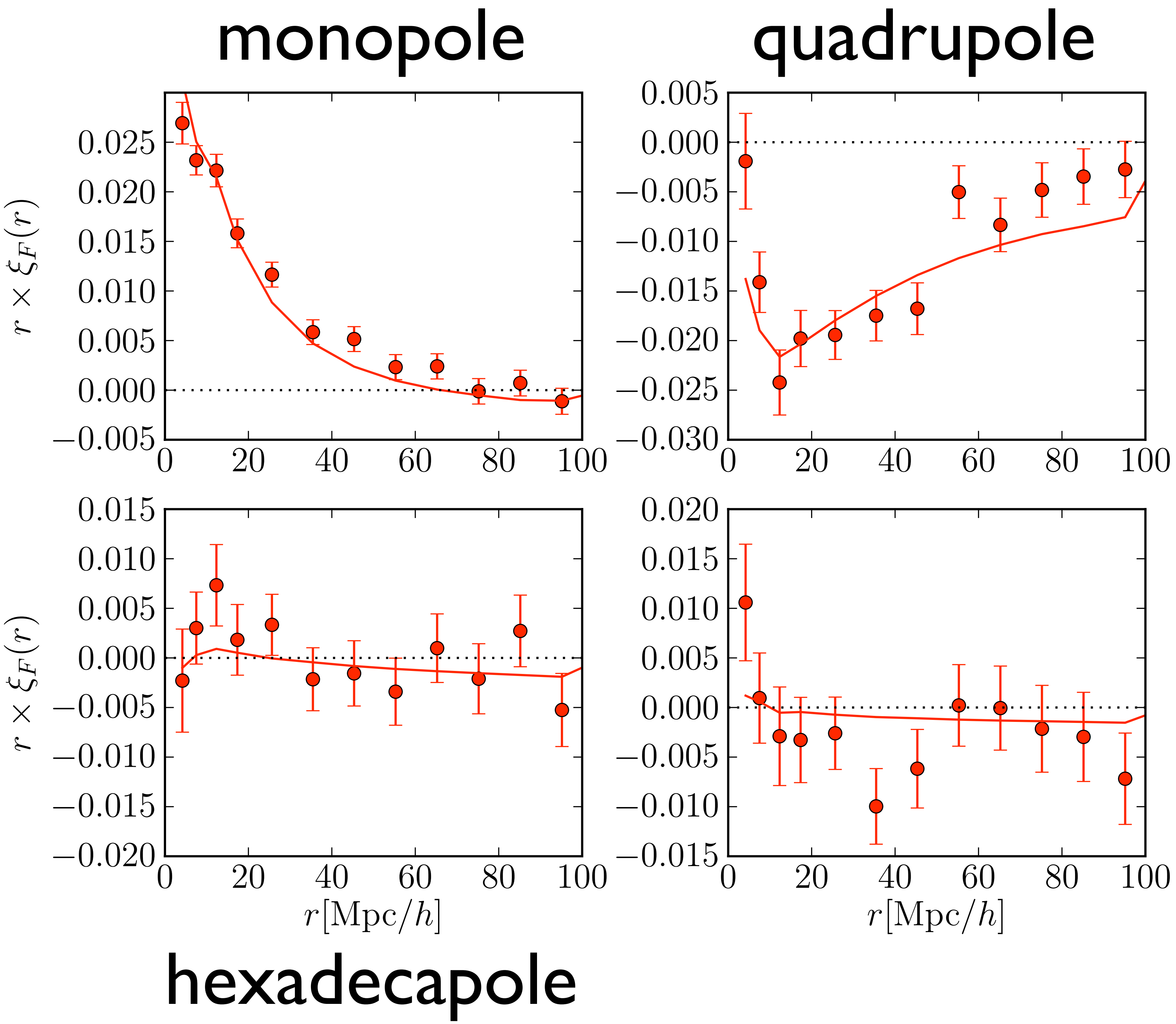


mu increasing top-to-bottom

Good fit to detailed angular dependence

$$P_F(k, \mu) = b^2(1 + \beta\mu^2)^2 P_m(k)$$

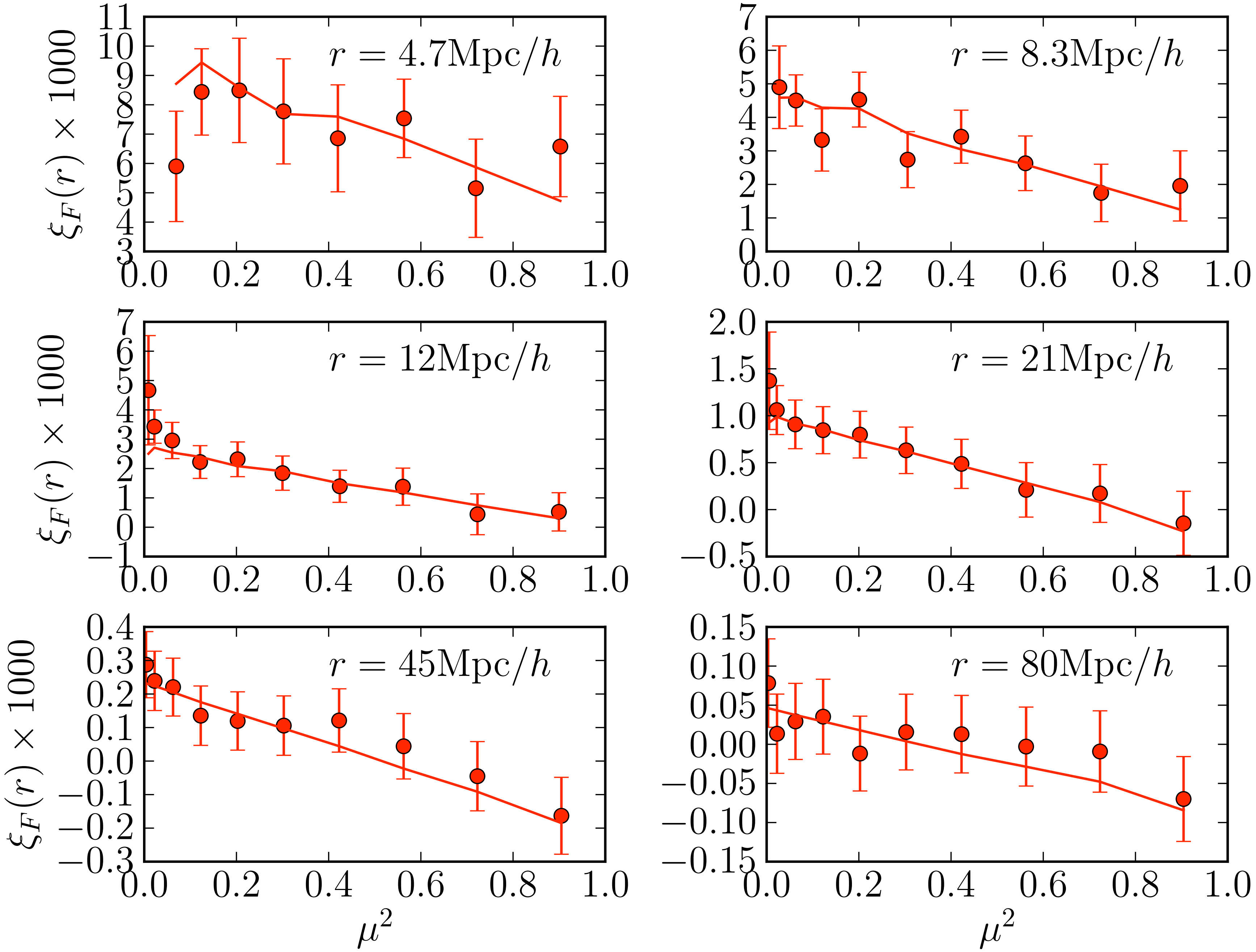
Other views of anisotropy:



$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

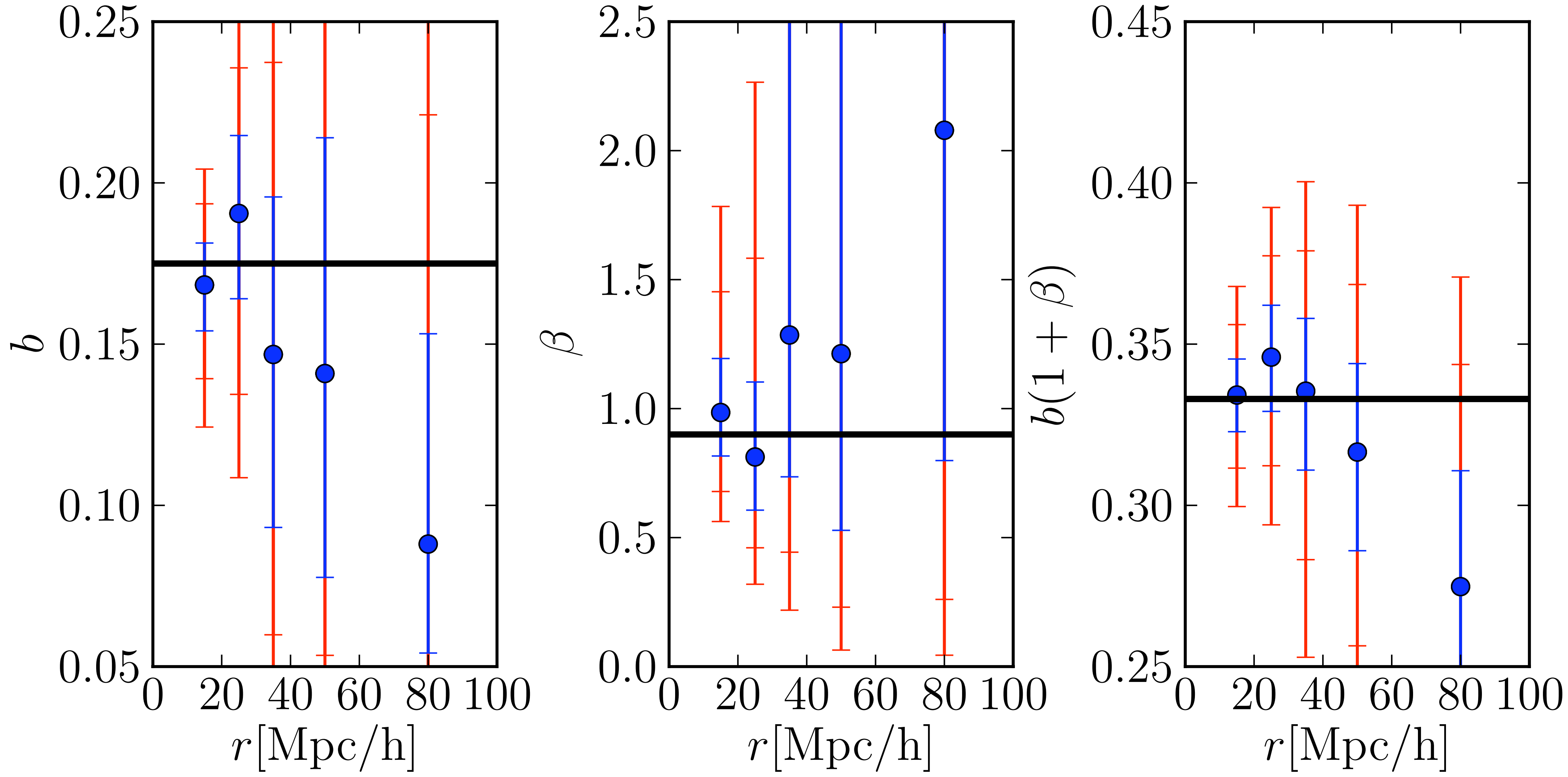
Other views of anisotropy:

Correlation vs. mu, for different r



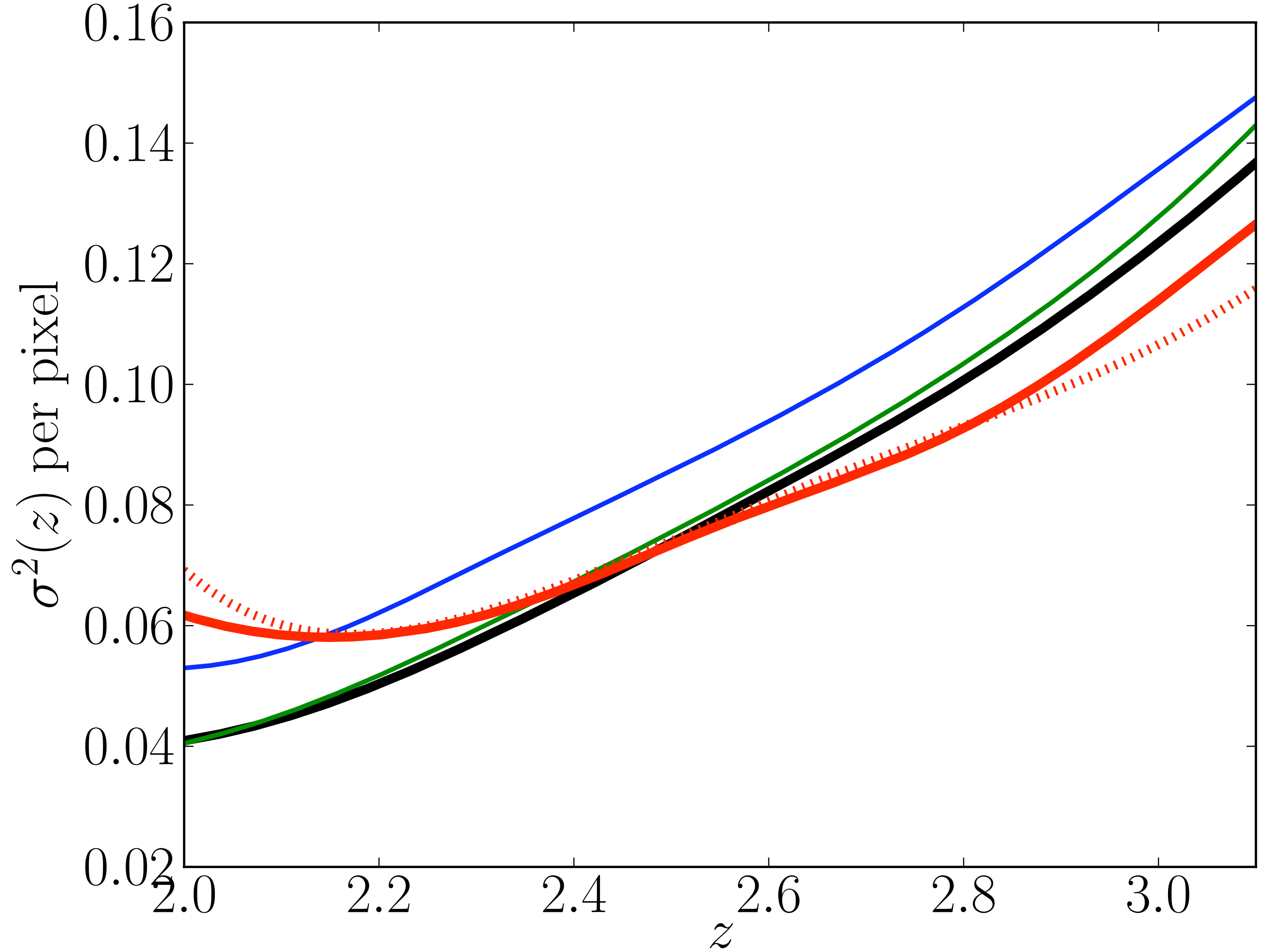
$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

Scale-independent bias parameters, as far as we can tell.
(no dominating non-gravitational effects)



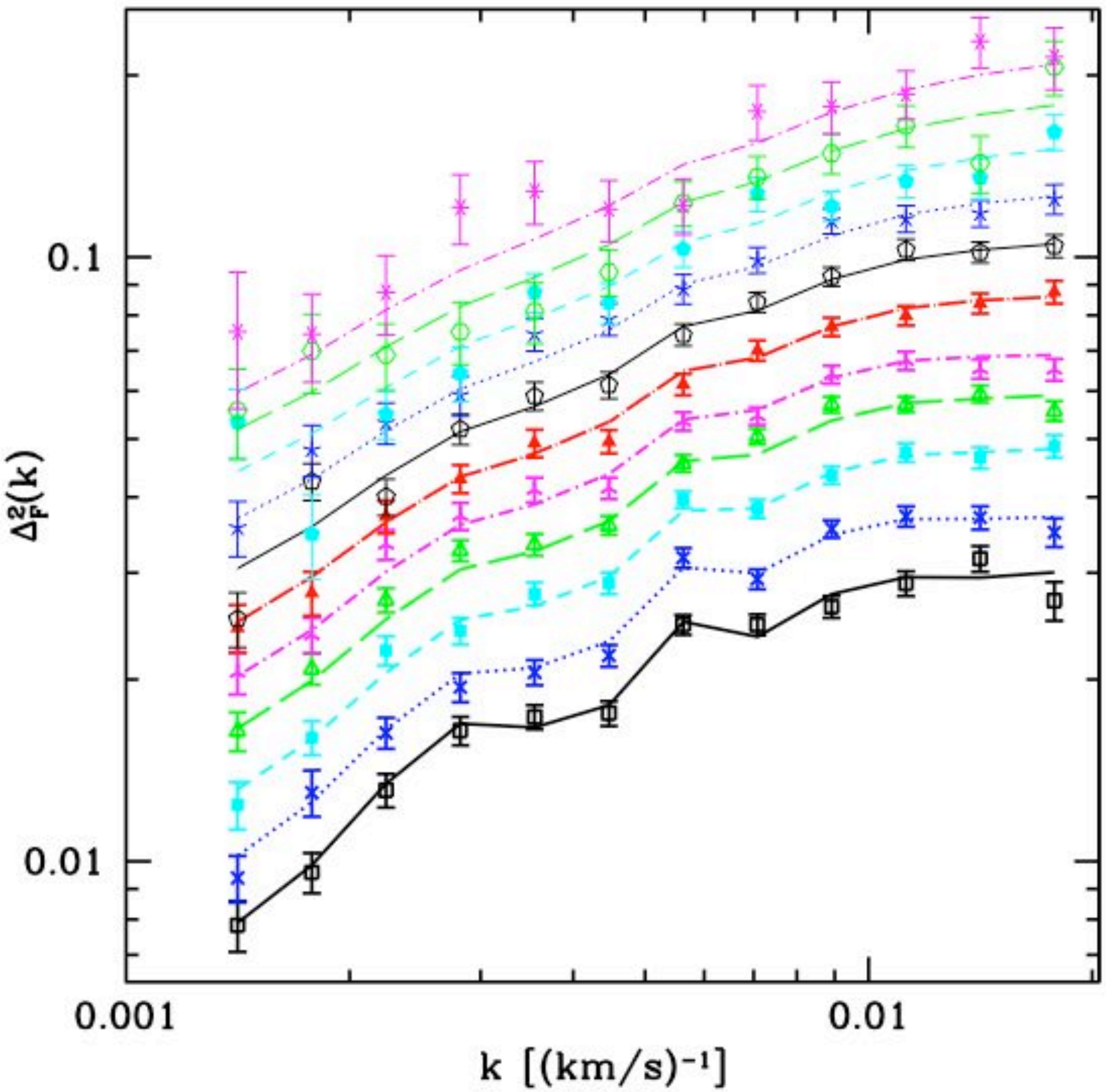
This is all good, but it is not unambiguously correct to say that the xi push results should make us more optimistic about future measurements.

- Following "xi push" philosophy, we never went back to reconcile our theoretical model with the measurements.



Pixel variance
black: expected
red: measured

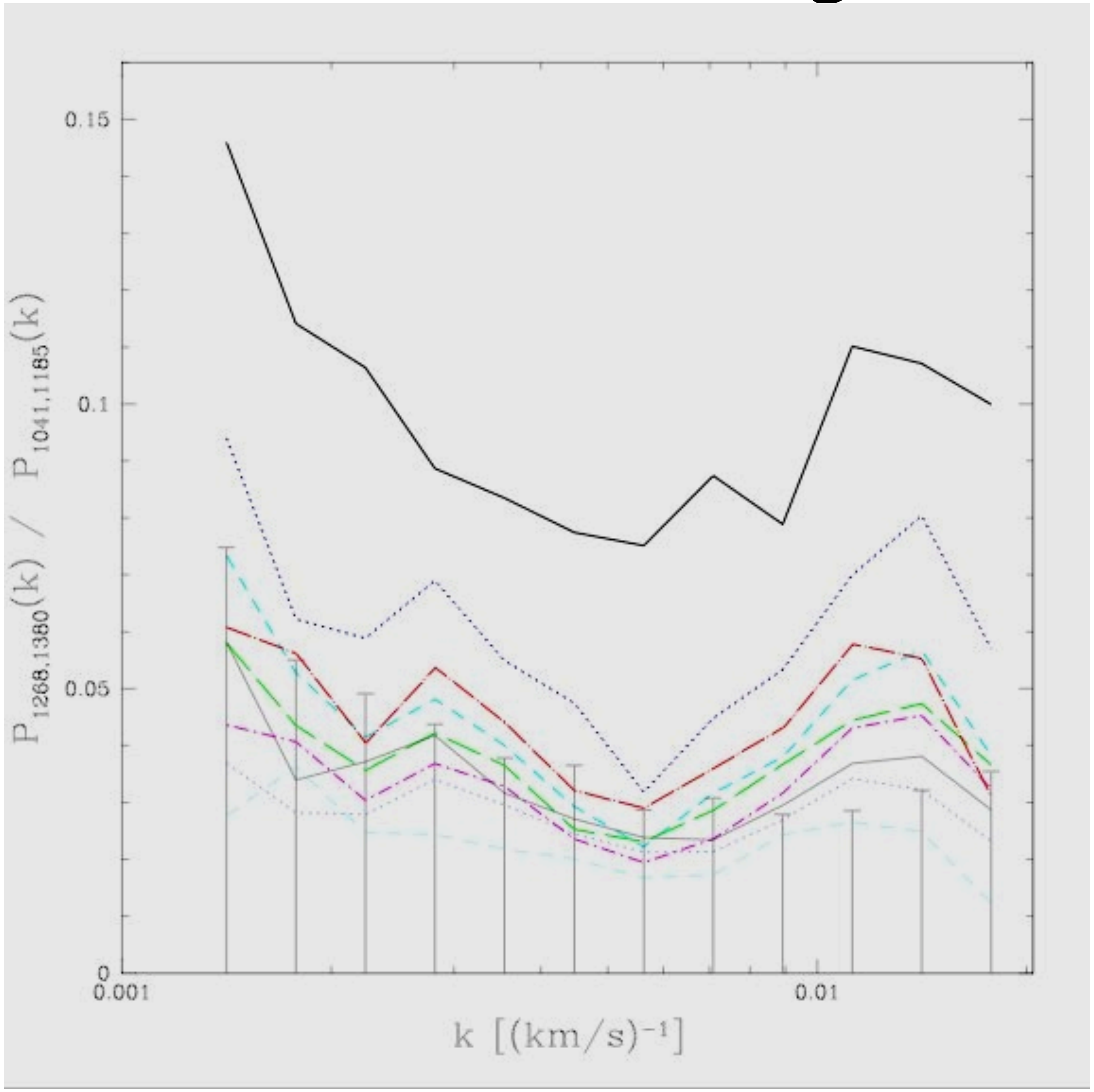
SDSS 1D power spectrum



bottom: z=2.2
top: z=4.2

Smooth evolution for well-understood reasons: the universe is getting less dense with time.

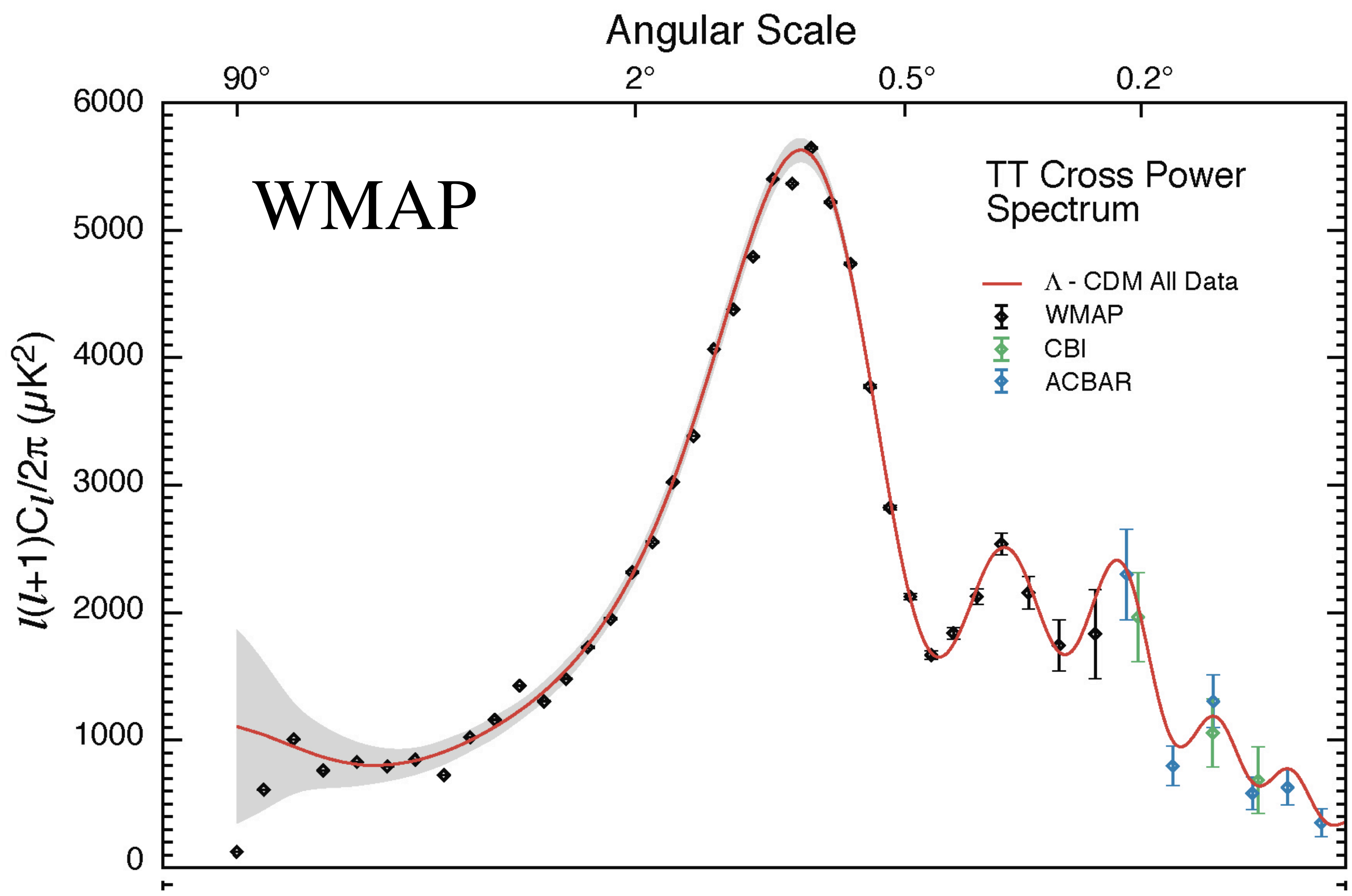
SDSS "background" power



- McDonald et al. (2006)
- Black line z=2.2
- Probably mostly metals (CIV), but not all.
- Error bars starting at zero show error on the forest power.

- The fitted redshift evolution of large-scale bias is pretty consistent with this anomalous variance evolution, and the biases are scale invariant, suggesting that the contaminant is a tracer of large-scale structure.
- RSD parameter beta is also somewhat lower than theoretically expected at the low z end, which may be related.
- Maybe not bad - much work to do to figure out what is going on.

BOSS future: Baryonic acoustic oscillations



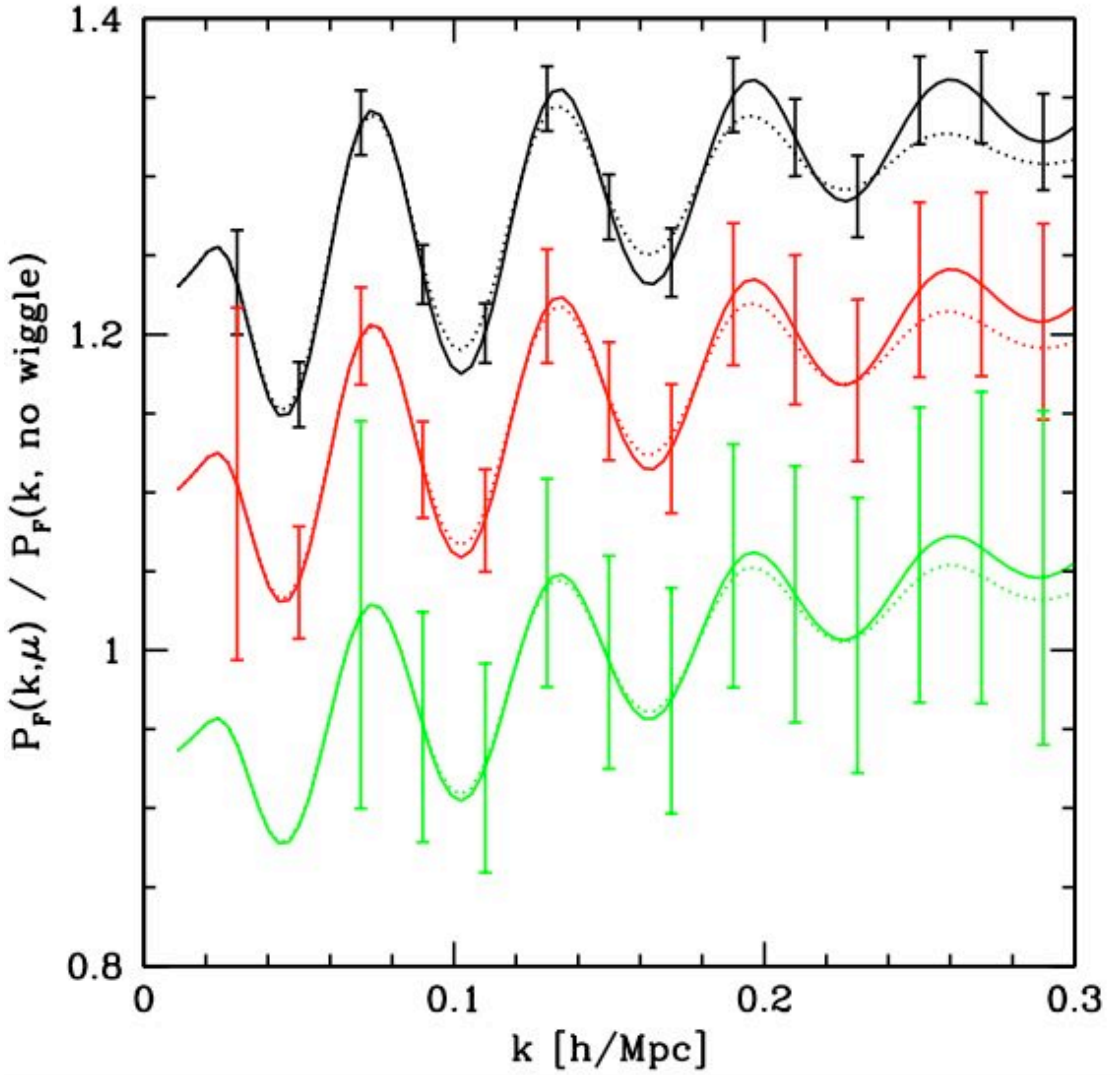
- Observable in principle in any tracer of LSS
- Standard ruler used to study dark energy and curvature
- See Daniel Eisenstein or Martin White's webpages for basic explanation and movies.

Fisher matrix projection for BOSS LyaF:

- Finished survey: 10000 sq. deg., ~150000 quasars (~10 times larger than xi push)
- Radial BAO distance (H) error 3.0%, transverse (D_A) 7.7%
- Isn't that terrible!?! (especially if, from galaxies, you're used to just quoting D_A)

- Not really. We don’t distinguish H from D_A very well (basically, don’t measure transverse modes very well), and this degeneracy blows up the errors on each parameter.
- Expect 1.9% error on overall distance, i.e., dilation factor
- ~7.5 sigma detection of wiggles

BOSS 3D band power projection



- Black: radial
- Green: transverse
- Red: diagonal
- Dotted: Seo & Eisenstein non-linear smearing
- Normalizations compressed.

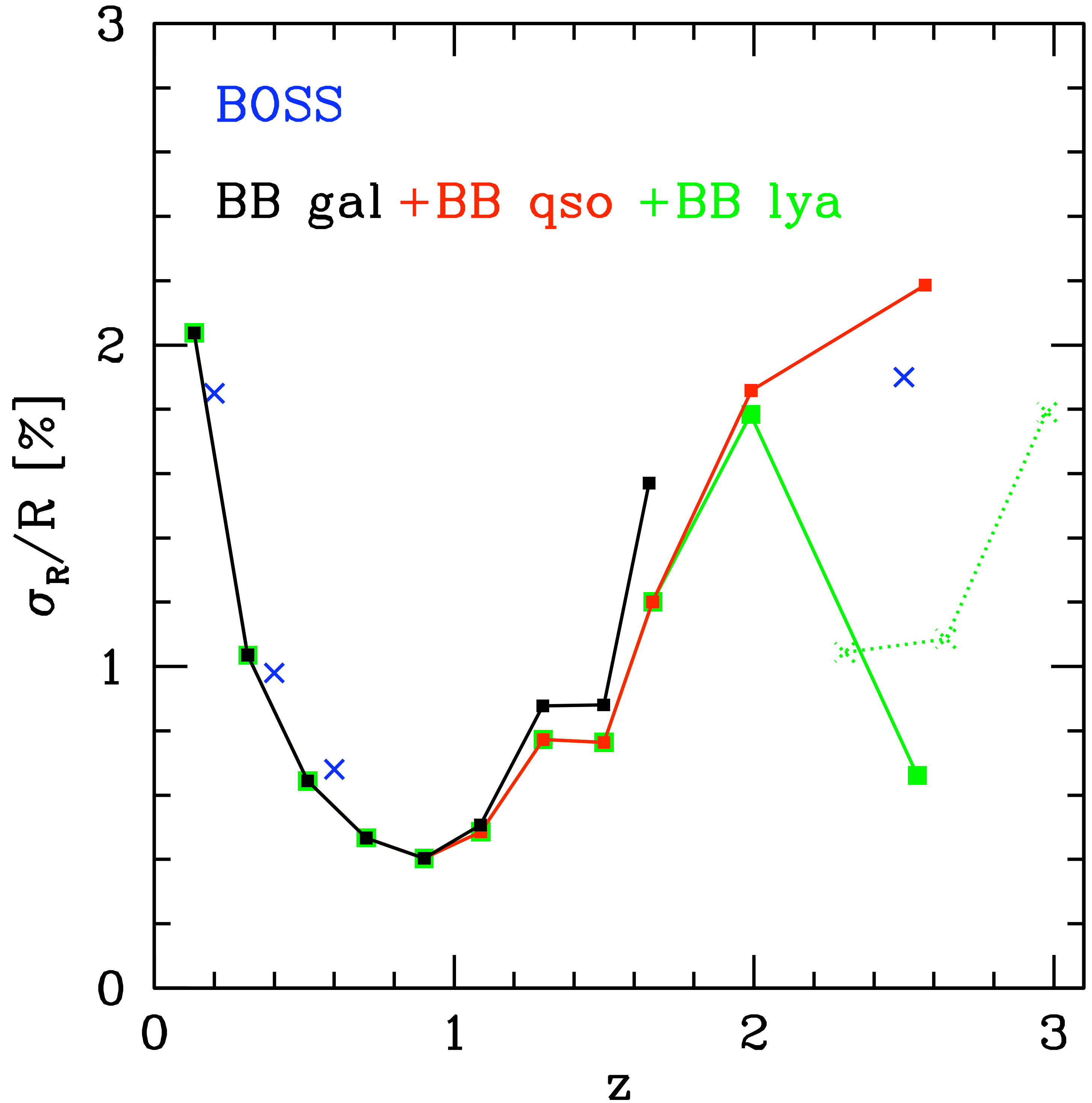
DR9 (data release)

- ~1/3 of the full survey - data taken by this July, released next July
- sqrt(3) larger errors that full survey, i.e., 3.3% distance measurement and 4.3 sigma detection

BigBOSS

- 14000 sq. deg. (+potentially 10000 sq. deg. in South, not in these projections)
- Proposal had 45 quasars per sq. deg. for LyaF so I'm using that ($2.2<z<3.5$, $g<23$).
- More (~65) could easily be possible (Ch. Yeche). rms distance errors improve like ~1/n.

Fisher projections for BigBOSS



- Dilation factor % error
- Proposal number densities (except for qso clustering)
- FoM gains justify fiber allocation

General constraints (not just BAO)

- Running of the inflationary spectral index

	ω_m	ω_b	$\log_{10}(A)$	n_s	α_s	τ	h	Ω_m
value	0.133	0.0227	−8.67	0.963	0.00	0.0890	0.719	0.257
P+gB	0.00068	0.00015	0.0087	0.0029	0.0063	0.0098	0.0037	0.0035
P+gB+hr+BOSS	0.00066	0.00012	0.0081	0.0029	0.0027	0.0092	0.0033	0.0035
P+gB+hr+BB	0.00041	0.00012	0.0076	0.0022	0.0022	0.0086	0.0017	0.0017

- Neutrino mass (eV)

	ω_m	ω_b	Σm_ν	$\log_{10}(A)$	n_s	τ	h	Ω_m
value	0.133	0.0227	0.0500	−8.67	0.963	0.0890	0.714	0.260
P+gB	0.00069	0.00017	0.094	0.0084	0.0046	0.0097	0.0046	0.0039
P+gB+hr+BOSS	0.00057	0.00013	0.056	0.0080	0.0035	0.0095	0.0041	0.0035
P+gB+hr+BB	0.00045	0.00012	0.035	0.0076	0.0030	0.0089	0.0022	0.0021

Also improve measurement of effective number of light neutrinos (~3), i.e., amount of radiation in the universe.

Why these (non-BAO) projections might be conservative:

- Use only the power spectrum, while we know that the bispectrum can help break degeneracies between cosmological and gas model parameters.
- Similarly, other statistics, e.g., measurements in the Ly-beta forest, can help break degeneracies.
- Plenty of consistency checks: other statistics, redshift evolution, data splitting.

Interpreting the xi push results.

- I've said that the scale independence of the xi push bias parameters implies gravity only, but why is that? Isn't "biasing" some ad hoc prescription that generally can do pretty much anything? (e.g., delta_F(k) = b(k) delta_m(k))
- We understand things better now.

Simulated 3D flux power, relative to real-space linear theory (McDonald 2003)

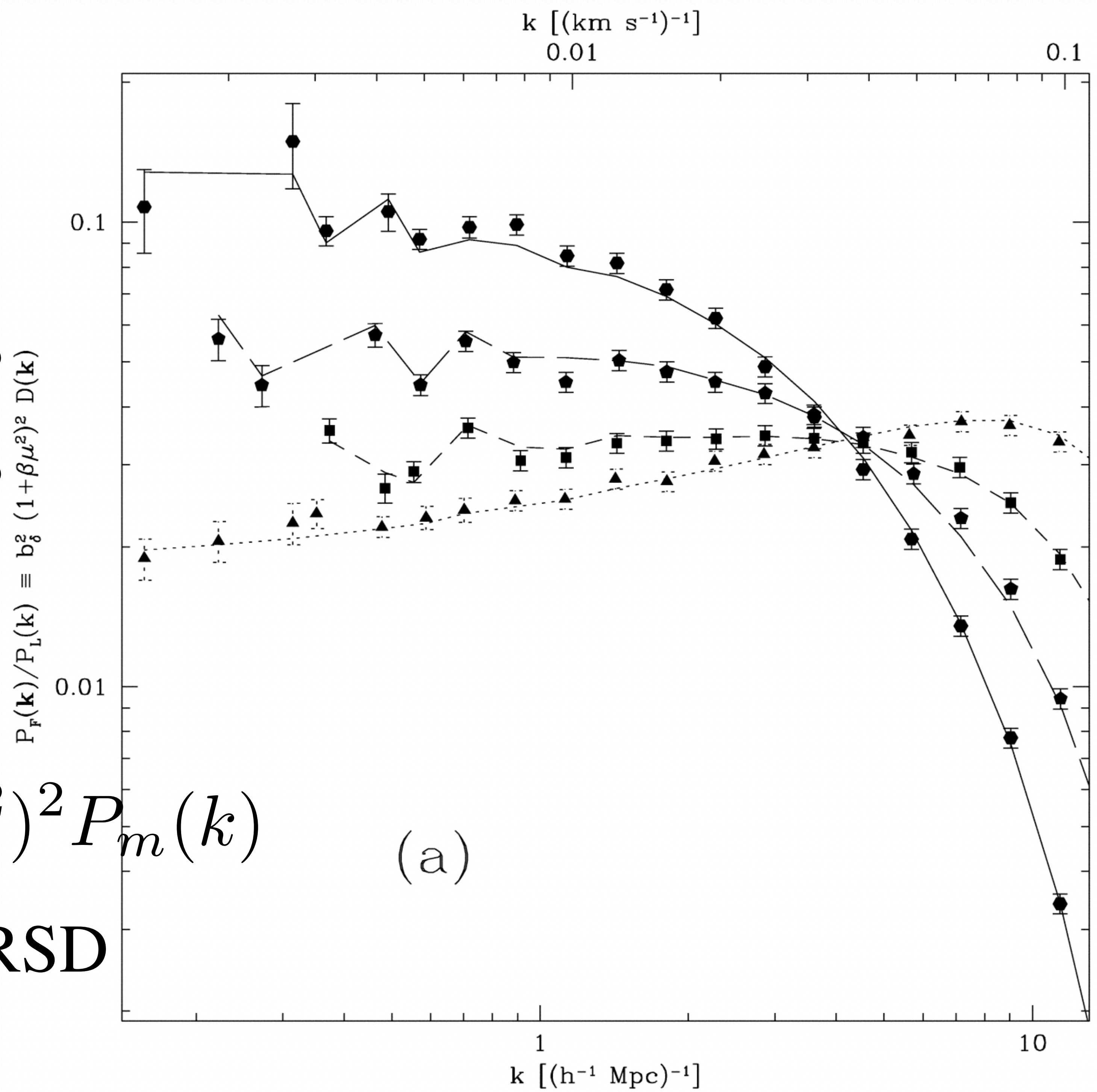
$$\mu = \frac{k_{\|}}{k}$$

$\mu = 0.75 - 1$

$\mu = 0.5 - 0.75$

$\mu = 0.25 - 0.5$

$\mu = 0 - 0.25$



$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

Linear theory (~Kaiser) RSD w/beta a free parameter

Derivation of linear bias: generally, perturbative bias

- Tracer density is a Taylor series in the local mass density perturbation (Fry & Gaztanaga 1993):

$$\rho_g(\delta) = \rho_0 + \rho_0' \, \delta + \frac{1}{2}\rho_0'' \, \delta^2 + \frac{1}{6}\rho_0''' \, \delta^3 + \dots$$

$$\delta_g(\delta) = \frac{\rho_g(\delta) - \bar{\rho}_g}{\bar{\rho}_g} = c_1\delta + \frac{1}{2}c_2\left(\delta^2 - \sigma^2\right) + \frac{1}{6}c_3\delta^3 + \dots$$

Defining this to be a local relation implies that the relation applies at arbitrarily small scales, but fluctuations are not small if one goes to small scales!

Standard LyaF picture is an explicit example of "tracer density depends on local mass density".

- Baryons in the IGM trace dark matter except on small scales where pressure matters (~100 kpc).
- Photoionization equilibrium with a near-uniform ionizing background gives the neutral density (the gas is almost completely ionized).

$$\Gamma n_{HI} = \alpha(T) n_p n_e \qquad n_{HI} \propto \frac{\alpha(T)\rho_b^2}{\Gamma}$$

- Competition between photoionization heating and adiabatic expansion cooling produces a roughly power law relation between temperature and gas density.

$$T \simeq T_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma-1} \qquad n_{HI} \propto \left(\frac{\rho}{\rho_0}\right)^{2-0.7(\gamma-1)}$$

- If you believe locality leads to scale-independent bias, something here needs to break to give scale-dependent bias.

Renormalizing bias (McDonald 2006)

(what to do about the fact that your Taylor series is nonsense)

- Tracer density is a Taylor series in mass density perturbation (local for now):

$$\rho_g(\delta) = \rho_0 + \rho_0' \, \delta + \frac{1}{2}\rho_0'' \, \delta^2 + \frac{1}{6}\rho_0''' \, \delta^3 + \ldots$$

$$\delta_g(\delta) = \frac{\rho_g(\delta) - \bar{\rho}_g}{\bar{\rho}_g} = c_1\delta + \frac{1}{2}c_2\left(\delta^2 - \sigma^2\right) + \frac{1}{6}c_3\delta^3 + \ldots$$

Correlation function:

$$\xi_g\left(|\mathbf{x}_a - \mathbf{x}_b|\right) = \xi_g^{ab} = \left\langle \delta_g^a \delta_g^b \right\rangle =$$
$$c_1^2 \left\langle \delta_a \delta_b \right\rangle + \tfrac{1}{3}c_1 c_3 \left\langle \delta_a \delta_b^3 \right\rangle + \tfrac{1}{4}c_2^2 \left(\left\langle \delta_a^2 \delta_b^2 \right\rangle - \sigma^4\right) + c_1 c_2 \left\langle \delta_a \delta_b^2 \right\rangle + \ldots$$

Assuming Gaussian IC

$$\xi_g^{ab} = c_1^2 \xi_{ab} + c_1 c_3 \sigma^2 \xi_{ab} + \frac{1}{2}c_2^2 \xi_{ab}^2 + c_1 c_2 \left\langle \delta_a \delta_b^2 \right\rangle + \ldots$$

$$\sigma^2 = \left\langle \delta^2 \right\rangle \sim \text{large}$$

- Continuing the calculation, other terms further renormalize bias, and also shot-noise (i.e., add a constant to the power spectrum as k->0), but nothing new appears.
- Bottom line: in the low k limit, scale-independent (single constant) linear bias plus white noise is an inevitable prediction for a tracer that depends locally on mass density.

- How could the LyaF deviate from this?

$$n_{HI} \propto \frac{\alpha(T)\rho_b^2}{\Gamma}$$

- Basically, T or Gamma must not be local functions of density. The latter is straightforward - the radiation background seen by a point is a non-local convolution over sources and absorbers. Temperature fluctuations are essentially a time-delayed version of this, i.e., due to inhomogeneous reionization.

What about local dependence on things other than density? (McDonald & Roy 2009)

- The basic quantities that appear in gravitational evolution (w/Gaussian IC) are density, velocity, and gravitational potential, suggesting:

$$\rho_g = f\left(\delta, \mathbf{v}, \phi\right)$$

- But a *homogeneous* velocity field, change in potential, or change in gravitational force, should not be observable, suggesting:

$$\rho_g = f\left(\delta,\ \partial_i v_j,\ \partial_i \partial_j \phi\right)$$

What can galaxy density depend on?

- But all the terms in a Taylor series for the galaxy density must be scalars (because galaxy density is), and homogeneity and isotropy require our bias parameters (the coefficients in the Taylor series) to be scalars, so we must always contract indices to make scalars, e.g., use velocity divergence:

$$\theta \equiv \partial_i v_i$$

What can galaxy density depend on?

- But in linear theory (with velocity appropriately normalized relative to the Hubble flow) $\theta(\mathbf{x}) = \delta(\mathbf{x})$
- So it would have been silly to have the linear bias model

$$\delta_g = a\delta + b\theta \quad [= (a+b)\delta]$$

What can galaxy density depend on?

- For this reason, we use a variable which is non-zero only at 2nd order:

$$\psi(\mathbf{x}) = \theta(\mathbf{x}) - \delta(\mathbf{x})$$

- For the same reason, we define the traceless tensor (for potential normalized such that $\nabla^2\phi = \delta$

$$s_{ij}(\mathbf{x}) \equiv \nabla_i \nabla_j \phi(\mathbf{x}) - \frac{1}{3}\delta^K_{ij}\ \delta(\mathbf{x}) = \left[\nabla_i \nabla_j \nabla^{-2} - \frac{1}{3}\delta^K_{ij}\right]\delta(\mathbf{x}) \equiv \gamma_{ij}\delta(\mathbf{x})$$

- and $t_{ij}(\mathbf{x}) = \gamma_{ij}\psi(\mathbf{x})$

Probably everyone is confused at this point, and it gets worse before it gets better.

- The bottom line, after computing the galaxy power spectrum and identifying more equivalencies between terms, is that the model with the following terms is sufficient to represent the power spectrum (and bispectrum) to 4th order in the perturbations:

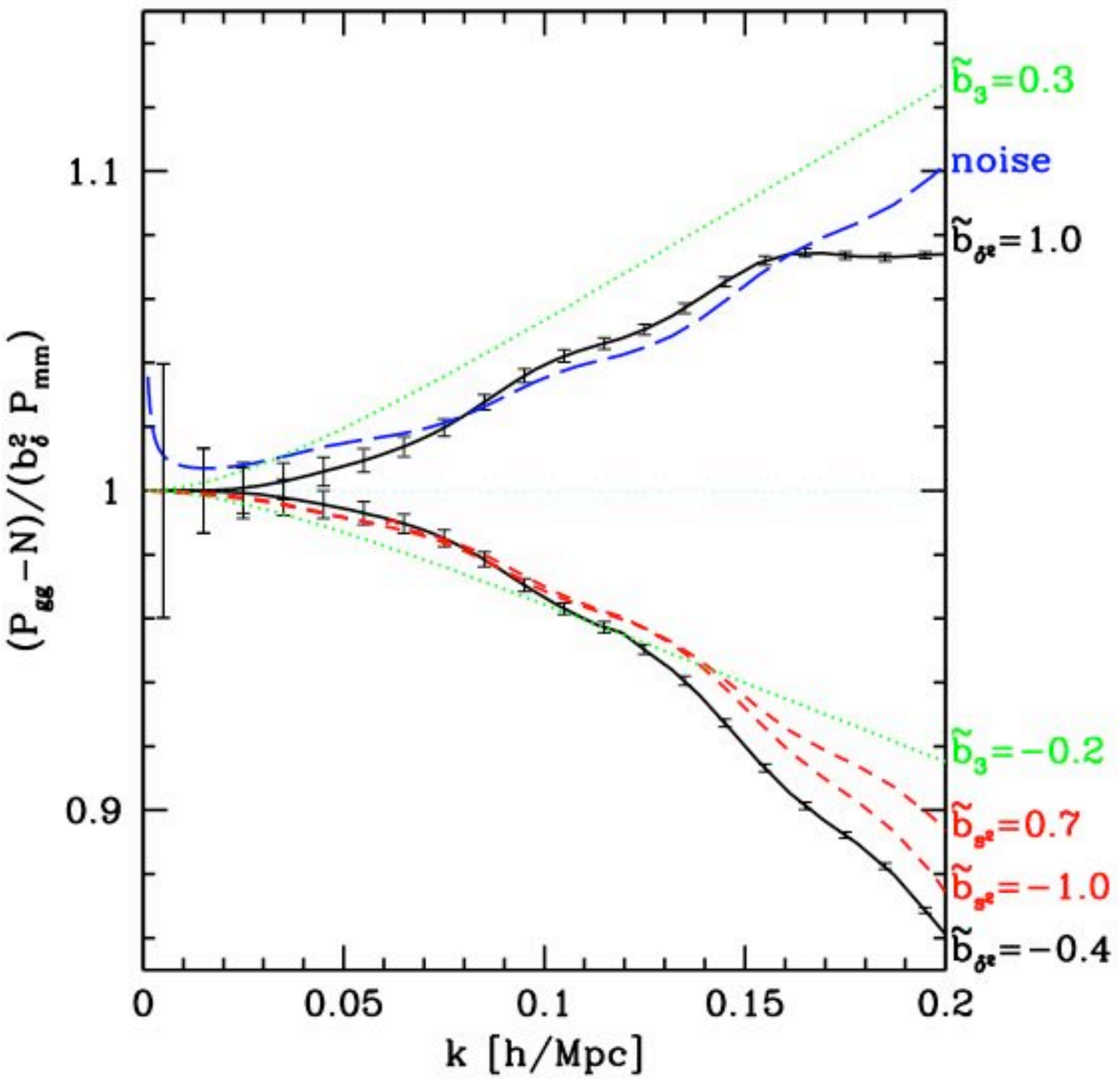
$$\delta_g = b_\delta\ \delta + \frac{1}{2}\ b_{\delta^2}\ \delta^2 + \frac{1}{2} b_{s^2}\ s^2 + b_{st}\ st + \ldots + \epsilon$$

$$s^2 = s_{ij} s_{ji},\ \ st = s_{ij} t_{ji}$$

$$s_{ij} = \gamma_{ij}\delta, \quad t_{ij} = \gamma_{ij}(\theta - \delta)$$

$$\gamma_{ij} = \left[\nabla_i \nabla_j \nabla^{-2} - \frac{1}{3}\delta^K_{ij}\right]$$

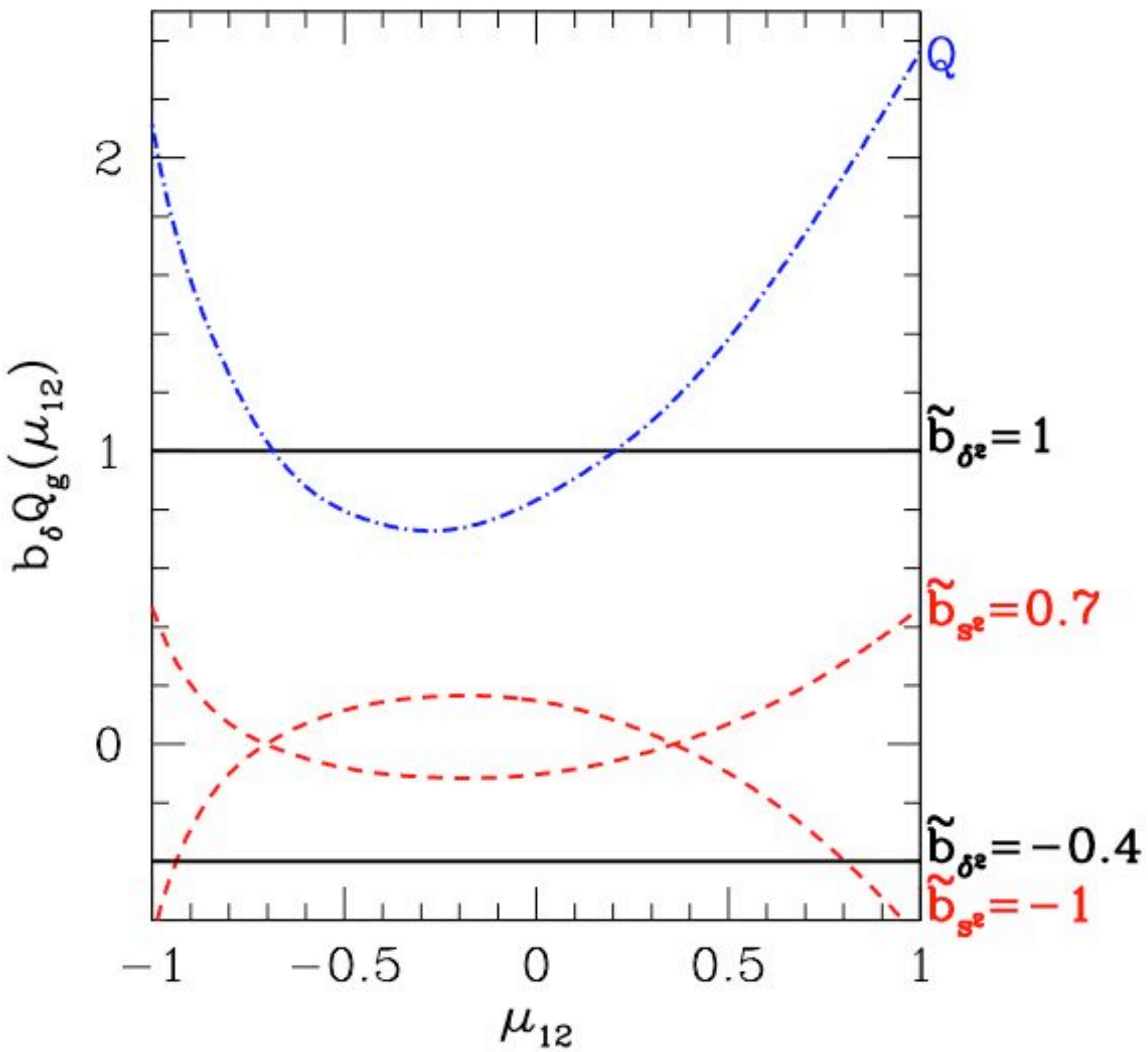
Deviation from linearity in the galaxy power spectrum $\langle\delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\rangle \propto P(k_1)$



- Errors for 100 cubic Gpc/h CHIME/ ADEPT-like survey
- Over *most* of this range, corrections to linear theory are both *significant* and *small* (<10%)

Bispectrum $\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle \propto B(\mathbf{k}_1, \mathbf{k}_2)$

$$Q_X(k_1,k_2,k_3) = \frac{B_X(k_1,k_2,k_3)}{P_X(k_1)P_X(k_2)+P_X(k_2)P_X(k_3)+P_X(k_3)P_X(k_1)}$$



- k_1=0.1 h/Mpc
- k_2=0.2 h/Mpc
- mu is the cosine of the angle between k_1 and k_2

Requirements for standard linear bias model:

- No long-range non-gravitational interactions (i.e., tracer formation local, aside from gravitational effects)
- Gaussian initial conditions (no mode-coupling built into IC)
- GR (linear growth scale-independent)

Conclusions

- Xi push paper was qualitatively great. Demonstrated that the signal is there, more or less as expected.
- Hopefully detect BAO in BOSS before DR9 release, July 2012.
- BigBOSS gives a factor of 3 *rms* improvement in BAO distance over BOSS.
- Anything does *not* go with bias. Scale-independent linear bias == gravity-only on large scales.