Lyman-\(\alpha\) Forest in 3 Dimensions with BOSS

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Outline:

- Concepts: BAO
- SDSS-III - BOSS
- Quasar Target Selection
- Proof of principle: First 3D HI map

International Europhysics Conference on HEP
Grenoble - July 21-27, 2011
BAO

- Concepts
A probe for Dark Energy: Baryonic Acoustic Oscillations

Acoustic propagation of an overdensity:
- Sound wave through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination (z~1100).
- Then, the radius of the baryonic overdensity is frozen at 150 Mpc.

A special distance:
- Galaxies form in the overdense shells about 150 Mpc in radius.
- For all z, small excess of galaxies 150 Mpc (in comobile coordinates) away from other galaxies.
  ⇒ Standard Ruler
Observation of baryonic acoustic peak

First observation:
- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at \( \sim 150 \text{ Mpc} \)
- SDSS: \( \sim 50,000 \) LRGs
  "Luminous Red Galaxies"
  \( \langle z \rangle \sim 0.35 \)

A 3D measurements:
- Position of acoustic peak \( \Rightarrow \) Size of the sound horizon \( s \)
- Transverse direction:
  \[ \Delta \theta = s/(1+z)/D_A(z) \]
  \( \Rightarrow \) Sensitive to angular distance \( D_A(z) \)
- Radial direction (along the line of sight):
  \[ \Delta z = s \cdot H(z)/c \]
  \( \Rightarrow \) Sensitive to Hubble parameter \( H(z) \).
Current status of BAO

Power spectrum:

- Bump in the correlation function:
  - In Fourier space, oscillations in the power spectrum $P(k)$.
- Measurement at 2.7% of BAO scale
- Constraints on Dark Energy content

More recent results with WiggleZ (next talk)

Ch. Yèche
EPS-HEP 2011
Grenoble, July 22, 2011
SDSS-III - BOSS

- A brief overview
BOSS coverage

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

SDSS-I + SDSS-II
Luminous Red Galaxies (LRG)
- $<z> \sim 0.35$
- ~ 50000 galaxies by 2004
- ~ 80000 galaxies by 2008
- 8000 deg$^2$ by 2008

SDSS-III - BOSS
- 1.5M LRG with $z$ up to 0.7
- 10000 deg$^2$
- Volume x2
- Density x5
- + 2.2$<z<4$ with Lyman-α forest of ~160000 quasars
From SDSS to SDSS-III

SDSS Consortium
- 2.5m Sloan Telescope
- Apache Point, NM
- Wide field telescope ~ 7 deg²
- Camera equipped with 5 filters (~120 millions pixels)

Upgrade for SDSS-III
- New fiber system ⇒ 1000 fibers
- Replacement of red CCDs by LBNL/SNAP CCDs ⇒ LRG with higher z
- Replacement of blue CCDs with e2v CCDs with better throughput in UV ⇒ Lyman-α forest program
**BOSS Status**

**Observing plan**
- Fall 2008 + Fall 2009: Complete imaging survey (10 700 deg\(^2\))
- Fall 2009: Commissioning of spectrograph
- 14-15 Sept. 2009: First light
- Jan. 2010: Begin spectroscopic survey
- July 2014: End survey

**Public data releases**

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- Spring: 7600 deg\(^2\)
- Fall: 3100 deg\(^2\)

Quasar
Target Selection
QSO Selection with Photometry

Challenging target selection

- QSOs and stars overlap: QSO with 2.2<z<3.5 are in the stellar locus
- Many more stars than QSOs (x 200-500), worse at the edge of Galaxy
- At z=2.4/3.3 Ly-α emission line falls between two band filters

SDSS 4 colors (u-g, g-r, r-i, i-z)

BOSS: Selection of Ly-α QSO Using Photometry

- Photometric surveys
  - ugriz bands: SDSS
  - NIR: UKIDSS
  - UV: GALEX

- Combination of the different surveys by using Likelihood and NN algorithms

- Results:
  - Budget: 40 targets deg^{-2}
  - ~15-20 deg^{-2} QSOs with z>2.15

N. Ross et al., arXiv:1105.0606 (2011)
Target selection with Variability

- Intrinsic variability of QSOs (~90-95% of QSOs)
- QSO variability:
  - Long period (~ few years)
  - Possible background: variables stars, RR Lyrae (tens of days)
- Test with SDSS stripe 82 (observations over 7-9 years) with spectroscopically confirmed objects
- Results:
  - only for stripe 82 (220 deg²)
  - ~28 deg⁻² QSOs with z>2.15
  - Proof of principle for future surveys (e-BOSS, BigBOSS)

N. Palanque-Delabrouille et al., A&A 530, A122 (2011)
Status of the survey

- On average ~4000 high-z QSOs per month
- So far, ~92 000 new QSOs (including ~61 500 z>2.15 QSOs) over ~4000 deg$^2$
- This sample (1/3 of entire survey) will be DR9 (July 2012)
- End of the survey: 150k - 200k high-z QSOs !!!
Proof of Principle

- 3D mapping of HI

A. Slosar et al.,
Ly-\(\alpha\) forests for BAO

**Principles**
- Use Ly-\(\alpha\) forests of quasars (2.2<z<4)
- HI absorption in IGM along the line of sight of QSOs
- We expect low density gas (IGM) to follow the dark matter density (validations: measured 1D power spectrum and N-body simulations...)

**BAO specifications:**
- 3D BAO: Correlation between the different lines of sight
- BAO measurement for z~2.5
- Better precision in radial direction (H(z) measurement).
**Measurement of HI absorbed flux**

**Flux definition**

- Transmitted Flux Fraction $F$: 
  Flux/Continuum $0 < F < 1$:
- The power spectrum of the $\delta_F$ has the same shape as the power spectrum of matter density $\delta = \rho / \bar{\rho} - 1$

**Pedagogical example**

- Single absorbing "cloud" at $z_{\text{cloud}}$ with $z_{\text{cloud}} < z_{\text{qso}}$
- QSO Ly-$\alpha$ emission: 
  $1216\AA (1 + z_{\text{qso}})$
- HI "cloud" absorption: 
  $1216\AA (1 + z_{\text{cloud}})$
- In real life, many absorbing "clouds" + noise

$$\delta_F \equiv \frac{F}{\bar{F}} - 1$$

$$\bar{F} \propto e^{-\tau(z)}$$

$$\tau(z) \propto (1 + z)^{3.8}$$
**QSO Ly-α Forest**

**Typical BOSS QSO**
- Redshift $z = 3.28$
- Very noisy QSOs (on average SNR~1-2)
- $\lambda > \lambda_{\text{Ly-α}}$: fluctuations from noise
- $\lambda < \lambda_{\text{Ly-α}}$: fluctuations from noise and absorption

**Data Set**
- Year one: 14000 QSOs, $z>2.15$
- Demonstration of the method
- Correlation function for $r<100$Mpc/h (below BAO scale)
Ly-$\alpha$ absorption correlations

\[ \xi_F(\vec{r}) = \left\langle \delta_F(\vec{x}) \cdot \delta_F(\vec{x} + \vec{r}) \right\rangle \]
Correlation Function

- Correlations in HI seen to 50 Mpc/h
- First observation in 3D of matter in IGM
- Results consistent with \( \Lambda \)CDM simulations

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

\( \Lambda \)CDM + 2 free parameters (related to HI bias and mean absorption)
Large-scale Redshift Distortions

- Acceleration toward overdense regions
- Flattening in radial direction from real space to redshift space (over tens Mpc)
- Measurable with Kaiser formula

N. Kaiser
*MONRAS 227, 1 (1987)*

\[ P_F(\overrightarrow{k}) = P_F(k, \cos(\theta)) \]
\[ = b^2 P_L(k) \cdot (1 + \beta \cos(\theta)^2)^2 \]

- \( P_L(k) \) linear power spectrum
- \( \theta \) angle between vector \( k \) and QSO line of sight
Large-scale Redshift Distortions

- Redshift distortion clearly observed with 44000 LRGs $<z> \sim 0.6$ in BOSS (spring 2010)
- Excellent agreement between data and N-body simulations


- Flattening of $(r_{\text{tran}}, r_{\text{rad}})$ correlation function distribution
- First observation of redshift distortion at $z \sim 2.5$
- Distortion are quantitatively measured by multi-poles decomposition
Correlation Function (multi-poles)

\[ \xi_F(r,\cos(\theta)) = \sum_{\ell=0,2,4,6} b^2 C\ell \xi(r) P_\ell(\cos(\theta)) \]

- \(P_1\) : Legendre polynomials

- Negative quadrupole as predicted by GR
- Gravity works at \(z \sim 2.5\)
- Gravity is forming structures at \(z \sim 2.5\)
- Results consistent with \(\Lambda\)CDM simulations
Conclusions and Prospects
Largest 3-D map of the Distant Universe

- First 3-D map at so distant part (z~2.5) of Universe
- Proof that Ly-α absorption is a reliable techniques for cosmology
- Future maps 10 times bigger and BAO peak should be soon seen with Ly-α forests

A slice through the 3-D map of the universe
BAO with BOSS

- 1/3 of the survey is already observed (~450k LRG and ~60k Ly-α QSOs for DR9)
- Everything is in place to measure the Equation of State of Dark Energy with BOSS
- With LRG: ~1.5M galaxies
  BAO scale: 1.0% at $z \approx 0.35$
  1.1% at $z \approx 0.6$
- With Ly-α forests: ~150k QSOs
  BAO scale: 1.7% at $z \approx 2.5$

$w = \frac{p_{DE}}{\rho_{DE}} = w_0 + w_a z/(1+z)$