Precision cosmology with voids in the final BOSS data

Alice Pisani

Papers and collaborators:

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.
Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP
Pisani, Massara, Spergel et al. 2019; ArXiv: 1903.05161
Hamaus, Cousinou, Pisani, Aubert, Escoffier, Weller 2017; ArXiv: 1705.05328 JCAP
Hamaus, Pisani, Sutter, Lavaux, Escoffier, Wandelt, Weller 2016; ArXiv: 1602.01784 PRL
Pisani, Lavaux, Sutter, Wandelt 2014; ArXiv: 1306.3052 MNRAS
Lavaux & Wandelt 2011; ArXiv: 1110.0345 ApJ
Ryden, B. S. 1995, ApJ, 452, 25

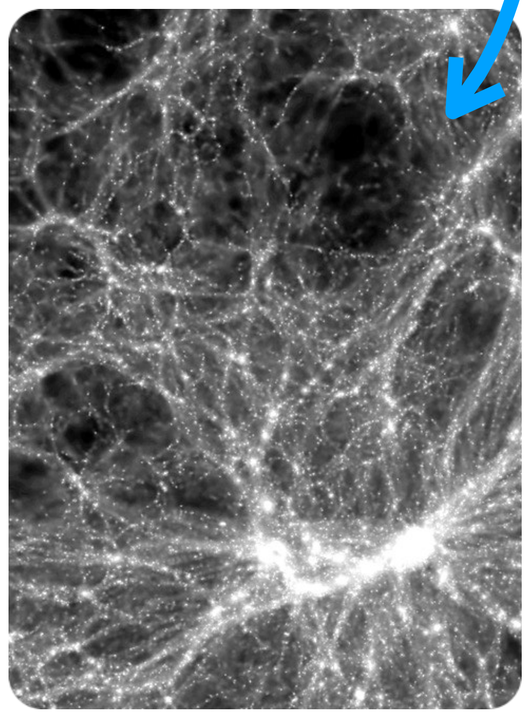
PRINCETON UNIVERSITY

Outline

- Voids for cosmology ?
- The void-galaxy cross-correlation function
- Constraints so far and recent results

Why are voids great for cosmology?

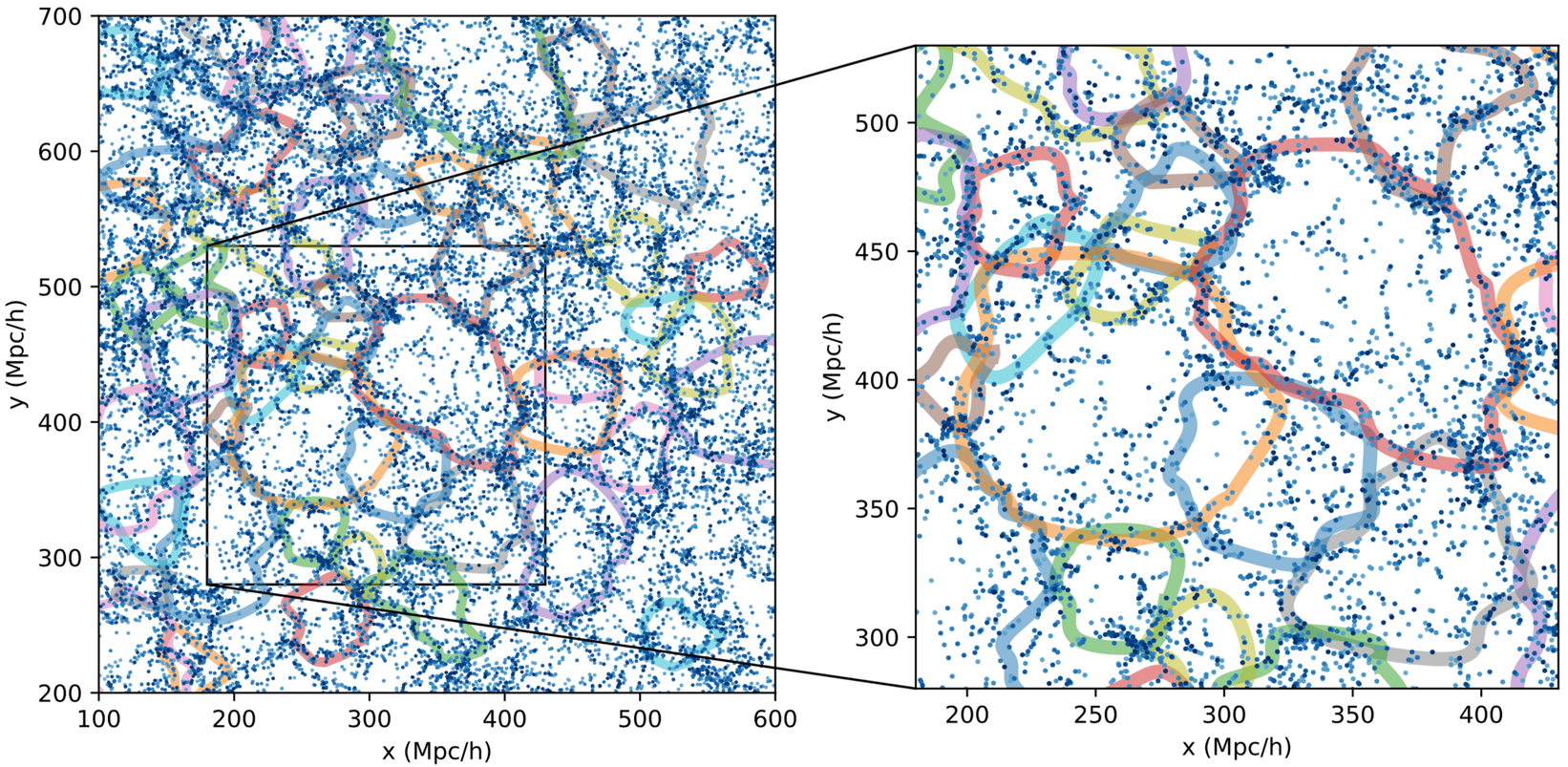
- By definition **dark energy** dominated objects (first regions to be dominated)
- Low density + large scale= mimic current accelerated expansion status
- Sweet spot: potential deviations from **General Relativity** more prominent
- Generically sensitive to diffuse components (Σm_ν)
- Allow to go beyond 2 pt correlation function
- **Multi-scale** sensitivity (span sizes from 10-100 Mpc/h)
- easier to modeling (exploit traditional GC techniques)



Void definition

- Voronoi tessellation + watershed transform = VIDE
- Provides void detailed shape, takes mask into account
- Widely used: BOSS (DR7, DR10, DR11, DR12), eBOSS (DR14), DES, Euclid, Roman, PFS, DESI

https://bitbucket.org/cosmicvoids/vide_public/src/master/, Sutter et al. 2015 A&C



Understand the void finder

=> ensure suitability for observed quantity, enhances S/N, **tested**

Verza, Pisani, Carbone, Hamaus, Guzzo 2019; ArXiv: 1906.00409 JCAP

What quantities do we measure to extract cosmological information ?

We have void centers, void radii, and tracers!

Void-galaxy cross-correlation function $\xi_{\rm vg}$

Void size function $N_{\rm v}$

Void-void correlation function $\xi_{\rm vv}$

What quantities do we measure to extract cosmological information ?

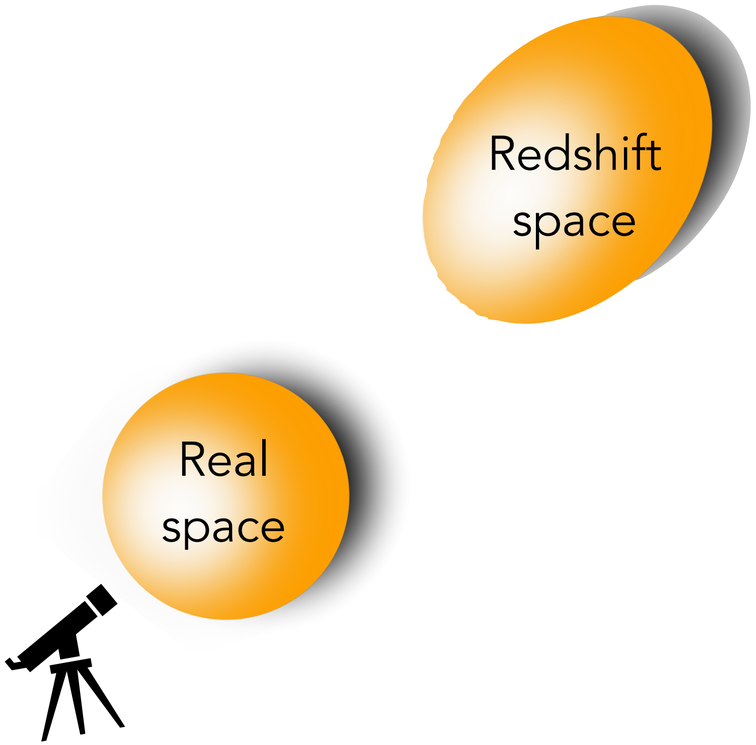
We have void centers, void radii, and tracers!

Void-galaxy cross-correlation function	$\xi_{\rm vg}$
Void size function	$N_{\rm v}$
Void-void correlation function	$\xi_{\rm vv}$

The void-galaxy cross-correlation function $\xi_{\rm vg}$

Void stacks are **spherically symmetric** => tool for cosmology

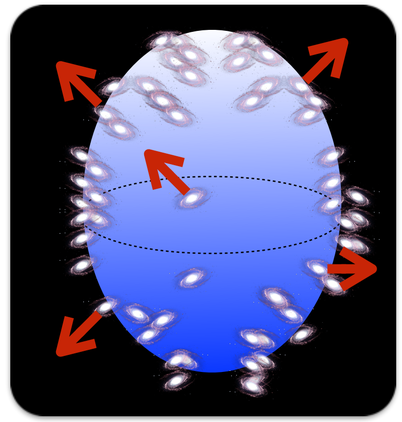
Observed shape = the relationship between angular diameter distance and redshift (Alcock-Paczynski test) + redshift-space distortions (**RSD**) (deviation from the Hubble flow)



$$c\Delta z = H(z) r_{\parallel}$$
$$r_{\perp} = D_A(z)\Delta\theta$$
$$r_{\perp} = r_{\parallel}$$

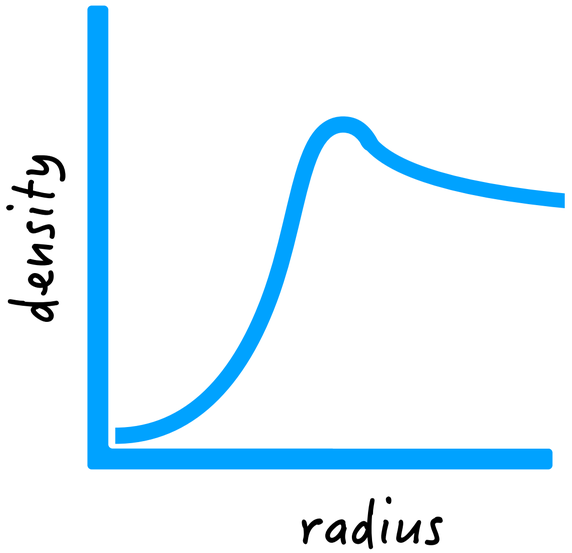
$$\frac{c\Delta z}{\Delta\theta} = D_A(z)H(z)$$

$$\varepsilon = \frac{[D_A(z)H(z)]_{\rm meas}}{[D_A(z)H(z)]_{\rm fid}}$$



Lavaux & Wandelt 2011; ArXiv: 1110.0345 ApJ
Ryden, B. S. 1995, ApJ, 452, 25

The void-galaxy cross-correlation function ξ_{vg}



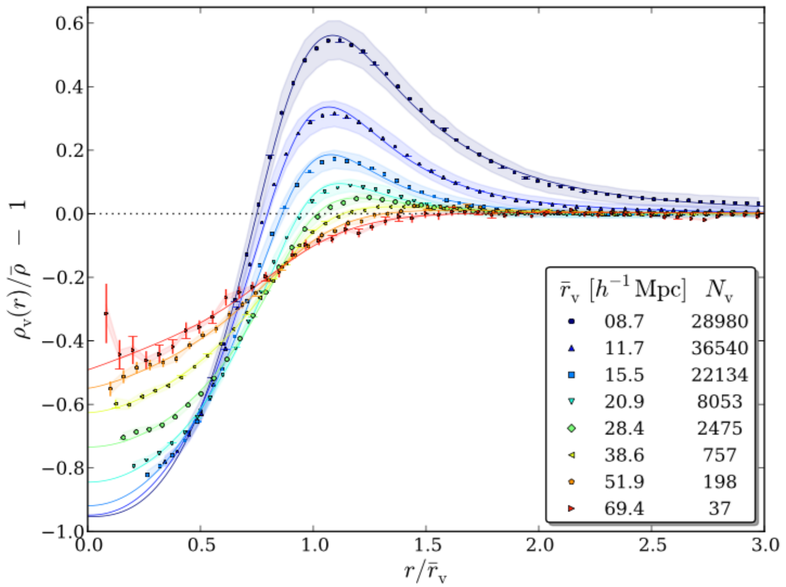
Ingredients { Density profile modeling
RSD modeling

The void-galaxy cross-correlation function $\xi_{\rm vg}$

Density profile modeling: No robust theoretical prediction, rely on commonly used prescriptions

Fitting function

Hamaus, Sutter, Wandelt 2014; ArXiv: 1403.5499 PRL

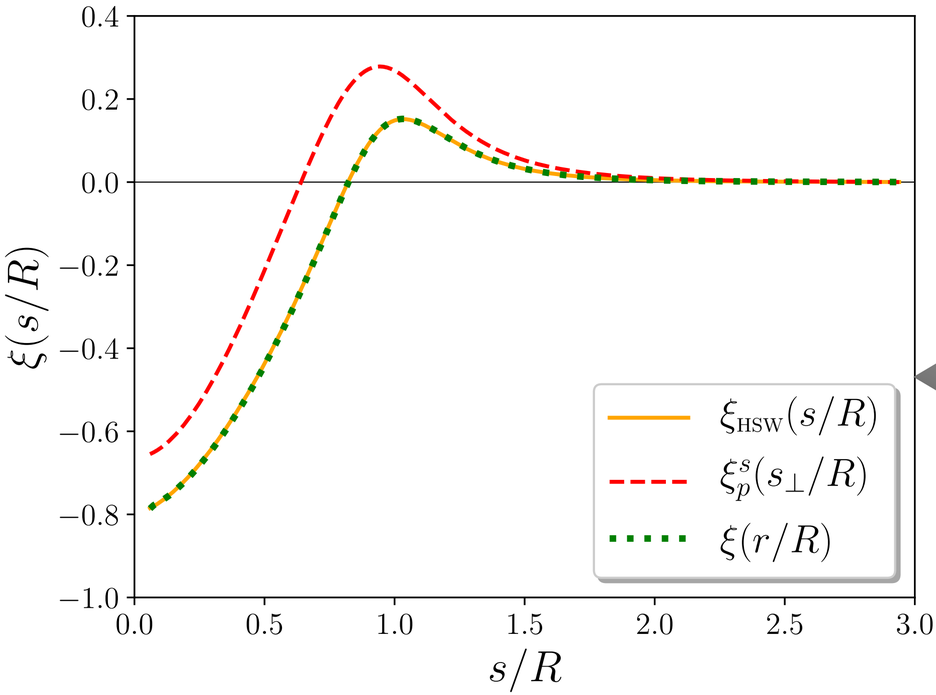


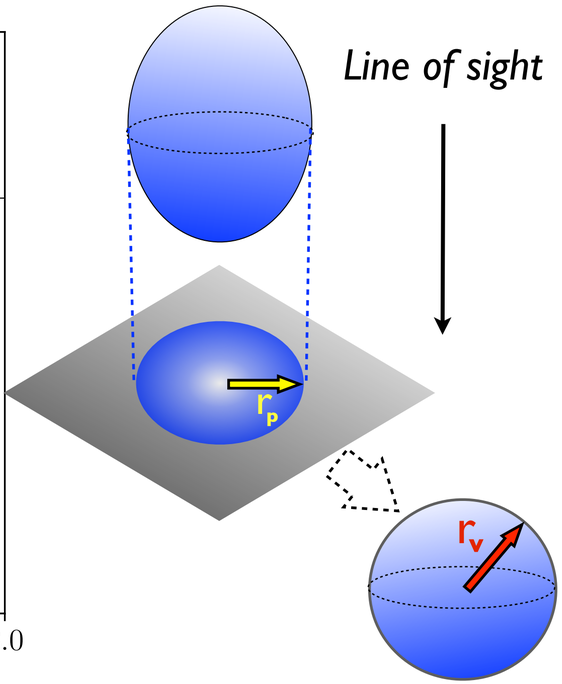
$$\frac{\rho_{\rm vm}(r)}{\bar{\rho}_{\rm m}} - 1 = \delta_c \frac{1-(r/r_s)^{\alpha}}{1+(r/r_{\rm v})^{\beta}}$$

density contrast
R : $\rho = \bar{\rho}$
slopes before/after wall
linear fxs of $r_s/r_{\rm v}$

Real-space density profile reconstruction (Abel inverse transform)

Pisani, Lavaux, Sutter, Wandelt 2014; ArXiv: 1306.3052 MNRAS
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP





RSD modeling

Very first papers in the field would try to mitigate the effect of peculiar velocities to measure the AP information.

…but velocities **embed** information!

$$\mathrm{v}(r) \simeq -\frac{1}{3}\frac{f(z)H(z)}{1+z} r\Delta(r)$$

P. J. E. Peebles, The large-scale structure of the universe (1980), mass conservation at linear order.

$$\Delta(r) = \frac{3}{r^3}\int_0^r \delta(r') r'^2 dr'$$

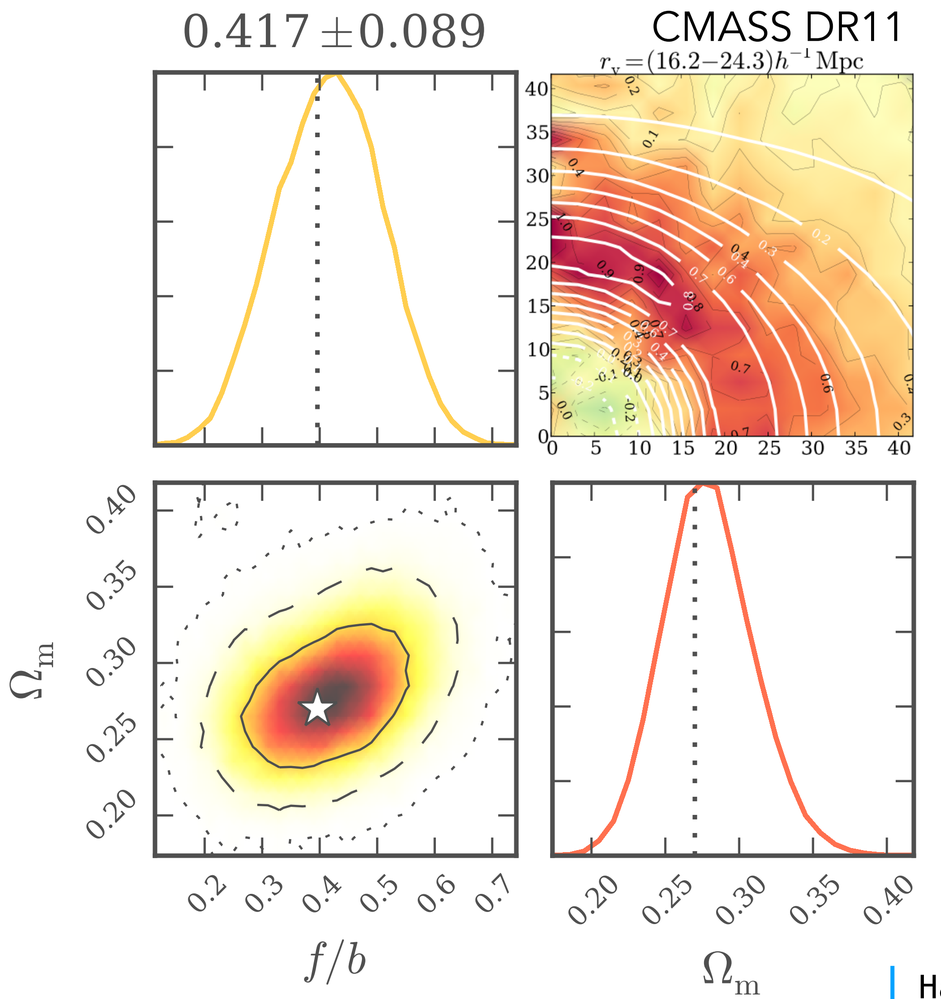
2 ``mainstream"prescriptions

both have been applied to data

RSD modeling with **Gaussian streaming model**

$$1+\xi^s(\mathbf{s}) = \int P(\mathbf{v},\mathbf{r})[1+\xi(\mathbf{r})]\mathrm{d}^3v = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_v(\mathbf{r})}\exp\left[-\frac{(v_\parallel - \mathrm{v}(r)\frac{r_\parallel}{r})^2}{2\sigma_v^2(\mathbf{r})}\right]\frac{\rho_\mathrm{v}(r)}{\bar{\rho}}\mathrm{d}v_\parallel$$

Gaussian probability distribution function for velocities
Gaussian streaming model, Fisher 1995



Constraints accuracy

Ω_m	11%
β	22%
$\mathcal{E}$	1.2%

Profile from fitting function and marginalization
Gaussian streaming model
RSD & AP

Hamaus, Pisani, Sutter, Lavaux, Escoffier, Wandelt, Weller 2016; ArXiv: 1602.01784 PRL

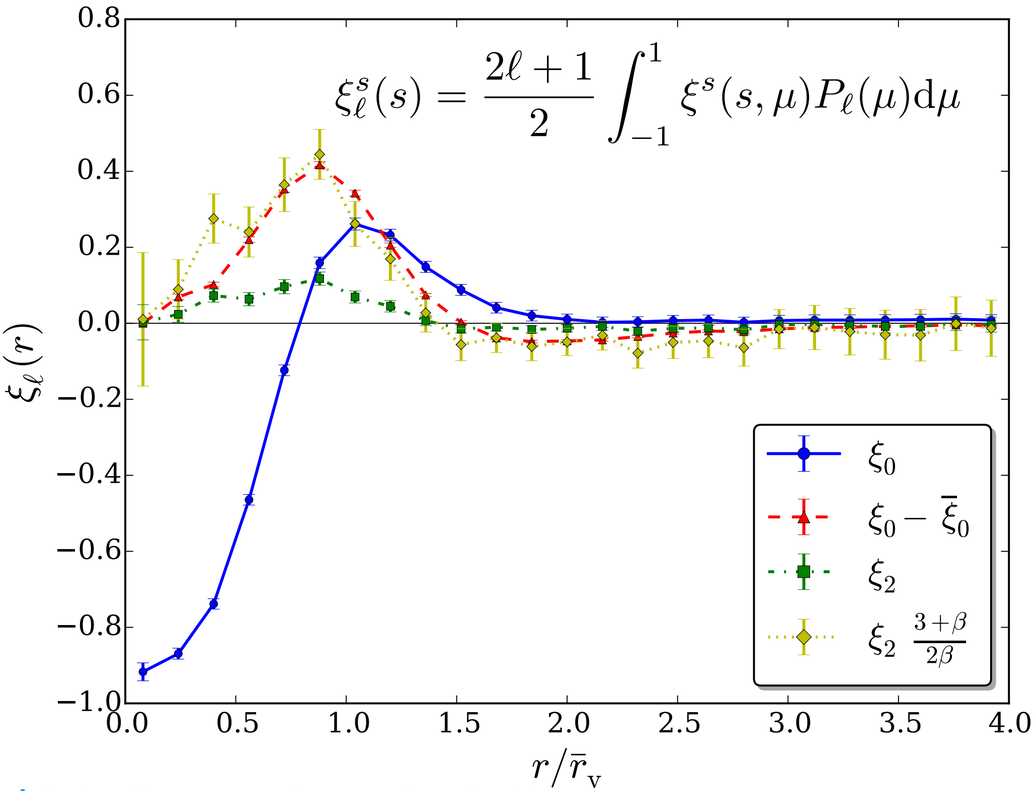
RSD modeling with **linear model**, multipole analysis of RSD

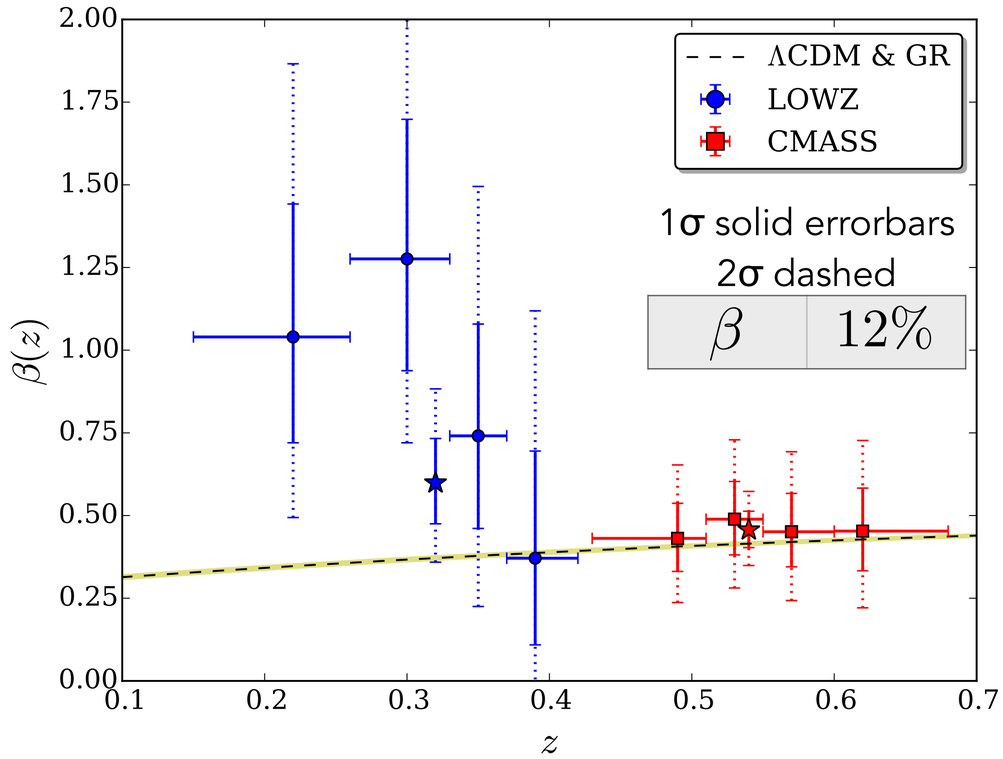
$$\xi^s(\mathbf{s}) = \xi(r) - \frac{1+z}{H(z)}\frac{\mathrm{d}v_\parallel(r)}{dr} = \xi(r) + \frac{f}{3}\Delta(r) + f\mu^2[\delta(r) - \Delta(r)] = \xi(r) + \frac{f}{3b}\bar{\xi}(r) + \frac{f}{b}\mu^2[\xi(r) - \bar{\xi}(r)]$$

$$\bar{\xi}(r) = \frac{3}{r^3}\int_0^r \xi(r')r'^2\mathrm{d}r'$$

$$\xi_0(r) - \bar{\xi}_0(r) = \xi_2(r)\frac{3+\beta}{2\beta}$$

Linear model
Only RSD, No AP

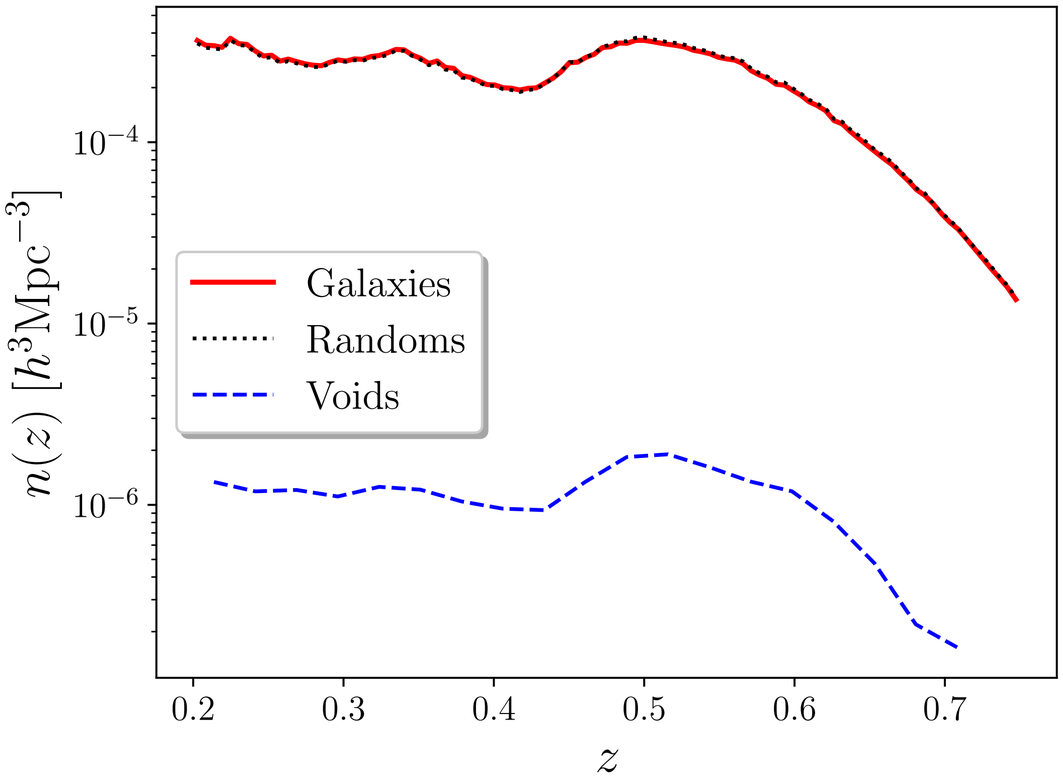


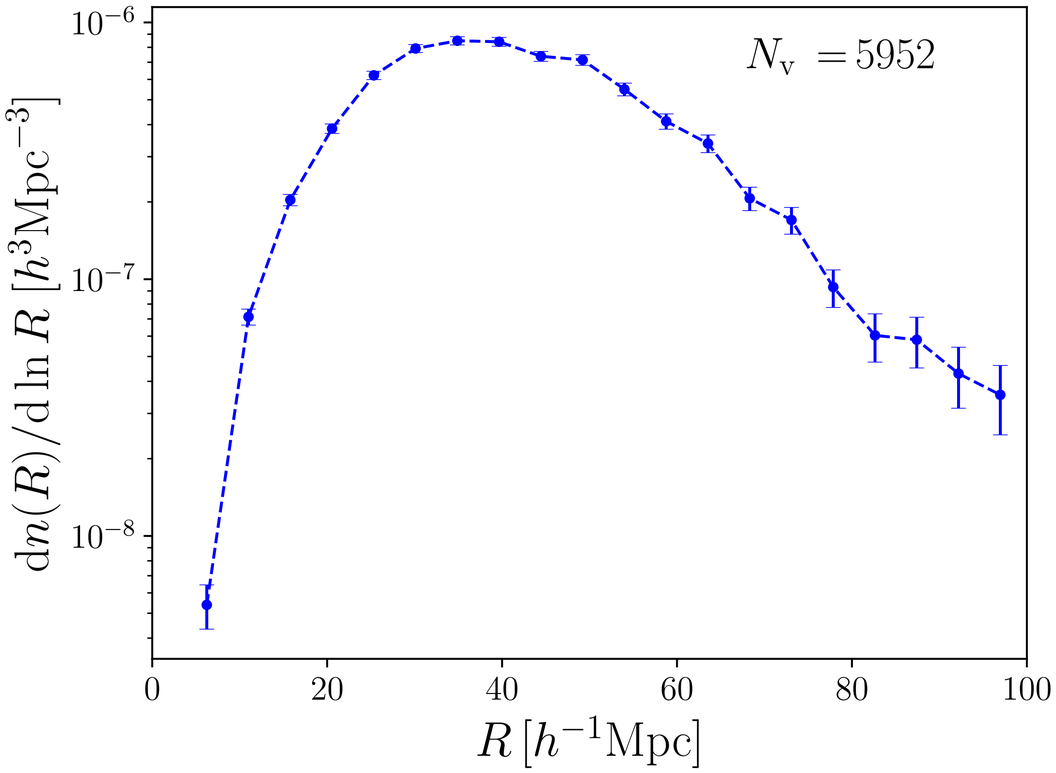


Cai, Taylor, Peacock, Padilla 2016; ArXiv: 1603.05184; MNRAS

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross correlation: Final analysis from the combined BOSS sample





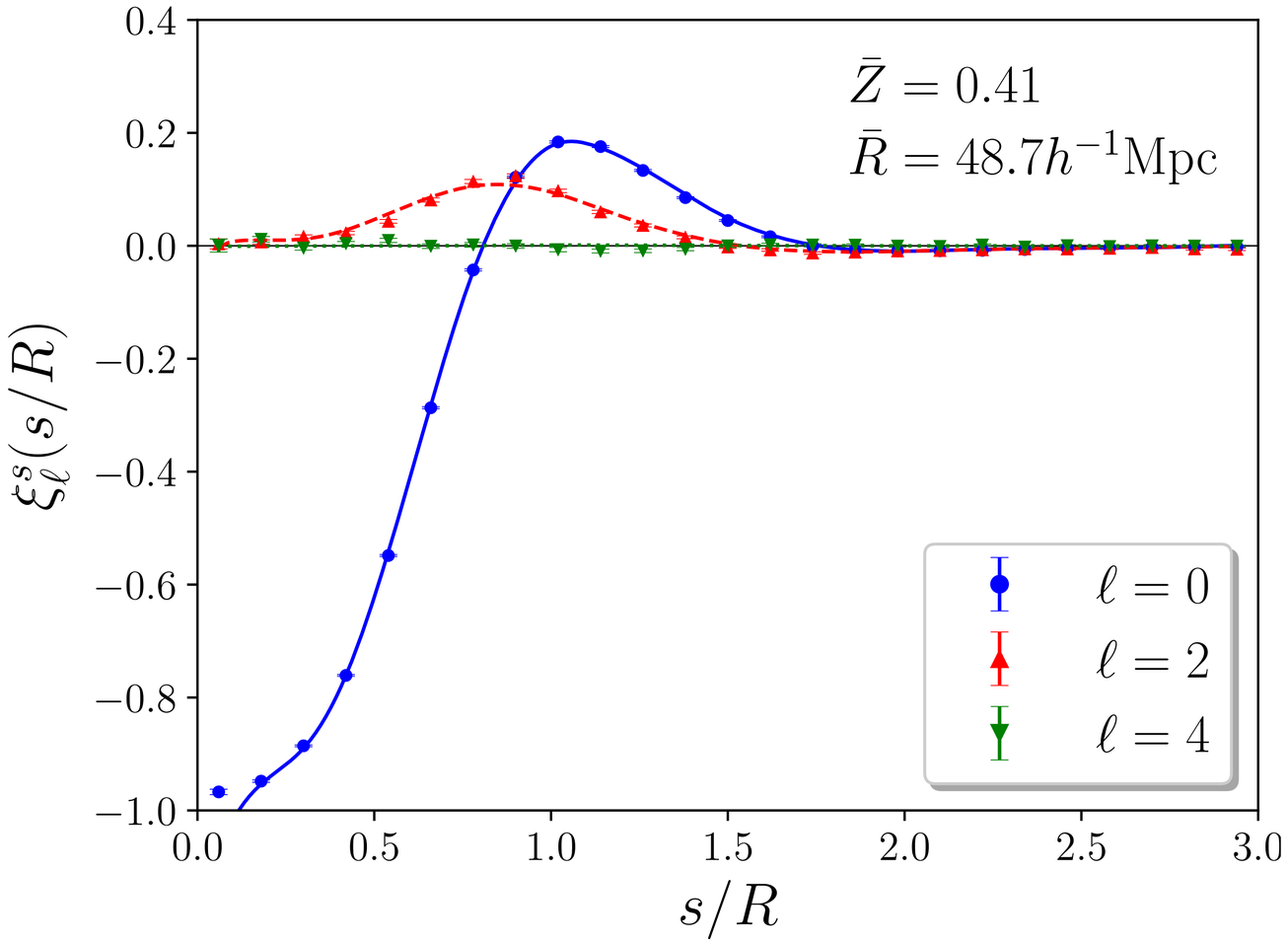
State of the art methodology

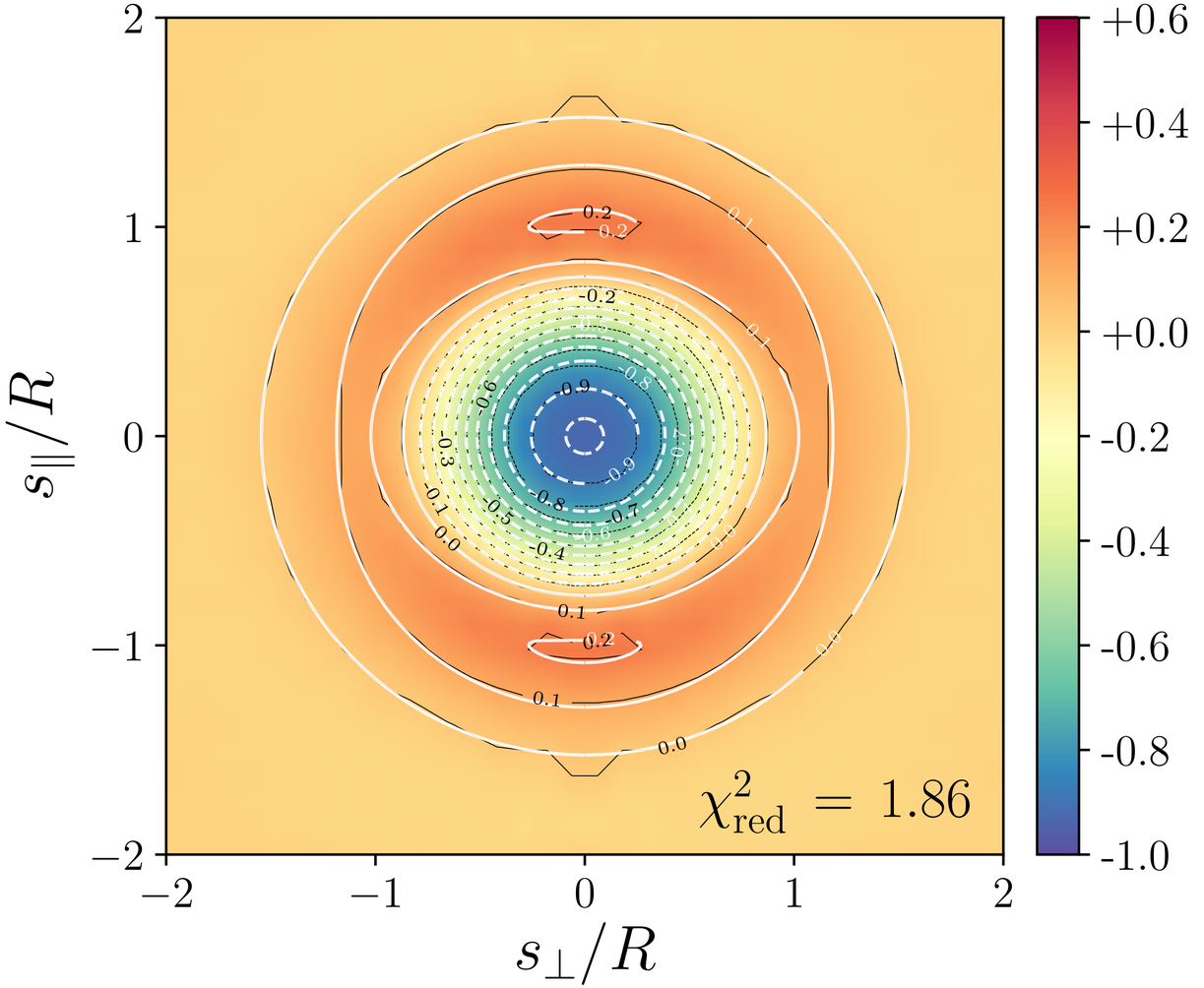
- Model profile from deprojection (model independent)
- Linear model as for multipoles analysis
- Accounts for AP & RSD

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross correlation: Final analysis from the combined BOSS sample

Tested on mocks

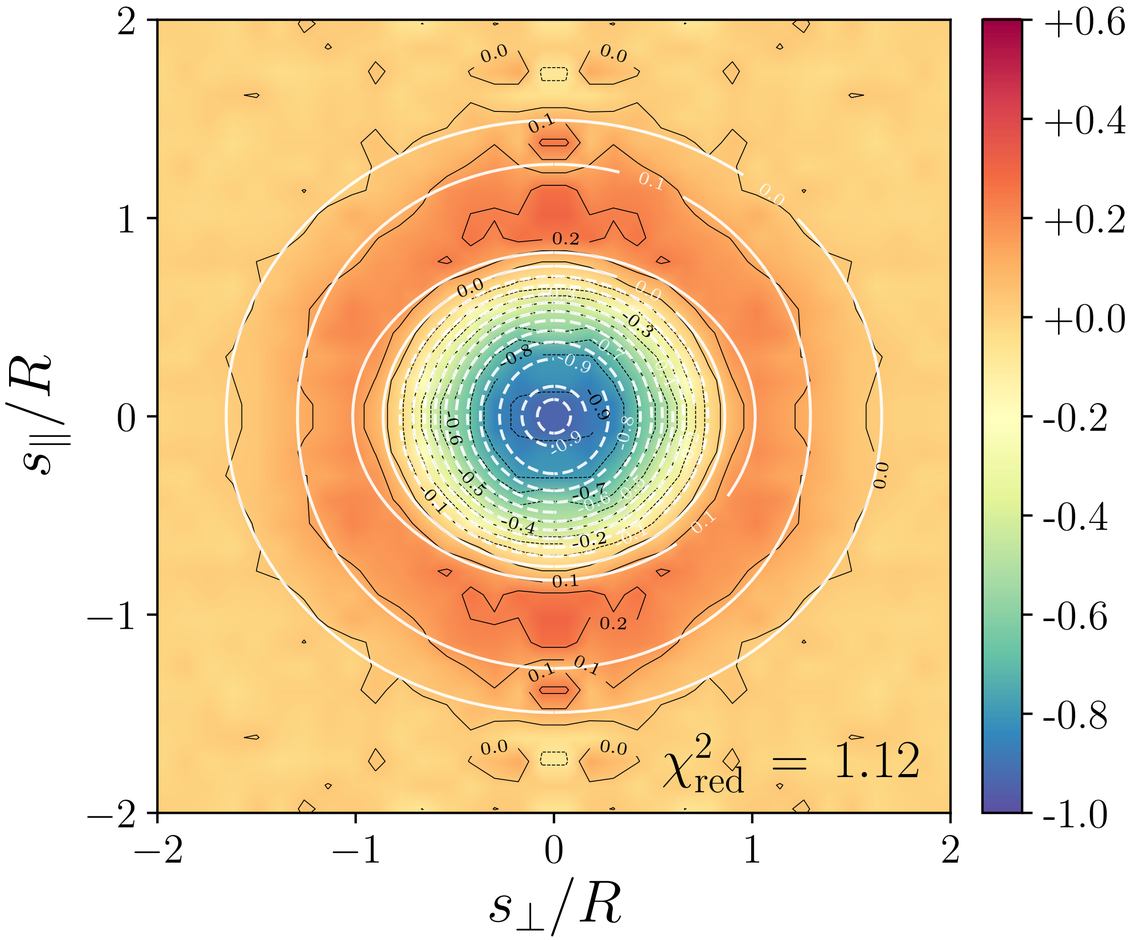


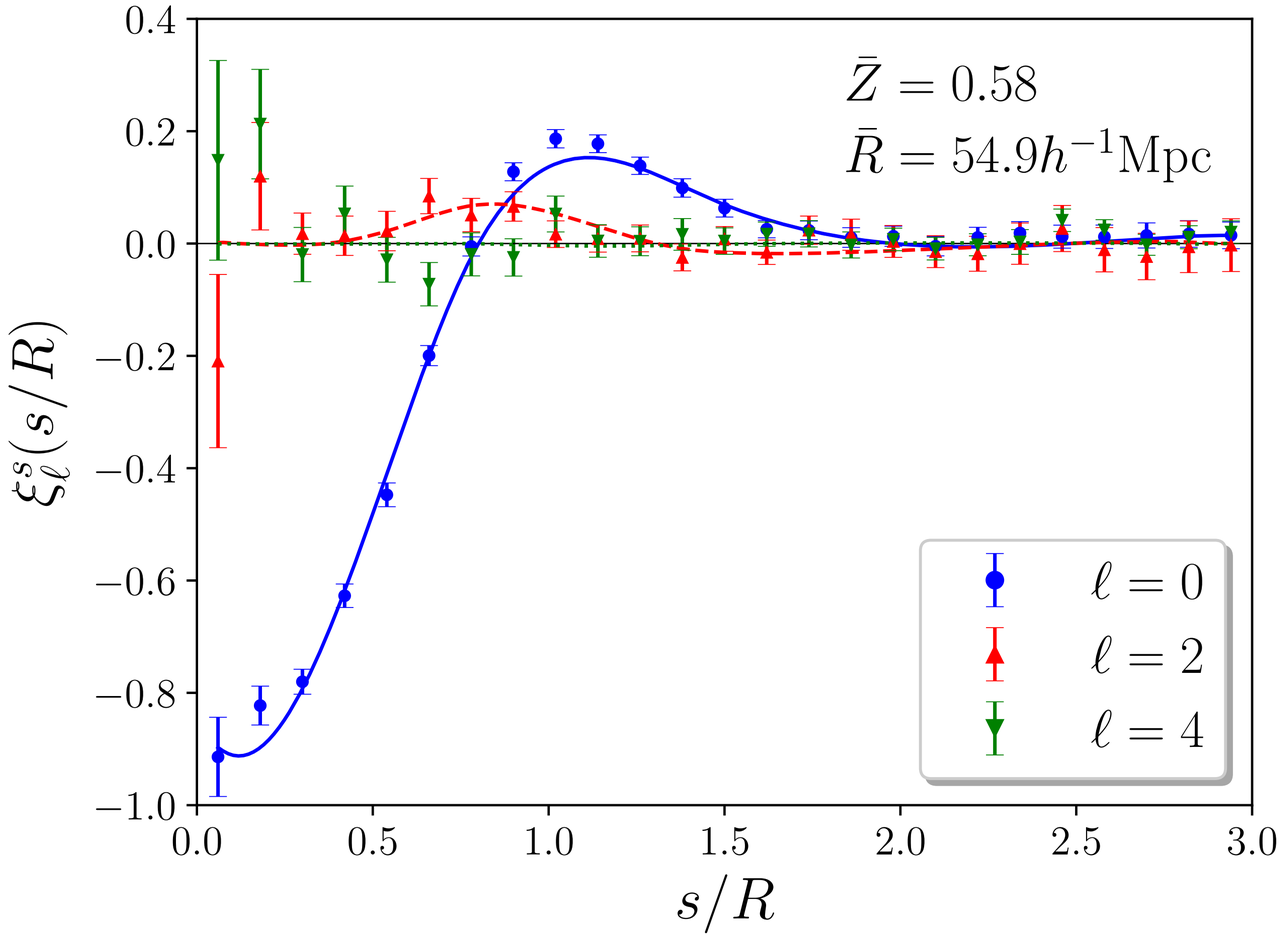


Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Void-galaxy cross correlation: Final analysis from the combined BOSS sample

Applied on data





Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

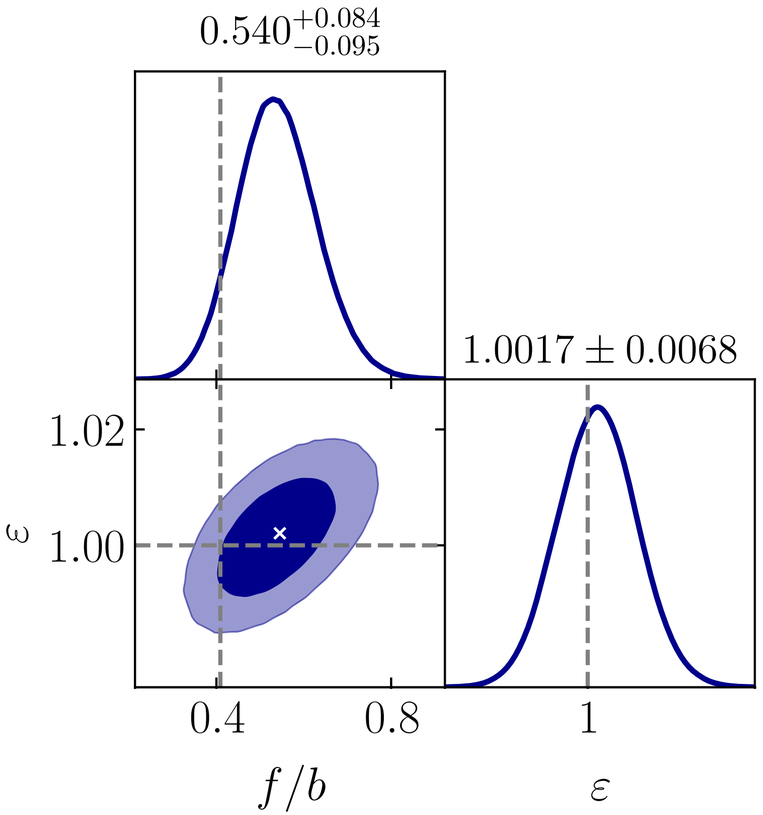
Void-galaxy cross correlation: Final analysis from the combined BOSS sample

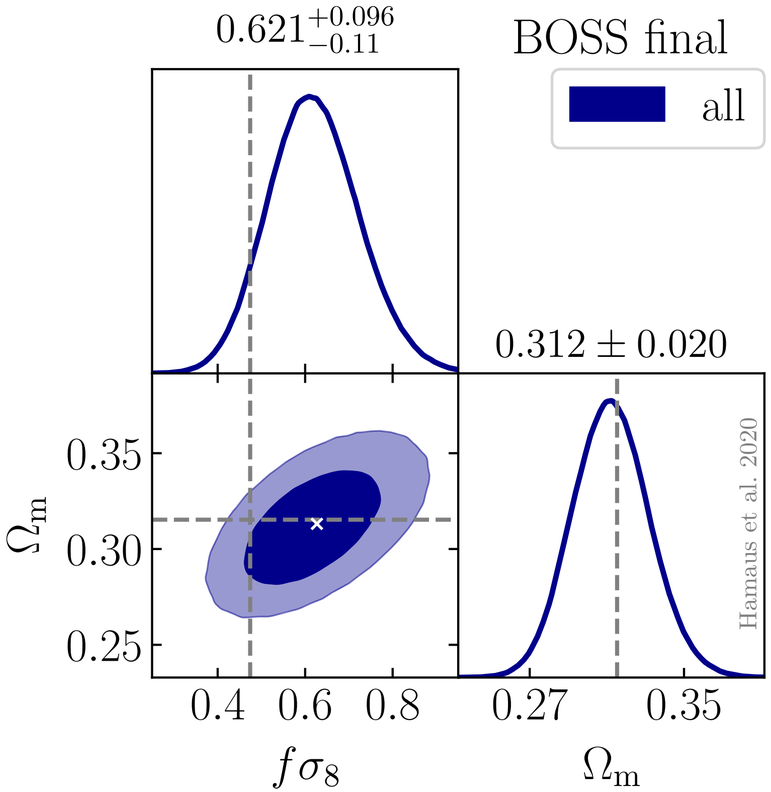
Results

$$\beta = \frac{f}{b}$$

$$\varepsilon = \frac{[D_A(z)H(z)]_{\rm meas}}{[D_A(z)H(z)]_{\rm fid}}$$

	indep	calib
β	16.9%	6.6%
ε	0.68%	0.60%

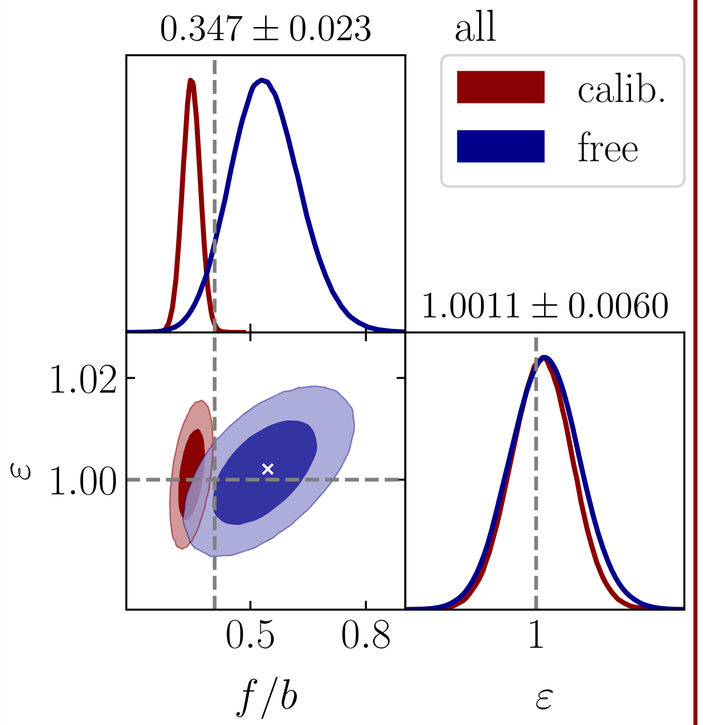


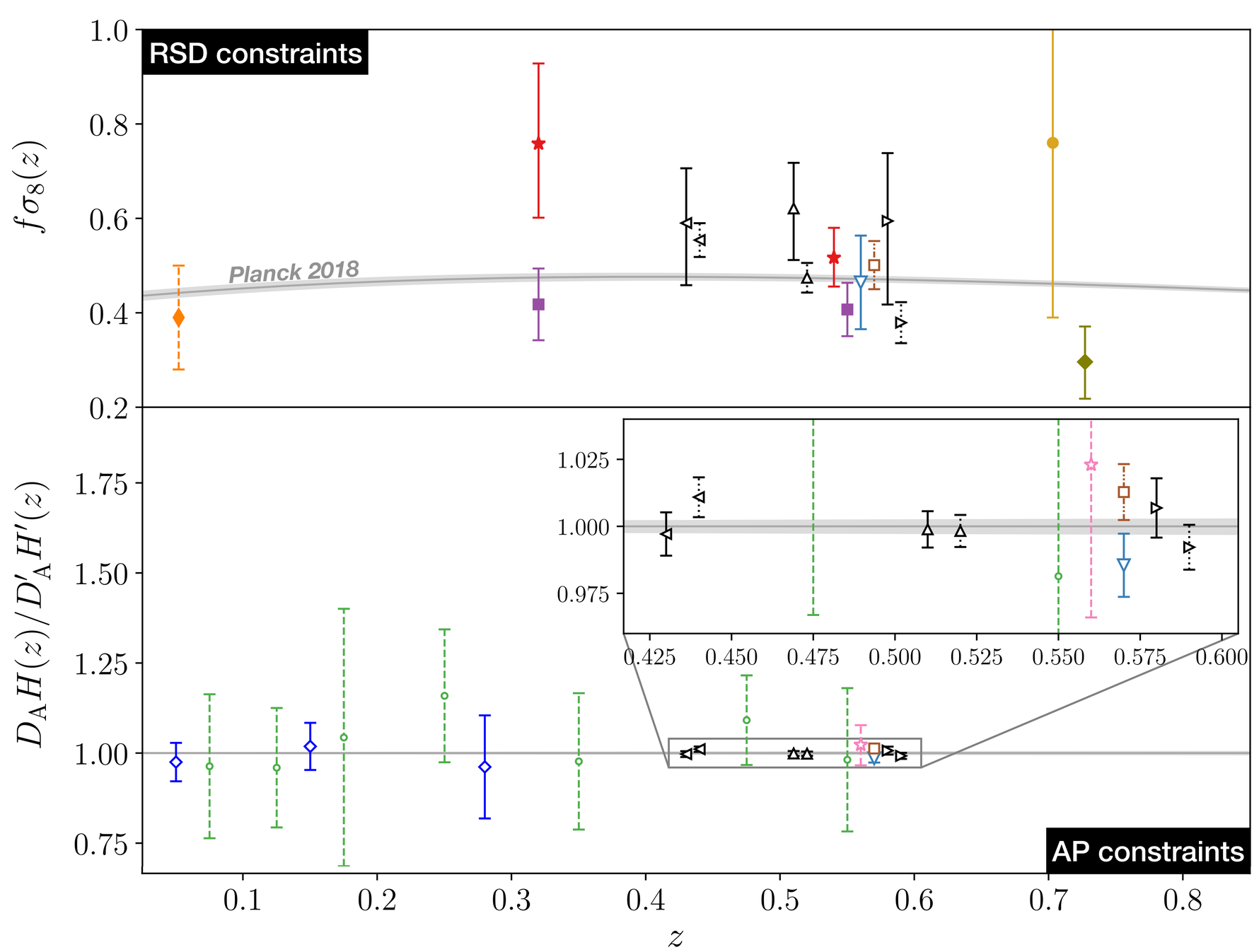


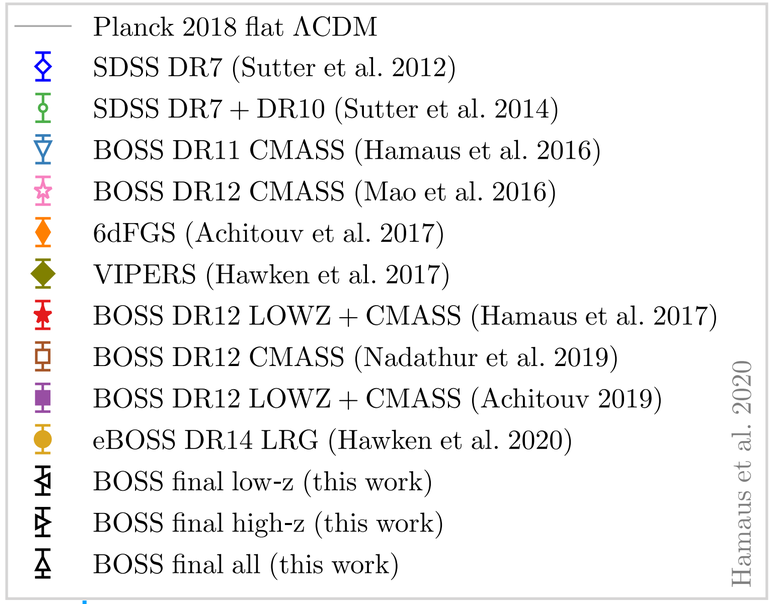
Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

=> 2 nuisance parameters

Amplitude { monopole, quadrupole





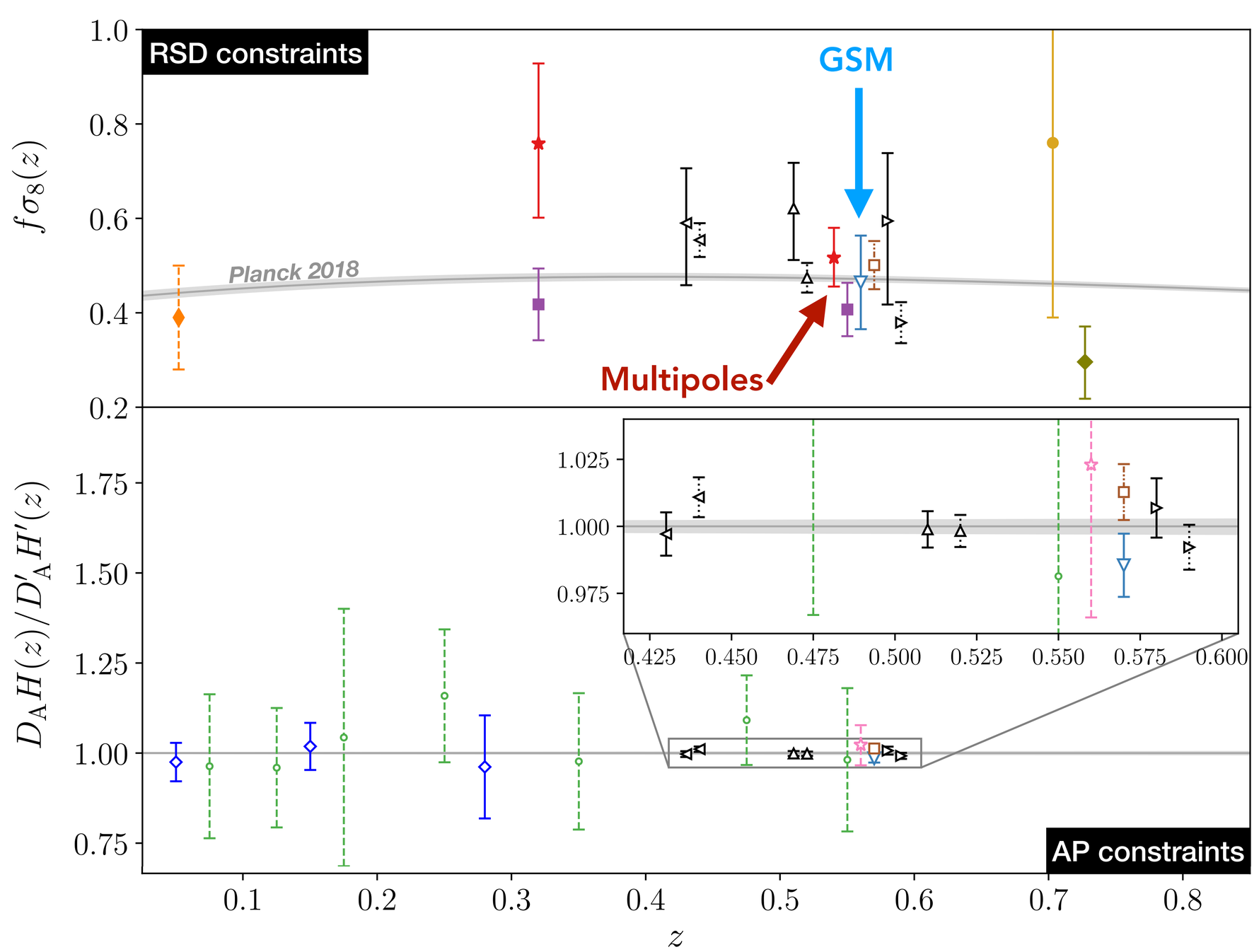


+ eBOSS DR16 void constraints (eg Aubert et al. 2020)

RSD only (filled markers)
RSD+AP (open markers)

Calibration
… calibrated on mocks
- - calibrated on sims
-· calib. on mocks and sims
— none (model independent)

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.



Planck 2018 flat ΛCDM
SDSS DR7 (Sutter et al. 2012)
SDSS DR7 + DR10 (Sutter et al. 2014)
BOSS DR11 CMASS (Hamaus et al. 2016)
BOSS DR12 CMASS (Mao et al. 2016)
6dFGS (Achitouv et al. 2017)
VIPERS (Hawken et al. 2017)
BOSS DR12 LOWZ + CMASS (Hamaus et al. 2017)
BOSS DR12 CMASS (Nadathur et al. 2019)
BOSS DR12 LOWZ + CMASS (Achitouv 2019)
eBOSS DR14 LRG (Hawken et al. 2020)
BOSS final low-z (this work)
BOSS final high-z (this work)
BOSS final all (this work)

Hamaus et al. 2020

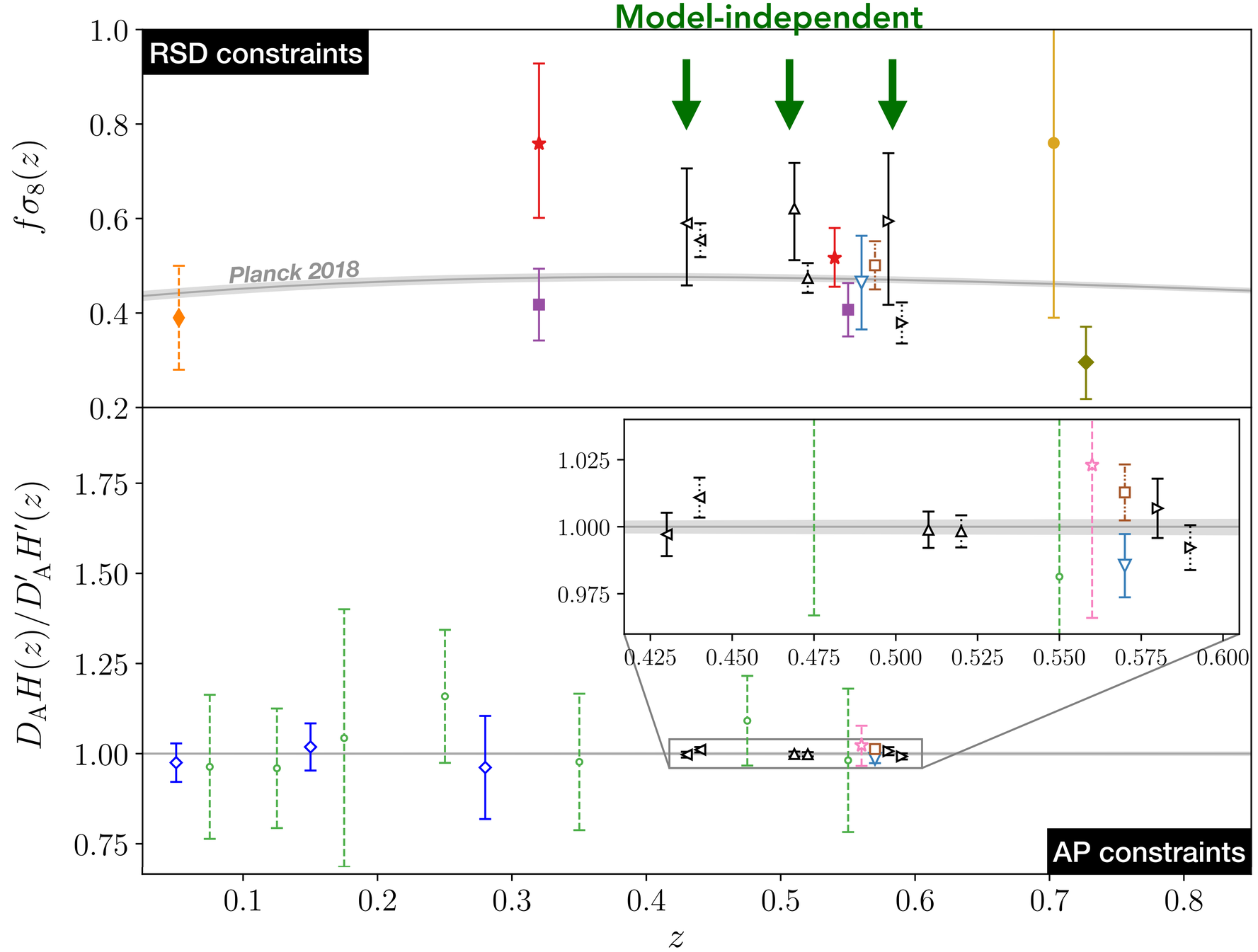
+ eBOSS DR16 void constraints
(eg Aubert et al. 2020)

RSD only (filled markers)
RSD+AP (open markers)

Calibration
… calibrated on mocks
- - calibrated on sims
-· calib. on mocks and sims
— none (model independent)

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Model-independent



- Planck 2018 flat ΛCDM
- SDSS DR7 (Sutter et al. 2012)
- SDSS DR7 + DR10 (Sutter et al. 2014)
- BOSS DR11 CMASS (Hamaus et al. 2016)
- BOSS DR12 CMASS (Mao et al. 2016)
- 6dFGS (Achitouv et al. 2017)
- VIPERS (Hawken et al. 2017)
- BOSS DR12 LOWZ + CMASS (Hamaus et al. 2017)
- BOSS DR12 CMASS (Nadathur et al. 2019)
- BOSS DR12 LOWZ + CMASS (Achitouv 2019)
- eBOSS DR14 LRG (Hawken et al. 2020)
- BOSS final low-z (this work)
- BOSS final high-z (this work)
- BOSS final all (this work)

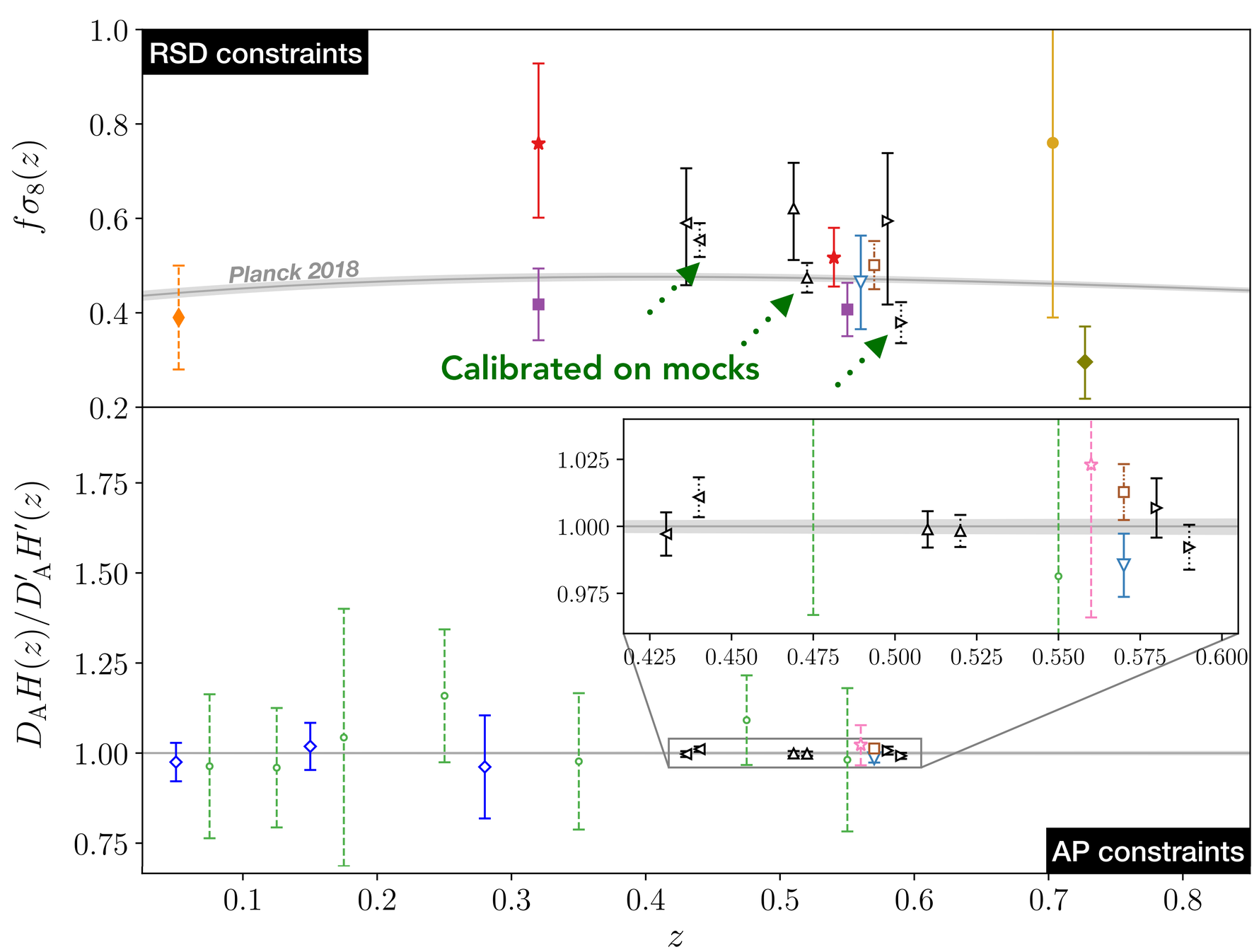
Hamaus et al. 2020

+ eBOSS DR16 void constraints
(eg Aubert et al. 2020)

RSD only (filled markers)
RSD+AP (open markers)

Calibration
… calibrated on mocks
- - calibrated on sims
-· calib. on mocks and sims
— none (model independent)

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.



Planck 2018 flat ΛCDM
SDSS DR7 (Sutter et al. 2012)
SDSS DR7 + DR10 (Sutter et al. 2014)
BOSS DR11 CMASS (Hamaus et al. 2016)
BOSS DR12 CMASS (Mao et al. 2016)
6dFGS (Achitouv et al. 2017)
VIPERS (Hawken et al. 2017)
BOSS DR12 LOWZ + CMASS (Hamaus et al. 2017)
BOSS DR12 CMASS (Nadathur et al. 2019)
BOSS DR12 LOWZ + CMASS (Achitouv 2019)
eBOSS DR14 LRG (Hawken et al. 2020)
BOSS final low-z (this work)
BOSS final high-z (this work)
BOSS final all (this work)

Hamaus et al. 2020

+ eBOSS DR16 void constraints
(eg Aubert et al. 2020)

RSD only (filled markers)
RSD+AP (open markers)

Calibration
… calibrated on mocks
- - calibrated on sims
-· calib. on mocks and sims
— none (model independent)

Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.

Take home messages

- The void-galaxy cross-correlation function $\xi_{\rm vg}$ is a robust tool for Cosmology.
- Brings competitive cosmological constraints! AP constraint reach sub-percent level.
- Importance of model independent techniques.
- Velocities have turned from being a systematic effect into becoming a powerful source of information to constrain the growth rate of structure.
- DESI, Euclid, LSST, Roman, SPHEREx will provide $\mathcal{O}(10^5)$ voids each!

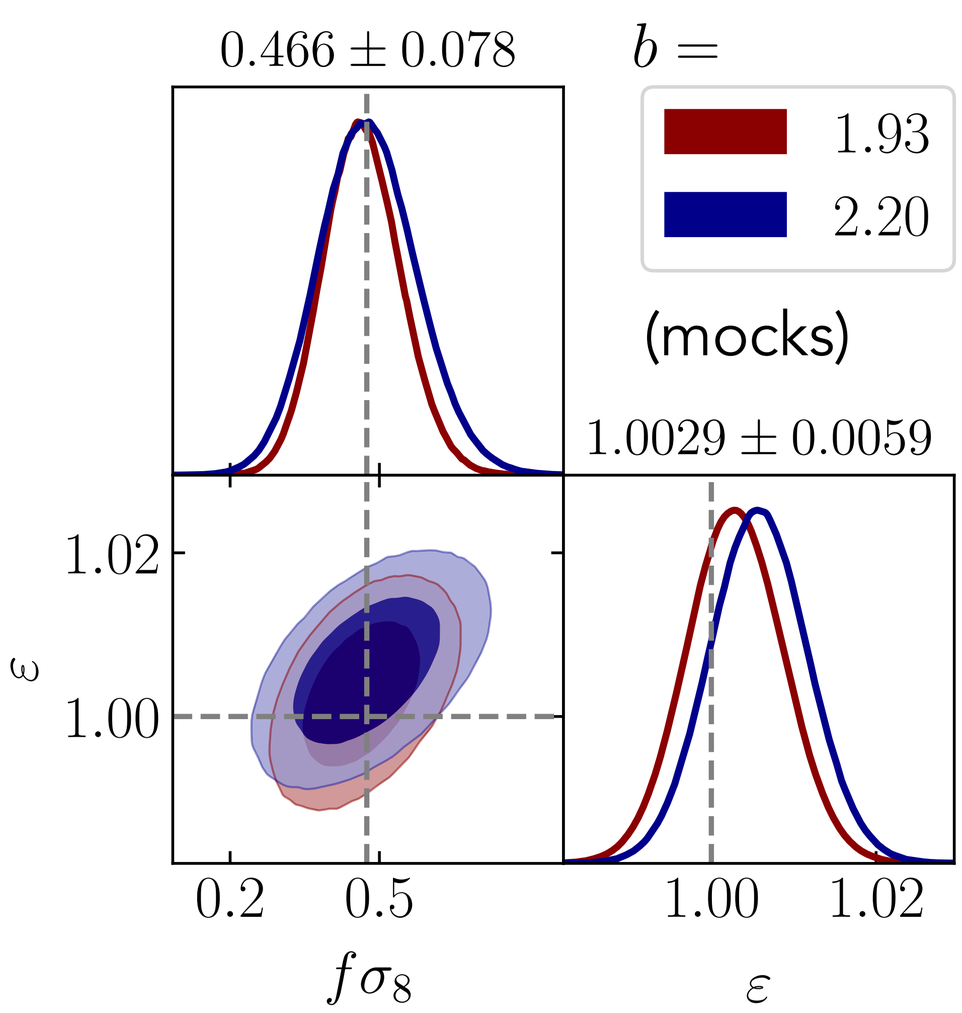
Take home messages

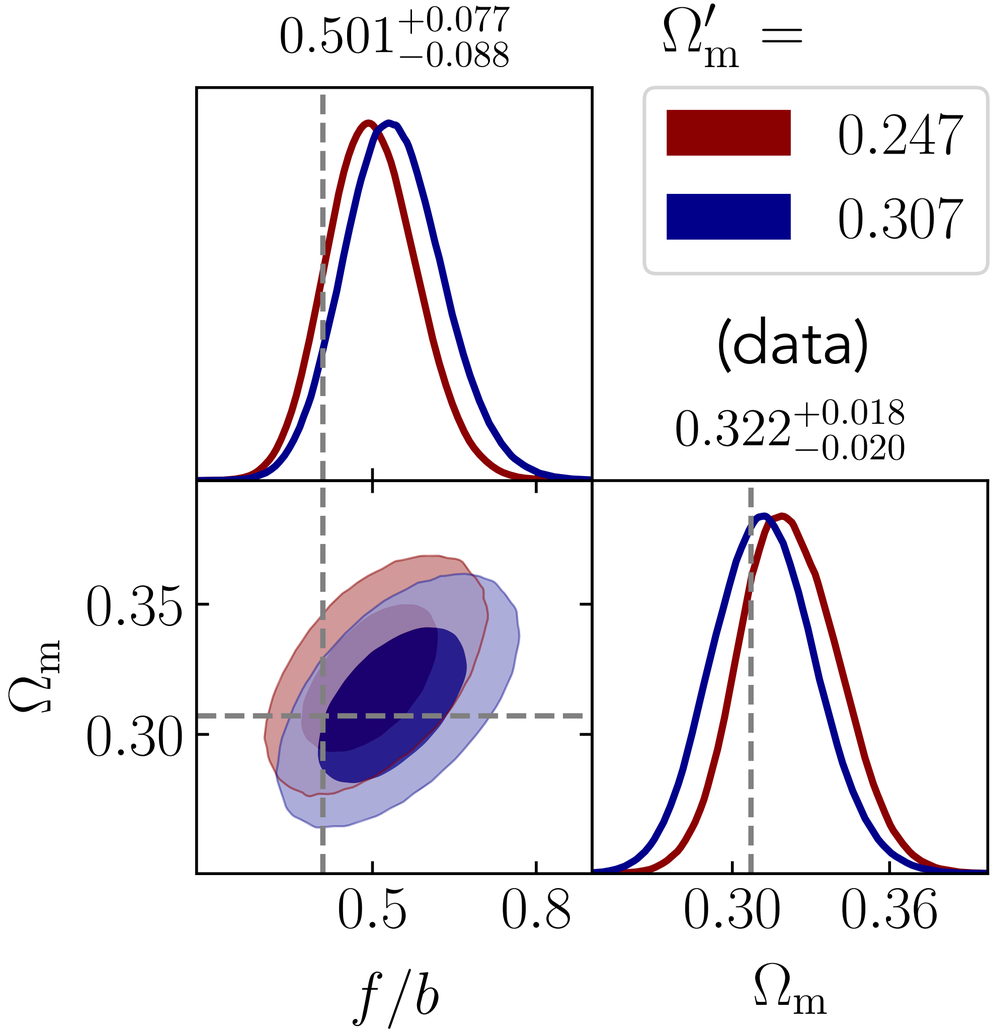
- The void-galaxy cross-correlation function $\xi_{\rm vg}$ is a robust tool for Cosmology.
- Brings competitive cosmological constraints! AP constraint reach sub-percent level.
- Importance of model independent techniques.
- Velocities have turned from being a systematic effect into becoming a powerful source of information to constrain the growth rate of structure.
- DESI, Euclid, LSST, Roman, SPHEREx will provide $\mathcal{O}(10^5)$ voids each!

Thank you for your attention!

Supplementary slides:

Systematic tests: tracer bias and fiducial cosmology





Hamaus, Pisani, Choi, Lavaux, Wandelt, Weller 2020; ArXiv: 2007.07895 JCAP sub.