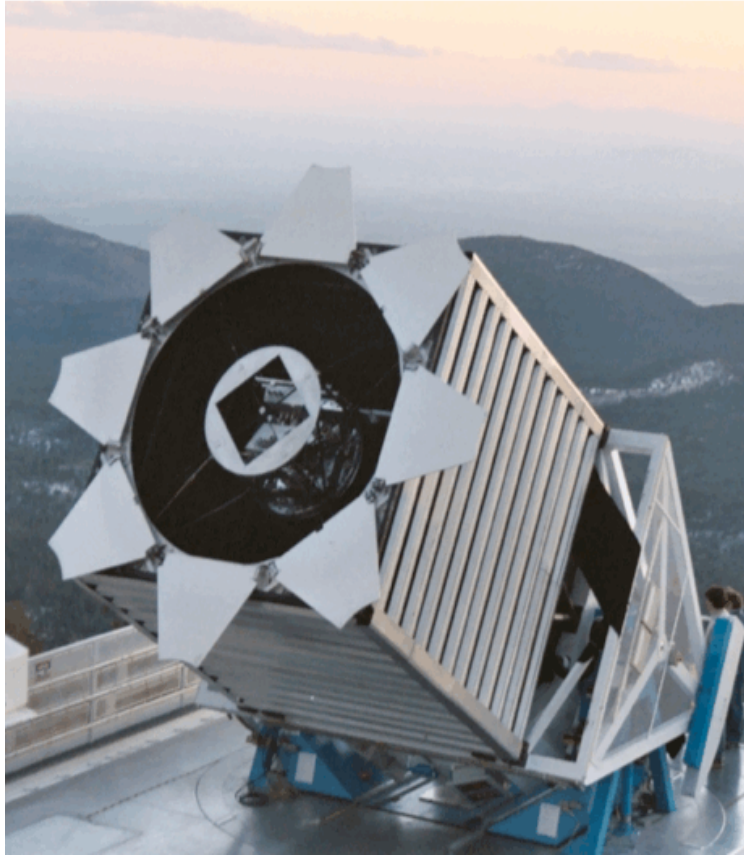
BAO and Lyman-α with BOSS

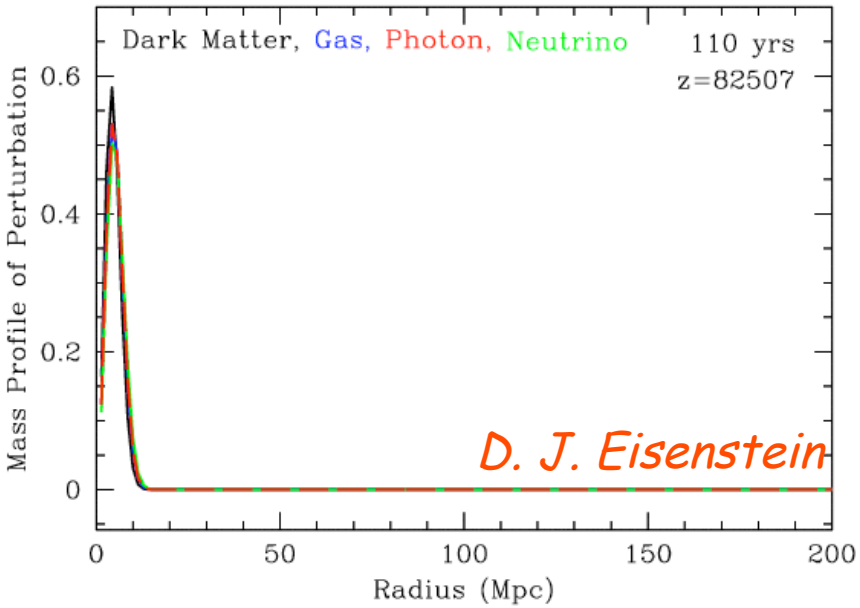
Nathalie Palanque-Delabrouille (CEA-Saclay)



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

Deep surveys, Large Scale Structures and dark energy
Valencia, Mar 29-30, 2012

Baryonic Acoustic Oscillations

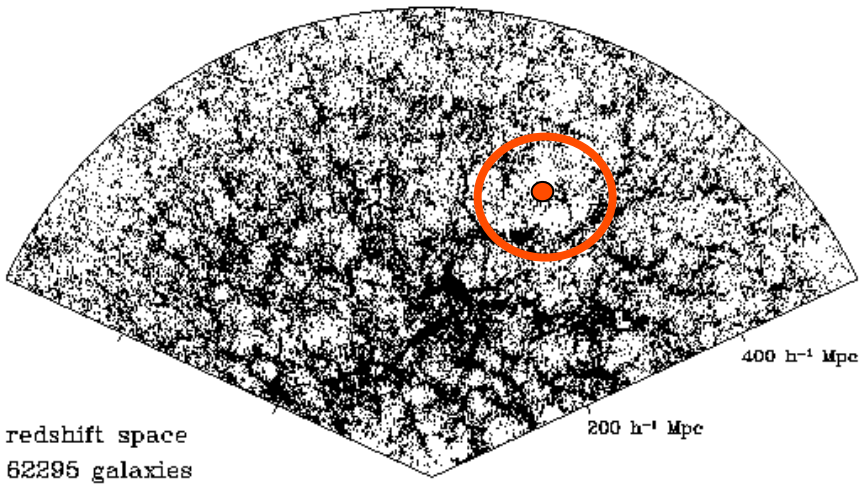


Acoustic propagation of an overdensity:

- Sound wave through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination (z~1100).
- 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 BAO peak

3D observation of density excess

- Position of acoustic peak ⇒ size of sound horizon s

- **Transverse direction**

  $\Delta\theta = s/(1+z)/D_A(z)$

  ⇒ 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)

  $\Delta z = s \cdot H(z)/c$

  ⇒ Sensitive to Hubble parameter H(z)

- Requires accurate z ⇒ spectroscopy

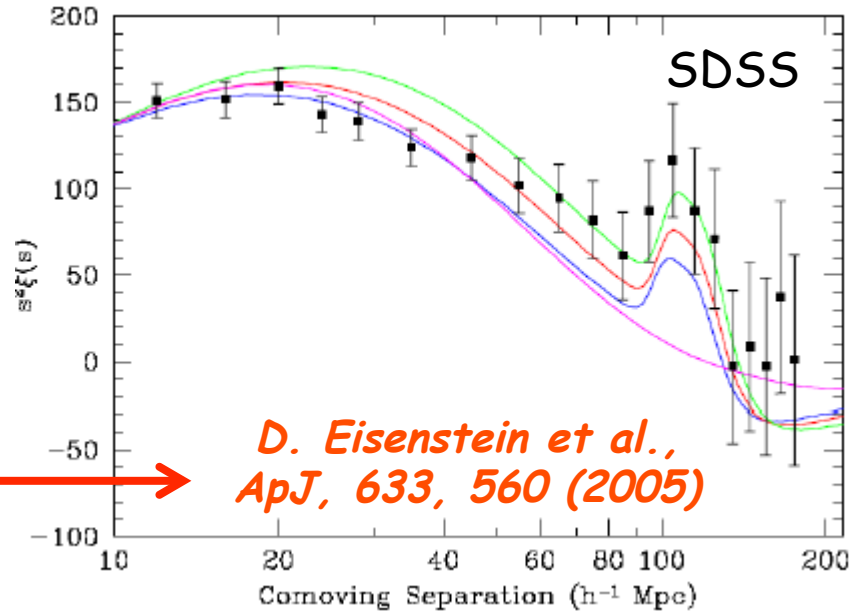
  (5x more volume to probe if photo-z)

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"
  <z> ~ 0.35

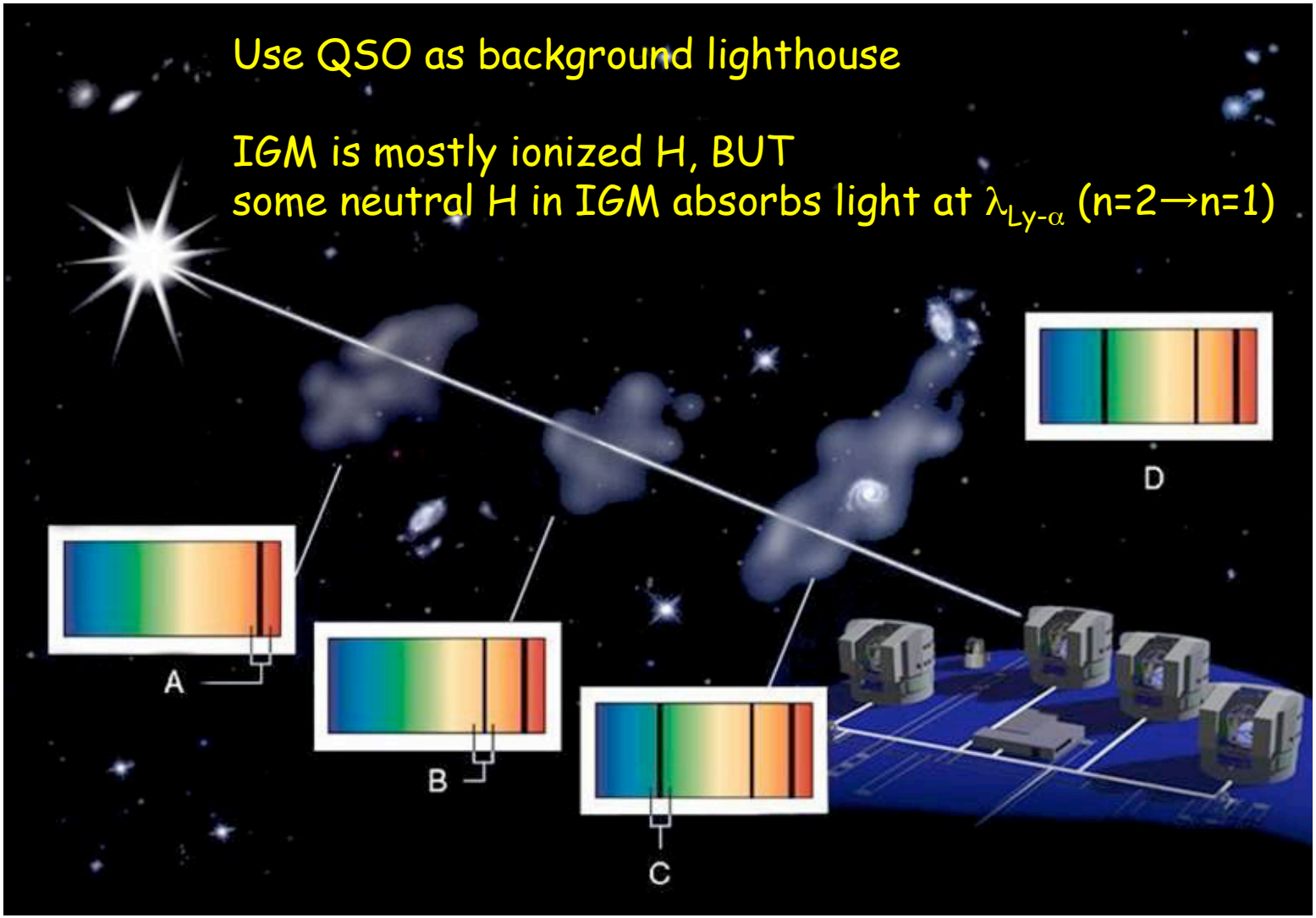


D. Eisenstein et al., ApJ, 633, 560 (2005)

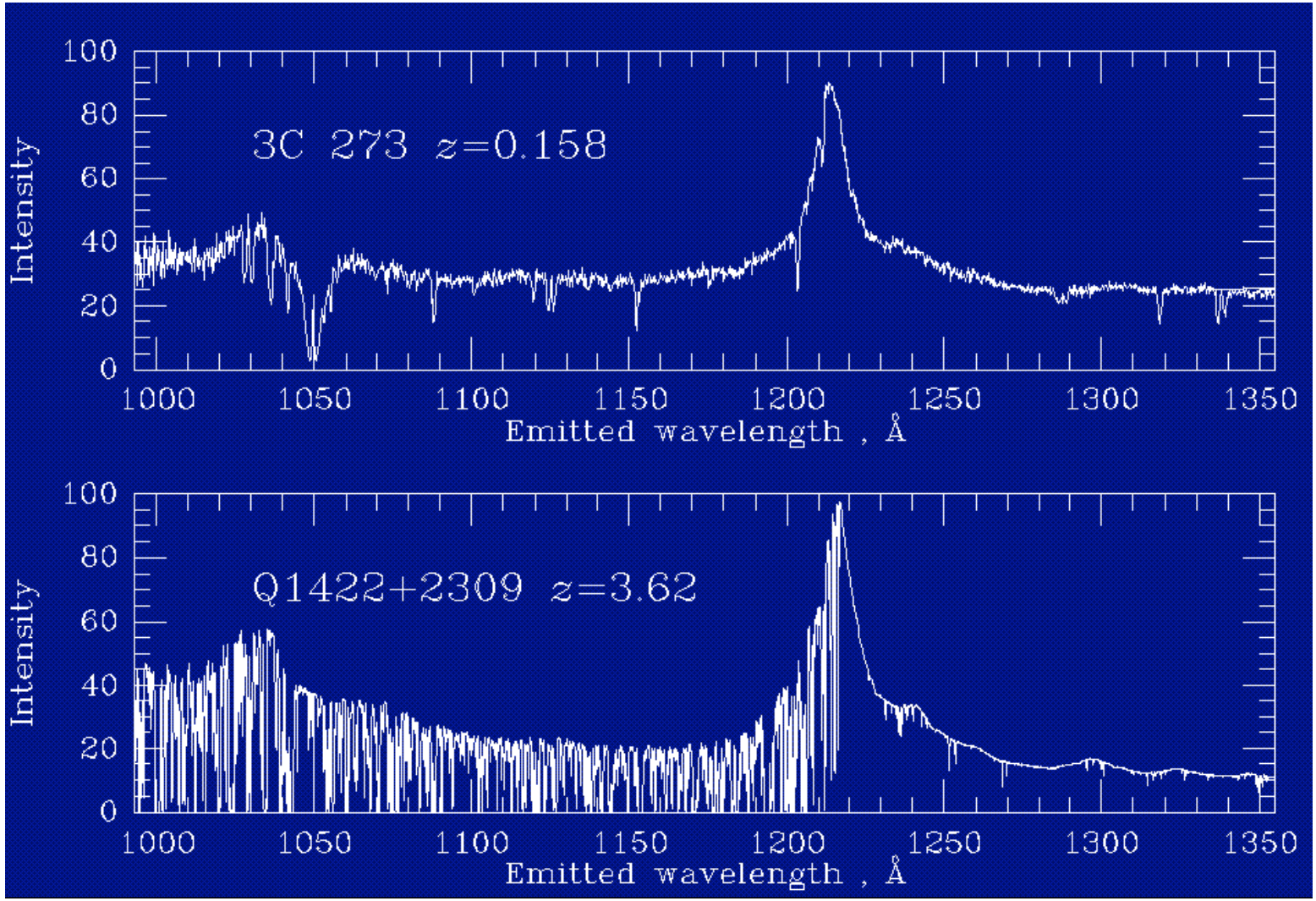
Improvements?

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

QSO's as IGM probe

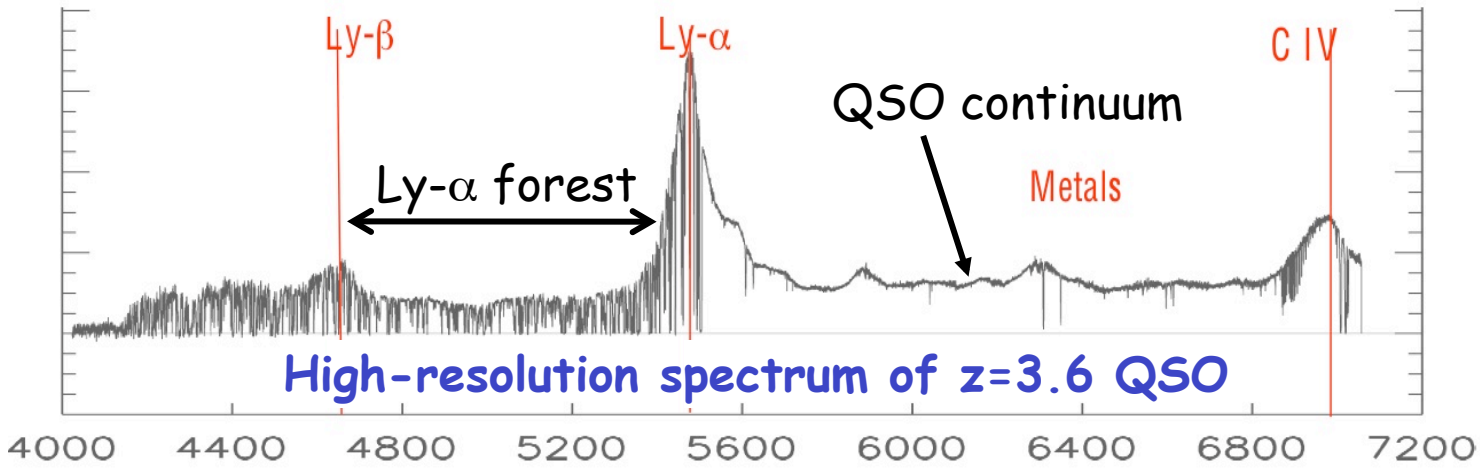


QSO's as IGM probe



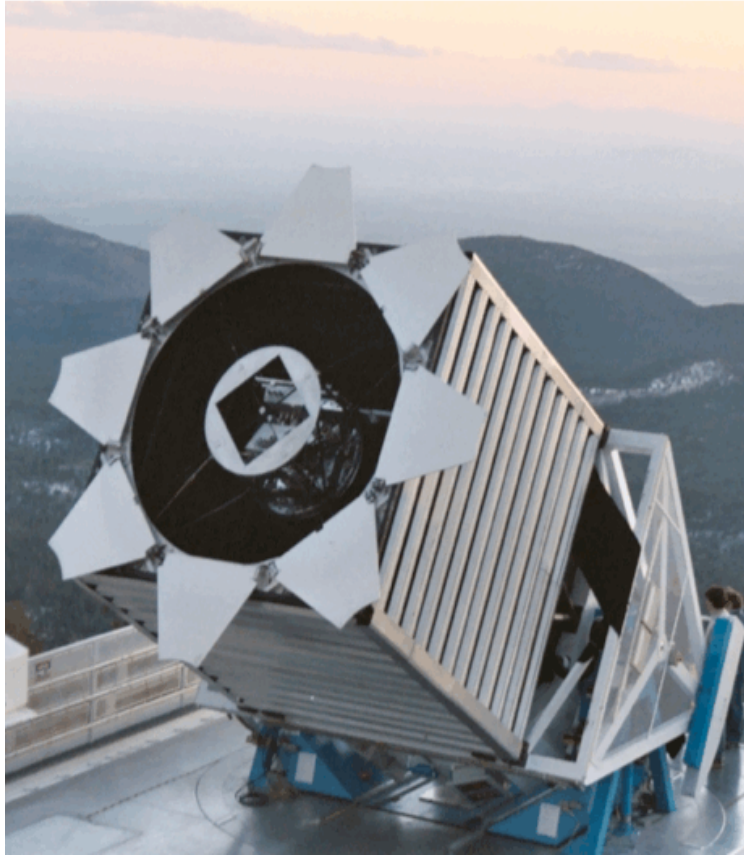
QSO's as IGM probe

- Use Ly-α forests of quasars ($2.2<z<4 \rightarrow$ visible range)
  Transmitted flux fraction $\propto \exp(-\tau)$ where $\tau \propto n_{HI} \propto (1+z)^{3.8}$
- Low density gas (IGM) expected to follow dark matter density
- **BAO** measurement for **z~2.5**



BAO and Lyman-α with BOSS

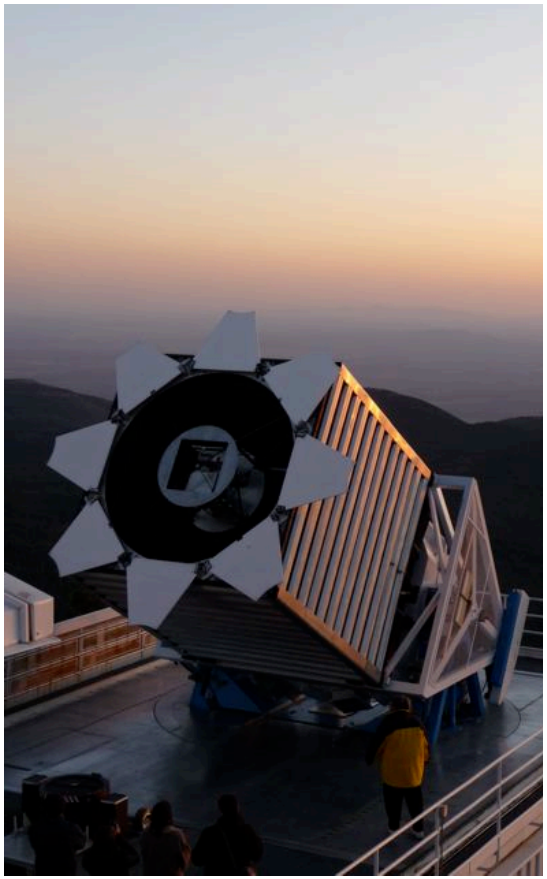
- BAO and Ly-α
- **The SDSS-III/BOSS experiment**
- Current results with BOSS
  - 3D BAO analysis with QSOs
  - 1D Ly-α power spectra and ν mass
  - Highlights on BAO with galaxies



SDSS-III / BOSS

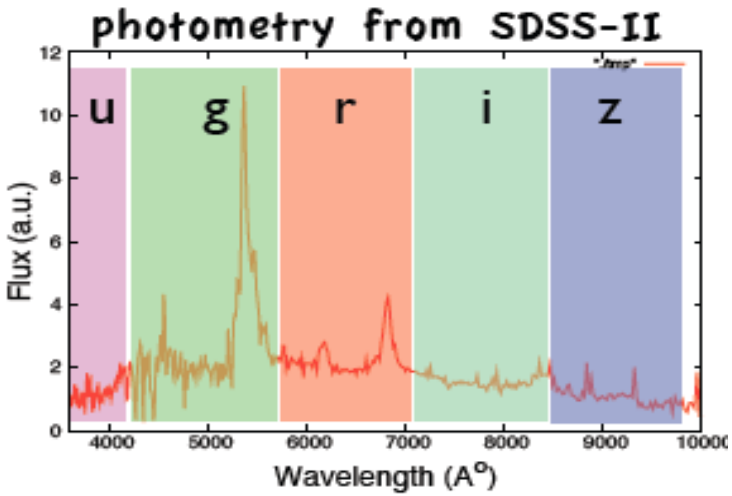
Sloan Telescope
- 2.5m telescope at Apache Point (New Mexico)
- 7 deg^2 field
- Total survey area: 10,000 deg^2

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-α forest program



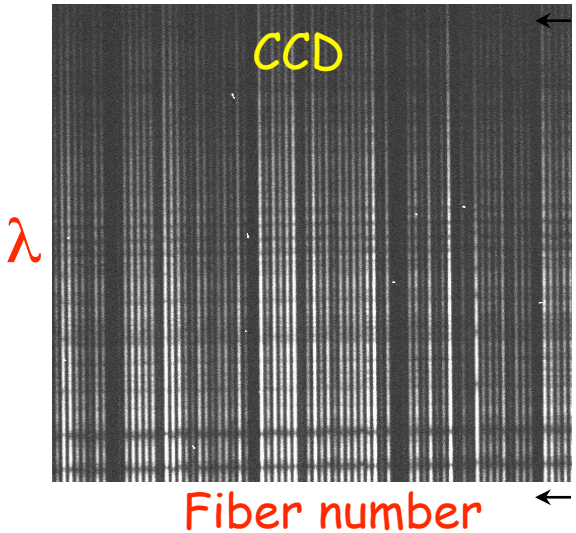
Data taking
2009-2014

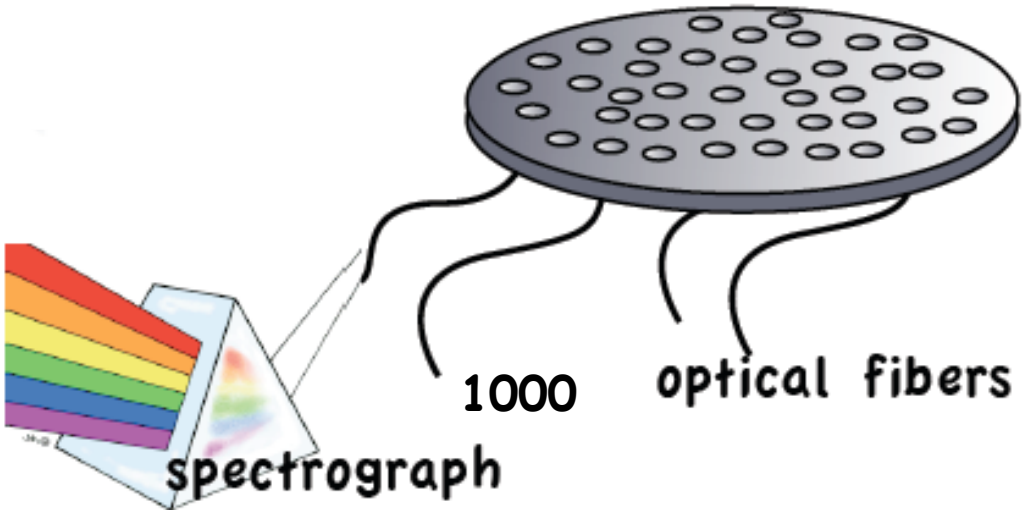
SDSS-III / BOSS



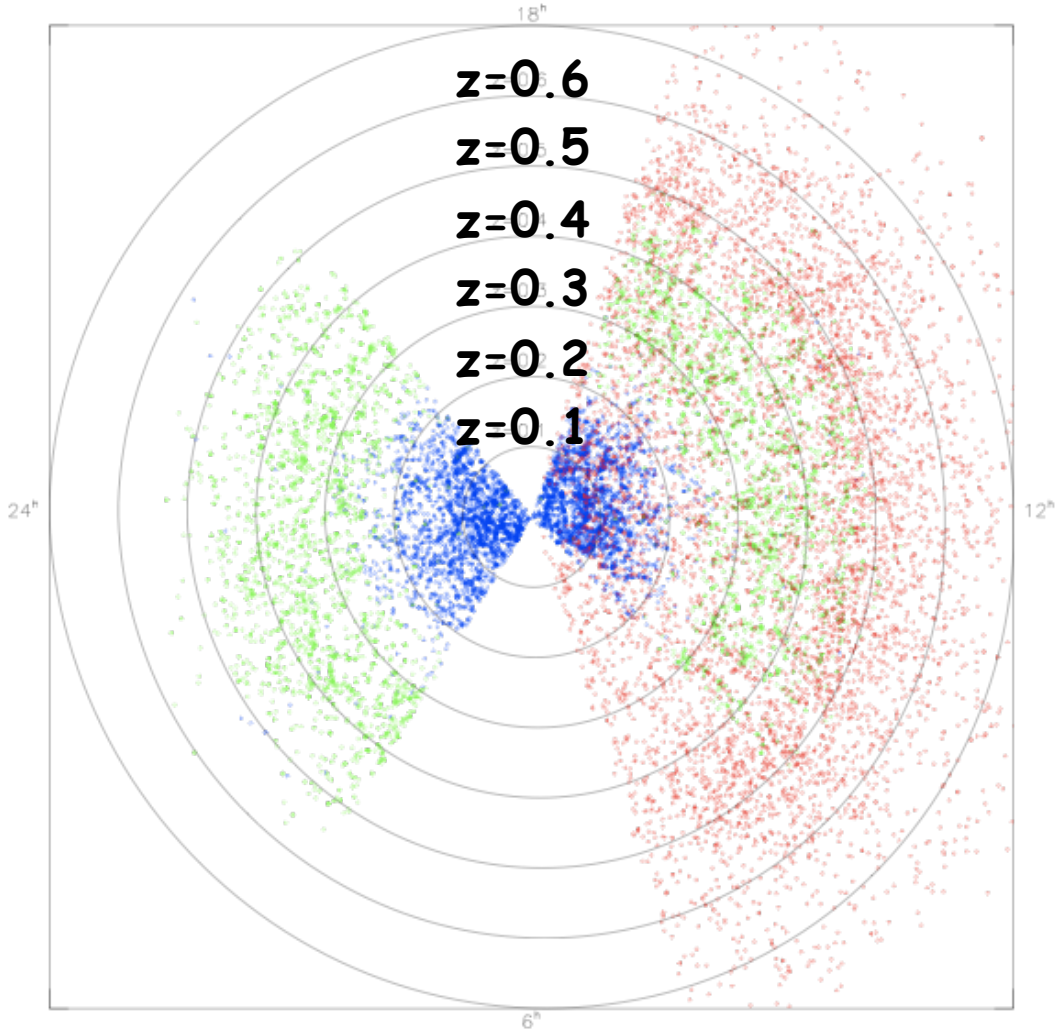
List of targets

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
....





SDSS-III coverage



SDSS main galaxy survey

1 million galaxies

Too little volume for BAO

SDSS-I + SDSS-II

Luminous Red Galaxies (LRG)

z ~ 0.35

80,000 galaxies

8,000 deg^2

SDSS-III – BOSS

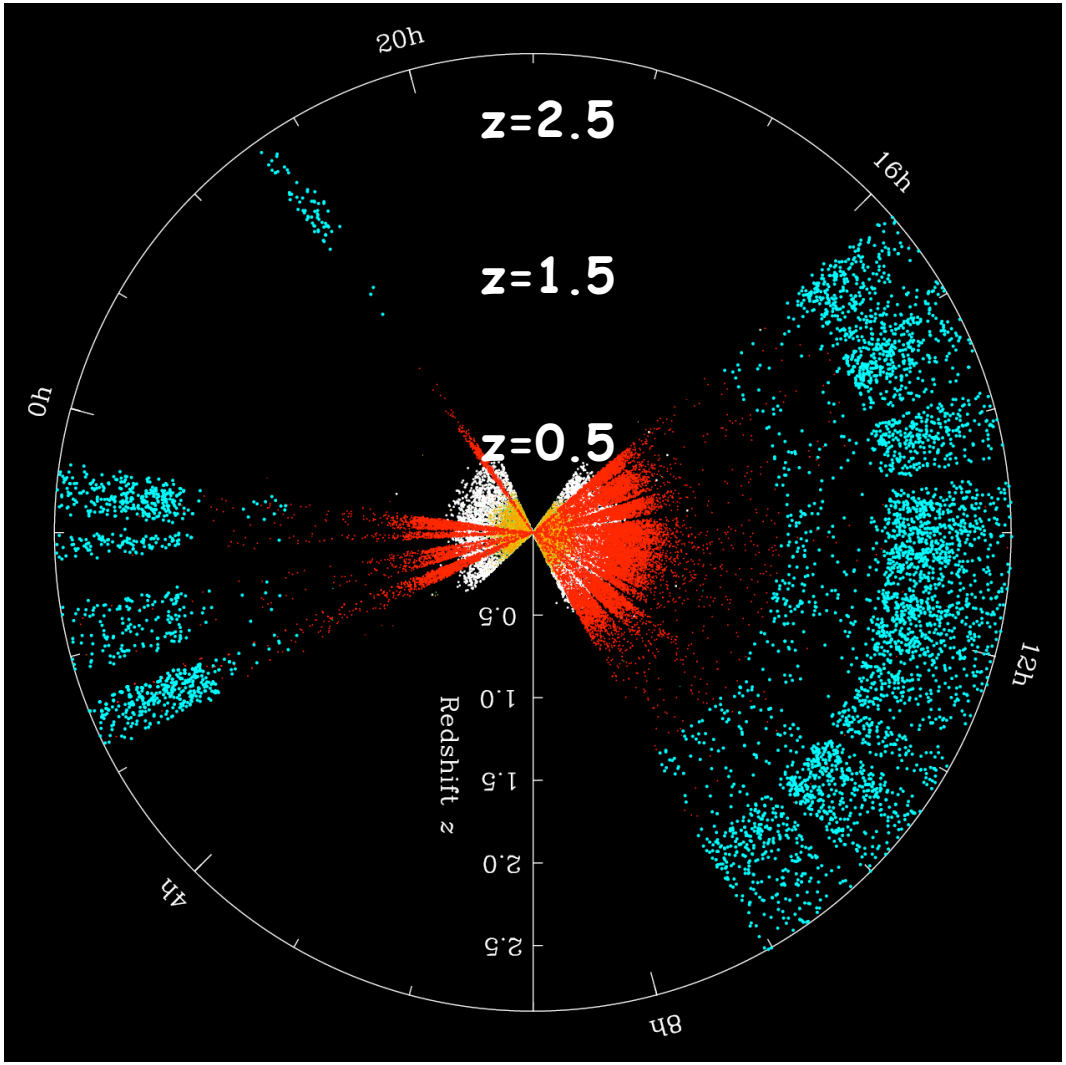
1.5M LRG with z up to 0.7

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 deg^2
Volume x2, Density x5

160,000 2.2<z<4.5 quasars

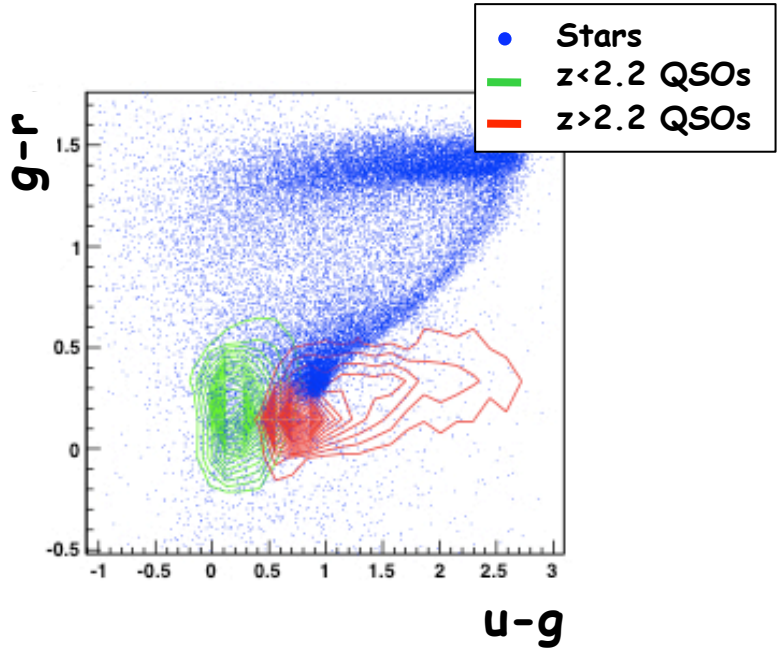
QSO target selection in SDSS

Hard to distinguish z>2.2 QSOs from stars

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

Dedicated algorithms
Yèche et al., A&A 523, A14 (2010)
Bovy et al., ApJ 729, 141 (2011)
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)

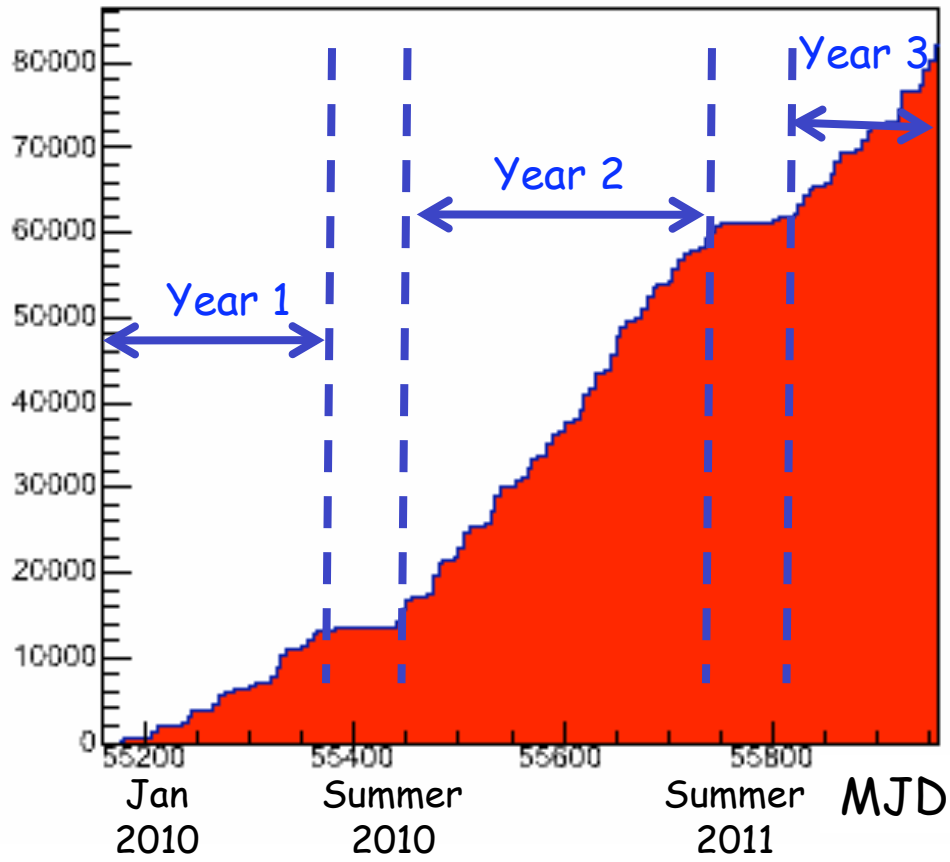
QSO target selection in SDSS

So far
130,000 QSOs
including 85,000 z>2.2 QSOs
over 5500 deg^2

On average
4000 z>2.2 QSOs per month

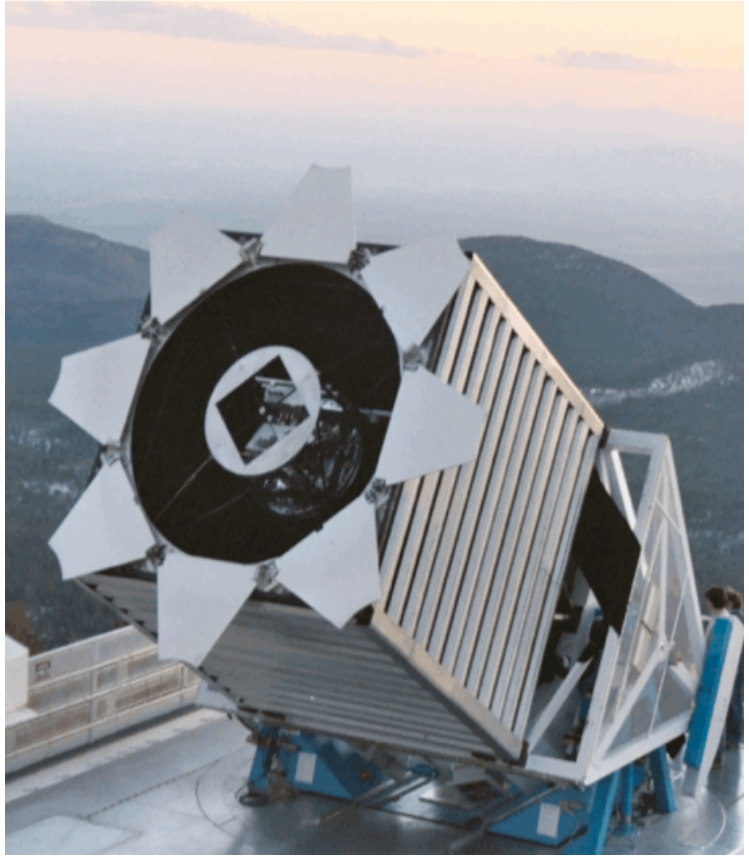
End of survey (July 2014)
150,000 to 200,000 z>2.2 QSOs

Cumulative number of z>2.2 QSOs



BAO and Lyman-α with BOSS

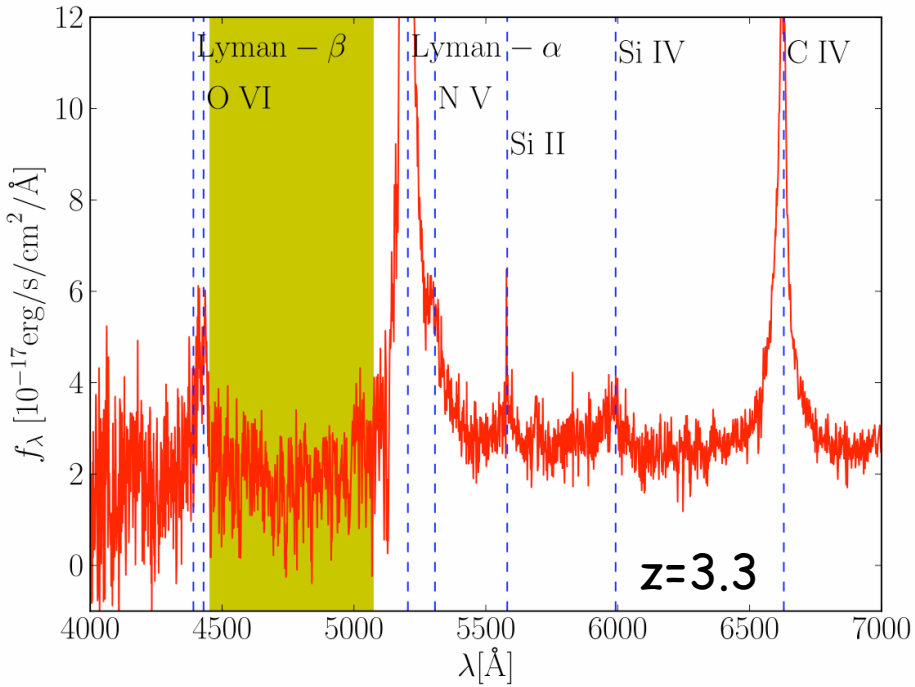
- BAO and Ly-α
- The SDSS-III/BOSS experiment
- **Current results with BOSS**
  - 3D BAO analysis with QSOs
  - 1D Ly-α power spectra and ν mass
  - Highlights on BAO with galaxies



QSO Ly-α forest

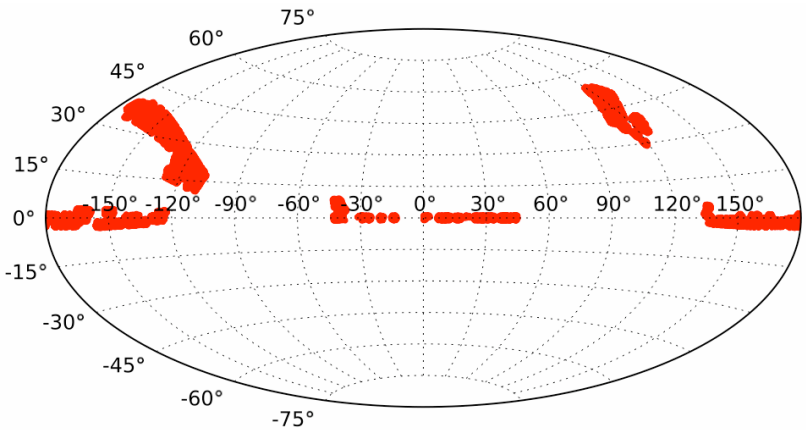
1st year BOSS results

A. Slozar et al., JCAP 09, 001 (2011)



Typical BOSS QSO

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



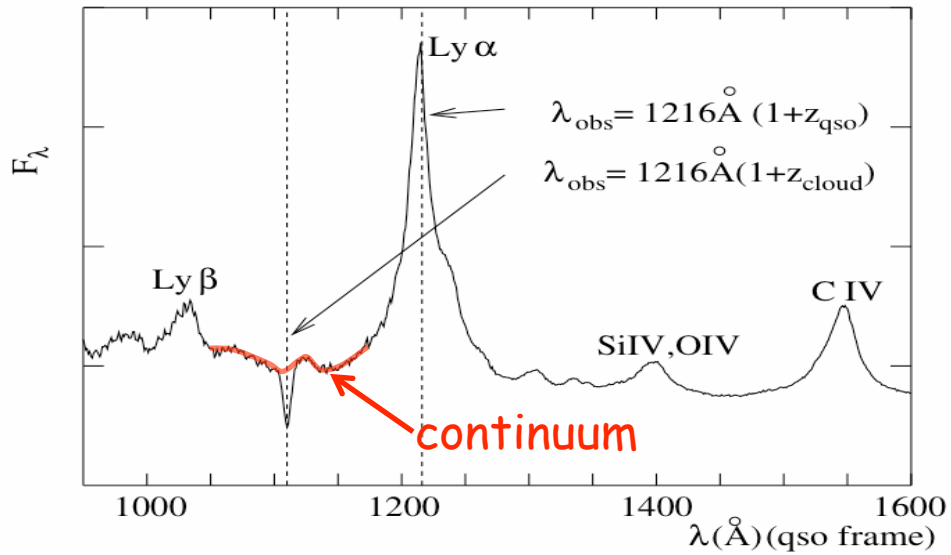
Data Set

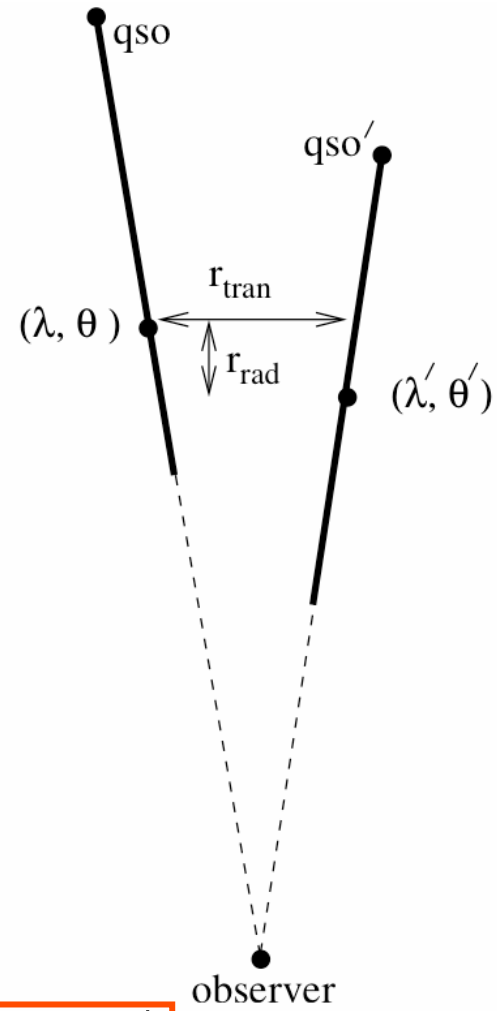
- Year one : 14,000 QSOs with z>2.15
- Demonstration of the method
- Correlation function for r<100Mpc/h (below BAO scale)

Correlation function of QSO Ly-α forests

Transmitted flux fraction
F = Flux / QSO continuum

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





$$\xi_F(\vec{r}) = \left\langle \delta_F(\vec{x}) \cdot \delta_F(\vec{x} + \vec{r}) \right\rangle$$

Correlation function of QSO Ly-α forests

1st year BOSS results

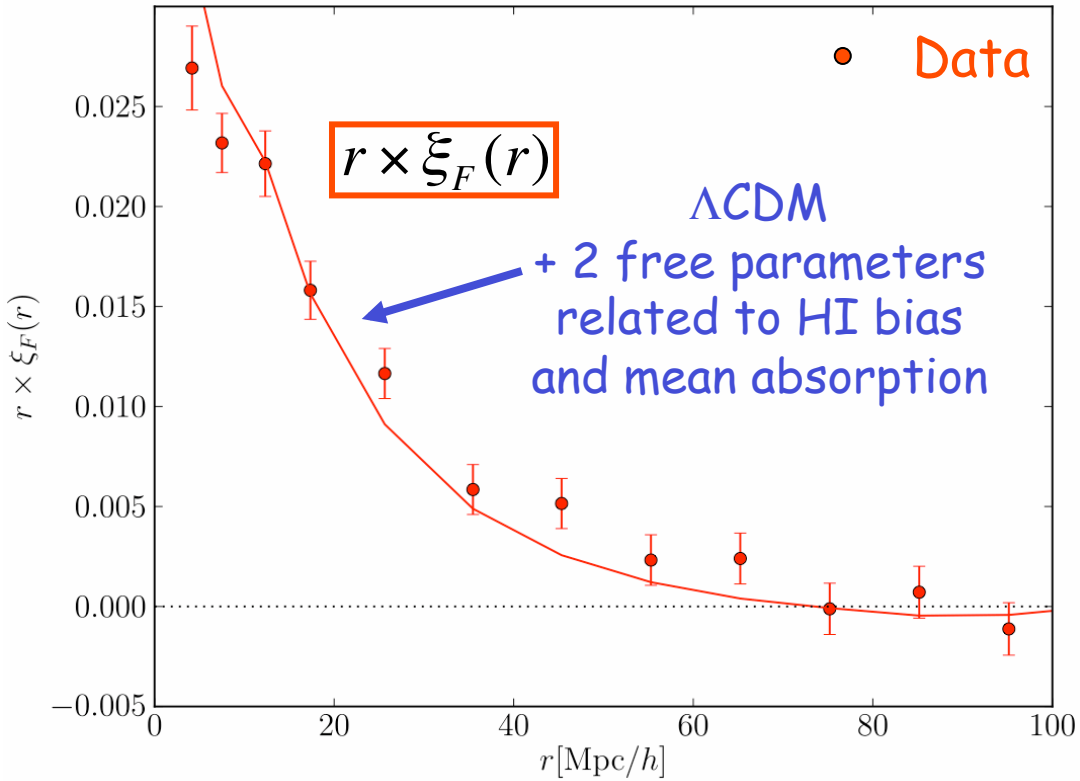
A. Slozar et al., JCAP 09, 001 (2011)

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

First observation in 3D of clustering in IGM

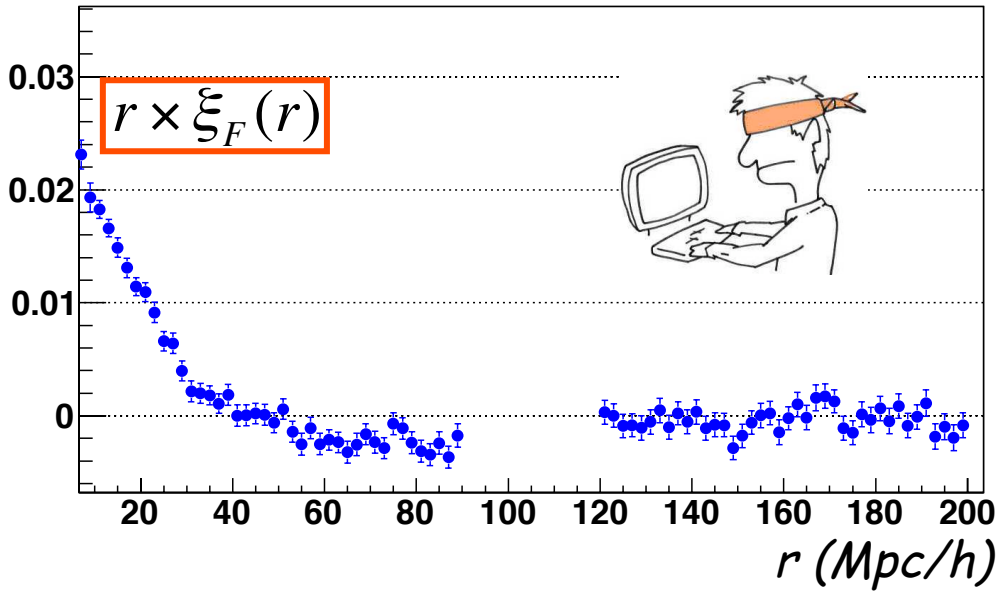
Correlations in HI seen to 60 Mpc/h

Results consistent with ΛCDM simulations



Correlation function of QSO Ly-α forests

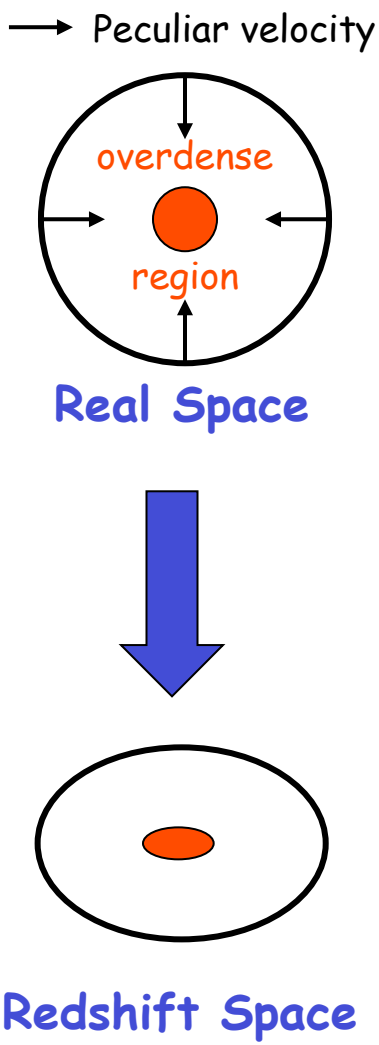
Next step : out to r> BAO peak (105 Mpc/h)
coming out soon…



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

$D_V \propto (D_A^2/H)^{1/3}$ $\delta D_v \sim 2\%$

Large-scale redshift distortions



Acceleration towards overdense regions

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

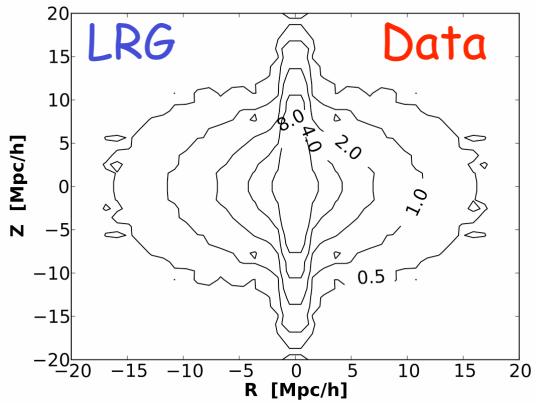
Measurable with Kaiser formula
N. Kaiser, MNRAS 227, 1 (1987)

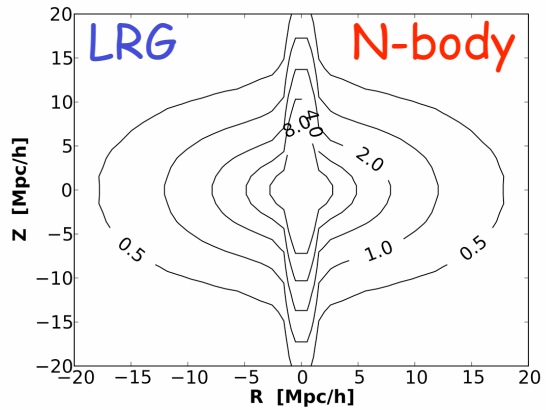
$$P_F(\vec{k}) = P_F(k, \cos(\theta))$$
$$= b_F^{\,2} \times (1 + \beta \cos(\theta)^2)^2 \times P_L(k)$$

$P_L(k)$: linear power spectrum

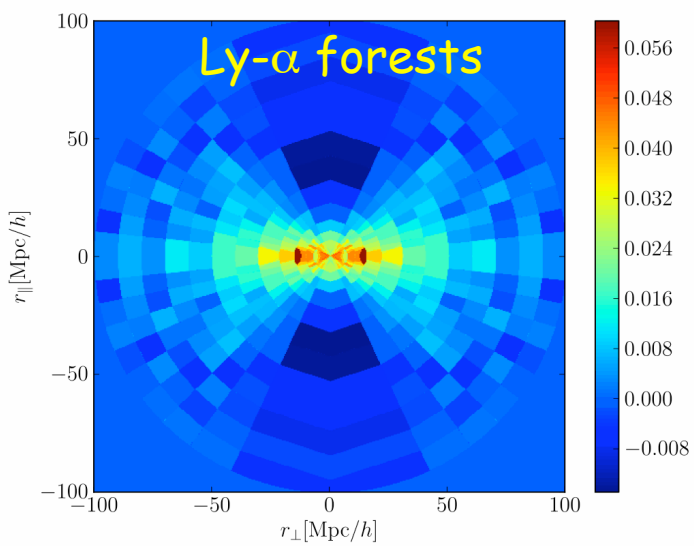
θ: angle between vector and QSO line of sight

Large-scale redshift distortions





Clearly seen with
44,000 LRGs <z>~0.6 in BOSS
M. White et al., ApJ 728, 126 (2011)



Flattening of correlation function distribution

First observation of redshift distortion at z~2.5
(β=0 excluded at 5σ)

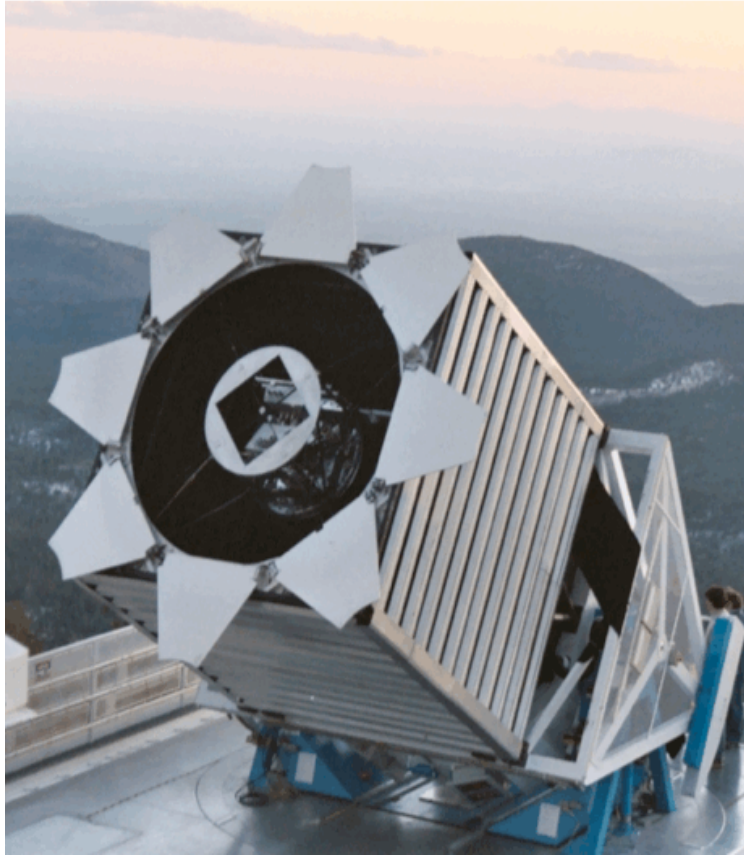
Gravity is forming structures at z~2.5

Distortions quantified with multipole decomposition

$$0.16 < b < 0.24 \quad @95\%$$
$$0.44 < \beta < 1.20 \quad @95\%$$

BAO and Lyman-α with BOSS

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



Large-scale structures and neutrinos

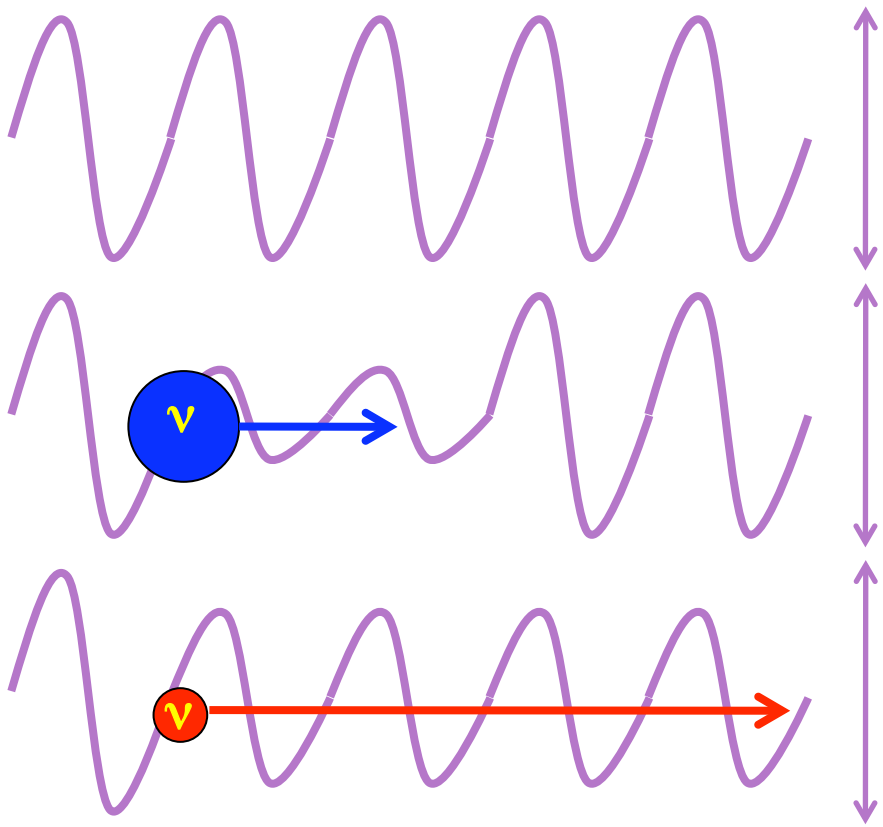
Neutrinos are massive but m_ν is small
→ relativistic during most of history of Universe
→ $\delta_\nu \sim 0$ at high z (free streaming)

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

- Spreading out grav. potential, growth suppressed on small scales by free-streaming ν

- **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



Large-scale structures and neutrinos

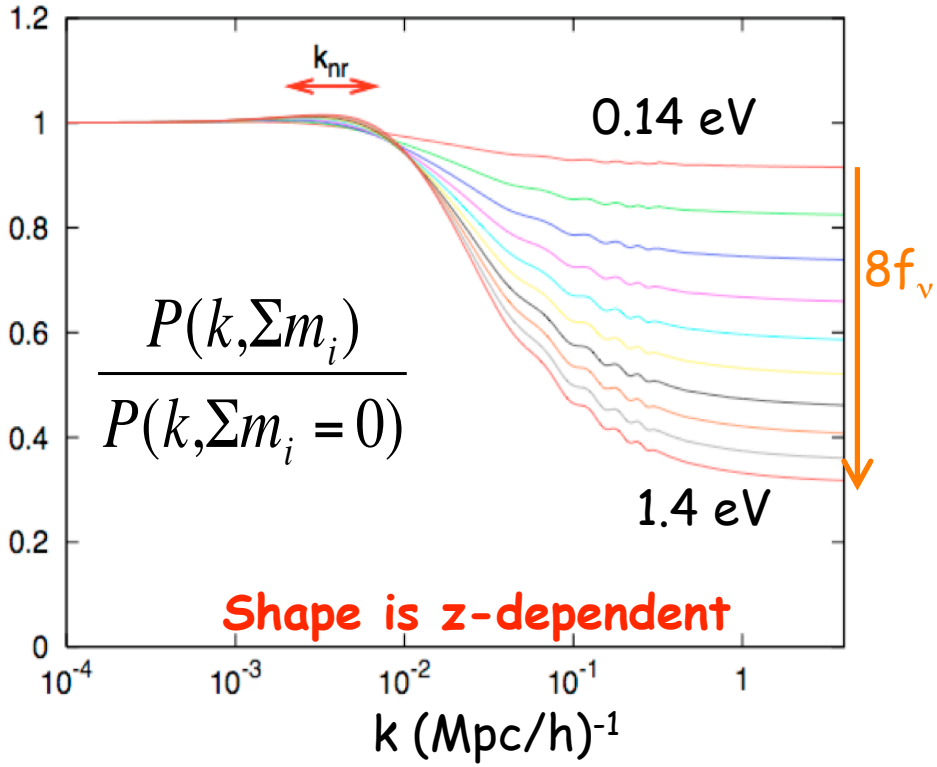
Neutrinos are massive but m_ν is small
→ relativistic during most of history of Universe
→ $\delta_\nu \sim 0$ at high z (free streaming)

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

- Spreading out grav. potential, growth suppressed on small scales by free-streaming ν

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

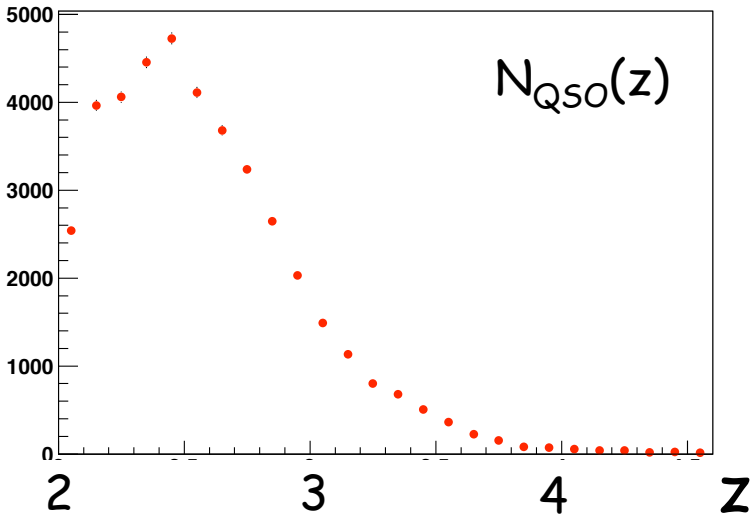
- **Light neutrinos:**
  Weak suppression over **long** range

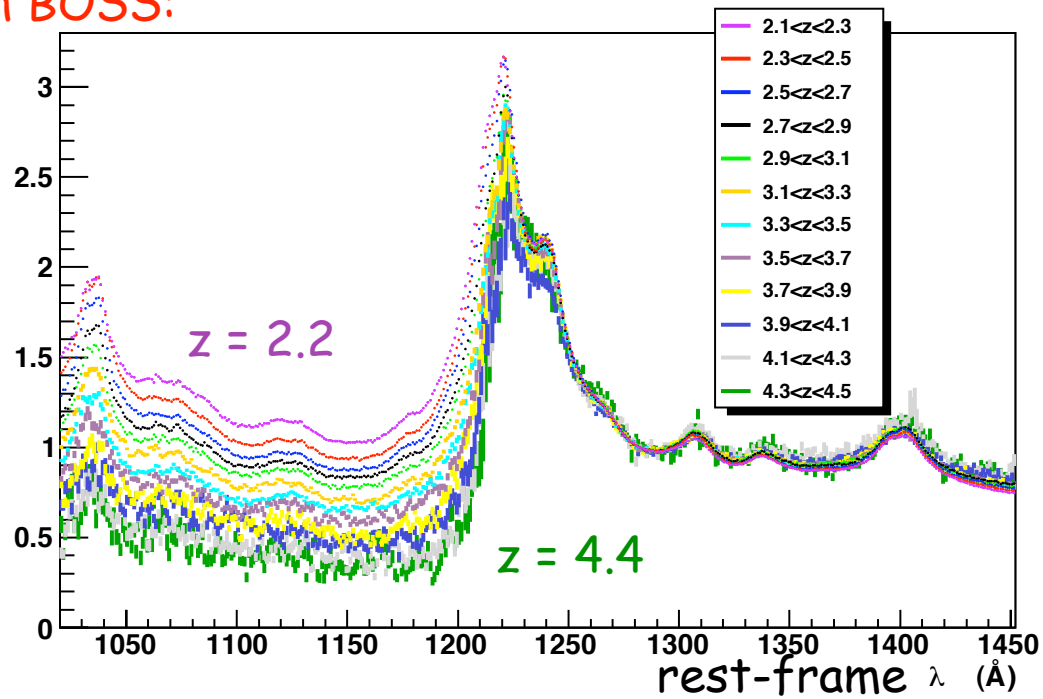


Large-scale structures and neutrinos

Best seen on small scales → Ly-α data
z-dependence → large z range

With BOSS:

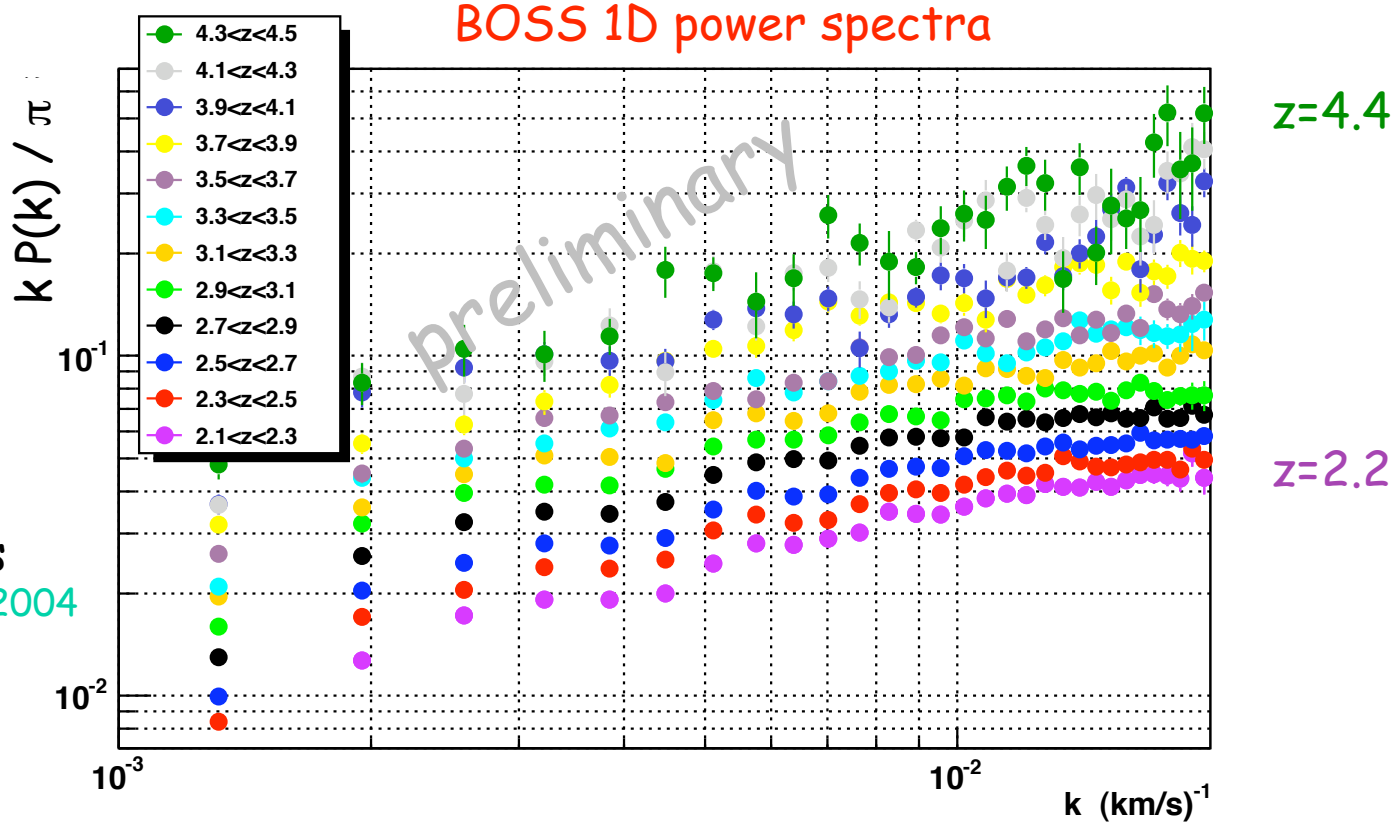




~16,000 QSOs
after cuts on S/N and spectrograph resolution in QSO spectrum

Large-scale structures and neutrinos

BOSS 1D power spectra



σ_{stat}
5x smaller than previous measurements
Mc Donald et al., 2004
SDSS-I

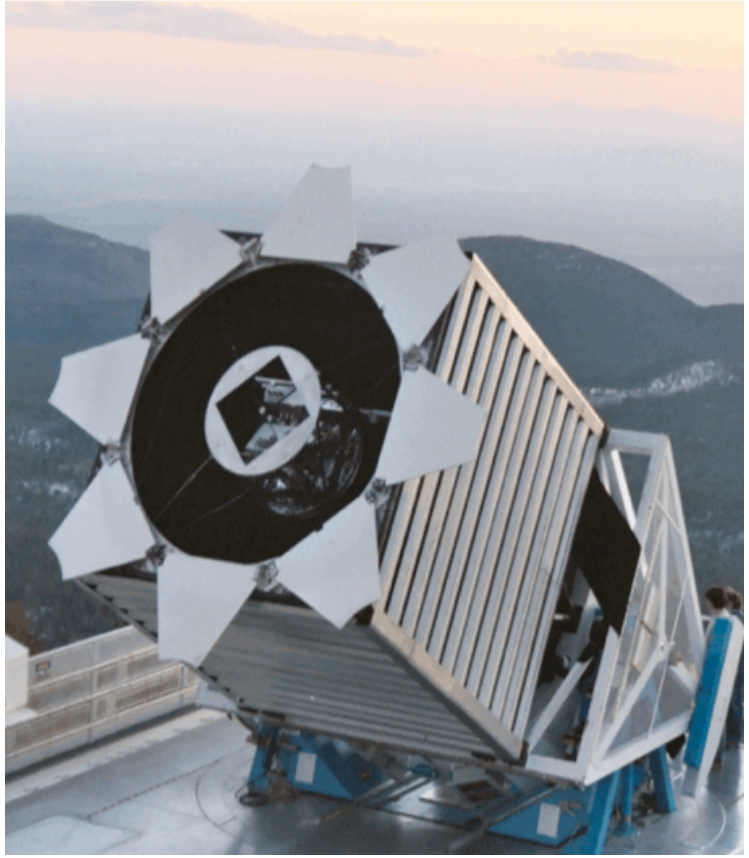
to be compared to hydro-simulations including neutrinos…

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-α only)

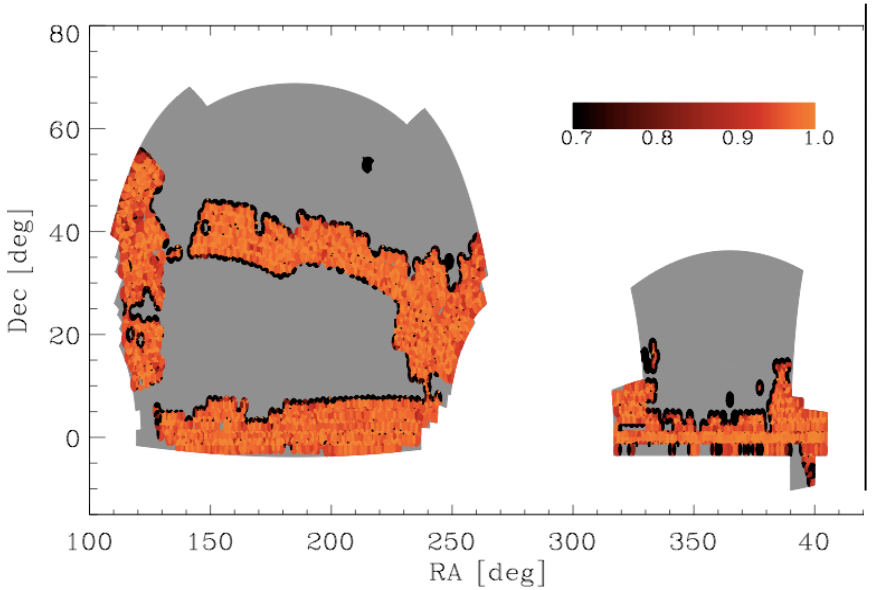
BAO and Lyman-α with BOSS

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

on arXiv TODAY !
(arXiv:1203.6594)

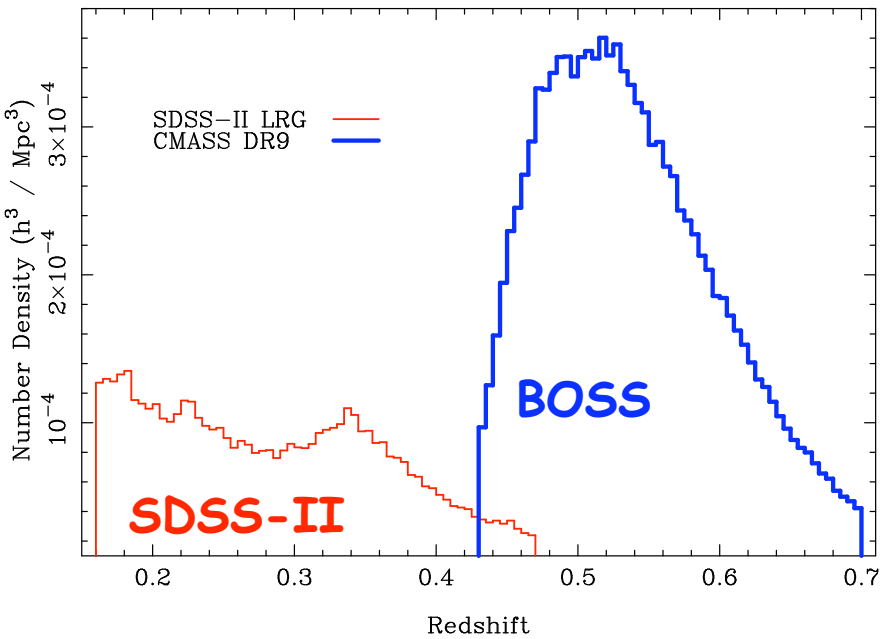


BAO with BOSS massive galaxies



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

DR9 sample (July 2012)
1/3 of total BOSS



Deeper and denser
than SDSS-II (DR7)

80,000 LRGs, <z> = 0.35

BAO with BOSS massive galaxies

position of BAO peak ⟷ distance D_V relative to sound horizon s

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

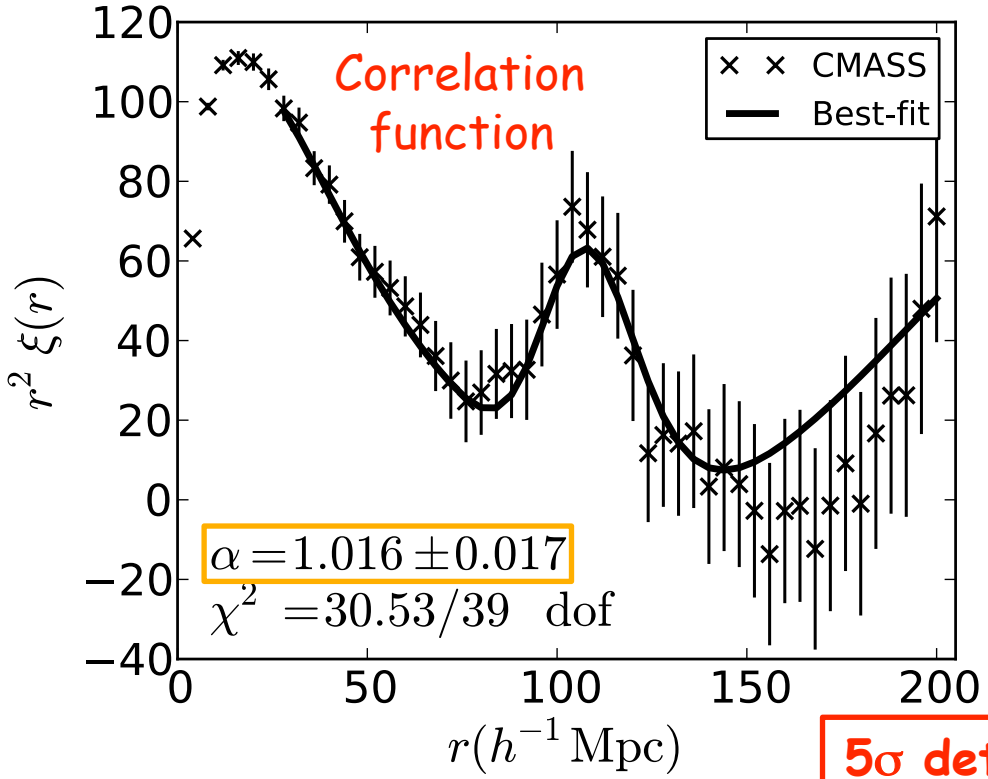
$$D_V / s = \alpha \left(D_V / s\right)_{fiducial}$$

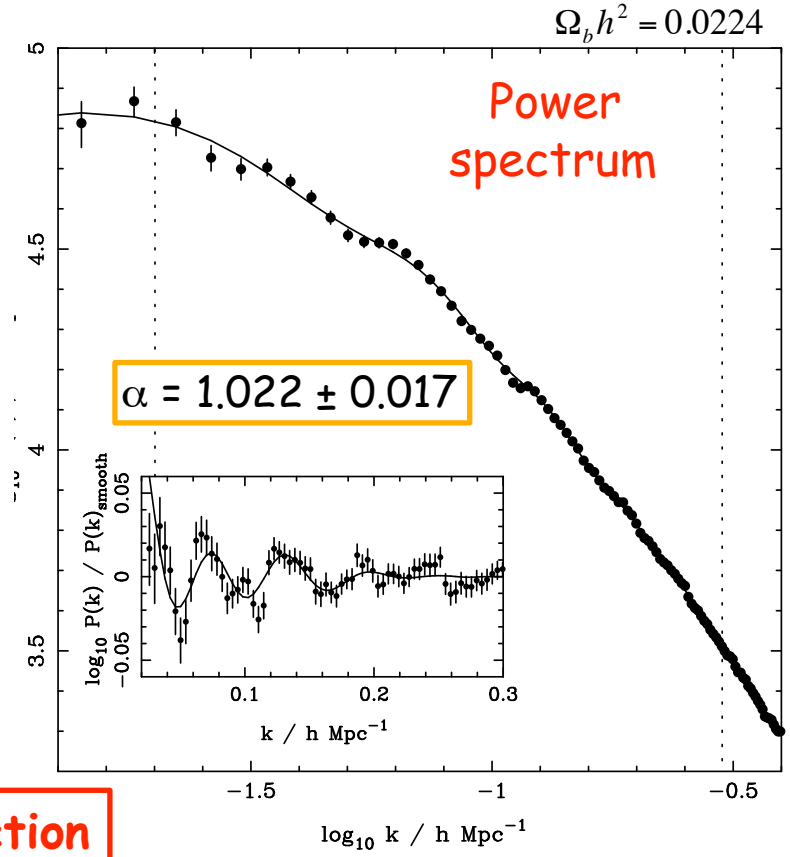
fiducial = WMAP7

$\Omega_M = 0.274$

$h = 0.7$

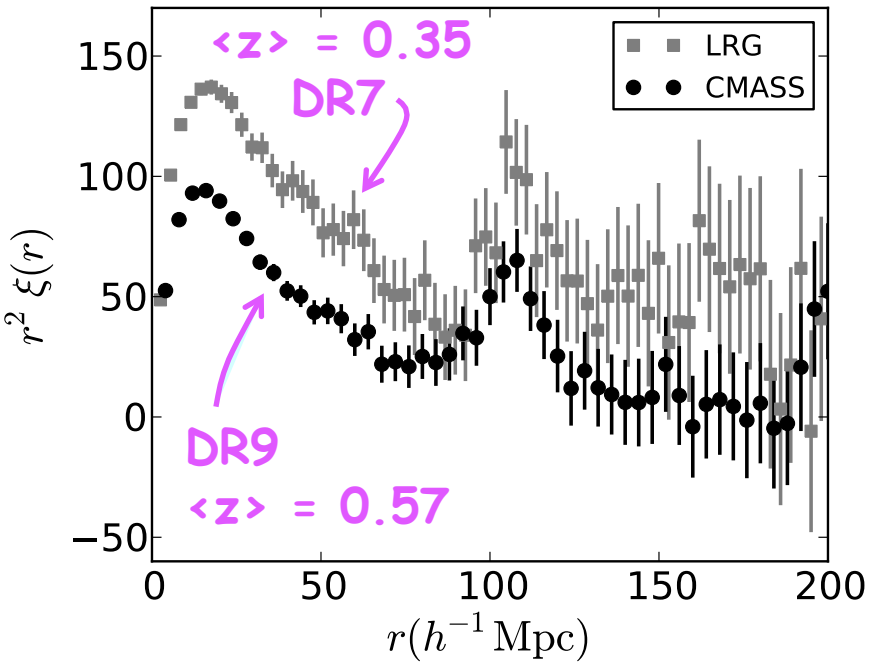
$\Omega_b h^2 = 0.0224$

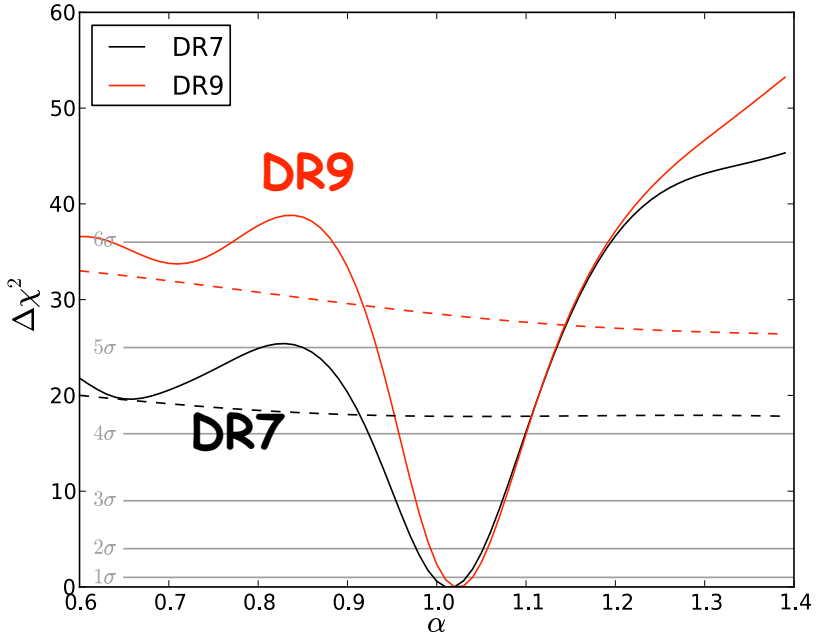


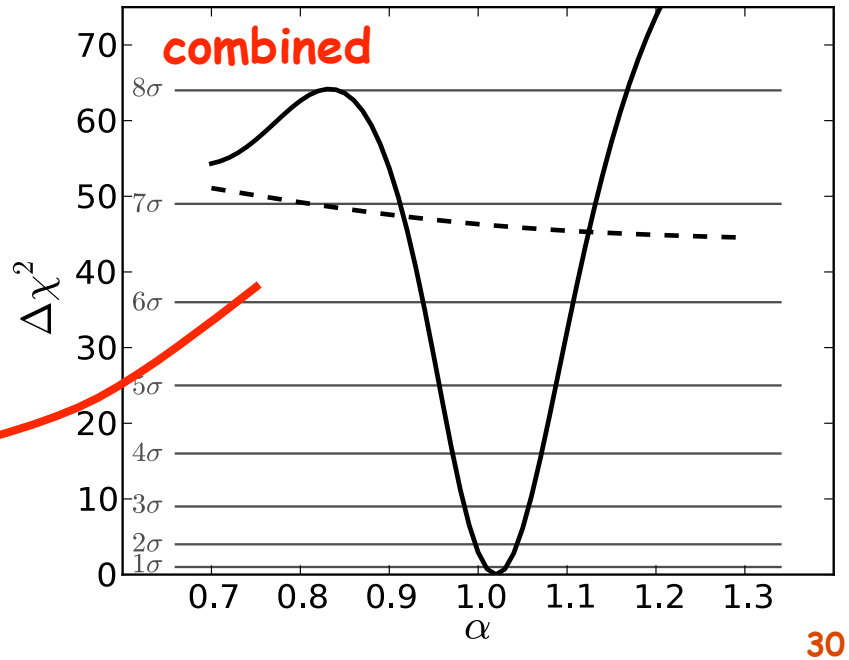


5σ detection

BOSS (DR9) + SDSS-II (DR7)

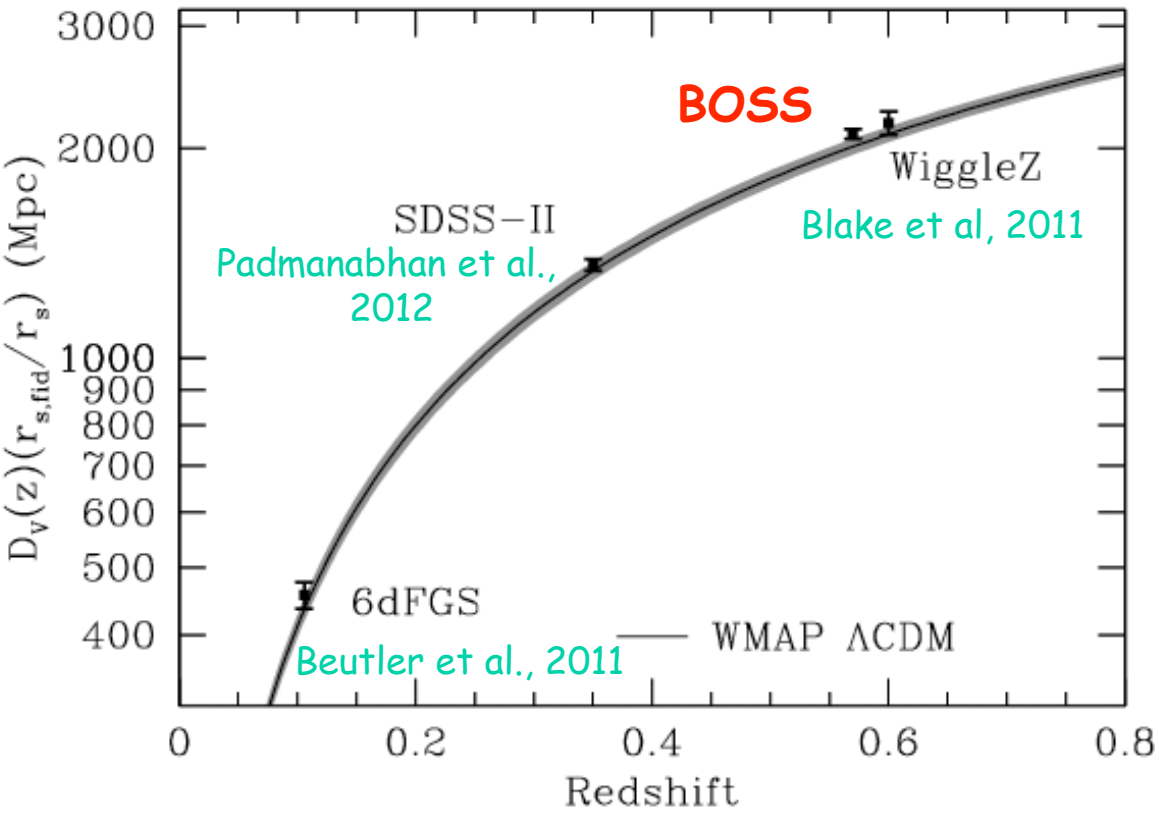


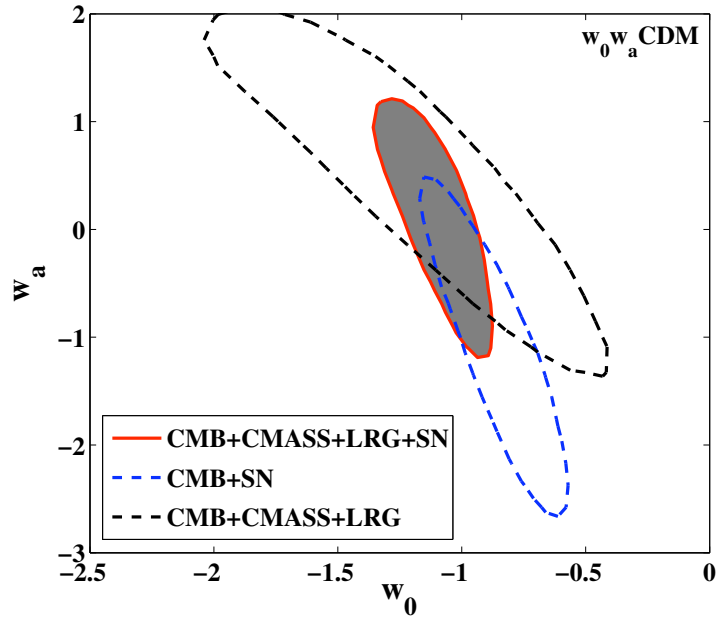




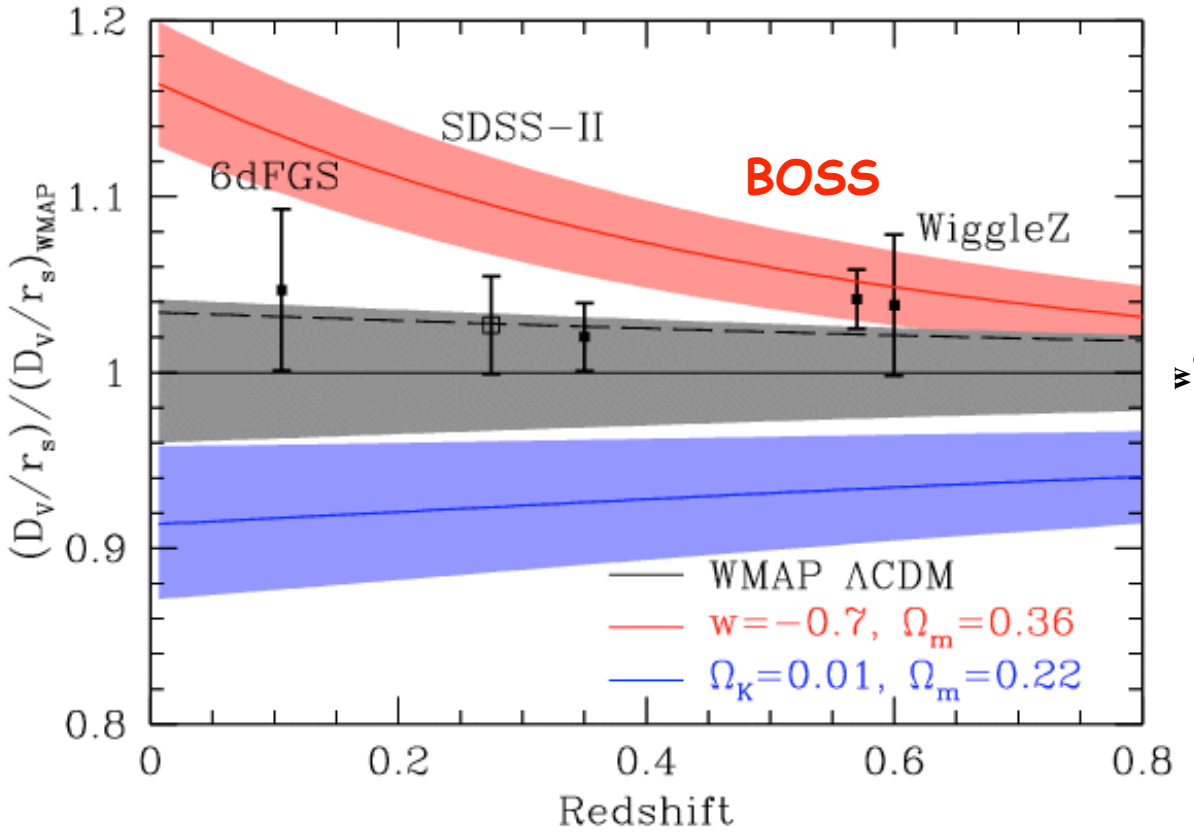
BAO peak detected at 6.7 σ

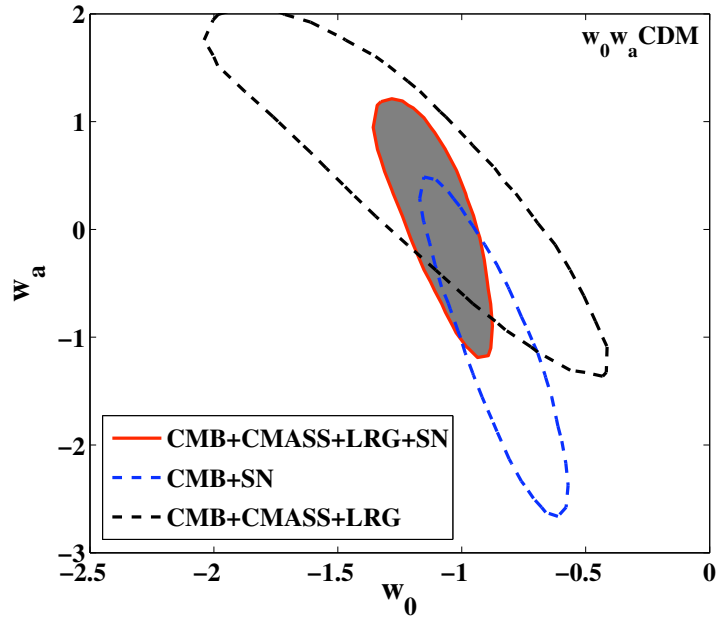
BAO and ΛCDM


BOSS
WiggleZ
Blake et al, 2011
SDSS−II
Padmanabhan et al., 2012
6dFGS
Beutler et al., 2011
WMAP ΛCDM
$D_V(z)(r_{s,fid}/r_s)$ (Mpc)
Redshift
3000
2000
1000
900
800
700
600
500
400
0
0.2
0.4
0.6
0.8


w_0w_aCDM
CMB+CMASS+LRG+SN
CMB+SN
CMB+CMASS+LRG
w_a
w_0
2
1
0
−1
−2
−3
−2.5
−2
−1.5
−1
−0.5
0

BAO and ΛCDM


1.2
1.1
1
0.9
0.8
0
0.2
0.4
0.6
0.8
Redshift
$(D_V/r_s)/(D_V/r_s)_{WMAP}$
SDSS−II
6dFGS
BOSS
WiggleZ
WMAP ΛCDM
w=−0.7, Ω_m=0.36
Ω_K=0.01, Ω_m=0.22


w_0w_aCDM
CMB+CMASS+LRG+SN
CMB+SN
CMB+CMASS+LRG
w_a
w_0
2
1
0
−1
−2
−3
−2.5
−2
−1.5
−1
−0.5
0

Conclusions on BOSS results

Massive galaxies at <z> = 0.57

Detection of BAO peak in BOSS at 5σ
→ 7σ (all SDSS data combined)

Lyman-α 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 → m_ν