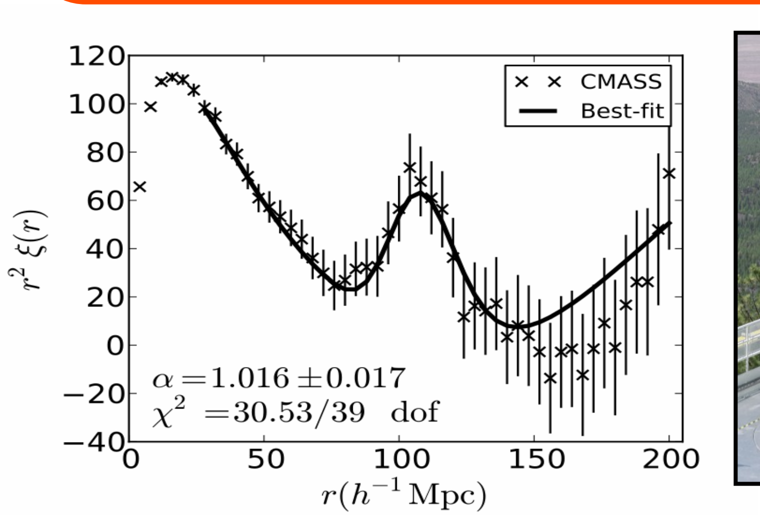
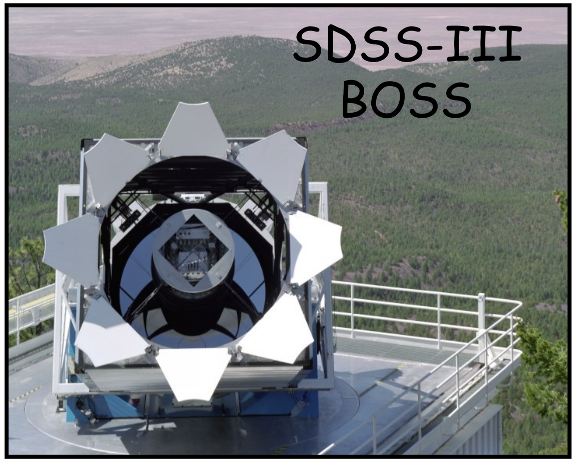
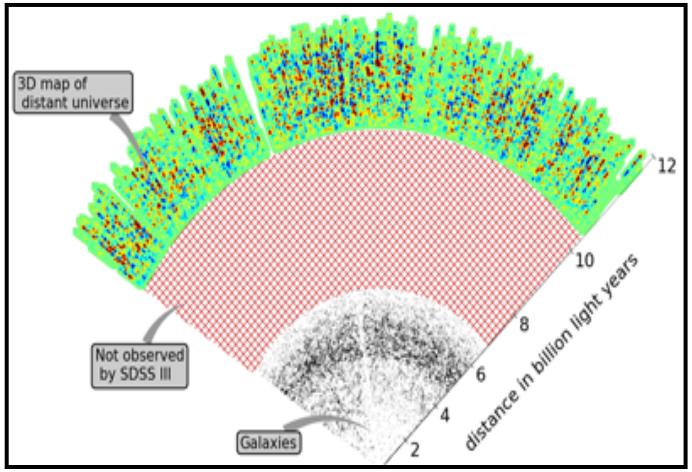
Dark Energy
First results with BOSS

Ch. Yèche
(CEA-Saclay Irfu)







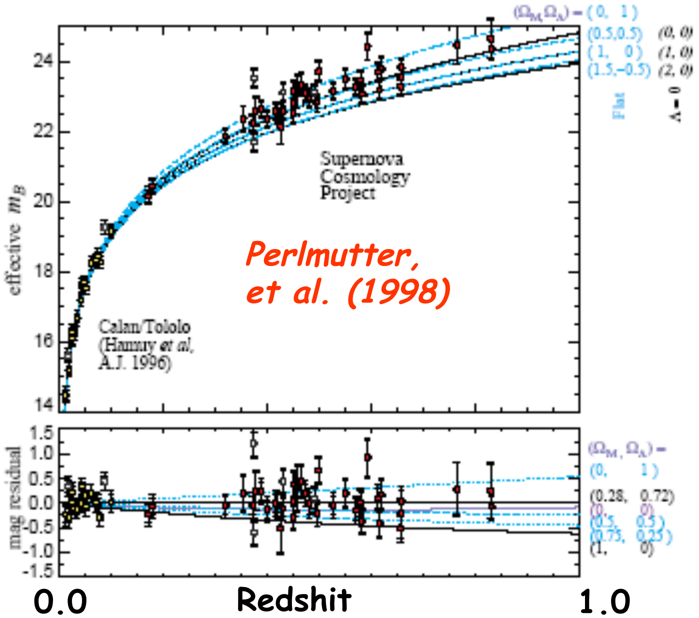
Outline:

- Concepts : BAO
- SDSS-III - BOSS
- Confirmation of BAO with galaxies
- First observation of BAO with Ly-α forests

LPNHE Seminar
Jussieu – November 19, 2012

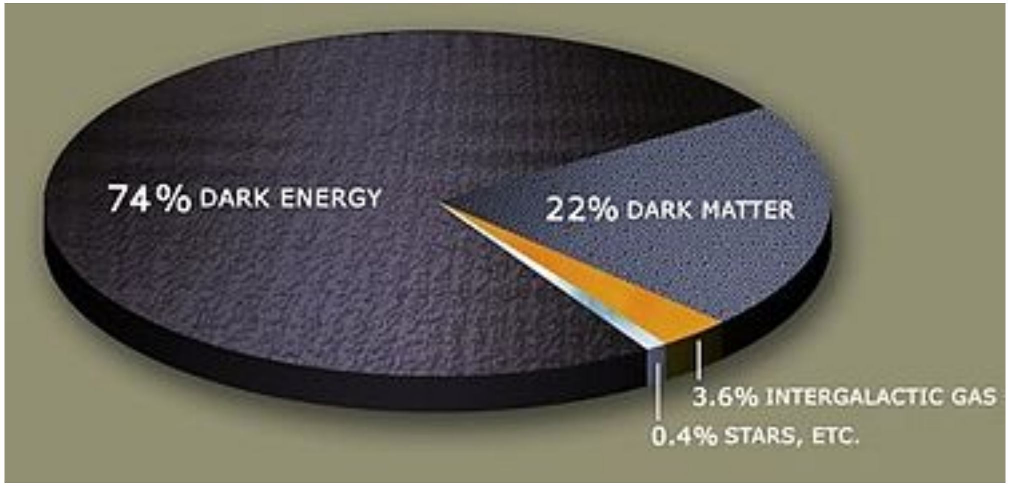
BAO
-
Concepts

Dark energy



Acceleration of Universe expansion

- In 1998 revolution of cosmology with standard candles, SNIa
- SNIa were dimmer (~0.2 mag), ~10% further away than expected with Ω_m =1

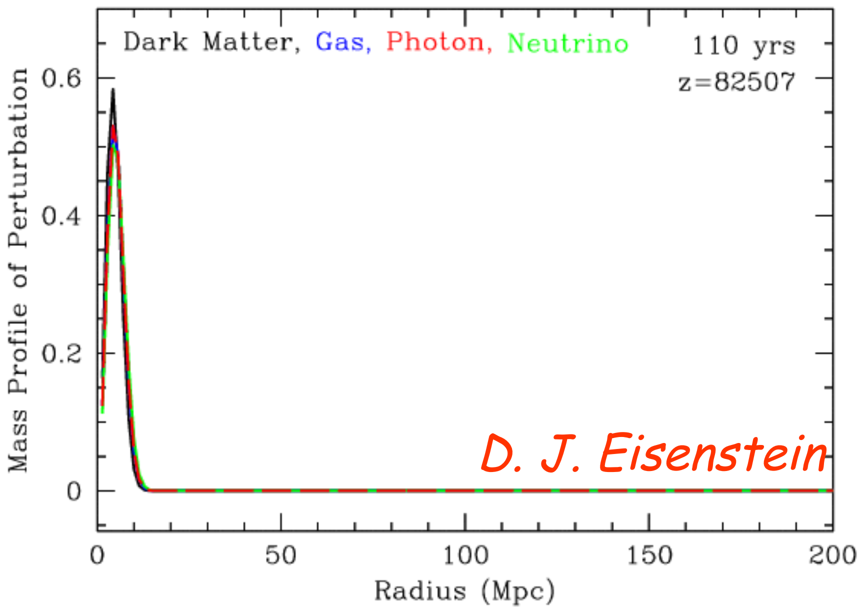


Concordance Model

- ΛCDM with GR
- Study of the nature of DE

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

A probe for Dark Energy: Baryonic Acoustic Oscillations



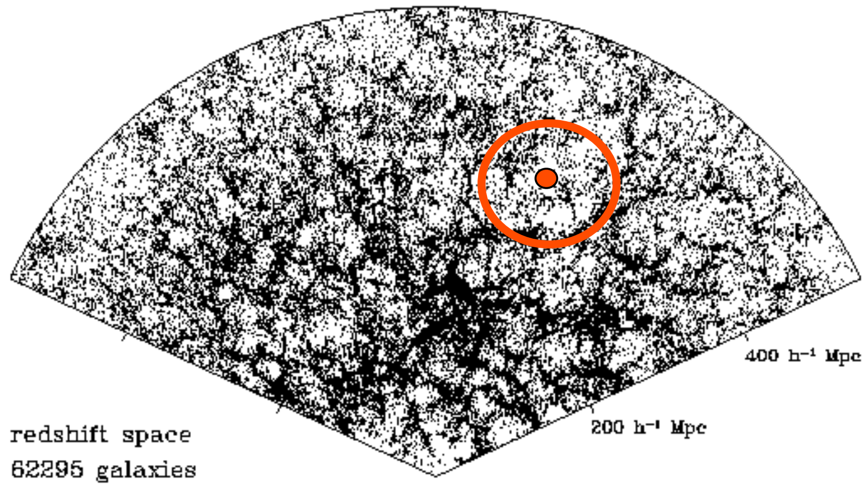
Acoustic propagation of an overdensity:

- 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.

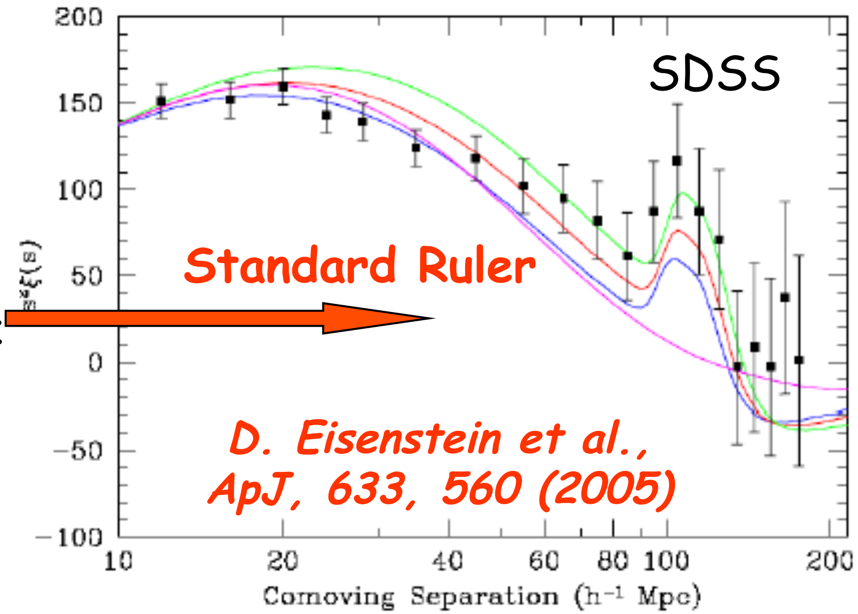
⇒ **Standard Ruler**

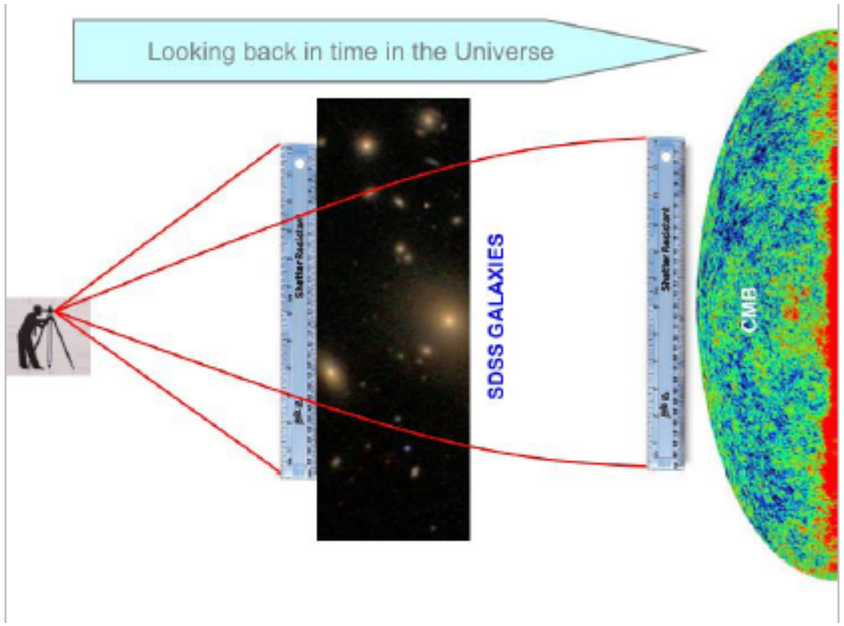


Observation of baryonic acoustic peak

First observation:

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs
  "Luminous Red Galaxies"
  <z> ~ 0.35





A 3D measurements:

- Position of acoustic peak ⇒ Size of the sound horizon r_s
- **Transverse direction:**

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

⇒ Sensitive to angular distance $D_A(z)$

- **Radial direction** (along the line of sight):

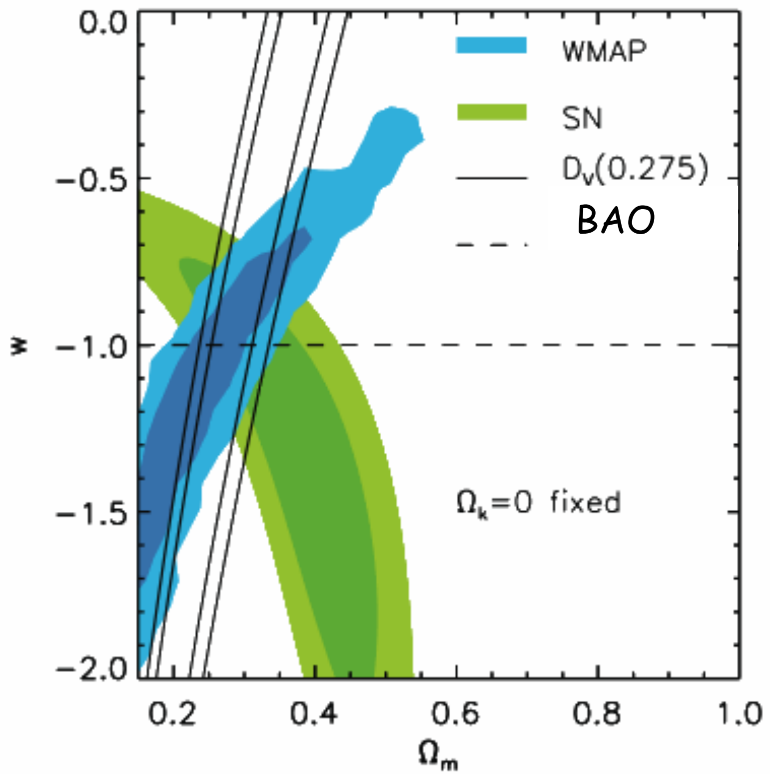
$\Delta z = r_s \cdot H(z)/c$

⇒ Sensitive to Hubble parameter $H(z)$.

Status of BAO before BOSS

SDSS-II (DR7) and 2dFGRS:

- BAO confirmed for several redshit bins
- BAO Significance (just BAO peak) : **3.6σ**
- Measurement at **2.7% of BAO scale**
- Constraints on DE content

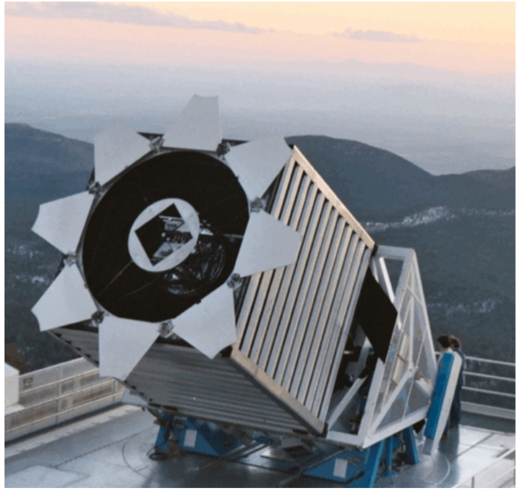


- SDSS <z> ~0.35 : 80 000 LRG
- SDSS <z> ~0.15 : 30 000 LRG
- 2dFGRS <z> ~0.15 : 140 000 Galaxies

Percival et al., MNRAS, 401 2148 (2010)

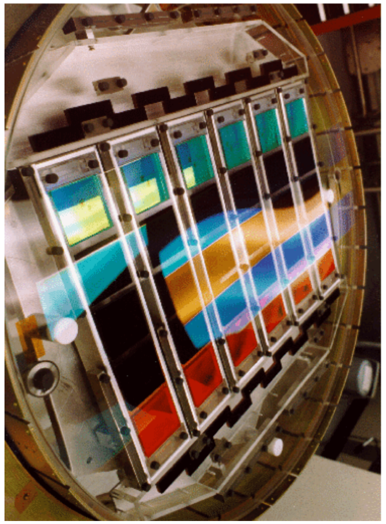
SDSS-III - BOSS
-
A brief overview

BOSS in SDSS-III



Sloan Telescope

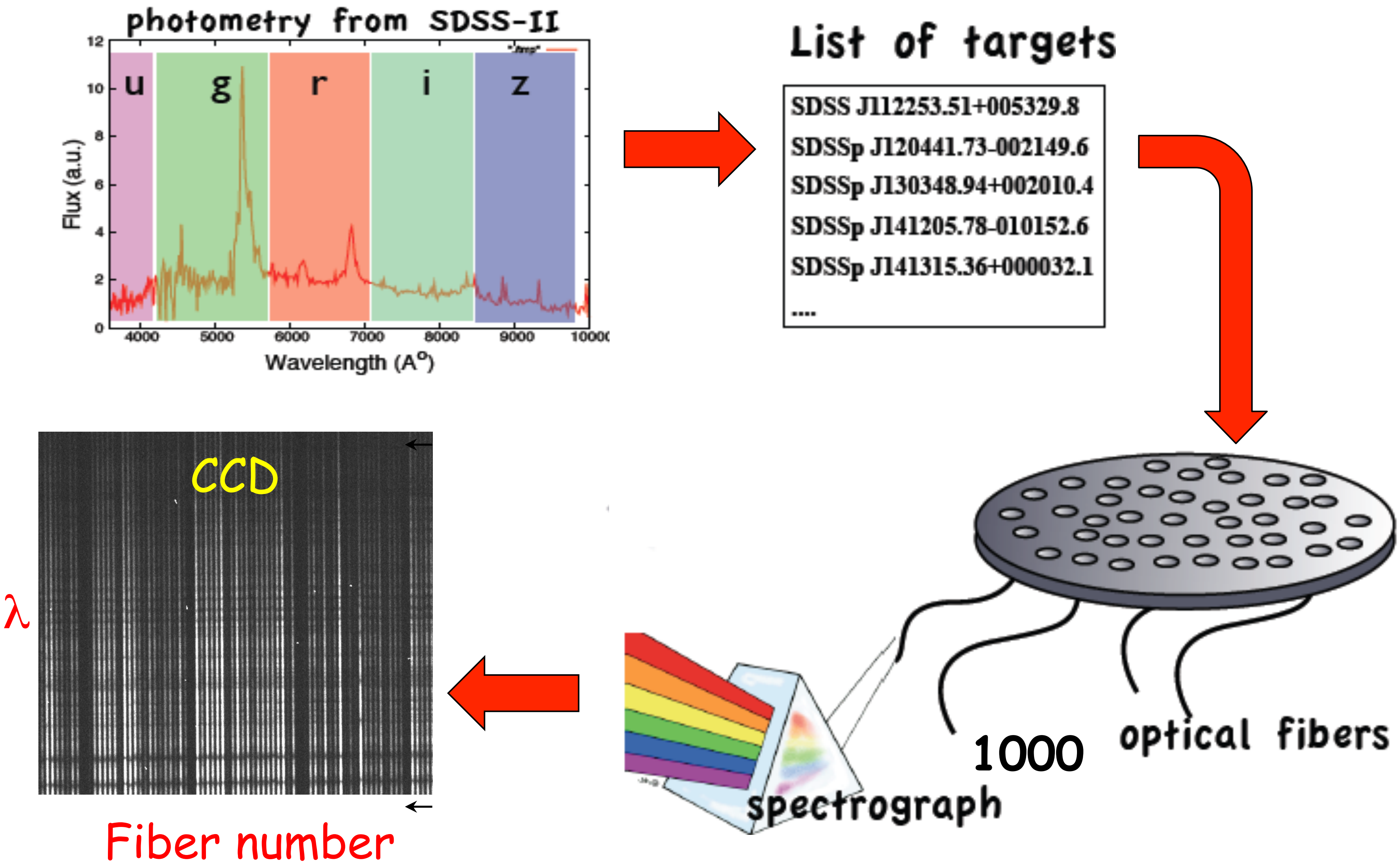
- 2.5m telescope at Apache Point (New Mexico)
- Wide field telescope ~ 7 deg^2
- Camera equipped with 5 filters (~120 millions pixels)
- Extension of imaging survey in SGC
  - ⇒ ~10,700 deg^2



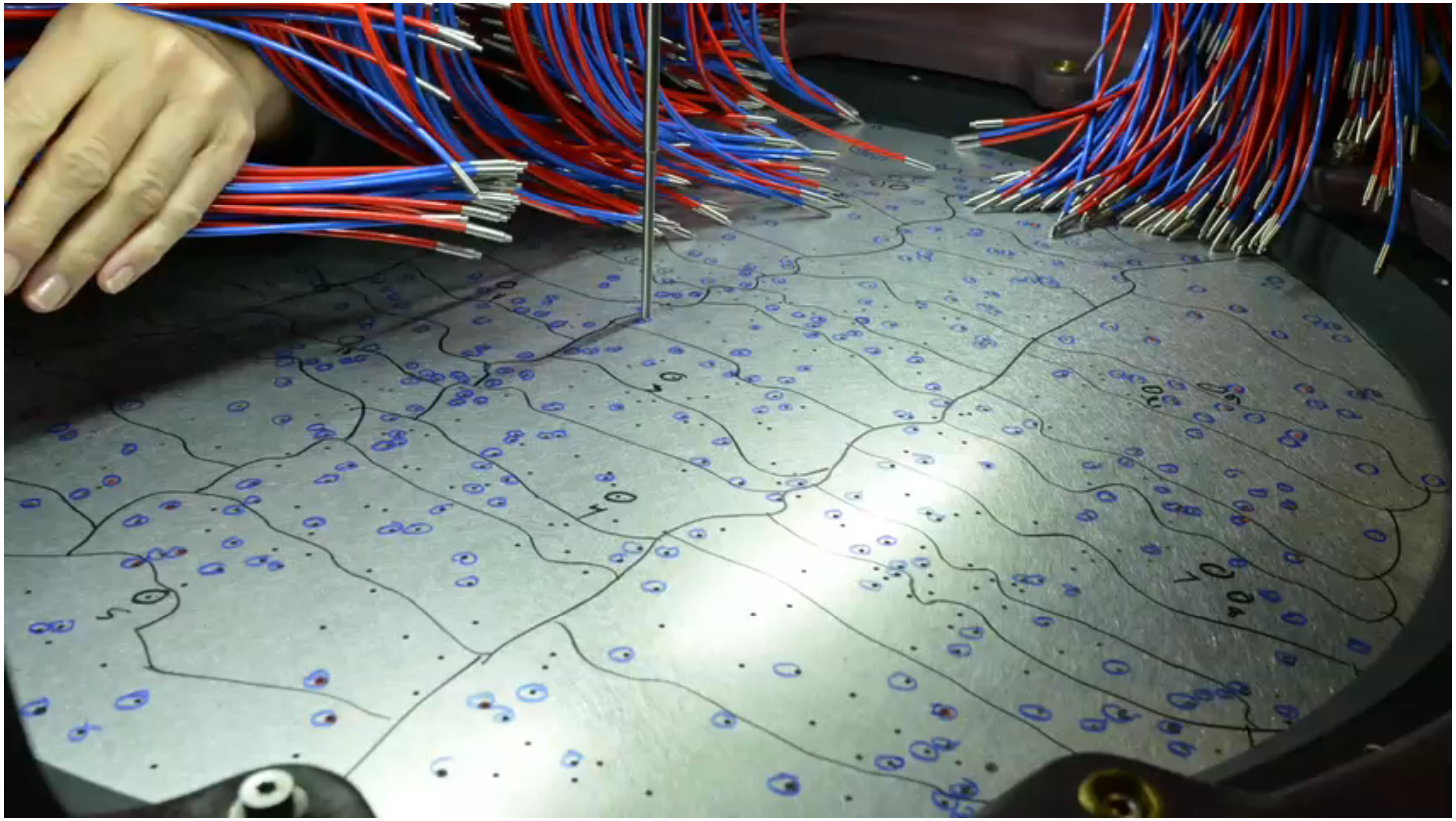
Upgrade of spectrograph

- New fiber system
  - ⇒ 1000 fibers
- Replacement of red CCDs
  - ⇒ LRG at higher z
- Replacement of blue (UV)
  - ⇒ Lyman-α forest program

BOSS Observation Strategy



Plug and Observe

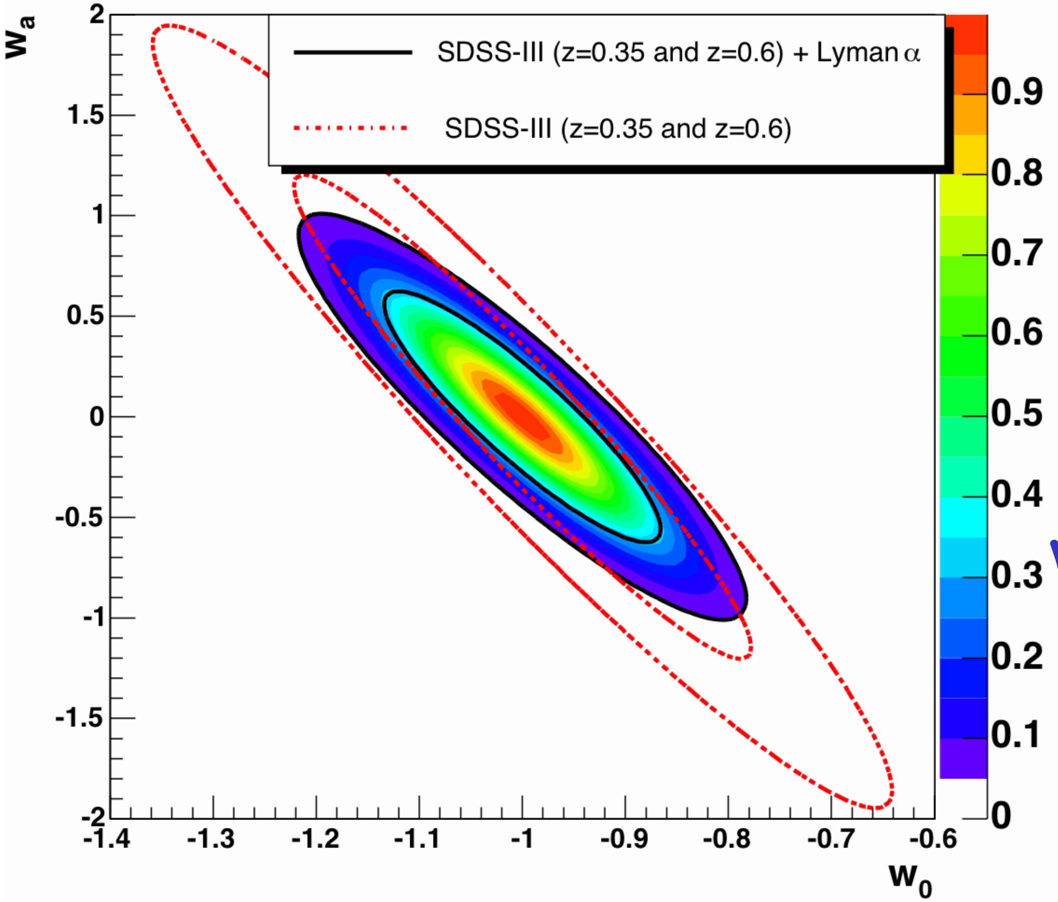


Several steps (~3 months)

- Target selections (~40 QSOs deg^{-2} and ~150 galaxies deg^{-2})
- Drill plates (1000 holes per plate)
- Plug plates on cartridges during day
- Observation of 5-9 cartridges per night.

BAO with BOSS

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



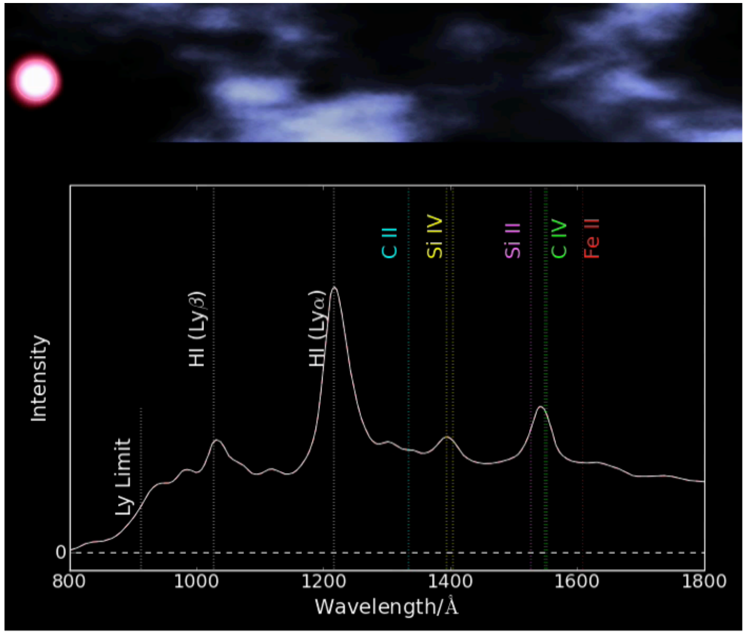
With galaxies: ~1.2M (LRG+CMASS)

- ~10,700 deg^2, 0.3<z<0.7
  Volume x2 , Density x5
- BAO scale: 1.0% at z~0.35
  1.1% at z~0.6
- Observation of BAO both in transverse and radial directions

With Ly-α forests: ~150k QSOs

- 2.2<z<4.0
- BAO scale: 1.7% at z~2.3
- New approach (see next slide)
- Method studied by FPG (IAP, APC and Saclay)

Additional method: Ly-α forests



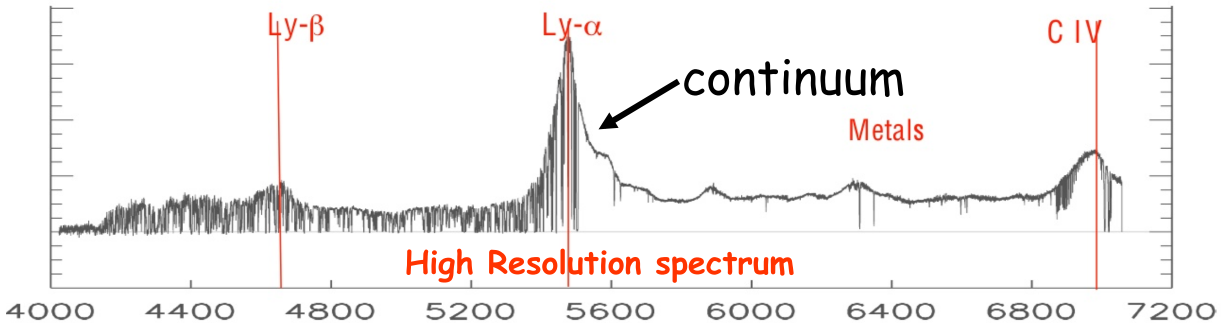
Principles

- Use Ly-α 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, N-body simulations and 3D power spectrum…)

BAO specifications:

- 3D BAO: Correlation between the different lines of sight
- BAO measurement for z~2.3
- Better precision in radial direction (H(z) measurement).

z~3.6 Quasar

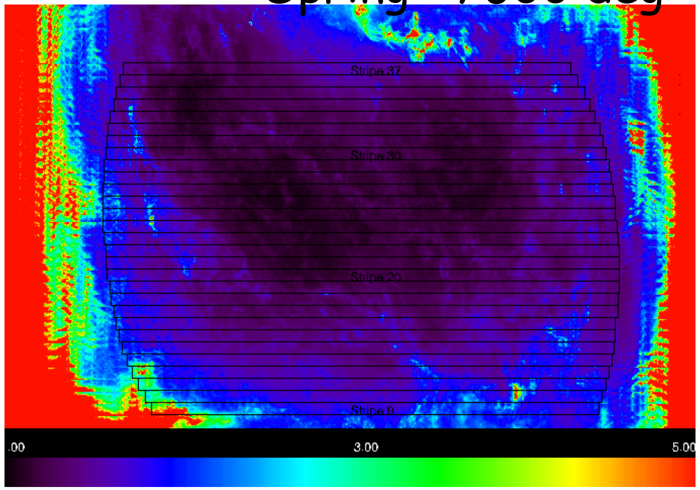


BOSS Status

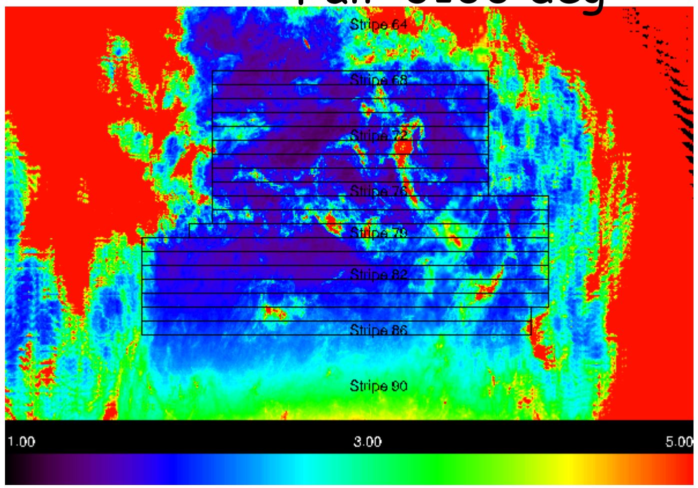
Observing plan

- 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

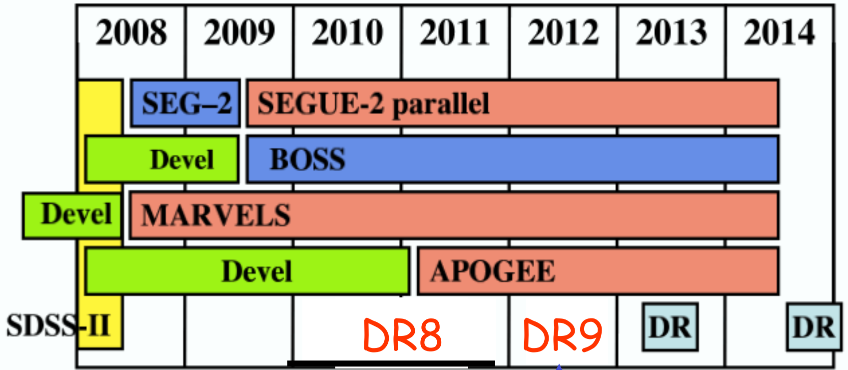
Spring: 7600 deg^2



Fall: 3100 deg^2



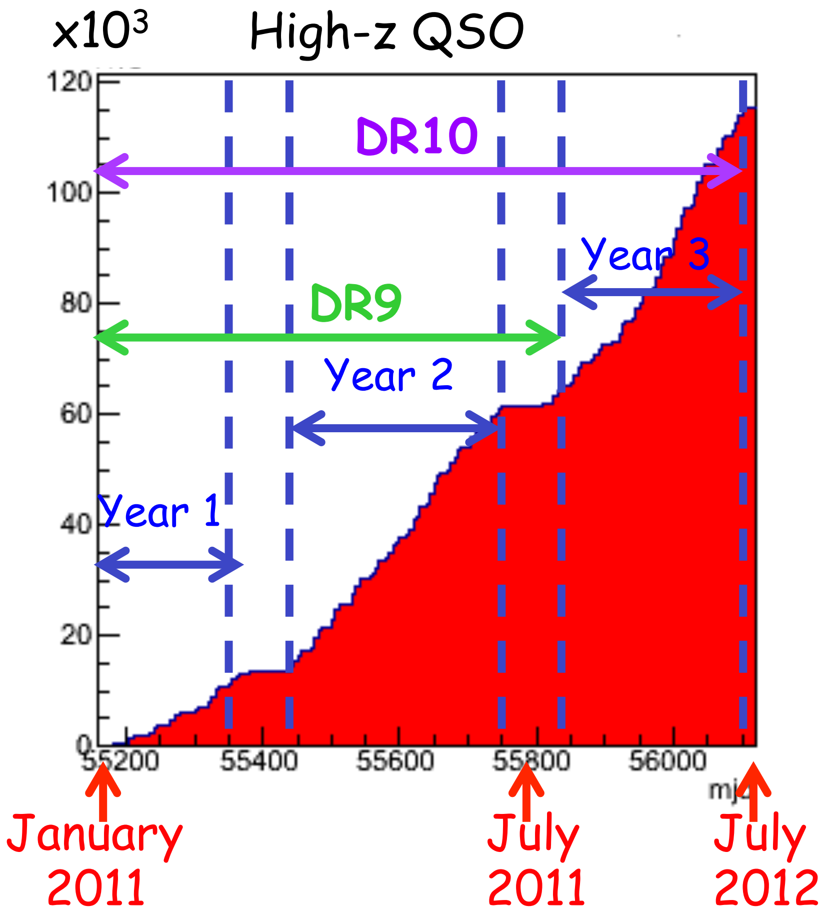
Public data releases

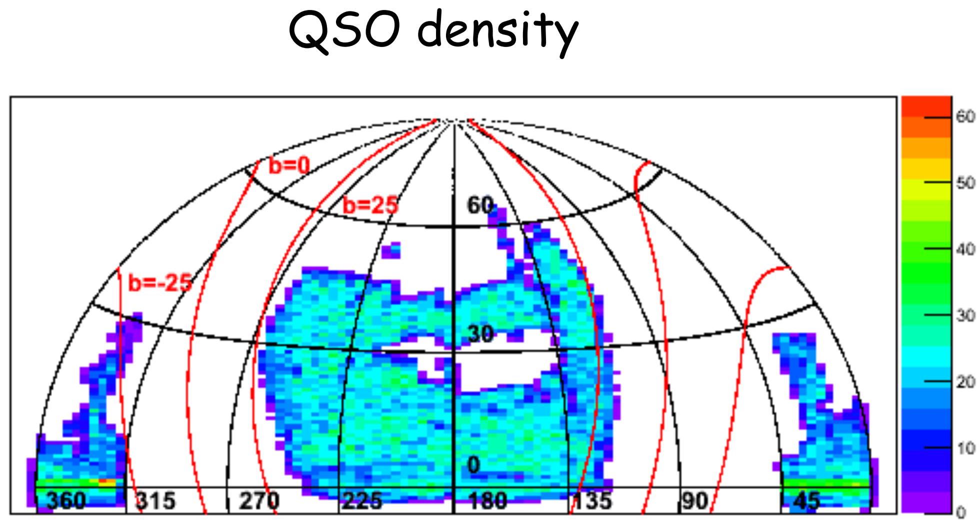


BOSS Imaging } Jan. 2011

Jul. 2012 { BOSS Spectro. ~1/3

Status of the survey

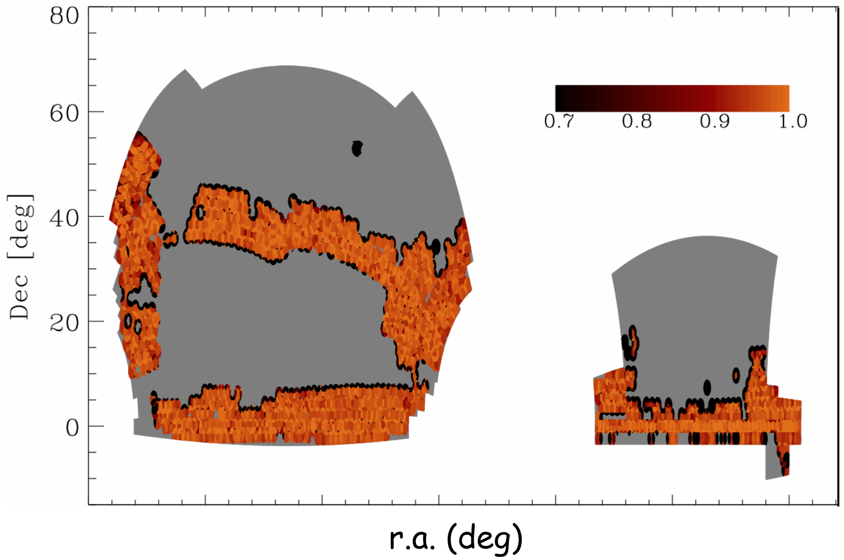




- So far, **~120 000 QSOs and ~700 000 galaxies** over ~6700 deg²
- **End of the survey (10700 deg²):**
  - 1.2-1.5M galaxies !!!
  - 150k - 200k high-z QSOs !!!

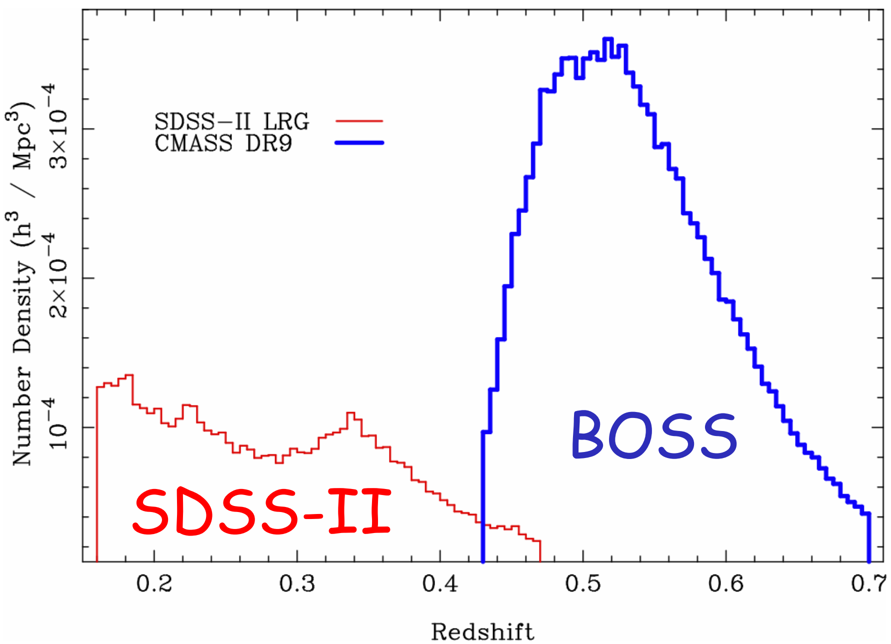
BAO with galaxies

Footprint - galaxy sample



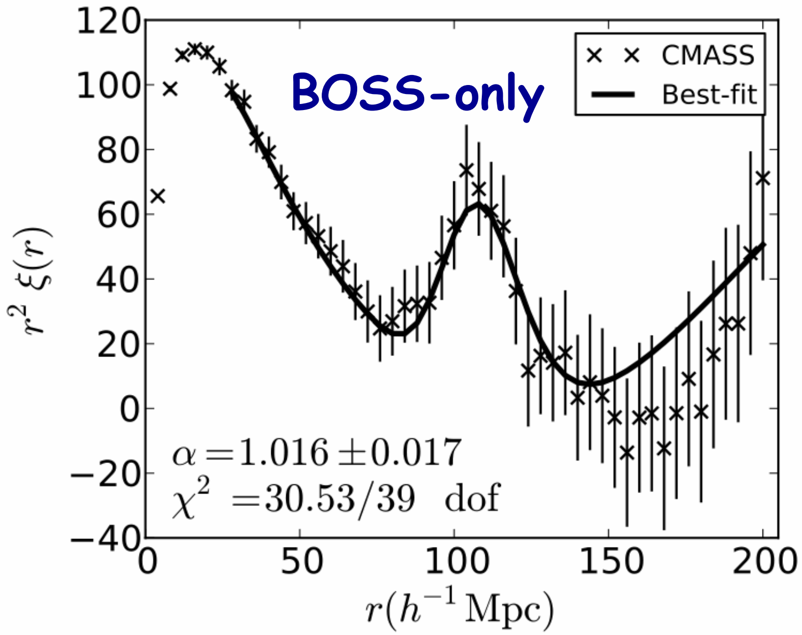
- 1/3 of the final survey
- Data released in summer 2012: DR9

- Deeper and denser survey compare to SDSS-II
- z~0.5-0.6

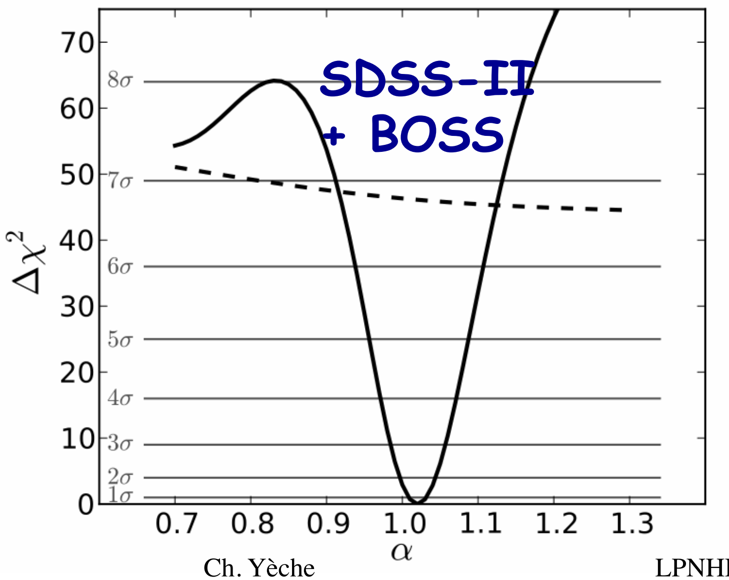


BAO in Correlation Function

➢ Use a fiducial model to compare against observed features in spherical average statistics.
➢ Departures quantified by dilatation scales α:
➡Fit of ξ(αr)

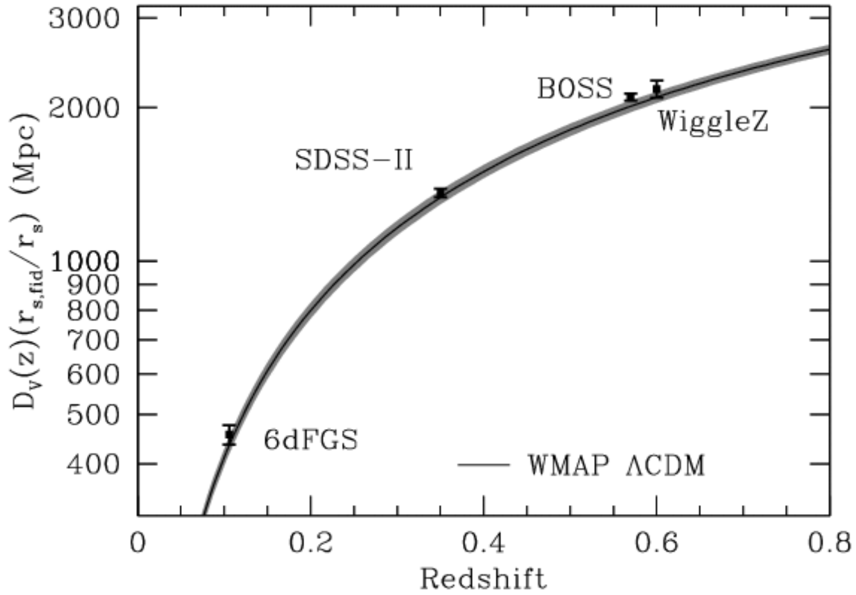


L. Anderson (alphabetical) et al., arXiv:1203.6565 (2012)



➢ BOSS-only 5-σ observation
➢ BOSS + SDSS-II:
7-σ observation!!!
➢ BAO scale consistent with WMAP: α=1.016±0.017

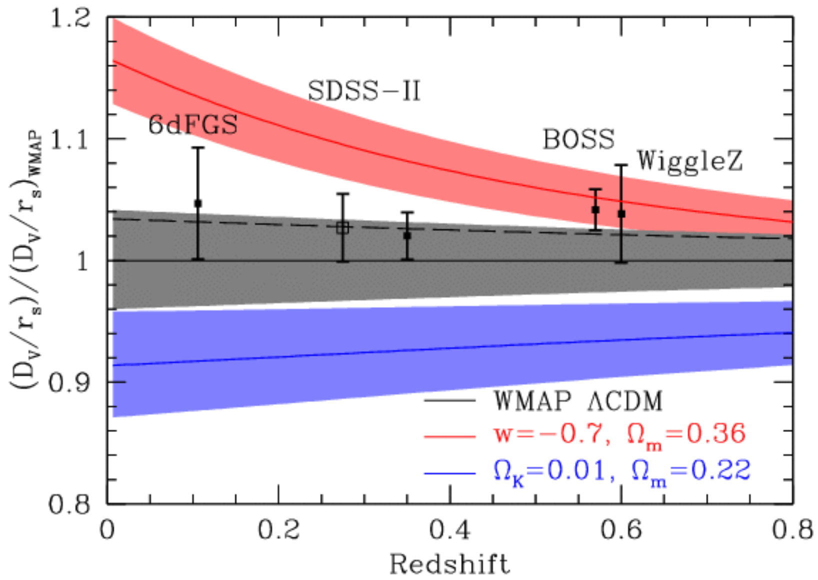
Isotropic BAO results



- Combine transverse and longitudinal direction with

$$D_V=(cz.H(z)^{-1}.(1+z)^2D_A(z)^2)^{1/3}$$

- New "Hubble" diagram with BAO like SNIa with D_V/r_S

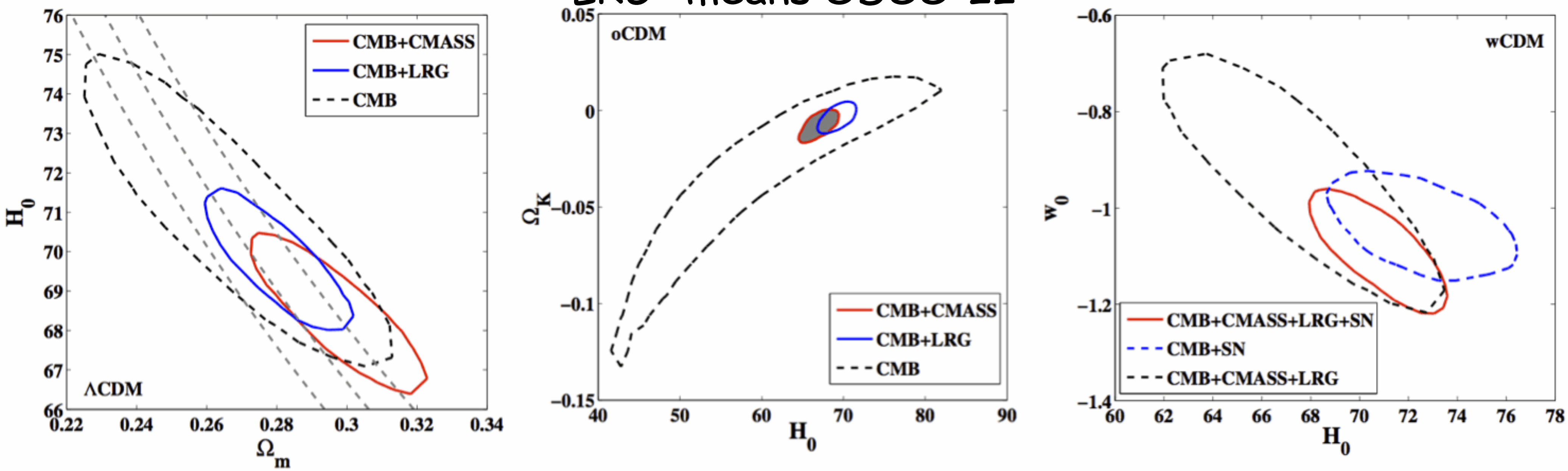


- BAO scale consistent with WMAP
- Mild tension…
- Ω_m=0.268±0.029 (WMAP)
  Ω_m=0.293±0.012 (WMAP+SDSS)

Constraints on Friedman equation

$$H^2(a) = H_0^2 \Big[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} \left[1 + w(a')\right] \right\} \Big]$$

"LRG" means SDSS-II

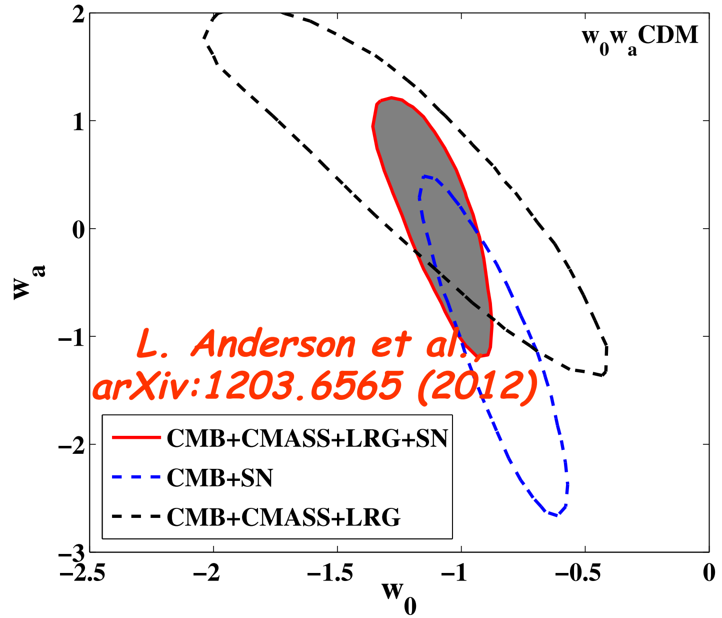


2-param. ΛCDM model

3-param. oCDM model

4-param. wCDM model

Dark Energy: Equation of state



- Eq. of state: $w=P/\rho$

  $w(z)=w_0+z/(1+z).w_a$
- Conservative approach: just fit of isotropic BAO peak position
- WMAP+BAO+SN:

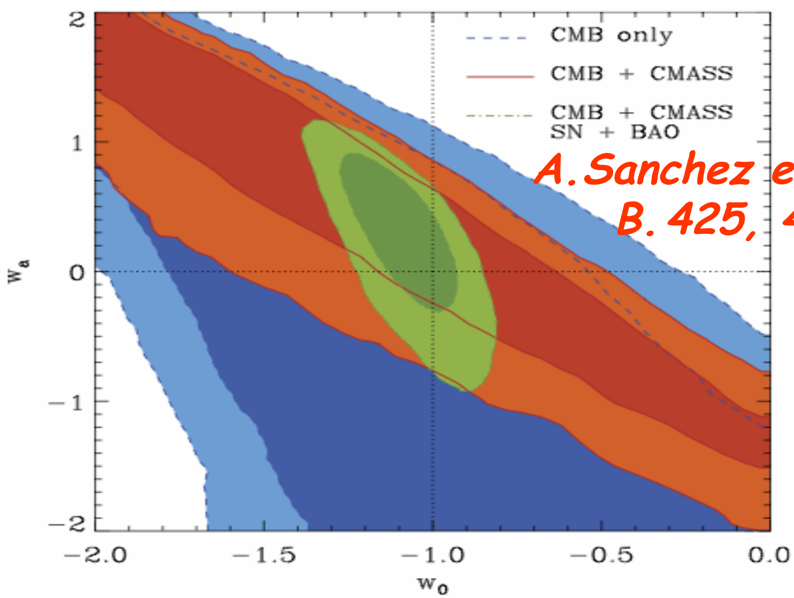
  $w_0 = -1.08 \pm 0.15$

  $w_a = 0.10 \pm 0.87$

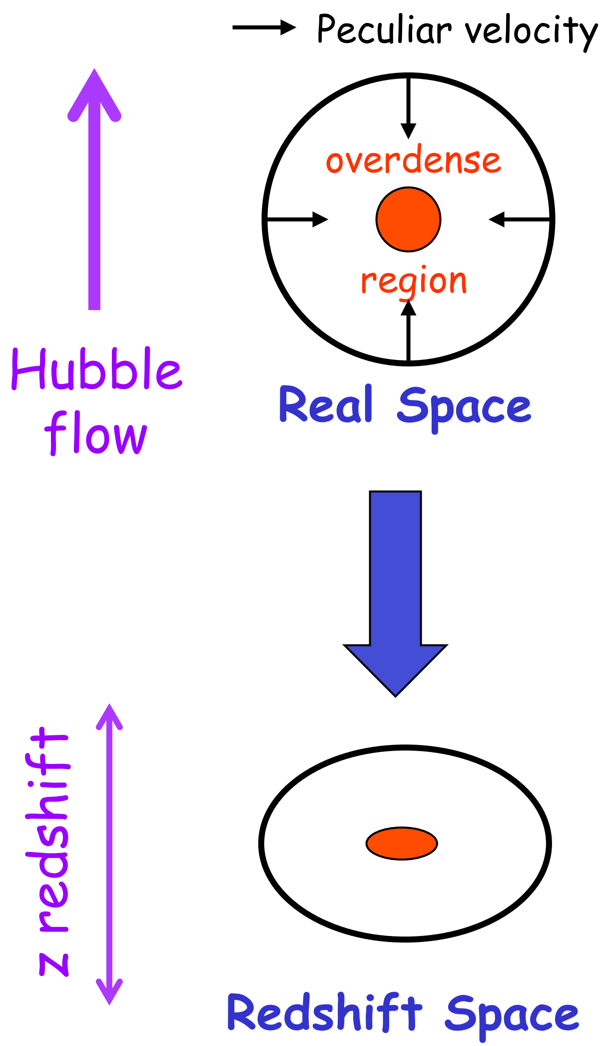
- Fitting the full shape of the correlation function.
- Broad bands model with N-body simulations
- WMAP+BAO+SN:

  $w_0 = -1.08 \pm 0.11$

  $w_a = 0.23 \pm 0.42$



Large-scale Redshift Space Distortions



- Acceleration toward overdense regions
- Flattening in radial direction from real space to redshift space (over tens Mpc)
- Distortion are quantitatively measured by multi-poles decomposition

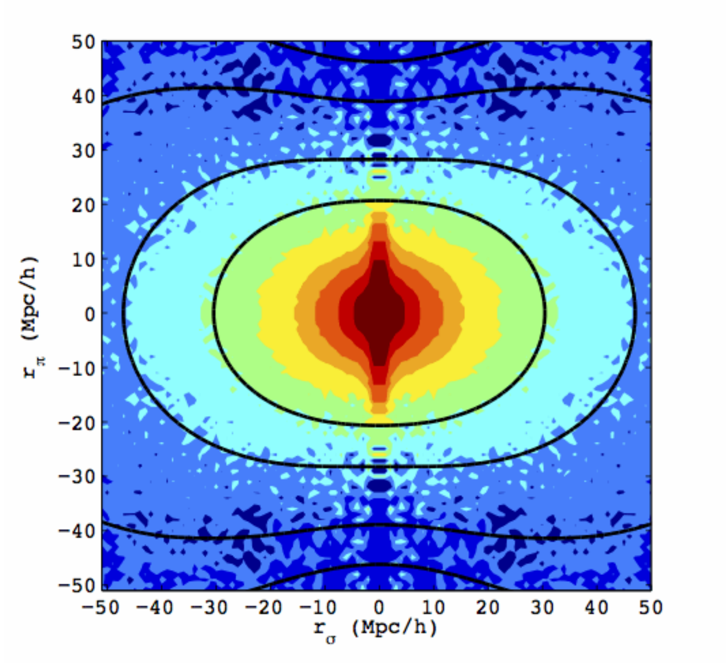
$$\boxed{\xi(r,\cos(\theta)) = \sum_{\ell=0,2,4...} b^2 C_\ell \xi(r) P_\ell(\cos(\theta))}$$

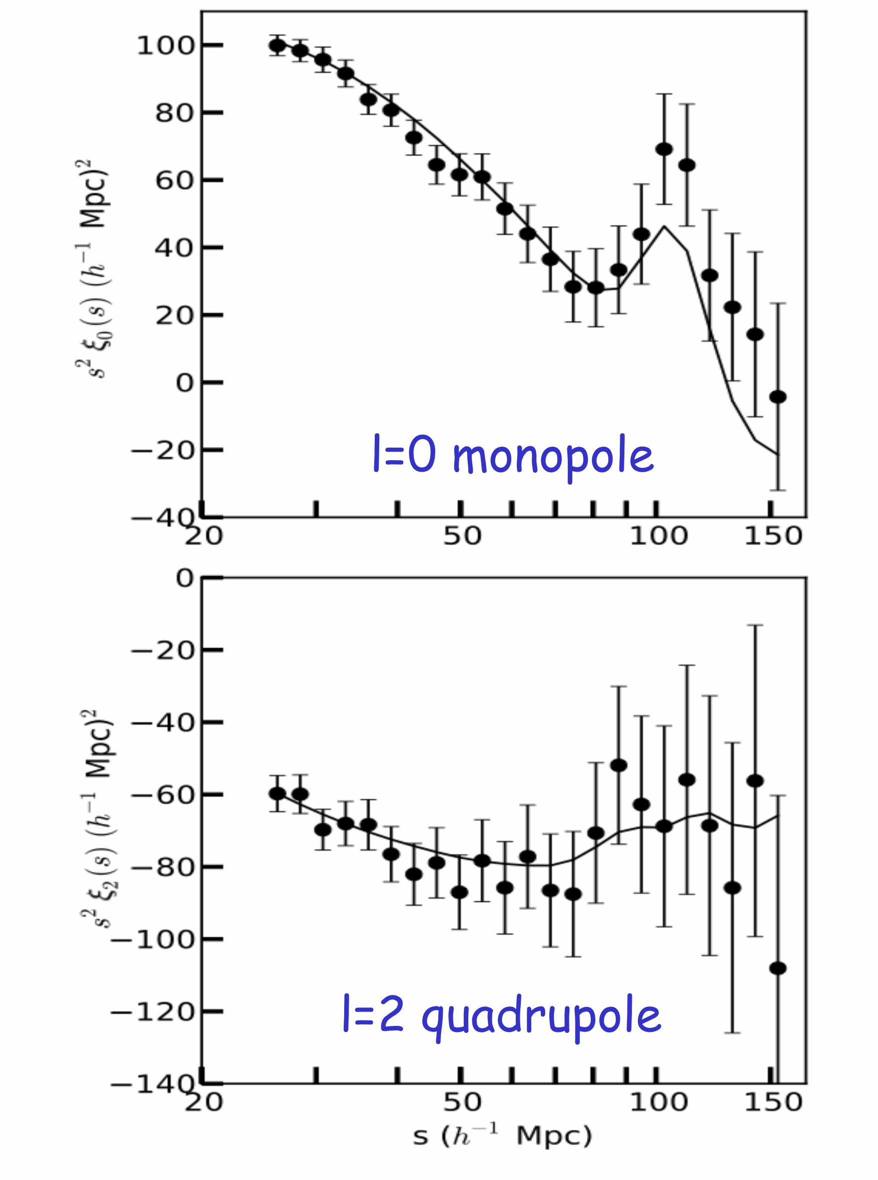
- *P_l: Legendre polynomials*
- *θ angle between pair vector and LoS*
- *b linear galaxy bias*

- Amplitude of the flattening gives a dependence on $f(z)\sigma_8(z) \propto dG/d\ln(a)$, where G is linear growth rate

N. Kaiser, MNRAS 227, 1 (1987)

Redshift Space Distortions



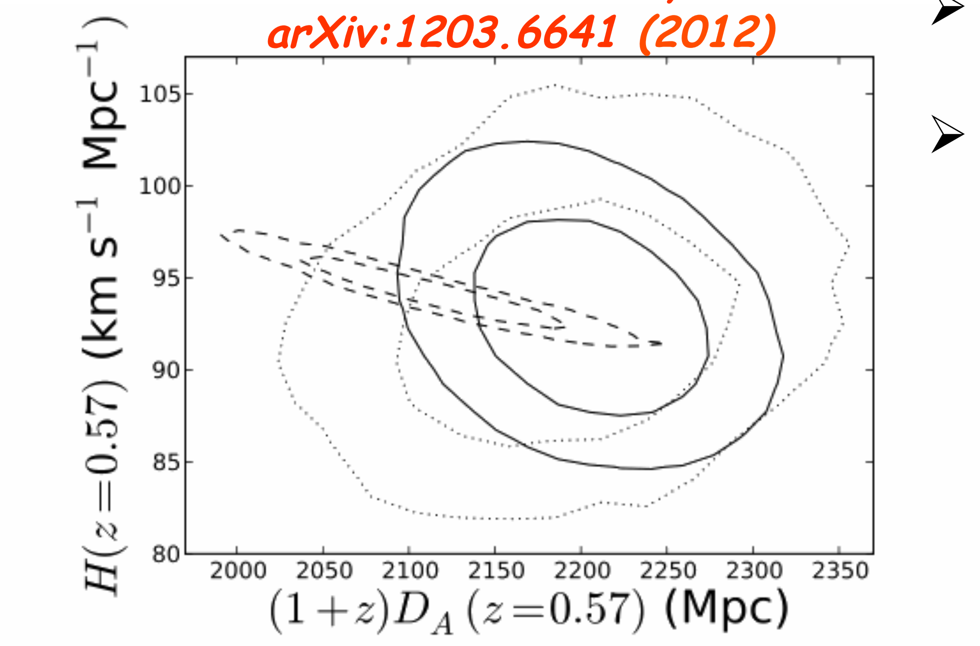


- Redshift distortion clearly at <z>~0.6 in BOSS
- Excellent agreement between data and N-body simulations

B. Reid et al., arXiv:1203.6641 (2012)

Results of the anisotropic fit

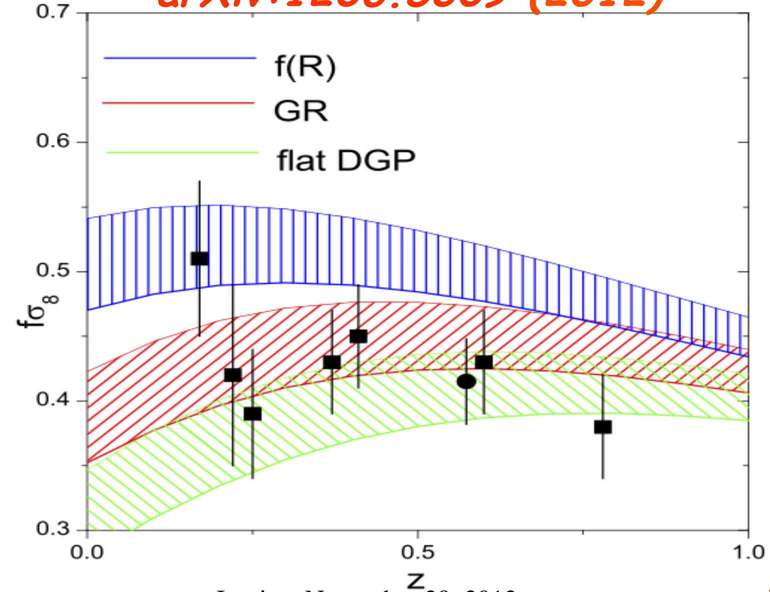
B. Reid et al., arXiv:1203.6641 (2012)



- First independent measurements of H(z) et D_A(z)
- Three configurations:
  Dotted: free growth ($f\sigma_8$), free geometry, ΛCDM only for large scales
  Solid: free geometry, ΛCDM growth
  Dashed: WMAP,flat ΛCDM, ΛCDM growth

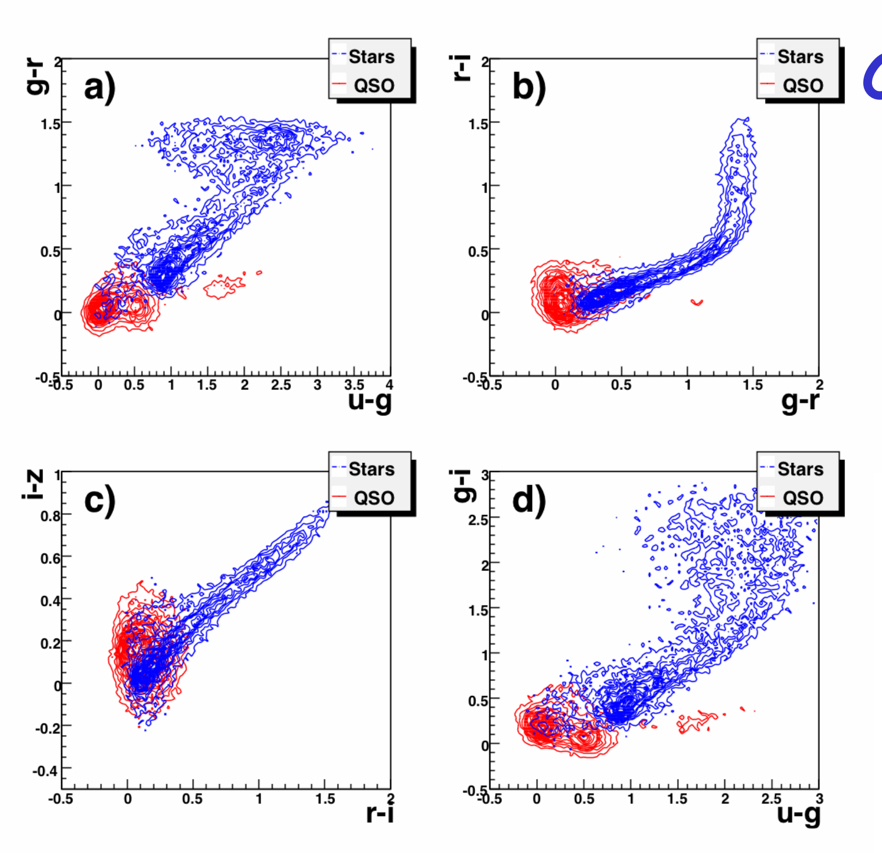
- Test of GR with $f\sigma_8$
- $f(z)\sigma_8(z) \propto dG/d\ln(a)$, G linear growth rate

L. Samushia et al., arXiv:1206.5309 (2012)



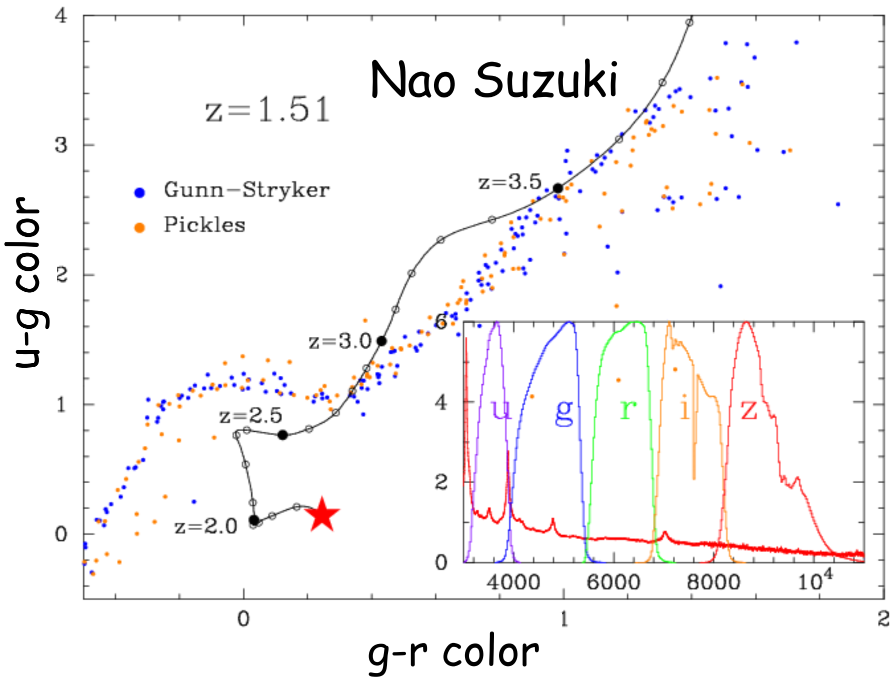
BAO with Ly-α forests

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

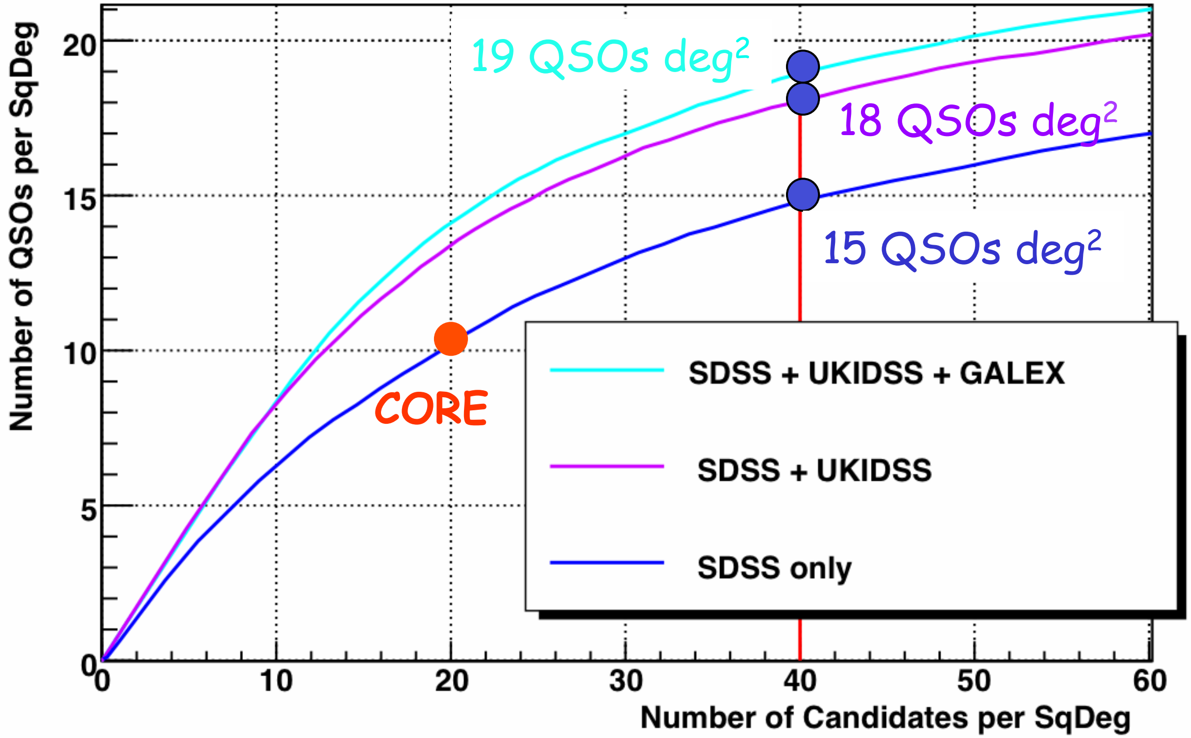


SDSS 4 colors
(u-g,g-r,r-i,i-z)

*Ch. Yèche et al.,
A&A 523, A14 (2010)*

BOSS: Selection of Ly-α QSO Using Photometry

Number of z>2.15 QSOs

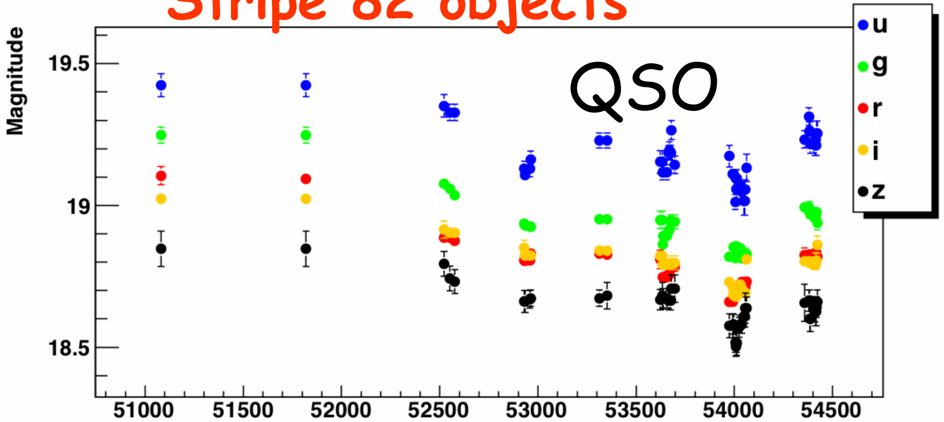


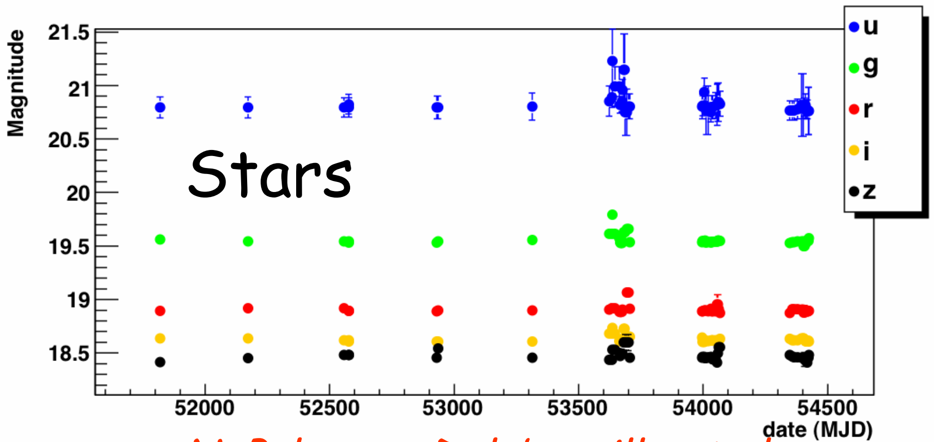
N. Ross, A. Myers, E. Sheldon. Ch. Yèche et al., APJS 199,3 (2011)

- 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

Target selection with Variability

Light curves of
Stripe 82 objects





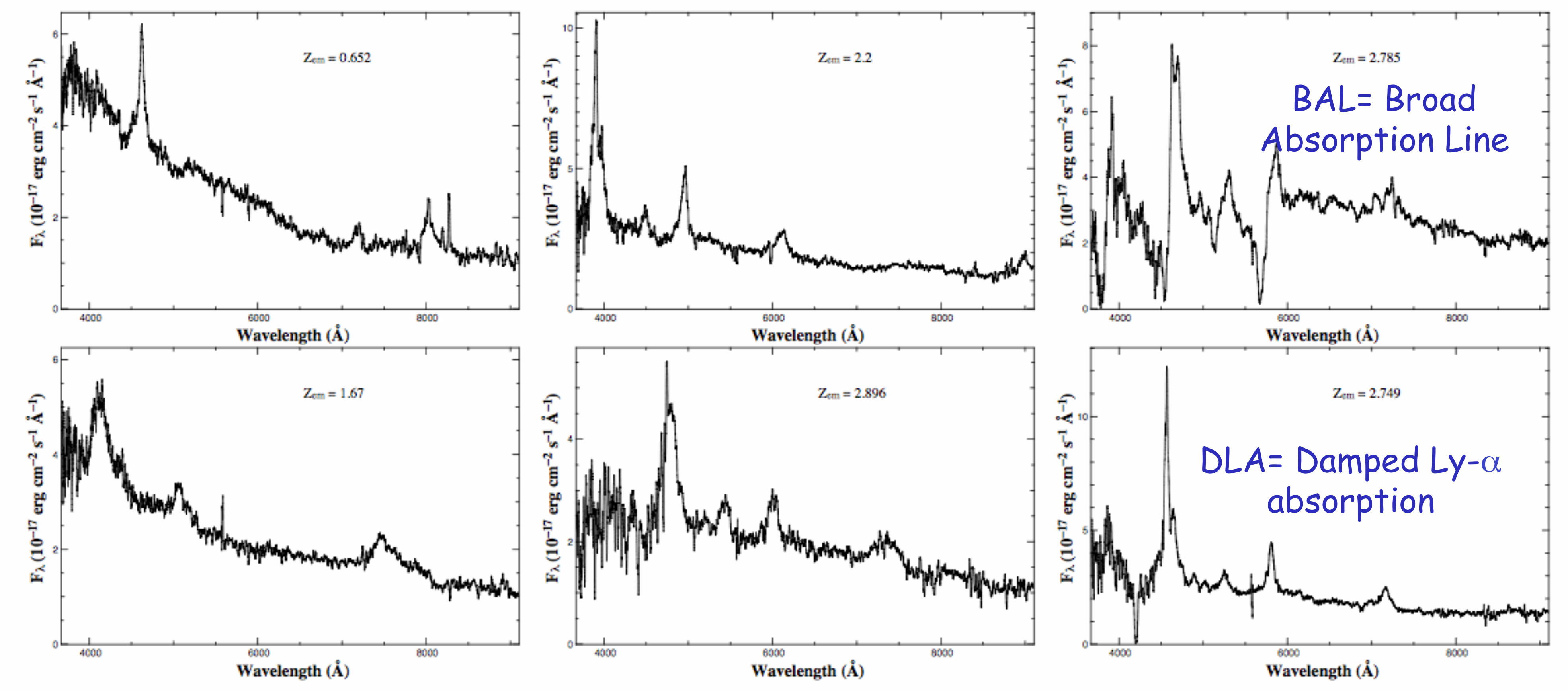
N. Palanque-Delabrouille et al., A&A 530, A122 (2011)
N. Palanque-Delabrouille et al. arXiv:1209.3968 (2012)

- 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 deg^2)
  - **~28 deg^{-2} QSOs with z>2.15**
  - Proof of principle for future surveys (e-BOSS, BigBOSS)

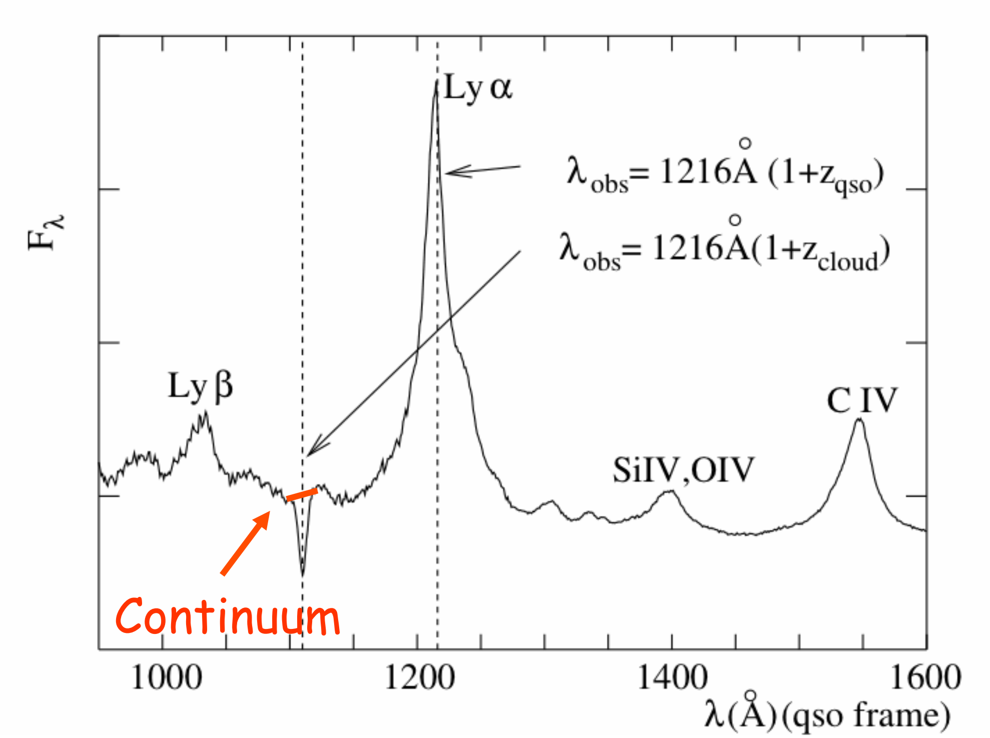
Visual inspection of all QSO targets



- All 180 000 quasars targets were visually inspected
- DLA and BALs tagged (~15% of the QSOs)
- Validation of the pipeline classification and redshifts
- Detection and tag of reductions problems.

I. Pâris, P. Petitjean et al. arXiv:1210.5166 (2012)

Measurement of HI absorbed flux



Pedagogical example

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

Flux definition

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

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

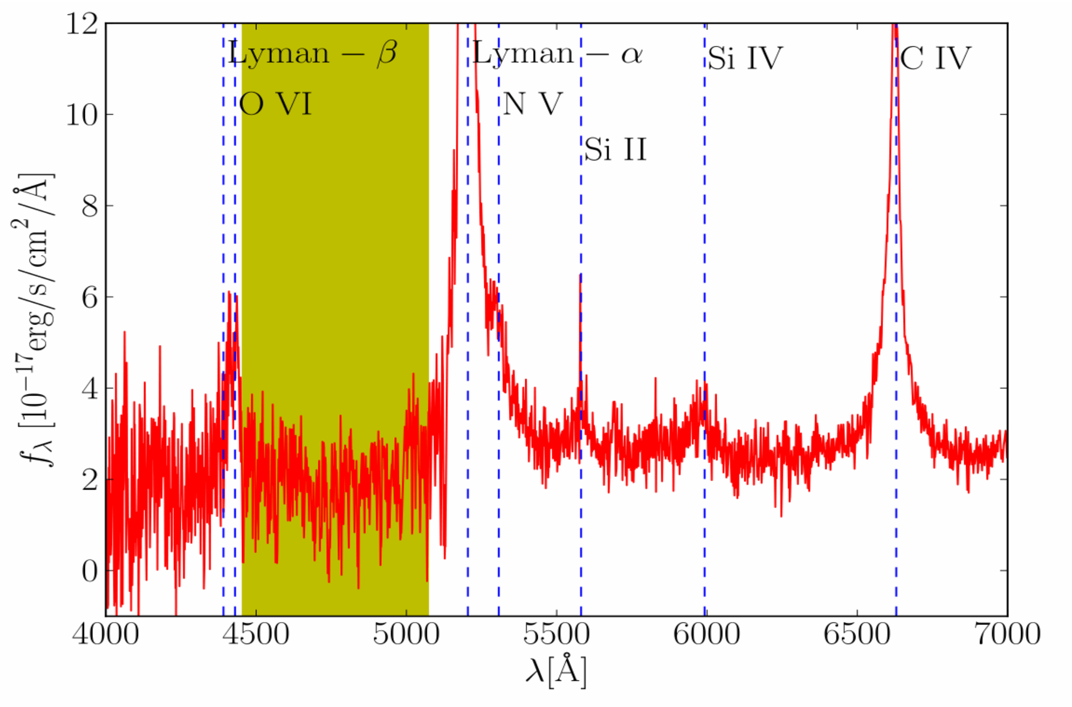
$$\overline{F} \propto e^{-\tau(z)}$$

$$\tau(z) \propto (1+z)^{3.8}$$

QSO Ly-α Forest

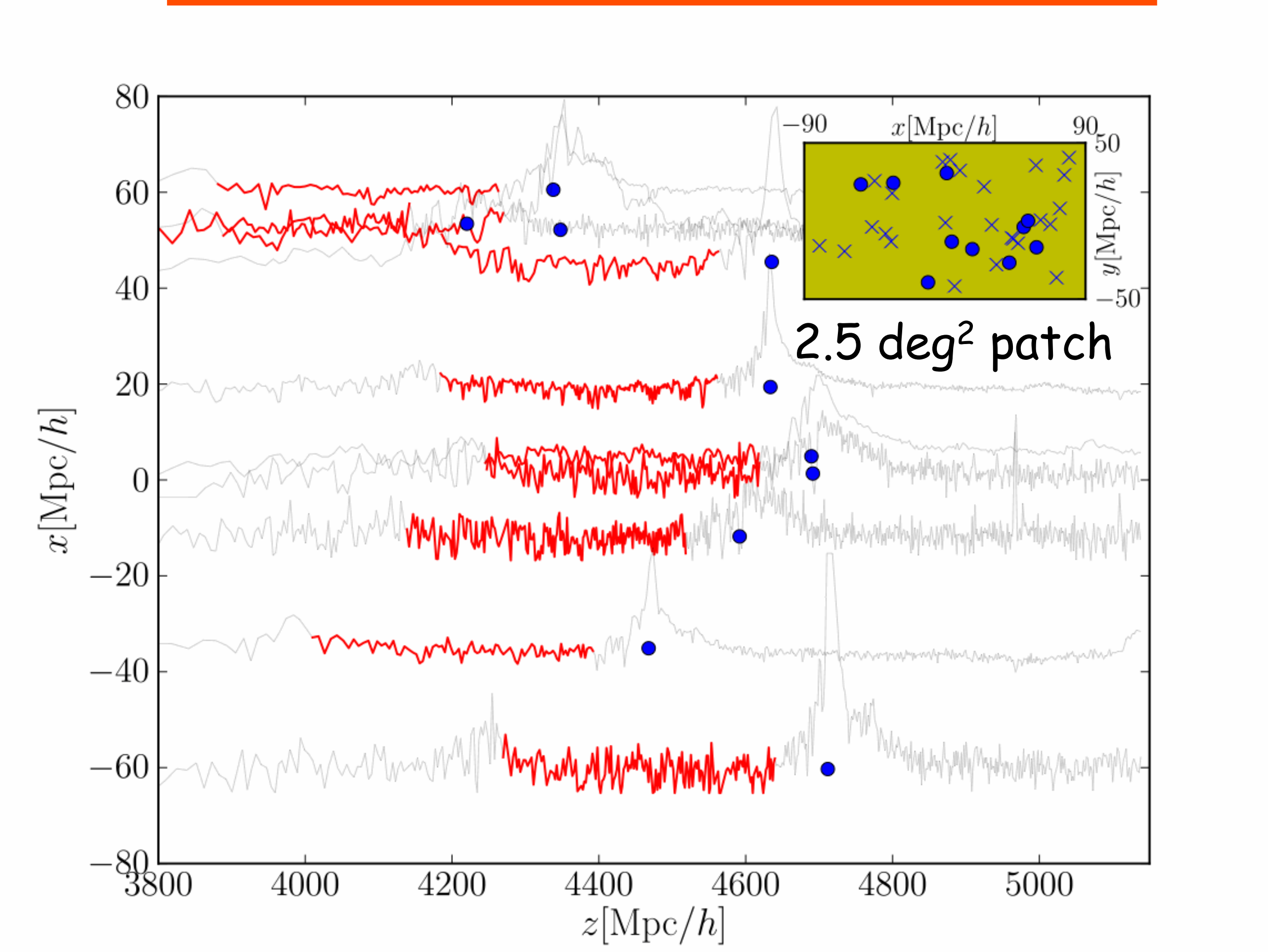
Typical BOSS QSO

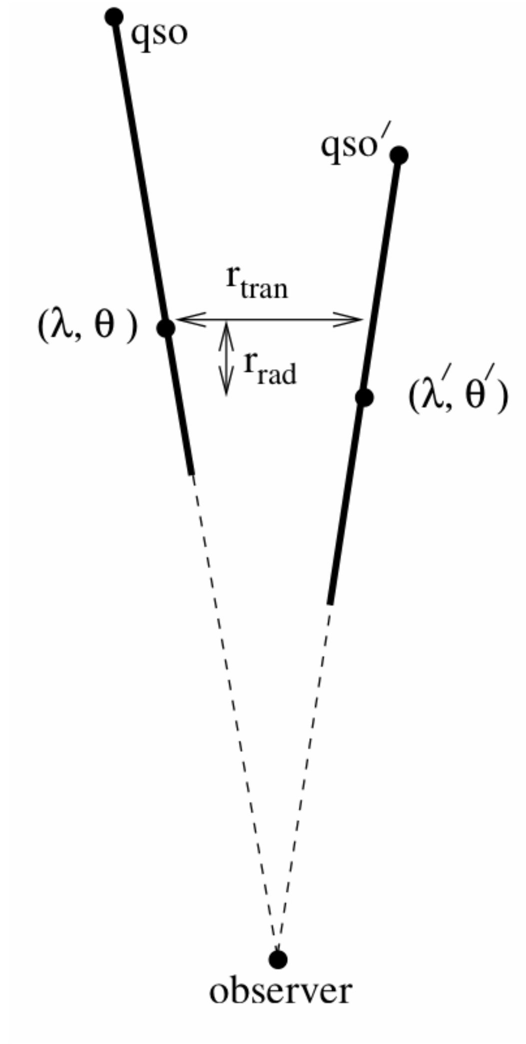
- Redshift z =3.28
- Very noisy QSOs (on average SNR~1-2)
- $\lambda > \lambda_{Ly\text{-}\alpha}$: fluctuations from noise
- $\lambda < \lambda_{Ly\text{-}\alpha}$: fluctuations from noise and absorption



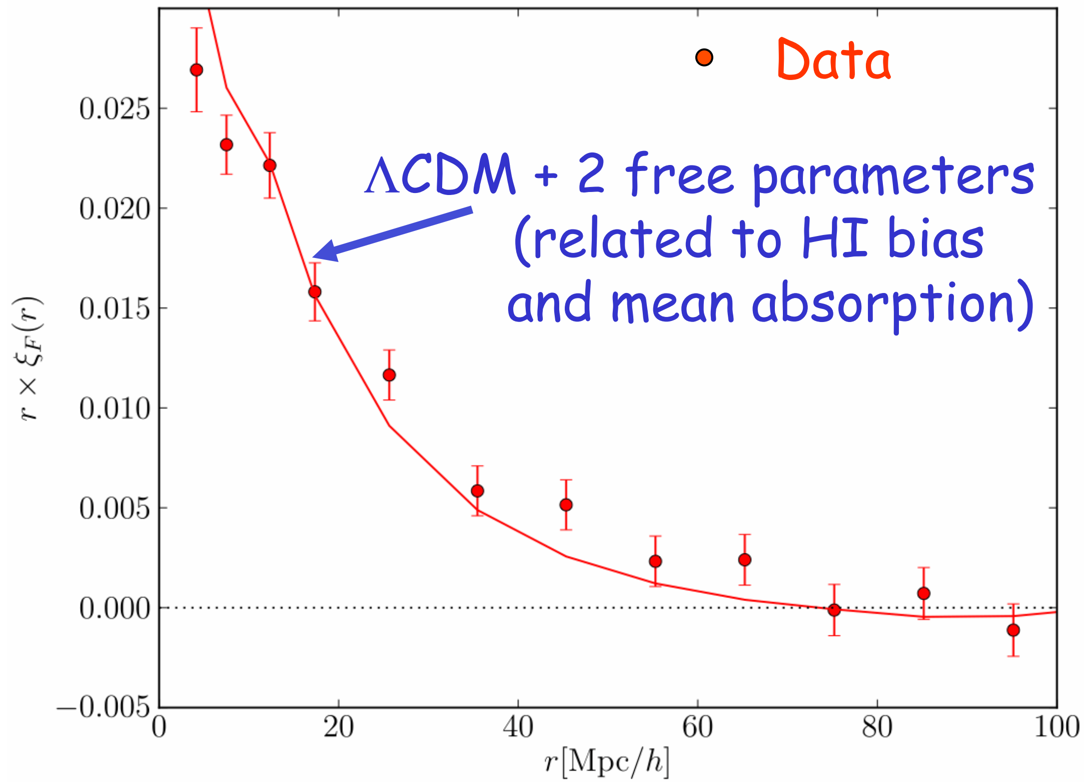
Ly-α absorption correlations

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

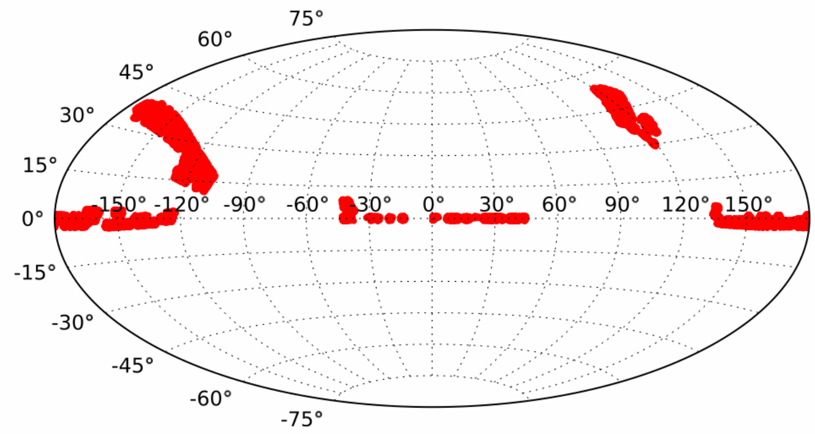




Correlation Function



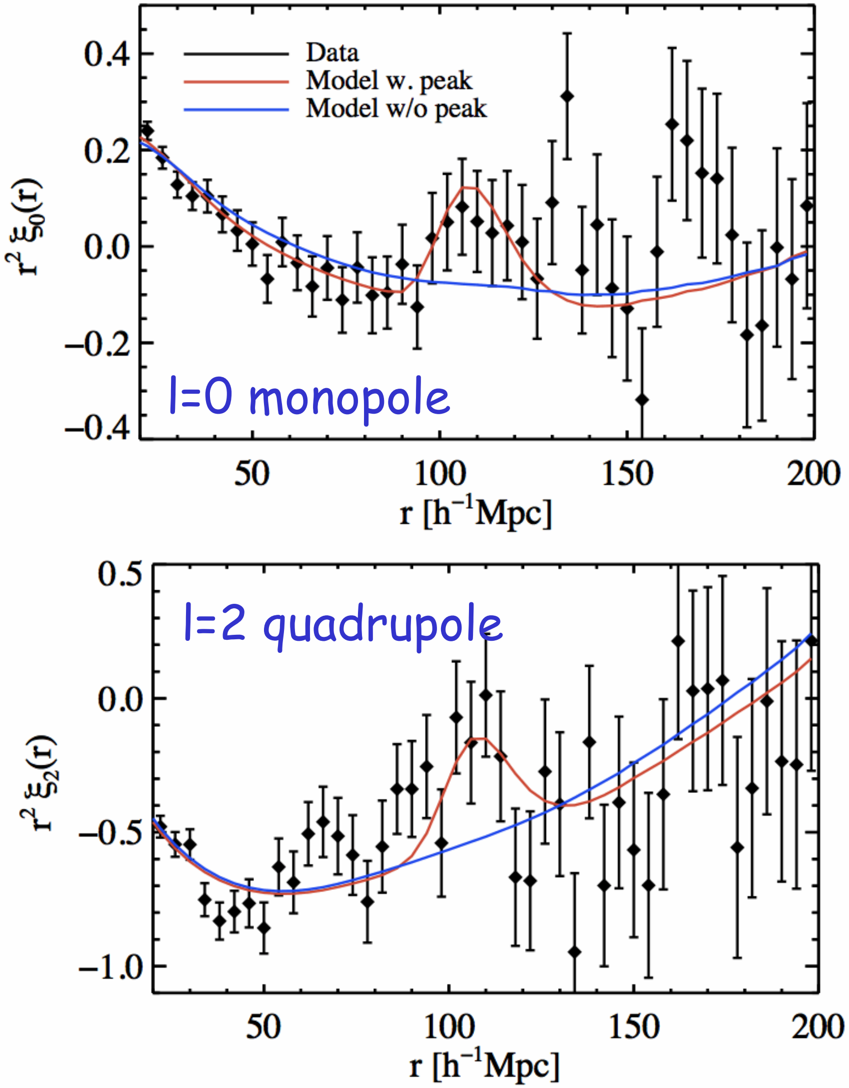
Projection over $r = |\vec{r}|$
of the 3D correlation function

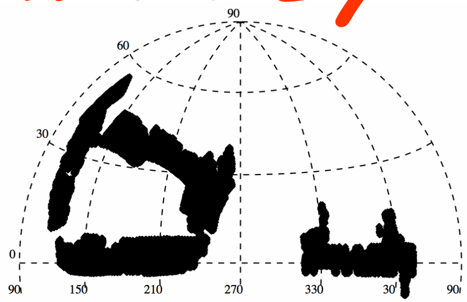


- Year one: 14000 QSOs
- Correlations in HI seen to 50 Mpc/h
- First observation in 3D of matter in IGM
- Results consistent with ΛCDM simulations

A.Slosar et al., JCAP, 09 1 (2011)

First look at BAO with Ly-α





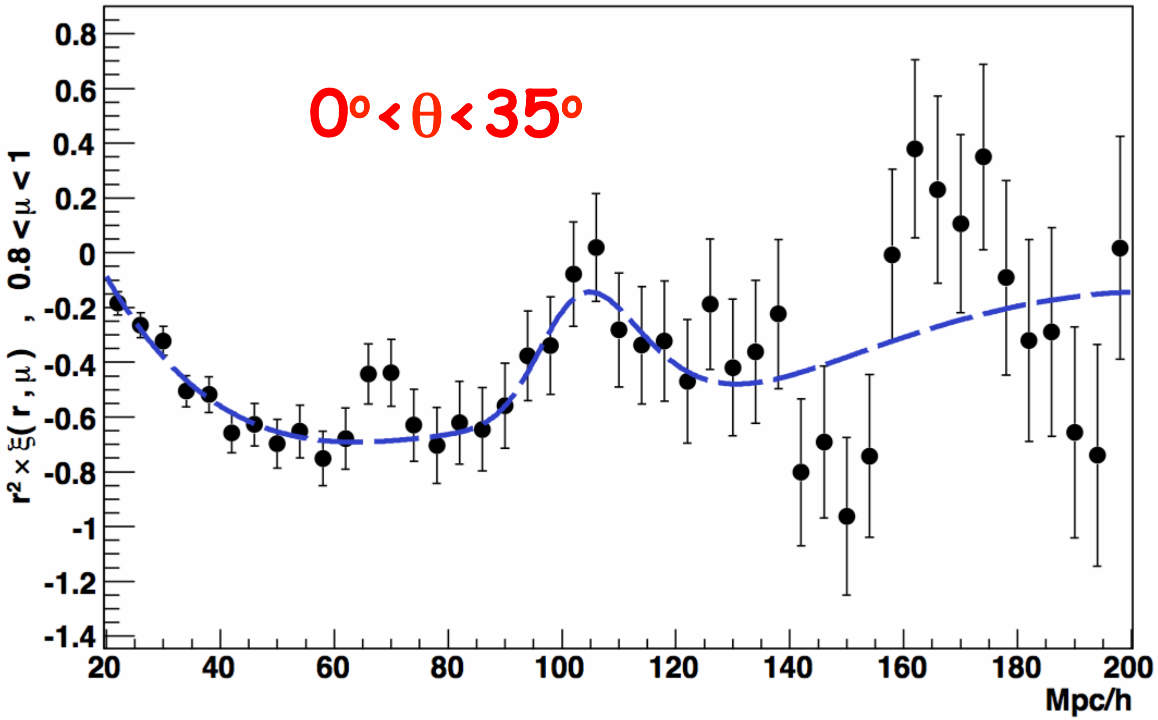
Data Set:
DR9: ~48000 selected QSOs with $2.1<z_{Abs}<3.5$

Significance:

- Fit the amplitude of peak
  χ^2_{peak}= 93.7 (85)
- Fix the peak amplitude to zero
  $\chi^2_{no\ peak}$= 111.8 (86)
- Local significance
  $\Delta\chi^2_{peak}$= **18.1 → 4.2σ**

N. Busca, T. Delubac, J. Rich et al. arXiv:1211.2616 (2012)

BAO in Ly-α Vs Galaxy



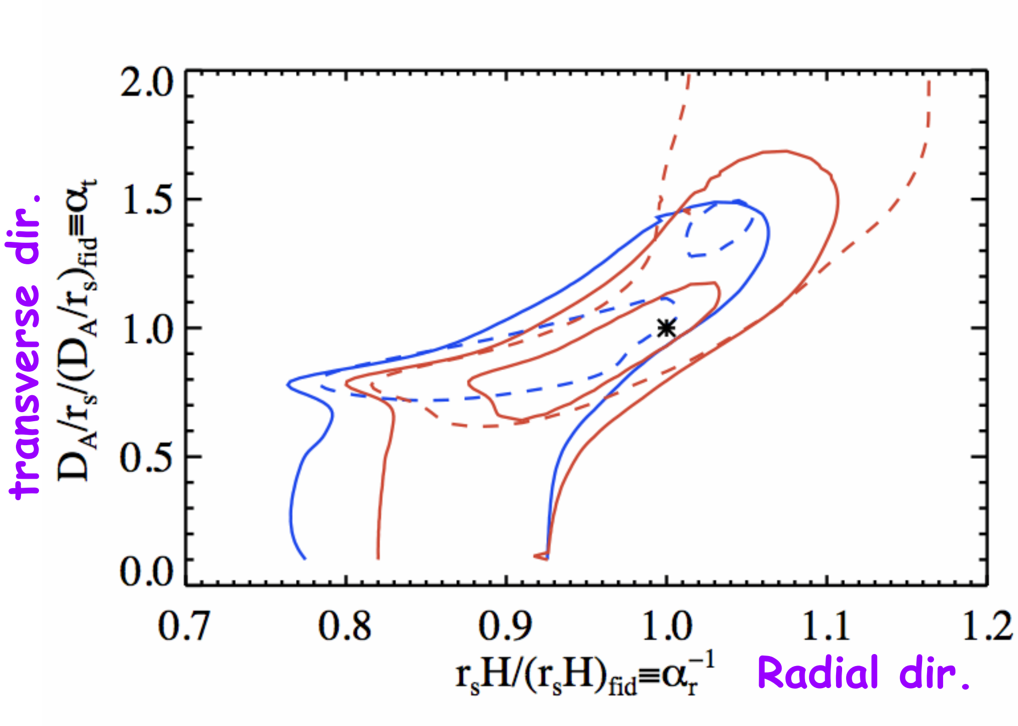
In radial direction

- $0.8<\cos(\theta)<1.0$
- Best image of the BAO peak

Much less dense region

- IGM is very scarce
- Several orders of magnitudes between galaxy and IGM, $\delta\rho/\rho$

Cosmological implications

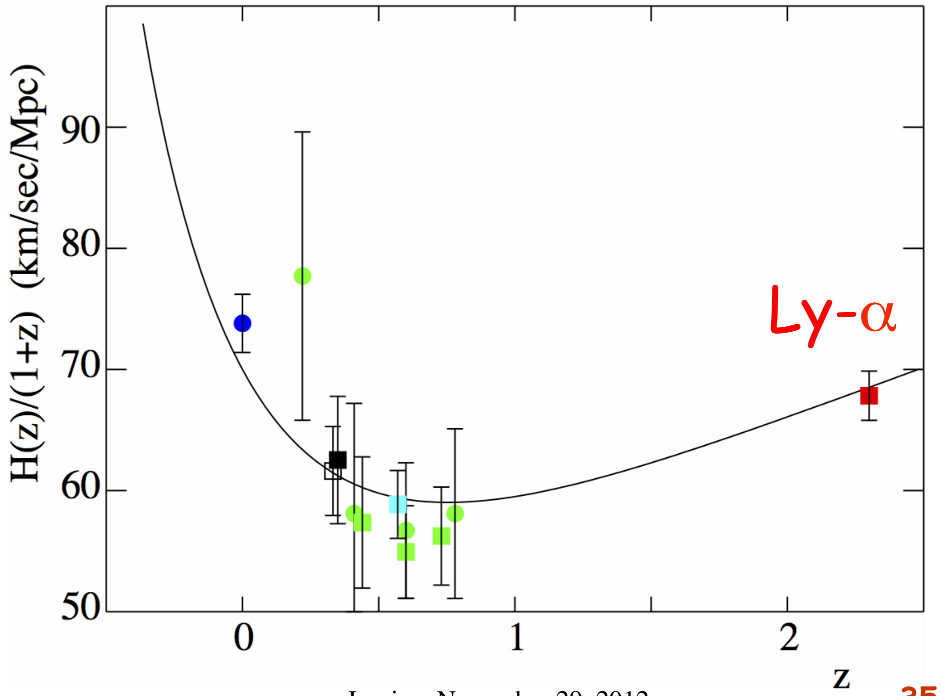


2D Fit

- Determination of the two dilatations scales in transverse and radial directions, α_t and α_l
- α_l much more precisely measured

Implications

- First measurement of H at z~2.3 (11 billions of years from now)
- Deceleration of the expansion of Universe for z>0.8!!!



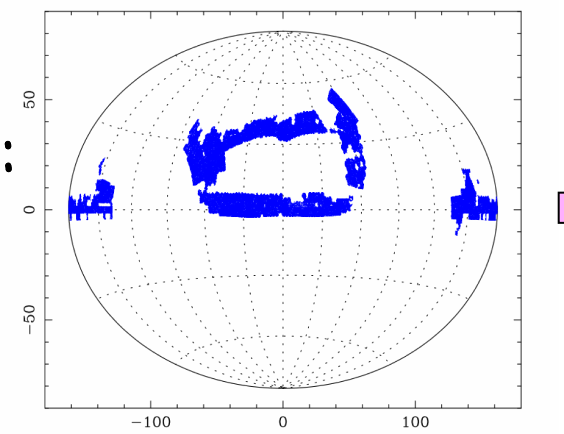
Conclusions and Prospects

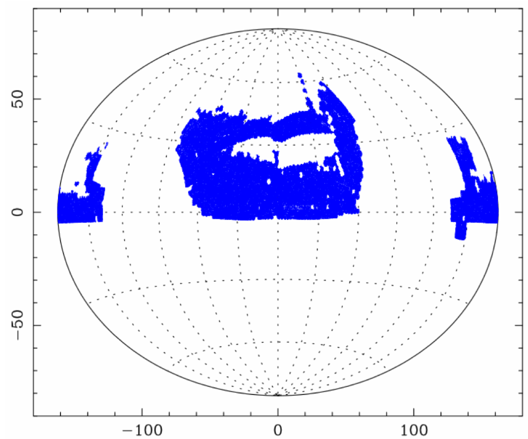
Conclusions

- With only DR9 (1/3 of the final survey). BOSS has already fulfilled these three goals:
  - Confirmation of BAO (7σ)
  - Measurement of BAO in transverse and radial directions
  - First observation in Ly-α

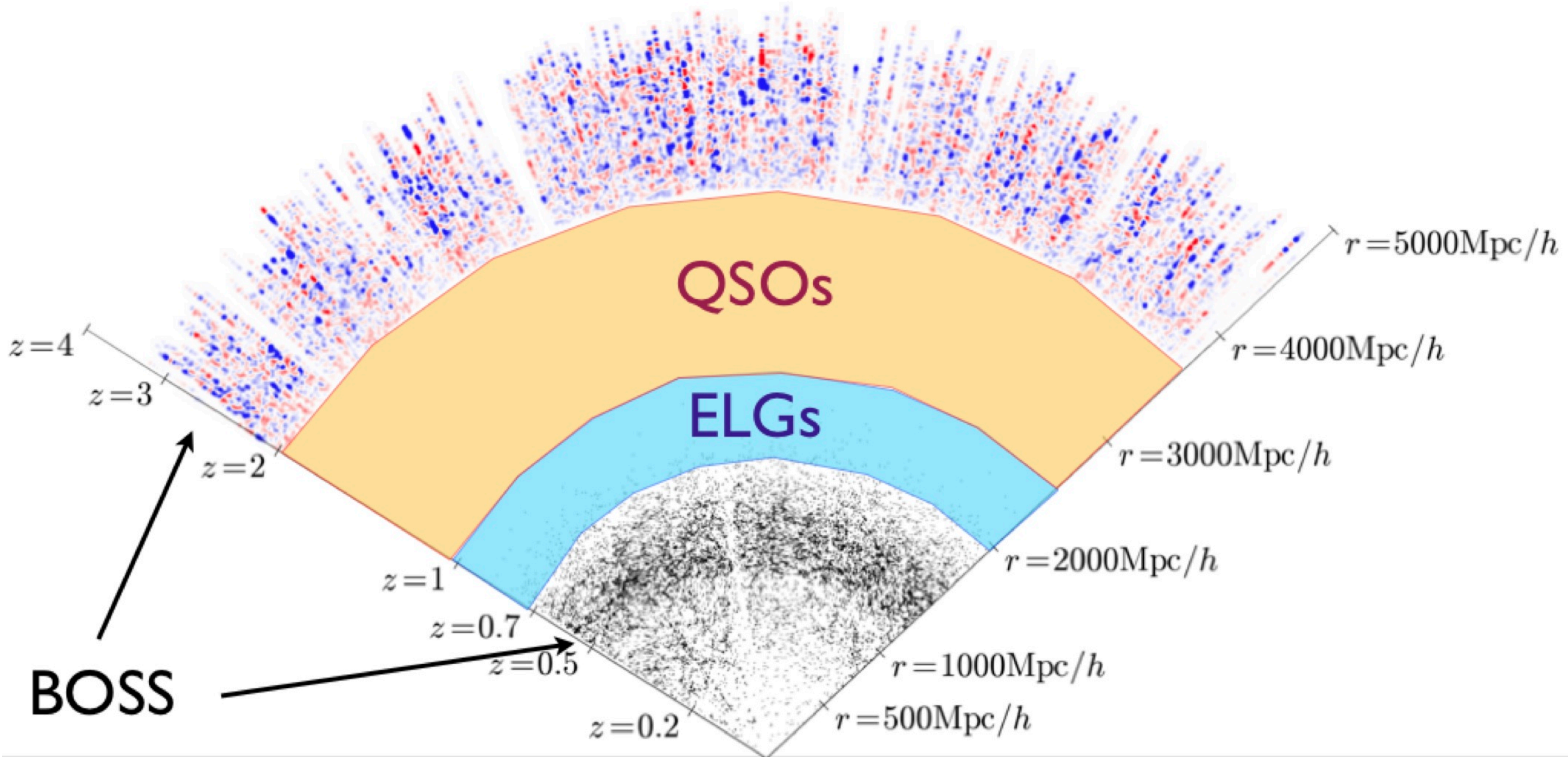
- Future DR9 science:
  - Low z galaxy clustering
  - Neutrino masses (galaxy and Ly-α)

- DR10 already available (x2 surface):





e-BOSS : Fill the Gap....



0.6<z<1.5 ELG:

- Emission line galaxies (stars forming)

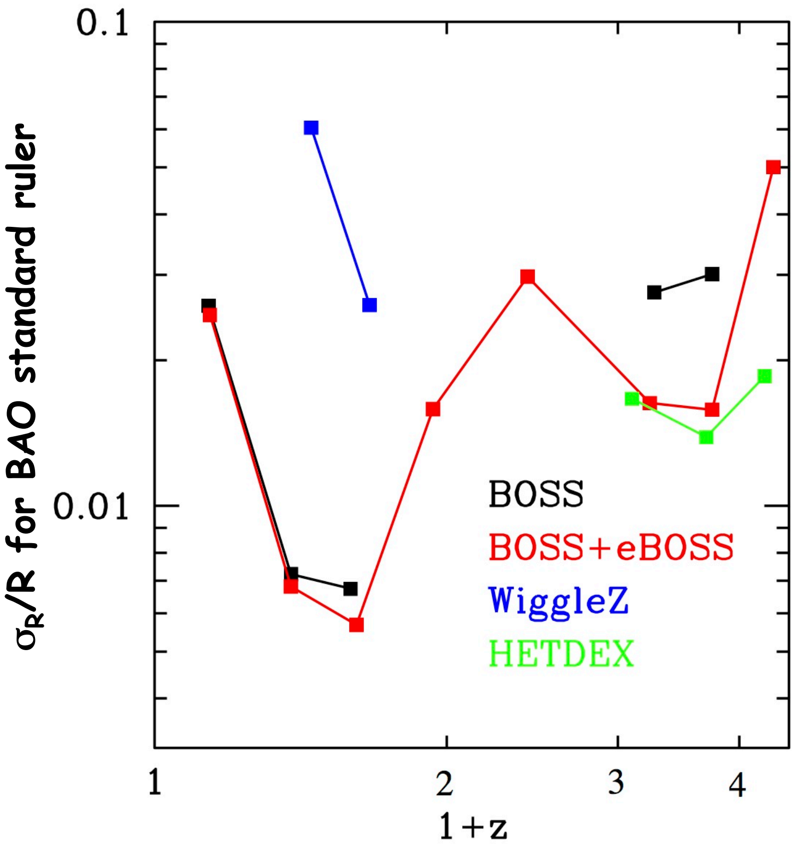
1<z<2.2 QSOs:

- Tracers of cosmic structures
- LF peaks at z ~1.5-2

Ly-α QSOs, 2.2<z<5:

- g<22 ⟹ g<22.5
- Improvement of selection
- ~15 deg^{-2} ⟹ ~35 deg^{-2}

e-BOSS performances



BAO

- Starts in summer 2014
- Continuous measurement for 0.3<z<4.0
- Improvement in Ly-α
- Improvement by a factor 2 of FoM (precision on the measurement of $\sigma(w_0) \times \sigma(w_a)$)

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