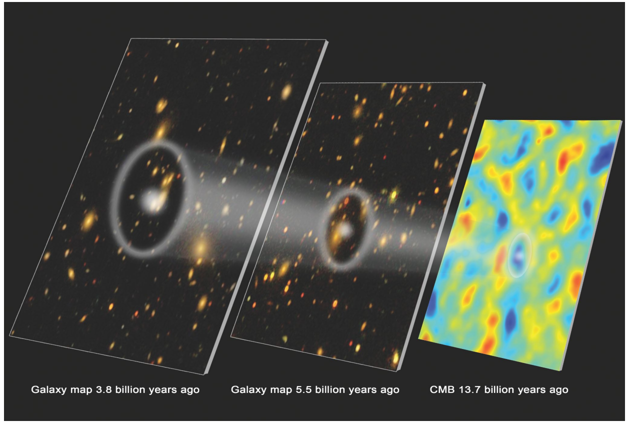
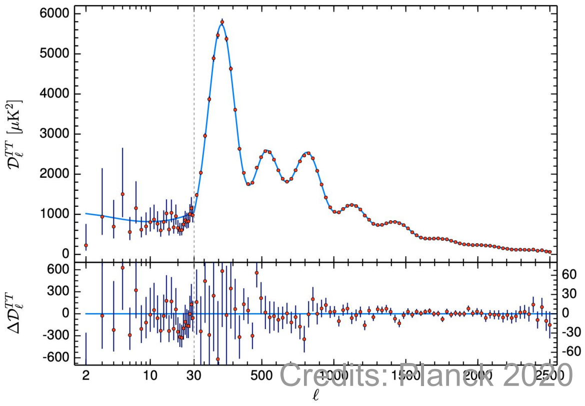
Cosmology Seminar Berkeley
16th of January 2024

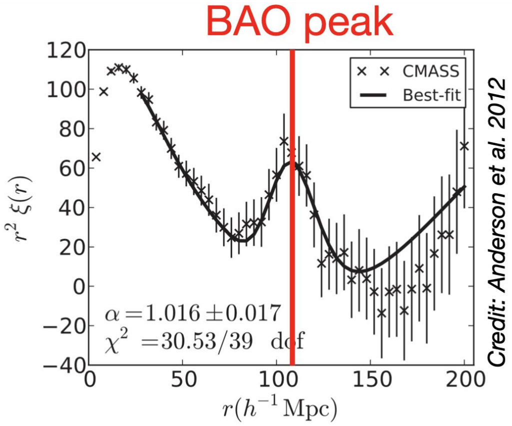
Improving BAO constraints with cosmic voids

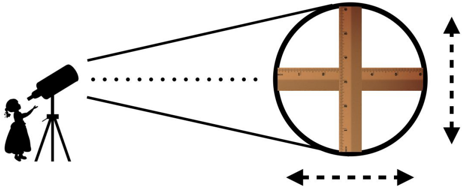
Amélie Tamone
Collaborators: Chia-Hsun Chuang, Daniel Forero-Sanchez, Francisco Kitaura, Jean-Paul Kneib, Charling Tao, Andrei Variu, Cheng Zhao

Baryon Acoustic Oscillations as a Standard Ruler









$$dr_\perp = D_A(z)d\theta$$

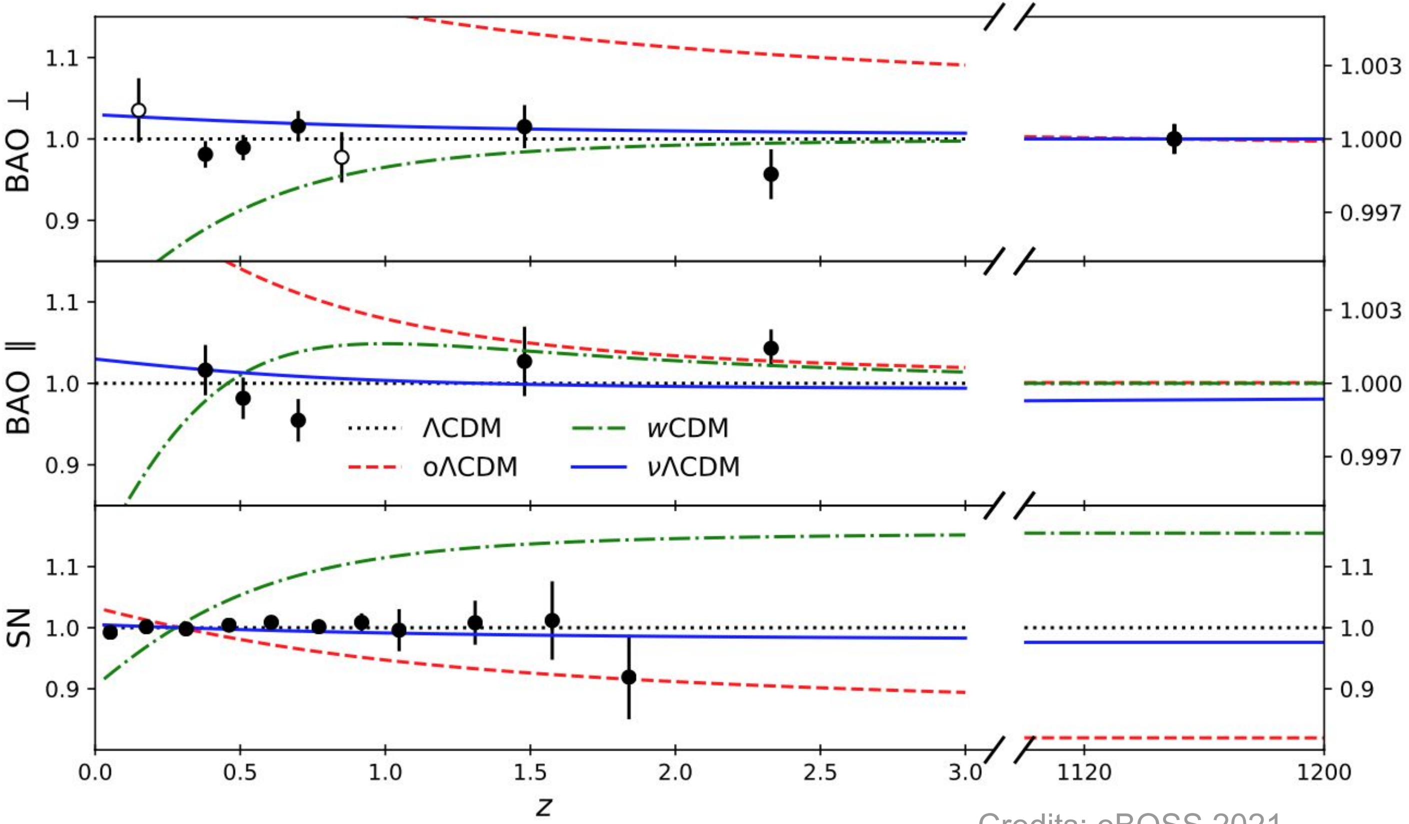
$$dr_\parallel = \frac{cdz}{H(z)}$$

→ Infer dilation parameter ***α***

BAO peak position: $(D_A^2/H)^{1/3}/r_s$

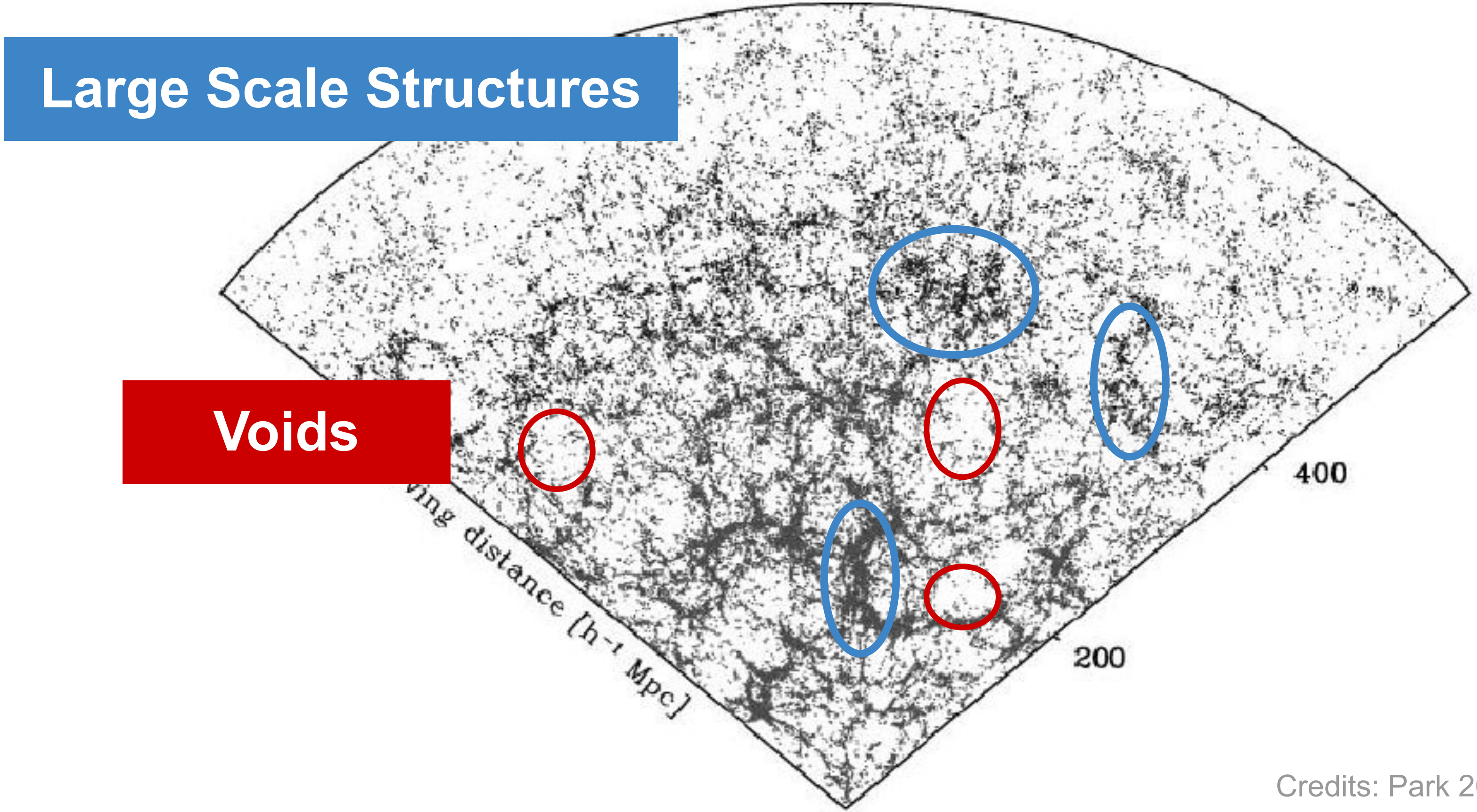
AP effect (relative dilation $\frac{\alpha_{/\!/}}{\alpha_\perp}$): HD_A

Distance Measurements from Spectroscopic Surveys



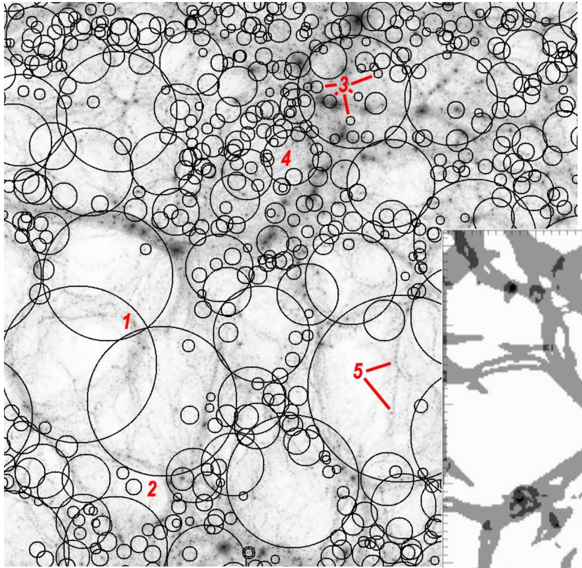
Credits: eBOSS 2021

Cosmic Web

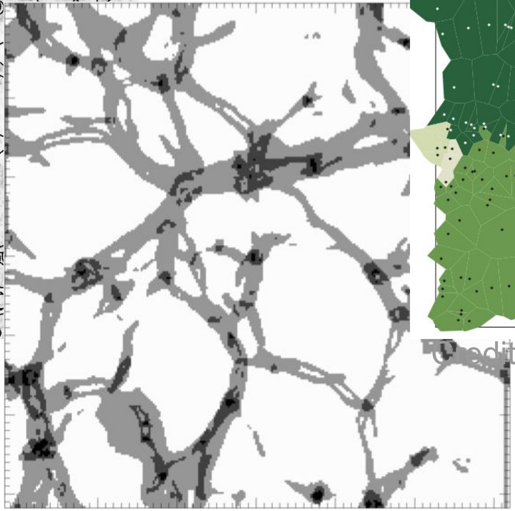


Credits: Park 2005

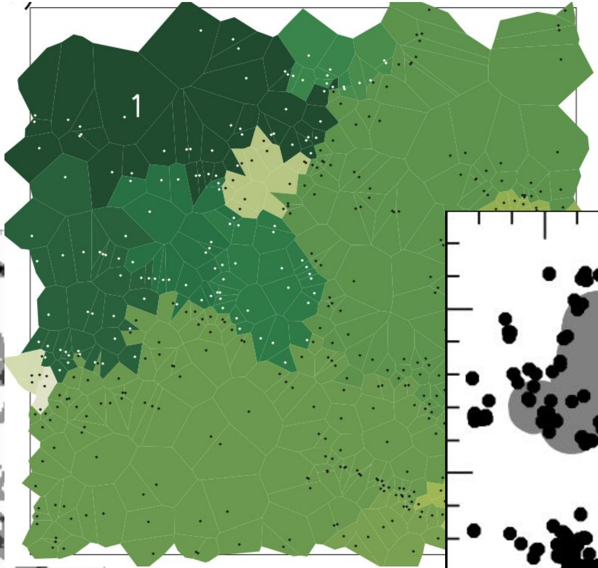
Cosmic Void Definitions



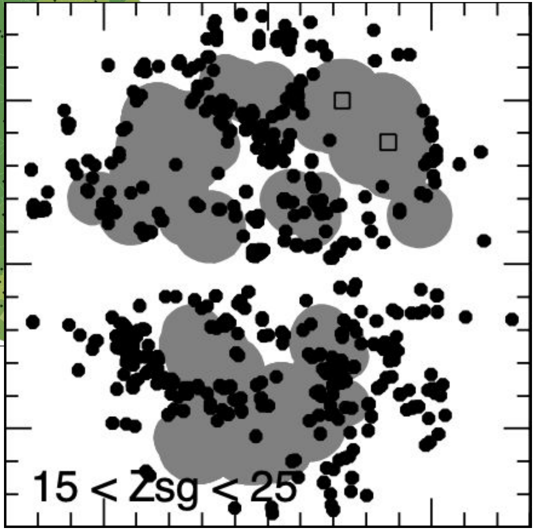
Credits: Colberg 2005



Credits: Hoffmann 2012

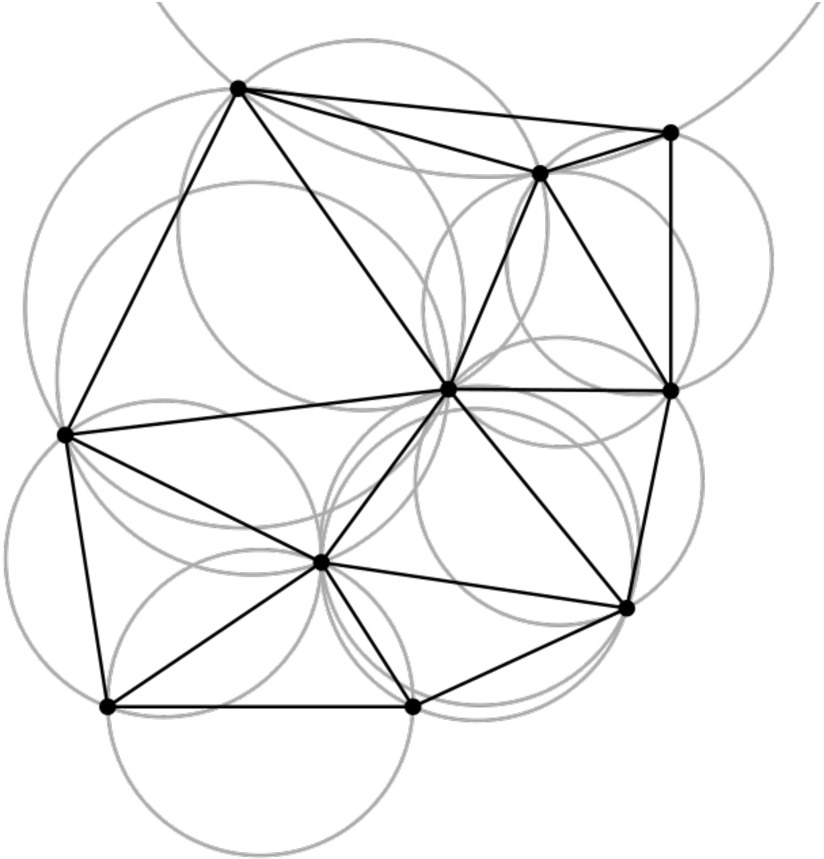


Credits: Neyrinck 2008



Credits: Hoyle 2002

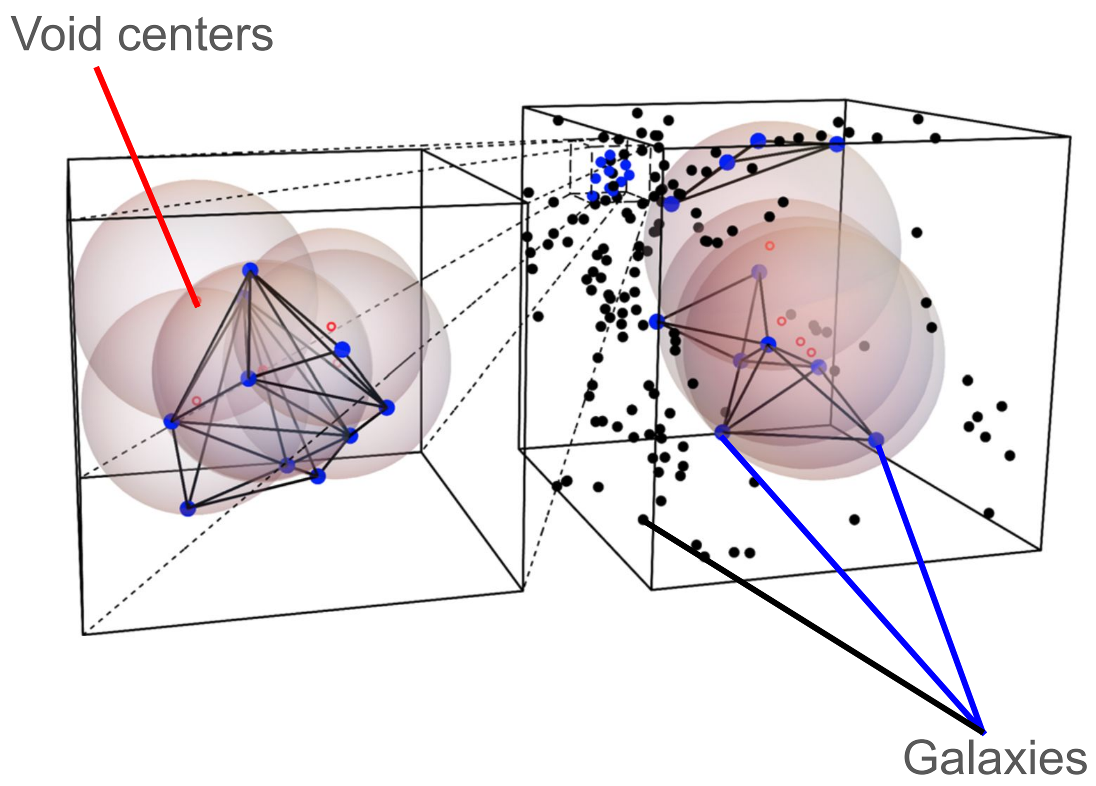
DIVE : **D**elaunay Tr**i**angulation **V**oid Find**e**r



Set of Points

Delaunay Tetrahedra (DT)
=
Empty Circumphseres

DIVE algorithm and DT Voids



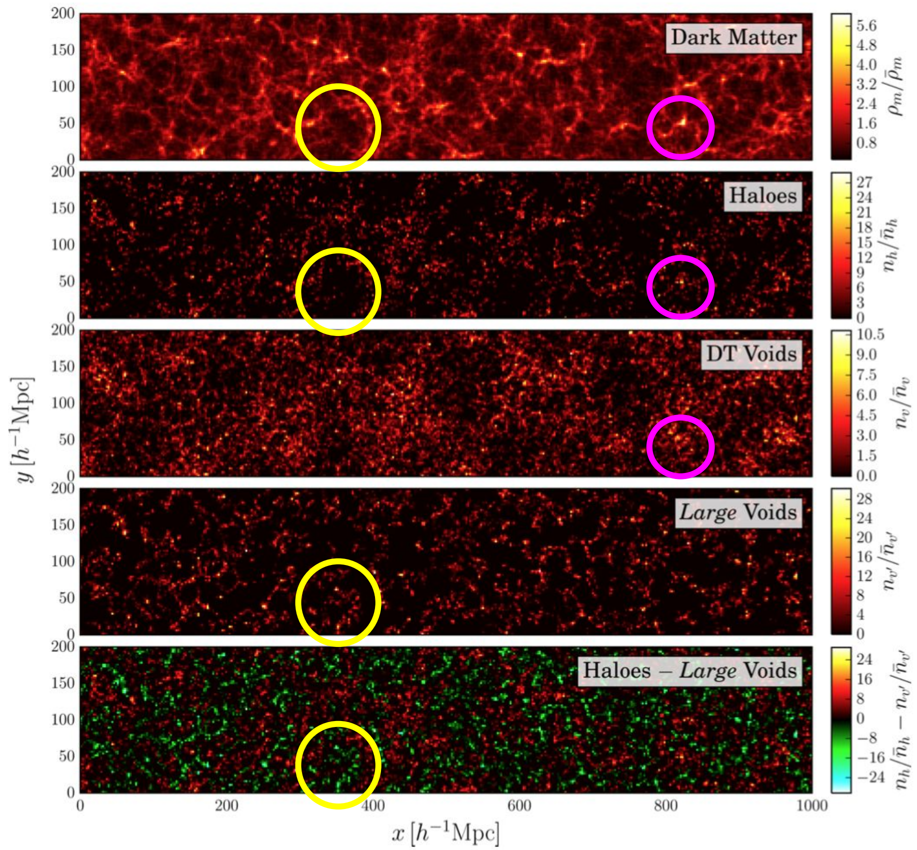
Galaxy Catalogue

DT Voids defined by their:
- centers
- radius

→ Allows overlapping

→ Larger statistics

Distribution of Voids



Two void populations:

- Void-in-clouds: small voids

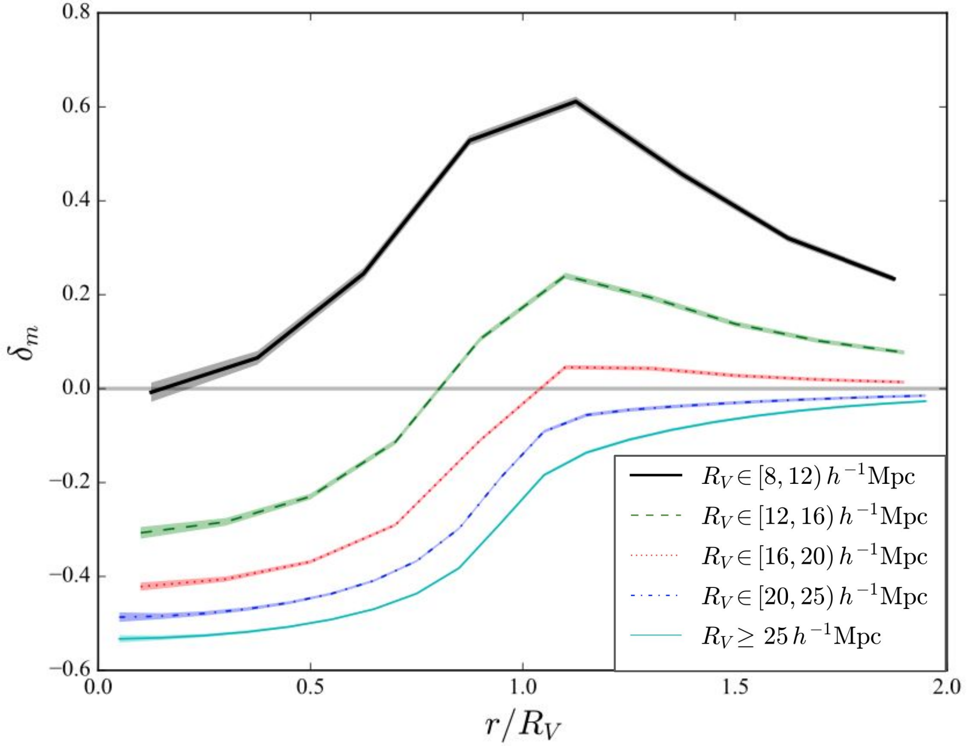
→ Follow halo distribution

- Void-in-voids: large voids

→ Follow underdensities

Radius Dependency

DTVoids Density Profiles



Two void populations:

- Void-in-clouds: small voids

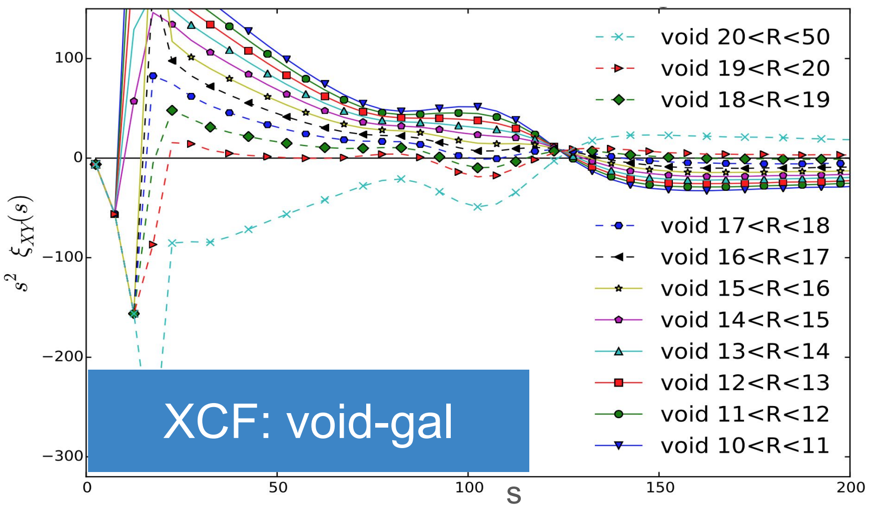
→ Follow underdensities

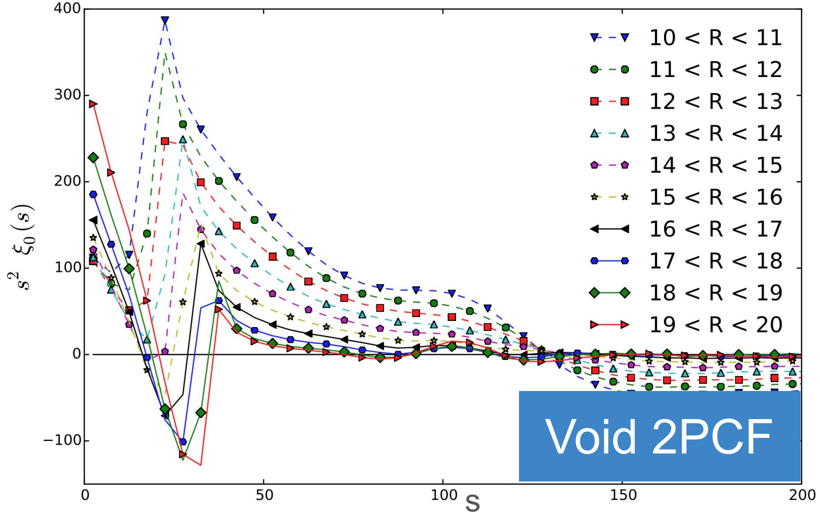
- Void-in-voids: large voids

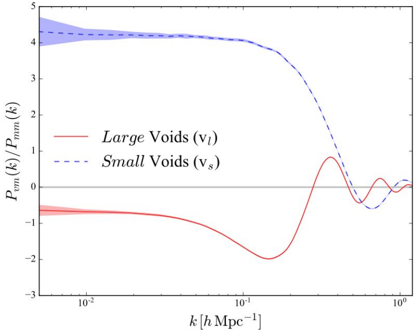
→ Follow halo distriubtion

Distinguishable by their radius

Void Correlations



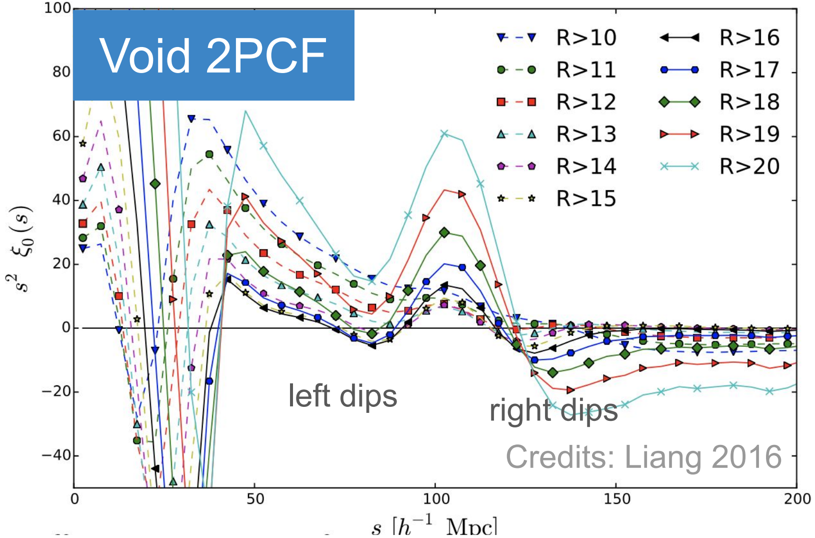


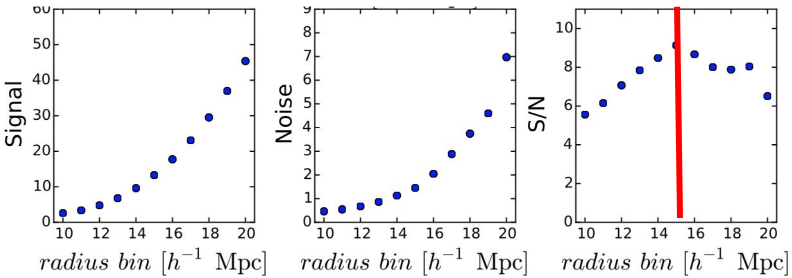


→ Small voids: positive bias

Large voids: negative bias

Optimal Radius Selection





$$S_{\mathrm{BAO}} = \left| \xi(s_{\mathrm{peak}}) - \frac{\xi(s_{\mathrm{left}}) + \xi(s_{\mathrm{right}})}{2} \right|$$

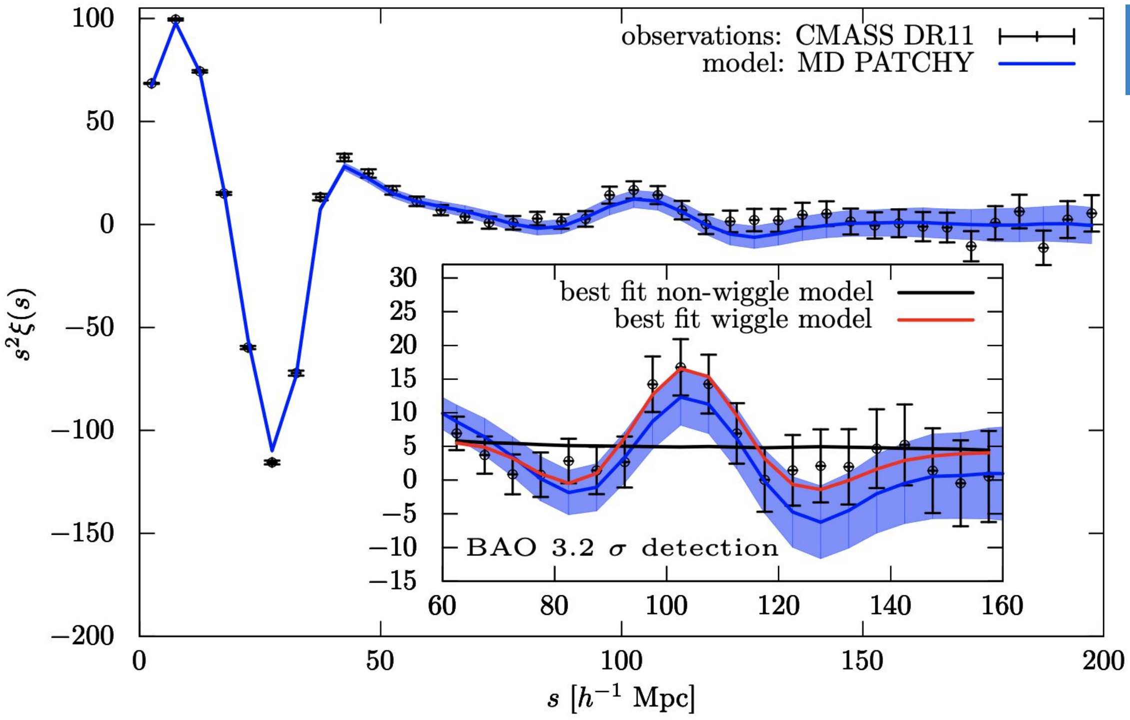
$$\mathrm{SNR} = \frac{\langle S \rangle}{\sigma_S}$$

$$\mathcal{V}_{\mathrm{large}} \equiv \{\mathrm{DT\ spheres} | R(\mathbf{s}) > R_c\}$$

→ Radius chosen to optimize BAO SNR

First BAO Detection with Voids

BOSS CMASS DR11

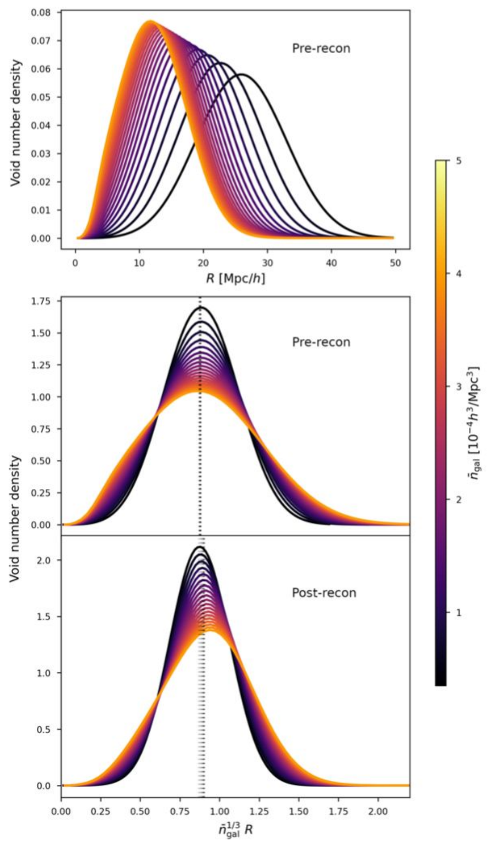


Void 2PCF

Rv > 16 Mpc/h

Credits: Kitaura 2016

Sensitivity to Number Density



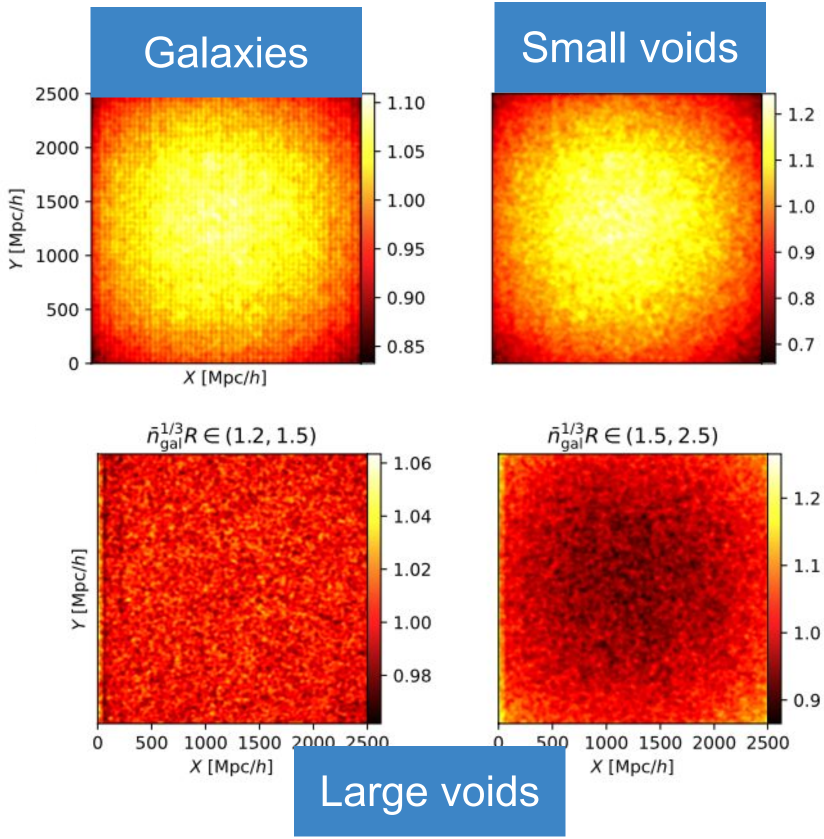
Tracer density: varies locally due to observational effects

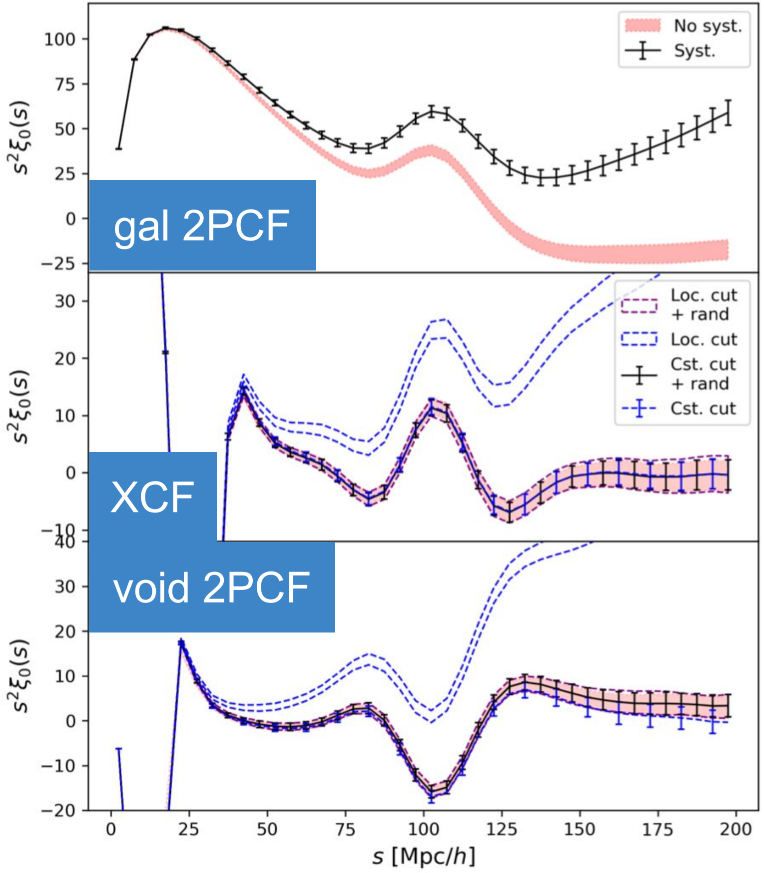
Underlying density field (cosmology, epoch)

DTVoids size function: depends on tracer density

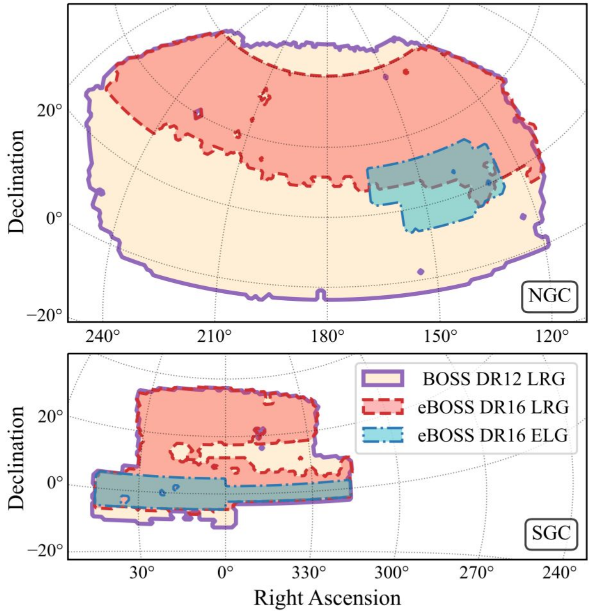
What is the impact on the clustering of voids?

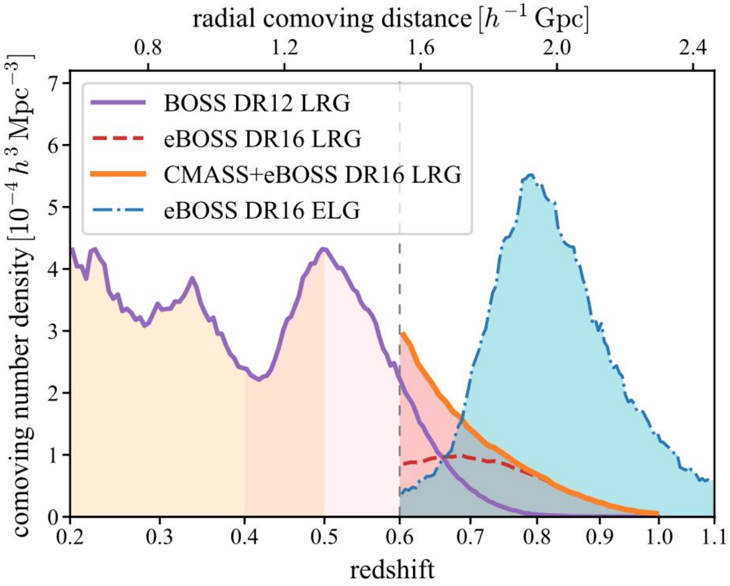
Sensitivity to Incompleteness





SDSS data: LRG and ELG samples





SAMPLES

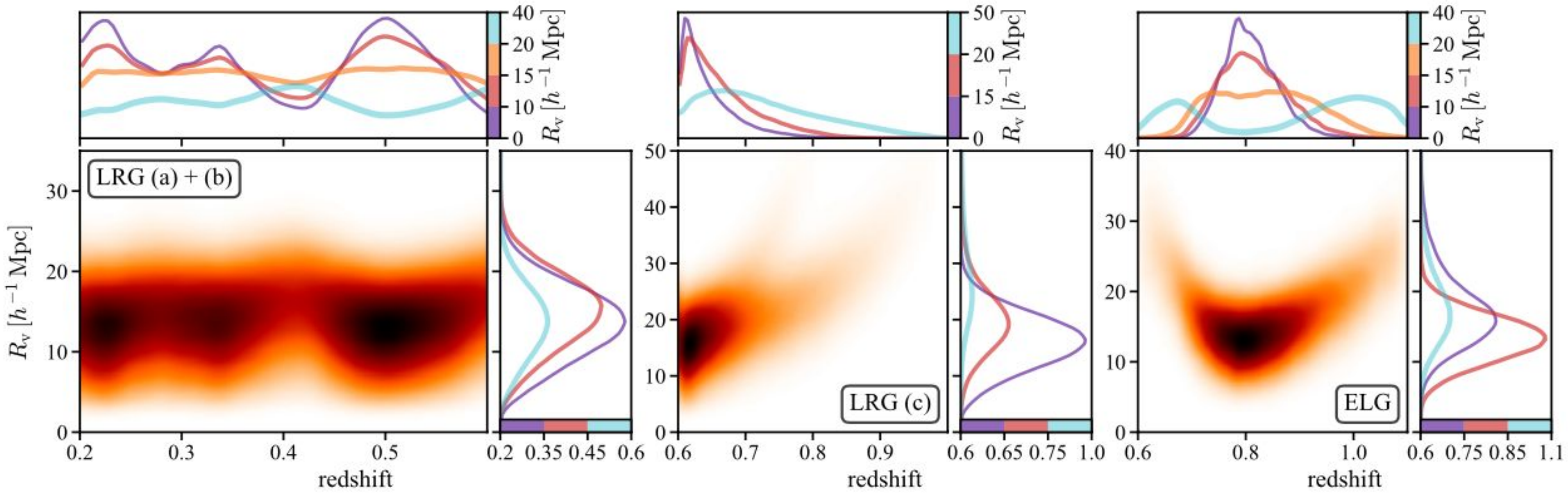
LRG (a): BOSS DR12 0.2<z<0.5

LRG (c): CMASS+eBOSS 0.6<z<1.0

LRG (b): BOSS DR12 0.4<z<0.6

ELG : eBOSS 0.6<z<1.1

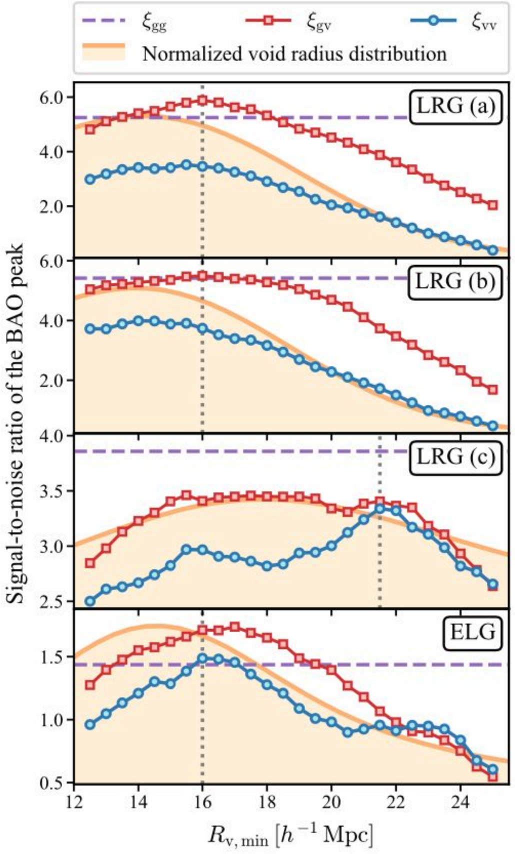
SDSS data: LRG and ELG Void samples



Void catalog obtained from post-reconstruction catalogs

SAMPLES		
	LRG (a): BOSS DR12 0.2<z<0.5	LRG (c): CMASS+eBOSS 0.6<z<1.0
	LRG (b): BOSS DR12 0.4<z<0.6	ELG : eBOSS 0.6<z<1.1

LRGs/ELGs: Optimal Radius



Sample	Redshift range	z_{eff}	Galactic cap	N_{gal}
LRG (a) *(BOSS DR12)*	(0.2, 0.5)	0.38	NGC	429182
			SGC	174819
			Total	**604001**
LRG (b) *(BOSS DR12)*	(0.4, 0.6)	0.51	NGC	500872
			SGC	185498
			Total	**686370**
LRG (c) *(CMASS+eBOSS DR16)*	(0.6, 1.0)	0.70	NGC	255741
			SGC	121717
			Total	**377458**
ELG *(eBOSS DR16)*	(0.6, 1.1)	0.85	NGC	83769
			SGC	89967
			Total	**173736**

x2

Sample	$(R_{v,\min}, R_{v,\max})$ (h^{-1} Mpc)	Galactic cap	N_{void}^{raw}	N_{void}
LRG (a)	(16, 40)	NGC	2639522	902637
		SGC	1047500	317737
		Total	**3687022**	**1220374**
LRG (b)	(16, 40)	NGC	3107491	995763
		SGC	1130310	359202
		Total	**4237801**	**1354965**
LRG (c)	(21.5, 40)	NGC	1485650	551265
		SGC	697680	243530
		Total	**2183330**	**794795**
ELG	(16, 40)	NGC	370356	172208
		SGC	362127	149988
		Total	**732483**	**322196**

remove
~60-70% voids

Multi-tracer BAO analysis: Two Approaches

Approach A

Fit multiple data vectors simultaneously

$$\left\{ \begin{array}{l} \xi_{gg} \\ \xi_{gv} \\ \xi_{vv} \end{array} \right\}$$

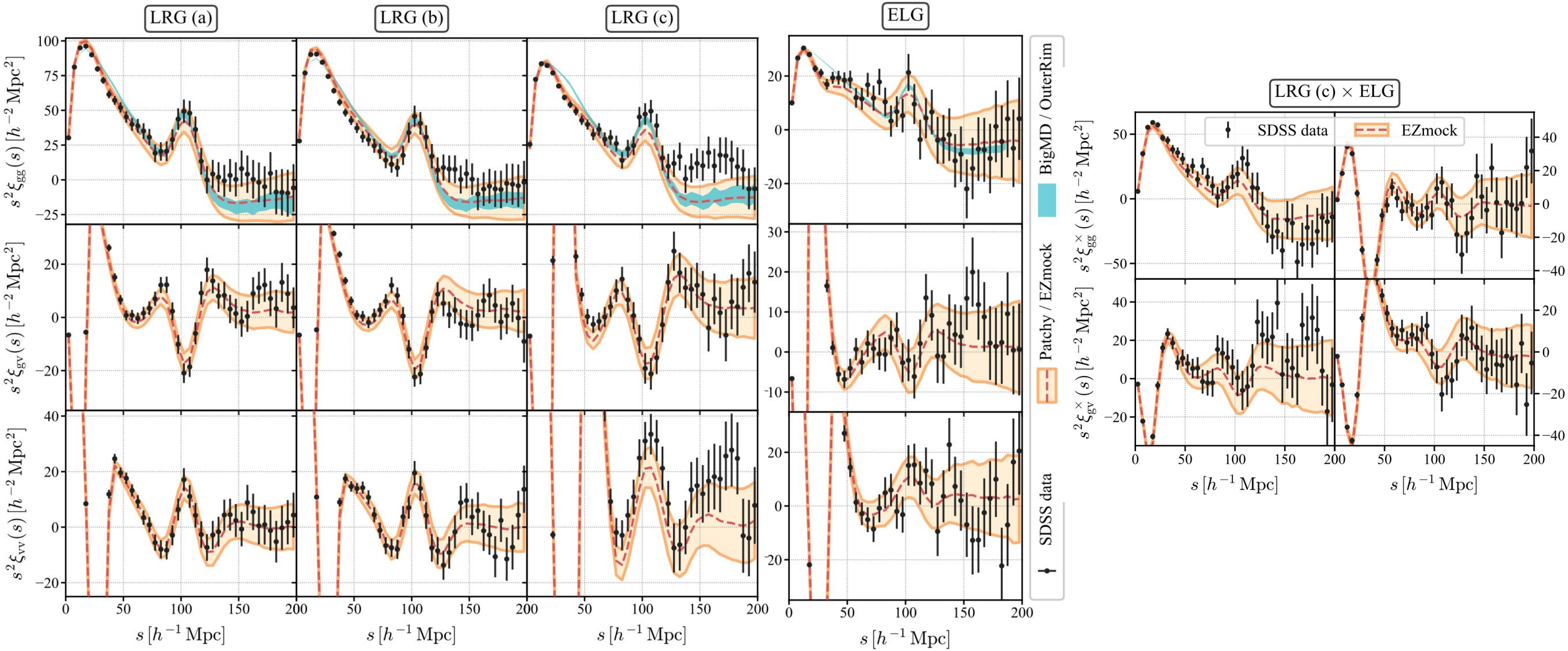
Approach B

Combine galaxies and voids by computing joint correlation function

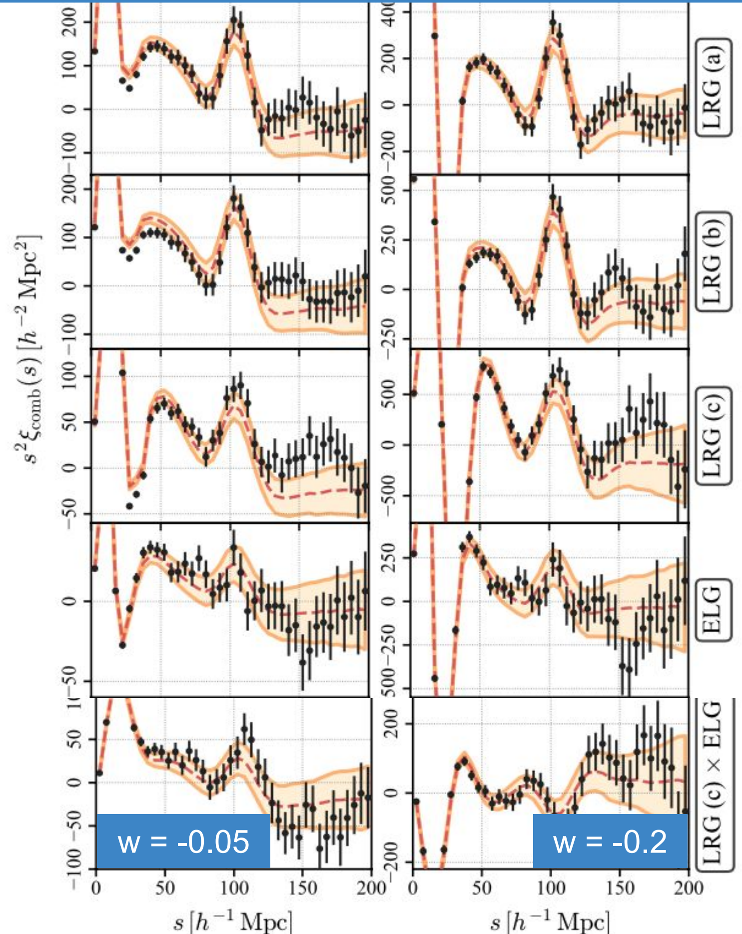
$$\xi_{\mathrm{comb}}(s) = \frac{n_g^2 \xi^{gg} R_g R_g + 2 n_g n_v w \xi^{gv} R_g R_v + n_v^2 w^2 \xi^{vv} R_v R_v}{n_g^2 R_g R_g + 2 n_g n_v w R_g R_v + n_v^2 w^2 R_v R_v}$$

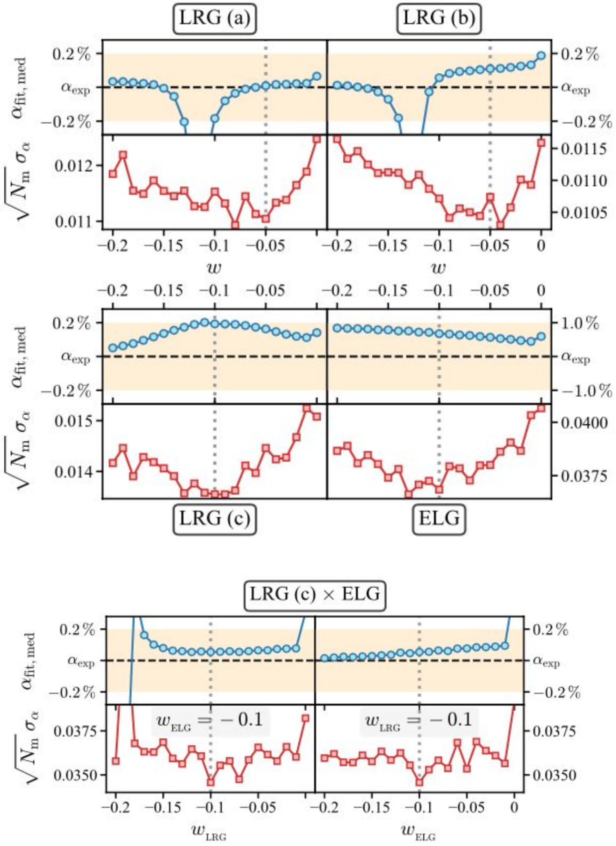
→ Constant weight

Multi-tracer BAO analysis: Approach A



Multi-tracer BAO analysis: Approach B





Void BAO model - Standard model

Typical dewiggled BAO power spectrum template:

$$P_{\mathrm{t,DW}}(k) = [P_{\mathrm{lin}}(k) - P_{\mathrm{lin,nw}}(k)]\mathrm{e}^{-k^2\Sigma_{\mathrm{nl}}^2/2} + P_{\mathrm{lin,nw}}(k)$$

Correlation:

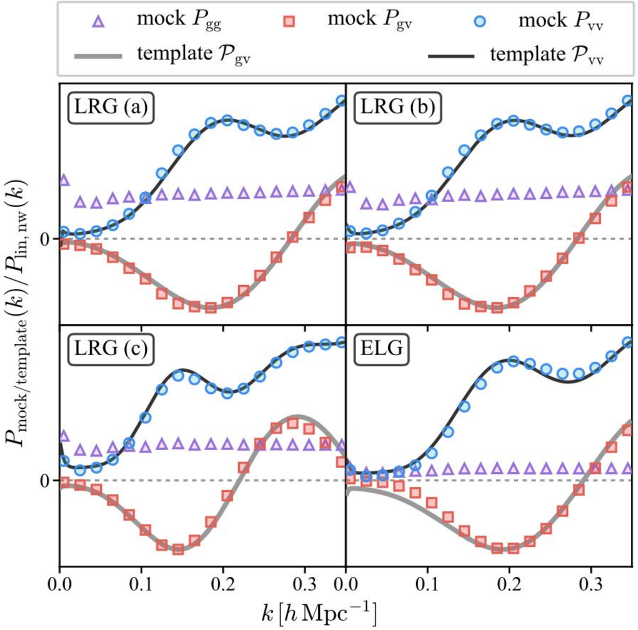
$$\xi_{\mathrm{temp}}(s) = \frac{1}{2\pi^2}\int P_{\mathrm{t,DW}}(k) j_0(ks) e^{-k^2a^2} k^2 dk$$

$$\xi_{\mathrm{m}}(s) = B\xi_{\mathrm{temp}}(\alpha s) + A_0 + A_1/s + A_2/s^2$$

Void BAO model - Voids

Typical dewiggled BAO power spectrum template:

$$P_{\mathrm{t,DW}}(k) = [P_{\mathrm{lin}}(k) - P_{\mathrm{lin,nw}}(k)]\mathrm{e}^{-k^2\Sigma_{\mathrm{nl}}^2/2} + P_{\mathrm{lin,nw}}(k)$$

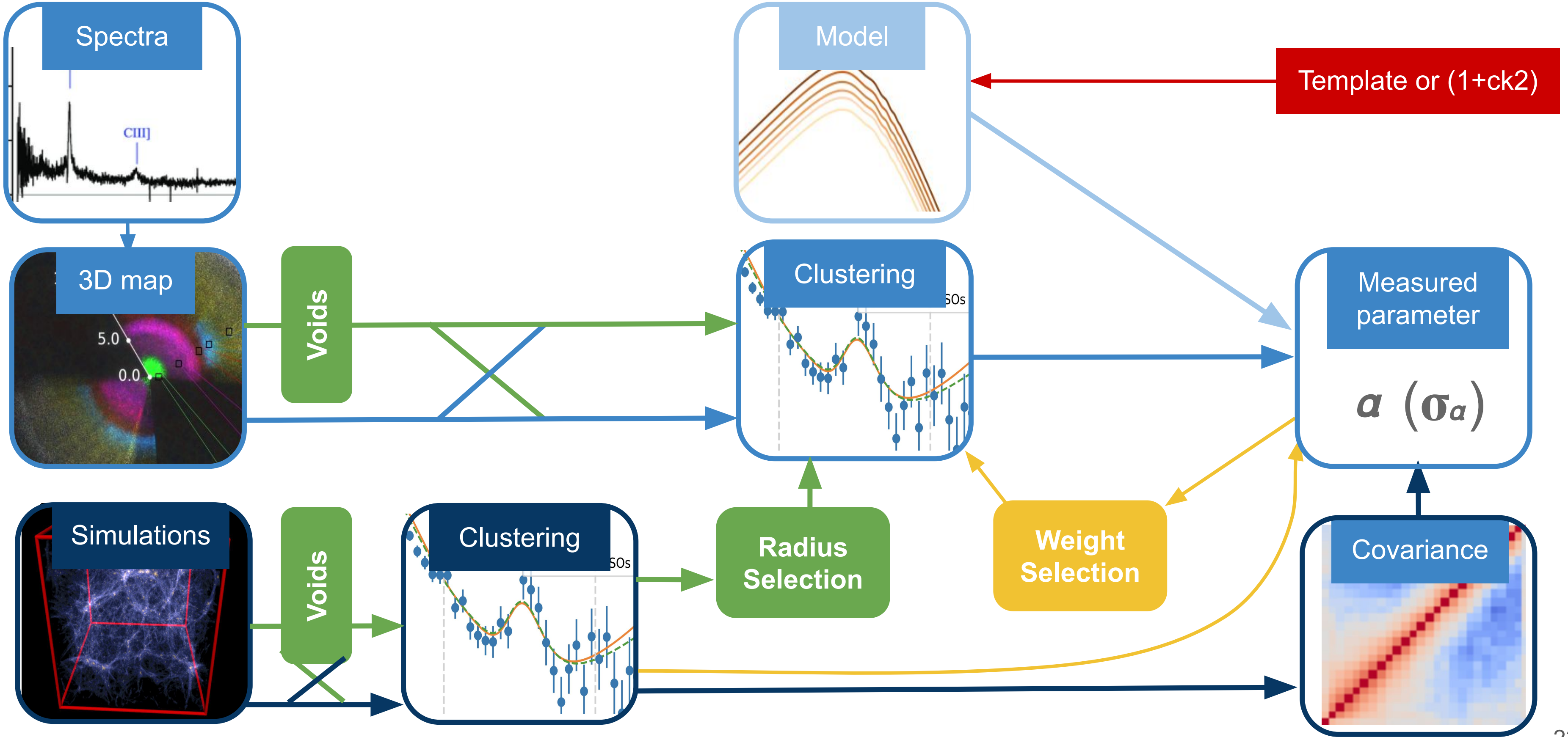


$$P_{\mathrm{t}}(k) = P_{\mathrm{t,DW}}(k) \times \boxed{\frac{P_{\mathrm{t,nw}}(k)}{P_{\mathrm{lin,nw}}(k)}}$$

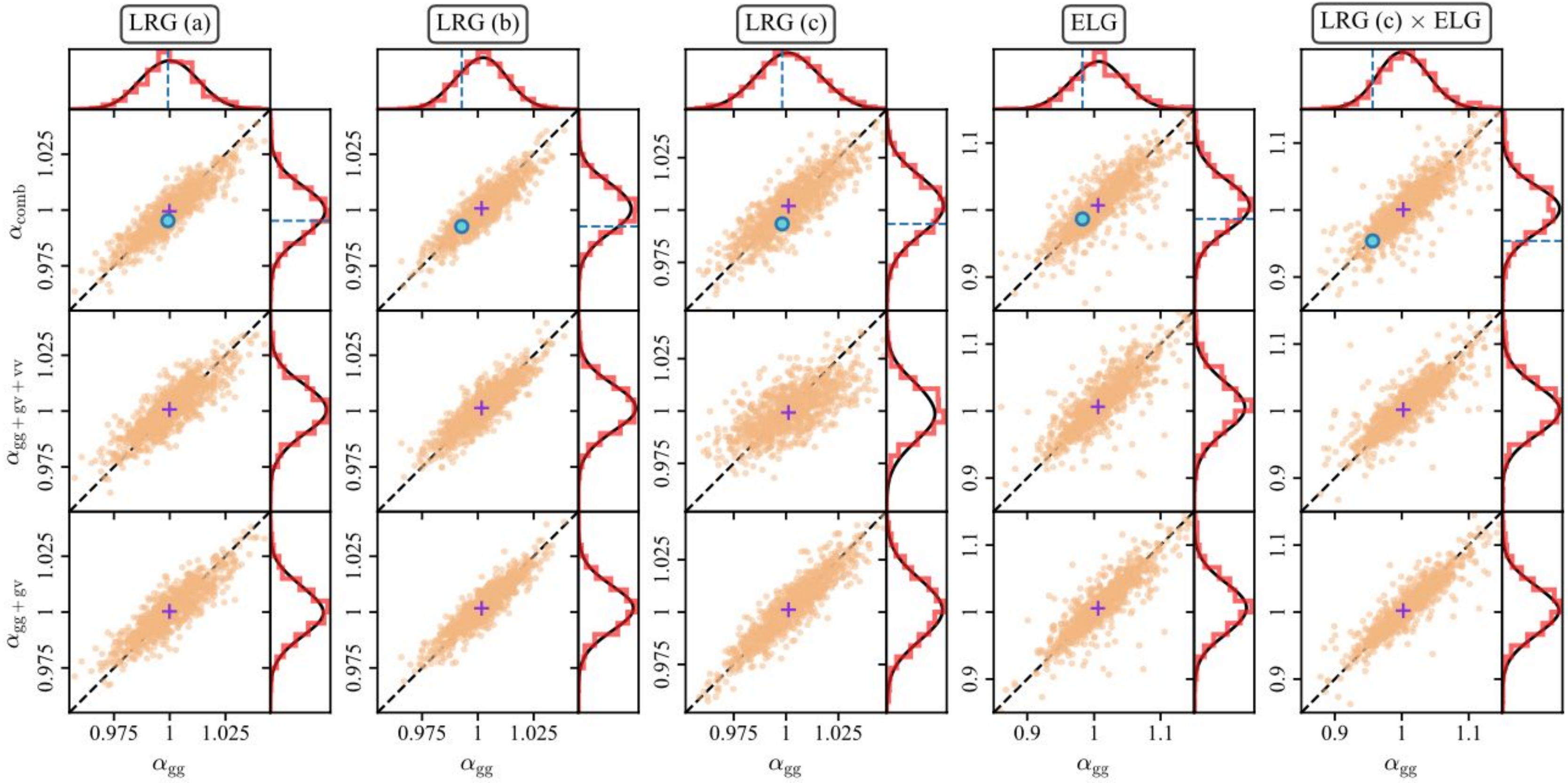
Template provided by mocks

~ (1+ck²)

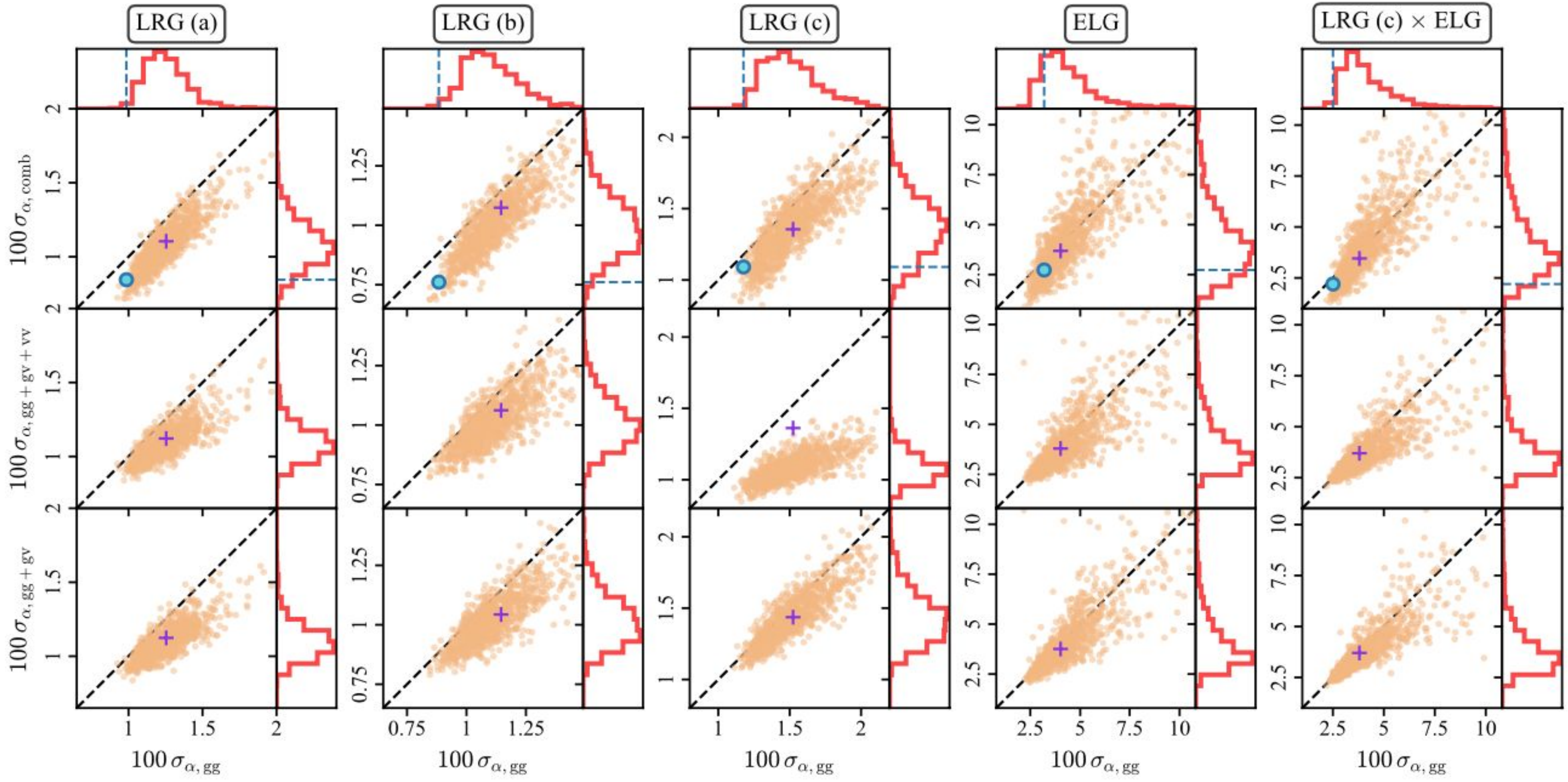
BAO Analysis Pipeline



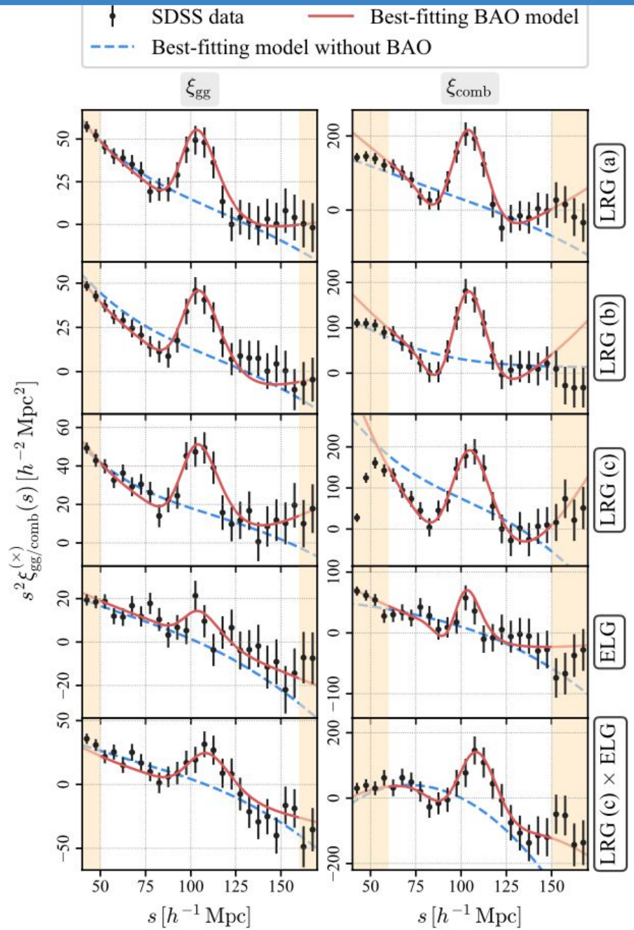
LRGs/ELGs: Results - Best-fitting alpha



LRGs/ELGs: Results - Uncertainty



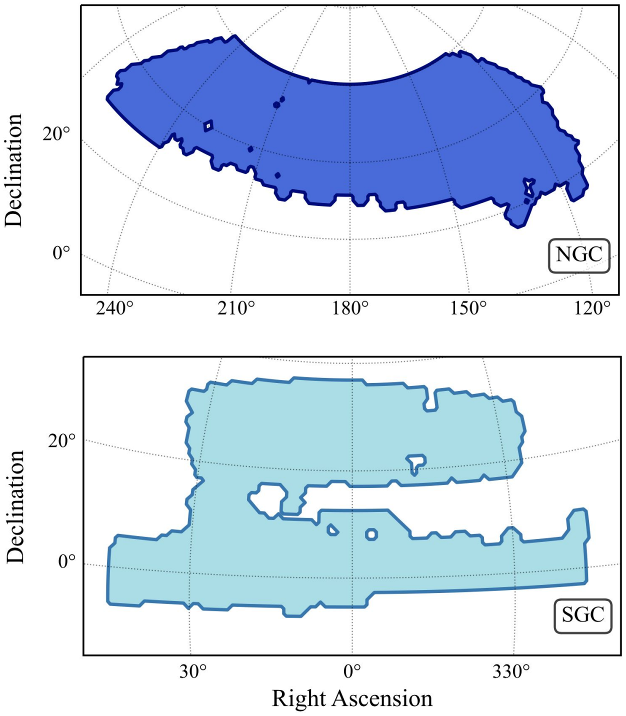
LRGs/ELGs: Results - Data

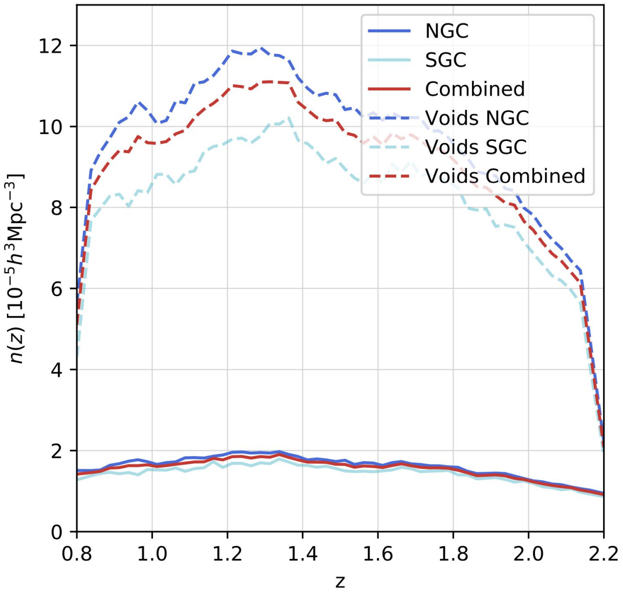


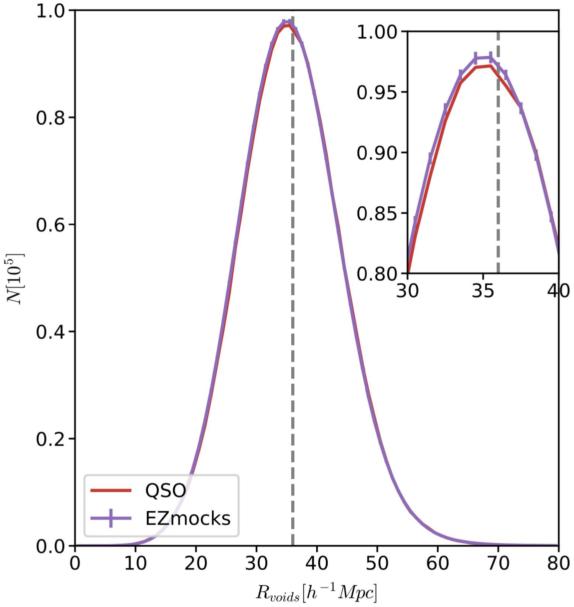
Sample	Data vector	$\alpha_{\rm fit}$	$\sigma_{\alpha,\rm syst}$
LRG (a)	$\{\xi_{\rm gg}\}$	$0.9992^{+0.0100}_{-0.0097}$	0.0009
	$\{\xi_{\rm comb}\}$	$0.9952^{+0.0083}_{-0.0086}$	0.0005
LRG (b)	$\{\xi_{\rm gg}\}$	$0.9928^{+0.0088}_{-0.0089}$	0.0021
	$\{\xi_{\rm comb}\}$	$0.9927^{+0.0076}_{-0.0076}$	0.0013
LRG (c)	$\{\xi_{\rm gg}\}$	$0.9982^{+0.0116}_{-0.0119}$	0.0013
	$\{\xi_{\rm comb}\}$	$0.9934^{+0.0110}_{-0.0109}$	0.0027
ELG	$\{\xi_{\rm gg}\}$	$0.9825^{+0.0321}_{-0.0318}$	0.0057
	$\{\xi_{\rm comb}\}$	$0.9867^{+0.0310}_{-0.0236}$	0.0069
LRG (c) × ELG	$\{\xi^{\times}_{\rm gg}\}$	$0.9565^{+0.0254}_{-0.0246}$	0.0022
	$\{\xi^{\times}_{\rm comb}\}$	$0.9539^{+0.0228}_{-0.0212}$	0.0010

Improvement ranging from 5 to 15%

SDSS data: eBOSS QSO sample

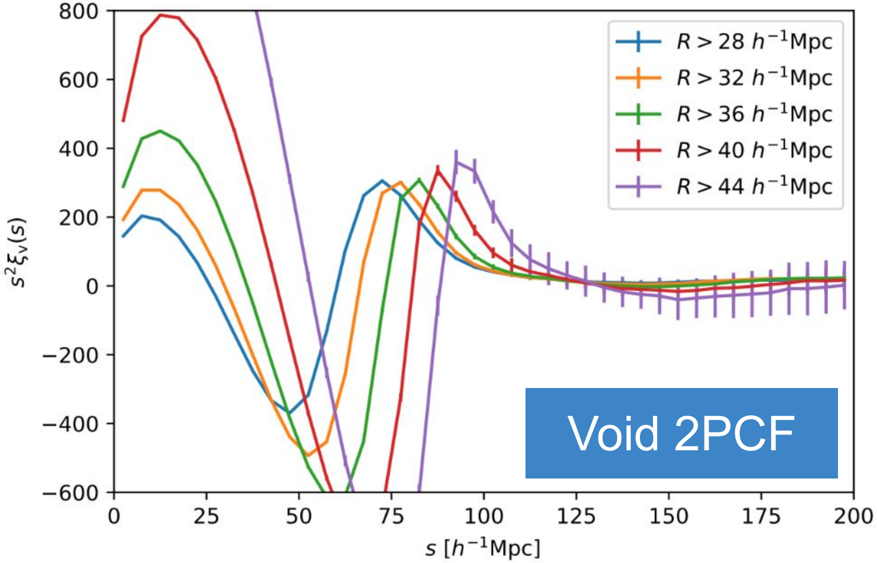


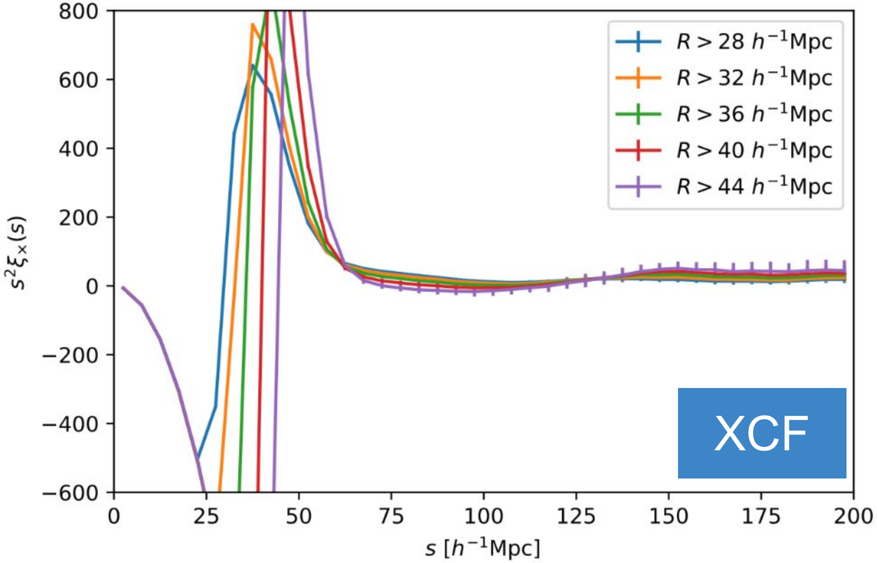




Low number density: an order of magnitude lower than for other SDSS tracers

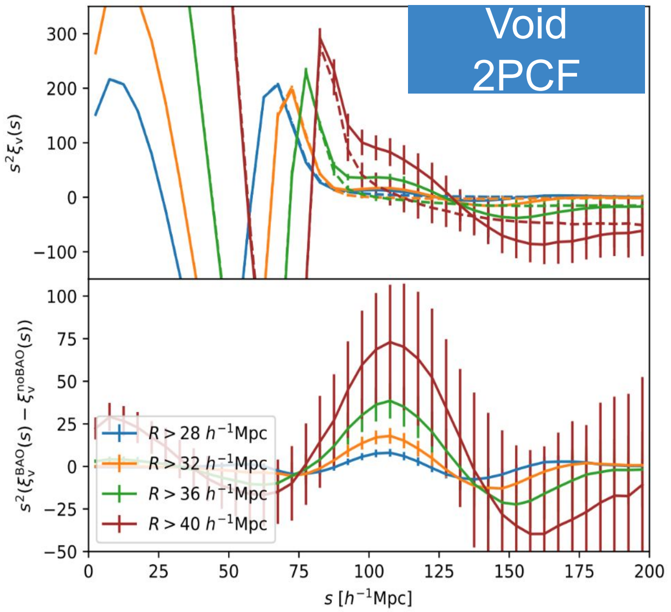
QSOs: Correlations of mocks

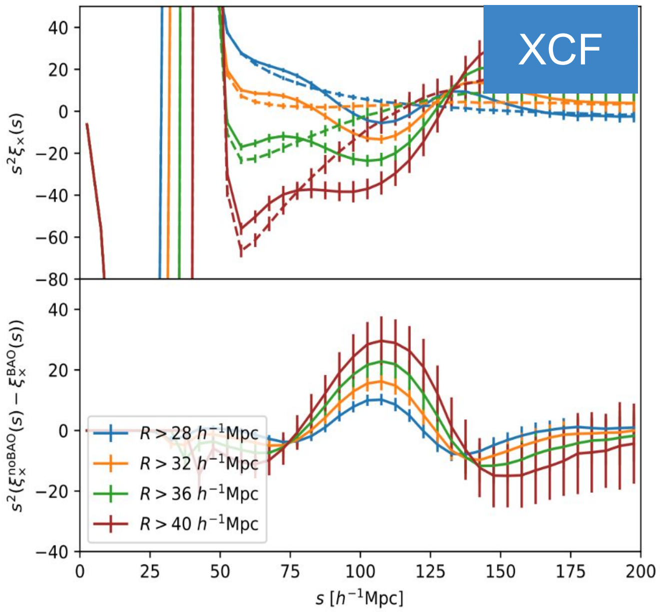


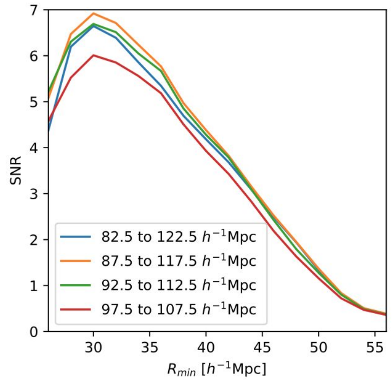


- Strong exclusion effect
- Difficult to understand the BAO signal
- Difficult to determine the best radius cut with SNR

QSOs: Void Optimal Radius

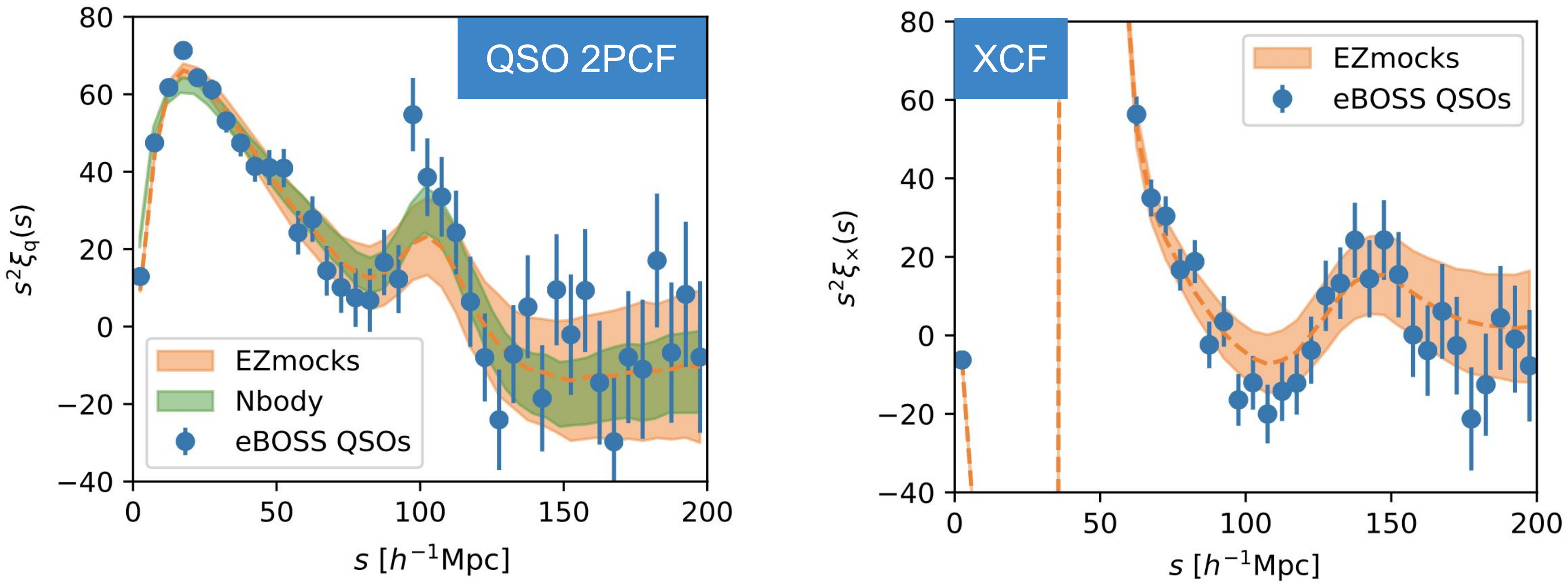






- Creation mocks **with** and **without** BAO wiggles
- Selection of optimal radius cut to enhance BAO SNR using the difference between the two kind of mocks

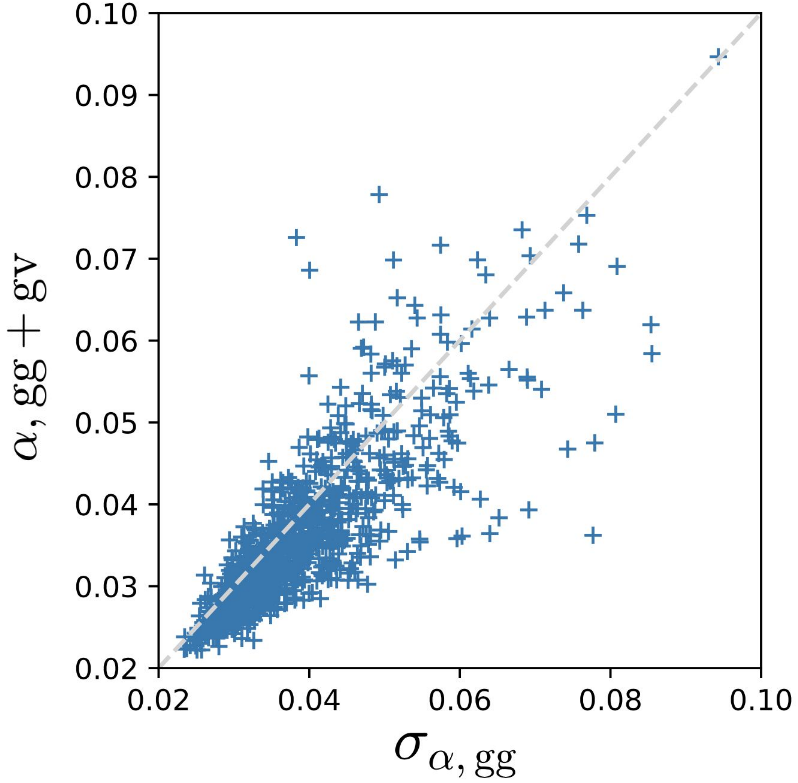
QSOs: Data Correlations



For the BAO analysis the XCF is used jointly with the QSOs 2PCF

Rmin is 36 Mpc/h

QSOs: Results - EZmocks

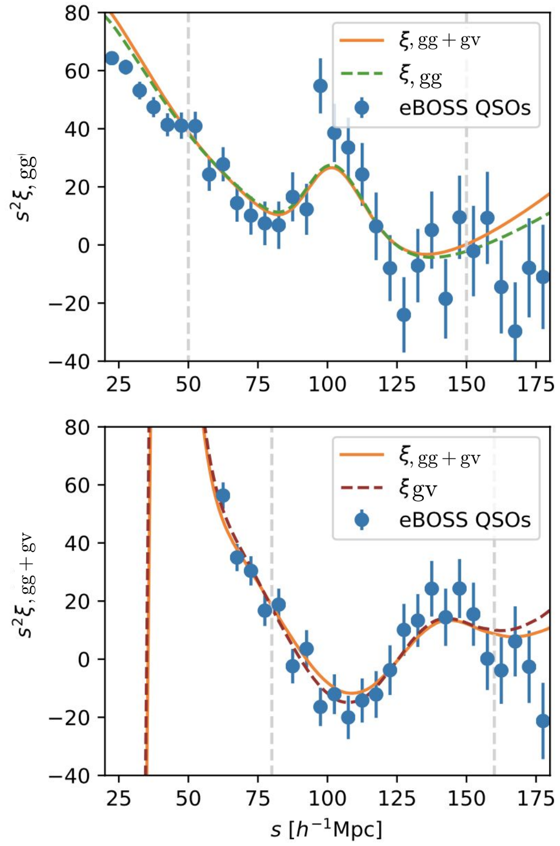


Joint fit 2PCF and XCF with template model compared to 2PCF alone:

- 5.41% average error improvement
- Improvement for 71.6% of the EZmocks

→ Similar results for DESI volume-like mocks

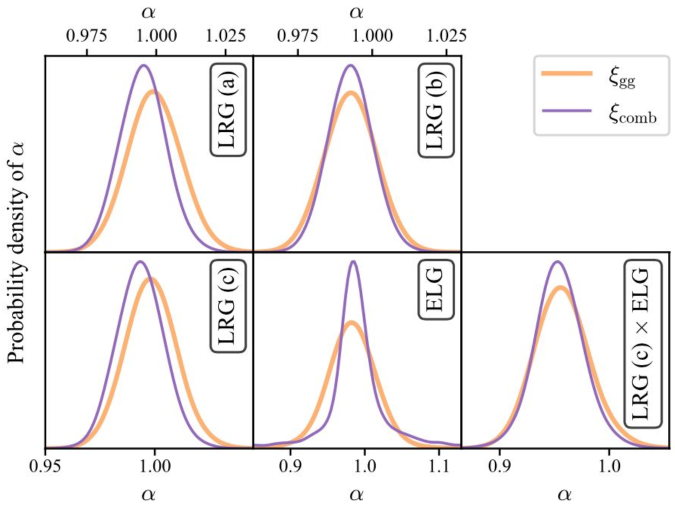
QSOs: Results - Data



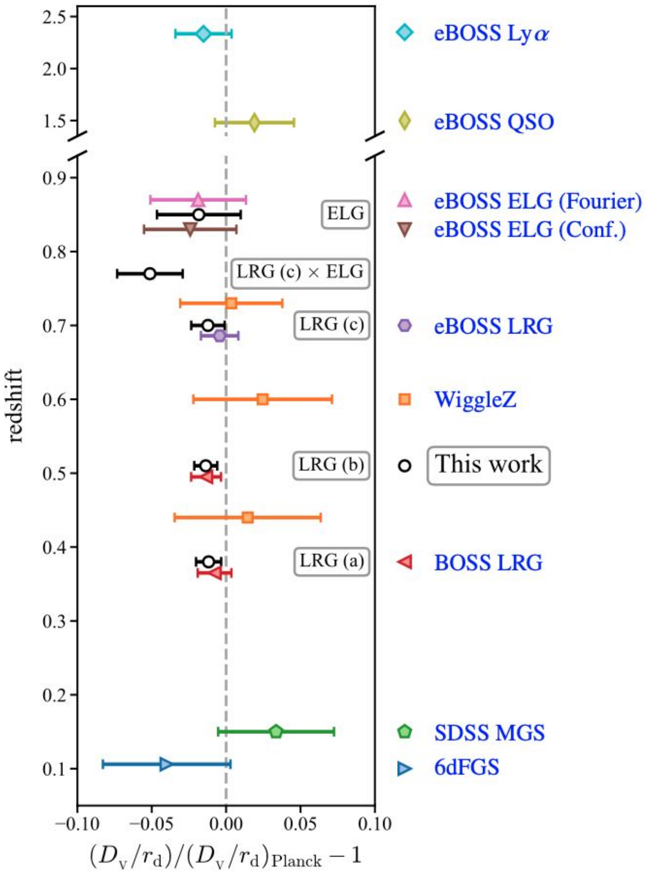
	α_{fit}	$D_V(z = 1.48)/r_s$
ξ, gg	$1.0172^{+0.0207}_{-0.0201}$	26.298 ± 0.547
ξ, gg + gv	$1.0171^{+0.0212}_{-0.0196}$	26.297 ± 0.547

- No improvement due to cosmic variance
- Subsampling the dataset recovers mocks statistics

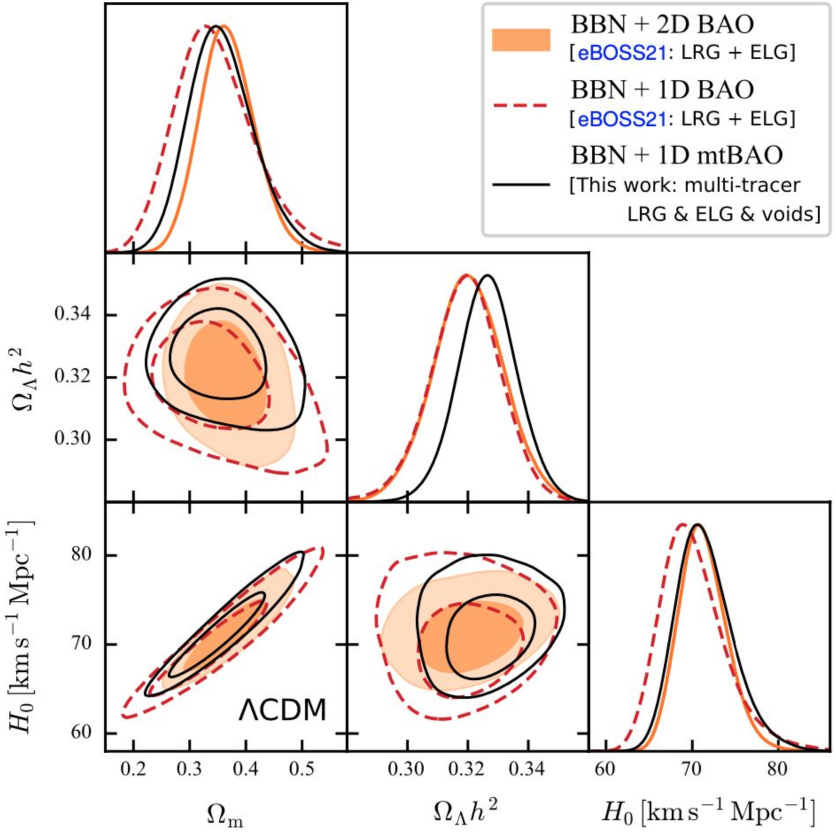
Cosmology Constraints from SDSS Voids

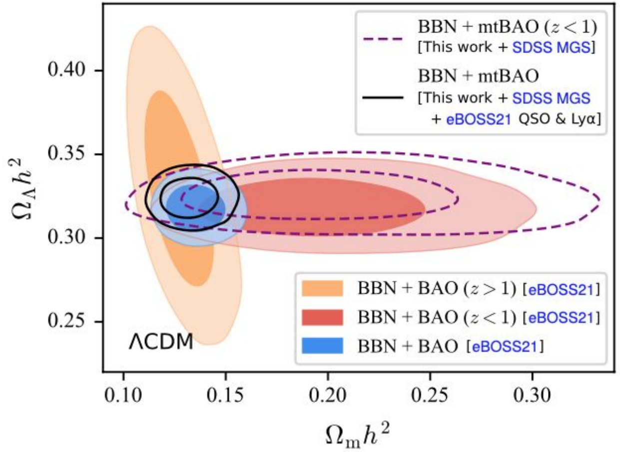


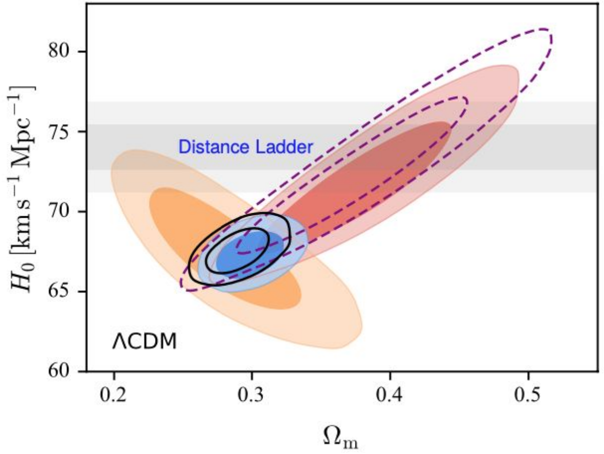
Sample	z_{eff}	ξ_{gg} D_V/r_d	ξ_{comb} D_V/r_d	ξ_{comb} Precision
LRG (a)	0.38	9.98 ± 0.10	9.94 ± 0.08	0.9 %
LRG (b)	0.51	12.67 ± 0.12	12.67 ± 0.10	0.8 %
LRG (c)	0.70	16.25 ± 0.19	16.17 ± 0.18	1.1 %
LRG (c) × ELG	0.77	16.67 ± 0.44	16.63 ± 0.39	2.3 %
ELG	0.85	18.33 ± 0.61	18.41 ± 0.53	2.9 %



Cosmology Constraints from SDSS Voids







Future work

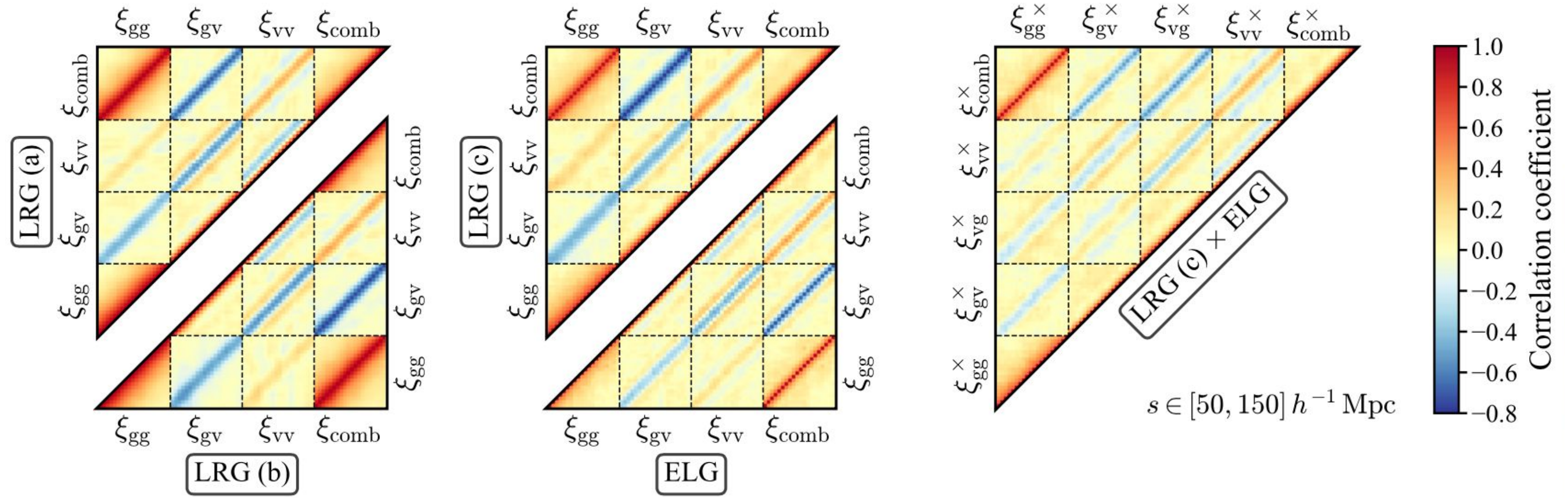
- DESI data
- Anisotropic distance measurements (2D alphas)
- Model improvement with theoretically modelling sphere exclusion

2021 - 2026
+30 M spectra

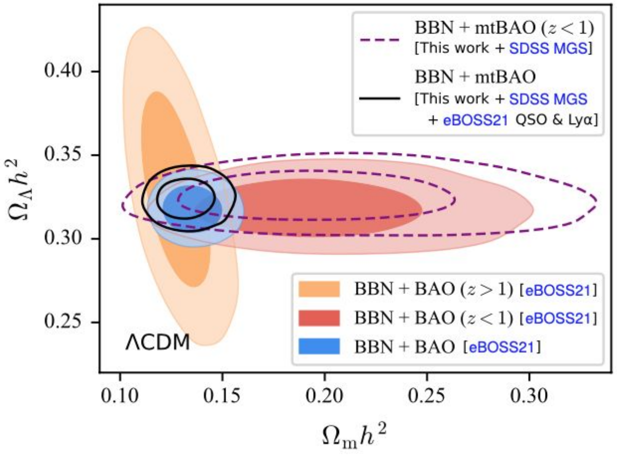
Summary

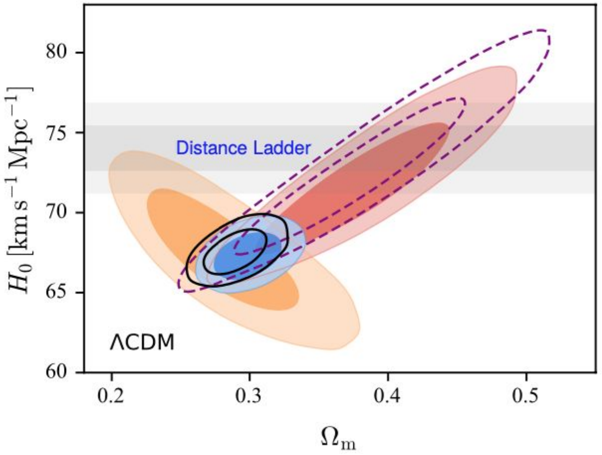
- BAO measurements from cosmic voids defined geometrically as empty spheres with a radius threshold as one more free parameter for under-densities selection
- Cosmic voids are robust to unknown sources of small incompleteness
- For most cases two multi-tracer approaches yield similar results
- Statistically voids contribute to ~10% improvement on BAO constraints for LRG and ELG post-reconstruction
- Statistically voids contribute to ~5% improvement on BAO constraints on 70% of the cases for QSO (pre-reconstruction)
- Combining voids and SDSS galaxies leads to a 17% improvement on OLh2, and 6% for Om and H0 from a joint BBN+BAO constraint in flat-LCDM compared to SDSS galaxies+QSOs only

Multi-tracer BAO analysis: Covariances



Cosmology Constraints from SDSS Voids





Model	Probe	H_0 (km s^{-1} Mpc^{-1})	Ω_m	$\Omega_\Lambda h^2$
ΛCDM	BBN + BAO	67.35 ± 0.98	0.299 ± 0.016	0.3179 ± 0.0094
	BBN + mtBAO	67.58 ± 0.91	0.290 ± 0.015	0.3241 ± 0.0079
	CMB	67.29 ± 0.61	0.3164 ± 0.0084	0.3096 ± 0.0094
	CMB + BAO	67.60 ± 0.43	0.3119 ± 0.0058	0.3145 ± 0.0066
	CMB + mtBAO	67.96 ± 0.39	0.3070 ± 0.0051	0.3201 ± 0.0060
	Distance ladder	74.0 ± 1.4	–	–
	Distance Ladder + BAO	74.0 ± 1.4	0.299 ± 0.016	0.384 ± 0.017
	Distance Ladder + mtBAO	74.0 ± 1.4	0.290 ± 0.015	0.390 ± 0.017