Model-independent constraints on clustering and growth of cosmic structures from BOSS DR12 galaxies in harmonic space [arXiv: 2107.00026]

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What is galaxy number counts or galaxy clustering?

Distribution of galaxies usually studied with the 3D galaxy Fourier PS: Fourier mode of the 3D separation between pairs of galaxies in the sky at a given redshift:

$$P_{gg}(k, \bar{z}) = b(\bar{z})^2 \, D^2(\bar{z}) \, P_{lin}(k) \text{ (approximation; leading order)}$$

What are the redshift-space distortions (RSD)?

- The background galaxies recede: expanding universe

- Galaxies also have their own peculiar velocities whose contributions are added to the main component of cosmological recession

- Result: Distribution of the galaxies in the redshift space is squashed and deformed : Kaiser effect (linear) & FoG (non-linear)

$$P_{gg}(k, \bar{z}) = [b(\bar{z}) + f(\bar{z})\mu^2]^2 \, D^2(\bar{z}) \, P_{lin}(k) \text{ [Kaiser effect]}$$

with $f(\bar{z}) = -d \, lnD(\bar{z})/d \, ln(1+\bar{z})$ and $\mu = \hat{\boldsymbol{r}} \cdot \boldsymbol{k}/k, \;\; k = |\boldsymbol{k}|$

Why to use the harmonic space PS instead of the galaxy Fourier PS?

- Natural tool and a direct observable (just measuring redshifts and angles); No Alcock-Paczynski correction
- Accounts for cosmic evolution
- Wide angle effects included
- Lensing is naturally included
- Tomography between different redshift shells is possible

$$C^{gg}_{ij,\ell} := \langle \Delta^i_{\ell m} \Delta^{j*}_{\ell m} \rangle = \frac{2}{\pi} \int dk\, k^2\, P_{lin}(k) \Delta^i_\ell(k) \Delta^j_\ell(k)\,, \quad \text{[FULL]}$$

$$\Delta^i_\ell(k) = \int dr\, n^i(r) D(r) [b(r) j_\ell(kr) - f(r) j''_\ell(kr)]$$

We can introduce the following derived quantities

$$b\sigma_8(z) := b(z)D(z)\sigma_8$$

$$\mathrm{f}\sigma_8(z) := f(z)D(z)\sigma_8$$

where σ_8 the r.m.s variance of clustering in spheres of radius $8h^{-1}$Mpc

Terms $b\sigma_8(z)$ and f$\sigma_8(z)$ can be factorised out of the integral for almost arbitrarily narrow redshift bins (possible in galaxy surveys with spectroscopic redshift accuracy). f$\sigma_8(z)$ is a good probe to discriminate between different Dark Energy models.

$$C^{gg}_{ij,\ell} = b\sigma_8^i b\sigma_8^j C^{\delta\delta}_{ij,\ell} + f\sigma_8^i f\sigma_8^j C^{VV}_{ij,\ell} - 2b\sigma_8^{(i} f\sigma_8^{j)} C^{\delta V}_{ij,\ell}\,,$$ [APPROX.]

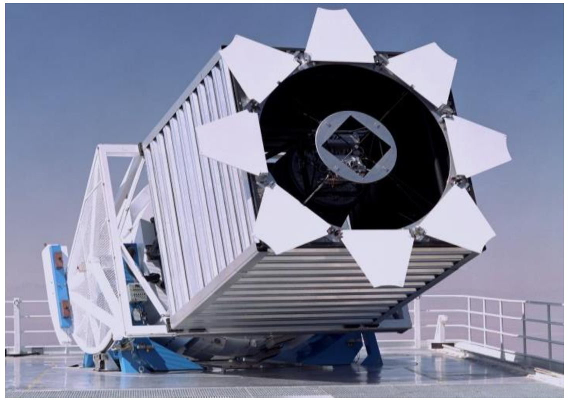
$$C^{\delta\delta}_{ij,\ell} := \frac{2}{\pi}\int dk\, dr\, d\tilde{r}\, k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^i(r) n^j(\tilde{r}) j_\ell(kr) j_\ell(k\tilde{r})\,,$$

$$C^{VV}_{ij,\ell} := \frac{2}{\pi}\int dk\, dr\, d\tilde{r}\, k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^i(r) n^j(\tilde{r}) j''_\ell(kr) j''_\ell(k\tilde{r})\,,$$

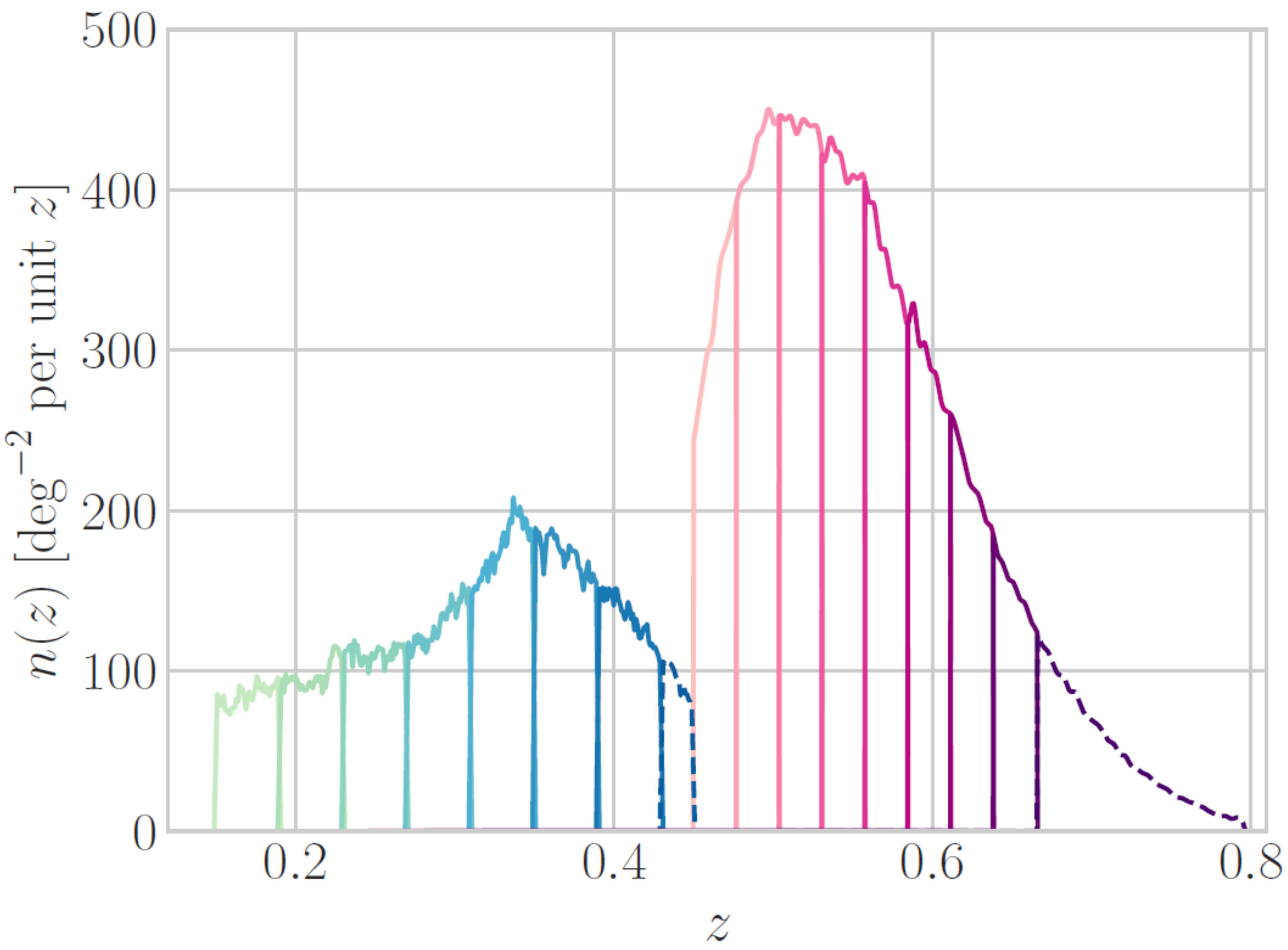
$$C^{\delta V}_{ij,\ell} := \frac{2}{\pi}\int dk\, dr\, d\tilde{r}\, k^2 \frac{P_{lin}(k)}{\sigma_8^2} n^{(i}(r) n^{j)}(\tilde{r}) j_\ell(kr) j''_\ell(k\tilde{r})\,,$$

Let’s measure it with BOSS data

BOSS DR12 spectroscopic survey

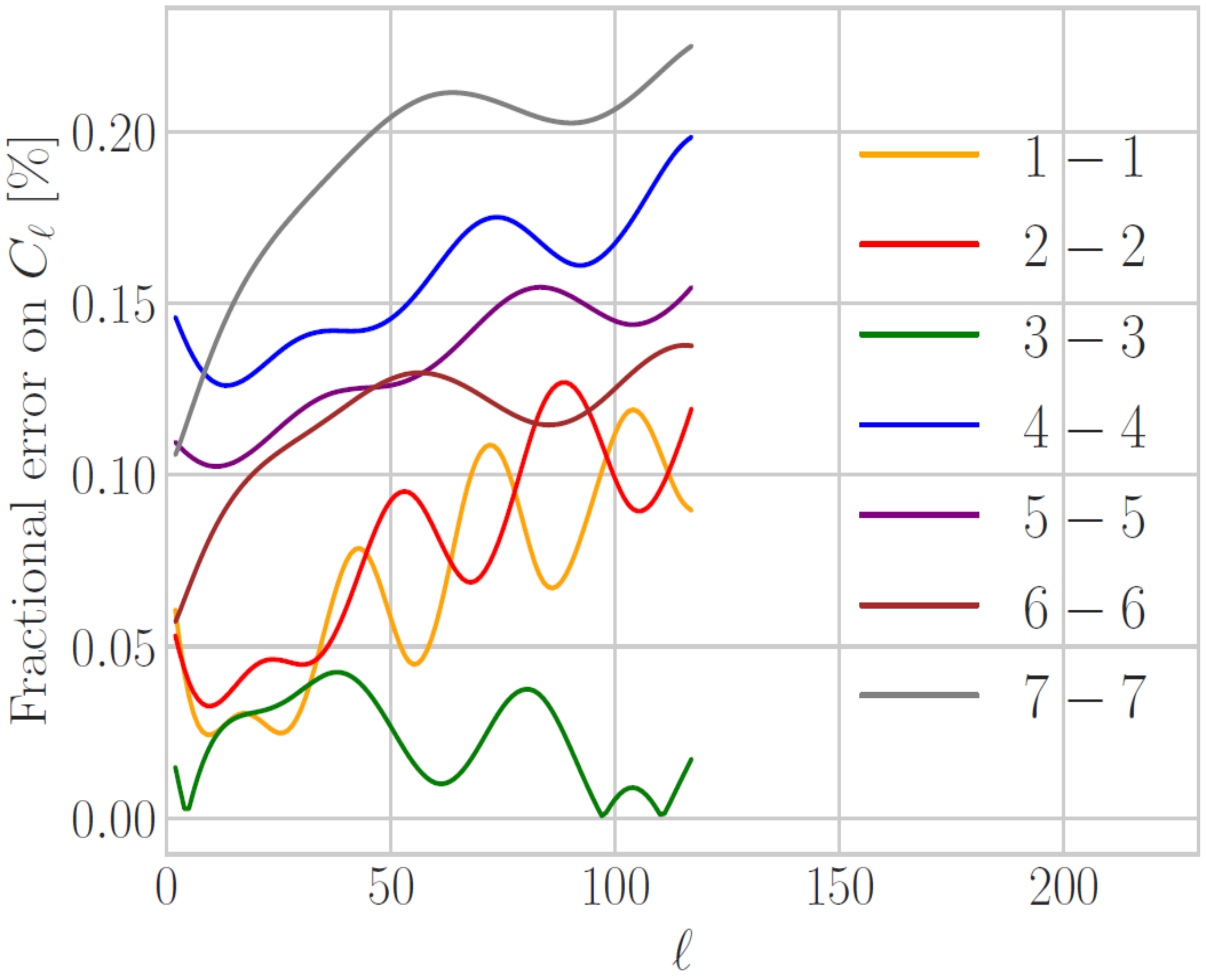


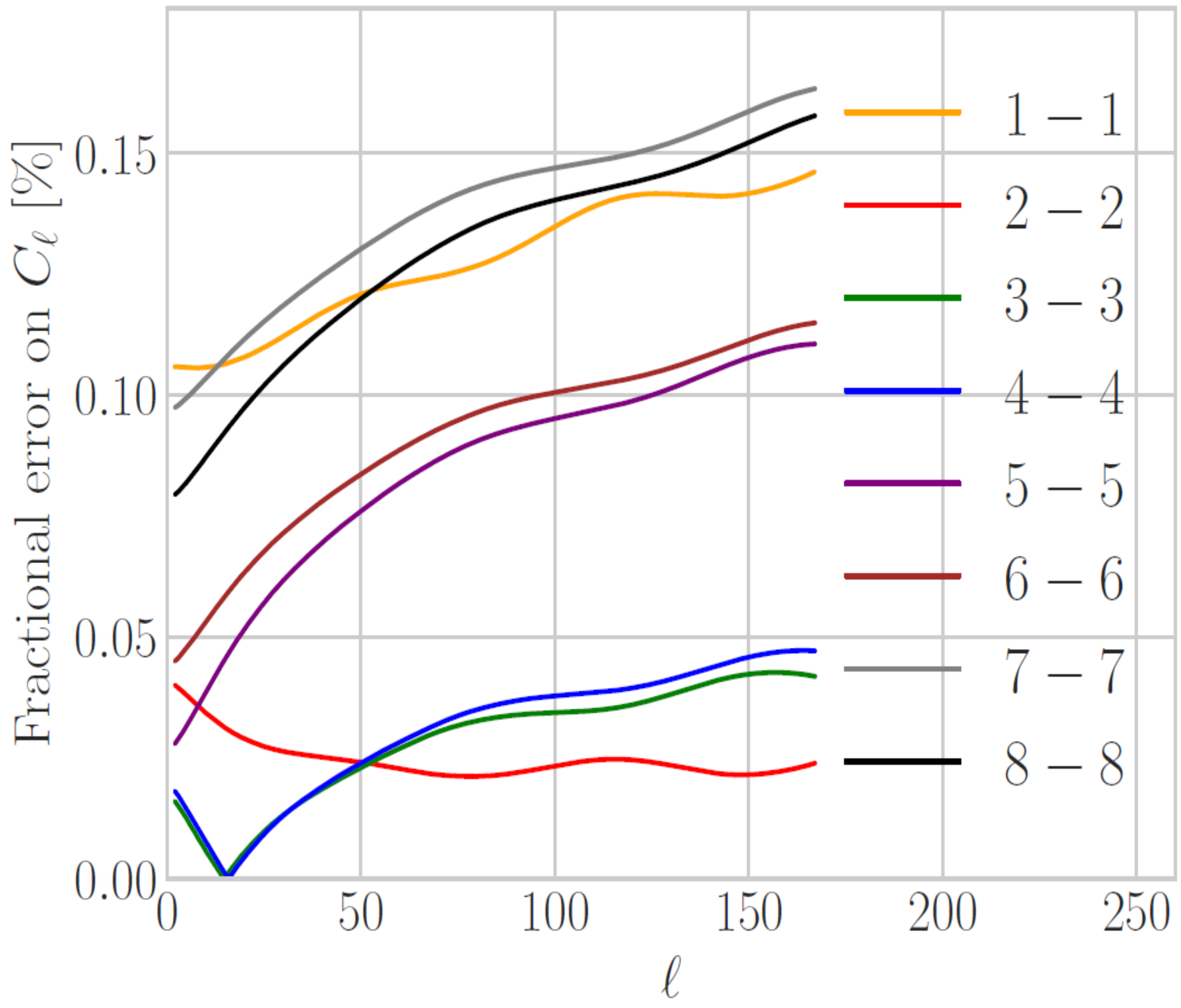
- Apache Point Observatory (APO): 2.5m telescope for 5 yr (2009-2014)
- Part of SDSS-III project: Baryon Oscillation Spectroscopic Survey
- About 10,000 sq.deg
- Two LRG subsamples: LOWZ and CMASS
- About 10^6galaxies in total



LOWZ CMASS

|FULL/APPROX.-1| X 100%





- Restrict analysis to strictly linear scales, $k_{max} = 0.1\ h\ Mpc^{-1}$,

$$\ell^i_{max} = k_{max} r(\bar{z}_i)$$

- Minimum multipole resolved, $\ell_{min} = \frac{\pi}{2 f_{sky}}$

Table 1. Redshift range, number of sources, shot noise, and maximum multipole for the redshift bins considered in the analysis.

Bin ID	$[z_{min}, z_{max}]$	# of gals	shot noise [sr]	ℓ^i_{max}
LOWZ-1	[0.150, 0.190]	33 906	8.08×10^{-5}	49
LOWZ-2	[0.190, 0.230]	38 728	7.07×10^{-5}	60
LOWZ-3	[0.230, 0.270]	44 291	6.18×10^{-5}	71
LOWZ-4	[0.270, 0.310]	51 781	5.27×10^{-5}	81
LOWZ-5	[0.310, 0.350]	70 879	3.86×10^{-5}	91
LOWZ-6	[0.350, 0.390]	68 701	3.98×10^{-5}	101
LOWZ-7	[0.390, 0.430]	53 191	5.15×10^{-5}	111
CMASS-1	[0.450, 0.477]	81 836	3.71×10^{-5}	123
CMASS-2	[0.477, 0.504]	112 589	2.67×10^{-5}	129
CMASS-3	[0.504, 0.531]	118 915	2.55×10^{-5}	135
CMASS-4	[0.531, 0.558]	113 139	2.68×10^{-5}	141
CMASS-5	[0.558, 0.585]	99 672	3.04×10^{-5}	147
CMASS-6	[0.585, 0.612]	80 914	3.75×10^{-5}	153
CMASS-7	[0.612, 0.639]	61 551	4.93×10^{-5}	159
CMASS-8	[0.639, 0.670]	44 057	6.89×10^{-5}	164

Construct the galaxy overdensity maps

- Galaxy catalogues public from BOSS collaboration

- Random catalogues are also available; 50 times denser than galaxy catalogues, taking into account:

1. Completeness masks (extent of complete observations)
2. Veto masks (various observational effects)

- Can be used to build binary angular masks
  - $N_{side} = 1024$ using HEALPix
  - Construct galaxy overdensity maps as

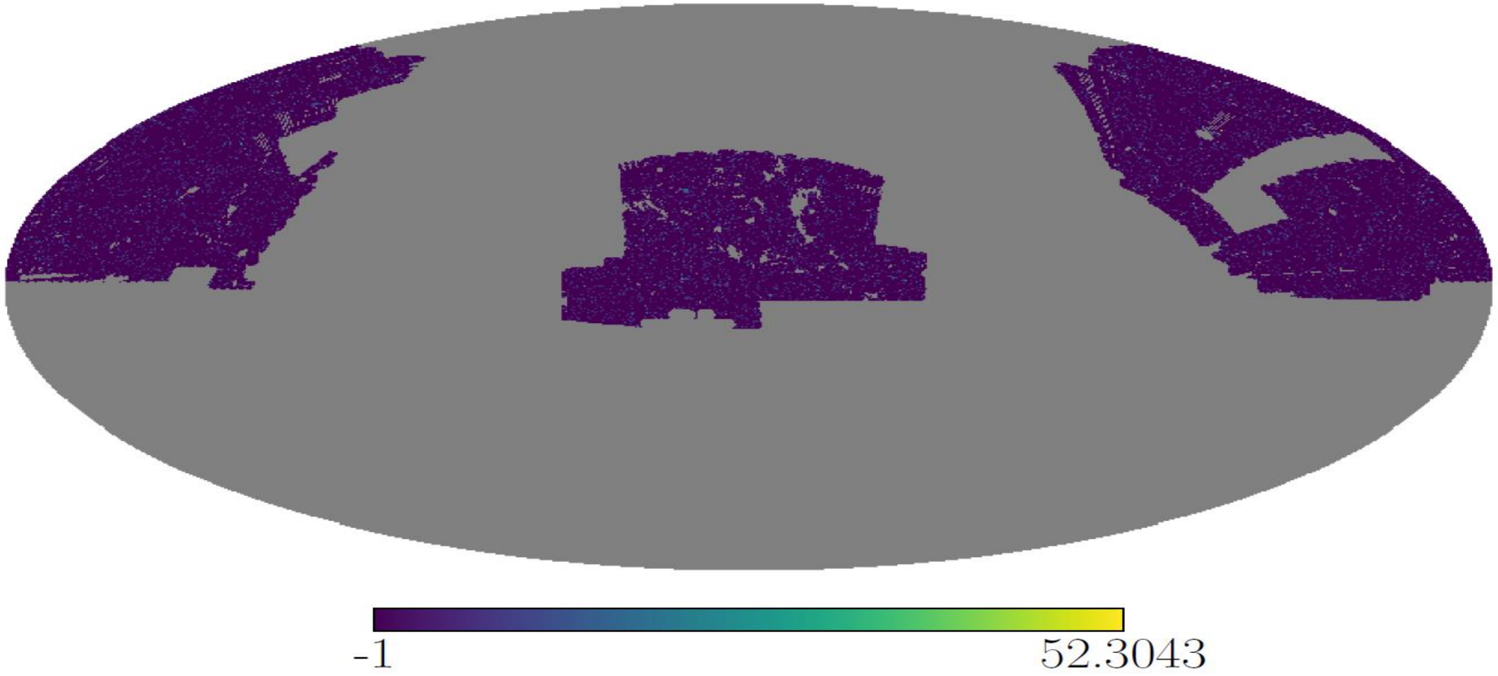
$$\delta_g^p = (n_g^p - \bar{n}_g) / \bar{n}_g$$

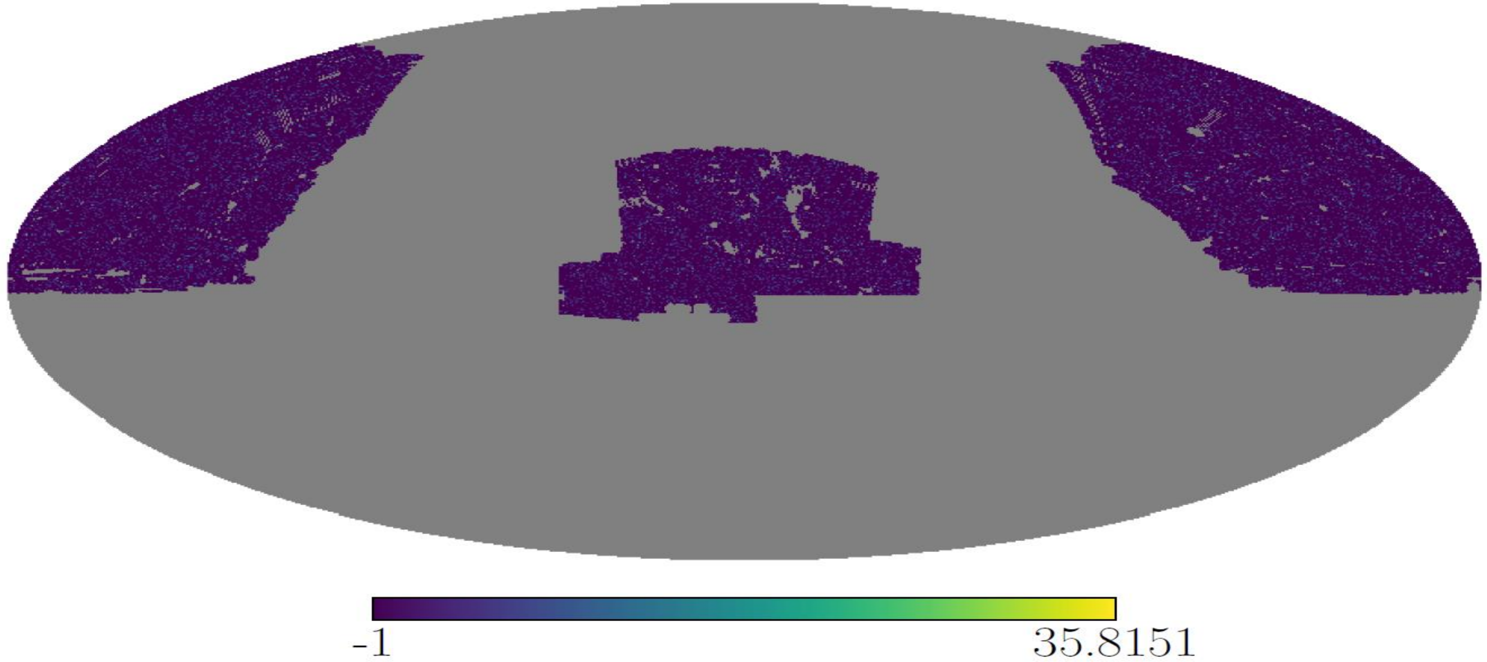
with n_g^p the number of weighted galaxies in a given pixel p
and $\bar{n}_g$ the mean number of weighted galaxies per pixel

$f_{sky} = 0.2081$ for LOWZ

$f_{sky} = 0.2416$ for CMASS

A common $\ell_{min} \approx 7$





Pseudo-C_ℓ approach & mask effects

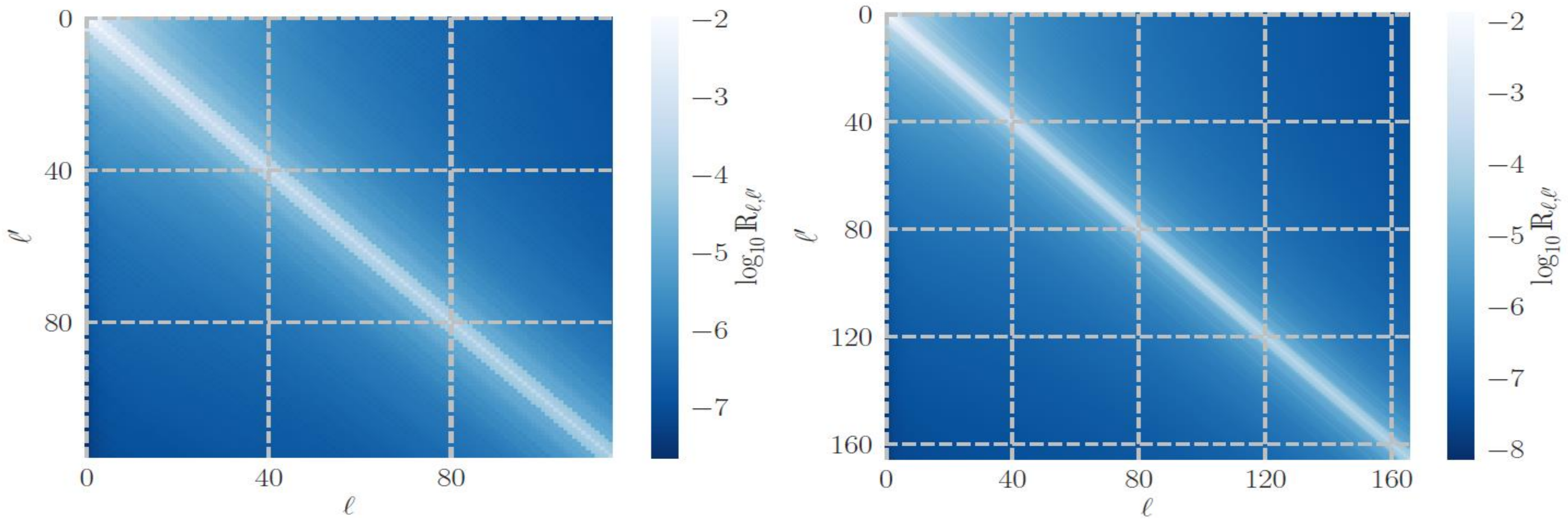
- Project the observed field onto the celestial sphere
- Decompose it to spherical harmonics
- Analyse statistically the coefficients of the decomposition

$$\widetilde{C_{ij,\ell}^{gg}} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}\left|\delta_g^{\ell m}\right|^2 - \delta_{ij}^K/\bar{n}_g^i$$

- The mask introduces coupling between different modes: Measured field is related to the unmasked field

$$\left\langle\widetilde{C_{ij,\ell}^{gg}}\right\rangle = \sum_{\ell'}\mathcal{R}_{\ell\ell'}\,\widetilde{C_{ij,\ell}^{gg}}$$

With the coupling matrix $\mathcal{R}_{\ell\ell'} = \frac{2\ell'+1}{4\pi}\sum_{\ell''}(2\ell''+1)W_{\ell''}\begin{pmatrix}\ell & \ell' & \ell''\\ 0 & 0 & 0\end{pmatrix}^2$



- A way to overcome this is with the forward modelling; convolve the coupling matrix with the theory spectra (usually time consuming)
- Another is to invert the coupling matrix and deconvolve it from the data; Direct inversion impossible since matrix becomes singular; A solution is to introduce bandpowers (pymaster package)

Let s a set of 8 multipoles with weights w_s^ℓ, and $\sum_{\ell \in s} w_s^\ell = 1$

The coupled pseudo-C_ℓ in s bandpower:

$$\widetilde{B_{ij,\ell}^{gg}} = \sum_{\ell \in S} w_s^\ell \langle \widetilde{C_{ij,\ell}^{gg}} \rangle,$$

With expectation value:

$$\left\langle \widetilde{B_{ij,\ell}^{gg}} \right\rangle = \sum_{\ell \in S} w_s^\ell \sum_{\ell'} \boldsymbol{\mathcal{R}}_{\ell\ell'} \widetilde{C_{ij,\ell'}^{gg}}$$

Thus assuming the true power spectrum is a stepwise function related to bandpowers:

$$\widetilde{C_{ij,\ell}^{gg}} = \sum_{s} \widetilde{B_{ij,s}^{gg}} \, \Theta(\ell \in s)$$

Then an unbiased estimator can be derived:

$$B_{ij,s}^{gg} = \sum_{s'} \boldsymbol{\mathcal{M}}_{ss'}^{-1} \widetilde{B_{ij,s'}^{gg}}$$

With the binned coupling matrix now $\boldsymbol{\mathcal{M}}_{ss'} = \sum_{\ell \in s} \sum_{\ell' \in s'} w_s^\ell \boldsymbol{\mathcal{R}}_{\ell\ell'}$

The theory spectra should be binned accordingly

$$B_{ij,s}^{gg,th} = \sum_{\ell} \left(\sum_{s'} \boldsymbol{\mathcal{M}}_{ss'}^{-1} \sum_{\ell' \in S'} w_{s'}^{\ell'} \boldsymbol{\mathcal{R}}_{\ell'\ell} \right) \cdot C_{ij,\ell}^{gg}$$

Construct the Gaussian likelihood

$$\chi^2(\boldsymbol{\theta}) = [\boldsymbol{d} - \boldsymbol{t}(\boldsymbol{\theta})]^T \, \boldsymbol{C}^{-1}[\boldsymbol{d} - \boldsymbol{t}(\boldsymbol{\theta})]$$

with $\boldsymbol{d} = \{B_{ij,s}^{gg}\}$, $\boldsymbol{t}(\boldsymbol{\theta}) = \{B_{ij,s}^{gg,th}(\boldsymbol{\theta})\}$ and $\boldsymbol{\theta} = \{b\sigma_8^i, f\sigma_8^i\}$

For the theory spectra we assume a ΛCDM fiducial cosmology as from Planck 2016

We will put constraints on the parameter set $\boldsymbol{\theta}$ using three different approaches to estimate the data covariance matrix $\boldsymbol{C}$

Gaussian Covariance: diagonal in multipole space

$$\boldsymbol{C}_{ss'}^{ij,kl} = \frac{\delta_{ss'}^{K}}{(2s+1)\Delta s\, \mathrm{f_{sky}}} \left(\widehat{B_{ik,s}^{gg}}\ \widehat{B_{jl,s}^{gg}} + \widehat{B_{il,s}^{gg}}\ \widehat{B_{jk,s}^{gg}}\right)$$

with Δs the multipole range in the bandpower binning

$$\widehat{B_{ij,s}^{gg}} = B_{ij,s}^{gg} + \frac{\delta_K^{ij}}{\bar{n}_g^i}$$

PolSpice Covariance: accounting for coupling due to the mask

$$\mathcal{C}_{ss'} = \mathcal{M}^{-1}_{ss'} \mathcal{V}_{ss'} [(\mathcal{M}^{-1})_{ss'}]^T$$

with $\mathcal{V}_{ss'} = \frac{2 \boldsymbol{d}_s \boldsymbol{d}_{s'} \mathcal{M}_{ss'}}{2s'+1}$

and $\boldsymbol{d}_s$ the data vector in bandpower s

Mocks Covariance

- Realistic way to estimate covariances is with data simulations

- BOSS offers simulated galaxy catalogues with PATCHY and QPM mocks

  1. Constructed with a fixed cosmological model
  2. Include various observational and systematics effects

- Due to their different redshift ranges, for LOWZ we use QPM mocks ($z>1.5$) while for CMASS the PATCHY ones ($0.2<z<0.75$)

- A further test to validate our analysis by using different mocks for each sample

$$\mathcal{C}_{ss'} = \frac{1}{\mathrm{N_m} - 1} \sum_{m=1}^{N_m} (d_s^m - \bar{d}_s^m)\,(d_{s'}^m - \bar{d}_{s'}^m)^T$$

With $m = 1 \ldots N_m$, $N_m = 1000(2048)$ mocks for QPM(PATCHY), $d_s^m = \{B_{ik,s}^{gg,m}\}$ and

$$\bar{d}_s^m = \frac{1}{\mathrm{N_m}} \sum_{m=1}^{N_m} \bar{d}_s^m$$

Modify the likelihood:

- The inverse of the simulated covariance matrix is not an unbiased estimator of the true covariance

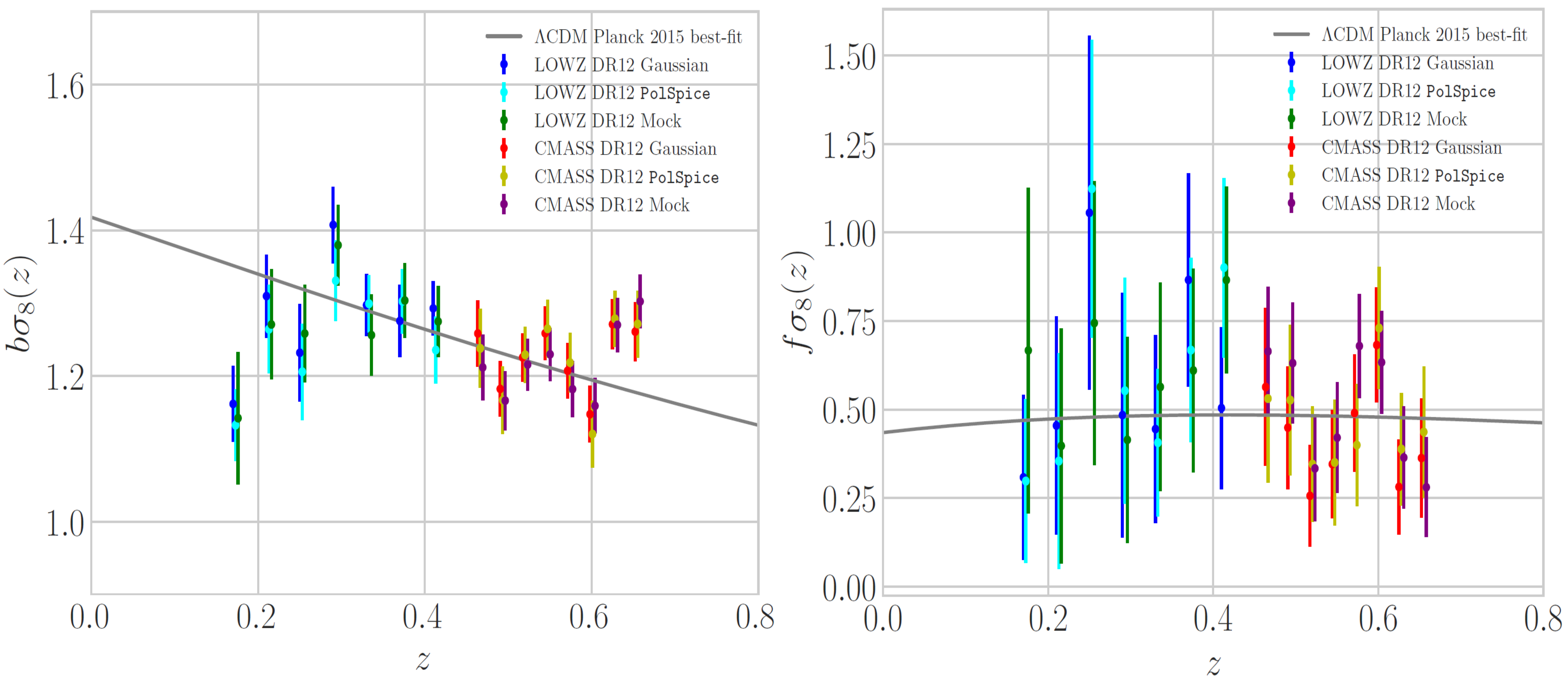
$\mathcal{C}^{-1} \rightarrow \frac{\mathrm{N_m - N_d - 2}}{\mathrm{N_m - 2}}\, \mathcal{C}^{-1}$ and keep the Gaussian likelihood, **OR**

- Replace the Gaussian likelihood with a t-Student

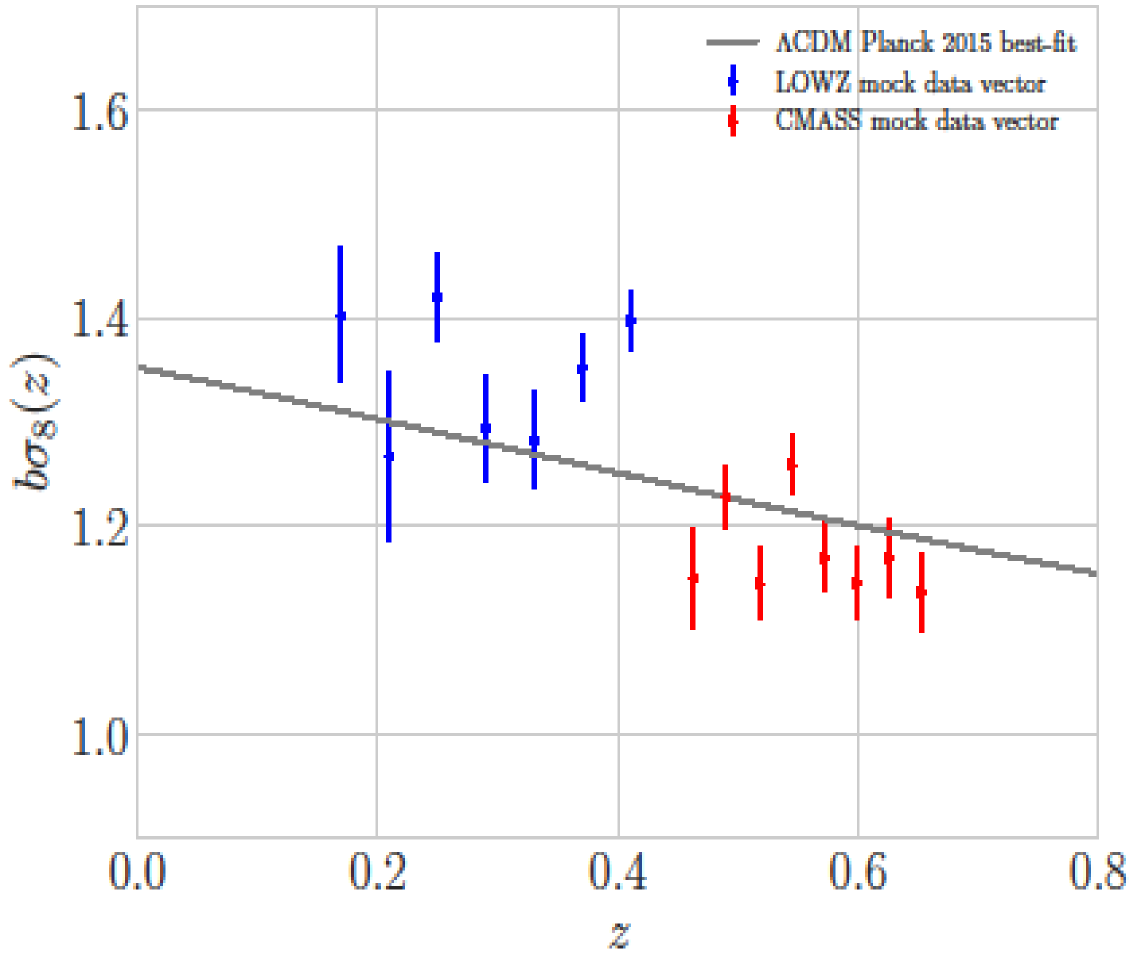
$\mathcal{L} \propto \left[1 + \frac{\chi^2}{N_m}\right]^{-N_m/2}$ and normalising with $\frac{\Gamma(N_m/2)[\det(\mathcal{C})]^{-1/2}}{[\pi(N_m-1)]^{N_d/2} - \Gamma[(N_m-N_d)/2]}$ assuming $N_m > N_d$

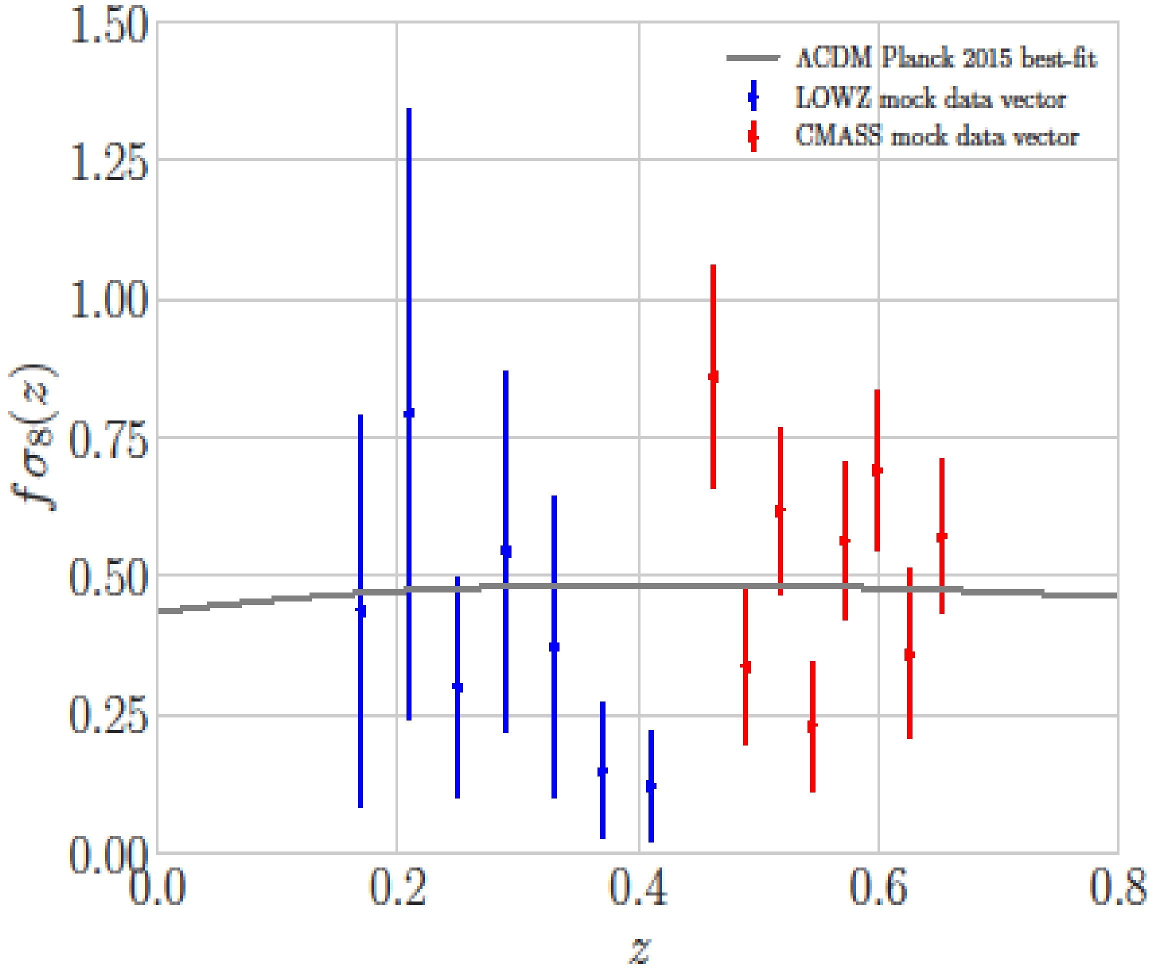
Both methods equivalent

Results: sampling with emcee, equal bin correlations only

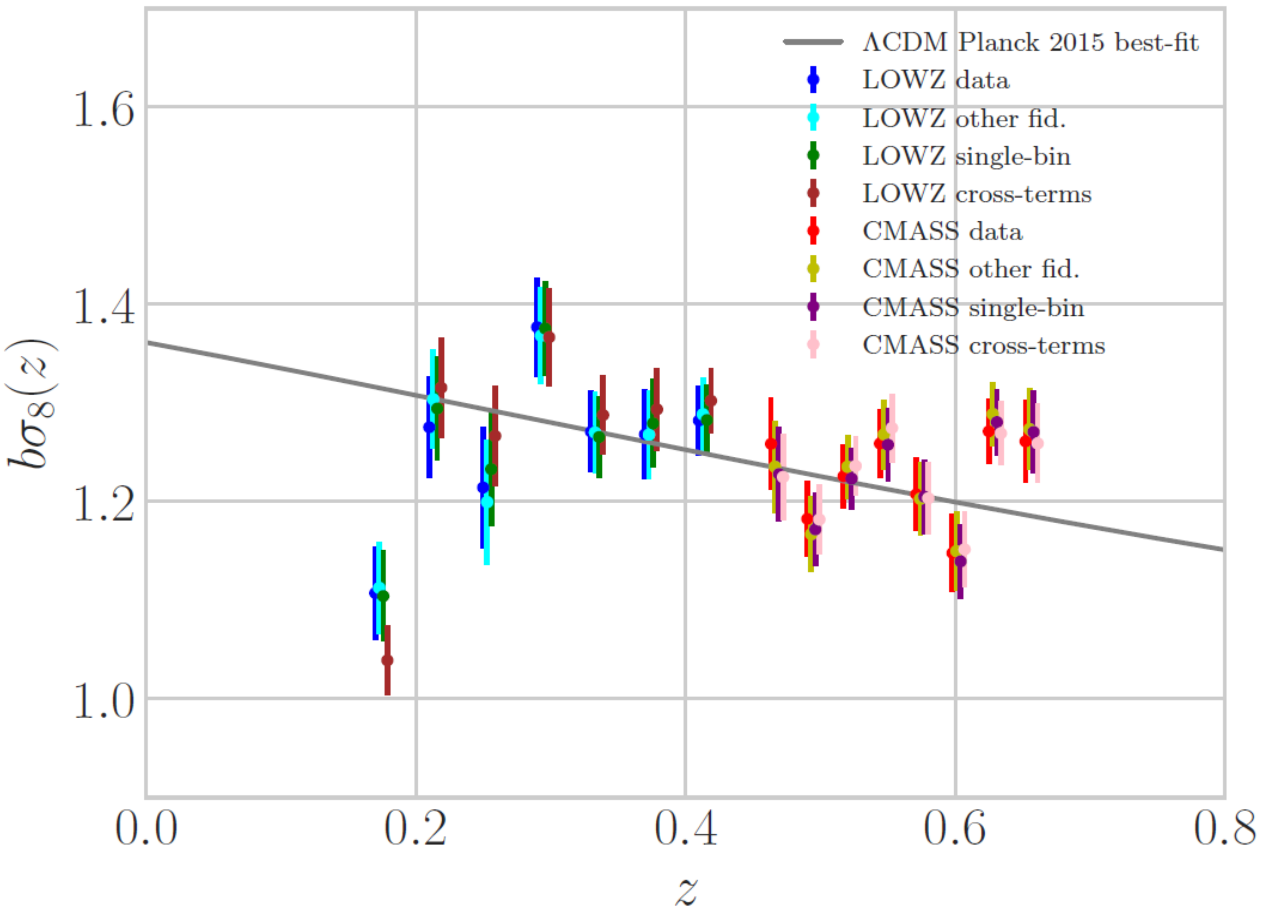


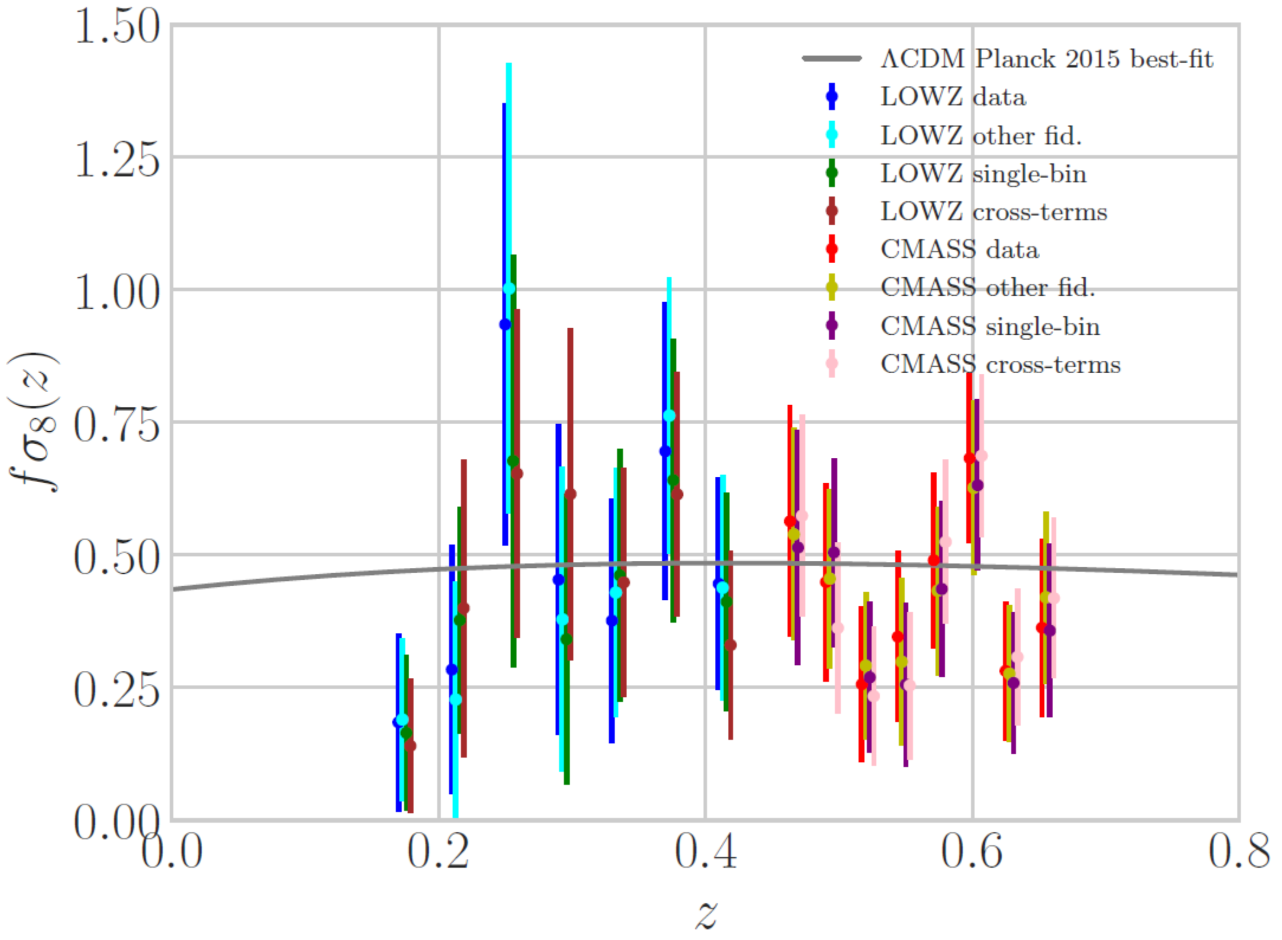
Consistency checks: Replacing data vectors with mock data vectors





Consistency checks: 1) Different fiducial cosmology (change parameters at the 95% C.L of the Planck best-fit values), 2) Single bin estimation, 3) Include cross-bin correlations in the covariance





Consistency checks: Residual distribution

- Diagonalise the covariance matrix:

$$\mathcal{C} = \mathcal{Q}\mathcal{K}\mathcal{Q}^{-1}$$

with $\mathcal{Q}$ the eigenvector matrix, and $\mathcal{K}$ the diagonal eigenvalue matrix as from $\mathcal{C}$

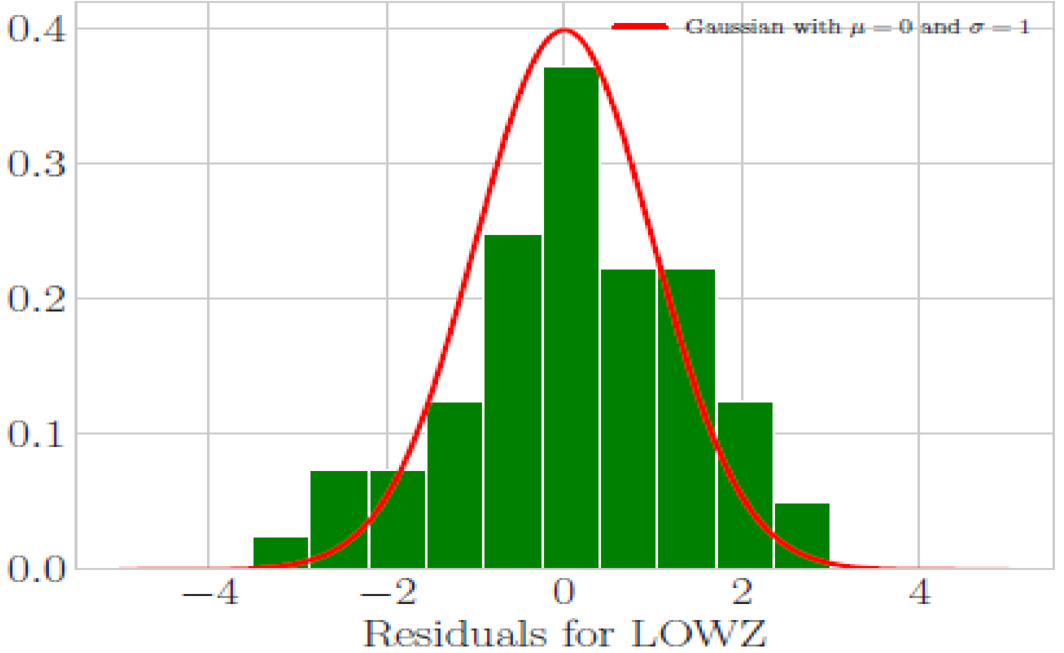
- Now the residual reads:

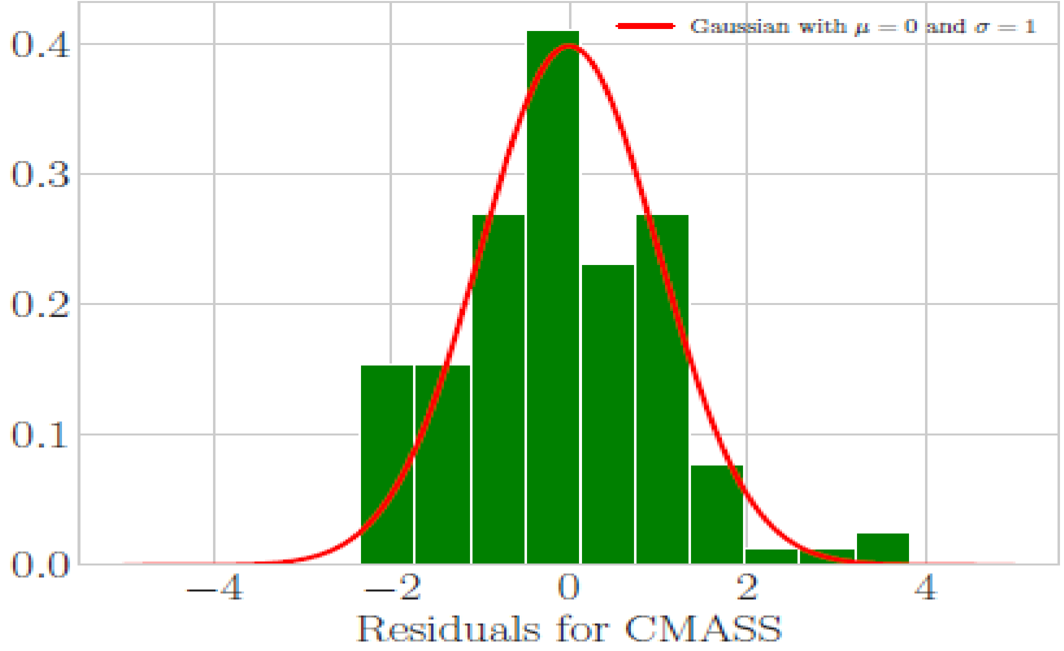
$$R = \mathcal{O}^{-1}\mathcal{Q}^{-1}[\boldsymbol{d} - \boldsymbol{t}(\boldsymbol{\theta}_{best-fit})]$$

and $\mathcal{O} = diag\left(\sqrt{\mathcal{K}_{\alpha\alpha}}\right)$

- If residuals follow the normal distribution $(\mu = 0, \sigma = 1)$ then the model is the 'true' one or the data are not good enough to show model preference, otherwise reject the model

- KS-tests accept null hypothesis





Conclusions

- Novel method to put constraints on the amplitude of the galaxy clustering $\mathrm{b}\sigma_8$ and the growth rate $f\sigma_8$ using the harmonic space (angular) PS.
- Test it against synthetic data and simulations using the BOSS DR12 galaxy subsamples LOWZ and CMASS
- Take into account observational and mask effects in a pseudo-C_ℓ approach
- Construct data covariance with three different implementations (Gaussian, PolSpice, Mocks) yielding consistent results
- Considerable independence from the theory model; passes successfully a series of sanity and systematics tests
- Findings agree very well with literature
- Potential of improving constraints with forthcoming datasets (Euclid, SKA,..) to shed light on the physics of the history of the Universe

Thank you for your attention!