Backlit Universe: how distant quasars illuminate the Large Scale Structure

APS, Annaheim, MJD 55682

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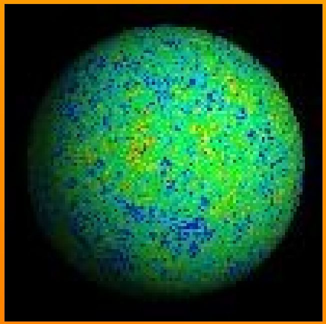
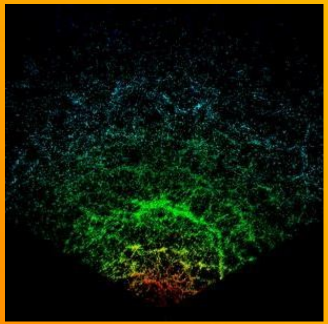
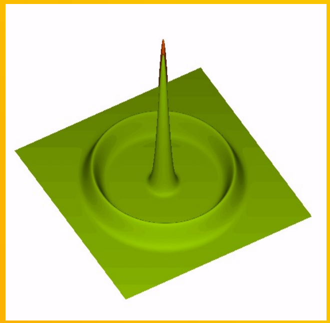
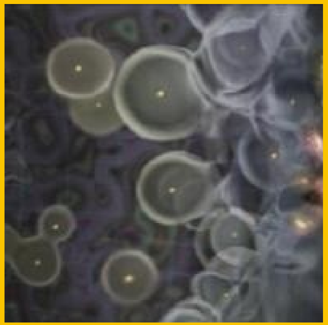
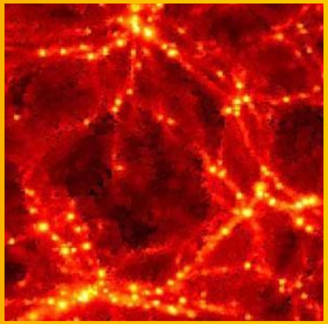
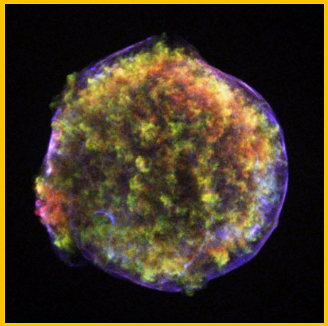
Measurements in Cosmology

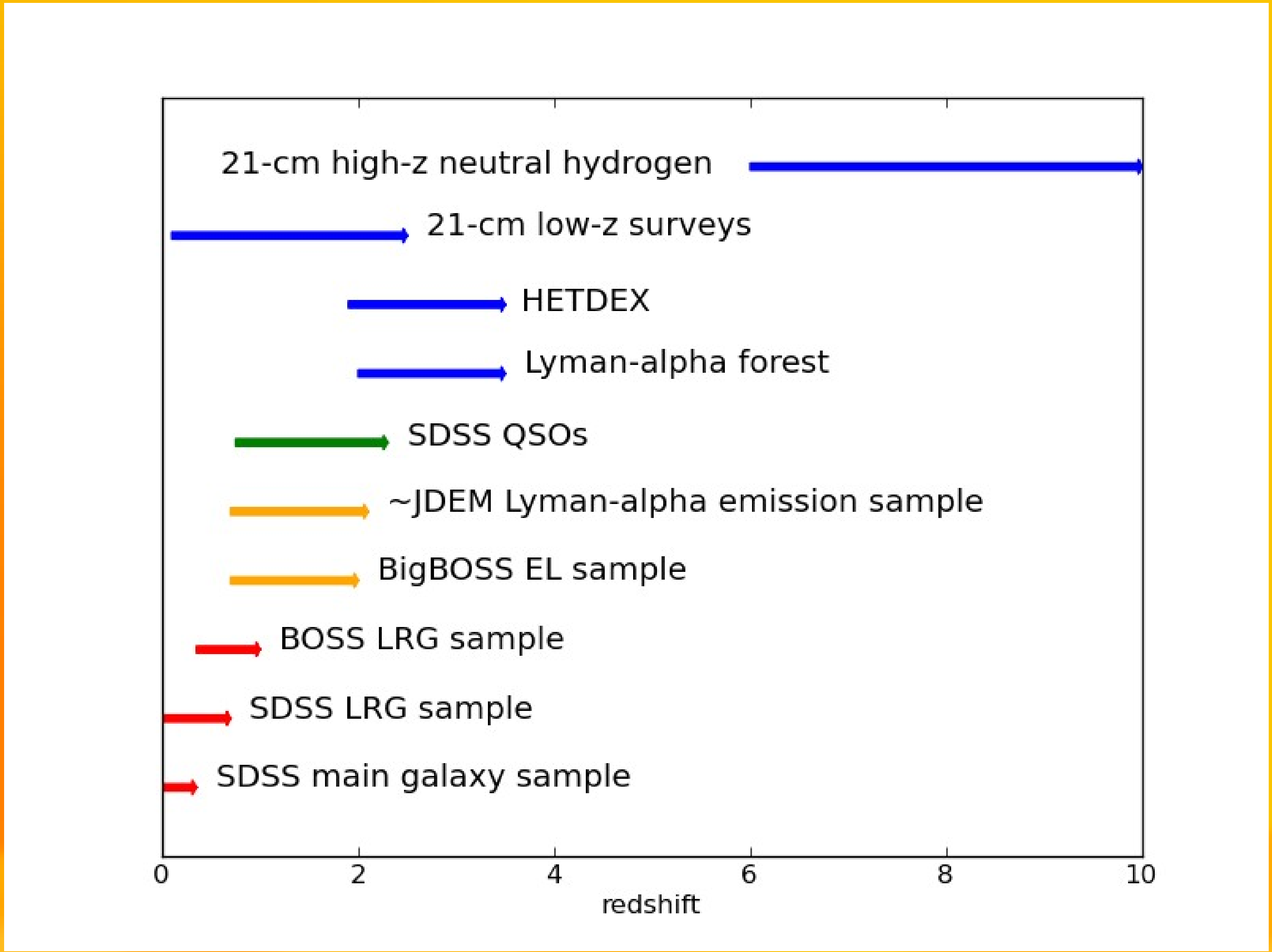
- Majority of measurements in cosmology depend on:
  - Measuring some tracer of structure in the universe
  - Calculating its correlation properties

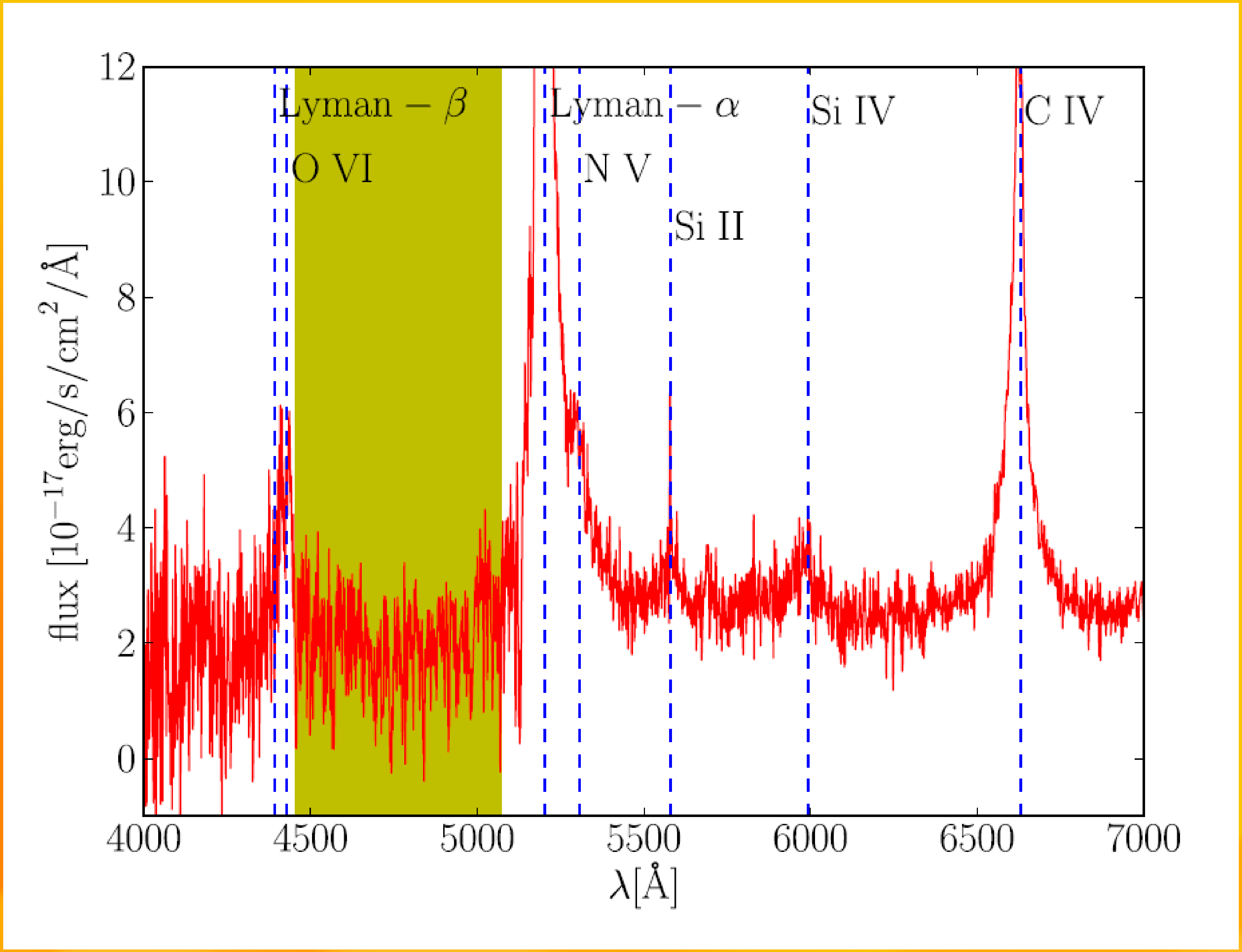




- To do it comprehensively, you really need to measure structure in the Universe over the widest possible range of redshifts.

Measuring density fields

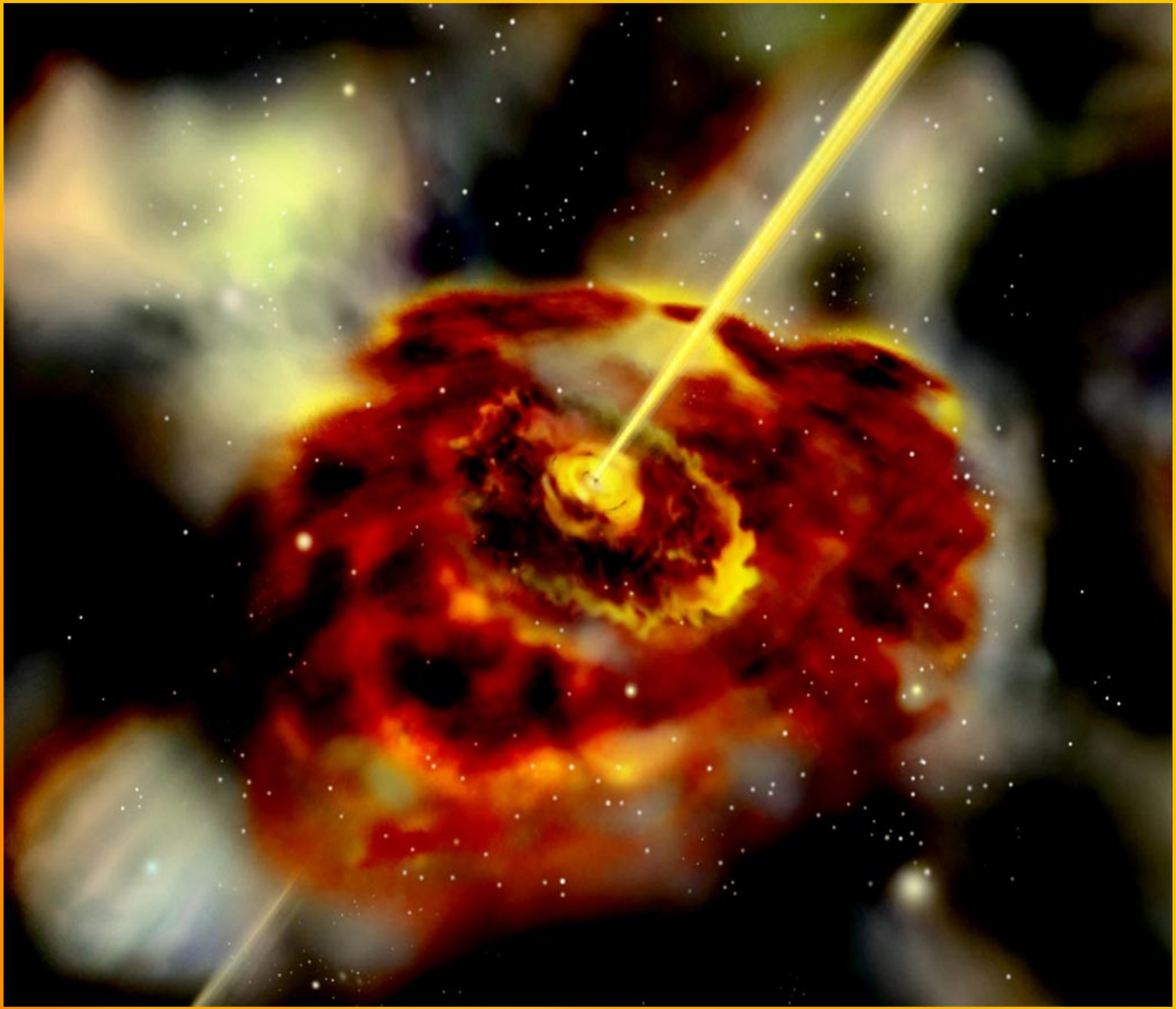


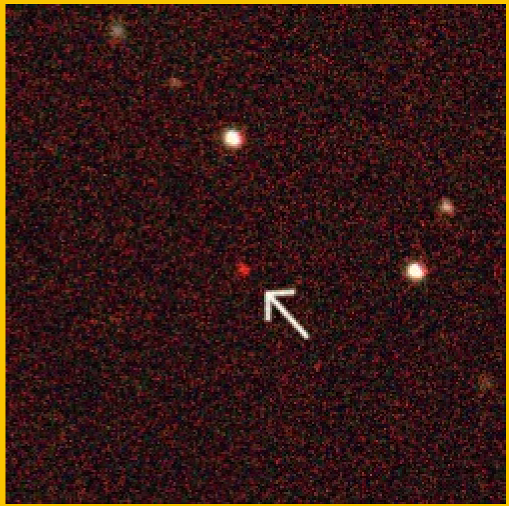
Galaxies are few and faint at high-redshift



- A spectrum is worth a thousand pictures.

What are quasars



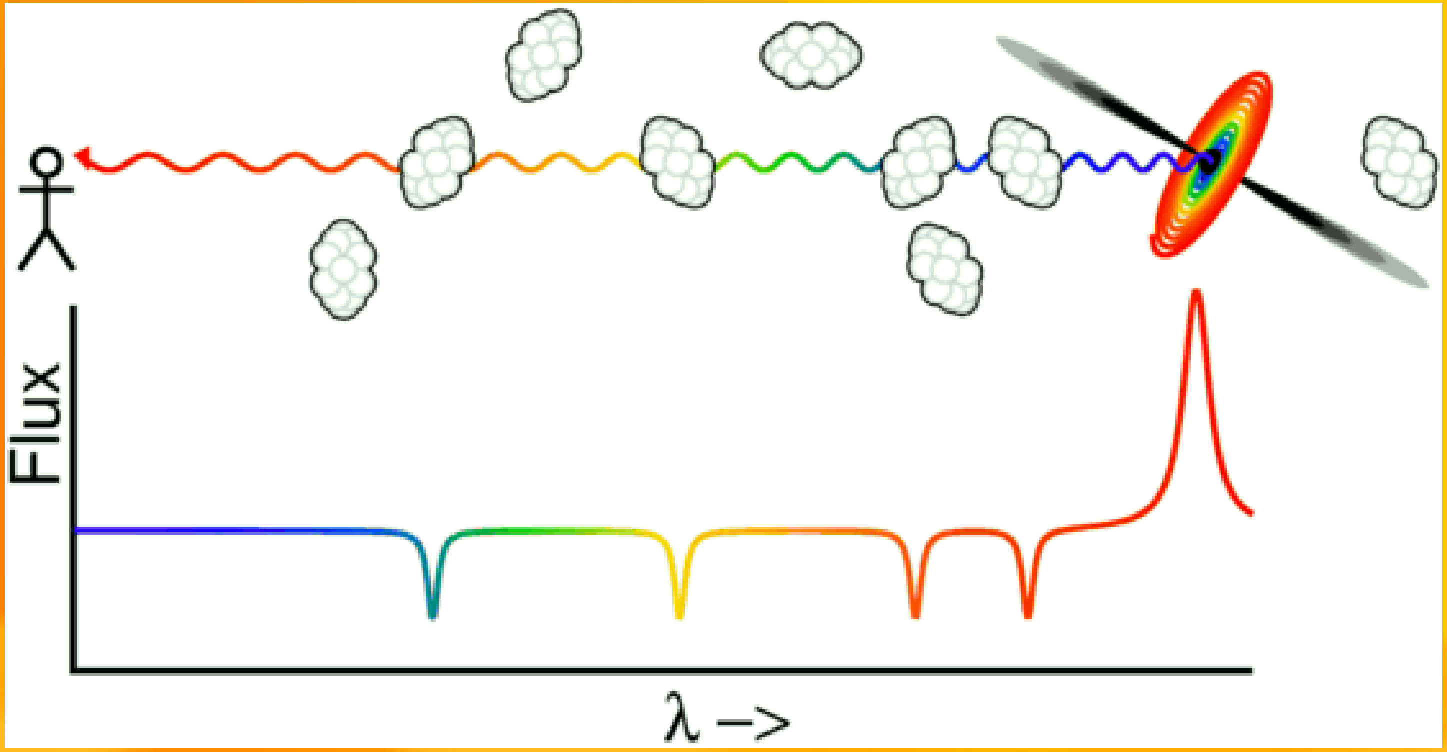


- Brightest things in the Universe
- Bright, energetic AGN – can see them very far
- Featureless spectrum with a few broad emissions

- 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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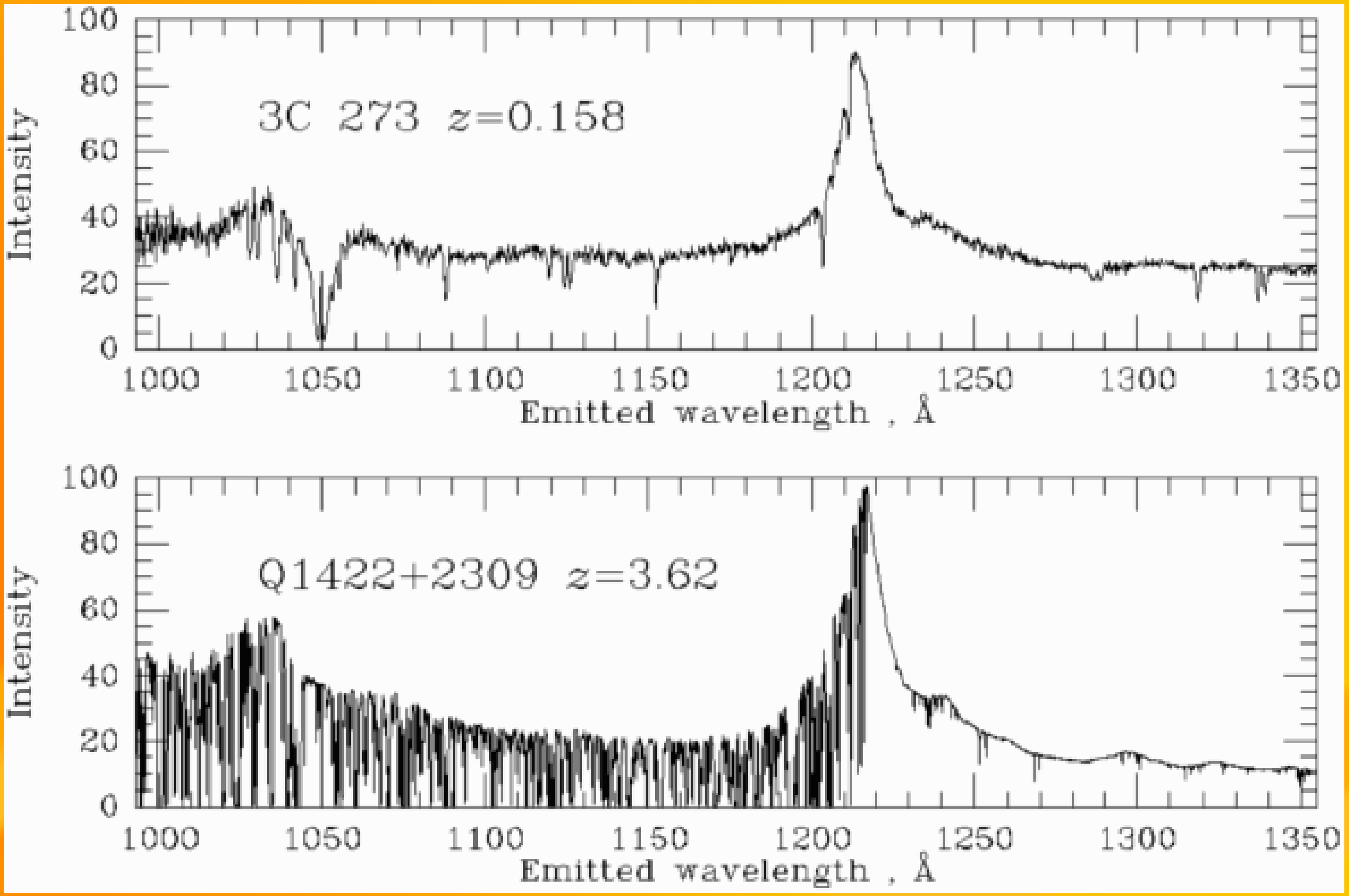


From dark matter to flux

- Absorption done by neutral hydrogen in photo-ionisation equilibrium, but we can connect it to dark-matter fluctuations:
  - **dark matter → baryons**: On large scales baryons follow dark matter
  - **baryons → neutral hydrogen**: neutral hydrogen in photoinization equilibrium
  - **neutral hydrogen → flux** : atomic physics

Ly-alpha forest history

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

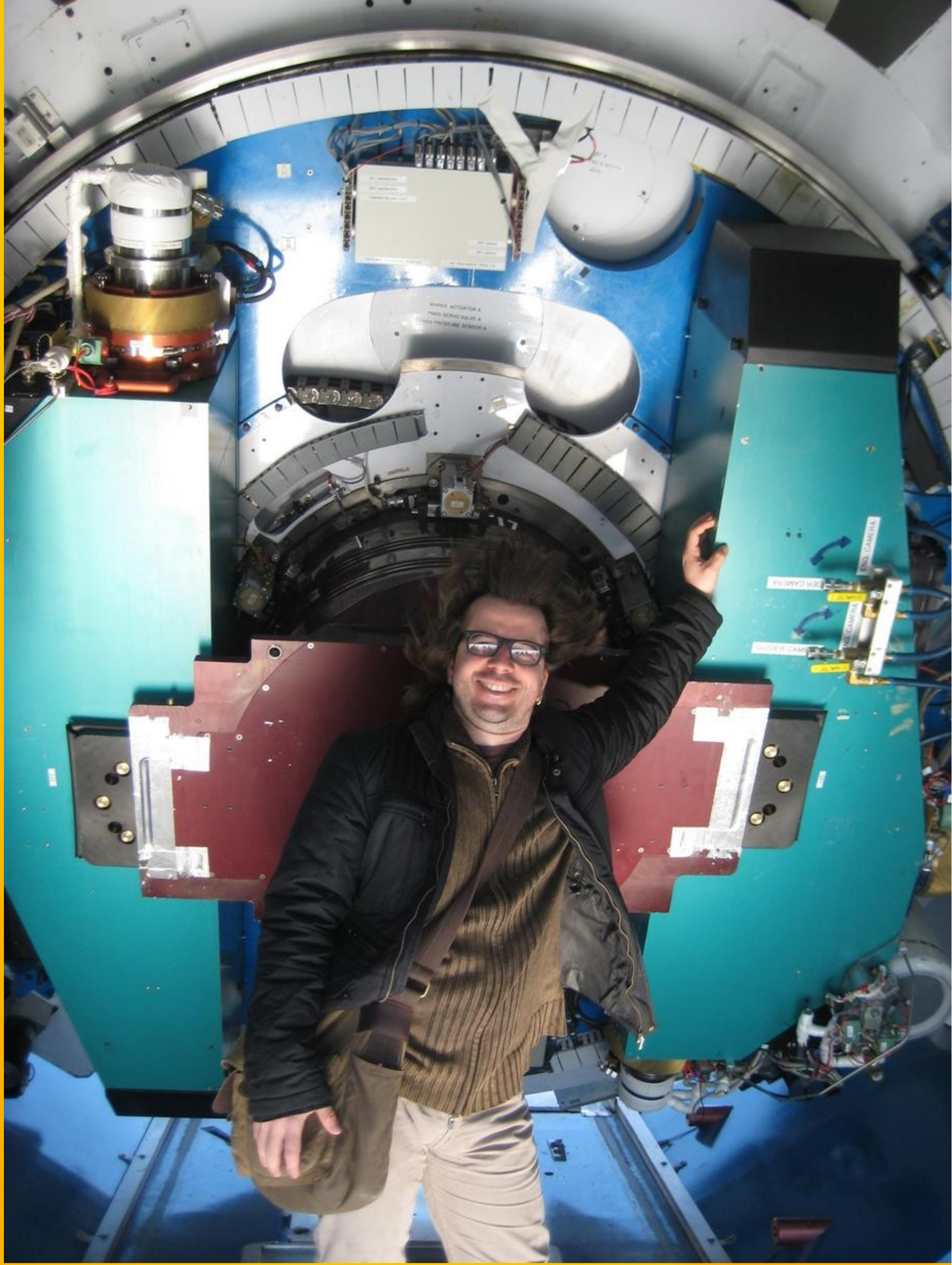
Ly-alpha forest history

- 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

Baryon Oscillation Spectroscopic Survey

- BOSS is one of 4 experiments making up SDSS3.
- Uses 2.5m SDSS scope:
  - Large etendue
- A 1000 fiber spectrograph
- Medium resolution: R~2000
- Wavelength: 360 (UV) – 1000 nm (IR)
- 5 year experiment

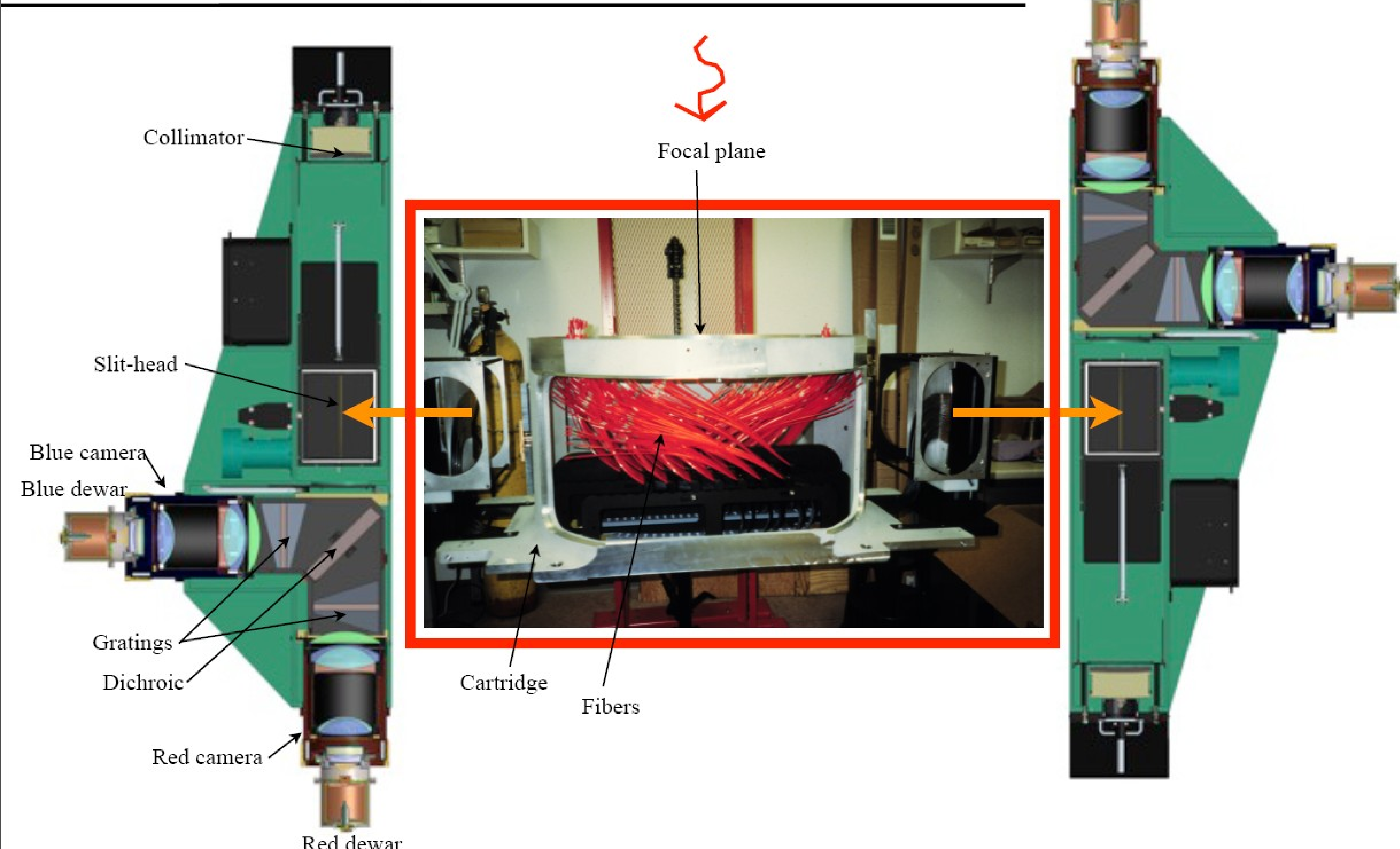
BOSS



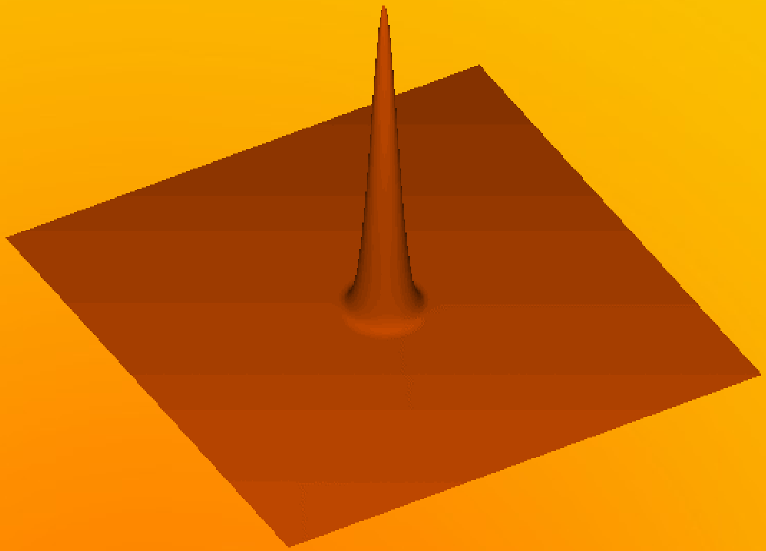
- Spectra of:
  - million LRGs ($z<0.7$)
  - 160,000 QSOs with usable forest
- 10,000 sq degrees
- Comissioning: from Aug 09
- Science data: from Dec 09
- Expected to complete in 2014

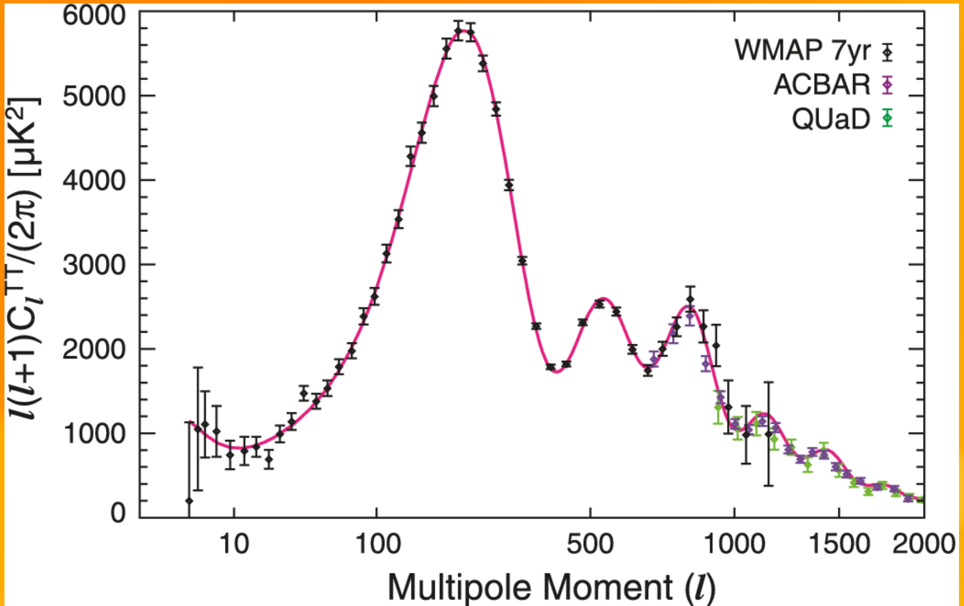

3945

How BOSS works



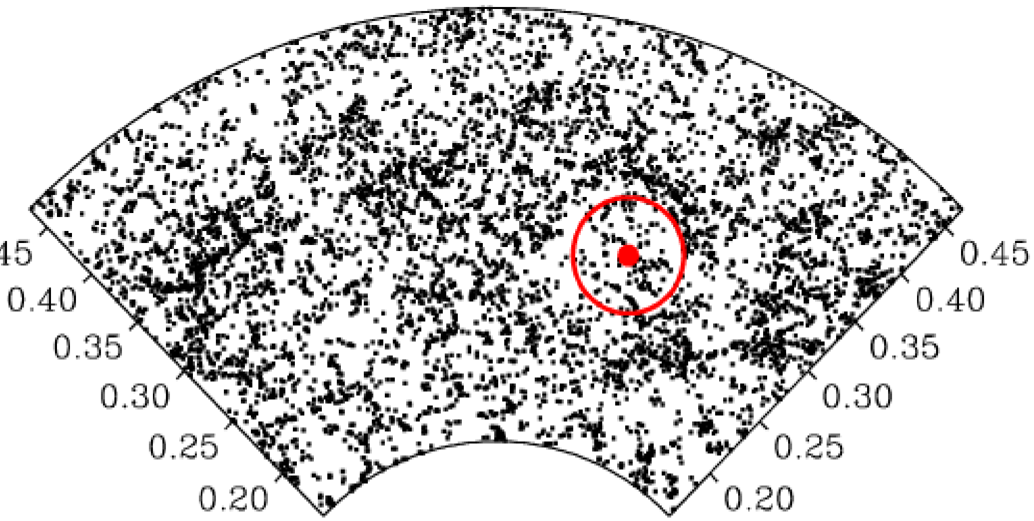
Baryonic acoustic oscillations



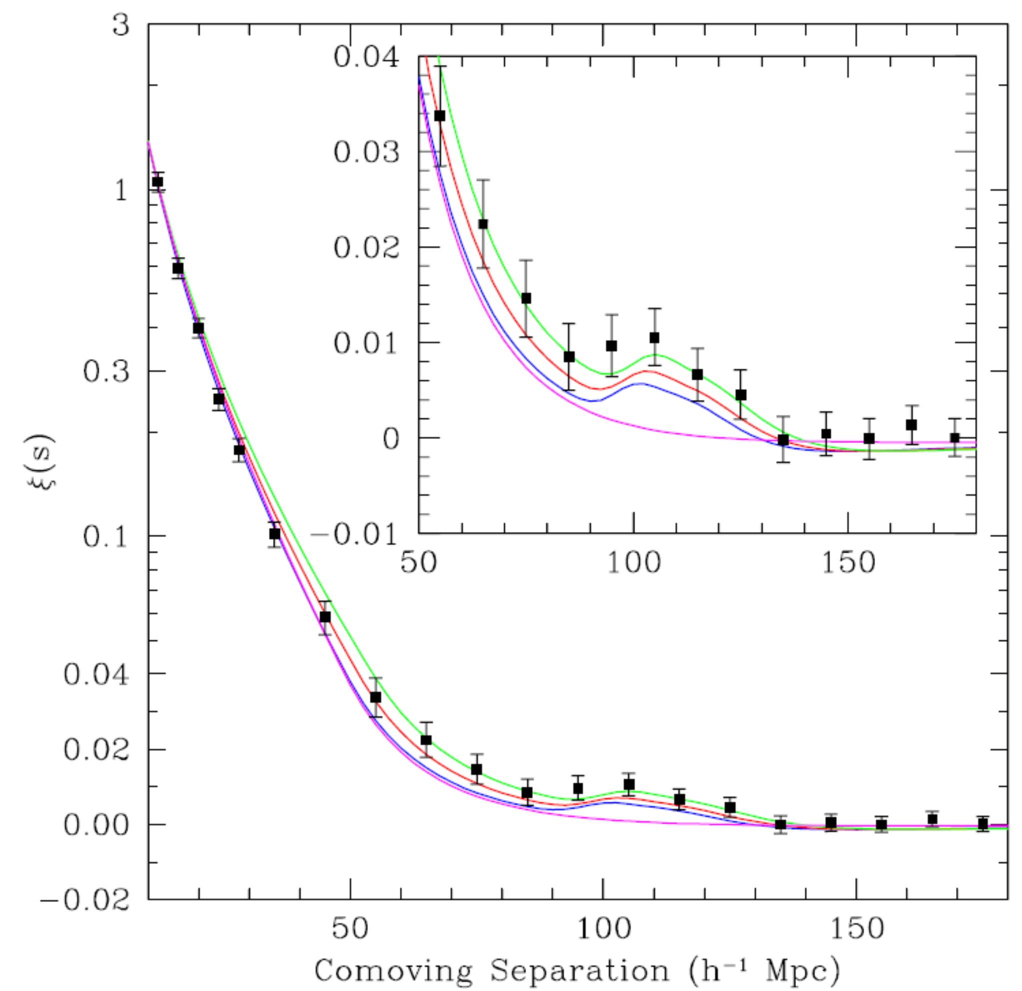


- Before recombination, primordial plasma supports acoustic waves
- These imprint a characteristic scale into the correlation properties of dark matter

Baryonic acoustic oscillations

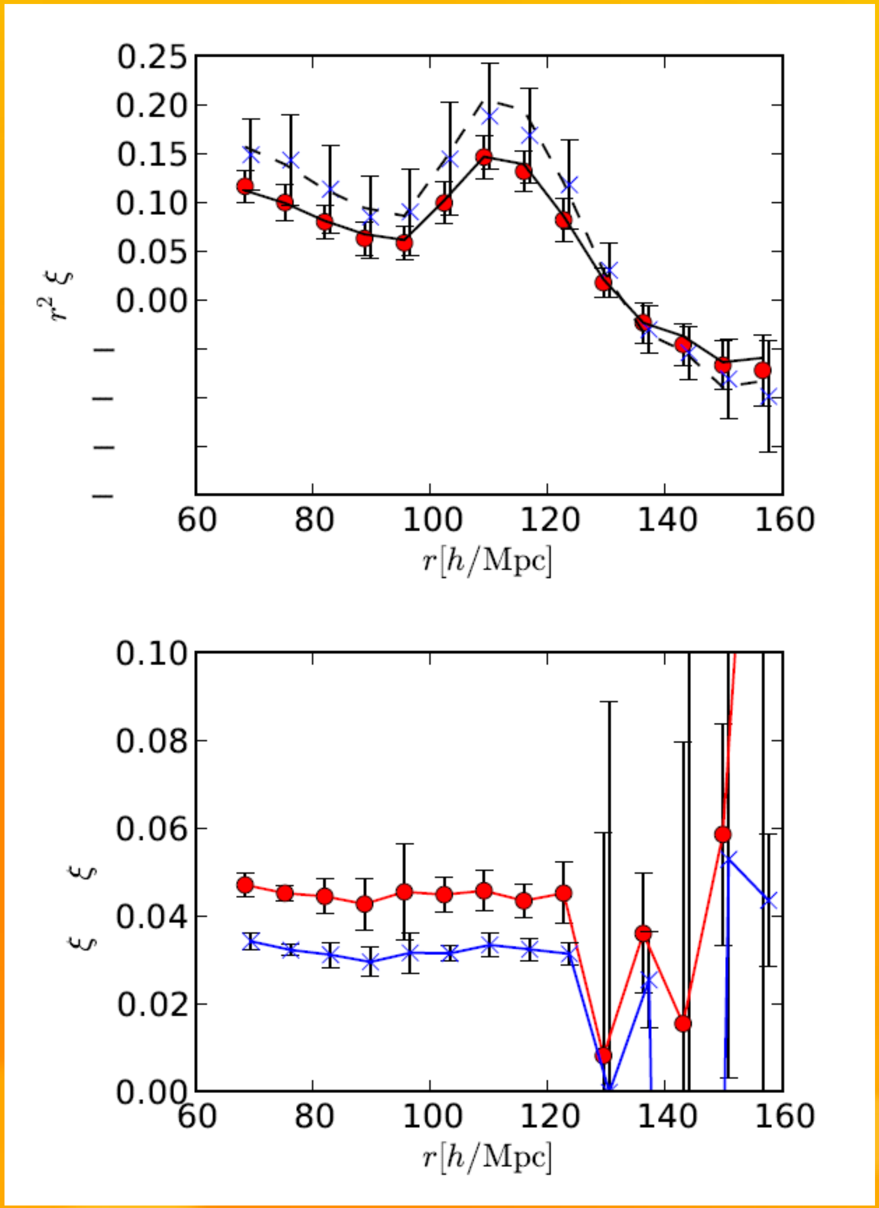


SDSS data
From Eisenstein et al, 2005



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

BAO with LYA



- Mentioned by PM in 2001, 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 and LyA

- Measuring BAO with LyA one of the primary goals of BOSS
- Leap of faith: nobody has measured LSS with LyA so far, yet alone BAO
- Our first effort was to publish a convincing detection of correlations on cosmological scales

The Lyman-α forest in three dimensions: measurements of large scale flux correlations from BOSS 1st-year data

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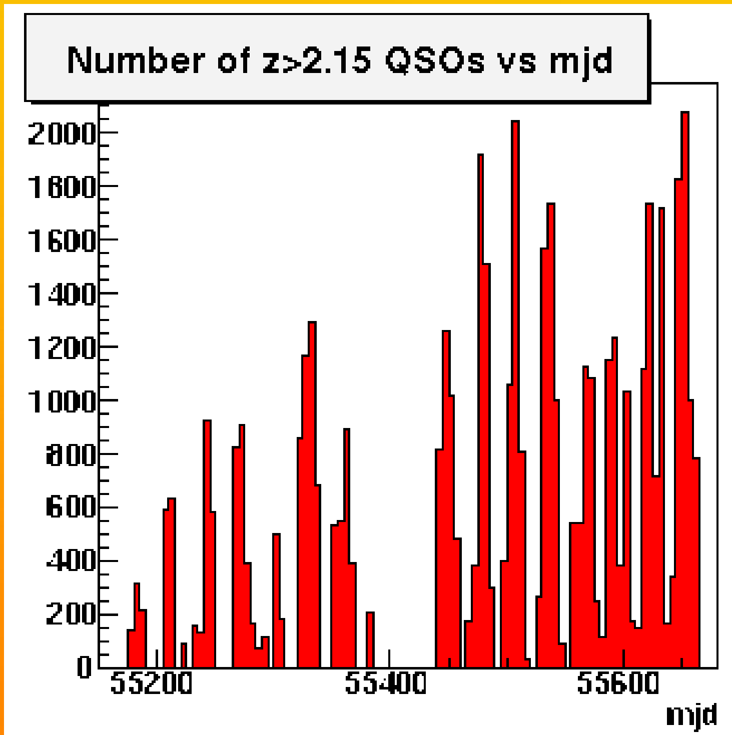
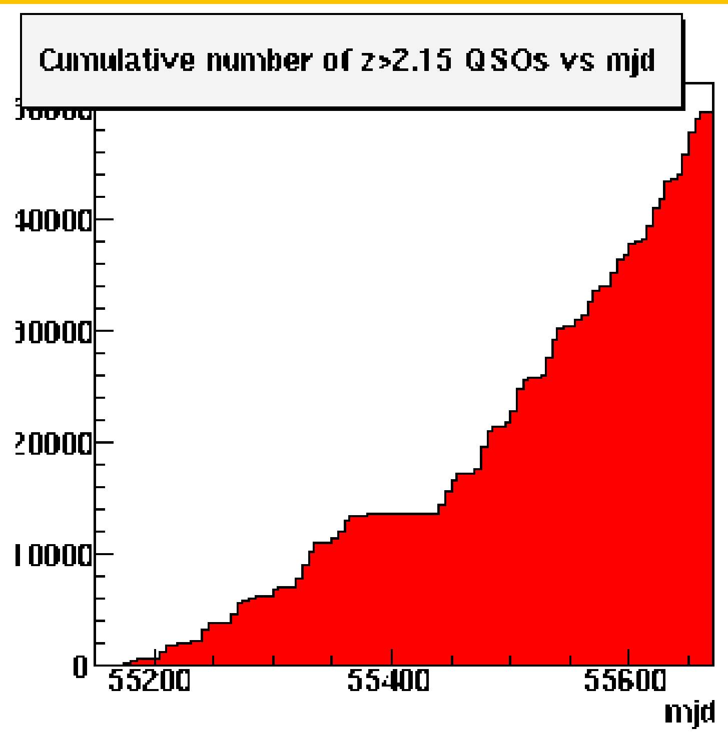
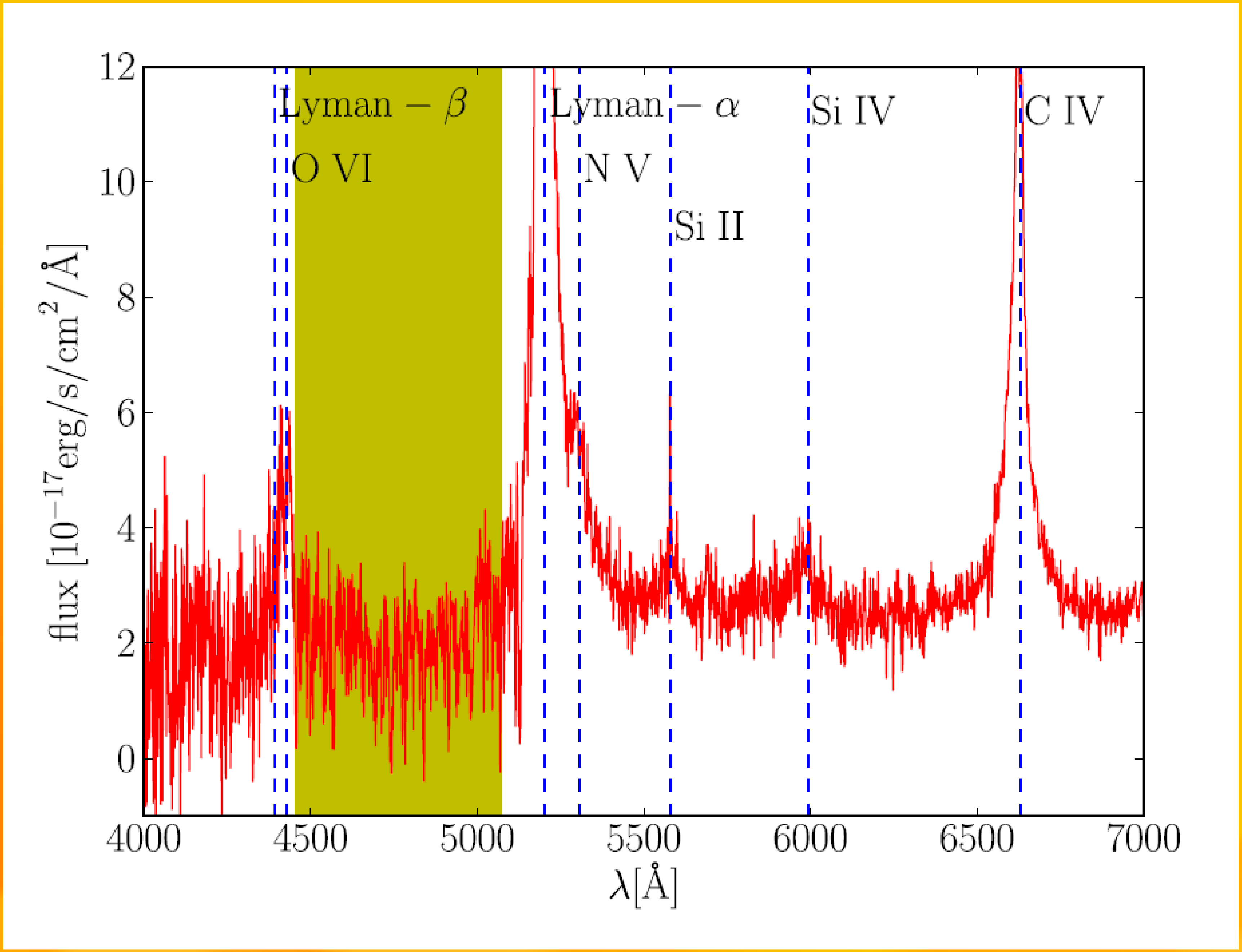
Targets



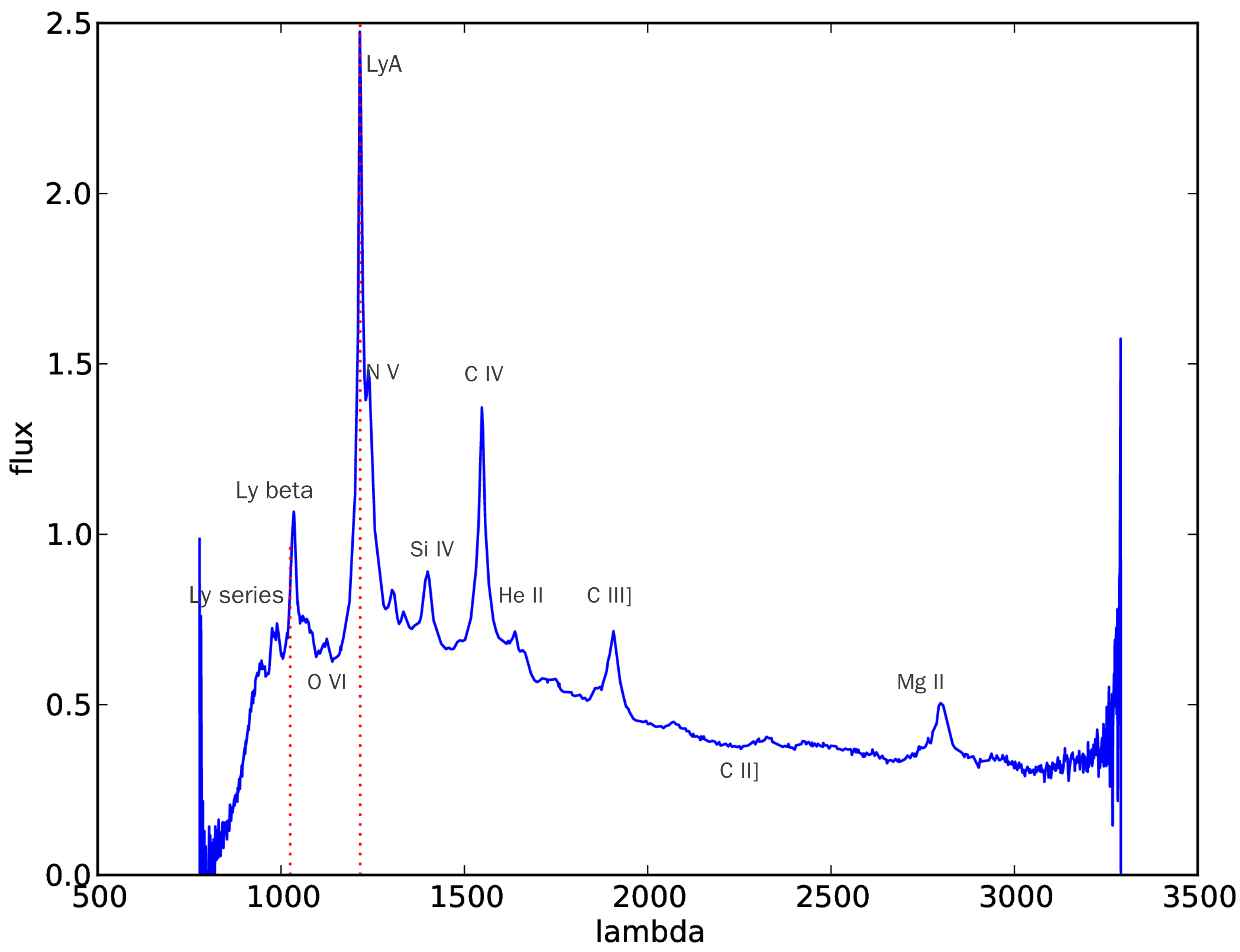


- Efficiency relatively low to start, but getting better every day
- Failed targets are stars, low z QSOs
- Efficiency increase dramatically if one uses UV, IR or variability information – this has been put in place slowly but certainly

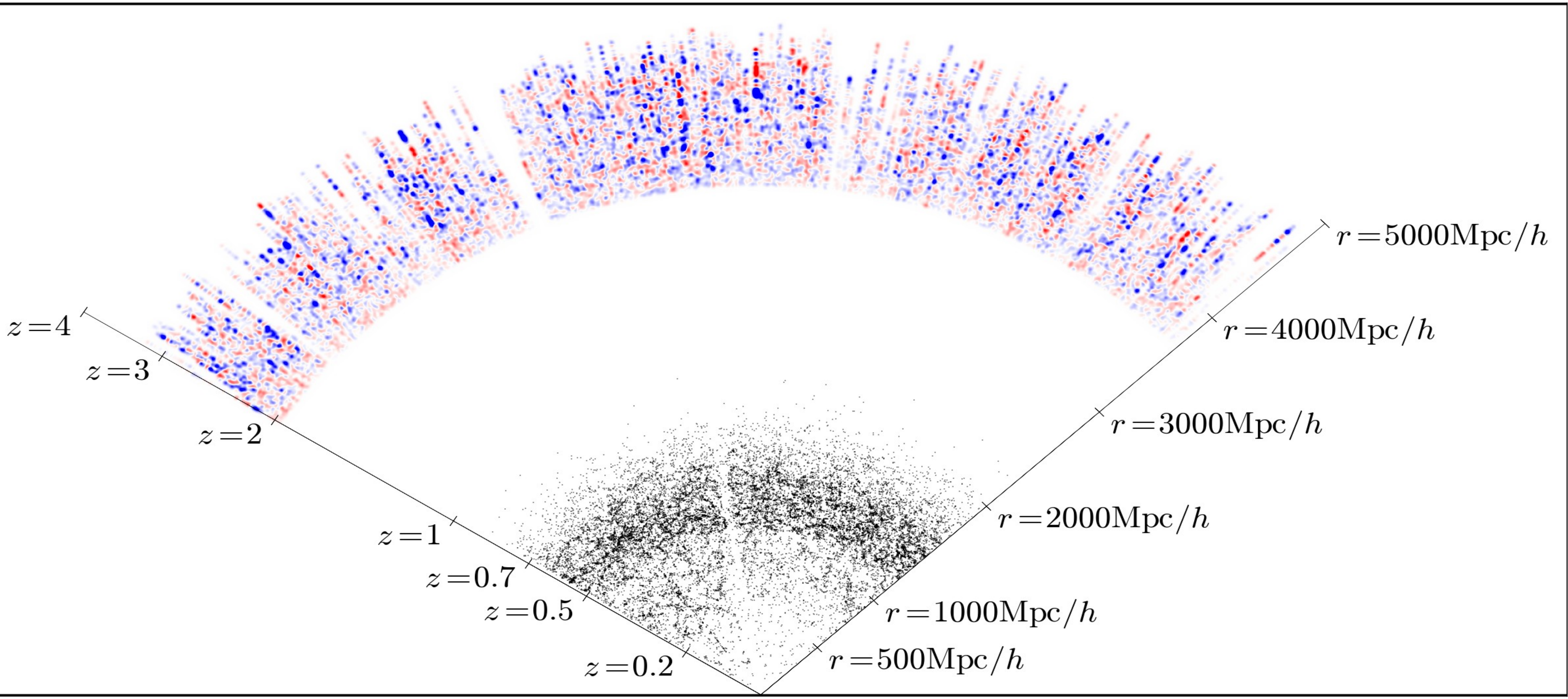


- A typical spectrum: a noisy survey.

4800 BOSS QSOs



BOSS average rest frame spectrum


$z = 4$
$z = 3$
$z = 2$
$z = 1$
$z = 0.7$
$z = 0.5$
$z = 0.2$
$r = 5000\mathrm{Mpc}/h$
$r = 4000\mathrm{Mpc}/h$
$r = 3000\mathrm{Mpc}/h$
$r = 2000\mathrm{Mpc}/h$
$r = 1000\mathrm{Mpc}/h$
$r = 500\mathrm{Mpc}/h$

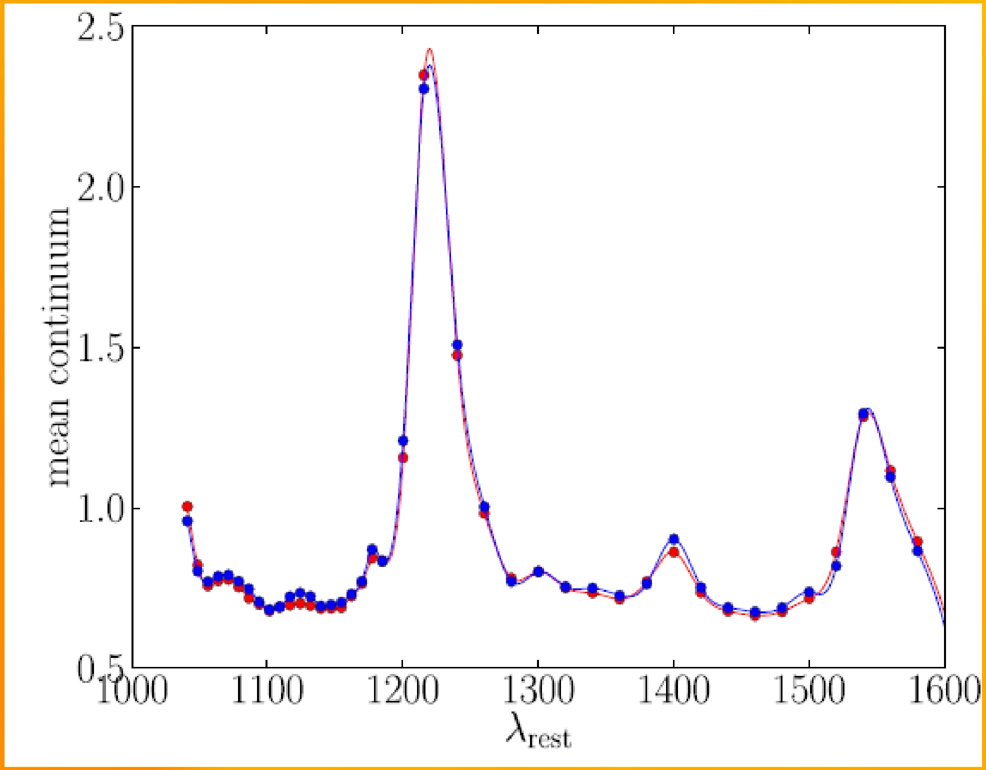
Measuring correlations

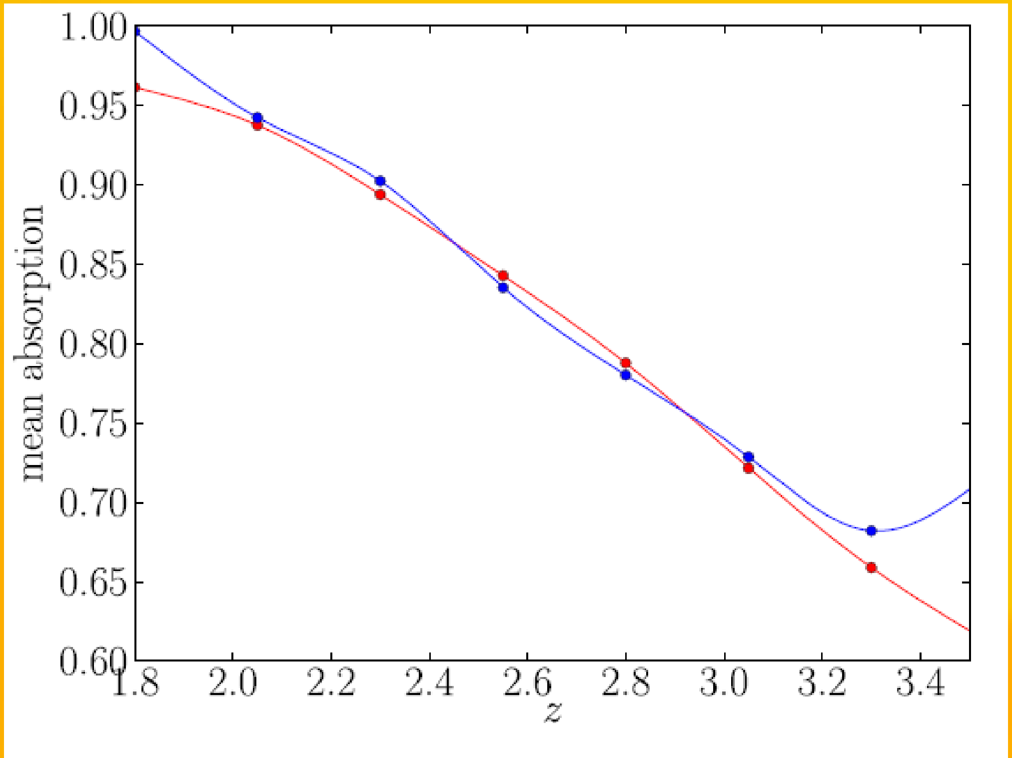
- First one fits for mean continuum and mean absorption
- Then derive estimates of the mean flux fluctuations
- The one measures the correlation function as function of: redshift, distance, angle along the line ofsight
- Will show results for 1^{st} year data (14,000 QSOs)
- We currently have around 38,000 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:
  - Redshift evolution, non-parallel los.
  - high-density systems: LLS/DLA
  - metal correlations

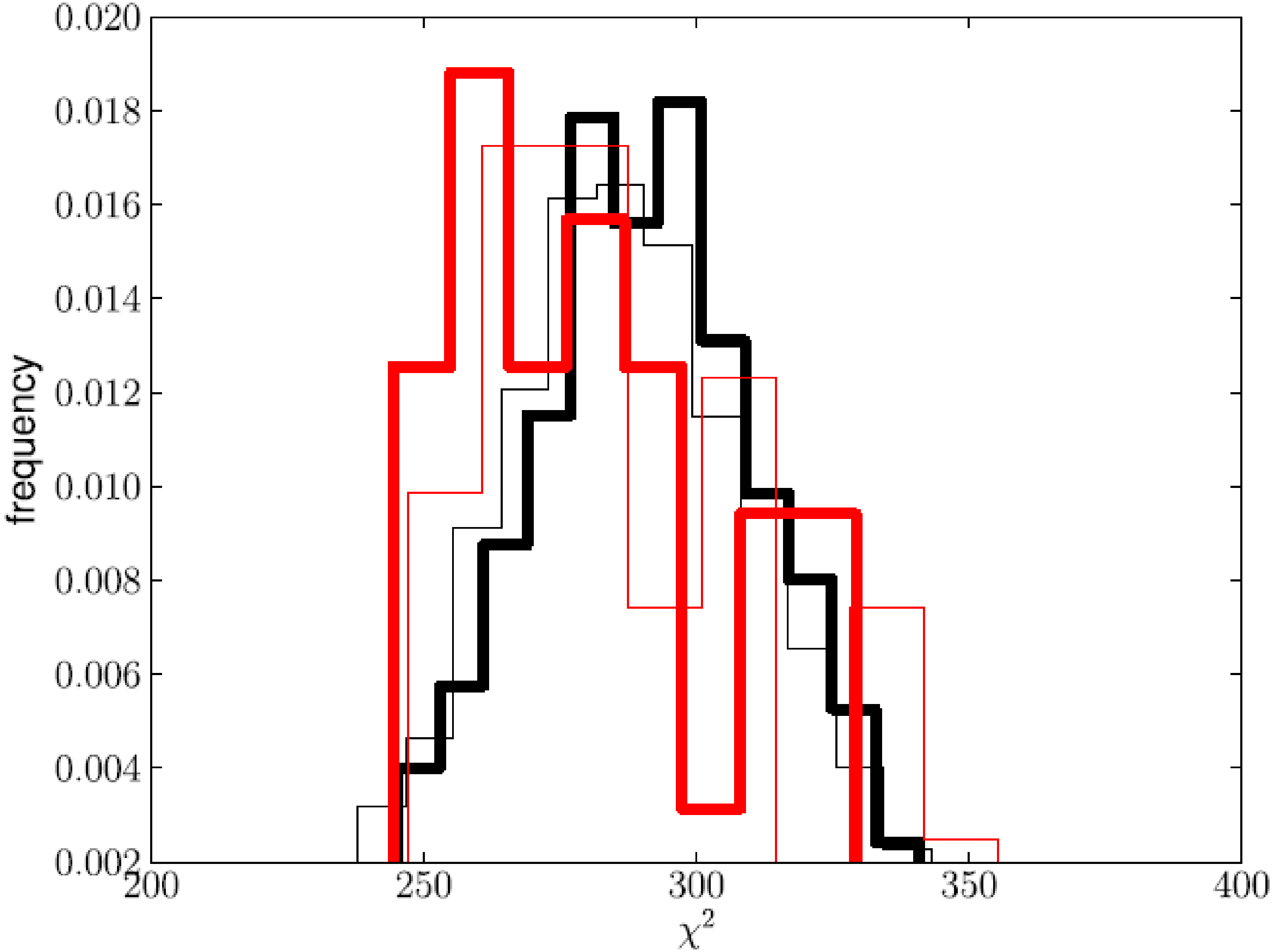
Continuum fitting

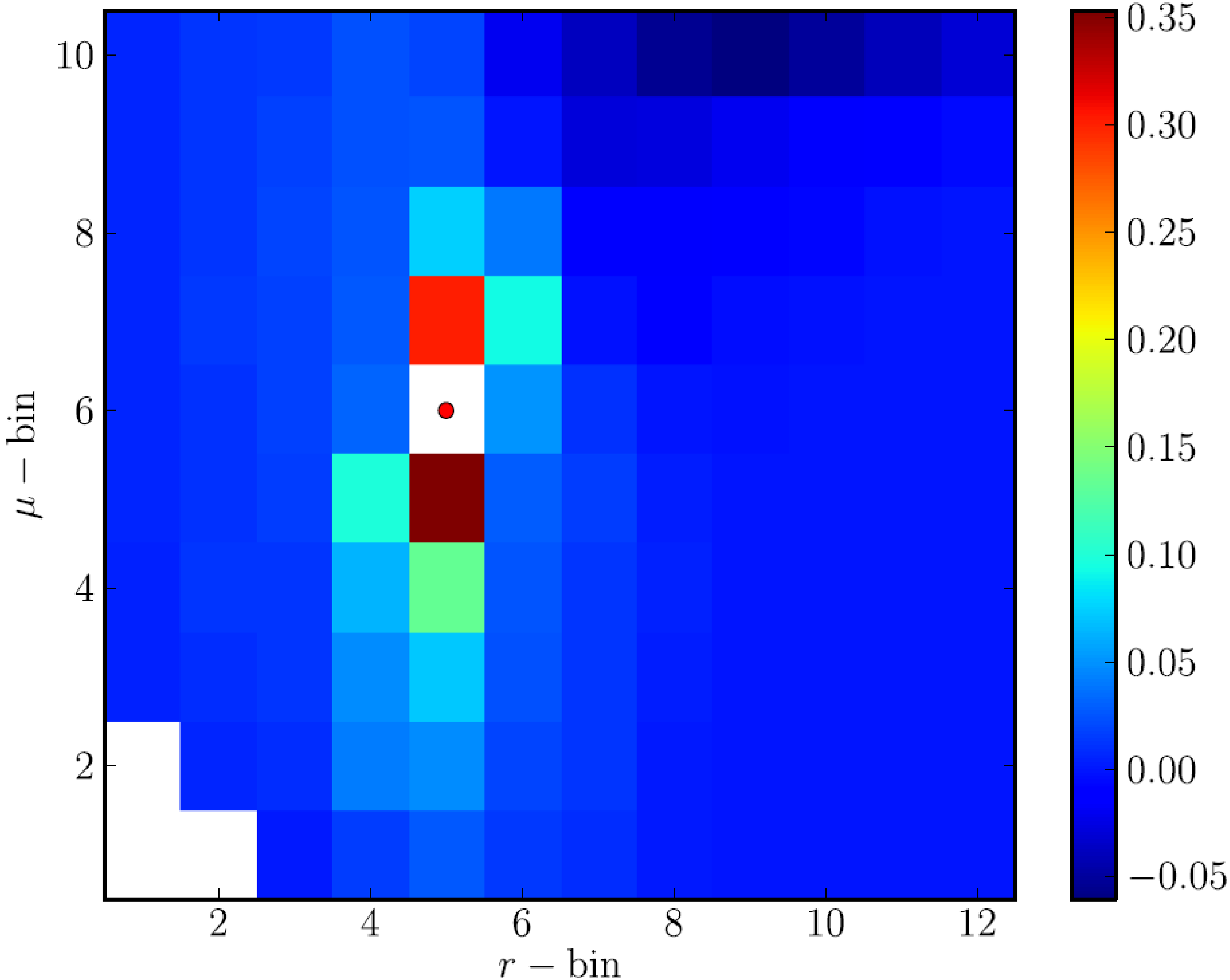




Errorbars

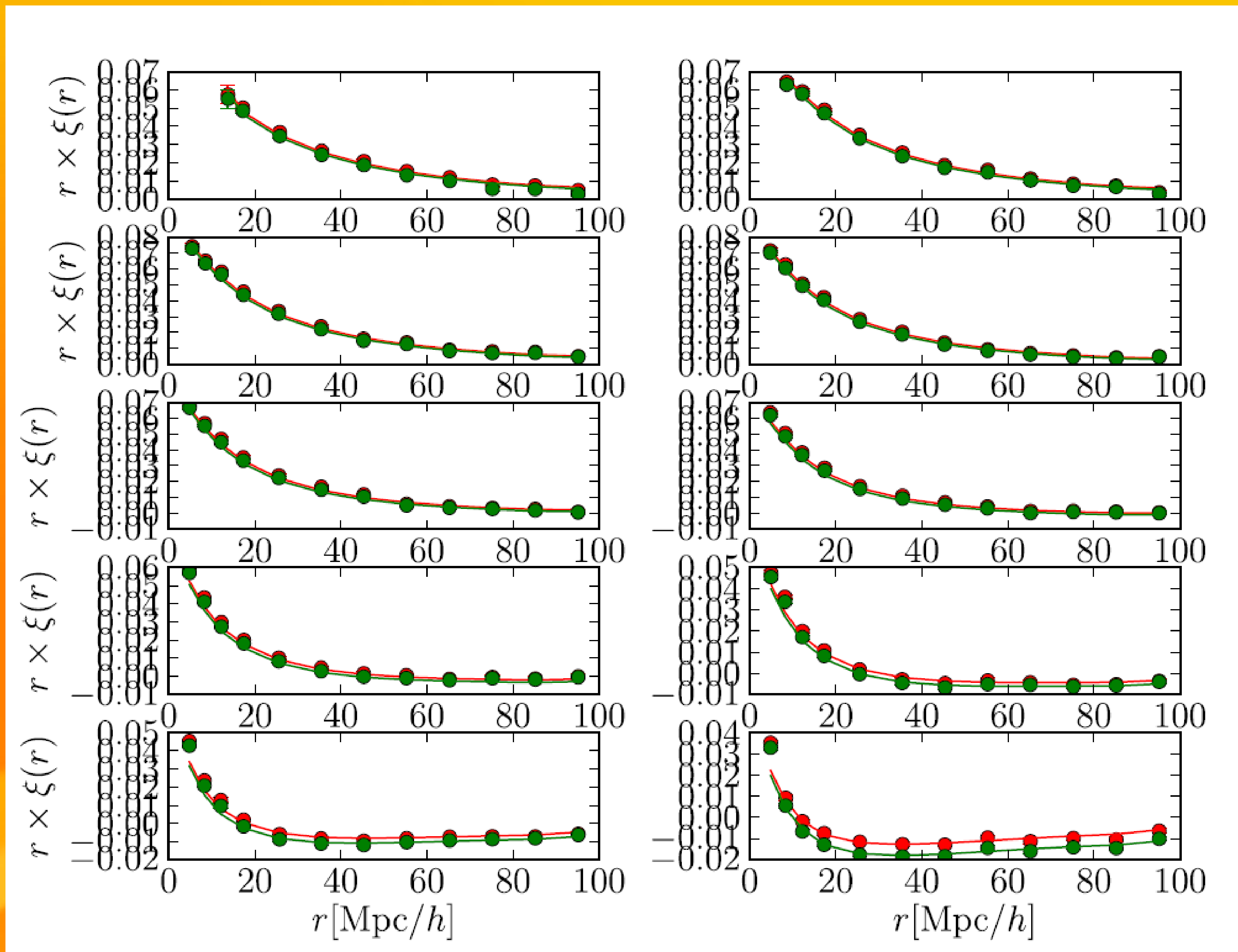
- Errorbars are very though
- Measurements very correlated – we have 330 data-points → over 50,000 matrix elements
- Trivial estimator is N^4 operation, 10^12 times slower than correlation function estimation
- We developed a novel MC technique, that uses the **measured** two-points


0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
frequency
200
250
300
350
400
χ^2

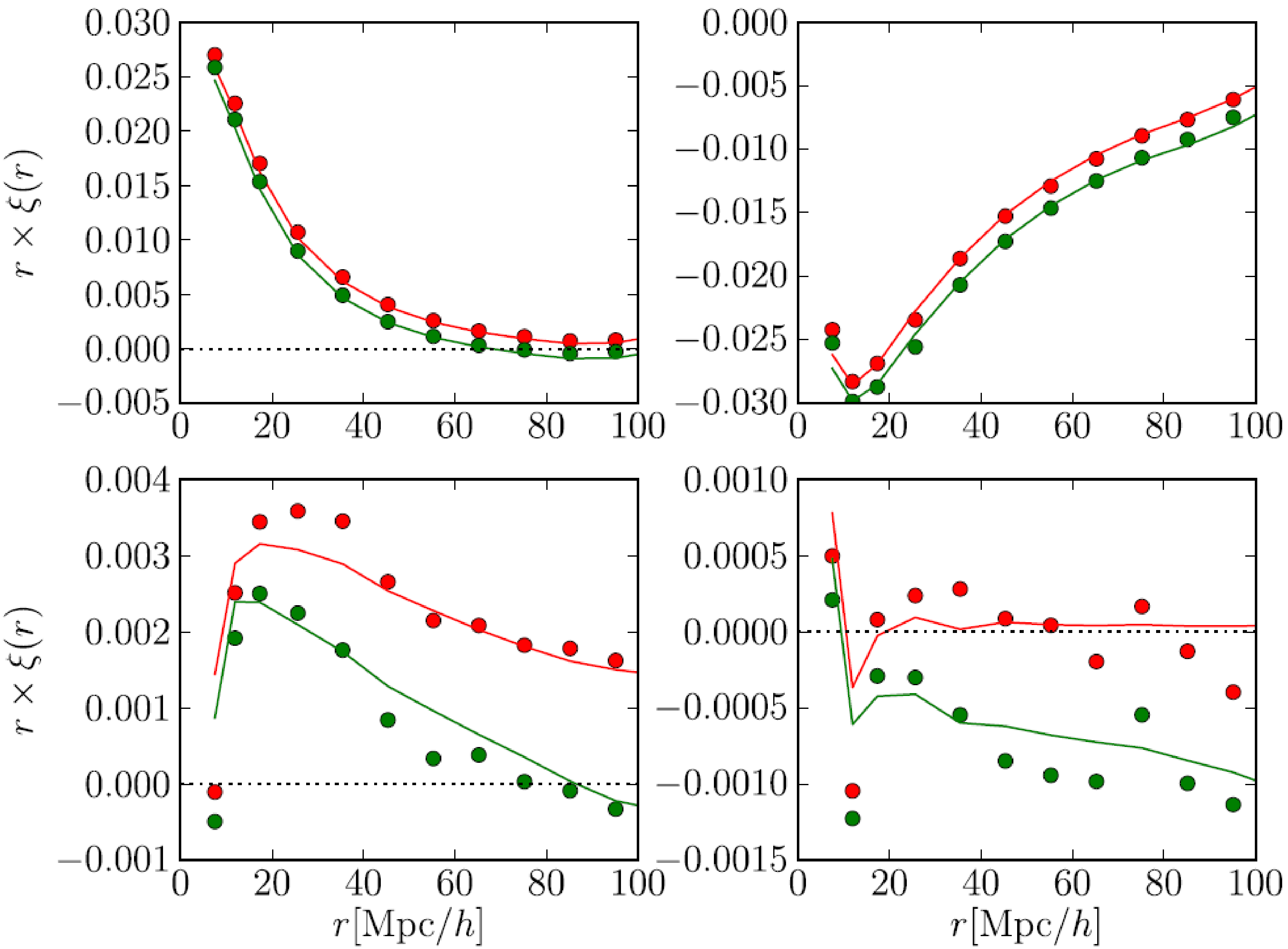


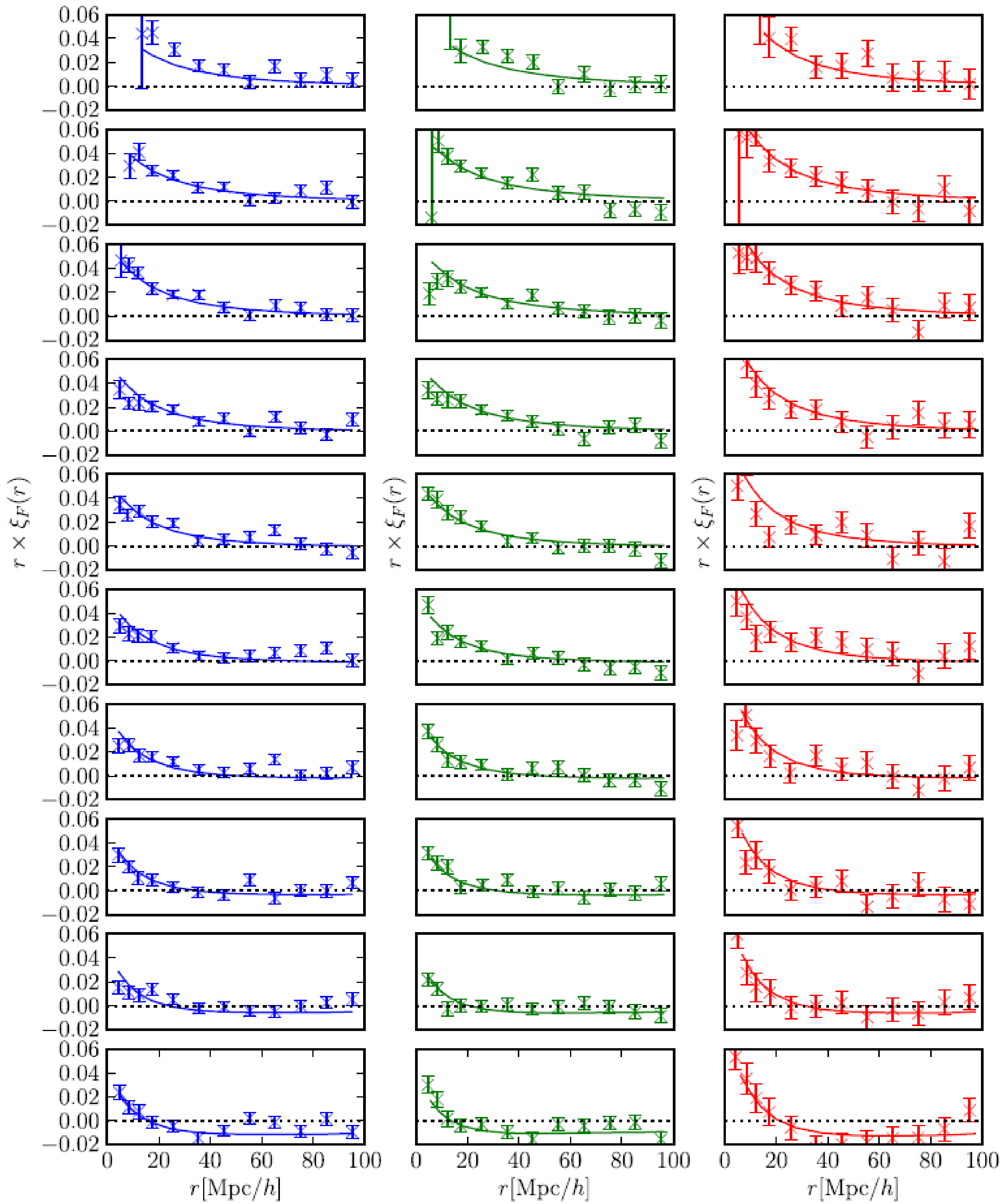
10
8
6
4
2
μ − bin
2
4
6
8
10
12
r − bin
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05

Synthetic data-sets

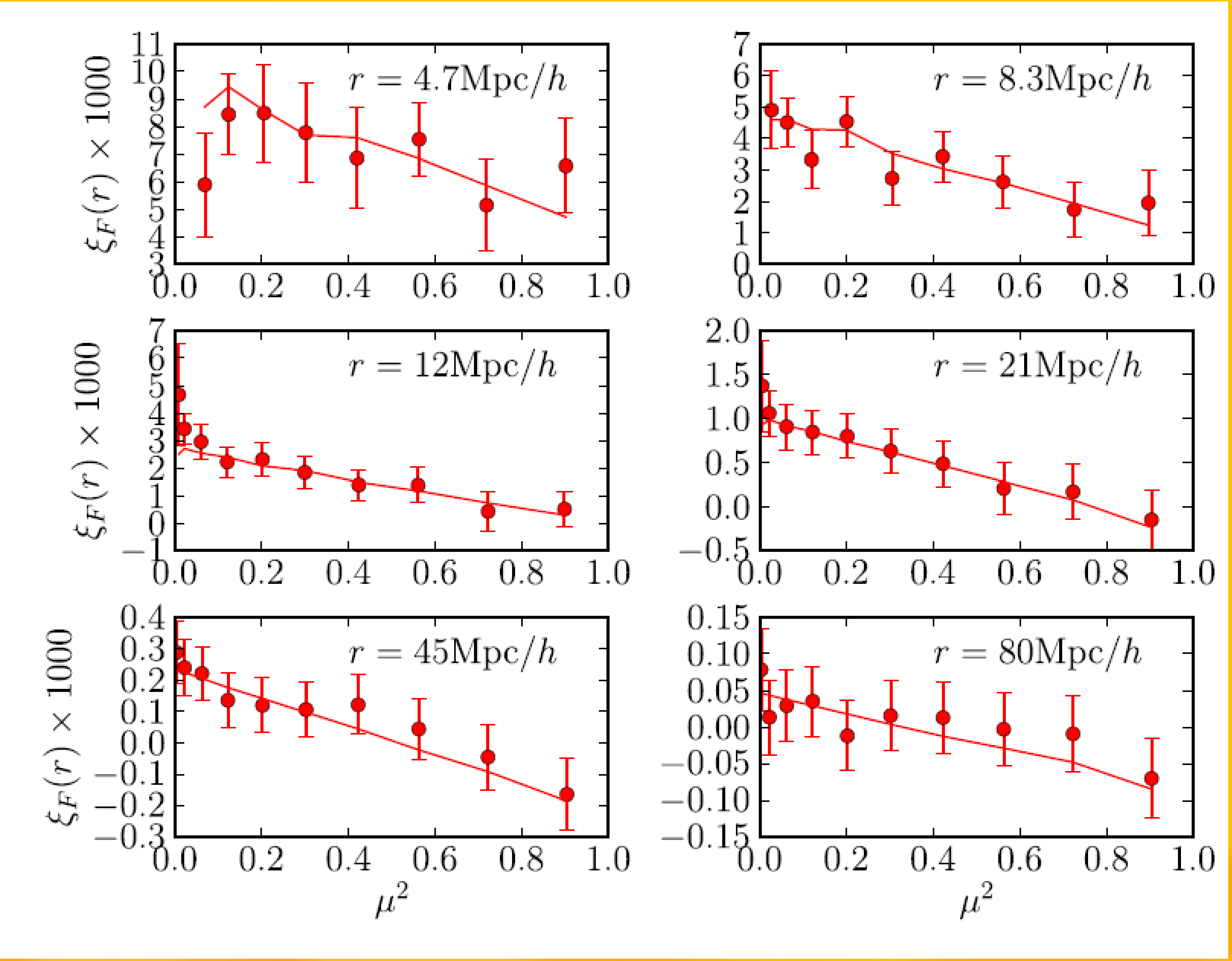


Synthetic data-sets

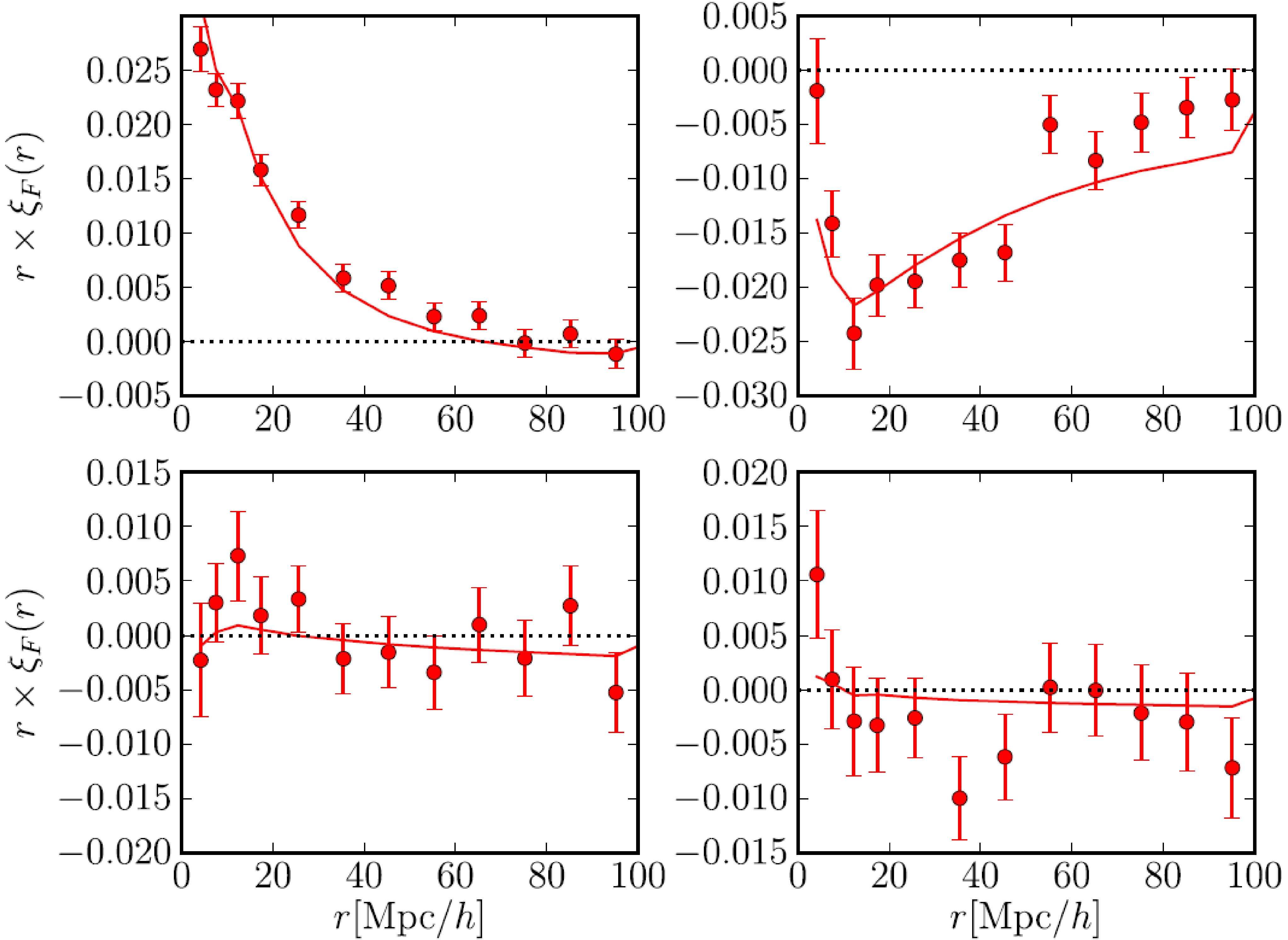




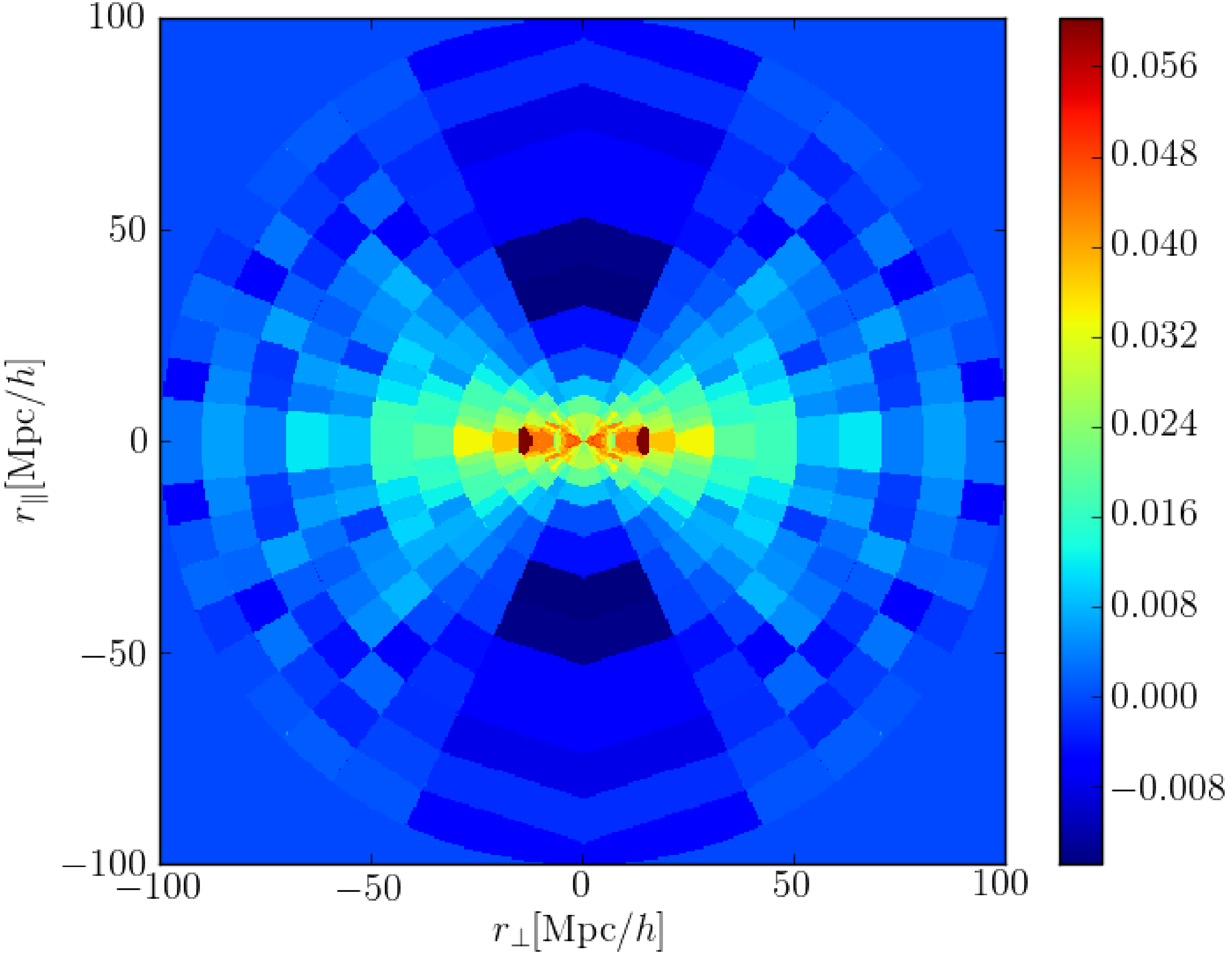
0.06
0.04
0.02
0.00
−0.02
$r \times \xi_F(r)$
0
20
40
60
80
100
r[Mpc/h]

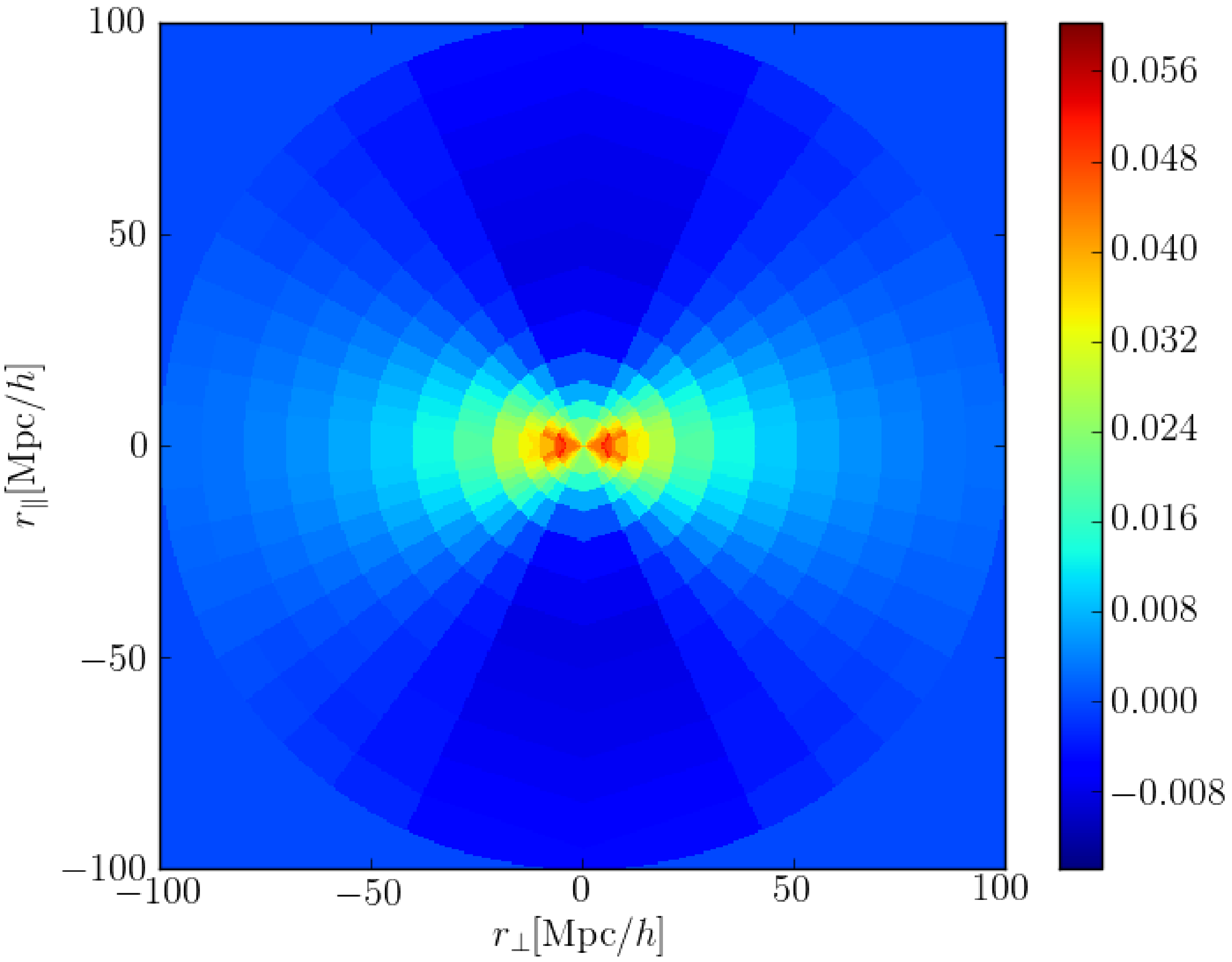


r = 4.7Mpc/h
r = 8.3Mpc/h
r = 12Mpc/h
r = 21Mpc/h
r = 45Mpc/h
r = 80Mpc/h
ξ_F(r) × 1000
μ²



$r \times \xi_F(r)$
$r \times \xi_F(r)$
$r[\mathrm{Mpc}/h]$
$r[\mathrm{Mpc}/h]$


100
50
0
−50
−100
$r_\parallel$[Mpc/h]
−100
−50
0
50
100
$r_\perp$[Mpc/h]
0.056
0.048
0.040
0.032
0.024
0.016
0.008
0.000
−0.008


100
50
0
−50
−100
−100
−50
0
50
100
$r_\parallel$[Mpc/h]
$r_\perp$[Mpc/h]
0.056
0.048
0.040
0.032
0.024
0.016
0.008
0.000
−0.008

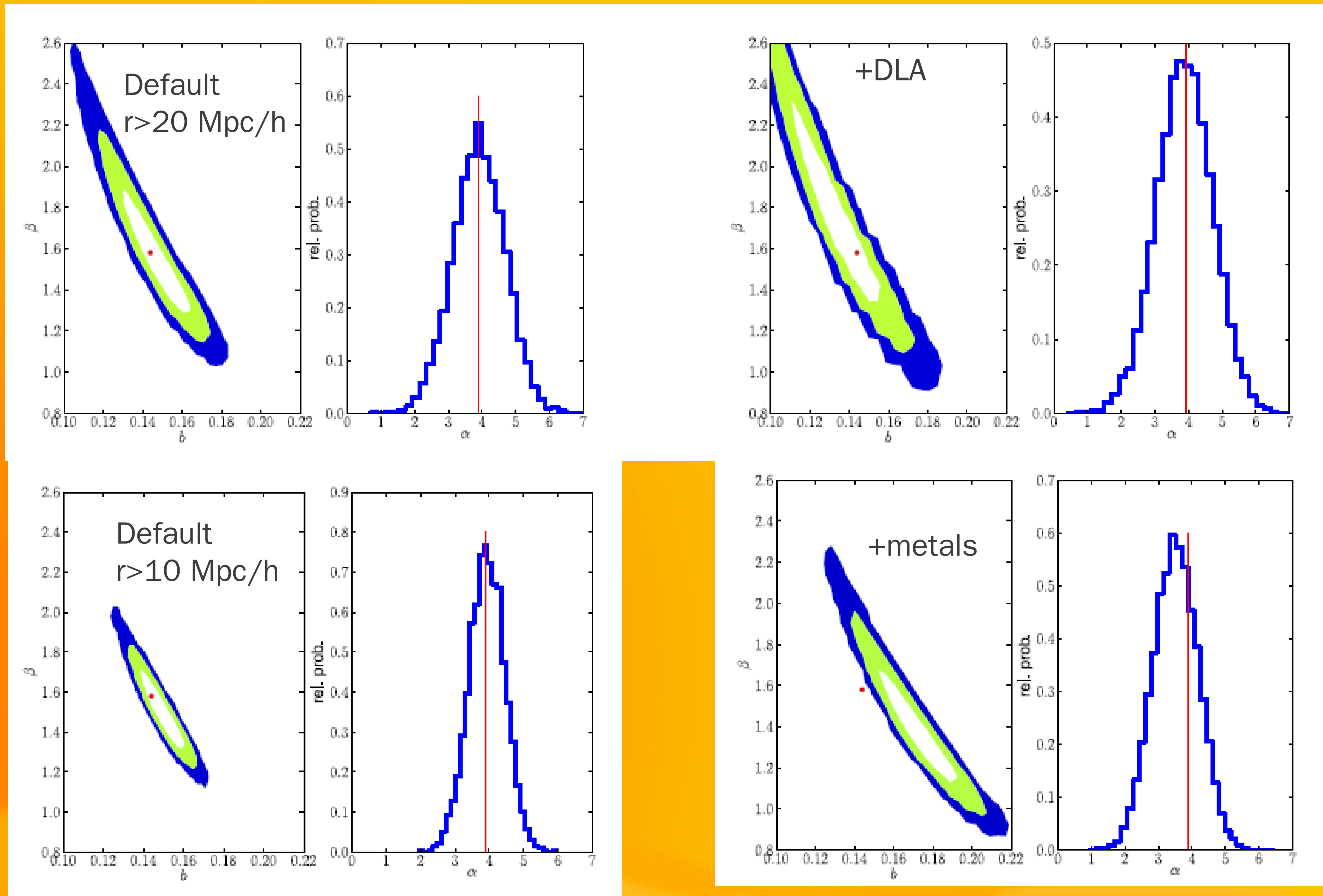
So, what?

- This it the first time, correlations have been seen on scales >5 Mpc.
- Crucially, simplest theory seems to work:
  - Chi^2 around 280 with 300 dof
  - No overwhelming photoionization rate fluctuations
  - No overwhelming HeII reionization
  - No overwhelming instrumental contamination: sky subtraction in particular was a big unknown

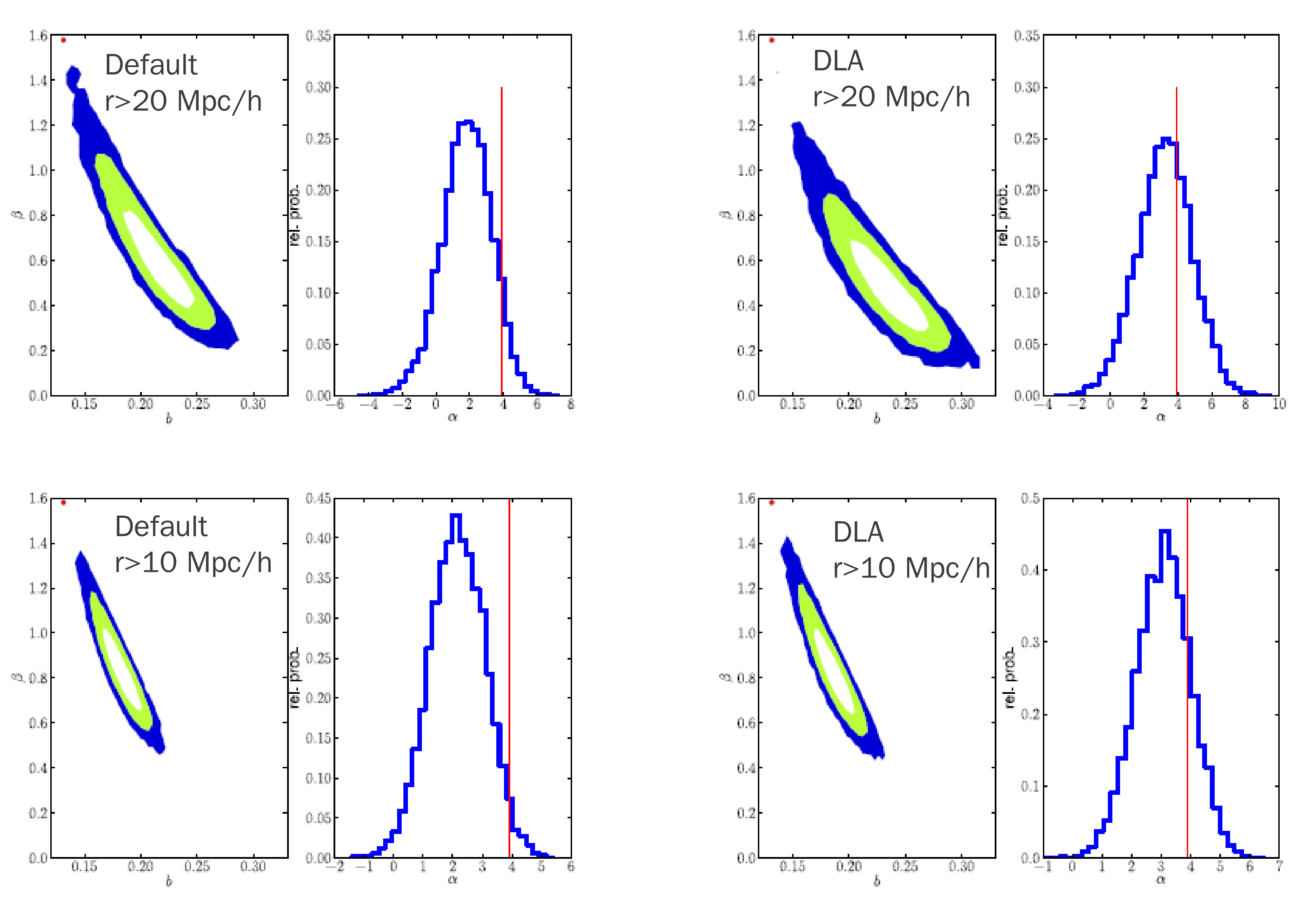
Parameters Fitting

- 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.

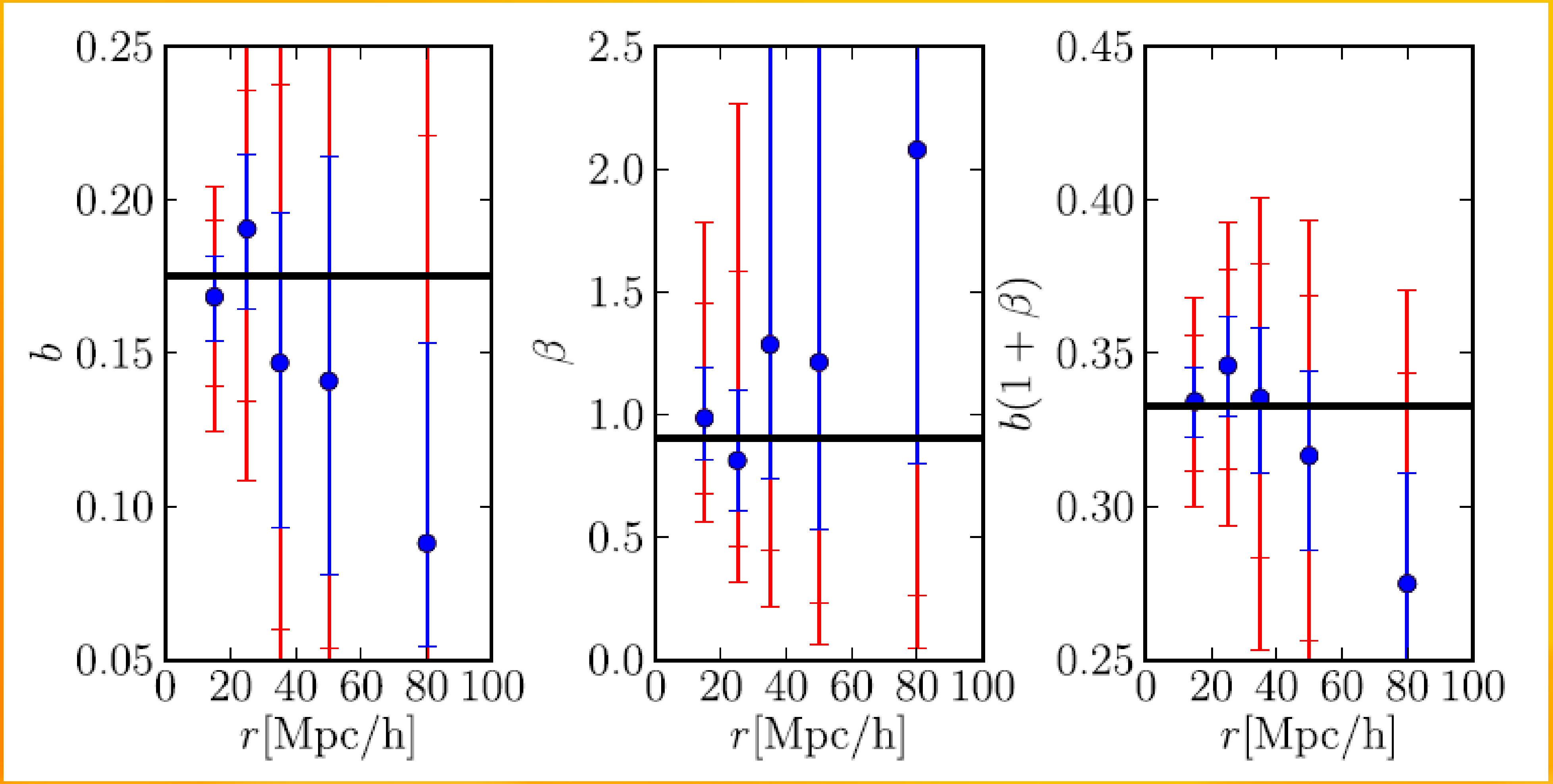
Synthetic data



Real data



Default
r>20 Mpc/h
DLA
r>20 Mpc/h
Default
r>10 Mpc/h
DLA
r>10 Mpc/h
β
b
rel. prob.
α

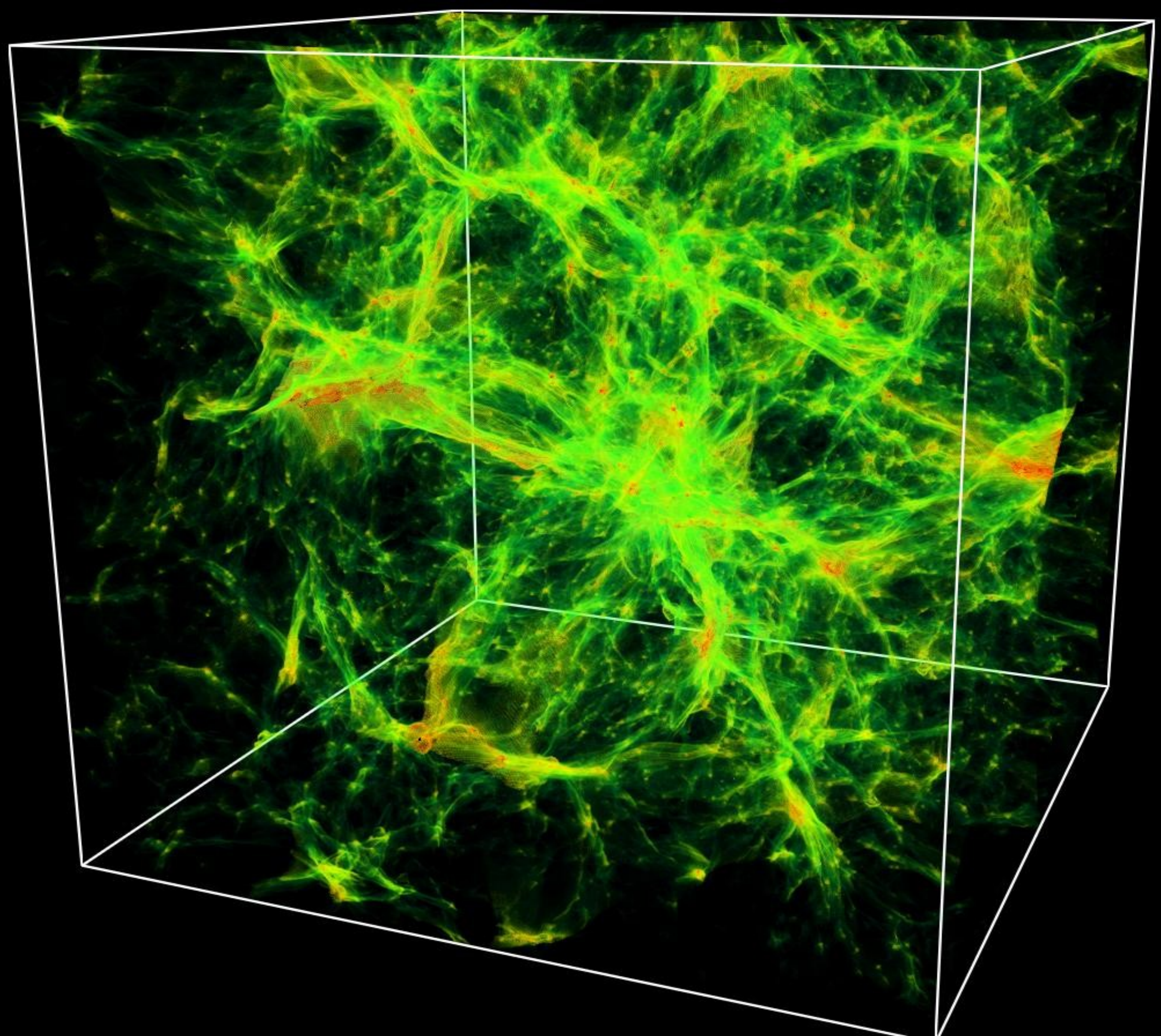


0.25
0.20
0.15
0.10
0.05
b
0 20 40 60 80 100
r[Mpc/h]
2.5
2.0
1.5
1.0
0.5
0.0
β
0 20 40 60 80 100
r[Mpc/h]
0.45
0.40
0.35
0.30
0.25
$b(1+\beta)$
0 20 40 60 80 100
r[Mpc/h]

Conclusions

- BOSS was the first to measure three-dimensional fluctuations in Lya forest to cosmological distances
- Data well described by a biased linear theory
- High bias → good for BAO detection
- If you believe there are no systematics, EdS excluded at Delta chi^2=95
- We don't measure pure flux fluctuations, but a mixture of forest, high column systems, metals...
- Next target is BAO

End

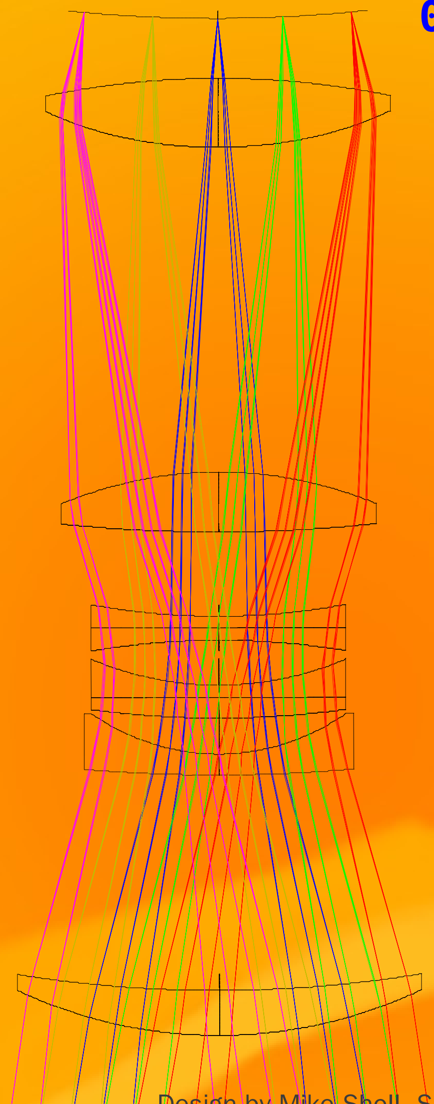


Cen et al

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



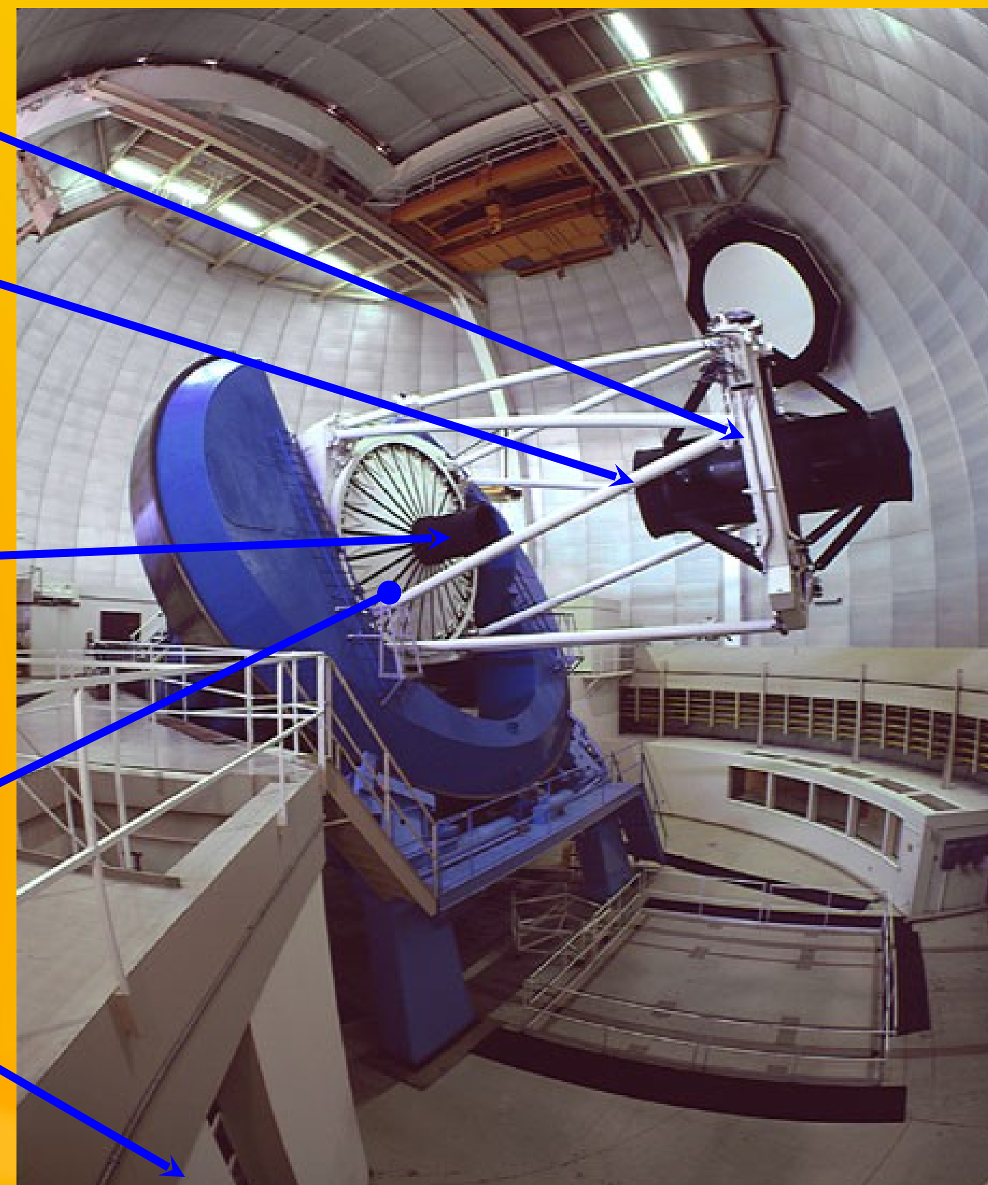
5000 fiber positioners, 0.9m focal plane

Corrector Lens + ADC

Fiber positioning Camera

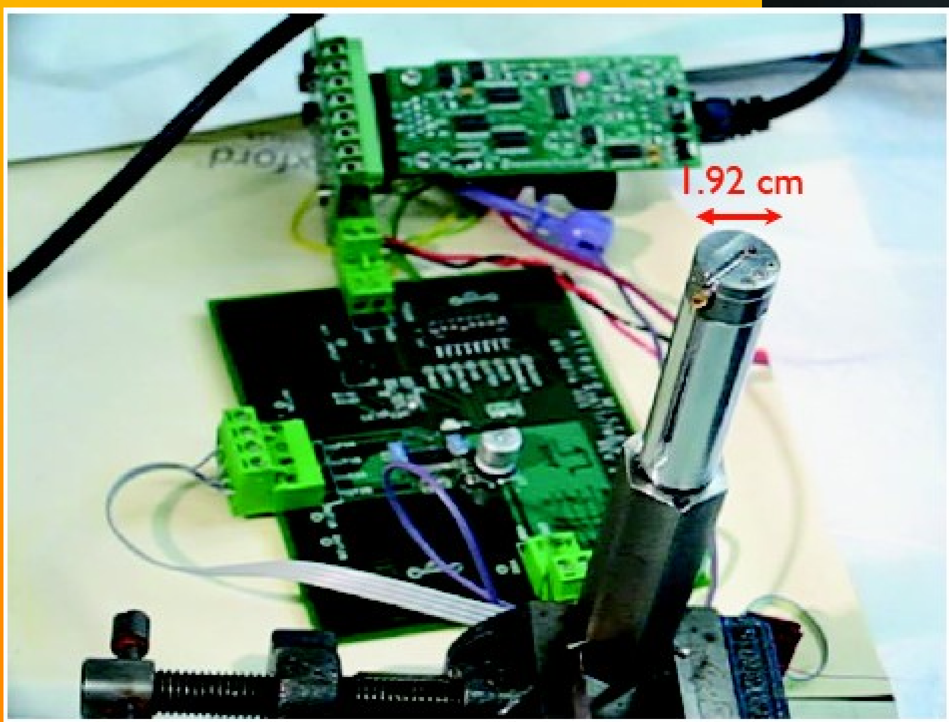
Fiber run (bare fibers)

10 spectrographs



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

Fiber positioner



LBNL prototype

LAMOST focal plane fiber positioner

BigBOSS: 3 percent of Universe