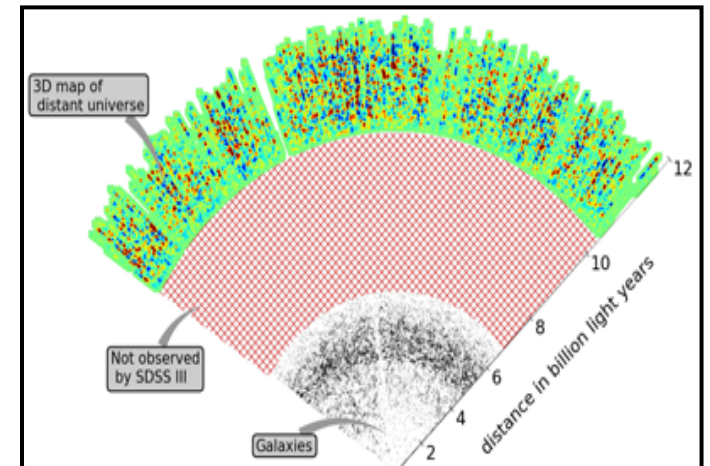
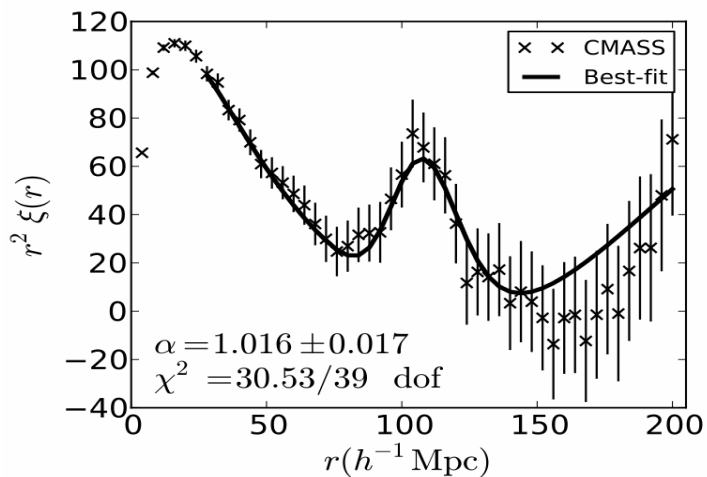


Dark Energy First results with BOSS

Ch. Yèche
(CEA-Saclay Irfu)



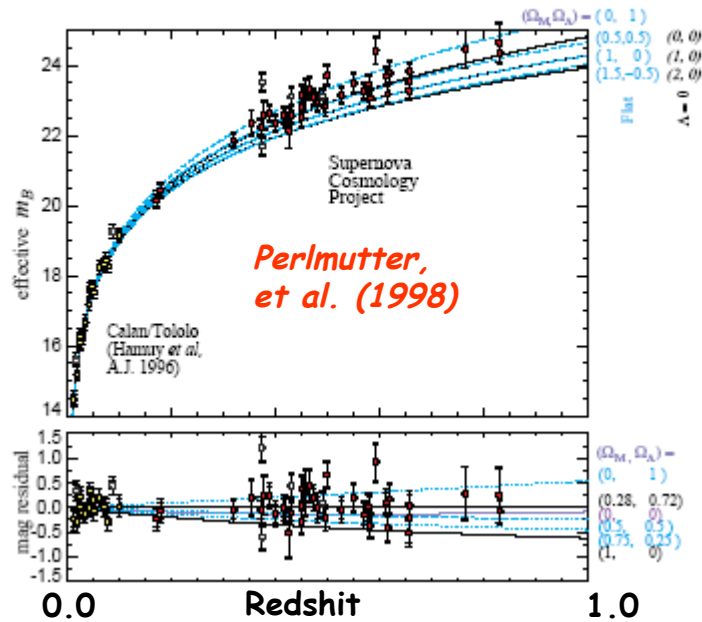
Outline:

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

LAL Seminar
Orsay - November 6, 2012

BAO - *Concepts*

Dark energy



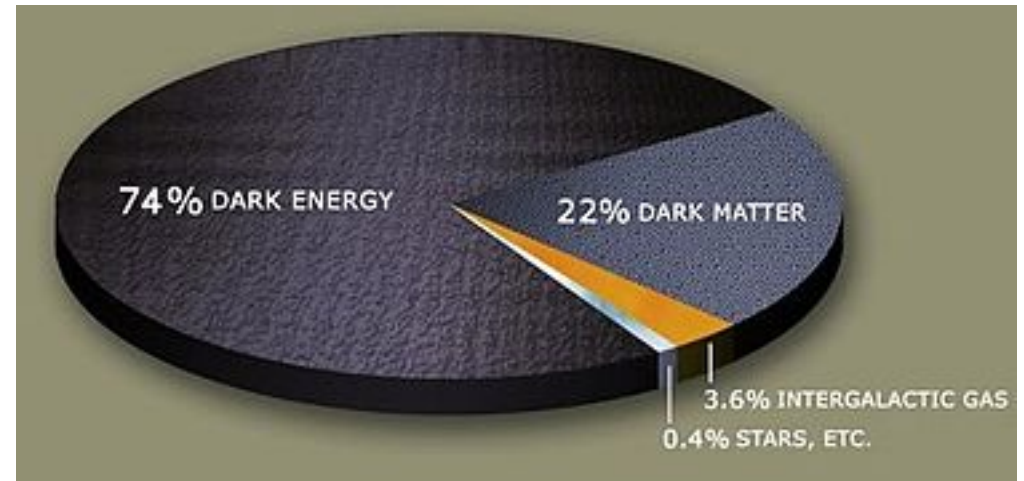
Acceleration of Universe expansion

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

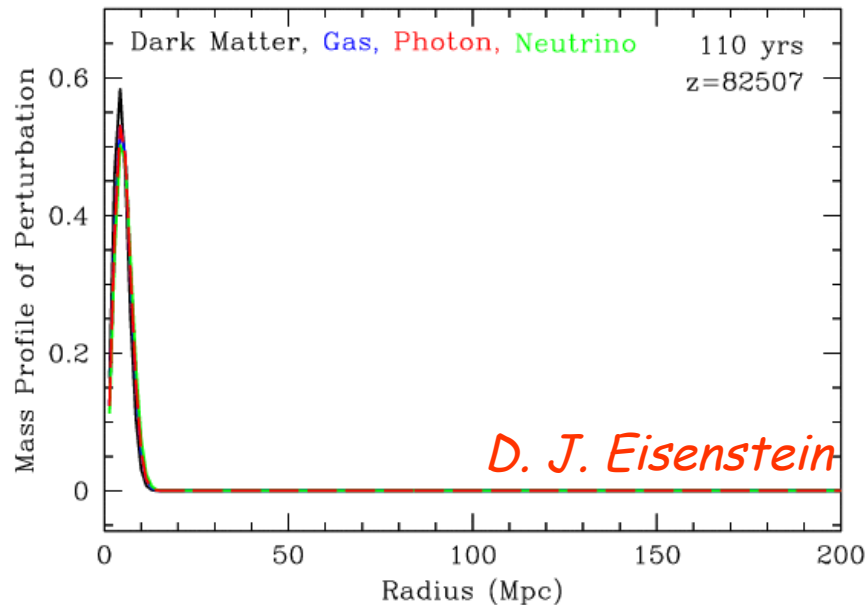
Concordance Model

- Λ CDM with GR
- Study of the nature of DE

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



A probe for Dark Energy: Baryonic Acoustic Oscillations



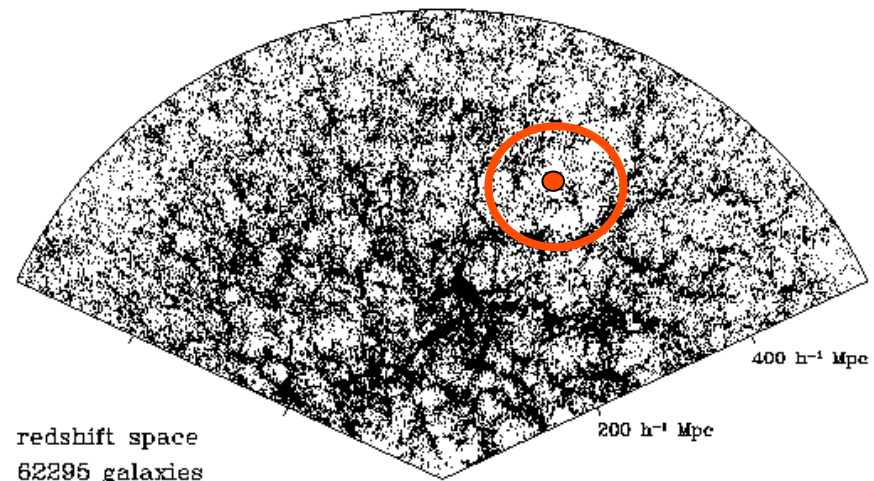
Acoustic propagation of an overdensity:

- Sound wave through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination ($z \sim 1100$).
- 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.

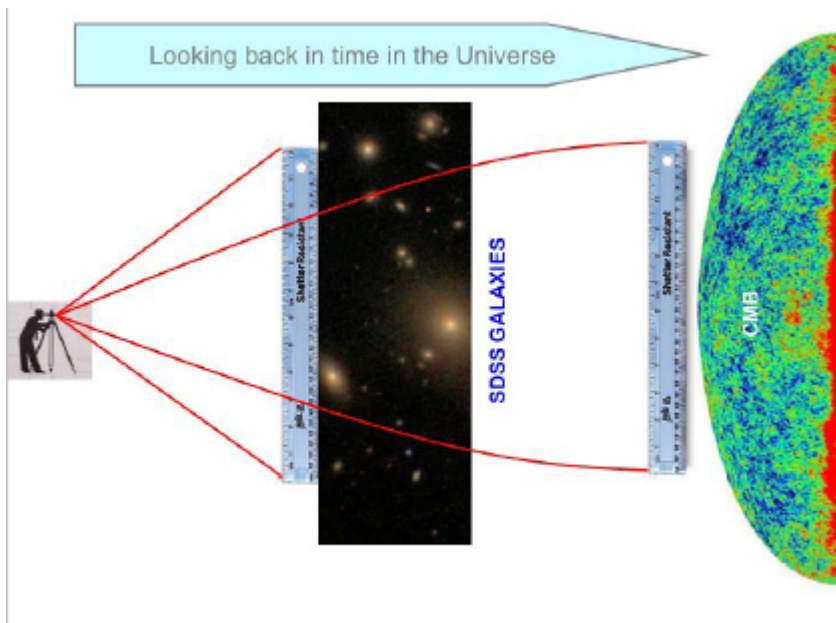
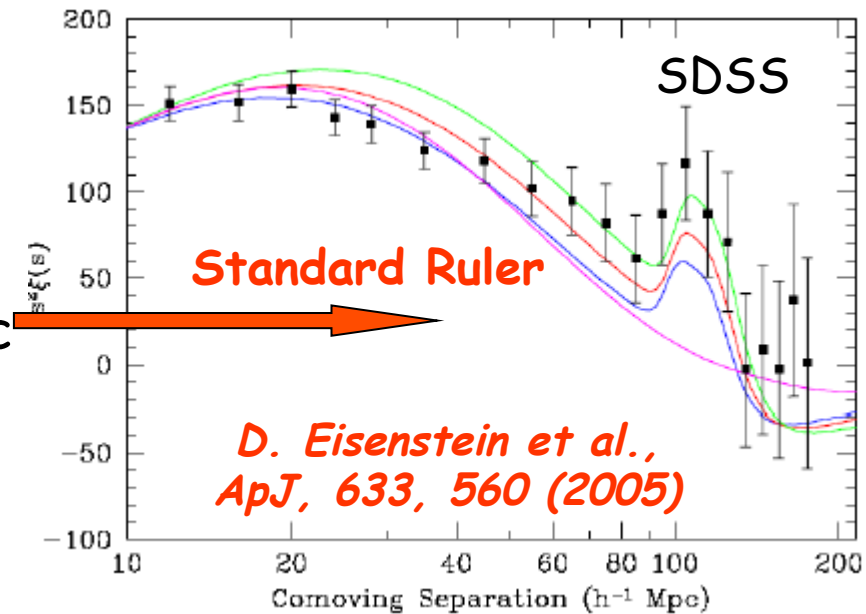
⇒ **Standard Ruler**



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: $\sim 50\,000$ LRGs
“Luminous Red Galaxies”
 $\langle z \rangle \sim 0.35$



Ch. Yèche

LAL Seminar

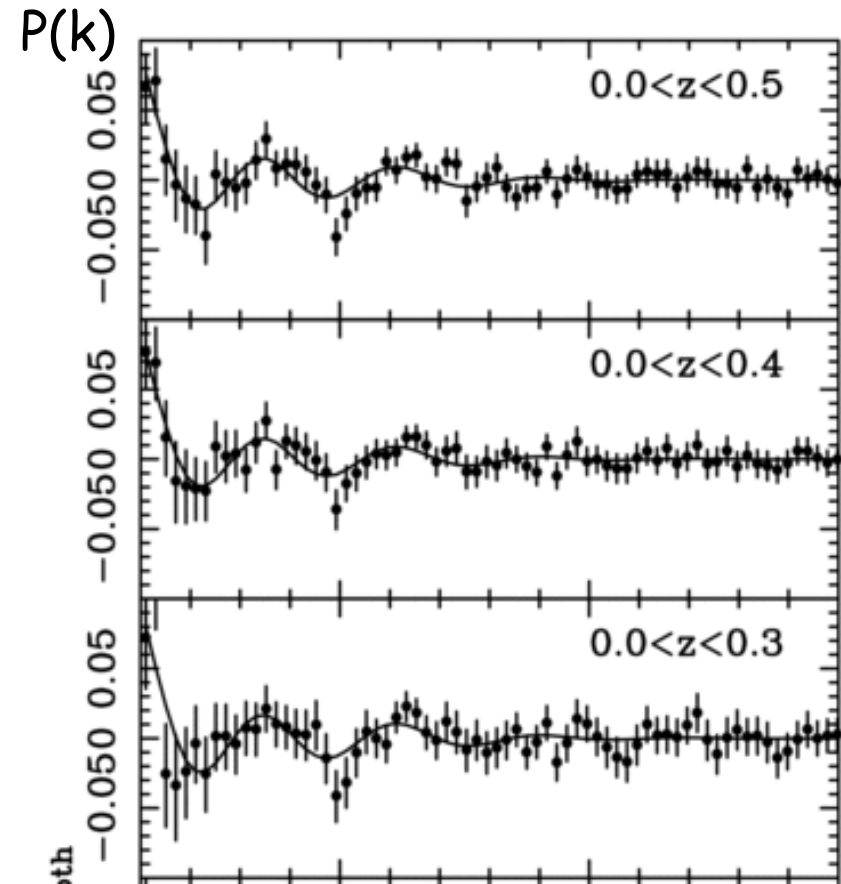
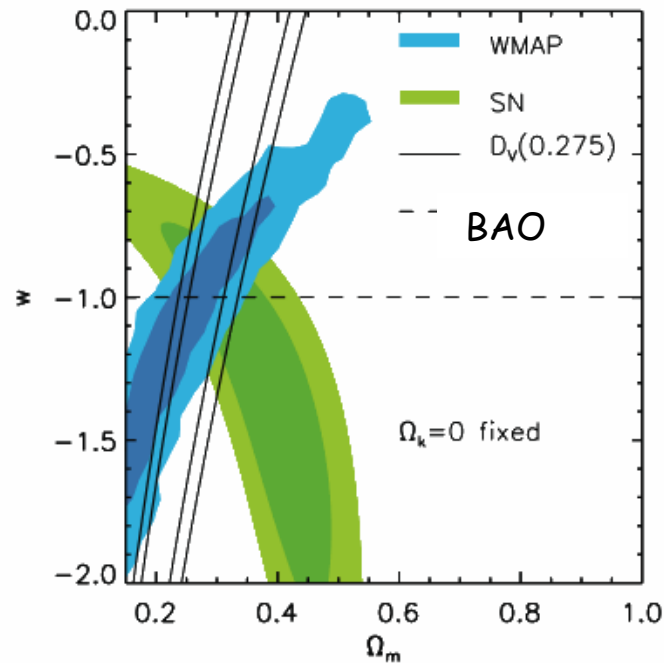
A 3D measurements:

- Position of acoustic peak \Rightarrow Size of the sound horizon r_s
- **Transverse direction:**
 $\Delta\theta = r_s / (1+z) / D_A(z)$
 \Rightarrow Sensitive to angular distance $D_A(z)$
- **Radial direction** (along the line of sight):
 $\Delta z = r_s \cdot H(z) / c$
 \Rightarrow Sensitive to Hubble parameter $H(z)$.

Status of BAO before BOSS

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



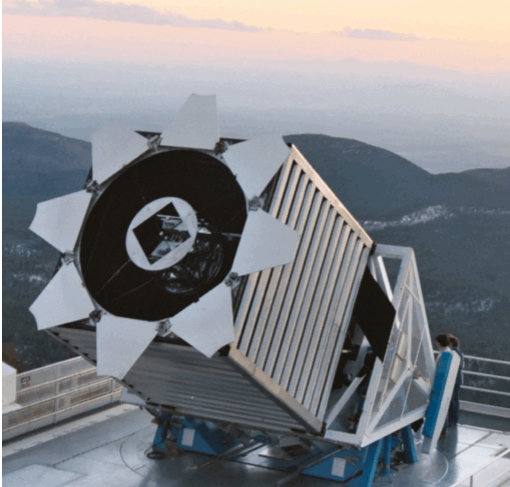
- SDSS $\langle z \rangle \sim 0.35$: 80 000 LRG
 - SDSS $\langle z \rangle \sim 0.15$: 30 000 LRG
 - 2DFGRS $\langle z \rangle \sim 0.15$: 140 000 Galaxies
- Percival et al., MNRAS, 401 2148 (2010)*

SDSS-III - BOSS

-

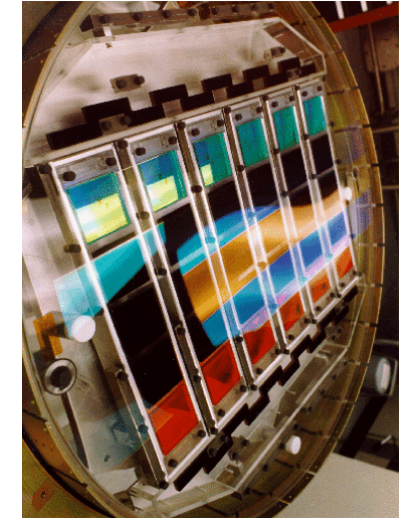
A brief overview

From SDSS to SDSS-III



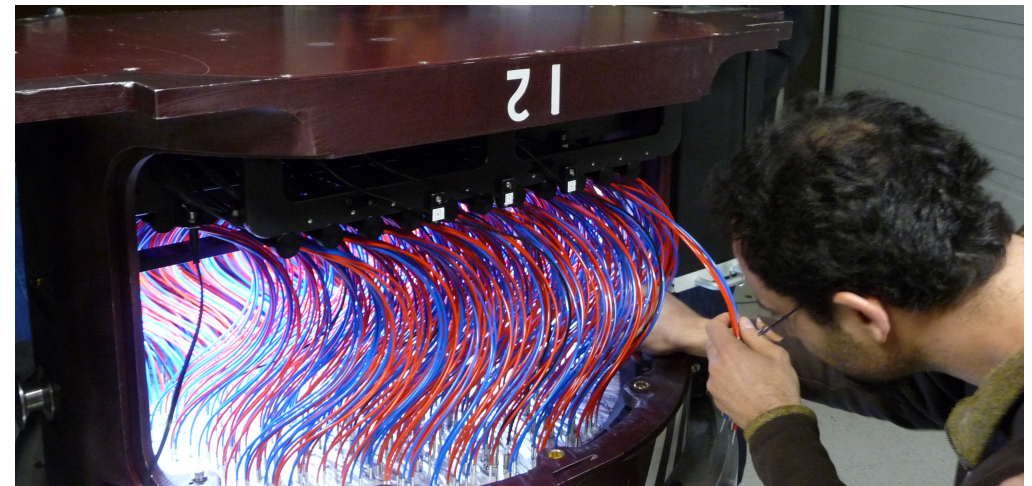
SDSS Consortium

- 2.5m Sloan Telescope
- Apache Point, NM
- Wide field telescope $\sim 7 \text{ deg}^2$
- Camera equipped with 5 filters (~ 120 millions pixels)
- Extension of imaging survey in SGC

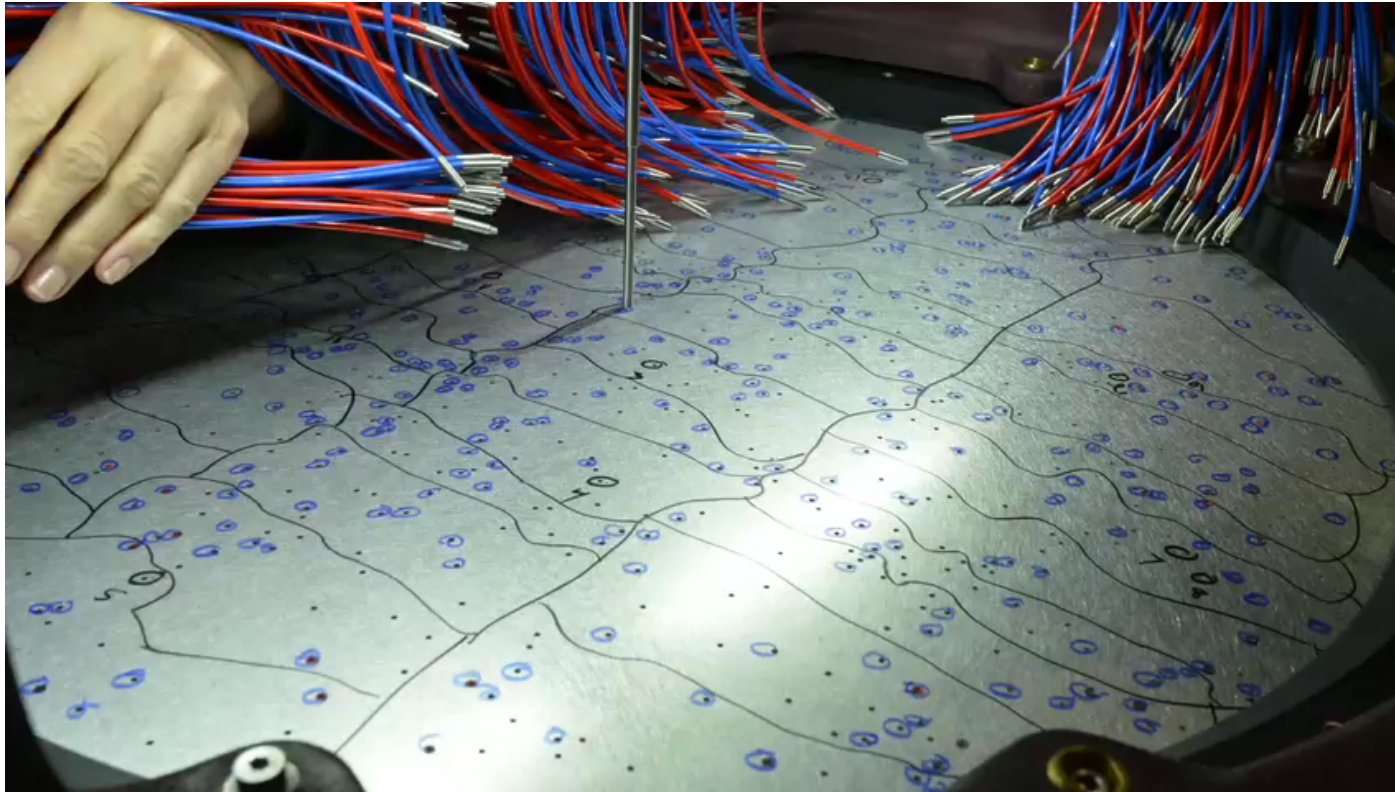


Upgrade for SDSS-III

- New fiber system \Rightarrow 1000 fibers
- Replacement of red CCDs by LBNL CCDs \Rightarrow LRG with higher z
- Replacement of blue CCDs with e2v CCDs with better throughput in UV \Rightarrow Lyman- α forest program



Plug and Observe

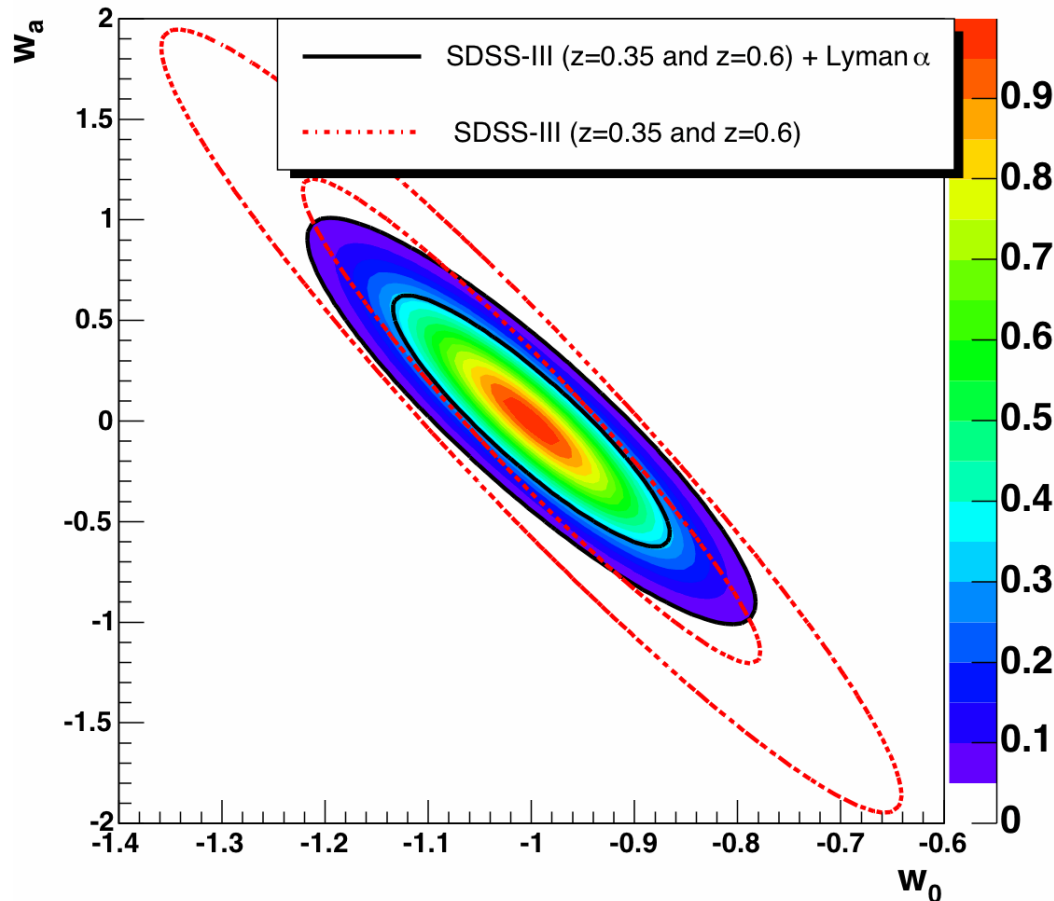


Several steps

- 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

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



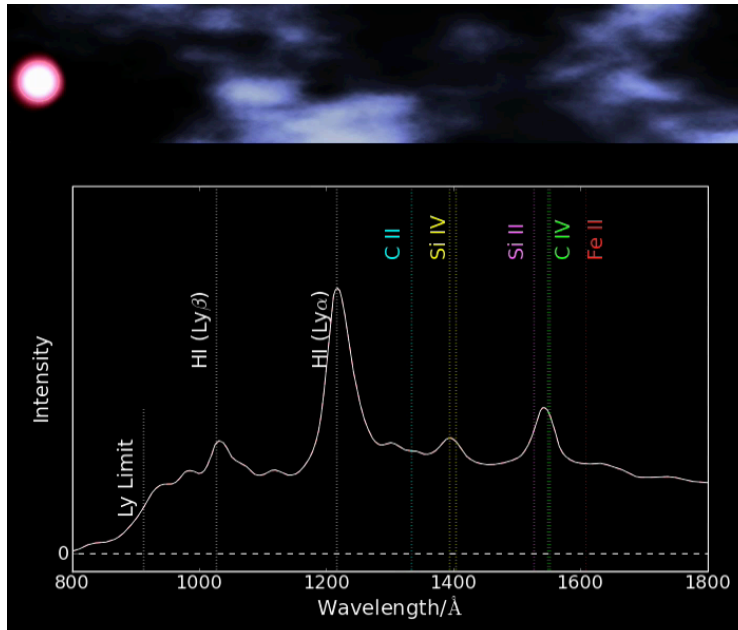
With galaxies: ~1.2M (LRG+CMASS)

- ~11000 deg², 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: $\text{Ly-}\alpha$ forests



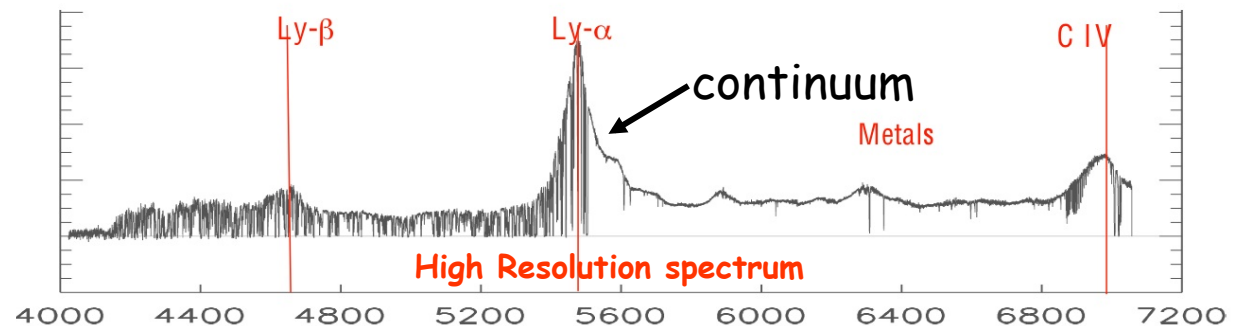
Principles

- Use $\text{Ly-}\alpha$ 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, N-body simulations and 3D power spectrum...)

BAO specifications:

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

$z \sim 3.6$ Quasar

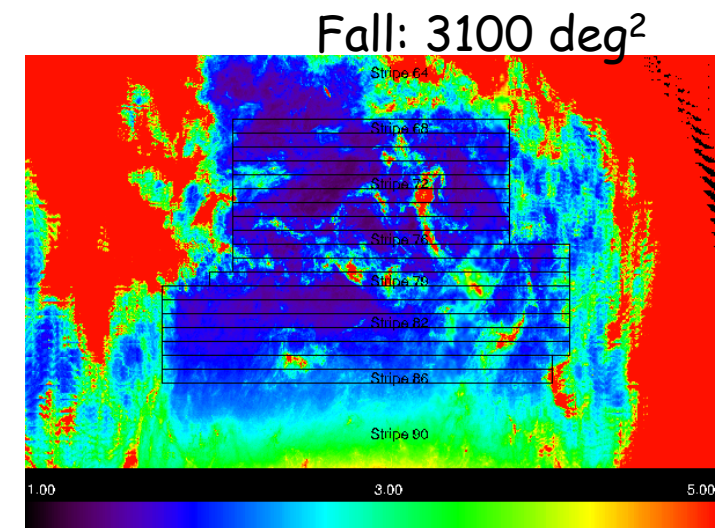
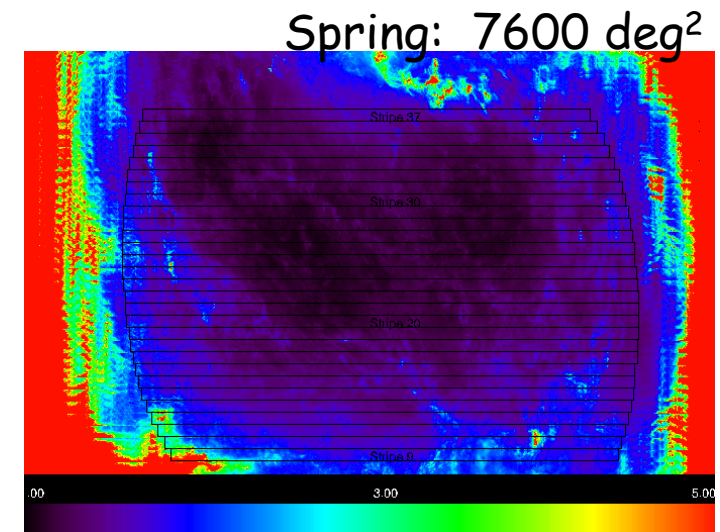
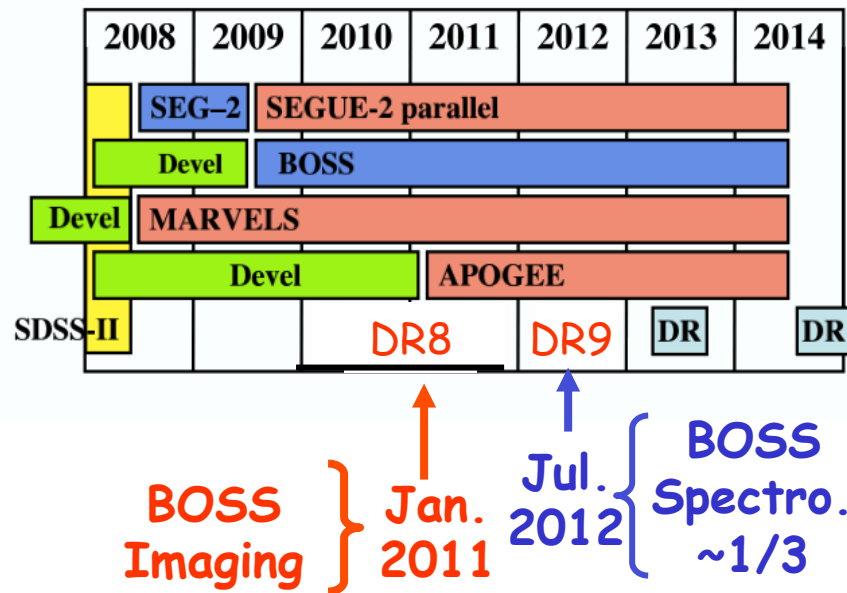


BOSS Status

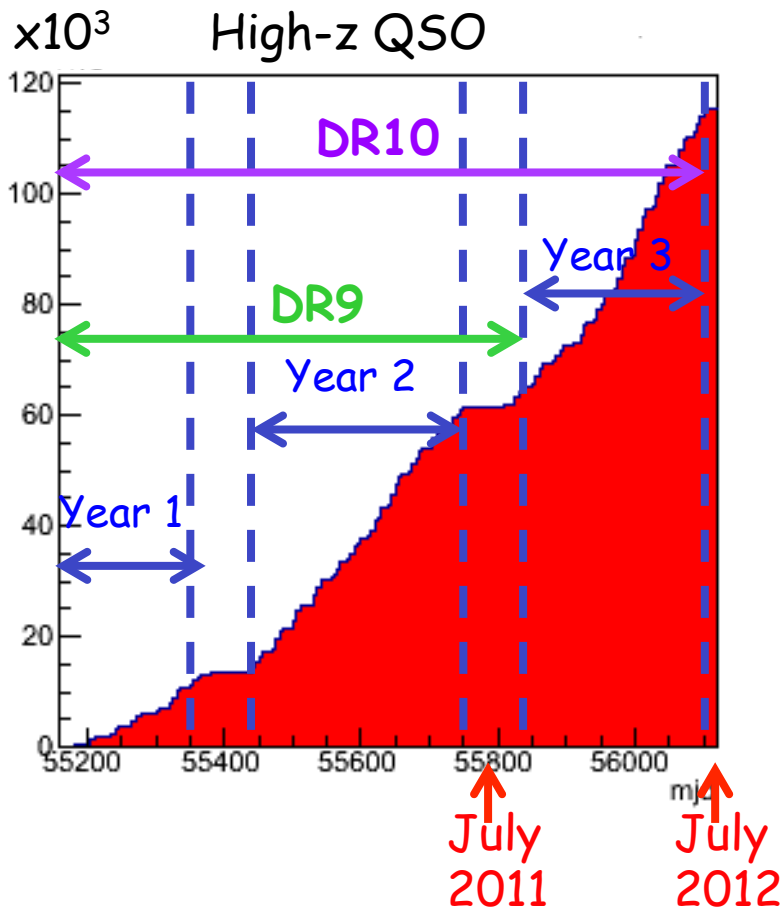
Observing plan

- Fall 2008 + Fall 2009: Complete imaging survey (10 700 deg²)
- Fall 2009: Commissioning of spectrograph
- **14-15 Sept. 2009 : First light**
- Jan. 2010: Begin spectroscopic survey
- July 2014: End survey

Public data releases



Status of the survey



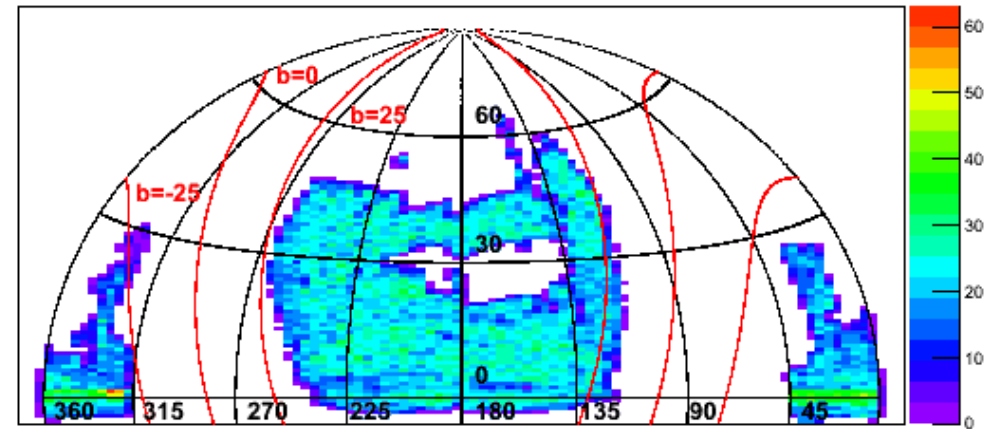
Ch. Yèche

Ch. Yèche

LAL Seminar

LAL Seminar

QSO density

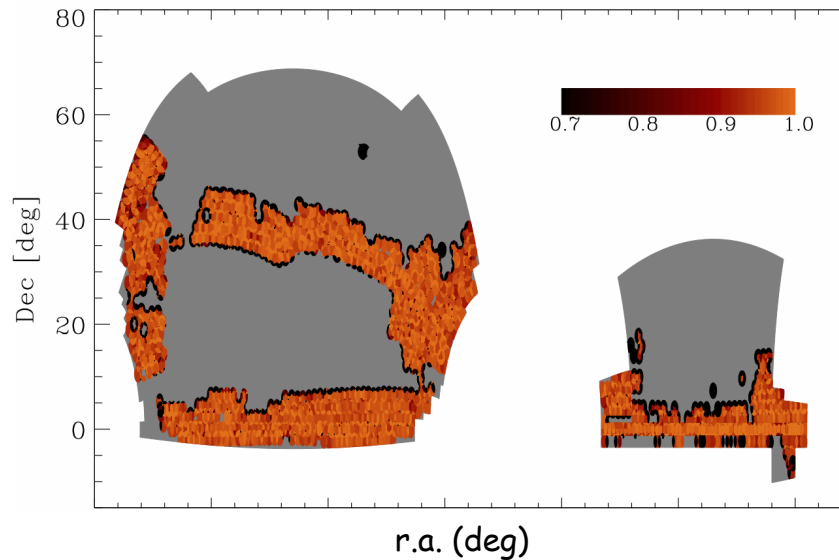


- So far, **~120 000 QSOs** and **~700 000 galaxies** over **~6700 deg²**
- **End of the survey (10700 deg²):**
 - 1.2-1.5M galaxies !!!
 - 150k - 200k high-z QSOs !!!

Orsay, November 6, 2012, November 6, 2012

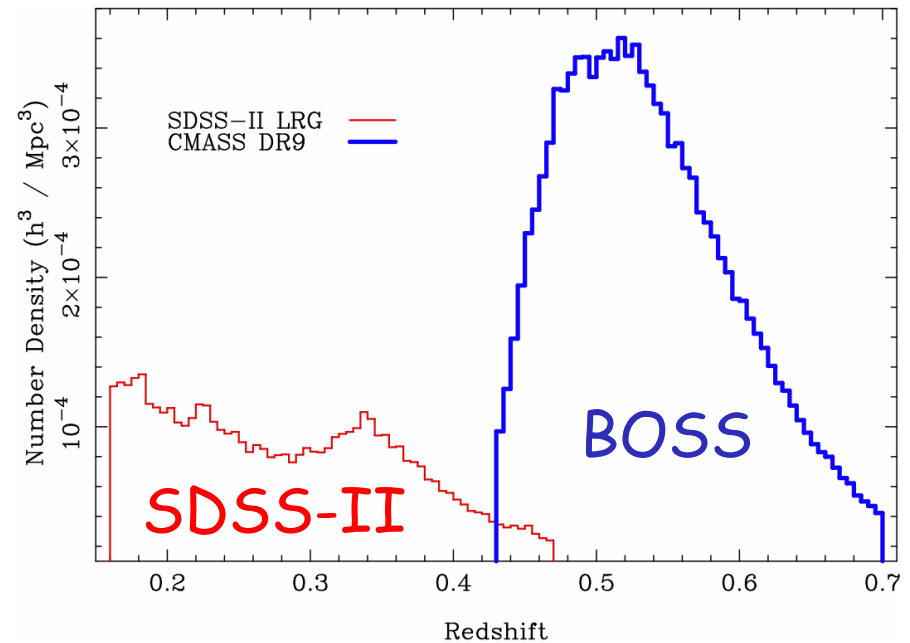
BAO *with galaxies*

Footprint - galaxy sample



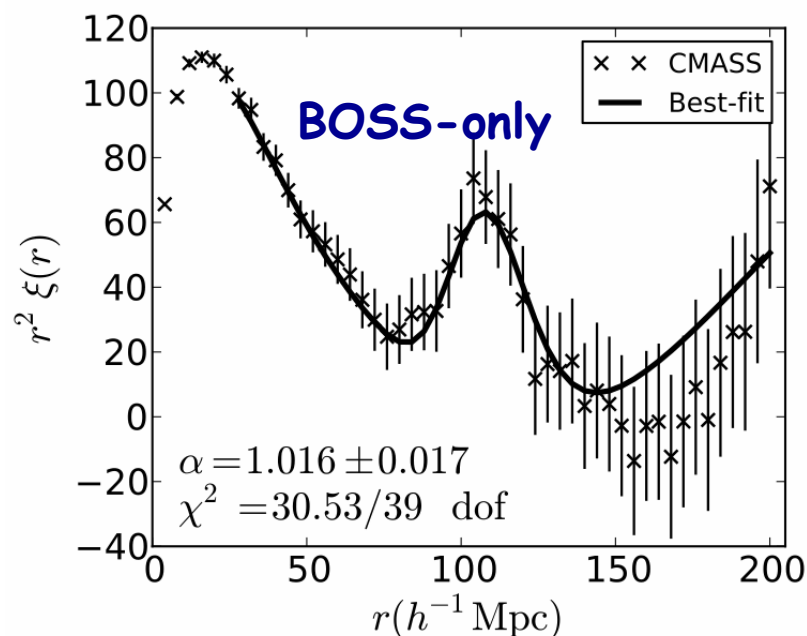
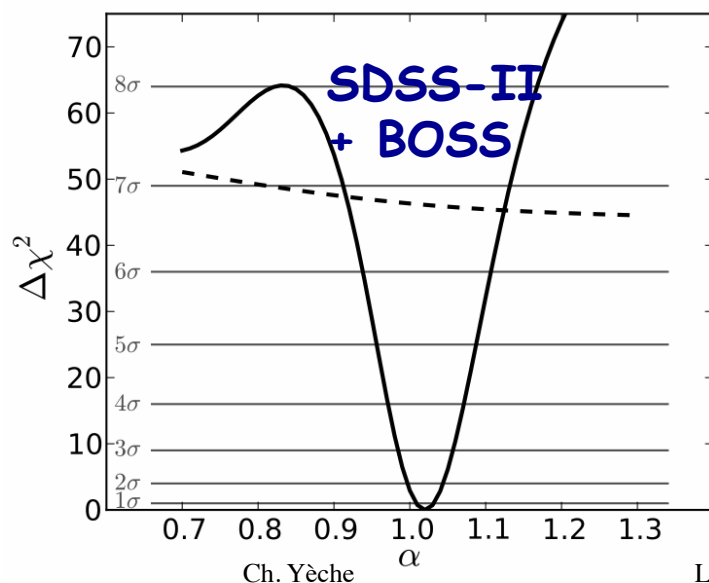
- Deeper and denser survey compare to SDSS-II
- $z \sim 0.5-0.6$

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



BAO in Correlation Function

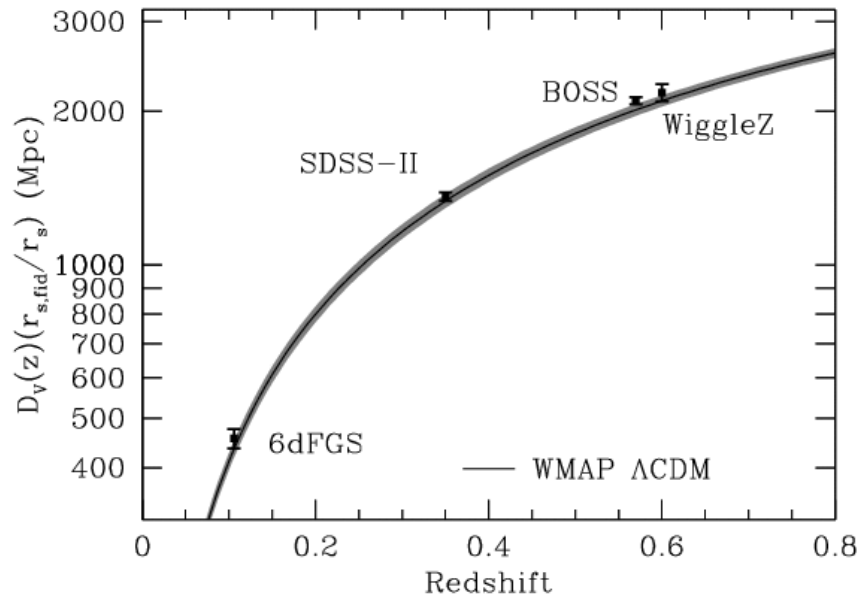
- Use a fiducial model to compare against observed features in spherical average statistics.
- Departures quantified by dilatation scales α :
 ➔ Fit of $\xi(\alpha r)$



*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: $\alpha = 1.016 \pm 0.017$

Isotropic BAO results

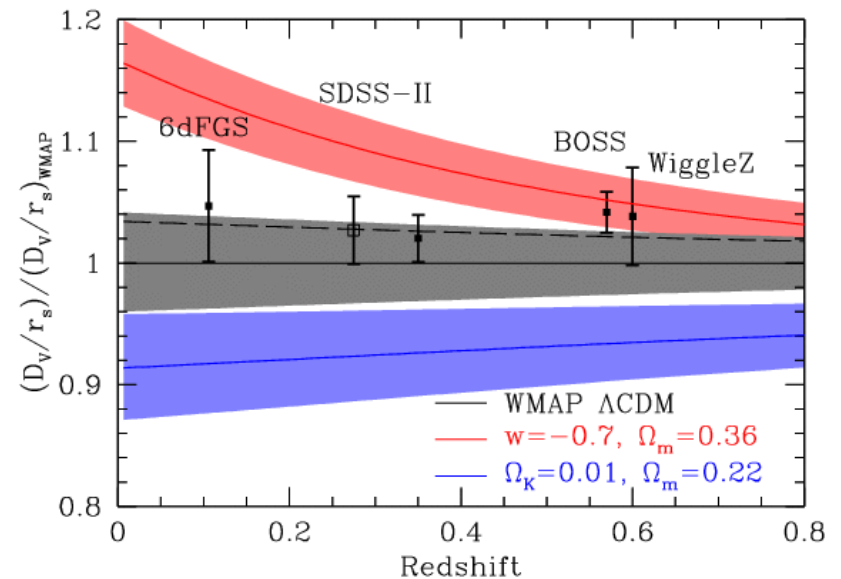


➤ Combine transverse and longitudinal direction with

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

➤ New "Hubble" diagram with BAO like SNIa with D_V/r_s

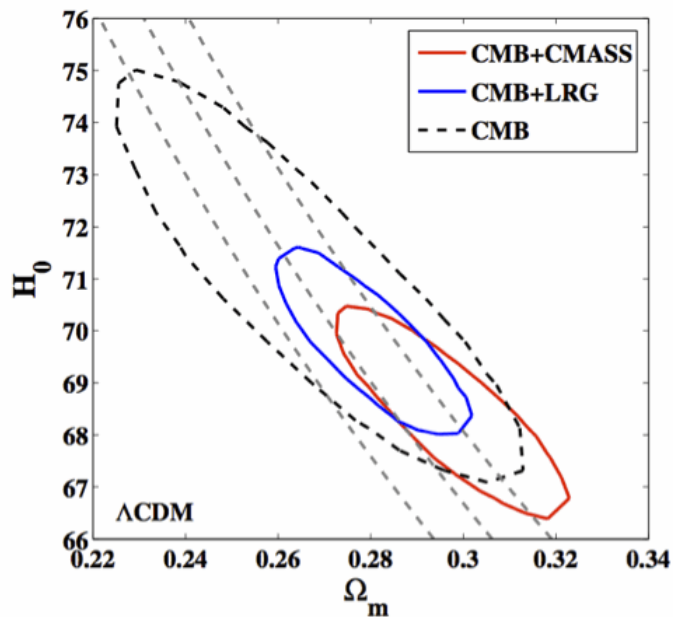
- BAO scale consistent with WMAP
- Mild tension...
- $\Omega_m = 0.268 \pm 0.029$ (WMAP)
- $\Omega_m = 0.293 \pm 0.012$ (WMAP+SDSS)



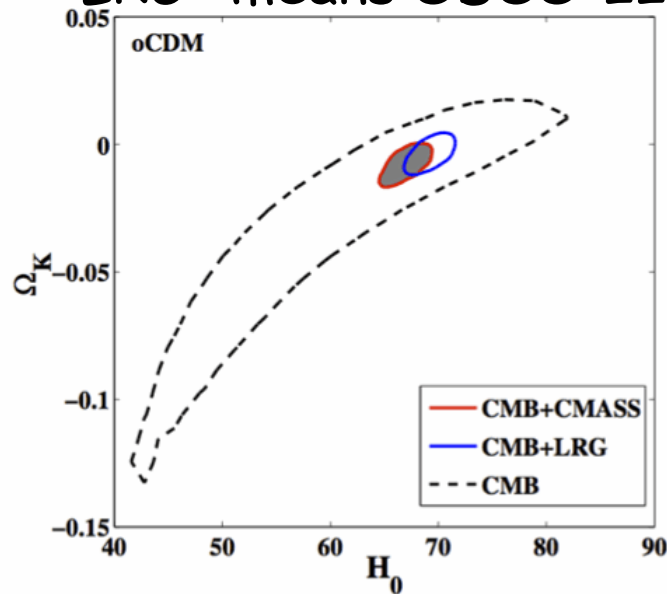
Constraints on Friedman equation

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

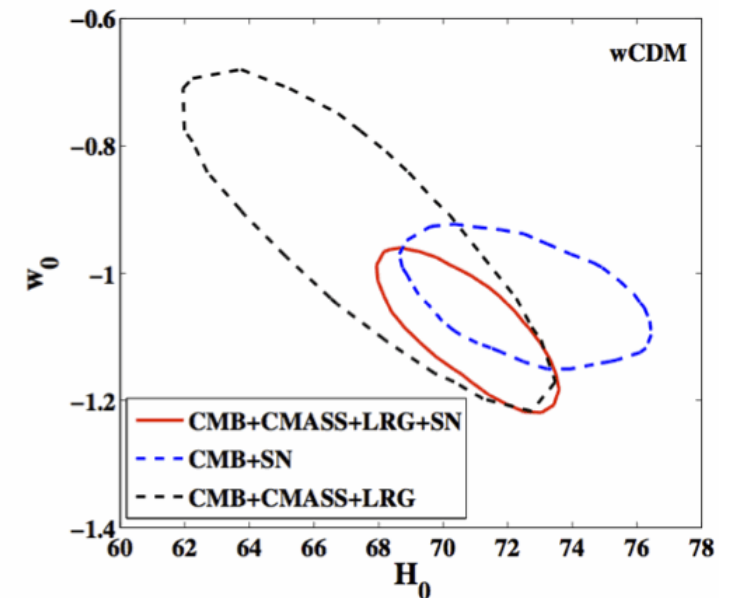
"LRG" means SDSS-II



2-param. Λ CDM
model

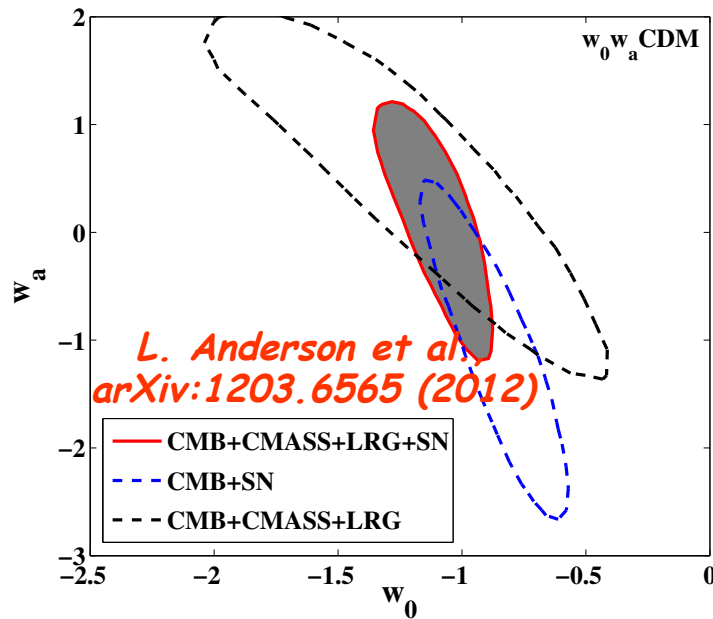


3-param. o CDM
model



4-param. w CDM
model

Dark Energy: Equation of state



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

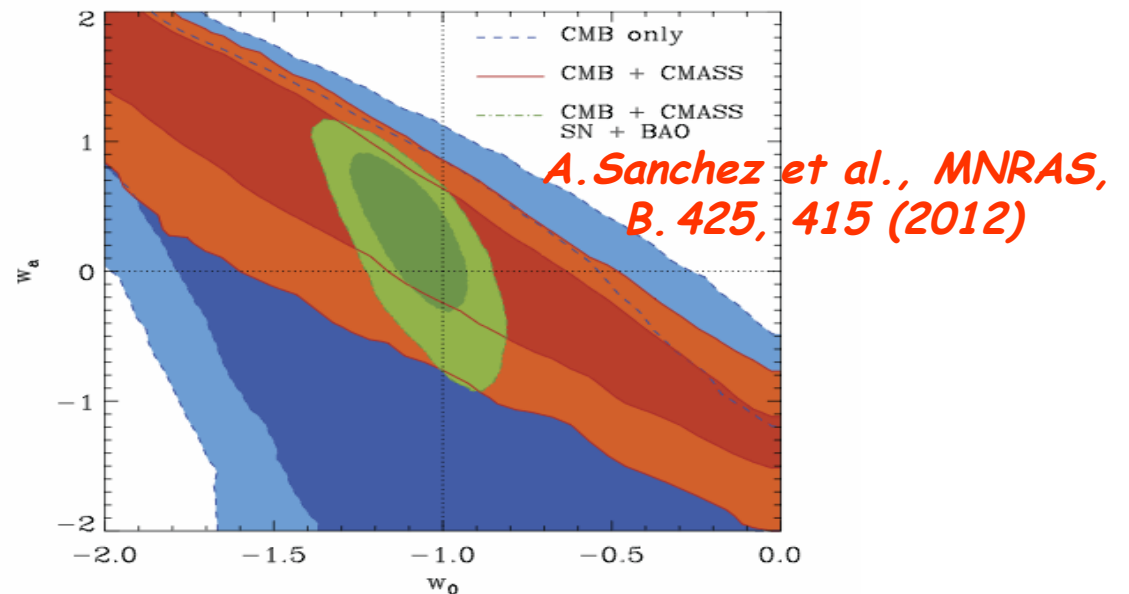
$$w_0 = -1.08 \pm 0.11$$

$$w_a = 0.23 \pm 0.42$$

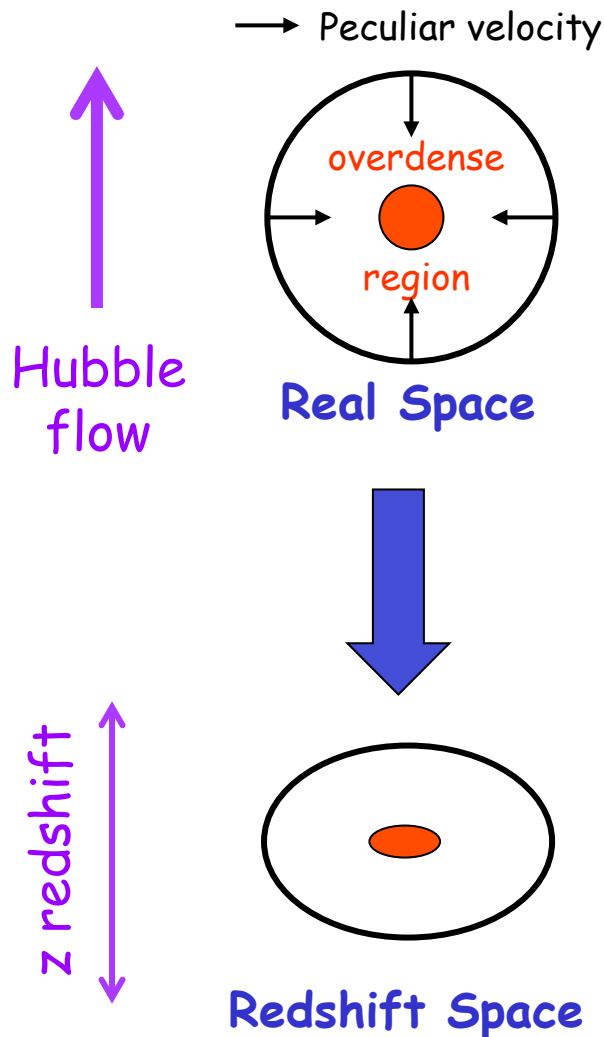
- Eq. of state: $w = P/\rho$
- $w(z) = w_0 + z/(1+z) \cdot w_a$
- Conservative approach: just fit of isotropic BAO peak position
- WMAP+BAO+SN:

$$w_0 = -1.08 \pm 0.15$$

$$w_a = 0.10 \pm 0.87$$



Large-scale Redshift Space Distortions



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

$$P_F(\vec{k}) = P_F(k, \cos(\theta))$$

$$= P_L(k) \cdot (b + f \cos(\theta))^2$$

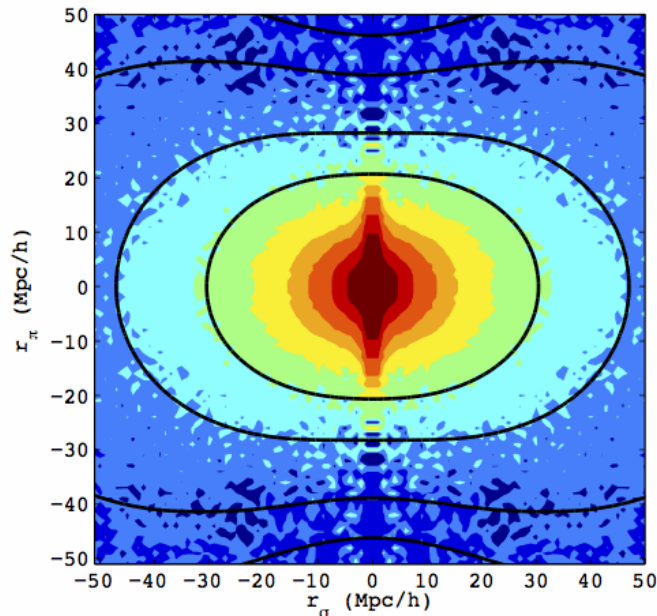
*N. Kaiser,
MNRAS 227, 1
(1987)*

- $P_L(k)$ linear power spectrum
 - θ angle between vector k and LoS
 - b linear galaxy bias, f log. growth rate
- Distortion are quantitatively measured by multi-poles decomposition

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

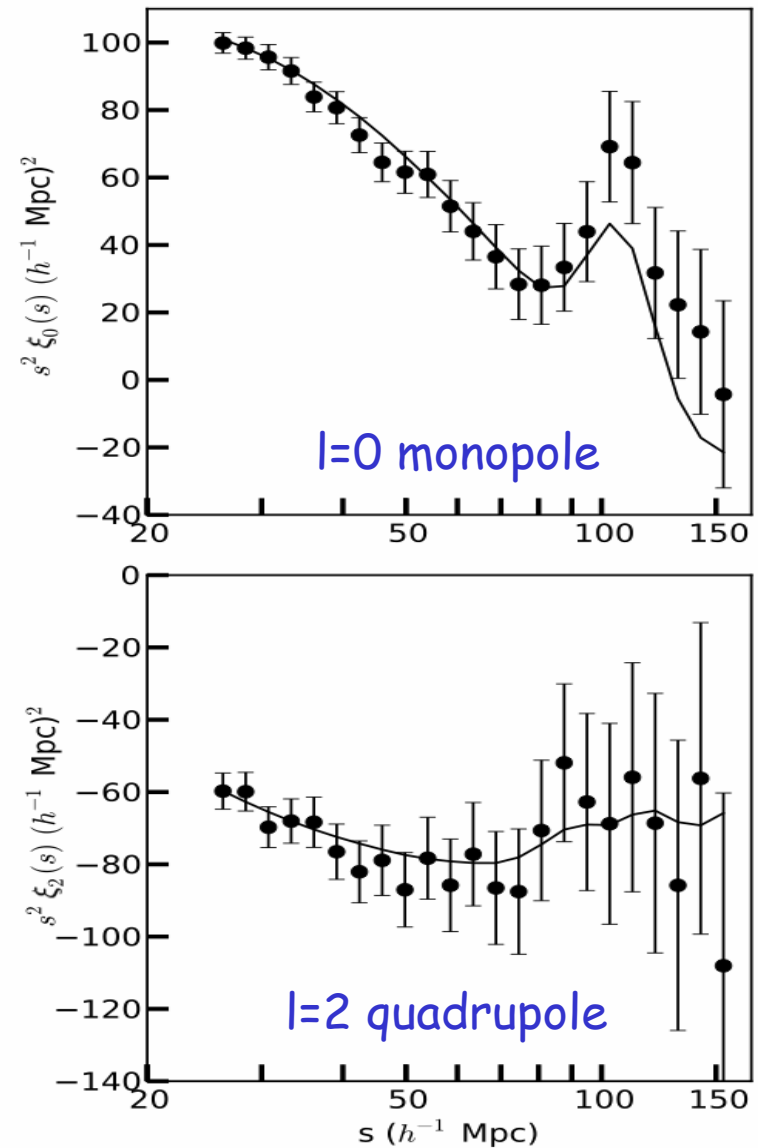
P_ℓ : Legendre polynomials

Redshift Space Distortions

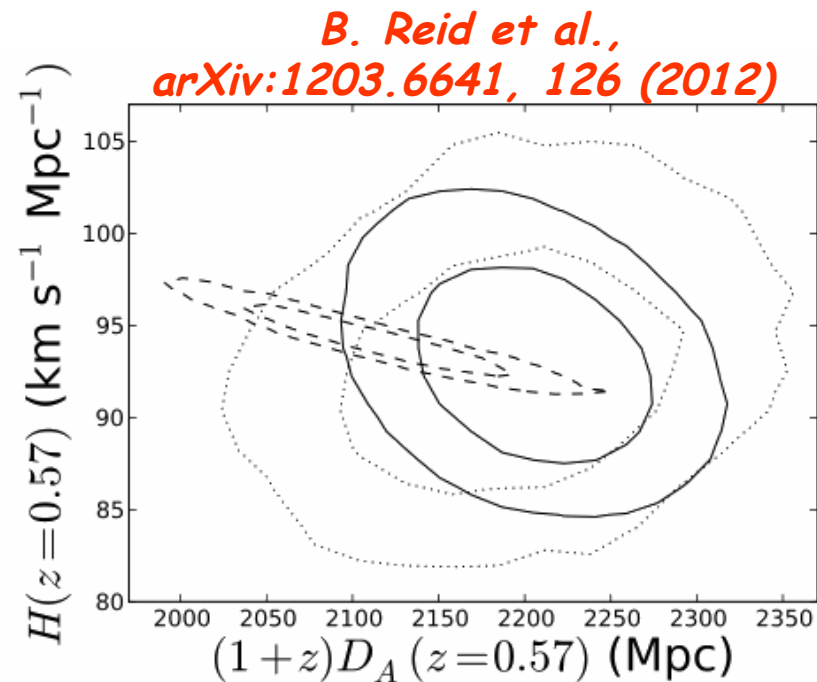


- Redshift distortion clearly at $\langle z \rangle \sim 0.6$ in BOSS
- Excellent agreement between data and N-body simulations

*B. Reid et al.,
arXiv:1203.6641, 126 (2012)*

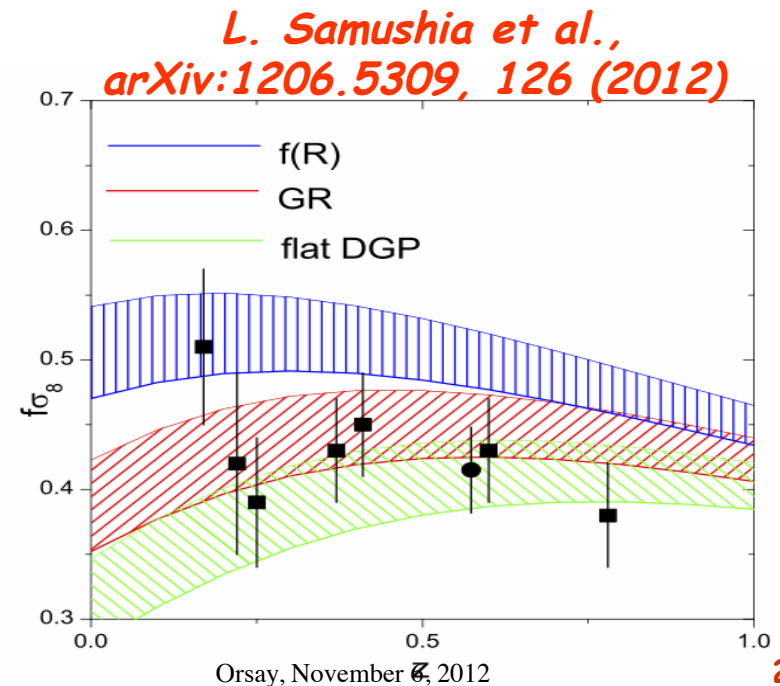


Results of the anisotropic fit



- 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

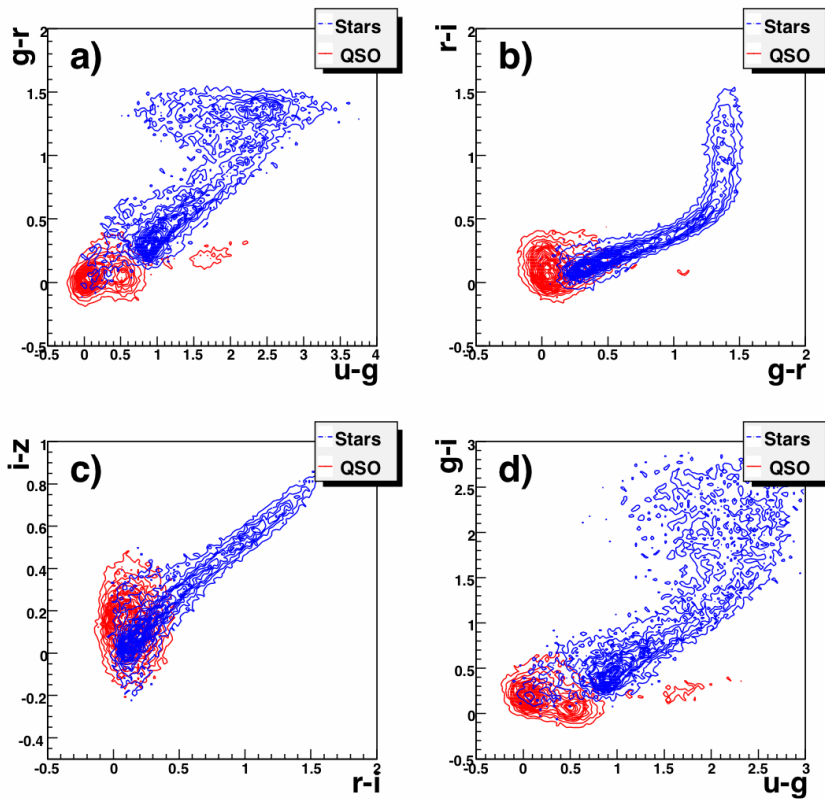
- Test of GR with $f\sigma_8$
- $f(z)\sigma_8(z) \propto dG/d\ln(a)$, G linear growth rate



BAO

with $Ly-\alpha$ forests

QSO Selection with Photometry

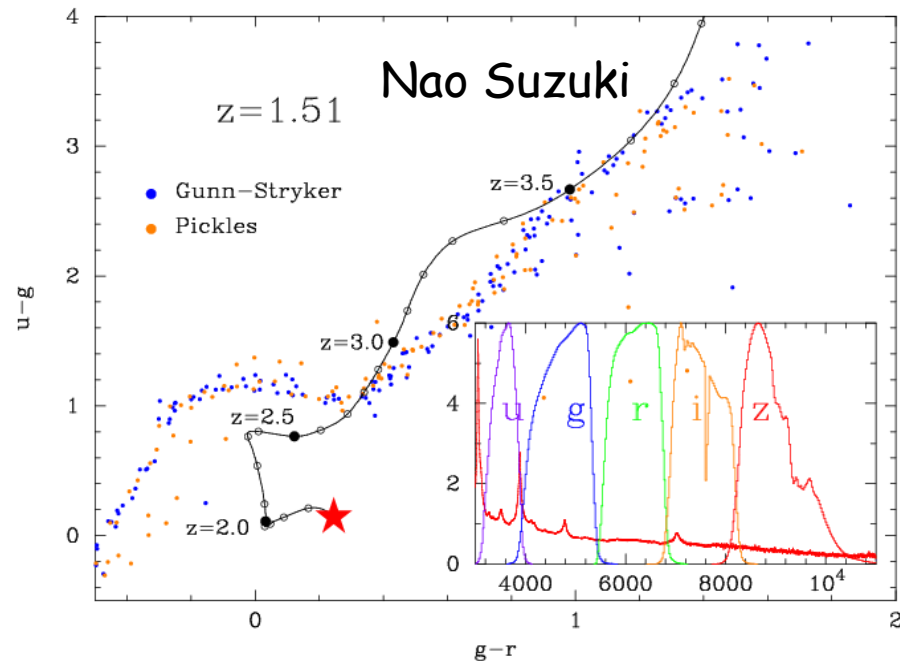


SDSS 4 colors
(u-g, g-r, r-i, i-z)

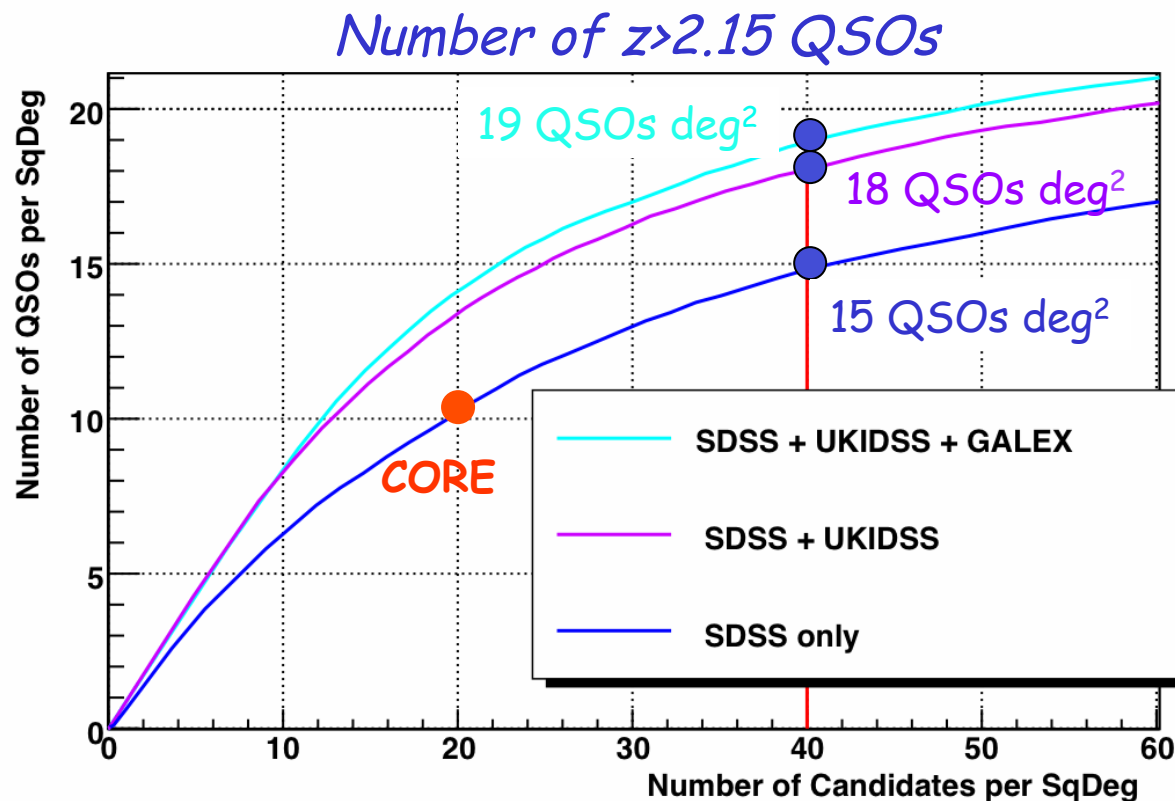
*Ch. Yèche et al.,
A&A 523, A14 (2010)*

Challenging target selection

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



BOSS: Selection of Ly- α QSO Using Photometry

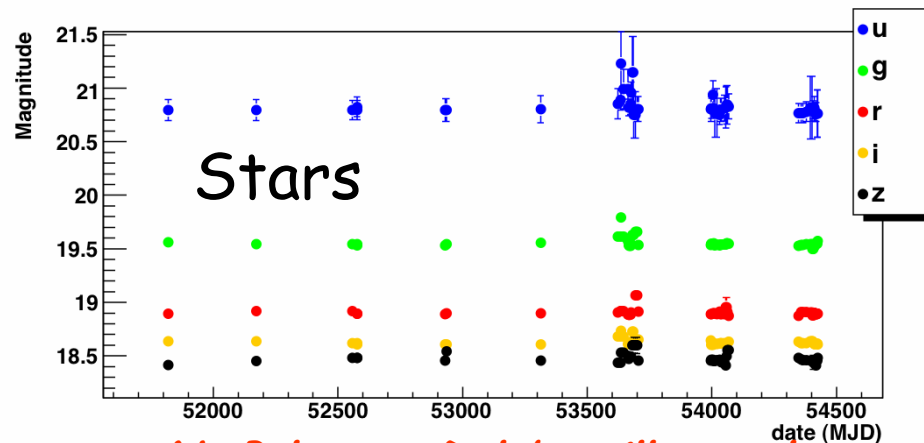
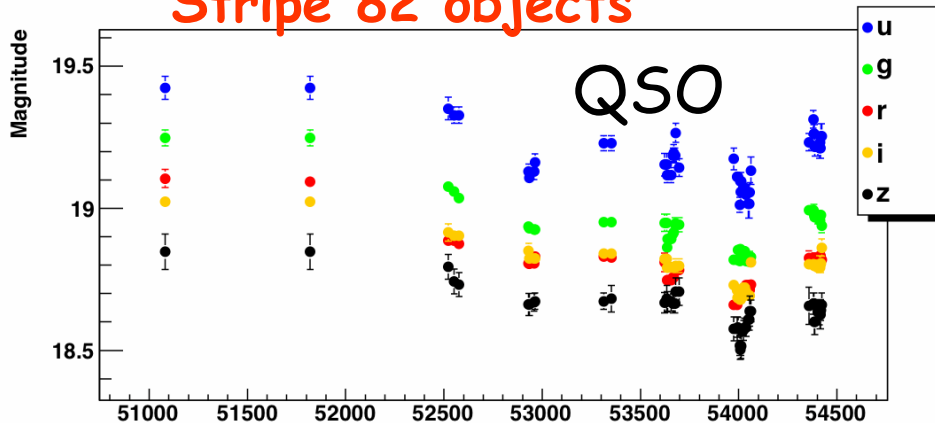


N. Ross, A. Myers, E. Sheldon. Ch. Yèche et al., APJS 199,3 (2011)

- 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

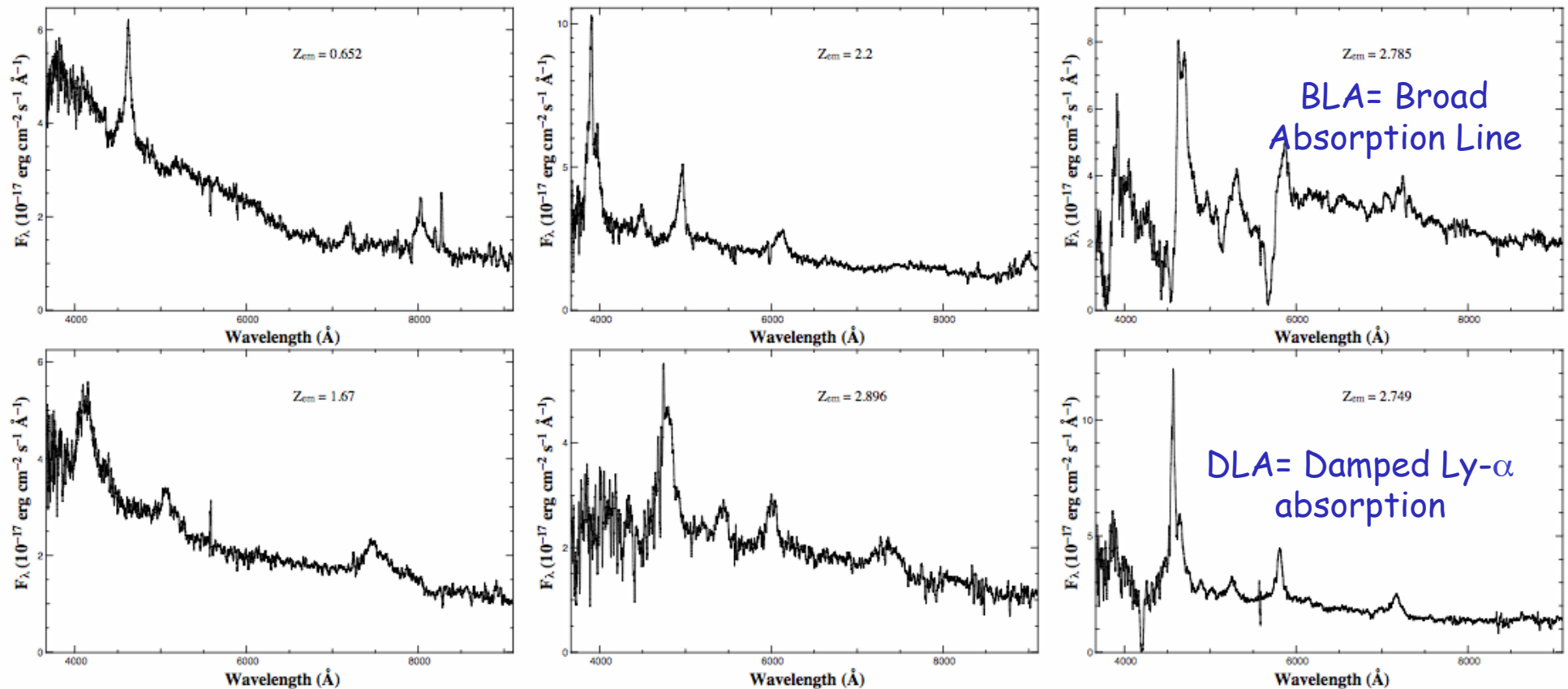
Light curves of Stripe 82 objects



*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 deg²)
 - **~28 deg⁻² QSOs with $z > 2.15$**
 - Proof of principle for future surveys (e-BOSS, BigBOSS)

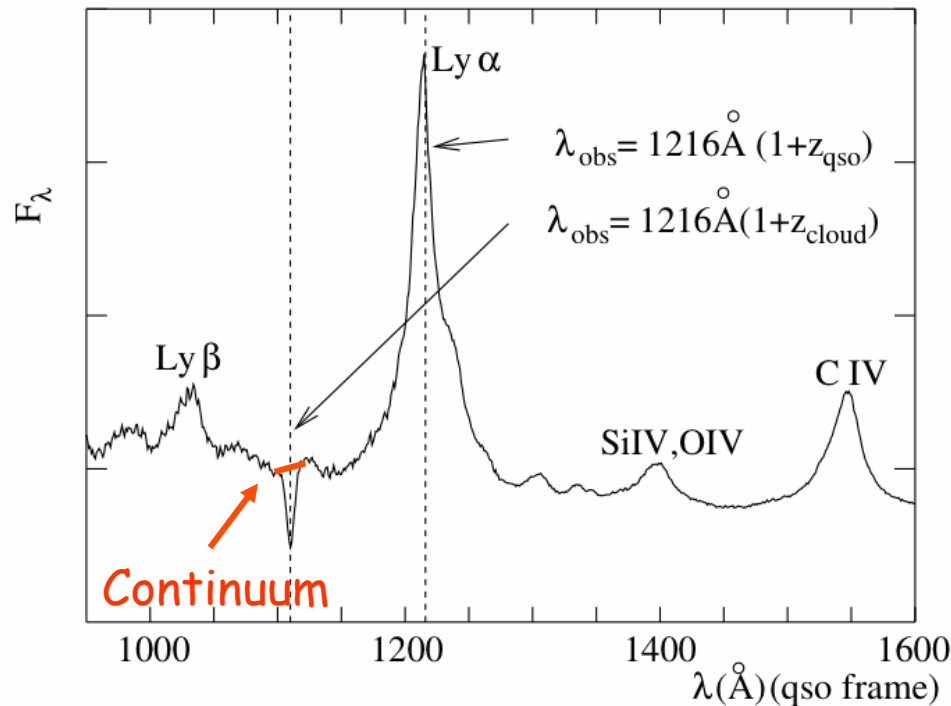
Visual inspection of all QSO targets



- 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 $z_{\text{cloud}} < z_{\text{qso}}$
- QSO Ly- α emission:
 $1216\text{Å}(1 + z_{\text{qso}})$
- HI "cloud" absorption:
 $1216\text{Å}(1 + z_{\text{cloud}})$
- 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 $\delta = \rho/\bar{\rho} - 1$

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

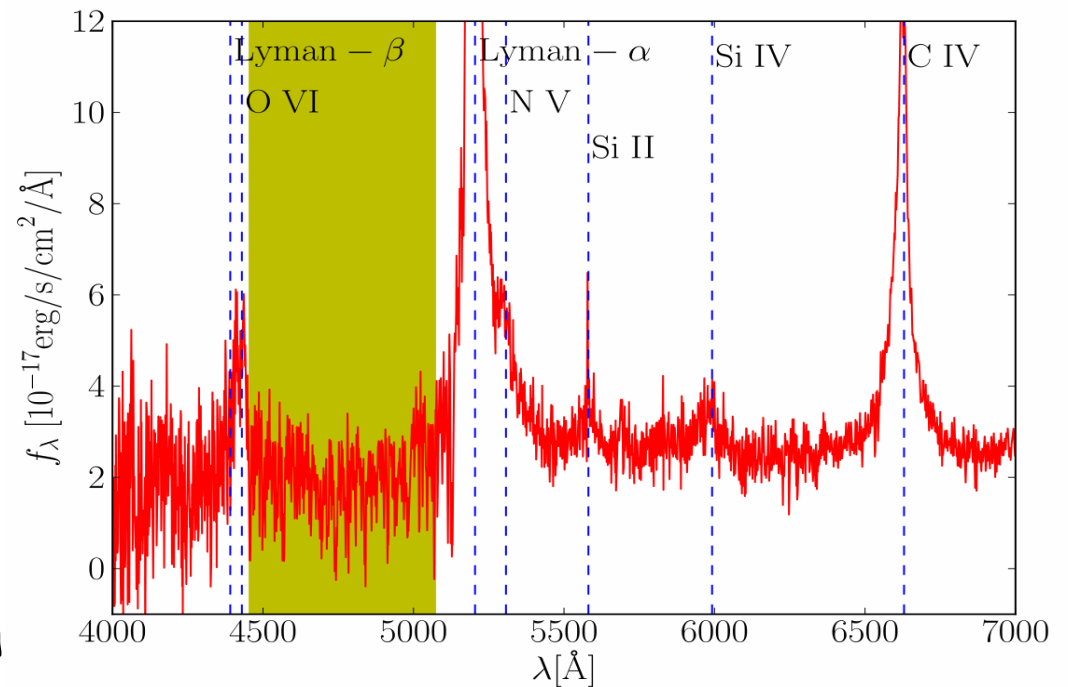
$$\bar{F} \propto e^{-\tau(z)}$$

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

QSO Ly- α Forest

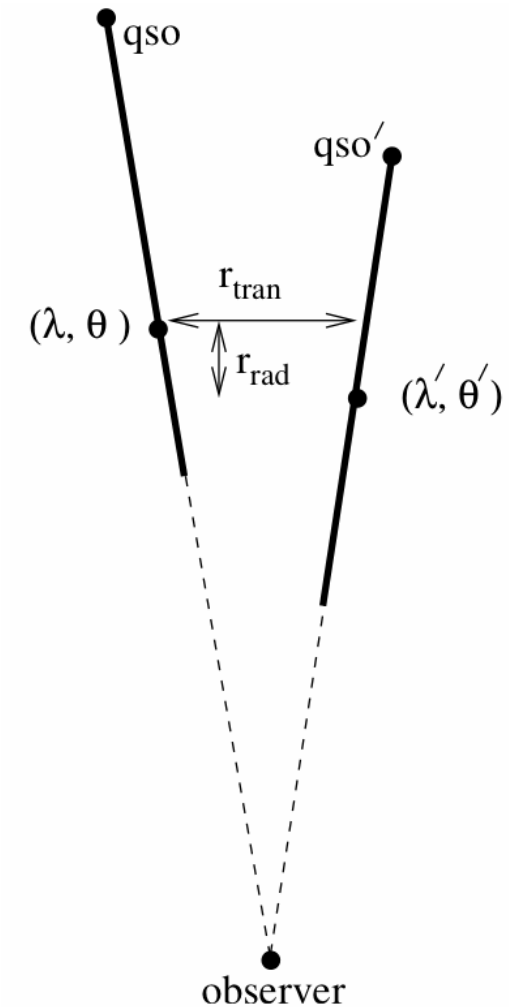
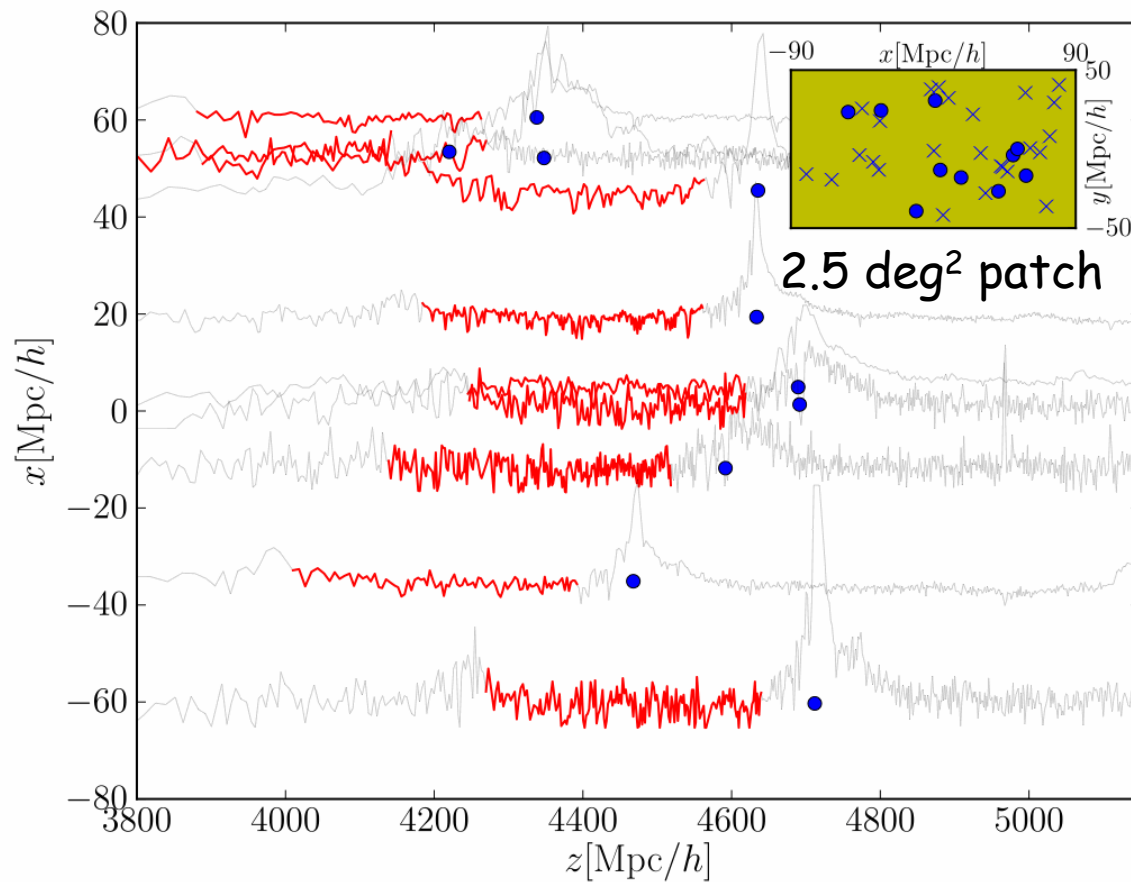
Typical BOSS QSO

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

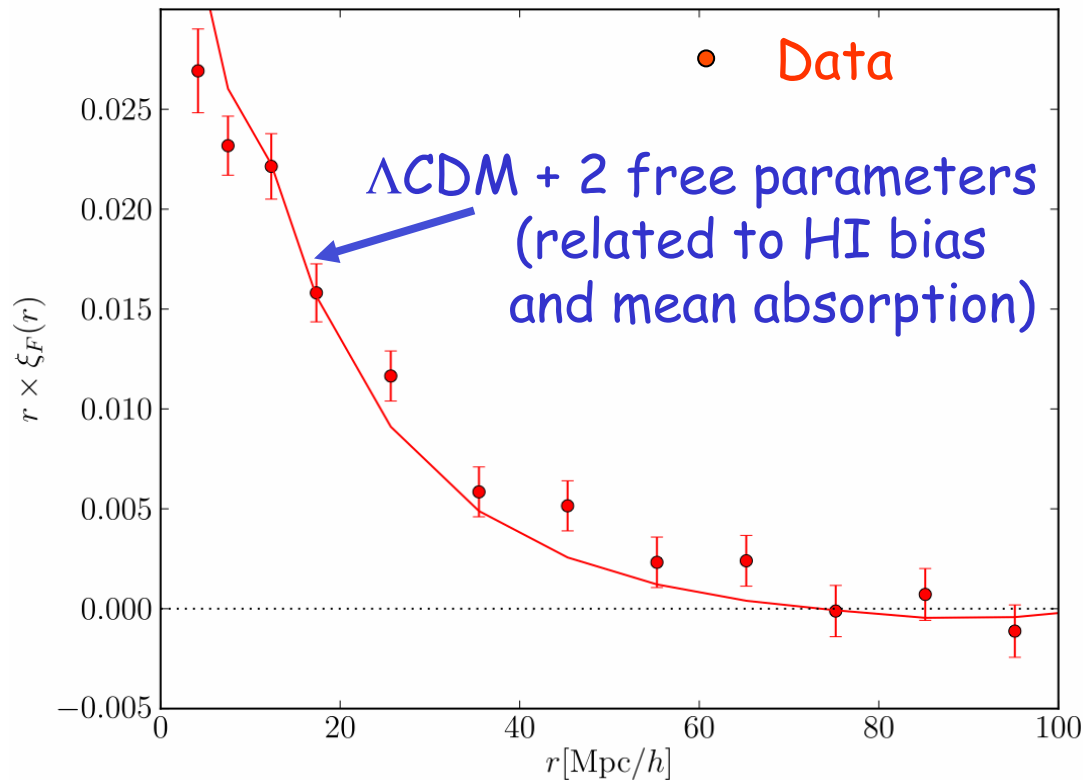


Ly- α absorption correlations

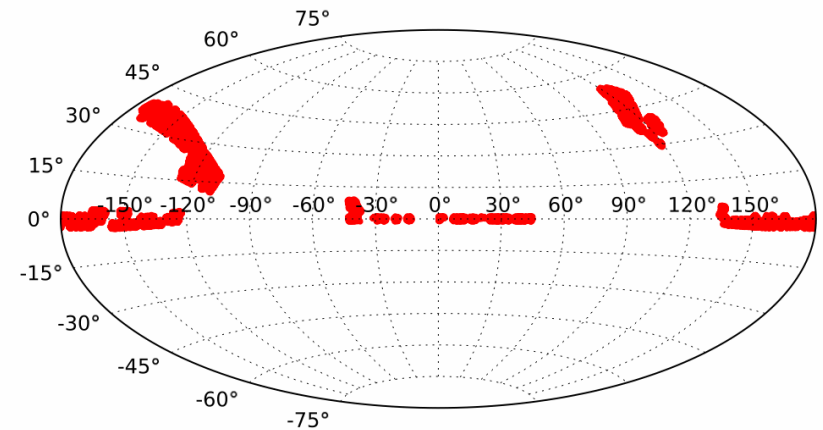
$$\xi_F(\vec{r}) = \langle \delta_F(\vec{x}) \cdot \delta_F(\vec{x} + \vec{r}) \rangle$$



Correlation Function



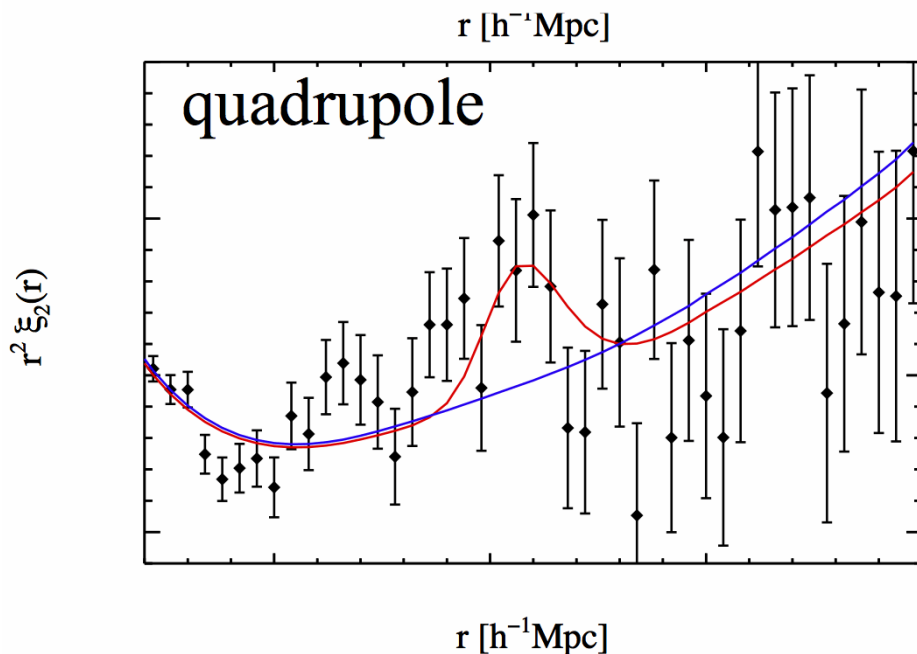
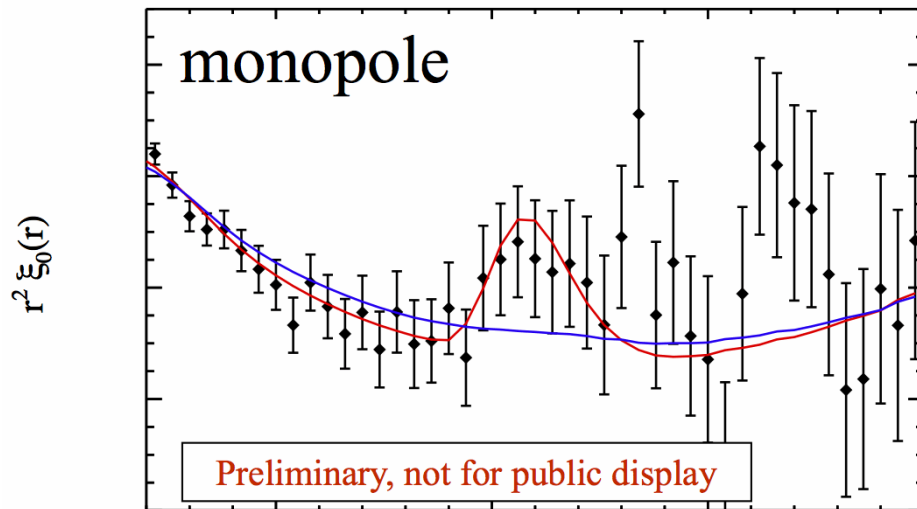
Projection over $r = |\vec{r}|$
of the 3D correlation function



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

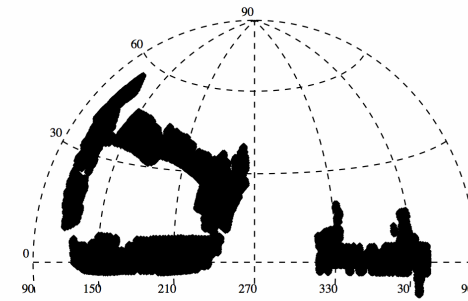
*A. Slosar et al.,
JCAP, 09 1 (2011)*

First look at BAO with Ly- α



Ch. Yèche

LAL Seminar



Data Set:

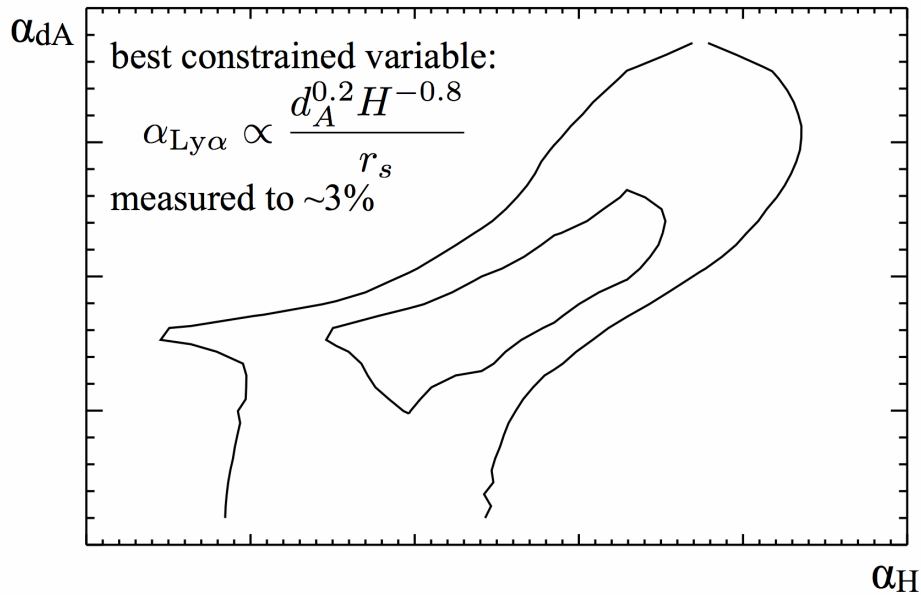
DR9: ~48000 selected QSOs
with $2.1 < z_{\text{Abs}} < 3.5$

Significance:

- Fit the amplitude of peak
 $\chi^2_{\text{peak}} = 93.4$ (84)
- Fix the peak amplitude to zero
 $\chi^2_{\text{no peak}} = 111.7$ (85)
- Local significance
 $\Delta\chi^2_{\text{peak}} = 18.3 \rightarrow 4.2\sigma$

Orsay, November 6, 2012

Cosmological implications

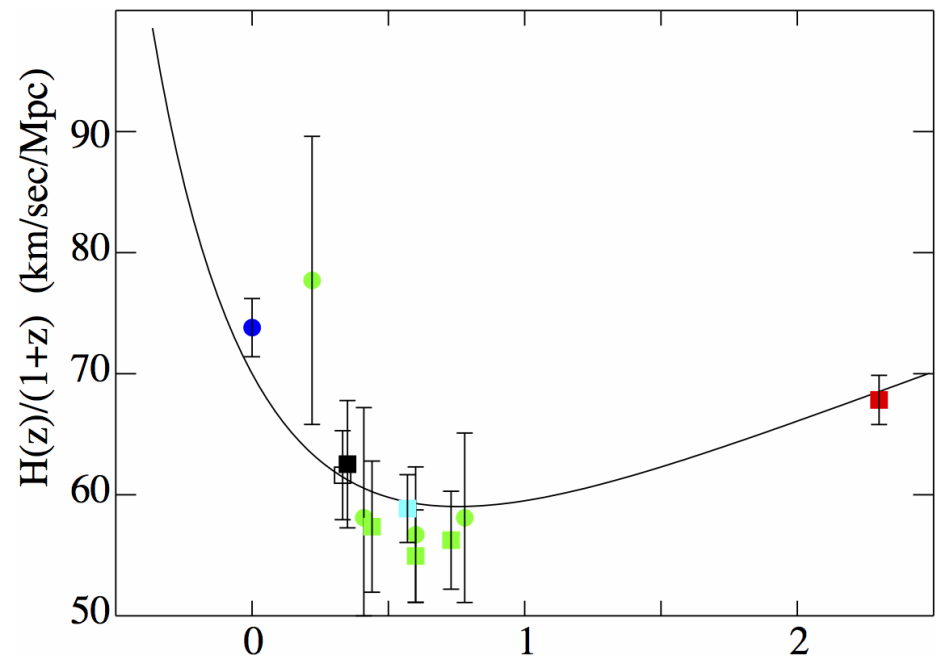


Implications

- Embargo on this result (PR on Nov. 12)!!!
- First measurement of H at $z \sim 2.3$ (11 billions of years from now)
- Deceleration of the expansion of Universe for $z > 0.8$!!!

2D Fit

- Determination of the two dilatations scales in transverse and longitudinal directions, α_{dA} and α_{H}
- α_{H} much more precisely measured

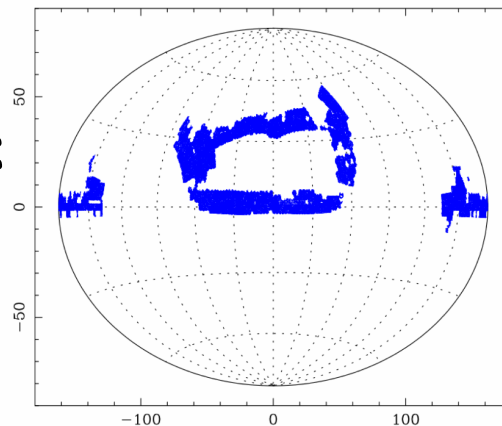


Conclusions and Prospects

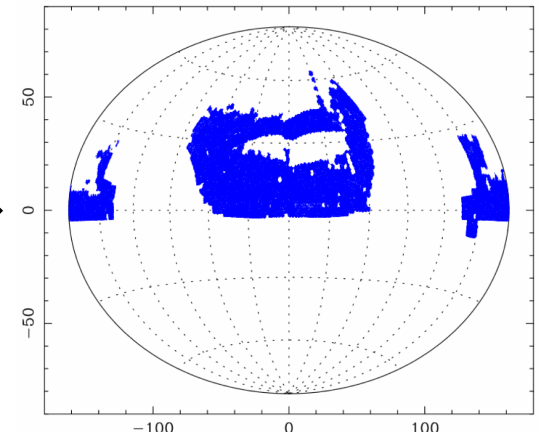
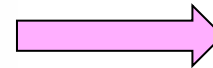
Conclusions

- 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):



LAL Seminar



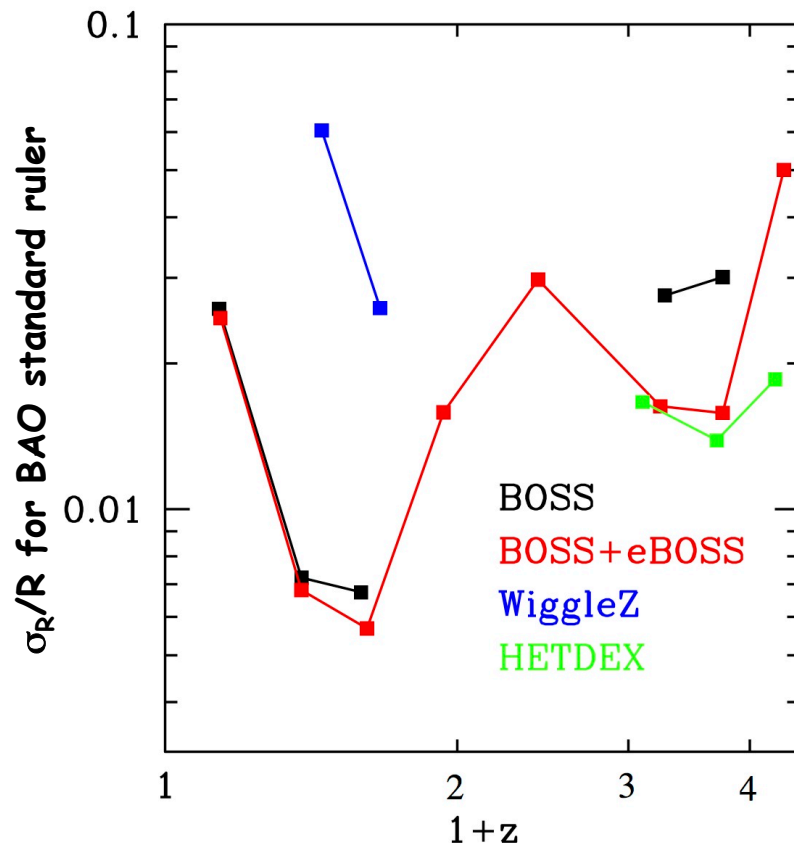
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- Emission line galaxies (stars forming)

- Tracers of cosmic structures
- LF peaks at $z \sim 1.5-2$

- $g < 22 \Rightarrow g < 22.5$
- Improvement of selection
- $\sim 15 \text{ deg}^{-2} \Rightarrow \sim 35 \text{ deg}^{-2}$

e-BOSS performances



BAO

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

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