Measuring the 3D Universe with the Lyα forest

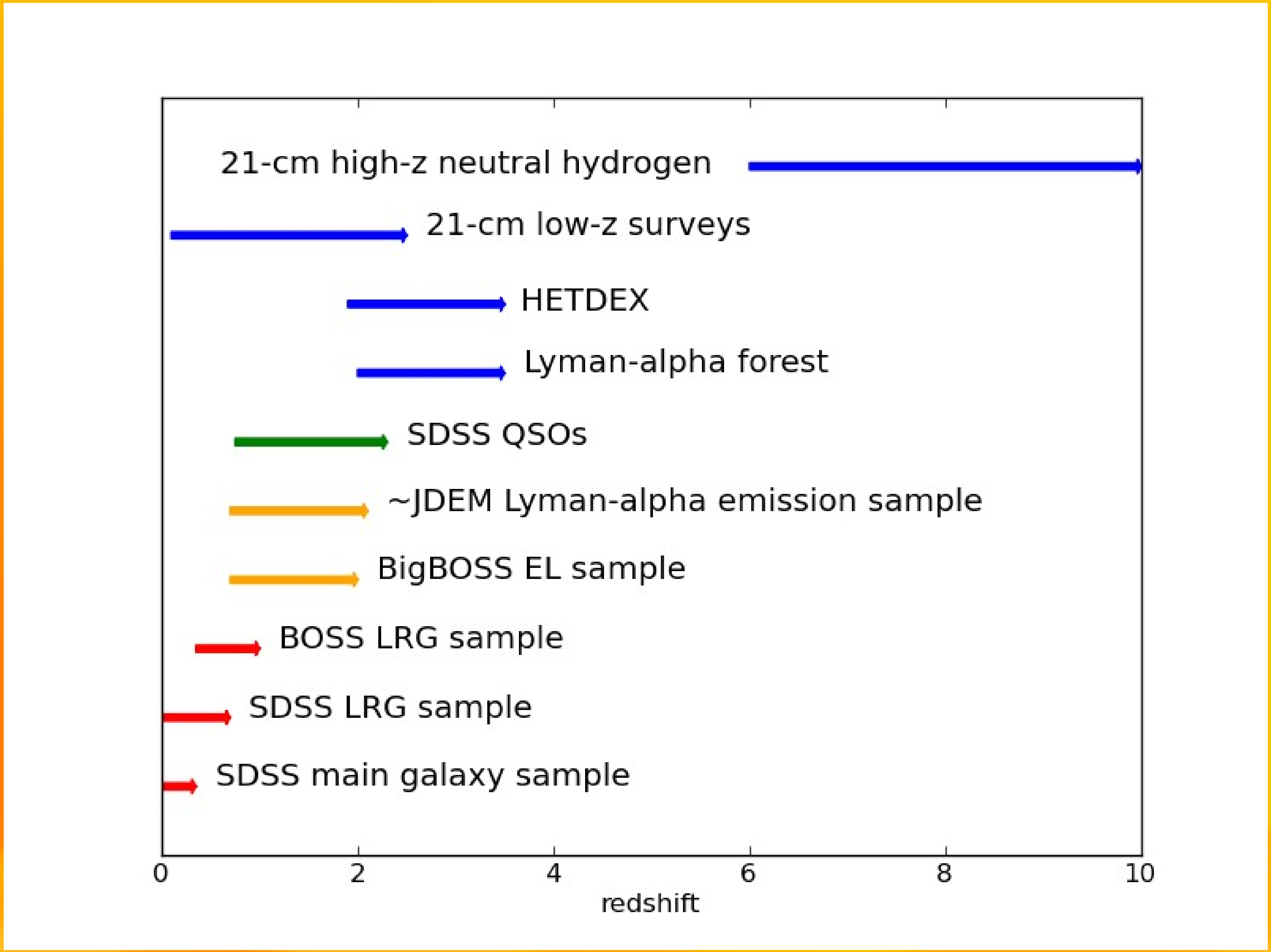
Fermilab, Jan 2011

Anže Slosar, BNL

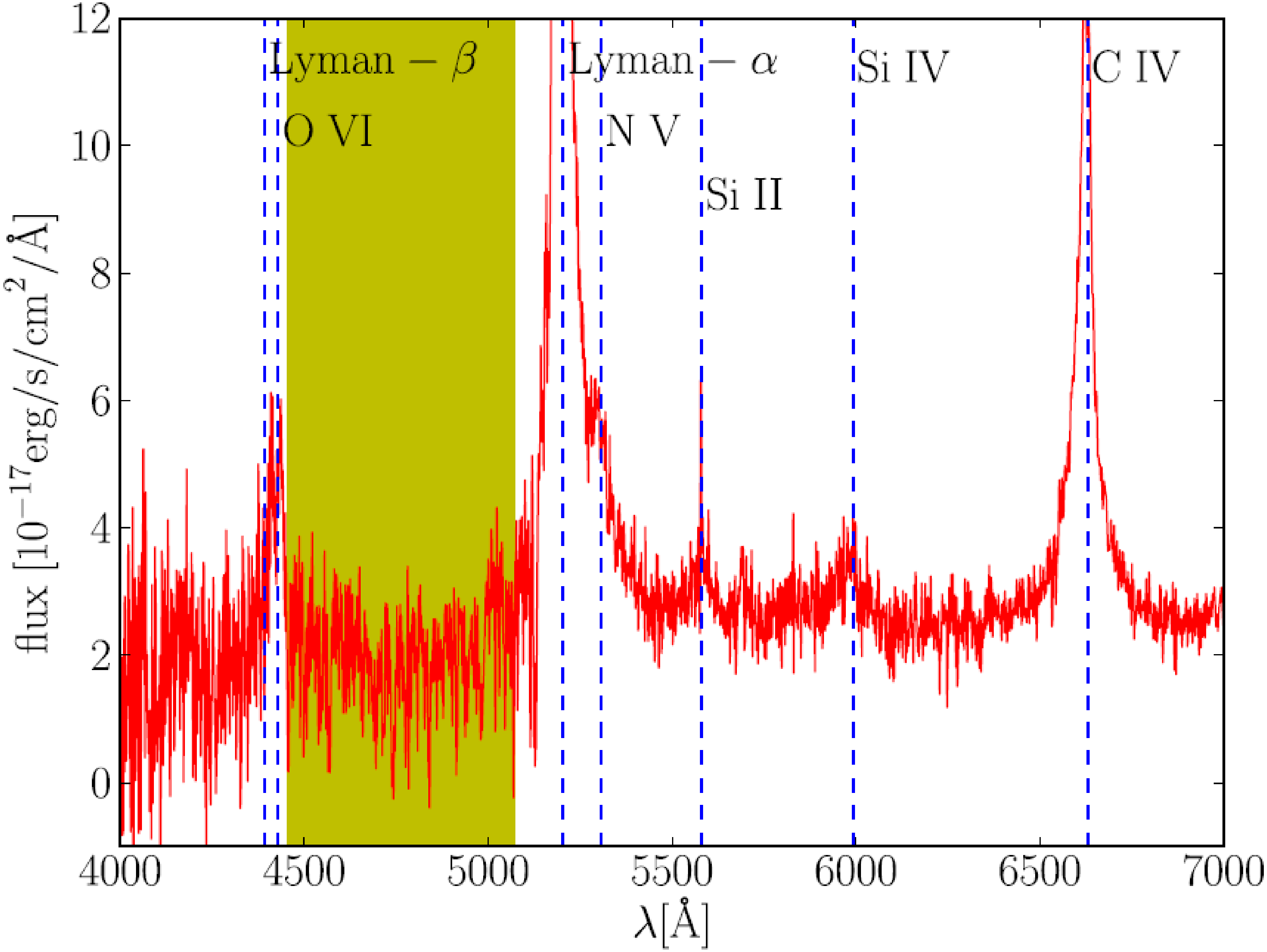
Measurements in Cosmology

- Majority of measurements in cosmology are either:
  - Measurements of background evolution (e.g. SN, cepheids, etc.)
  - Measurements of fluctuations and their evolution – power spectrum of something
- Combinations of these measurements very powerful: can probe general relativity, neutrino masses, inflationary physics, hints at microscopic structure of the dark matter / dark energy
- To do it, you really need to measure structure in the Universe over the widest possible range of redshifts.

Measuring density fields

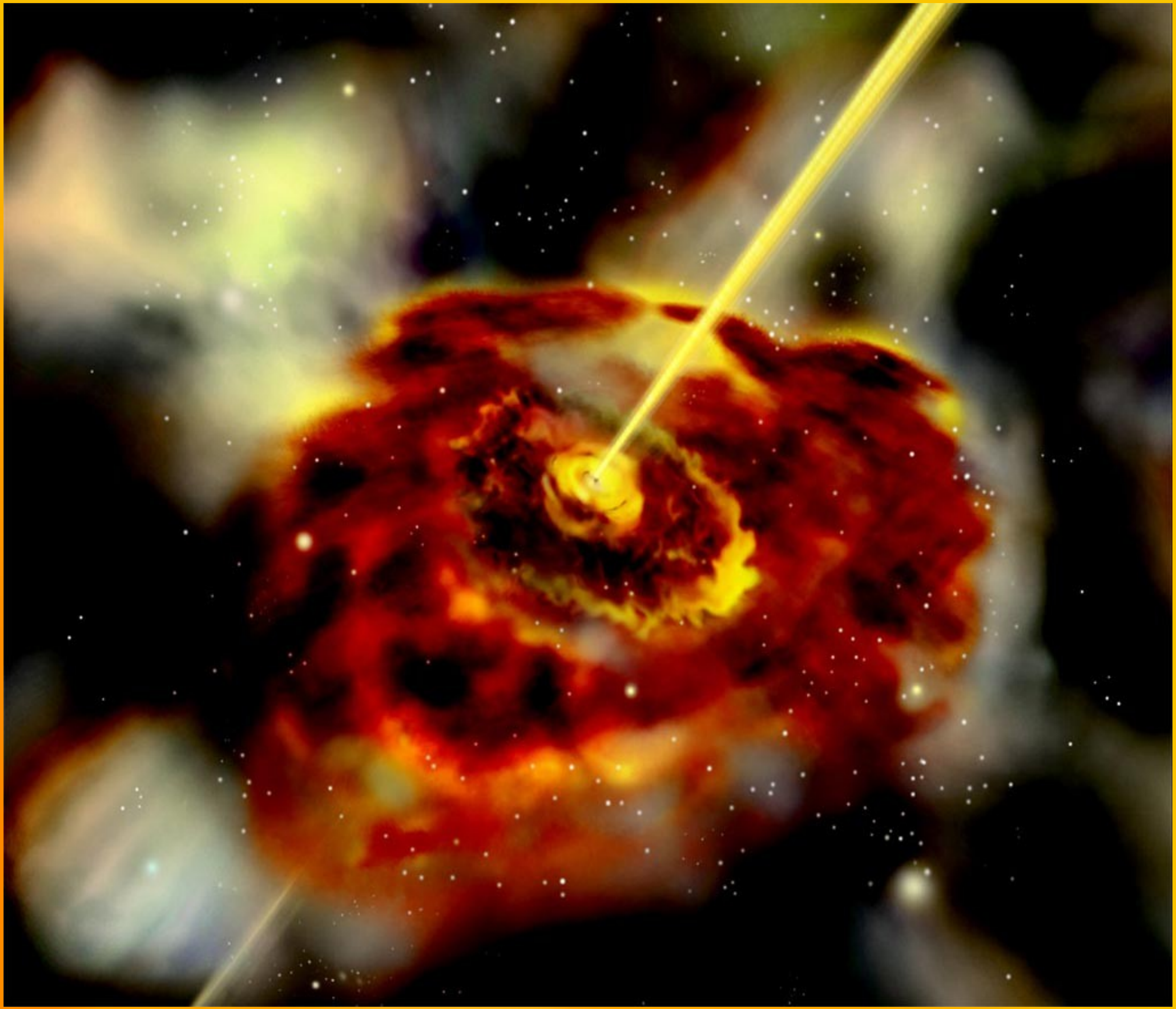


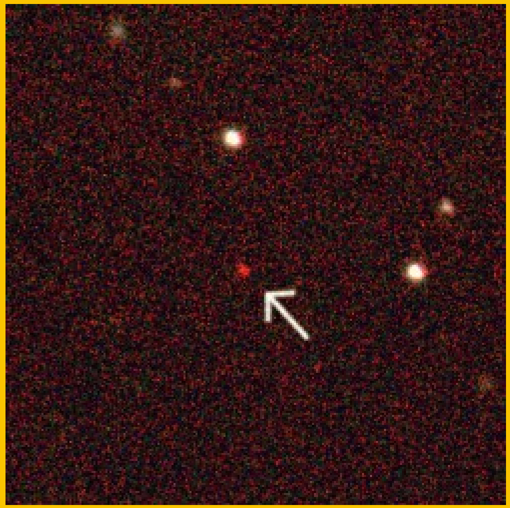
Galaxies are few and faint at high-redshift



* A spectrum is worth a thousand pictures.

What are quasars



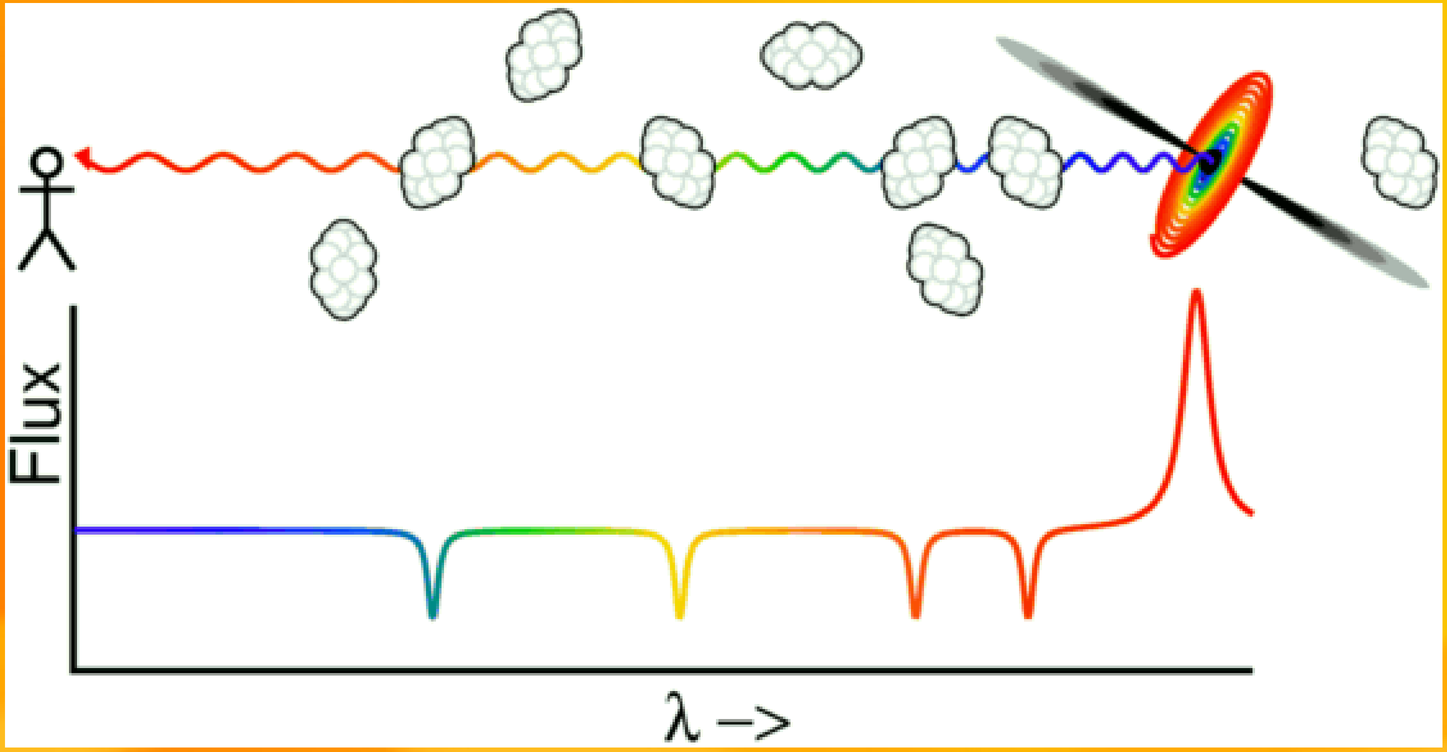


- Brightest things in the Universe
- Bright, energetic AGN – can see them very far
- Featureless spectrum with a few broad emissions

- Quasar=quasi-stellar object

Lyman-alpha forest

- hydrogen absorbs light from distant quasars, blueward of Lyman-alpha emission



Lyman-alpha forest

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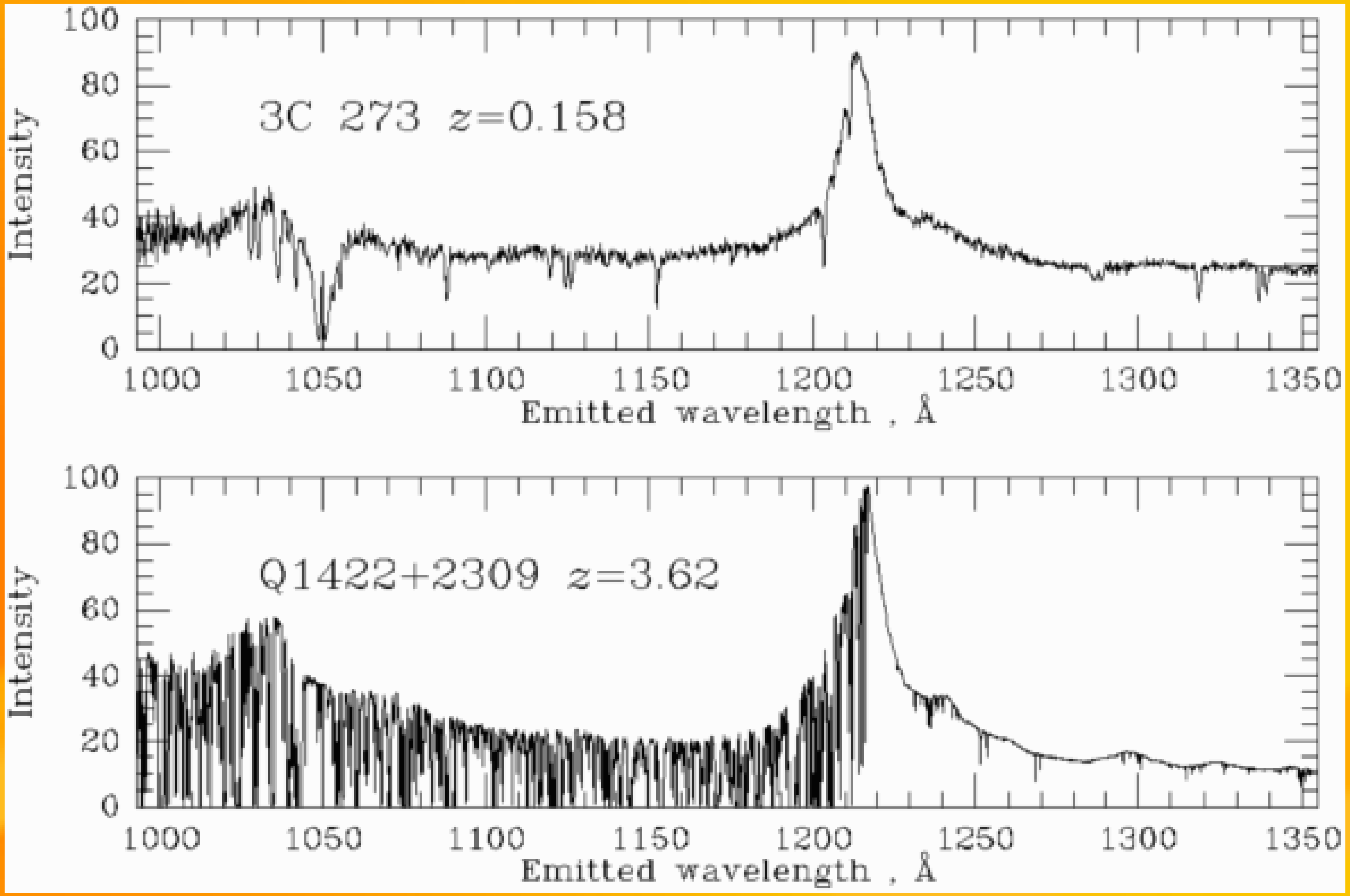


From baryons to flux

- Absorption done by neutral hydrogen in photo-ionisation equilibrium:

$$\Gamma n_{HI} = \alpha(T) n_p n_e$$

$$n_{HI} \propto \frac{\alpha(T)\rho_b^2}{\Gamma} \ll 1$$

and so, optical depth:

$$\tau \sim A \frac{(1+\delta)^{1.7}}{\Gamma}$$

$$f = e^{-\tau}$$

What we really measure is some non-linear transformation of the underlying matter field.

Evolution of baryons

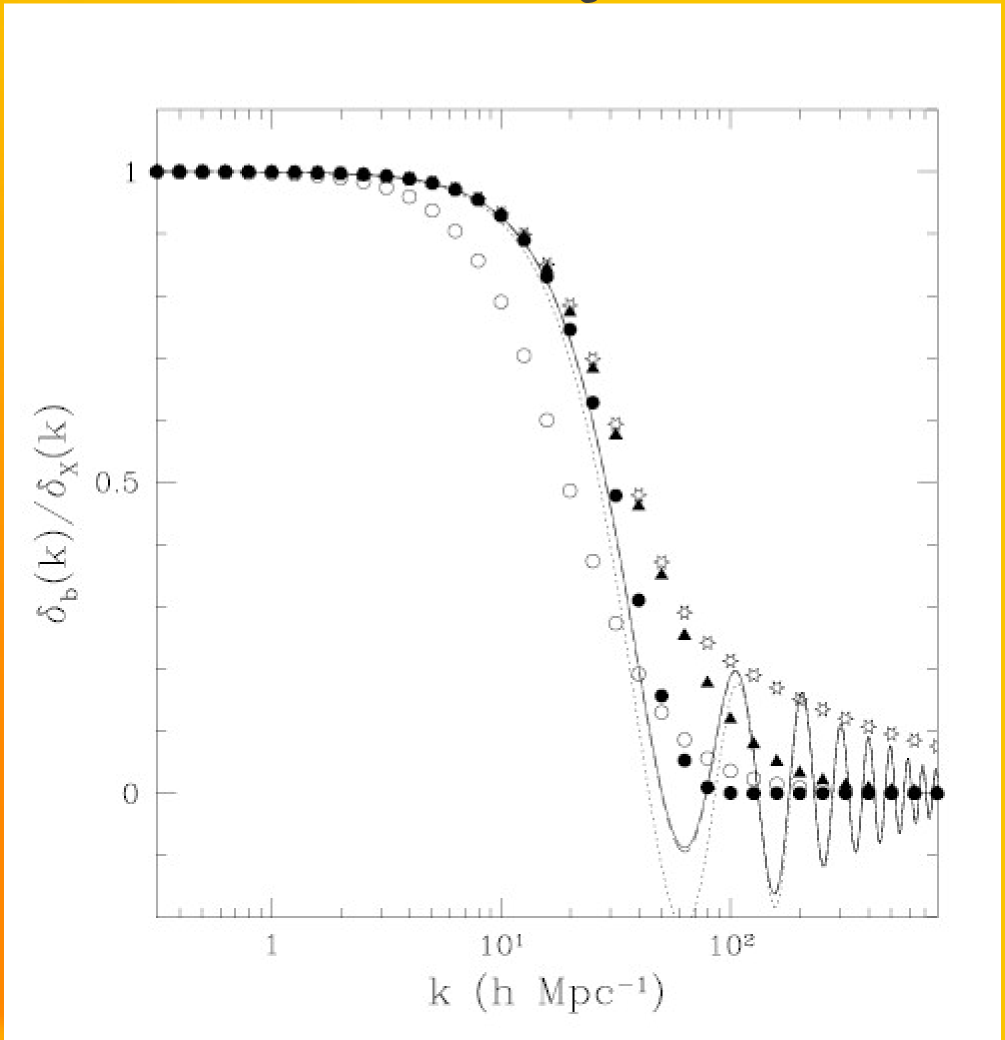
- Seminal papers by Gnedin and Hui
- At linear order

$$\frac{\partial^2 \delta_x}{\partial t^2} + 2H\frac{\partial \delta_x}{\partial t} = 4\pi G\bar{\rho}\left(f_x\delta_x + f_b\delta_b\right)$$

$$\frac{\partial^2 \delta_b}{\partial t^2} + 2H\frac{\partial \delta_b}{\partial t} = 4\pi G\bar{\rho}\left(f_x\delta_x + f_b\delta_b\right) - \frac{c_s^2}{a^2}k^2\delta_b$$

- On large scales baryons follow dark matter
- On small scales, pressure suppresses fluctuations

Pressure filtering



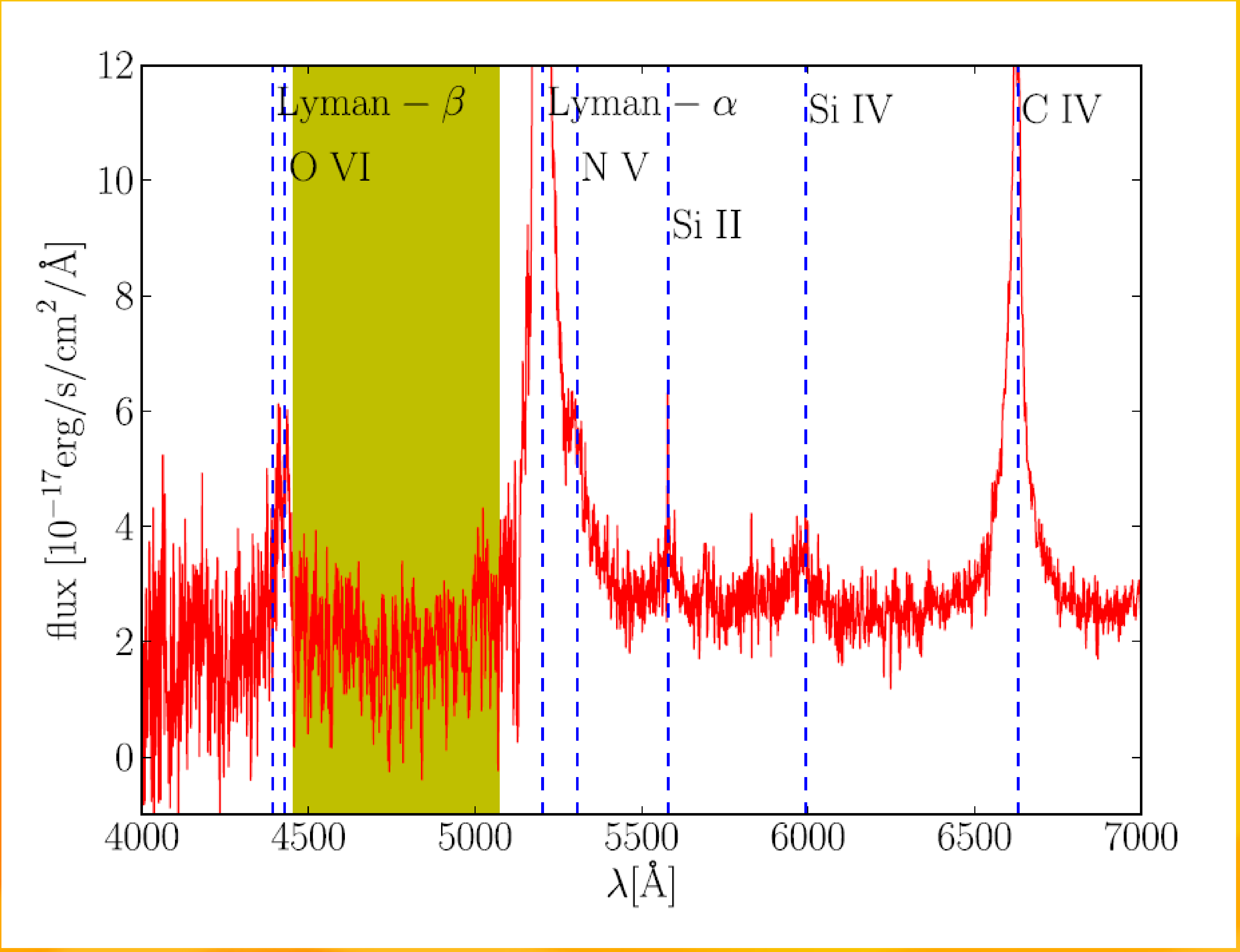
- Amount of filtering depends on the thermal history of the inter-galactic medium

Ly-alpha forest history

- < 1998: no measurable correlation on scales > 1 Mpc
- Forest still thought to be due to “clouds”

Ly-alpha forsest history

- 1998 : maybe there is a weak clustering (Rauch in AR)
- 2000s: First "CMB-like" analysis of 1D power spectra, ideas about 3D measurements: AP test, BAO
- Need tens of thousands of close quasar pairs to do it, but they can be noisy
- 2009 BOSS



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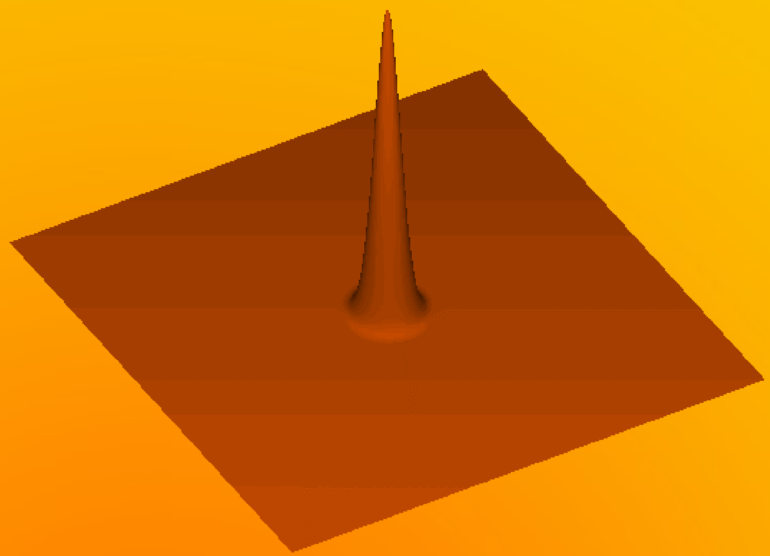
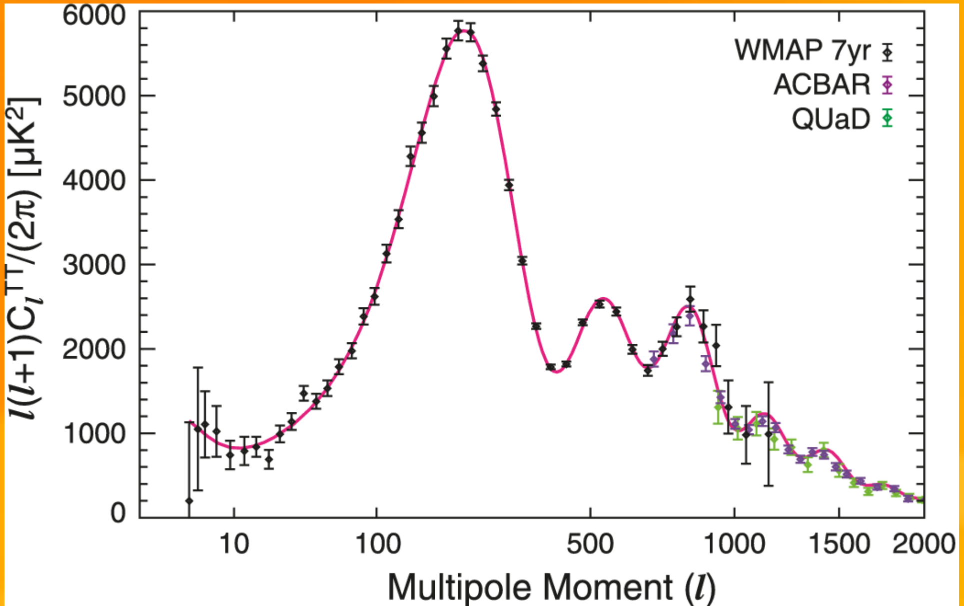
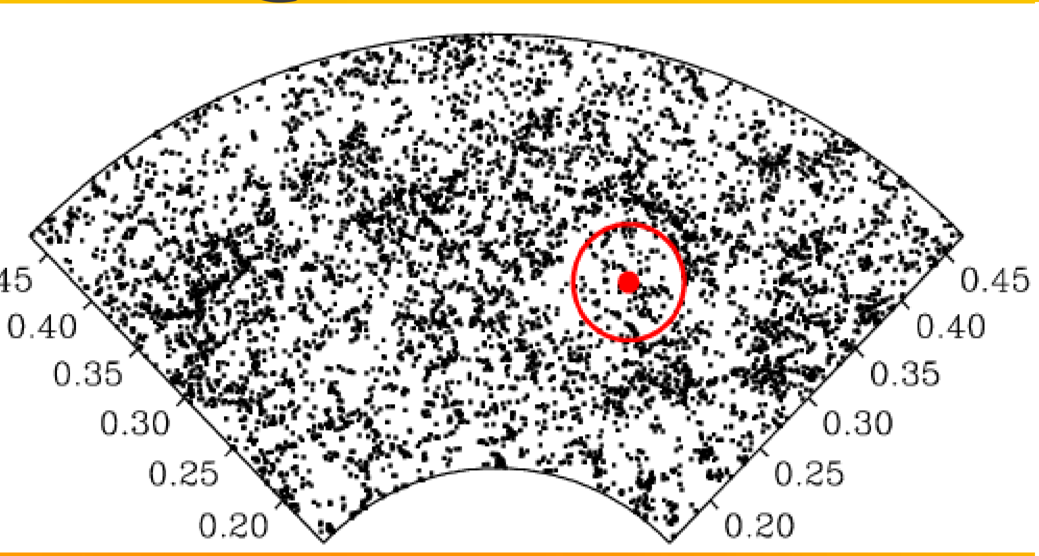
Baryonic acoustic oscillations

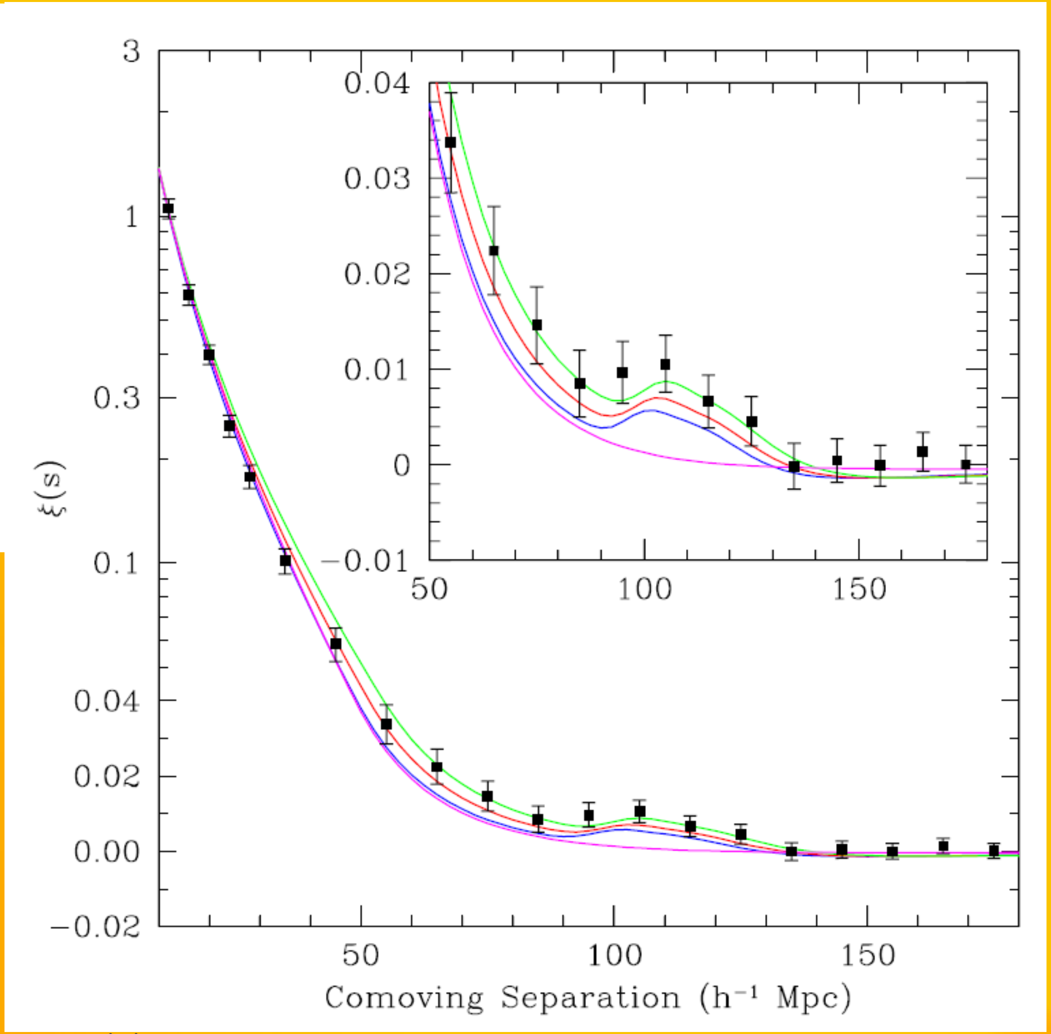




- Before recombination, primordial plasma supports acoustic waves
- These imprint a characteristic scale into the correlation properties of dark matter

Baryonic acoustic oscillations

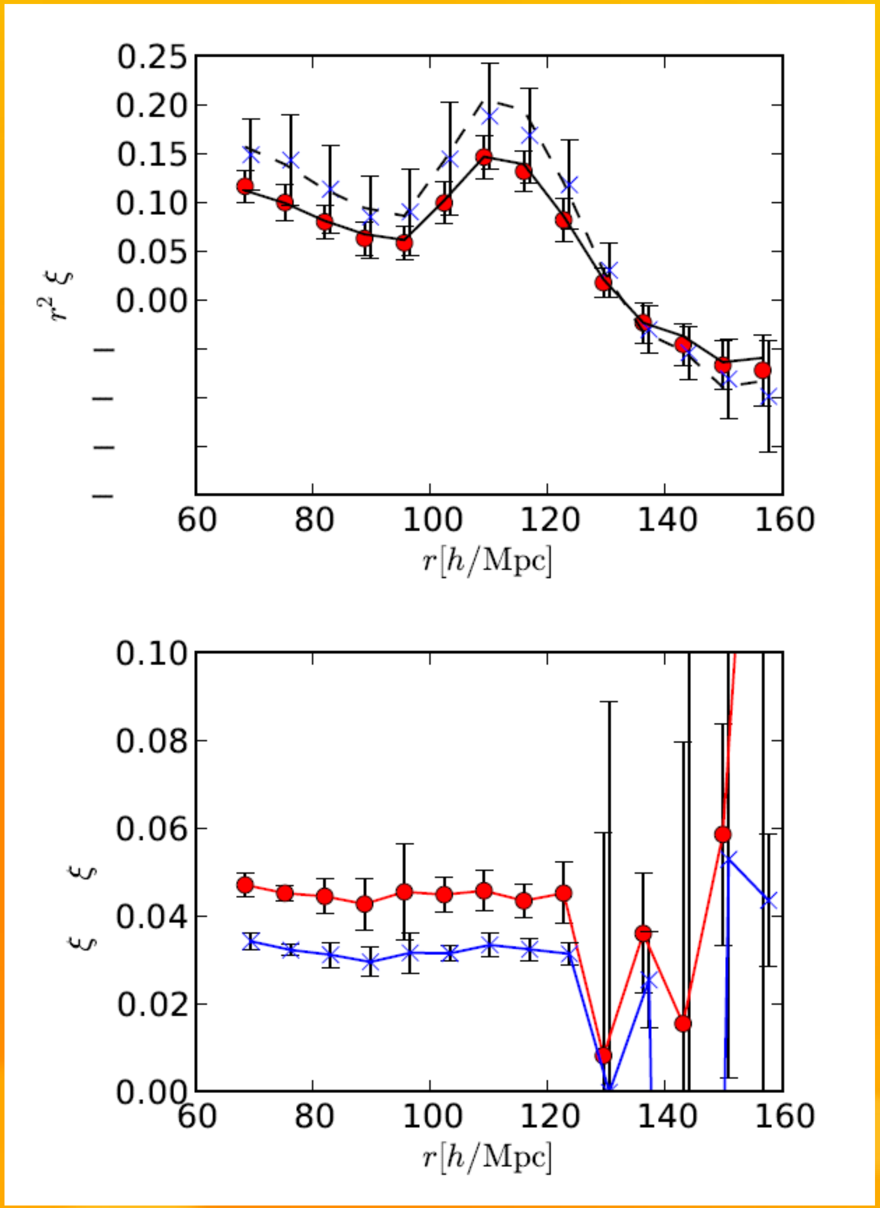




SDSS data
From Eisenstein et al, 2005

- Baryonic acoustic oscillations are a standard rod allowing measurements of the expansion history of the Universe

BAO with LYA



- Proposed by MW in 2003
- McDonald & Eisenstein did forecast that motivated BOSS
- Slosar et al did some large scale LyA simulations by converting DM only simulations

BOSS

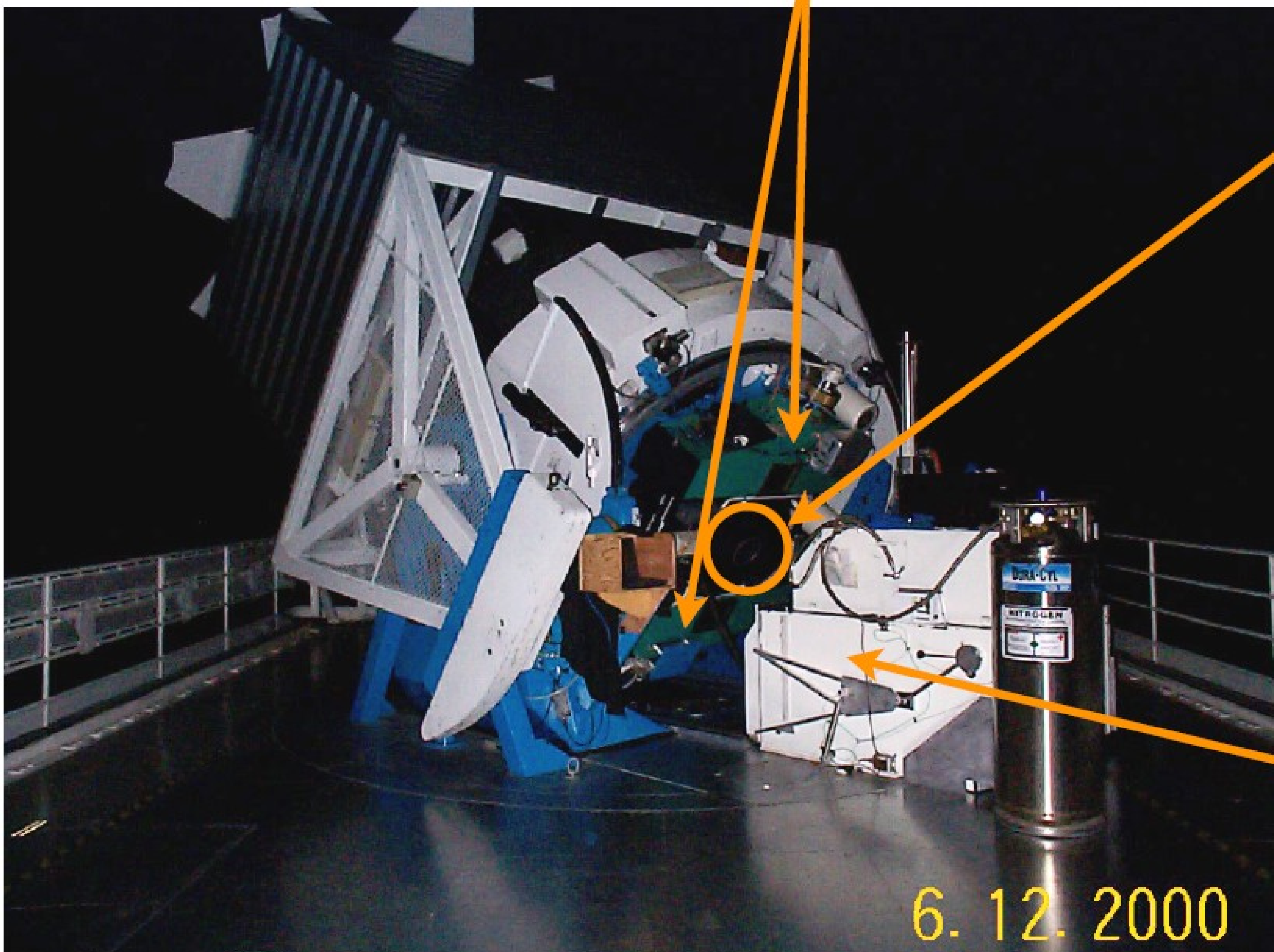
- BOSS is one of 4 experiments composing SDSS3.
- Uses 2.5m SDSS scope.
- A 1000 fiber spectrograph, R~2000, wavelength: 360 - 1000 nm
- 5 year experiment

BOSS

- Spectra of:
  - million LRGs ($z<0.7$)
  - 160,000 QSOs with usable forest
- 10,000 sq degrees
- Comissioning: from Aug 09
- Science data: from Dec 09

How BOSS works

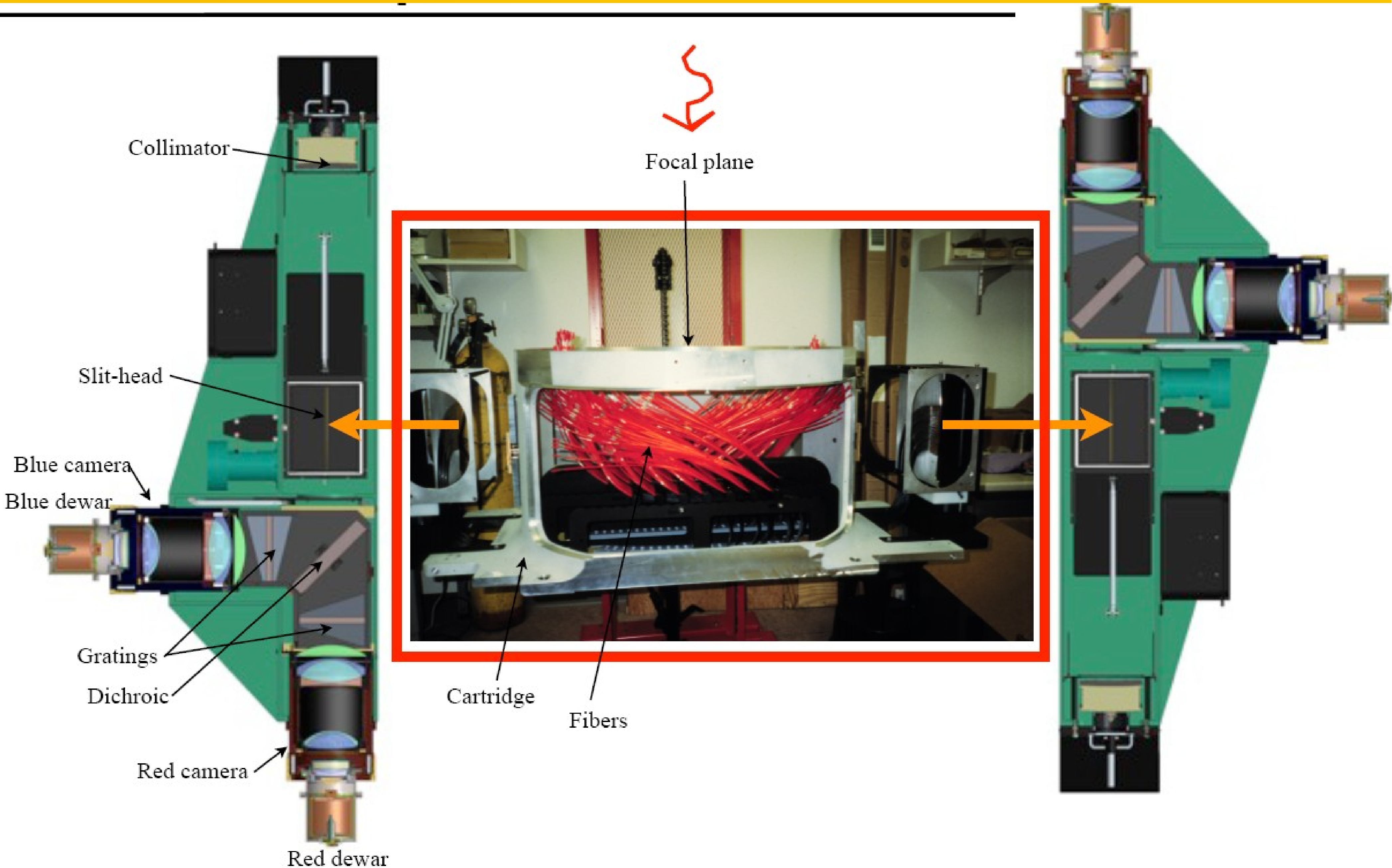
Two double-spectrographs
(permanently mounted)



3° focal plane:
Either imaging camera
or 1 of 8 spectro cartridges
(swapped during night)

“Doghouse”:
Stores imaging camera
when not in use

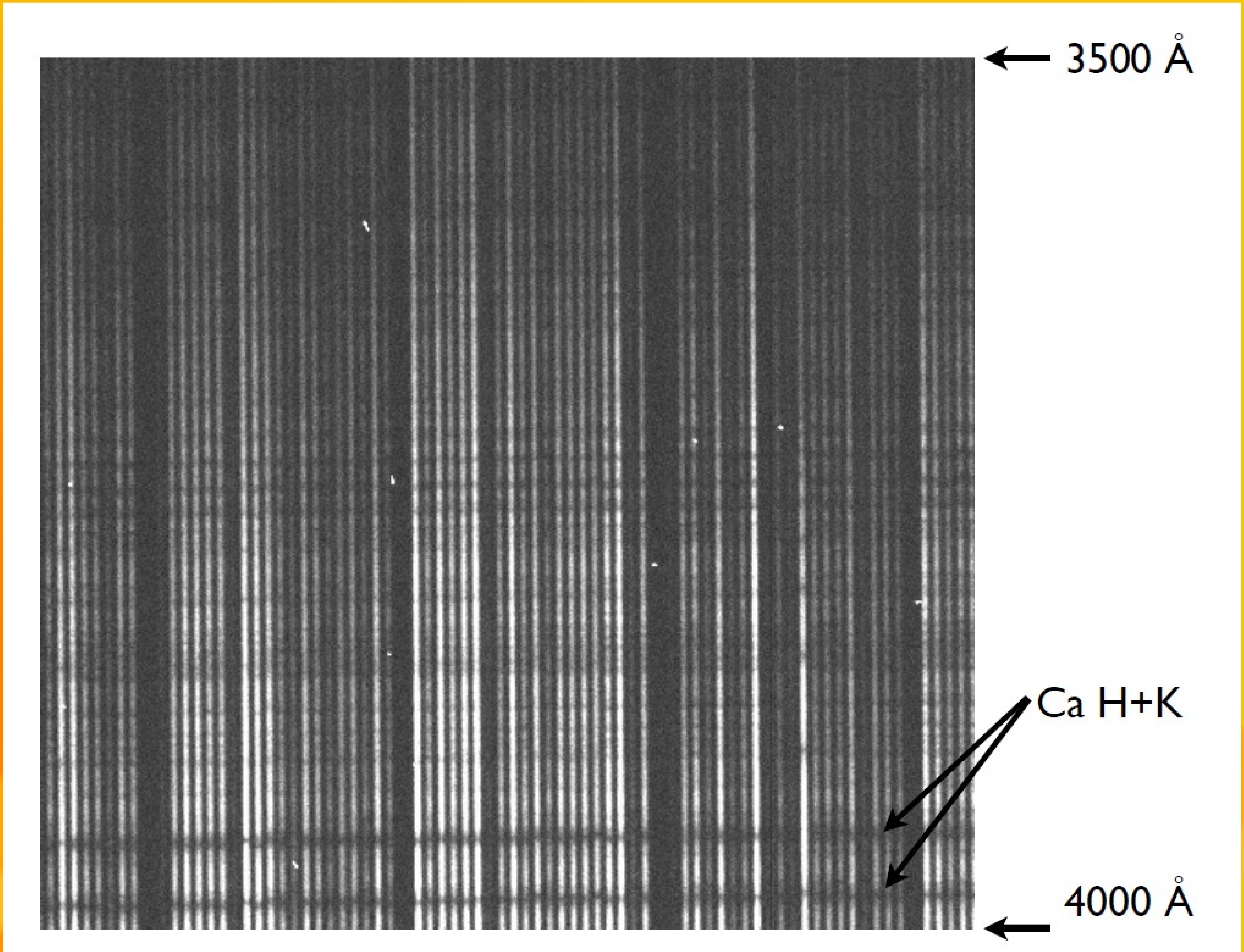
How BOSS works



How BOSS works

Norm Blythe plugging fibers

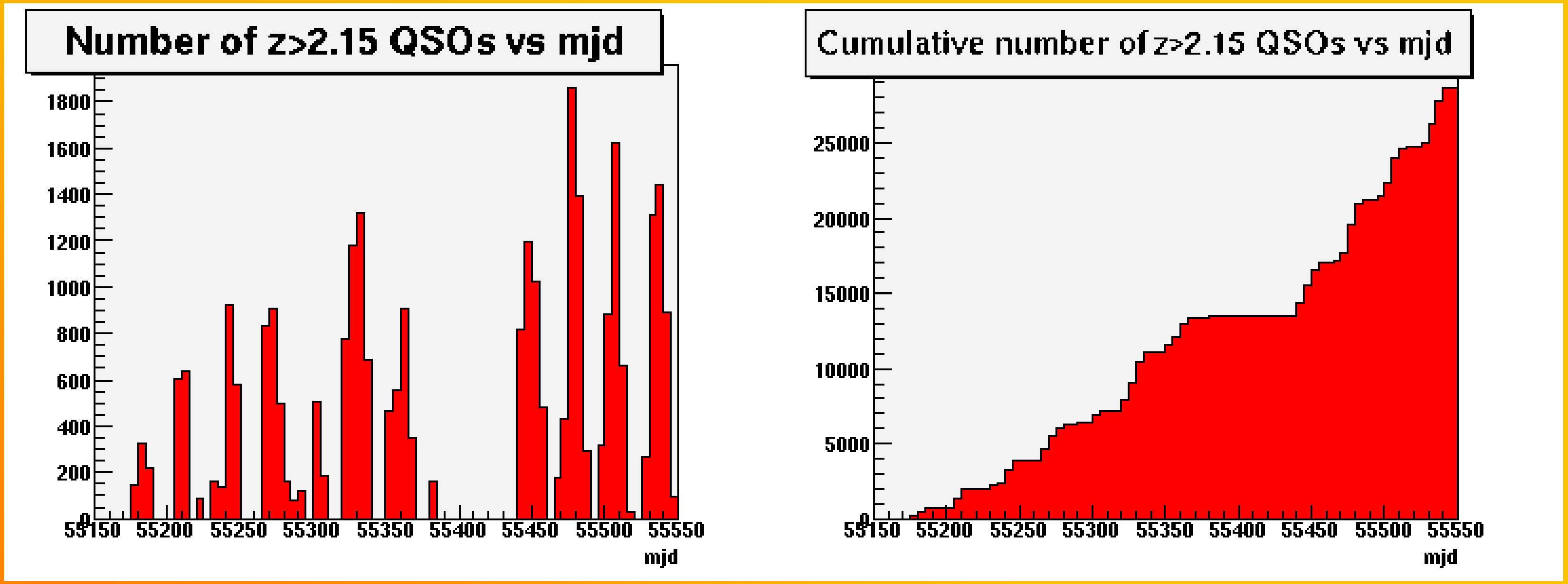
First Light: 08/28/09



Let's try! Problem 1: Targets!

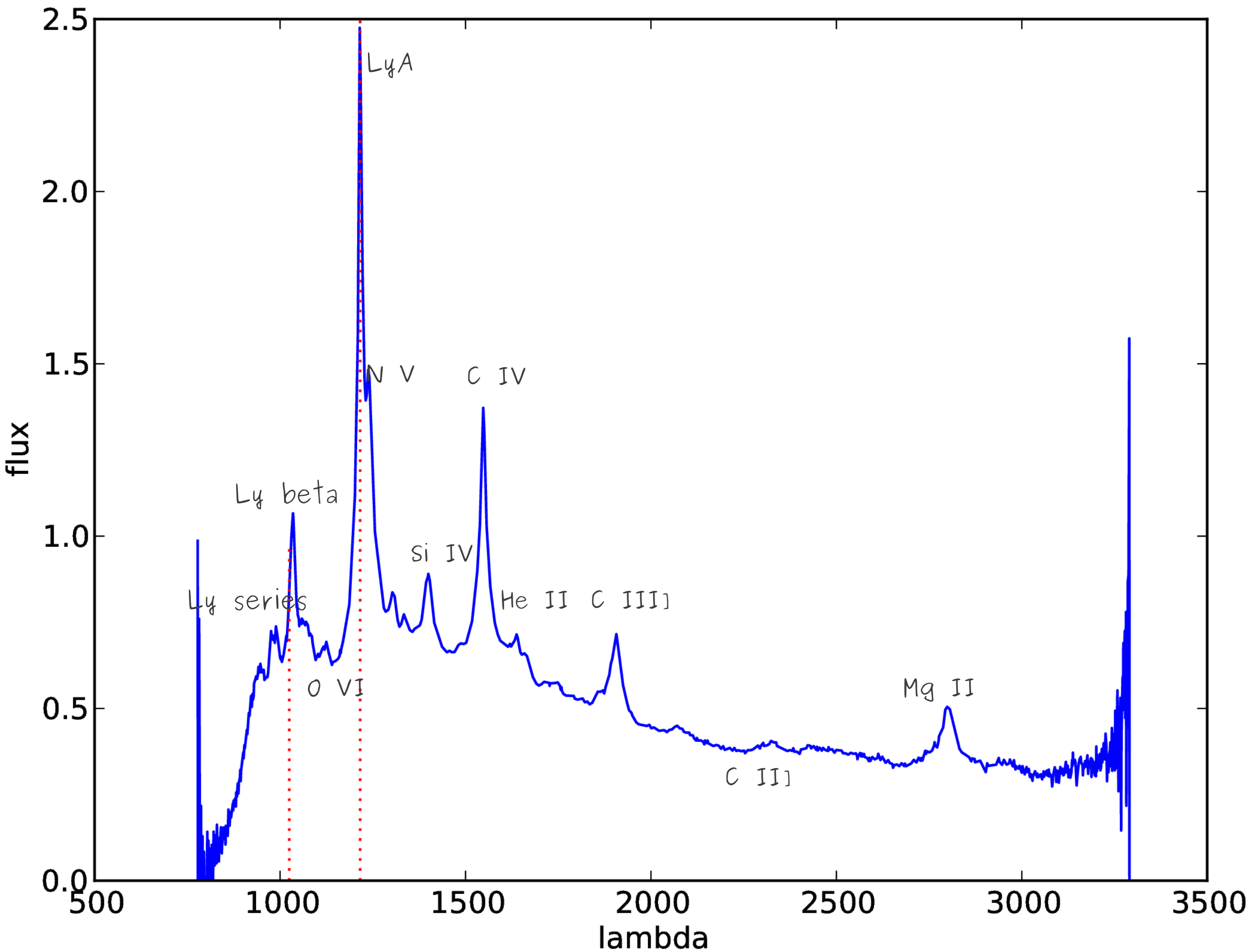
- Target selection is done by a three different methods and bunch of people
- 40 fibers/sq deg, but efficiency in finding quasars Is just around 50%

Targets



- Efficiency relatively low, but getting better...
- Failed targets are stars
- Efficiency increase dramatically if one uses UV, IR or variability information

4800 BOSS QSOs



BOSS average rest frame spectrum

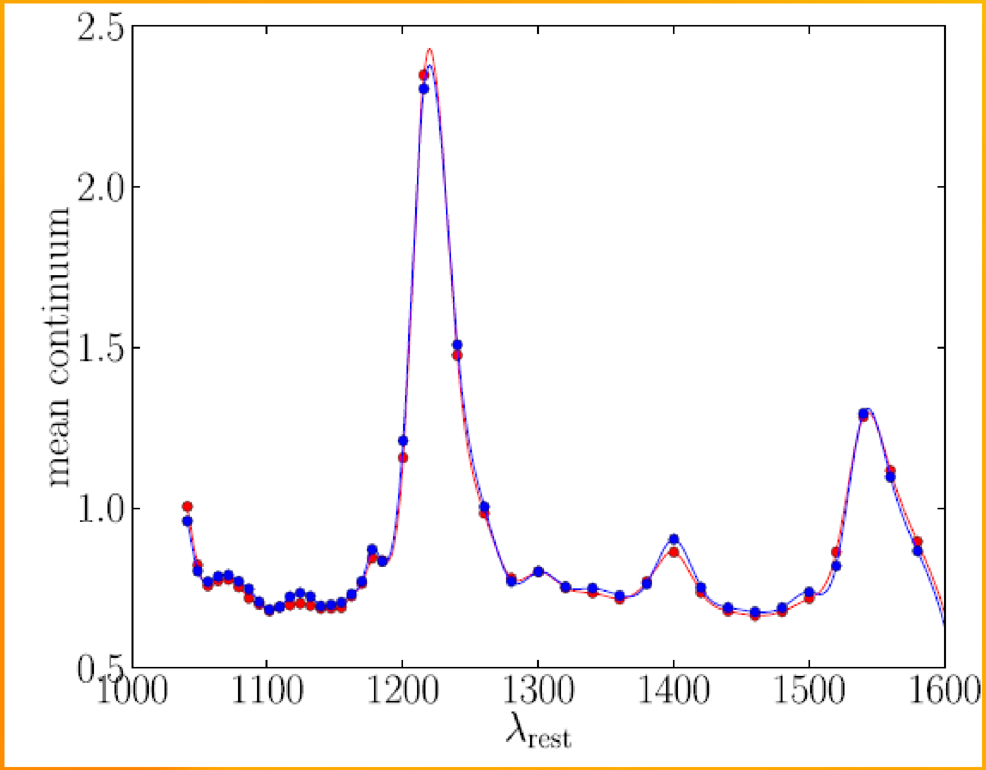
Measuring correlations

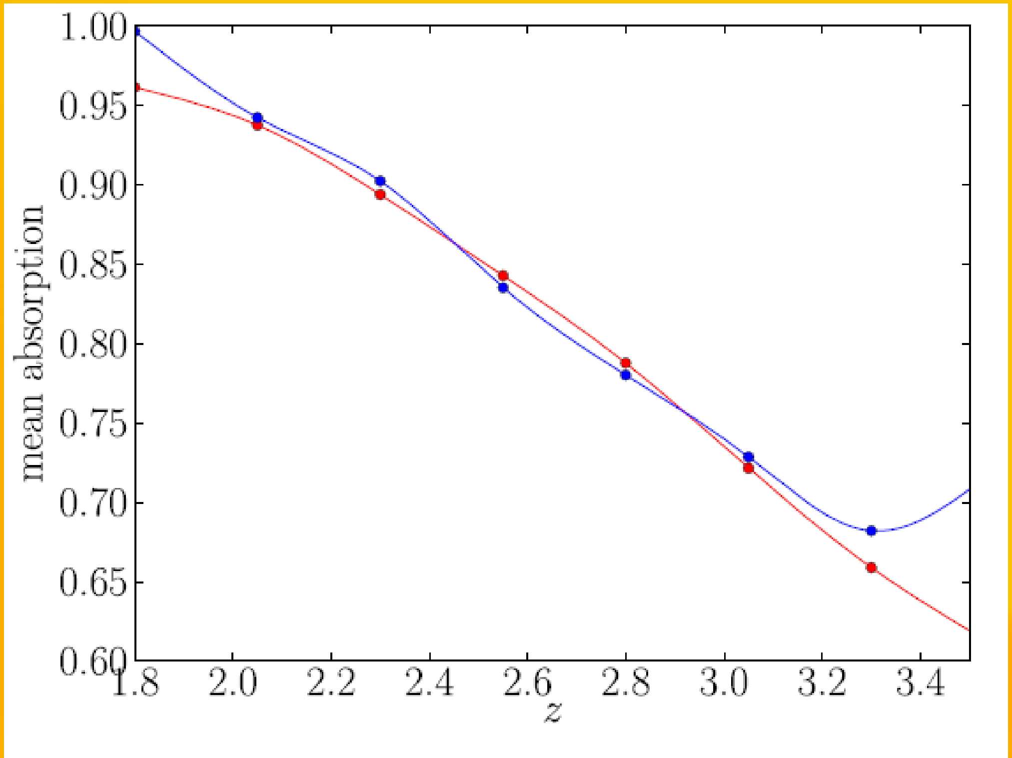
- First one fits for mean continuum and mean absorption
- Then derive estimates of the mean flux fluctuations
- The one measures the correlation function as function of: redshift, distance, angle along the line ofsight
- Preliminary results for 1st year data (14000 QSOs)

Synthetic datasets

- 30 sets of full dataset mocks
- Mock datasets are formed from log-normal model and have parameters from McDonald 2003 sims
- Continua from Suzuki PCAs
- Quite sophisticated: possibility of adding high-density systems, metal correlations

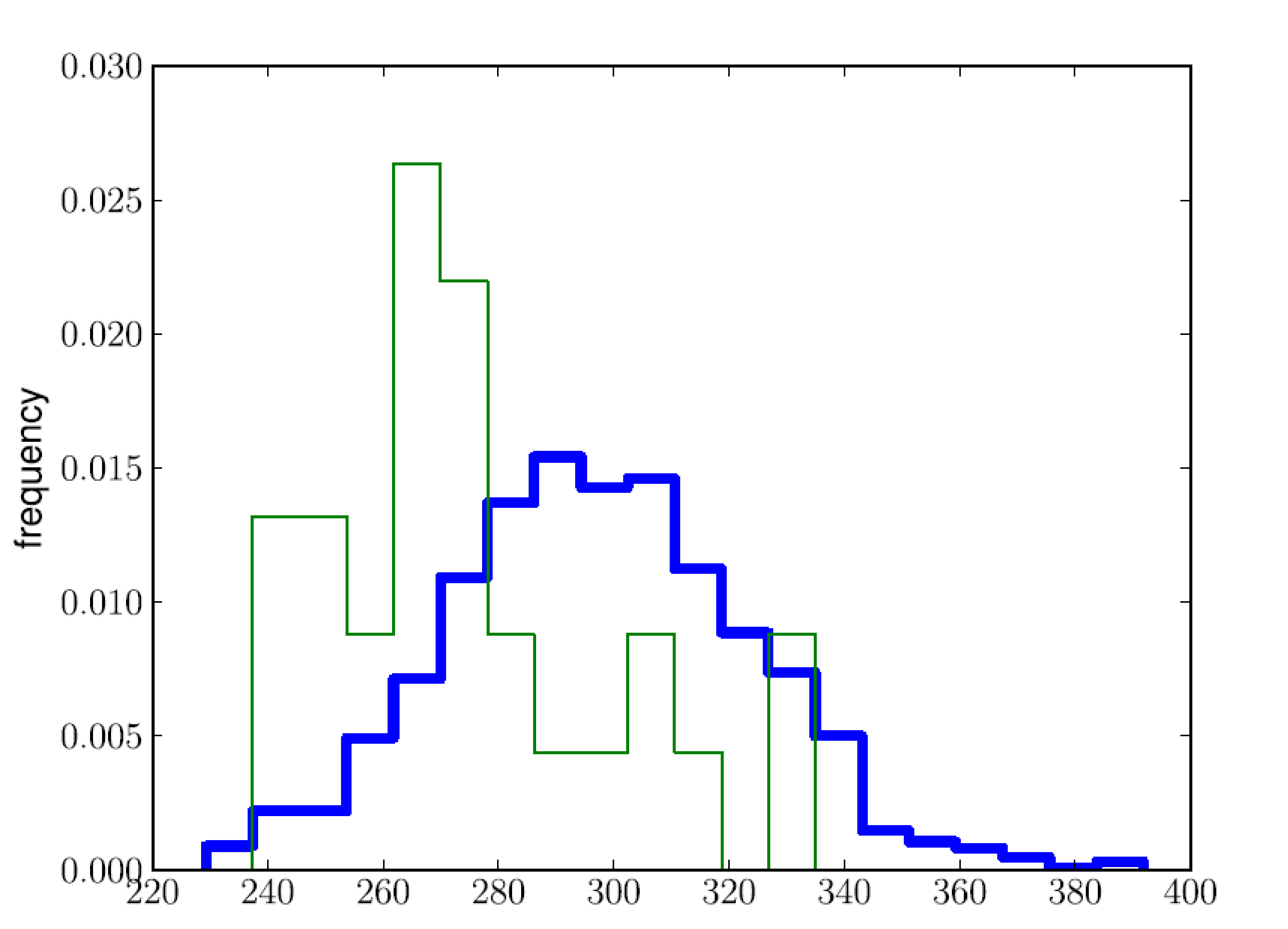
Continuum fitting





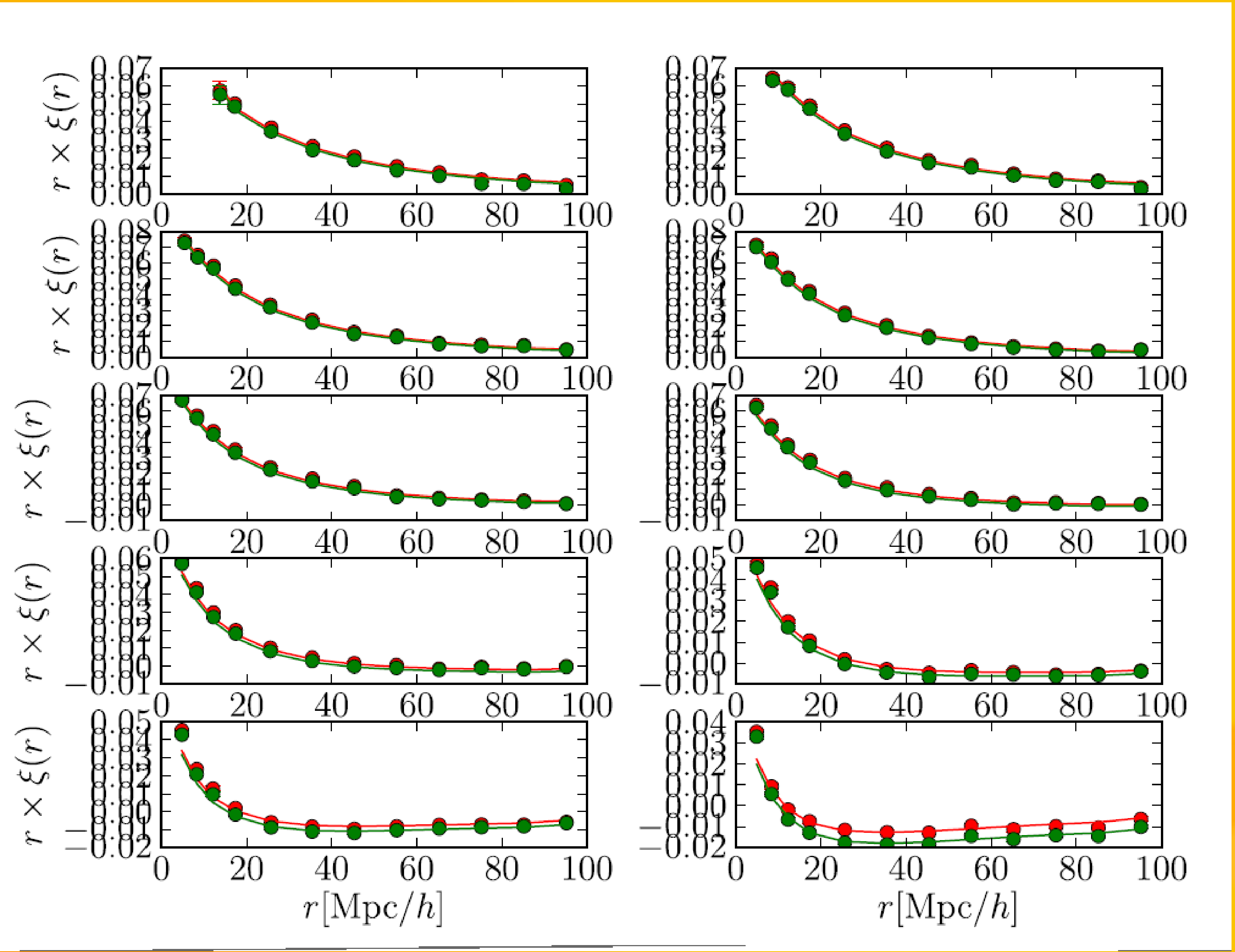
Errorbars

- Errorbars are very though
- Measurements very correlated - we have 330 data-points → over 50,000 matrix elements
- Trivial estimator is N^4 operation, 10^12 times slower than correlation function estimation
- We developed a novel MC technique, that uses the **measured** two-points

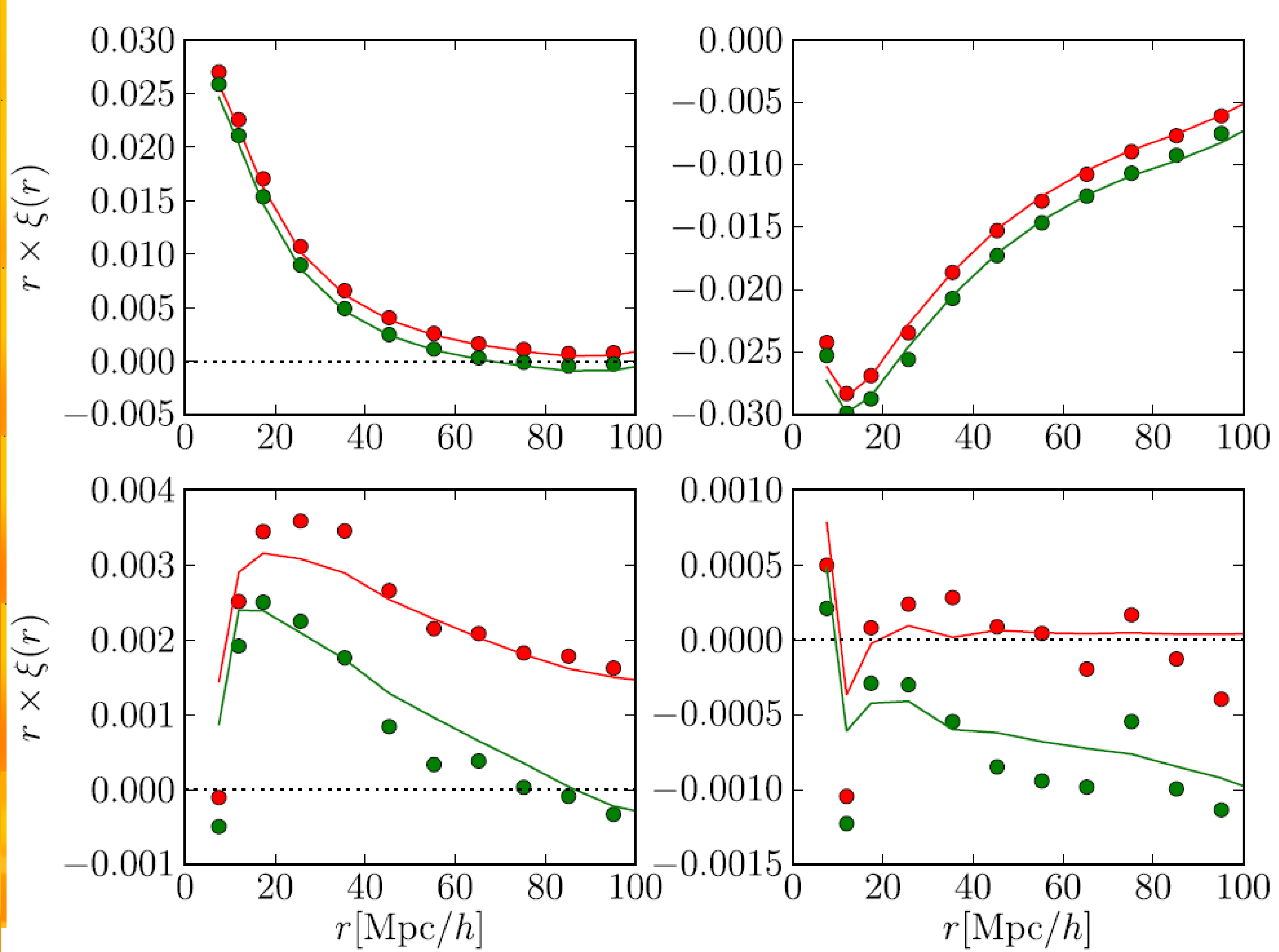


0.030
0.025
0.020
0.015
0.010
0.005
0.000
frequency
220
240
260
280
300
320
340
360
380
400

Synthetic data-sets



Synthetic data-sets

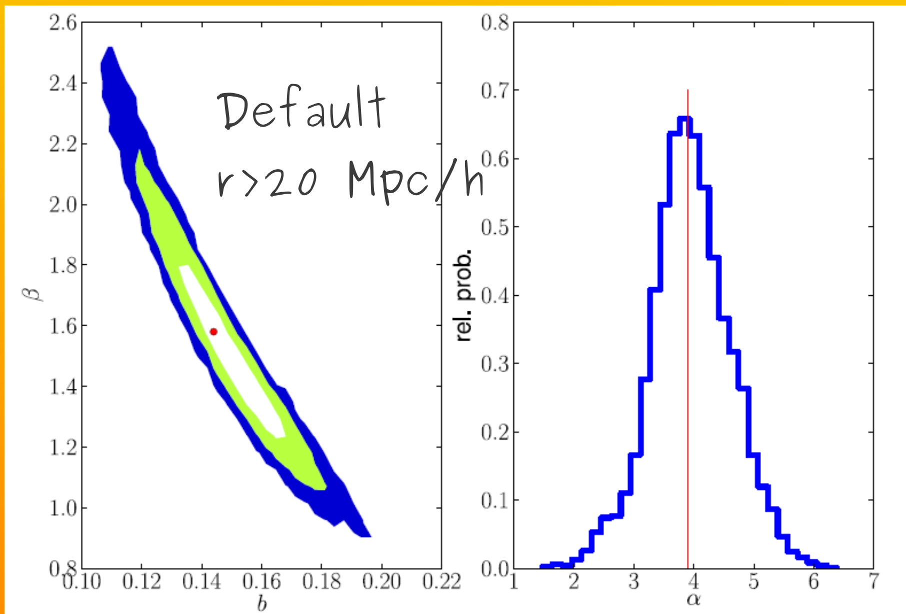


CENSORED

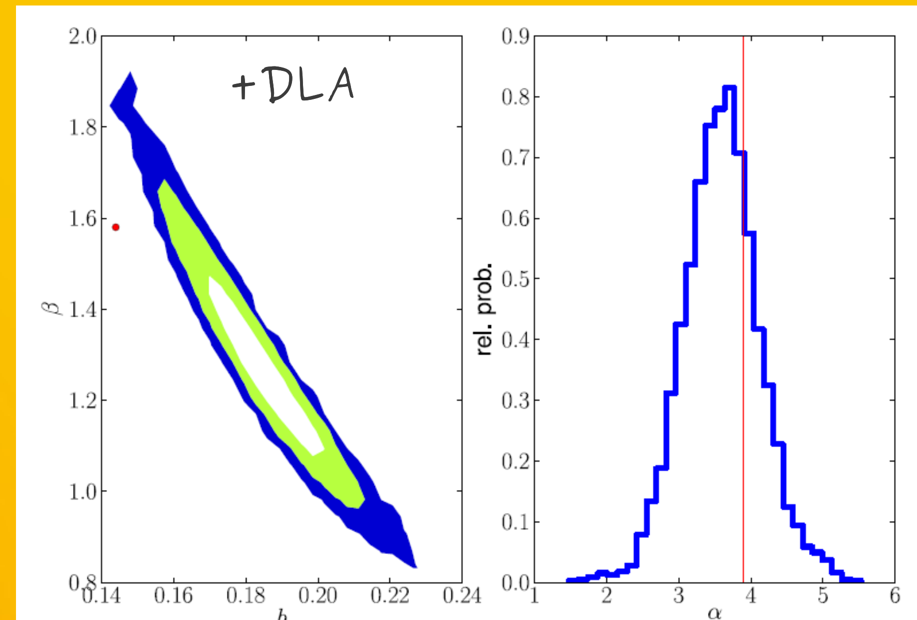
Parameters Fitting

- When one has 300 points with very correlated errors it is very hard to tell small effects
- Mocks are well fit, by construction, with 3 parameter model: 1 bias, 1 beta, 1 $(1+z)^{\alpha}$ power evolution
- Fix covariance matrix to 1 dataset, but feed data averaged over 30 mocks.

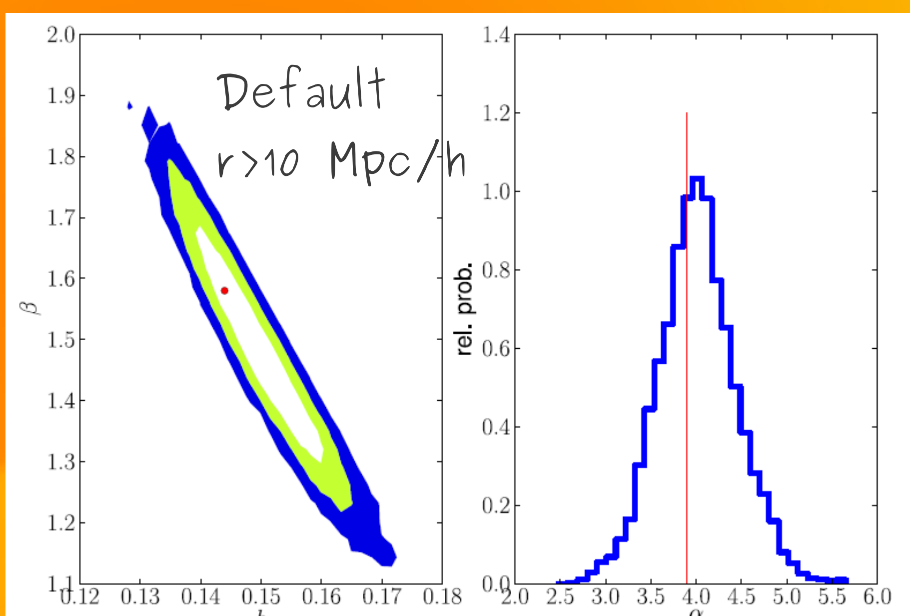
MOCKS



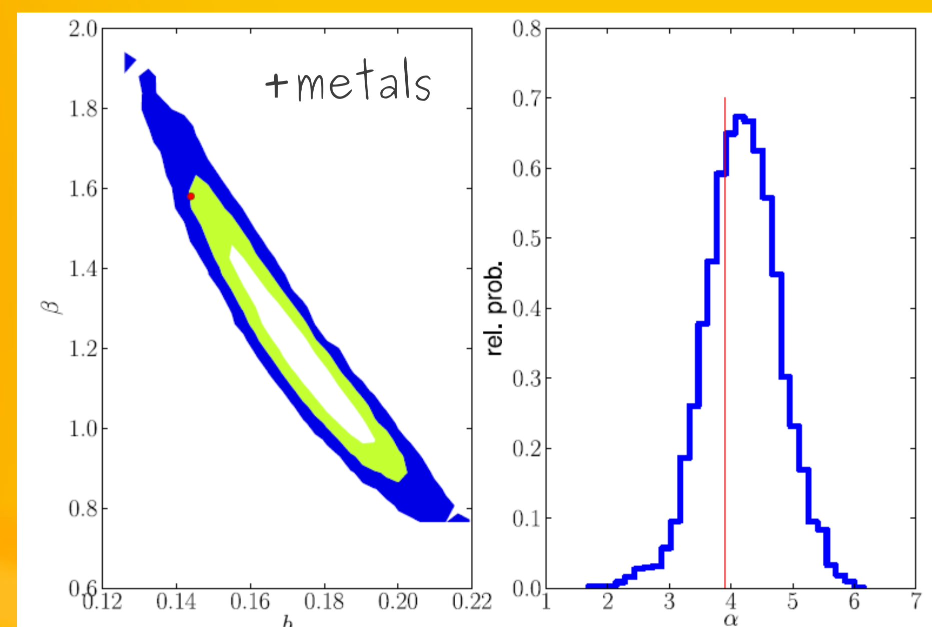
Default
r>20 Mpc/h
β
b
rel. prob.
α
2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8
0.10 0.12 0.14 0.16 0.18 0.20 0.22
0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
1 2 3 4 5 6 7



+DLA
β
b
rel. prob.
α
2.0 1.8 1.6 1.4 1.2 1.0 0.8
0.14 0.16 0.18 0.20 0.22 0.24
0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
1 2 3 4 5 6



Default
r>10 Mpc/h
β
b
rel. prob.
α
2.0 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1
0.12 0.13 0.14 0.15 0.16 0.17 0.18
1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0



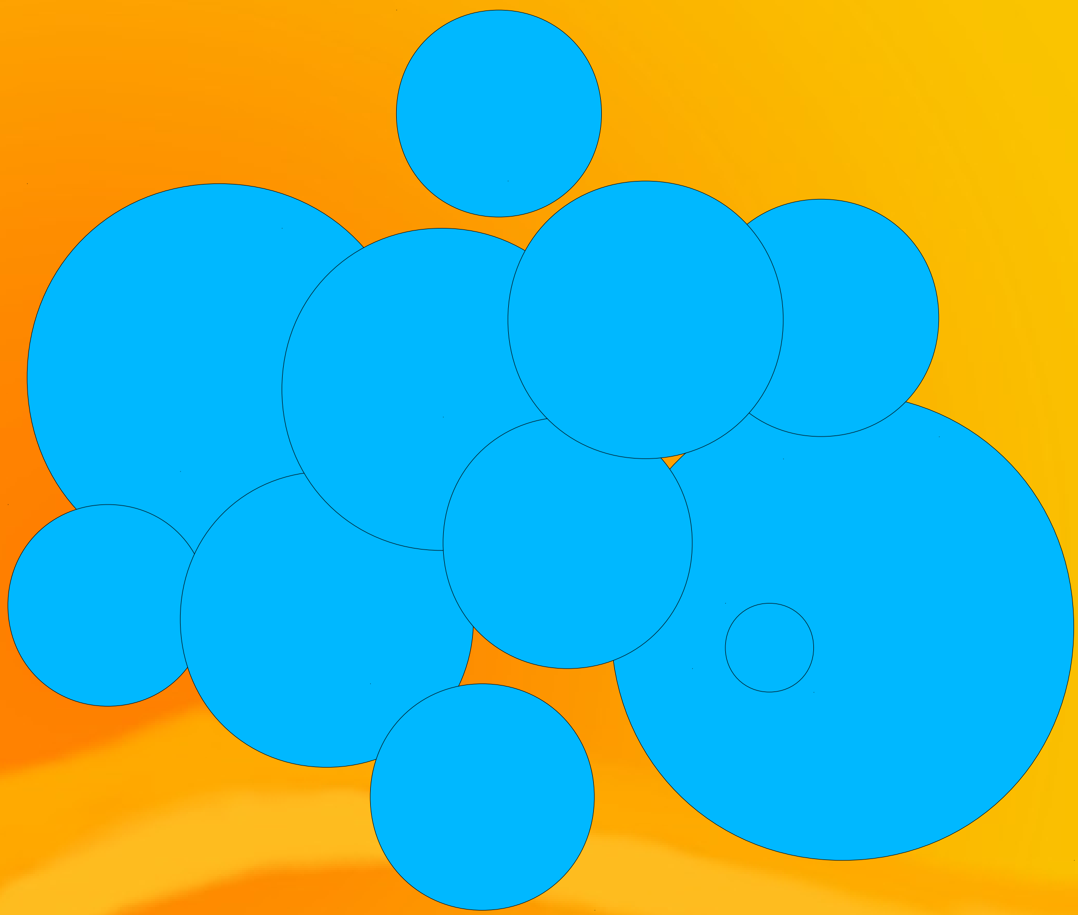
+metals
β
b
rel. prob.
α
2.0 1.8 1.6 1.4 1.2 1.0 0.8 0.6
0.12 0.14 0.16 0.18 0.20 0.22
0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
1 2 3 4 5 6 7

CENSORED

So, what?

- This it the first time, correlations have been seen on scales >5 Mpc.
- Crucially, simplest theory seems to work:
  - Chi^2 around 200 with 300 dof
  - No photoionization rate fluctuations
  - No overwhelming HeII reionization
  - No overwhelming instrumental contamination: sky subtraction in particular was a big unknown

Photoionization rate fluct's

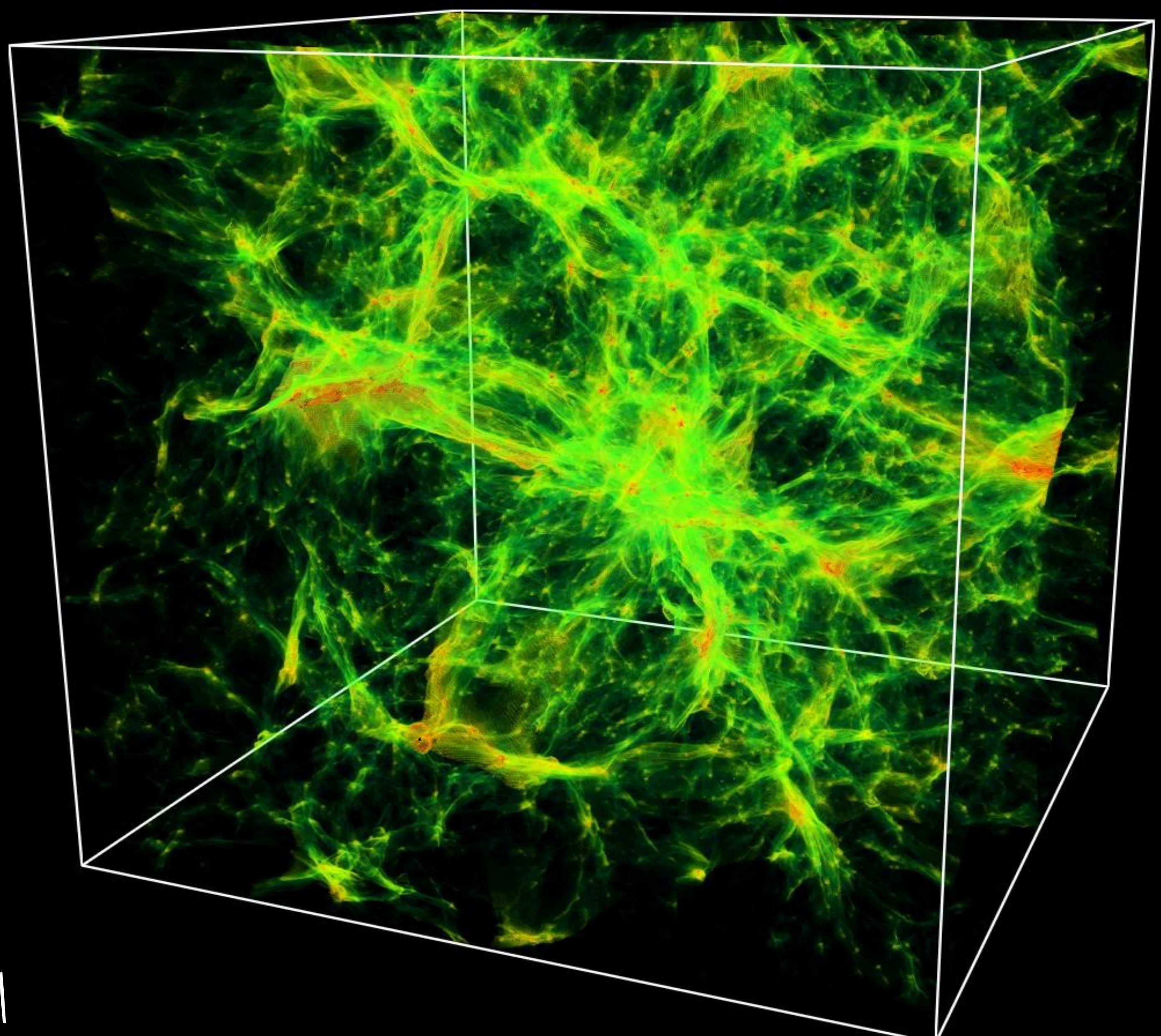


- Have not been seen
- At some large scale they have to be there at some level
- Need to marginalised over in a sufficiently clever manner

Conclusions

- Lyman-alpha forest unique probe of $z=2-3$ Universe
- BOSS was the first to measure three-dimensional fluctuations in Lya forest to cosmological distances
- Data well described by a biased linear theory
- Inferred amplitude OK, inferred redshift evolution OK, we prefer somewhat lowish beta
- On track to see BAO soon.

End

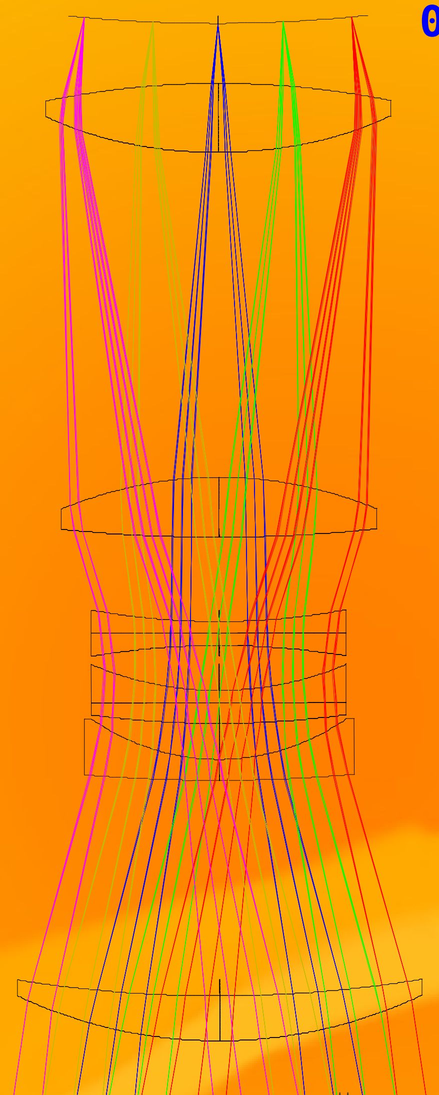


Cen et al

BigBOSS

- Put a 4000 fiber robotic spectrograph on Kitt Peak 4m
- Measure spectra of:
  - 30 million galaxies
  - 1 million quasars
- Measure the dark-energy through BAO + lots of ancillary science
- Move to southern hemisphere to Blanco 4m

Kitt Peak 4-m (Mayall) at Kitt Peak, Arizona



Design by Mike Sholl, SSL, [observatory,debug][optics,overeng]

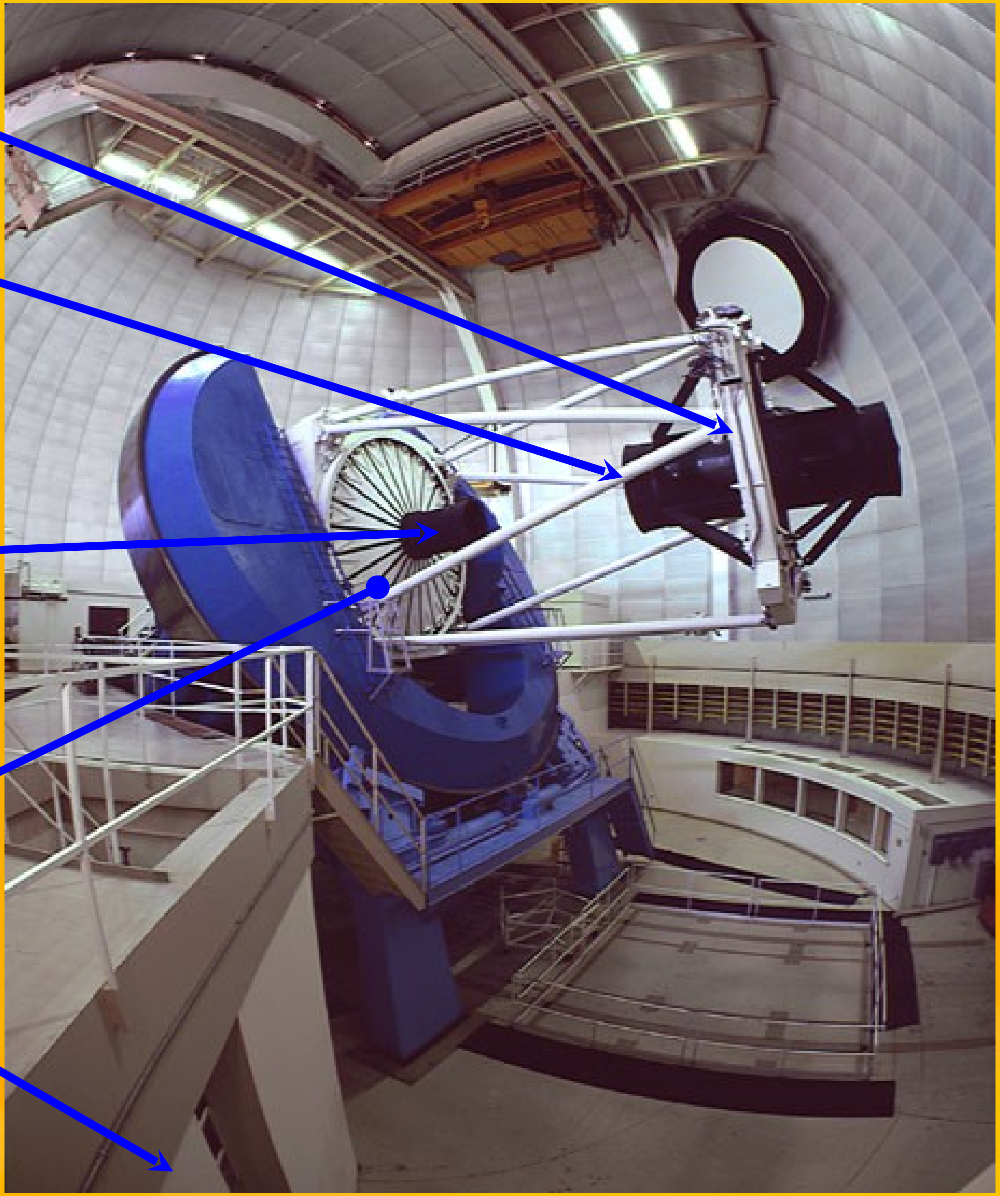
5000 fiber positioners, 0.9m focal plane

Corrector Lens + ADC

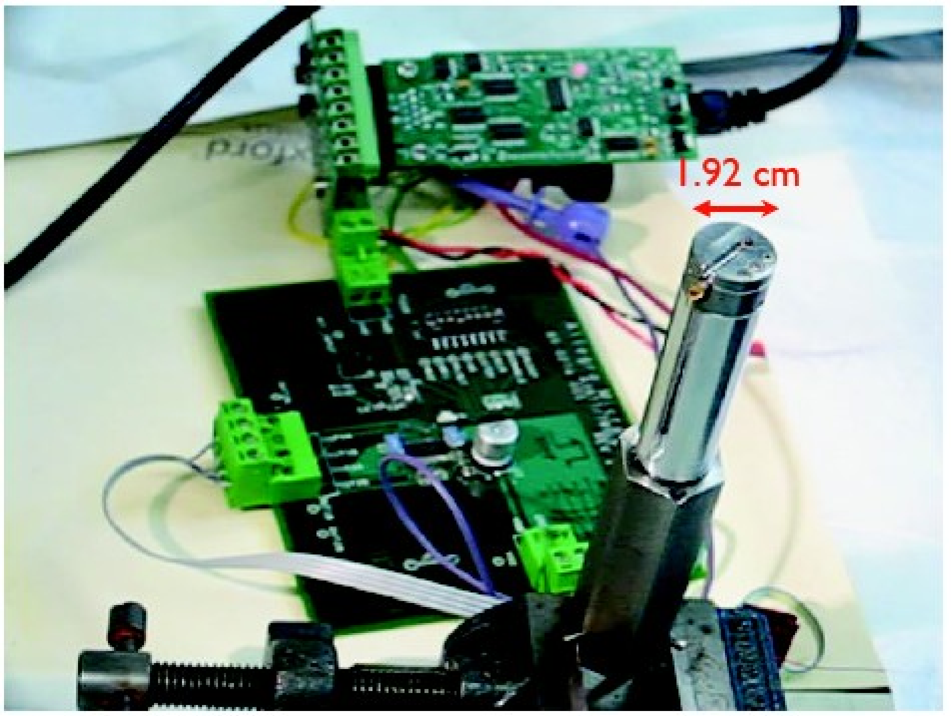
Fiber positioning Camera

Fiber run (bare fibers)

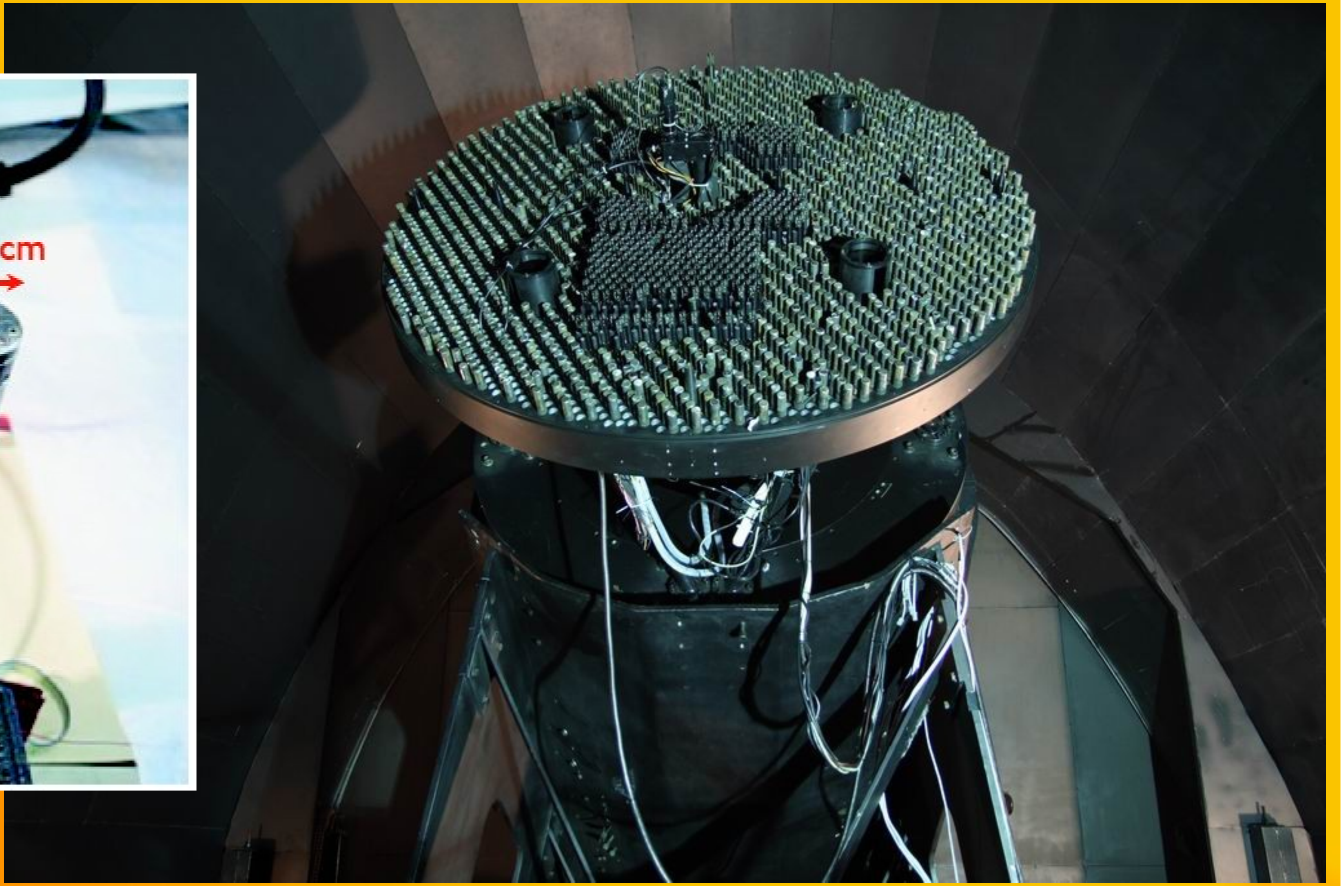
10 spectrographs



Fiber positioner



LBNL prototype



LAMOST focal plane fiber positioner

BigBoss: 5 percent of $V_{Universe}$