BAO and Lyman-α with BOSS

Nathalie Palanque-Delabrouille (CEA-Saclay)

- BAO and Ly-α
- The SDSS-III/BOSS experiment
- Current results with BOSS
  - 3D BAO analysis with QSOs
  - 1D Ly-α power spectra and $\nu$ mass
  - Highlights on BAO with galaxies

Deep surveys, Large Scale Structures and dark energy
Valencia, Mar 29-30, 2012
Acoustic propagation of an overdensity:
- Sound wave through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination ($z \approx 1100$).
- Radius of baryonic overdensity then frozen at 150 Mpc (comobile).

Standard ruler:
- Structures form in overdense shells
- At all $z$, small excess of galaxies 150 Mpc (comobile) away from other galaxies.
3D observation of density excess

- Position of acoustic peak $\Rightarrow$ size of sound horizon $s$

- **Transverse direction**
  $$\Delta \theta = s/(1+z)/D_A(z)$$
  $\Rightarrow$ Sensitive to angular distance $D_A(z)$
  same as SNIa: $D_L(z) = (1+z)^2 D_A(z)$

- **Radial direction** (along the line of sight)
  $$\Delta z = s \cdot H(z)/c$$
  $\Rightarrow$ Sensitive to Hubble parameter $H(z)$

- Requires accurate $z$ $\Rightarrow$ spectroscopy
  (5x more volume to probe if photo-z)
3D observation of BAO peak

First observation:

- **2005**: BAO peak measured through galaxy-galaxy power spectrum (2dFGRS) or correlation function (SDSS)

- **SDSS**: ~50 000 LRGs
  “Luminous Red Galaxies”
  \(\langle z\rangle \sim 0.35\)

**Improvements?**

- Increase significance
  → more LRGs
- Probe different (higher) redshifts
  → new probes
  → QSOs

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QSO’s as IGM probe

Use QSO as background lighthouse

IGM is mostly ionized H, BUT
some neutral H in IGM absorbs light at $\lambda_{\text{Ly-\alpha}}$ (n=2→n=1)
QSO’s as IGM probe

3C 273 $z=0.158$

Q1422+2309 $z=3.62$
QSO’s as IGM probe

- Use Ly-α forests of quasars (2.2<z<4 → visible range) 
  Transmitted flux fraction $\propto \exp(-\tau)$ where $\tau \propto n_{\text{HI}} \propto (1+z)^{3.8}$

- Low density gas (IGM) expected to follow dark matter density

- BAO measurement for $z \approx 2.5$

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High-resolution spectrum of $z=3.6$ QSO
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Sloan Telescope
- 2.5m telescope at Apache Point (New Mexico)
- 7 deg$^2$ field
- Total survey area: 10,000 deg$^2$

Upgrades for SDSS-III spectroscopic survey
- New fiber system → 1000 fibers
- Replacement of red CCDs → LRG at higher z
- Replacement of blue CCDs (UV) → Ly-$\alpha$ forest program
SDSS-III / BOSS

Photometry from SDSS-II

List of targets

SDSS J112253.51+005329.8
SDSSp J120441.73-002149.6
SDSSp J130348.94+002010.4
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....

Fiber number

CCD

λ

optical fibers

spectrograph

1000
**SDSS-III coverage**

**SDSS main galaxy survey**
- 1 million galaxies
- Too little volume for BAO

**SDSS-I + SDSS-II**
- Luminous Red Galaxies (LRG)
  - $z \sim 0.35$
  - 80,000 galaxies
  - 8,000 deg$^2$

**SDSS-III - BOSS**
- 1.5M LRG with $z$ up to 0.7
- 10,000 deg$^2$
- Volume x2, Density x5
+ ...
SDSS-III coverage

SDSS-III – BOSS

1.5M LRG with z up to 0.7
10,000 deg²
Volume x2, Density x5

160,000 2.2<z<4.5 quasars
QSO target selection in SDSS

Hard to distinguish z>2.2 QSOs from stars

Intensive use of photometric surveys
ugriz (SDSS) + NIR (UKIDSS) + UV (GALEX)

Dedicated algorithms
Kirkpatrick et al., AJ 743, 125 (2011)

Time variability
Palanque-Delabrouille et al., A&A 530, A122 (2011)

Results N. Ross et al., AJ Suppl., 199, 3 (2012)

Target budget: 40 deg$^{-2}$
15-20 deg$^{-2}$ QSOs at z>2.2
28 deg$^{-2}$ QSOs with variability (220 deg$^2$ only)
So far
130,000 QSOs
including 85,000 z>2.2 QSOs
over 5500 deg²

On average
4000 z>2.2 QSOs per month

End of survey (July 2014)
150,000 to 200,000 z>2.2 QSOs
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QSO Ly-\(\alpha\) forest

1st year BOSS results
A. Slozar et al., JCAP 09, 001 (2011)

Typical BOSS QSO
- Very noisy (SNR~1-2)
- \(\lambda > \lambda_{\text{Ly-\(\alpha\)}}\): fluctuations from noise
- \(\lambda < \lambda_{\text{Ly-\(\alpha\)}}\): fluctuations from noise and absorption

Data Set
- Year one: 14,000 QSOs with \(z > 2.15\)
- Demonstration of the method
- Correlation function for \(r < 100\text{Mpc}/h\) (below BAO scale)
Correlation function of QSO Ly-α forests

Transmitted flux fraction
\[ F = \frac{\text{Flux}}{\text{QSO continuum}} \]

\[ \delta_F \equiv \frac{F}{F} - 1 \]

\[ \xi_F(r) = \langle \delta_F(x) \cdot \delta_F(x + r) \rangle \]
**Correlation function of QSO Ly-α forests**

1\textsuperscript{st} year BOSS results

\textit{A. Slozar et al., JCAP 09, 001 (2011)}

First observation in 3D of clustering in IGM

Correlations in HI seen to 60 Mpc/h

Results consistent with \(\Lambda\)CDM simulations

Projection over \( r = |\mathbf{r}| \) of the 3D correlation function

\[ r \times \xi_F(r) \]

\(\Lambda\)CDM

+ 2 free parameters related to HI bias and mean absorption

Correlation function of QSO Ly-\(\alpha\) forests

Next step: out to \(r > \) BAO peak (105 Mpc/h)
coming out soon...

\[ r \times \xi_F(r) \]

Expected performance at end of BOSS survey
with 15 QSO/deg\(^2\), \(<z>=2.5\) and 10,000 deg\(^2\)

\[ D_V \propto (D_A^2/H)^{1/3} \quad \delta D_V \sim 2\% \]
Large-scale redshift distortions

→ Peculiar velocity

overdense region

Real Space

Flattening of radial length in redshift space
(over tens Mpc)

Measurable with Kaiser formula

\[ P_F(k) = P_F(k, \cos(\theta)) \]

\[ = b_F^2 \times (1 + \beta \cos(\theta)^2)^2 \times P_L(k) \]

\[ P_L(k): \text{ linear power spectrum} \]
\[ \theta: \text{ angle between vector and QSO line of sight} \]
Large-scale redshift distortions

Clearly seen with 44,000 LRGs $<z>\sim 0.6$ in BOSS


Flattening of correlation function distribution

First observation of redshift distortion at $z\sim 2.5$ ($\beta=0$ excluded at 5$\sigma$)

Gravity is forming structures at $z\sim 2.5$

Distortions quantified with multipole decomposition

$0.16 < b < 0.24 \quad @ 95\%$

$0.44 < \beta < 1.20 \quad @ 95\%$
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Neutrinos are massive but $m_\nu$ is small
$\rightarrow$ relativistic during most of history of Universe
$\rightarrow \delta_\nu \sim 0$ at high $z$ (free streaming)

**At $z < z_{NR} \propto m_\nu$:**

- Spreading out grav. potential, growth suppressed on small scales by free-streaming $\nu$

- **Heavy neutrinos:**
  - Strong suppression over short range
  - $\Delta P/P = -8 \Omega_\nu / \Omega_m = -8 f_\nu$

- **Light neutrinos:**
  - Weak suppression over long range
Neutrinos are massive but $m_\nu$ is small
$\rightarrow$ relativistic during most of history of Universe
$\rightarrow$ $\delta_\nu \sim 0$ at high $z$ (free streaming)

At $z < z_{NR} (\propto m_\nu)$:

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Shape is $z$-dependent
Large-scale structures and neutrinos

Best seen on small scales → Ly-\(\alpha\) data
z-dependence → large \(z\) range

With BOSS:

\[ N_{\text{QSO}}(z) \]

~16,000 QSOs
after cuts on S/N and spectrograph resolution in QSO spectrum
Large-scale structures and neutrinos

BOSS 1D power spectra

$\sigma_{\text{stat}}$ 5x smaller than previous measurements

McDonald et al., 2004 SDSS-I

to be compared to hydro-simulations including neutrinos...

current limits: $m_\nu < 0.2$ eV (95% CL) (Seljak et al. 2006, issue of bias)
$m_\nu < 0.9$ eV (95% CL) (Viel et al. 2010, Ly-$\alpha$ only)
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on arXiv TODAY!
(arXiv:1203.6594)
Deeper and denser than SDSS-II (DR7)

80,000 LRGs, \( <z> = 0.35 \)

330,000 galaxies over 3300 deg\(^2\)
\( <z> = 0.57 \)

DR9 sample (July 2012)
1/3 of total BOSS
BAO with BOSS massive galaxies

Position of BAO peak $\leftrightarrow$ distance $D_V$ relative to sound horizon $s$

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

$$D_V / s = \alpha \left( D_V / s \right)_{\text{fiducial}}$$

$\Omega_M = 0.274$

$h = 0.7$

$\Omega_b h^2 = 0.0224$

Correlation function

Power spectrum

$\alpha = 1.022 \pm 0.017$

$\chi^2 = 30.53 / 39$ dof

$5\sigma$ detection
BOSS (DR9) + SDSS-II (DR7)

$\langle z \rangle = 0.35$

DR7

$\langle z \rangle = 0.57$

DR9

BAO peak detected at 6.7 $\sigma$
BAO and $\Lambda$CDM

$w_0$ vs $w_a$ CDM

$D_v(r_{\text{std}}/r_s)$ (Mpc)

Redshift

BOSS

SDSS-II
Padmanabhan et al., 2012

WiggleZ
Blake et al., 2011

6dFGS
Beutler et al., 2011

WMAP $\Lambda$CDM
BAO and $\Lambda$CDM

\[ w_0 = -2.5, -2, -1.5, -1, -0.5, 0 \]

CMB+CMASS+LRG+SN

CMB+SN

CMB+CMASS+LRG

WiggleZ

SDSS-II

BOSS

6dFGS

Redshift

\[ \left( \frac{D_V}{r_s} \right) / (D_V/r_s)_{WMAP} \]
Conclusions on BOSS results

Massive galaxies at $<z> = 0.57$
- Detection of BAO peak in BOSS at $5\sigma$
- $\rightarrow 7\sigma$ (all SDSS data combined)

Lyman-\(\alpha\) forests at $<z> = 2.5$
- First detection of redshift space distortions at $z=2.5$
- Ongoing blind analysis for 3D BAO in IGM
- 1D power spectrum soon $\rightarrow m_\nu$