Baryon Oscillation Spectroscopic Survey (BOSS)

Beyond BAO …

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Santa Fe, 2012
BOSS in a nutshell
(Eisenstein et al. 2011)

• BOSS has:
  • ~8,000 deg$^2$ footprint in Spring
  • ~3,000 deg$^2$ footprint in Fall
• Upgraded spectrographs (with better throughput c.f. SDSS-I & II)
  • 1000x 2-arcsec fibers in cartridges
  • Increase wavelength range to 3600-10,000A (R=1500-2600)

• Finished ~3,000 deg$^2$ southern imaging in Fall 2008.
  • Released as part of DR8, published in ApJS (2011).

• Currently doing only spectroscopy
  • 1.3 million galaxies, i<19.9, z<0.8, over 10,000 deg$^2$
  • 150,000 QSOs, g<22, 2.3<z<3, over 8,000 deg$^2$
## BOSS data release schedule

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Outline
Summary of results from DR9

• The galaxy survey
• Constraining dark energy/modified gravity.
  – Redshift space distortions.
• Constraining quasar demographics.
• The Lyα forest survey.
Sky coverage for DR9

Approximately ~1/3 of the final data, though with a slightly worse geometry ...
>800,000 galaxy and >170,000 quasar redshifts, over a million spectra in total!
BOSS DR9 CMASS papers

(264,283 CMASS galaxies over 3275 deg$^2$ at $z_{\text{eff}}=0.57$)

- Ross et al.: Systematics  
arXiv:1203.6499
- Anderson et al.: BAO  
arXiv:1203.6594
- Reid et al.: fits to anisotropic clustering  
arXiv:1203.6641
- Sanchez et al.: fits to monopole $\xi(s)$  
arXiv:1203.6616
- Tojeiro: RSD with passive galaxies  
arXiv:1203.6565
- Manera et al.: Mock catalogs  
arXiv:1203.6609
- Samushia et al.: Model constraints  
arXiv:1206.5309

~150 journal pages!

And more on the way …
Growth of structure

- A key test of dark energy vs. modified gravity models is the growth of structure.
  - Also helps break some DE degeneracies …
- For fixed expansion history/contents, GR makes a unique prediction for the growth of structure (and velocities).
  - Growth predicted to ~1% for a BOSS-like survey for $\Lambda$CDM.
- We can measure the growth of structure using redshift space distortions.
  - $z_{obs} = Hr + v_{pec}$.
  - $v_{pec} \sim a t \sim (\nabla \Psi) t \sim (\nabla \nabla^2 \rho) t$
  - Distortion correlated with density field.
- Constrain $dD/d\ln(a) \sim f \sigma_8$. 
Two dimensional clustering
(Reid++12)

Anisotropy in the 2-point function due to peculiar velocities allows measurement of the growth of structure and tests of gravity on cosmological scales.
FoG a small correction for us

(Marginalize over a single nuisance parameter)

Smallest scale used for analysis
Legendre Polynomial moments: $\xi_\ell(s)$

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

$S^2 \xi_0(s)$

$S^2 \xi_2(s)$
Results: Fitting to 2d clustering

Use full model of \( \xi_{0,2}(s \geq 25 \, h^{-1} \, \text{Mpc}) \) to constrain:

- \( D_V = [\chi^2 \, cz/H]^{1/3} \)
- Growth of structure (\( f\sigma_8 \))
- Alcock-Paczynski \( F(z) \equiv (1+z) \, D_A(z) \, H(z)/c \)
  - Has a different shape-dependence than RSD, distinguishable if have enough dynamic range.
- Marginalize over shape of underlying linear \( P(k), b\sigma_8, \sigma^2_{\text{FOG}} \)

Results including shape information with our model and the anisotropic clustering is fully consistent with the results using just BAO.
Alcock-Paczynski has different scale-dependence, distinguishable from RSD

\[ (D_A \times H) \pm 10\% \]

\[ D_v \text{ stretches } s \text{ axis} \]
Measure isotropic and distortion parameters
Best fit model: $\chi^2 = 39$ (41 DOF)

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

Growth & geometry “free”*: $f\sigma_8 = 0.43 \pm 0.07$
$\chi = 2190 \pm 61\text{Mpc}$
$H = 92.4 \pm 4.5\text{km/s}$

WMAP7 $\Lambda$CDM:
$f\sigma_8 = 0.45 \pm 0.03$
$\chi = 2113 \pm 53\text{Mpc}$
$H = 94.2 \pm 1.4\text{km/s}$

•Can be used to constrain models with arbitrary EoS and growth history providing physics at recombination is unaltered and growth remains scale-independent.
•Approx. almost as good as fitting to $\xi_0$ and $\xi_2$ directly.
Cosmological implications: flat wCDM
(Samushia++2012)

- Anisotropic clustering allows huge improvement on $w^*$!
- $w = -0.95 \pm 0.25$
  (WMAP + $D_V/\sigma_s (0.57)/\sigma_s$)
- $w = -0.88 \pm 0.055$
  (WMAP + anisotropic)
- NB: $\Lambda$CDM has $\Delta \chi^2 \sim 2.5$ even though $w=-1$ is $\sim 2\sigma$ off.

(* Thanks to fortuitous degeneracy direction between $F_{AP}$ and $f\sigma_8$)
Quintessence

• Assume “standard” gravity and a scalar field with canonical kinetic term and a simple potential $V(\phi)$.

• No “interesting” models left, only those which can be tuned arbitrarily close to $\Lambda CDM$.
  – No explanation of “why now”, or “sudden onset” problems.
  – No explanation of why $\Lambda$ is the value it has.
  – Frequently no connection to particle-physics-inspired models.

• However does replace phenomenology with physics and is completely calculable!
  – Like $f(R)$ models!!

• What are the current limits on such models?
Scalar field model: PNGB

Constraints on a particular scalar-field DE model:

\[ V(\phi) = M^4[1 + \cos(\phi/f)] \]

This model* is technically “natural” and “explains” the 2\textsuperscript{nd} tooth fairy, that \( m \sim H \), given the 1\textsuperscript{st} tooth fairy, that \( M^4 \sim \Lambda \).

The limit \( f \rightarrow \infty \) is \( \Lambda \text{CDM} \).

Dark Energy or modified gravity?

(Not all analyses make the same assumptions or use the same priors so direct comparison is slightly tricky.)
Future constraints?

- Expect non-negligible increase in volume (and number of galaxies).
  - Roughly factor of 3.
- Get an additional boost by steadily improving survey footprint
  - Fewer “edges” and “gaps”.
- Minor improvements from systematics and reduction improvements, efficiency of survey operations, etc.
Summary

• BOSS BAO has provided the most precise high-z distance in the DE-turn-on epoch to date!
  – \( D_v(z=0.57)=2094\pm34 \) Mpc (1.7%).

• RSD measurements significantly improve constraining power on models/parameters.

• \( \rho_{DE}/\rho_m \) is 4.5x smaller at \( z=0.57 \) than \( z\sim0 \).
  – The “why now” problem!

• \( \Lambda CDM \) provides a good fit to the data (\( \chi^2/dof \)).

• Growth measures show a 2\( \sigma \) preference for \( w>-1 \) or MG.
  – Inclusion of other data brings you back closer to \( \Lambda CDM \).

But wait, there’s more …
Quasar demographics

• BOSS is providing a large sample of less luminous QSOs at $z \sim 2.5$, near peak of QSO $dN/dz$.
  – Better constraints on faint-end of LF.
  – Better clustering measurements.
    • Which halos? Duty cycle? Triggering?
• Also “double” the number of $z > 3.6$ QSOs, reaching $\sim 1$ magnitude fainter.
  – Early generations of BHs.
  – Tests of QSO formation.
  – Probes IGM evolution and end of reionization.
• Have multiple QSO selections along Stripe 82.

(BOSS currently has good redshifts for $>60K$ quasars with $z > 2.2$)
Comparison with SDSS

BOSS probes significantly further down the LF at \(z>2.2\) than did SDSS-I & II. It is inefficient for \(1<z<2.2\) by design.

New LF results coming out very soon …
The typical BOSS quasar

Median QSO has $M_i(z=2)=-26$, $L_{bol}=2.5\times10^{39}$ W, $M_{BH}=2\times10^8 M_{\odot}$
Clustering at $z \sim 2.5$: Real space

Clustering of 27,129 quasars with $2.2 < z < 2.8$ over 3,600 deg$^2$ or $9.7\,(\text{Gpc}/h)^3$.

No detection of luminosity or redshift dependent clustering: as expected given our dynamic range.
Clustering at $z \sim 2.5$: Redshift

Redshifts very difficult to measure in this range with the BOSS spectrograph (3,600-10,000Å).

End up using broad emission lines in the rest-frame UV (CIII], CIV).

(White++12)
Clustering at $z \sim 2.5$

Consistent with “merger scenario” of starburst->submm->QSO. Wide range of descendents, “typical” descendent is a luminous elliptical galaxy.

$b \sim 3.5$, $M_{\text{halo}} \sim 10^{12}$, duty cycle $\sim 1\%$ ($t_Q \sim 10^7$yr).

$M_{\text{BH}}/M_{\text{gal}} \sim 5x$ local relation.
QSOs at the peak of the QSO epoch

• These constraints are the by far the strongest in the redshift range z~2.5.
  – Surprisingly difficult to rule out/in models however.
• The diversity of QSO models isn’t as large as it might at first seem.
  – Steeply falling mass function.
  – Mostly 2-halo information, and $n$ not known.
• Beware “derived” statistics.
  – Methodological differences can inflate discrepancies.

These quasars also make great backlights …
BAO and the IGM

- Distance constraints become tighter as one moves to higher $z$
  - More volume per sky area.
  - Less non-linearity.
- Expensive if use galaxies as tracers.
- Any tracer will do: H\textsubscript{i}
  - 21cm from H\textsubscript{i} in galaxies: SKA or custom expt.
  - Ly\textsubscript{\alpha} from IGM as probed by QSOs.
    - Absorption traces mass in a calculable way.
    - A dense grid of QSO sightlines could probe BAO
      - (White 2003, McDonald & Eisenstein 2007, Slosar++09, White++10, McQuinn & White 2011)
    - BOSS is providing 1\textsuperscript{st} ever constraints from 3D Ly\textsubscript{\alpha} forest mapping.
Spectrum ‘=’ density
BAO at high $z$

Signal in “theory”

Signal in “simulations”

BAO feature survives in the Ly$\alpha$ flux correlation function, because on large scales flux traces density. Relatively insensitive to astrophysical effects.
On large scales

• Differences with the galaxies
  – Not yet a proven technique (but will be very soon…!)
  – Signal is $e^{-\tau}$, so downweights high-$\delta$ (unlike galaxies which trace high-$\delta$).
  – Need to be slightly careful about redshift space distortions ($\tau$ conserved, not $n$, except in line-dominated regime).
  – Noise comes in two forms:
    • Noise in an individual spectrum.
    • Projection/finite sampling: dominant for us and BigBOSS.
    • Balance is important for optimization!
    • See my Santa Fe talk from last year.

• Additional physics
  – Absorption could be affected by non-gravitational physics
    • Fluctuations in the UV background
    • Temperature fluctuations due to HeII reionization
    • Your favorite astrophysical phenomenon here.
Clustering in the Lyα Forest

- First detection of large-scale clustering of the IGM using cross-correlations between QSO lines of sight.
- Matches ΛCDM prediction well.
- Lyα Forest Working Group has been very active.

Slosar et al. (2011)
Lyα forest cosmology

• New cosmology paper in few months.
  – Looks very promising for BAO detection.
• Lots of other projects in the early stages
  – “Old fashioned” 1D analysis (for $m_\nu$ and inflation, …)
    • Expect ~20x data in McDonald++
• Or in the “thinking about it” stage
  – Lots of cross-correlation projects.
  – …
Gravity working at $z \sim 0.5$ and $z \sim 2.5$

BOSS galaxies
(years 1+2)

BOSS Ly$\alpha$
(year 1 only)

Lado Samushia + galaxy WG

Nicolas Busca + Ly$\alpha$ WG
Galaxy formation/evolution

- BOSS will allow us to trace galaxy evolution over half the age of the Universe.
  - Period when “stellar mass growth” decouples from “dark matter/halo growth”.
- Models traditionally have trouble reproducing properties of massive galaxies.
  - Too massive & too blue.
  - Much progress in theory related to progress on these issues.
- Many galaxy properties highly covariant, need large samples.

- Large volume/area allows BOSS to provide strong constraints on the massive end of the mass function.
  - Targeting was changed from old LRG selection to try to get both red and blue galaxies at high stellar mass at “high” $z$.
- Spectra allow us to measure many physical properties with higher fidelity.
Published papers

- Morphology of CMASS galaxies from HST/COSMOS – Masters++
- BOSS spectroscopic strong lens survey – Browstein++
- Stellar masses and SFHs from spectral fitting – Chen++
- Direct observation of the LF of LRG satellites out to z~0.7 – Tal++

And a very large number of papers in preparation … … this next year will be a “big one” for galaxy evolution modeling with BOSS.
Summary

• BOSS is working extremely well!
• From DR9 we have
  – 1.7% BAO distance constraint at $z=0.57$
  – (First?) Best measurement of $H(z)$ using BAO + Alcock-Paczynski effect
  – 8% growth rate measurement
• Constraining power on dark energy substantially improved.
• New results on quasar demographics.
• Soon to publish new IGM results.
• New galaxy evolution results.
• Data for DR10 is essentially all “in the can” and we are ahead of schedule …
The End