Tomographic BAO analysis of BOSS DR12 combined sample

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Gong-Bo Zhao, YW, et al BOSS collaboration, arXiv:1607.03153
YW, Gong-Bo Zhao, et al BOSS collaboration, arXiv:1607.03154

Part I

BAO as Dark Energy probe

Part II

Fits from CMASS/LOWZ

Part III

tomographic BAO analysis

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Concluding remarks

Part I

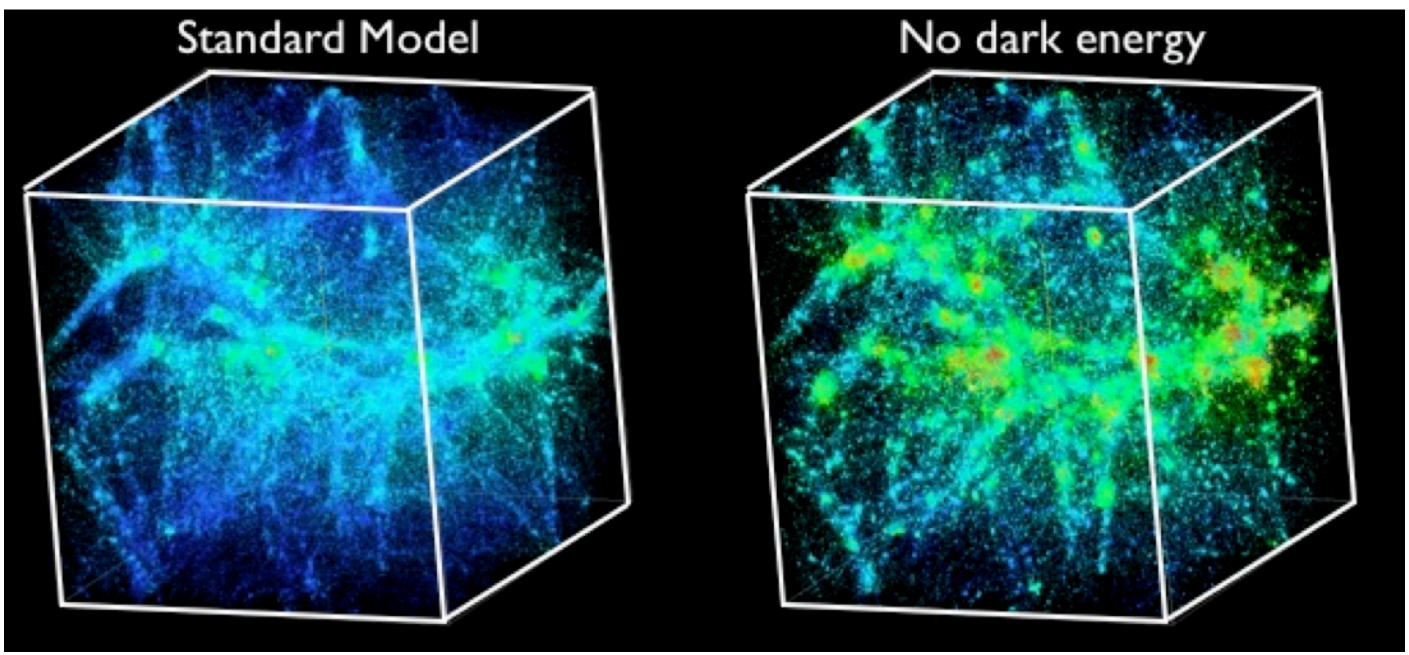
BAO as Dark Energy probe

Expansion of Universe is accelerating

$$\ddot{a} > 0$$

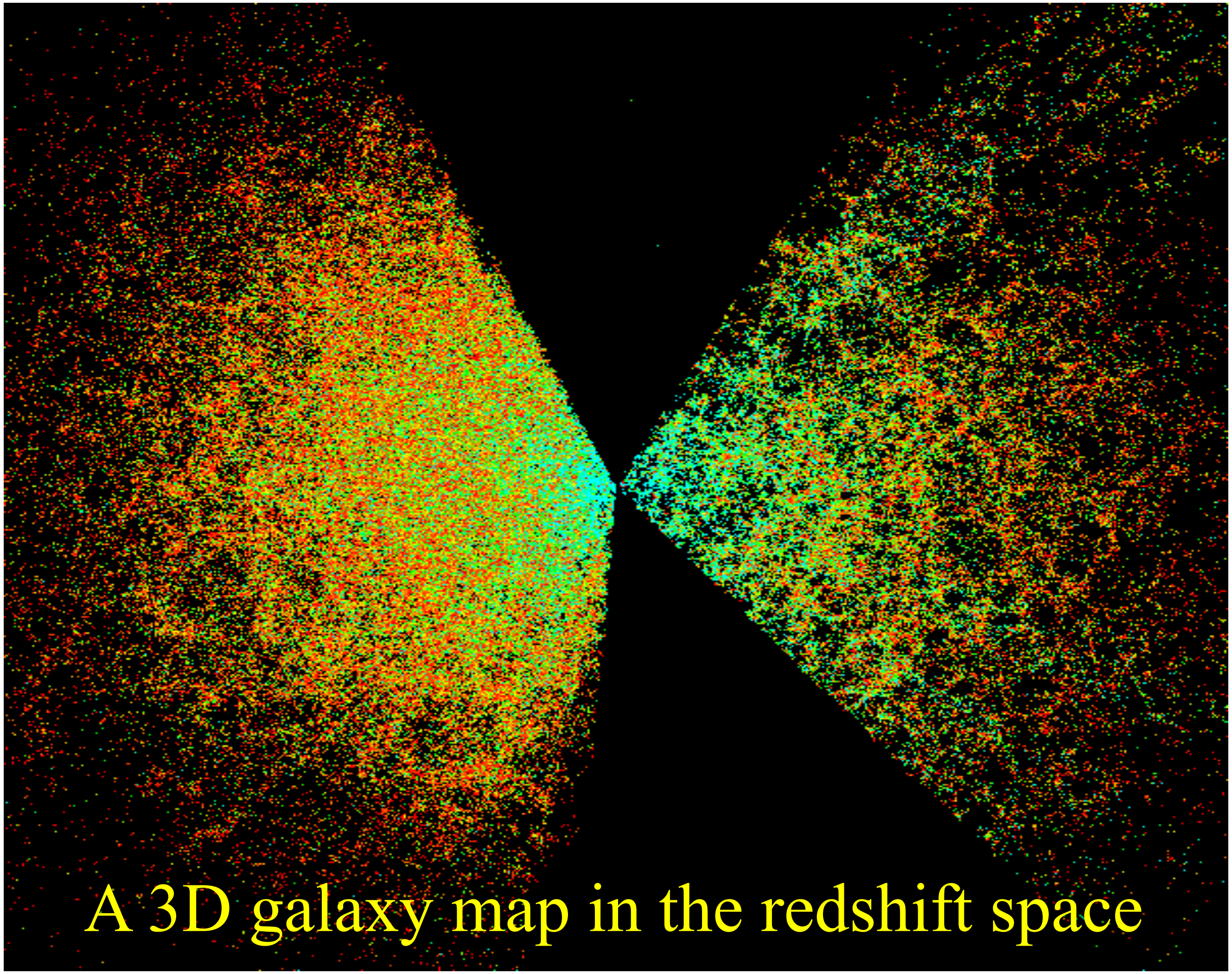
$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

Dark Energy dominates



Credit Katrin Heitmann

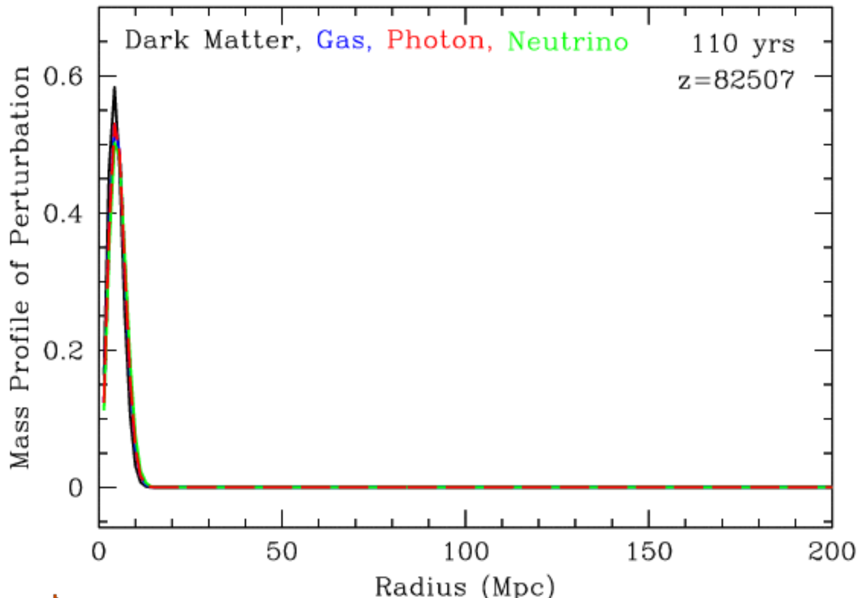
Past:2dFGRS, 6dFGRS,WiggleZ, SDSS III/BOSS

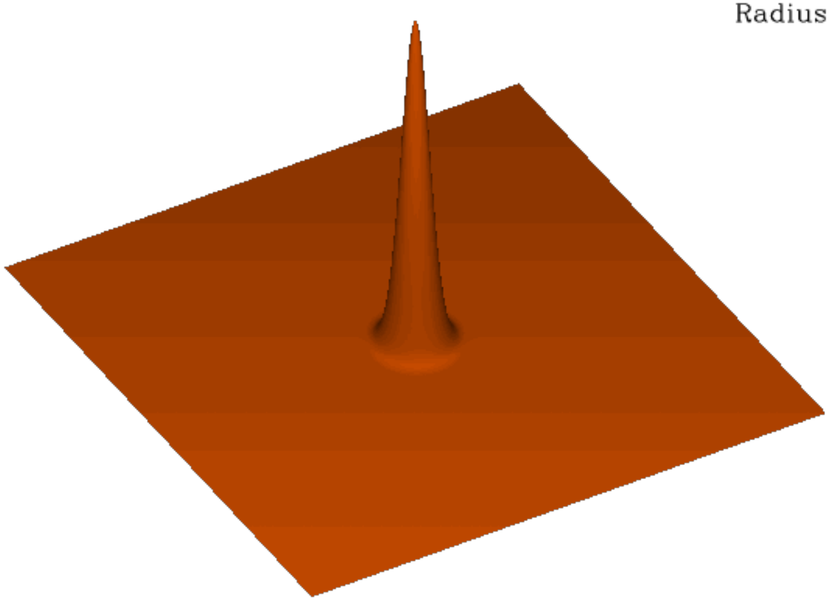


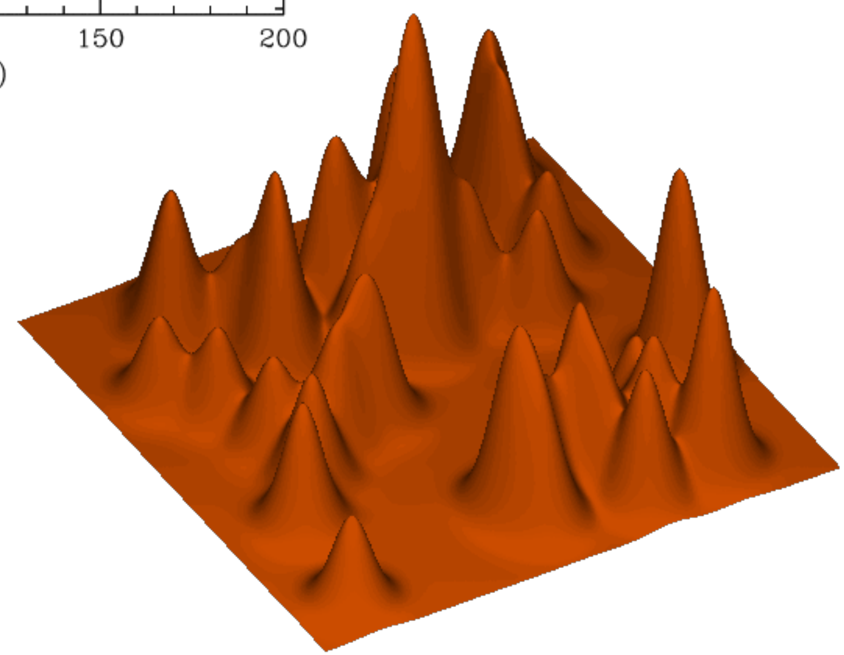
Credit SDSS team

Ongoing: SDSS IV/eBOSS Future: DESI, PFS, Euclid

Baryon acoustic oscillations (BAOs)



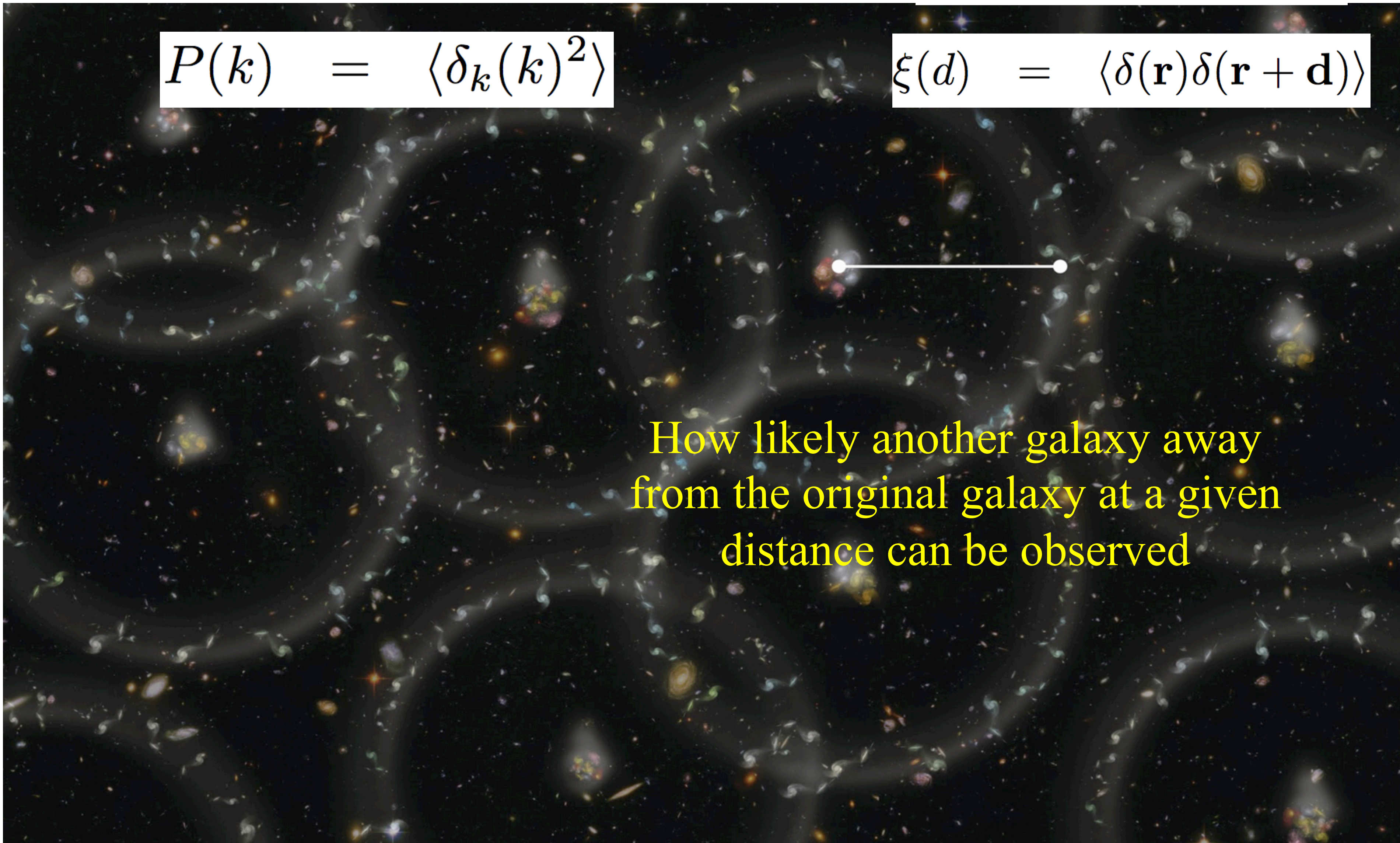




http://galaxies-cosmology-2015.wikidot.com/baryon-acoustic-oscillations

Density fluctuations:

$\delta_k(k)$ ⟷ **Fourier transformation** ⟷ $\delta(x) = \rho(x)/\bar{\rho}(x) - 1$

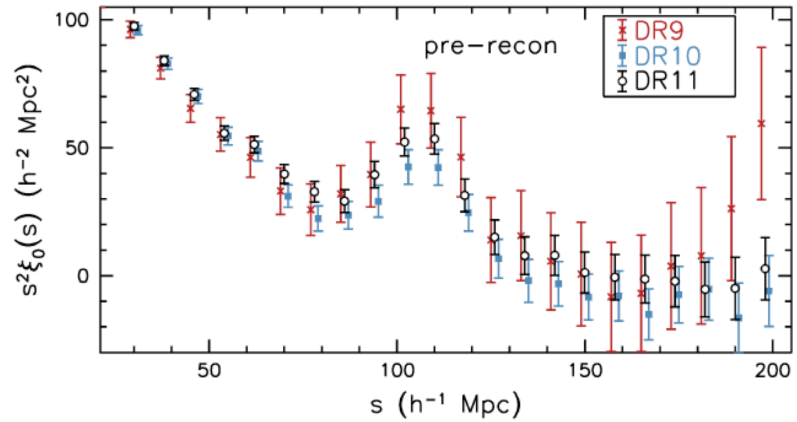


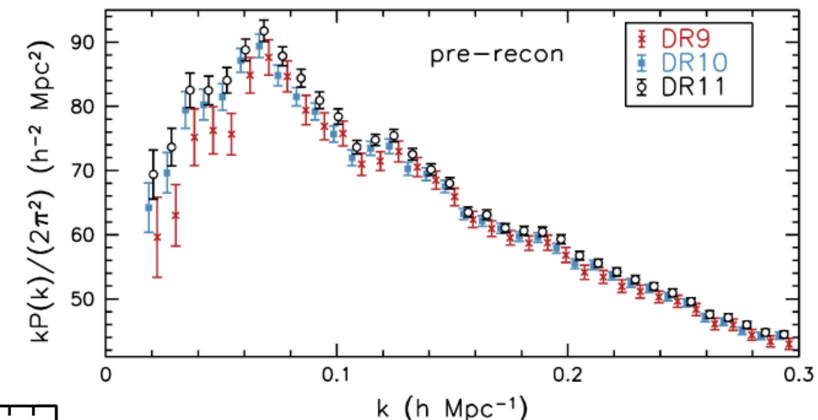
$$P(k) \quad = \quad \langle \delta_k(k)^2 \rangle$$

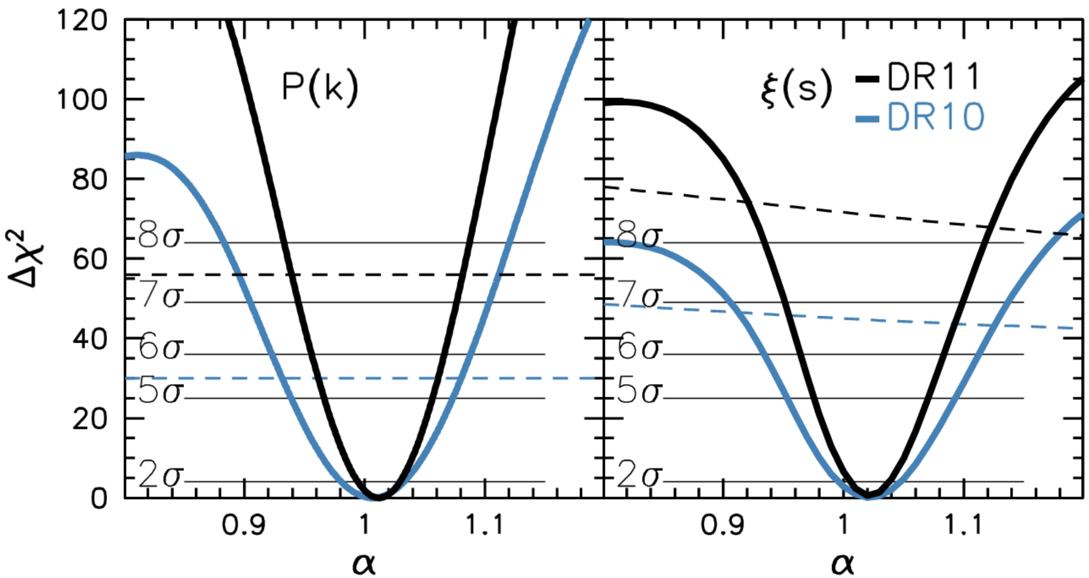
$$\xi(d) \quad = \quad \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

BOSS DR11

The isotropic BAO signal is detected at a significance of ~7σ in both correlation function and power spectrum







Anderson et al. 2014

BAO scale, as a cosmic standard ruler, can be used to determine cosmic expansion history

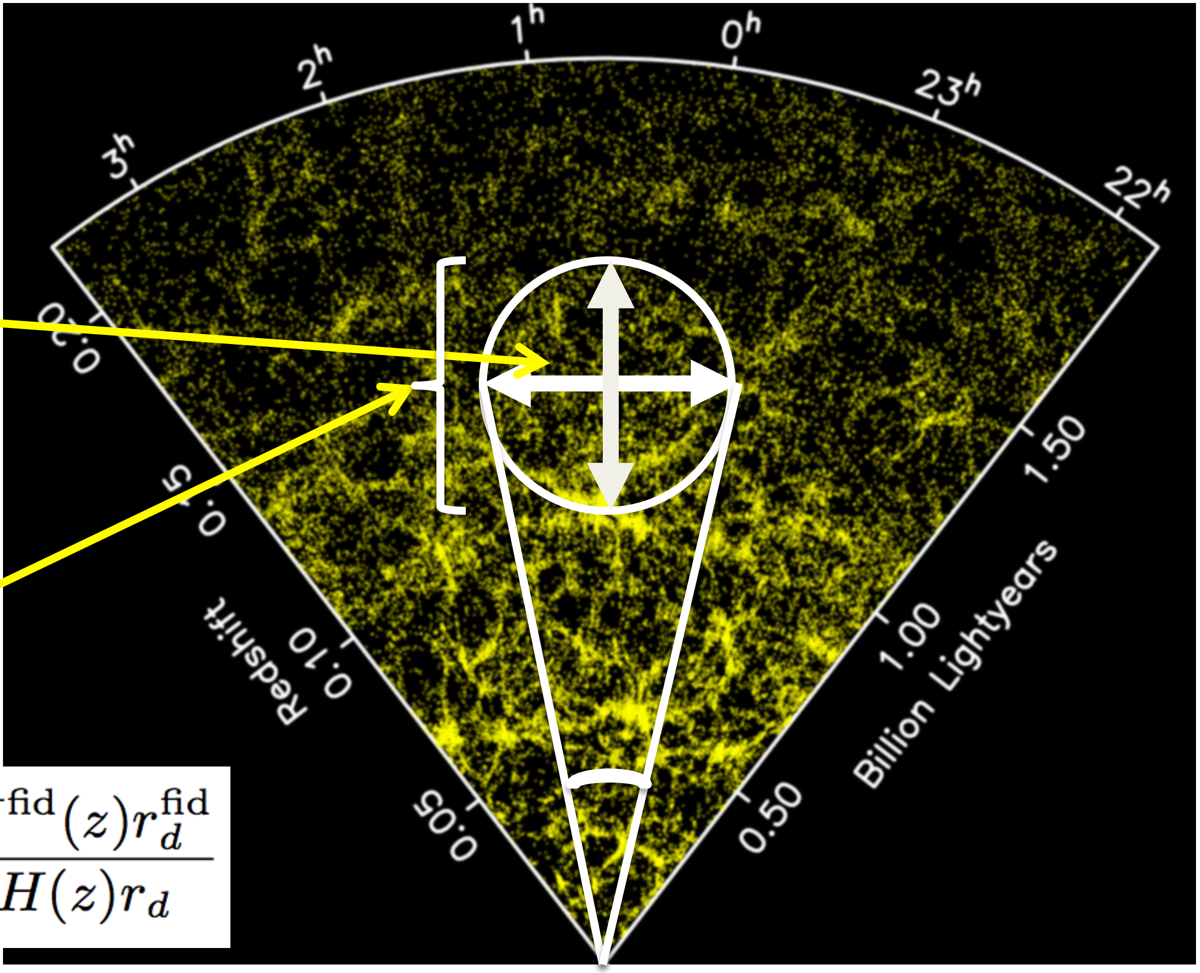
Anisotropic:

Transverse measurement

$$\Delta r_\perp = D_A \Delta\theta$$

Radial measurement

$$\Delta r_\parallel = (c/H)\Delta z$$



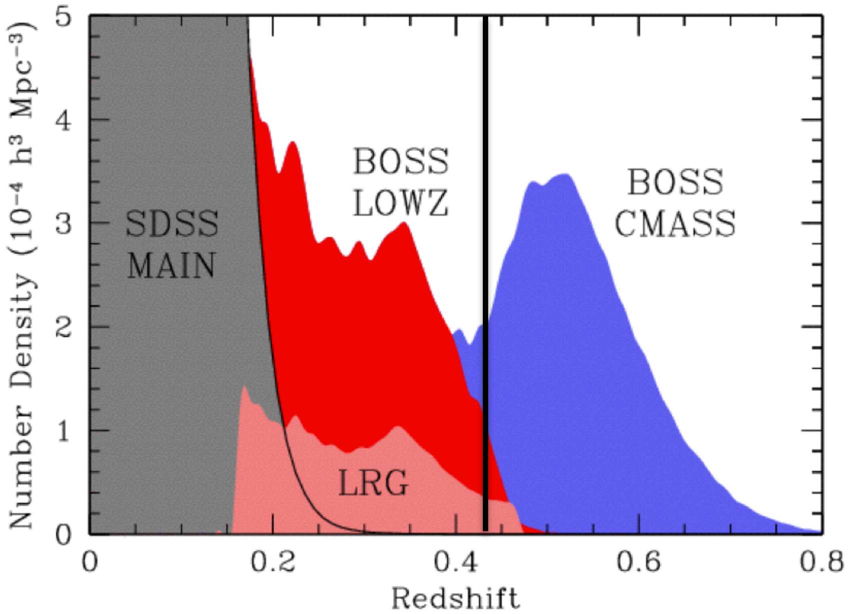
observer

$$\alpha_\perp = \frac{D_A(z) r_d^{\text{fid}}}{D_A^{\text{fid}}(z) r_d}, \quad \alpha_\parallel = \frac{H^{\text{fid}}(z) r_d^{\text{fid}}}{H(z) r_d}$$

Isotropic:

$$D_V(z) \equiv \left[cz(1+z)^2 D_A(z)^2 H^{-1}(z)\right]^{1/3}$$

$$\alpha \equiv \frac{D_V(z) r_{d,\text{fid}}}{D_V^{\text{fid}}(z) r_d}$$



Part II

Fits from CMASS/LOWZ

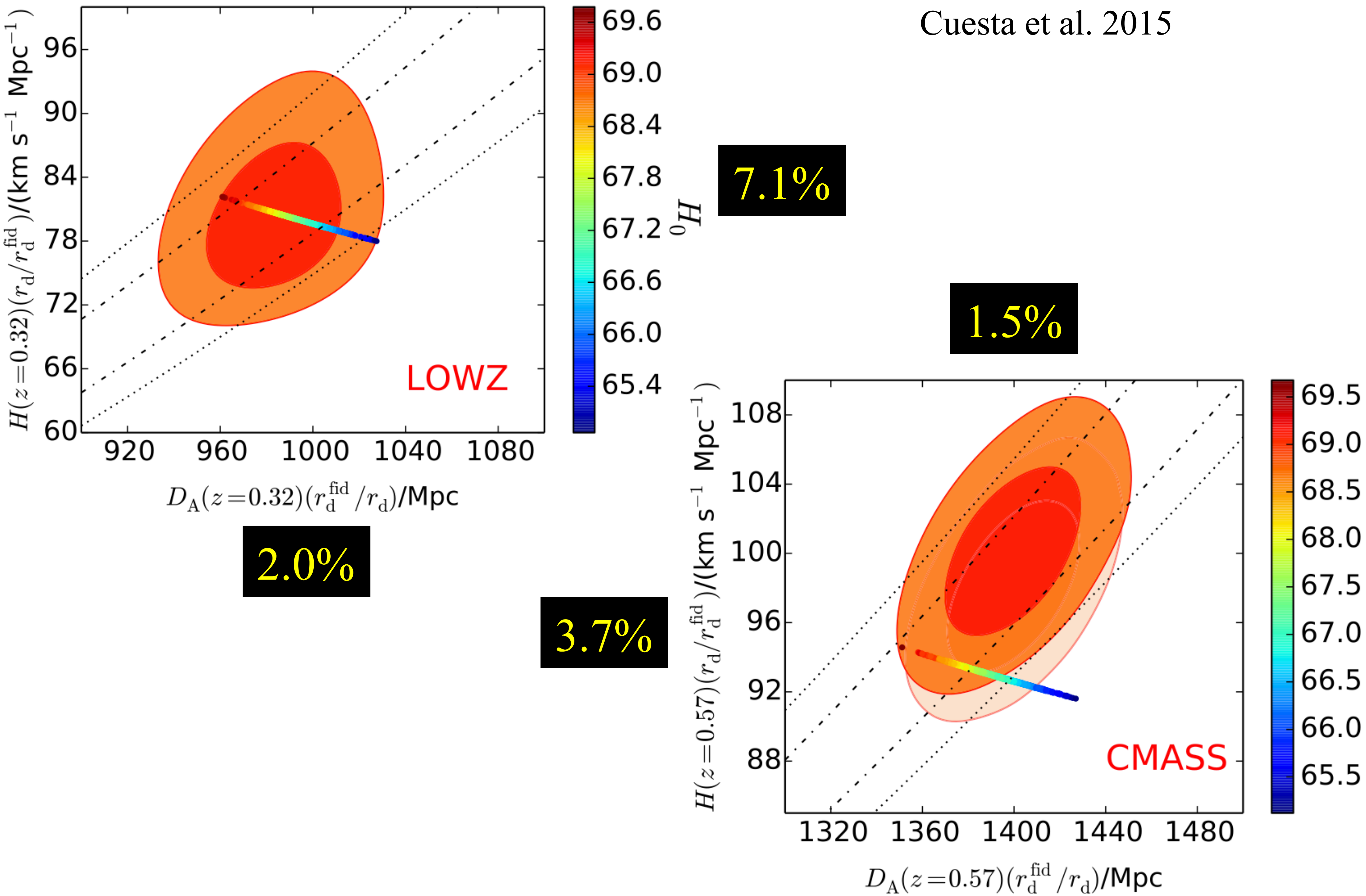
	NGC	SGC	Total
LOWZ	248 237	113 525	361 762
CMASS	568 776	208 426	777 202
LOWZ+CMASS	817 013	321 951	1138 964

	NGC	SGC	Total
LOWZ DR11	5290.82	2050.60	7341.42
LOWZ DR12	5836.21	2501.26	8337.47
CMASS DR11	6307.94	2068.96	8376.90
CMASS DR12	6851.42	2524.67	9376.09

Cuesta et al. 2015

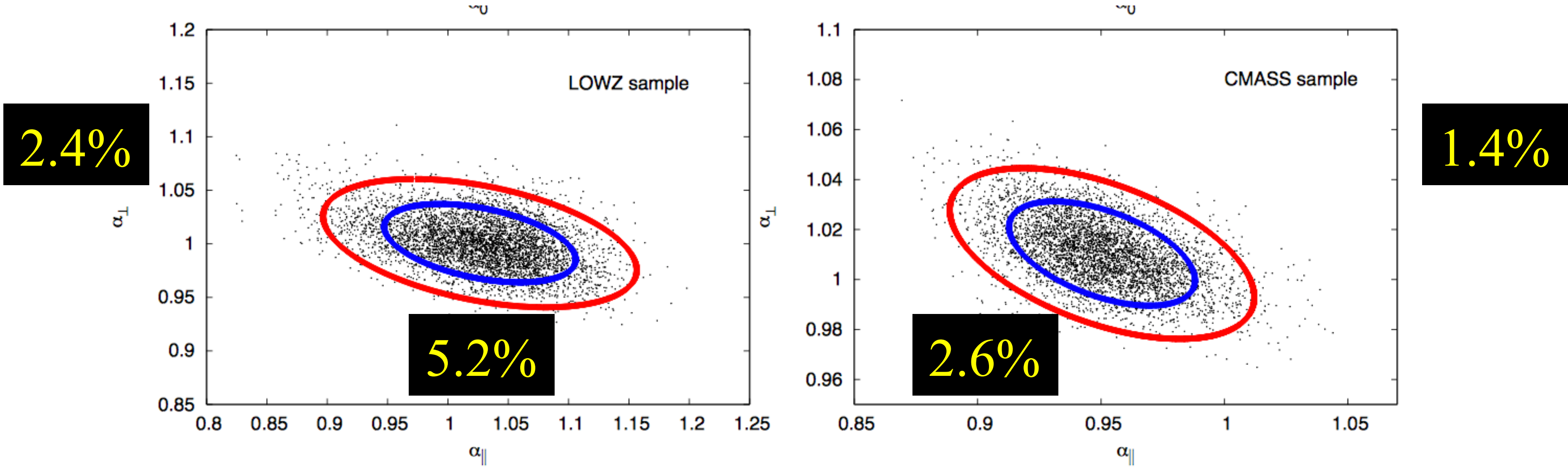
Fitting results in Configuration space

Cuesta et al. 2015



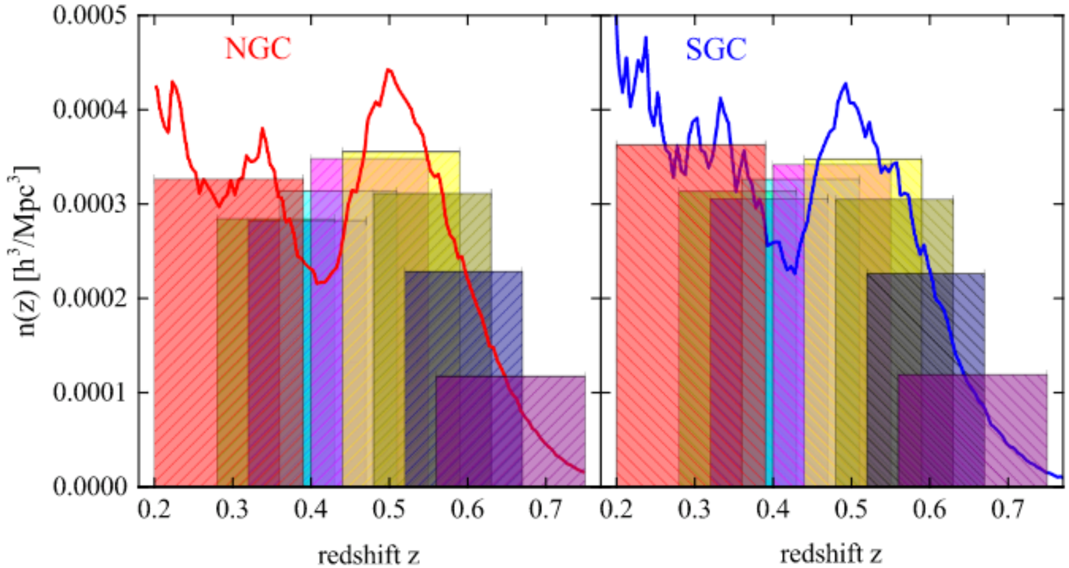
Fitting results in Fourier space

Hector et al. 2015



Sample	Statistic	$H(z)r_s(z_d)$ $[10^3\ \mathrm{kms}^{-1}]$	$D_A(z)/r_s(z_d)$	r_{HD_A}	$D_V(z)/r_s(z_d)$
LOWZ	Power Spectrum	11.60 ± 0.60	6.66 ± 0.16	0.41	8.62 ± 0.15
	Correlation Function	11.65 ± 0.81	6.67 ± 0.14	0.29	8.59 ± 0.15
	Consensus	11.63 ± 0.69	6.67 ± 0.15	0.35	8.61 ± 0.15
CMASS	Power Spectrum	14.56 ± 0.37	9.42 ± 0.13	0.47	13.70 ± 0.12
	Correlation Function	14.75 ± 0.50	9.52 ± 0.13	0.57	13.79 ± 0.14
	Consensus	14.67 ± 0.42	9.47 ± 0.12	0.52	13.74 ± 0.13

An analysis of the **"same" DR12 sample** not split into LOWZ and CMASS, but **combined together**



Part III

tomographic BAO analysis

Goal: extracting redshift information as much as possible from the samples within $0.2<z<0.75$

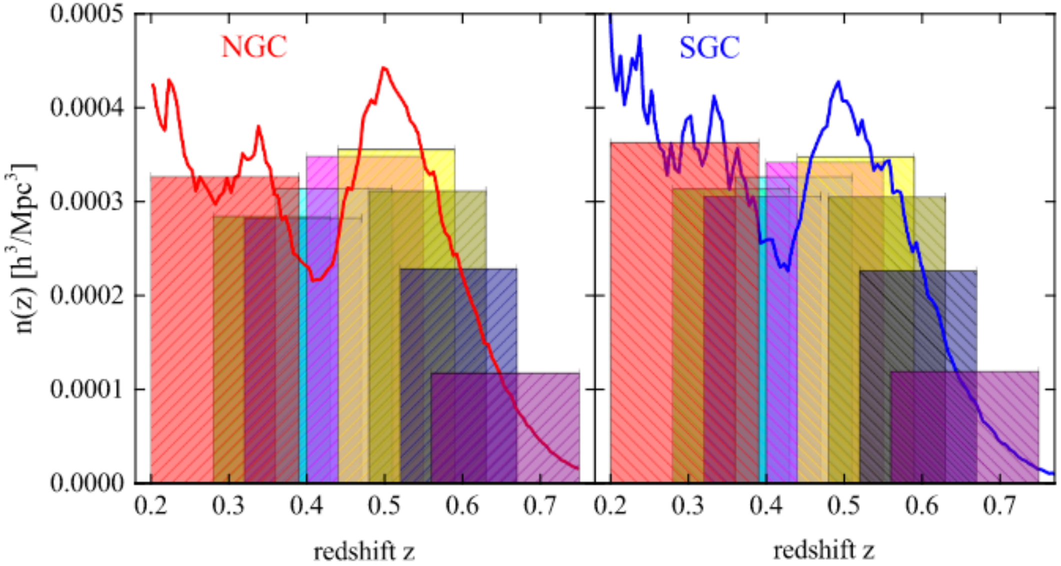
Method: splitting the whole redshift range into **overlapping** z bins

Binning scheme through Fisher forecast

$$F_{ij} = \int_{\vec{k}_{\rm min}}^{\vec{k}_{\rm max}} \frac{\partial \ln P(\vec{k})}{\partial p_i} \frac{\partial \ln P(\vec{k})}{\partial p_j} V_{\rm eff}(\vec{k}) \frac{d\vec{k}}{2(2\pi)^3}$$

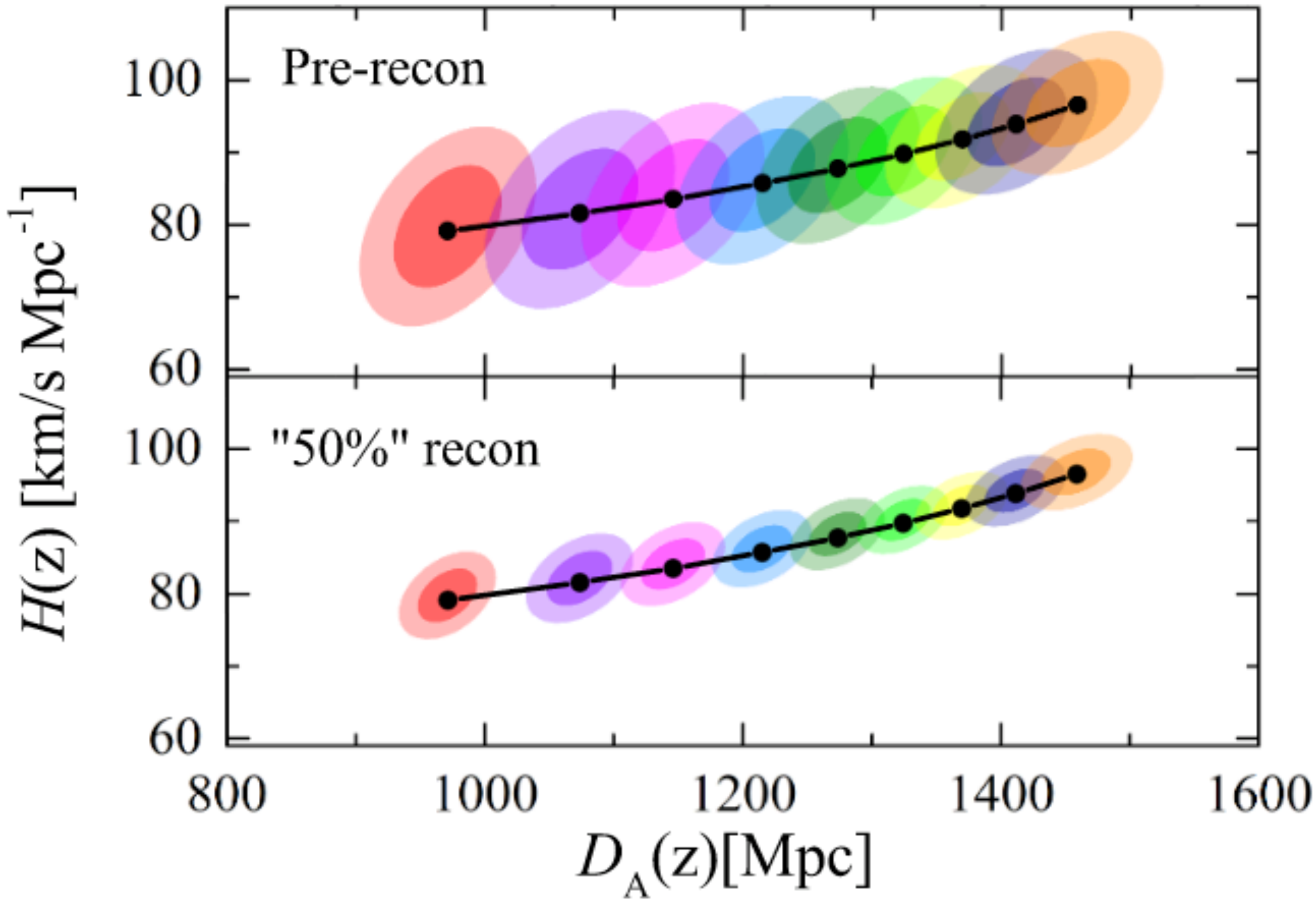
$$\Delta\theta_i \geq (\mathbf{F}^{-1})_{ii}^{1/2}$$

Isotropic BAO measurement
Precision <3%



z bins	$z_{\rm eff}$	σ_{D_A}/D_A	σ_H/H	σ_{D_V}/D_V
$0.20 < z < 0.39$	0.31	0.0289 (159)	0.0705 (309)	0.0236 (114)
$0.28 < z < 0.43$	0.36	0.0281 (159)	0.0681 (307)	0.0229 (113)
$0.32 < z < 0.47$	0.40	0.0254 (145)	0.0616 (281)	0.0207 (104)
$0.36 < z < 0.51$	0.44	0.0226 (130)	0.0553 (253)	0.0185 (093)
$0.40 < z < 0.55$	0.48	0.0203 (118)	0.0502 (230)	0.0167 (085)
$0.44 < z < 0.59$	0.52	0.0188 (110)	0.0464 (214)	0.0155 (079)
$0.48 < z < 0.63$	0.56	0.0180 (108)	0.0441 (208)	0.0147 (077)
$0.52 < z < 0.67$	0.59	0.0183 (113)	0.0436 (214)	0.0147 (080)
$0.56 < z < 0.75$	0.64	0.0187 (122)	0.0418 (222)	0.0144 (085)

"50%" reconstructed efficiency



Better constraints on the distance parameters

The multipole power spectrum estimator (ie Yamamoto estimator):

$$\hat{P}_\ell^{\rm Yama}(k) = \frac{(2\ell+1)}{I}\int\frac{d\Omega_k}{4\pi}\left[\int d\mathbf{r}_1\, F(\mathbf{r}_1)e^{i\mathbf{k}\cdot\mathbf{r}_1} \times \int d\mathbf{r}_2\, F(\mathbf{r}_2)e^{-i\mathbf{k}\cdot\mathbf{r}_2}\mathcal{L}_\ell(\hat{\mathbf{k}}\cdot\hat{\mathbf{r}}_2) - P_\ell^{\rm noise}(\mathbf{k})\right]$$

overdensity field $F(\mathbf{r}) = \frac{w(\mathbf{r})}{I^{1/2}}[n(\mathbf{r}) - \alpha n_s(\mathbf{r})]$

Yamamoto et al 2006, Davide et al 2015

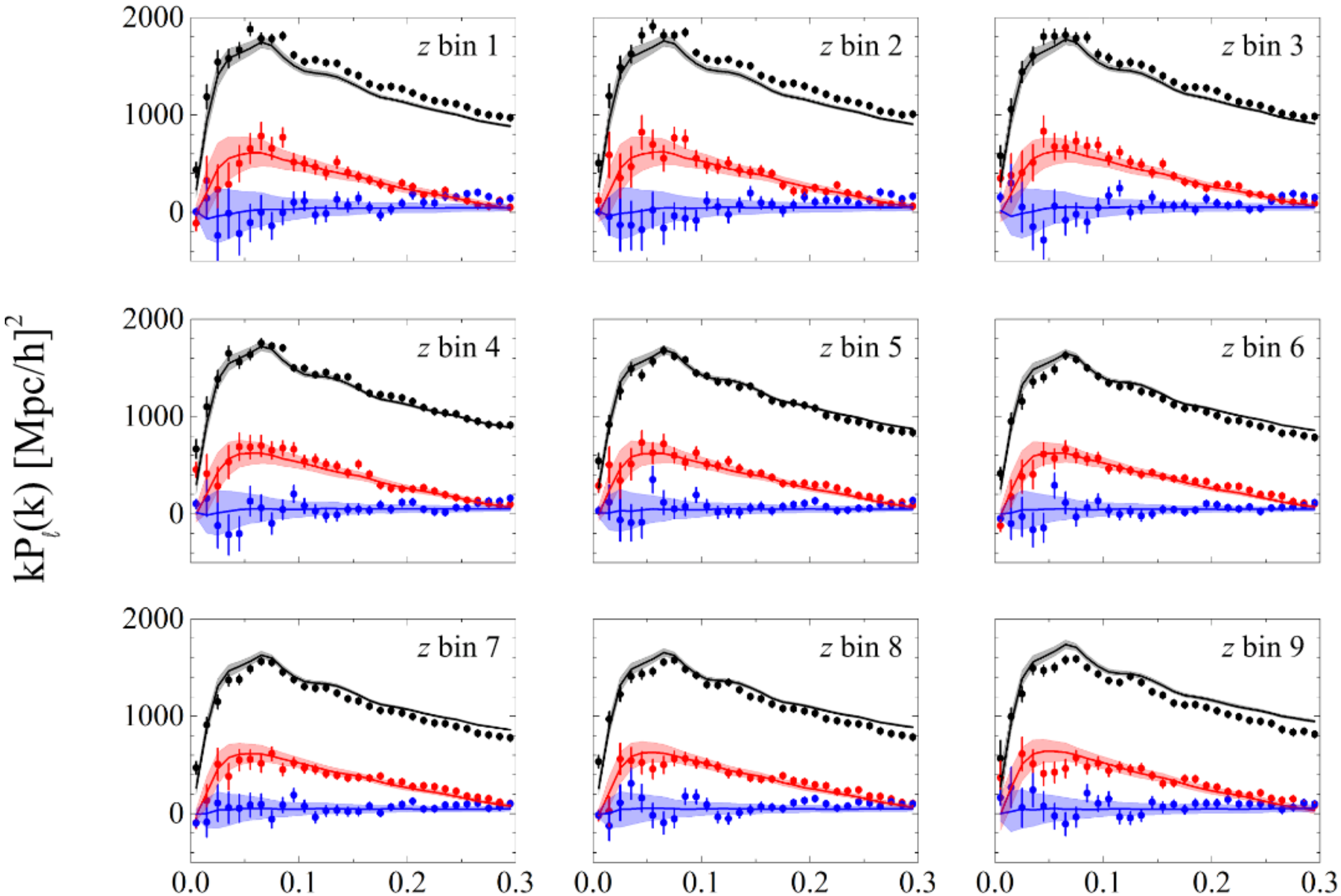
The correlation function estimator (ie Landy & Szalay estimator)

$$\xi(s,\mu) = \frac{DD(s,\mu) - 2DR(s,\mu) + RR(s,\mu)}{RR(s,\mu)}$$

$$\xi_l(s) = \frac{2l+1}{2}\int_{-1}^{1} \mathrm{d}\mu\, \xi(s,\mu)\mathcal{L}_\ell(\mu)$$

Landy & Szalay 1993

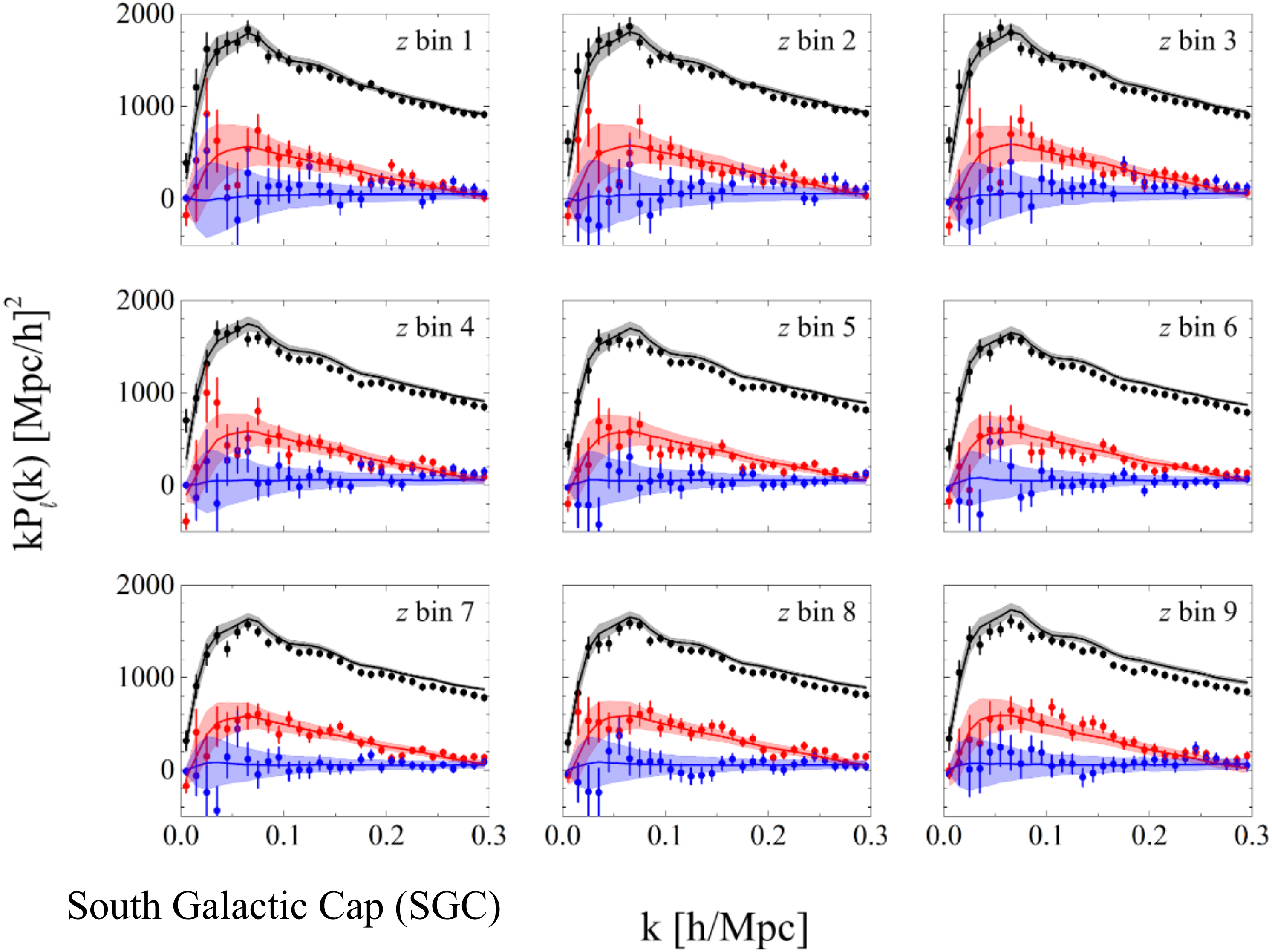
Tomographic BAO measurements in Fourier space



North Galactic Cap (NGC)

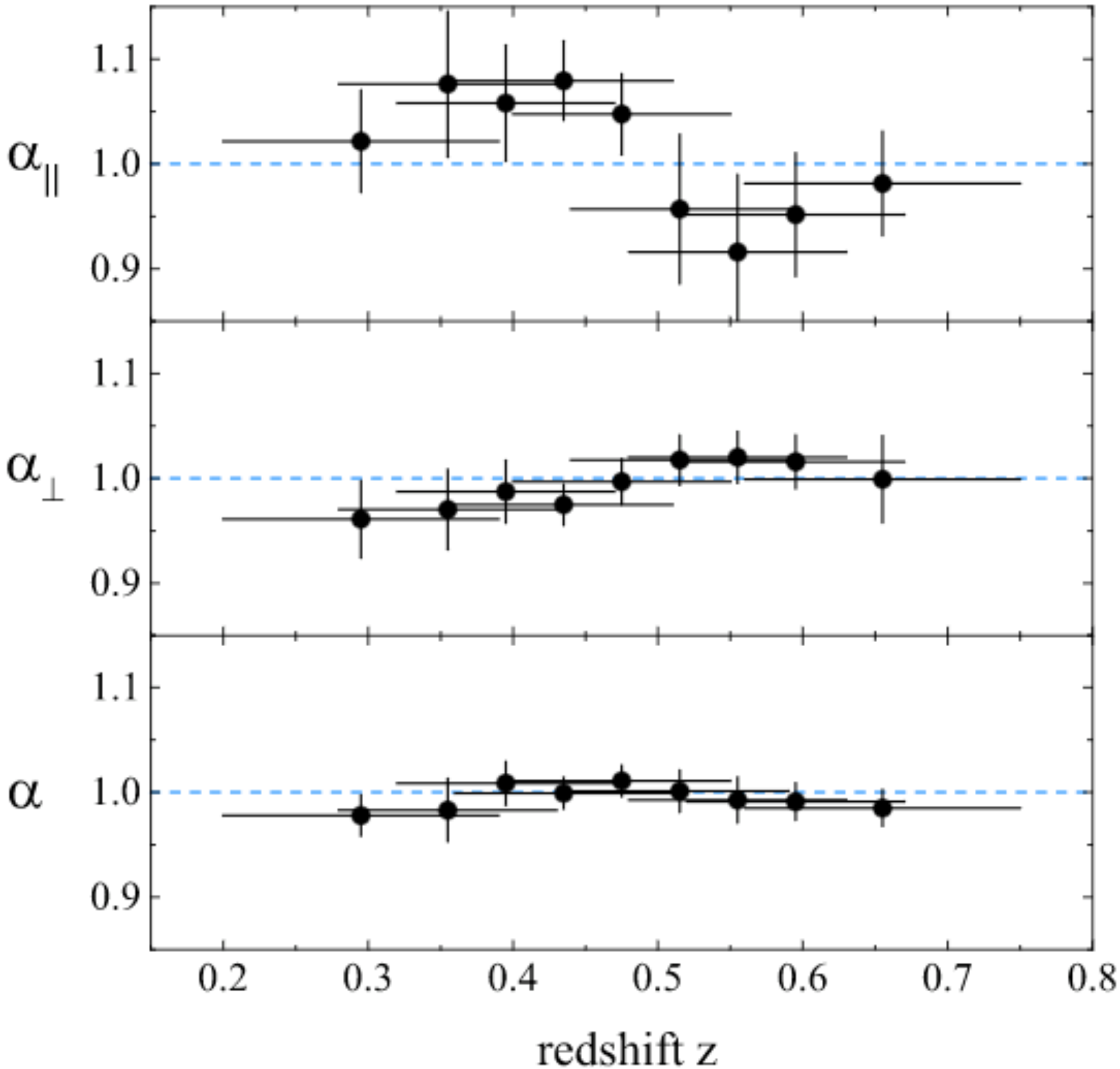
k [h/Mpc]

Tomographic BAO measurements in Fourier space

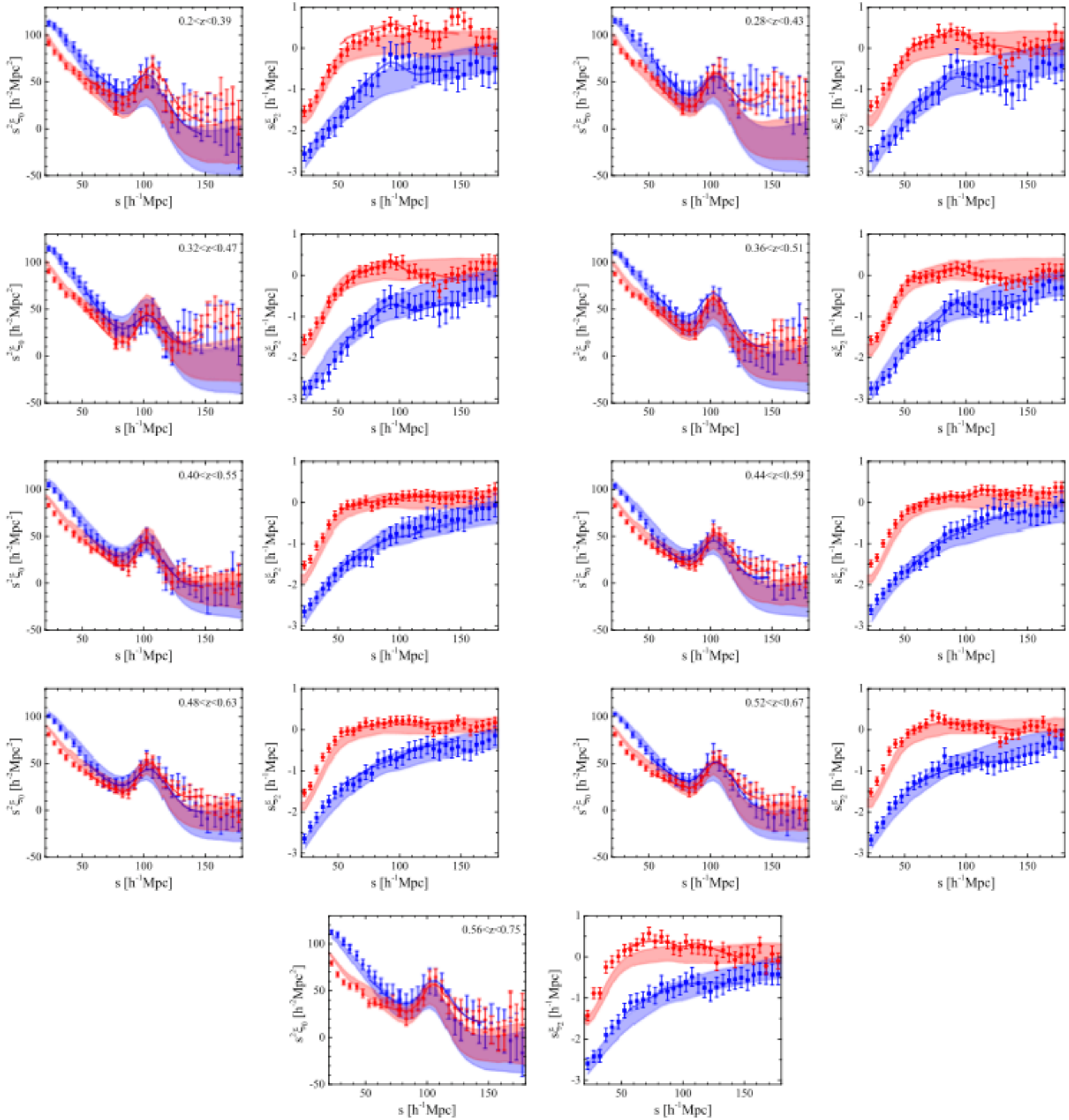


South Galactic Cap (SGC)

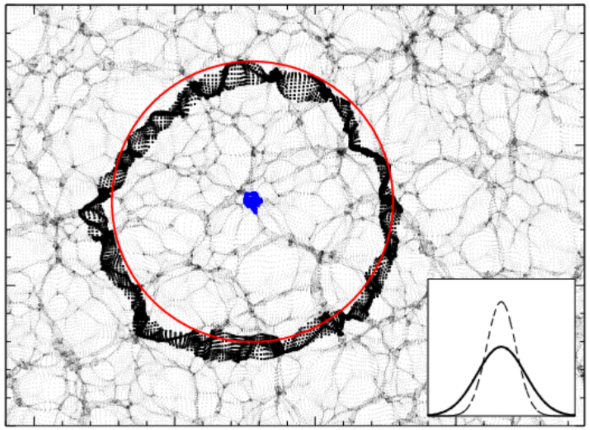
Tomographic best fits in Fourier space

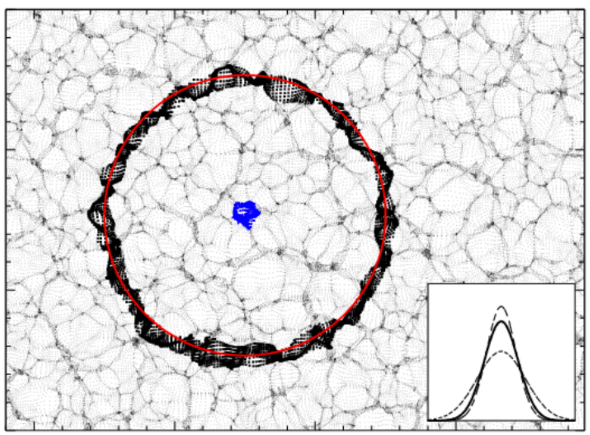


Tomographic BAO measurements in Configuration space



Reconstruction sharpens the BAO feature in the correlation function





Nikhil et al 2012

Basic procedure

Observed redshift-space density field

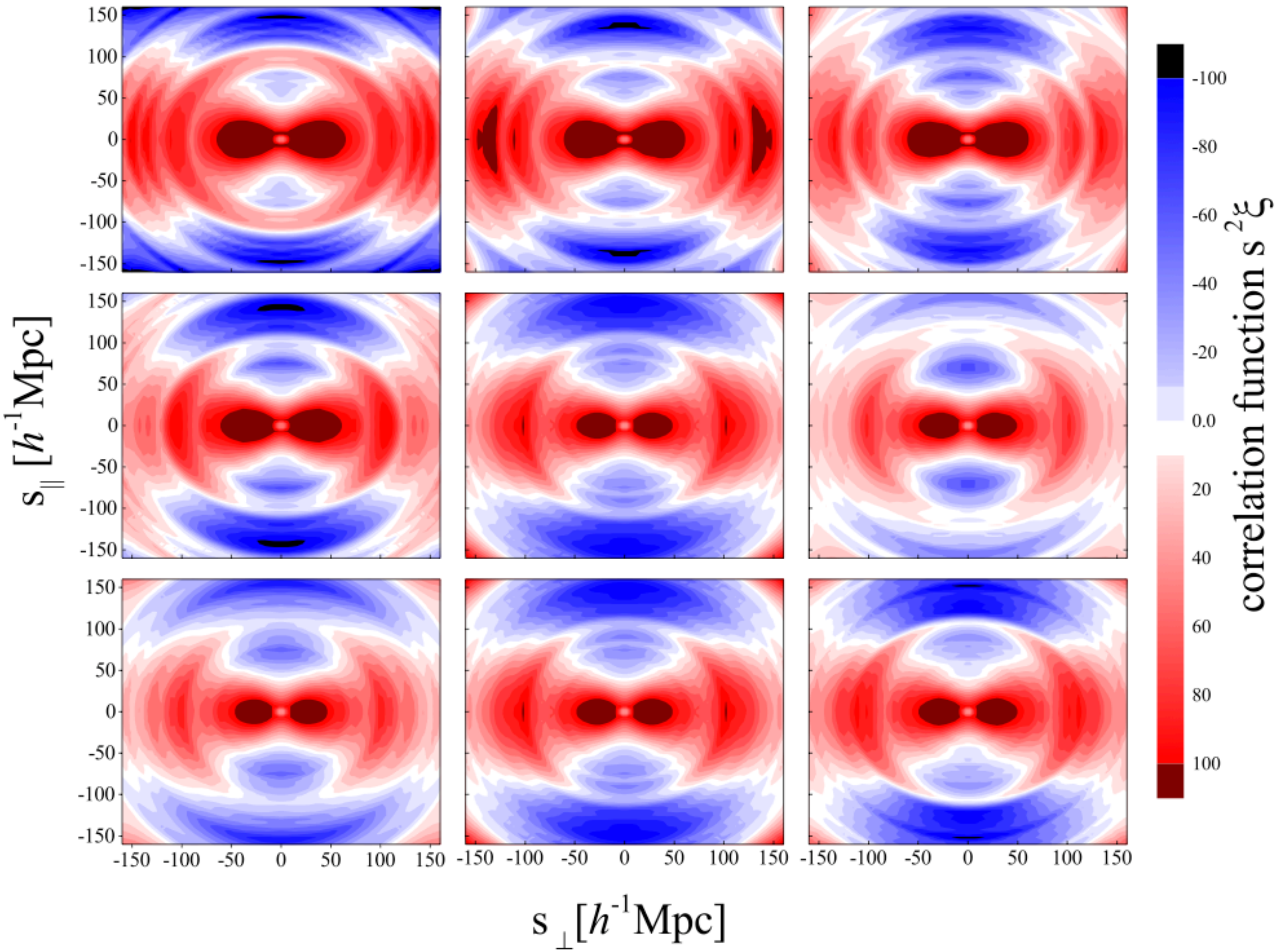
Estimate redshift-space displacement field

Derive displacement field in configuration space

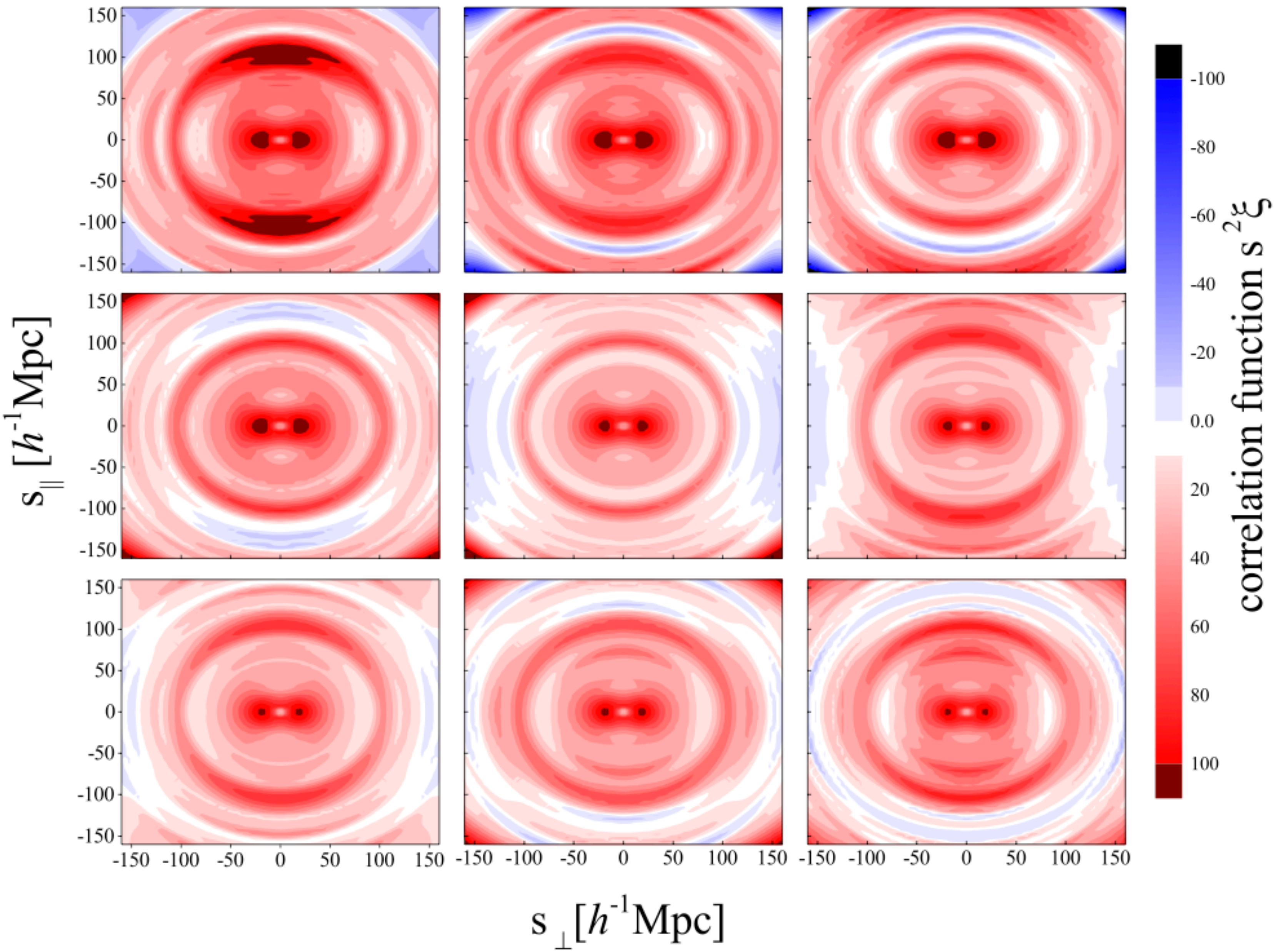
displace the observed galaxies back to their original positions

Reconstructed field

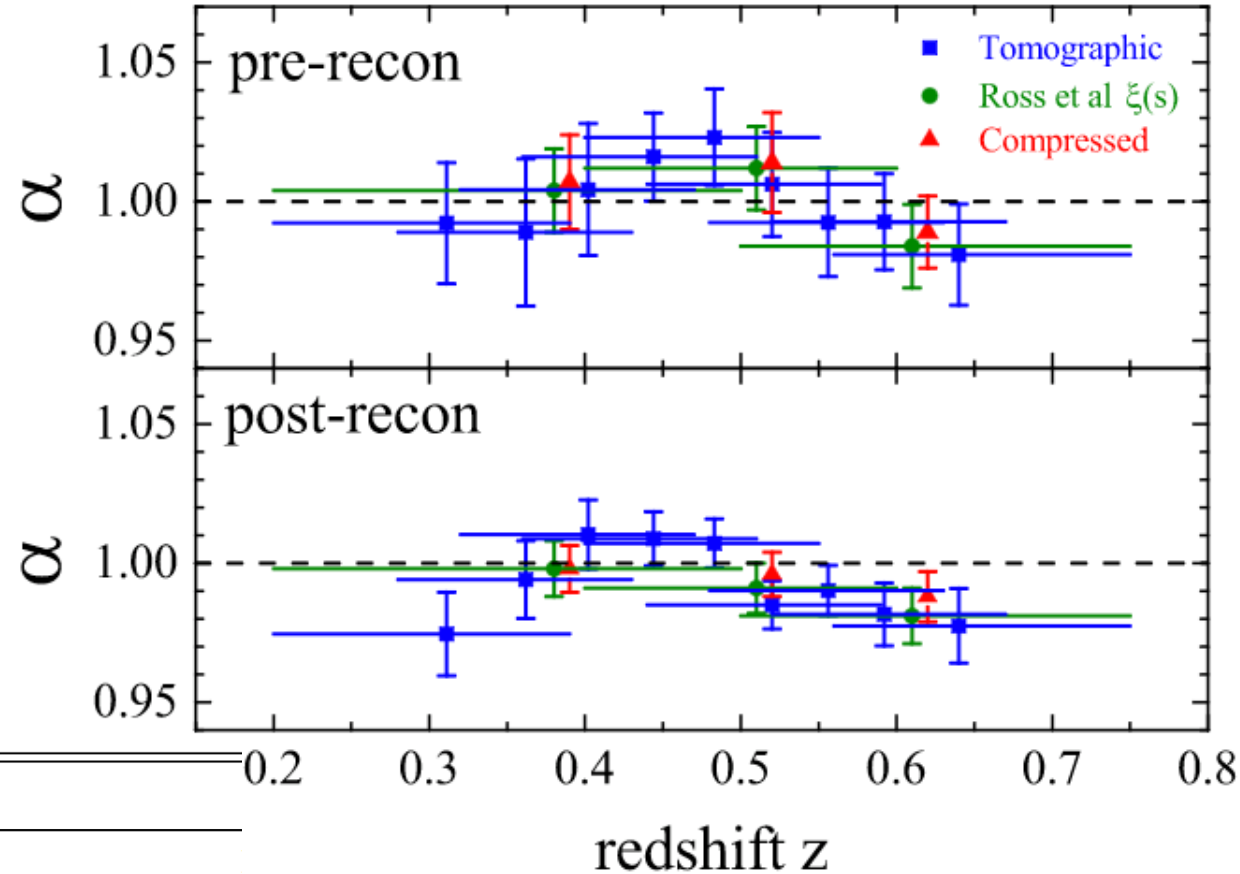
CF before reconstruction



CF after reconstruction



Tomographic best fits in Configuration space

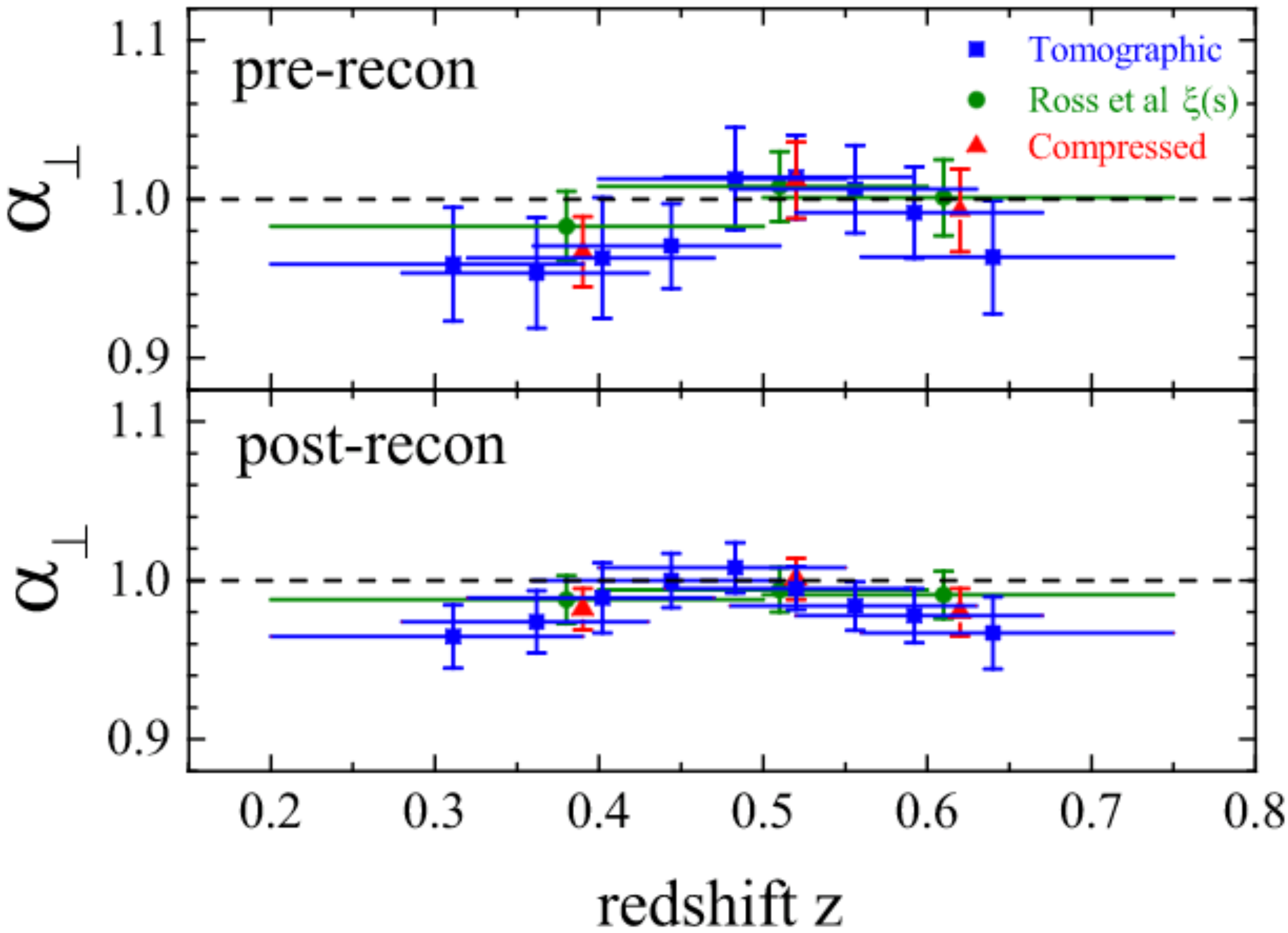


z bins
$0.20 < z < 0.39$
$0.28 < z < 0.43$
$0.32 < z < 0.47$
$0.36 < z < 0.51$
$0.40 < z < 0.55$
$0.44 < z < 0.59$
$0.48 < z < 0.63$
$0.52 < z < 0.67$
$0.56 < z < 0.75$

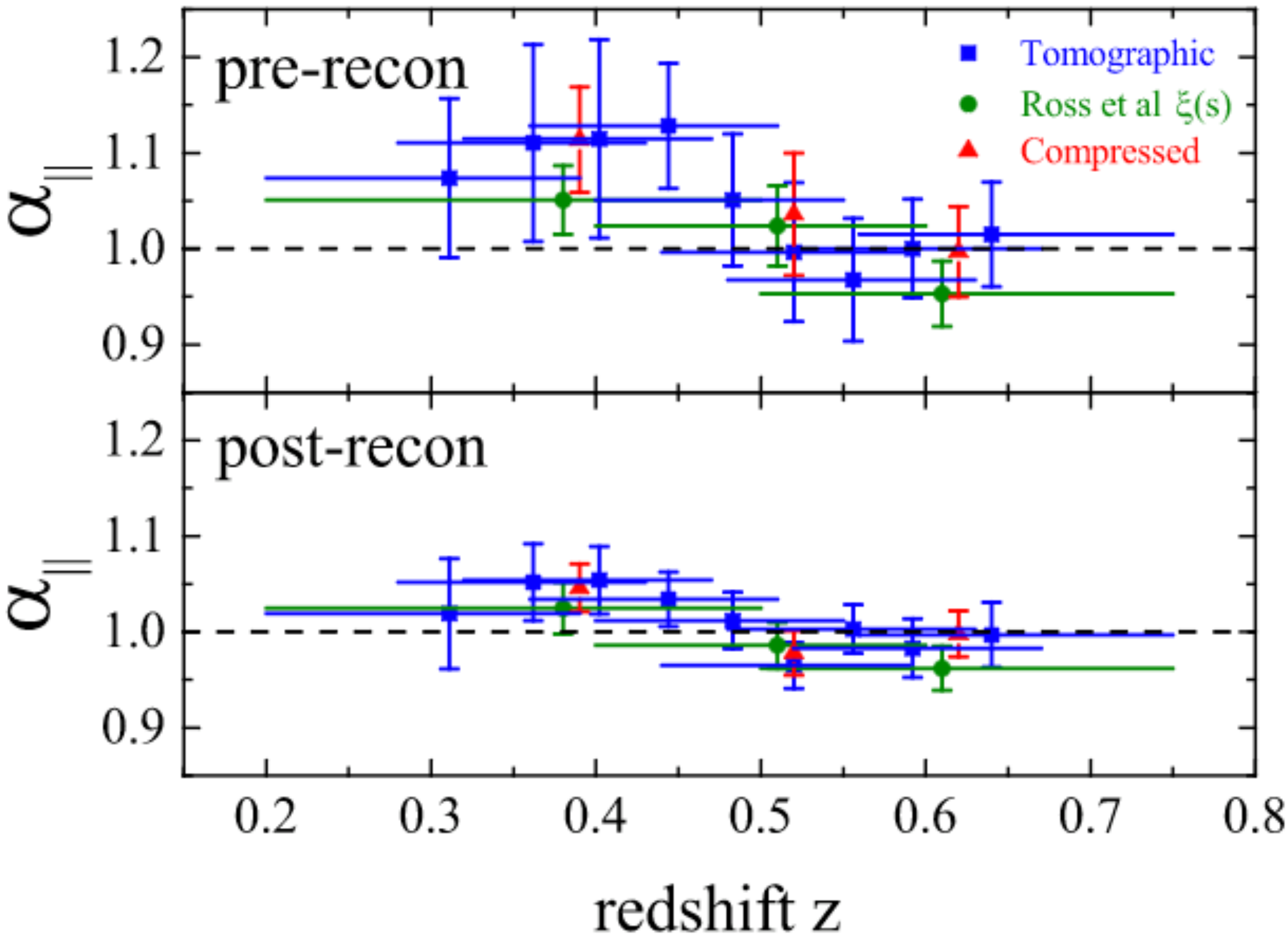
$0.2 < z < 0.5$
$0.4 < z < 0.6$
$0.5 < z < 0.75$

BOSS DR12 papers: Alam et al, Ashley et al 2016

Tomographic best fits in Configuration space



Tomographic best fits in Configuration space



Combination of the binned measurements

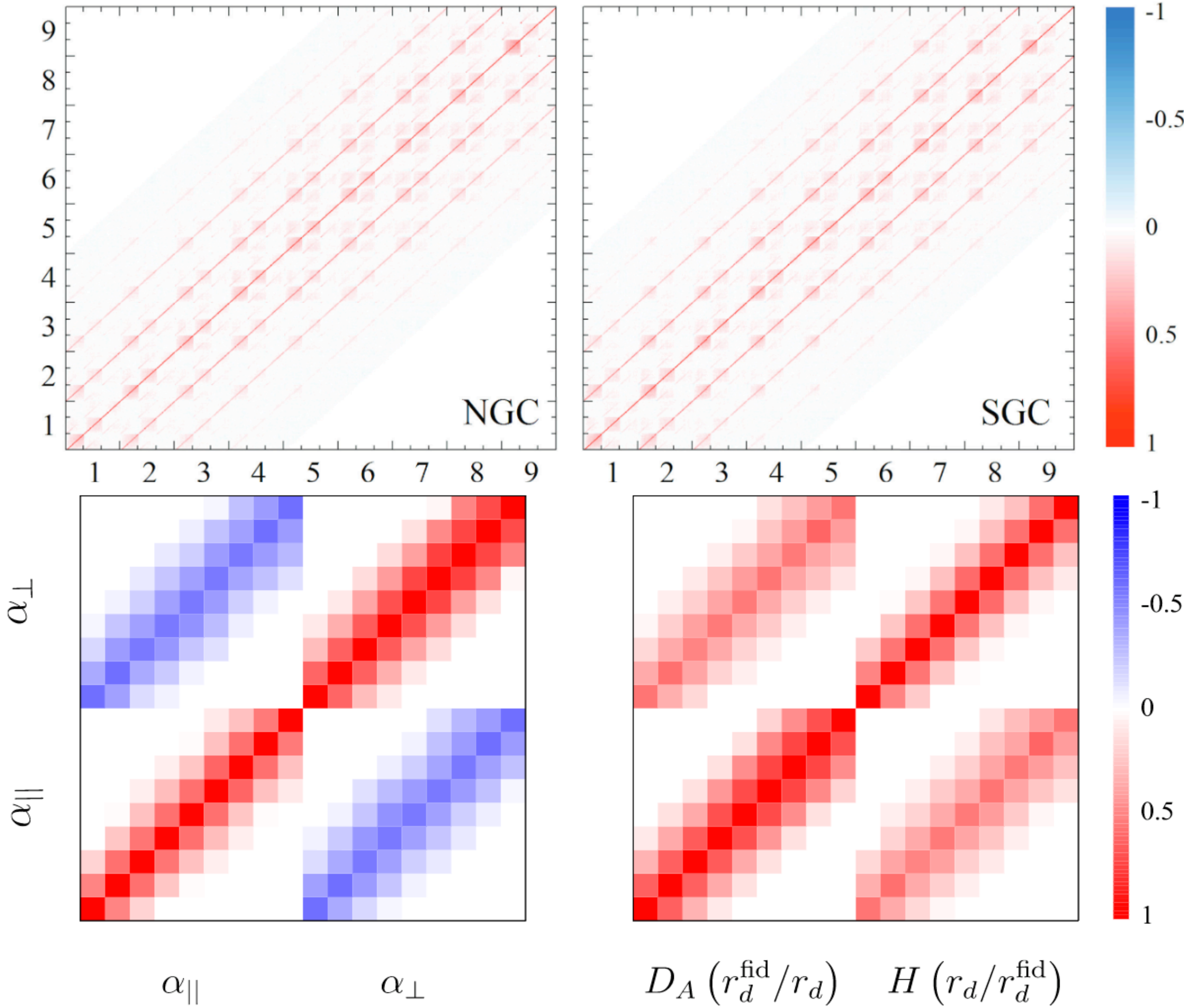
Method 1: Calculate the covariance between the measured like Pk across all the redshift bins

$$C_{ij,mn}^{\ell,\ell'} = \frac{1}{N_{\rm mock}-1}\sum_{q=1}^{N_{\rm mock}}\left[P_\ell^q(k_i,z_m)-\bar{P}_\ell(k_i,z_m)\right]\times \left[P_{\ell'}^q(k_j,z_n)-\bar{P}_{\ell'}(k_j,z_n)\right], \quad (12)$$

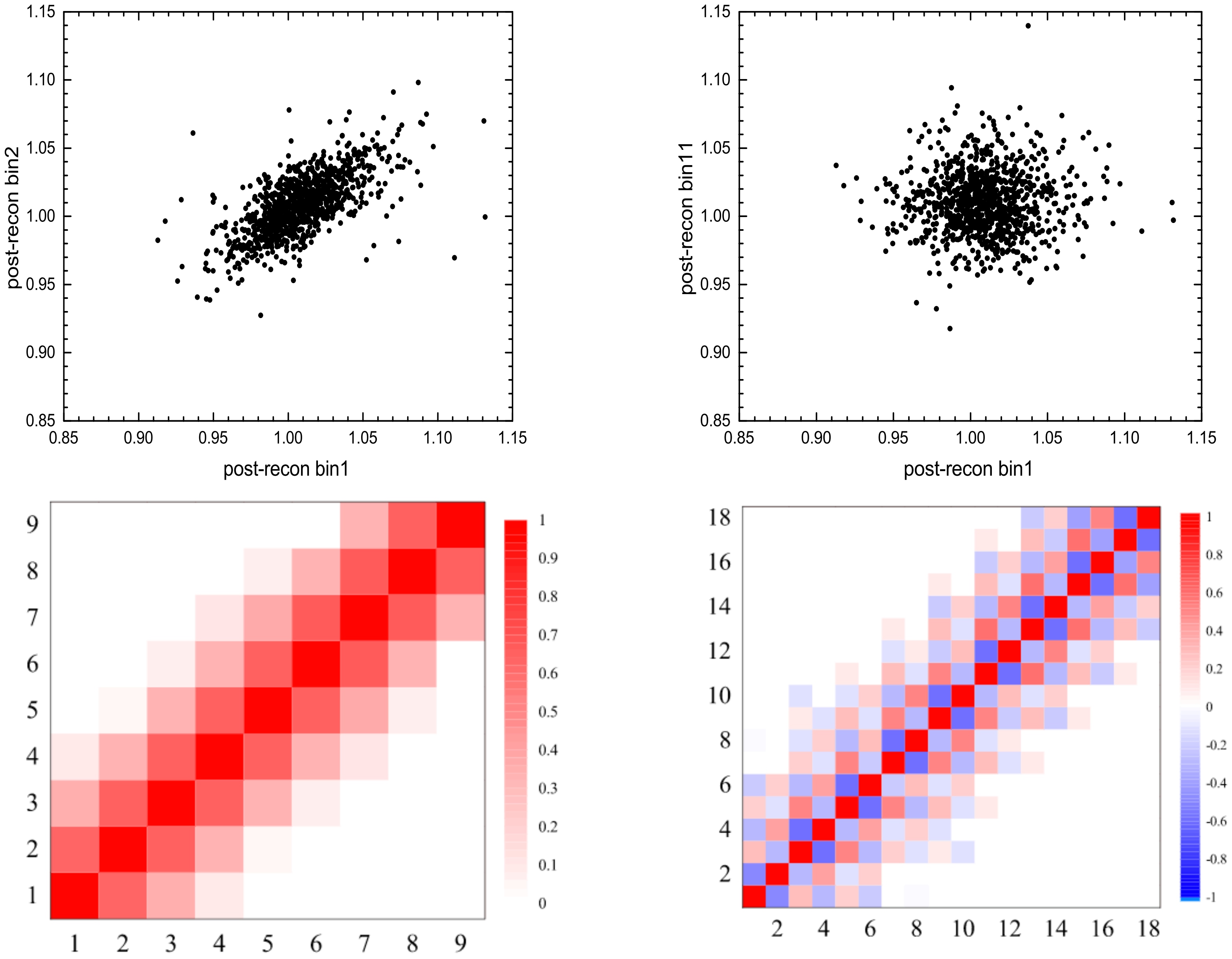
Method 2: Calculate the correlation using best fit parameters in each redshift bin

$$C_{ij} \equiv \langle\alpha_i\alpha_j\rangle - \langle\alpha_i\rangle\langle\alpha_j\rangle$$

Full correlation matrix of Pk between different redshift slices

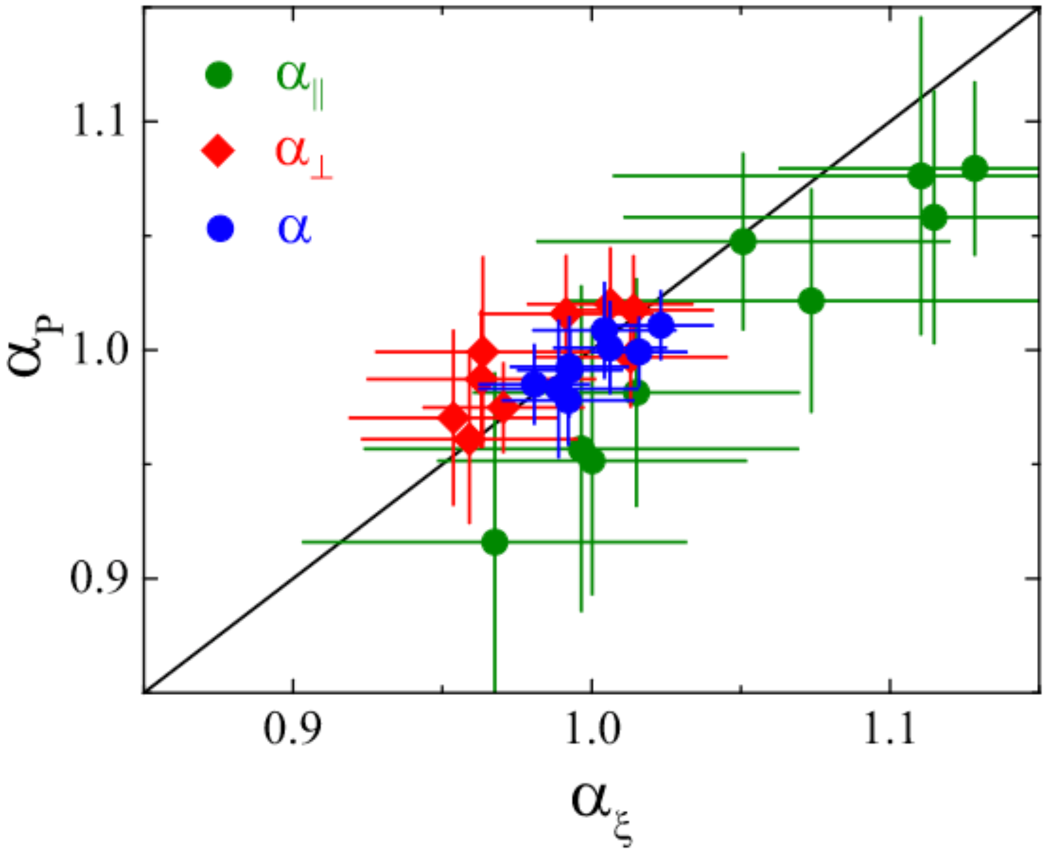


Correlation of fitting parameters between different redshift slices

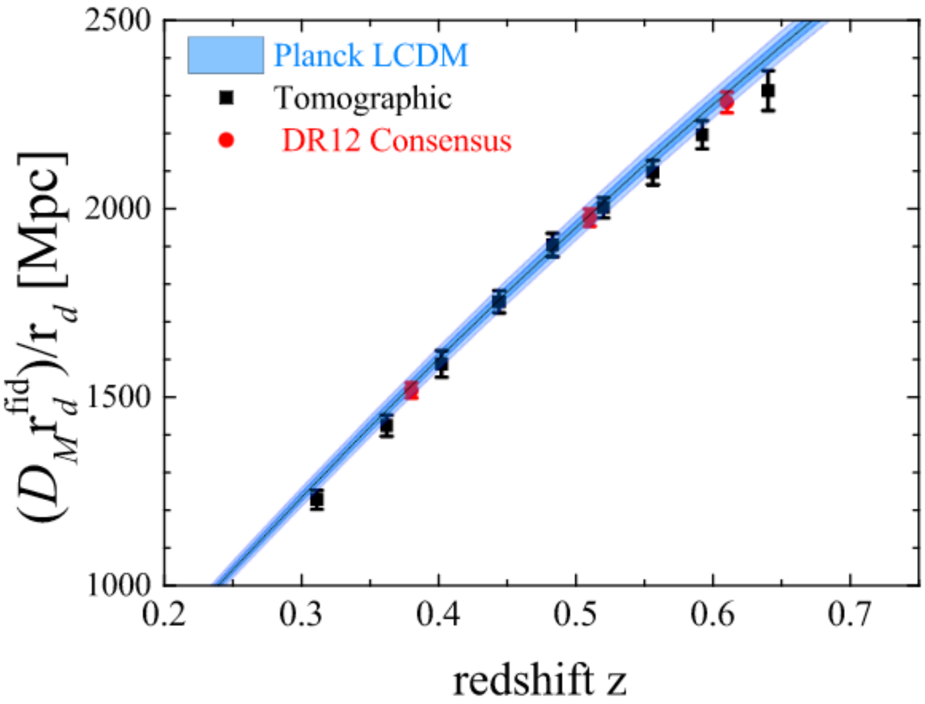


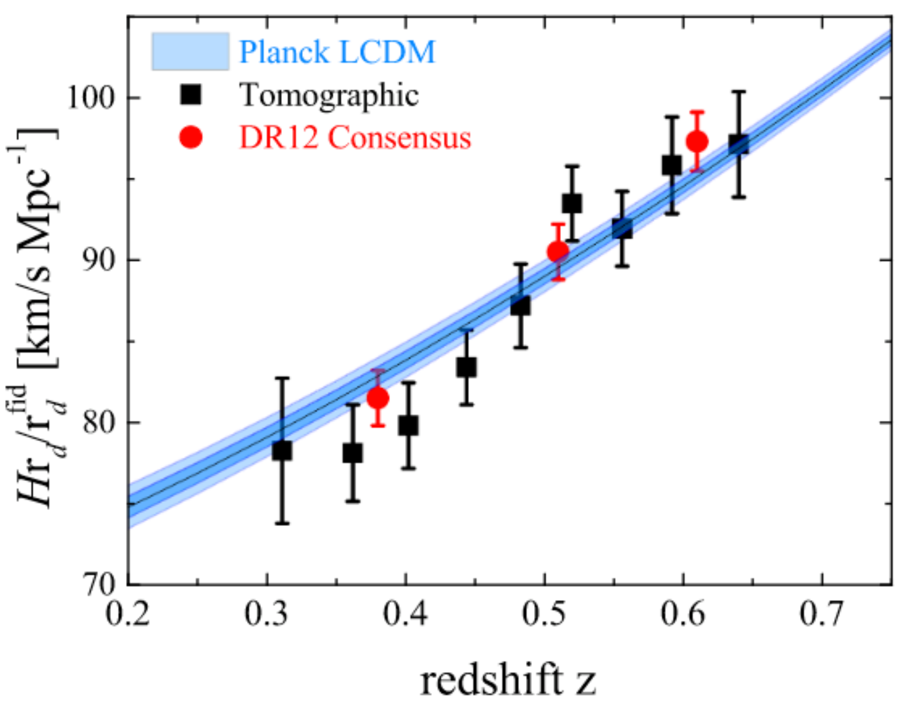
Result Comparisons

Pre-recon results
P0+P2+P4 vs ξ0+ξ2



Result Comparisons

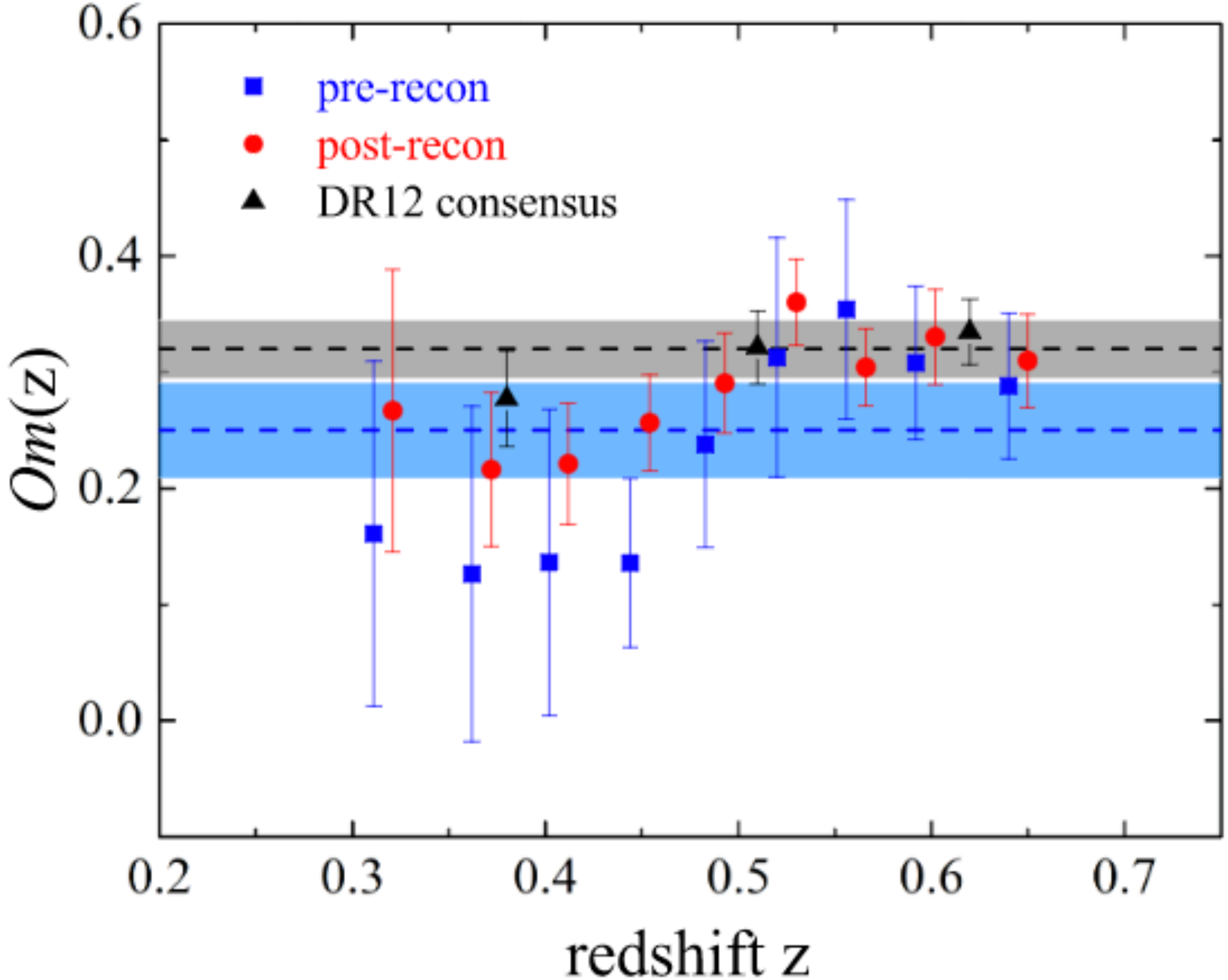




DR12 consensus from Adam et al 2016

Constraints on cosmological models

Om diagnostic $$Om(z) \equiv \frac{[H(z)/H_0]^2 - 1}{(1+z)^3 - 1}.$$



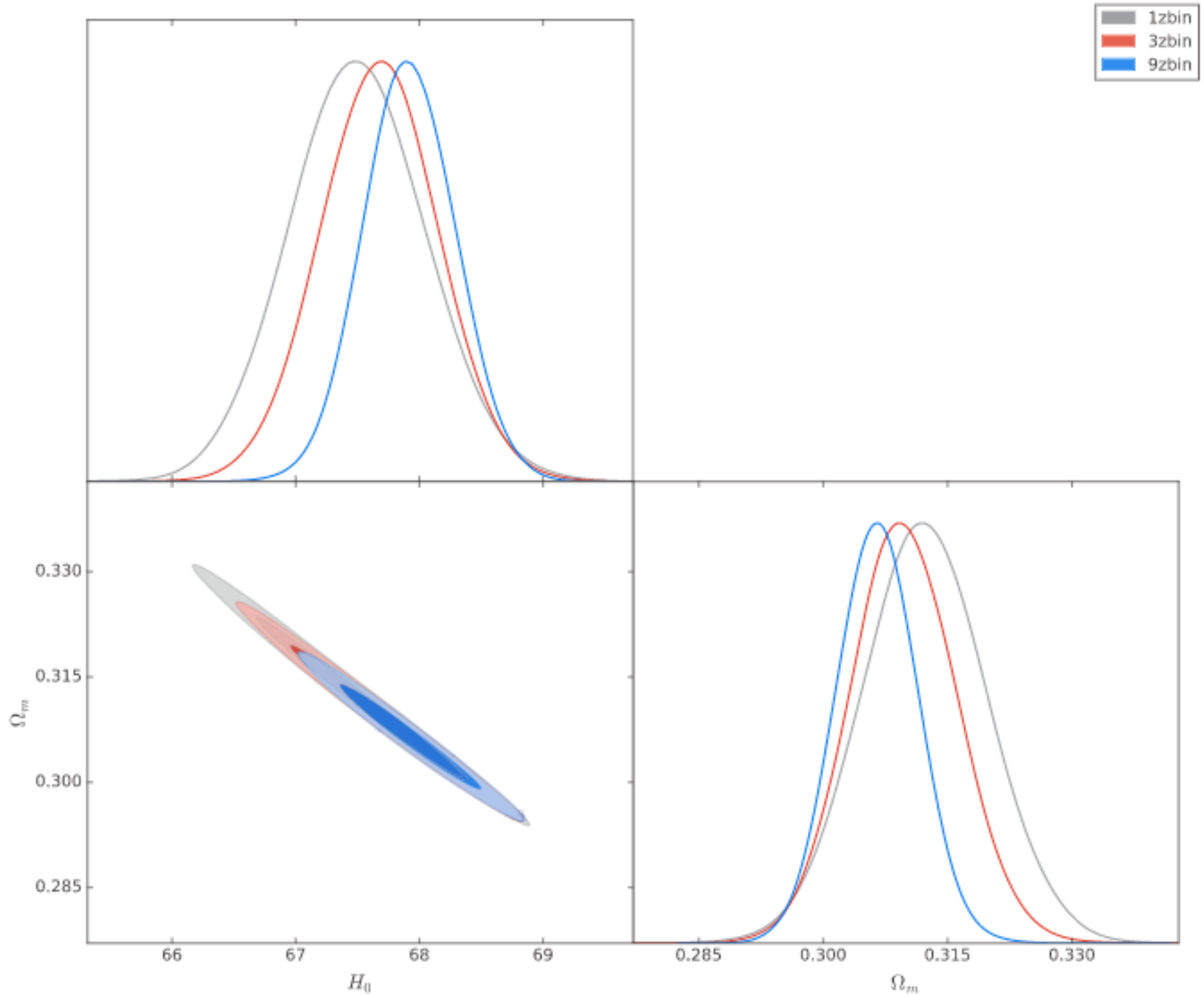
Flat LCDM model

Model	Joint Data set Planck+JLA+BOSS	Ω_m	H_0
ΛCDM	Tomographic (9 $z$bin)	0.3065 ± 0.0049	67.92 ± 0.38
ΛCDM	DR12 Consensus (3 $z$bin)	0.3098 ± 0.0065	67.68 ± 0.48
ΛCDM	Compressed (1 $z$bin)	0.3122 ± 0.0076	67.50 ± 0.56

Adam et al 2016

Cosmological Model	Data Sets	$\Omega_{\rm m} h^2$	$\Omega_{\rm m}$	H_0 km/s/Mpc
ΛCDM	Planck	0.1429 (14)	0.317 (9)	67.2 (7)
ΛCDM	Planck + BAO	0.1418 (10)	0.309 (6)	67.7 (5)
ΛCDM	Planck + BAO + FS	0.1419 (10)	0.311 (6)	67.6 (5)
ΛCDM	Planck + BAO + FS + SN	0.1419 (10)	0.310 (6)	67.6 (5)

Flat LCDM model



9 *z*bin vs 1 *z*bin , 9 *z*bin vs 3 *z*bin : the errors are obviously improved

Flat CPL DE model

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

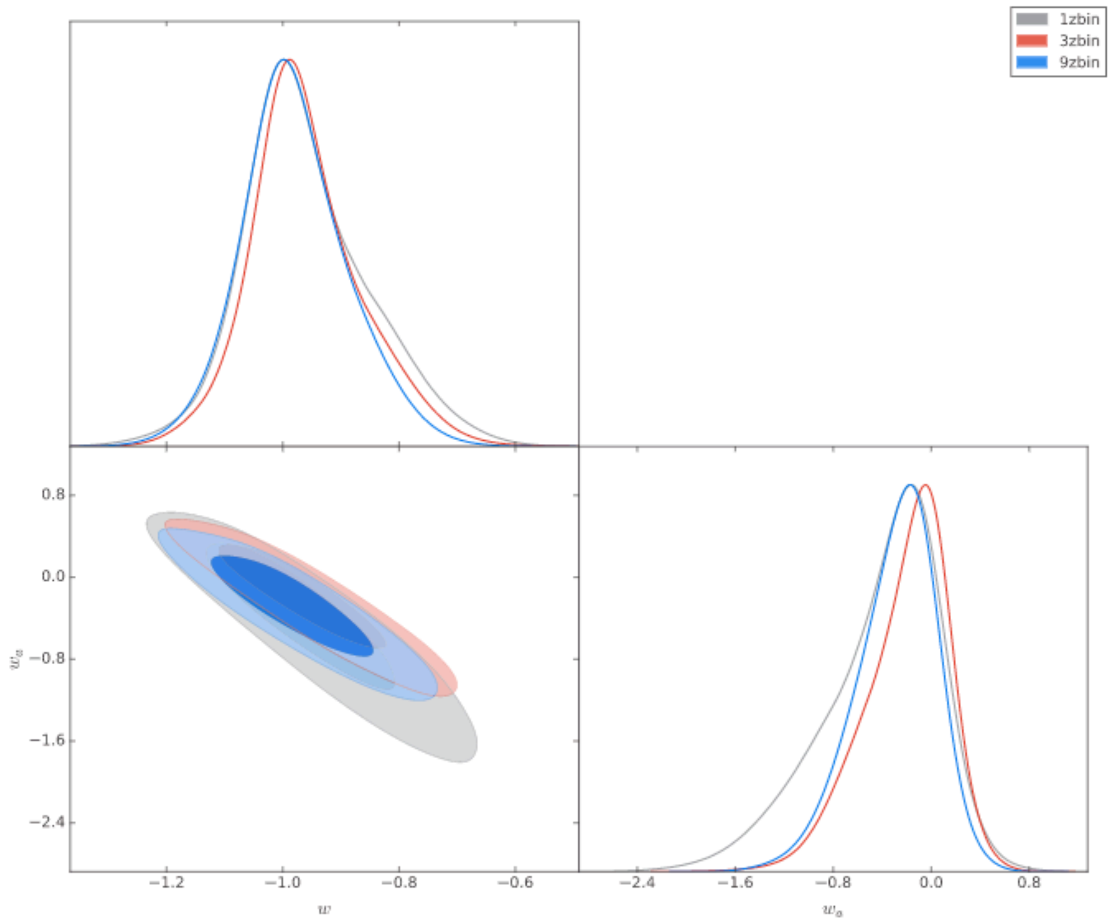
Model	Joint Data set Planck+JLA+BOSS	Ω_m	H_0	w_0	w_a
$w_0 w_a$CDM	Tomographic (9 $z$bin)	0.3031 ± 0.0090	68.69 ± 1.01	-0.9795 ± 0.0926	-0.2897 ± 0.3352
$w_0 w_a$CDM	DR12 Consensus (3 $z$bin)	0.3102 ± 0.0098	67.80 ± 1.02	-0.9417 ± 0.1010	-0.2877 ± 0.3587
$w_0 w_a$CDM	Compressed (1 $z$bins)	0.3024 ± 0.0115	68.83 ± 1.28	-0.9609 ± 0.1096	-0.4006 ± 0.4856

Adam et al 2016

Cosmological Model	Data Sets	$\Omega_m h^2$	Ω_m	H_0 km/s/Mpc	Ω_K	w_0	w_a
$w_0 w_a$CDM	Planck + SN	0.1428 (14)	0.294 (16)	69.8 (18)	...	−0.85 (13)	−0.99 (63)
$w_0 w_a$CDM	Planck + BAO	0.1427 (11)	0.336 (21)	65.2 (21)	...	−0.63 (20)	−1.16 (55)
$w_0 w_a$CDM	Planck + BAO + FS	0.1427 (11)	0.334 (18)	65.5 (17)	...	−0.68 (18)	−0.98 (53)
$w_0 w_a$CDM	Planck + BAO + FS + SN	0.1426 (11)	0.313 (9)	67.5 (10)	...	−0.91 (10)	−0.39 (34)

Flat CPL DE model

$$w(z) = w_0 + w_a \frac{z}{1+z}$$



9 *z*bin vs 1 *z*bin : FoM is improved by a factor of 1.35

9 *z*bin vs 3 *z*bin : the errors are slightly improved

In order to extract the redshift information of galaxy clustering, we split the whole redshift range of BOSS combined sample.

Based on the galaxy redshift survey, we got the high redshift-resolution measurements on the cosmic expansion history.

We also test the constraining power of our tomographic measurements. The constraint precisions of cosmological parameters are improved, compared with that from a single BAO measurement.

Improvements on extracting rich tomographic information in redshifts are expected in the next few years.

Thanks!

Part IV

Concluding remarks