Lyman-α forest as a precision cosmology probe

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IG matters,
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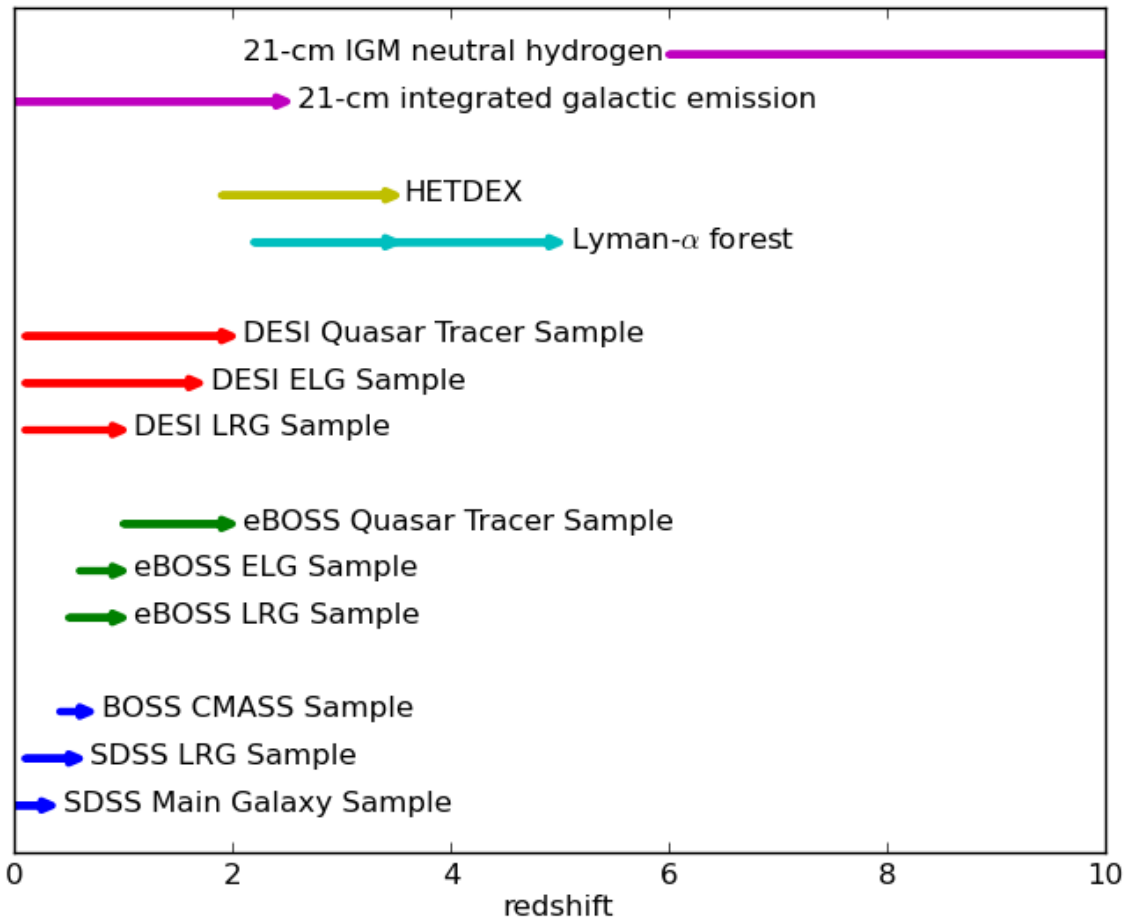
Introduction

- Lyman-α forest as a tracer of structure in the high-z universe
- Field revolutionized by BOSS
- Joint BOSS BAO constraints
- I will *not* talk about:
  - Lyman-β forest power spectrum measurements
  - PDF constraints
- This will be a very BOSS-centric talk

Measuring Density fields



- Disclaimer: plot does not show number densities and does not include photometric experiments
- Lyman-α forest unique probe of three-dimensional structure at redshifts $z = 2 - 3.5$
- This is an important epoch: last time Universe was truly de-Sitter
- Systematics very different from galaxies as tracers

From baryons to flux

Absorption done by neutral hydrogen in photo-ionization equilibrium:

$$\Gamma n_{\rm HI} = \alpha(T) n_p n_e \tag{1}$$

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

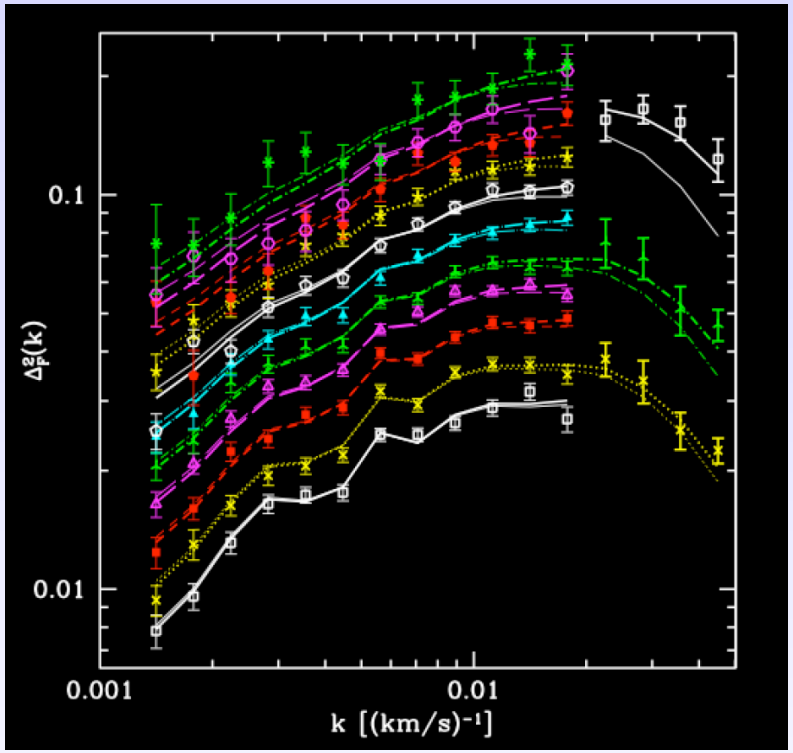
and so the absorbed flux fraction is given by

$$f = \exp\left(-\tau\right) \sim \exp\left(-A(1+\delta_b)^{1.7}\right) \tag{3}$$

- We are observing a very non-linear transformation of the underlying density field.
- **On large scales, Lyman-α forest is simply a biased tracer.**
- **On small scales, physics can be understood from first principles.**

1D vs 3D

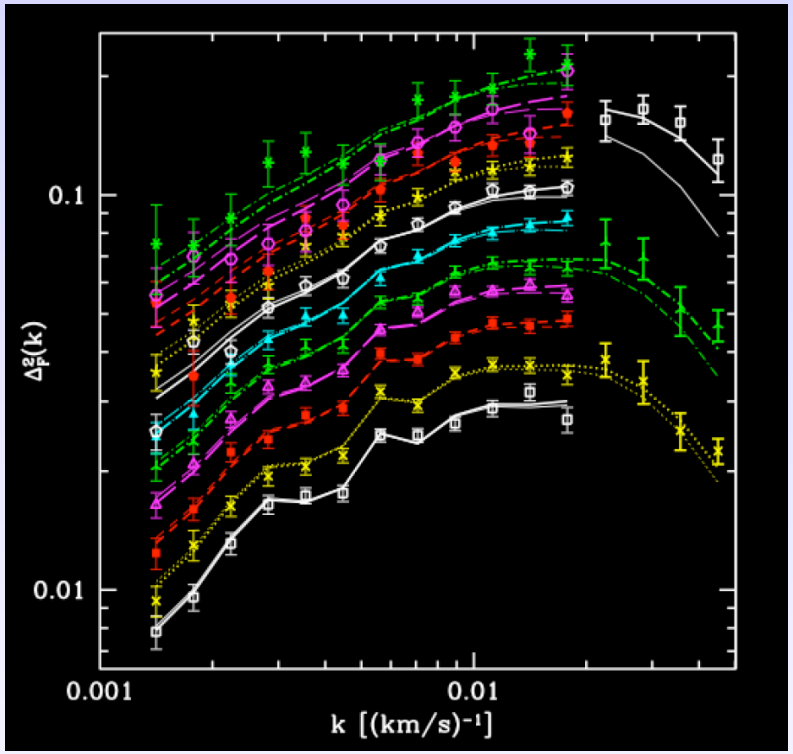
- Lyman-α forest is mapping the Universe through a very weird window function
- Historically: few and far apart high SNR measurements
- Quasars can be assumed independent in that limit: measure the 1D power spectrum of flux fluctuations
- With SDSS12: resolution down, noise up, quasar number up (from few tens to 15,000), but limited to 1D
- With SDSS3: noise further up, quasar number up (to 160,000): can finally measure correlations in three dimensions.



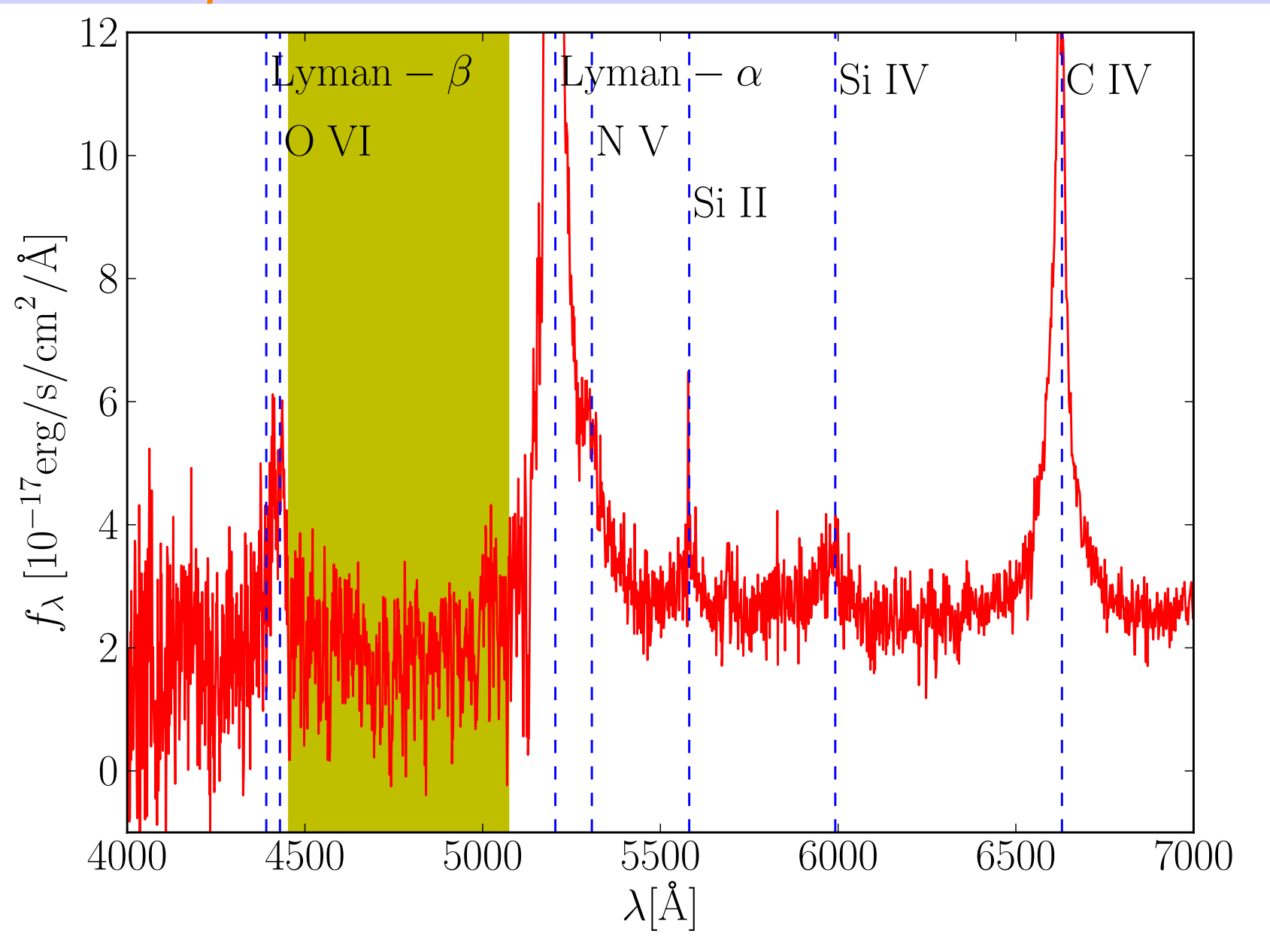
1D vs 3D

Power spectrum of Lyα measures:

- small scales (1D, $\sim 0.1\ \mathrm{Mpc/h}$): Effects of warm dark matter, sterile neutrinos, etc.
- medium scales (1D, $\sim 1\ \mathrm{Mpc/h}$): Inflation models, masses of light neutrinos, etc.
- large scales (3D, $> 10\ \mathrm{Mpc/h}$): Baryonic acoustic oscillations (dark energy, curvature of the universe), measurement of the shape of matter power spectrum

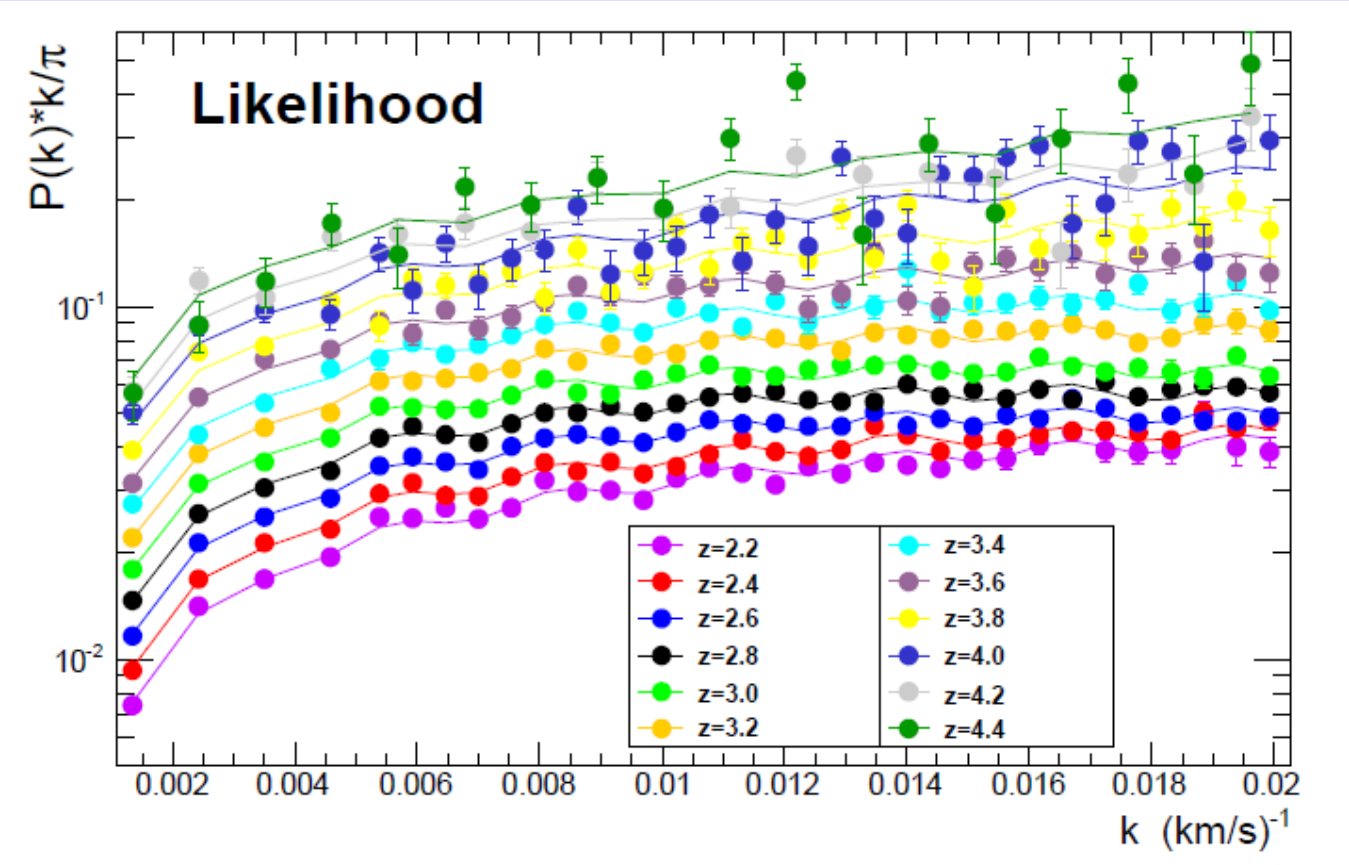


BOSS spectra

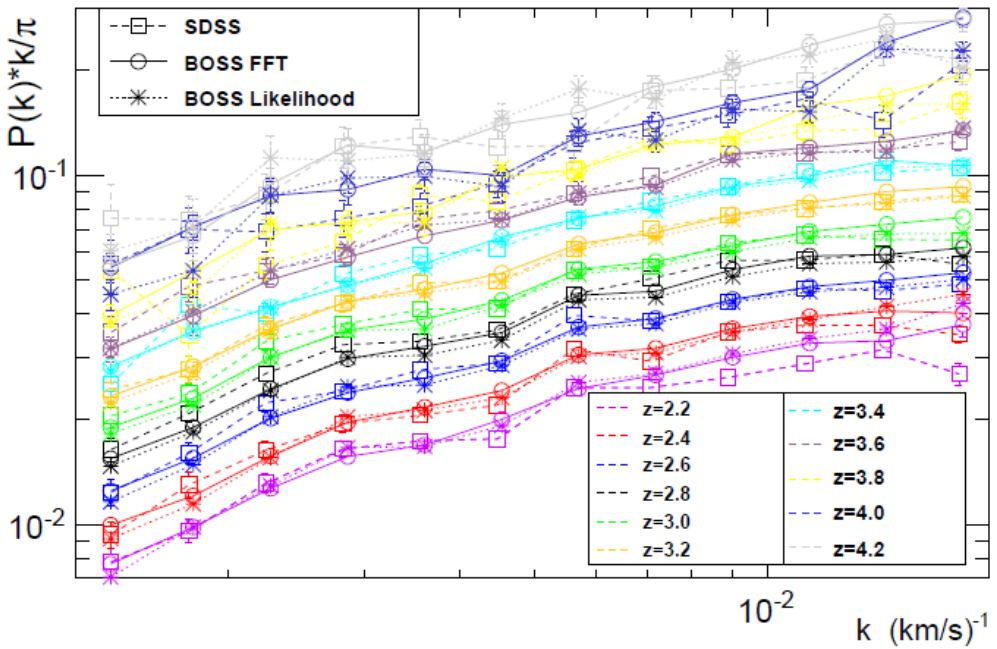


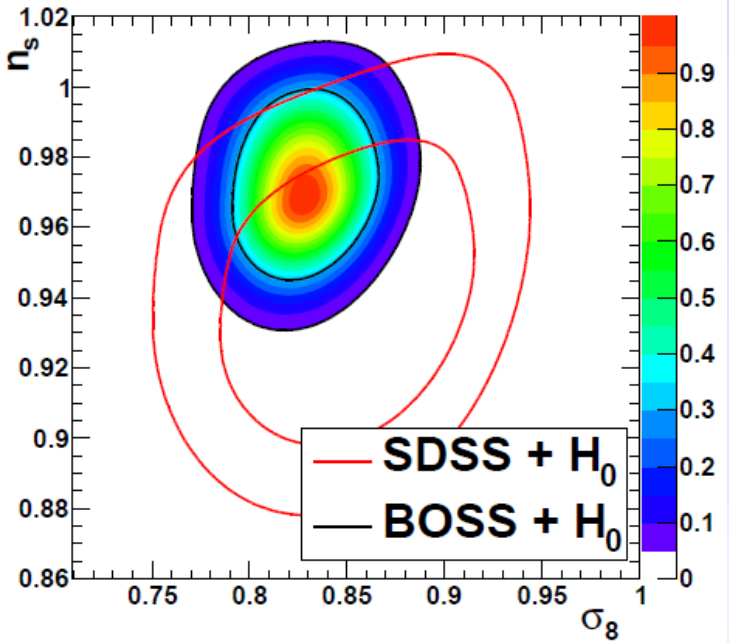
1D power spectrum from BOSS

- Work done by Saclay group
- Palanque-Delabrouille et al, `arxiv:1306.5896`
- Selected $\sim 14,000$ quasars from $\sim 90,000$
- Using two methods: the FFT and likelihood maximization

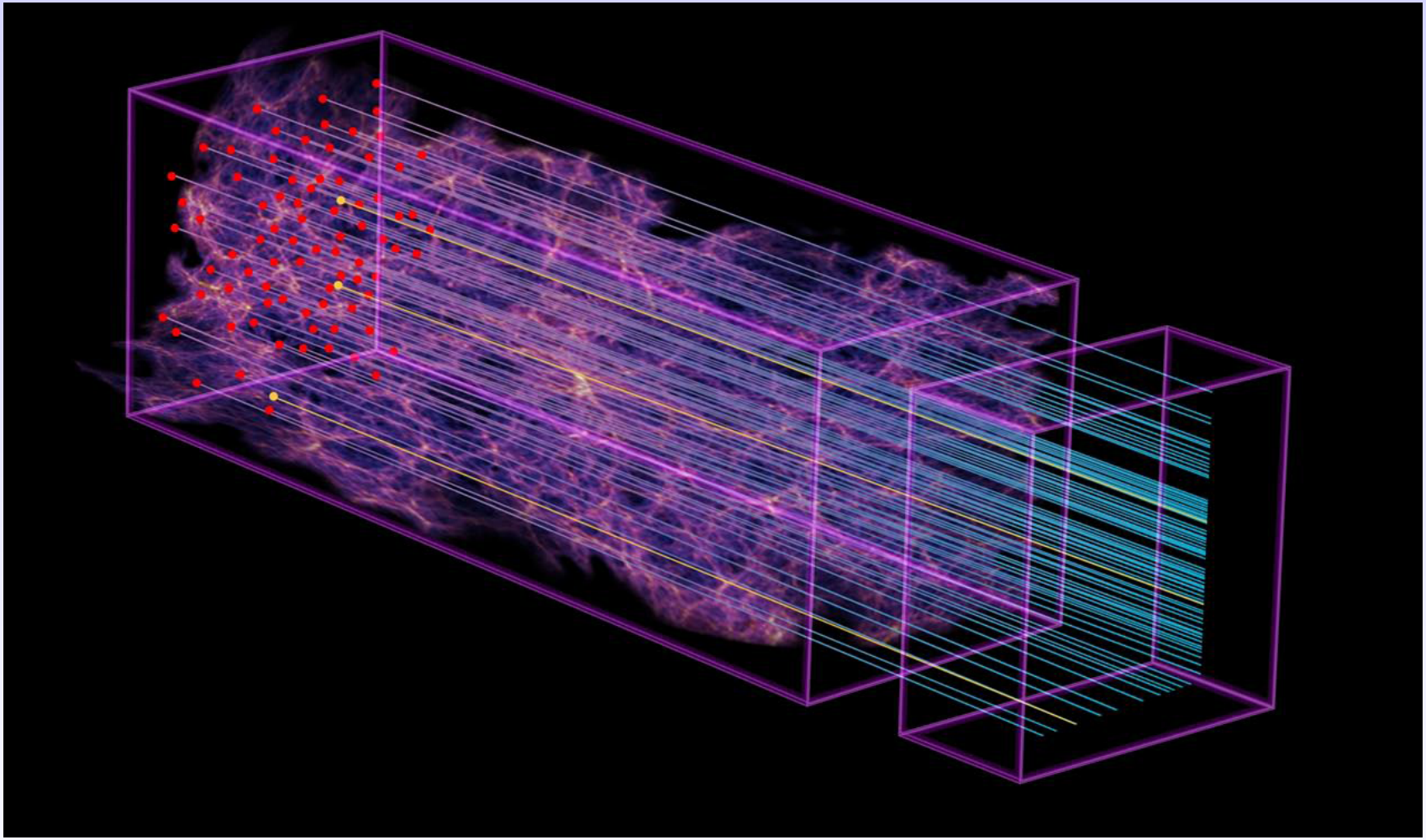


1D power spectrum from BOSS

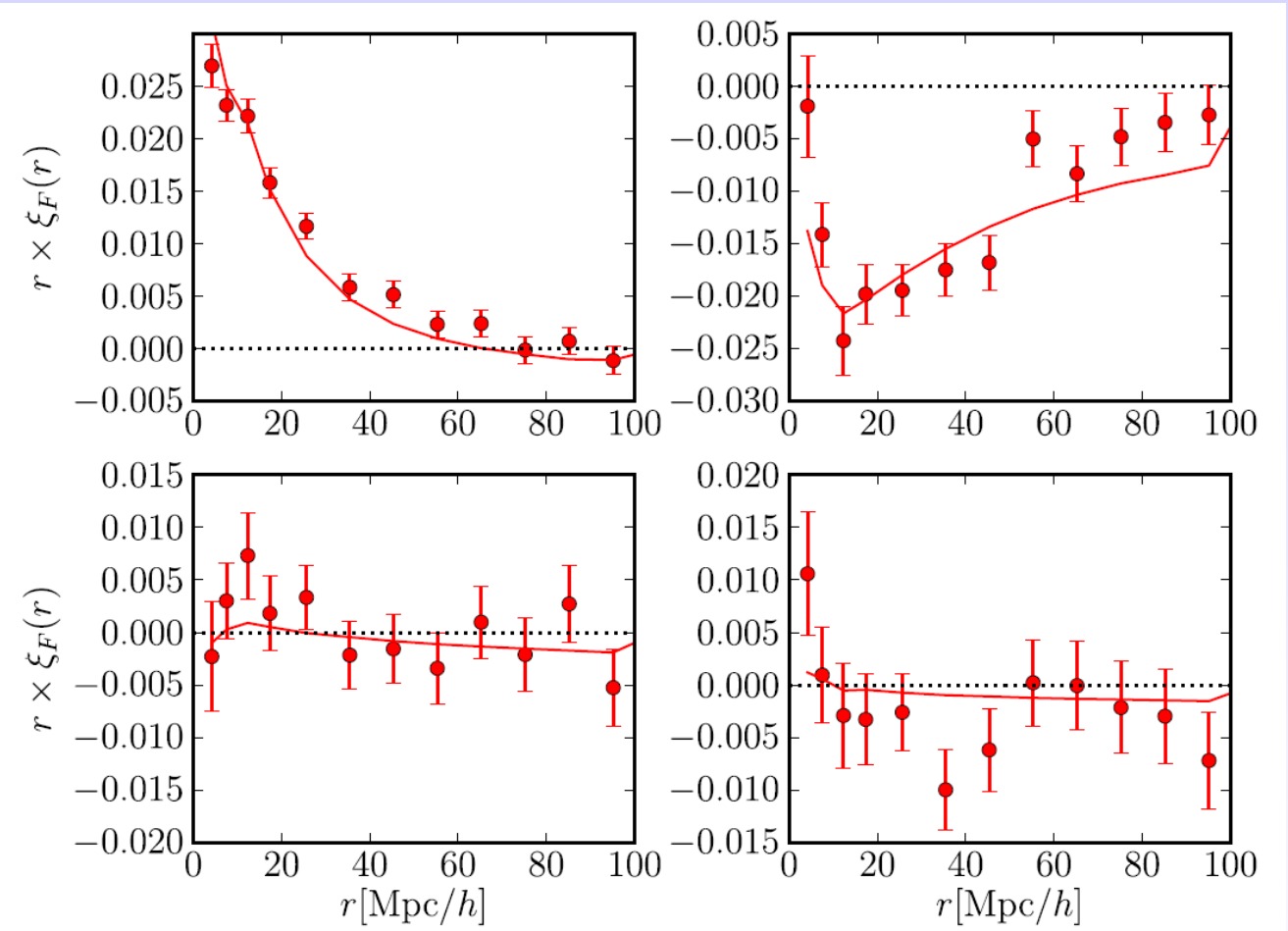




3D sampling of the universe

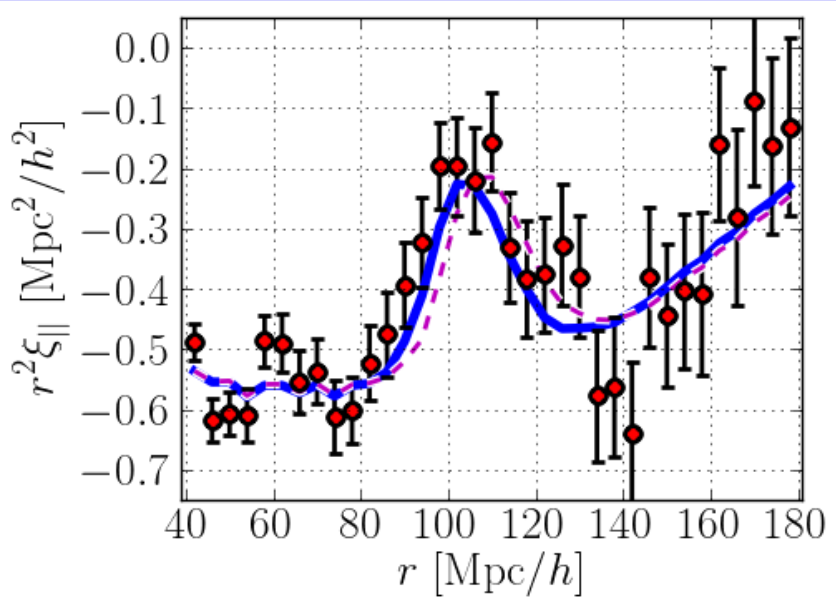


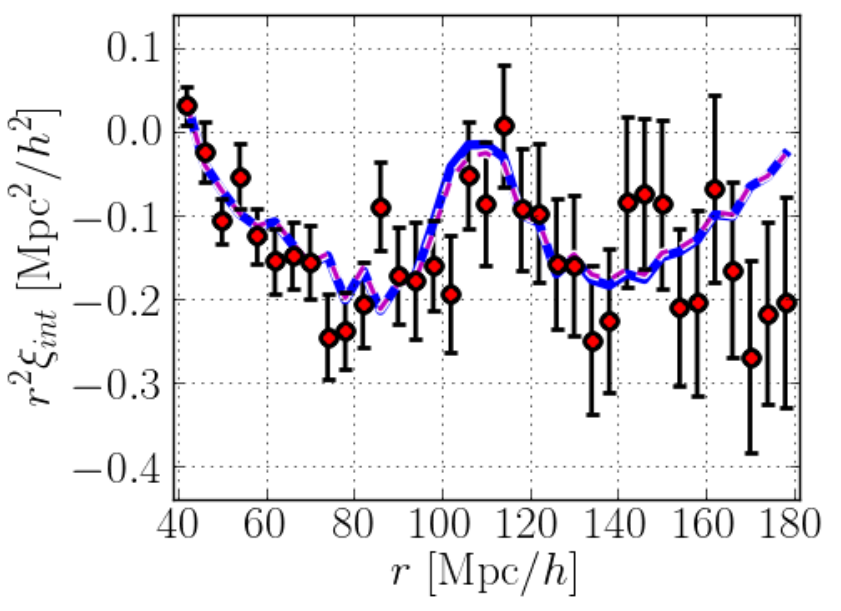
14k QSOs: ξ push

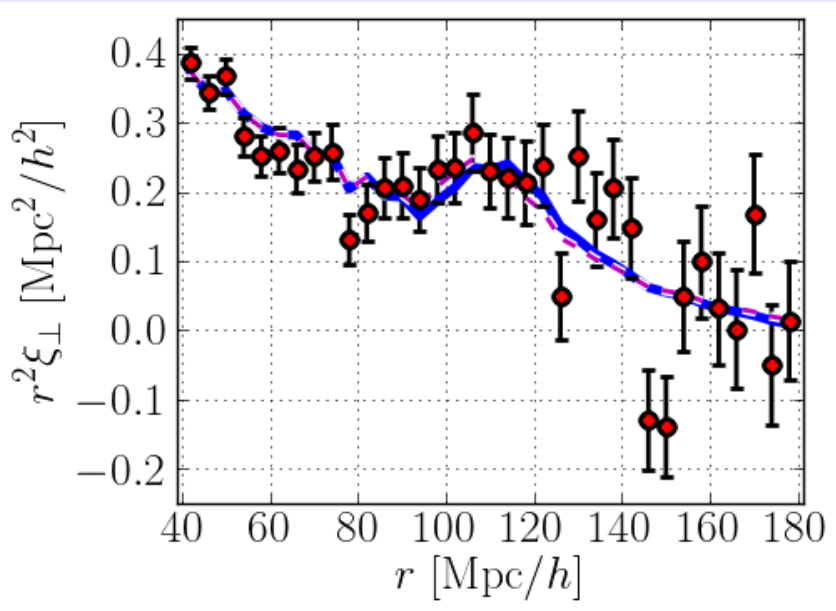


- Clear detection of correlations with no significant contamination
- The measured correlation function is distorted due to continuum fitting
- Analysis is harder than galaxy analysis:
  - Redshift-space distortions always matter
  - Redshift-evolution does matter

140k QSOs in DR11: BAO

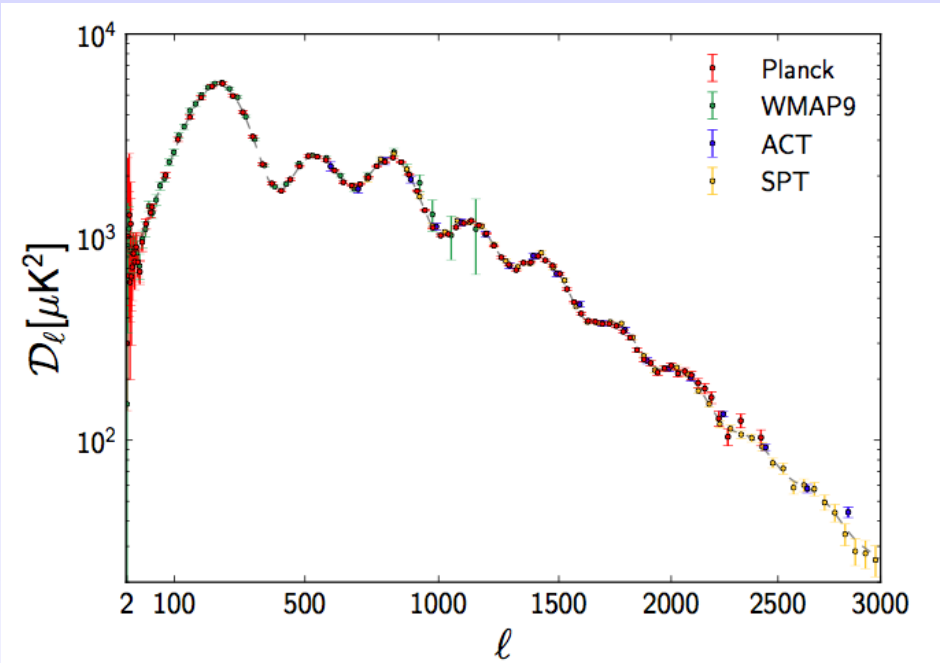




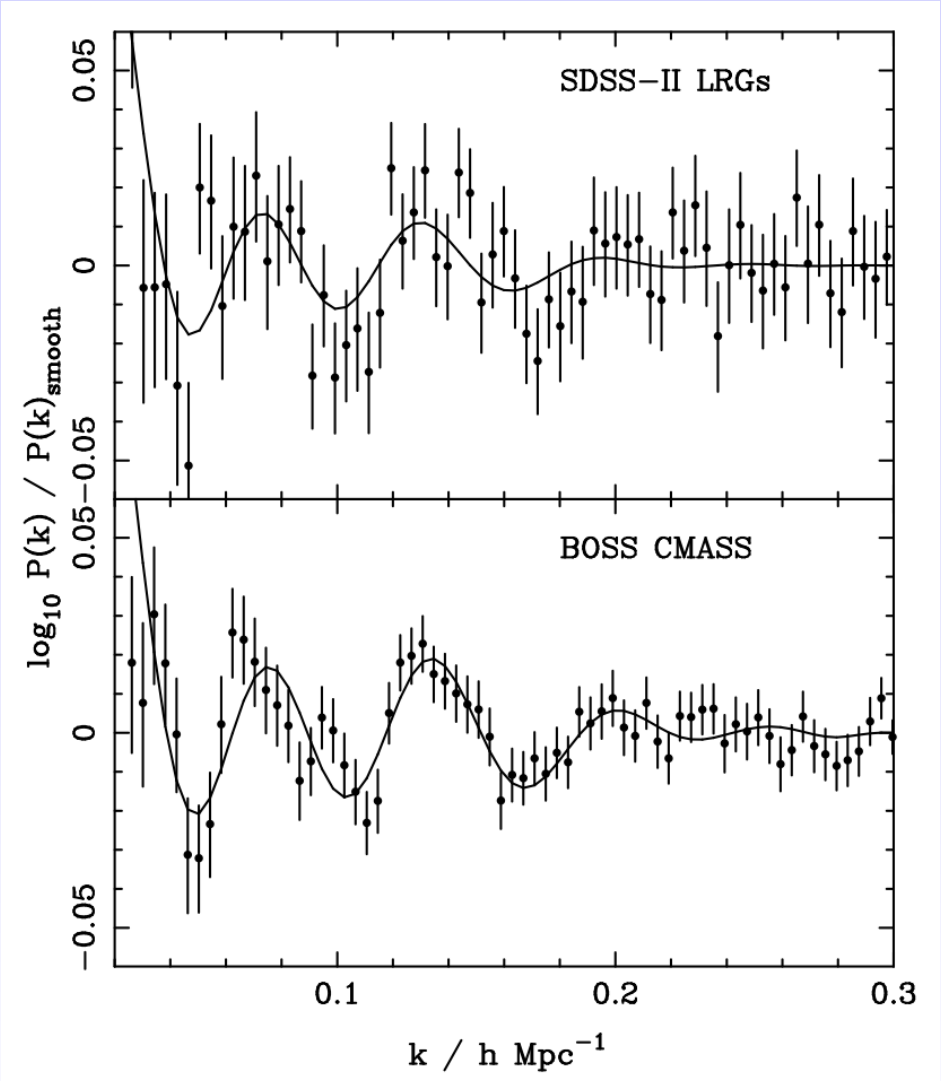


from de Lubac et al, 2014

What is BAO?

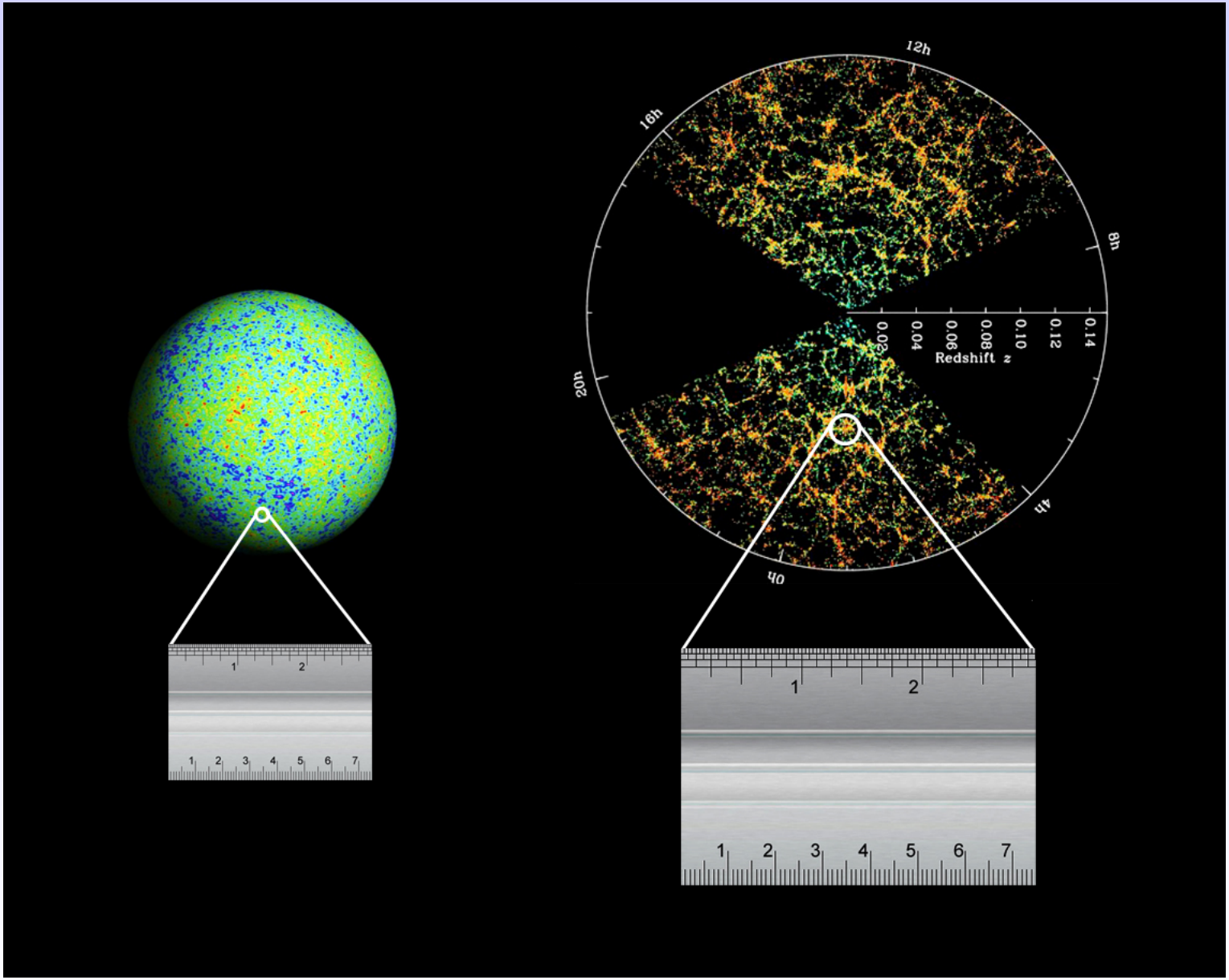


BAO in Cosmic Microwave Background



BAO in CMASS galaxies

BAO is a statical ruler



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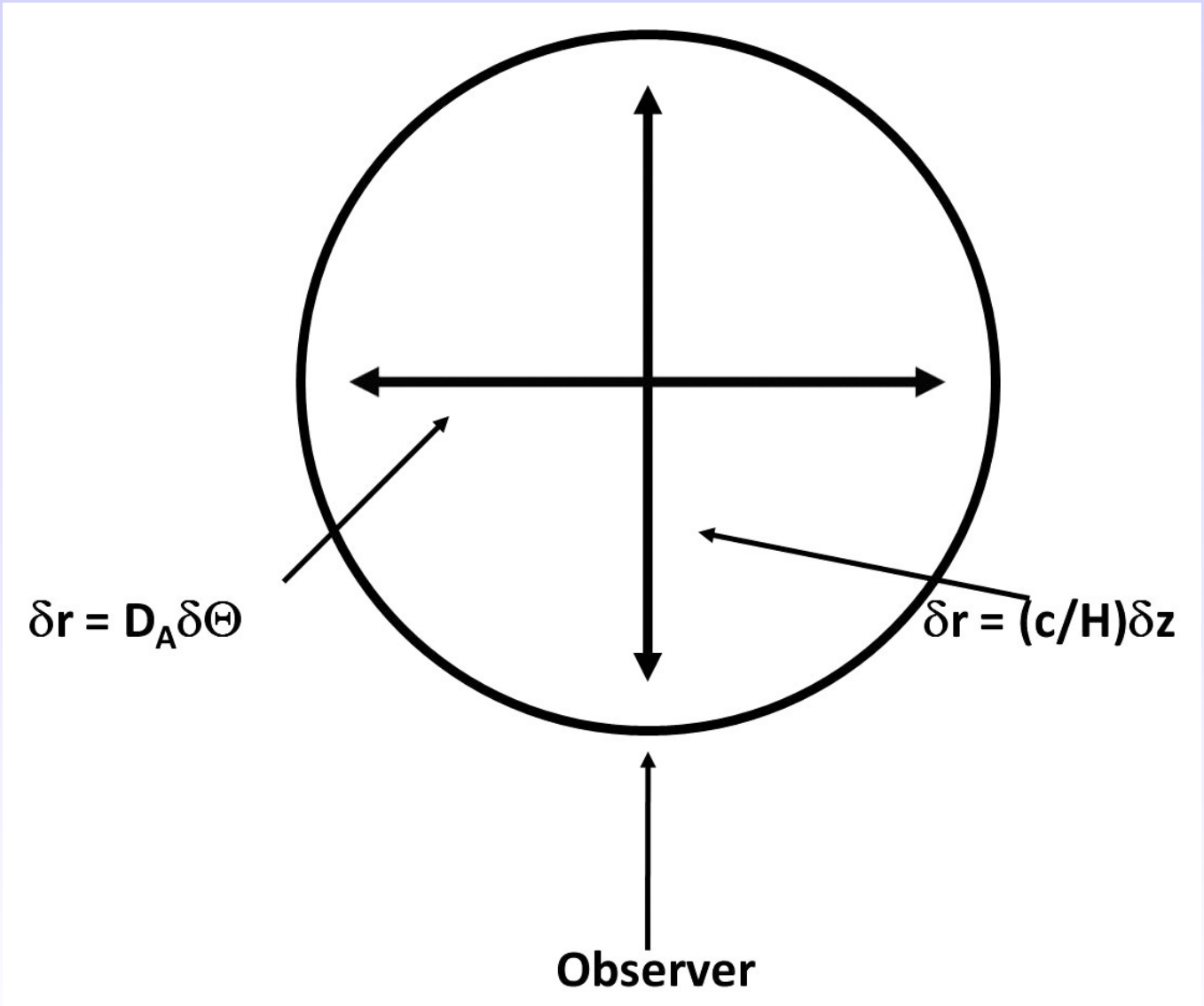
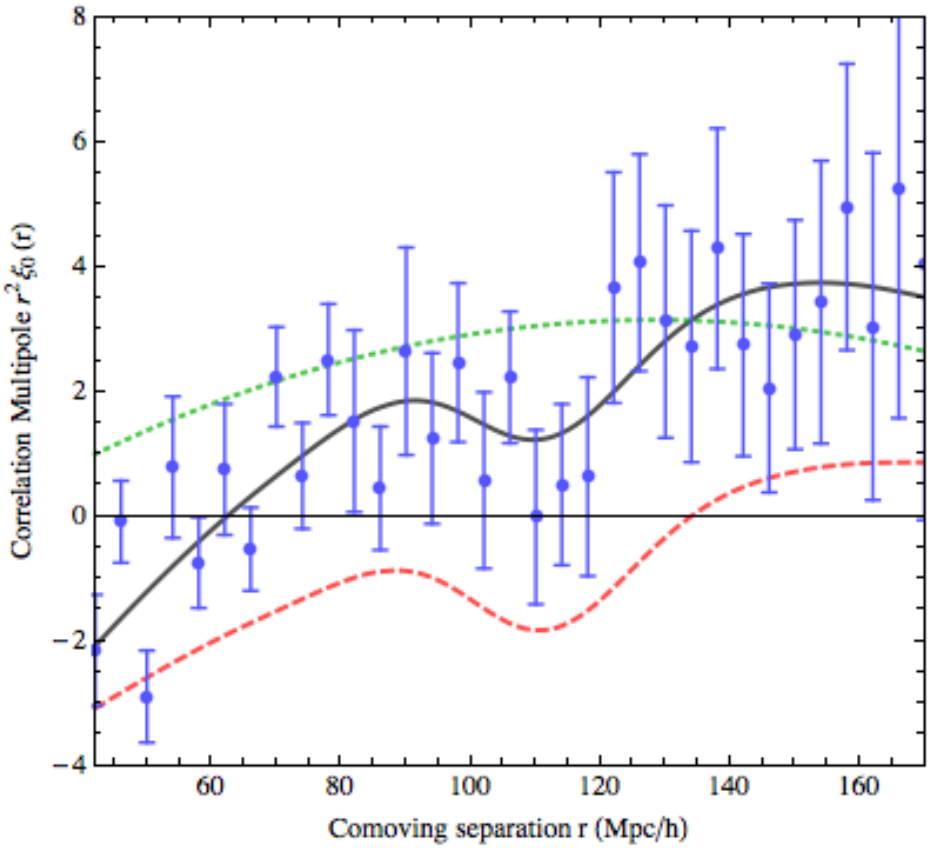
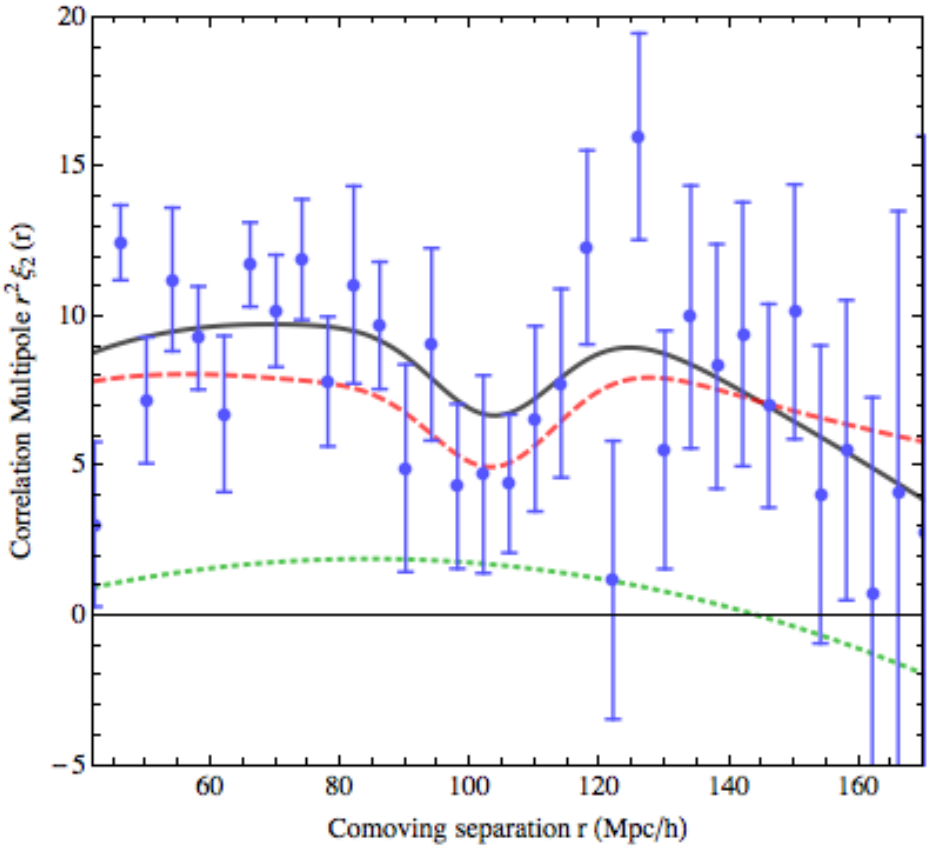


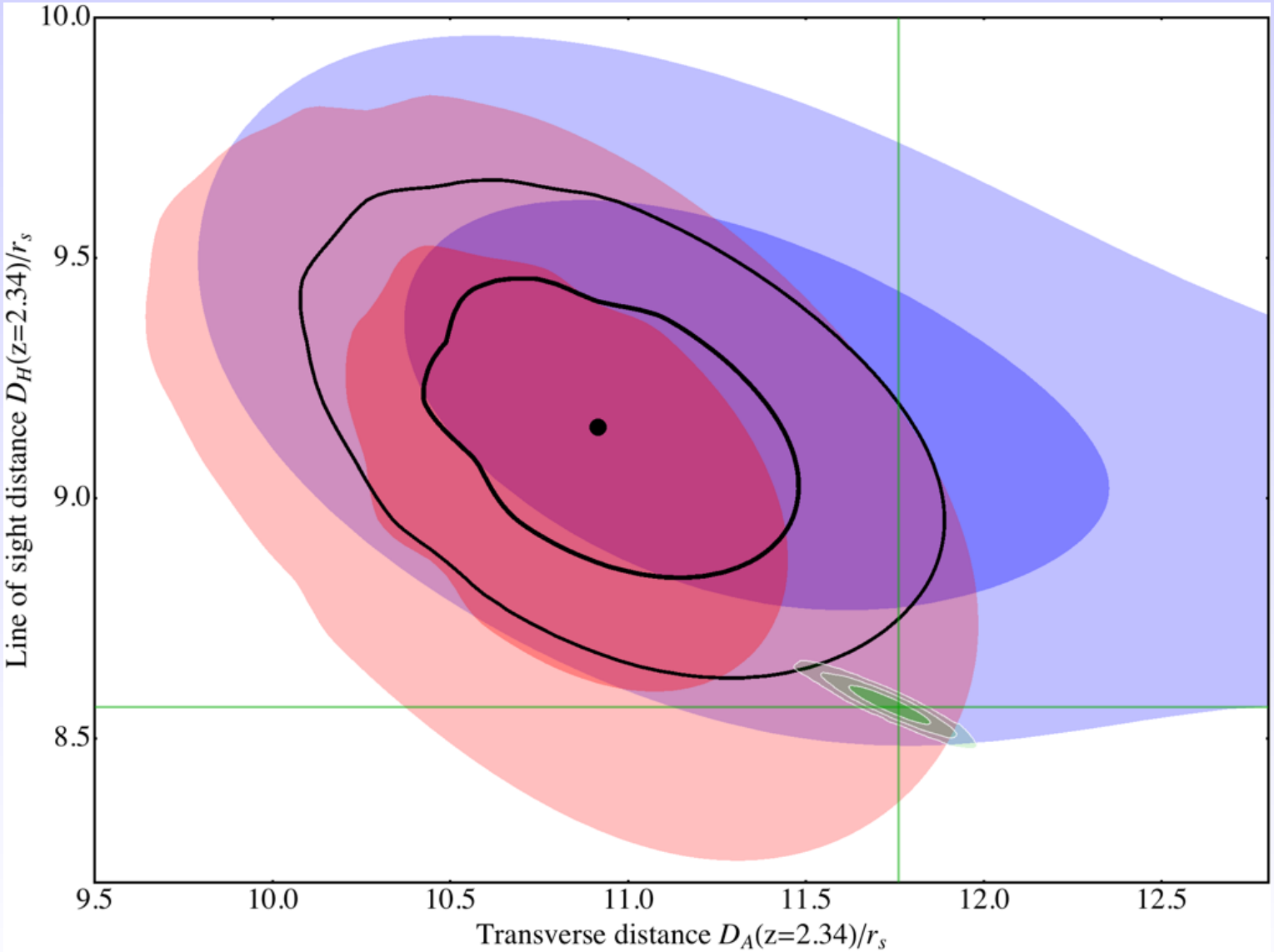
Quasar - forest cross-correlation in BOSS



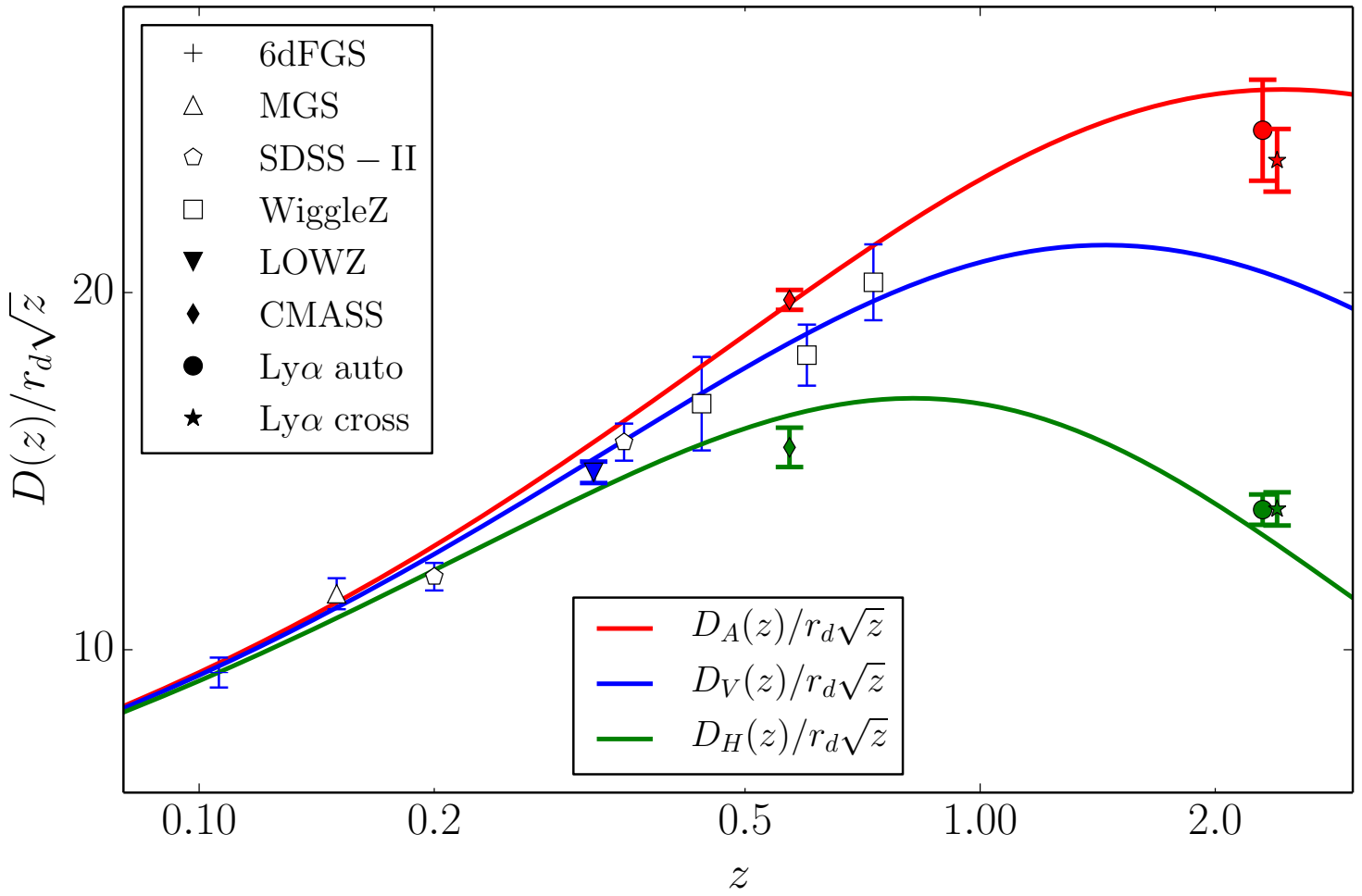


- Detection of the BAO in the cross-correlation between QSO and forest by Andreu Font & co.
- Ability for BOSS to do this has not been predicted, but constraining power nearly as powerful as with flux auto-correlation

Houston, we have a problem

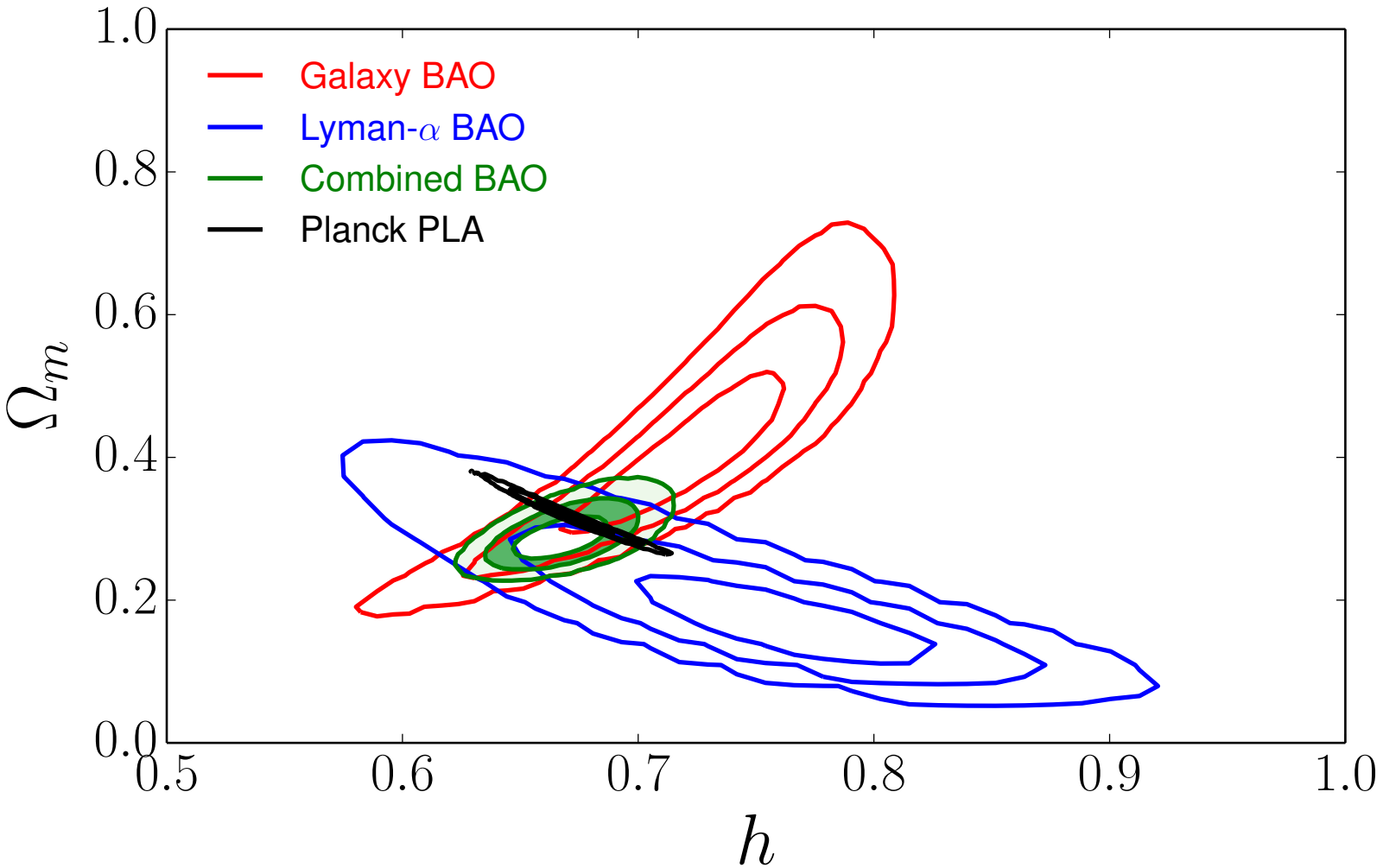


World BAO data

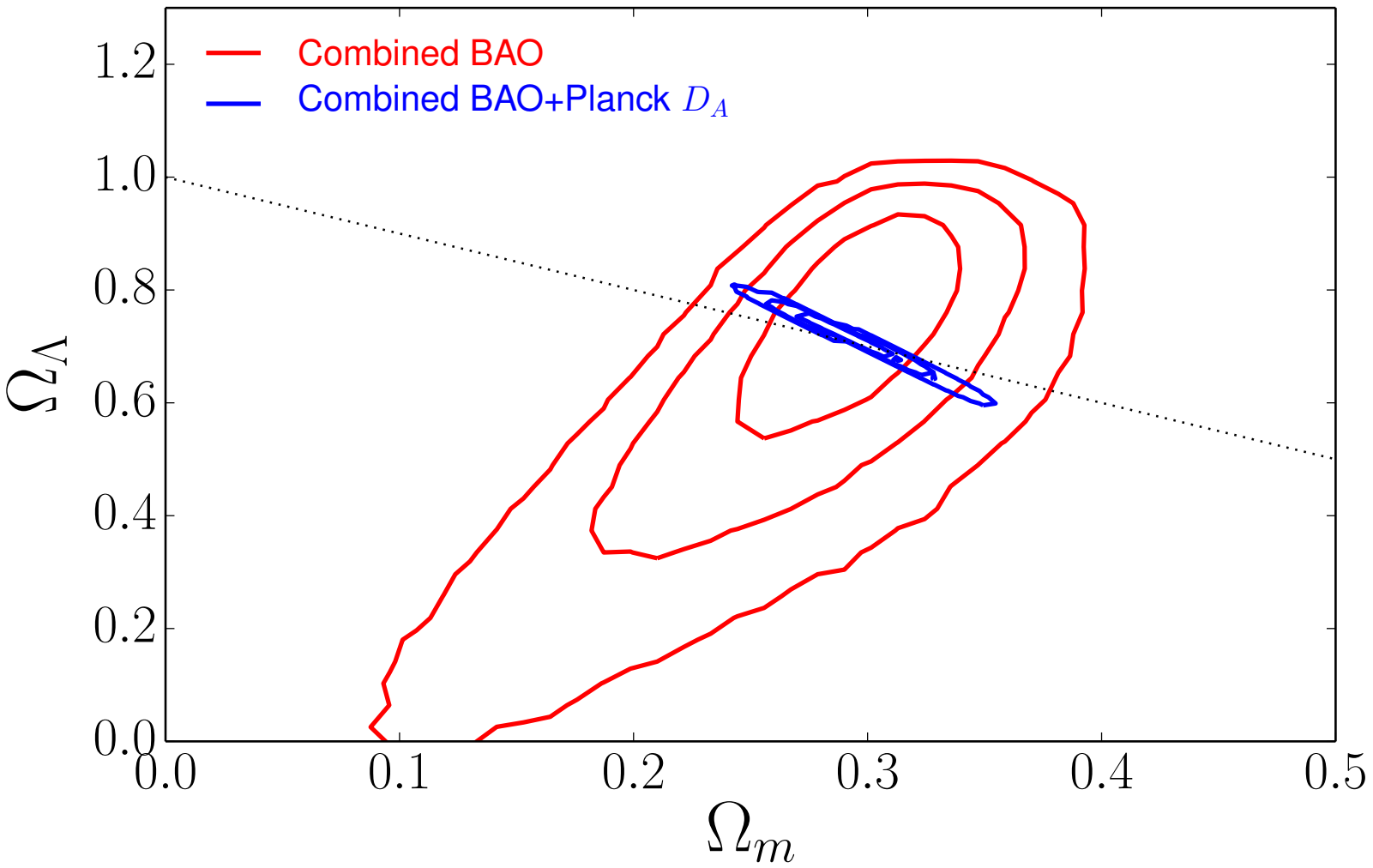


- Collection of world BAO data
- Lines are Planck best fit *predictions*

ΛCDM BOSS BAO

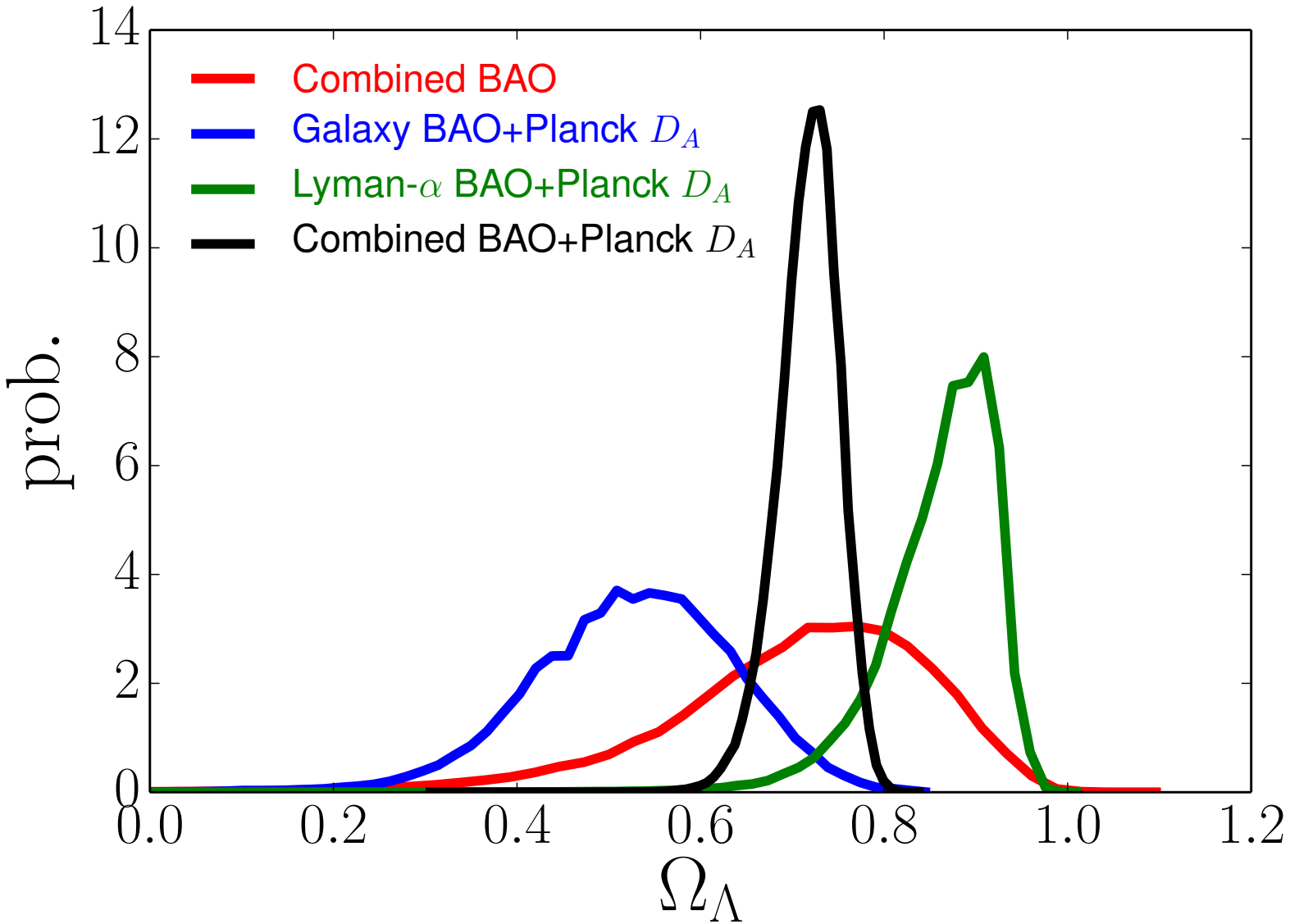


World BAO data

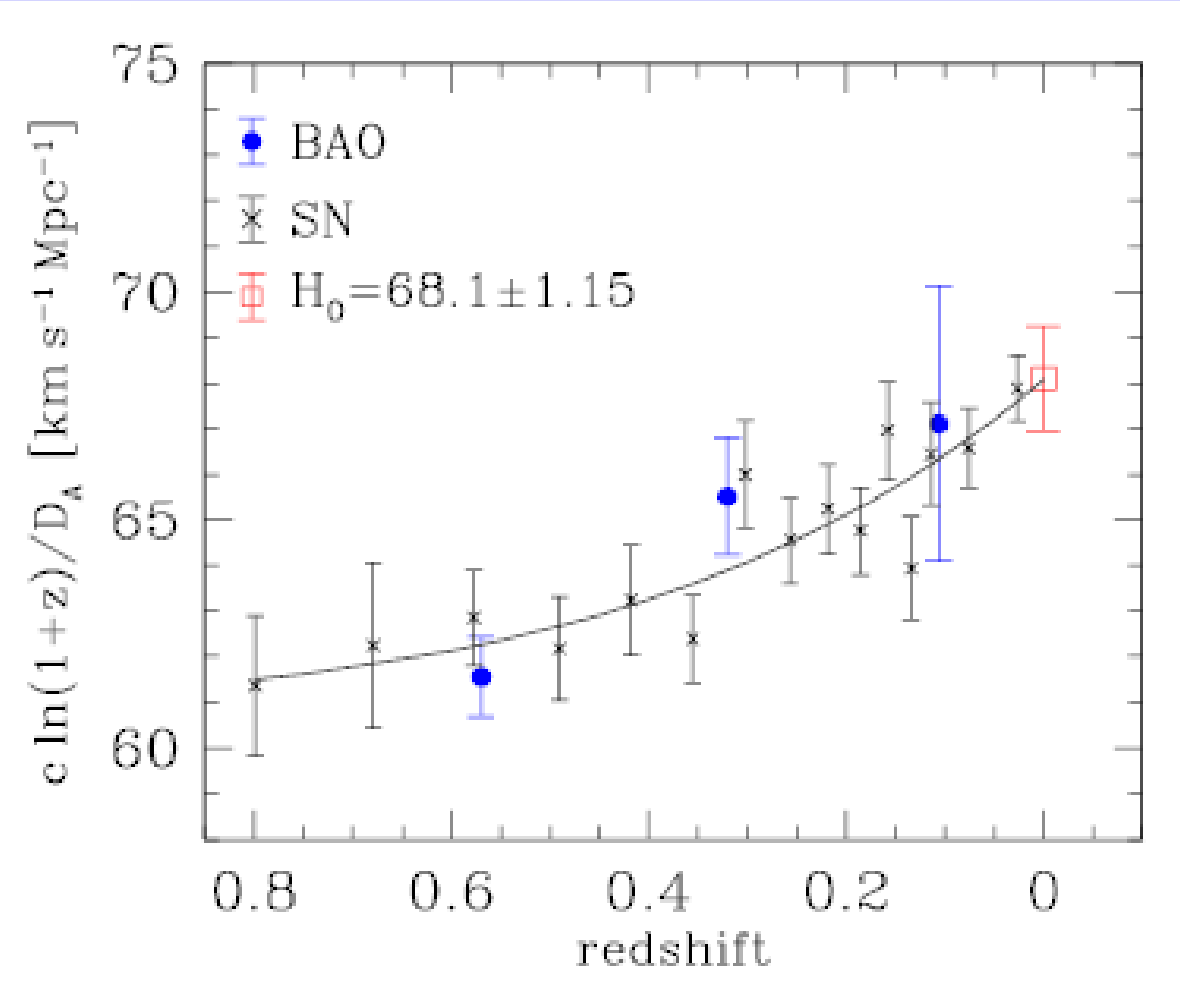


- BAO data alone detect the dark energy at $> 3\sigma$

World BAO data

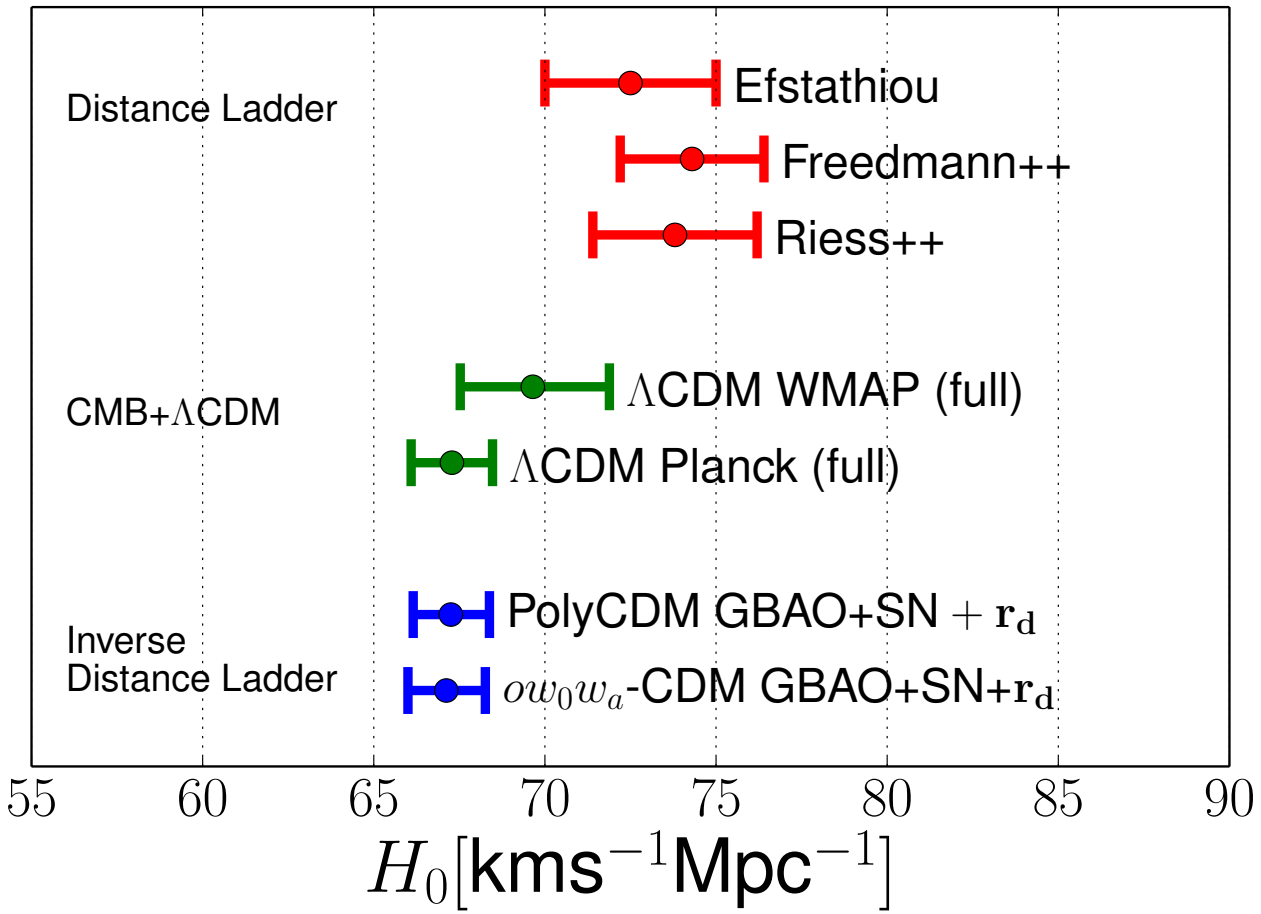


Inverse distance ladder



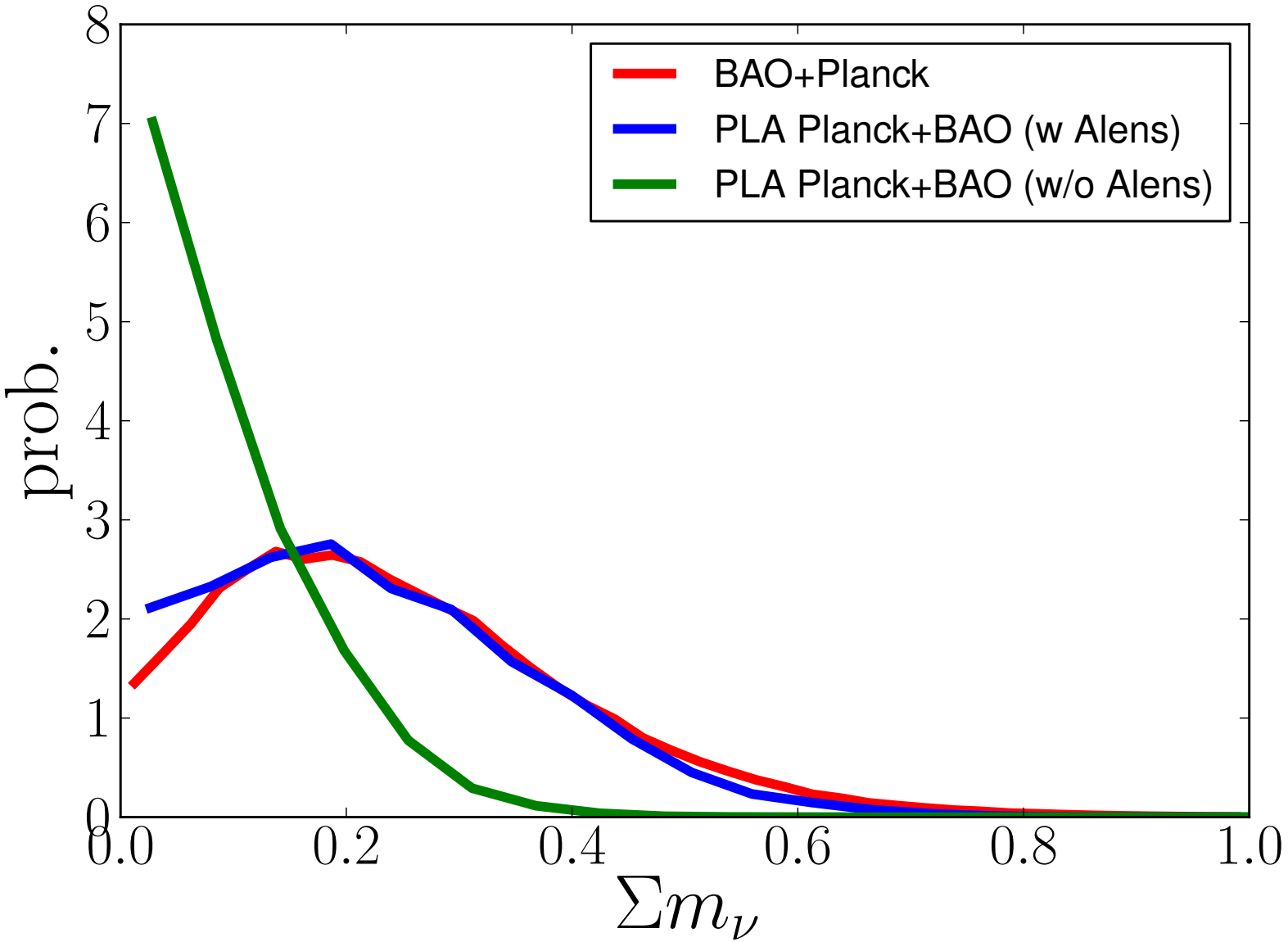
- Inverse distance ladder transfer H_0 measurement from redshift of observation to $z = 0$ using Supernovae Type Ia

Inverse distance ladder

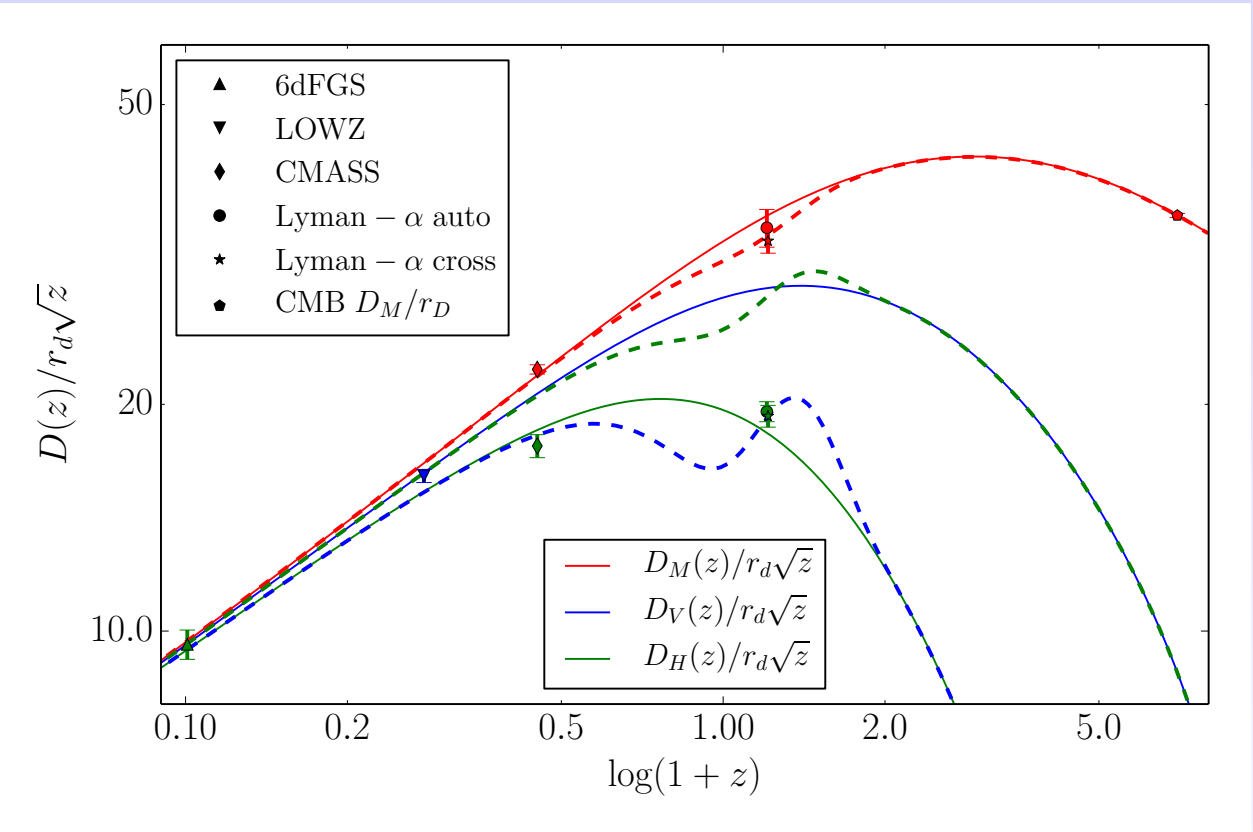


- BOSS prefers low-h Universe: $H = 68.1 \pm 1.2$

Neutrino mass from geometry:



"the tension"



- Tension just about $\sim 2.5\sigma$
- Very hard to solve it with e.g. early dark energy
- Fine-tune solutions possible, but contrived
- Increasing $N_{\rm eff}$ helps with Lyman-α , increases $z = 0$ Hubble parameter, lowers low-z σ_8, ~~decreases tension with BICEP~~.
- The price you pay is incompatibility with galaxy BAO and $n_s \sim 1$.

Conclusions

- Life is good
- Lyman-α BAO exhibits a small tension with ΛCDM cosmology
- The future is bright, most promise in small scale P1D:
  - Neutrino mass
  - $N_{\rm eff}$
  - running of spectral index
- More data on horizon: the 400 public hi resolution QSO spectra, eBOSS, DESI