New Results from SDSS-III BOSS: cosmic expansion and growth of structure

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in collaboration with Martin White, Will Percival, Lado Samushia, Baryon Oscillation Spectroscopic Survey [BOSS] collaboration
Outline

• Baryon Oscillation Spectroscopic Survey (BOSS) status
• Measuring geometry and growth with redshift surveys
• BOSS DR9 results and cosmological implications
• DR10/11 coming soon!
SDSS-III Baryon Oscillation Spectroscopic Survey

- 10,000 deg$^2$, 1.35M new redshifts
- %-level distances at $z = 0.35, 0.6, 2.3$

QUASARS

BOSS galaxies

SDSS Main

SDSS LRGs
The BAO standard ruler:
[see Mariana Vargas-Magana’s talk]

\[ r_s = 151.4 \pm 0.66 \text{ Mpc} \quad \text{(Planck 2013)} \]

Planck 2013 #16

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Friday, August 16, 2013
SDSS-III Baryon Oscillation Spectroscopic Survey
Ly-\(\alpha\) forest BAO detection

- Busca et al. 2012,
  Slosar et al. 2013,
  Kirkby et al. 2013
- \(H(z=2.3)\) to <4%!

Slosar et al. 2013

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SDSS-III Baryon Oscillation Spectroscopic Survey

- 10,000 deg$^2$, 1.35M new redshifts

- CMASS $0.43 < z < 0.7$
- LOWZ $0.2 < z < 0.4$

QUASARS

BOSS galaxies

SDSS Main

SDSS LRGs

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BOSS survey status

Results presented today
$A_{\text{eff}}: 3275$ deg$^2$

Public!
data.sdss3.org
6161 deg$^2$

Currently analyzing
8387 deg$^2$

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Motivation

- There is *much* more information in this 3d map than the BAO feature.
- Rocky III: RSD is “among the most powerful ways of addressing whether the acceleration is caused by dark energy or modified gravity”

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Let’s start simple: what can we extract from the full 2d correlation function $\xi(r_\sigma, r_\pi)$?
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Geometric constraints from galaxy surveys

Observer space: ra, dec, z

depends on H(z) for z in [0, z_{max}]

Theory space: (physical) Mpc

\[ \xi(s) \]

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BAO standard ruler

- The BAO feature in the angle-averaged correlation function constrains $\alpha = \left[ \frac{D_V(z_{\text{eff}})/r_s}{D_V(z_{\text{eff}})/r_s}_{\text{fiducial}} \right]$

\[ D_V \equiv \left[ (1+z)^2 D_A(z_{\text{eff}})^2 \ast \frac{cz}{H} \right]^{1/3} \]

comoving angular diameter distance $\equiv (1+z) D_A(z)$
Alcock-Paczynski effect

- Even without a standard ruler, comparing clustering along and perpendicular to the LOS allows us to measure $D_A \times H$

\[
\text{comoving angular diameter distance} \equiv (1+z) D_A(z)
\]
Redshift Space Distortions (RSD)

real to redshift space separations: $\chi(z) = \chi_{\text{true}} + v_p/aH$

$\nabla \cdot \mathbf{v}_p = -aHf \delta_m$

$|v_p| \sim d \sigma_8/d \ln a = \sigma_8 \ast f$

isotropic

squashed along line of sight

$f = d \ln \sigma_8 / d \ln a \approx \Omega_m^Y$

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Putting it all together

isotropic dilation

\[ D_V \propto D_A^{2/3} \times H^{-1/3} \]

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

\[ D_A/D_{A,fid} \]

\[ D_{A,fid}/D \]

peculiar velocities \( \propto f\sigma_8 \)

\[ F_{AP} \propto D_A \times H \]

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

BOSS DR9

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Information compression step 2: Legendre Polynomial moments $\xi_\ell(s)$

$$\xi(s, \mu_s) = \sum_\ell \xi_\ell(s) L_\ell(\mu_s)$$

$$L_0 = 1$$

$$L_2 = (3\mu^2 - 1)/2$$

$$\mu = r_{\text{LOS}}/(r_{\text{LOS}}^2 + r_\perp^2)^{1/2}$$

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Outline

- Baryon Oscillation Spectroscopic Survey (BOSS) status
- Measuring geometry and growth with redshift surveys
- **BOSS DR9 results and cosmological implications**
- DR10/11 coming soon!
Anderson et al. 2012: fits to $\alpha$ for “reconstructed” $\xi(s)$ and $P(k)$

Reid et al.: $\alpha = 1.023 \pm 0.019$
BAO Hubble Diagram

The Hubble diagram shows the relationship between the distance to a galaxy and its redshift. The WMAP curve is a prediction, not a fit!
BAO Hubble Diagram: Comparison with CMB, $H_0$, and SN

$+1\sigma$ in $\Omega_m h^2$ (WMAP7)
BAO Hubble Diagram: Comparison with Planck

\( \pm 1 \sigma \) in \( \Omega_{mh^2} \) (Planck)

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DR9 $\xi_0$ BAO + $\xi_2$: $D_A$, $H$, $f\sigma_8$ at $z=0.57$

- $f\sigma_8(0.57) = 0.43 \pm 0.069$
- $H(0.57) = 92.4 \pm 4.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$
- $D_A(0.57) = 2190 \pm 61 \text{ Mpc}$

Marginalize over:
- CMB $P(k)$ shape prior
  - $b\sigma_8$
  - $\sigma^2_{\text{FOG}}$

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• Modeling $\xi(s,\mu)$ buys you a lot of statistical power on dark energy parameters and testing gravity

**BOSS DR9**

$w = -0.88 \pm 0.06$
DR9 Results

- Modeling $\xi(s,\mu)$ buys you a lot of statistical power on dark energy parameters and testing gravity.

BOSS DR9

Line of constant $D_A(z=1091)$

lower $D_A(z=0.57)$, more growth of structure from $z=1091$ to $z=0.57$
Modeling $\xi(s, \mu)$ buys you a lot of statistical power on dark energy parameters and testing gravity.

lower $D_A(z=0.57)$, more growth of structure from $z=1091$ to $z=0.57$
Dark Energy or modified gravity?

- CMASS geometric constraints tighten $\Lambda$CDM $f\sigma_8$ prediction, shift it up
- CMASS $f\sigma_8$ is low by $\sim 1.5\sigma$

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Samushia, BR, et al., 2012

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Future prospects

- Including 2d broadband $P(k)/\xi(r)$ increases DETF FOM by factor of $\sim 2-4$ and allows modified gravity tests using RSD, if we can control the theoretical uncertainties
DR11 coming soon...

credit Lado Samushia

BOSS DR9

BOSS DR11

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EXTRAS
Modeling the full shape of $\xi_{0,2}$ (Reid & White 2011)

- $b\sigma_8, f\sigma_8$ determine amplitude of $\xi_{0,2}$

$\sigma_8$: amplitude of matter fluctuations

$b$: unknown conversion factor between galaxy and matter fluctuations

$f = d \ln \sigma_8 / d \ln a$; conversion factor between matter and velocity fluctuations

Reid & White '11 vs 70 (Gpc/h)$^3$ of sims

[final BOSS is 5 (Gpc/h)$^3$]
Alcock-Paczynski has different scale-dependence, distinguishable from RSD

\( (D_A \ast H) \pm 10\% \)
Dark Energy or modified gravity?

- Our strongest evidence for DE is from geometric measures: SNIa, BAO, $H_0 +$ distance to CMB, AP, ... [probes homogeneous universe]

- We can distinguish modified gravity from exotic fluid in GR as the reason for cosmic acceleration by the growth of inhomogeneities

growth in GR:

$$\frac{d^2 G}{d \ln a^2} + \left(2 + \frac{d \ln H}{d \ln a}\right) \frac{d G}{d \ln a} = \frac{3}{2} \Omega_m(a) G$$
Effect of intrahalo satellite velocities (aka “Fingers of God”)

DR9 Battle plan: marginalize over nuisance parameter $\sigma^2_{\text{FOG}}$ with hard prior informed by small-scale galaxy clustering

DRx: derive FOG velocity distribution directly from observed small-scale clustering

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CMB precisely predicts full $P(k)$, not just BAO feature

photon-baryon fluid

dark matter dominated

$P(k) = r^2 \xi(r)$

$k \text{ [Mpc}^{-1}] = [0.014 - 0.09]$

$n_s = 0.96$

$n_s = 1.00$

$r_s = 151.4 \pm 0.66 \text{ Mpc}$

(Planck 2013)

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