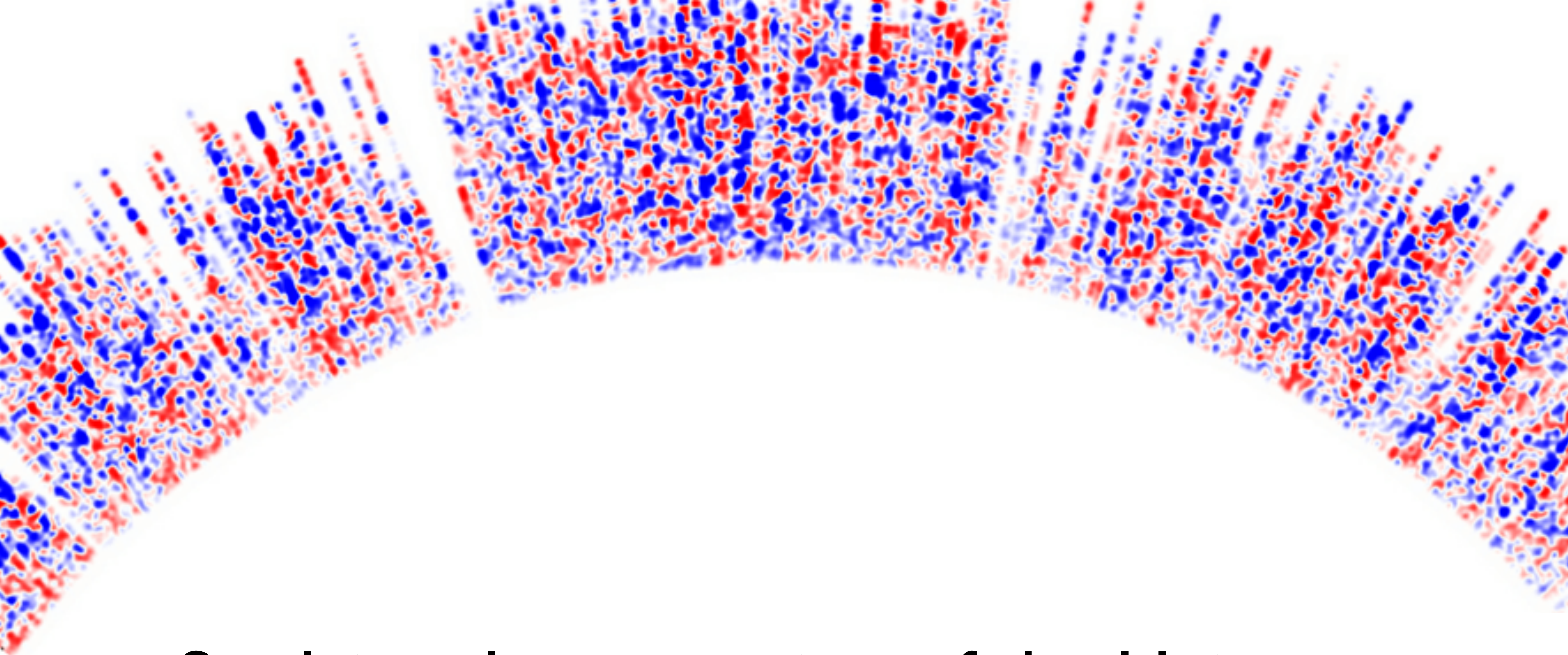
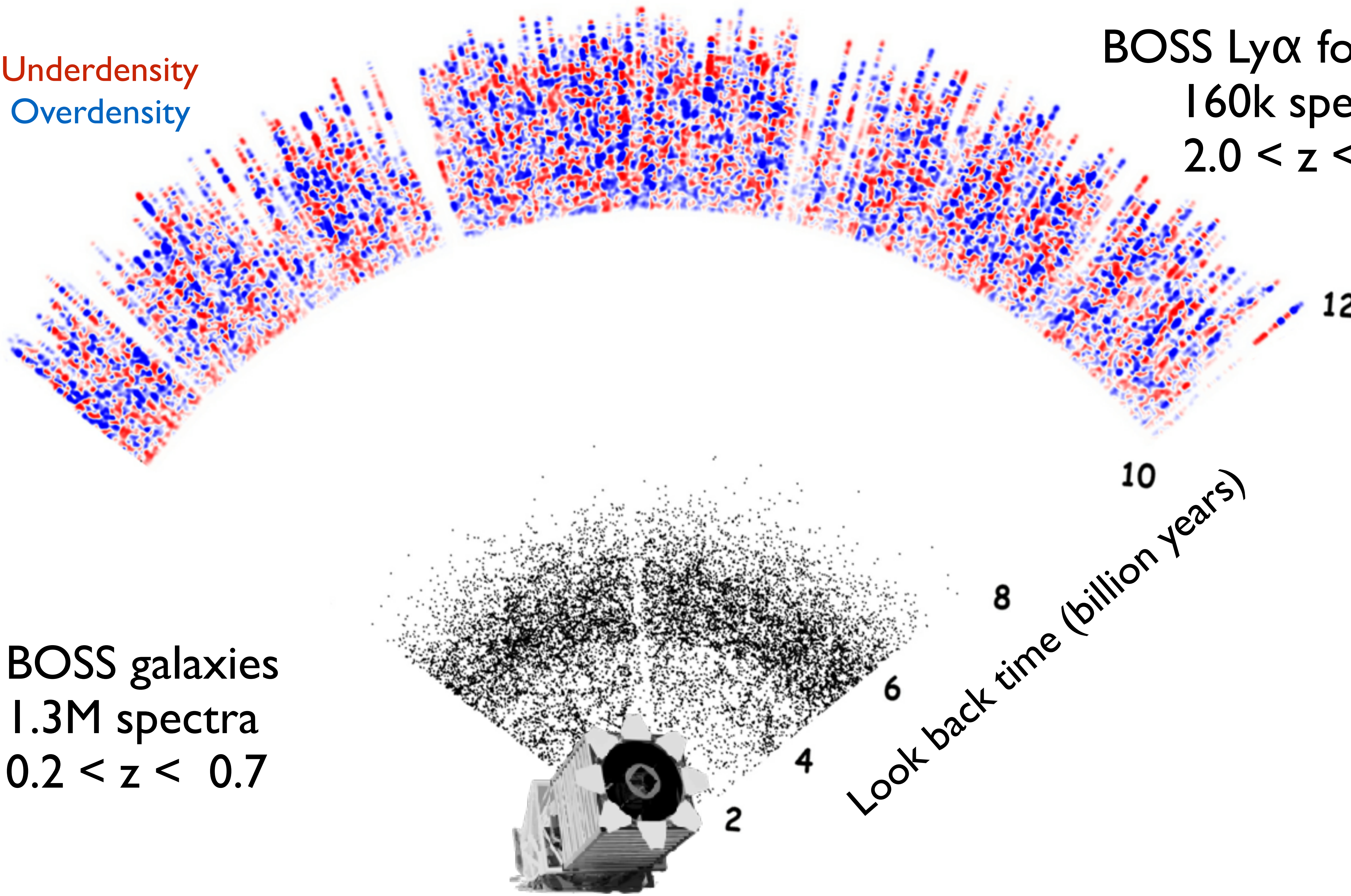


Studying the expansion of the Universe with quasar spectra

Andreu Font-Ribera

STFC Ernest Rutherford Fellow at University College London

Redshift Surveys



BOSS Lyα forest
160k spectra
$2.0 < z < 3.5$

BOSS galaxies
1.3M spectra
$0.2 < z < 0.7$

Outline

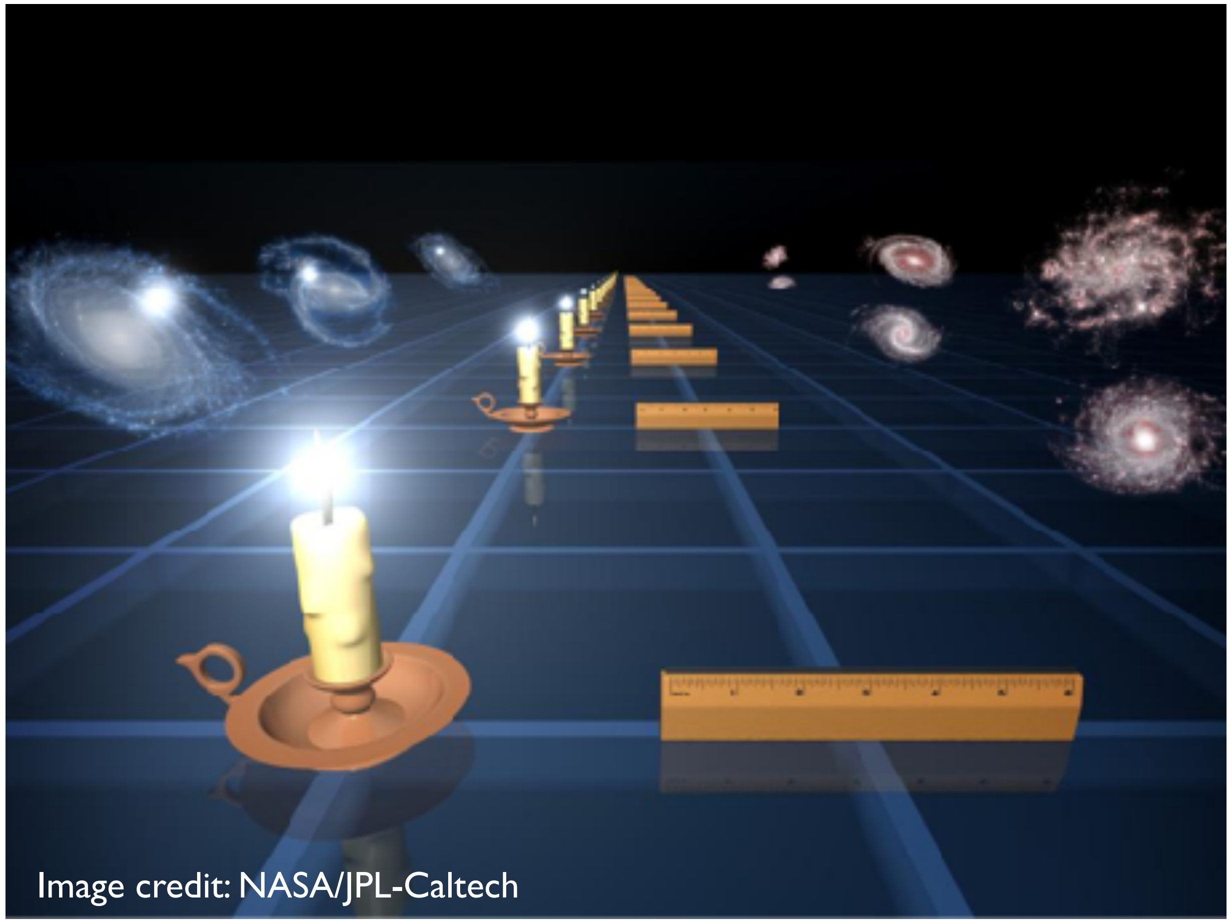
- **Baryon Acoustic Oscillations (BAO)** **Skip?**
- Baryon Oscillation Spectroscopic Survey (BOSS)
- The Lyman-α forest (Lyα)
- Lyα results from BOSS
- Dark Energy Spectroscopic Instrument (DESI)
- Going beyond BAO (there is more than dark energy) **Skip?**

Baryon Acoustic Oscillations

To study the expansion we want to measure the distance to different redshifts

Standard candle (Supernovae)

known luminosity
+
measure flux
↓
distance

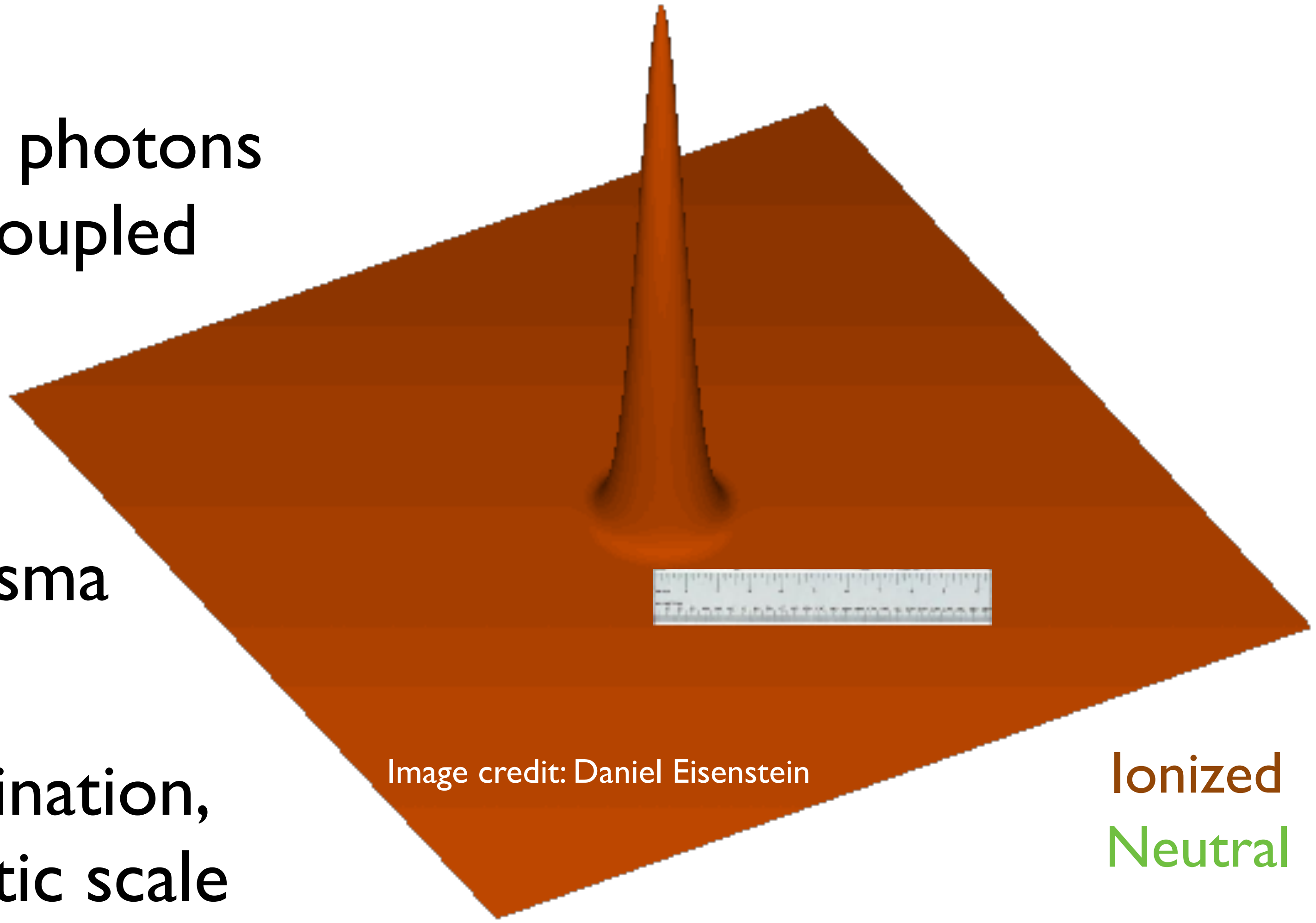


Standard ruler (BAO)

known size
+
measure apparent size
↓
distance

Baryon Acoustic Oscillations

Before recombination (z >1100), photons and ionized matter were tightly coupled



Primordial density fluctuations generated sound waves in the plasma

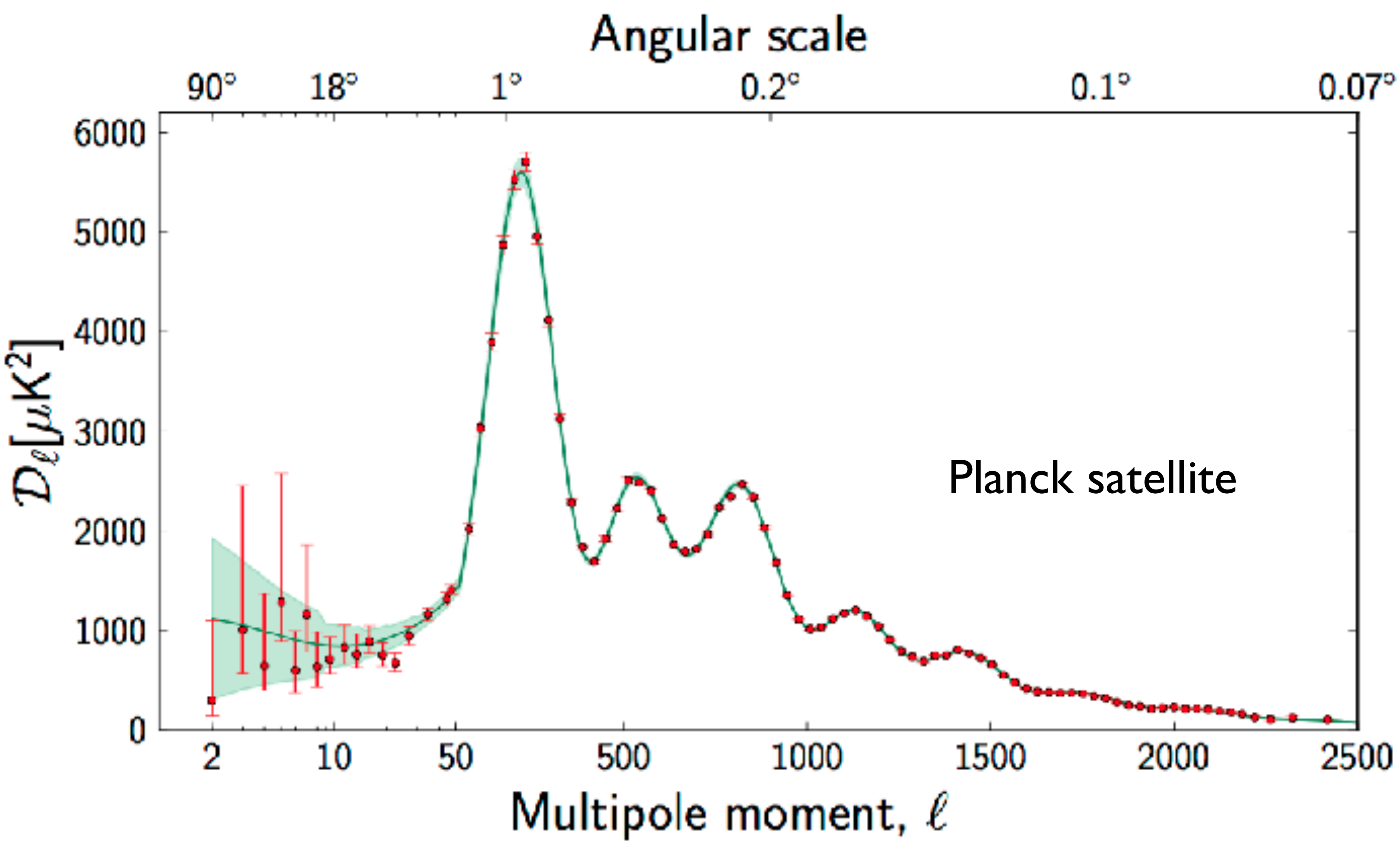
These waves froze out at recombination, leaving an imprint at a characteristic scale

Sound horizon at recombination (from Planck): $r_d = 147.49 \pm 0.59 \ \mathrm{Mpc}$

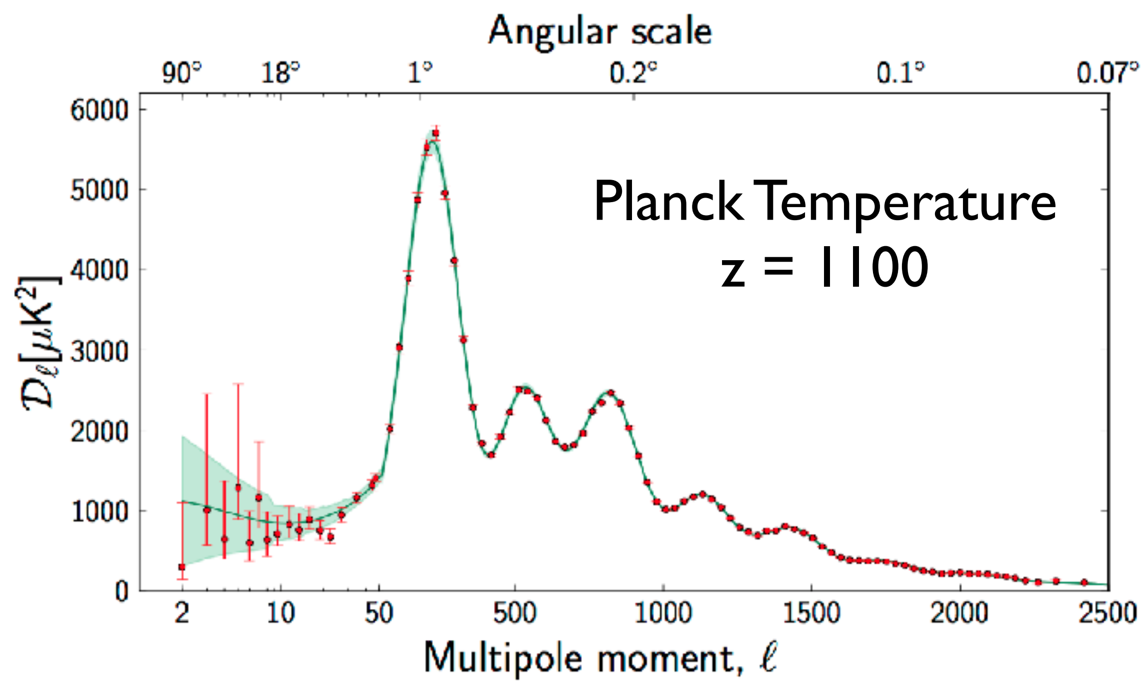
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \qquad c_s(z) = 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

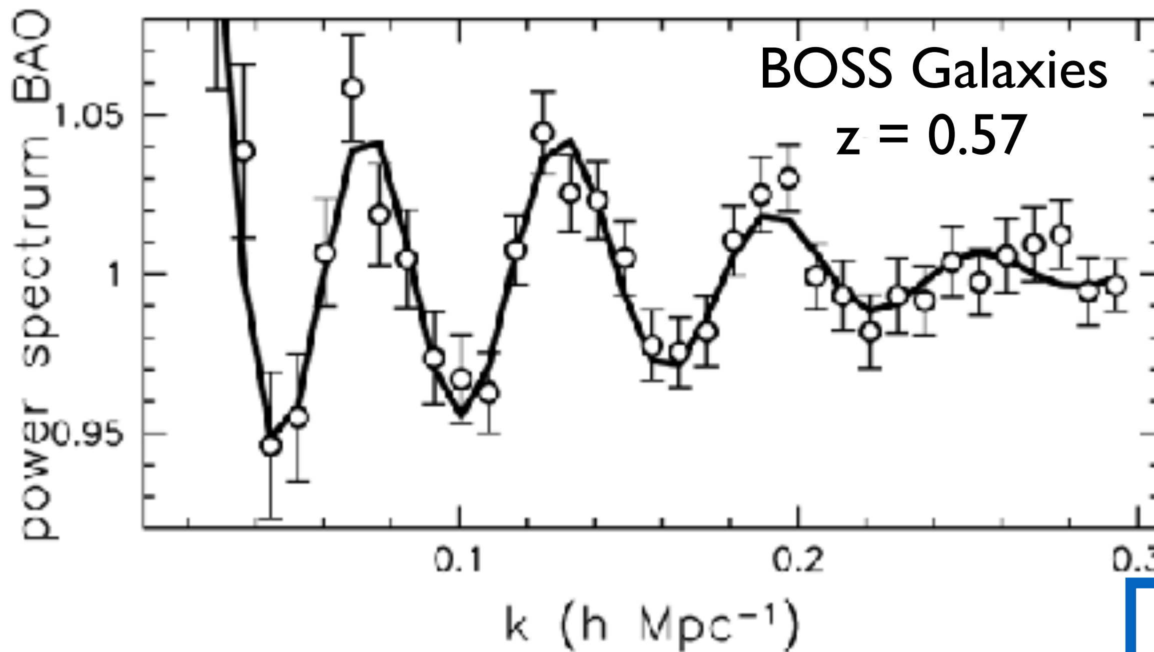
Baryon Acoustic Oscillations

Oscillations clearly seen in the CMB temperature power spectrum

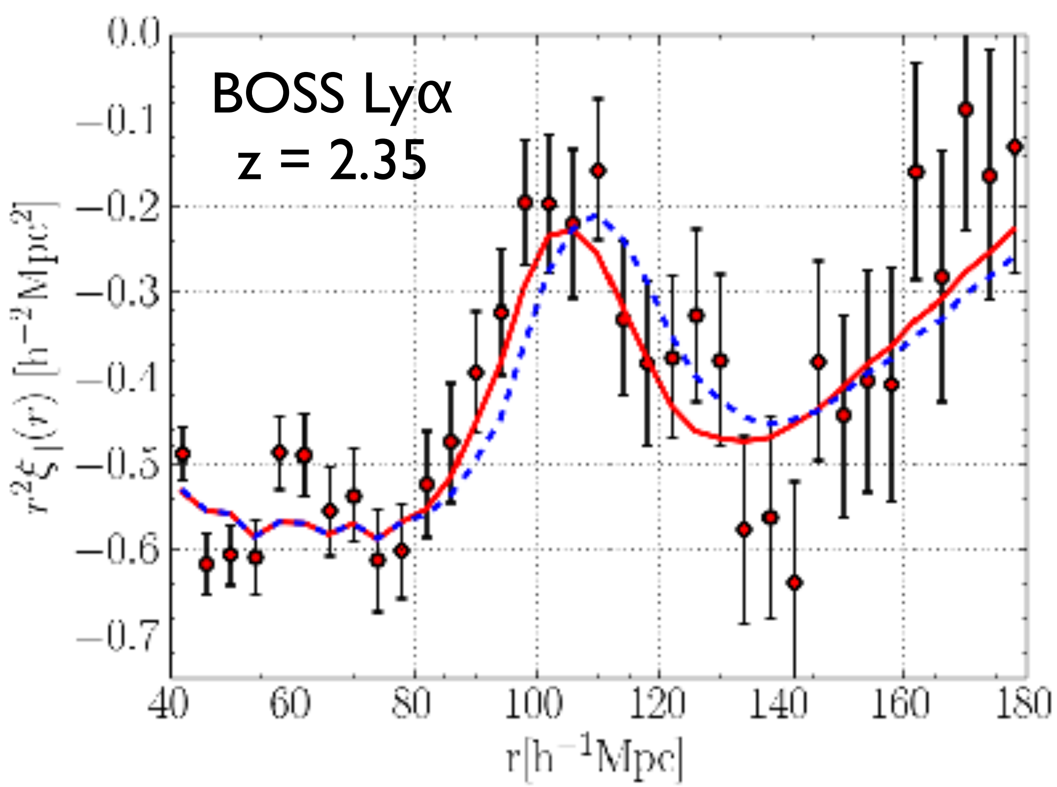


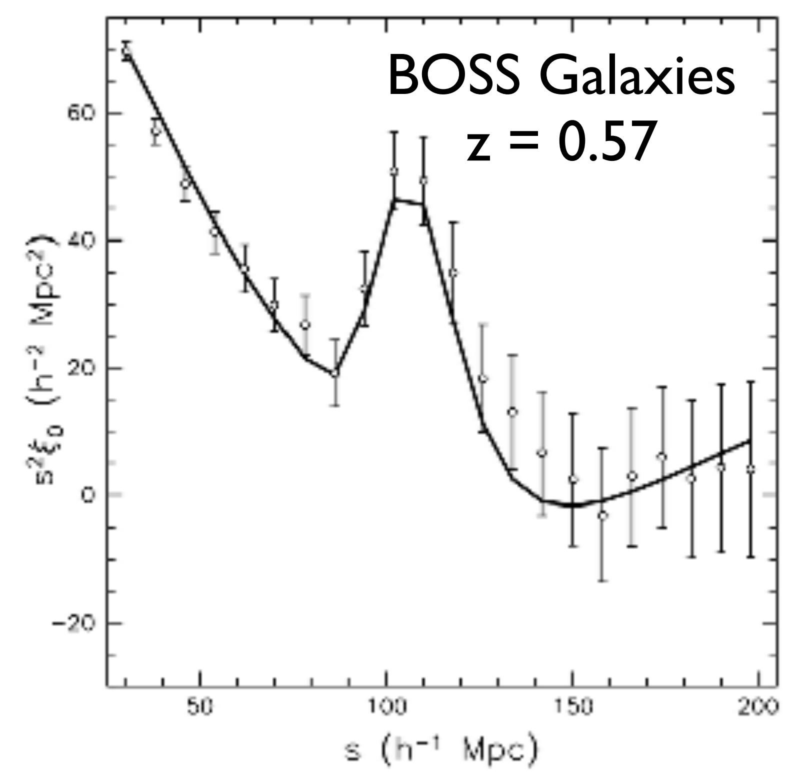
Baryon Acoustic Oscillations

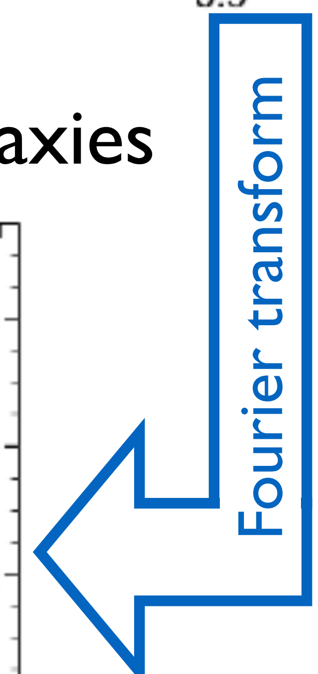




Oscillations clearly seen in CMB, but also in clustering of galaxies







Baryon Acoustic Oscillations

Sound horizon at recombination (from Planck): $r_d = 147.49 \pm 0.59 \text{ Mpc}$

We measure BAO peak in the transverse direction in BOSS : $\Delta\theta_{BAO}$

We measure BAO peak along the line of sight in BOSS : Δv_{BAO}

$$\Delta\theta_{BAO} = \frac{r_d}{1+z} \frac{1}{\boxed{D_A(z)}} \qquad \Delta v_{BAO} = \frac{r_d}{1+z} \boxed{H(z)}$$

We learn about the expansion!

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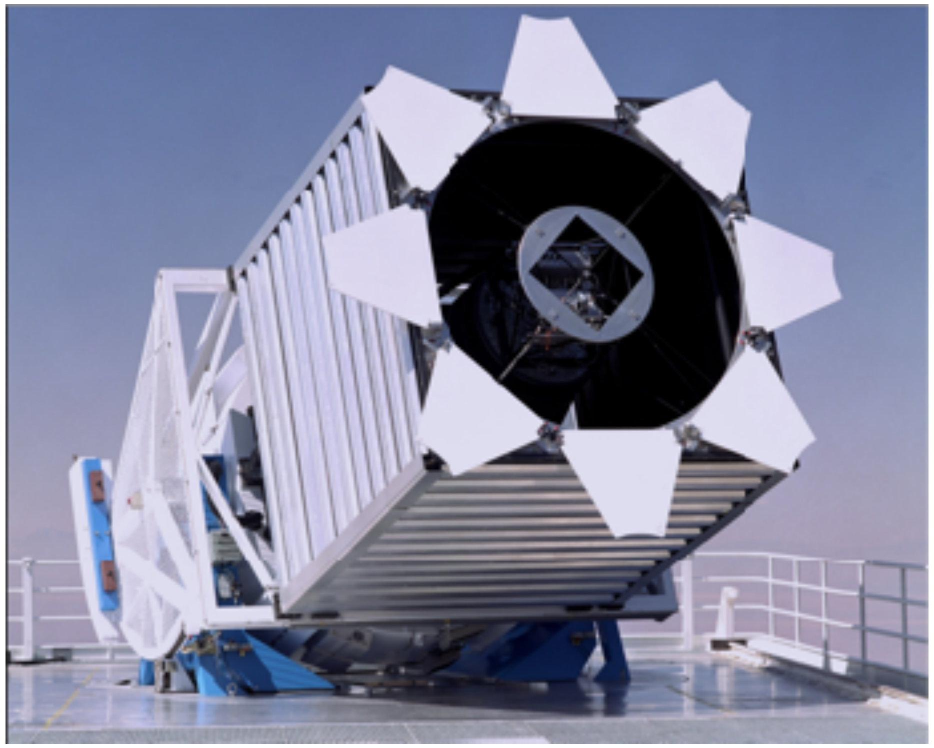
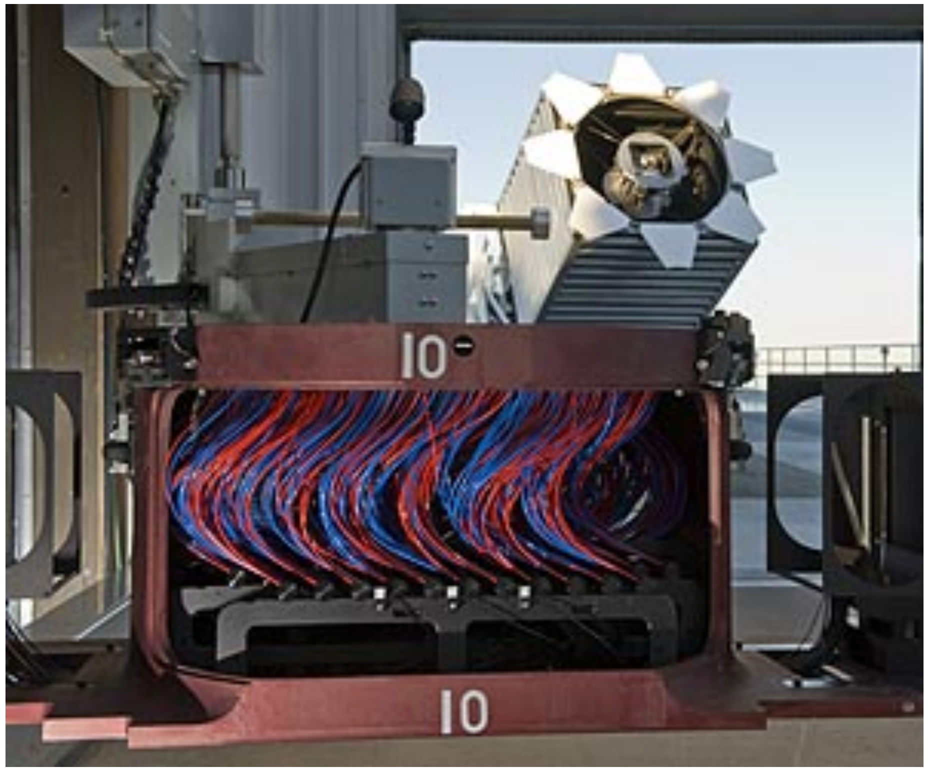
BOSS

SDSS Telescope (2.5m)
Apache Point Observatory
(Cloudcroft, New Mexico)





2 optical spectrographs
Mid resolution (R~2000)
1000 spectra at a time

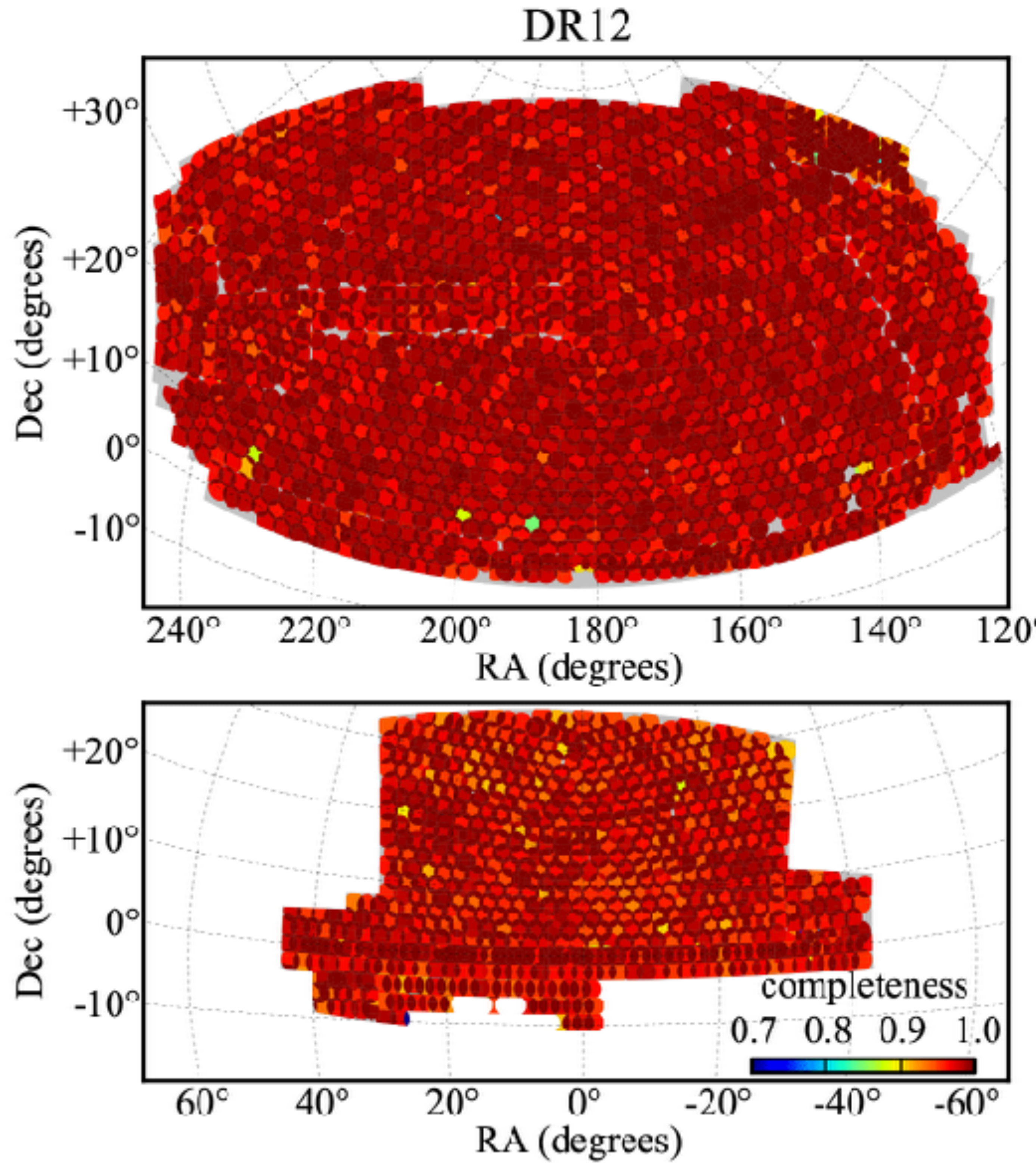
BOSS

10.000 sq. deg. (1/4 sky)

5 years survey (2009-2014)

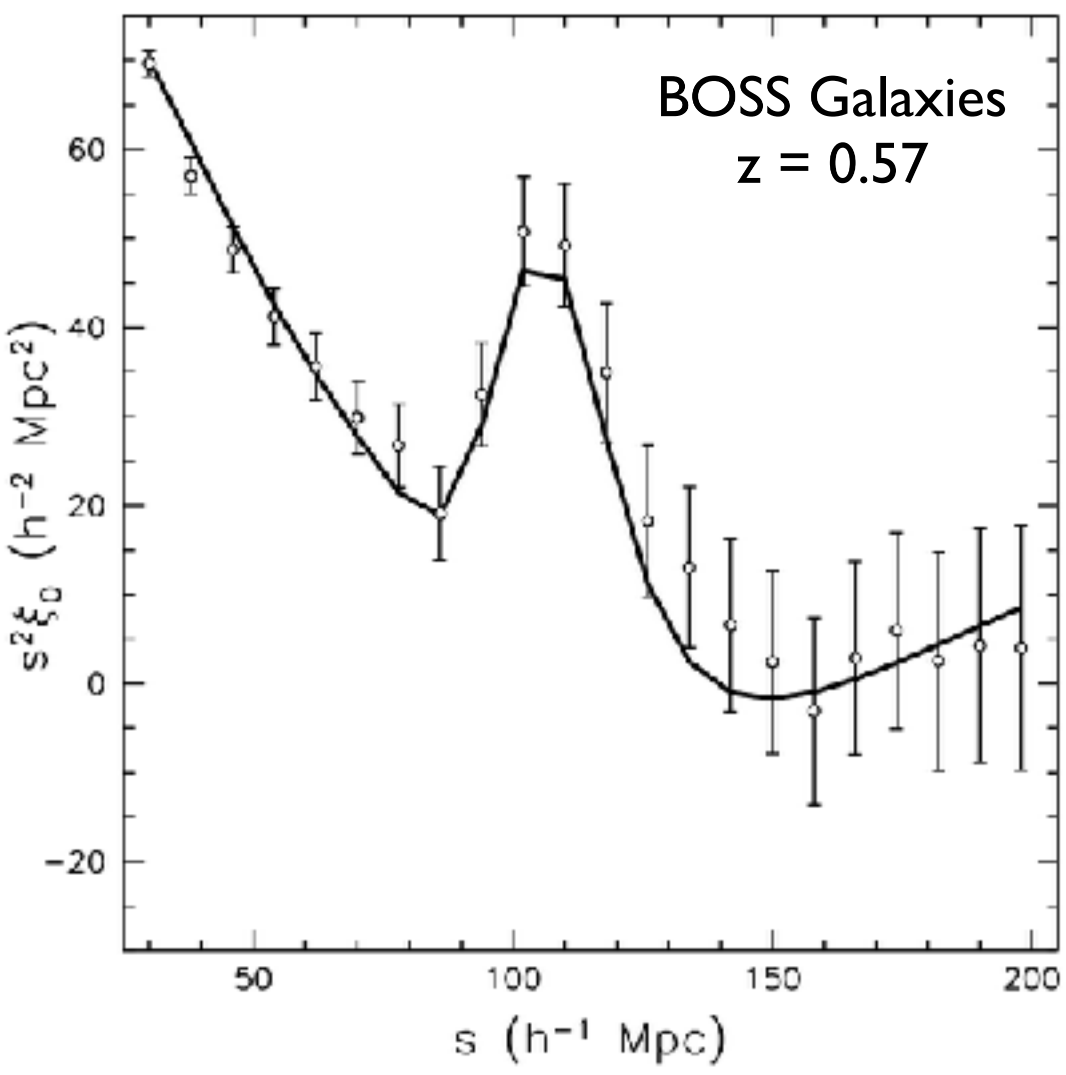
All data (DR12) already public

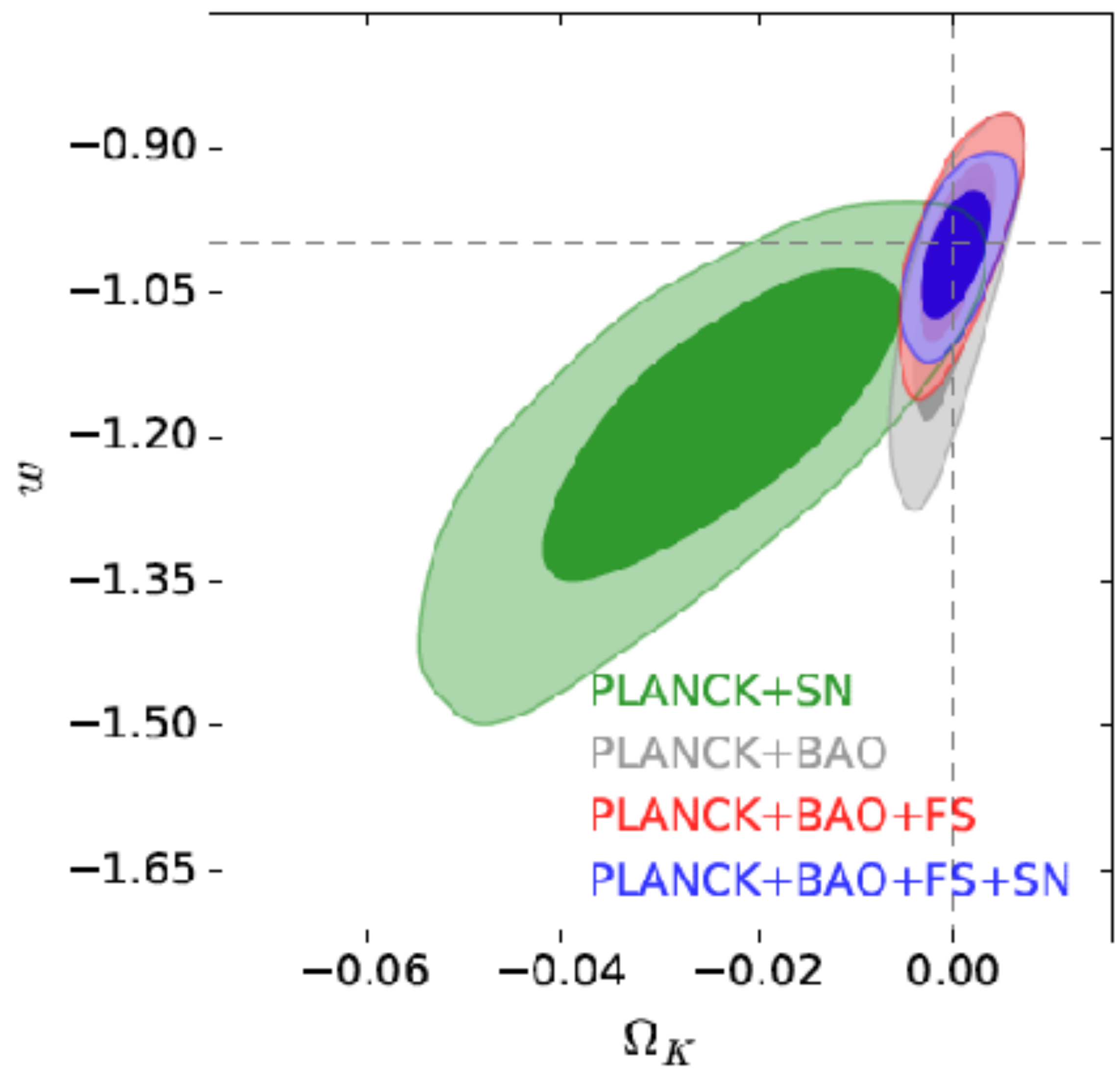
Main target:
1.3M galaxies $0.2 < z < 0.7$



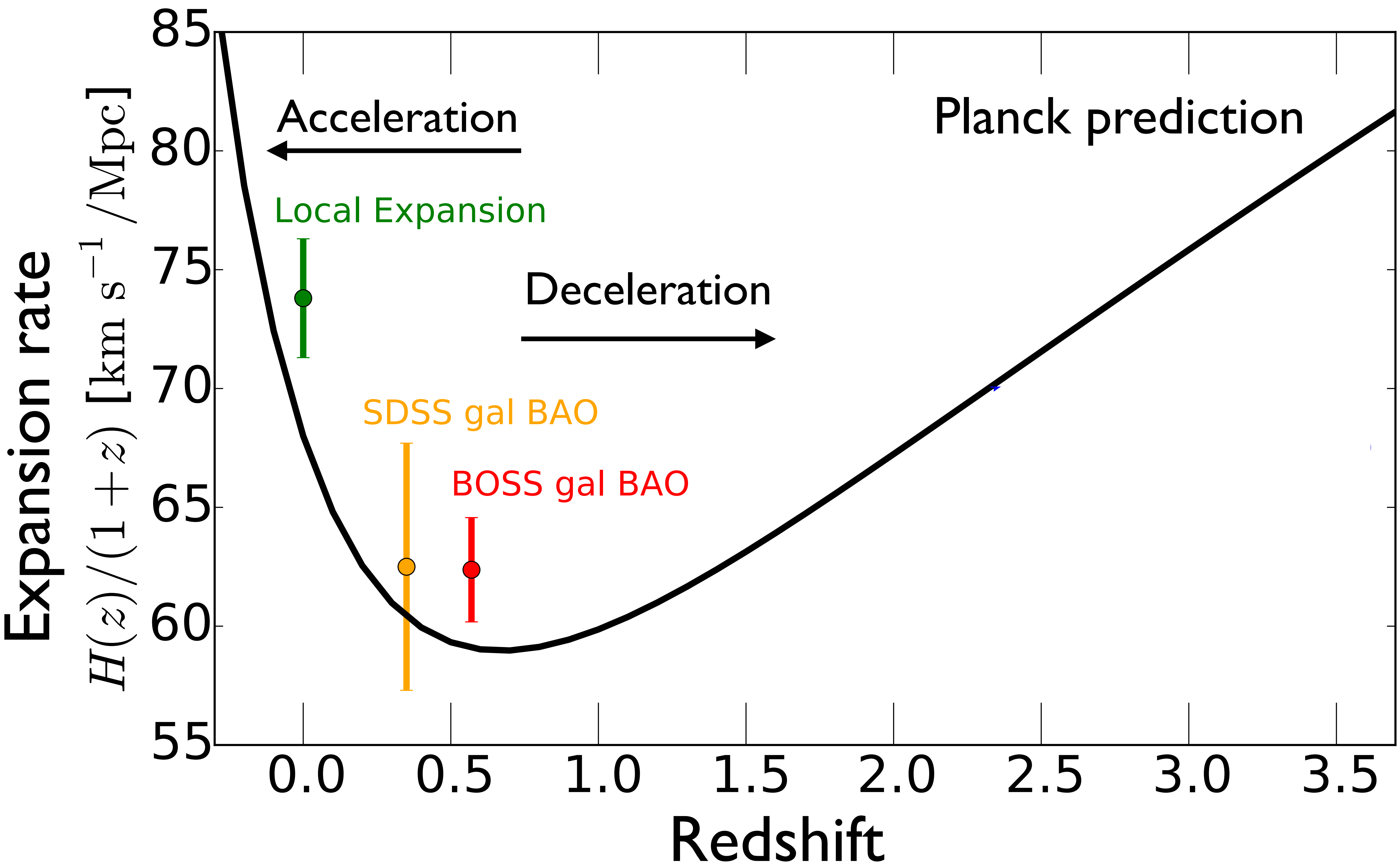
BOSS

Galaxy BAO measured at 1% precision





BOSS



Acceleration
Planck prediction
Local Expansion
Deceleration
SDSS gal BAO
BOSS gal BAO
Expansion rate
$H(z)/(1+z)$ [km s^{-1} /Mpc]
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Redshift

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The Lyman-α forest

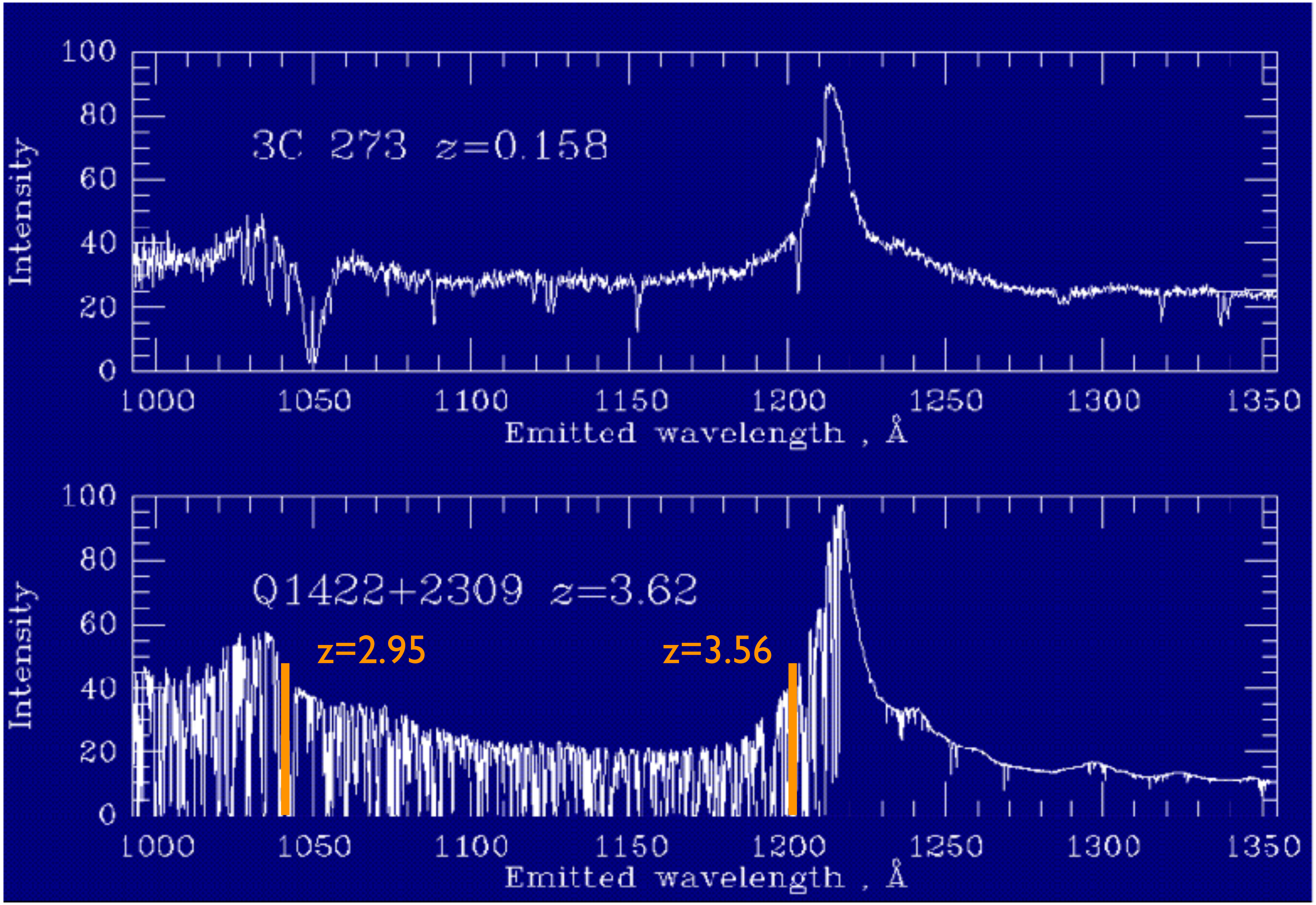
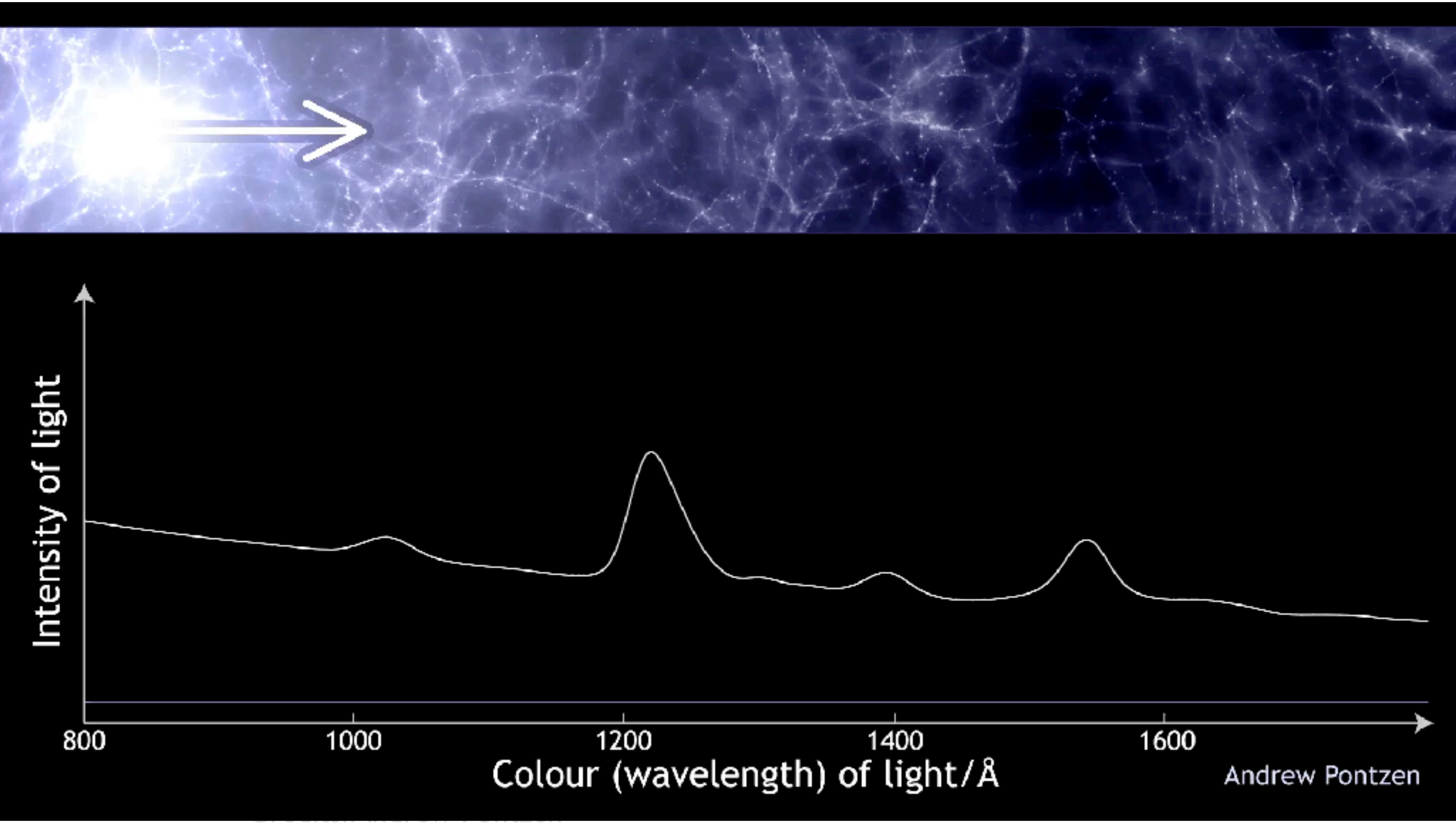
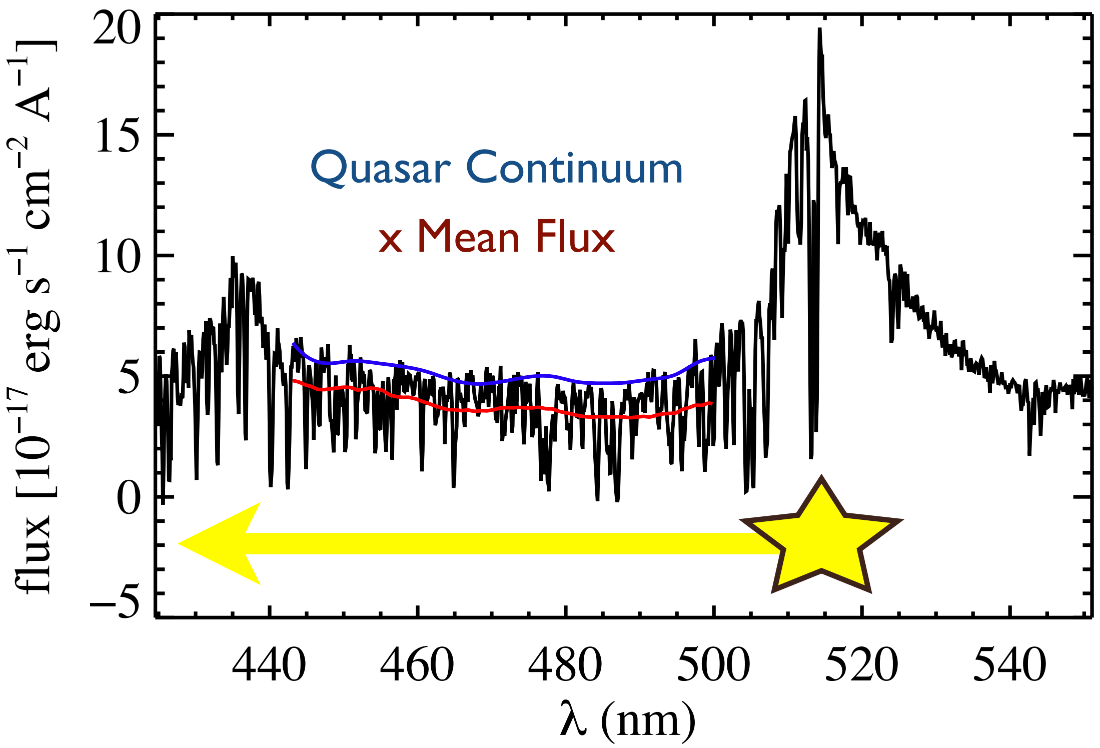


Figure from William C. Keel

The Lyman-α forest



The Lyman-α forest



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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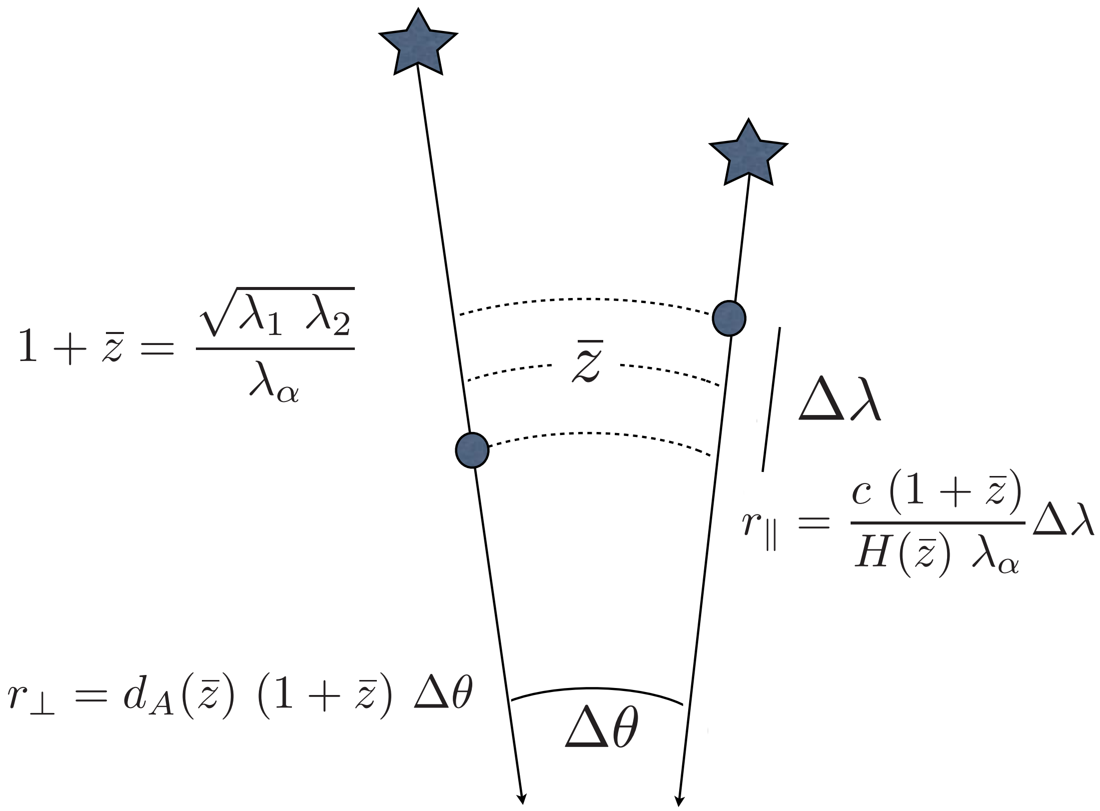
BOSS Lyman-α BAO

Andreu Ariño-i-Prats, Eduard Arnau, Eric Aubourg, Stephen Bailey, **Julián Bautista**, Vaishali Bhardwaj, Michael Blomqvist, Arnaud Borde, Nicolás Busca, Bill Carithers, Stefano Cristiani, Rupert Croft, Kyle Dawson, Timothée Delubac, **Helion du Mas des Bourboux**, **Andreu Font-Ribera** (co-chair), Satya Gontcho a Gontcho, Julien Guy, Jean-Christophe Hamilton, Shirley Ho, Khee-Gan Lee, Jean-Marc Le Goff, David Kirkby, Britt Lundgren, Daniel Margala, Patrick McDonald, Brice Ménard, Jordi Miralda-Escude, Pasquier Noterdaeme, Ross O'Connell, Nathalie Palanque-Delabrouille, Isabelle Paris, **Ignasi Pérez-Ràfols**, Patrick Petitjean, Mat Pieri, **Jim Rich** (co-chair), Emmanuel Rollinde, Nic Ross, Graziano Rossi, David Schlegel, Anze Slosar, Nao Suzuki, Matteo Viel, David Weinberg, Martin White, Christophe Yeche, Don York

Weekly telecon during 7 years!

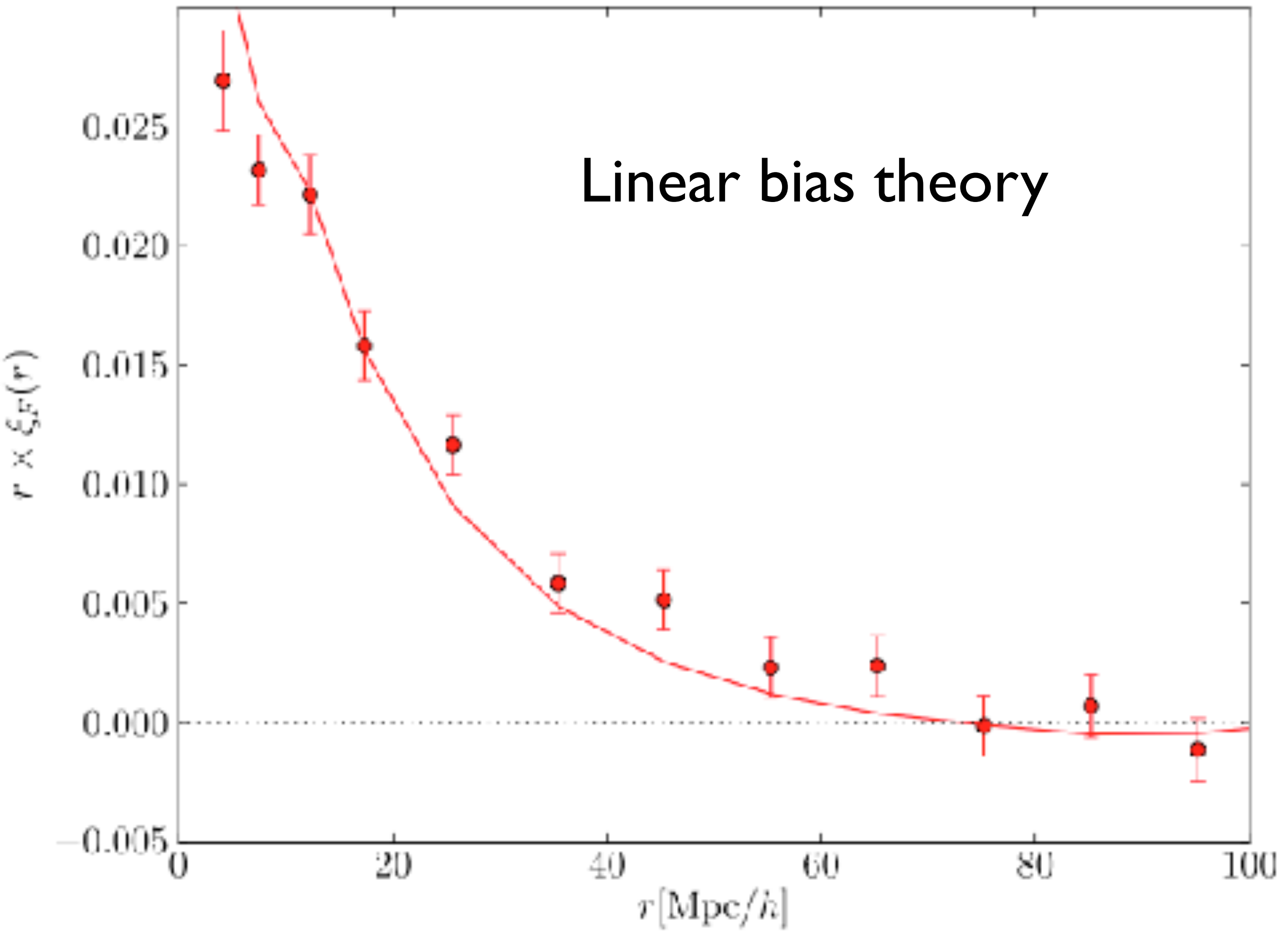
BOSS Lyman-α BAO

BOSS : 160k quasar spectra over 10k sq.deg.
(x10 number of quasars at 2.15 < z < 3.5)



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

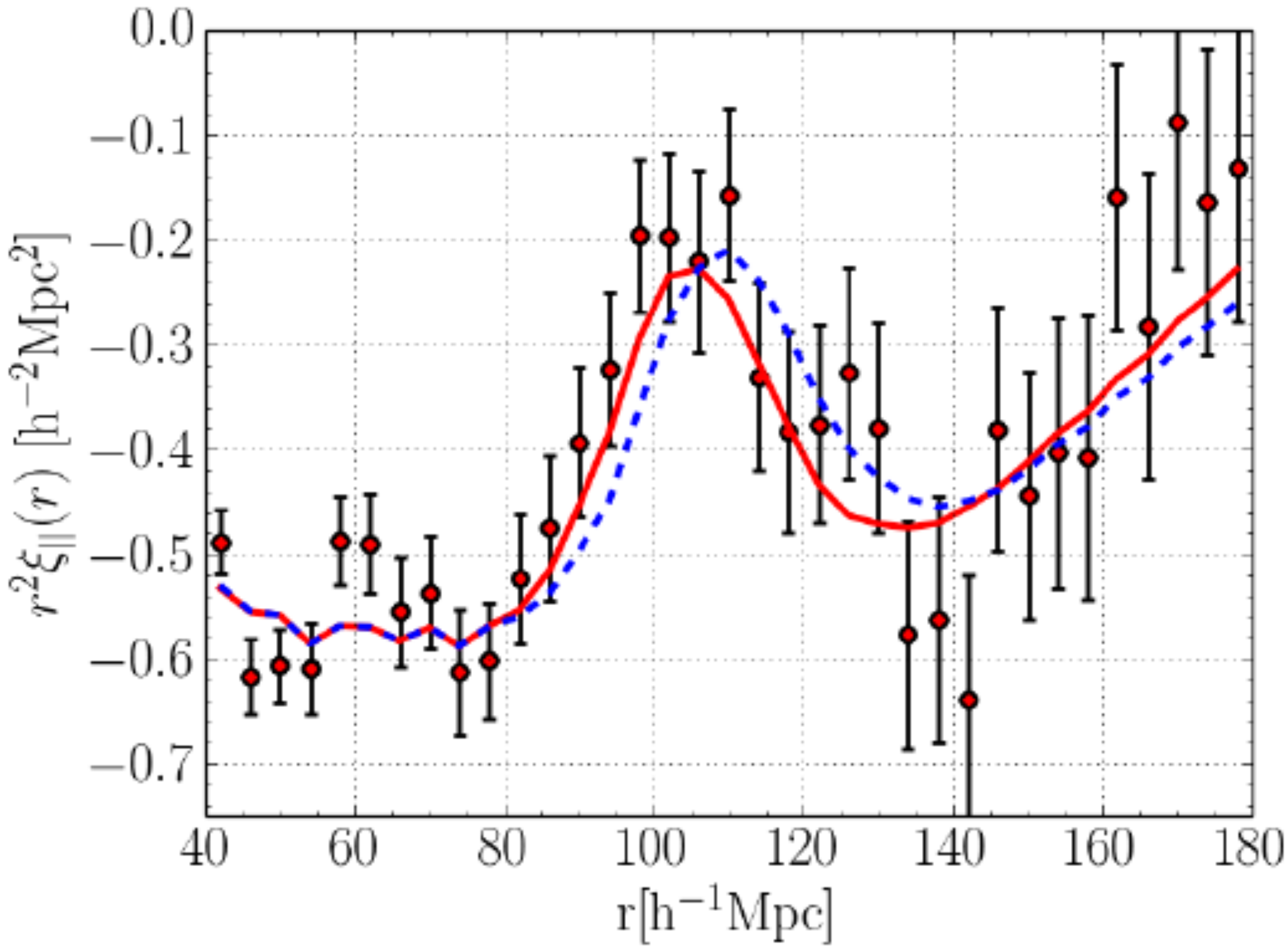
$$1\,\mathring{A} \sim 70\,\mathrm{km\,s^{-1}} \sim 0.7\,h^{-1}\,\mathrm{Mpc}$$



First year of BOSS data
(Slosar, Font-Ribera et al. 2011)

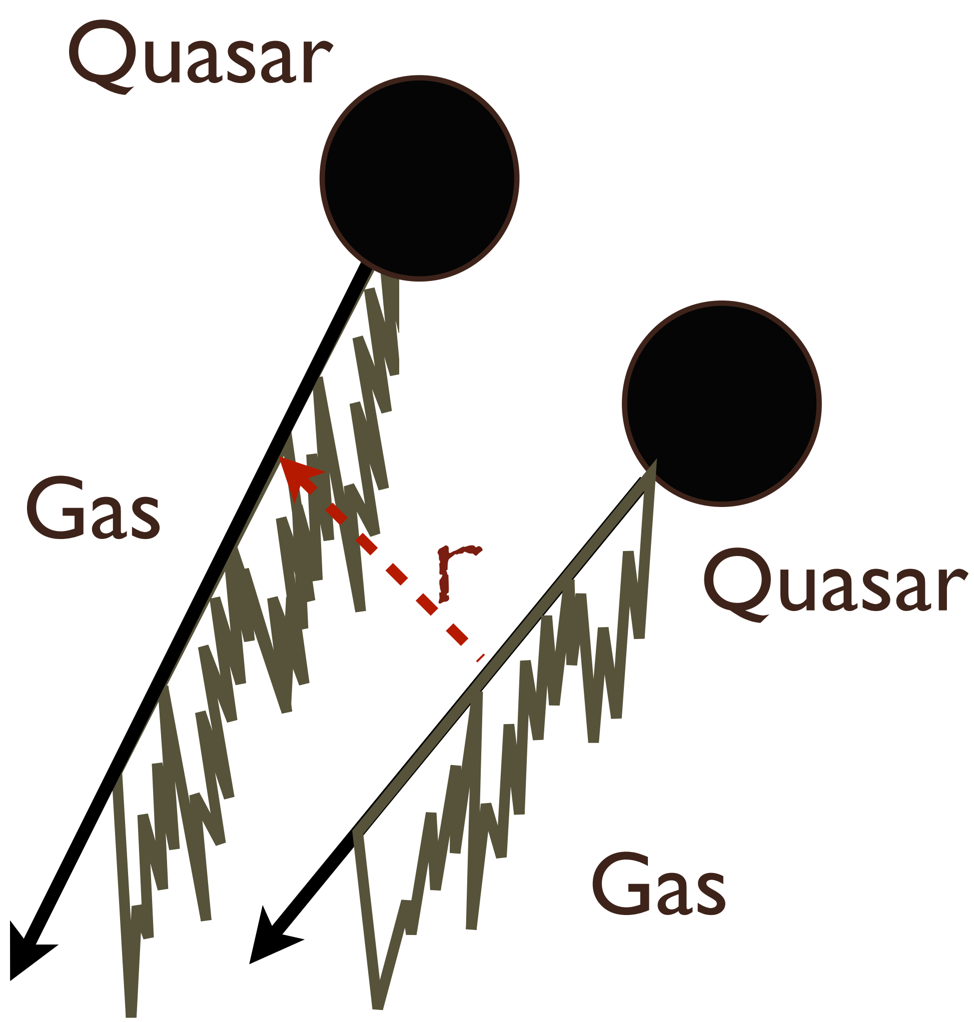
BOSS Lyman-α BAO

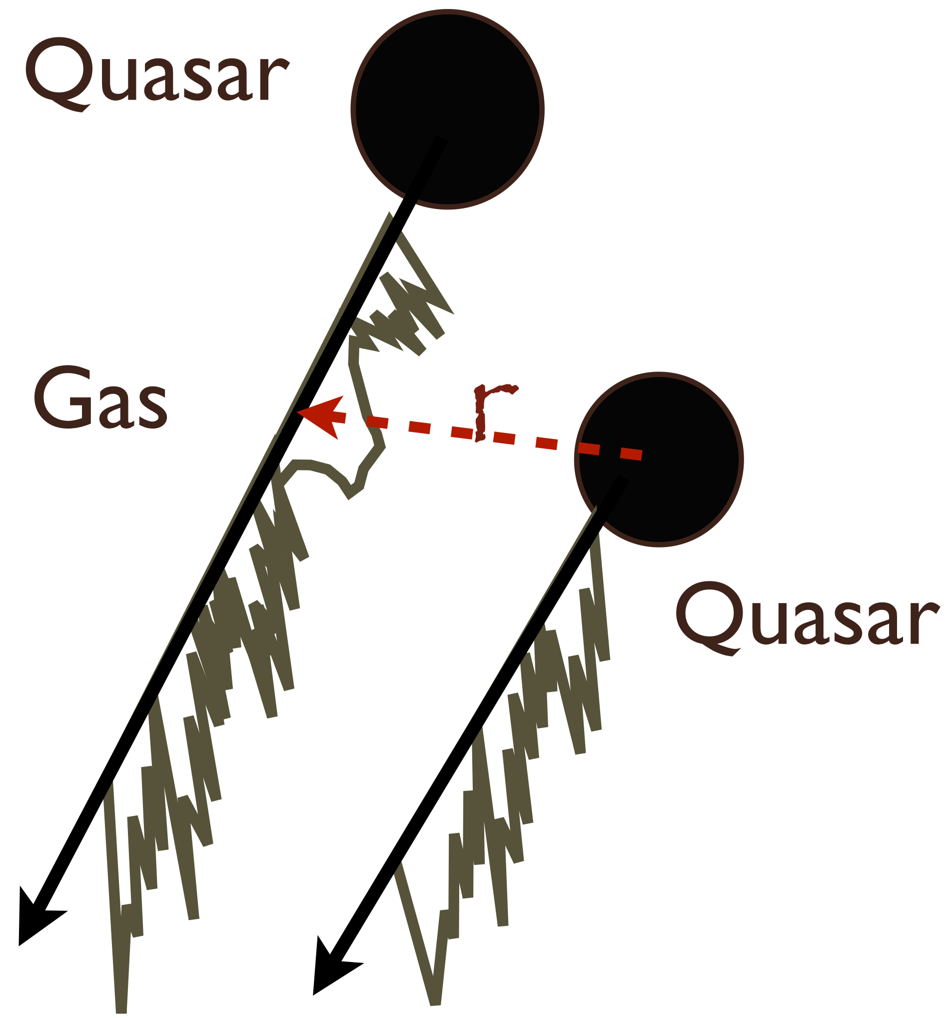
Few years later: BAO clearly detected in the correlation function!



BOSS Lyman-α BAO

Two independent ways of measuring the BAO scale



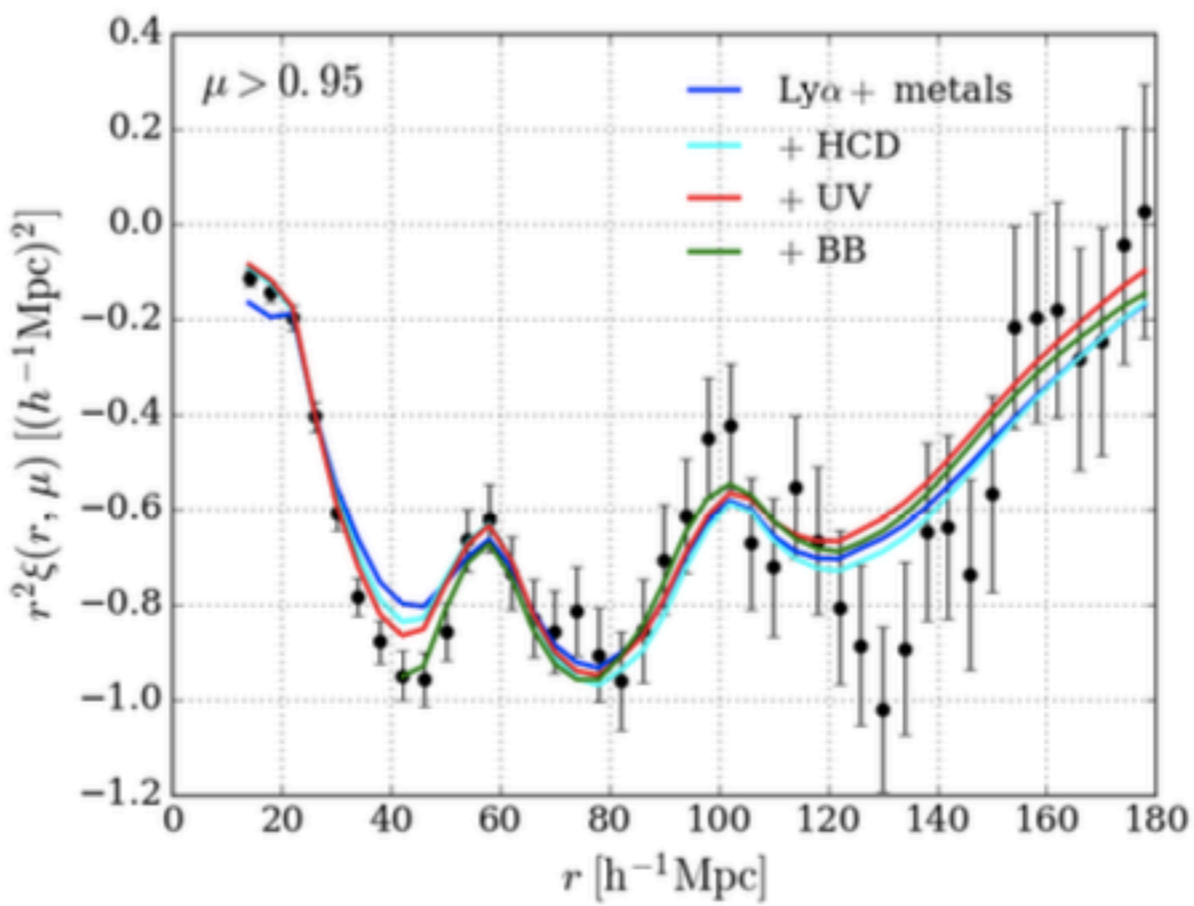


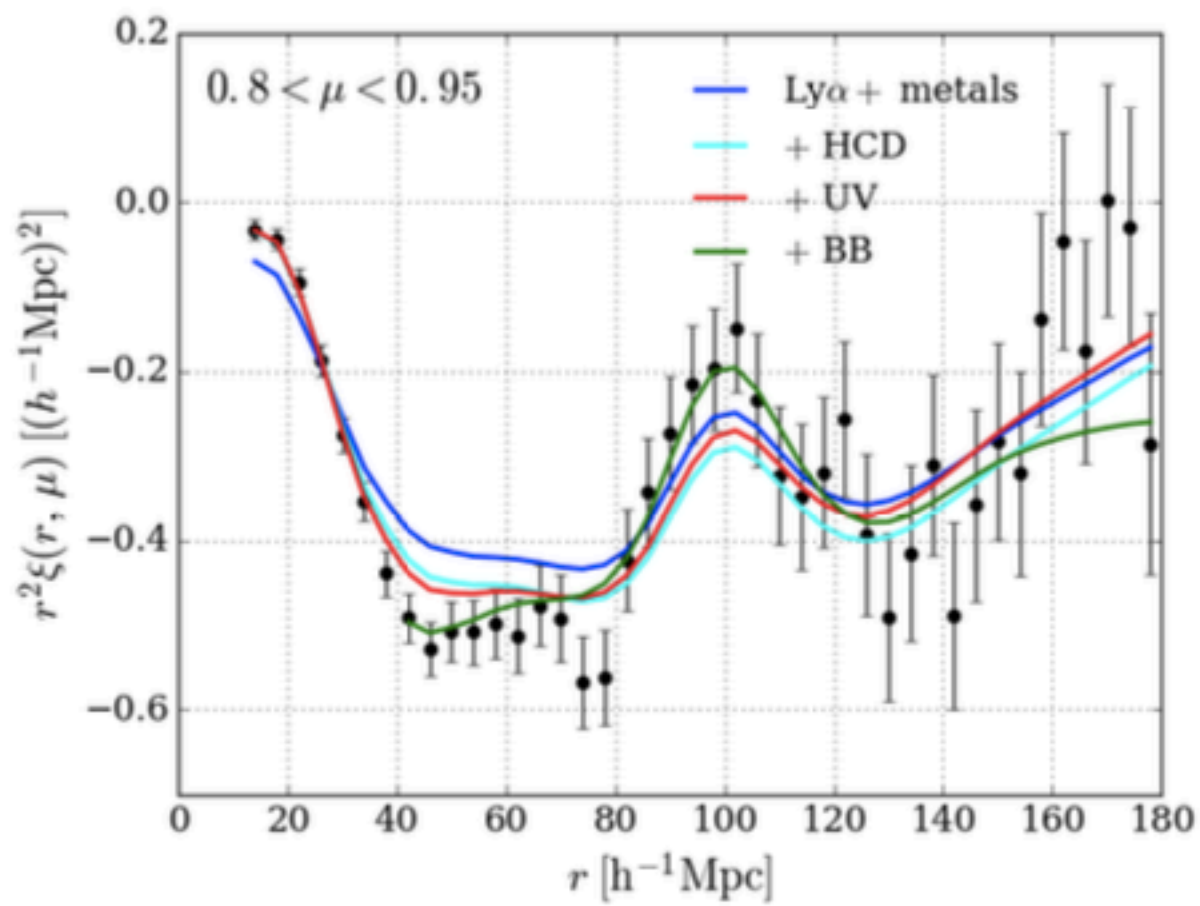
Delubac et al. (2015)	—— DR11 ——	Font-Ribera et al. (2014)
Bautista et al. (2017)	—— DR12 ——	du Mas des Bourboux (2017)

Lya auto-BAO

Julian Bautista
(Moving from Utah
to Portsmouth)

Bautista et al 2017
BAO from DR12
Lya auto-correlation



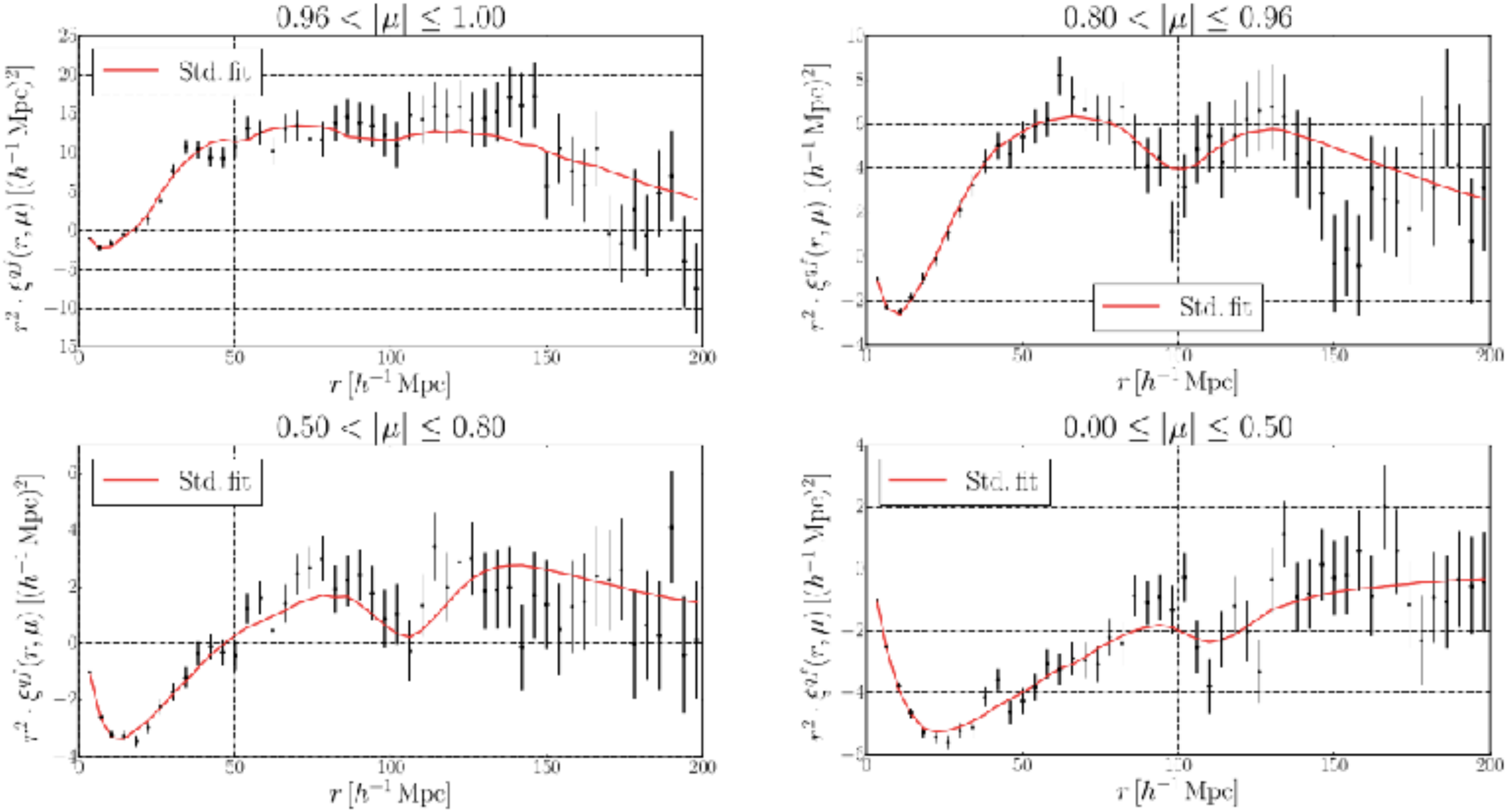


QSO-Lya cross-BAO

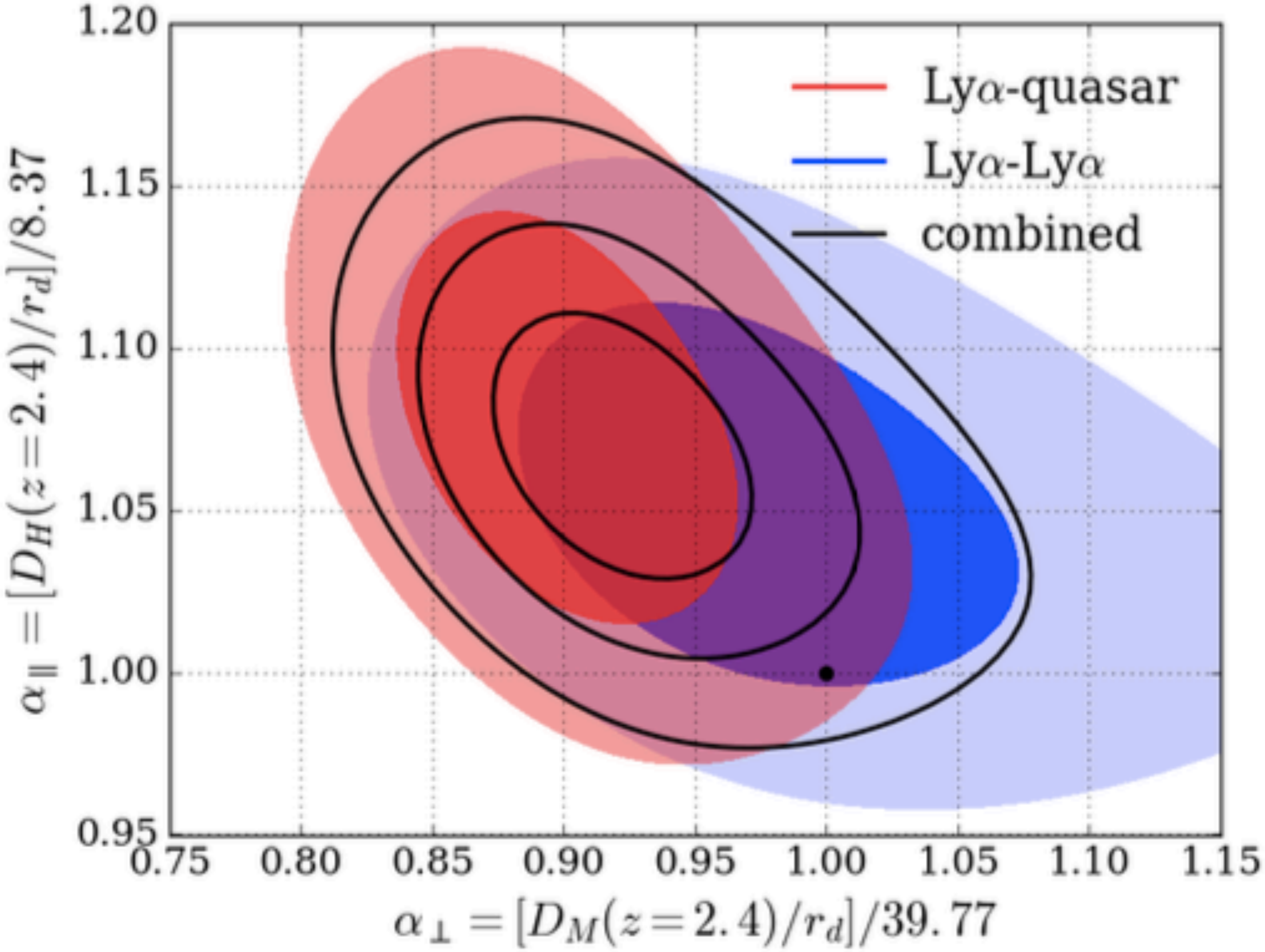
Helion du Mas des Bourboux
(Moving from Saclay to Utah)

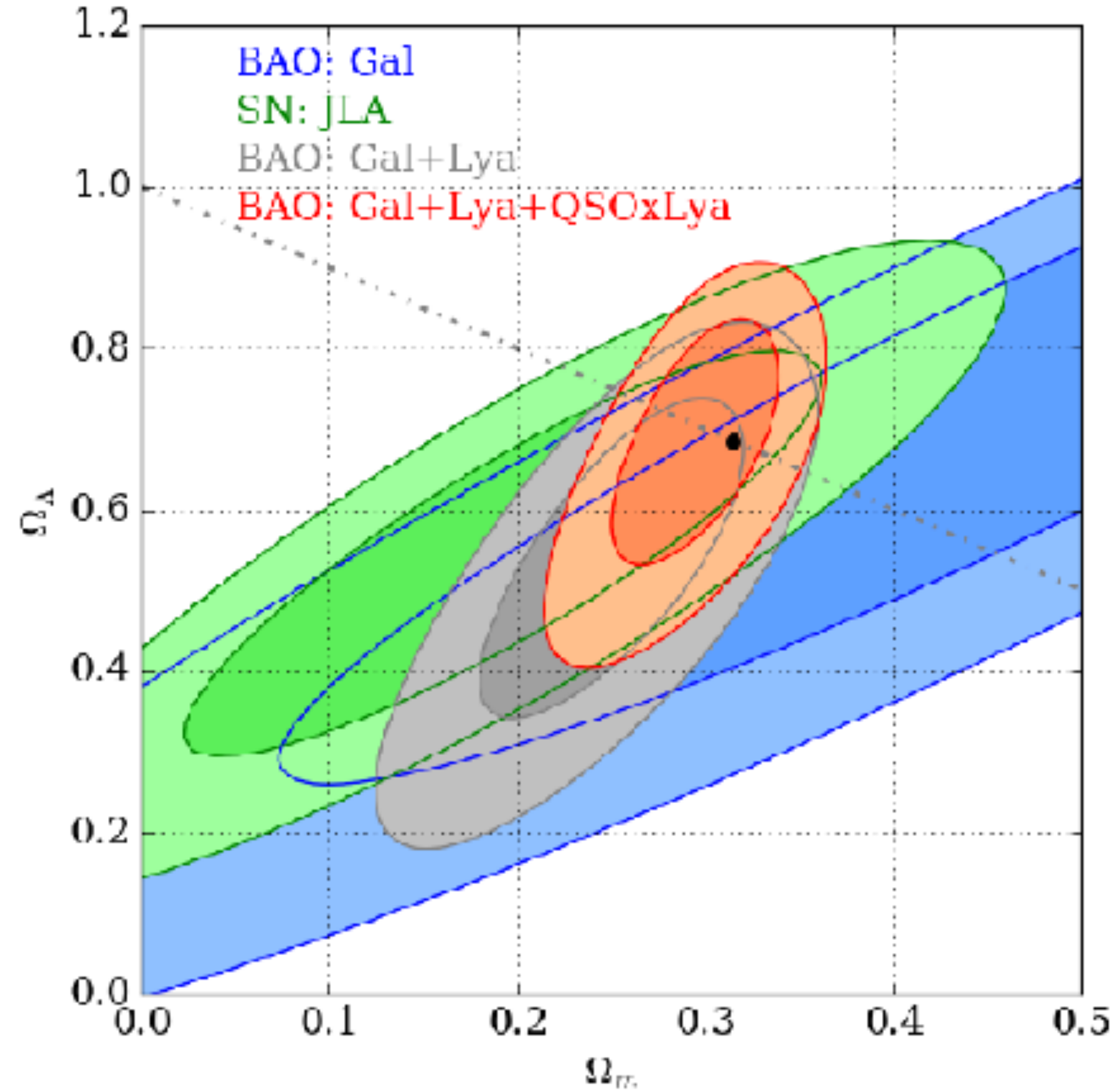
On arXiv today!

dMdB et al. 2017
BAO from DR12
Quasar-Lya cross



Combined BOSS BAO



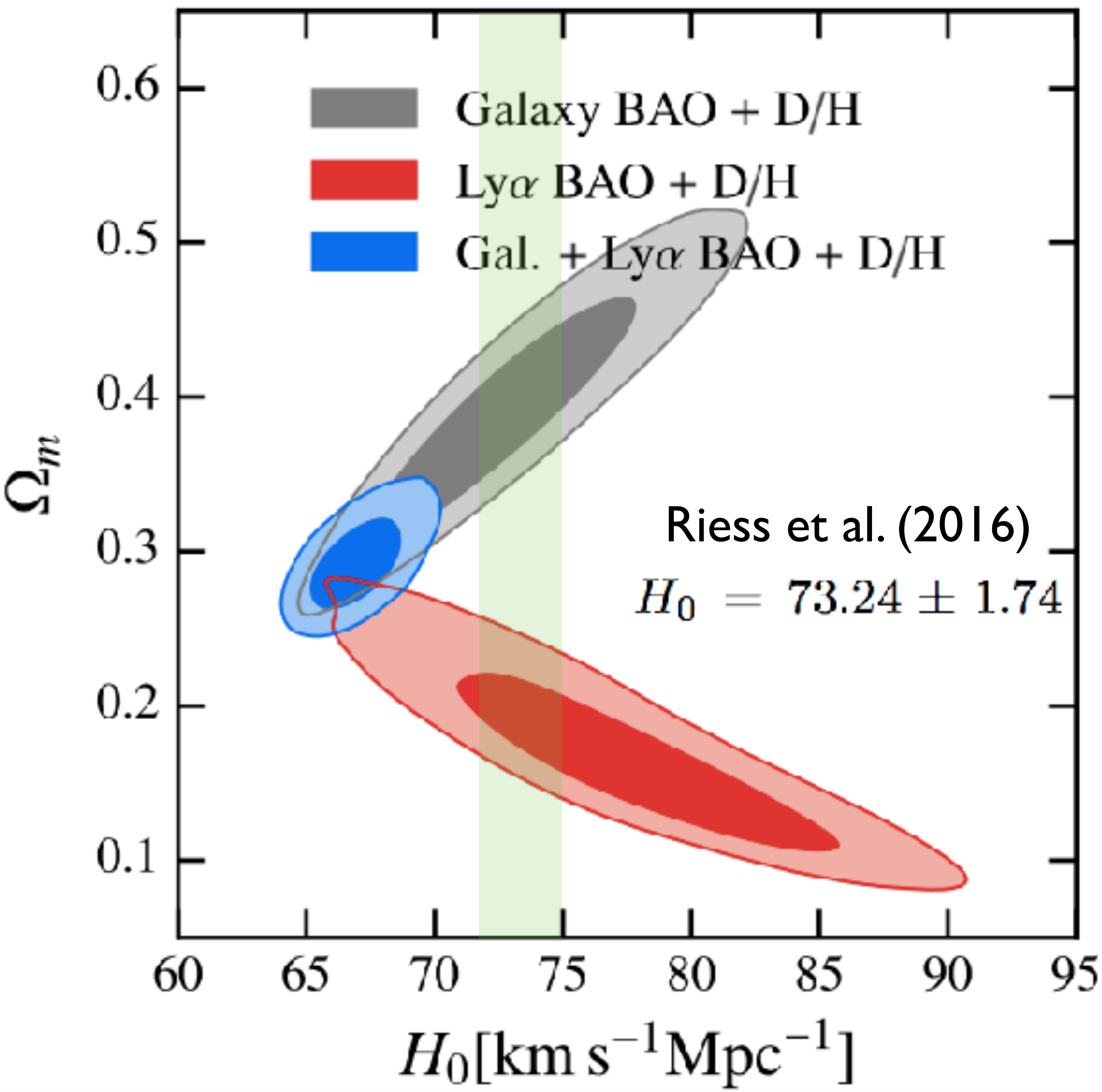


In a flat LCDM model

$$\Omega_m = 0.292 \pm 0.019$$ BAO

$$\Omega_m = 0.315 \pm 0.017$$ Planck

Combined BOSS BAO

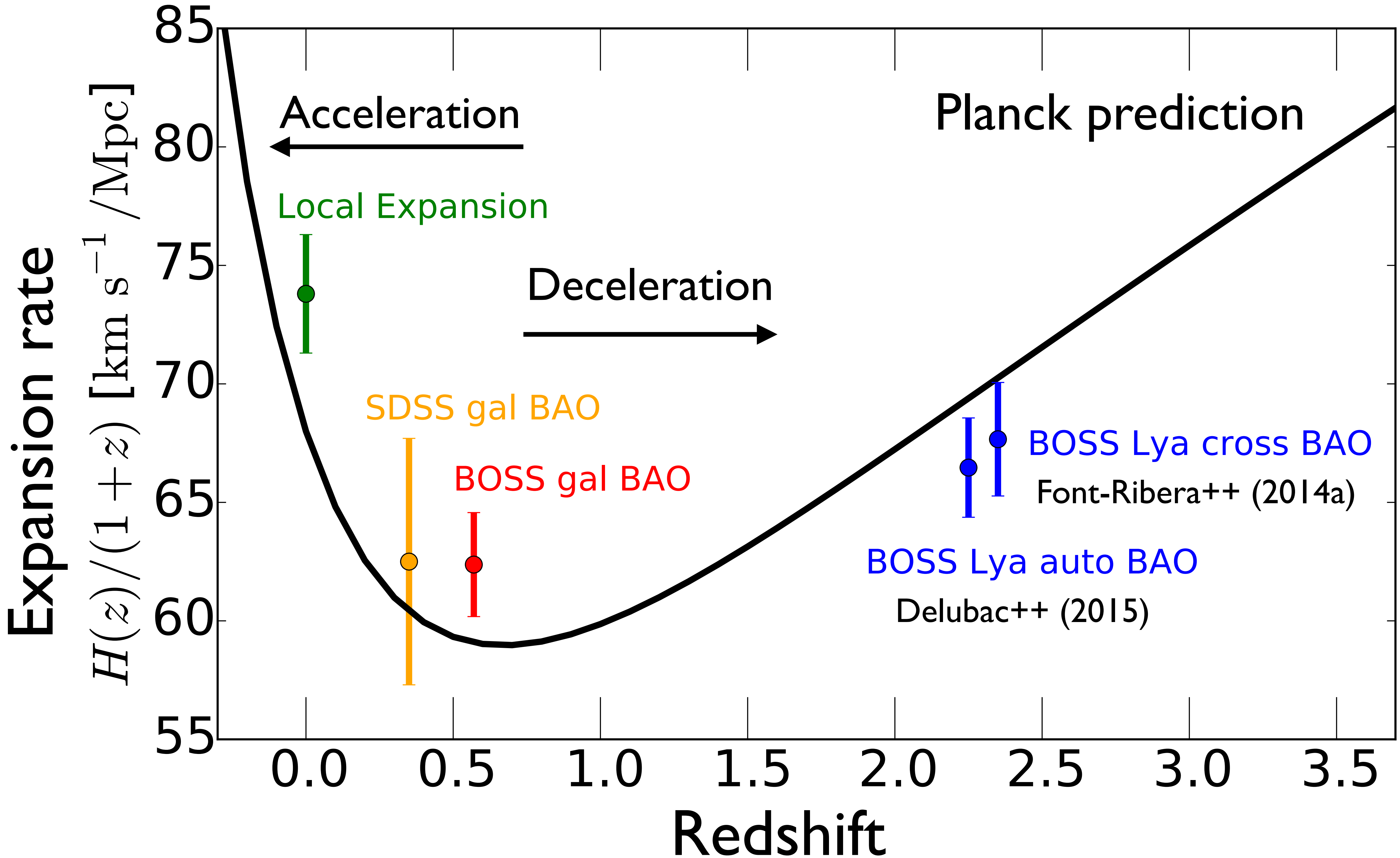


BBN + BAO find low value of H_0

Addison et al. (2017)

Figure 4. Adding an estimate of the baryon density, $\Omega_b h^2$, in this case from deuterium abundance (D/H) measurements, breaks the BAO $H_0 - r_d$ degeneracy in ΛCDM. The same contours are shown as in Figure 3, with the addition of a Gaussian prior $100\Omega_b h^2 = 2.156 \pm 0.020$ (Cooke et al. 2016). In contrast to Figure 3, here Ω_m determines both the early time expansion, including the absolute sound horizon, r_d, as well as the late-time expansion history. The radiation density is fixed from *COBE*/FIRAS CMB mean temperature measurements. The combined BAO+D/H constraint, $H_0 = 66.98 \pm 1.18$ km s^{-1} Mpc^{-1} is 3.0σ lower than the Riess et al. (2016) distance ladder determination and is independent of CMB anisotropy data.

BOSS Lyman-α BAO

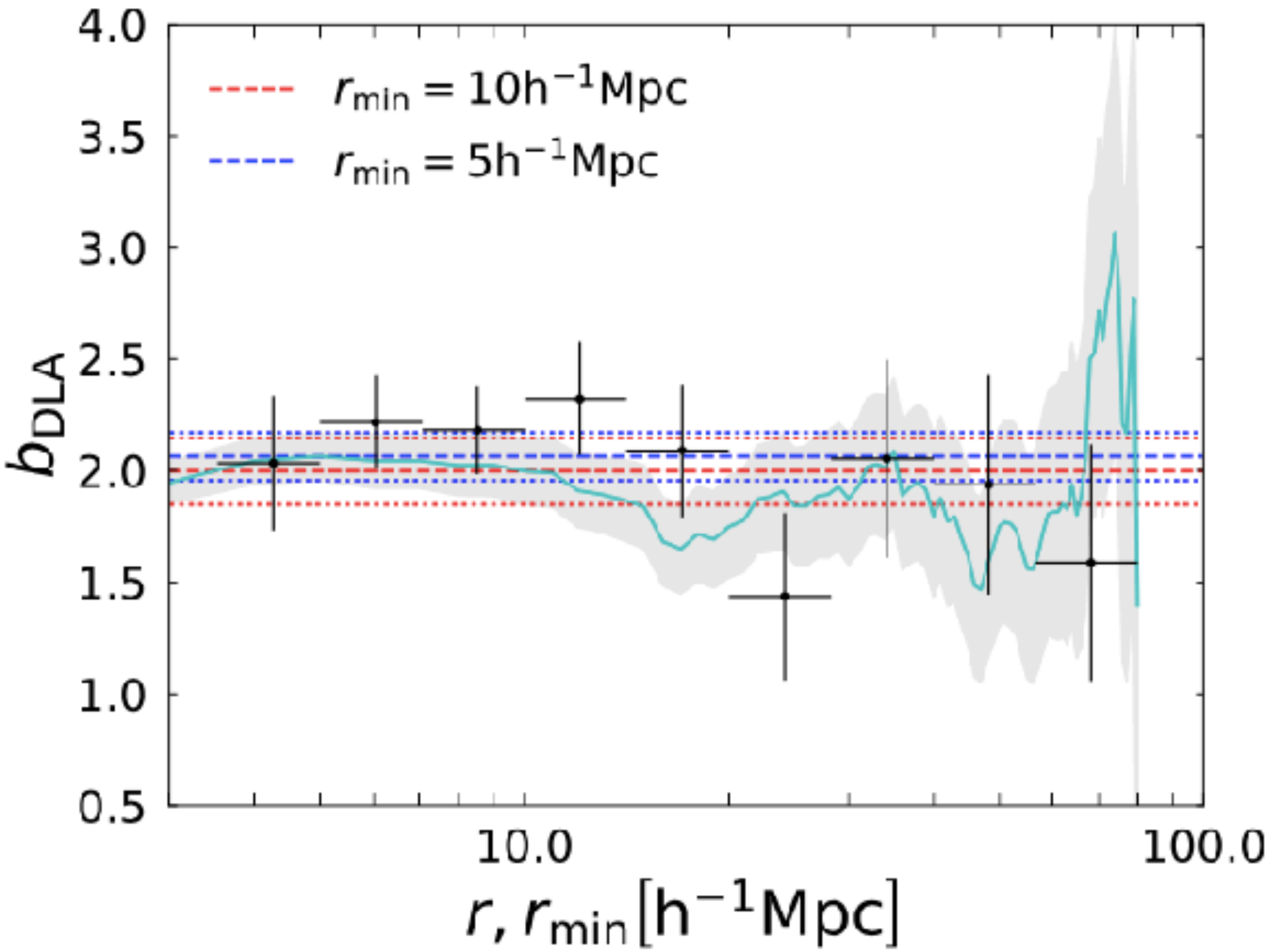


DLA-Lya cross-correlation

Ignasi Pérez-Ràfols
(moving from Barcelona
to Marseille)

Sent to MNRAS today!

Pérez-Ràfols et al 2017
DLA bias from DR12
DLA-Lya cross



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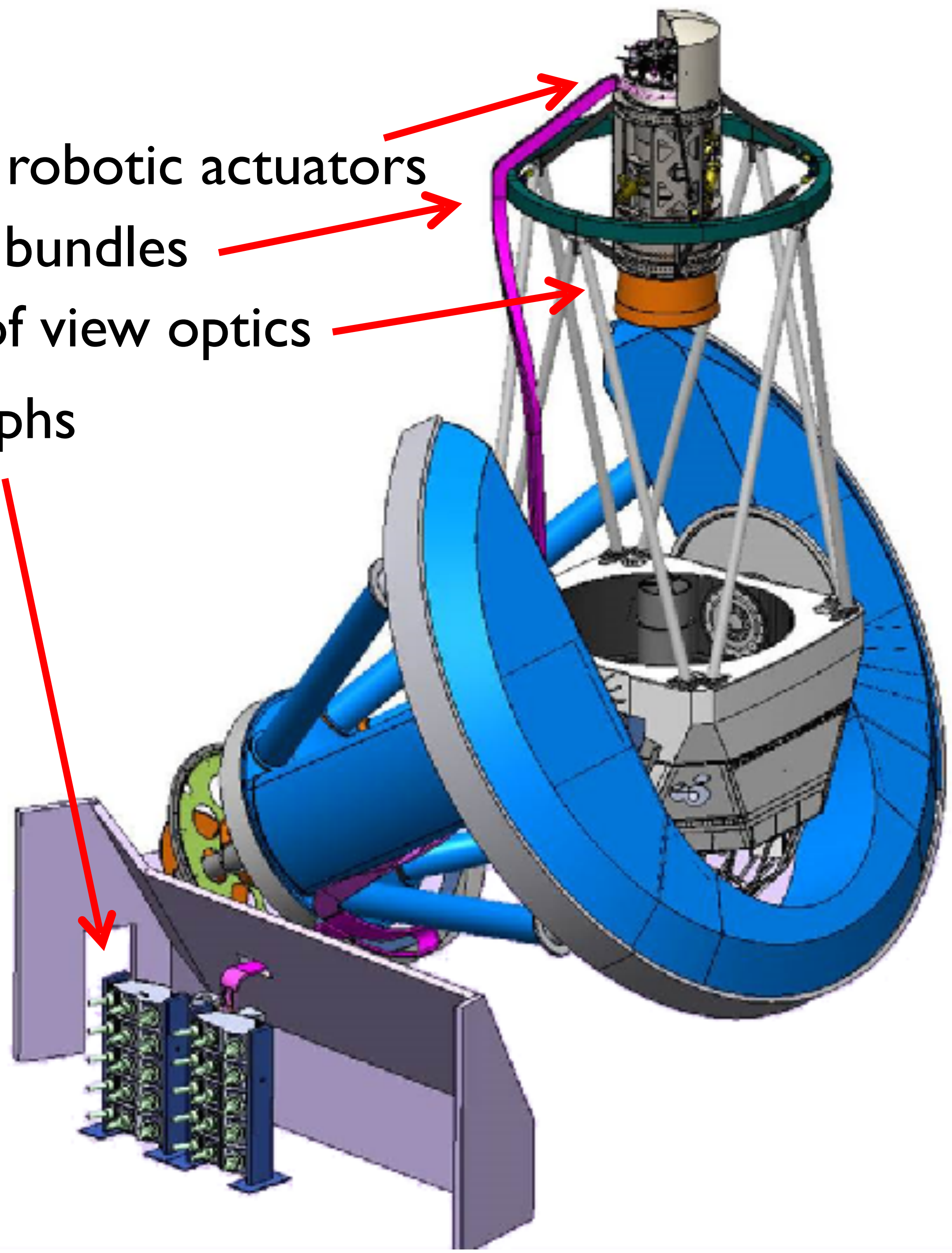
Dark Energy Spectroscopic Instrument

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



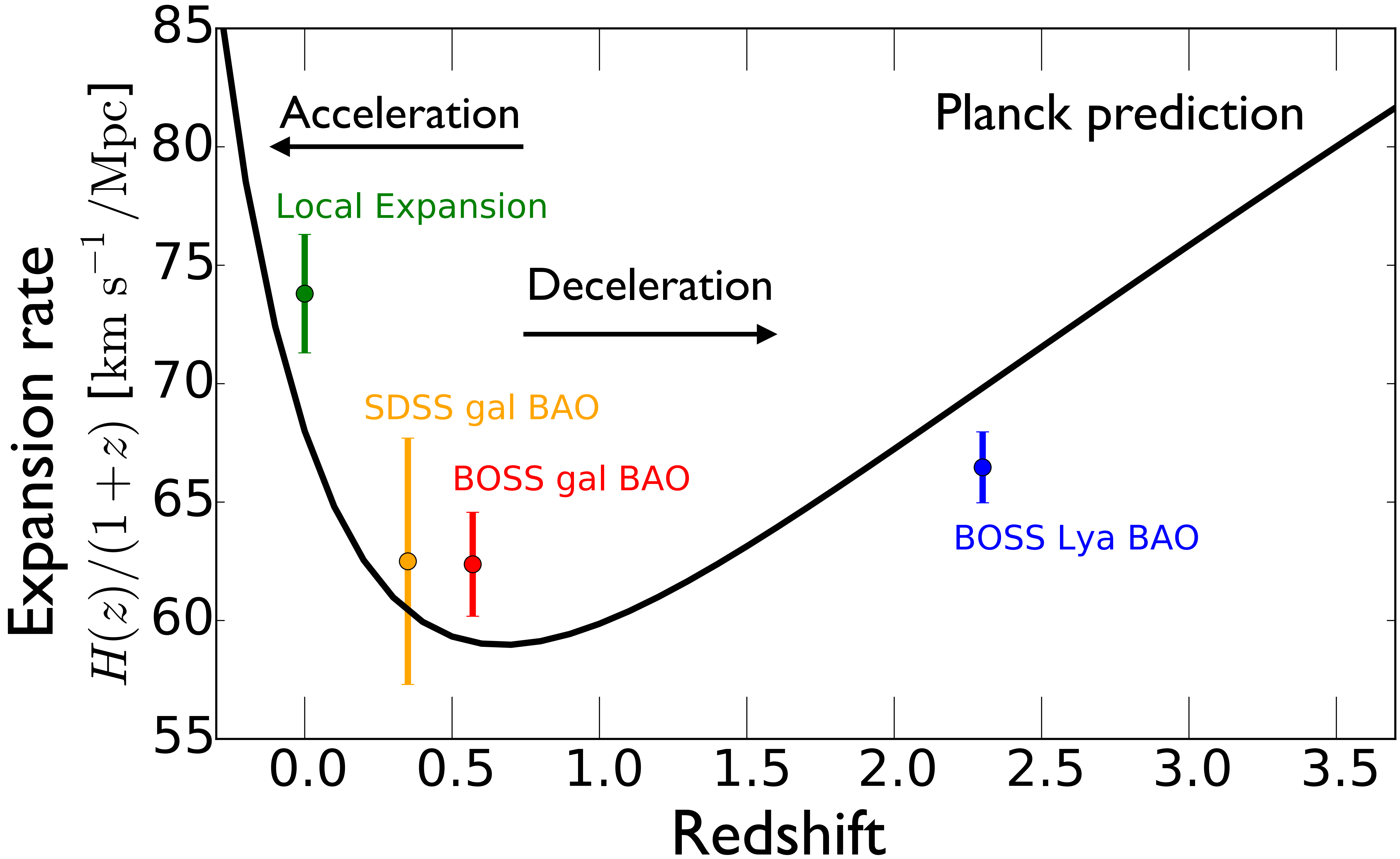
Readout
& Control

Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS dataset by an order of magnitude

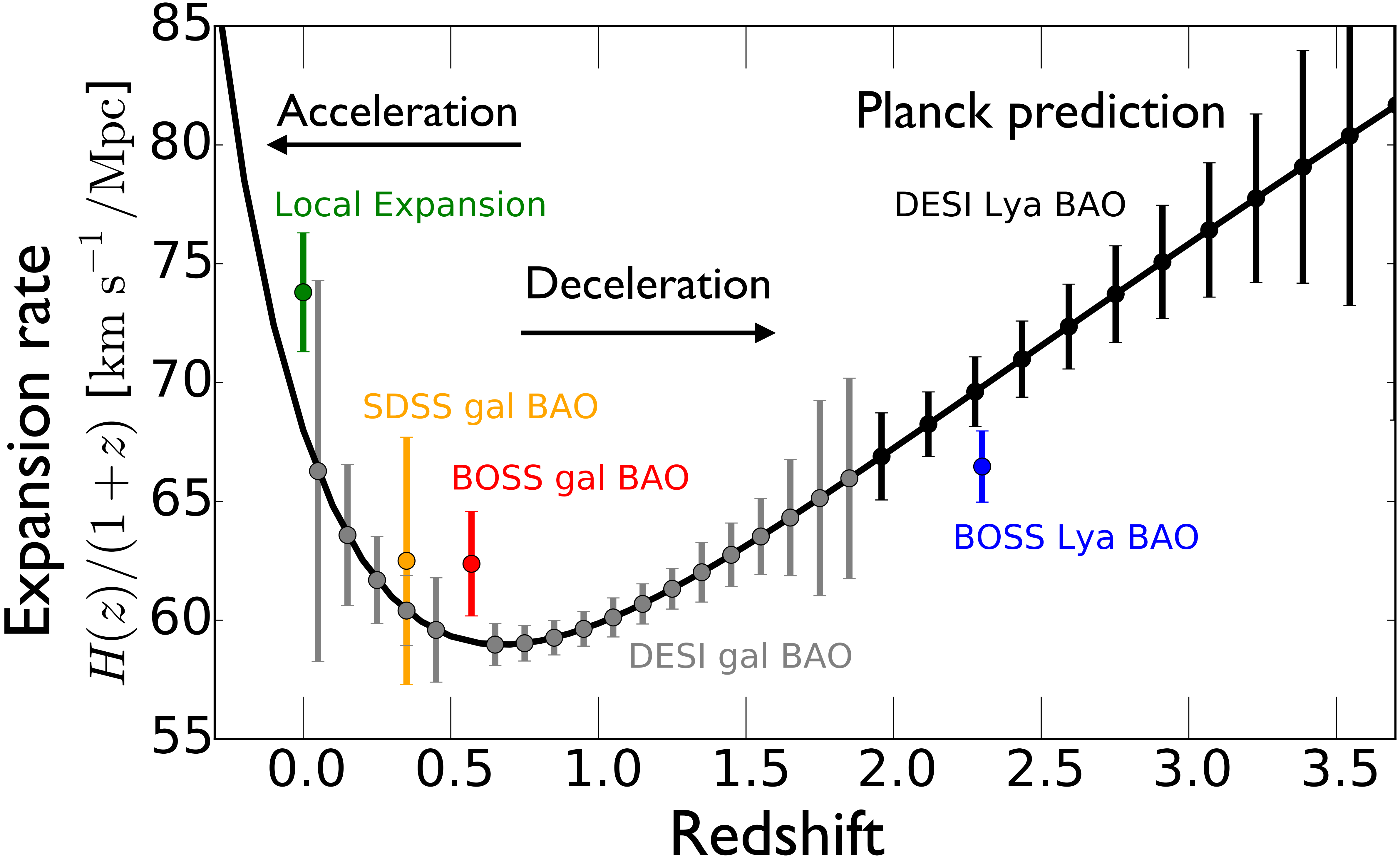
Scheduled to start in 2019

Dark Energy Spectroscopic Instrument



Dark Energy Spectroscopic Instrument

DESI projections (Font-Ribera++ 2014b)



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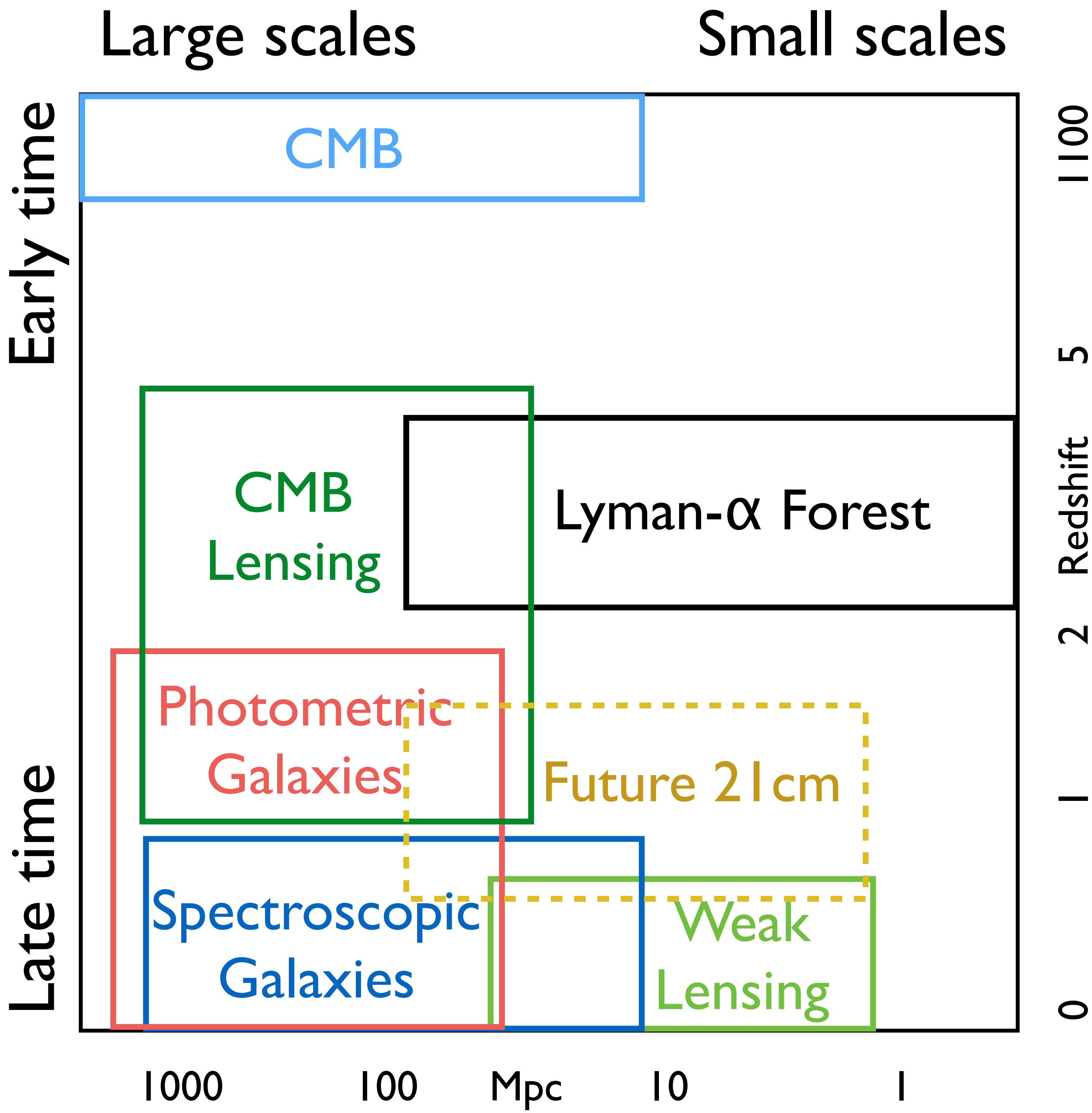
Small scale clustering



Lyman-α forest offers a unique window to study small scale clustering

Combined with CMB, it allows us to study:

- shape of primordial P(k)
- dark matter properties
- neutrino mass

Estimating the 3D P(k)

An efficient algorithm for estimating the 3D Lyα forest power spectrum

Andreu Font-Ribera [a,1,†] Patrick McDonald,[2,‡] and Anže Slosar[3,§]

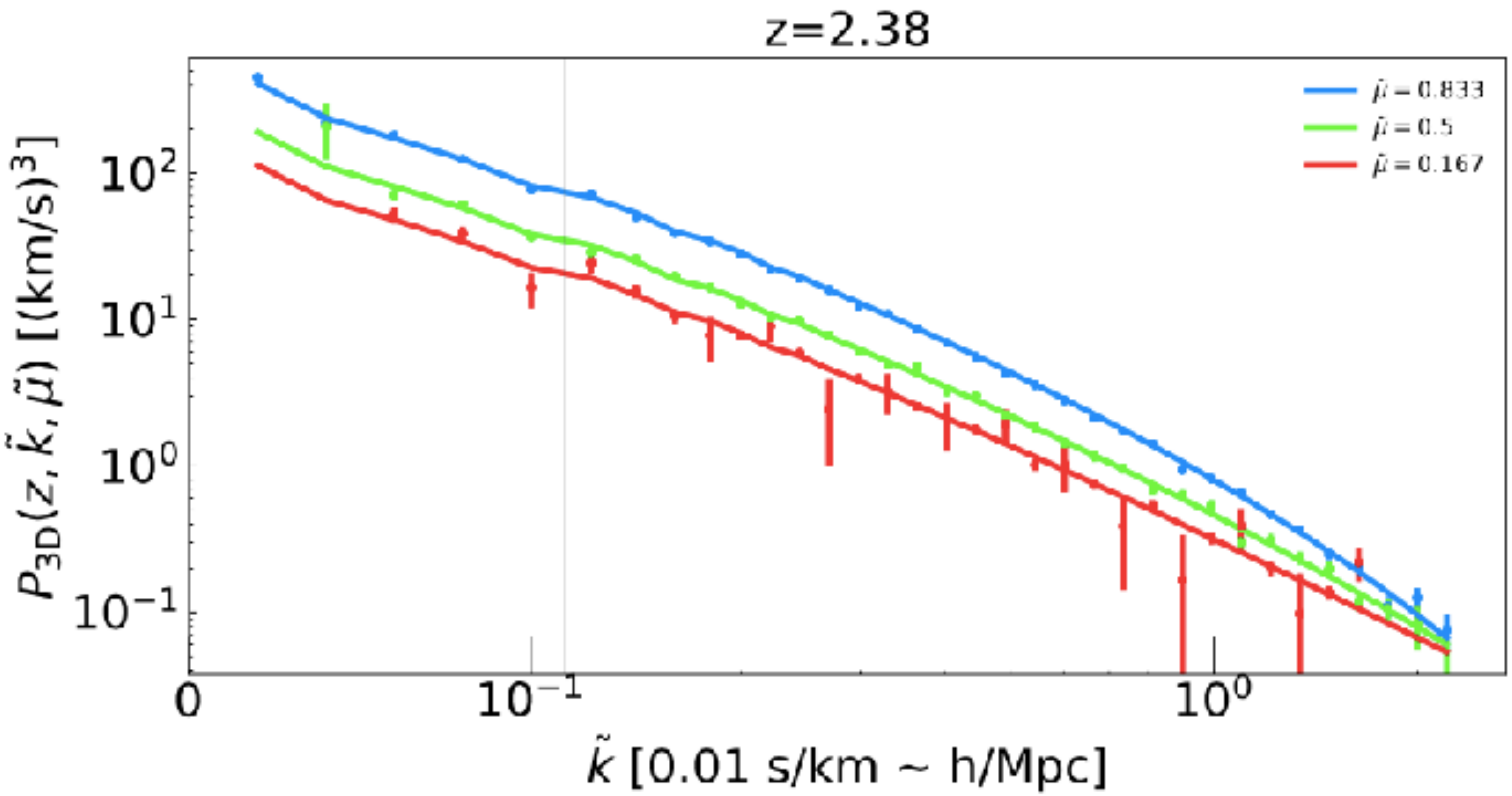


FIG. 10. Measured $P_{3D}(z, \tilde{k}, \tilde{\mu})$ as a function of wavenumber $\tilde{k}$, for different angular directions $\tilde{\mu}$. Measurement from 40 synthetic realizations of the BOSS survey. The solid lines show the input theory used to generate the mocks. The wavenumbers in the x-axis have been multiplied by 100 so they can be approximately compared to wavenumbers in units of $h\mathrm{Mpc}^{-1}$. The vertical line divides the linearly spaced bins (to the left) from the logarithmically spaced bins (to the right).

Primordial power spectrum

Inflationary models predict nearly scale-invariant primordial fluctuations

$$P_{\rm prim}(k) \propto (k/k_0)^{n_s + \frac{1}{2}\alpha_s \ln(k/k_0)}$$

Slow-roll models of inflation predict non-zero running:

$$\alpha_s \sim (1-n_s)^2 > 0$$

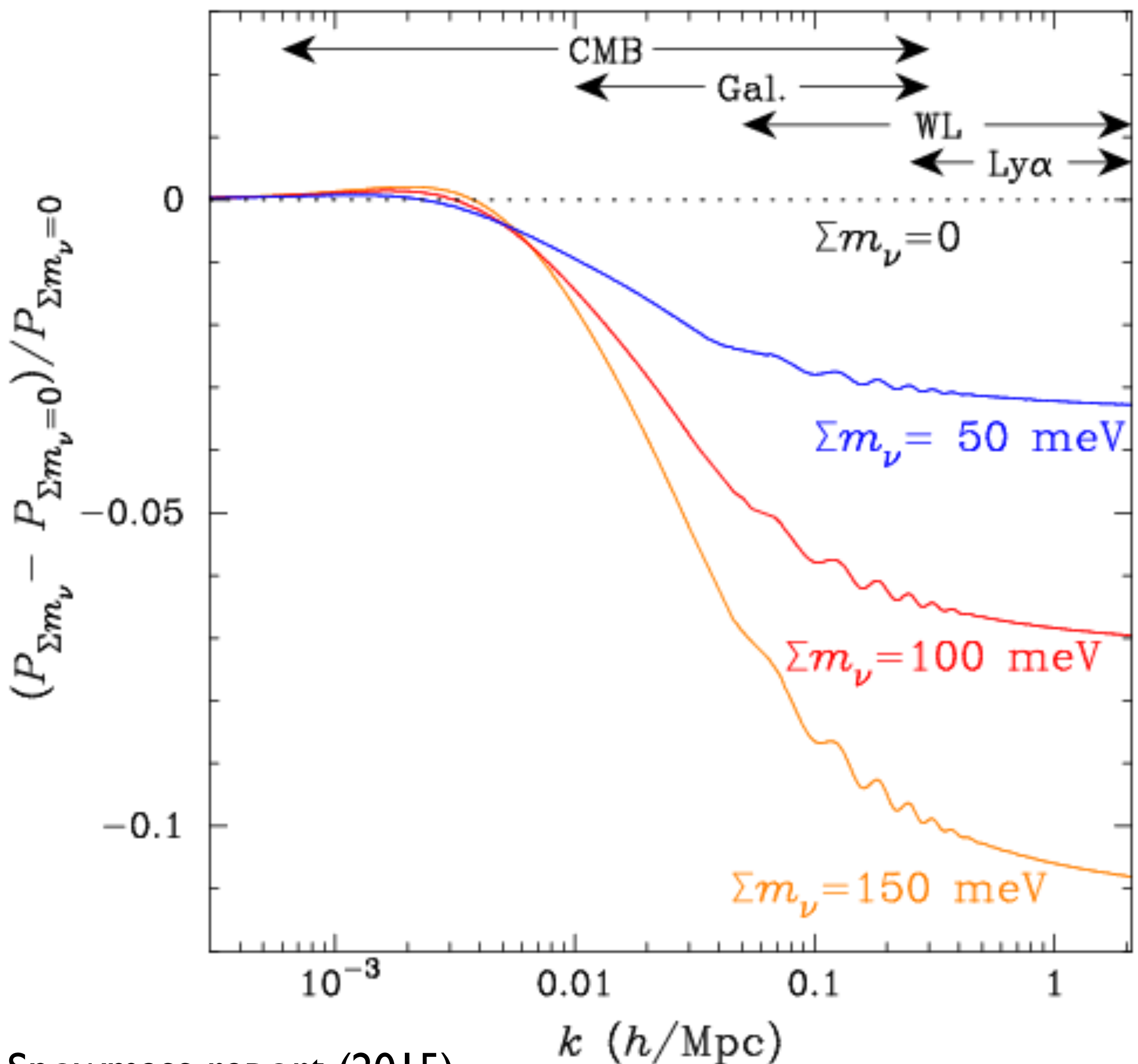
Is there a non-zero running?

Are there deviations from a power law?

CMB experiments (Planck) measure very accurately the clustering on large scales

Lyman-α forest provides unique window to linear power on very small scales

Neutrino Mass



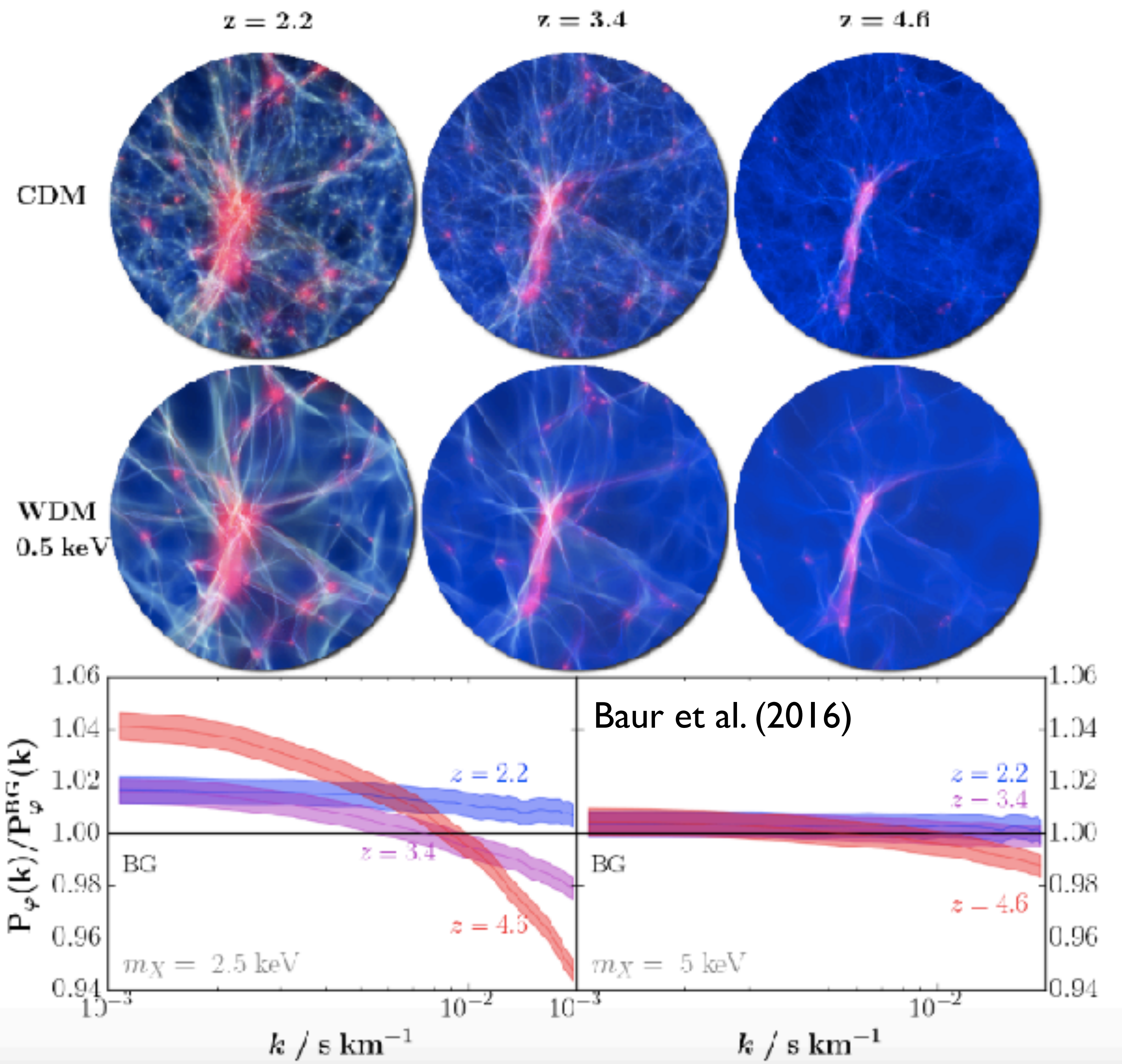
Snowmass report (2015)

Massive neutrinos are hot dark matter, do not cluster on small scales

Comparing the power on large and small scales we can constraint neutrino masses

Best constraints from Planck + BOSS Lyα
$\Sigma m_\nu < 0.12$ eV (95%)
(Palanque-Delabrouille++ 2015)

Small scale clustering



Some argue the so-called "small scale crisis" of CDM (missing satellites, cusp/core problem…) could be solve if dark matter was warm or fuzzy

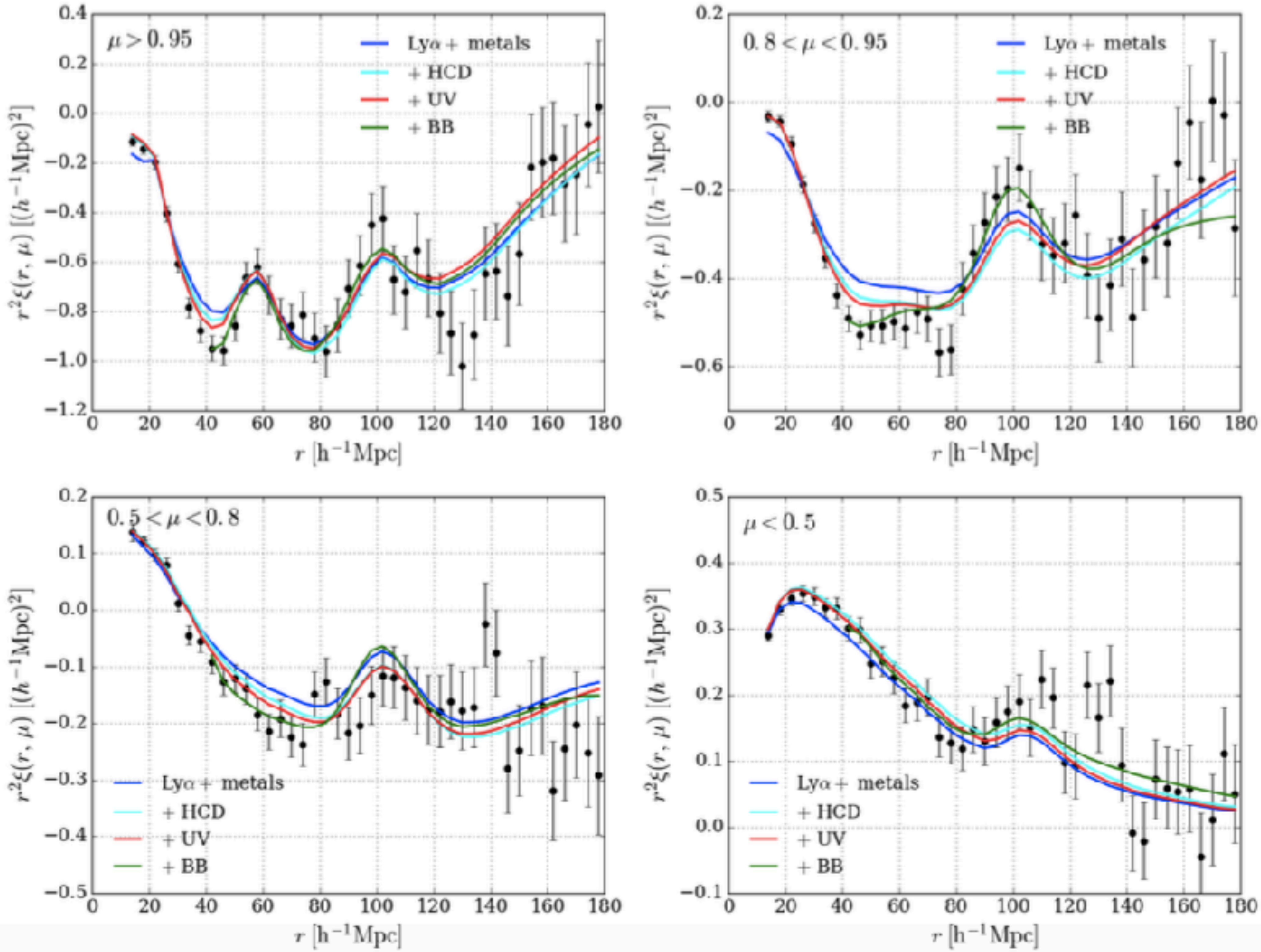
Warm or fuzzy dark matter would suppress power on smaller scales, and would also modify Lyα statistics

Summary

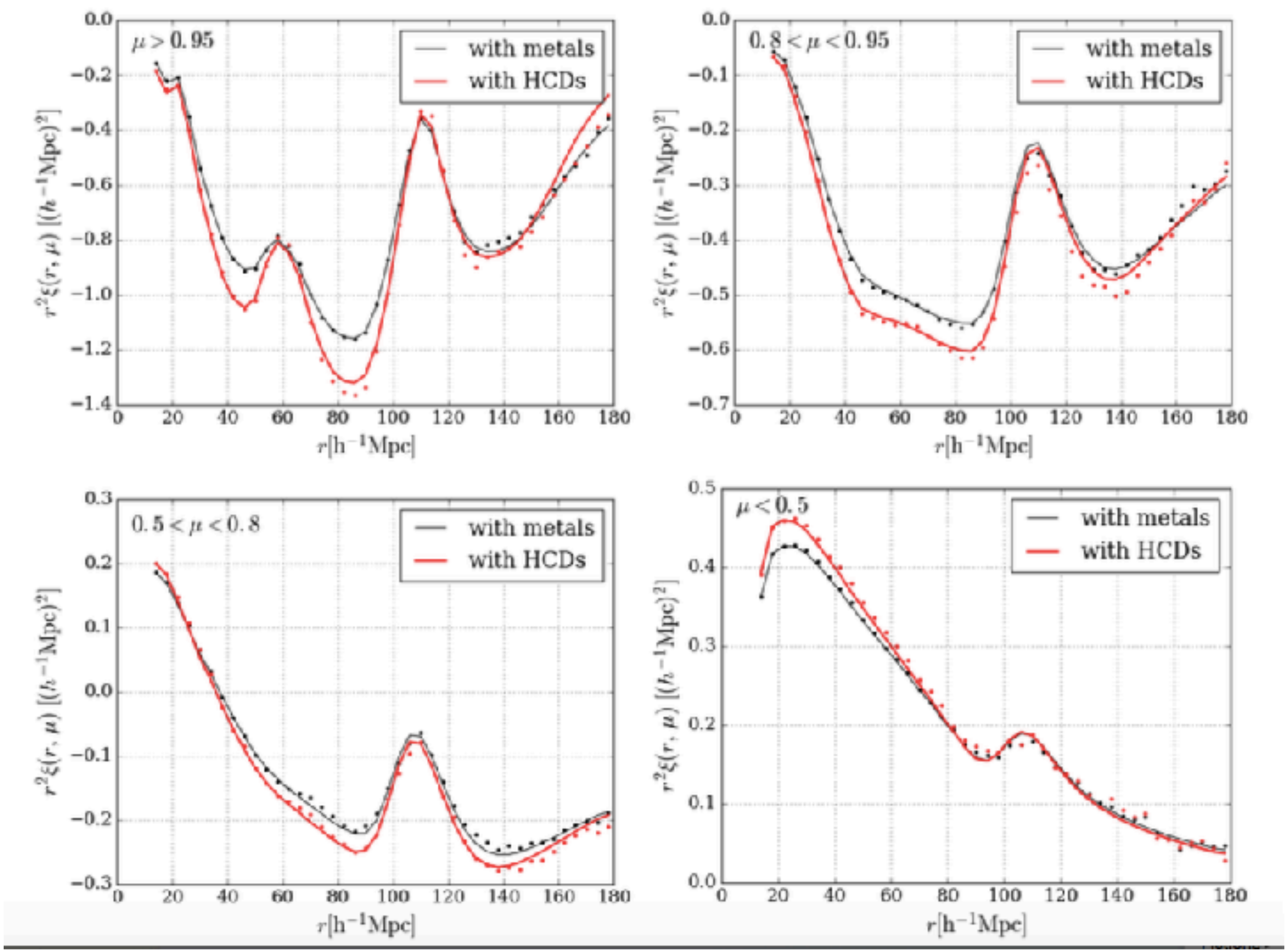
- BAO in BOSS: 1% measurement at z ~ 0.5 (galaxies) and 2% measurement at z~2.3 (quasars and the Lyman-α forest)
- BOSS Ly-α showed the forest is ready for precision cosmology
- DESI will be an order of magnitude jump in precision, but it will also explore uncharted territory (in z and in k)
- Ly-α forest also offers a unique window to small scales (warm dark matter, neutrino mass, primordial power…)

Extra slides

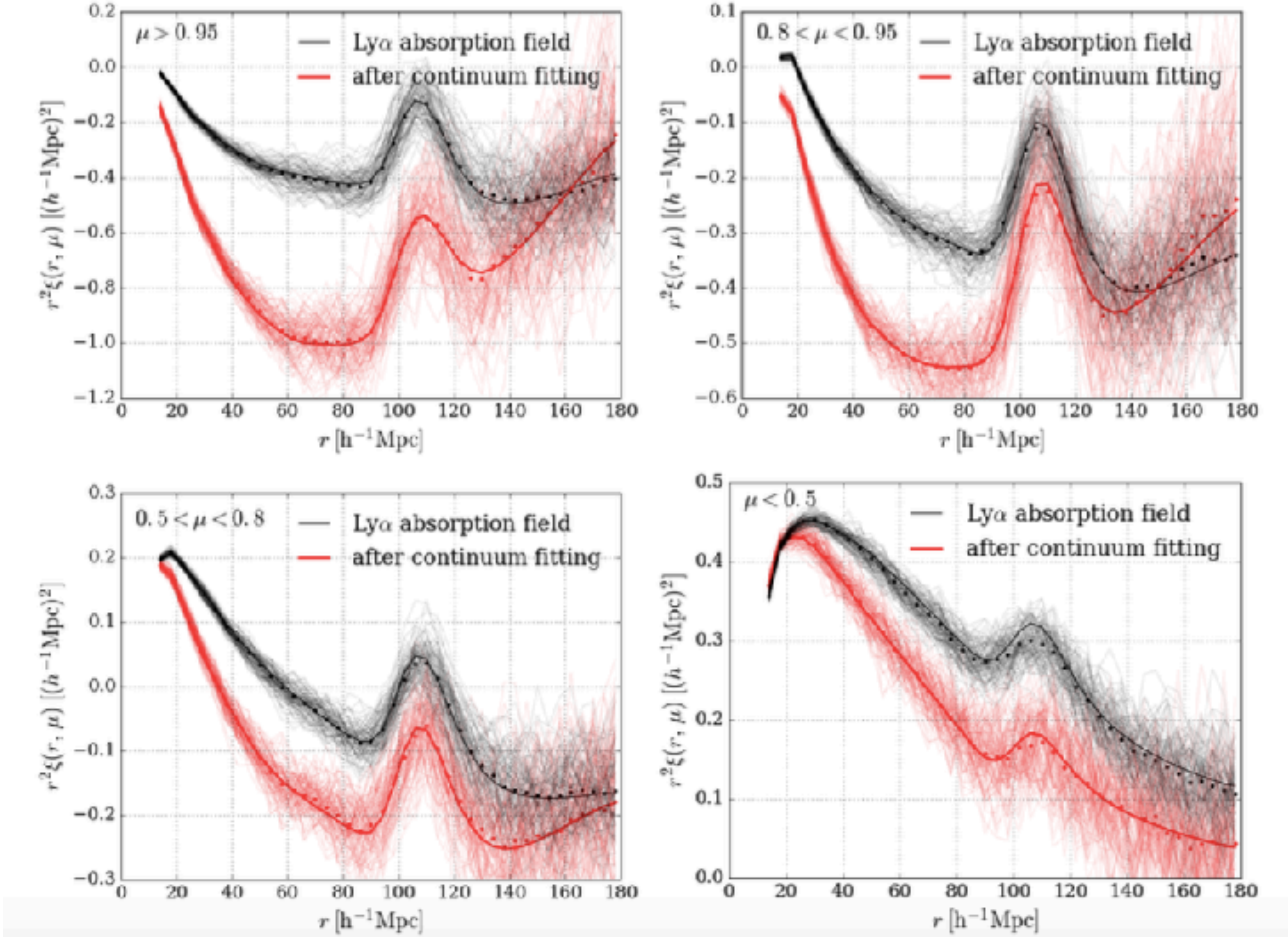
Bautista et al. 2017



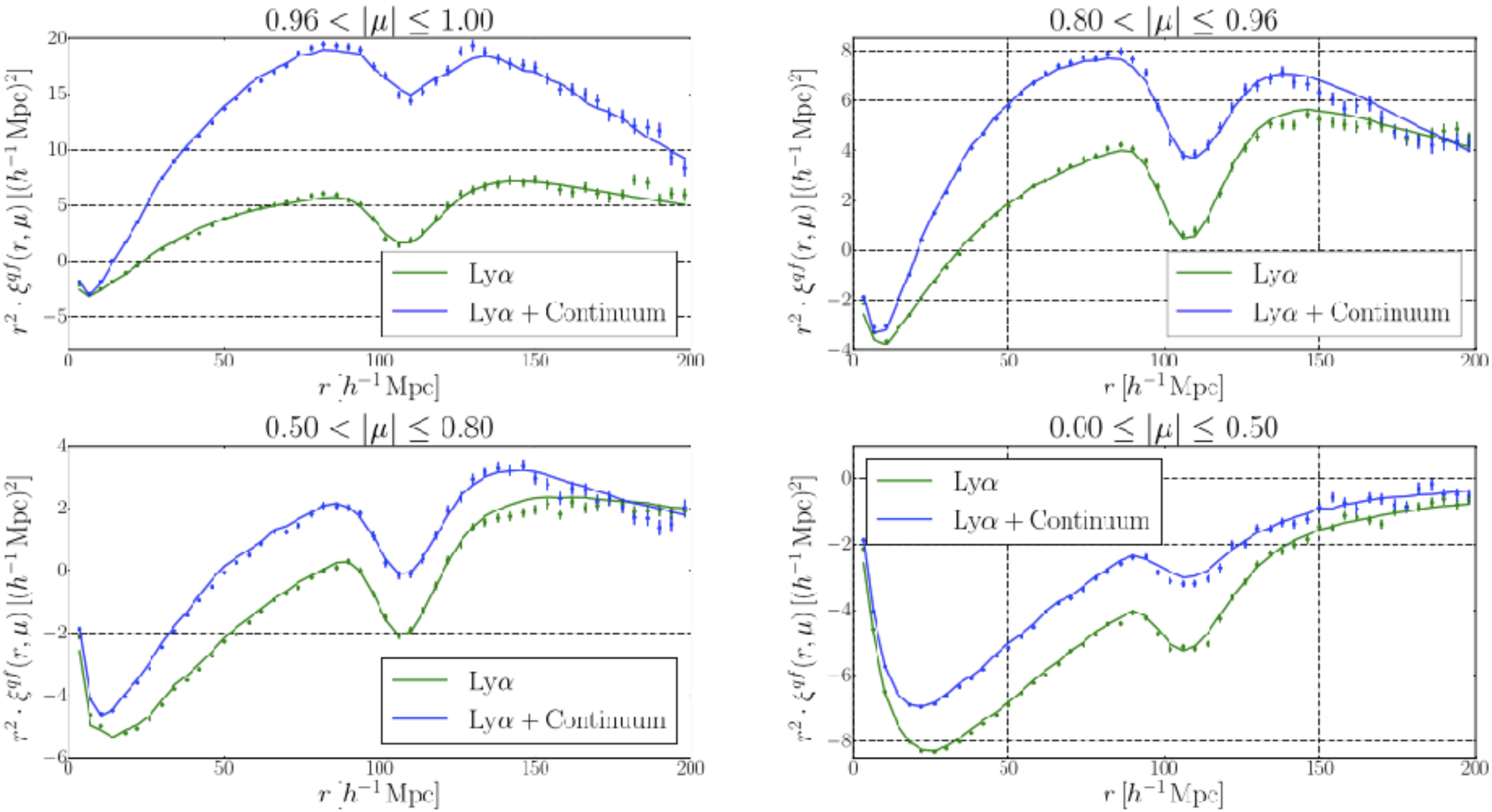
Bautista et al. 2017



Bautista et al. 2017



du Mas des Bourboux et al 2017



Forecasts

Just like galaxies, the forest is a tracer of the density field

Galaxy clustering

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

$$\sigma_g^2(\mathbf{k}) = 2 \left(P_g(\mathbf{k}) + n_g^{-1}\right)^2$$

Forest clustering

$$P_F(\mathbf{k}) = b_F^2 \left(1 + \beta_F \mu_k^2\right)^2 \; P(k)$$

$$\sigma_F^2(\mathbf{k}) = 2 \left(P_F(\mathbf{k}) + \frac{P^{1D}(k\mu) + P_N}{n_q^{2D}}\right)^2$$

Cross-correlation

$$P_{FQ}(\mathbf{k}) = b_F \; b_Q \left(1 + \beta_F \mu_k^2\right) \left(1 + \beta_Q \mu_k^2\right) \; P(k)$$

$$\sigma_{FQ}^2(\mathbf{k}) = P_{FQ}^2(\mathbf{k}) + \left(P_F(\mathbf{k}) + \frac{P^{1D}(k\mu) + P_N}{n_q^{2D}}\right) \left(P_Q(\mathbf{k}) + \frac{1}{n_q^{3D}}\right)$$

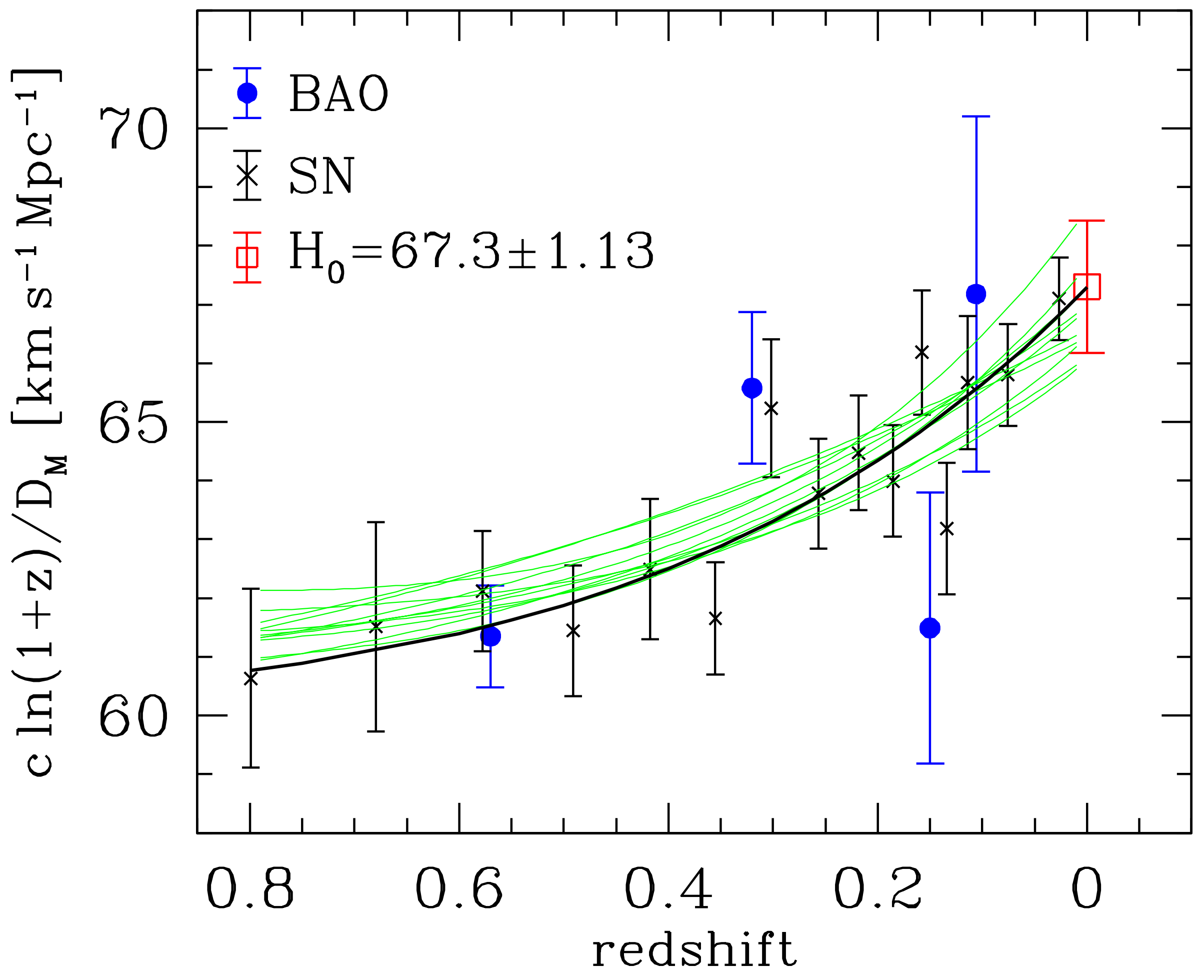
Shot noise

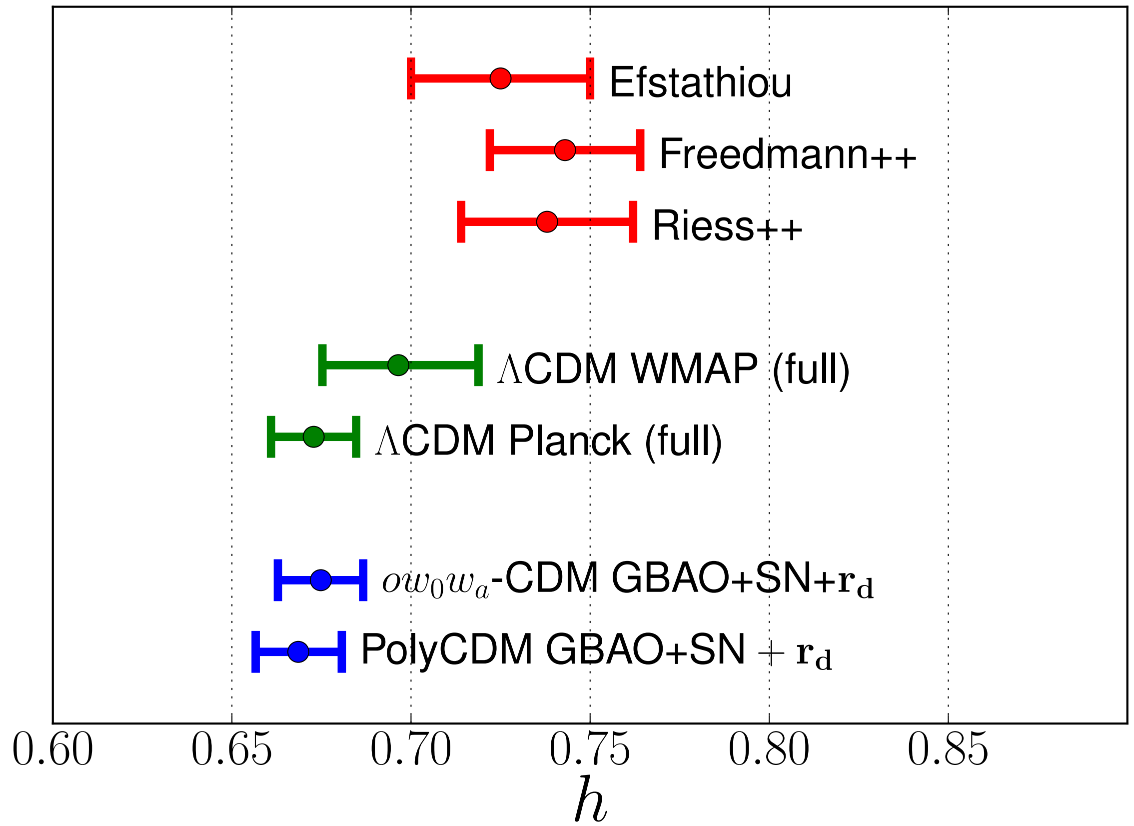
Cosmic variance

BOSS

SN measure relative distance between redshifts (from SNLS + SDSS-II, Betoule++ 2014)

Galaxy BAO measures absolute distance to intermediate redshifts





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

$$r_d \approx \frac{56.067 \exp\left[-49.7(\omega_\nu + 0.002)^2\right]}{\omega_{cb}^{0.2436}\,\omega_b^{0.128876}\left[1 + (N_{\rm eff} - 3.046)/30.60\right]}\ \mathrm{Mpc}$$

Somewhat sensitive to effective number of neutrino species!

Inflation: Initial Conditions

Inflationary models predict different primordial power spectrum

$$P_{\rm primordial}(k) \propto (k/k_0)^{n_s + \frac{1}{2}\alpha_s \ln(k/k_0)}$$

Slow roll inflation:
$\alpha_s \sim (1-n_s)^2 > 0$

Planck + DESI forecasts (improve over Planck alone)

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{\rm max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{\rm max} = 0.2$ h^{-1}Mpc)	0.0022 (1.7)	0.0040 (1.3)
Ly-α forest	0.0029 (1.3)	0.0027 (2.0)
Ly-α forest + Gal ($k_{\rm max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

Font-Ribera++ (2014b)

These constraints include Lyman-α power spectrum only

Bispectrum would improve σ_{α_s} by an extra factor of 2

The Lyman-α forest

Intervening gas imprints absorption features in high-z quasar spectra

These fluctuations are tracing the underlying density field along the line of sight