



## Extract cosmological constraints from galaxy clustering using SDSS-III/BOSS final data release (DR12)

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#### Chuang et al. 2017 & Pellejero-Ibanez et al. 2017, submitted with the BOSS collaboration papers

The Clustering of Galaxies in the Completed SDSS-III Baryon Oscillation Spectroscopic Survey: single-probe measurements from DR12 galaxy clustering – towards an accurate model

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Rubiñ<br/>J. EiseThe clustering of galaxies in the completed SDSS-III BaryonNiklasOscillation Spectroscopic Survey: double-probe measurements fromSáncheBOSS galaxy clustering & Planck data – towards an analysisMariaiwithout informative priors

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#### SDSS-III/BOSS

#### (Sloan Digital Sky Survey-III / Baryon Oscillation Sky Survey)



- Final data release (DR12) in Dec. 2014
- Final data release for large scale structure catalgoues in July 2016.
- 1,000-fiber spectrograph, resolution R~2000
- Wavelength: 360-1000 nm
- 10,200 square degrees (~quarter of sky)
- Redshifts of 1.35 million luminous galaxies to z ~ 0.7
- Lyman-α forest spectra of 230,000 quasars (160,000 redshifts > 2.15)



#### SDSS-III/BOSS









#### Main Goal of the BOSS

Measure Dark Energy

# Density distribution measured from galaxy sample (correlation function)

#### Chuang et al. 2017



We can measure the evolution of dark energy by measuring the evolution of the density distribution.





#### 2-D Correlation Functions & multipoles

$$\xi(s,\mu) = \frac{DD(s,\mu) - 2DR(s,\mu) + RR(s,\mu)}{RR(s,\mu)}, \quad (1)$$

where s is the separation of a pair of objects and  $\mu$  is the cosine of the angle between the directions between the line of sight (LOS) and the line connecting the pair the objects. DD, DR, and RR represent the normalized data-data, data-random, and random-random pair counts, respectively, for a given distance range. The LOS is defined as the direction from the observer to the centre of a galaxy pair. Our bin size is  $\Delta s = 1 h^{-1}$ Mpc and  $\Delta \mu = 0.01$ . The Landy and Szalay estimator has minimal variance for a Poisson process.

$$\xi_l(s) \equiv \frac{2l+1}{2} \int_{-1}^{1} d\mu \,\xi(s,\mu) P_l(\mu),$$
  
where  $P_l(\mu)$  is the Legendre Polynomial  $(l = 0 \text{ and } 2 \text{ here})$ 

## Monopole and quadrupole from BOSS DR12 CMASS and LOWZ sample (Chuang et al. 2017)





Correct the systematics from star density



#### Covariance matrix

 We use 2000 mock galaxies based on the PATCHY code, one of the three methodologies which have good performance in the mock comparison paper (Chuang et al. 2015).



#### Theoretical model at small scales relies on the understanding of the hosting halos of the given galaxy sample

Monopole Quadrupole 50 120Selection 1 Selection 2 2510080 0  $(s)^{-25} \xi_{5}(s)$  $s^2 \xi_0(s)$ 60 40-50Selection 2 -75200.10.2 $\xi_2/\xi_{2,sel1}$  $-\xi_0/\xi_{0,sel1}$ T -----0.1-0.210 20 40 500 10 203030 60

s(Mpc/h)

Two halo (main halo+subhalo) catalogues selected from the same BigMultiDark simulation box with the same number density have the same monopole (same bias) but very different quadrupole at s < 40 Mpc/h.

50

s(Mpc/h)

60



## Priors for Markov Chain Monte Carlo (MCMC) analysis

- For galaxy clustering, we have at least 8 parameters for fitting:
  - H(z), D<sub>A</sub>(z),  $\Omega_m h^2$ ,  $\beta$ , and b  $\sigma_8$  are well constrained
  - $\Omega_b h^2$ , n<sub>s</sub>, and f (or bias) are NOT well constrained
- How to handle those parameters not well constrained by galaxy clustering? We need priors

## **Informative Priors**

- Strong priors:
- 1. Fix  $\Omega_b h^2$ ,  $n_s$ , and  $\Omega_m h^2$  to the best fit values from CMB
- 2. Use 1 $\sigma$  Gaussian priors of  $\Omega_b h^2$ ,  $n_s$ , and  $\Omega_m h^2$  from CMB
- Concerns raise when combining the CMB data later
- Weak priors:
- $\succ$  10  $\sigma$  flat priors on  $\Omega_{\rm b}$ h<sup>2</sup> and n<sub>s</sub> measured from CMB  $\rightarrow$  Single-probe
- No priors:
- $\succ$  Use joint data set of CMB and galaxy clustering  $\rightarrow$  Double-probe

#### Problem of Single-probe methodology

- Wide priors make MCMC analysis difficult to converge.
- It was OK when we used the 2-D dewiggle model which requires only few seconds for the computation for a model.
- It is NOT OK when we use more complicate model (e.g. Gaussian streaming model by Reid & White 2011) since it takes minutes for one computation.

Solution for the problem of Single-probe methodology

- Use fast model (i.e. 2-D dewiggle model) to narrow down the parameter space first.
- Calibrate the likelihood with slow model (e.g. Gaussian streaming model) by applying importance sampling  $W_{new} = W_{old} \frac{L_{slow}}{L_{fast}},$

#### Dark-energy-model-independent parameters from galaxies

1. H(z), Hubble parameter

2.  $D_A(z)$ , Angular diameter distance

3.  $\Omega_m h^2$ , physical matter fraction

4.  $f\sigma_8$ , normalized growth rate

	0.15 < z < 0.43	0.43 < z < 0.75	0.15 < z < 0.30	0.30 < z < 0.43	0.43 < z < 0.55	0.55 < z < 0.75
$D_A r_s^{fid} / r_s$	$956\pm28$	$1421\pm23$	$826\pm45$	$993\pm65$	$1288\pm31$	$1444\pm41$
$Hr_s/r_s^{fid}$	$75.0\pm4.0$	$96.7\pm2.7$	$78.8\pm5.6$	$74.8\pm6.3$	$87.5\pm4.8$	$98.4 \pm 3.7$
$f\sigma_8$	$0.397\pm0.073$	$0.497 \pm 0.058$	$0.493 \pm 0.105$	$0.378\pm0.076$	$0.456 \pm 0.068$	$0.454 \pm 0.064$
$\Omega_m h^2$	$0.143 \pm 0.017$	$0.137 \pm 0.015$	$0.136 \pm 0.017$	$0.147 \pm 0.014$	$0.144\pm0.016$	$0.140 \pm 0.017$
$D_V r_s^{fid} / r_s$	$1268\pm26$	$2106\pm23$	$987\pm40$	$1402\pm69$	$1837\pm36$	$2220\pm39$
β	$0.301\pm0.066$	$0.435 \pm 0.070$	$0.389 \pm 0.096$	$0.287\pm0.067$	$0.367\pm0.072$	$0.410\pm0.077$
$b\sigma_8$	$1.332\pm0.099$	$1.154\pm0.090$	$1.287\pm0.129$	$1.332\pm0.137$	$1.256\pm0.112$	$1.120\pm0.094$

$$\chi^2_{\rm CMASS} = \Delta_{\rm CMASS} M^{-1}_{ij,\rm CMASS} \Delta_{\rm CMASS},$$

$$\Delta_{\text{CMASS}} = \begin{pmatrix} D_A(z) \frac{r_{s,fid}}{r_s} - 1421 \\ H(z) \frac{r_s}{r_{s,fid}} - 96.7 \\ f(z)\sigma_8(z) - 0.497 \\ \Omega_m h^2 - 0.137 \end{pmatrix}$$

Use our measurements one can derive the constraints of the cosmological parameters of a given model, e.g. ACDM.

			$M_{ij, CMASS}$ :	_
0.53559E + 03	0.27875E + 02	0.70092E + 00	-0.29507E - 01	
0.27875E + 02	0.74866E + 01	0.85855E - 01	$-0.92898E\!-\!02$	
0.70092E + 00	0.85855E - 01	0.33643E - 02	$-0.51341E\!-\!03$	'
-0.29507E - 01	-0.92898E - 02	-0.51341E - 03	0.22673E - 03	

,

## Assume dark energy models



#### Double-probe methodology

 Goal: dark-energy-model independent measurements from CMB + Galaxies

#### Dark-energy-model-independent parameters from CMB

- 1.  $R = (\Omega_m h^2)^{1/2} r(z^*)$
- 2.  $I_a = \pi r(z^*)/r_s(z^*)$
- 3.  $\Omega_b h^2$  = physical baryon fraction
- 4.  $n_s = scalar index of the power law primordial fluctuation$
- 5.  $A_s = scalar amplitude of the power law primordial fluctuation$
- $r(z^*) \rightarrow$  comoving distance to the last scattering
- $r_s(z^*) \rightarrow$  comoving sound horizon at the last scattering

Dark-energy-model-independent parameters from CMB+galaxies

- 1.  $R = (\Omega_m h^2)^{1/2} r(z^*)$
- 2.  $I_a = \pi r(z^*)/r_s(z^*)$
- 3.  $\Omega_b h^2$  = physical baryon fraction
- 4.  $n_s = scalar index of the power law primordial fluctuation$
- 5.  $A_s = scalar amplitude of the power law primordial fluctuation$
- 6. H(z), Hubble parameter
- 7. D<sub>A</sub>(z), Angular diameter distance
- 8.  $f\sigma_8(z)$ , normalized growth rate

Pellejero-Ibanez, Chuang, et al.

#### Results of double probe from Planck + BOSS

Planck15

BOSS DR12



$f\sigma_8(0.59)$	0.510 :
$H(0.59)r_s/r_{s,fid}$	97.9
$D_A(0.59)r_{s,fid}/r_s$	1422
$f\sigma_8(0.32)$	0.431 :
$H(0.32)r_s/r_{s,fid}$	79.1
$D_A(0.32)r_{s,fid}/r_s$	956
R	1.7430 :
$l_a$	301.70
$\Omega_b h^2$	0.02233 :
$n_s$	0.9690 :
$\ln(10^{10}A_s)$	3.040 :
$\Omega_k$	-0.003

 $\begin{array}{c} 0.510 \pm 0.047 \\ 97.9 \pm 3.1 \\ 1422 \pm 25 \\ 0.431 \pm 0.063 \\ 79.1 \pm 3.3 \\ 956 \pm 27 \\ 1.7430 \pm 0.0080 \\ 301.70 \pm 0.15 \\ .02233 \pm 0.00025 \\ 0.9690 \pm 0.0066 \\ 3.040 \pm 0.036 \\ -0.003 \pm 0.006 \end{array}$ 

# Double probe measurements

Assume a cosmology model and compute the likelihood  $\chi^{2}_{\text{CMB+galaxy}} = \Delta_{\text{CMB+galaxy}} M^{-1}_{ij,\text{CMB+galaxy}} \Delta_{\text{CMB+galaxy}}, \quad \Delta_{\text{CMB+galaxy}} =$ 

 $\begin{array}{c} f\sigma_8(0.59){-}0.510\\ H(0.59)r_s/r_{s,fid}{-}97.9\\ D_A(0.59)r_{s,fid}/r_s{-}1422\\ f\sigma_8(0.32){-}0.431\\ H(0.32)r_s/r_{s,fid}{-}79.1\\ D_A(0.32)r_{s,fid}/r_s{-}956\\ R{-}1.7430\\ l_a{-}301.70\\ \Omega_bh^2{-}0.02233\\ n_s{-}0.9690\\ \ln(10^{10}A_s){-}3.040\\ \Omega_k{-}0.003\\ \end{array}$ 

## Assume dark energy models



#### Constraints on neutrino masses using double probe measurements



#### Full likelihood analysis (Planck+BOSS+SNIa)



Figure 19. Probability density for  $\Sigma m_{\nu}$  from the full likelihood analysis measurement for joint and JLA data sets. We assume lensing likelihood with fixed  $A_{\rm L} = 1$ . All the measurements are consistent with  $\Sigma m_{\nu} = 0$  (see Sec. 7.2 and Table 13).

Figure 20. Probability density for  $\Sigma m_{\nu}$  from the full likelihood analysis measurement for joint and JLA data sets. We assume lensing likelihood with variable  $A_{\rm L}$  (see Sec. 7.2 and Table 14).

#### Remove overall shape information







Figure 11. Probability density for  $\Sigma m_{\nu}$  from the full-likelihood-analysis of the joint data set.  $\Sigma m_{\nu}$  is one of the parameters to be constrained. Planck data includes lensing with  $A_{\rm L} = 1$ . The overall shape information of the monopole of the correlation function from the BOSS galaxy clustering is removed with a polynomial function (see Sec. 7.2 and Table 10).

## Summary

- We have developed/improved the single probe and double probe methodologies and applied to the BOSS final galaxy sample.
- We provide a self-consistent and convenient way to study dark energy models.
- We will apply our methods to the eBOSS galaxy sample.