Cosmological results from the SDSS -III and (IV) (extended) Baryon Oscillation Spectroscopic Survey

Ashley J. Ross + BOSS and eBOSS collaborations
Dark Energy

• Expansion of Universe is accelerating!
• Dominant component of Universe today (~70%)
• Consistent with “cosmological constant” \( \Lambda \)
• something like \( 10^{100} \) off (smaller) from vacuum energy estimate
• ???
Measuring Dark Energy

- Equation of state $w = \frac{p}{\rho}$
- Cosmological constant, $\Lambda$, $w = -1$
- Common parameterization is $w(a) = w_0 + (1-a)w_a$
- Scale factor, $a = 1/(1+z)$

![Graph showing the equation of state](image)
Baryon Acoustic Oscillations

- early Universe radiation pressure/matter density -> standing wave in baryon density
Baryon Acoustic Oscillations

- CMB measurement gives calibrated “standard ruler” for feature found in galaxies
Finding BAO

- Need to construct large, 3D maps
- (Imaging + spectroscopy)
- SDSS III Baryon Oscillation Spectroscopic Survey (BOSS): 1.2 million galaxy redshifts, 9300 deg², 0.2 < z < 0.75

A Small Slice of BOSS
BOSS Galaxies

- 1.2 million galaxy redshifts, 9300 deg², 0.2 < z < 0.75
• Radial clustering measures $H(z)$
• Transverse clustering measures $D_M(z) = (1+z)D_A(z)$
• $D_V(z) \equiv [czH^{-1}(z)D_M^2(z)]^{1/3}$; (spherical average)
Figure 14. The "Hubble diagram" from the world collection of spectroscopic BAO detections. Blue, red, and green points show BAO measurements of $D_M(z)/r_d$, $D_V(z)/r_d$, and $zD_H(z)/r_d$, respectively, from the sources indicated in the legend. These can be compared to the correspondingly coloured lines, which represent predictions of the fiducial Planck $\Lambda$CDM model (with $\Omega_m = 0.3156$, $h = 0.6727$). The scaling by $p_z$ is arbitrary, chosen to compress the dynamic range sufficiently to make error bars visible on the plot. For visual clarity, the Ly-$\alpha$ cross-correlation points have been shifted slightly in redshift; auto-correlation points are plotted at the correct effective redshift. Measurements shown by open points are not incorporated in our cosmological parameter analysis because they are not independent of the BOSS measurements.

Alam et al. arXiv:1607.03155
Extra Information from full shape (FS)

Redshift Space Distortions (RSD)

- Measuring anisotropic clustering over all scales
- + modeling RSD
- -> structure growth measurement, better measurement of warping (AP effect)

Small Scale - Redshift Space Distortions

Structure growth

linear flow

non-linear structure

Actual shape

Apparent shape (viewed from below)

Anderson et al. 2014
• Degree of anisotropy depends on rate of structure growth, $f$
• $f(a) = \frac{d\ln(D)}{d\ln(a)}$; ($a = 1/(1+z)$); $f$ is determined given GR, $\Omega_m(z)$
Figure 16. Parameter constraints for the CDM cosmological model, comparing the BAO and BAO+FS results from this paper as well as the DR12 LOWZ+CMASS results from Cuesta et al. (2016a). One sees that adding a 3rd redshift bin has improved the constraints somewhat, but full-shape information, especially the constraint on $H(z)$ from the Alcock-Paczynski effect on sub-BAO scales, sharpens constraints substantially.

Figure 17. Parameter constraints for the CDM (left) and $w_0 w_a$ CDM (right) cosmological models, comparing the results from BAO and BAO+FS to those with JLA SNe. One sees that the galaxy clustering results are particularly strong in the $\Omega_K - w_a$ space and are comparable to the SNe in the $w_0 - w_a$ space.

9.2 Cosmological Parameter Results: Dark Energy and Curvature

We now use these results to constrain parametrized cosmological models. We will do this using Markov Chain Monte Carlo, following procedures similar to those described in Aubourg et al. (2015), but due to use of the full power spectrum shape data we do not run any chains using that paper's simplified "background evolution only" code. Instead, we calculate all our chains using the July 2015 version of the workhorse COWSO MC code (Lewis & Bridle 2002). The code was minimally modified to add the latest galaxy data points and their covariance, the Ly $\beta$ BAO datasets, and two optional $A_f$ and $B_f$ parameters described later in the text. We use a minimal neutrino sector, with one species with a mass of 0.06 eV/c$^2$ and two massless, corresponding to the lightest possible sum of neutrino masses consistent with atmospheric and solar oscillation experiments (Abe et al. 2014; Adamson et al. 2014; Gando et al. 2013), unless otherwise mentioned.

We first consider models that vary the cosmological distance scale with spatial curvature or parametrizations of the dark energy equation of state via $w(a) = w_0 + w_a(1 - a)$. These results are shown in Table 10 for various combinations of measurements. In all cases, the table shows the mean and 1σ error, marginalized over other parameters. Of course, some parameters are covariant, as illustrated by contours in some of our figures. Our model spaces always include variations in the matter density $\Omega_m h^2$, the baryon density $\Omega_b h^2$, the amplitude and spectral index of the primordial spectrum, and the optical depth to recombination. However, we do not show results for these parameters as they are heavily dominated by the CMB and are not the focus of our low-redshift investigations.

We begin with the standard cosmology, the $\Lambda$CDM model, which includes a flat Universe with a cosmological constant and cold dark matter. As is well known, CMB anisotropy data alone can constrain this model well: the acoustic peaks imply the baryon and matter density, and thereby the sound horizon, allowing the acoustic peak to determine the angular diameter distance to recombination.
• FS measures $f\sigma_8$, in GR $f = \Omega_m^{0.557}$

![Graph showing BAO+FS consensus and Planck ΛCDM models](image-url)
Neutrino mass constraints:

CMB+BAO

Fig. 20. 68% and 95% confidence regions on 1-parameter extensions of the base $\Lambda$CDM model for Planck TT $+$ lowP (grey), Planck TT,TE,EE $+$ lowP (red), and Planck TT,TE,EE $+$ lowP $+$ BAO (blue). Horizontal dashed lines correspond to the parameter values assumed in the base $\Lambda$CDM cosmology, while vertical dashed lines show the mean posterior values in the base model for Planck TT,TE,EE $+$ lowP $+$ BAO.
Neutrino mass constraints: CMB+BAO, BOSS DR12

![Graph showing likelihood of neutrino mass](image)

Relative Likelihood

$\sum m_\nu + A_L + A_{f\sigma_8}$

$\sum m_\nu + A_L$

$\sum m_\nu + A_{f\sigma_8}$

$\sum m_\nu$

$\sum m_\nu + A_L + A_{f\sigma_8}$

$\sum m_\nu + A_L$

$\sum m_\nu + A_{f\sigma_8}$

$\sum m_\nu$

‘+’ denotes parameter added to marginalize information

$\sum m_\nu$ [eV/c$^2$]

Alam et al. arXiv:1607.03155
eBOSS

• Use SDSS telescope/spectrograph to extend BAO to $z > 0.6$

• $7500 \text{ deg}^2$ in SDSS imaging footprint

• Supplement SDSS with infrared data from WISE

• $3 \times 10^5$ LRGs $0.6 < z < 1.0$

• $2 \times 10^5$ ELGs $0.7 < z < 1.1$

• $6 \times 10^5$ quasars $0.8 < z < 2.2$
First eBOSS BAO measurement

- SDSS IV extended BOSS (eBOSS) DR14 quasar sample
- 150,000 quasars with $0.8 < z < 2.2$
- 4.4% distance measurement to $z=1.5$

Clustering, compared to simulations

Isolating BAO

Ata et al. arXiv:1705.06373
Updated BAO Distance Ladder

- 6dFGS
- SDSS MGS
- SDSS DR7
- WiggleZ
- BOSS Galaxy DR12
- eBOSS QSO
- BOSS Lyα-auto DR12
- BOSS Lyα-cross DR12

Distance

- $D_M(z)/r_d\sqrt{z}$
- $D_V(z)/r_d\sqrt{z}$
- $zD_H(z)/r_d\sqrt{z}$

Redshift

- SDSS MGS
- WiggleZ
- DR14 quasars
- BOSS Lyα
- BOSS DR12
- 6dFGS
Testing Dark Energy with only BAO

- Treat BAO as *uncalibrated* standard ruler
- BOSS galaxies + eBOSS quasars > 3σ detection of DE
- All BAO, 6.5σ detection!

![Graph showing cosmological parameters comparison](image)

**Ata et al. arXiv:1705.06373**
Conclusions

• BOSS + eBOSS provide powerful tests of dark energy
  • Consistent with $\Lambda$CDM

• Look for more eBOSS results coming soon

• Sets stage for DESI, should shrink contours by $\sim$factor of 10
What BOSS measures: Combined

- Three BAO analyses and four full-shape analyses have been combined
- 9x9 likelihood: 3 redshift bins/3 parameters
Tension with direct $H_0$ measurements

Planck+BOSS $\Lambda$CDM:
$H_0 = 67.6 \pm 0.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Riess et al. (2016):
$H_0 = 73.0 \pm 1.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$

2.9$\sigma$ tension!
BAO is Robust!

- Observational systematics have $13\sigma$ effect on clustering.
- No effect on BAO!
- Similar results found for BOSS (Ross et al. 2012, 2017).
- Theoretical systematics (e.g., galaxy bias) < 0.5%
Reconstruction

1. • High z
   • Uniform
   • Sharp Gaussian

2. • Evolved to z=0
   • Ring distorted
   • Gaussian wider

3. • Lagrangian displacements

4. • Particles moved back.
   • Gaussian peak sharper

Figures from Padmanabhan et al. 2012

Removes RSD effects
• DR14 LRG data and DES Y3 data already observed
• Dark Energy Spectroscopic Instrument being built
• Goes on 4 meter Mayall telescope in 2019
• Basically, an order of magnitude improvement in BAO constraining power
SDSS-III BOSS

- Sloan Digital Sky Survey
- Uses Sloan telescope at Apache Point NM
- BOSS uses:
  - SDSS $ugriz$ imaging to select:
    1.5 million galaxies
    1.5×10^5 quasars
    (out of 3.6×10^8 sources)
- BOSS spectrograph
  3600Å < $\lambda$ < 10,000Å
  $R = \frac{\lambda}{\Delta\lambda} = 1300 - 3000$
  1000 spectra at a time
BOSS Galaxies

- 1.2 million galaxy redshifts, 9400 deg$^2$, $0.2 < z < 0.75$

BOSS Collaboration (in prep.)

![Graph showing the distribution of galaxy redshifts with different line types representing different surveys: Combined, LOWZE2, LOWZ, LOWZE3, CMASS. The x-axis represents redshift from 0.2 to 0.8, and the y-axis represents $10^4 n [h^{-1} Mpc]^3$ with values from 0 to 7.]

BOSS Collaboration (in prep.)
BOSS Galaxies

• Largest 3D map of galaxies
Galaxy Clustering

- Power spectrum
  \[ P(k) = \langle \delta_k(k)^2 \rangle \]
- Correlation function
  \[ \xi(r) = \langle \delta(x)\delta(x + r) \rangle \]
- \( k \sim 2\pi/r \)
- \( r \) and \( s \) interchangeable
Theoretical details

theoretical clustering of matter

observed clustering of galaxies

Galaxy bias: light ≠ mass
Theoretical results + simulations show:

- non-linearities smear BAO scale
- (small) bias (halo mass) dependent shift

Mehta et al. (2011)
Red and Blue Galaxies

- Galaxy population bi-modal red/blue
- Ideal for testing systematic effect from galaxy evolution
Red/Blue BOSS BAO

\[ \alpha = \frac{D_v}{D_{v,\text{fiducial}}} \]

\[ \chi^2 = \text{value} \]

\[ \text{(number of degrees of freedom)} \]

\[ \text{Ross et al. (2014)} \]

\[ \log_{10} \left[ \frac{P(k)}{P_{\text{NOBAO}}(k)} \right] \]

\[ s \text{ (h}^{-1} \text{ Mpc)} \]

\[ k \text{ (h Mpc}^{-1}) \]

\[ \text{Sep 15th 2016} \]

\[ \text{Ashley J. Ross} \]

\[ \text{LineA Webinar} \]
BOSS imaging systematics

Ross et al. 2011

- Fiducial
- Full weights

- sky (mag/arcsec²)
- airmass
- d⊥ offset (mag)

- n_star (deg⁻²)
- A_j (mag)
- seeing (arcsec)

- faint star density (deg⁻²)
- galaxy density (normalized)
Galaxies around stars $17.5 < i < 19.9$ (23 million stars)

Ross et al. 2011

Stars Occult Area

Sep 15th 2016
Ashley J. Ross
LineA Webinar
Stars and BOSS Surface Brightness

- Spectroscopic results confirm galaxy vs. stellar density relationship
- Depends on surface brightness
- Corrected with weights based on linear fits

(DR9 data)

Ross et al. 2012

\[ n_{\text{gal}} / n_{\text{ran}} \]

- brightest \[ i_{\text{fib2}} < 20.75 \]
- \[ 20.75 < i_{\text{fib2}} < 21 \]
- faintest \[ i_{\text{fib2}} > 21 \]
Effect on BOSS clustering

$\xi(s) \times s^2$

$\xi_0$

$\xi_{\text{MASS}} - \xi_{\text{meck}}$

$w_{\text{star}}$: correction for stellar systematic

No effect on BAO!

Ross et al. 2012

(DR9 data)
Systematics in final data set

- Stellar density effect remains strong
- Significant effect with seeing due to morphological star/galaxy separation cuts

![Graph showing systematics in final data set](Image)

Ross et al. (2016)
Systematics in final data set

- Only stellar density has strong effect over full footprint
- (LOWZE3 result is over full footprint, but it is only 660 deg² in combined)
- Simulating effects yield no bias in BAO, negligible effect on statistical uncertainty
What BOSS measures

- Pre-reconstruction, full-shape with RSD modeling:
  - $D_v(z)$
  - $F_{AP}(z)$ (with extra information from anisotropic clustering at all scales)
  - $f\sigma_8$