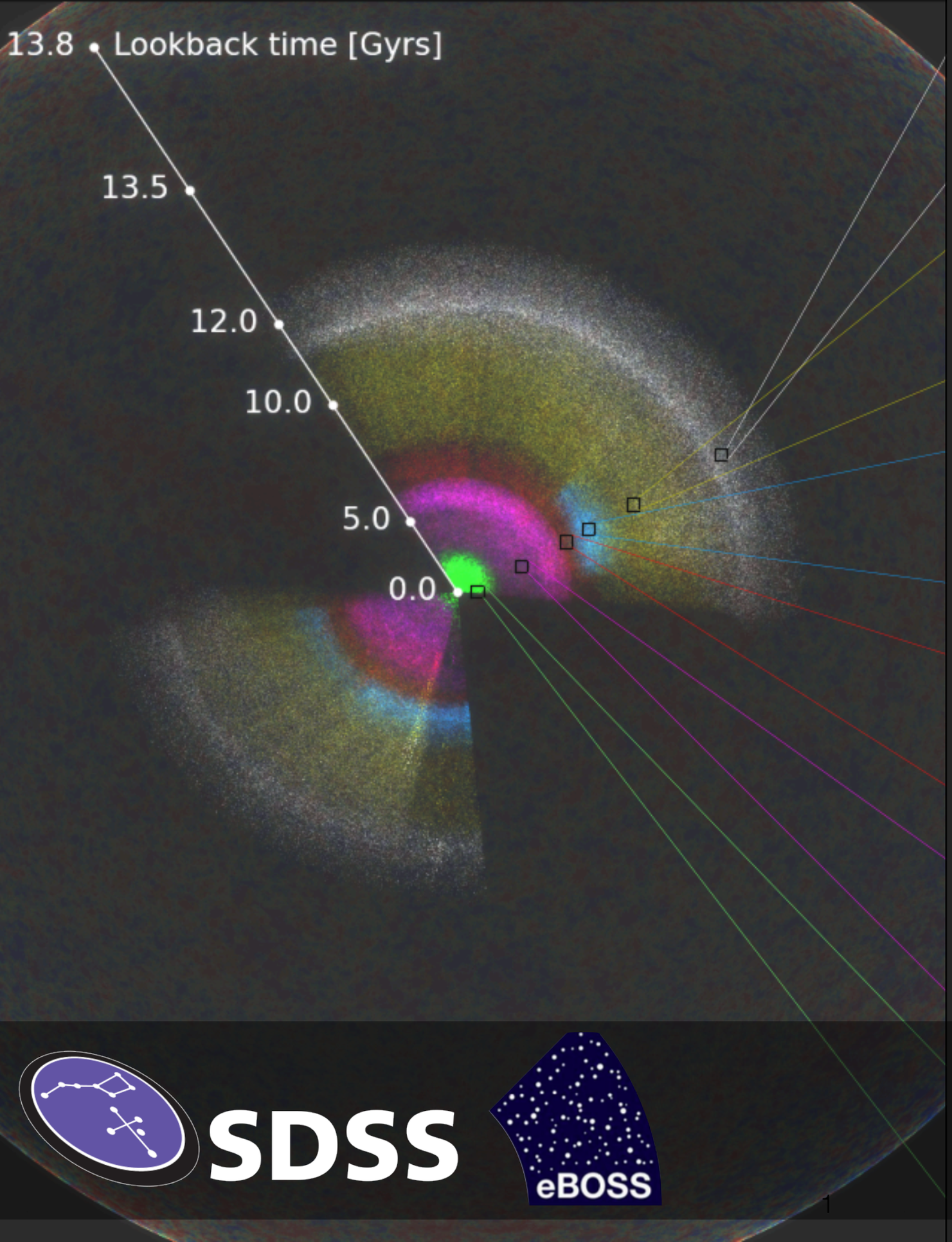


Beyond BAO: Cosmology with voids in (e)BOSS

Sesh Nadathur

seshadri.nadathur@port.ac.uk

SDSS eBOSS

UNIVERSITY OF PORTSMOUTH

eBOSS at CosmoHome

A series of talks:

- Overview and cosmological results – Eva and Julian
- Baryon Acoustic Oscillations – Mariana
- Redshift-space Distortions – Hector
- Multi-tracer approach – Gongbo
- + *this talk*

covers void-galaxy correlation analysis in LRG sample, SN+, 2008.06060

$$0.6 < z < 1.0$$

+

some earlier results from BOSS SN+, 1904.01030, 2001.11044

Related eBOSS void results (not discussed here): Aubert+, 2007.09013

Information from galaxy surveys

Standard procedure: 3D map of galaxy/quasar positions, measure 2-point statistics

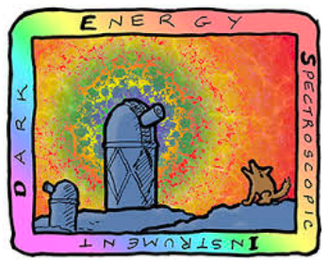
What information can we get?

– combinations of distance ($D_M(z)$) and expansion rate ($H(z)$)

– growth rate of structure, $f\sigma_8$ *(see Hector's talk)*

How can we get *MORE* information?

1. build a bigger map, get more data! (wait for DESI)



2. better modelling of 2-pt stats on small non-linear scales (eg EFT)

3. measure different things! – e.g. restrict to regions where linear theory works
   Voids allow us to do this.

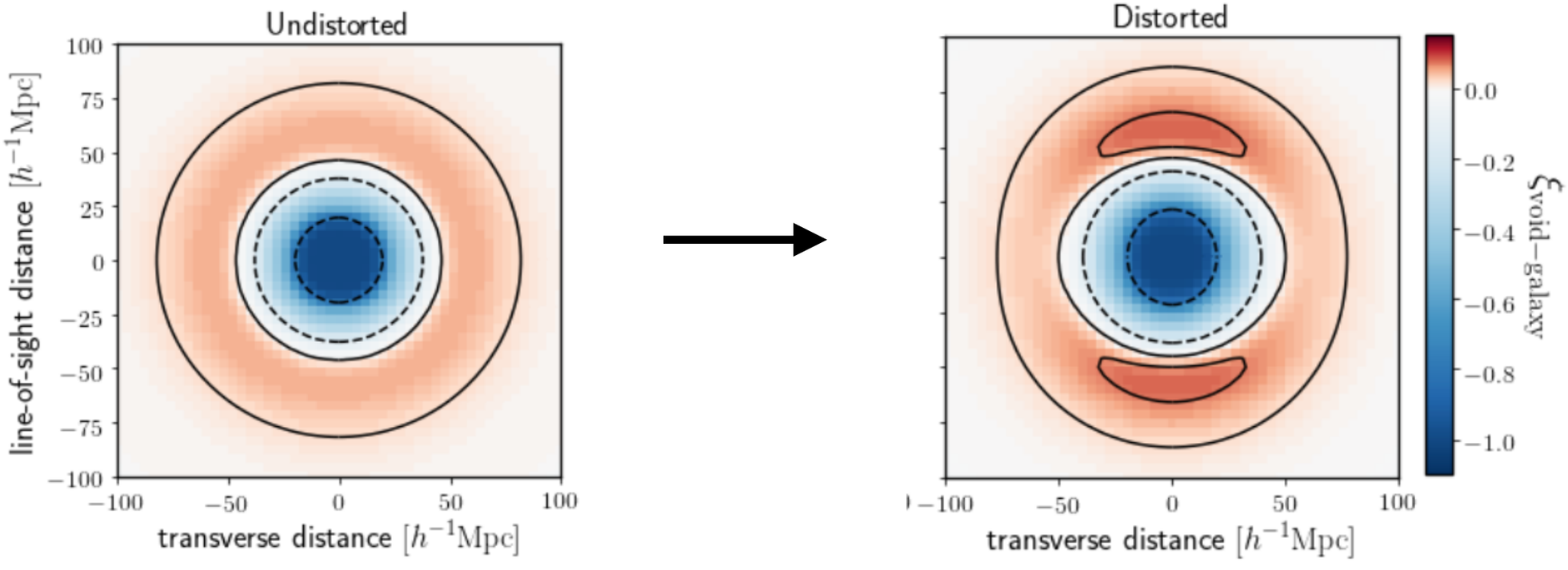
Void-galaxy correlation

Voids

- regions of few galaxies & low matter density
- algorithmically identified from 3D galaxy maps
- closer to Zeldovich behaviour

Void-galaxy correlation

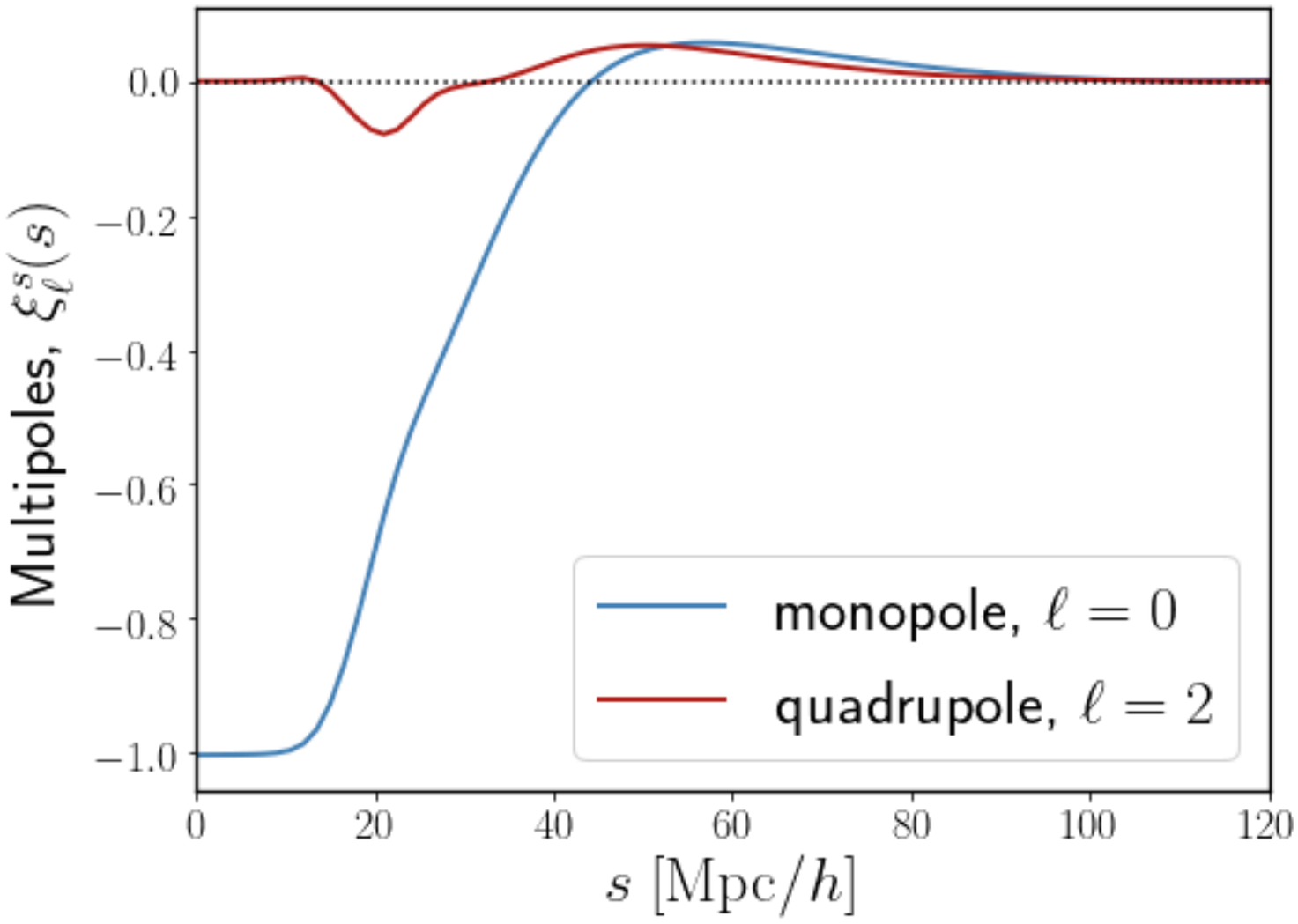
- cross-correlation of void centres* with galaxies
  *for our purposes, void centre = position of minimum density
- = galaxy number density around voids
- (mildly) anisotropic in redshift-space: redshift distortions



Multipole decomposition

Standard compression of measured anisotropic correlation function $\xi^s(\mathbf{s})$ into Legendre multipoles:

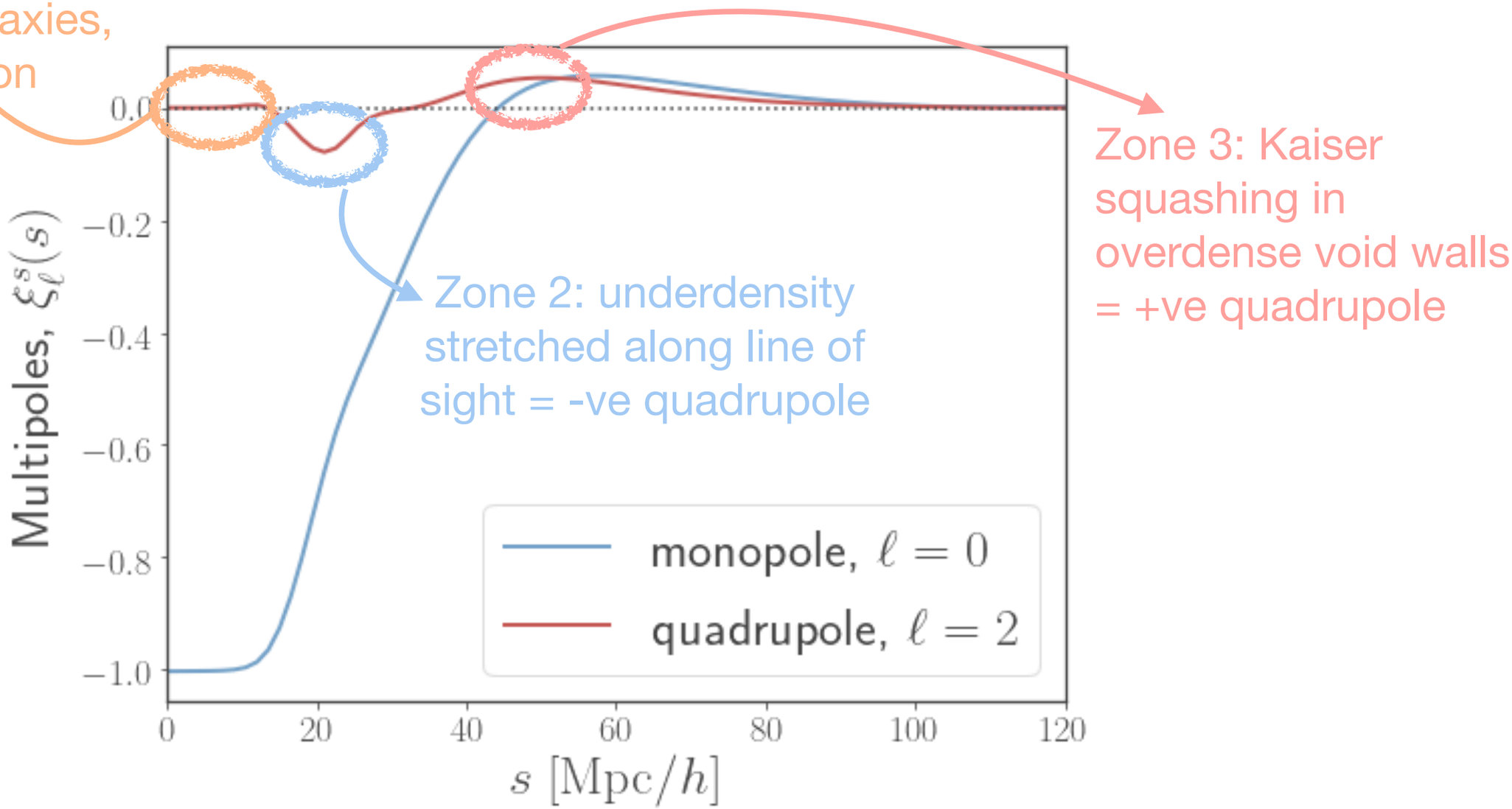
$$\xi^s_\ell(s) = (2\ell + 1) \int_0^1 \xi^s(s, \mu) L_\ell(\mu)\, \mathrm{d}\mu$$



Multipole decomposition

Standard compression of measured anisotropic correlation function $\xi^s(\mathbf{s})$ into Legendre multipoles:

$$\xi^s_\ell(s) = (2\ell + 1) \int_0^1 \xi^s(s, \mu) L_\ell(\mu)\, \mathrm{d}\mu$$



RSD and Alcock-Paczynski

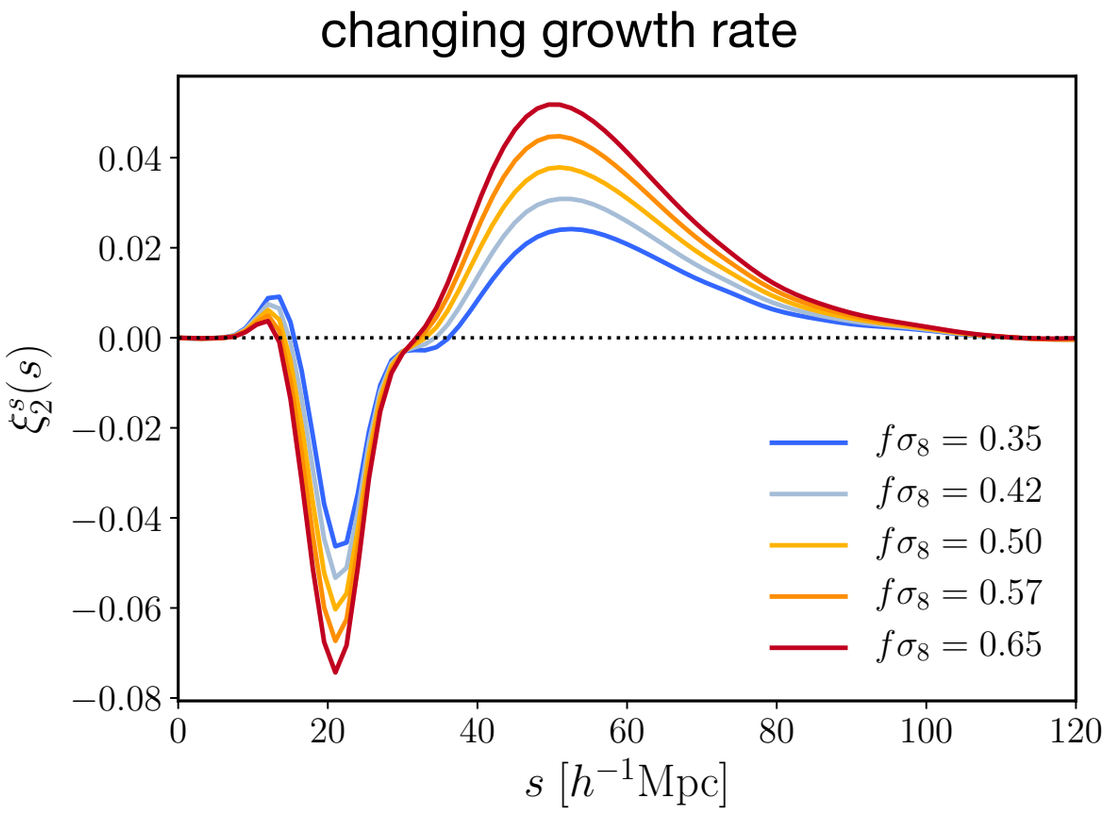
RSD: distortions introduced due to shifts in galaxy redshifts caused by velocity outflows from voids

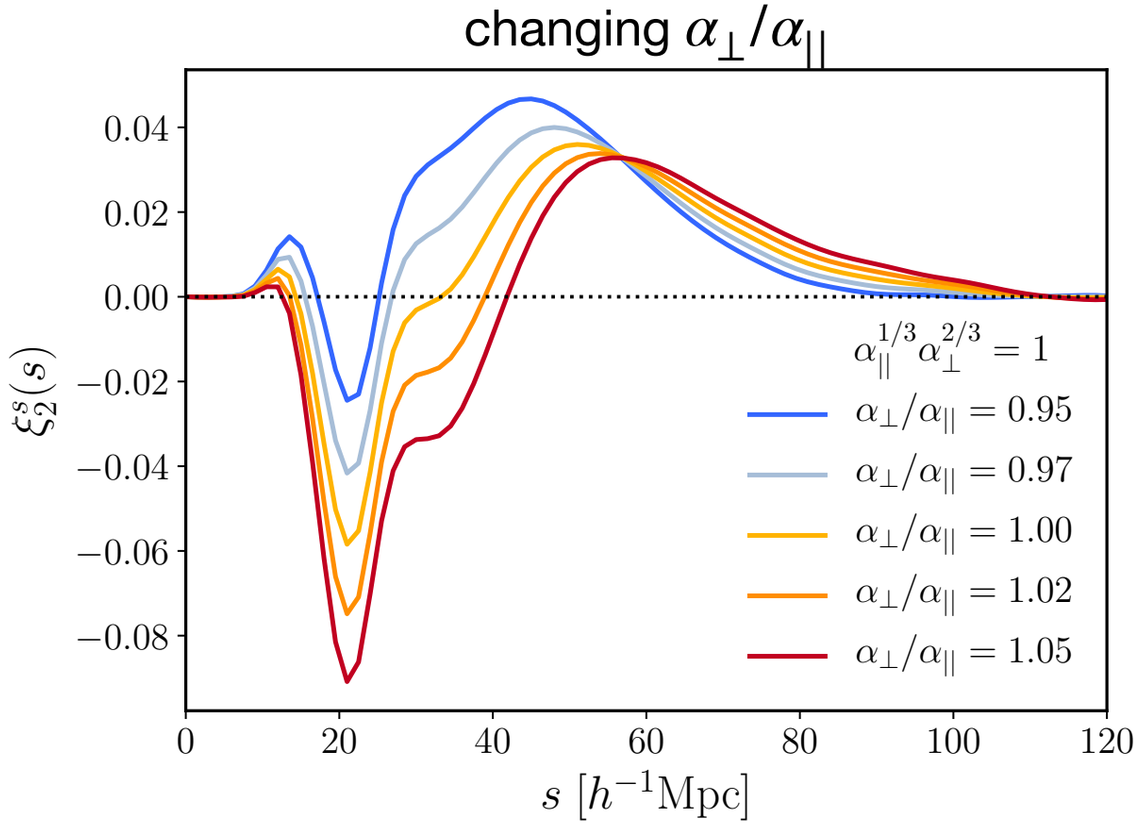
$$\text{distortion} \propto f\sigma_8$$

AP effect: distortion introduced due to transforming measured redshifts to distances using the wrong cosmological model *(see Hector's talk!)*

$$s_\perp = \alpha_\perp s_\perp^{\rm fid}, \;\; s_{||} = \alpha_{||} s_{||}^{\rm fid}$$

Both affect the quadrupole term, but in very distinct ways





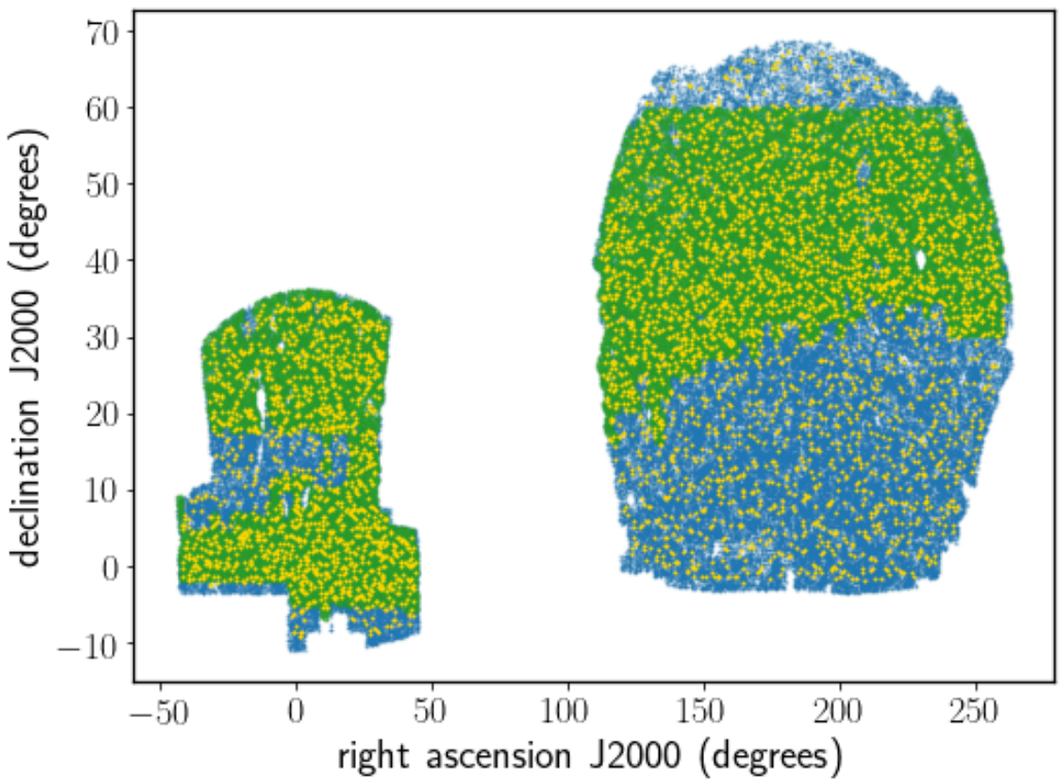
Voids in the eBOSS LRG sample

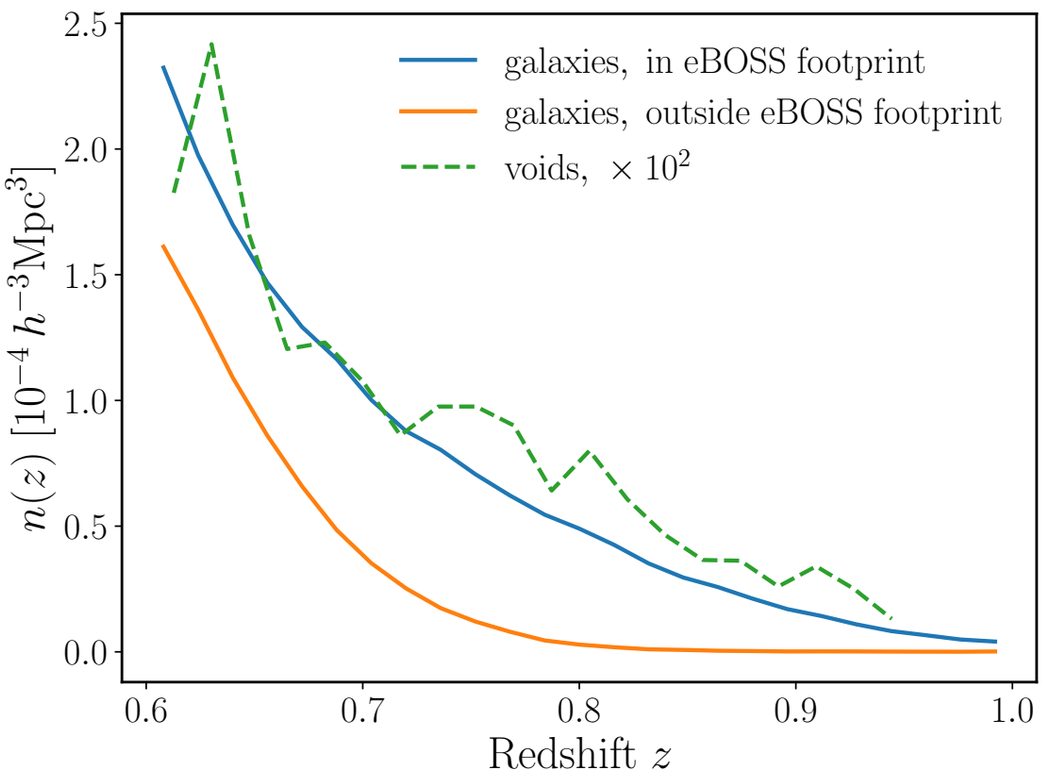
Voids identified using the REVOLVER code (https://github.com/seshnadathur/Revolver)

IMPORTANT: uses an RSD-removal technique to estimate real-space galaxy distribution before void-finding!

– removes selection biases in sample

– allows estimation of real-space (undistorted) correlation





SN+, 2008.06060, see also SN+, 1805.09349

Modelling the correlation

Basic model:

Jacobian of coordinate transform

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

redshift-space correlation

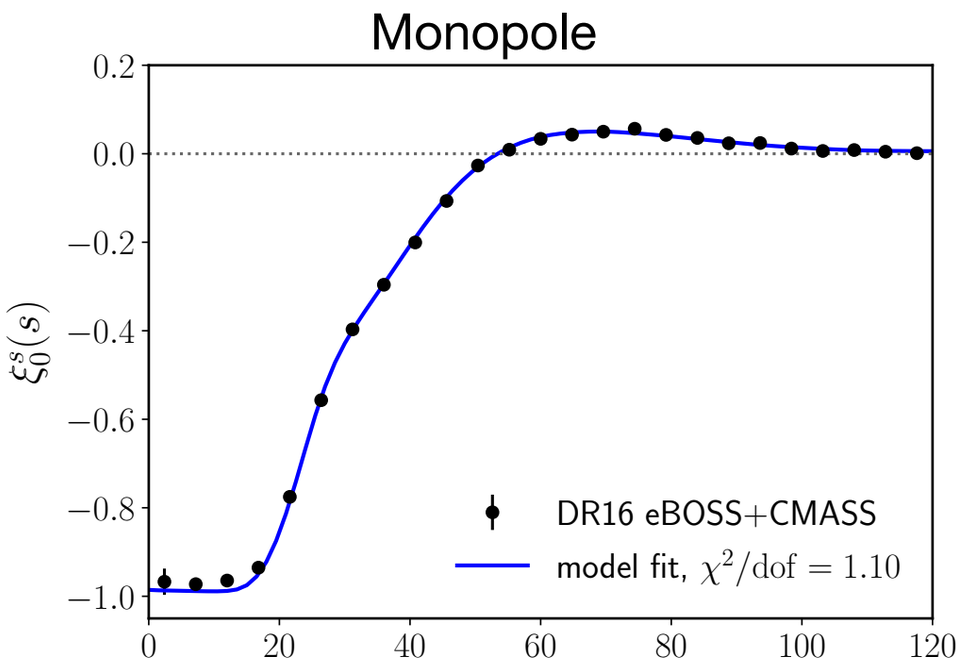
real-space correlation

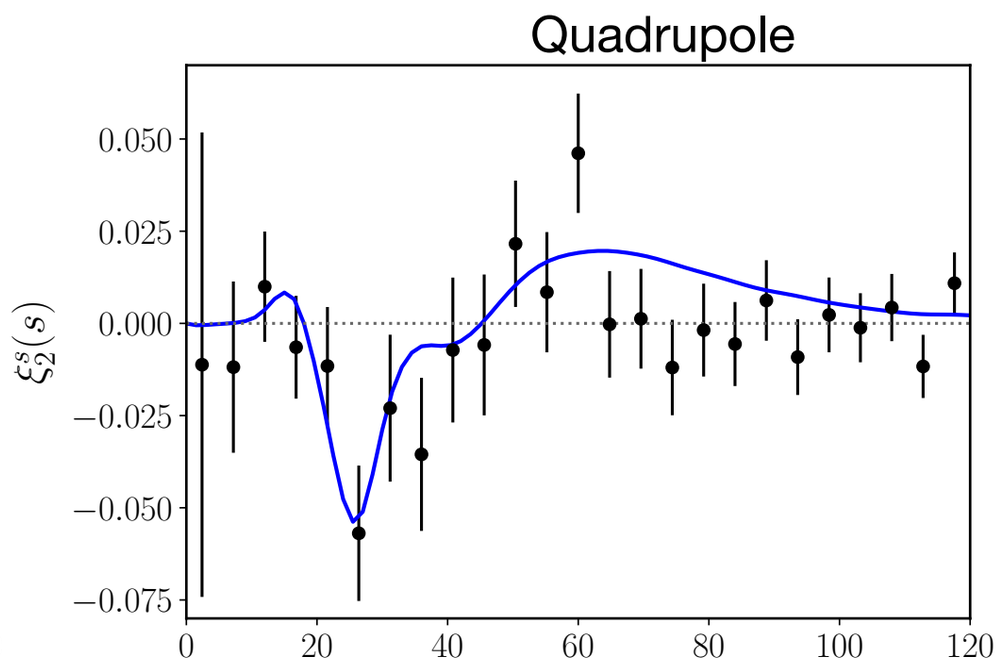
radial velocity outflow from void
(modelled by linear perturbation theory)

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

Model developed by SN & Percival, 1712.07575

Fits to the data

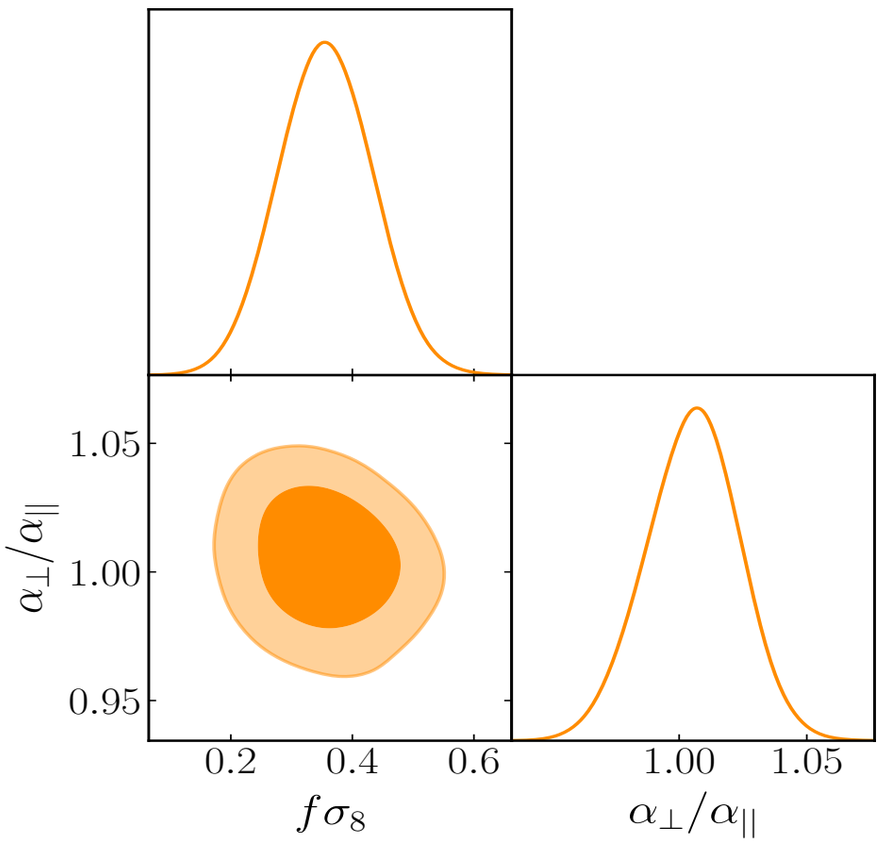




Model fit uses VICTOR code*

- fits for $f\sigma_8$ and $\alpha_\perp/\alpha_{||}$ + 2 nuisance parameters
- data vector & covariances depend on parameter $\beta = f/b$ via RSD-removal step: consistently accounted for in fits!
- MCMC exploration of posterior

*https://github.com/seshnadathur/victor



Tests for systematic errors

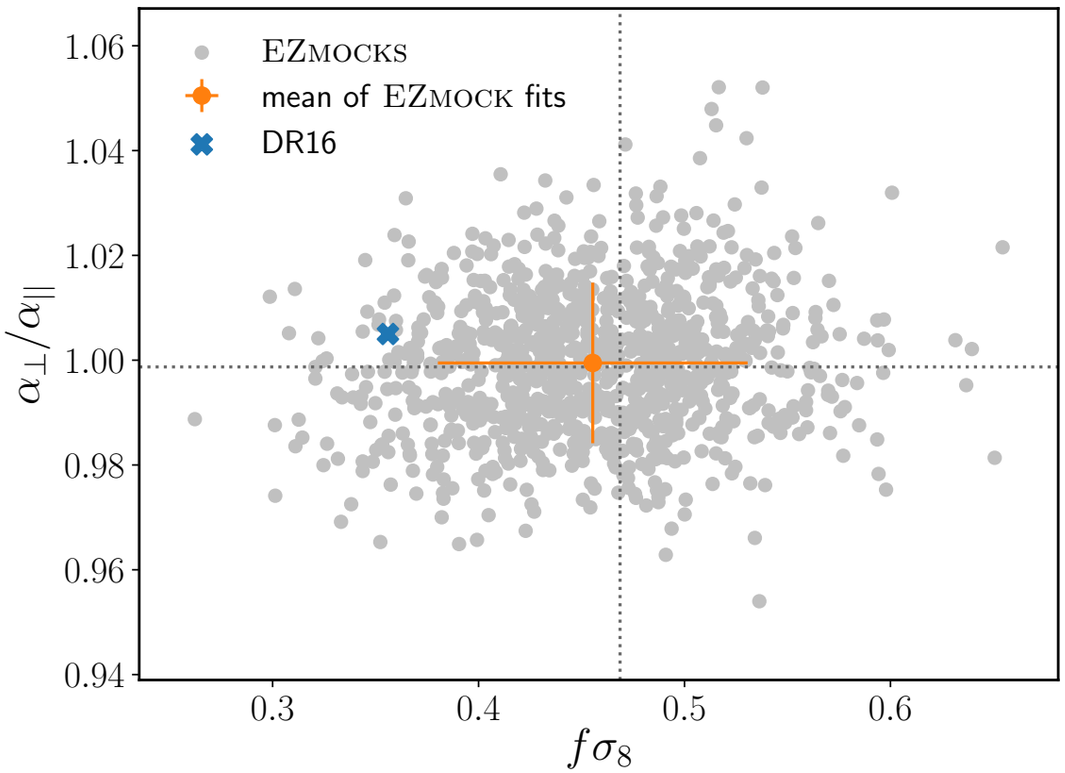
As for BAO+RSD analyses, systematics checks use simulated catalogues (fast EZMOCKS + N-body NSERIES)

Test for:

- modelling limitations + effects due to composite sample
- fiducial cosmology systematics

Systematics are small contribution to total error budget and are at $< 1\,\%$ level for $\alpha_\perp/\alpha_{||}$

Parameter	$\sigma_{\rm syst,model}$	$\sigma_{\rm syst,cosmo}$	$\sigma_{\rm syst,tot}$	$\sigma_{\rm stat}$	$\sqrt{\sigma^2_{\rm syst,tot}+\sigma^2_{\rm stat}}$
$f\sigma_8$	0.0144	0.0075	0.0162	0.077	0.079
$\alpha_\perp/\alpha_{\|}$	0.0042	0.0081	0.0091	0.018	0.020

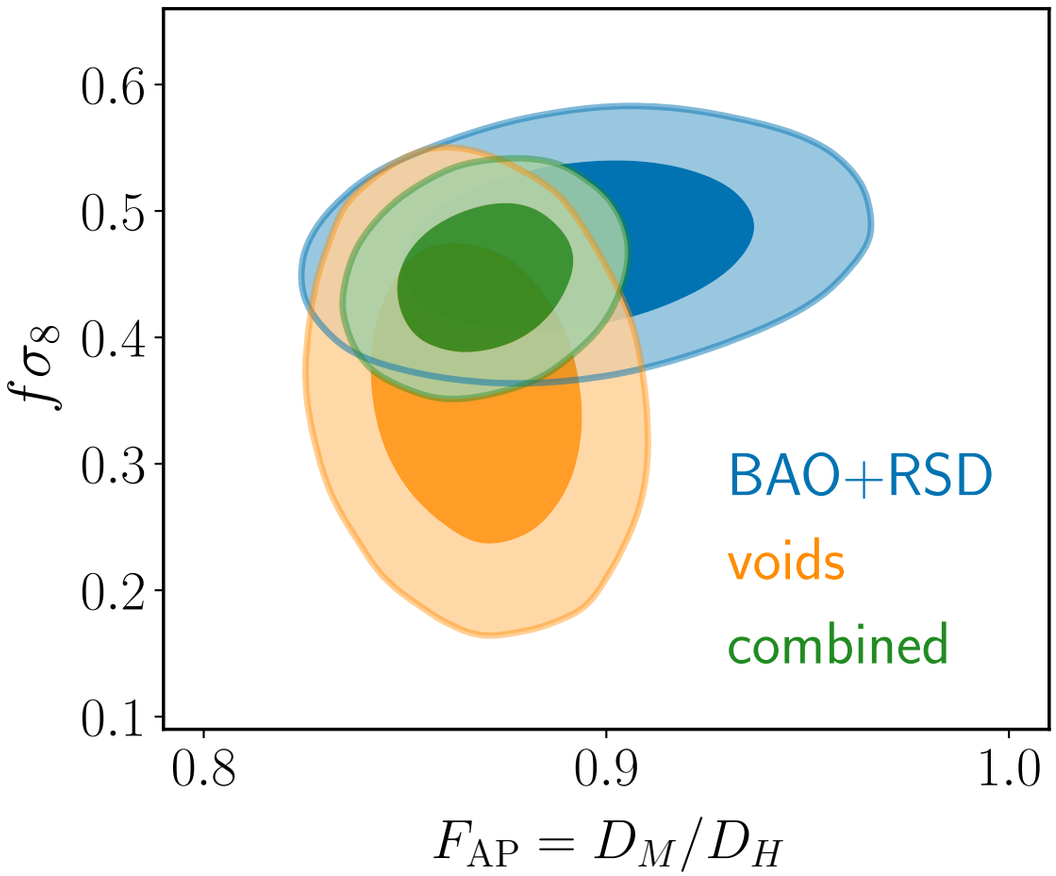


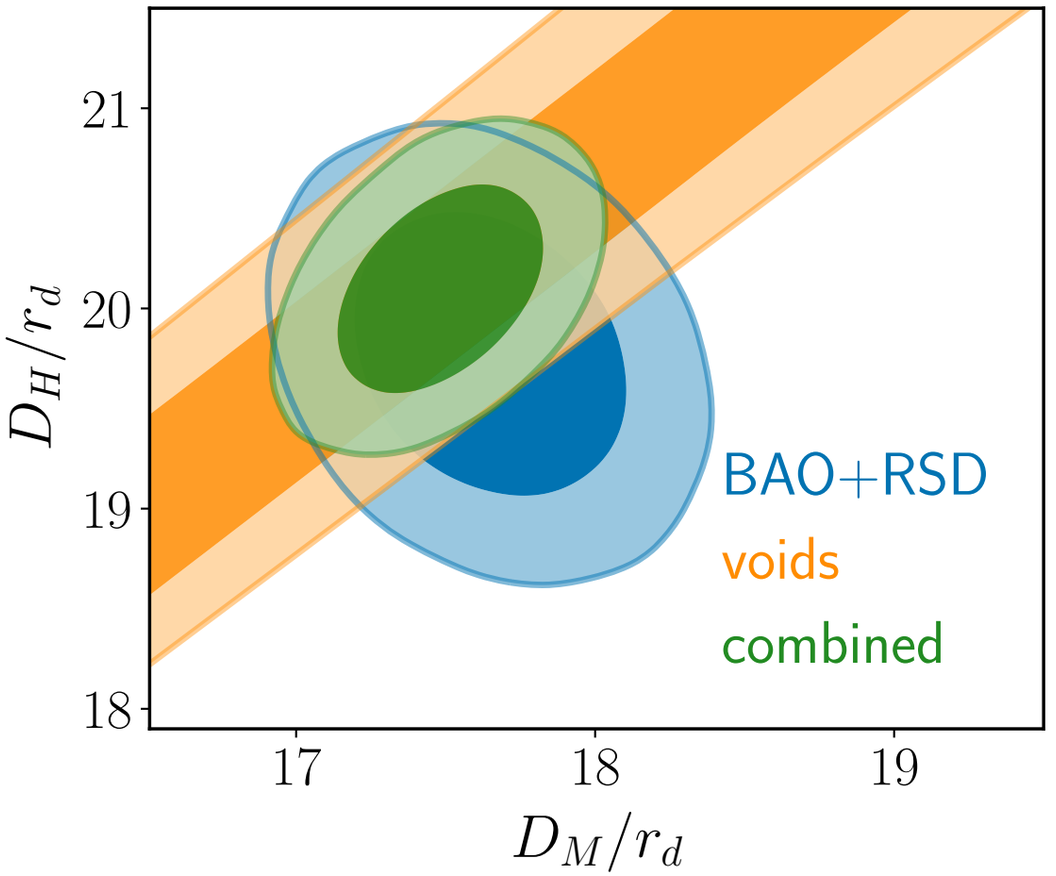
details in SN+, 2008.06060

Results

- Geometrical AP measurement to much higher precision than from BAO+RSD
- Parameter constraints ~orthogonal to those from galaxy clustering
- Low correlation with galaxy clustering measurements (inferred from mocks)

→ huge gain of information with no new data!





Consensus constraints

Combined with final BAO+RSD results, voids:

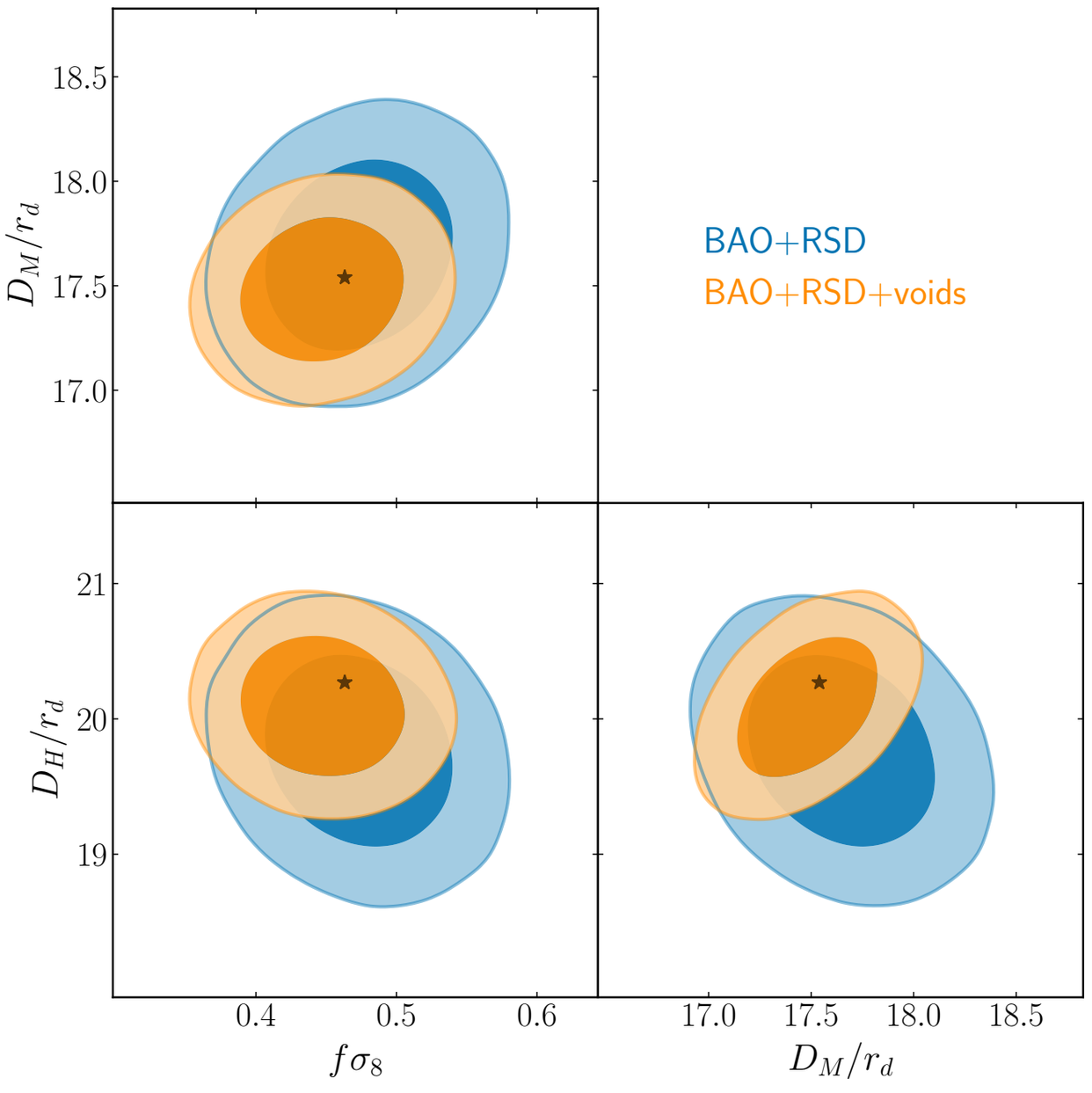
- improve errors in $f\sigma_8$, D_M/r_d and D_H/r_d by 13%, 23% and 28%
- reduce allowed volume by 55% (!)
- final measurements

$$D_M/r_d = 17.48 \pm 0.23 \quad (1.3\%)$$

$$D_H/r_d = 20.10 \pm 0.34 \quad (1.7\%)$$

$$f\sigma_8 = 0.447 \pm 0.039 \quad (8.7\%)$$

- consistent with Planck LCDM



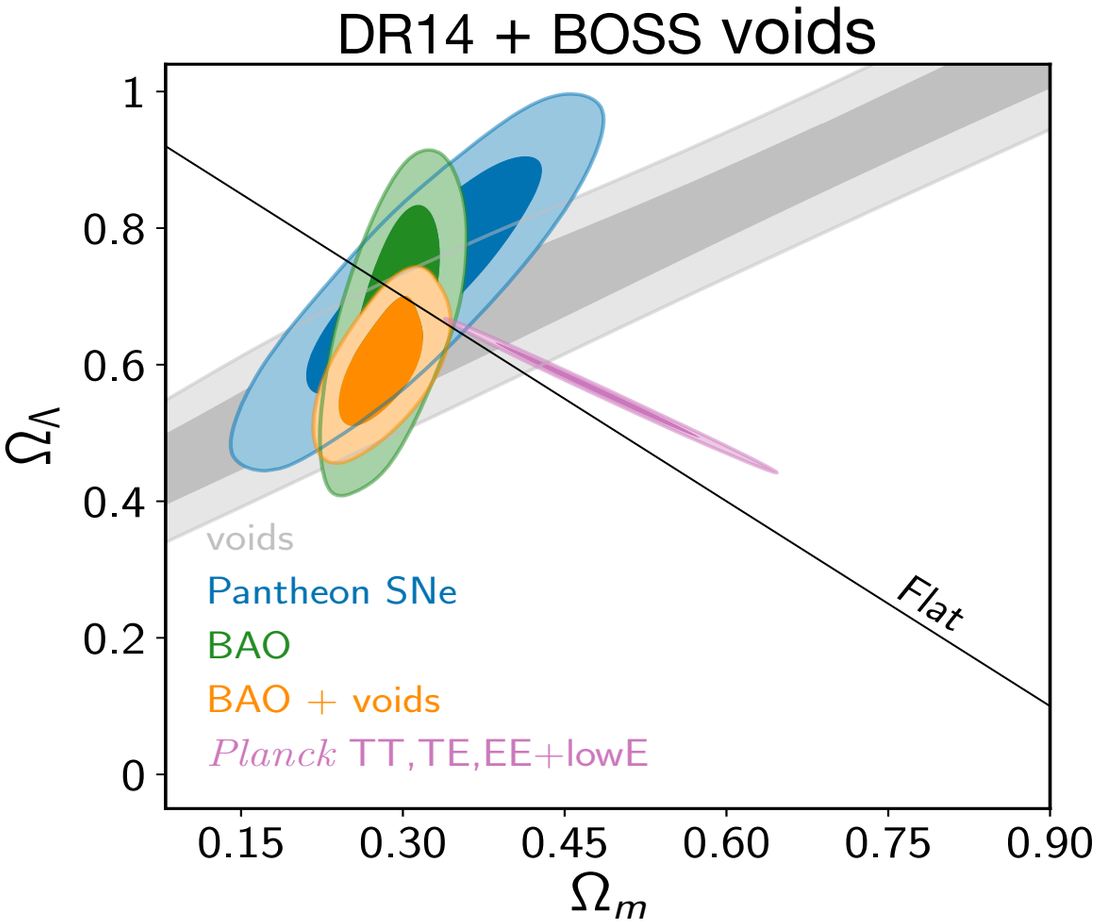
Similar to previous BOSS results, SN+, 1904.01030

Conclusions

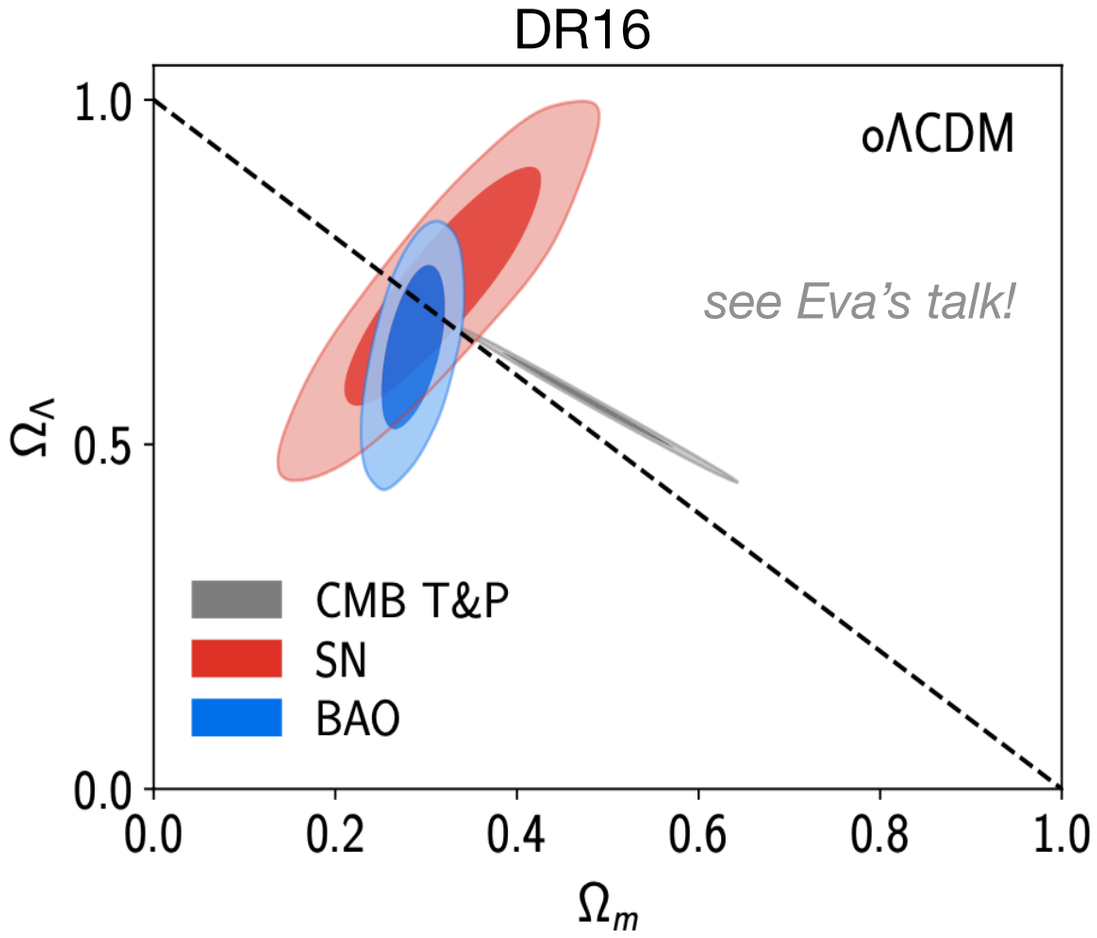
Robust demonstration of new method for LSS surveys

Voids add a lot *on top of* BAO and RSD from all tracers

E.g.: older (BOSS) void results ($z = 0.55$) + older (DR14) BAO results, vs latest eBOSS DR16 (w/o voids)



SN+, 2001.11044



eBOSS, 2007.08991