Baryon Acoustic Oscillations: Current Constraints on Cosmology and the new technique of the Lyman Alpha Forest.

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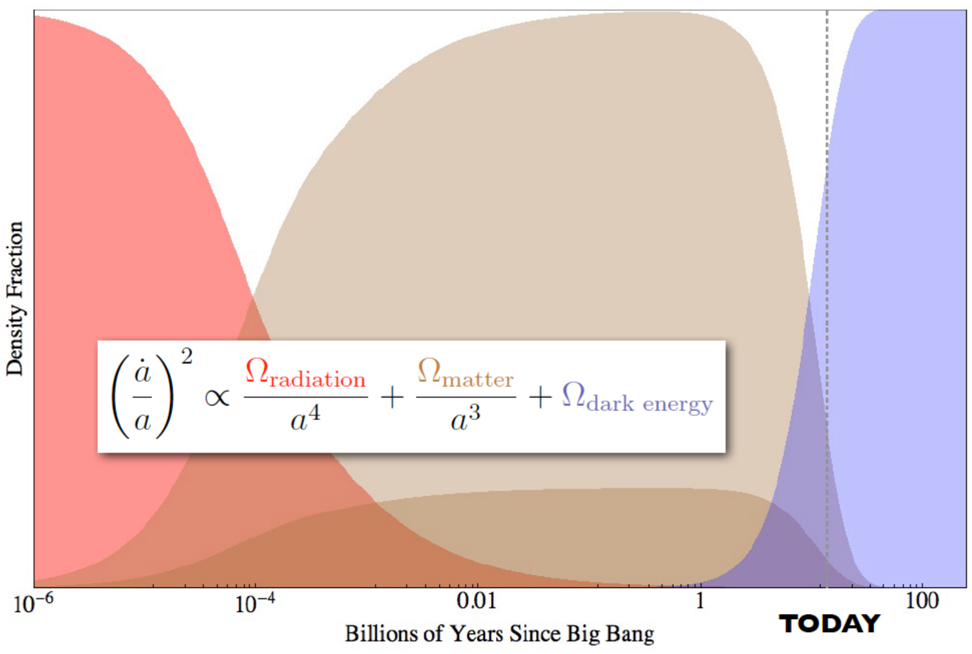
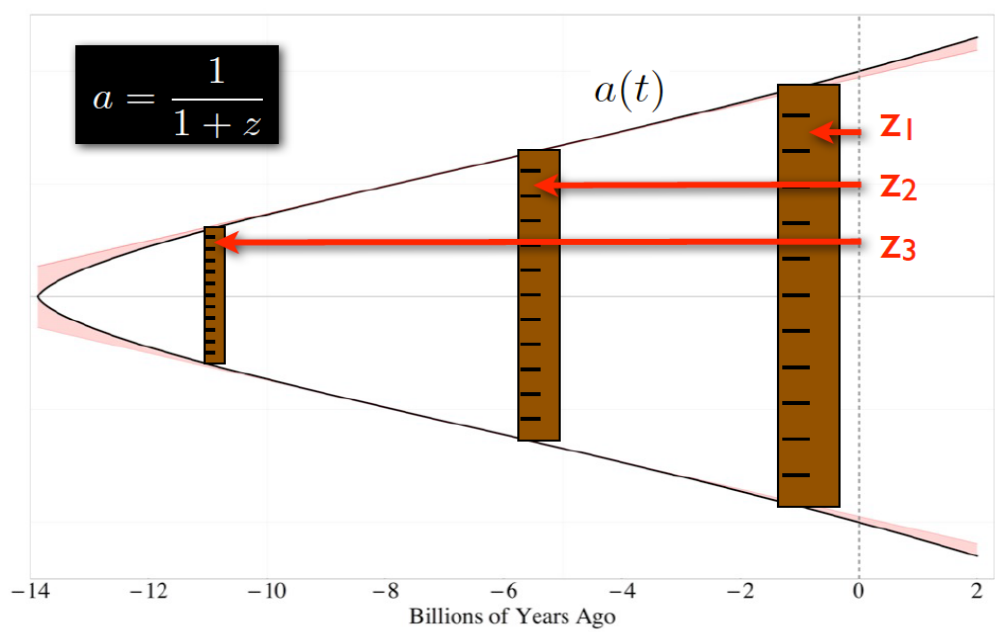
The main goal of BAO: measure distance and expansion rate at each redshift as a probe of the components of the Universe.

BAO acts as a standard ruler of fixed comoving length. We can infer the expansion rate from the span in redshift in the parallel direction, and from the subtended angle in the perpendicular direction.

$$\Delta z = \frac{\dot{a}}{a}\ell_{BAO} \qquad \theta = \frac{\ell_{BAO}}{(1+z)D_A(z)}$$





Images from David Kirkby

Physics of the BAO scale: the sound horizon as a standard ruler

Total density and pressure of the baryon-photon fluid:

$$\rho = \rho_b + \rho_\gamma$$

$$p = \frac{c^2}{3}\rho_\gamma$$

At fixed entropy:

$$\rho_\gamma \propto \rho_b^{4/3}$$

$$\frac{\partial \rho}{\partial \rho_\gamma} = 1 + \frac{3\rho_b}{4\rho_\gamma} = 1 + R$$

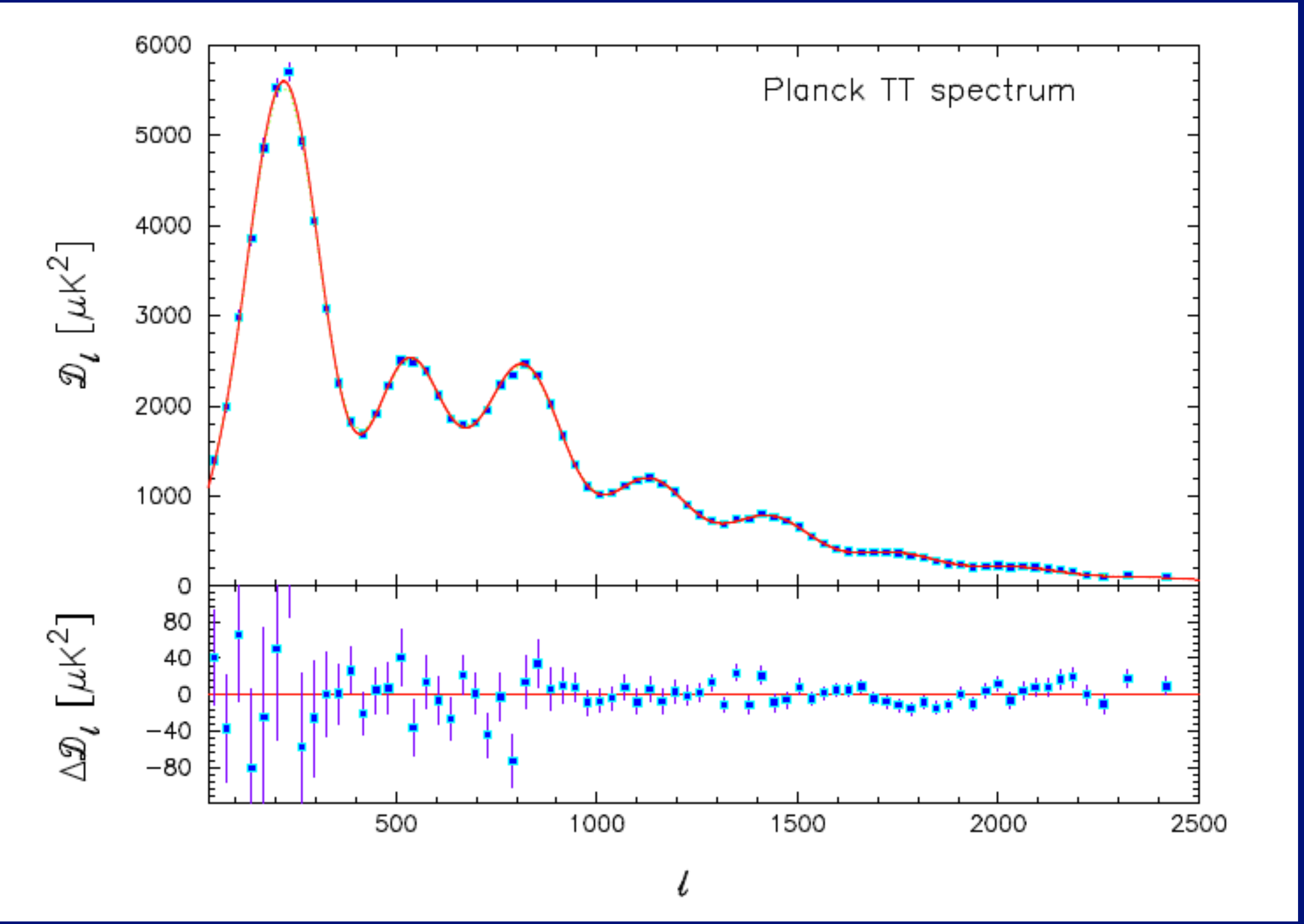
Sound speed before decoupling at recombination:

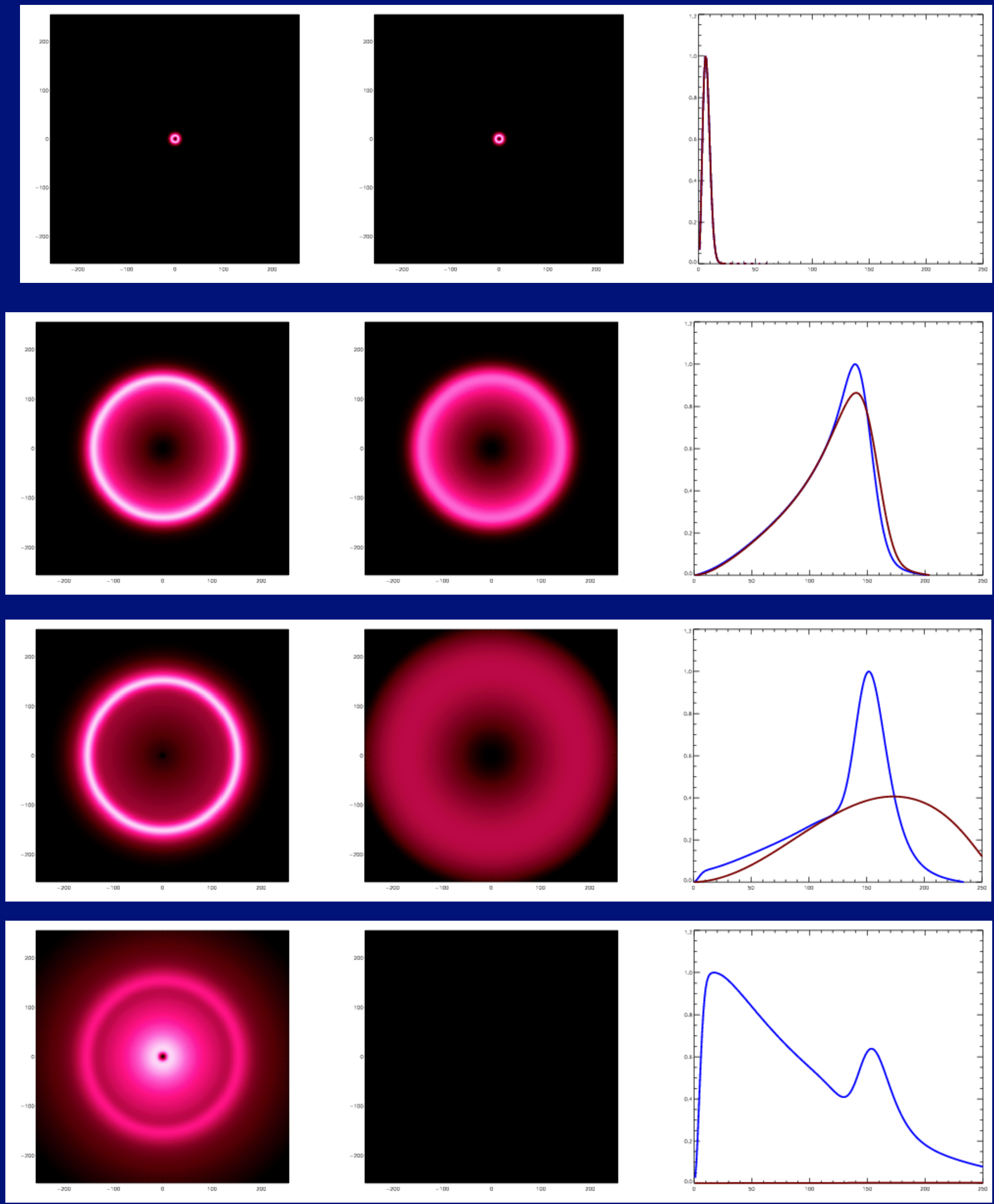
$$c_s^2 = \frac{\partial p}{\partial \rho} = \frac{\partial p}{\partial \rho_\gamma}\frac{\partial \rho_\gamma}{\partial \rho} = \frac{c^2}{3(1+R)}$$

Sound horizon: it depends on R (accurately known from the CMB) and on the energy components affecting the conformal time η(z) before decoupling (such as dark matter and neutrinos).

$$r_s(z) = \int_0^{\eta(z)} \frac{d\eta'}{\sqrt{3(1+R)}},$$

Acoustic oscillations are also present in the radiation, and Planck has measured the peaks very accurately.





Evolution of baryons and photons starting from a point-like perturbation.

- The photon-to-baryon ratio is very large, $n_\gamma/n_b \sim 2\cdot 10^9$

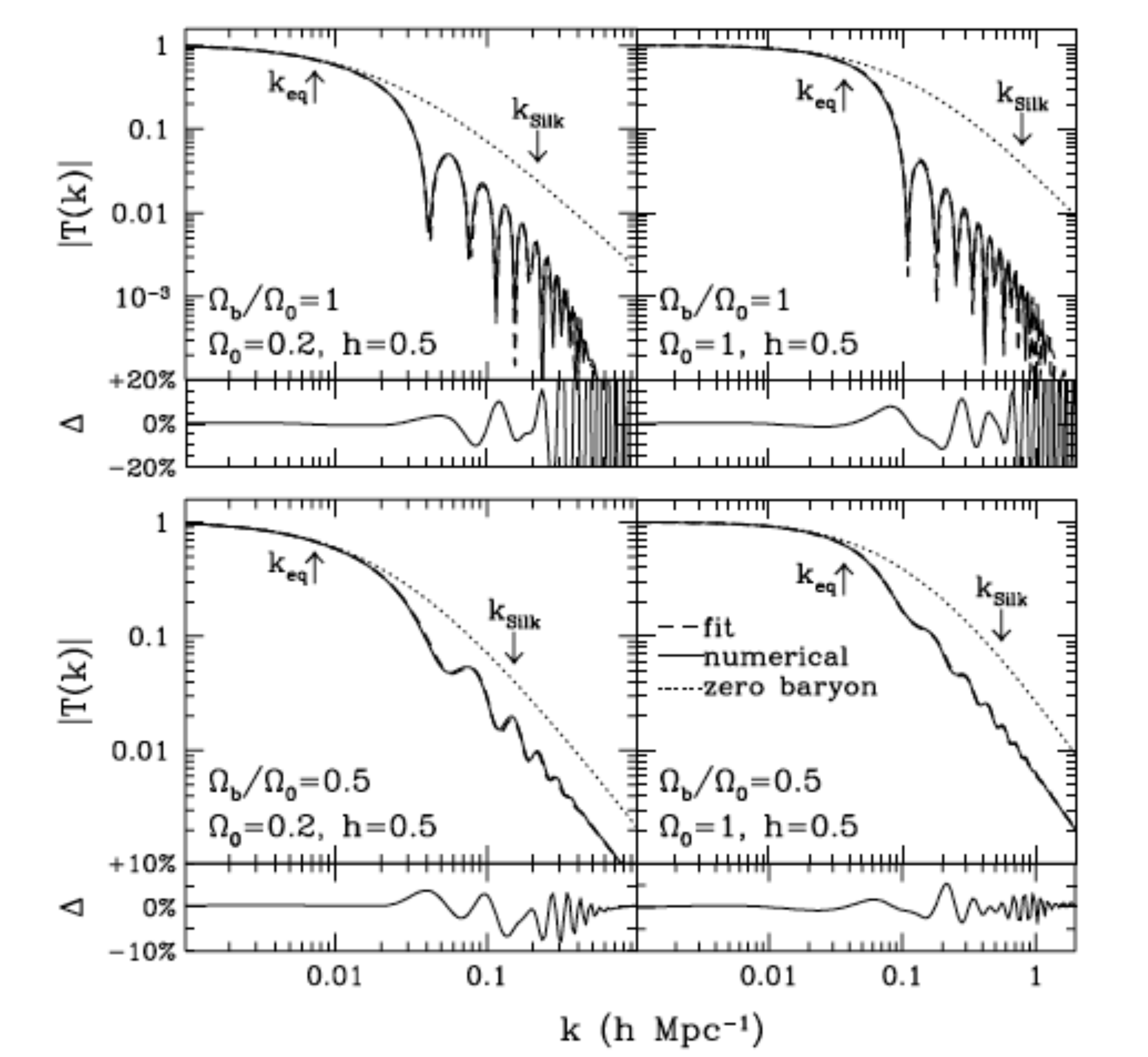
- The temperature at recombination is much less than the hydrogen ionization potential, so recombination occurs suddenly:

$T_{rec} \sim 3000$ K $<<$ 13.6eV/k $\sim$160000 K

- Photon diffusion occurs over the Silk scale, much less than the sound horizon, and the BAO peak is therefore narrow.

Lecture notes from Martin White

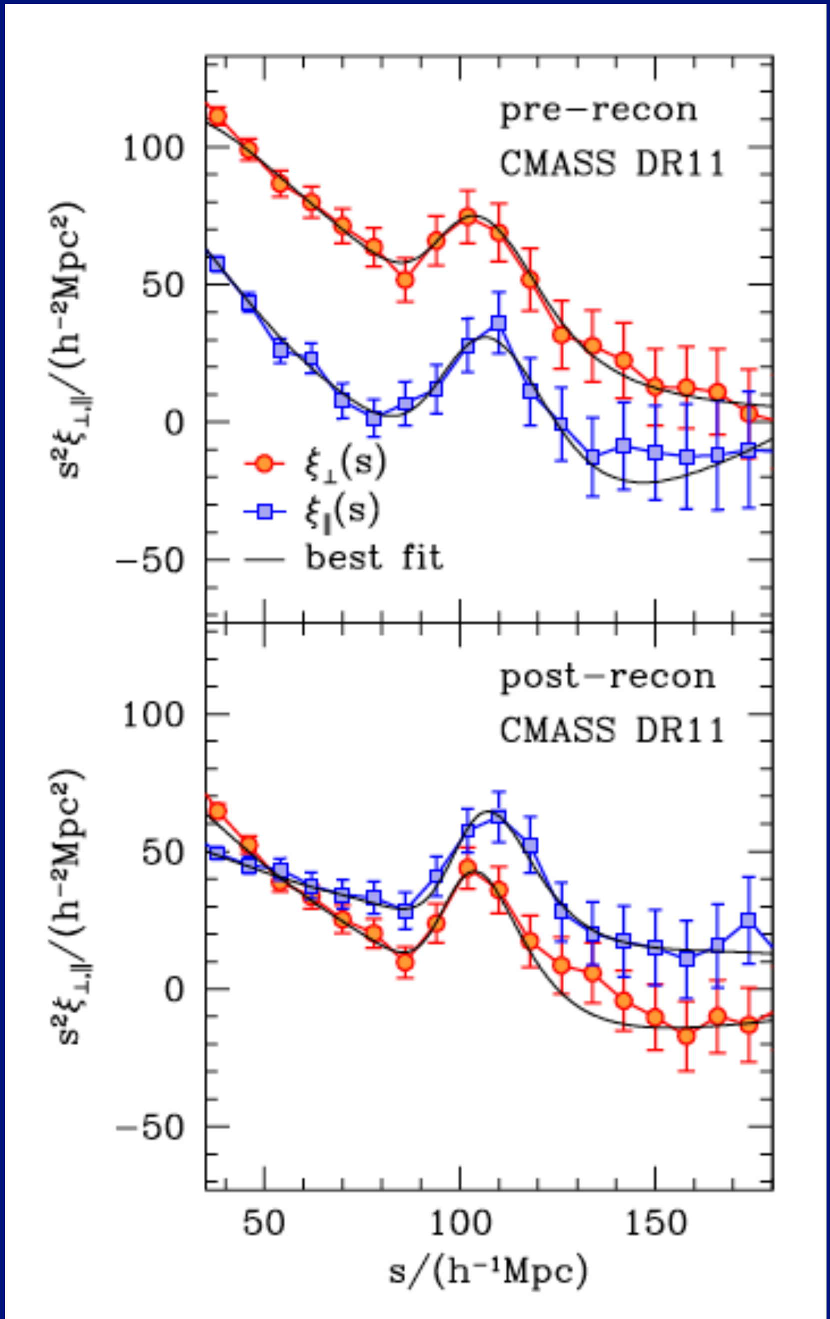
The reduction in the matter power spectrum due to Baryon Acoustic Oscillations



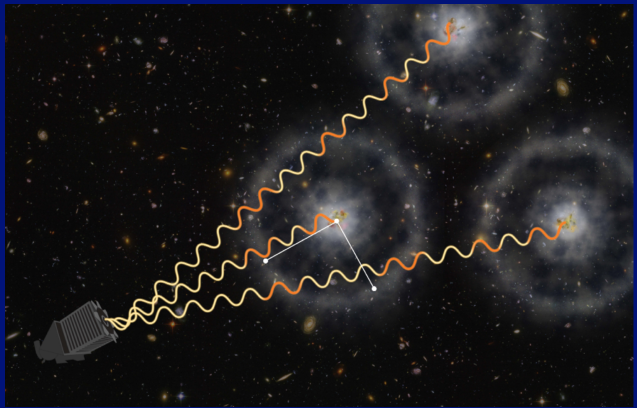
Oscillations in the power spectrum correspond to the narrow peak in the correlation function.

Eisenstein and Hu (1998)

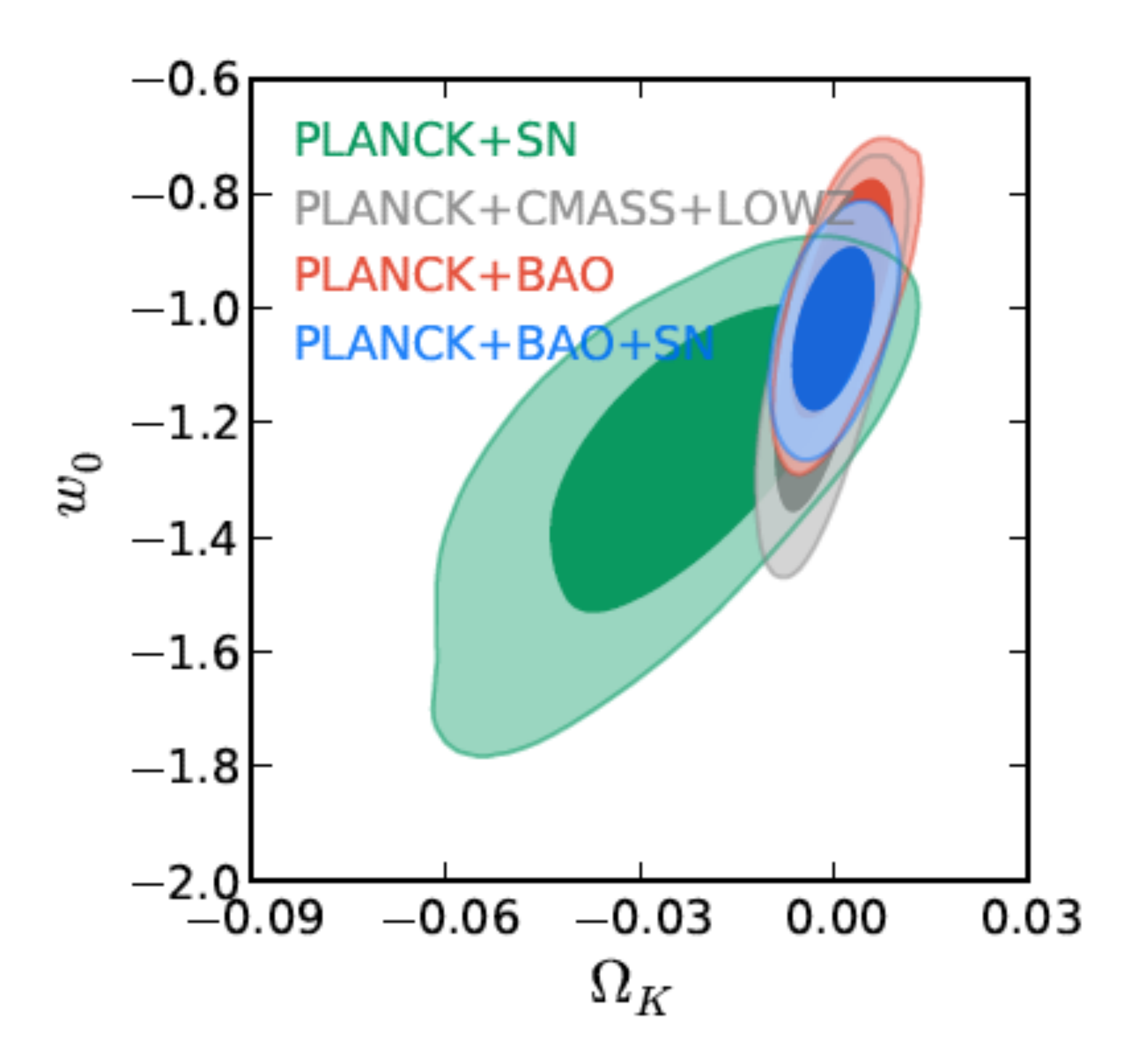
BAO measurements



- Example: BOSS galaxies (Anderson et al. 2014).
- The crucial advantage of detecting a narrow BAO peak is the insensitivity to broadband contamination (e.g., due to calibration errors, lensing effects, scale-dependent bias…)
- The reconstruction technique allows to remove some of the non-linear effects that broaden the BAO peak.



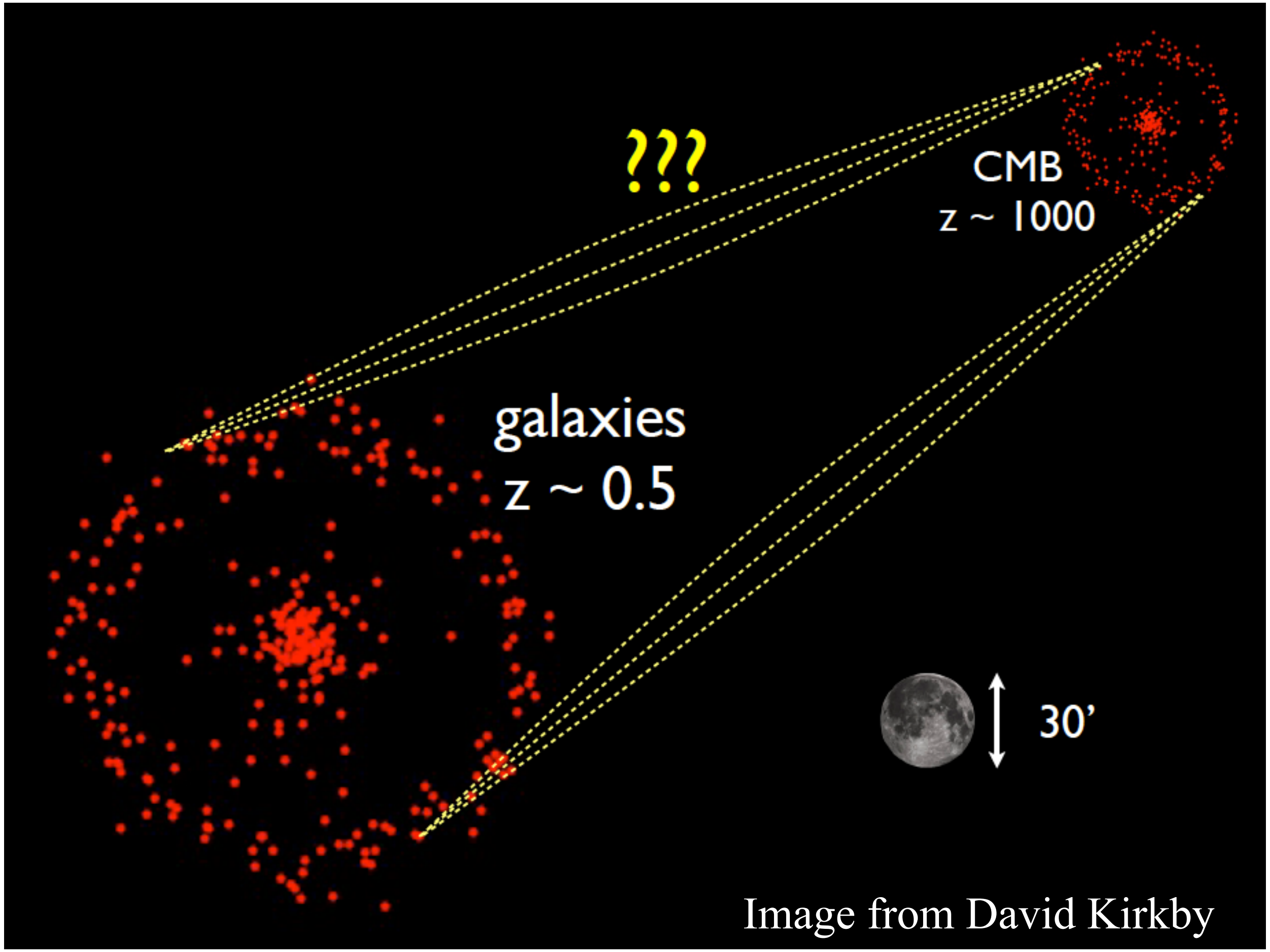
Constraints on standard cosmology



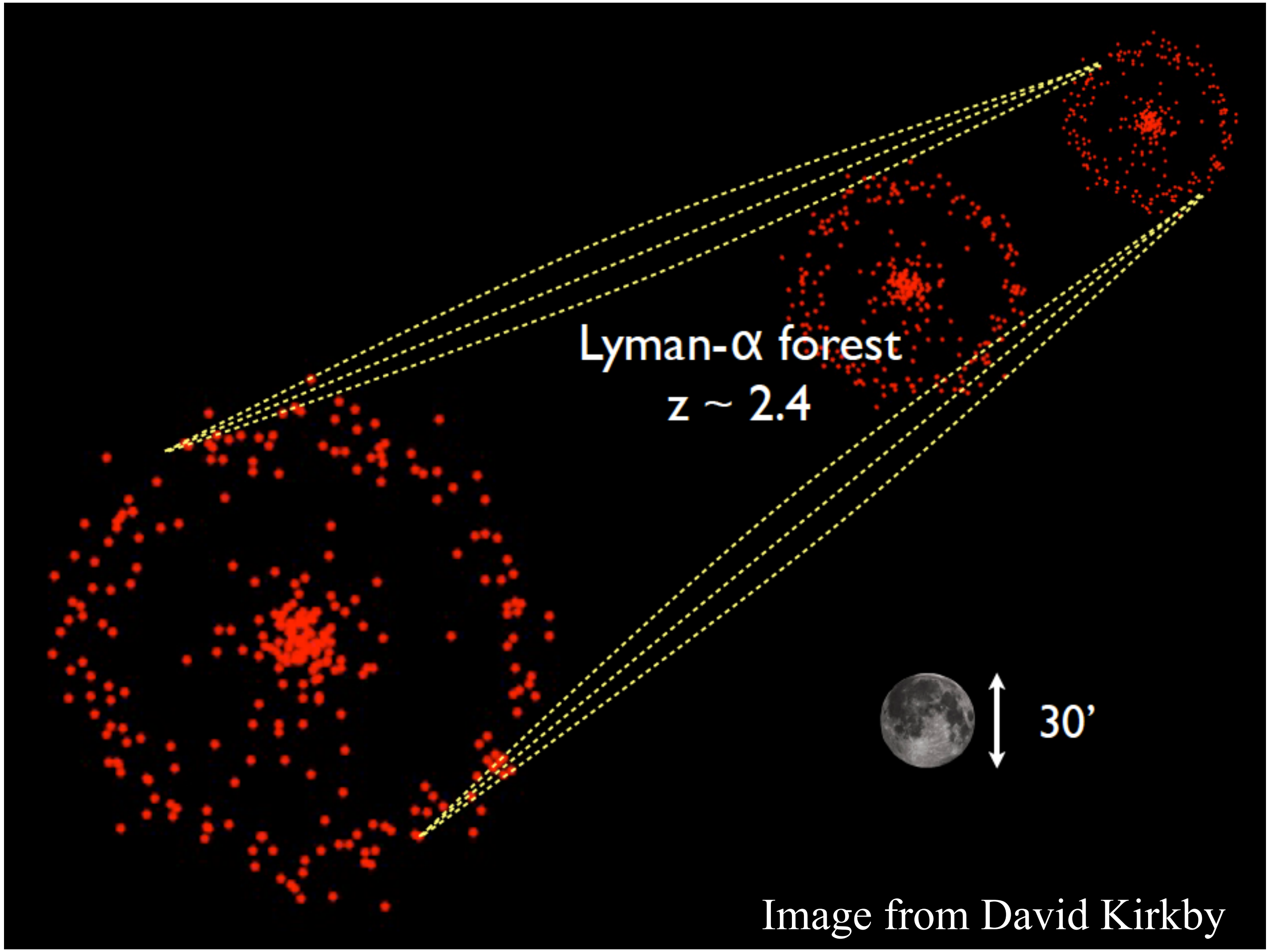
- The combination of CMB, BAO and Sne yields extremely accurate constraints on space curvature and the dark energy.
- The precise agreement with inflation's prediction of flat space, and of w=-1, is an impressive validation of inflation+Λ.

Anderson et al. (2014)

Once we have measured BAO with galaxies and CMB, what other tracer can be useful?

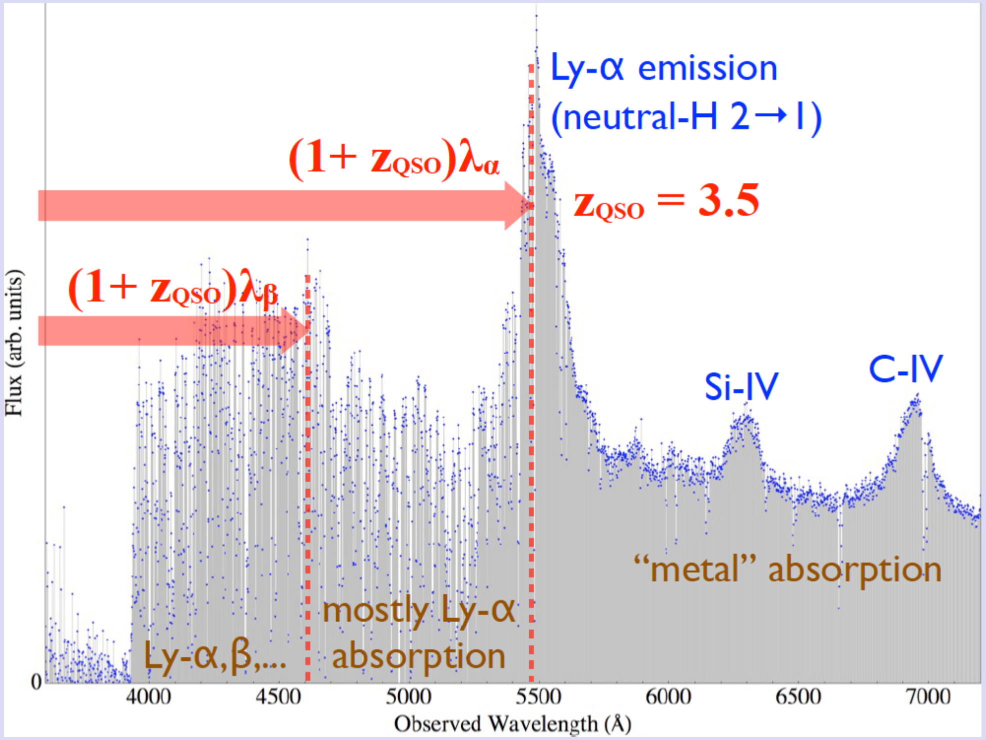


Lyman alpha forest is easily measured in spectra of luminous quasars at z ~3.



At each redshift, distances and expansion rates are measured in terms of the BAO scale r_d, the sound horizon at the drag epoch.

Lyα absorption spectra are a fluctuating Gunn-Peterson optical depth mapping large-scale structure of the universe



Without thermal broadening: the Lyα optical depth depends on the overdensity δ and peculiar velocity gradient η

$$\eta = -H^{-1}\frac{dv_{pec}}{dx}$$

$$\tau = \frac{\tau_0\,(1+\delta)x_{HI}}{1-\eta} \approx \frac{\tau_{GP}(1+\delta)^{2-0.7\gamma}}{1-\eta}$$

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

Measuring BAO with the Lyα forest

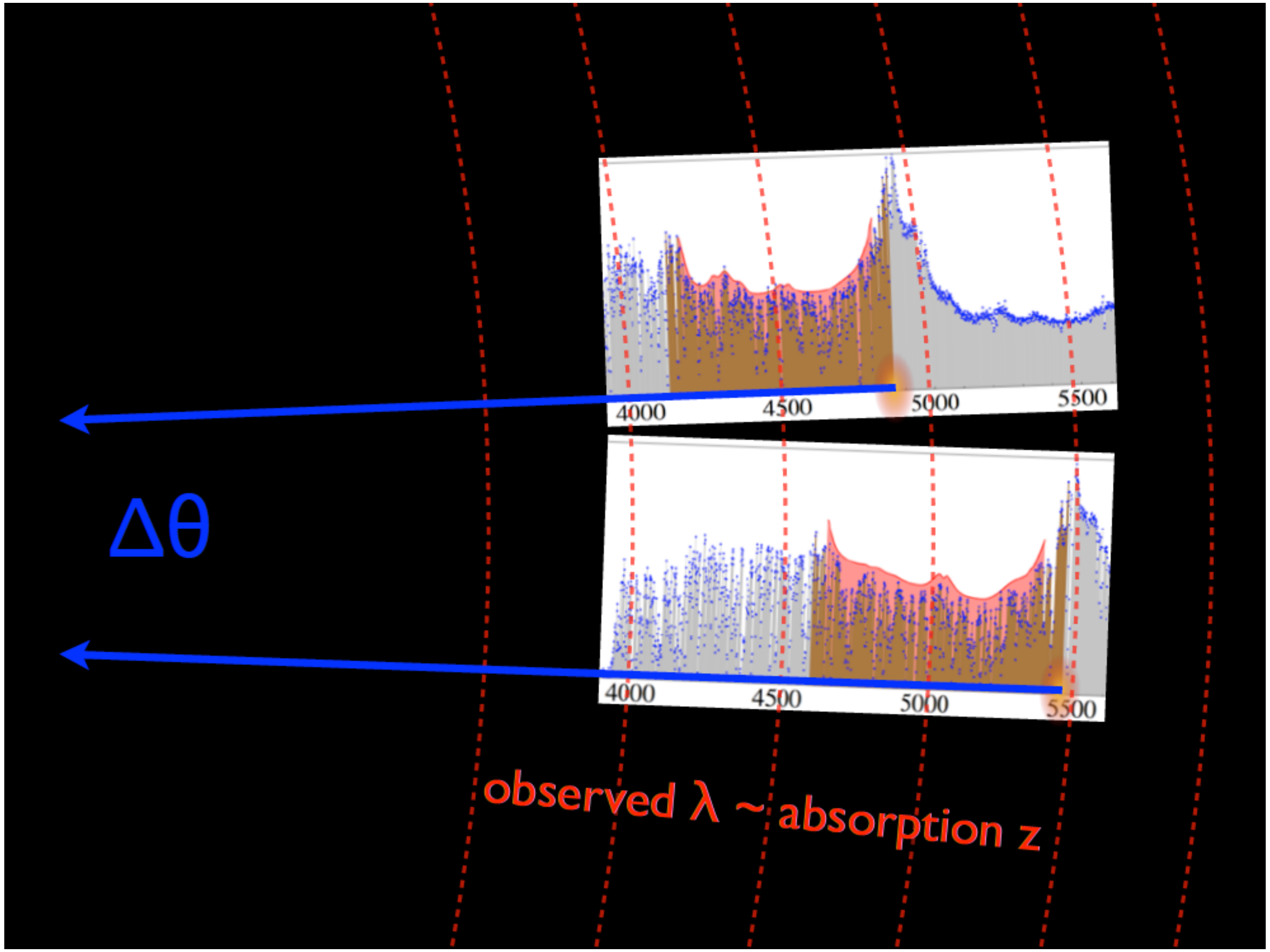


Image from David Kirkby

- After fitting a continuum model, the absorption at each redshift is a tracer of density fluctuations that we can correlate.
- Just like for galaxies, we can measure the BAO peak along and across the line of sight.

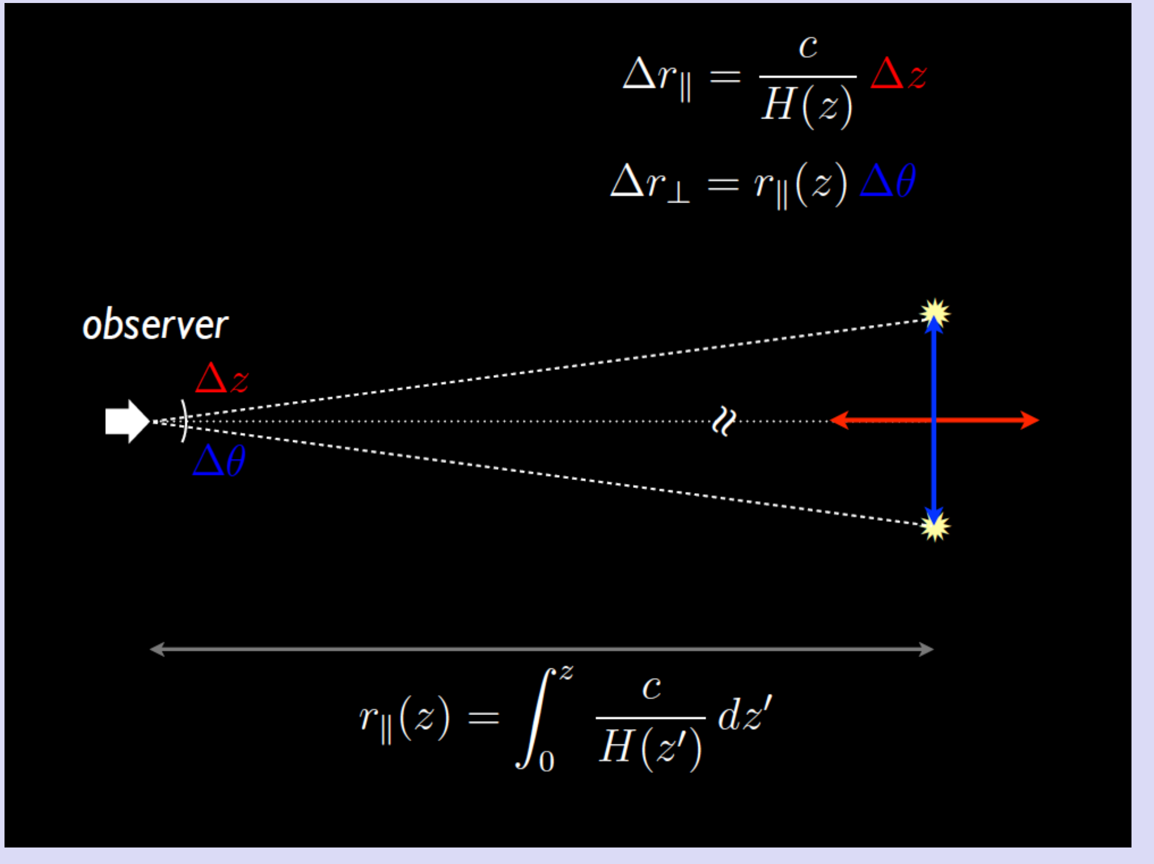
What we measure: Lyα correlation function

- In every quasar spectrum pixel: $\delta_F = F/\overline{F} - 1$

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

$$\vec{r} = (r_{\parallel}, r_{\perp}) = (r\mu,\ r\sqrt{1-\mu^2}) = [cH^{-1}\Delta z, D_A(1+z)\theta]$$

The small-scale variations in δ_F are large. Large-scale power is measured once the small-scale variance is averaged out with many lines of sight.



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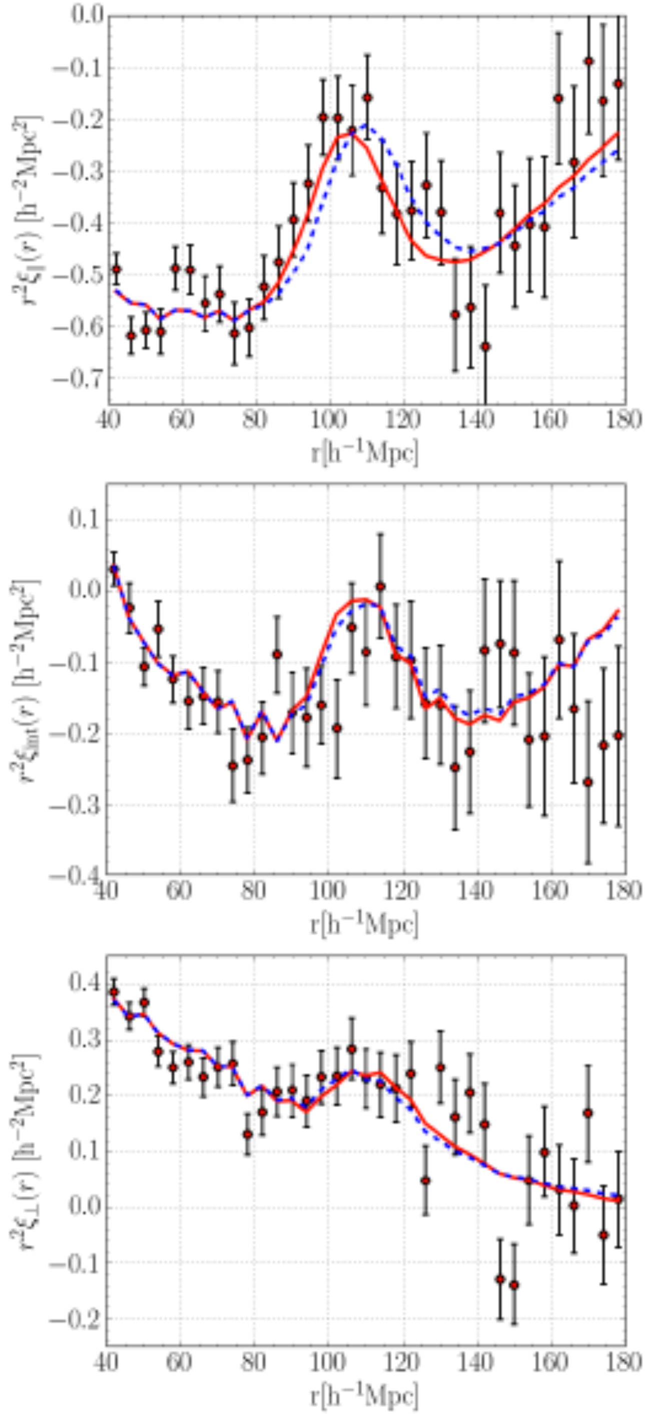
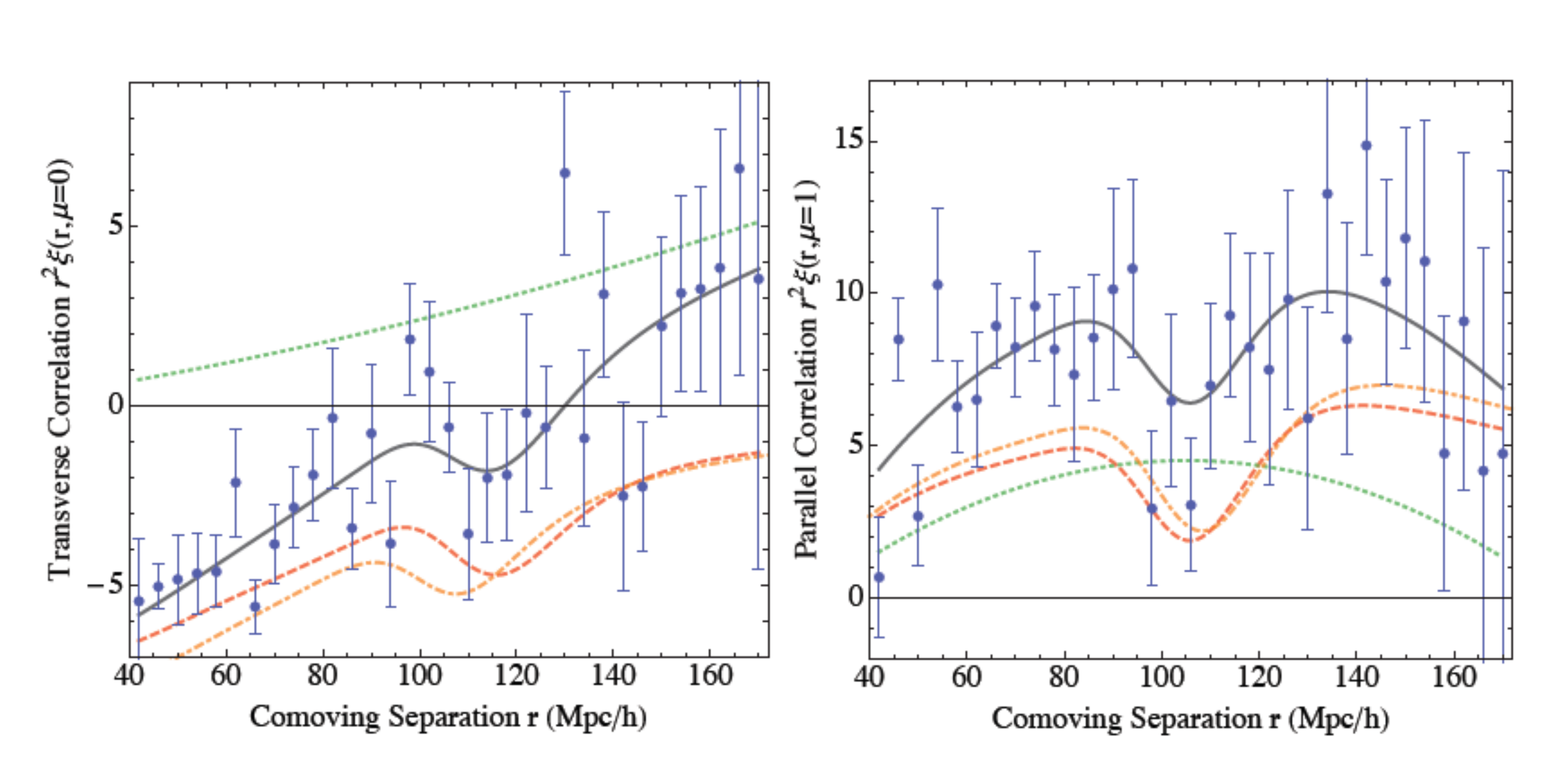


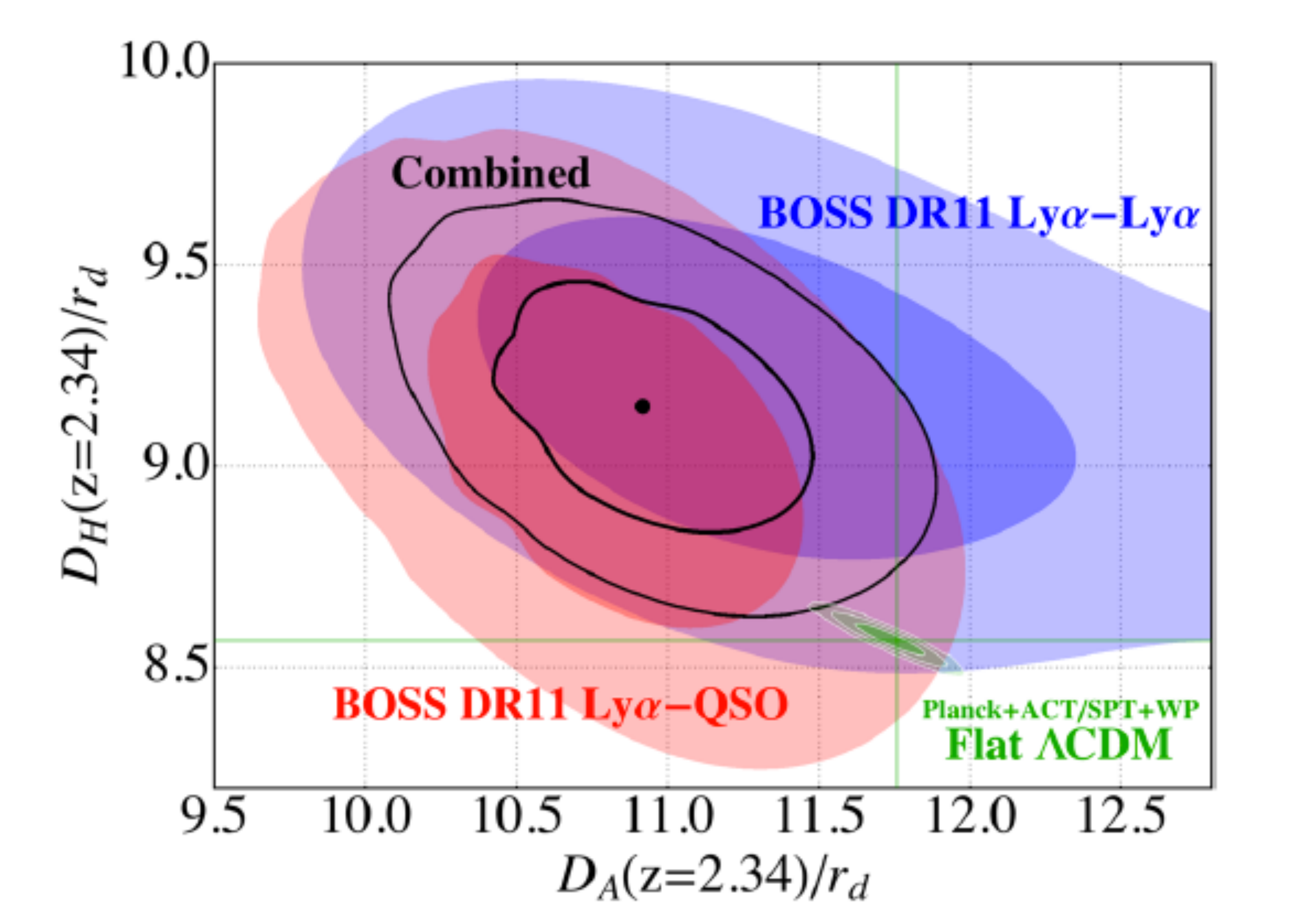
Lyα autocorrelation (Delubac et al. 2014)

- The correlation is measured in three wedges of μ (the cosine of the angle from the line of sight of the separation vector).
- The wedge closest to the line of sight has a higher amplitude BAO peak, owing to redshift distortion effects with a low bias for the Lyα forest.

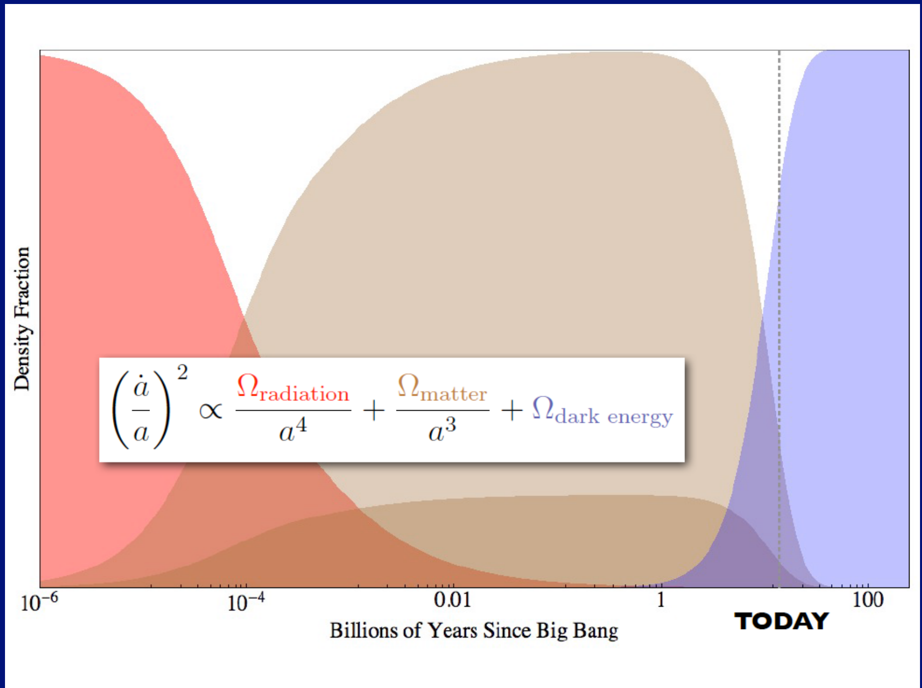
Cross-correlation of quasars and Lyα can also be measured, and the BAO is detected (Font-Ribera et al. 2014).



Combined constraints compared with Planck



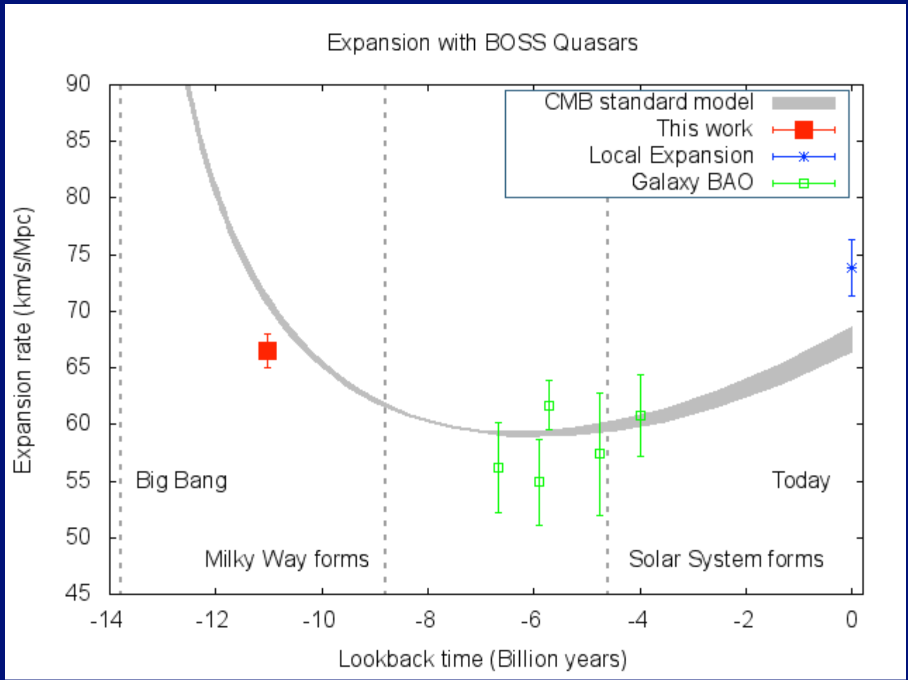
Are BAO measurements at high redshift useful?



- At high redshift, BAO measurements are less useful to constrain dark energy because most of the energy density of the universe was dominated by matter at that epoch.
- However, precisely for this reason and because we measure the matter density from the CMB very accurately, the high redshift BAO measurements are an excellent test of the standard model of cosmology.

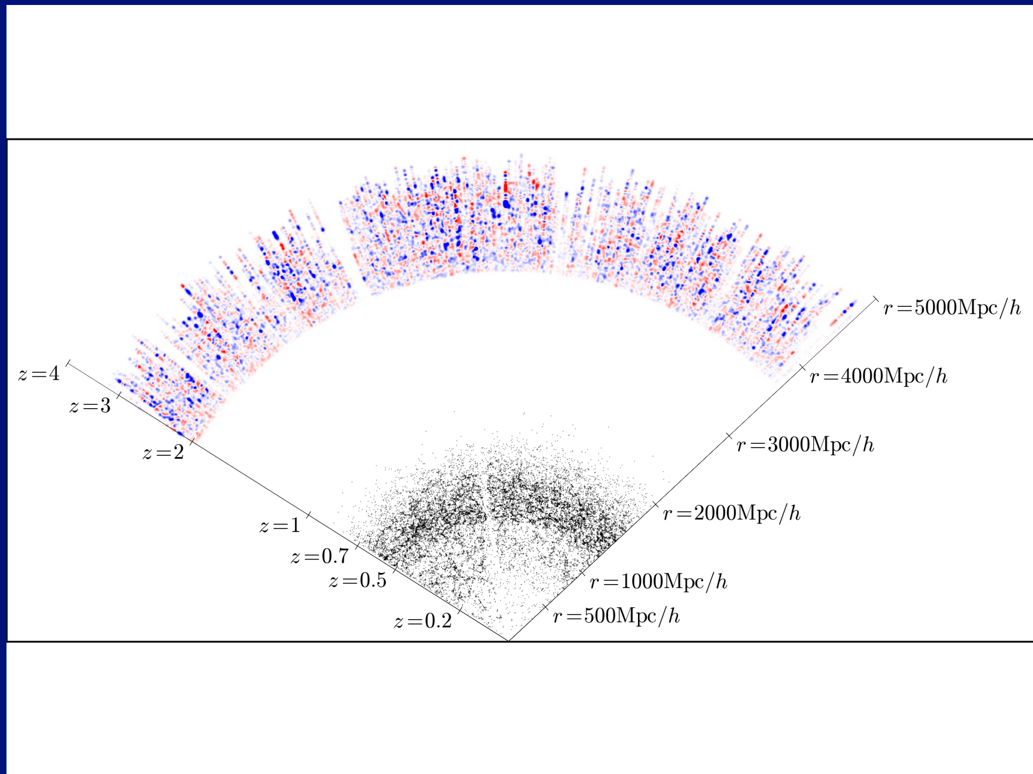
$$\frac{8\pi G}{3}\rho_{\rm de}(z) = H^2(z) - H_0^2\Omega_M(1+z)^3$$

Conclusions



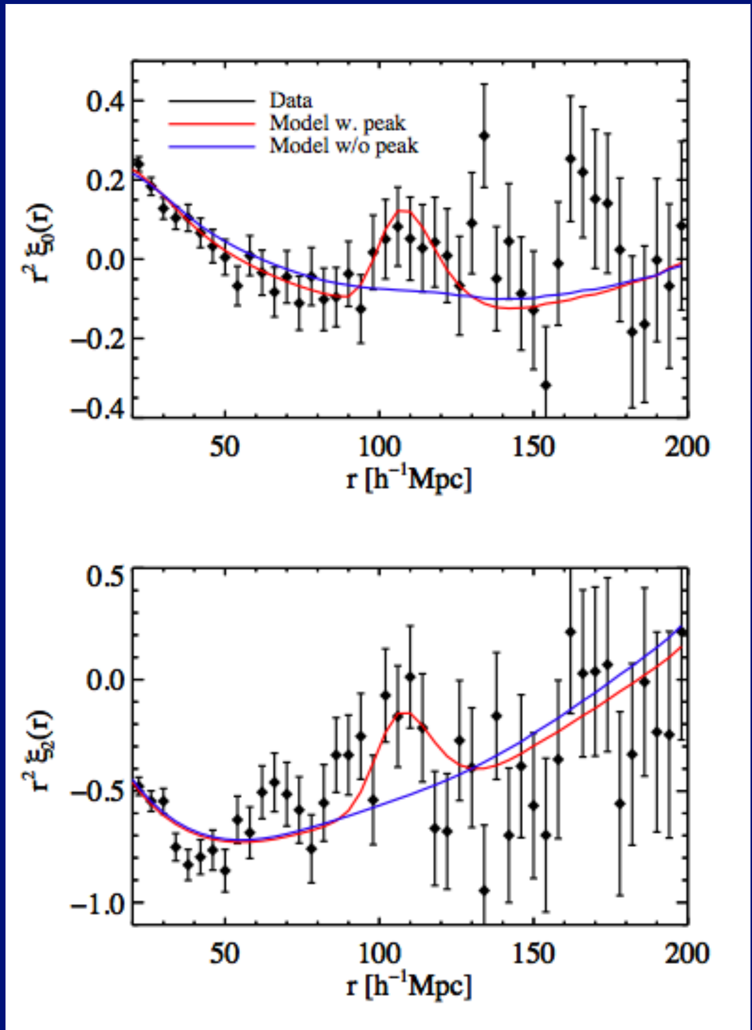
- The measurement of the BAO scale over a wide span of redshifts is a powerful probe to the precise values of cosmological parameters.
- Present measurements constitute an impressive confirmation of space flatness and the presence of a cosmological constant.
- The high-redshift Lyα measurements give a smaller expansion rate and smaller distance to $z \sim 2.3$ compared to the expected values, but the differences are still within the errors.

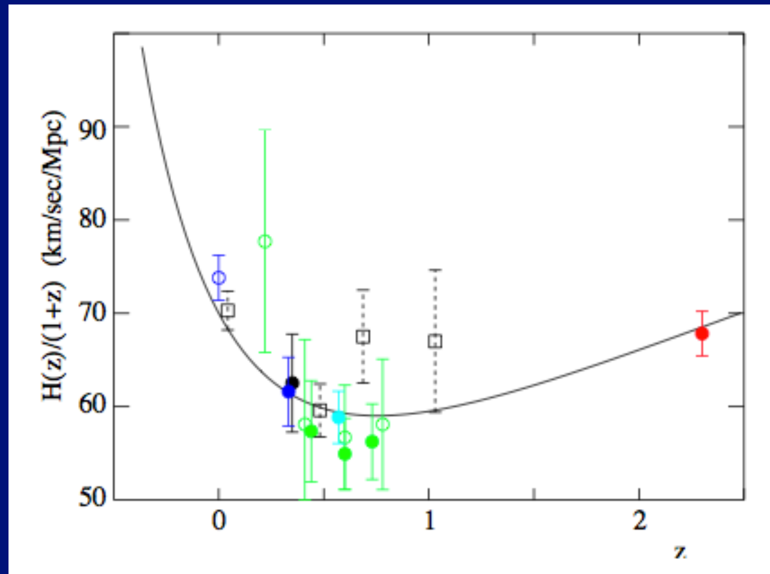
BOSS: galaxy and quasar spectroscopy

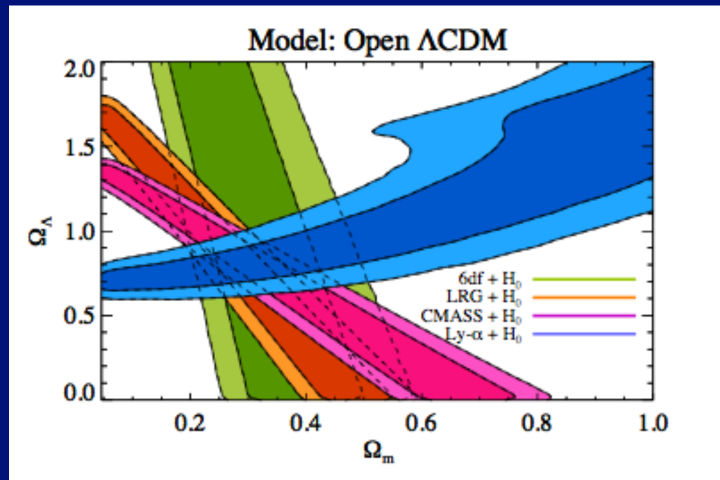


- McDonald & Eisenstein (2007) proposed to add z>2 quasar spectroscopy in BOSS with the promise to measure large-scale structure and Baryon Acoustic Oscillations using the Lyα forest.
- Over 100,000 quasar spectra at z>2 now offer a huge opportunity for doing large-scale structure studies with absorption systems.

BAO results from Lyα, DR9 (Busca et al. 2013)

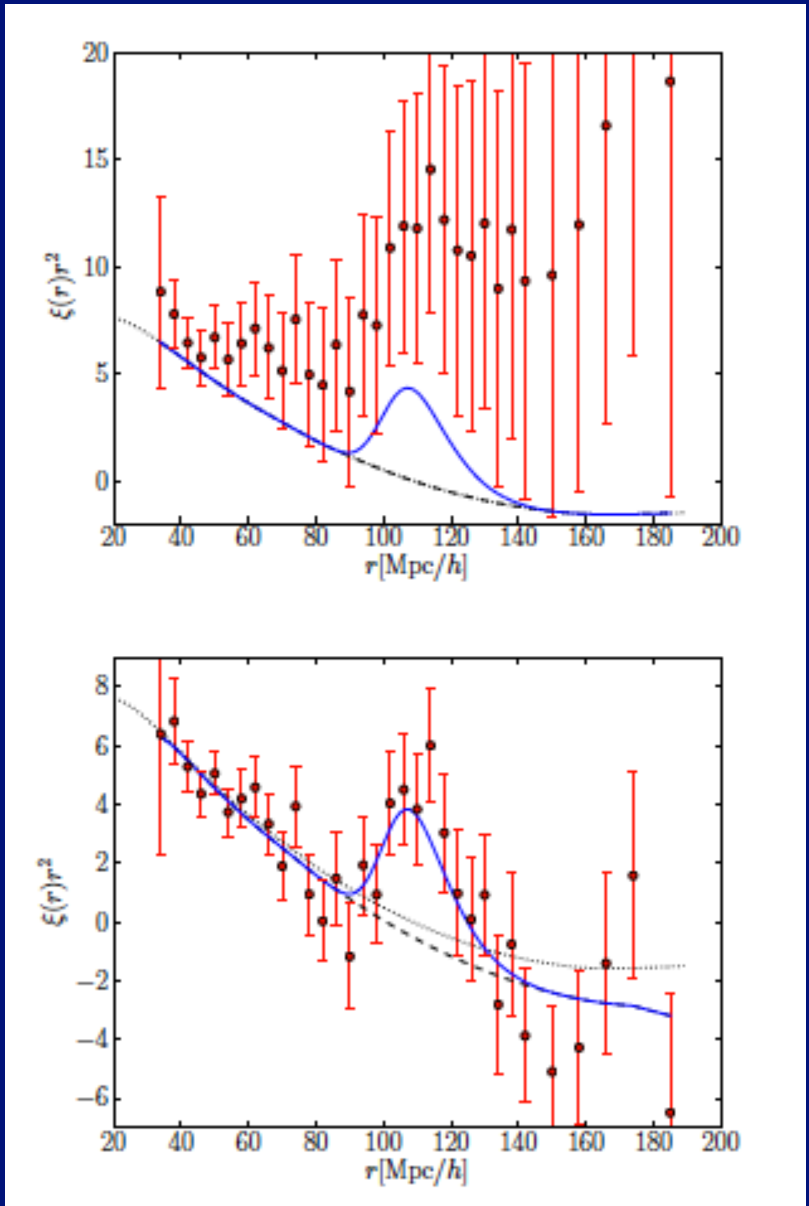


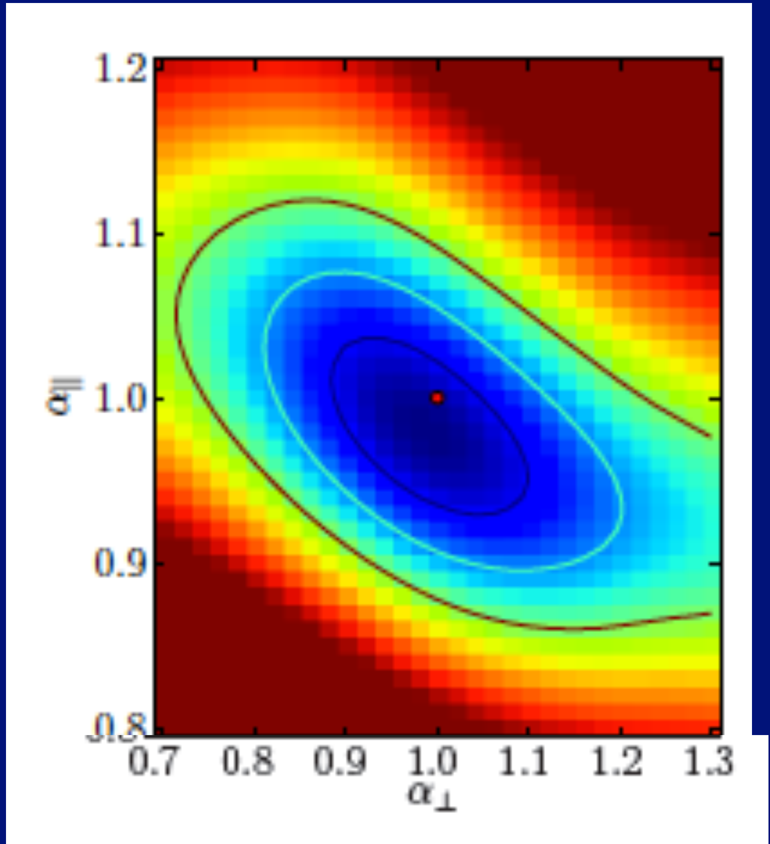




- Principal difficulty: calibration and continuum fitting systematics introduce broadband terms in the correlation (similarly to galaxies).

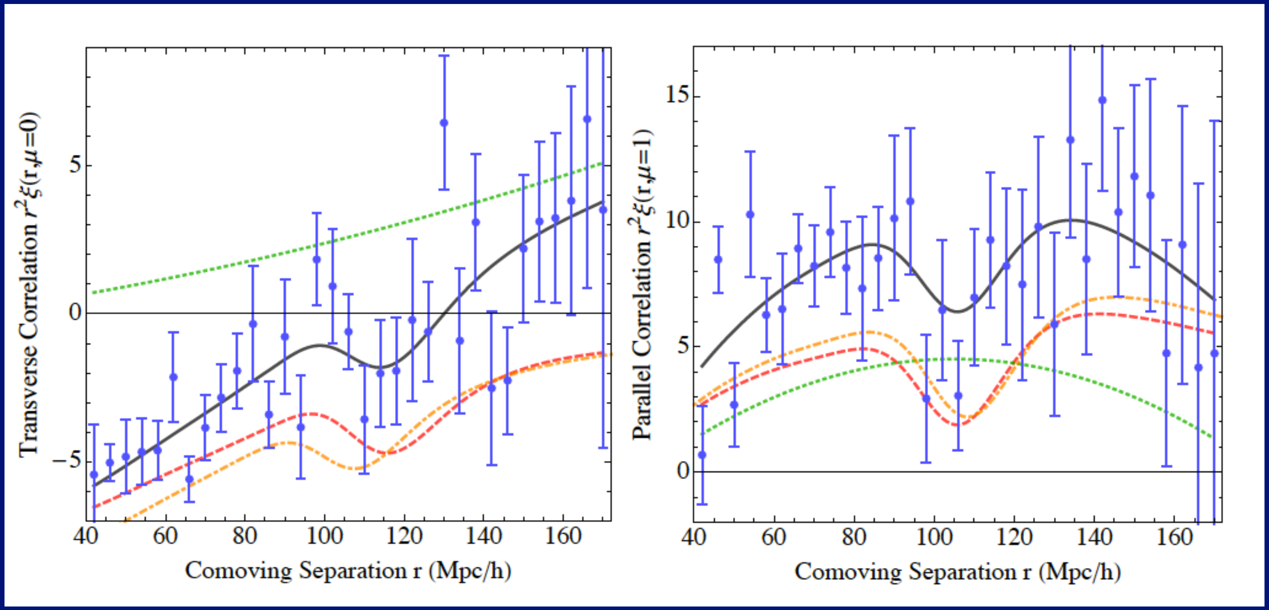
Alternative analysis for the BAO peak from the DR9 correlation of Lyα (Slosar et al. 2013)

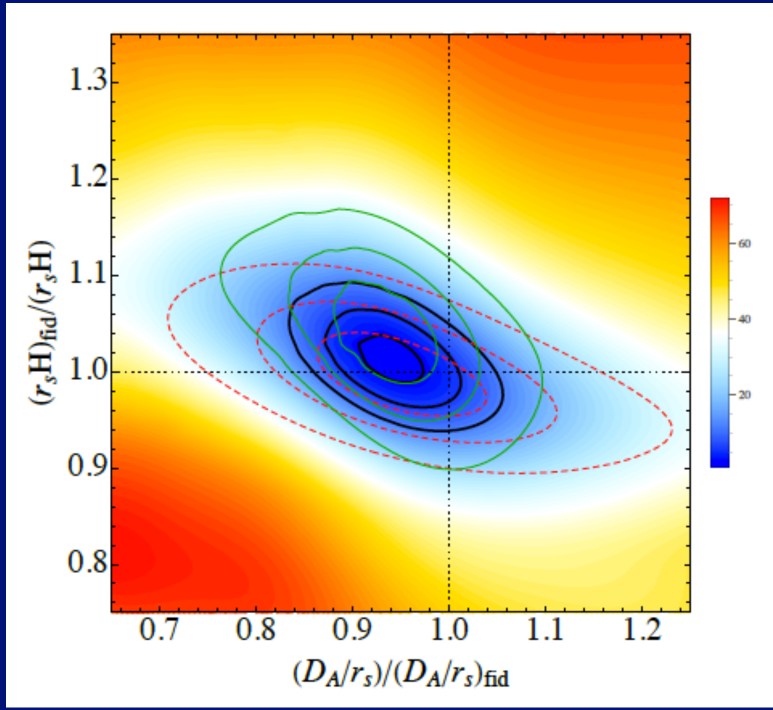




- The largest sensitivity is to H(z), although some measurement of D(z) is also done.

New results for DR11 QSO-Lyα cross-correlation





- The accuracy of the BAO measurement from the DR11 QSO-Lyα cross-correlation is comparable to the DR9 autocorrelation, and better for the perpendicular BAO measurement. The two measurements are nearly independent and the joint constraints become significantly improved.