BAO analysis from the DR14 QSO sample

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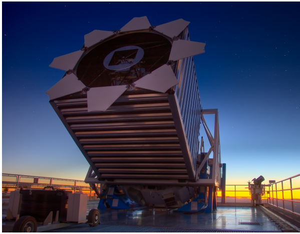
Introduction: the eBOSS survey

- Apache Point Observatory (APO) 2.5-m telescope.
- SDSS-III project. 2009-2014 BOSS: Baryon Oscillation Spectroscopic Survey
- SDSS-IV project. 2014-2019 eBOSS: extended Baryon Oscillation Spectroscopic Survey
- 3 galaxy clustering programs (ELG, LRG, quasars) + Ly-α

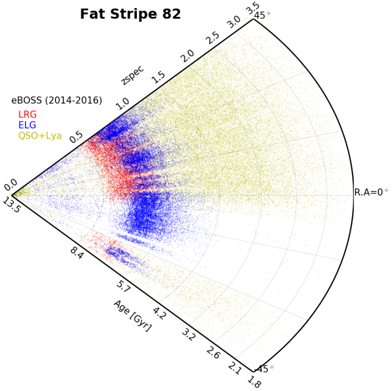
- new selection algorithms to identify redshift of galaxies
- BOSS had 99% success rate identifying redshifts of LRGs
- first eBOSS tests showed 70% of success rate on LRGs using same BOSS algorithms!



Introduction: the eBOSS survey

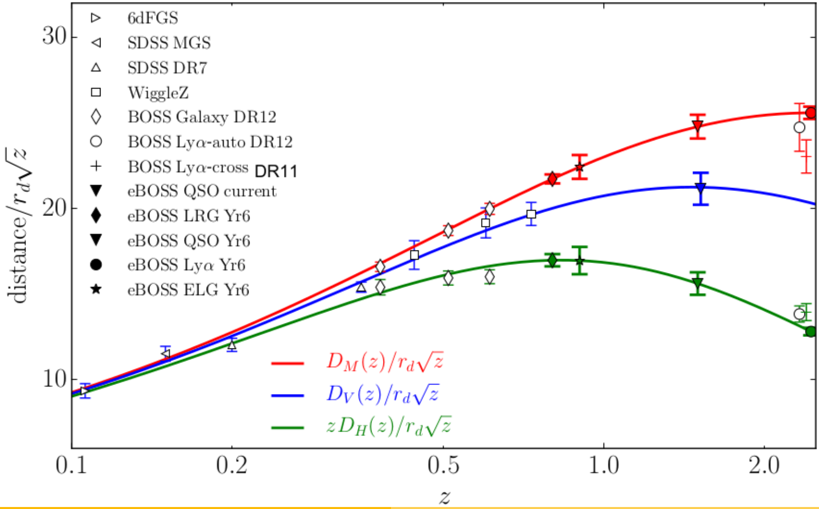
eBOSS survey: **ELG**, **LRG** and **QSO** samples

- **LRG** $0.6 < z < 1.0$; $z_{\rm eff} = 0.71$.
- **ELG** $0.6 < z < 1.1$; $z_{\rm eff} = 0.85$.
- **QSO** $0.8 < z < 2.2$; $z_{\rm eff} = 1.5$.
- Ly-α $z_{\rm eff} = 2.33$

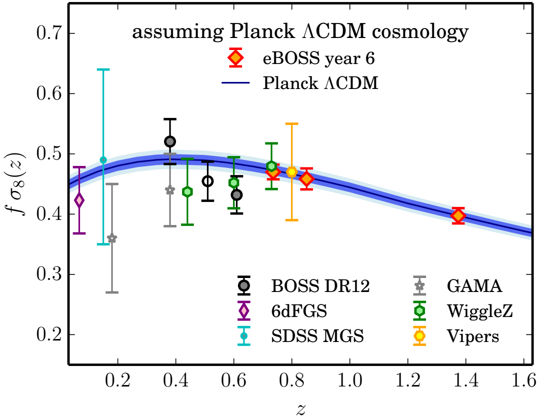


[Credit : Anand Raichoor]

Introduction: the eBOSS survey

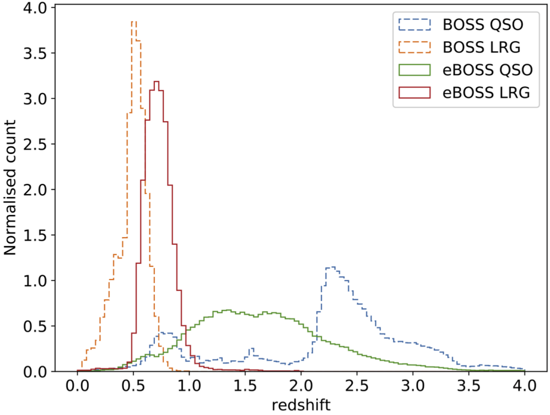


Introduction: the eBOSS survey



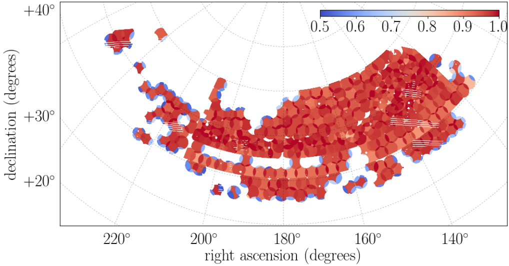
Low Density of Quasars!

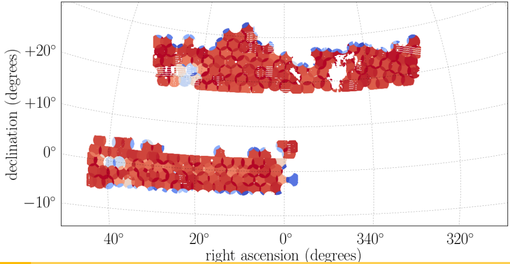
- Shot noise dominated covariance matrices
- (traditional) Reconstruction algorithms do not provide much signal gain



Introduction: the eBOSS survey

- QSO DR14 area 2044 deg^2.
- quasar range: $0.8 < z < 2.2$ ($z_{\text{eff}} \simeq 1.5$)
- Number quasars: 147,000
- Low density: $2 \times 10^{-5}\,[\mathrm{Mpc}/h]^3$
- 3 disconnected areas: 2 SGC & NGC.





Introduction: the eBOSS survey

The clustering of the SDSS-IV extended Baryon Oscillation Spectroscopic Survey DR14 quasar sample: First measurement of Baryon Acoustic Oscillations between redshift 0.8 and 2.2

Metin Ata[1], Falk Baumgarten[1,2], Julian Bautista[3], Florian Beutler[4], Jonathan A. Blazek[5], Jonathan Brinkmann[6], Joel R. Brownstein[3], Etienne Burtin[7], Chia-Hsun Chuang[1], Johan Comparat[8], Kyle S. Dawson[3], Axel De la Macorra[9], Wei Du[10], Héctor Gil-Marín[11,12], Julien Guy[13], Nick Hand[14], Shirley Ho[15,16,17], Timothy A. Hutchinson[3], Francisco-Shu Kitaura[18,19], Jean-Paul Kneib[20,21], Pierre Laurent[7], Jean-Marc LeGoff[7], Cameron K. McBride[22], Joseph E. McEwen[5], Eva-Maria Mueller[4], Adam D. Myers[3], Jeffrey A. Newman[23], Isabelle Pâris[21], Nathalie Palanque-Delabrouille[7], Marcos Pellejero-Ibanez[18,19], Will J. Percival[4], Patrick Petitjean[24], Francisco Prada[25,26,27], Abhishek Prakash[23], Sergio A. Rodríguez-Torres[25,26,28], Ashley J. Ross[5,4], Graziano Rossi[29], Rossana Ruggeri[4], Ariel G. Sánchez[8], Siddharth Satpathy[16,30], Donald P. Schneider[31,32], Hee-Jong Seo[33], Anže Slosar[34], Alina Streblyanska[18,19], Jeremy L. Tinker[35], Rita Tojeiro[36], Mariana Vargas Magaña[9], M. Vivek[3], Yuting Wang[10,4], Christophe Yèche[7,15], Liang Yu[37], Pauline Zarrouk[7], Cheng Zhao[37], Gong-Bo Zhao[10,4], Fangzhou Zhu[38]

ABSTRACT
We present measurements of the Baryon Acoustic Oscillation (BAO) scale in redshift-space using the clustering of quasars. We consider a sample of 147,000 quasars from the extended Baryon Oscillation Spectroscopic Survey (eBOSS) distributed over 2044 square degrees with redshifts $0.8 < z < 2.2$ and measure their spherically-averaged clustering in both configuration and Fourier space. Our observational dataset and the 1400 simulated realizations of our dataset allow us to detect a preference for BAO that is greater than 2.5σ. We determine the spherically averaged BAO distance to $z = 1.52$ to 4.4 per cent precision, $D_V(z = 1.52) = 3855 \pm 170 \frac{r_d}{r_{d,fid}}$Mpc. This is the first time the location of the BAO feature has been measured between redshifts 1 and 2. Our measurement is fully consistent with the prediction obtained by extrapolating the Planck flat ΛCDM best-fit cosmology. All of our results are consistent with basic large-scale structure (LSS) theory, confirming quasars to be a reliable tracer of LSS, and provide a starting point for numerous cosmological tests to be performed with eBOSS quasar samples.

Key words: cosmology: observations - (cosmology:) large-scale structure of Universe

1 INTRODUCTION

Using Baryon Acoustic Oscillations (BAOs) to measure the expansion of the Universe is now a mature field, with the BAO signal having been detected and measured to ever greater precision using data from a number of large galaxy surveys including: the Sloan Digital Sky Survey (SDSS) I and II (e.g., Eisenstein et al. 2005; Percival et al. 2010; Ross et al. 2015), the 2-degree Field Galaxy Redshift Survey (2dFGRS) (Percival et al. 2001; Cole et al. 2005), WiggleZ (Blake et al. 2011), the 6-degree Field Galaxy Survey (6dFGS) (Beutler et al. 2011). The Baryon Oscillation Spectroscopic Survey

ability in multi-epoch imaging from the Palomar Transient Factory. These selections are presented in Myers et al. (2015), alongside the characterisation of the final sample, as determined by the early data. The early data was observed as part of SEQUELS (The Sloan Extended QUasar, ELG and LRG Survey, undertaken as part of SDSS-III and SDSS-IV), which acted as a pilot survey for eBOSS. SEQUELS used a broader quasar selection algorithm than that adopted for eBOSS, and a subsampled version of SEQUELS forms part of the eBOSS sample.

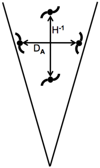
In this paper we present the first BAO measurements obtained

- Alphabetical paper Ata et al. 2017 submitted to the Journal arXiv:1705.06373
- First BAO measurement in $0.8 \leq z \leq 2.2$
- $D_V = 3855 \pm 170\, r_d / r_{d,\mathrm{fid}}$ Mpc at z=1.52 (4.4% precision)
- $\sim 2.5\sigma$ BAO significance
- DR14 Area: 2044 →4.4% precision
  DR16 Area: 5300→ 2.7% precision
- eBOSS is working!

Alcock-Paczynski effect

By assuming a wrong cosmological model (Ω_m) we change the line-of-sight clustering respect to the angular clustering, creating a measurable anisotropy: constrains $H(z)$ and $D_A(z)$ (or a combination of both).

$$d_{\mathrm{comov}}(z) = \int_0^z \frac{c dz'}{H(z'; \Omega_m)}$$



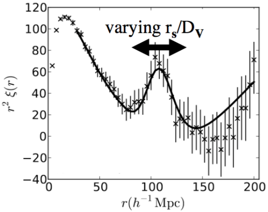
The BAO scale is determined by the comoving sound horizon at reconvination scale (standard ruler)

$$r_s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a*} da \frac{c_s}{(a + a_{\mathrm{eq}})^{1/2}}$$

Baryonic Acoustic Oscillations

$$k_{\parallel} \rightarrow \alpha_{\parallel} k_{\parallel} \qquad k_{\perp} \rightarrow \alpha_{\perp} k_{\perp}$$

$$\alpha_{\parallel} = \frac{H^{\rm fid}(z)}{H(z)} \qquad \alpha_{\perp} = \frac{D_A(z)}{D_A^{\rm fid}(z)}$$



[Anderson et al. 2014, BOSS DR11]

- Surveys measure angles and redshifts, and these are affected by the assumed fiducial model.
- This changes the apparent/observed position of the BAO peak in the power spectrum differently in the radial and angular direction
- Isotropic Correlation Function / Power Spectrum sensitive to

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Methodology

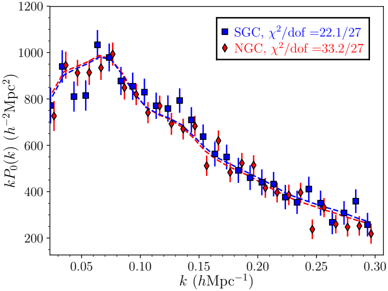
- We perform two complementary and independent analyses on the same dataset using the *i)* **Power Spectrum** and *ii)* **Correlation Function**.
- Both observables should contain the same amount of information, but in practice are affected differently by noise and systematic effects.
- We use mocks (1000 EZ mocks) and (400 QPM mocks) to estimate the covariance matrices and perform systematic tests.
- We model the broadband shape of the PS/CF phenomenologically and the BAO as linear+damping ($\Sigma_{\rm nl}$)

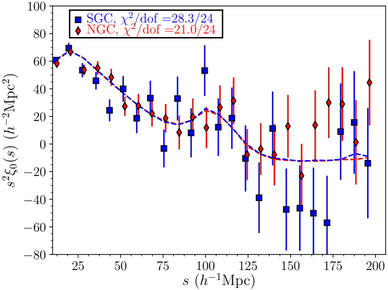
$$P(k,\alpha) = P_{\rm sm}(k)\left\{1 + \left[\mathcal{O}_{\rm lin}(k/\alpha) - 1\right] e^{-\frac{1}{2}\Sigma_{\rm nl}^2 k^2}\right\}$$

smooth PS: $P_{\rm sm}(k) \equiv B^2 P_{\rm nw}^{\rm lin}(k) + A_1 k + A_2 + A_3/k$

Measurement

DR14 QSO isotropic Power spectrum and Correlation function

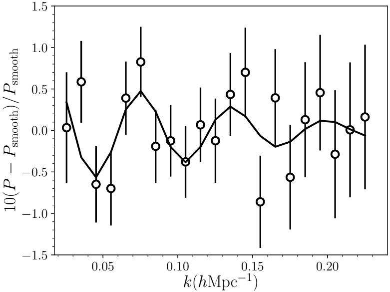


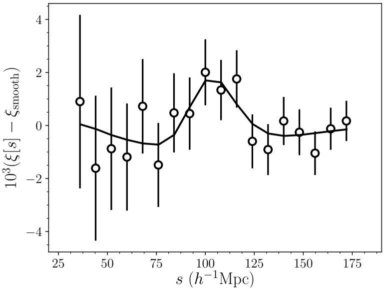


Actual data + diagonal errors from EZ mocks.
Dashed lines mean of the EZ-mocks

Measurement

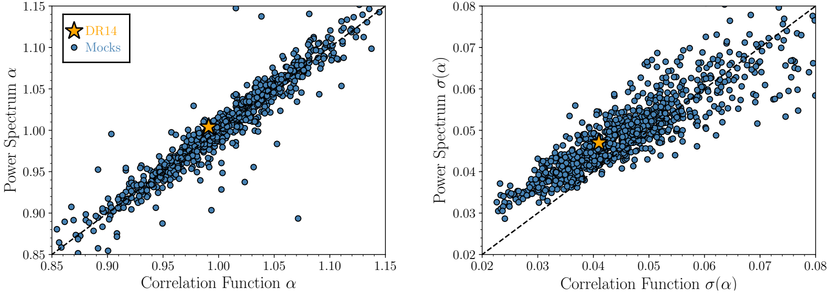
DR14 QSO isotropic Power spectrum and Correlation function





Actual data + diagonal errors from EZ mocks.
Solid lines best-fit model

Tests on Mocks



Correlation coefficient between PS and CF $\rho = 0.97$.
Data is a very typical case of mocks (both in measurement and error).

Tests on Mocks

case	$\alpha - \alpha_{\rm exp}$
EZ mocks:	
$\xi(s)$:	
fiducial	0.0023 ± 0.0016
$5h^{-1}$Mpc	0.0027 ± 0.0016
$P(k)$:	
fiducial	0.0019 ± 0.0017
$k_{\rm max} = 0.30\,h{\rm Mpc}^{-1}$	0.0009 ± 0.0017
$\Sigma_{\rm nl} = [6 \pm 3]\,h^{-1}{\rm Mpc}$	0.0021 ± 0.0016
$\Sigma_{\rm nl} = [6 \pm 3]\,h^{-1}{\rm Mpc}$ & $k_{\rm max} = 0.30$	0.0011 ± 0.0016
log$k$ - binning	0.0032 ± 0.0017
log$k$ - binning & $k_{\rm max} = 0.30\,h{\rm Mpc}^{-1}$	0.0022 ± 0.0016
A_4, A_5 terms	0.0037 ± 0.0017
QPM mocks:	
$\xi(s)$:	
fiducial	0.0017 ± 0.0028
$5h^{-1}$Mpc	0.0027 ± 0.0028
QPM cov	0.0023 ± 0.0026
$P(k)$:	
fiducial	0.0017 ± 0.0027
QPM cov	0.0012 ± 0.0026

case (+bin shift)	$\langle\alpha\rangle$	$\langle\sigma\rangle$	S	$N_{\rm det}/N_{\rm tot}$
EZ mocks:				
consensus $P(k) + \xi(s)$	1.003	0.050	0.050	944/1000
$\xi(s)$:				
combined	1.003	0.049	0.049	939/1000
fiducial	1.002	0.048	0.050	932/1000
+2	1.002	0.049	0.050	928/1000
+4	1.002	0.048	0.050	938/1000
+6	1.003	0.048	0.051	929/1000
$5h^{-1}$Mpc	1.003	0.049	0.050	937/1000
$P(k)$:				
combined	1.002	0.052	0.050	941/1000
fiducial	1.002	0.051	0.051	929/1000
+1/4	1.001	0.052	0.050	931/1000
+2/4	1.004	0.051	0.049	935/1000
+3/4	1.001	0.052	0.050	937/1000
log$k$ - binning	1.002	0.051	0.050	927/1000
$k_{\rm max} = 0.30\,h{\rm Mpc}^{-1}$	1.002	0.051	0.051	934/1000
QPM mocks:				
$\xi(s)$:				
fiducial	1.001	0.051	0.052	361/400
$5h^{-1}$Mpc	1.000	0.050	0.051	355/400
QPM cov	1.002	0.051	0.052	369/400
$P(k)$:				
fiducial	0.998	0.049	0.051	354/400
QPM cov	0.999	0.049	0.049	359/400

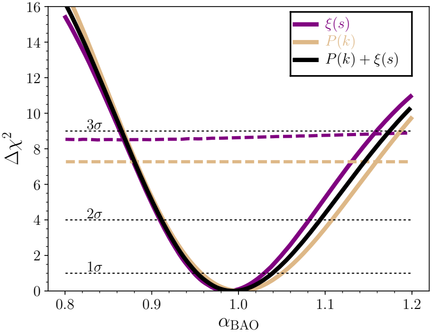
NL effects shift the BAO peak to higher α.

$\sim 0.1\%$ effect on measured α. Negligible on data!

Tests on data

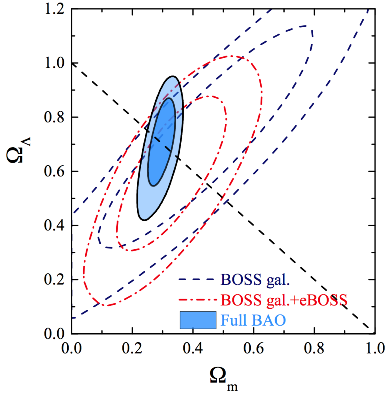
case	α	χ^2/dof
DR14 Measurement $P(k)+\xi(s)$	0.996 ± 0.044	–
$\xi(s)$ (combined)	0.991 ± 0.041	9.7/13
$P(k)$ (combined)	1.004 ± 0.047	26.5/33
Robustness tests		
$\xi(s)$:		
$Z_{\rm PCA}$ (combined)	0.992 ± 0.045	15.6/13
fiducial	0.997 ± 0.044	7.1/13
+2	1.001 ± 0.047	12.9/13
+4	0.978 ± 0.035	7.4/13
+6	0.996 ± 0.041	11.1/13
NGC	0.971 ± 0.056	7.7/13
SGC	1.027 ± 0.063	17.4/13
QPM cov	0.994 ± 0.043	6.8/13
$\Delta s = 5h^{-1}$Mpc	0.993 ± 0.040	18.7/24
no w_{sys}	0.998 ± 0.047	5.1/13
$50 < s < 150h^{-1}$Mpc	0.998 ± 0.048	4.8/8
$\Sigma_{\rm nl} = 3.0h^{-1}$Mpc	0.994 ± 0.043	7.2/13
$\Sigma_{\rm nl} = 9.0h^{-1}$Mpc	1.001 ± 0.048	7.3/13
$A_n = 0$	1.000 ± 0.044	7.3/16
no B prior	0.998 ± 0.043	6.9/13
$P(k)$:		
$Z_{\rm PCA}$ (combined)	1.005 ± 0.045	27.6/33
fiducial	1.002 ± 0.046	27.7/33
$+1/4$	0.994 ± 0.044	24.1/33
$+2/4$	0.993 ± 0.046	27.3/33
$+3/4$	1.009 ± 0.050	26.9/33
NGC	0.977 ± 0.060	17.5/16
SGC	1.029 ± 0.067	9.9/16
QPM cov	1.014 ± 0.045	27.3/33
log$k$ - binning	1.005 ± 0.046	30.4/39
log$k$ - binning, $k_{\rm max} = 0.30\,h$Mpc^{-1}	1.011 ± 0.047	34.9/45
no w_{sys}	1.003 ± 0.052	27.9/33
$k_{\rm max} = 0.30\,h$Mpc^{-1}	1.011 ± 0.048	44.5/47
$\Sigma_{\rm nl} = 3\,h^{-1}$Mpc	1.001 ± 0.041	27.5/33
$\Sigma_{\rm nl} = 9\,h^{-1}$Mpc	1.008 ± 0.054	28.2/33
$\Sigma_{\rm nl} = [6 \pm 3]\,h^{-1}$Mpc	1.002 ± 0.046	27.6/32

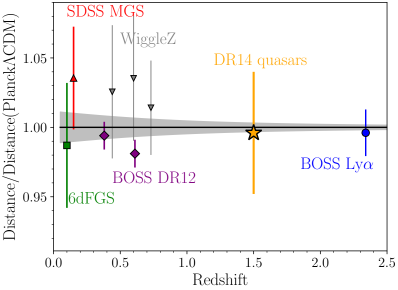
Both P(k) and $\xi(s)$ measurements are very consistent!



Cosmology

- Fully consistent with LCDM + Planck.
- Ly-α 2.5 measurement dominates at high z.
- Further analyses will focus on redshift weighting schemes.





BAO Summary

Summary,

- We have a robust BAO isotropic measurement at $z \simeq 1.5$. with 4.4% precision: $D_V(1.52) = 3855 \pm 170\, r_d/r_{d,\mathrm{fid}}\,\mathrm{Mpc}$.
- Very consistent with mocks and between P and ξ observables.
- Fully consistent with LCDM+Planck

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- We have a robust BAO isotropic measurement at $z \simeq 1.5$. with 4.4% precision: $D_V(1.52) = 3855 \pm 170\, r_d/r_{d,\mathrm{fid}}\,\mathrm{Mpc}$.
- Very consistent with mocks and between P and ξ observables.
- Fully consistent with LCDM+Planck
- First BAO science result from WG, but not last one. More complex BAO analyses will be done in the forthcoming months (weighting z evolution).
- Future quasar releases (DR16) will focus on the anisotropic quasar BAO $\rightarrow$ Constrain D_A and H.
- Further information on D_V can be extracted from RSD analysis (several papers to be released this Fall)