Lyman-α Forest in 3 Dimensions with BOSS

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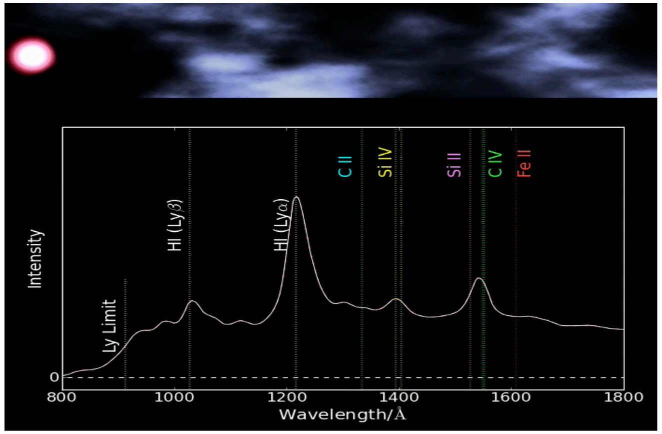

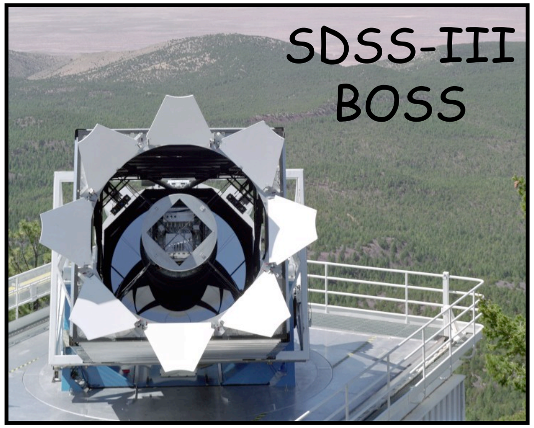

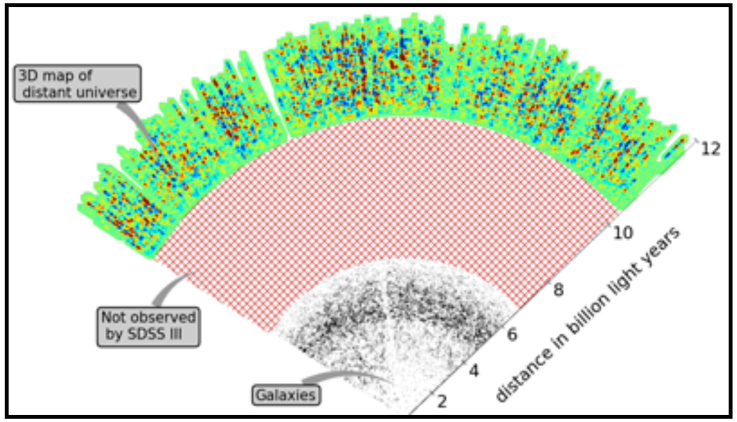

Outline:

- 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

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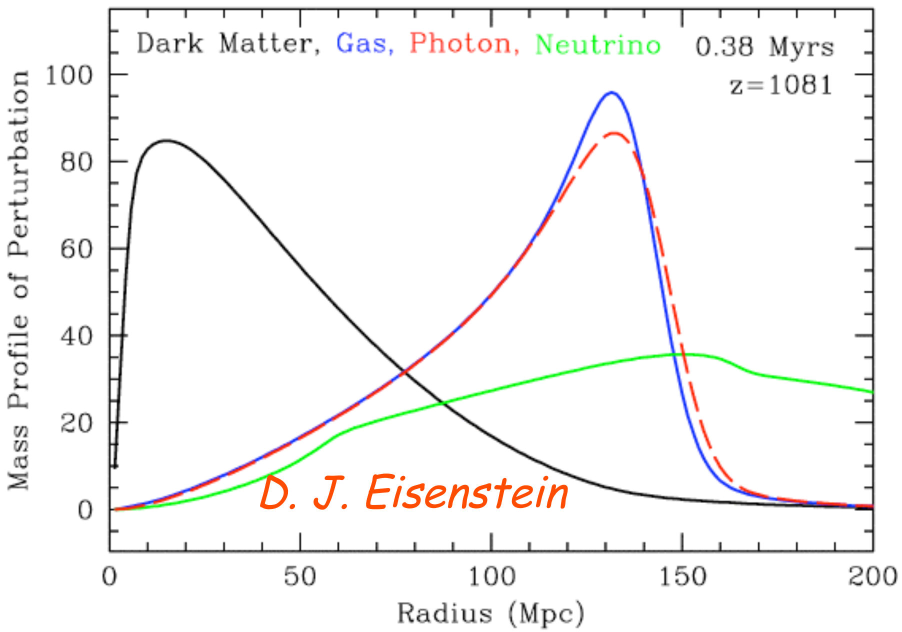
Concepts

A probe for Dark Energy: Baryonic Acoustic Oscillations



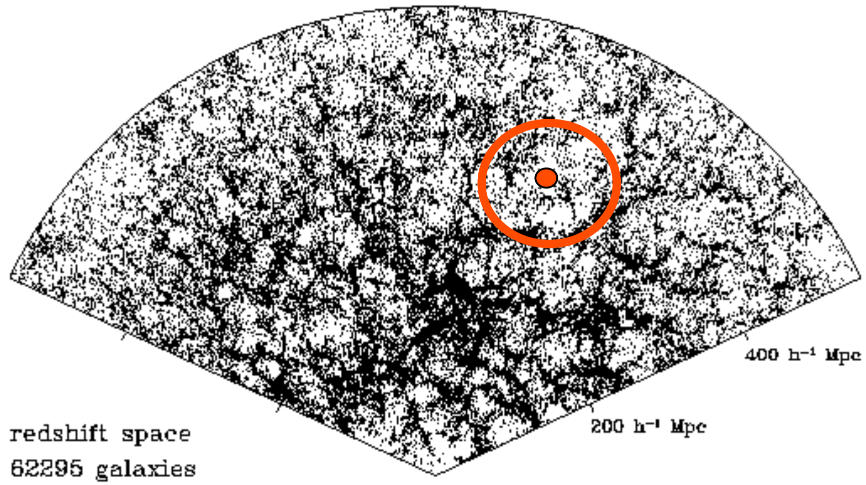
Acoustic propagation of an overdensity:

- 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.

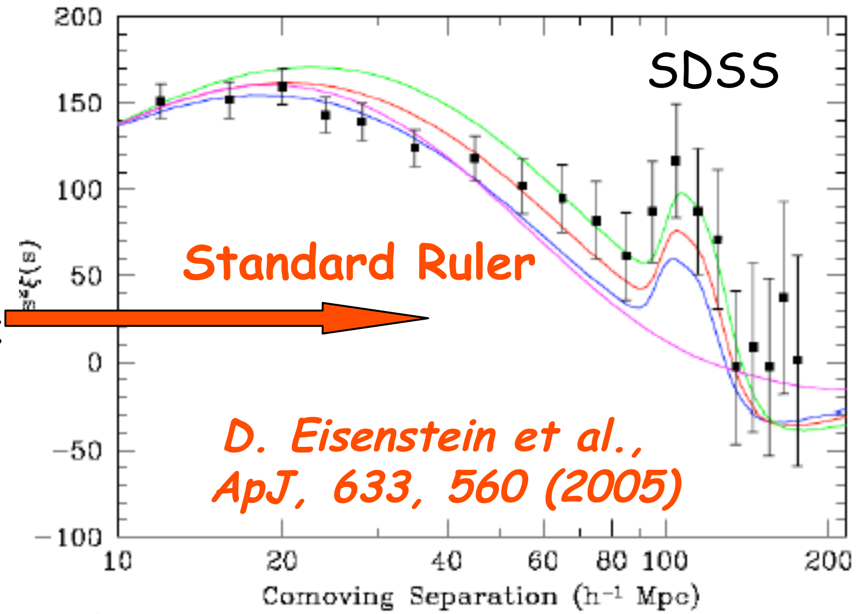
$\Rightarrow$ **Standard Ruler**

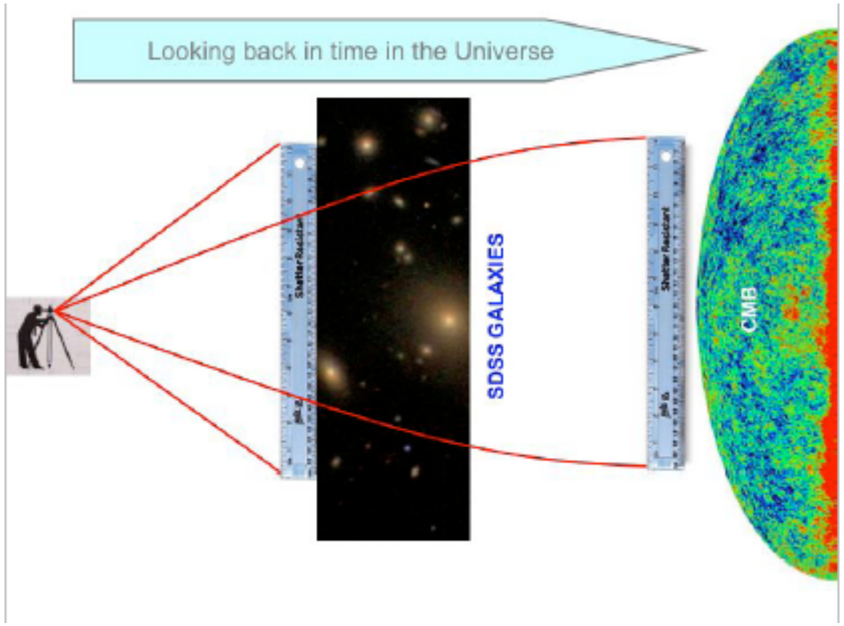


Observation of baryonic acoustic peak

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





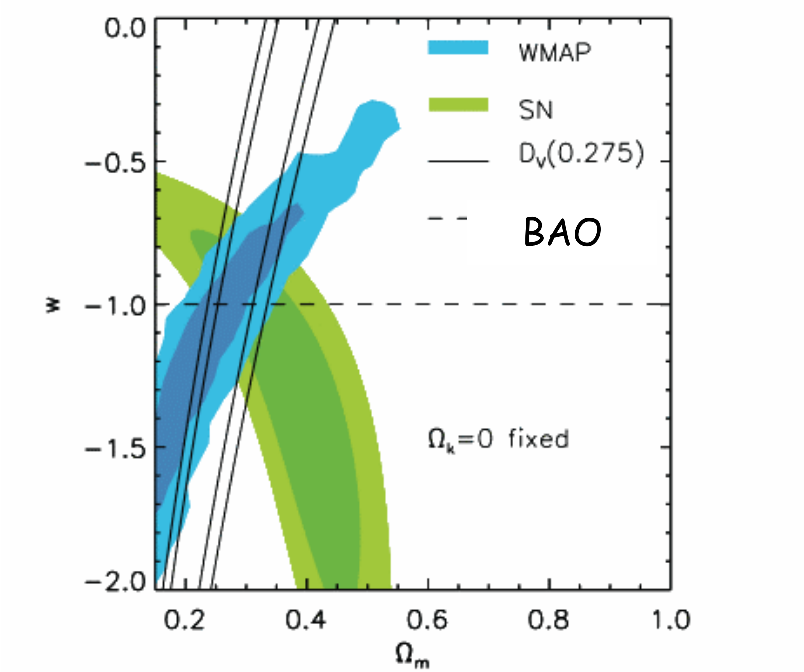
A 3D measurements:

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

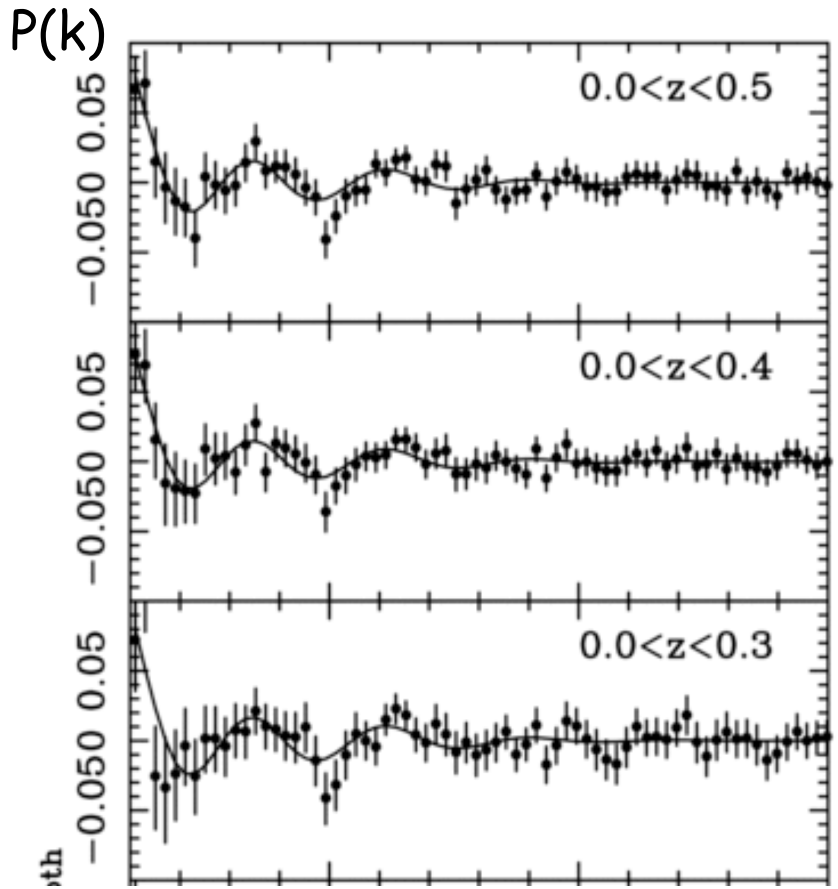
Current status of BAO

Power spectrum:

- Bump in the correlation function:
  $\Rightarrow$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)



- 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

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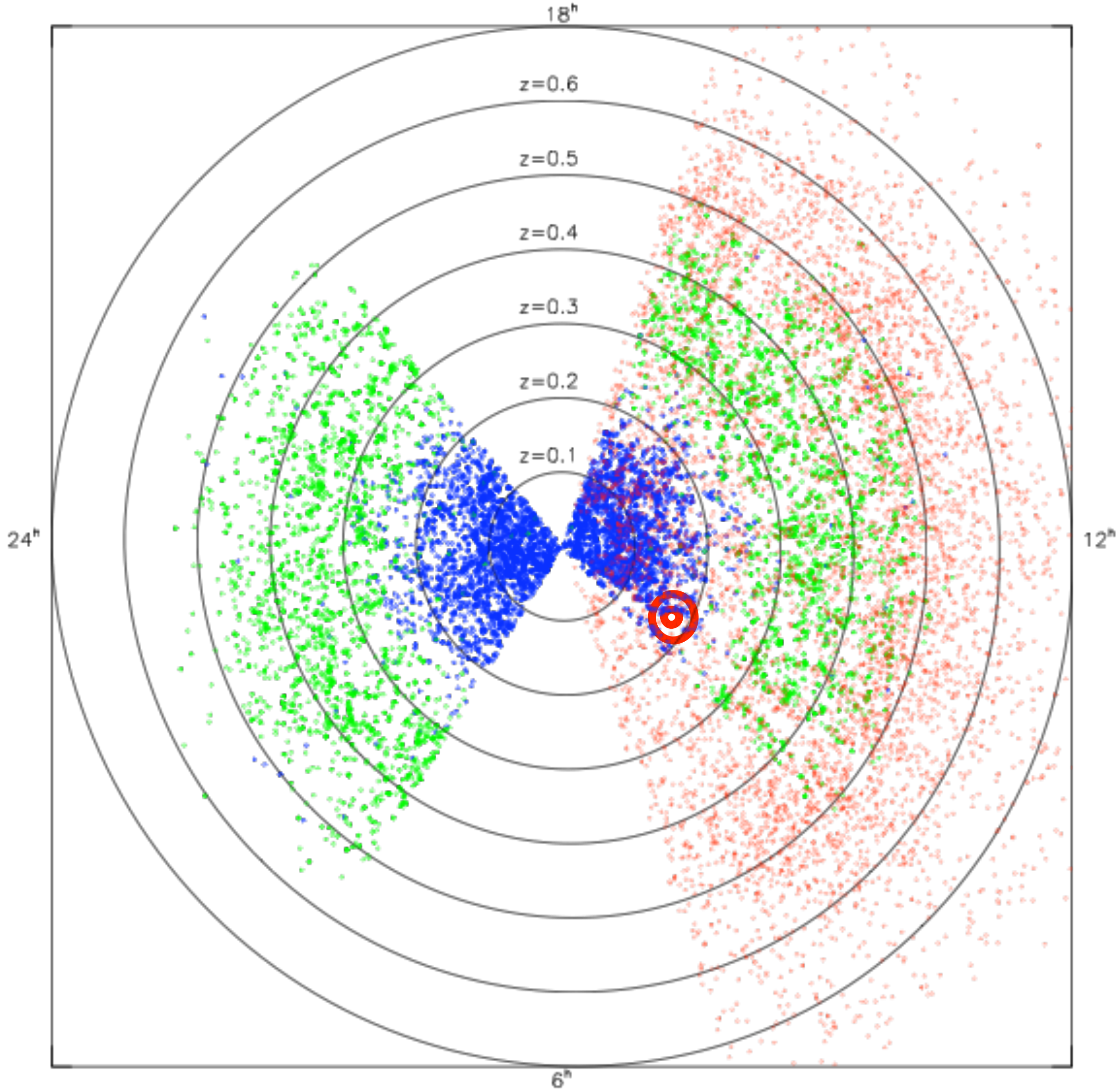
A brief overview

BOSS coverage



SDSS main galaxy survey

- ~1 million galaxies
- Too little volume for BAO

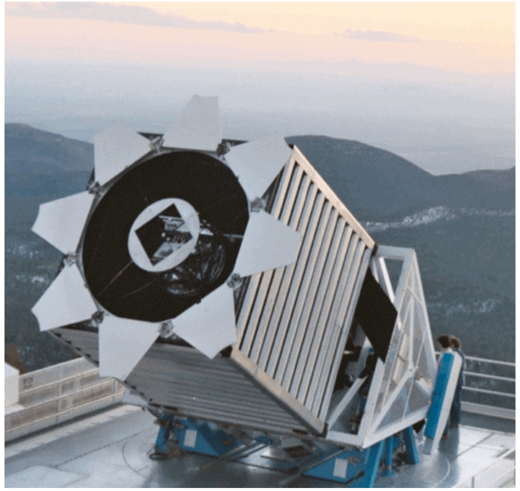
SDSS-I +SDSS-II
Luminous Red Galaxies (LRG)

- <z>~0.35
- ~ 50000 galaxies by 2004
- ~ 80000 galaxies by 2008
- 8000 deg^2 by 2008

SDSS-III - BOSS

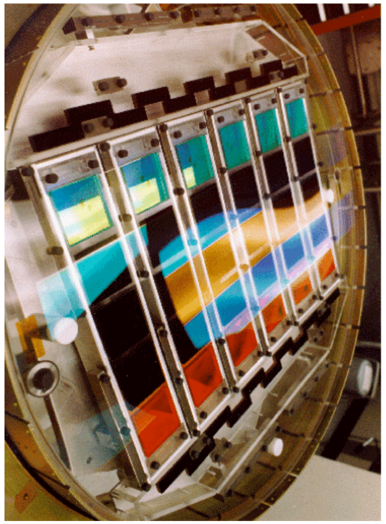
- 1.5M LRG with z up to 0.7
- 10000 deg^2
- Volume x2
- Density x5
- \+ 2.2<z<4 with Lyman-α forest of ~160000 quasars

From SDSS to SDSS-III



SDSS Consortium

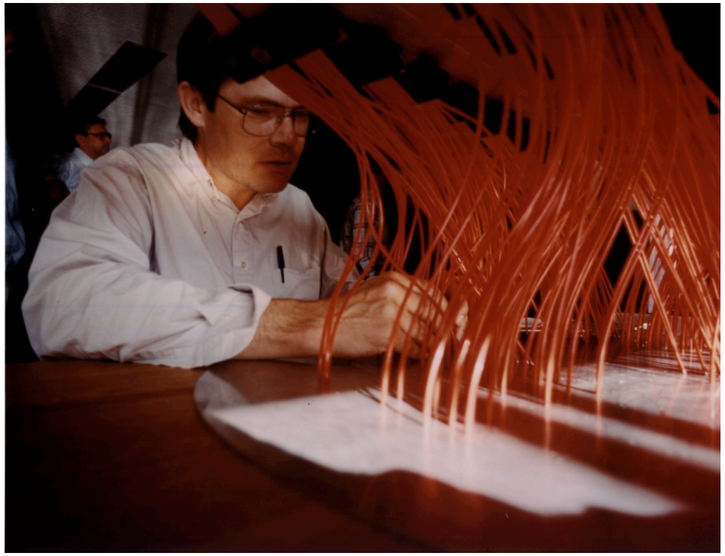
- 2.5m Sloan Telescope
- Apache Point, NM
- Wide field telescope ~ 7 deg^2
- Camera equipped with 5 filters (~120 millions pixels)



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

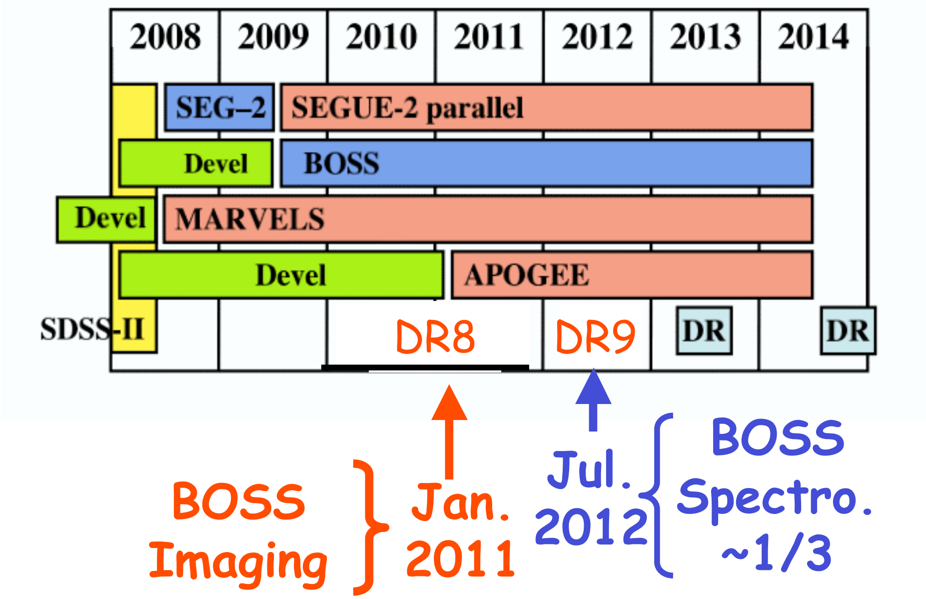


BOSS Status

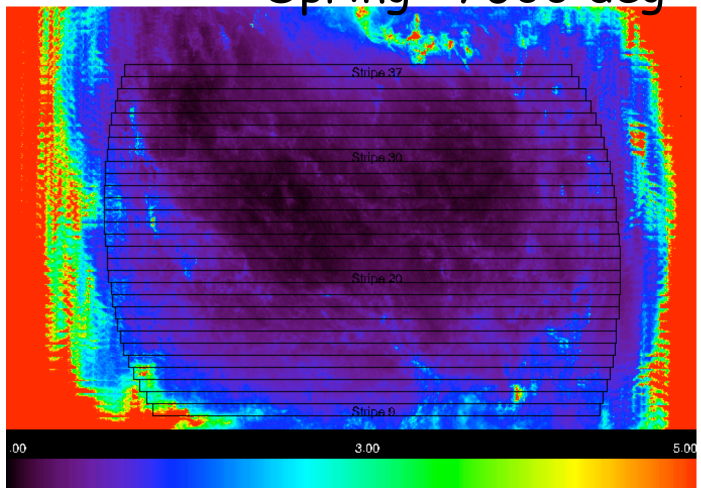
Observing plan

- 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

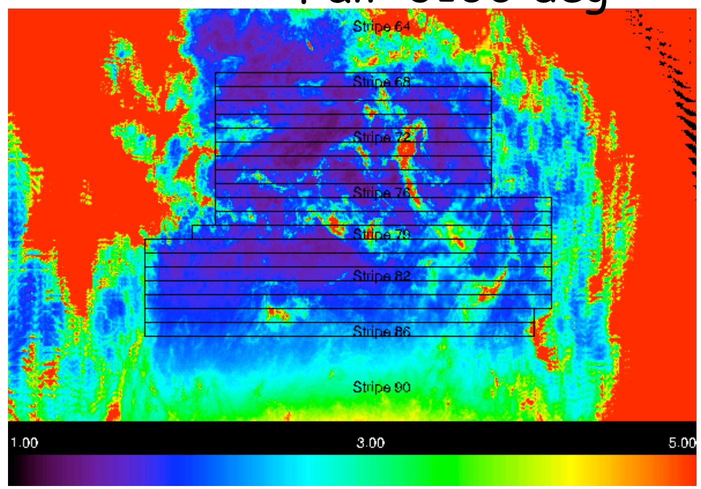
Public data releases



Spring: 7600 deg^2

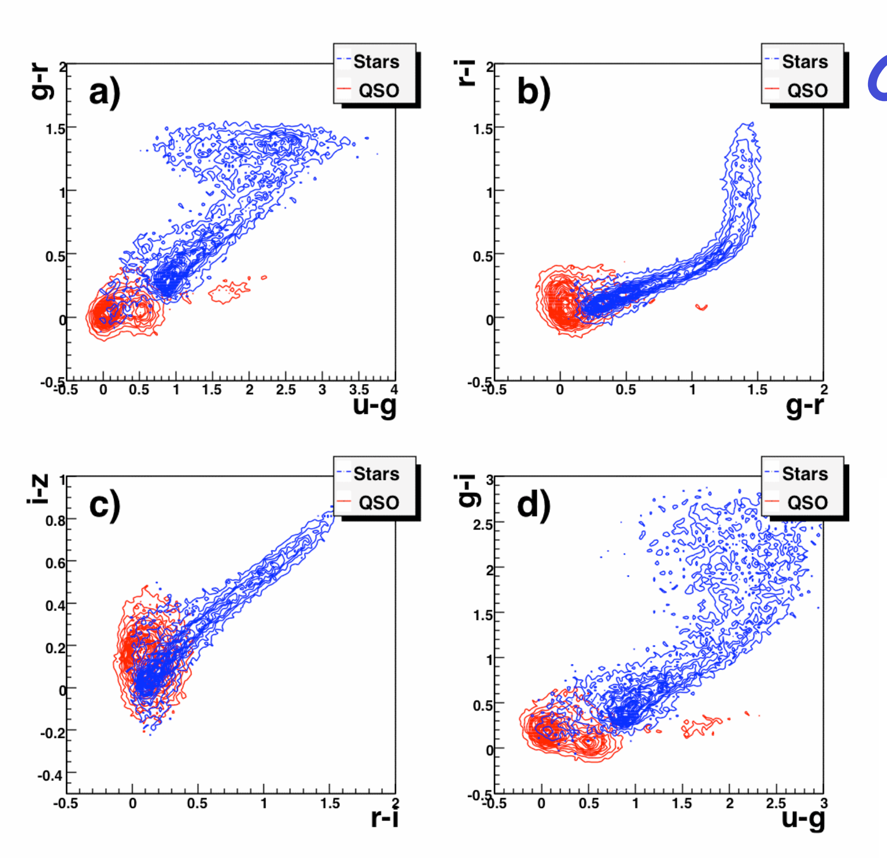


Fall: 3100 deg^2



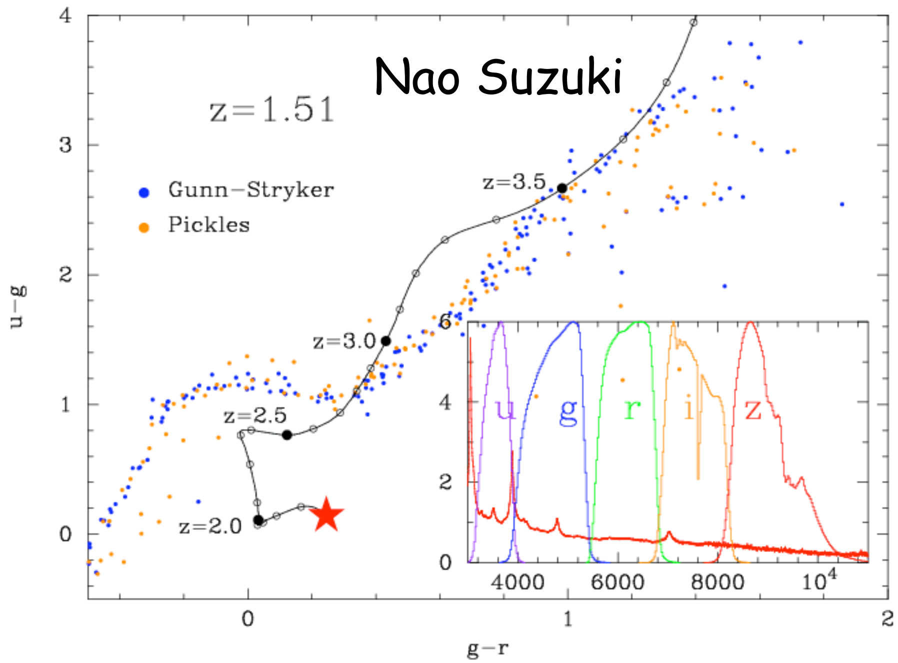
Quasar Target Selection

QSO Selection with Photometry



Challenging target selection

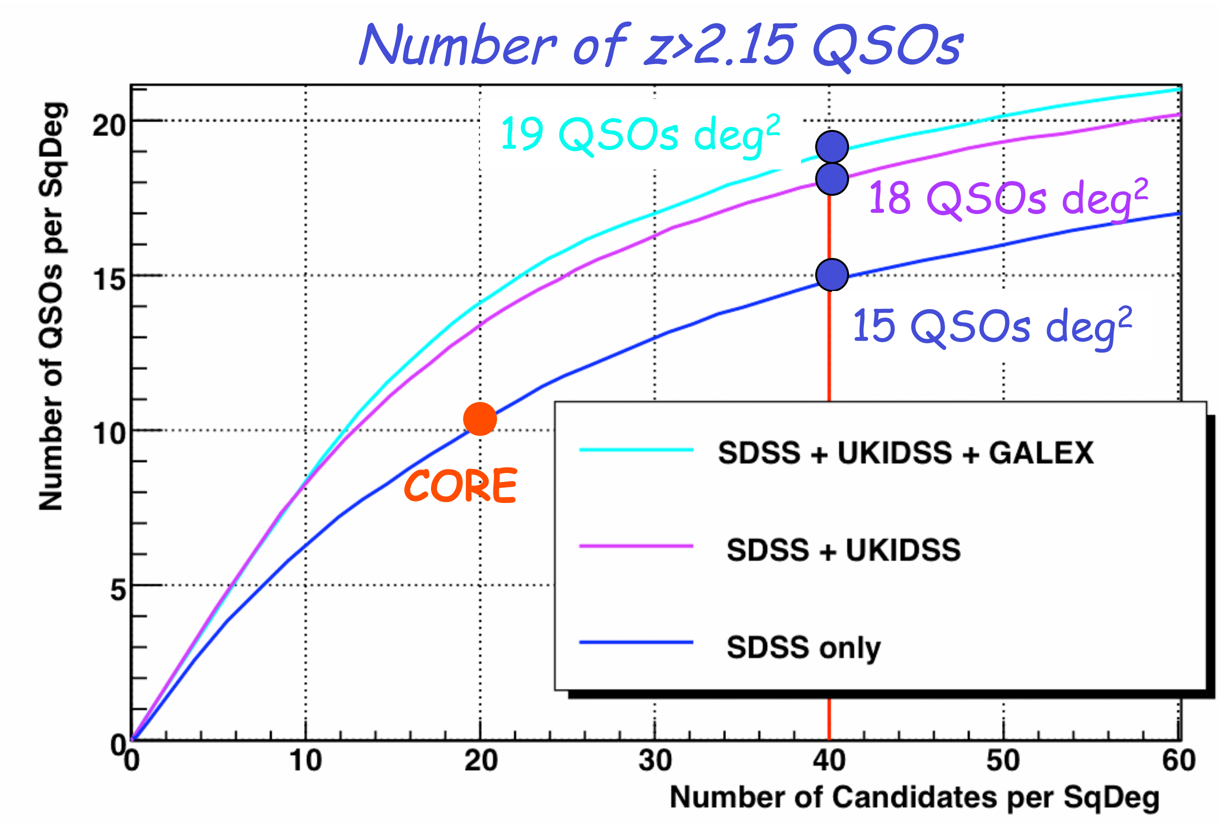
- QSOs and stars overlap: QSO with 2.2<z<3.5 are in the stellar locus
- Many more stars than QSOs (x 200-500), worse at the edge of Galaxy
- At z=2.4/3.3 Ly-α emission line falls between two band filters



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

Ch. Yèche et al., A&A 523, A14 (2010)

BOSS: Selection of Ly-α QSO Using Photometry

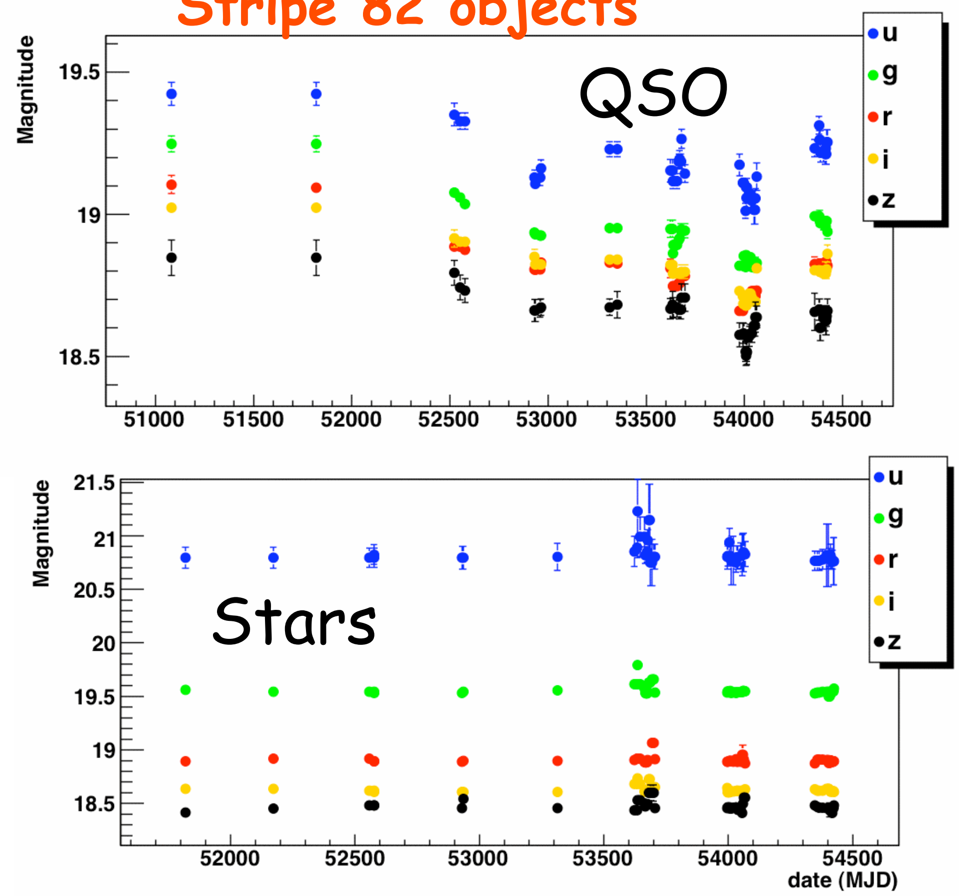


N. Ross et al., arXiv:1105.0606 (2011)

- 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



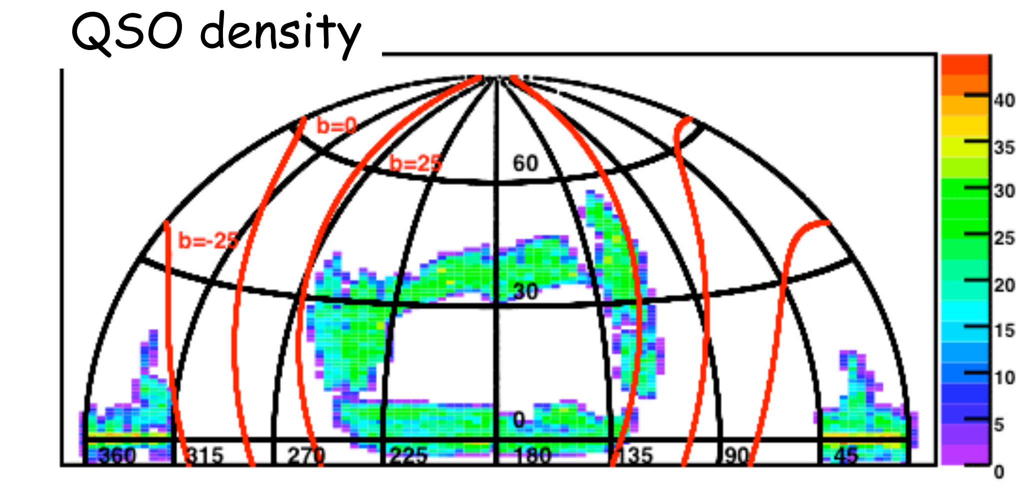
N. Palanque-Delabrouille et al., A&A 530, A122 (2011)

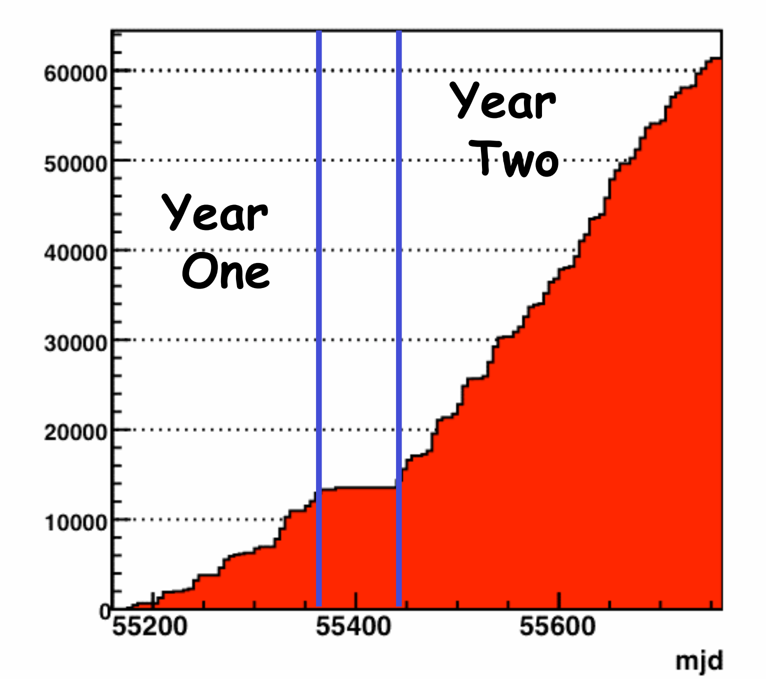
- Intrinsic variability of QSOs (~90-95% of QSOs)
- QSO variability:
Long period (~ few years)
- Possible background: variables stars, RR -Lyrae (tens of days)

- 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)

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

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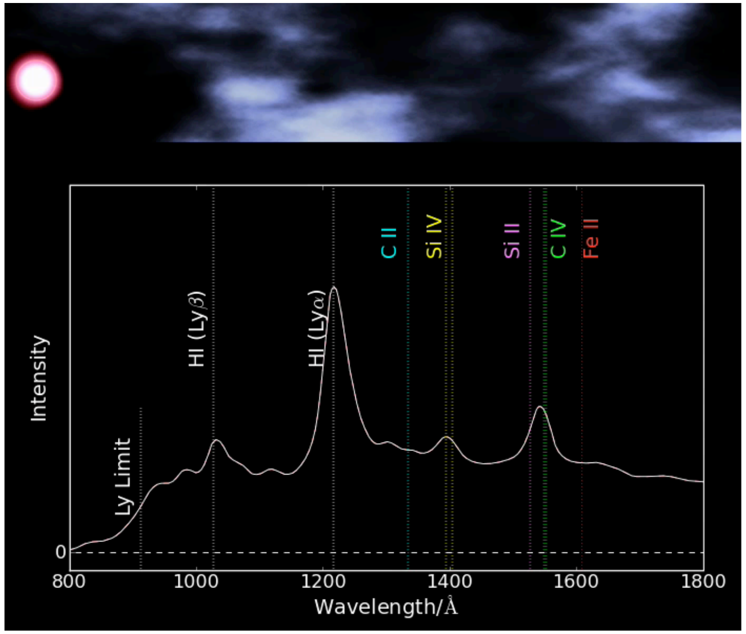
3D mapping of HI

A. Slosar et al.,
arXiv:1104.5244 (2011)

Ly-α forests for BAO



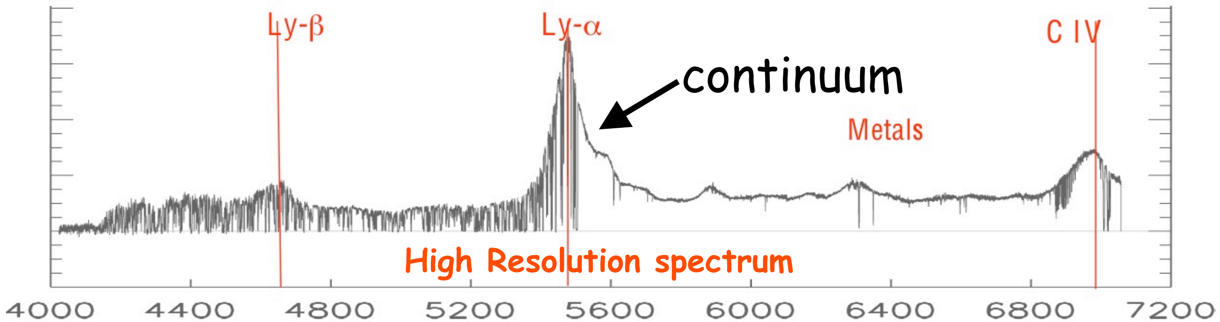
Principles

- 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 and N-body simulations…)

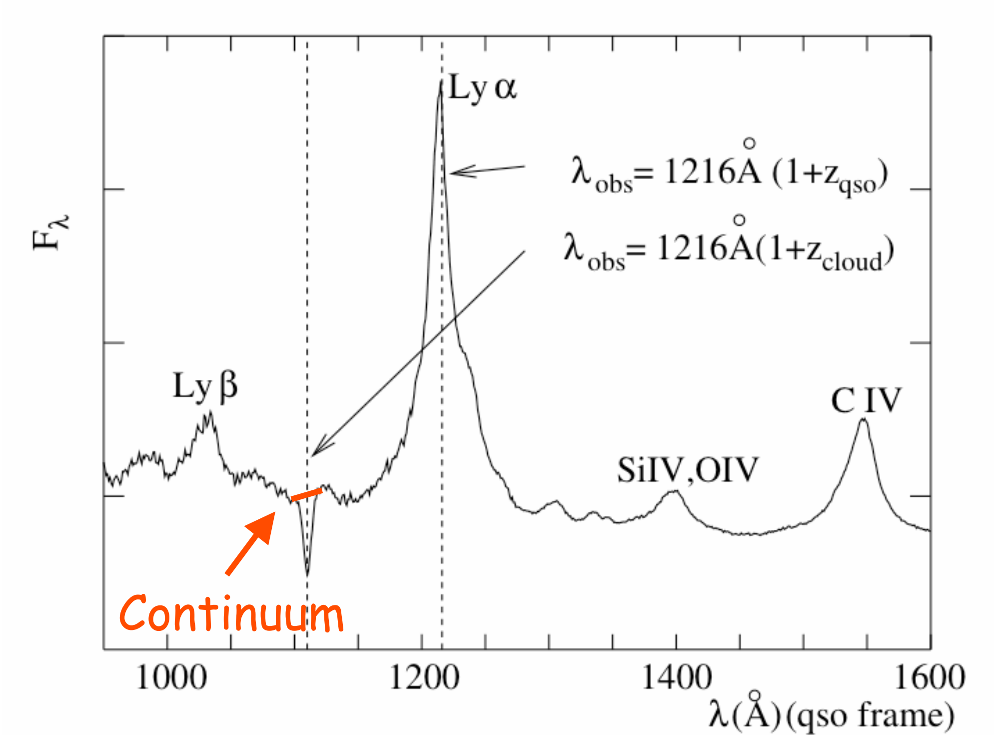
BAO specifications:

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

z~3.6 Quasar



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**

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

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

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

Flux definition

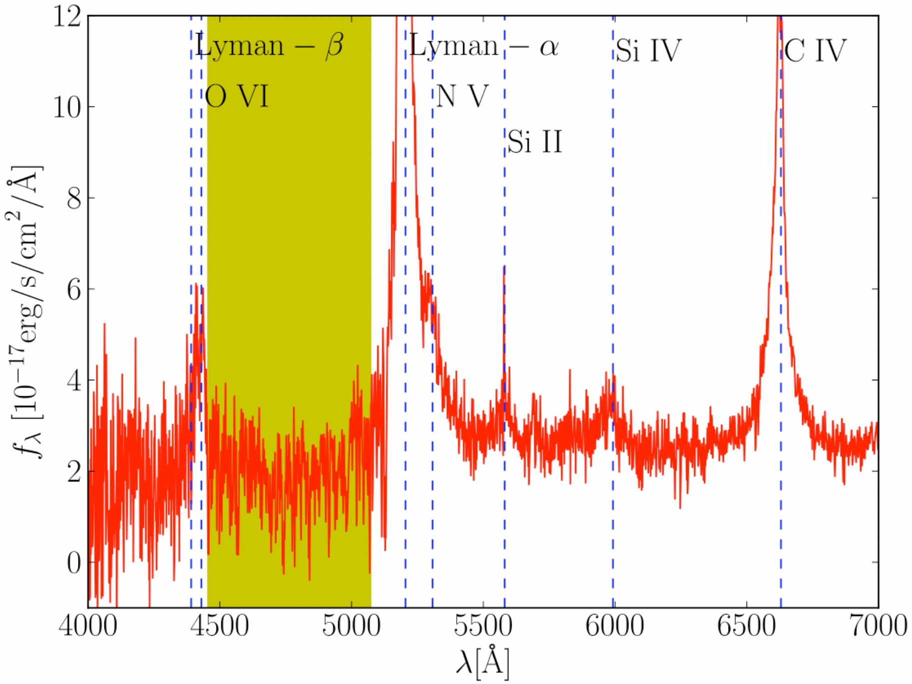
- Transmitted Flux Fraction F: Flux/Continuum 0<F<1:
- The power spectrum of the δ_F has the same shape as the power spectrum of matter density $\delta = \rho/\overline{\rho} - 1$

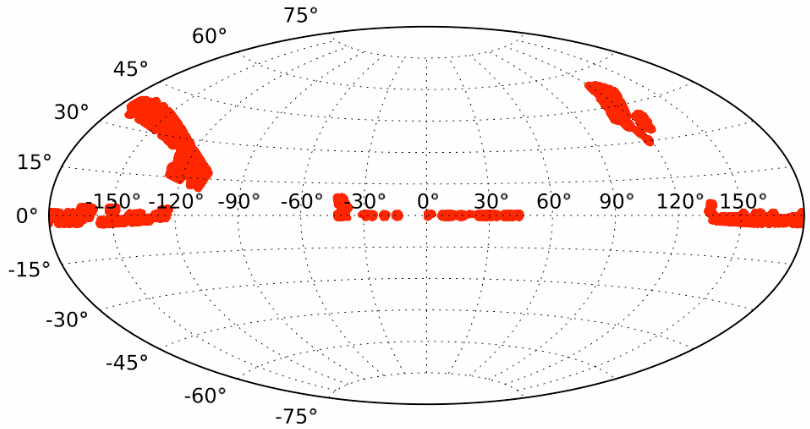
QSO Ly-α Forest

A. Slosar et al., arXiv:1104.5244 (2011)

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



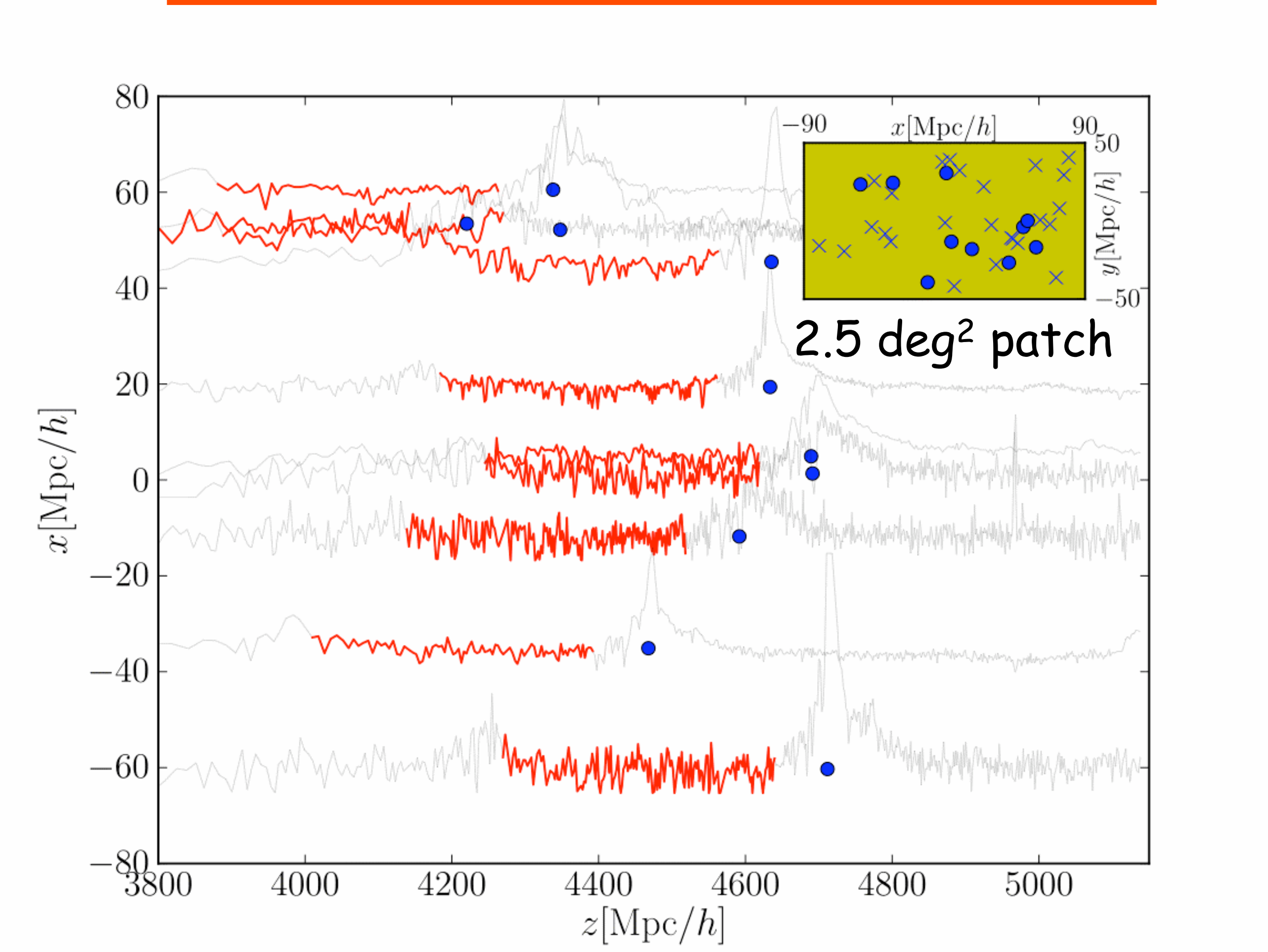


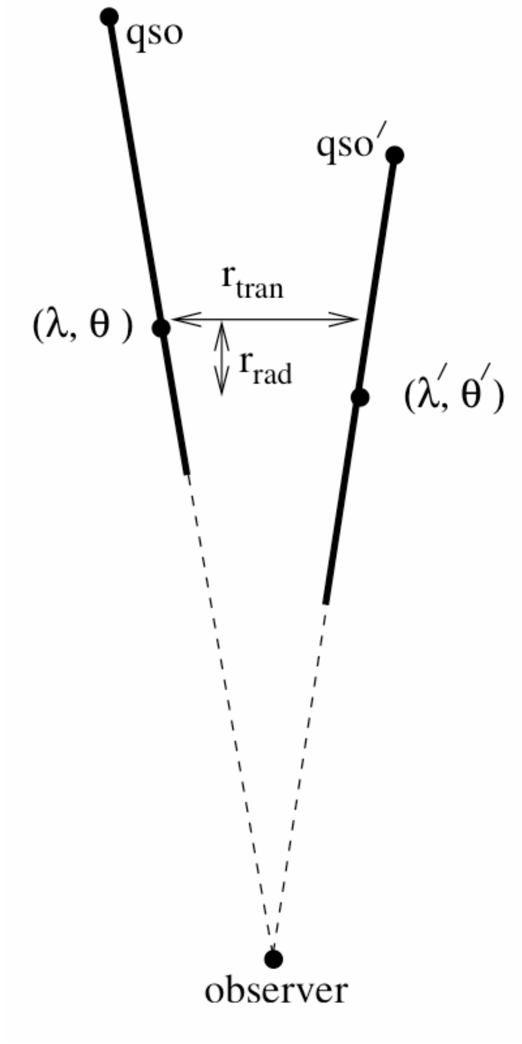
Data Set

- Year one : 14000 QSOs,z>2.15
- Demonstration of the method
- Correlation function for r<100Mpc/h (below BAO scale)

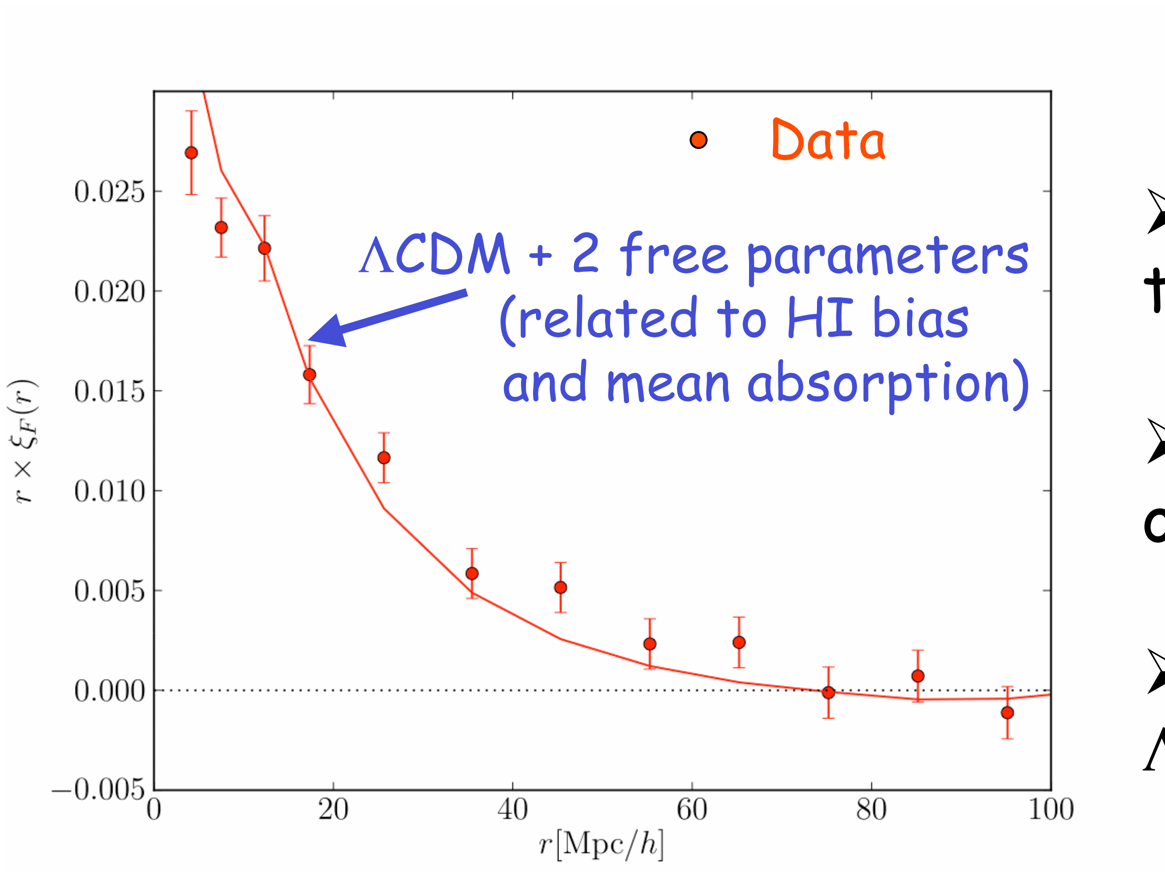
Ly-α absorption correlations

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





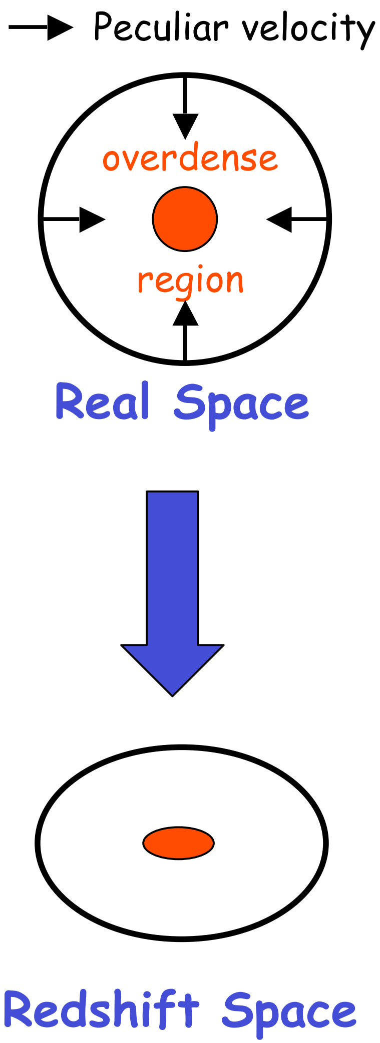
Correlation Function



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

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

Large-scale Redshift Distortions



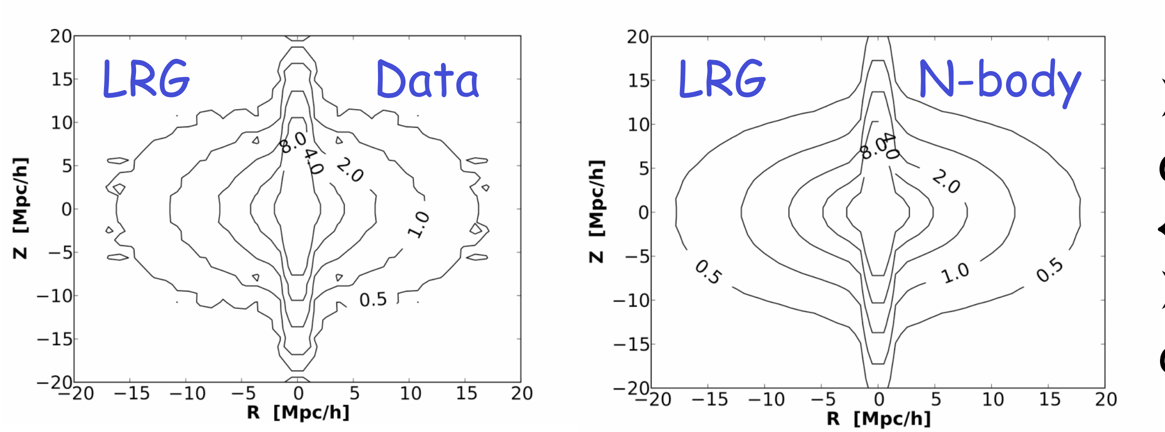
- Acceleration toward overdense regions
- Flattening in radial direction from real space to redshift space (over tens Mpc)
- Measurable with Kaiser formula

N. Kaiser
MNRAS 227, 1 (1987)

$$\boxed{\begin{aligned} P_F\left(\vec{k}\right) &= P_F\left(k, \cos(\theta)\right) \\ &= b^2 P_L(k)\cdot(1+\beta\cos(\theta)^2)^2 \end{aligned}}$$

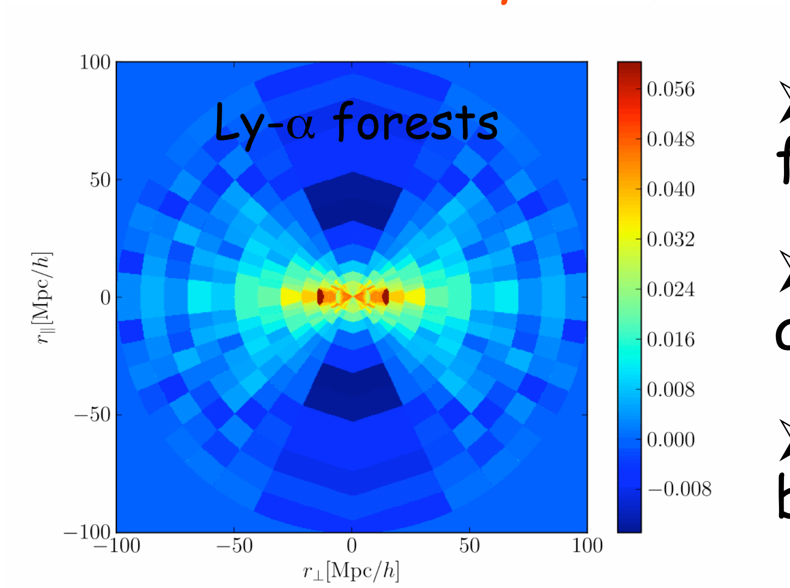
- $P_L(k)$ linear power spectrum
- θ angle between vector k and QSO line of sight

Large-scale Redshift Distortions



M. White et al.,
ApJ 728, 126 (2011)

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

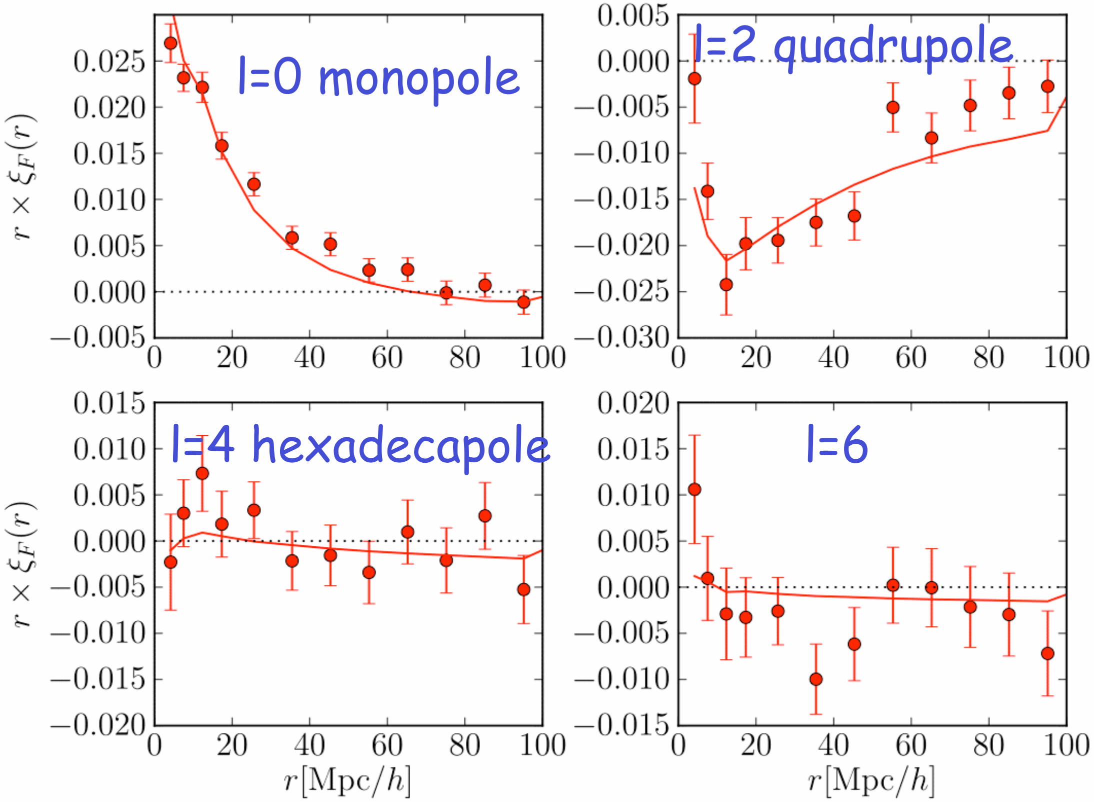


- Flattening of (r_{tran},r_{rad}) correlation function distribution
- First observation of redshift distortion at z~2.5
- Distortion are quantitatively measured by multi-poles decomposition

Correlation Function (multi-poles)

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

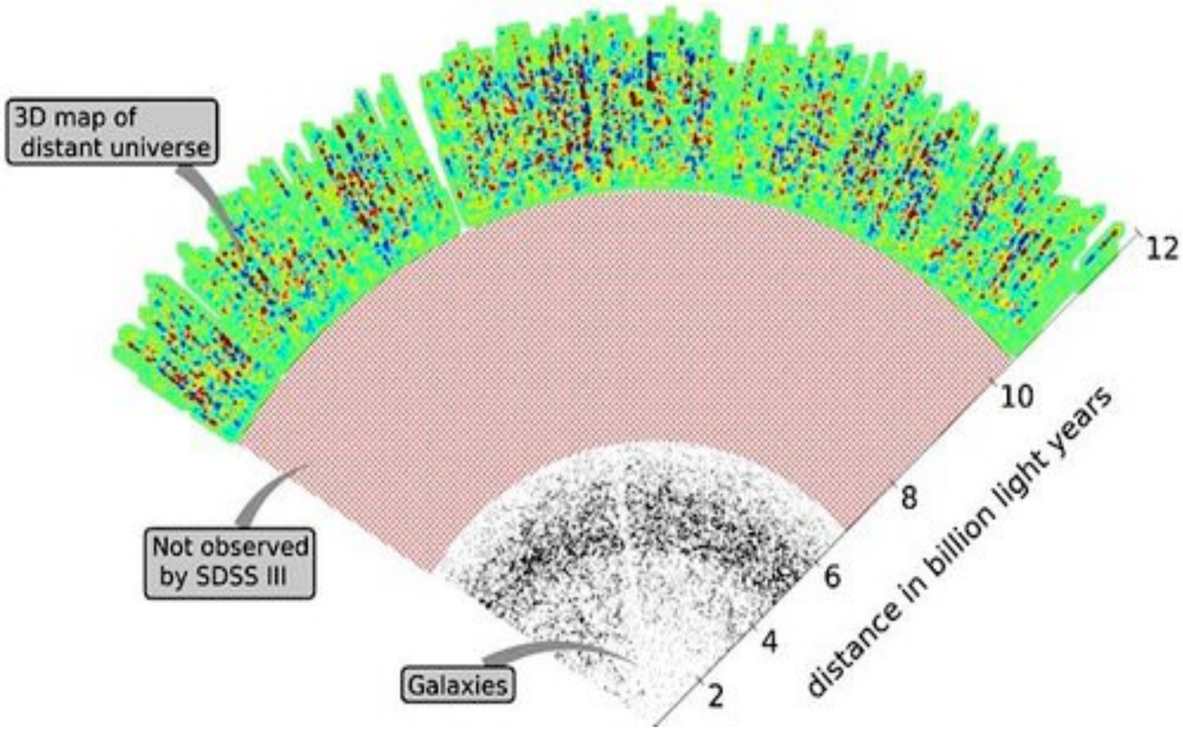
P_l : Legendre polynomials



- Negative quadrupole as predicted by GR
- Gravity works at z~2.5
- Gravity is forming structures at z~2.5
- Results consistent with ΛCDM simulations

Conclusions and Prospects

Largest 3-D map of the Distant Universe

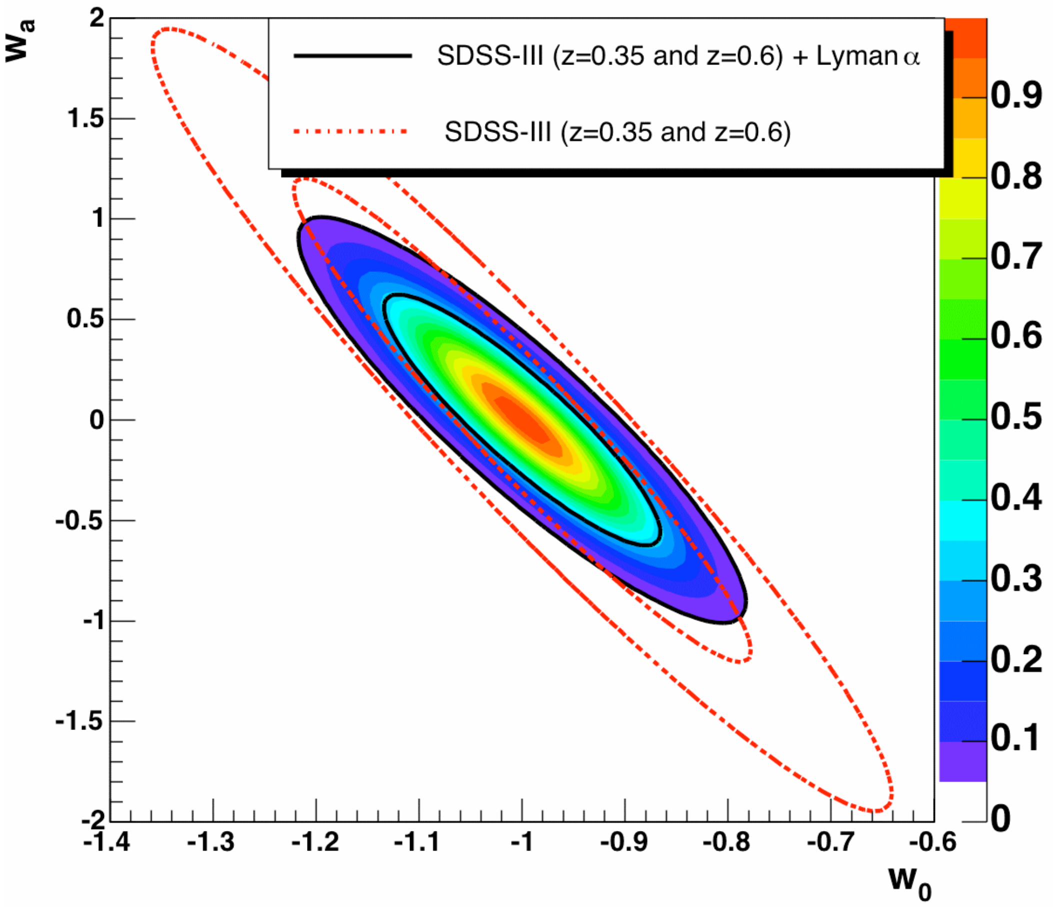


A slice through the 3-D map of the universe

- 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

BAO with BOSS

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



- 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~0.35
  1.1% at z~0.6
- With Ly-α forests: ~150k QSOs
  BAO scale: 1.7% at z~2.5