Measuring baryon acoustic oscillations using the distribution of intergalactic gas

Intergalactic Interconnections
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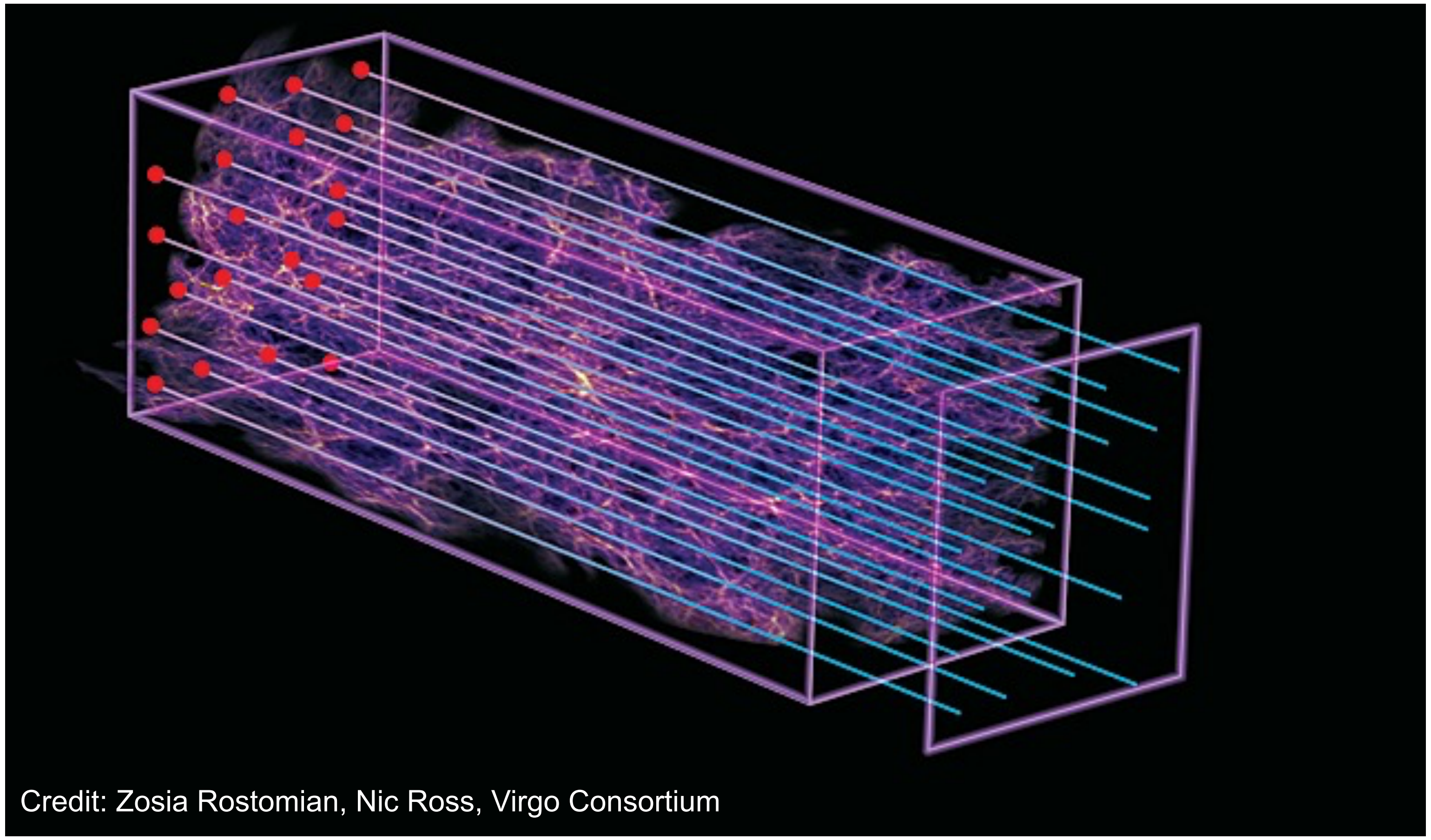
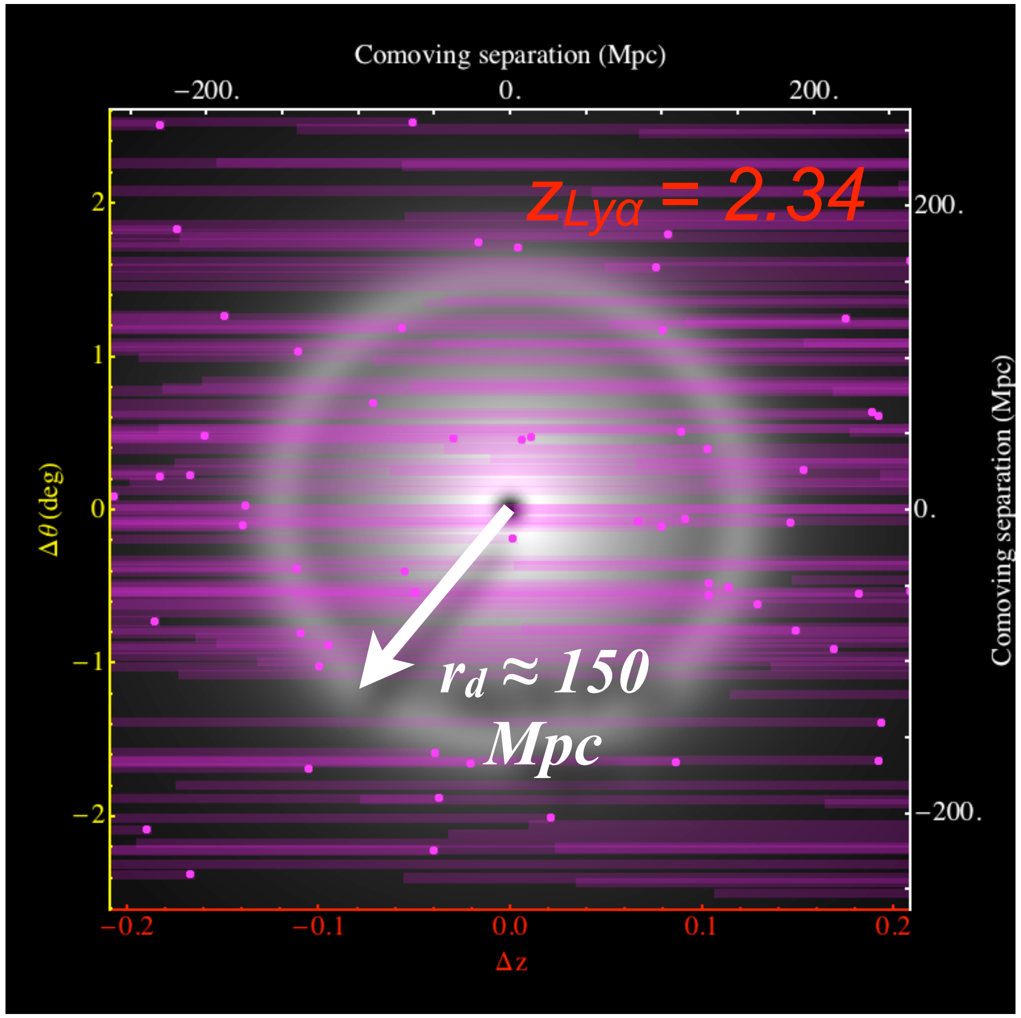
Outline

- Introduction
- Lyα forest BAO from BOSS
- CIV forest BAO from eBOSS
- BAO from galaxies in absorption

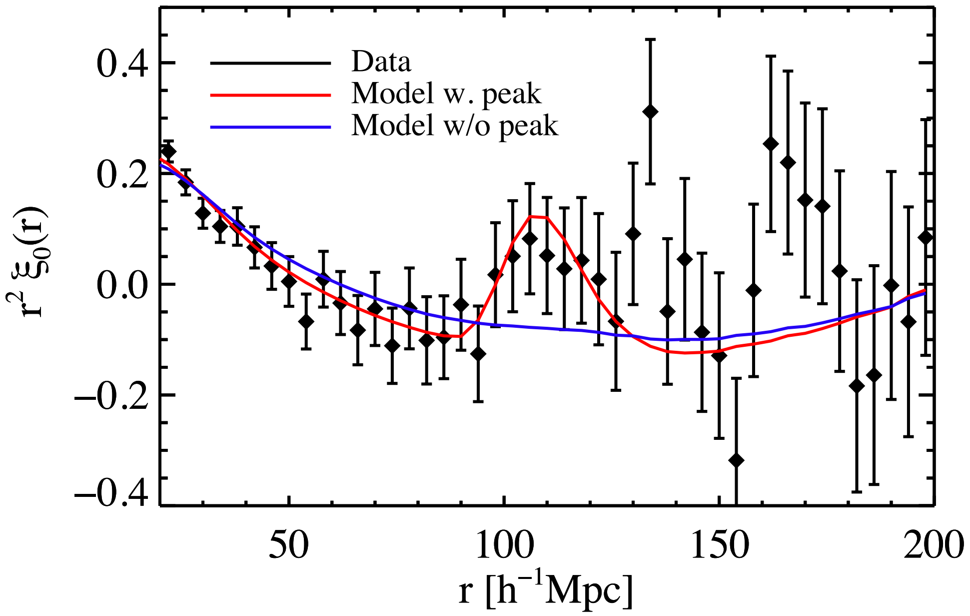
BAO in the Lyα forest





Use distant quasars to probe the distribution of hydrogen gas along the line of sight

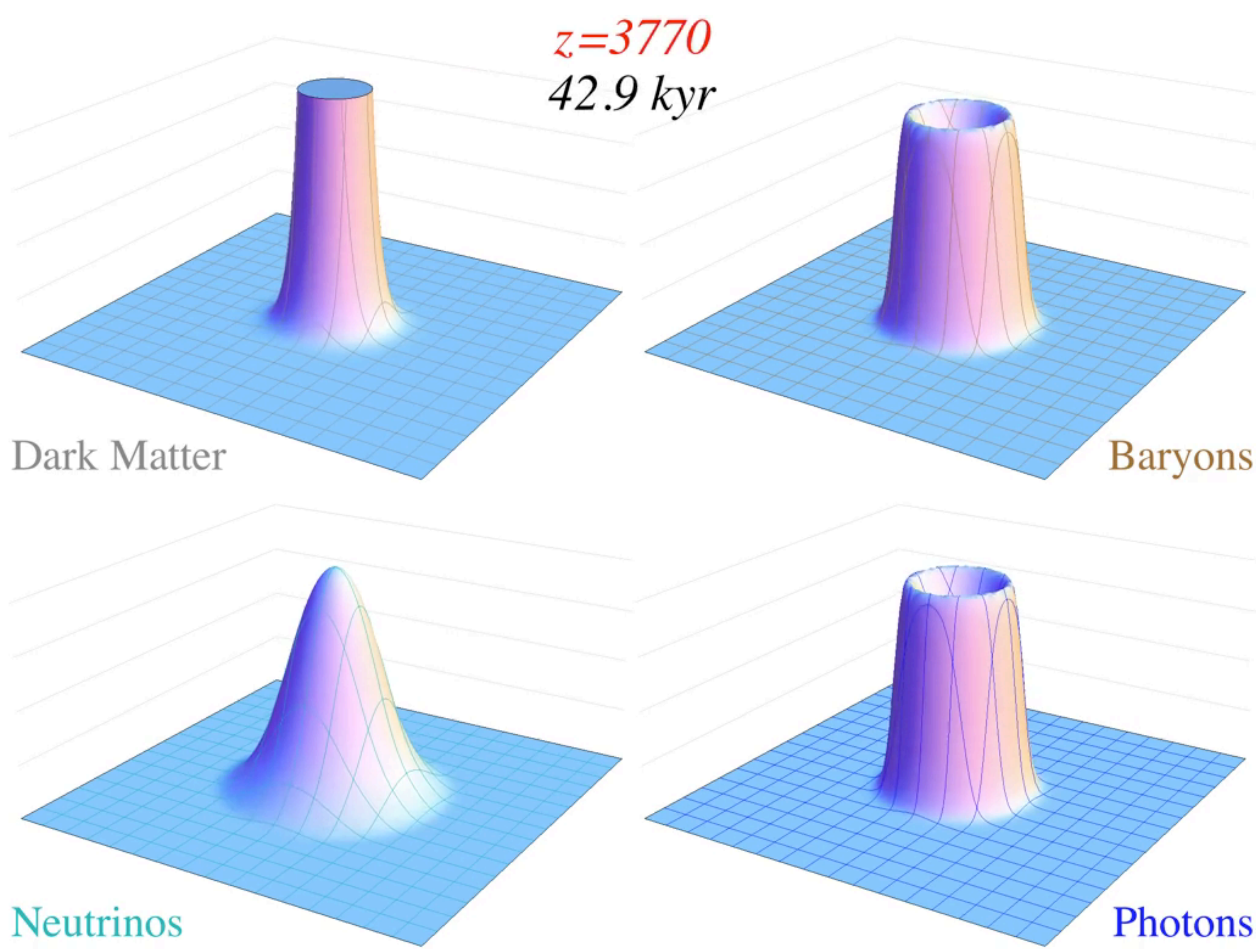
First detection of Lyα BAO published in 2013 (Busca++, Slosar++)



Baryon acoustic oscillations

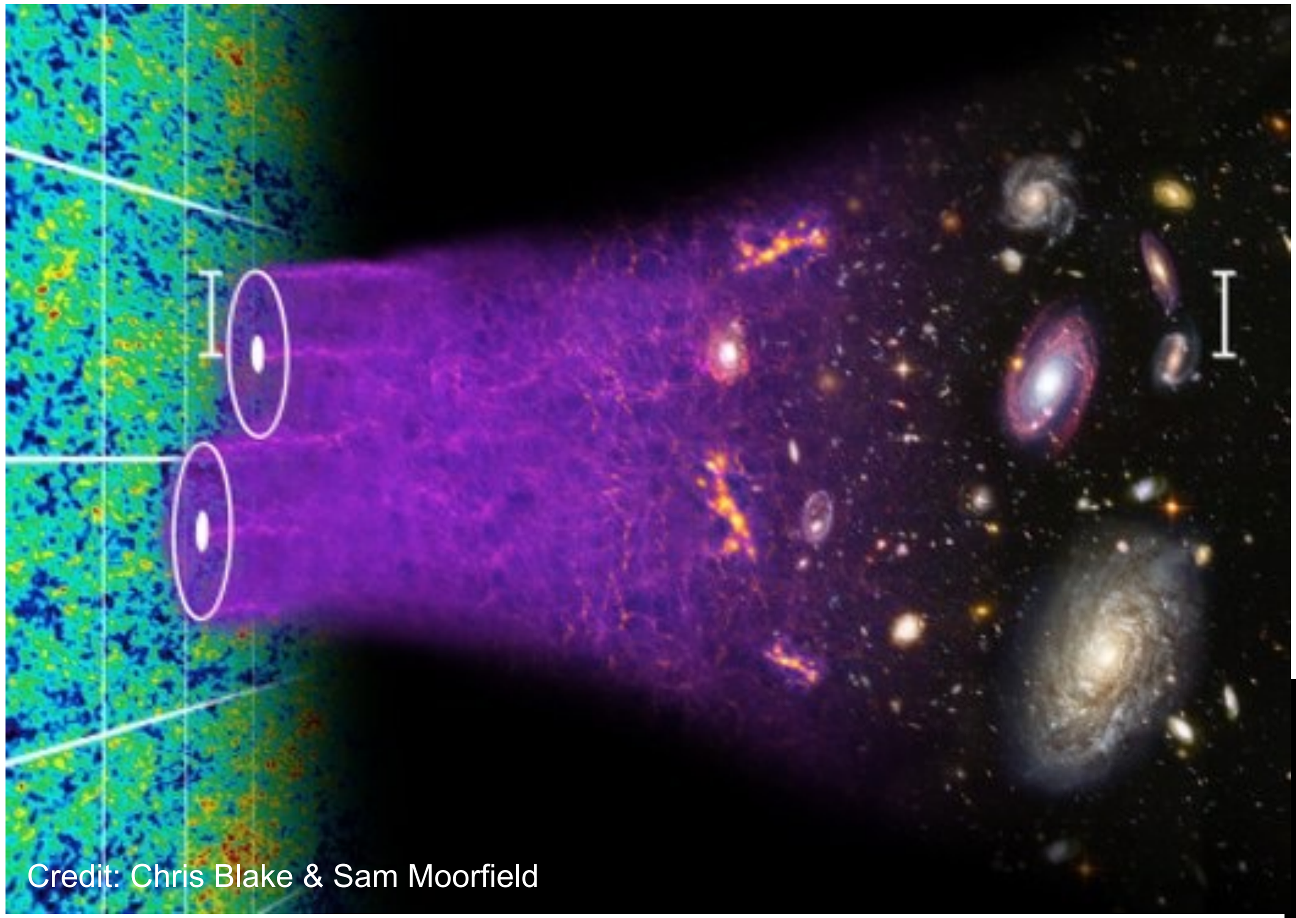
Sound waves propagating in the pre-recombination universe imprinted a characteristic length scale in the large-scale structure at recombination

Sound horizon: $r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$ ≈ 150 Mpc



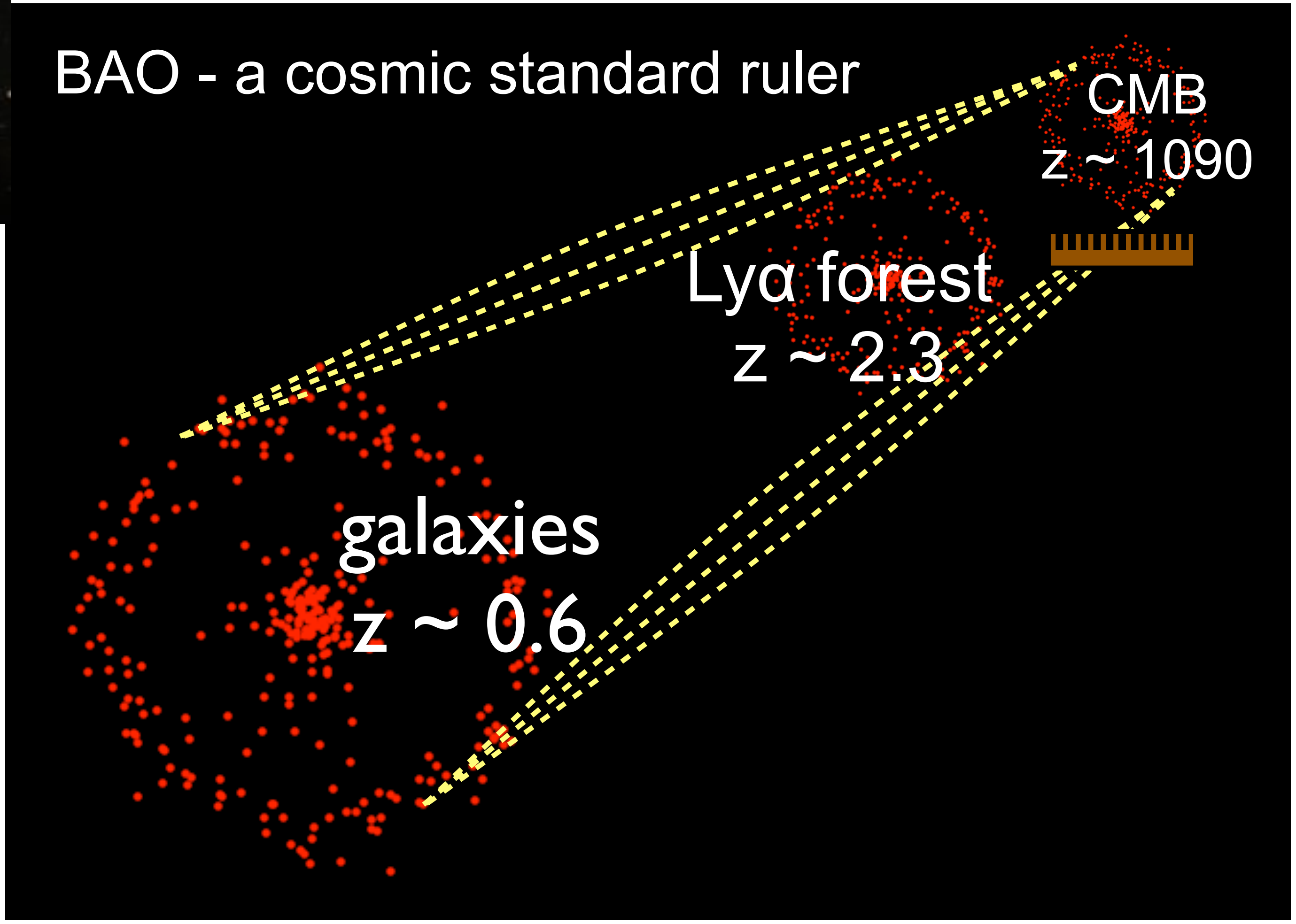
Credit: David Kirkby

Baryon acoustic oscillations



BAO measured in the large-scale distribution of galaxies, quasars, intergalactic gas (Lyα forest), …

Probes the cosmic expansion at different epochs



Line of sight:

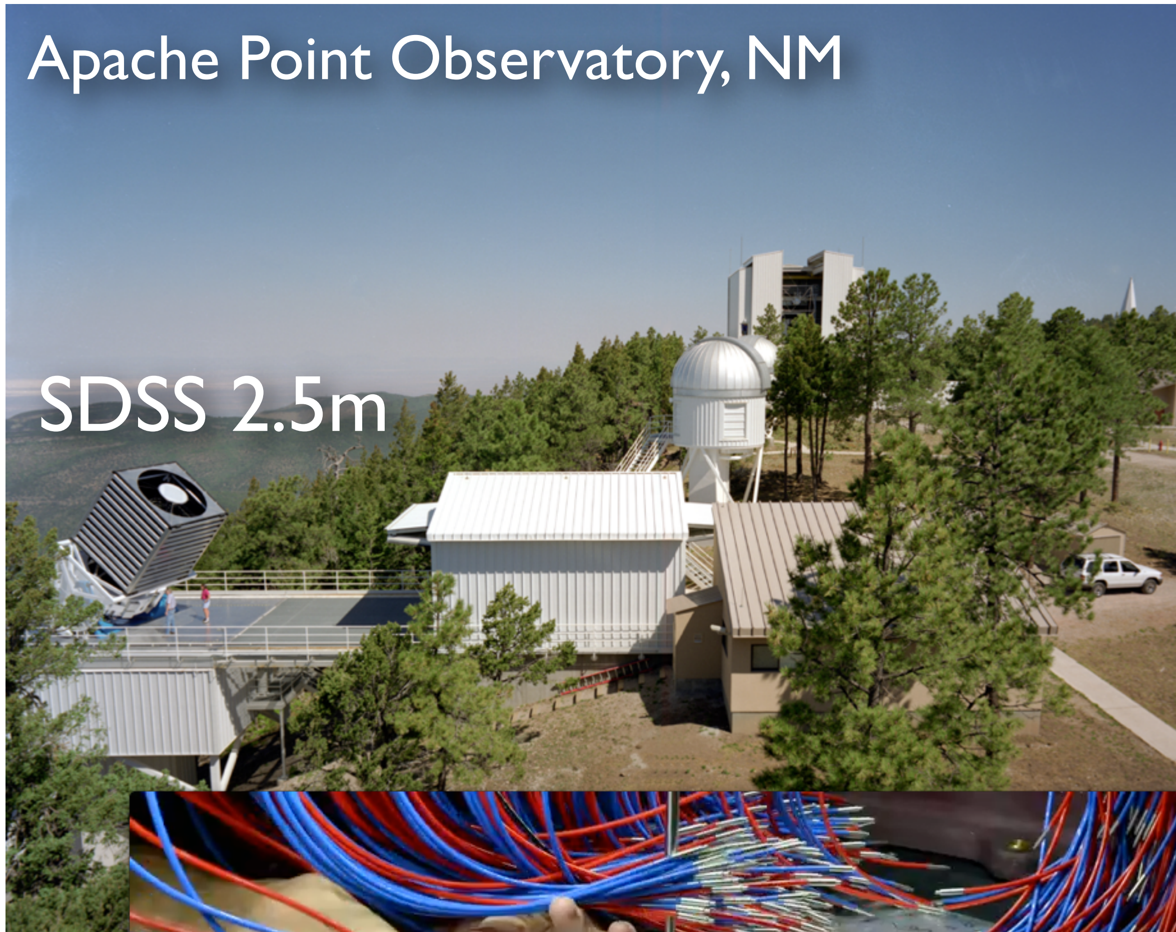
$$\Delta z = r_d \frac{H(z)}{c}$$

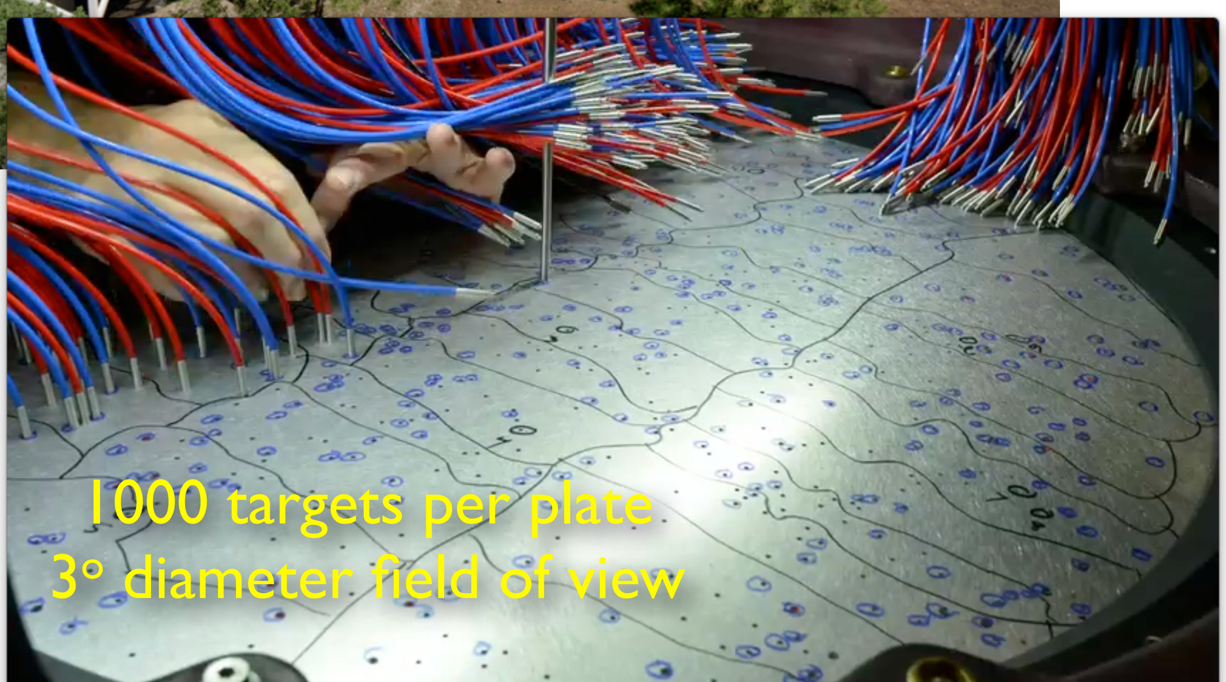
Transverse:

$$\Delta\theta = \frac{r_d}{1+z} \frac{1}{D_A(z)}$$

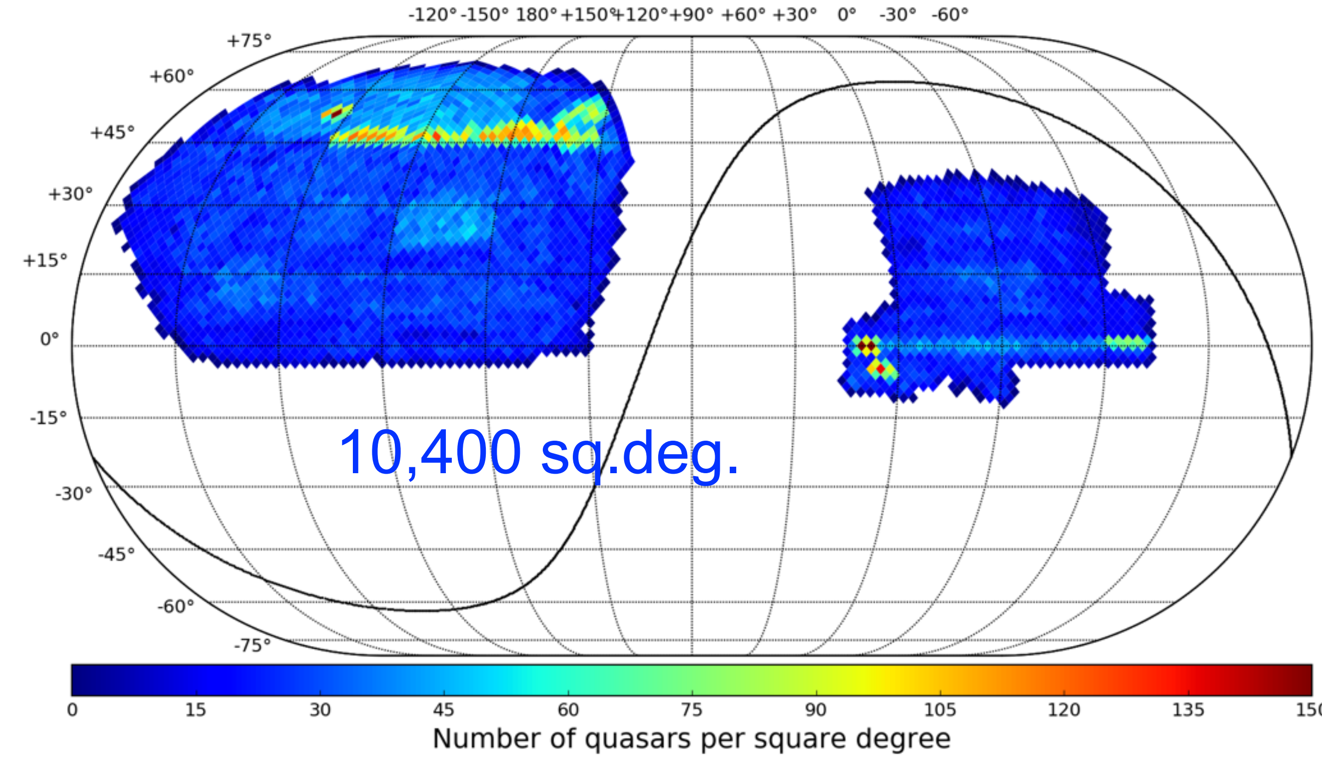
BOSS quasar survey

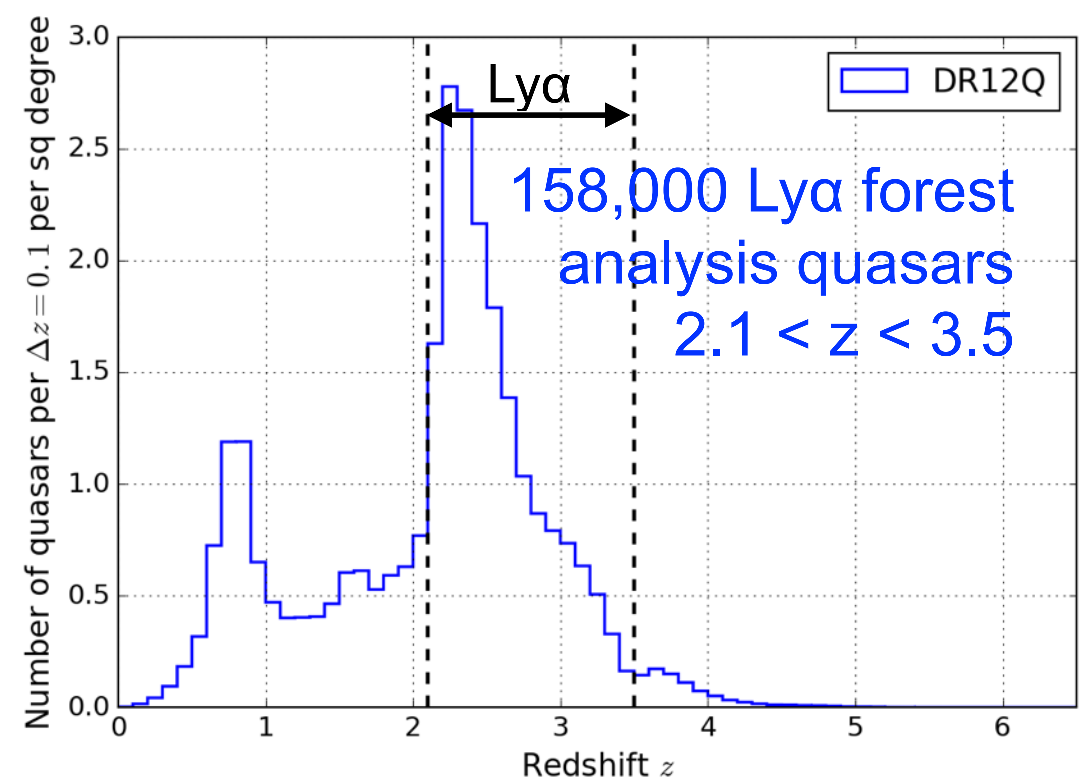
Baryon Oscillation Spectroscopic Survey (SDSS-III): 2009-2014





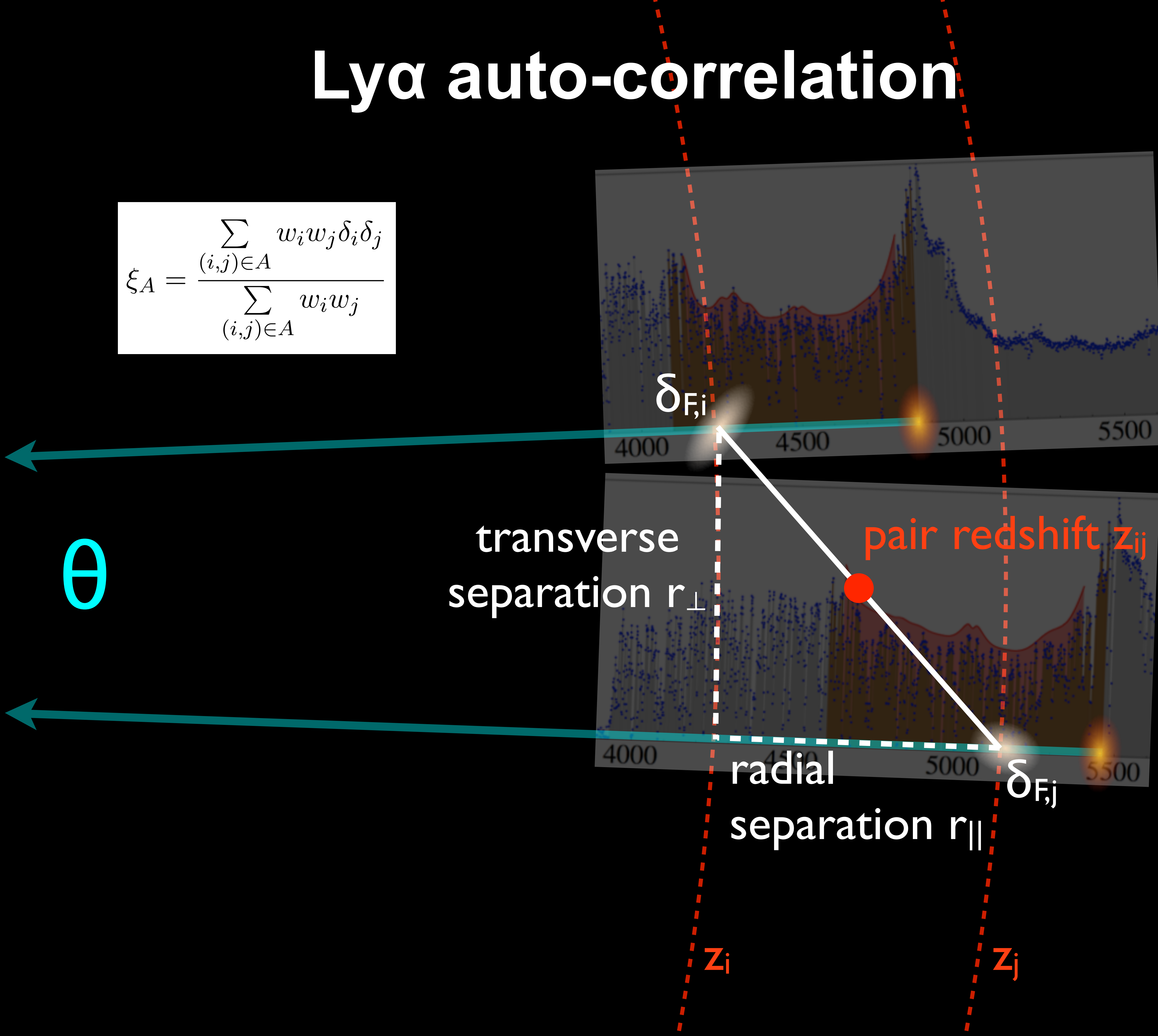
SDSS Data Release 12 (DR12)





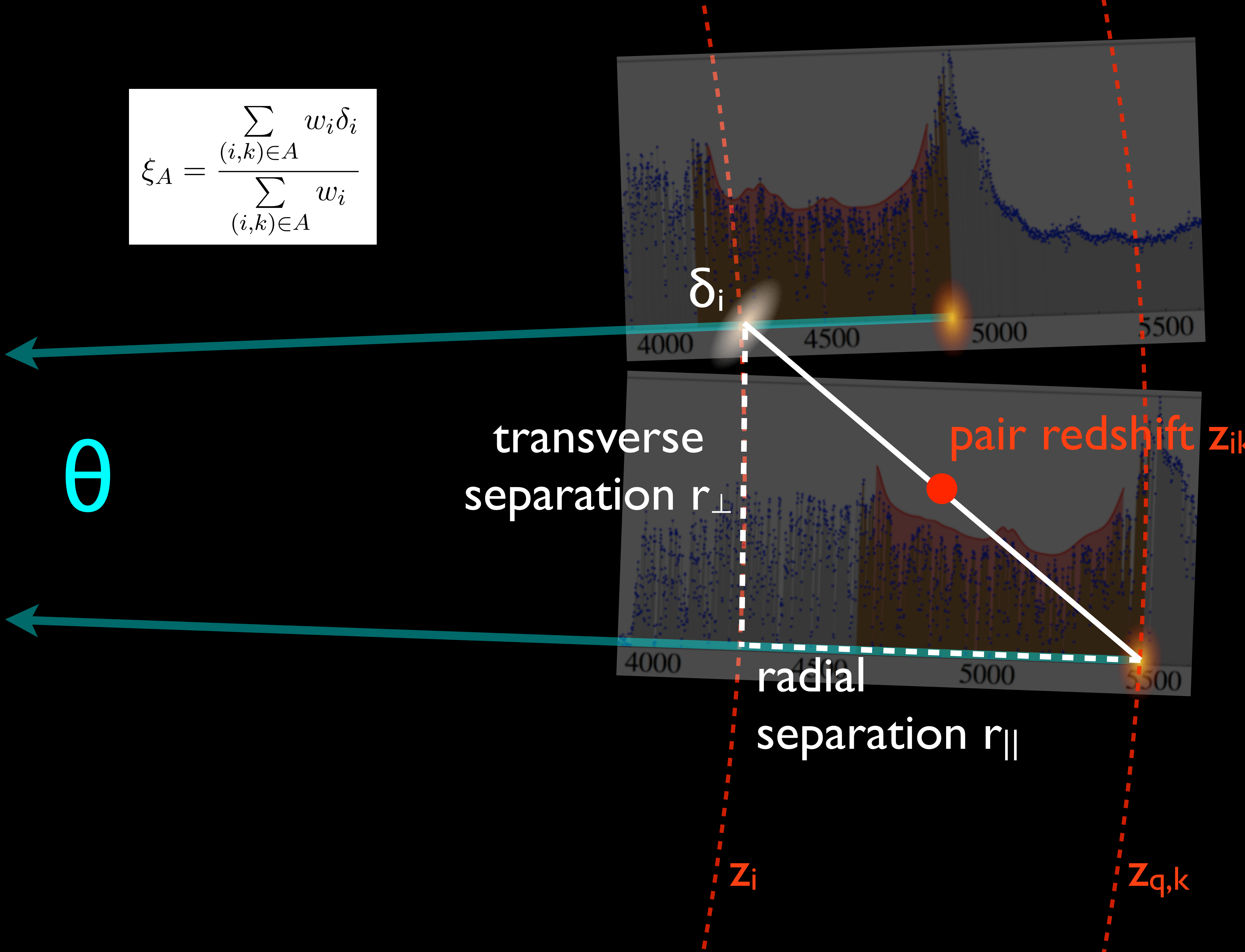
Lyα auto-correlation

$$\xi_A = \frac{\sum_{(i,j)\in A} w_i w_j \delta_i \delta_j}{\sum_{(i,j)\in A} w_i w_j}$$



Quasar-Lyα cross-correlation

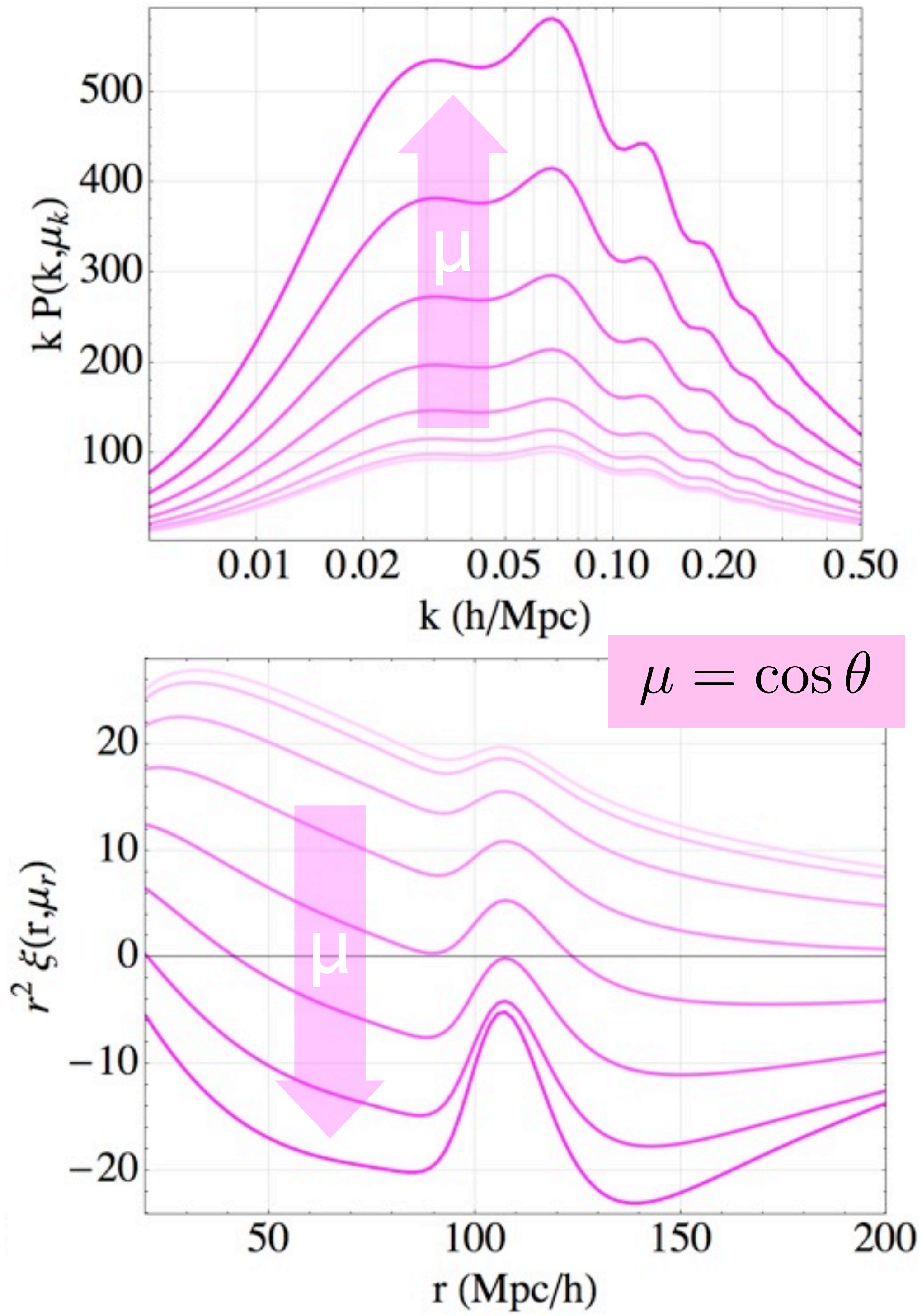
$$\xi_A = \frac{\sum_{(i,k)\in A} w_i \delta_i}{\sum_{(i,k)\in A} w_i}$$



Correlation function model

- Linear matter power spectrum from CAMB for fiducial cosmology (Planck 2015 flat ΛCDM)
- Linear tracer bias sets the amplitude
- Redshift-space distortion boosts the line-of-sight BAO peak

Lyα transmission power spectrum



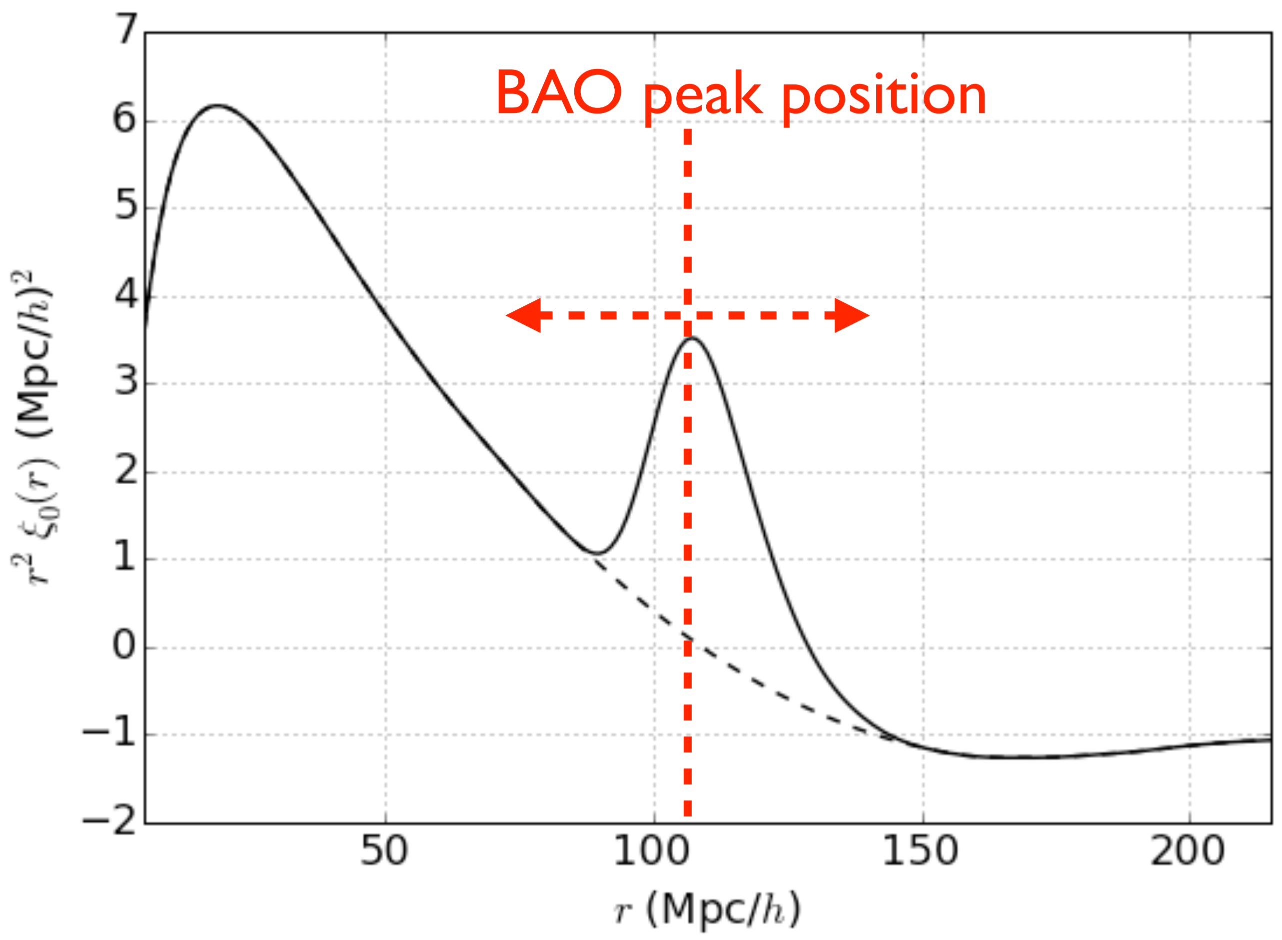
Lyα auto-correlation function

BAO fitting

- Decoupling of the BAO peak from the broadband
- Line-of-sight and transverse scale parameters adjust the peak position to the cosmology preferred by the data

$$r_{\parallel} \rightarrow \alpha_{\parallel} r_{\parallel}$$

$$r_{\perp} \rightarrow \alpha_{\perp} r_{\perp}$$



$$\alpha_{\parallel} = \frac{[D_H(\bar{z})/r_d]}{[D_H(\bar{z})/r_d]_{\rm fid}}$$

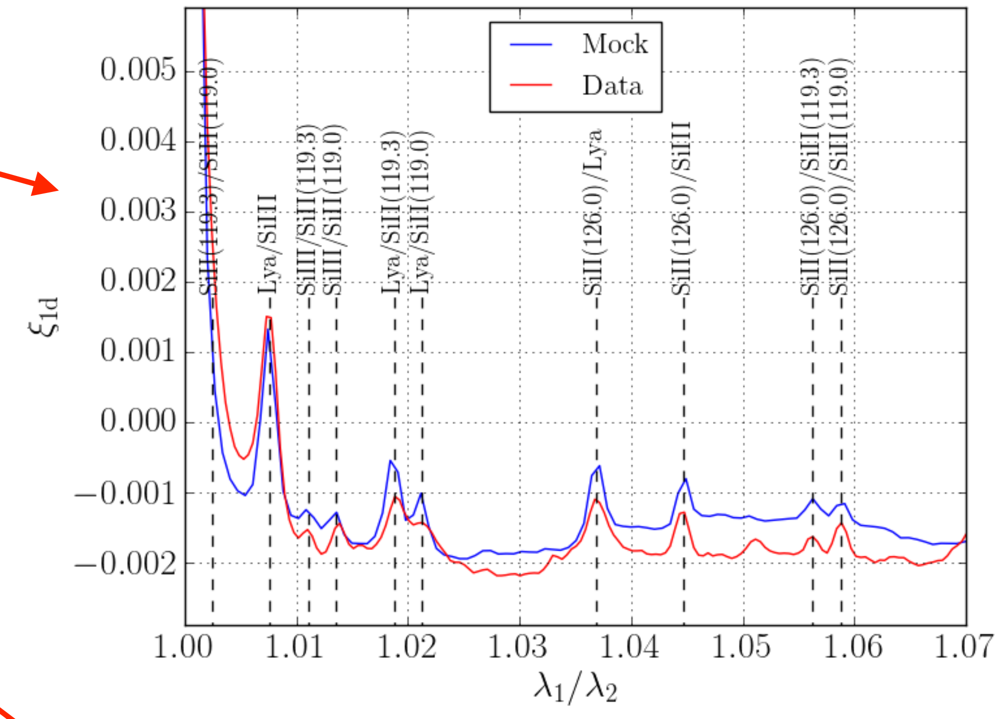
→ measure the Hubble distance $D_H(z) = c/H(z)$

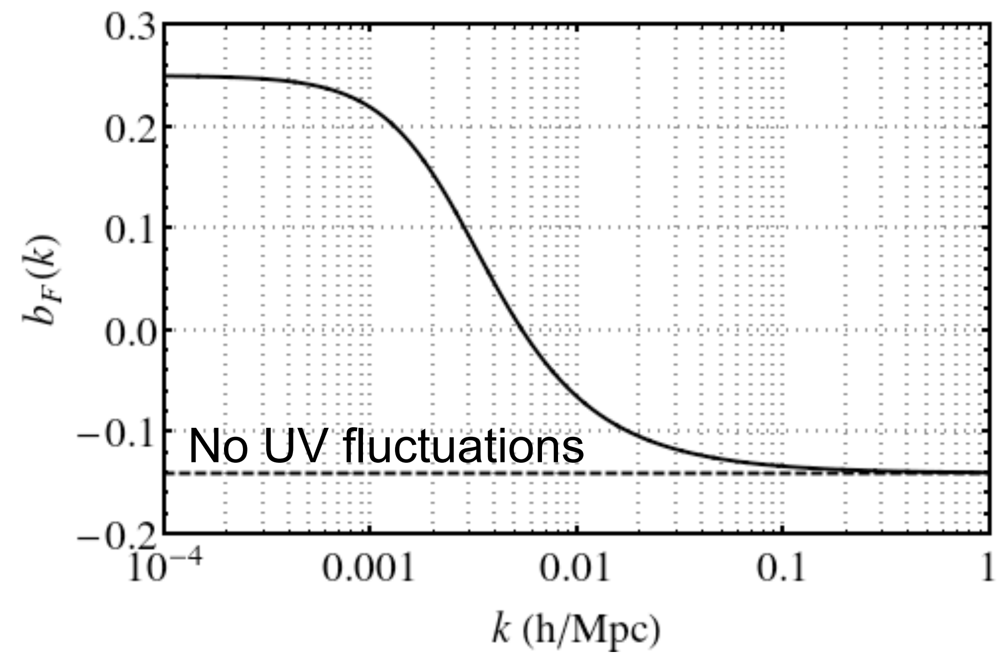
$$\alpha_{\perp} = \frac{[D_M(\bar{z})/r_d]}{[D_M(\bar{z})/r_d]_{\rm fid}}$$

→ measure the comoving angular diameter distance $D_M(z)$

Additional modeling

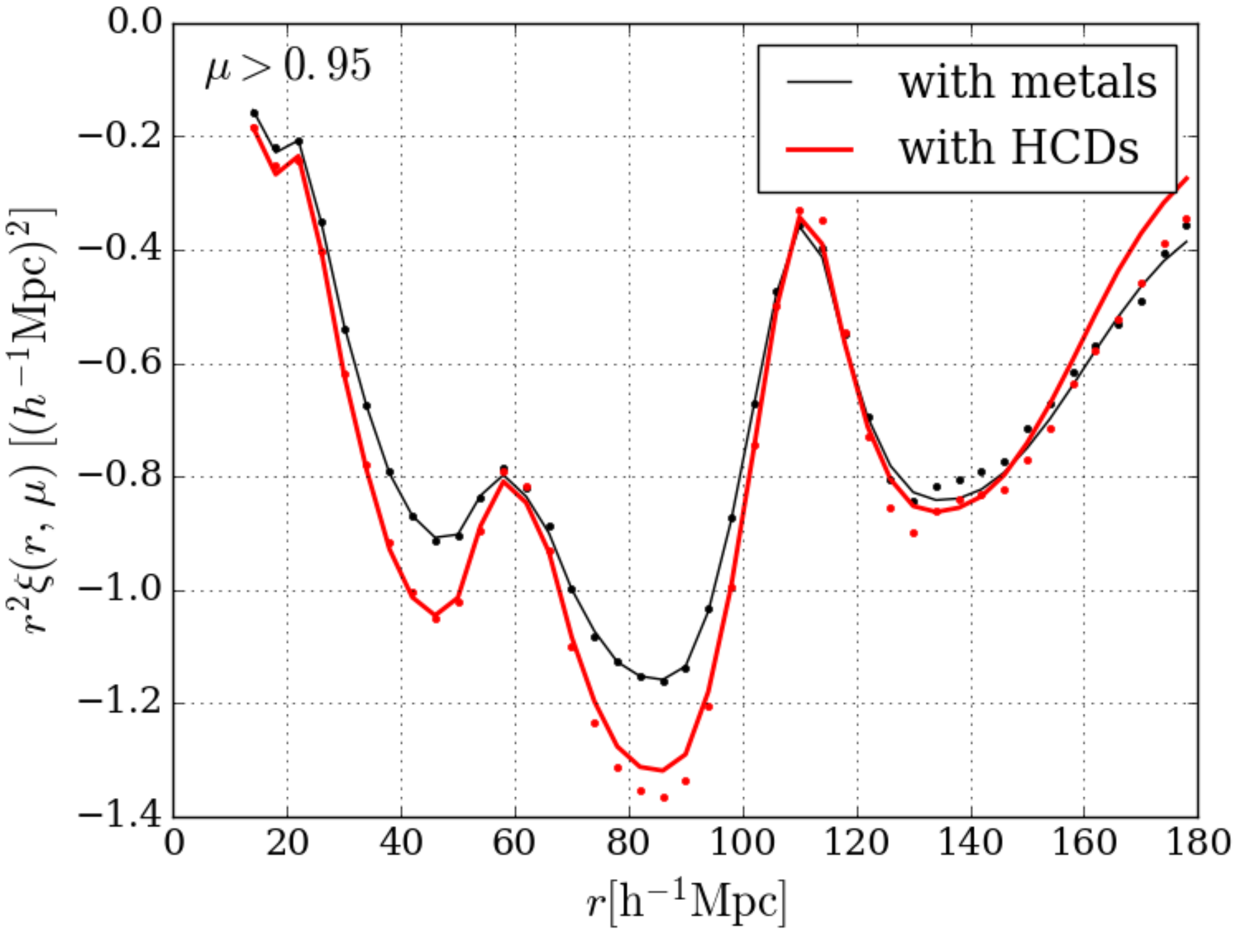
- **Metal correlations:** absorption in the forest by SiII (1190,1193, 1260 Å) and SiIII (1207 Å), and foreground CIV (1548, 1551 Å)
- **High-column density systems:** absorption in the forest by LLS and DLA (Font-Ribera++ 2012)
- **UV fluctuations:** intensity fluctuations in the ionizing background due to source clustering (Gontcho++ 2014, Pontzen 2014)
- **Non-linear correction:** effect of non-linear growth, pressure, peculiar velocity and temperature based on simulations (McDonald 2003, Arinyo-i-Prats++ 2015)
- **Non-linear peak broadening:** due to large-scale bulk velocity flows (Eisenstein++ 2007)
- **Quasar systematic redshift errors (cross):** asymmetry wrt foreground and background absorption
- **Quasar non-linear velocities and stochastic redshift errors (cross):** smoothing of the correlation function (Percival++ 2009)
- **Quasar radiation effect (cross):** transverse proximity effect (Font-Ribera++ 2013)

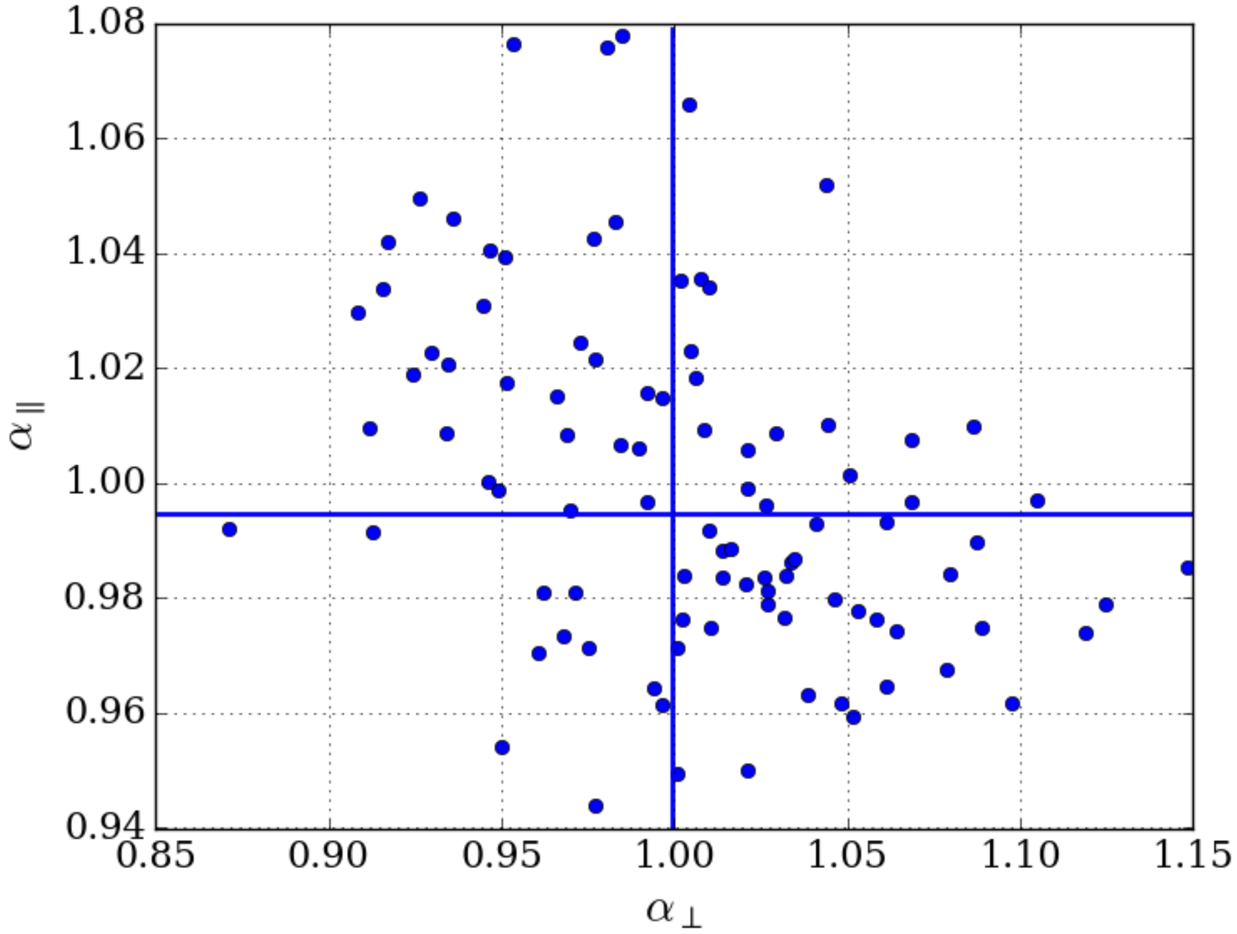




Mock samples

Generate sets of 100 mock samples with and w/o contamination from metals and high-column density (HCD) absorption systems in the Lyα forest



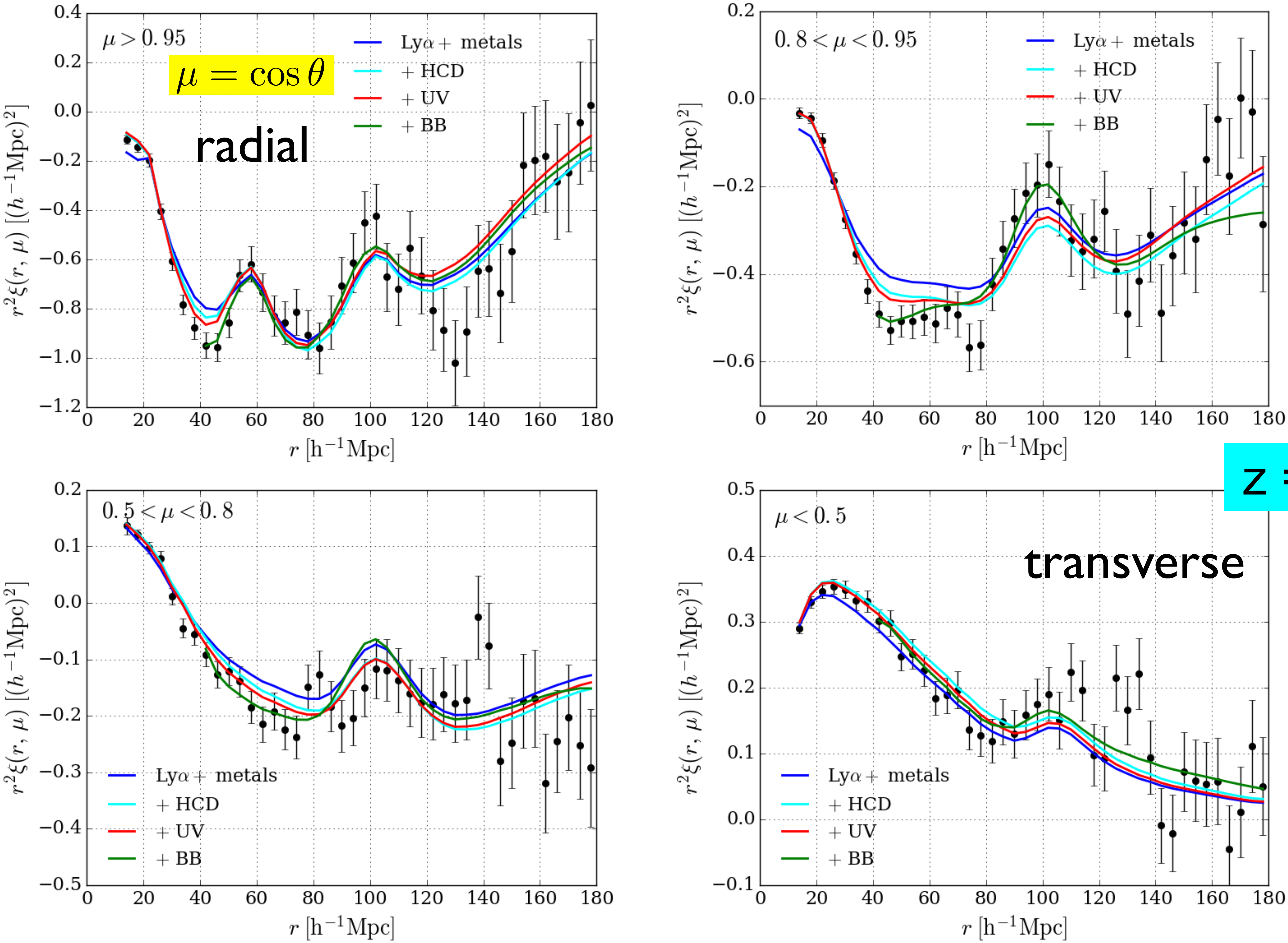


No significant bias in the BAO measurement

	$\langle\alpha_{\parallel}\rangle$	$\langle\sigma_{\parallel}\rangle$	$\langle\alpha_{\perp}\rangle$	$\langle\sigma_{\perp}\rangle$
Lyα	1.000	0.023	0.993	0.040
Lyα+metals	0.998	0.025	0.993	0.040
Lyα+metals+HCD	0.995	0.032	0.999	0.058

BOSS Lyα BAO results

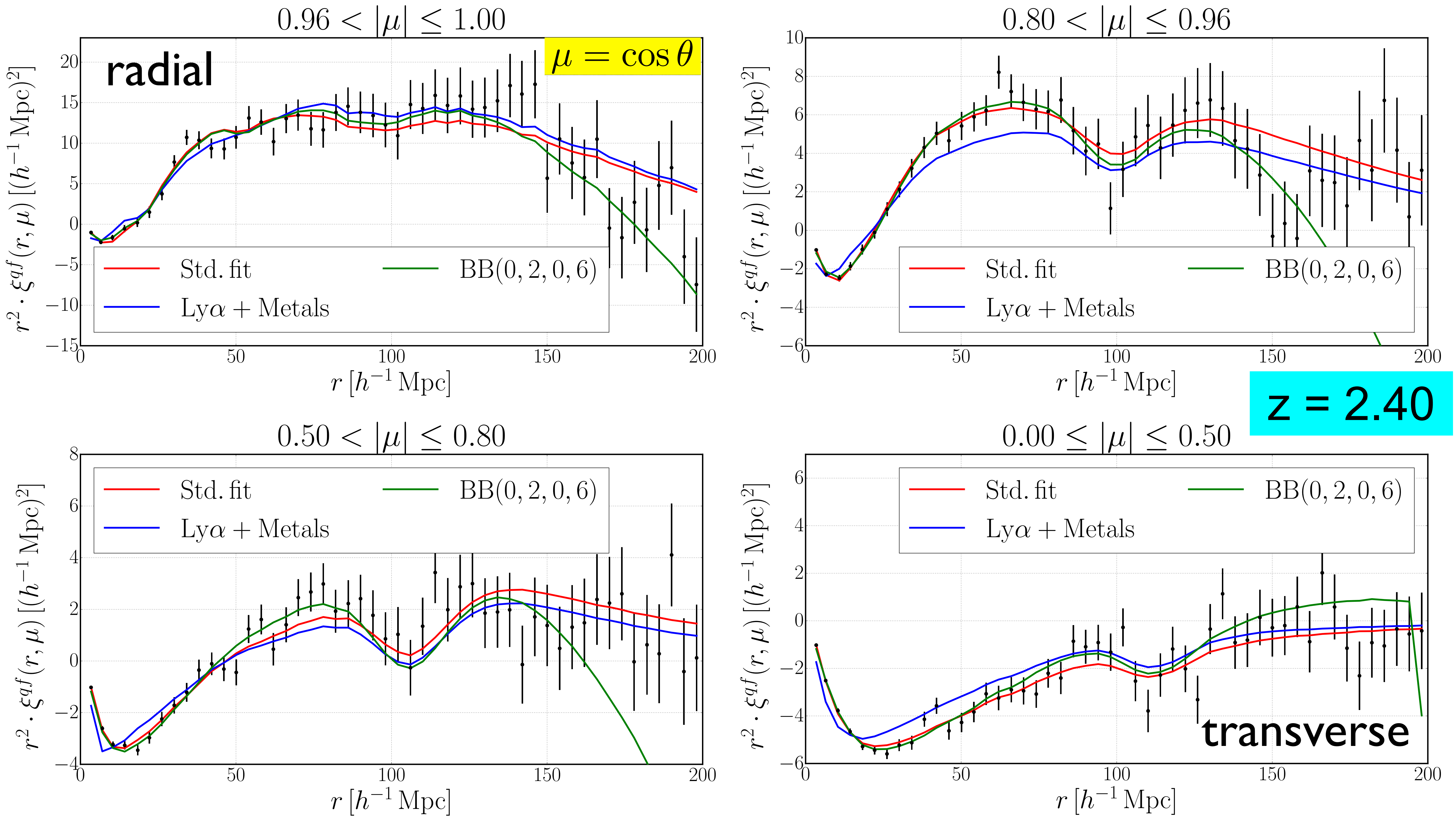
DR12 Lyα auto-correlation (Bautista++ 2017)



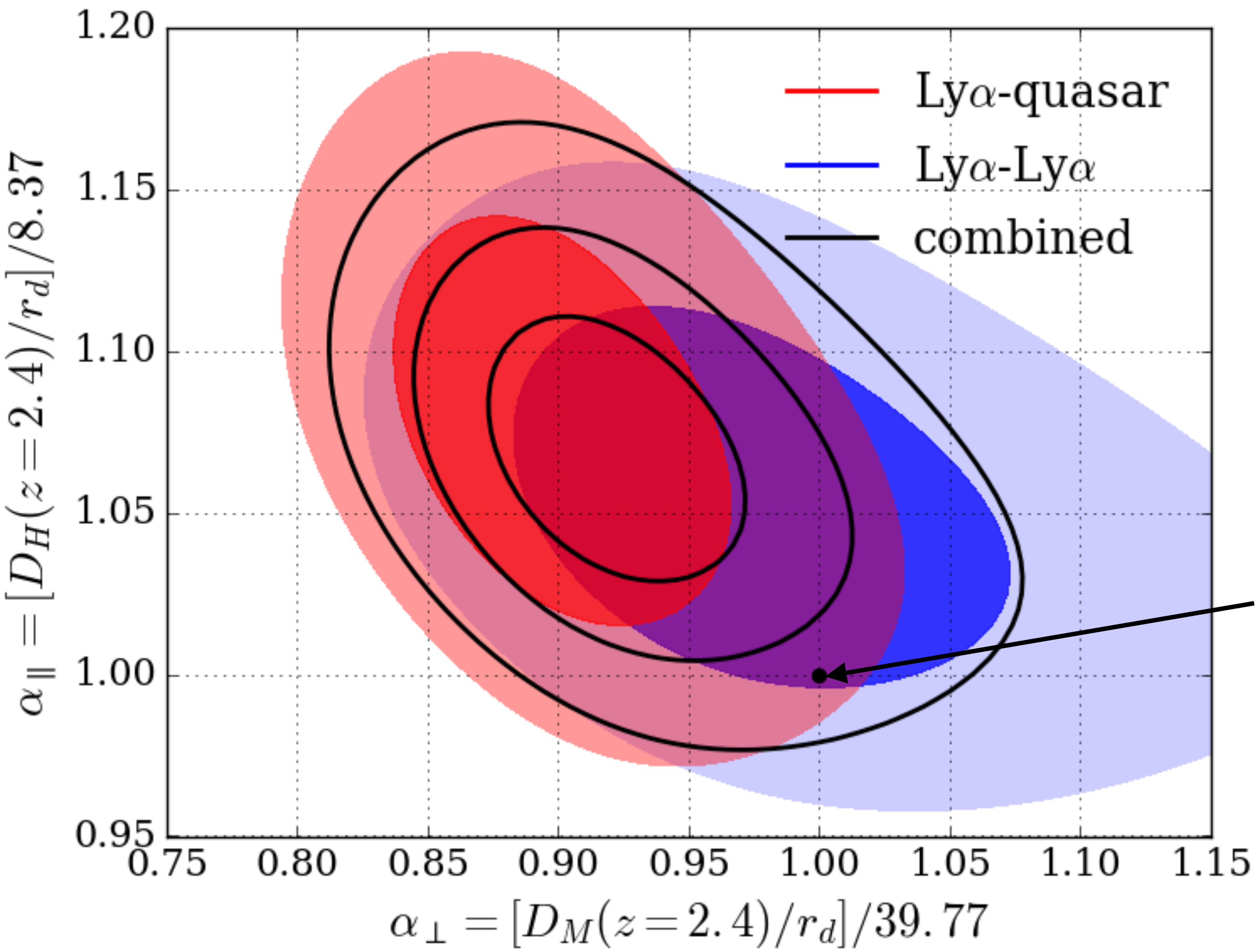
z = 2.33

BOSS Lyα BAO results

DR12 quasar-Lyα cross-correlation (du Mas des Bourboux++ 2017)



Cosmological implications

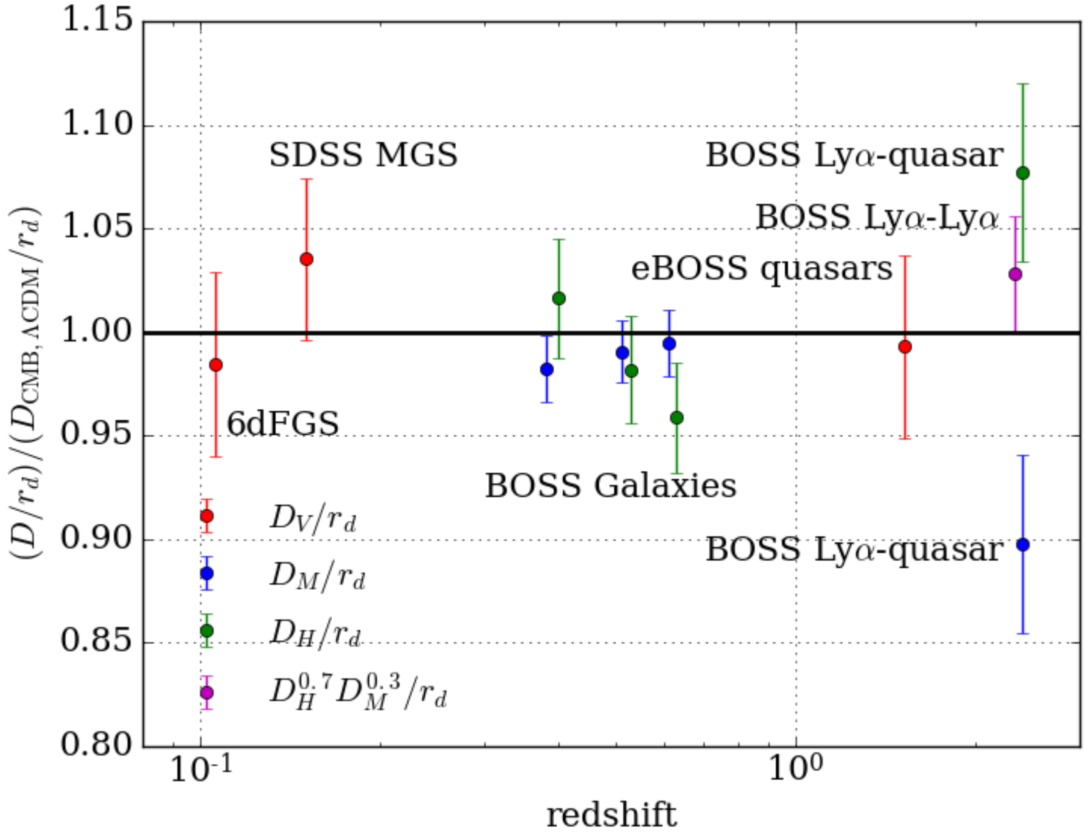


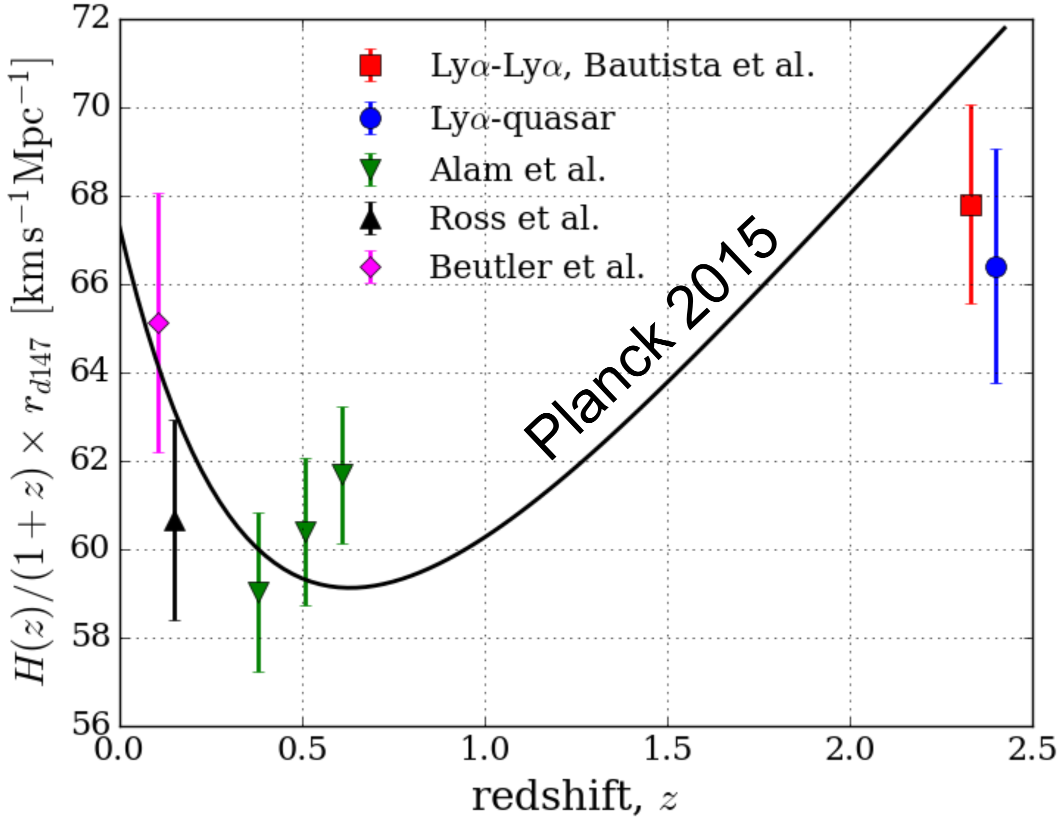
DR12 combined fit:

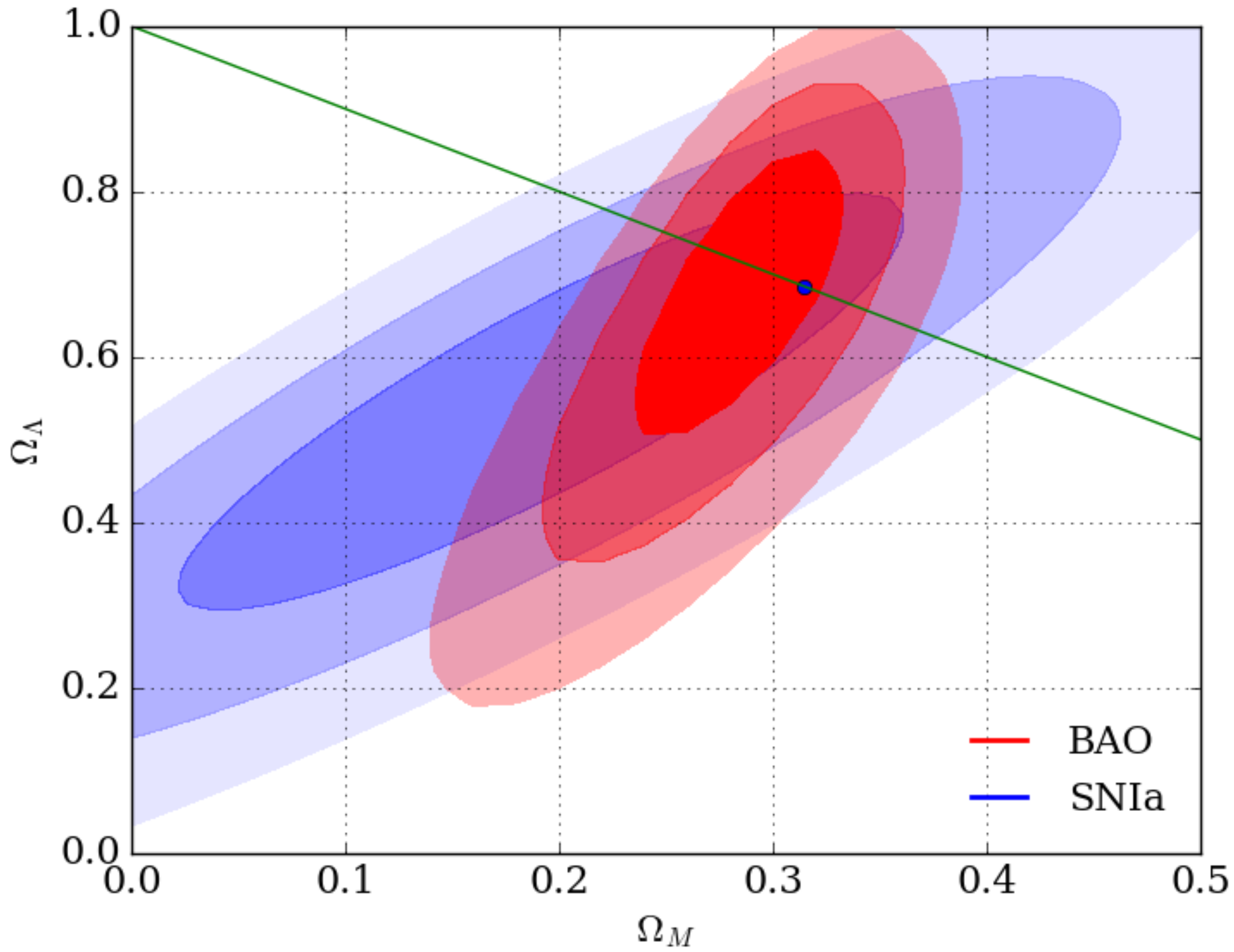
2.5% measurement of $D_H(z = 2.4)/r_d$
3.6% measurement of $D_M(z = 2.4)/r_d$

Moderate (2.3σ) tension with Planck 2015 flat ΛCDM cosmology

Cosmological implications







Systematic errors

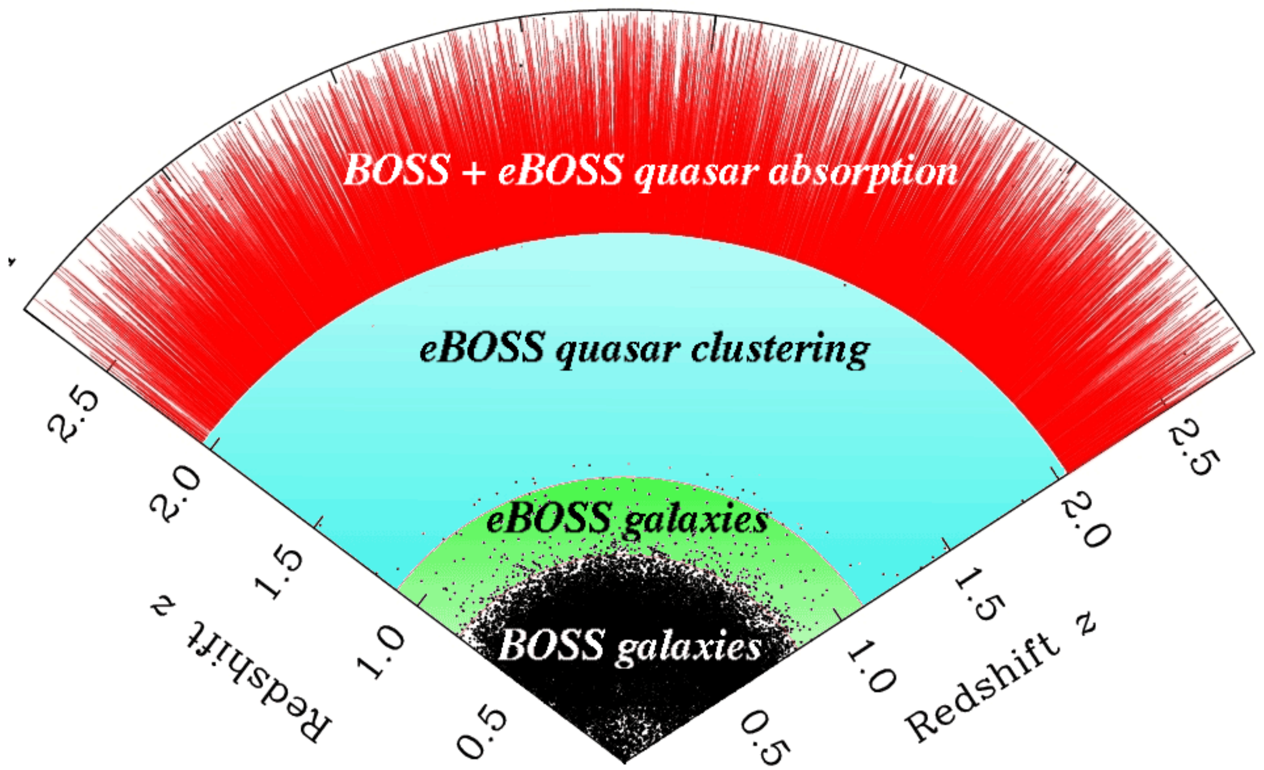
No identified significant systematic errors on the BAO measurements

… but a wide range of possible systematics need to be considered (many already are)

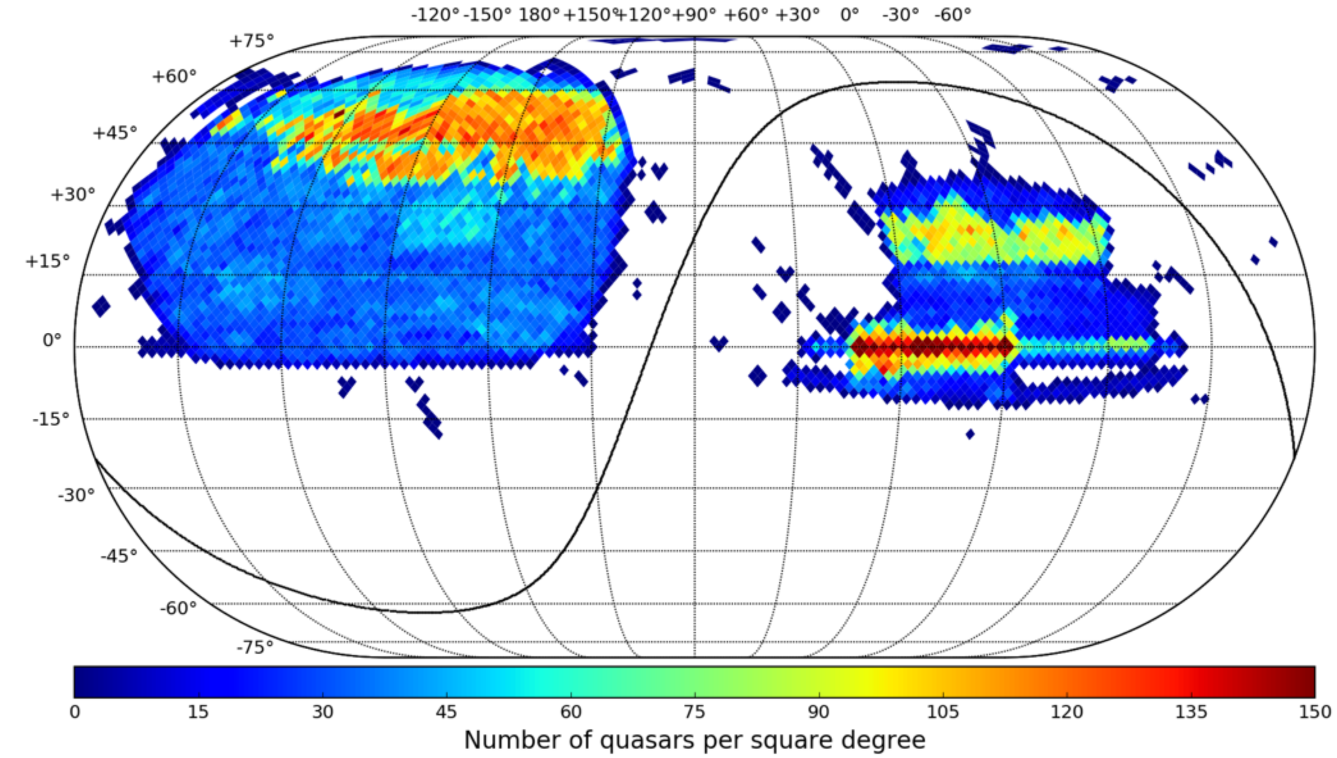
- **Astrophysical:** associated & unassociated metals, UV intensity fluctuations, IGM temperature fluctuations, high-column density systems, quasar radiation effects, non-linear correction, non-linear broadening, baryon-CDM relative velocity effect, relativistic effects, 3- and 4-point contributions, BAL, quasar diversity, …
- **Instrumental:** sky subtraction residuals, spectrophotometric calibration, Milky Way absorption lines, …
- **Analysis:** quasar redshift errors, continuum fitting, …

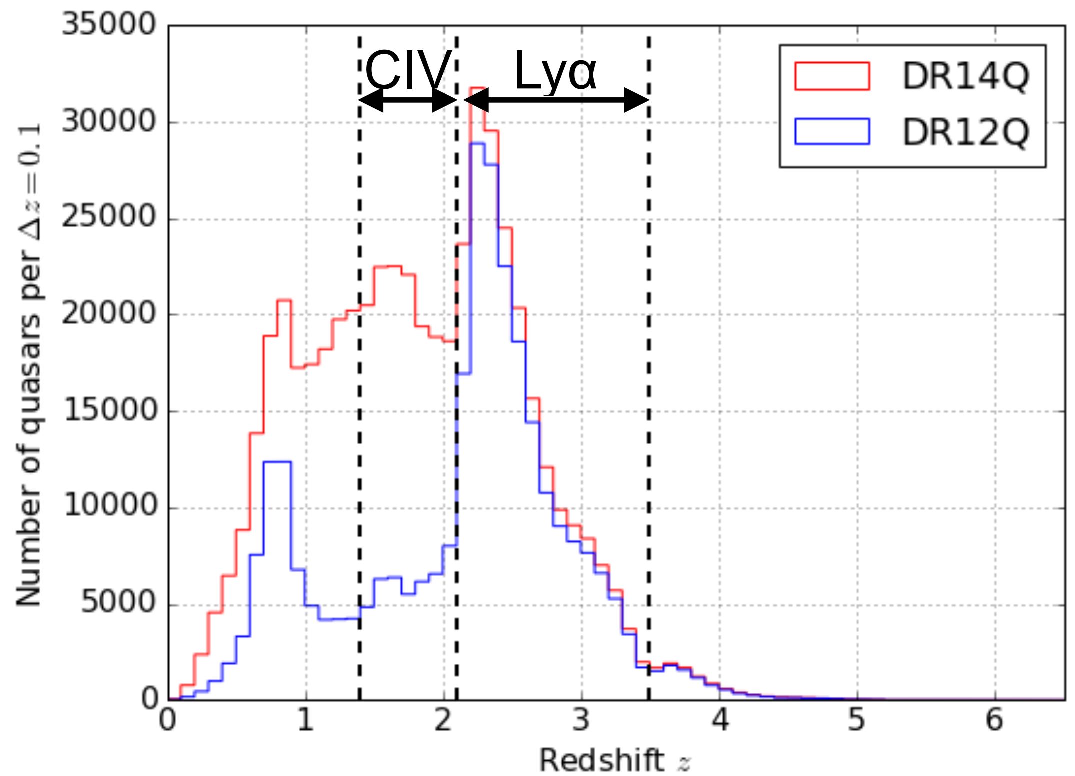
eBOSS quasar survey

Extended Baryon Oscillation Spectroscopic Survey (SDSS-IV): 2014-2020



SDSS Data Release 14 (DR14):
two years of eBOSS observations



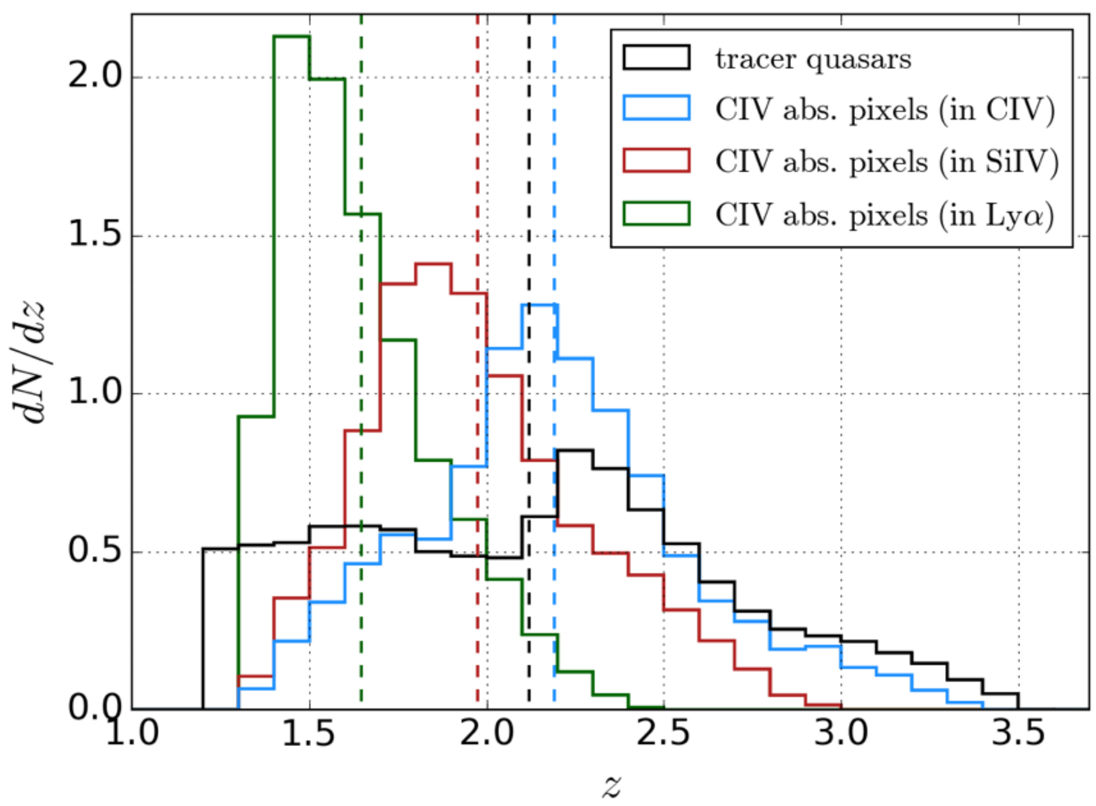


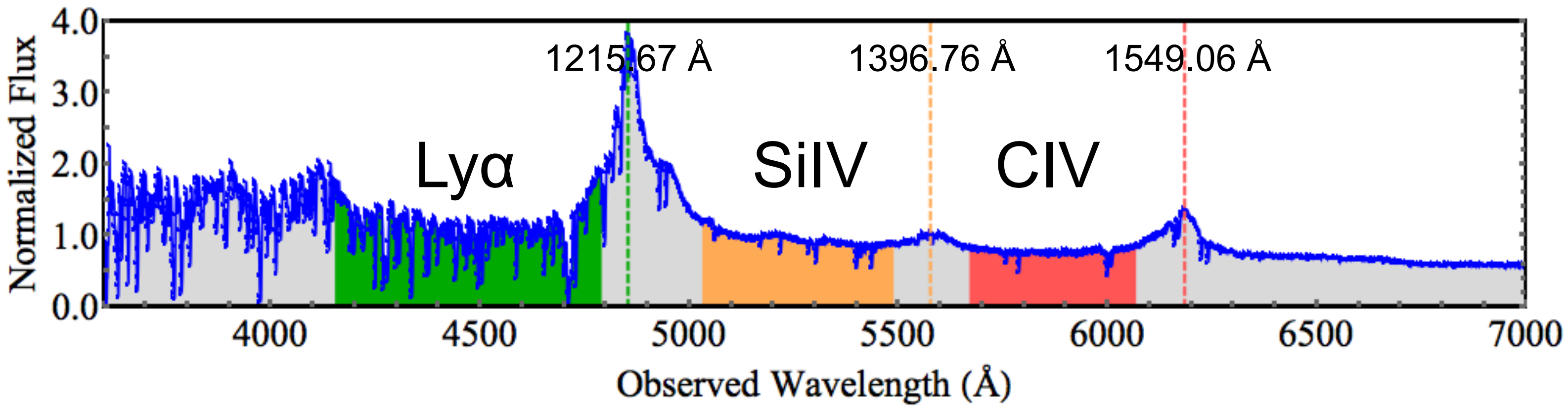
Full eBOSS:

- 500,000 quasars at z=0.9-2.2
- 60,000 new quasars at z>2.1
- 60,000 re-observations of BOSS quasars at z>2.1

CIV forest BAO

- Triply ionized carbon (CIV) a weaker tracer than Lyα, but accessible at $z<2$
- Rapidly growing eBOSS quasar sample in $0.9 < z < 2.2$
- New potential BAO tracer (Pieri 2014)
- First study of BAO in the cross-correlation of CIV absorption with quasars for DR14 by Blomqvist++ 2018
- 288k CIV forest quasars in $1.4 < z < 3.5$
  387k tracer quasars in $1.2 < z < 3.5$
- CIV absorption in three wavelength bands: CIV forest, SiIV forest and Lyα forest



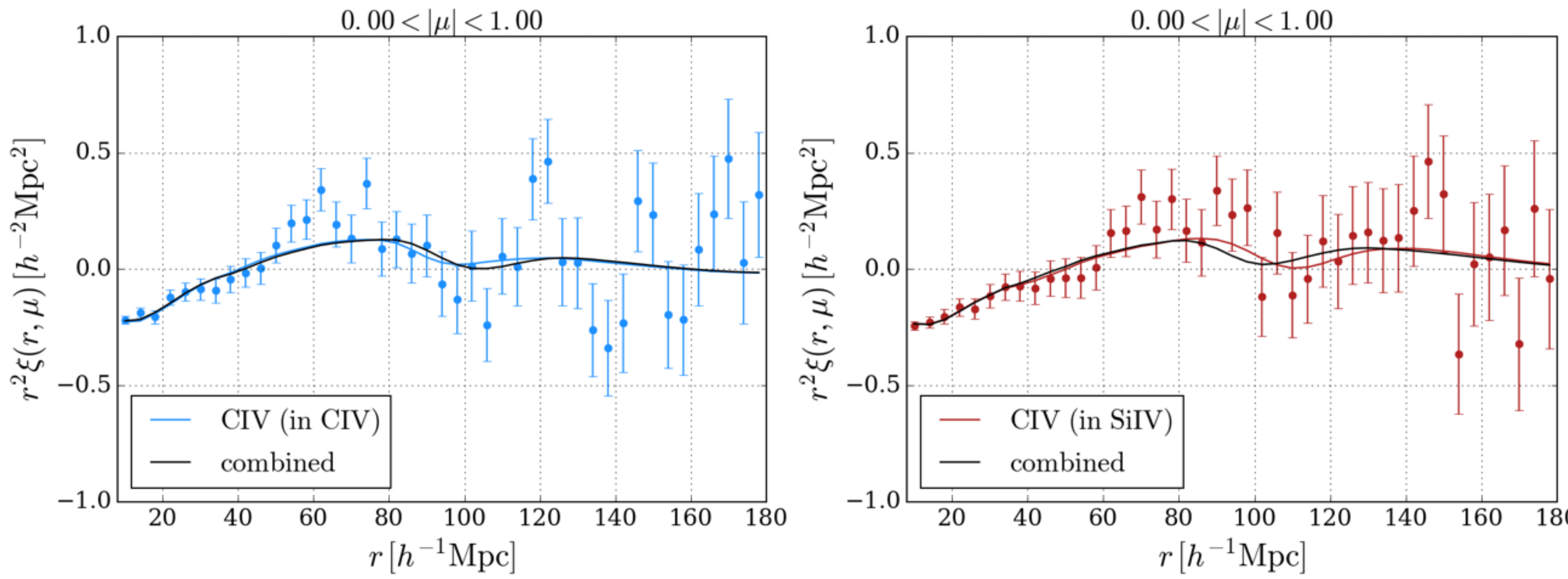


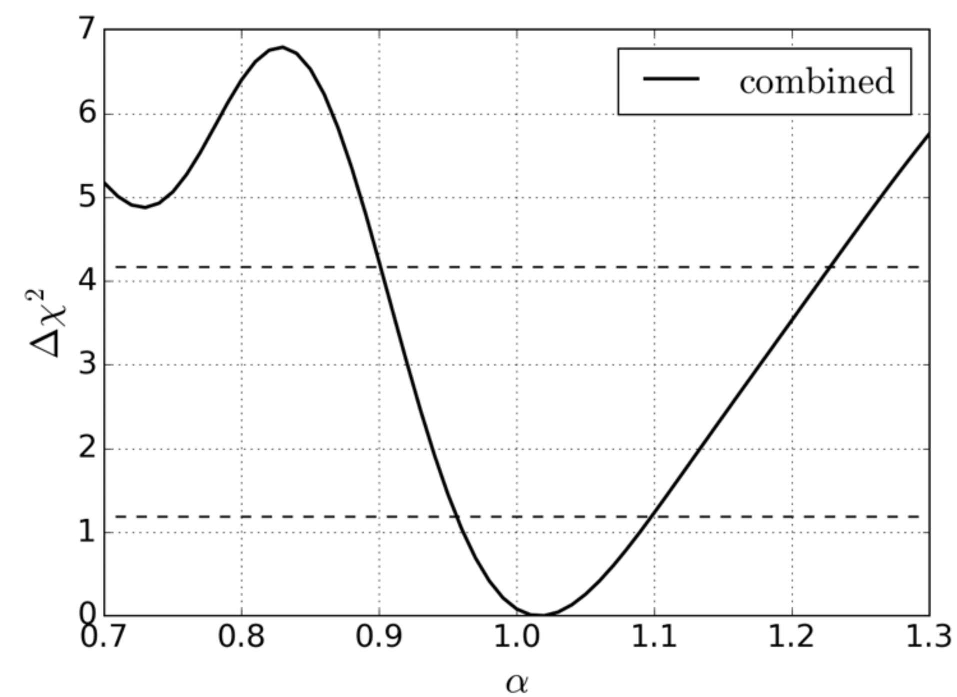
CIV forest BAO

- Combined fit at $z_{eff} = 2.0$
- Marginal (1.7σ) BAO detection with isotropic scale parameter

$$\alpha = 1.017\ ^{+0.081}_{-0.061}$$

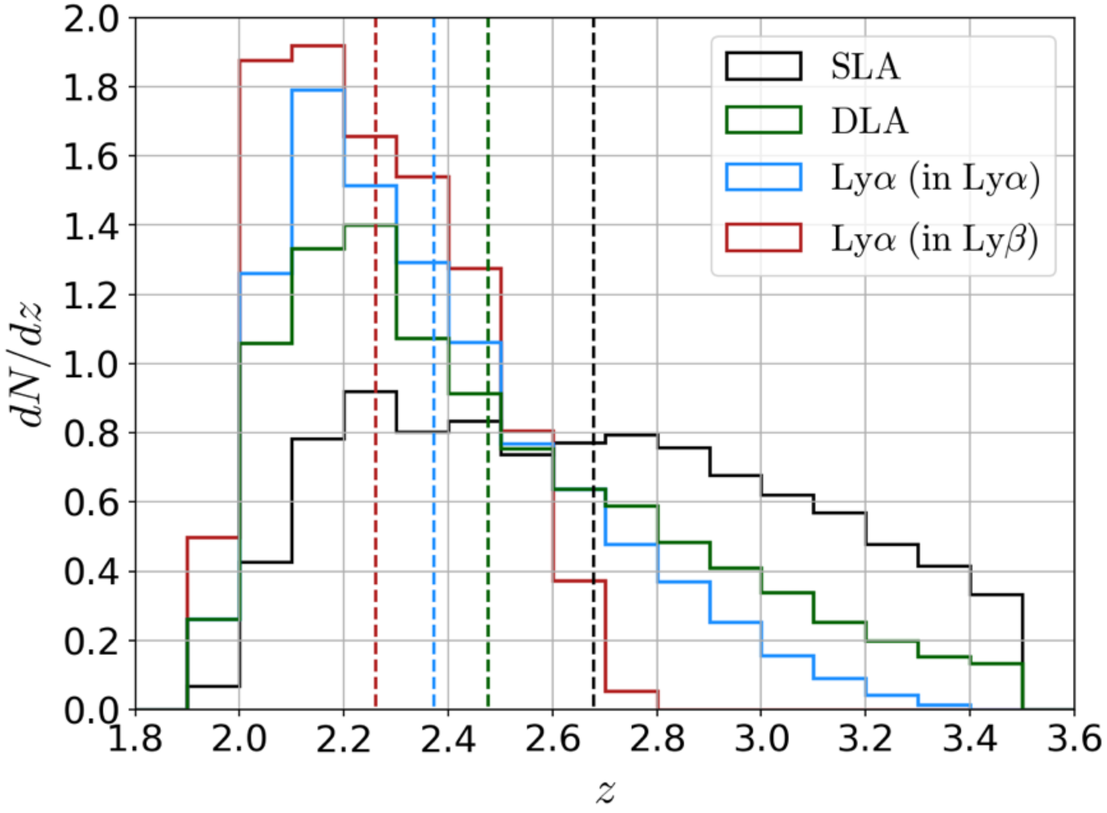
- Projections for future constraints at $z_{eff} \sim 1.6$ from intermediate-z quasars in $1.4 < z < 2.2$
  final eBOSS: $\sigma_\alpha \sim 7\%$
  final DESI: $\sigma_\alpha \sim 3\%$
- Ongoing study of BAO in the cross-correlation of MgII absorption with quasars and galaxies





BAO from galaxies in absorption

- Strong and blended Lyα absorbers (SLA) trace the circumgalactic medium (Pieri 2014; see talk by Debopam Som)
- DR12 catalog of 445,994 SLAs with -0.05 < F < 0.25
- Damped Lyα absorbers (DLA) also trace the circumgalactic medium
- Compile a super set of 54,902 DLAs from three available catalogs
- Cross-correlate SLA and DLA positions with the DR14 Lyα forest



BAO from galaxies in absorption

Preliminary results:

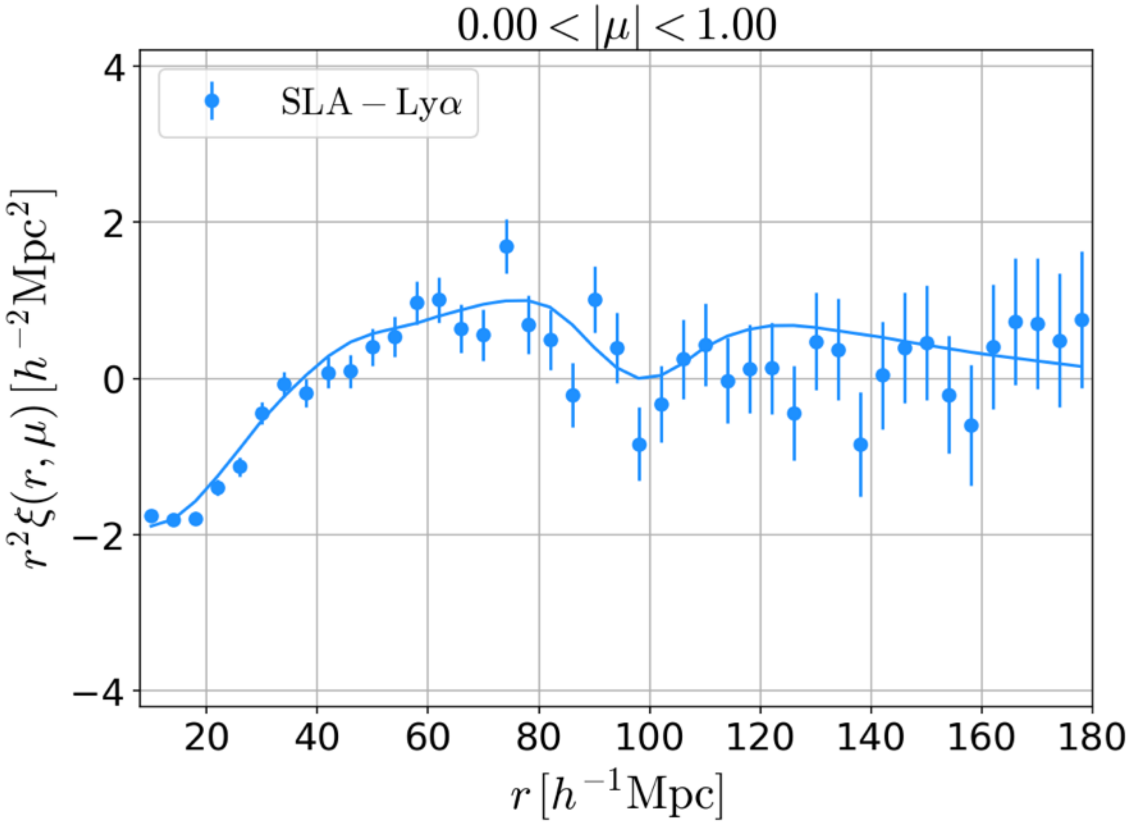
- SLA bias: 2.03 ± 0.08 (high-purity subset)
  DLA bias: 2.02 ± 0.07

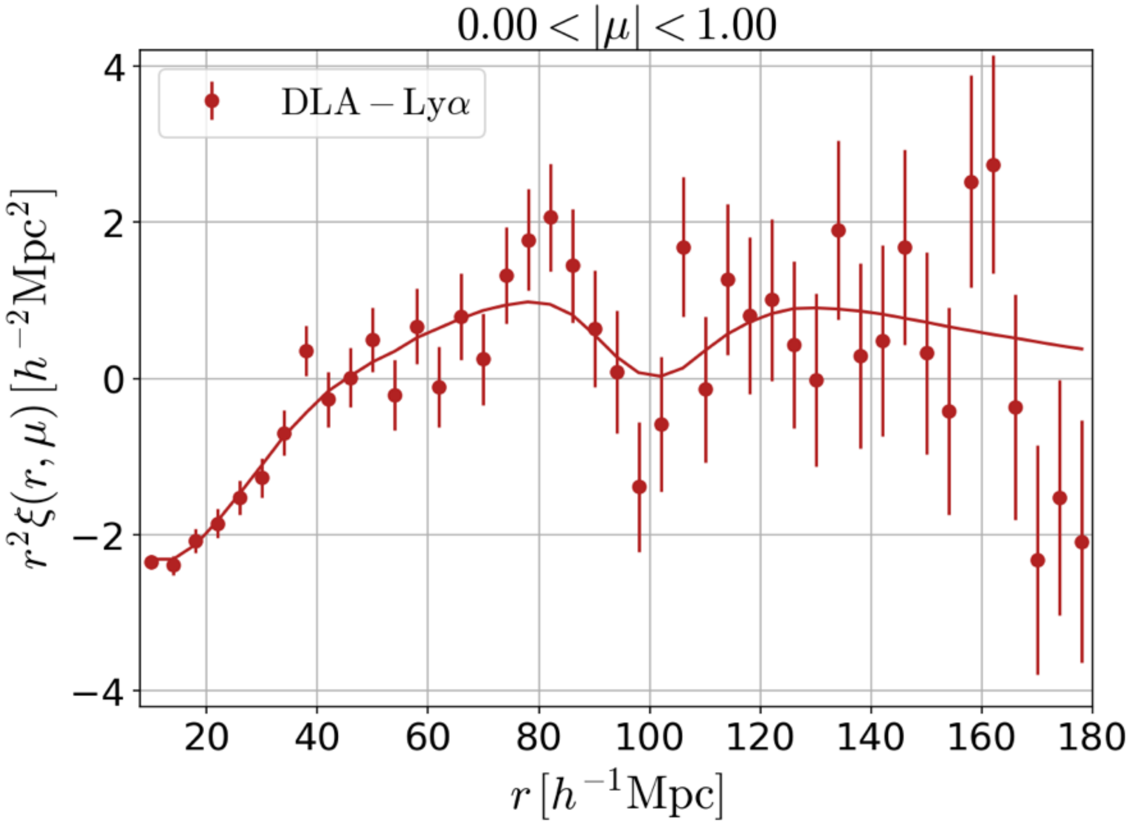
- SLA-Lyα BAO precision:
  ~5% on $\alpha_{||}$ and ~7% on $\alpha_{\perp}$

- DLA-Lyα BAO precision:
  ~7% on $\alpha_{||}$ and ~8% on $\alpha_{\perp}$

- Combined fit BAO precision:
  ~4.5% on $\alpha_{||}$ and ~7% on $\alpha_{\perp}$
  peak significance >3σ

- Significant (~25%) cross-covariance between SLA-Lyα and Lyα-Lyα can be removed by masking absorbers





Summary

- Lyα forest BAO is now an established cosmological probe. No significant systematic errors identified.
- BOSS DR12 measured cosmological distances D_H/r_d to 2.5% and D_M/r_d to 3.6% precision at $z = 2.4$.
- First eBOSS Lyα forest BAO analyses ongoing. More data from new quasars and by incorporating the Lyβ forest.
- BAO from metal absorption (CIV, MgII) provide consistency checks with galaxy/quasar clustering BAO at $z < 2$.
- Galaxies in absorption may provide competitive BAO constraints at $z > 2$.
- Exciting prospects for future BAO measurements with the upcoming surveys DESI and WEAVE (see talk by Mat Pieri).

Thank you!