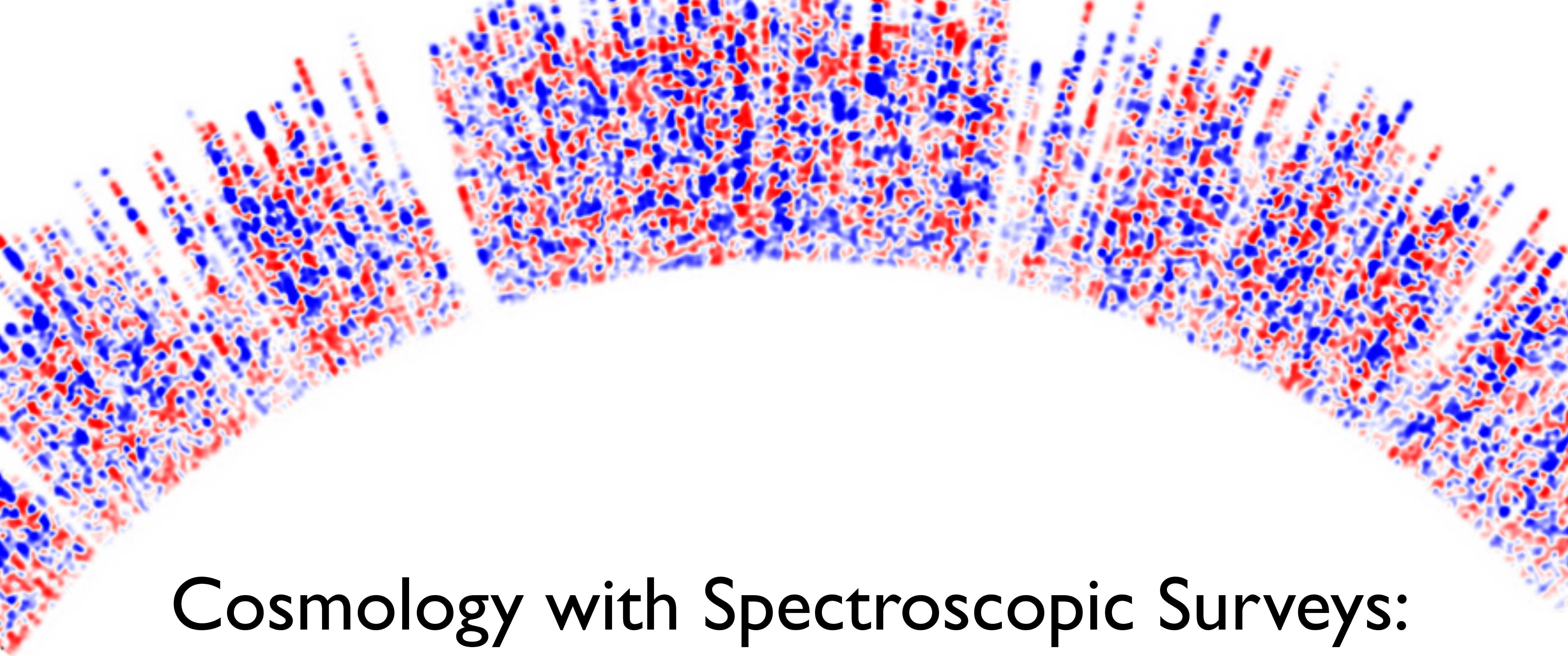
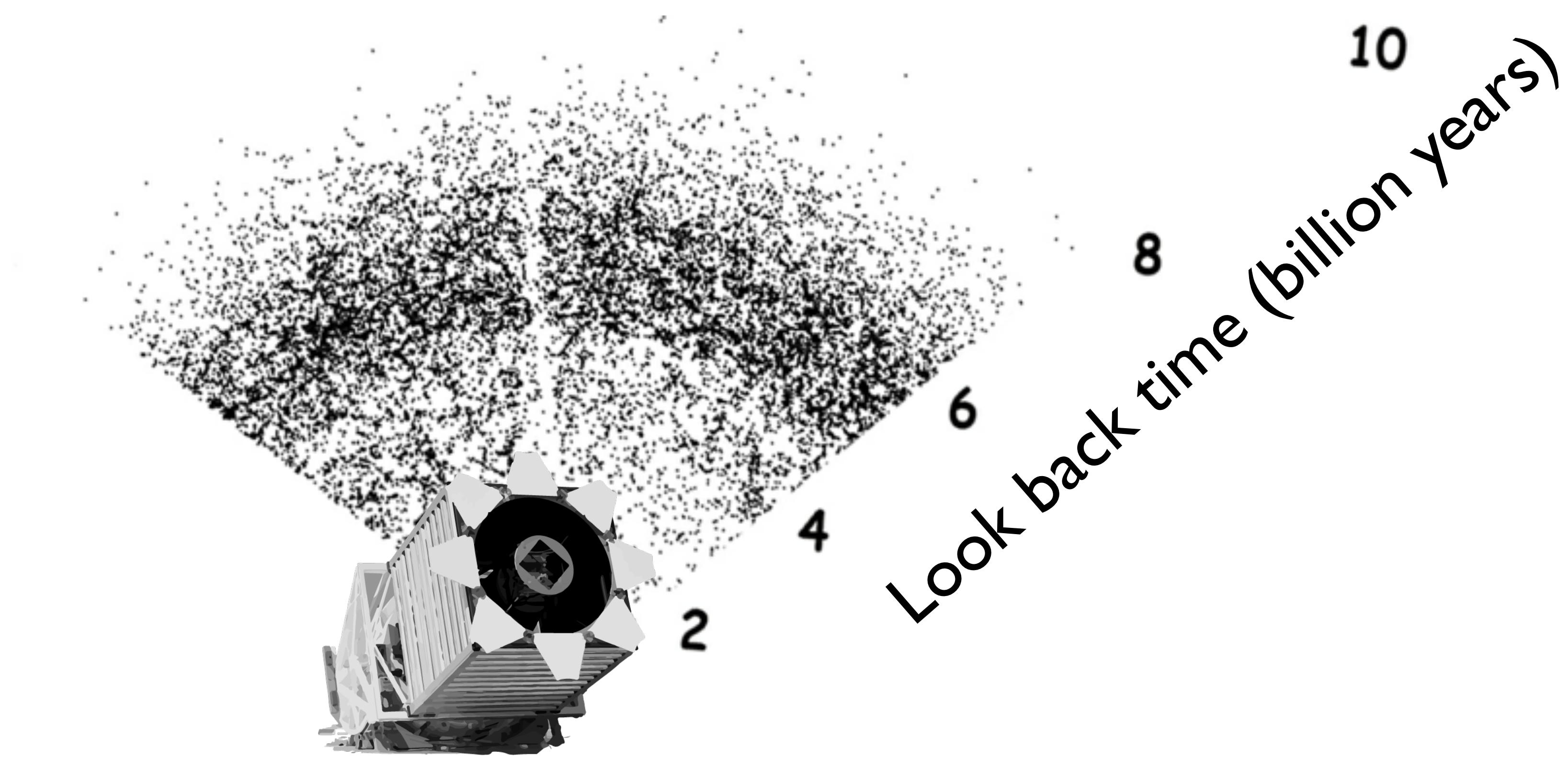


Cosmology with Spectroscopic Surveys: Past, Present and Future (II)

Andreu Font-Ribera

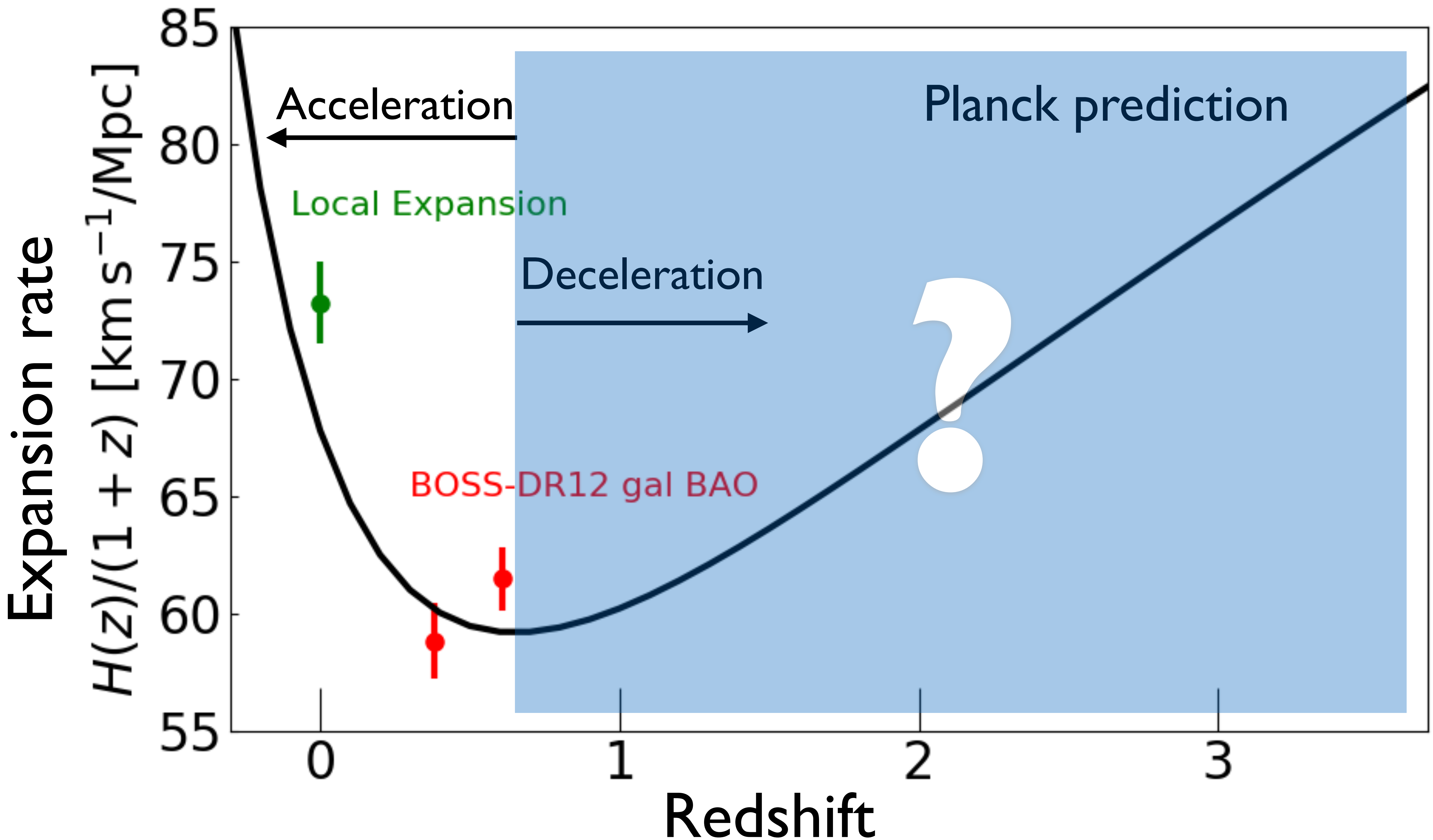
STFC Ernest Rutherford Fellow at University College London

Spectroscopic Surveys



BOSS galaxies
1.3M spectra
0.2 < z < 0.7

Spectroscopic Surveys



Outline

- High-z BAO: motivation
- Introduction to the Lyman-α forest
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- BAO take on the Hubble tension

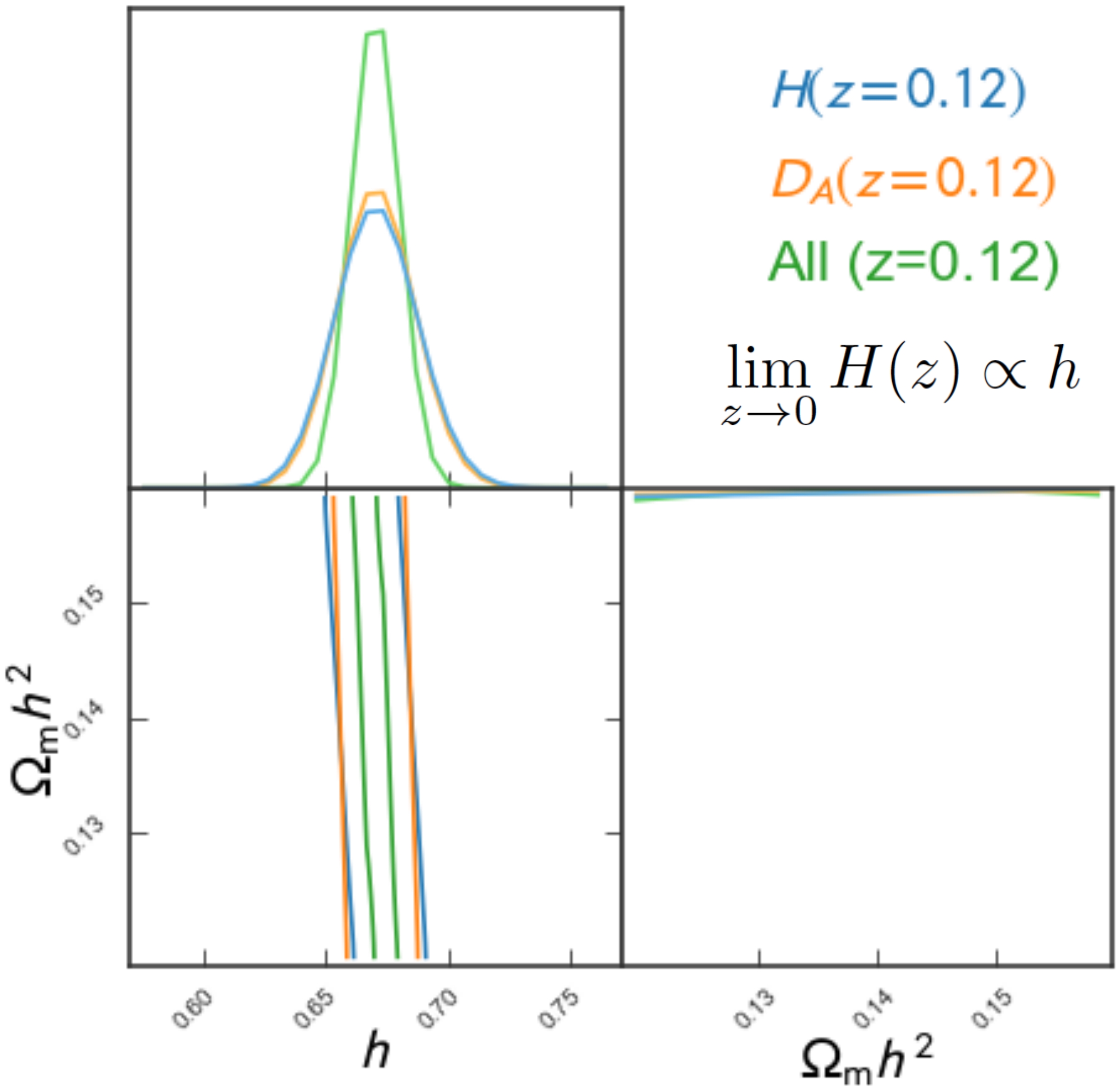
Why high-z BAO?

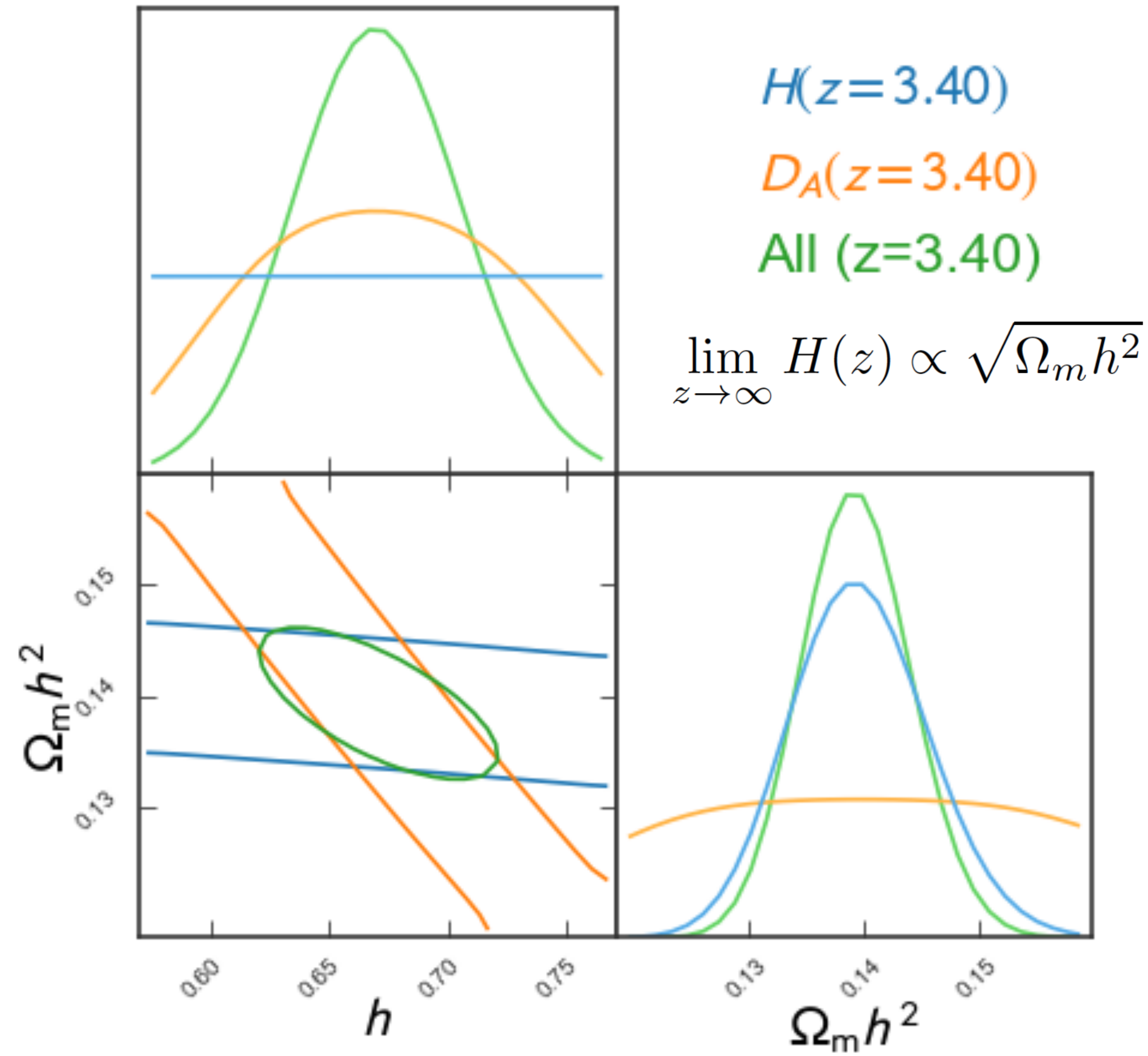
Flat LCDM - fixed r_d

$$H(z) = H_0 \sqrt{\Omega_m \, (1+z)^3 + (1-\Omega_m)}$$

Toy 2% BAO at different z ($\alpha_\perp$ and $\alpha_{||}$)

$$D_A(z) = \frac{1}{(1+z)} \int_0^z dz' \frac{c}{H(z')}$$





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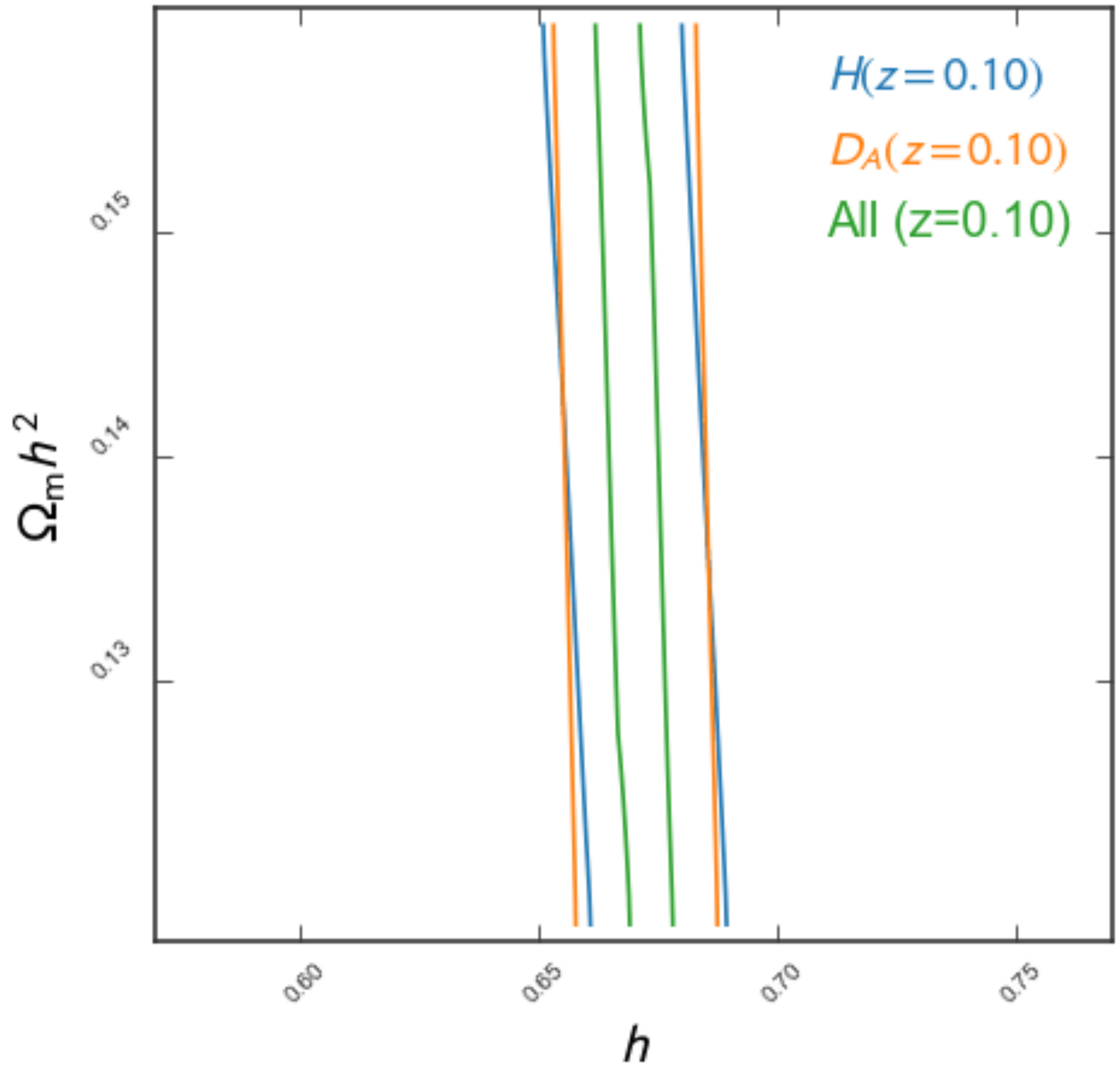
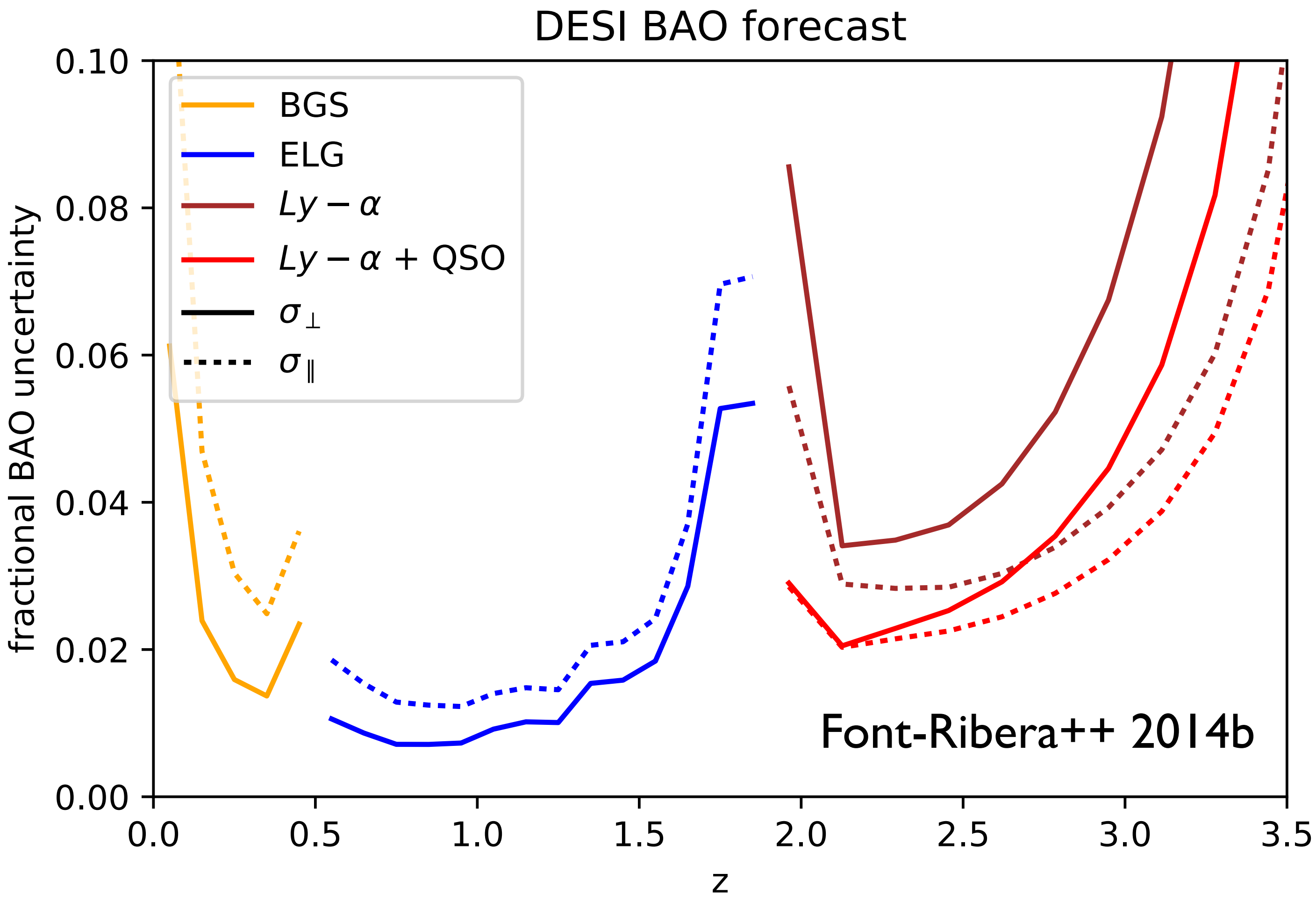
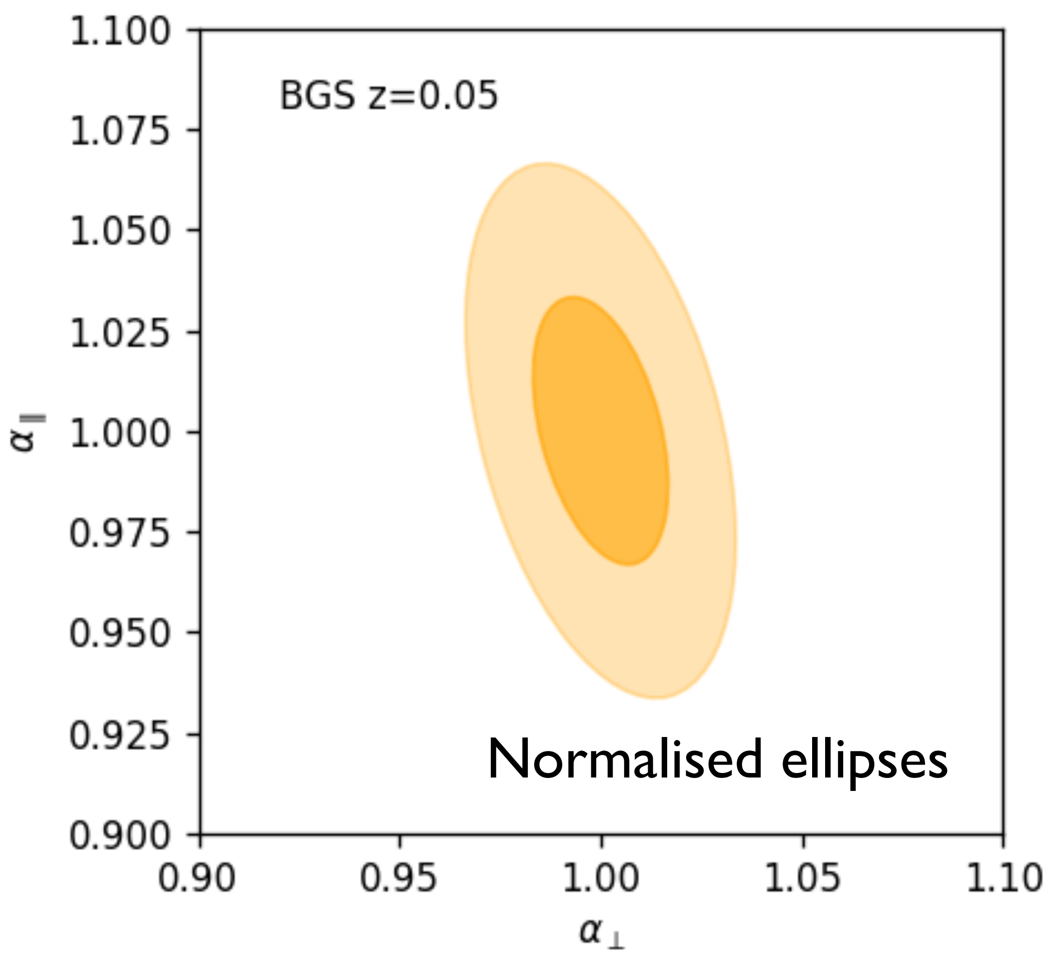


Why high-z BAO?

- Galaxy BAO measures better $\alpha_\perp$ (2D vs 1D)
- Ly-α BAO measures better $\alpha_{||}$ (RSD and shot-noise limited)

$$P_g(\mathbf{k}) = b_g^2 \left(1 + \beta_g \mu_k^2\right)^2 \; P(k) \qquad \sigma_g^2(\mathbf{k}) = 2\left(P_g(\mathbf{k}) + n_g^{-1}\right)^2$$





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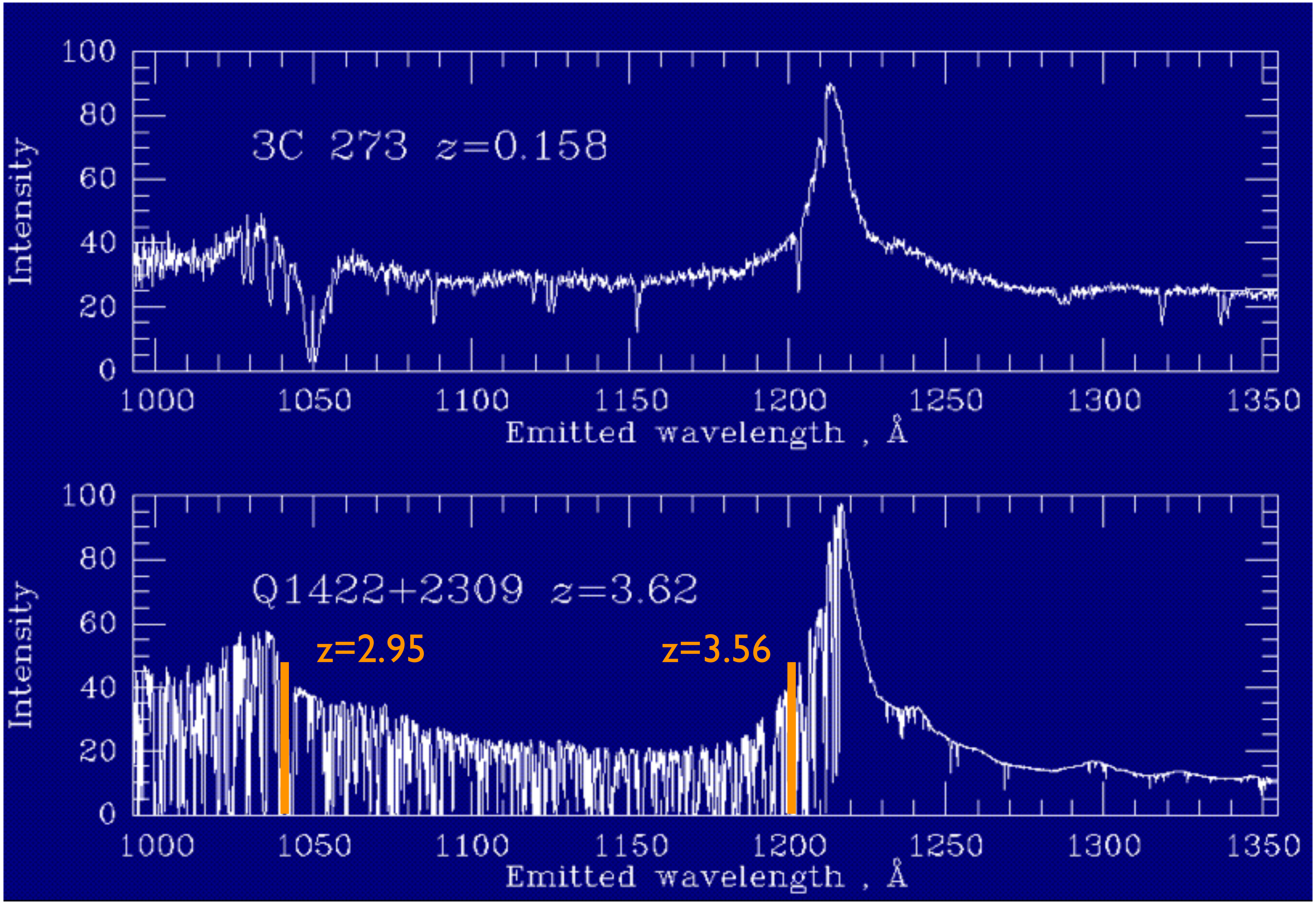
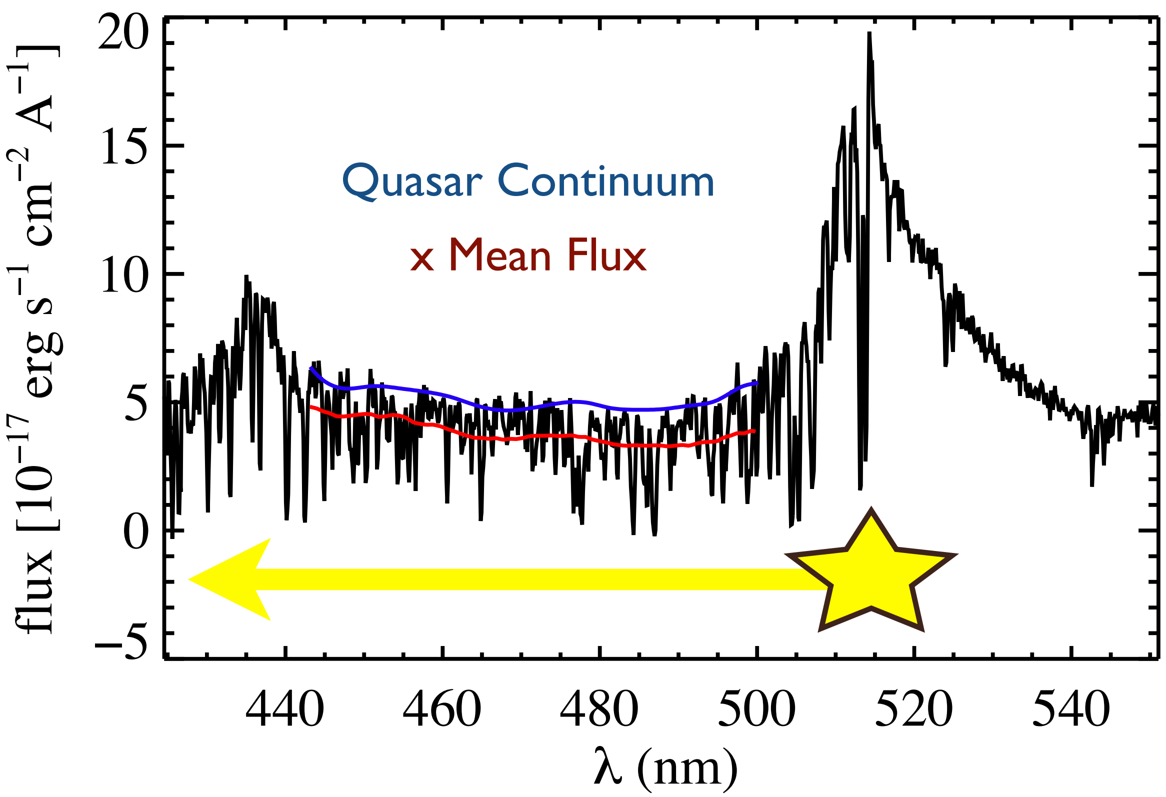
The Lyman-α forest



Credits: Andrew Pontzen Figure from William C. Keel

The Lyman-α forest

BOSS Lyα data analysis: from raw data to cosmological fluctuations



Observed flux — Transmitted fraction

$$f_q(\lambda) = C_q(\lambda) F_q(\lambda)$$

Quasar continuum

Observed wavelength — Absorption redshift

$$\lambda = \lambda_\alpha (1 + z)$$

LyaF wavelength (121.6 nm)

$$\delta_F(\mathbf{x}) = \frac{F(\mathbf{x}) - \bar{F}}{\bar{F}}$$

Flux fluctuations in pixels trace the density along the line of sight to the quasar

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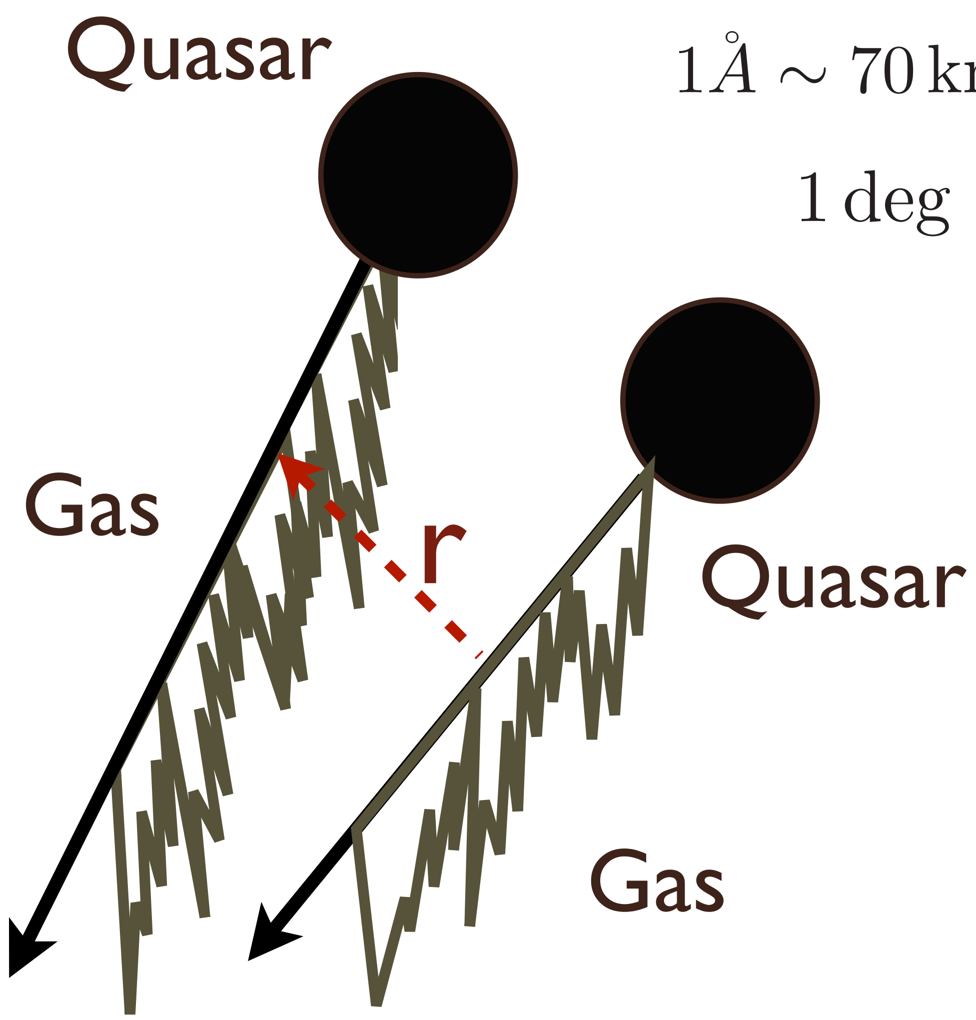
BOSS DR12 Lyα BAO

Two independent ways of measuring the BAO scale

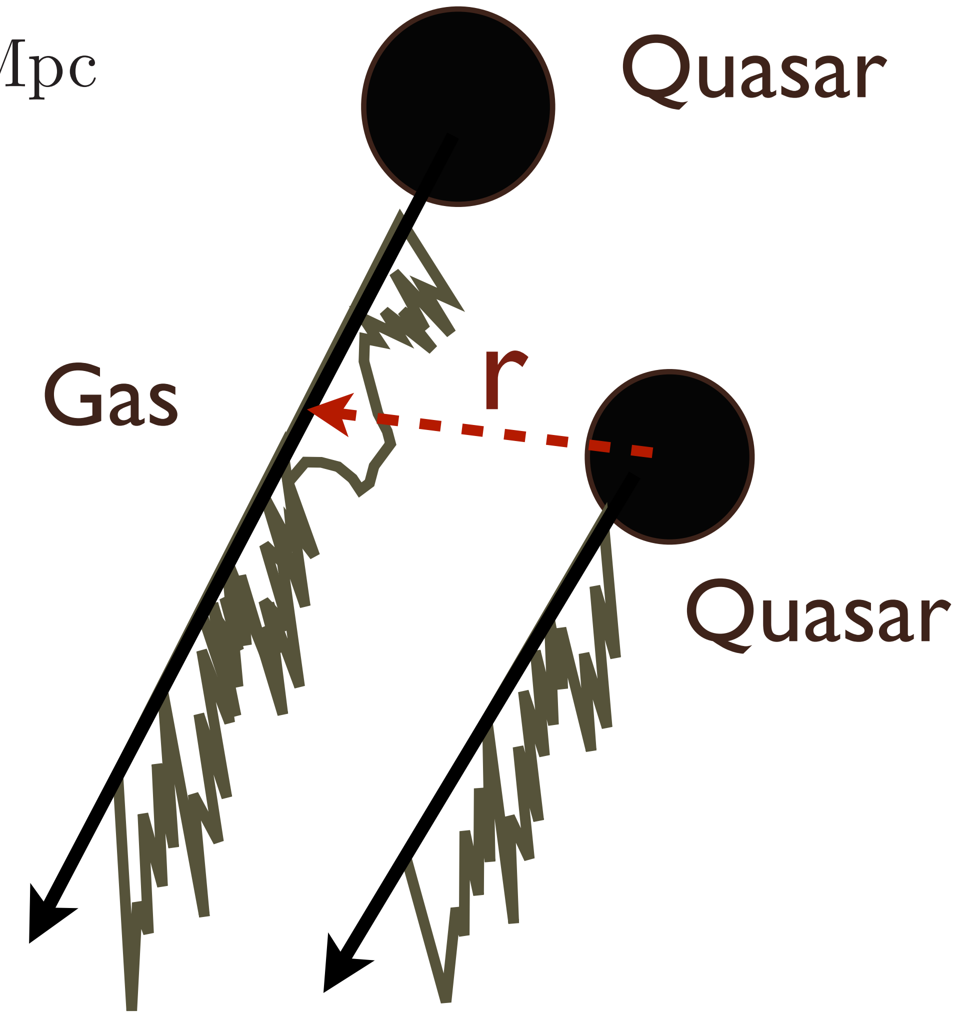
$$1\,\mathring{A} \sim 70\,\mathrm{km\,s^{-1}} \sim 0.7\,h^{-1}\,\mathrm{Mpc}$$

$$1\,\mathrm{deg} \sim 70\,h^{-1}\,\mathrm{Mpc}$$



Lyα auto-correlation

Bautista et al. (2017)

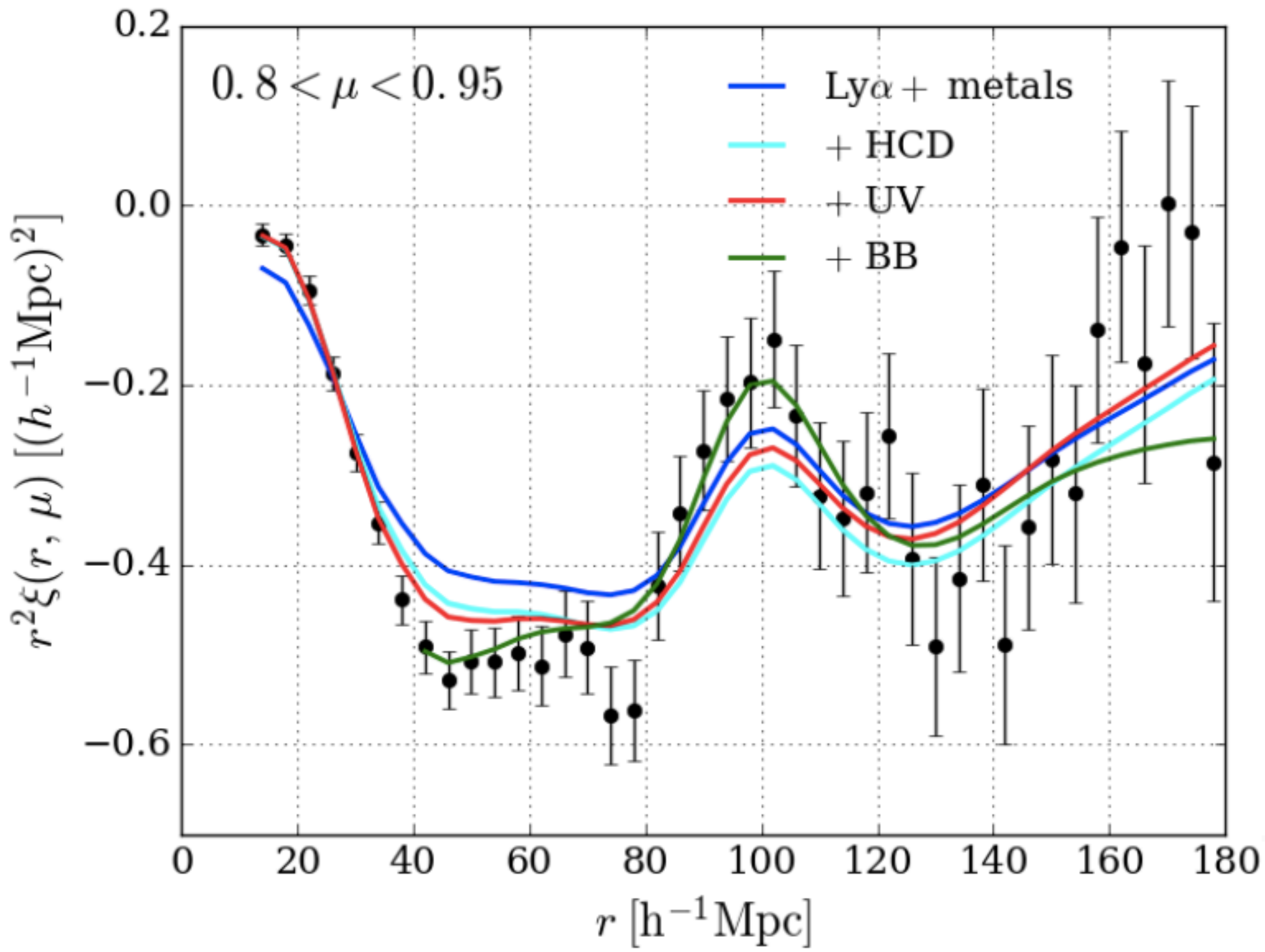


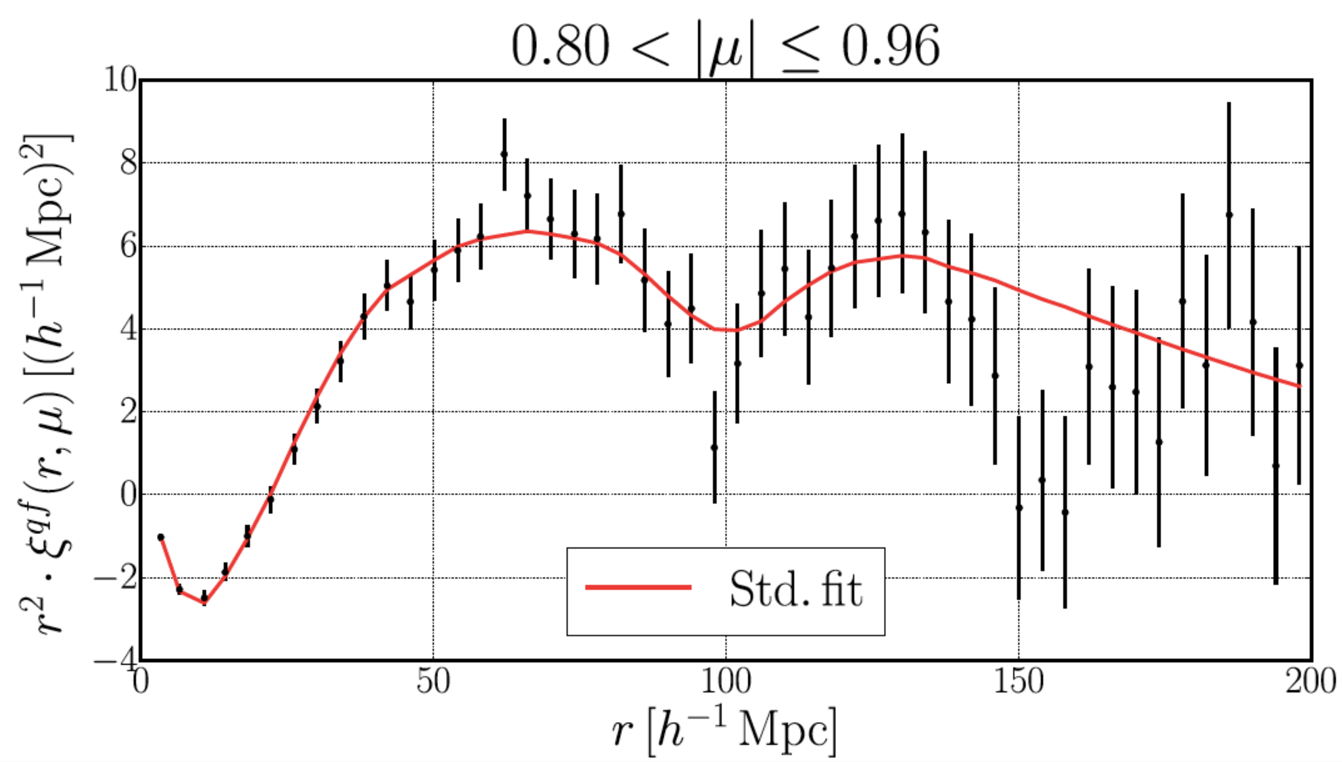
Lyα-quasar cross-correlation

du Mas des Bourboux (2017)

BOSS DR12 Lyα BAO

Two independent ways of measuring the BAO scale





DR12 Lyα auto-correlation

Bautista et al. (2017)

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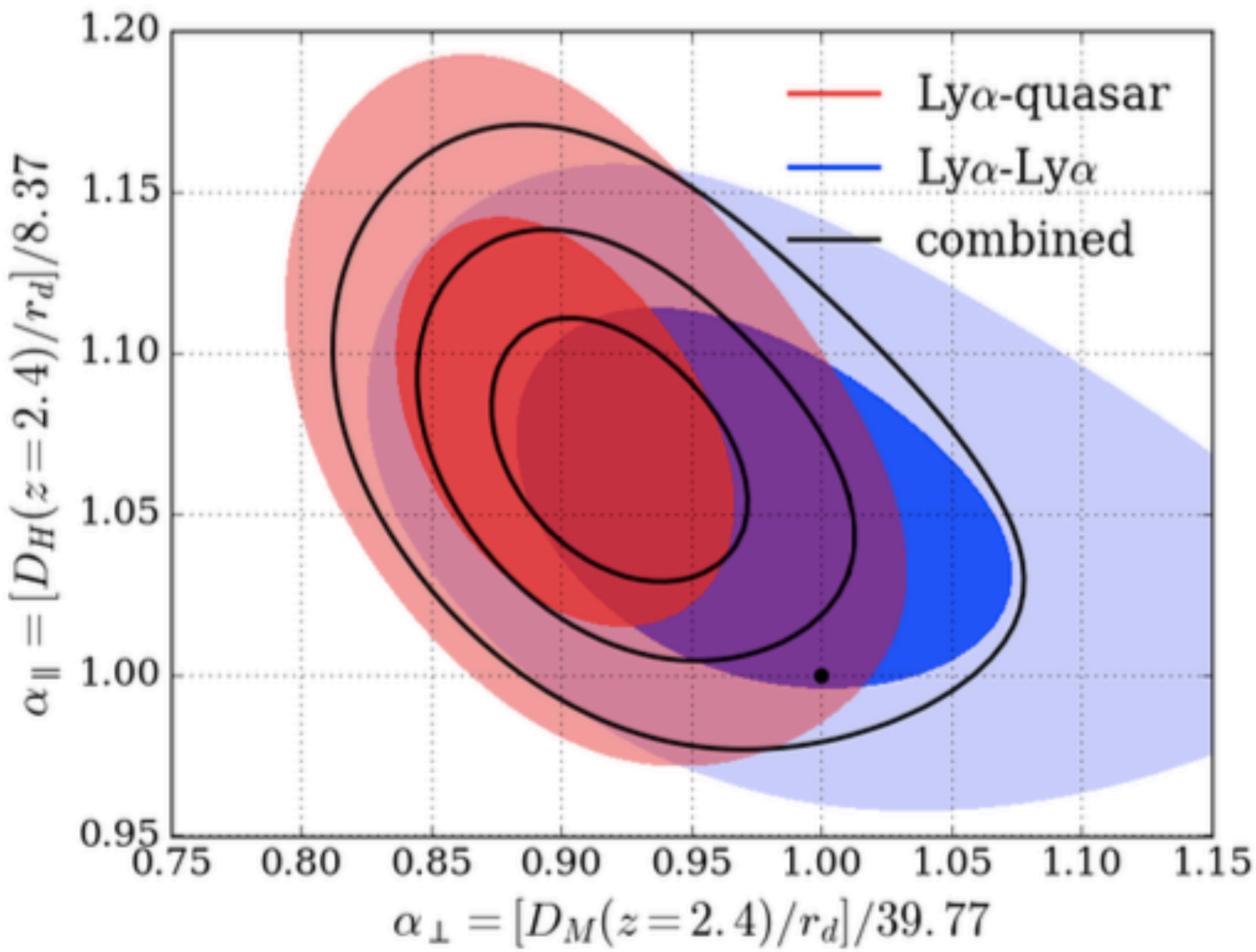
BOSS DR12 Lyα BAO



Marginal tension (2.3-σ) with Planck+LCDM prediction

BOSS DR12 Lyα BAO

BOSS DR12 had 15% more data than BOSS DR11, but it took three years to write the final results (Bautista et al. 2017)

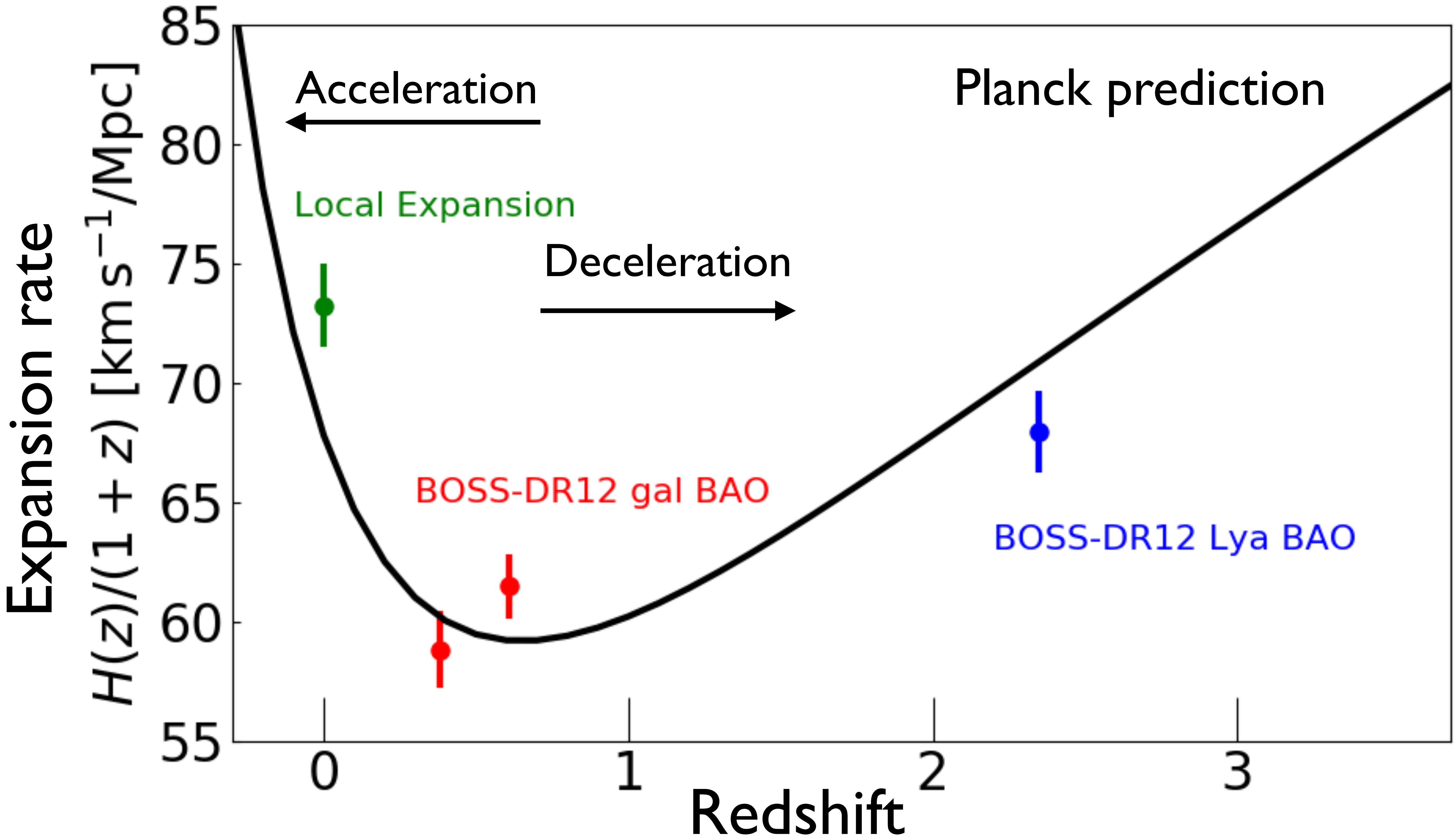
Astrophysical systematics

analysis	$\alpha_{\parallel}$	$\alpha_{\perp}$	$b_{\mathrm{Ly}\alpha}(1+\beta_{\mathrm{Ly}\alpha})$	$\beta_{\mathrm{Ly}\alpha}$	$\chi^2_{\mathrm{min}}/DOF$, prob
Lyα	1.040 ± 0.033	0.975 ± 0.056	-0.326 ± 0.002	1.246 ± 0.044	$1763.8/(1590-4)$ $p = 0.001$
+metals	1.050 ± 0.035	0.967 ± 0.054	-0.330 ± 0.002	1.275 ± 0.045	$1644.5/(1590-9)$ $p = 0.130$
+HCD	1.053 ± 0.036	0.962 ± 0.054	-0.321 ± 0.003	1.656 ± 0.086	$1561.4/(1590-12)$ $p = 0.612$
+UV	1.053 ± 0.036	0.965 ± 0.055	-0.326 ± 0.003	1.666 ± 0.085	$1556.5/(1590-13)$ $p = 0.639$

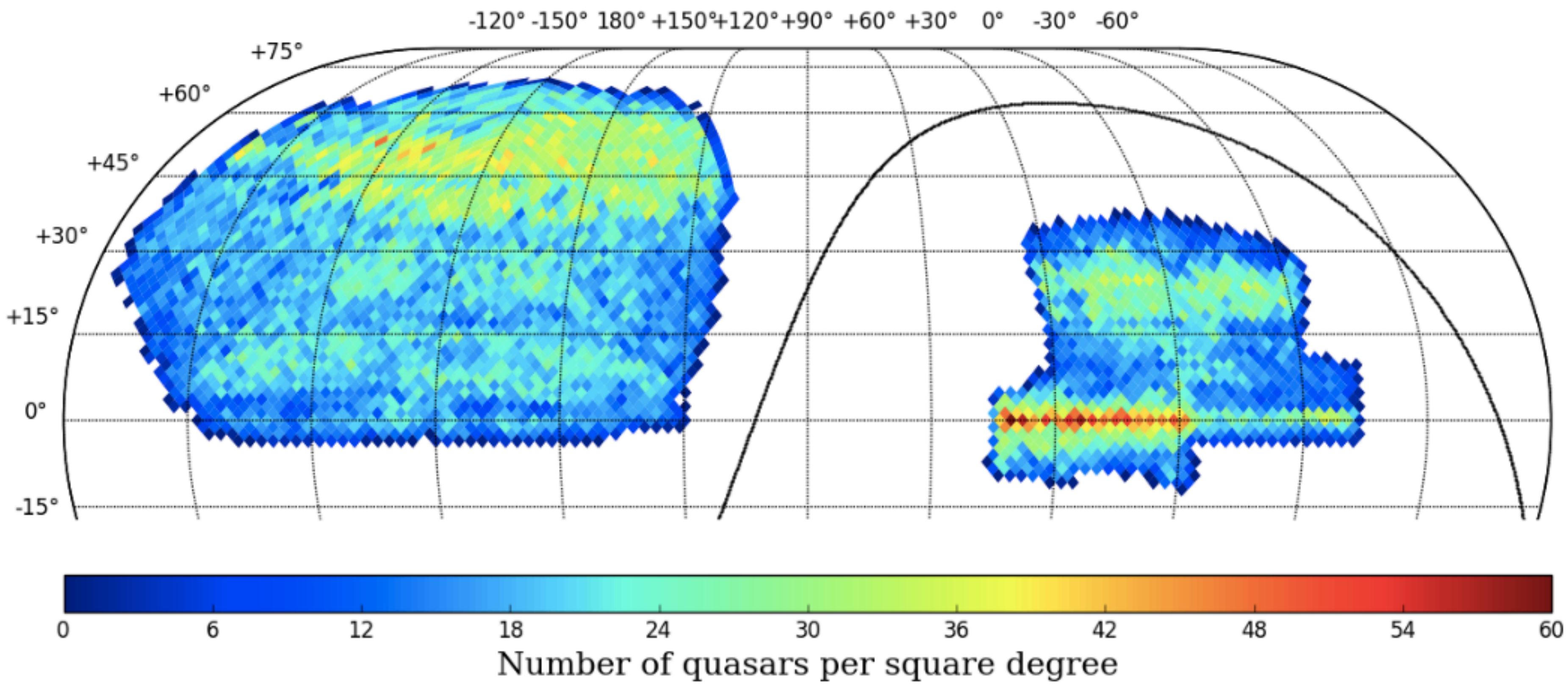
Instrumental systematics

	$\beta_{\mathrm{Ly}\alpha}$	$b(1+\beta)$	$\alpha_{\parallel}$	$\alpha_{\perp}$
Sky model noise	-0.026	-0.002	< 0.001	< 0.001
Calibration noise	$+0.047$	$+0.002$	< 0.001	$+0.001$
Fiber cross-talk	$+0.003$	< 0.001	< 0.001	< 0.001
ISM absorption	$+0.003$	< 0.001	< 0.001	< 0.001
Sum	$+0.027$	< 0.001	$+0.001$	< 0.001
Quadratic sum	$+0.054$	$+0.002$	< 0.001	$+0.001$

BOSS DR12 Lyα BAO



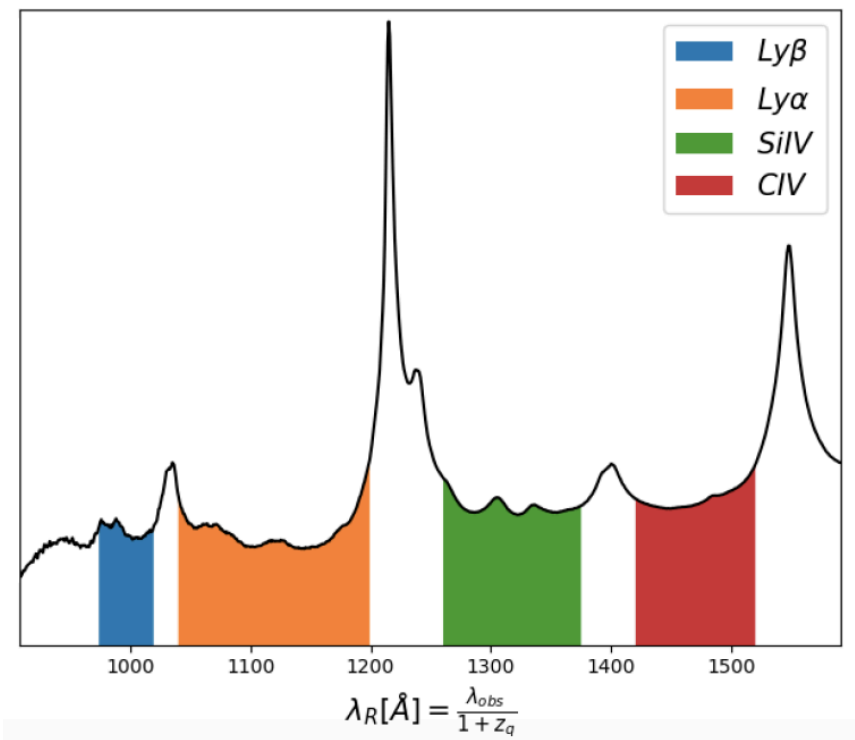
eBOSS DR14 Lyα BAO



Results from 2 first years of eBOSS (DR14) are public

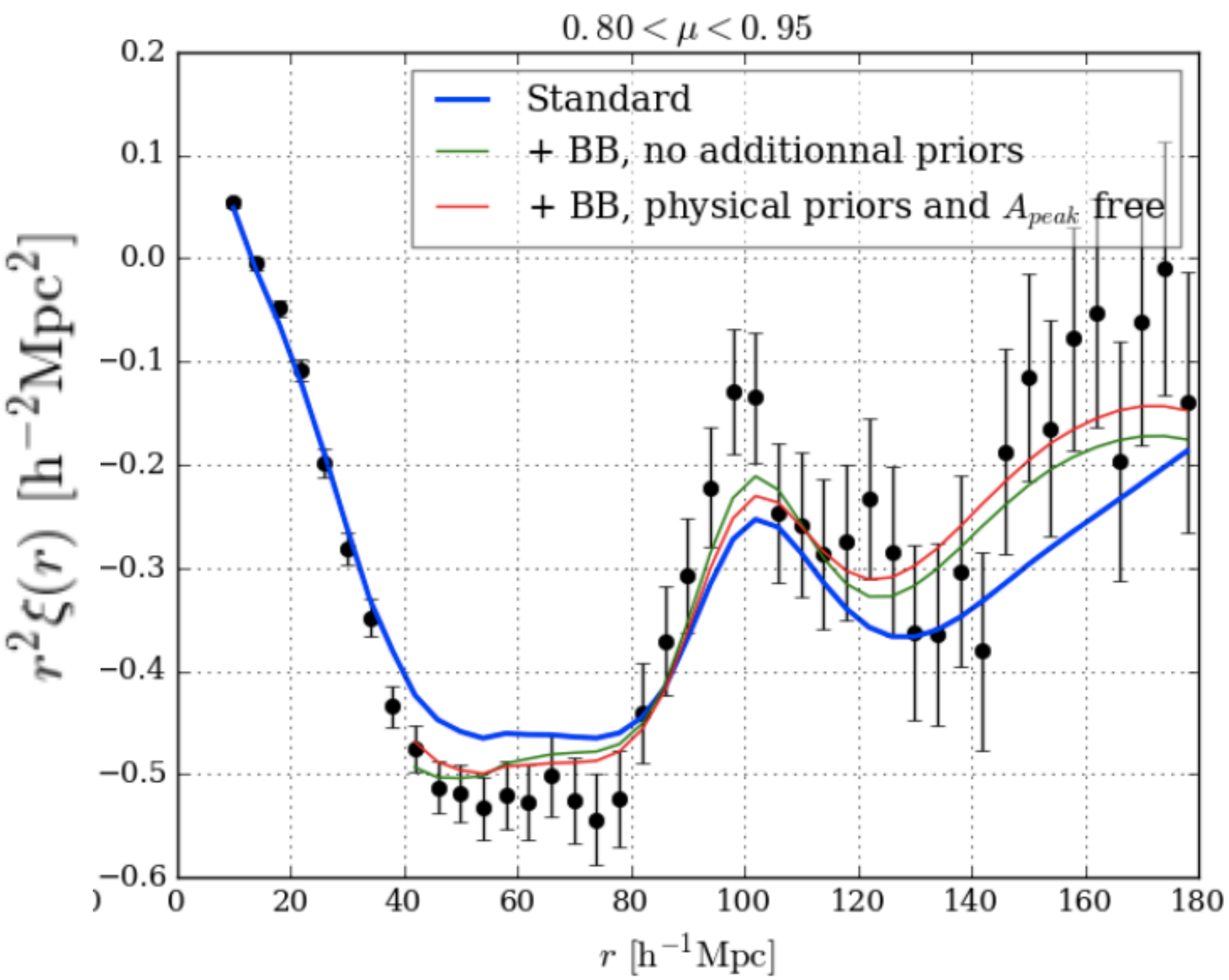
20% more quasars than BOSS

New in eBOSS analyses: use also the LyB region!



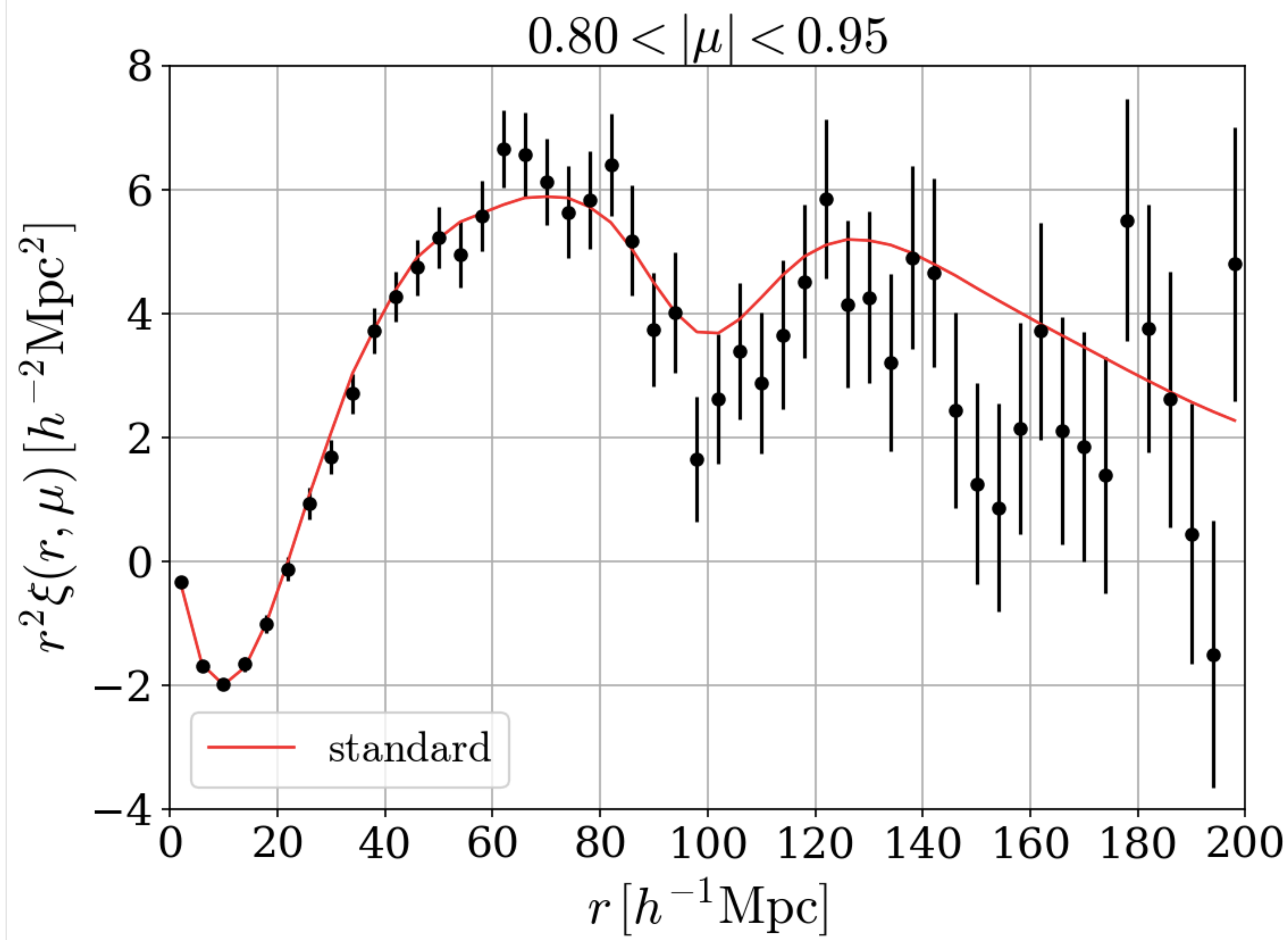
eBOSS DR14 Lyα BAO

DR14 Lyα auto-correlation



Sainte Agathe et al. (2019)

DR14 QSO-Lyα cross-correlation



Blomqvist et al. (2019)

Errorbars 20% smaller than BOSS DR12

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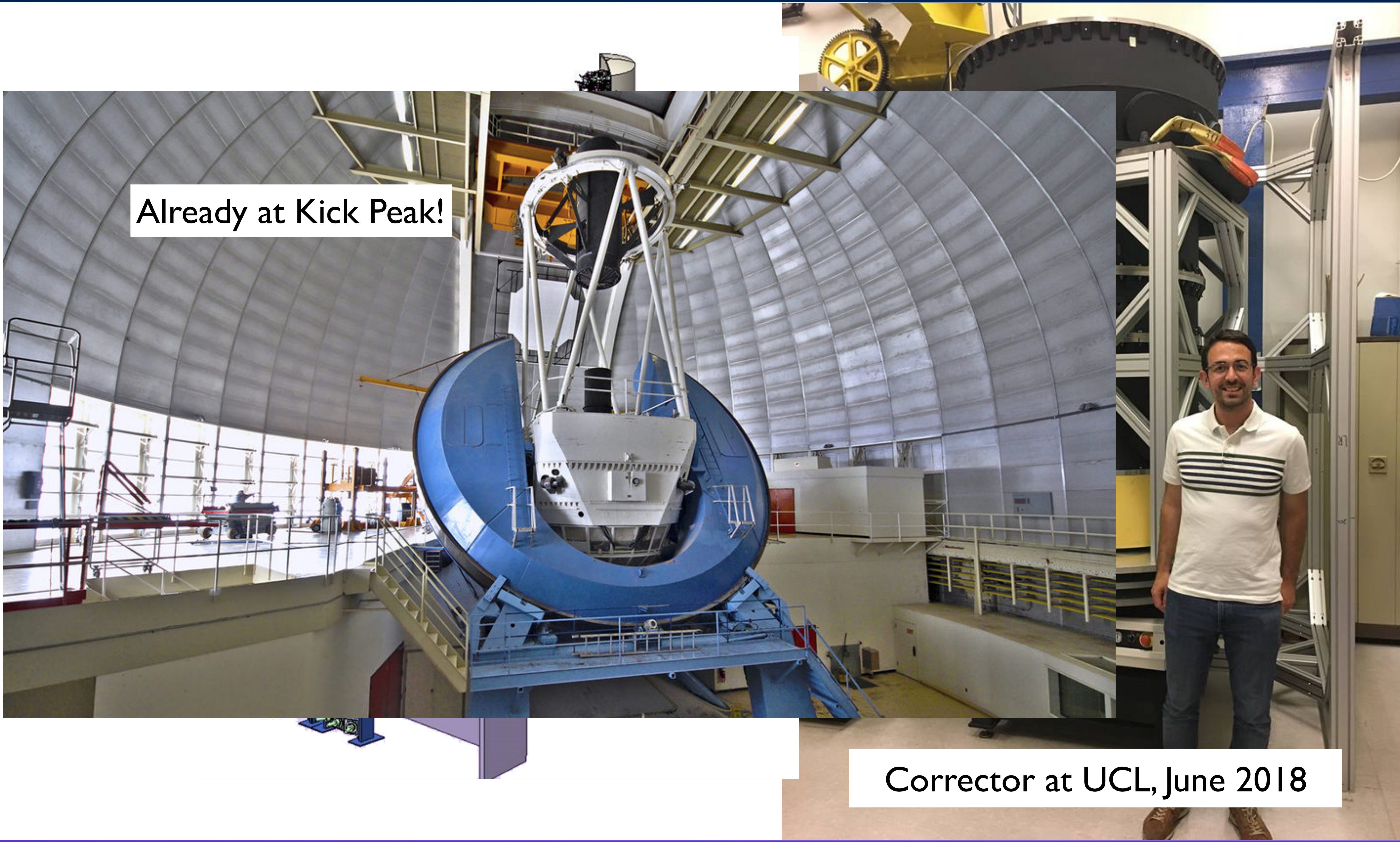
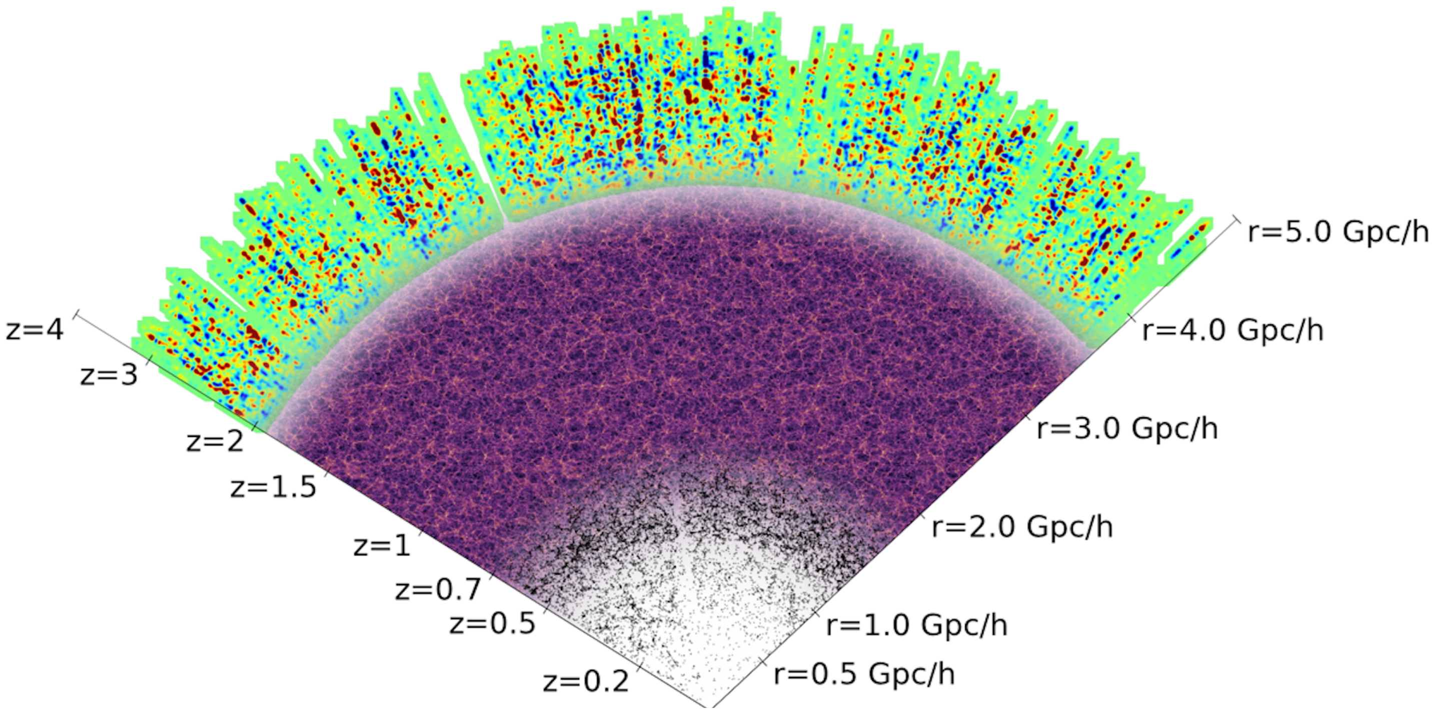
Dark Energy Spectroscopic Survey



Dark Energy Spectroscopic Survey

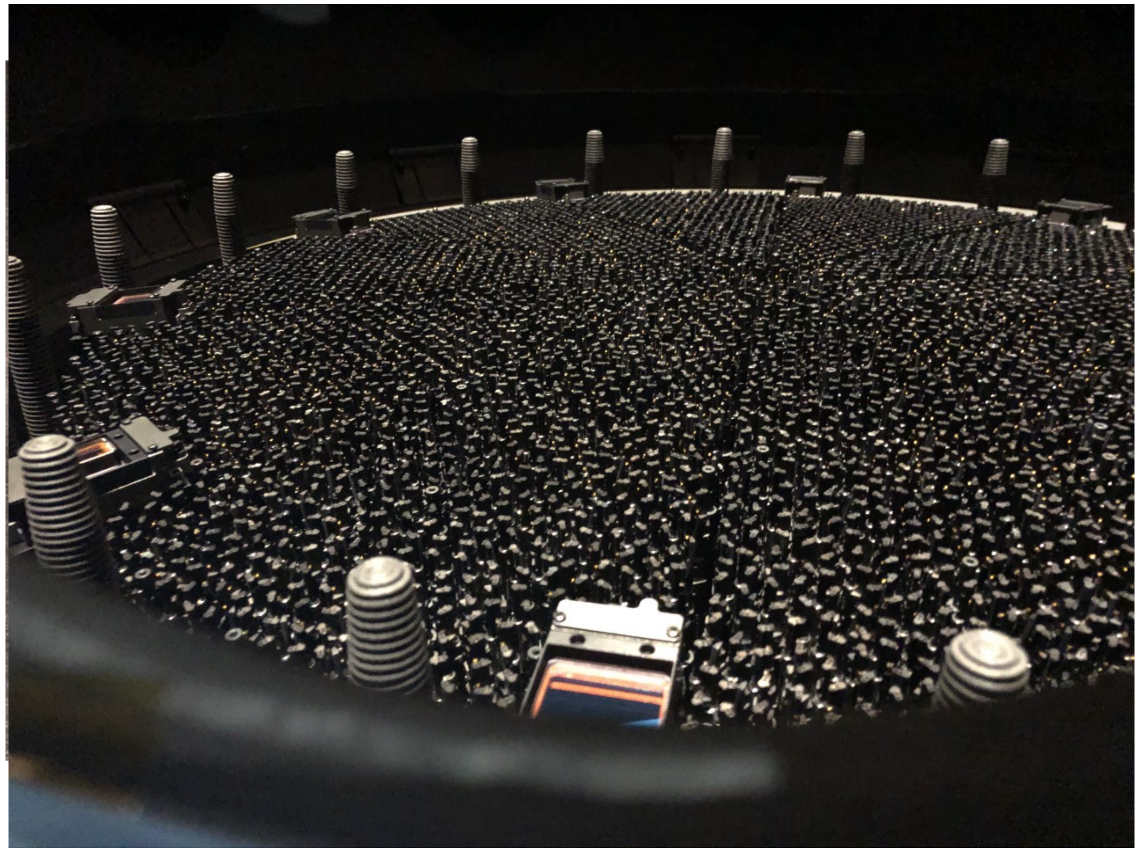


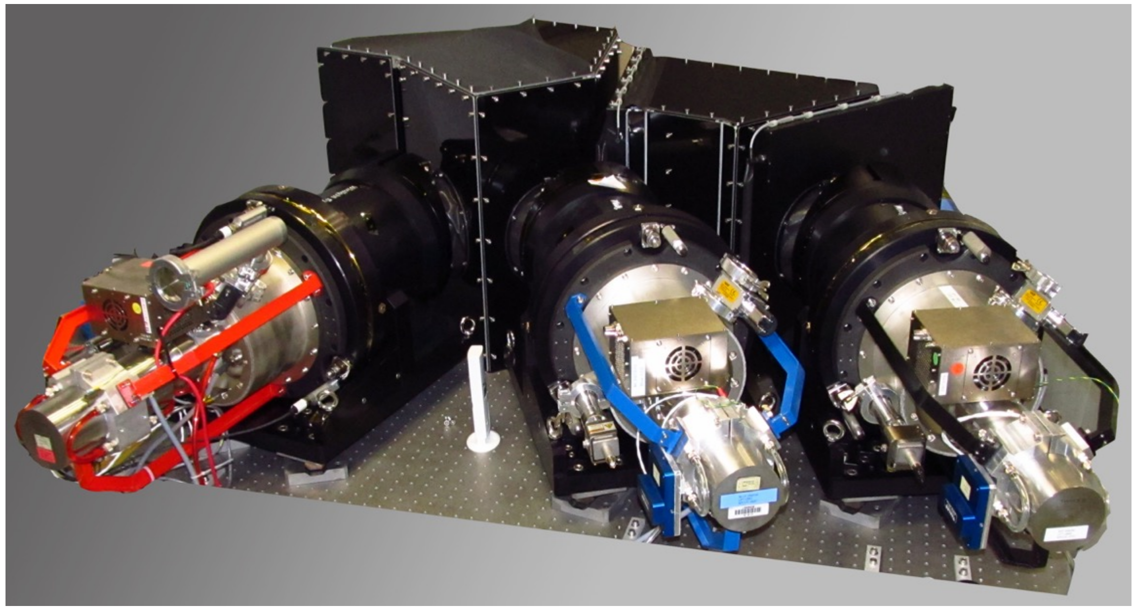
Two surveys

- Dark Time :
  - Dominated by ELGs
  - Bands optimized for ELG
- Bright Time :
  - ~4 nights/lunation
  - BGS/MWS share the observation time with the priority to BGS

Galaxy type	Redshift range	Bands used	Targets per deg^2	Exposures per deg^2	Good z's per deg^2	Baseline sample
LRG	0.4–1.0	$g,r,z,W1$	480	610	430	6.0 M
ELG	0.6–1.6	g,r,z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	$g,r,z,W1,W2$	170	170	120	1.7 M
QSO (Ly-α)	> 2.1	$g,r,z,W1,W2$	90	250	50	0.7 M
Total in dark time			**3140**	**2900**	**1820**	**25.5 M**
BGS	0.05–0.4	r	800	740	710	9.9 M
BGS–Faint	0.05–0.4	r	600	460	430	6.0 M
MWS	0.0	g,r (Gaia μ)	800+	720	720	10.1 M
Total in bright time			**2200+**	**1920**	**1860**	**26.0 M**

Dark Energy Spectroscopic Survey





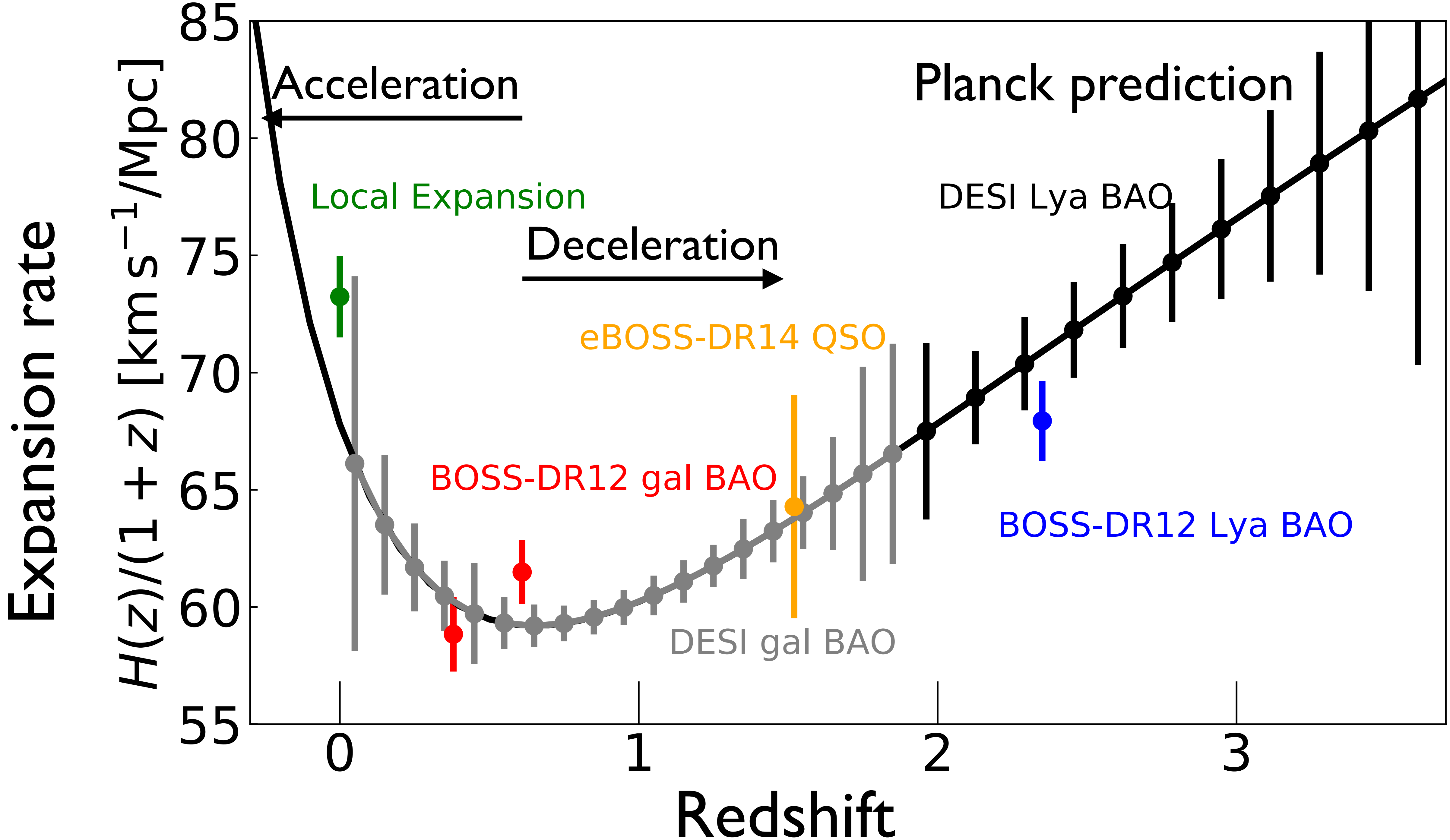
First 7 spectrograph verified and at Kitt Peak

DESI timeline:

- Corrector installed August 2018
- Commissioning ongoing
- Survey Validation January 2020
- Science starts in a year from now!

Dark Energy Spectroscopic Survey

DESI projections (Font-Ribera++ 2014b)



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BAO and the H_0 tension

Prefer low H_0

- Planck
- Planck + SPT
- Planck + BOSS
- WMAP + BOSS
- SPT + BOSS
- ACT + BOSS
- r_d + SN + BOSS → This does not assume Λ
- BBN + BOSS
- BBN + DES + BOSS

(BBN + BOSS and BBN + DES + BOSS) → These do not use CMB

Consistent with both

- SPT
- TRGB
- LIGO GW

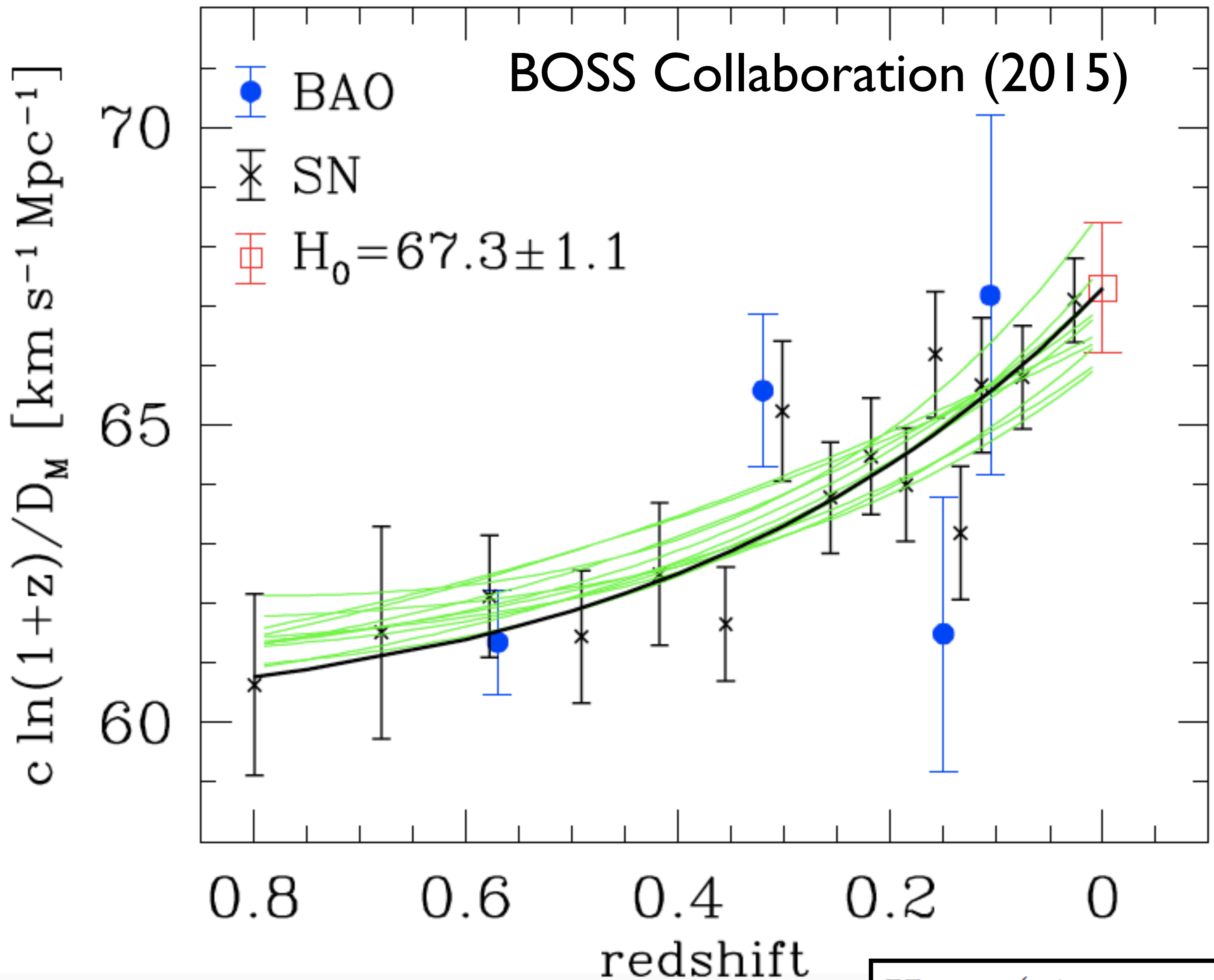
Prefer high H_0

- SHOES
- HoLICOW

They all assume we understand early universe physics (to compute r_d)

BAO and the H_0 tension

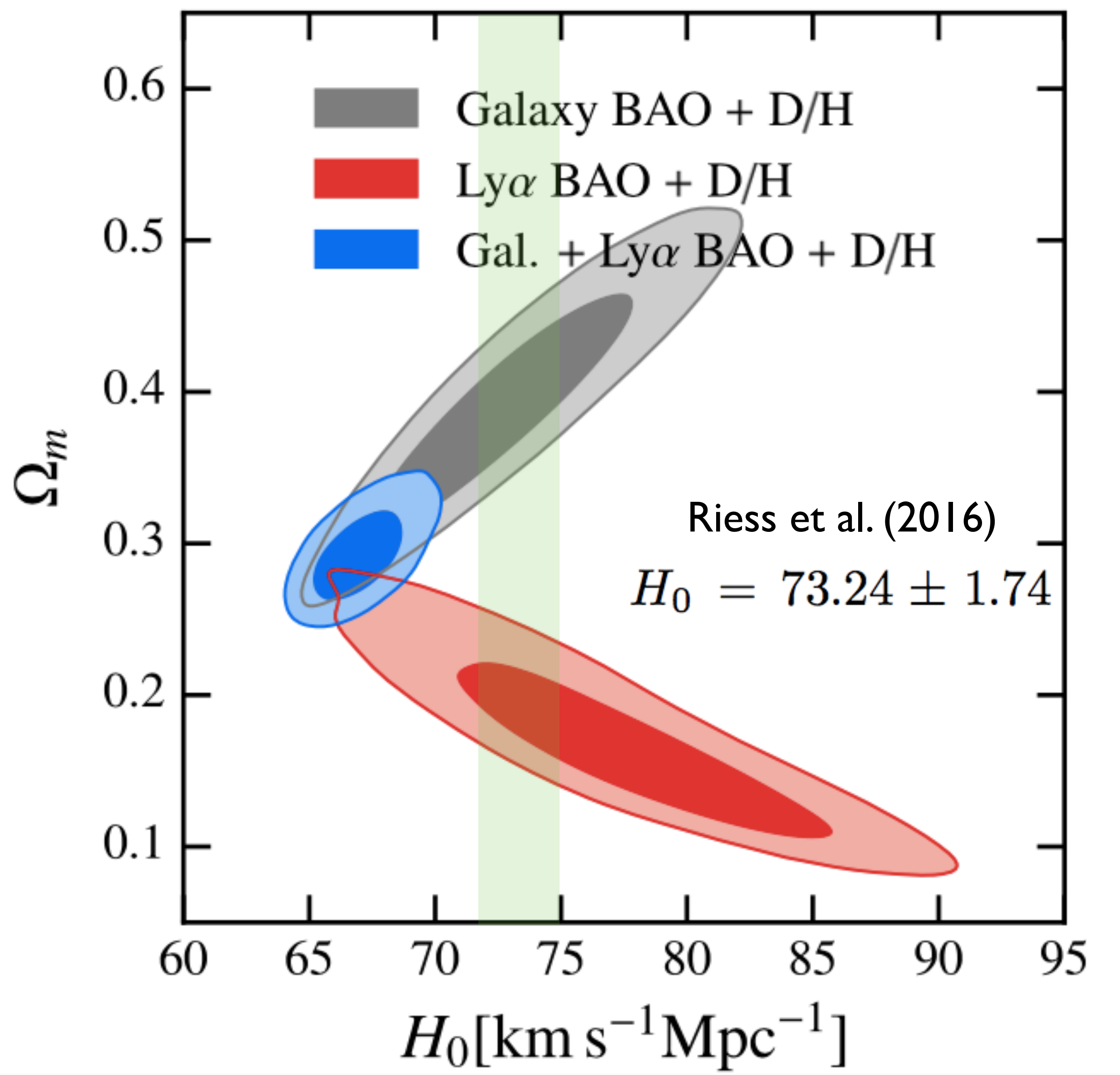
Inverse distance ladder (anchor SN with BAO at z=0.5)



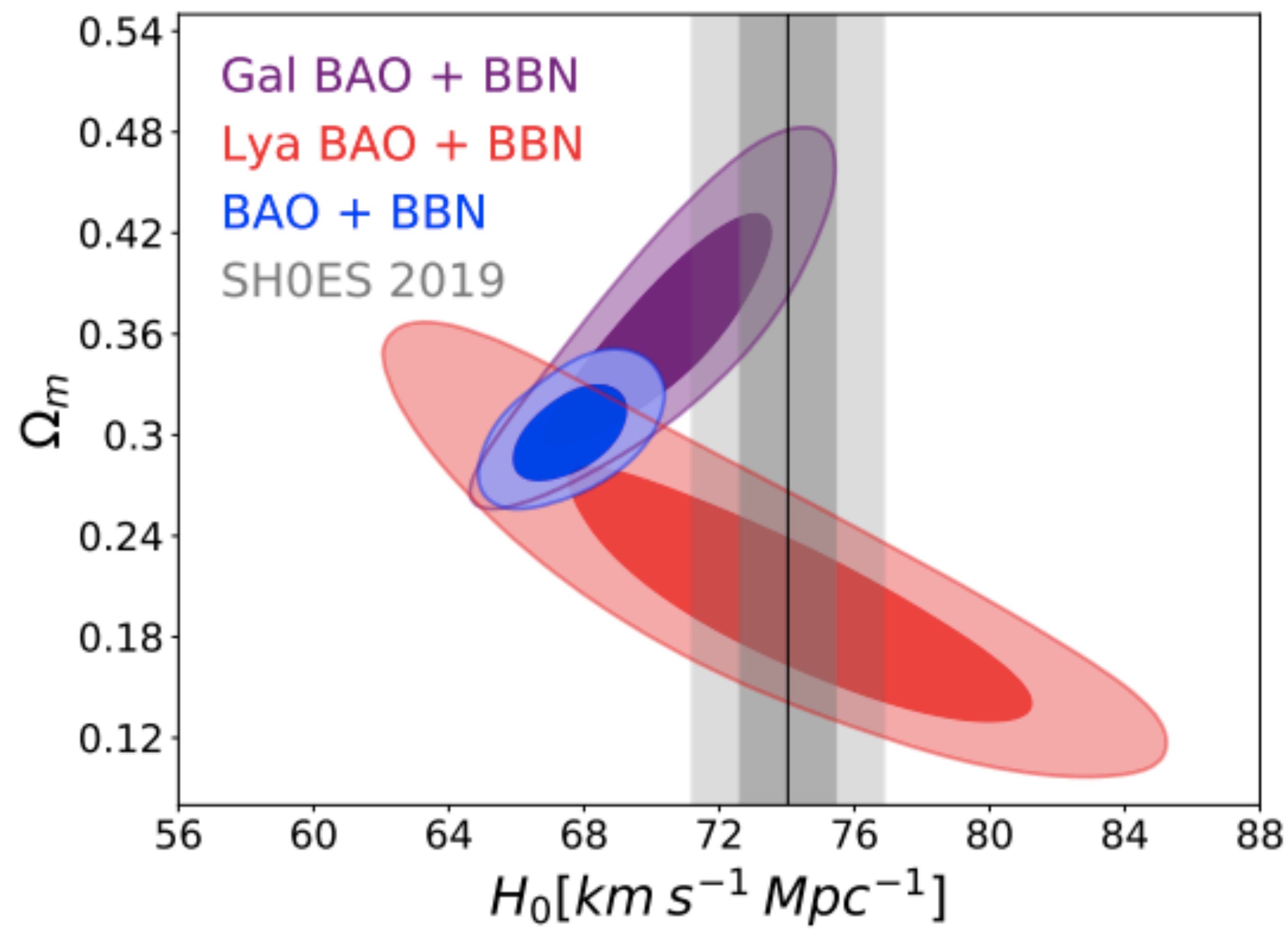
- BAO (SDSS/BOSS + 6dF)
- JLA SN (SDSS-II + SNLS)
- r_d from CMB
- Free dark energy model

$$H_0 = (67.3 \pm 1.1) \times (147.49\,\mathrm{Mpc}/r_d)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

BAO and the H_0 tension



Addison et al. (2018, Lya DR11)



Cuceu et al. (2019, Lya DR14)

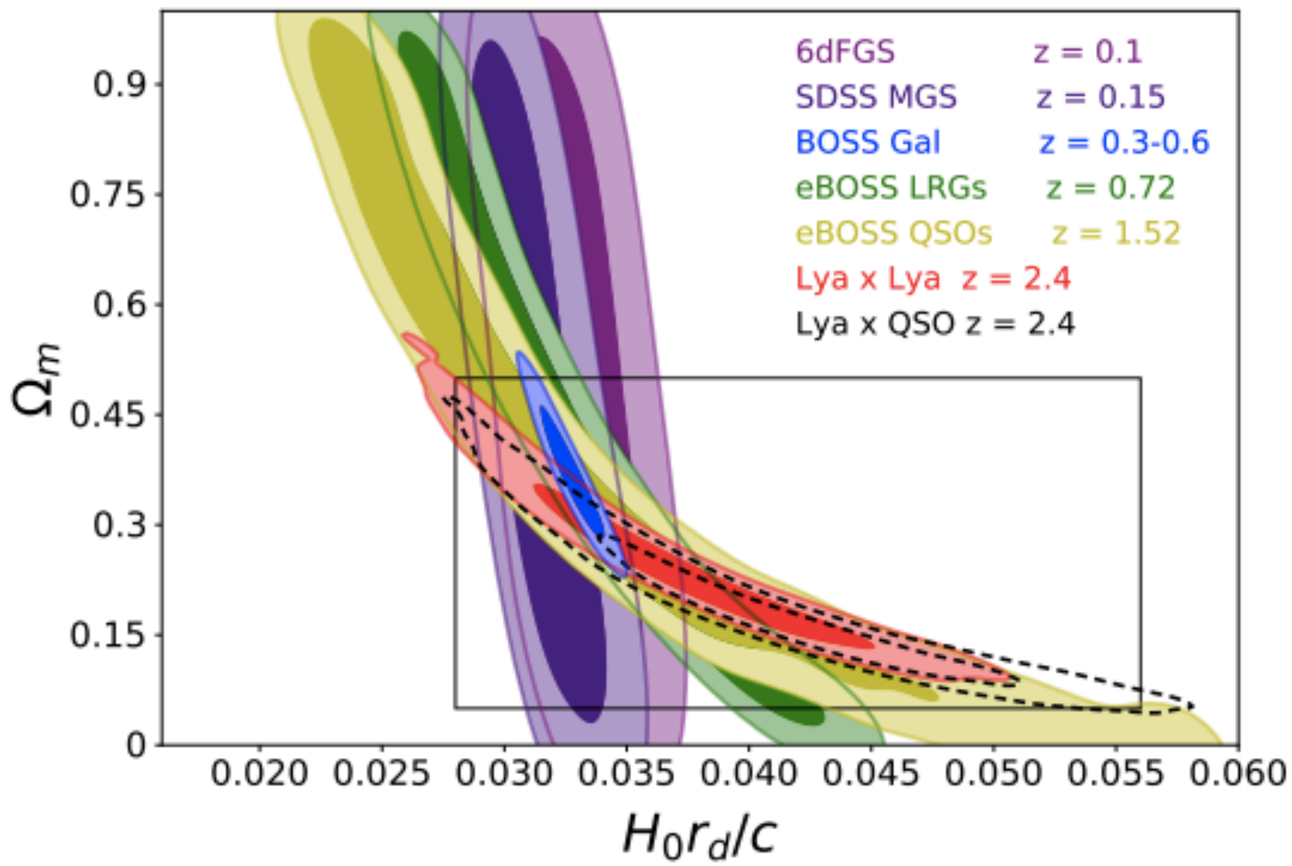
BAO and the H_0 tension

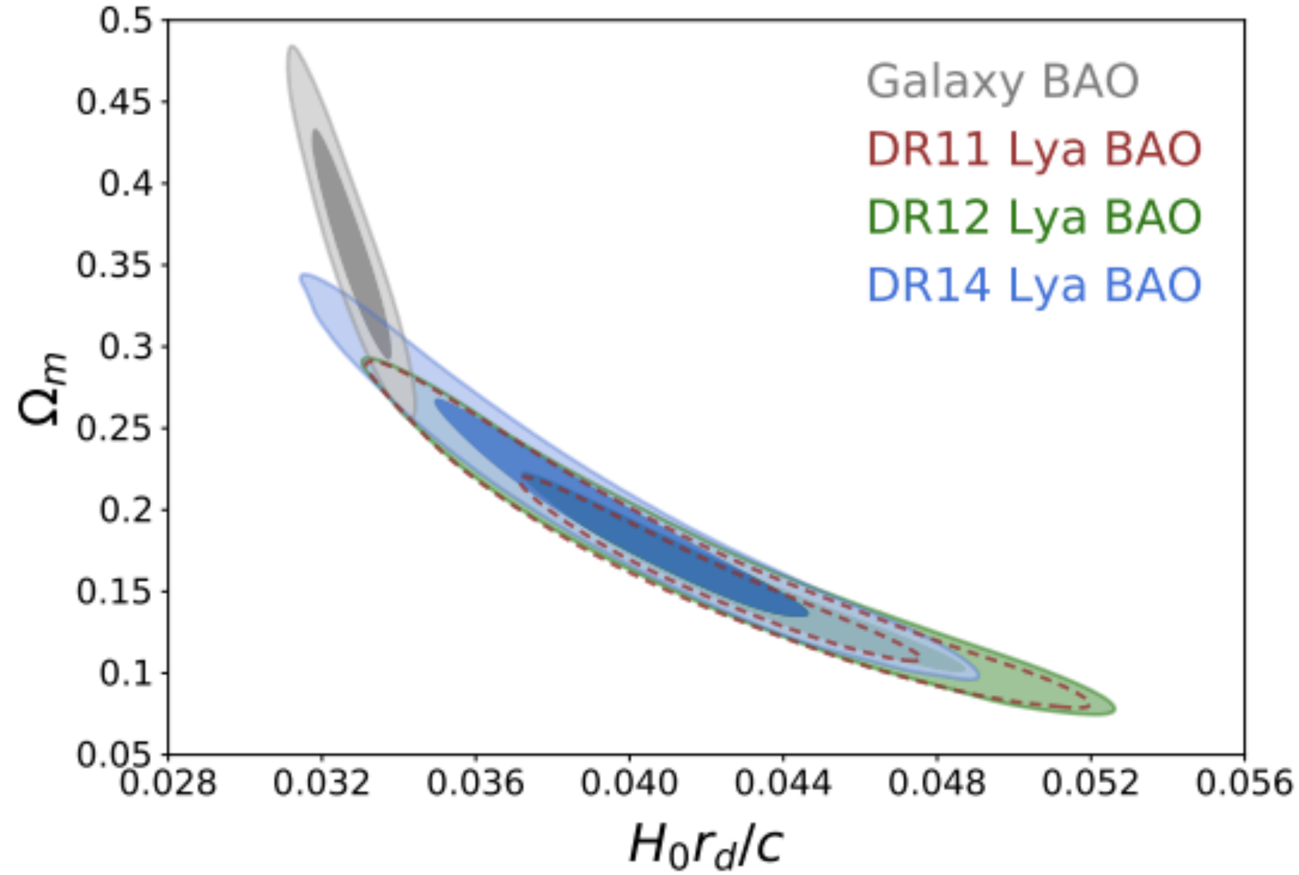
BAO and the Hubble Constant (Cuceu et al. 2019)

Galaxy BAO and Lya BAO have different information

BAOs in mild tension in BOSS, in better agreement in DR14

Andrei Cuceu
(PhD at UCL)





BAO and the H_0 tension

Prefer low H_0

Planck
Planck + SPT
Planck + BOSS
WMAP + BOSS
SPT + BOSS
ACT + BOSS
r_d + SN + BOSS
BBN + BOSS
BBN + DES + BOSS

Consistent with both

SPT
TRGB
LIGO GW

Prefer high H_0

SHOES
HoLICOW

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$c_s(z) \;=\; 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

They all assume we understand early universe physics (to compute r_d)

Summary

- Lyman-α forest BAO offers complementary information at high-z
- eBOSS DR14 Lyα BAO out in April, reduced tension with Planck
- Dark Energy Spectroscopic Survey (DESI) starts in less than a year!
- H_0 tension can not be explained by CMB systematics
- Need to modify early physics that sets sound horizon at z ~ 1000