Cosmological Geometry and Growth Measurements from Voids

6/24/22

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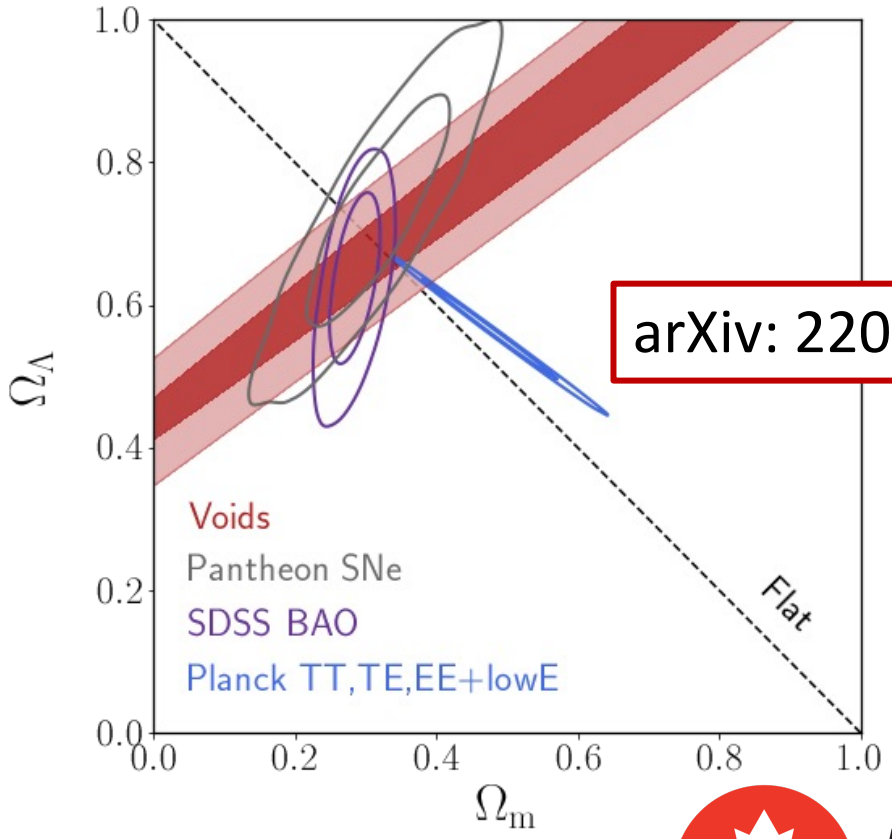

arXiv: 2205.06258

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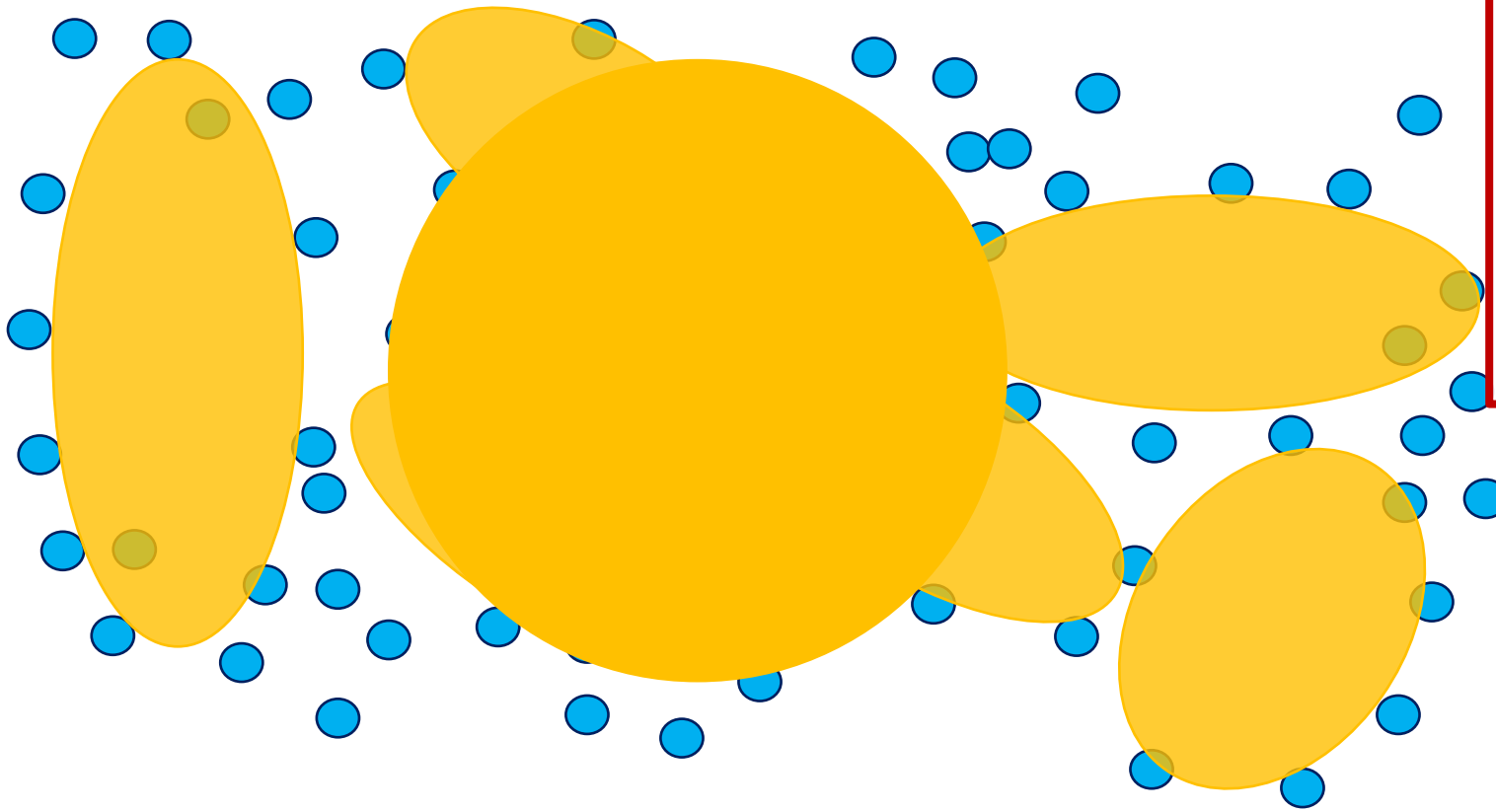
NSERC CRSNG

Goal

Establish voids as a pillar of observational cosmology

Basic Idea of Void Analysis

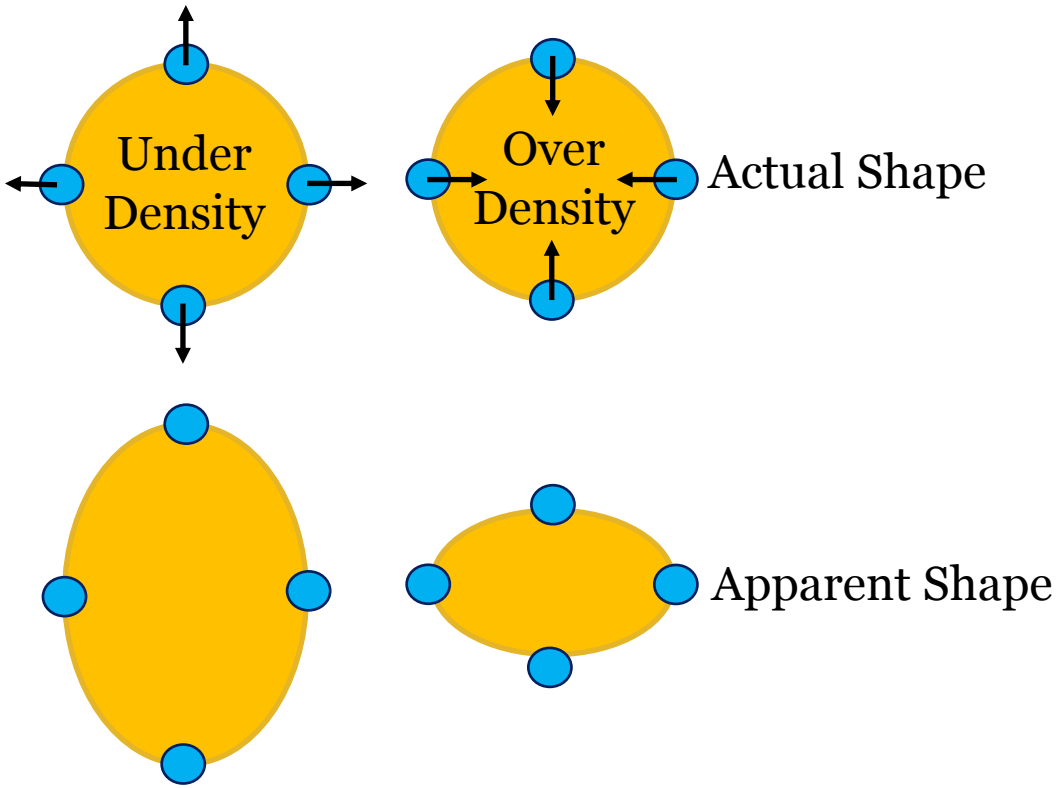


- Start with a tracer
  - Ex. LRGs
- Construct a density field
- Identify underdensities (i.e. voids)

RSD and AP

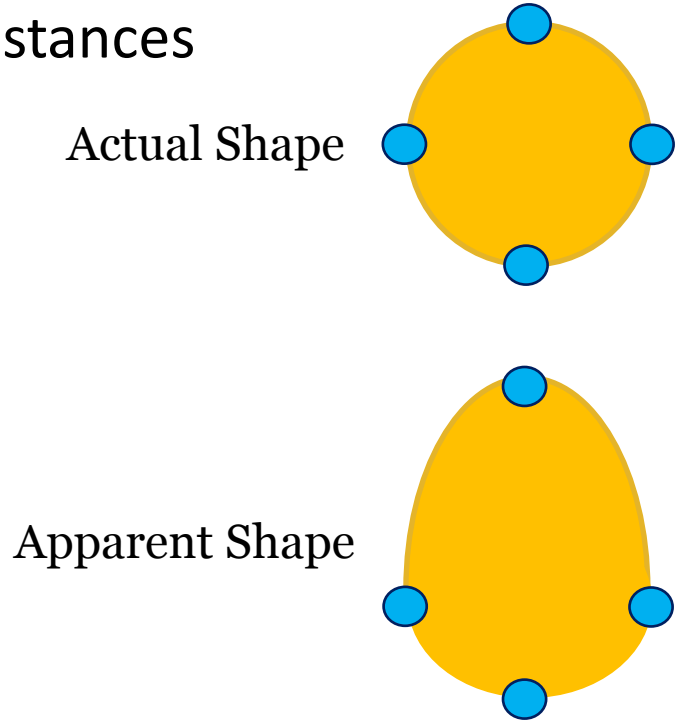
Redshift Space Distortions

- Doppler shift of a galaxies peculiar motion causing a distortion to the measured redshift

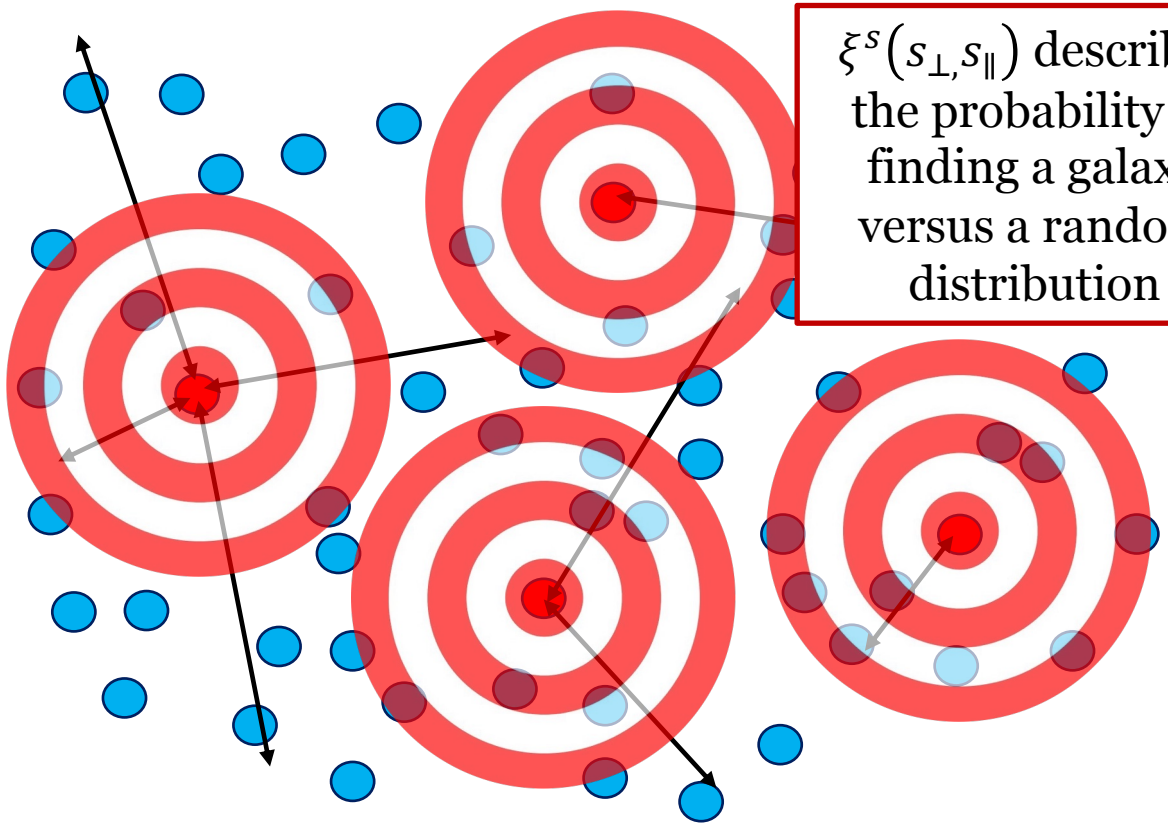


Alcock-Paczynski Effect

- Assuming a cosmology different than the truth leads to incorrect values when converting redshifts to distances

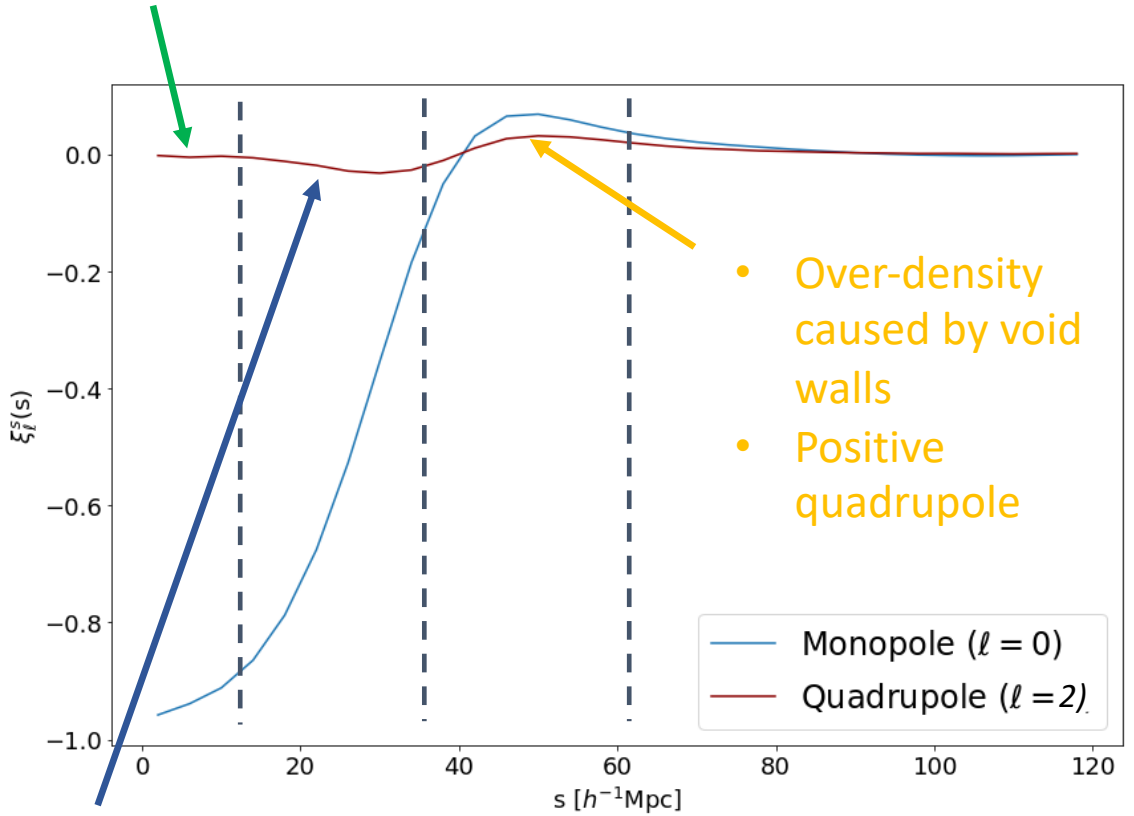


Our Observable



$\xi^s(s_\perp, s_\parallel)$ describes the probability of finding a galaxy versus a random distribution

- Few to no galaxies
- Quadrupole is undistorted



- Over-density caused by void walls
- Positive quadrupole

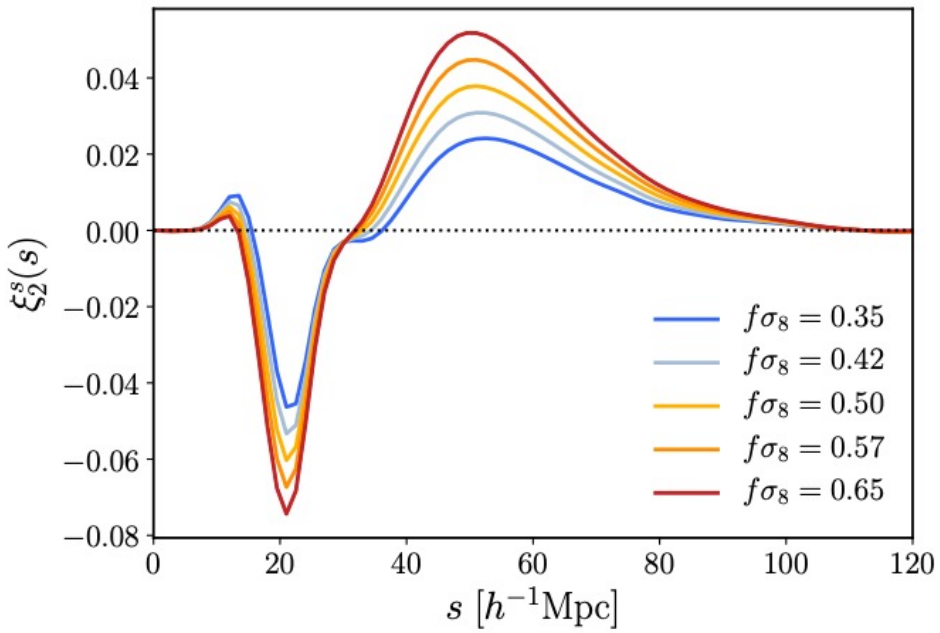
- Under-density stretched along line of sight
- Negative quadrupole

The anisotropic correlation function $\xi^s(\boldsymbol{s})$ can be compressed into Legendre multipoles:

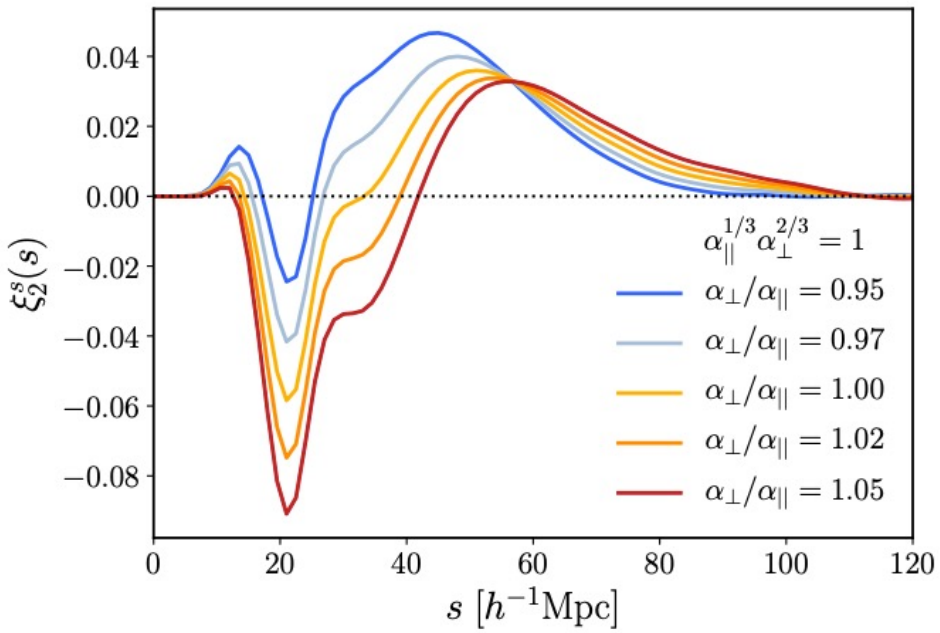
$$\xi_l^s(\boldsymbol{s}) = (2l+1)\xi^s(s,\mu)\mathrm{L_l}(\mu)d\mu$$

RSD and AP

Varying the Growth Rate (RSD)



Varying $\alpha_\perp/\alpha_\parallel$ (AP)



The Basic Model:

Jacobian of coordinate transformation

real-space correlation

$$1 + \xi^s(s,\mu) = [1 + \xi^r(r)]\left[1 + \frac{v_r}{raH} + \frac{rv_r' - v_r}{rah}\mu^2\right]^{-1}$$

Radial velocity outflow from void
(modelled by linear perturbation theory)

redshift-space correlation, where $\xi^s(s_\perp, s_\parallel) = \xi^{s,fid}\left(\alpha_\perp s_\perp^{fid}, \alpha_\parallel s_\parallel^{fid}\right)$ to account for the AP effect

Advanced Model:
Basic model + convolution with pdf for random l.o.s velocity component (i.e. adds a dispersion around a coherent outflow)

Advanced Model

The Basic Model:

Jacobian of coordinate transformation

real-space correlation

$$1 + \xi^{s,fid}(s,\mu) = \int \left(1 + \xi^{r}(\tilde{r})\right)\left[1 + \frac{\tilde{v}_r}{\tilde{r}aH} + \frac{\tilde{r}\tilde{v}_r' - \tilde{v}_r}{\tilde{r}ah}\mu^2\right]^{-1} P(v_\parallel)dv_\parallel$$

Radial velocity outflow from void
(modelled by linear perturbation theory)

redshift-space correlation

$$P(v_\parallel) \propto \exp\left(-\frac{v_\parallel^2}{2\sigma_{v_\parallel}^2(r)}\right)$$

Model AP:

$$\xi^s(s_\perp, s_\parallel) = \xi^{s,fid}\left(\alpha_\perp s_\perp^{fid}, \alpha_\parallel s_\parallel^{fid}\right)$$

And: Linear theory

$$v_r(r) = -\frac{1}{3} faHr\Delta(r)$$

3 input functions needed (templates):

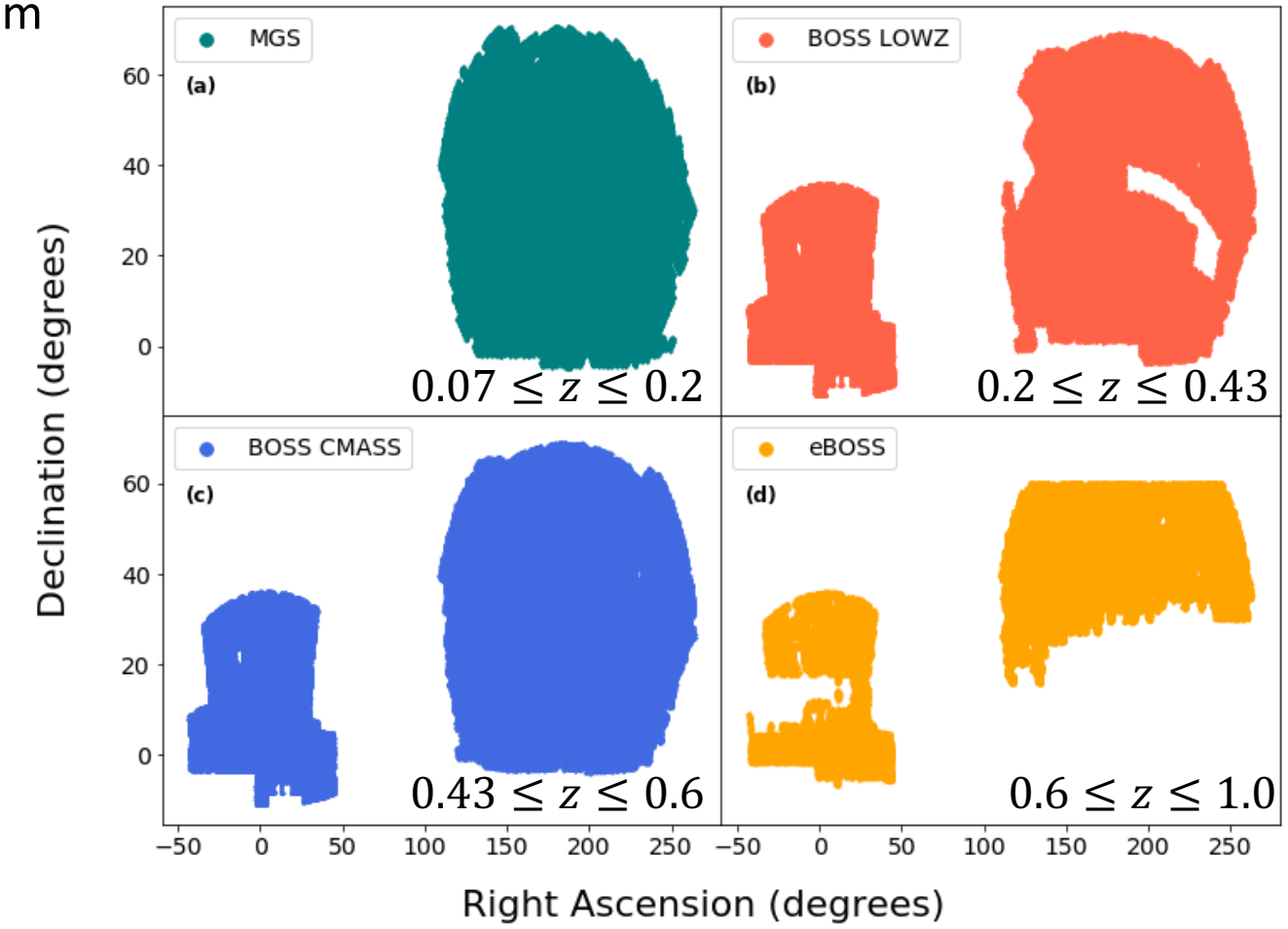
$\xi^r(r)$ - Measured approximately using RSD-removed galaxy positions from approximate mocks

$\Delta(r), \sigma_{v_\parallel}(r)$ - Measured from N-body simulation with full DM information available

SDSS

- Used galaxies from the full SDSS survey ($0.07 \leq z \leq 1$)
  - eBOSS results ($0.07 \leq z \leq 1$) taken from (Nadathur et al., 2020)

- Split into 6 bins in redshift
  - MGS – (0.07 < z < 0.2)
  - LOWZ – (0.2 < z < 0.3) & (0.3 < z < 0.4)
  - CMASS – (0.4 < z < 0.5) & (0.5 < z < 0.6)
  - eBOSS* – (0.6 < z < 1.0)



*github.com/seshnadathur/Revolver

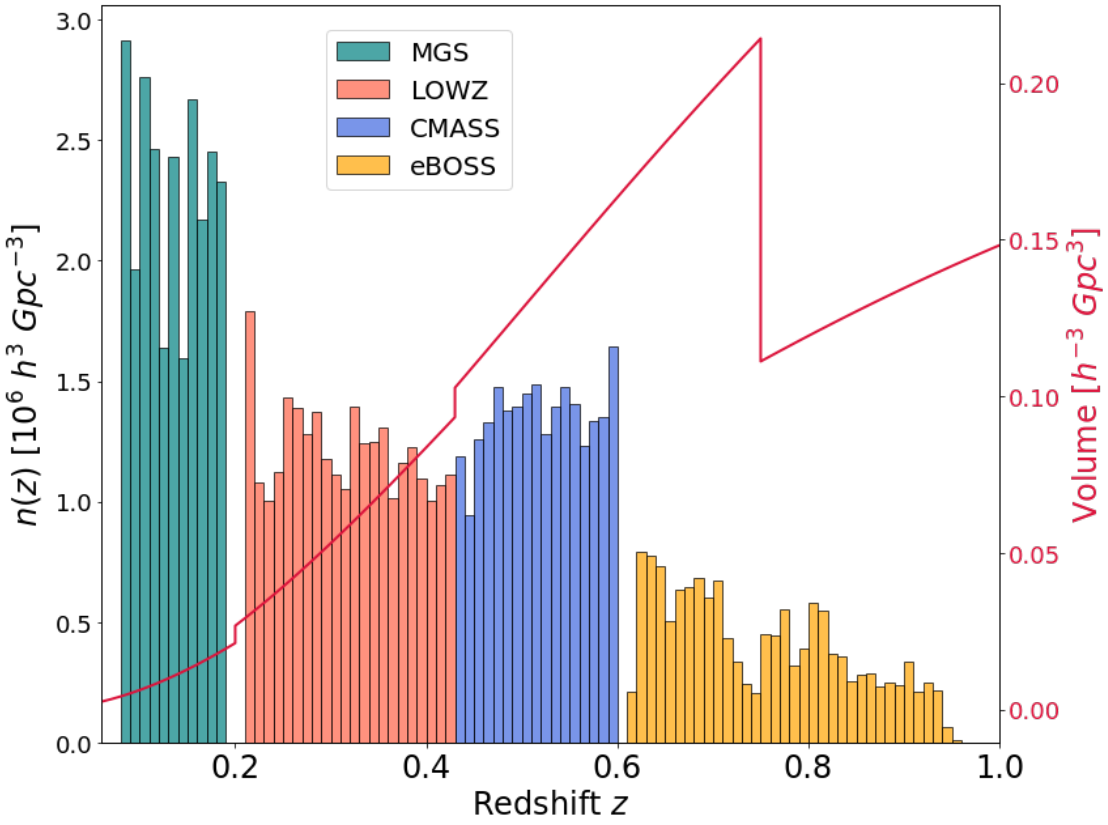
Void finding

Voids are identified using the REVOLVER code:
github.com/seshnadathur/Revolver/

Zobov algorithm is used, which is a watershed based void-finder

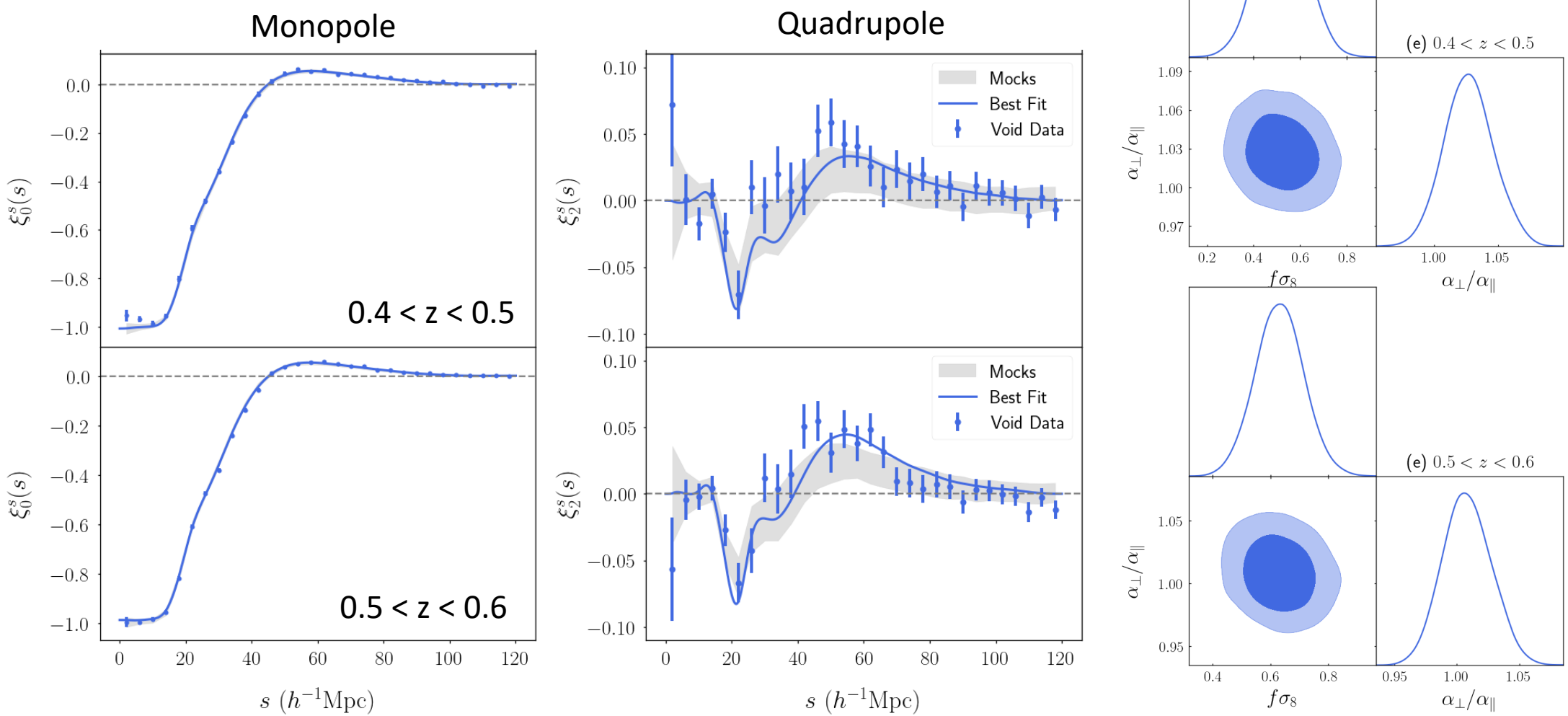
We use an RSD-removal technique to estimate real-space galaxy distribution prior to void-finding:

- Removes selction biases in the sample
  - (see 1805.09349 or 2107.01314)
- Allows for an estimation of the real-space correlation function needed



Results

- Model fits uses VICTOR code*
  - Fit for $f\sigma_8$ & $\alpha_\perp/\alpha_\parallel$ and 2 nuisance parameters
  - MCMC exploration of the posterior



Results shown are or 2 out of 6 redshift bins

*github.com/seshnadathur/victor

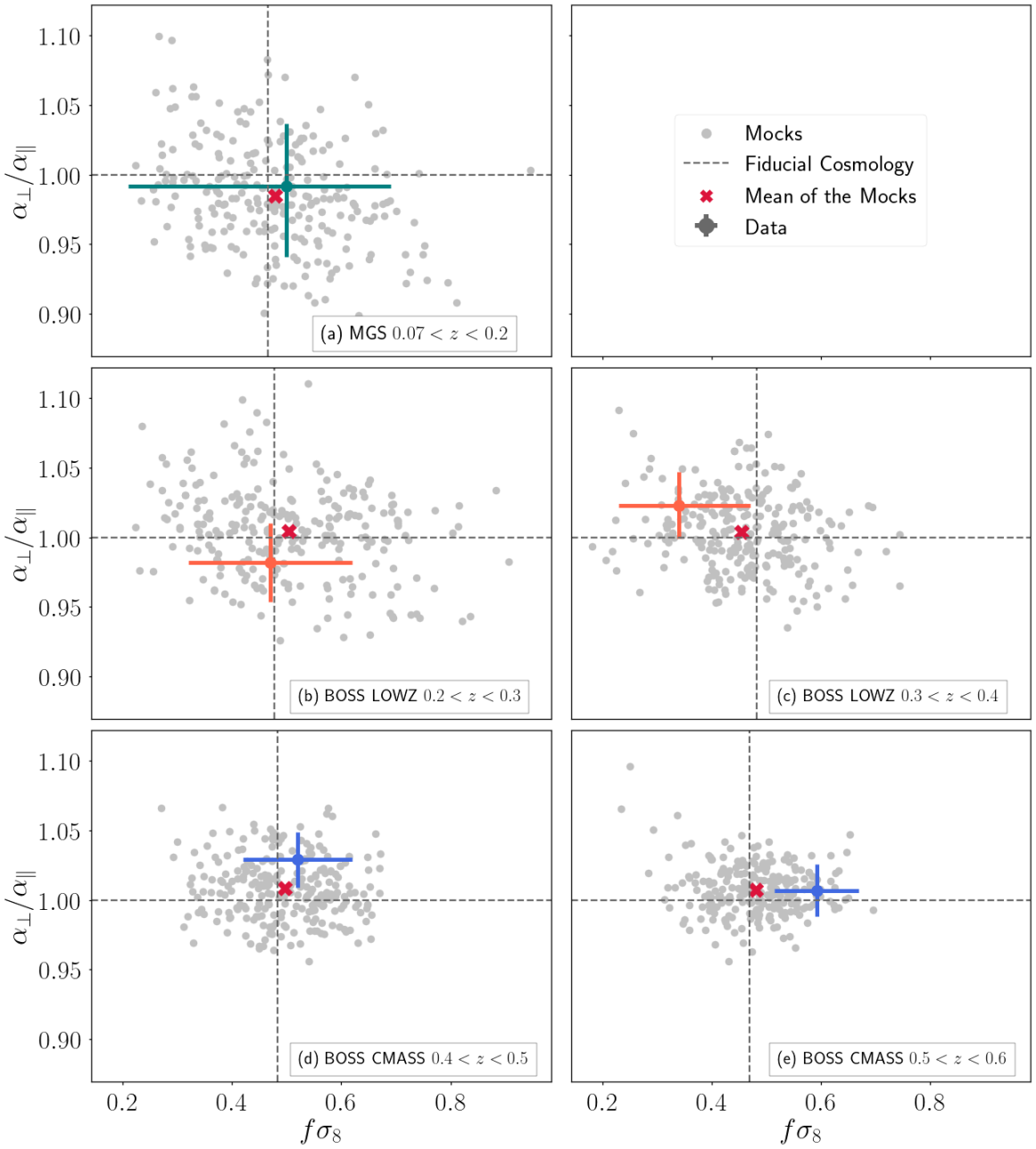
Systematics

- Use simulated catalogues to test for:
  - Modelling limitations
  - Fiducial cosmology systematics

- Systematics are a small contribution to the total budget
  - Will be more of a concern for future surveys

Table 3. Summary of the total error budget for measurement of $f\sigma_8$ and $\alpha_\perp/\alpha_\parallel$ in each redshift bin. Statistical errors $\sigma_{\rm stat}$ are determined from posterior fits to the data. The total systematic error budget is determined by adding in quadrature the individual contributions described in Section 4.3, $\sigma_{\rm total} = \sqrt{\sigma^2_{\rm syst,offset} + \sigma^2_{\rm syst,error} + \sigma^2_{\rm stat}}$. Here $\sigma_{\rm syst,offset} = -0.0113$ for $f\sigma_8$ and 0.0029 for $\alpha_\perp/\alpha_\parallel$, and $\sigma_{\rm syst,error} = 0.0161$ for $f\sigma_8$ and 0.0061 for $\alpha_\perp/\alpha_\parallel$.

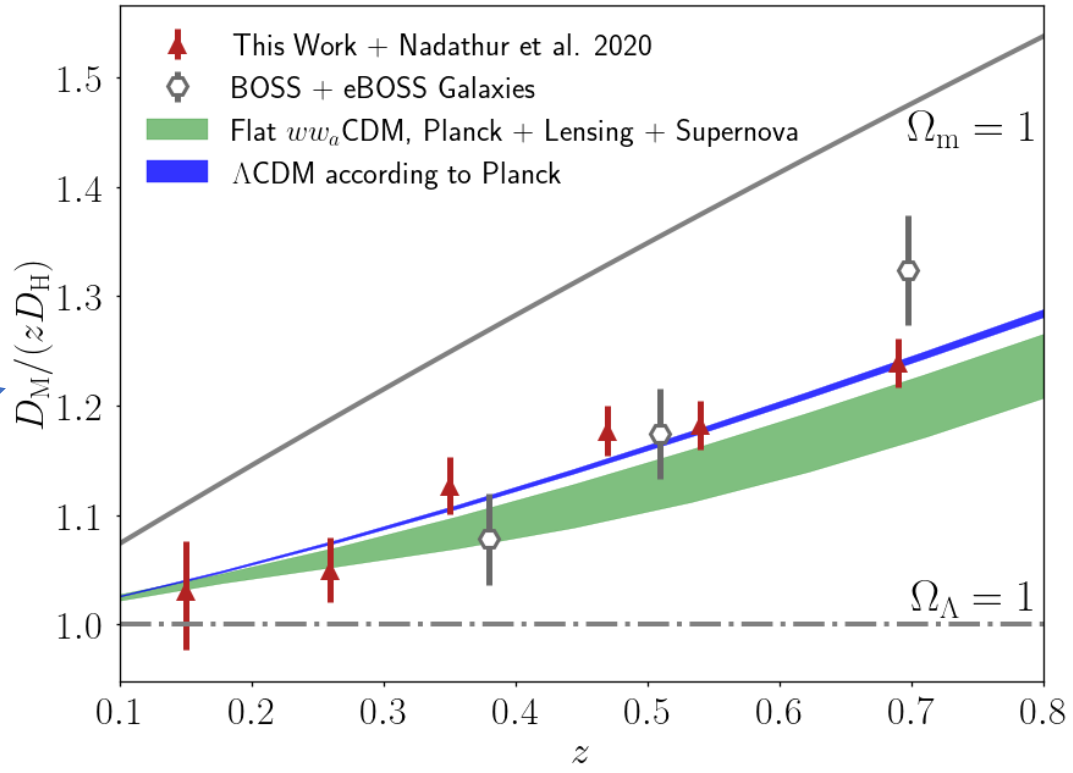
Redshift Range	Parameter	$\sigma_{\rm stat}$	$\sigma_{\rm total}$
$0.07 < z < 0.2$	$f\sigma_8$	$^{+0.16}_{-0.23}$	$^{+0.16}_{-0.23}$
	$\alpha_\perp/\alpha_\parallel$	$^{+0.044}_{-0.052}$	$^{+0.045}_{-0.053}$
$0.2 < z < 0.3$	$f\sigma_8$	$^{+0.14}_{-0.16}$	$^{+0.14}_{-0.16}$
	$\alpha_\perp/\alpha_\parallel$	$^{+0.028}_{-0.028}$	$^{+0.029}_{-0.029}$
$0.3 < z < 0.4$	$f\sigma_8$	$^{+0.11}_{-0.11}$	$^{+0.11}_{-0.11}$
	$\alpha_\perp/\alpha_\parallel$	$^{+0.024}_{-0.024}$	$^{+0.025}_{-0.025}$
$0.4 < z < 0.5$	$f\sigma_8$	$^{+0.10}_{-0.10}$	$^{+0.10}_{-0.10}$
	$\alpha_\perp/\alpha_\parallel$	$^{+0.020}_{-0.020}$	$^{+0.021}_{-0.021}$
$0.5 < z < 0.6$	$f\sigma_8$	$^{+0.084}_{-0.084}$	$^{+0.086}_{-0.086}$
	$\alpha_\perp/\alpha_\parallel$	$^{+0.019}_{-0.019}$	$^{+0.020}_{-0.020}$



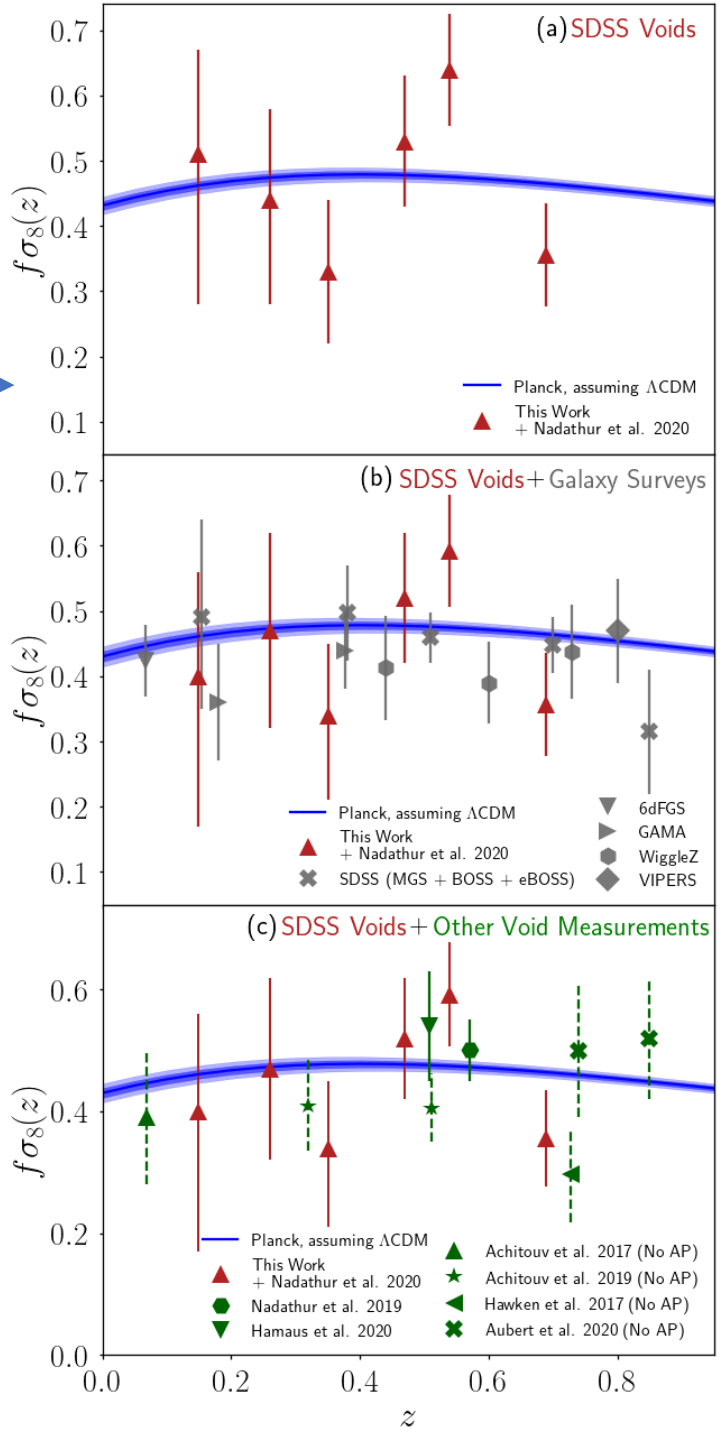
Results

Constraints on $f\sigma_8$ are comparable to galaxy clustering results

How to get DM and DH

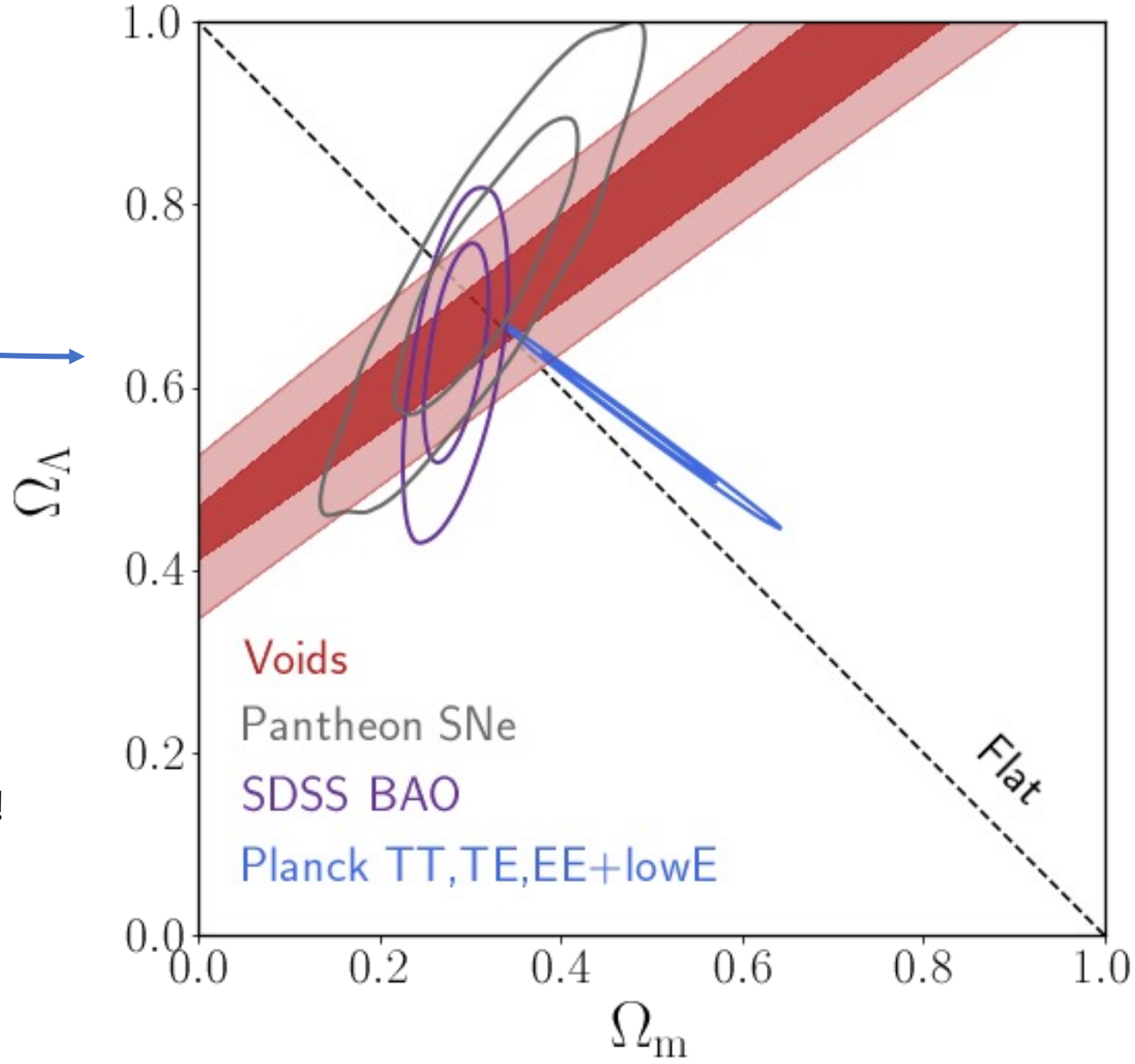


Constraints on D_M/D_H are tighter with voids than BAO + galaxy clustering



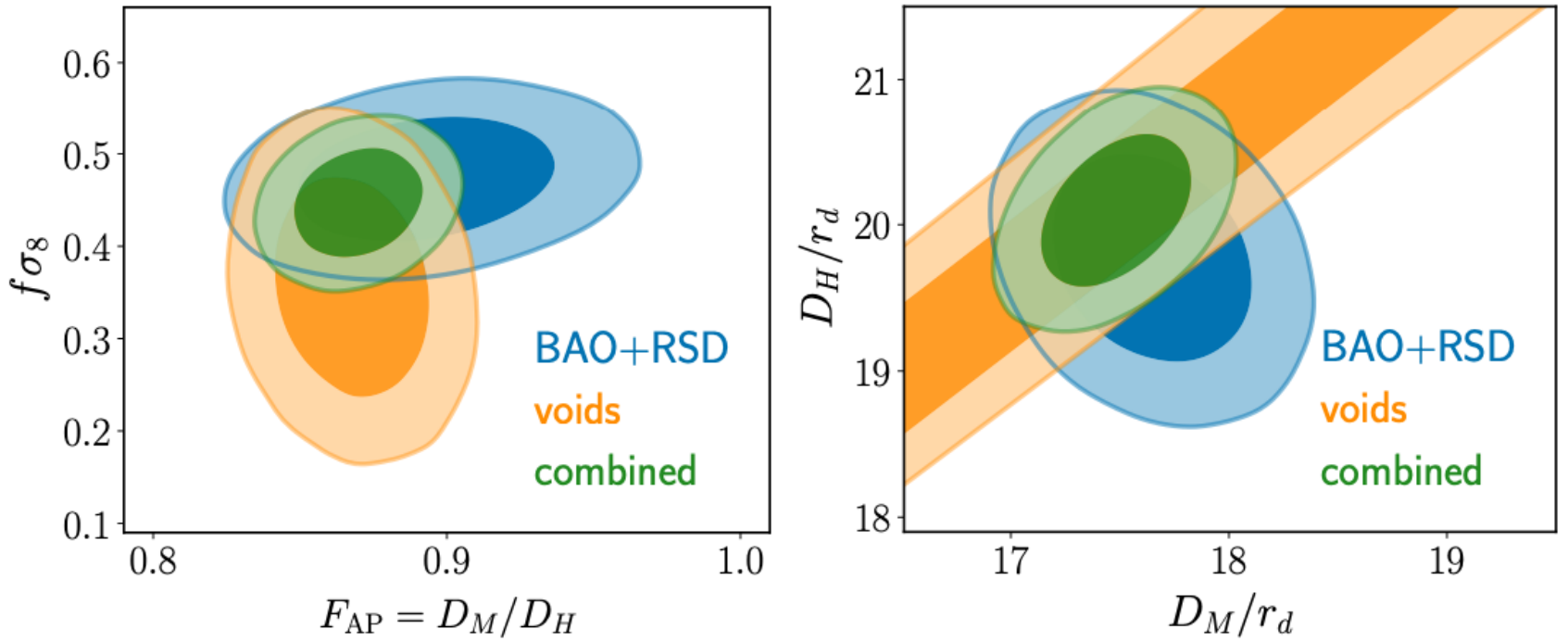
Results

Results for a flat ΛCDM Universe provide highly complimentary bounds in the Ω_m- Ω_Λ plane



Direct detection of Dark Energy from voids at a 8.7σ level!

Next Steps



Shown is eBOSS results only

Past work from Nadathur et. al, 2020 found a 55% reduction in the allowed volume in parameter space for eBOSS results alone!

Huge gain of information with no new data (this is all free!)

Summary

- We can extract more information from galaxy surveys! For free!
- This information provides powerful cosmological constraints on dark energy and other extended models
- BAO + RSD + Voids provide the best constraints from these surveys, will become standard for all galaxy surveys

See arXiv: 2205.06258 for more detail