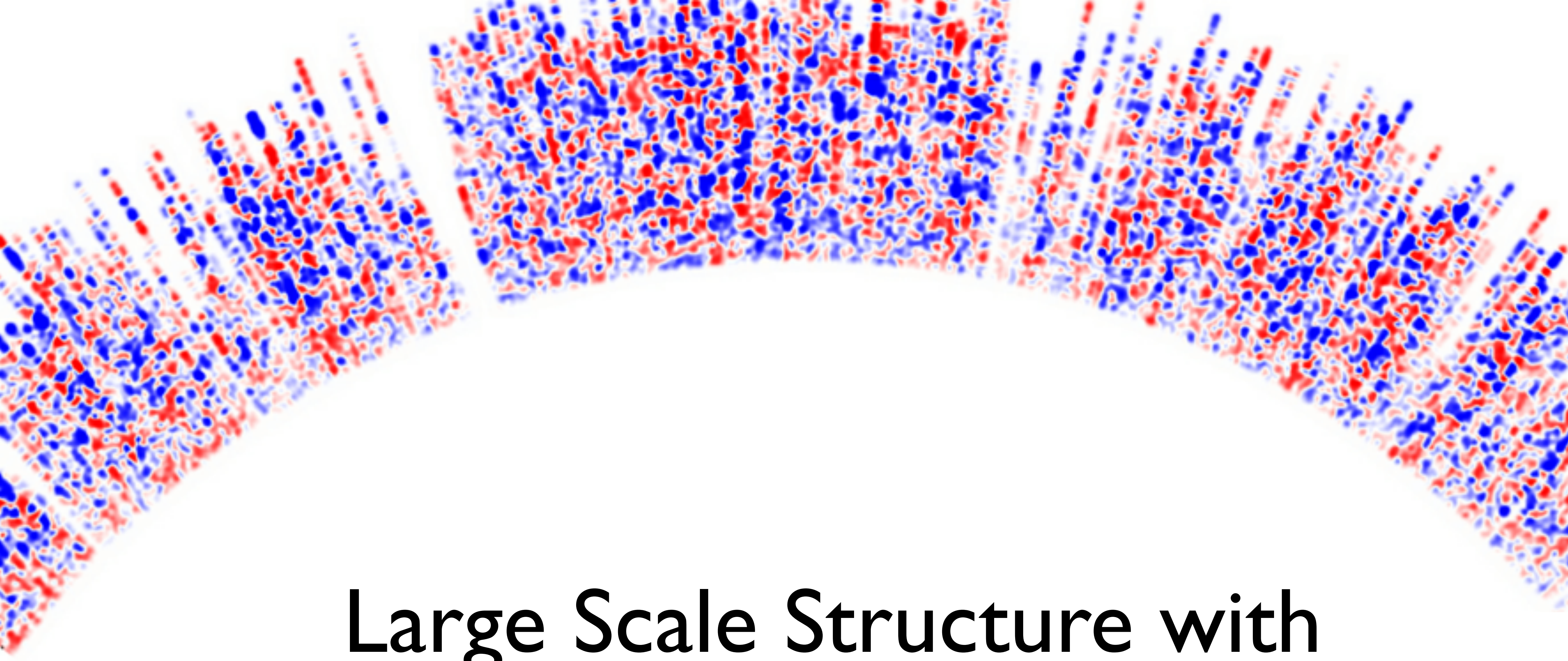
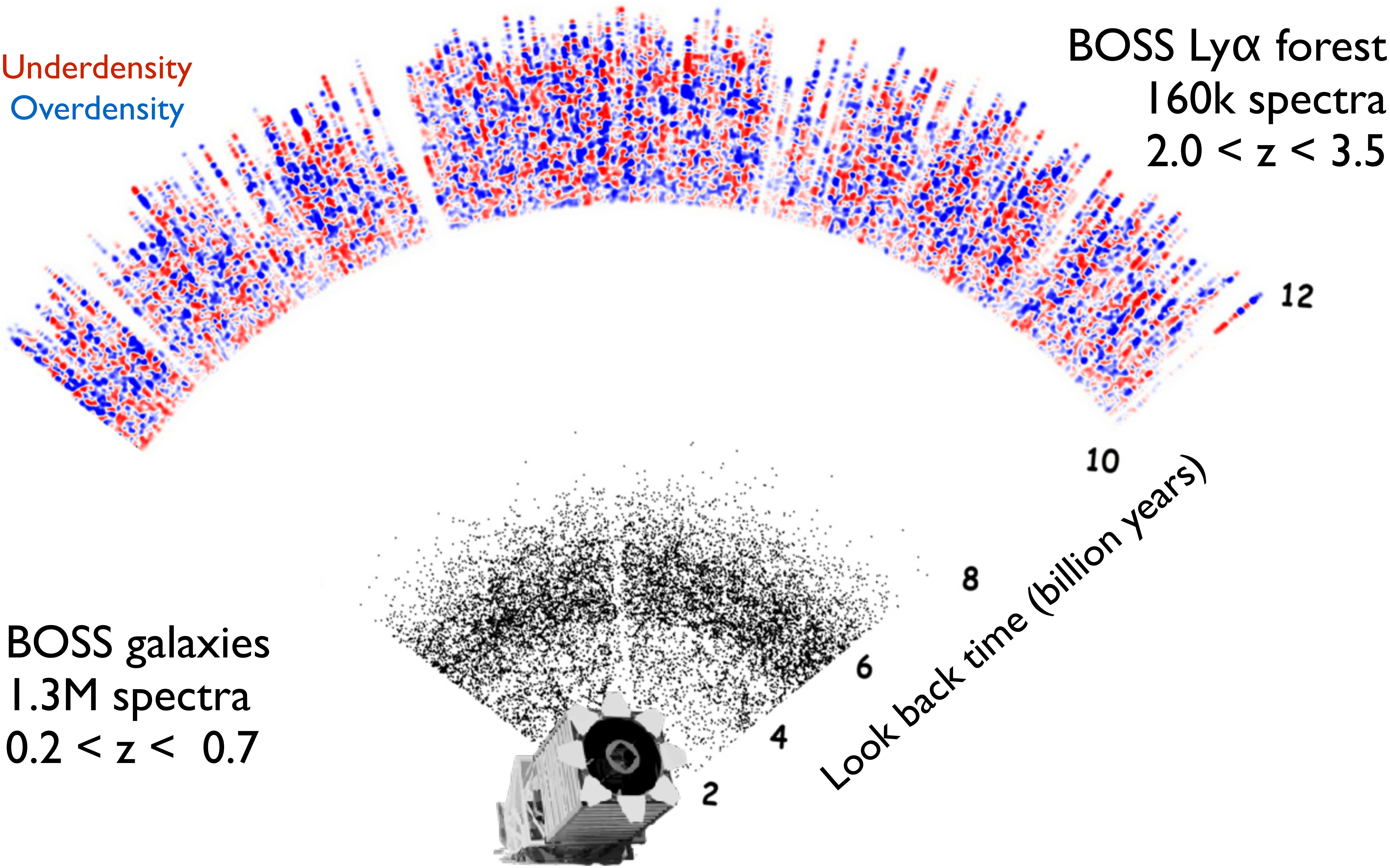


Large Scale Structure with the Lyman-α Forest

Andreu Font-Ribera - University College London

Redshift Surveys



Outline

- **Motivation**
- Introducing the Lyman-α forest
- Physics of the Lyman-α forest
- Lyman-α forest as a biased tracer
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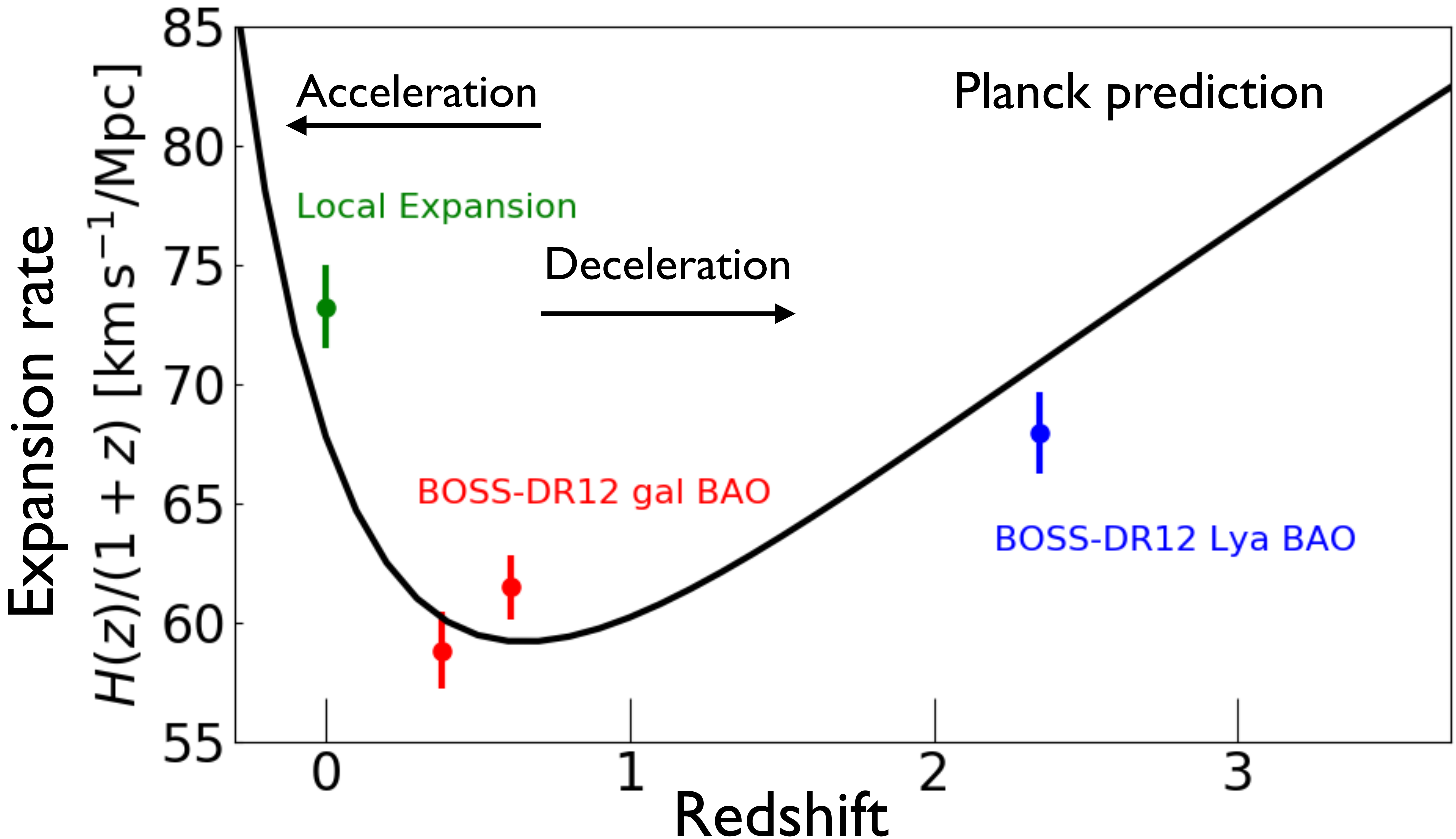
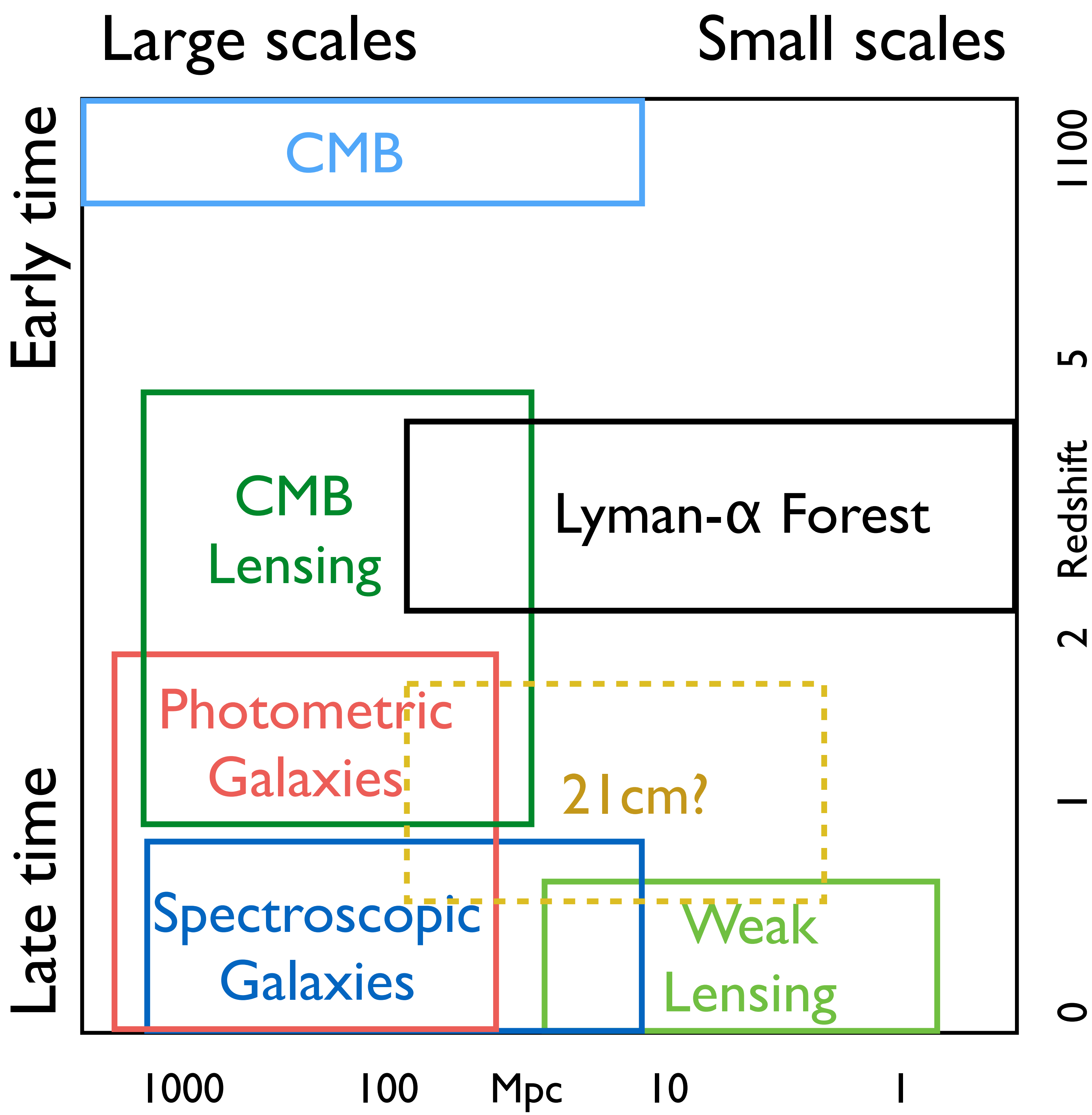
- Recent results from BOSS

Motivation I: expanding universe at high-z



Motivation II: small scale clustering



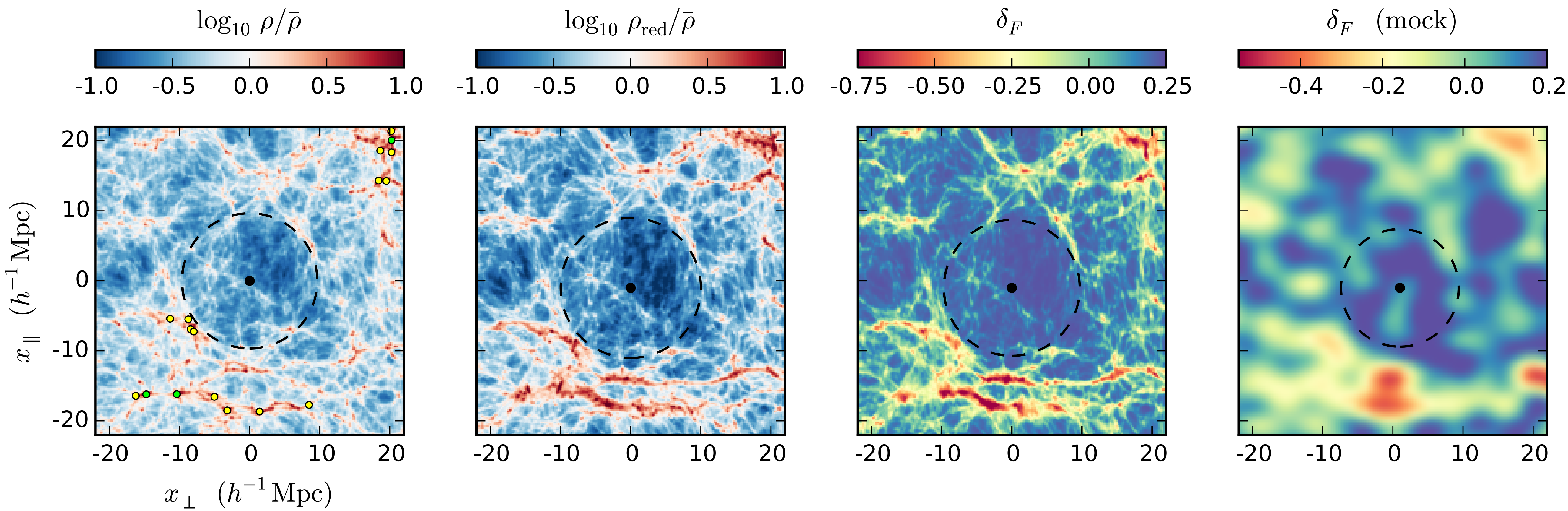
Lyman-α forest offers a unique window to study small scale clustering

Combined with CMB, it allows us to study:

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

Motivation III: 3D tomography

We can map the cosmic web at high redshift (z > 2)



CLAMATO (Lee et al. 2016): high-density survey over tiny area

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Introducing the Lyman-α forest

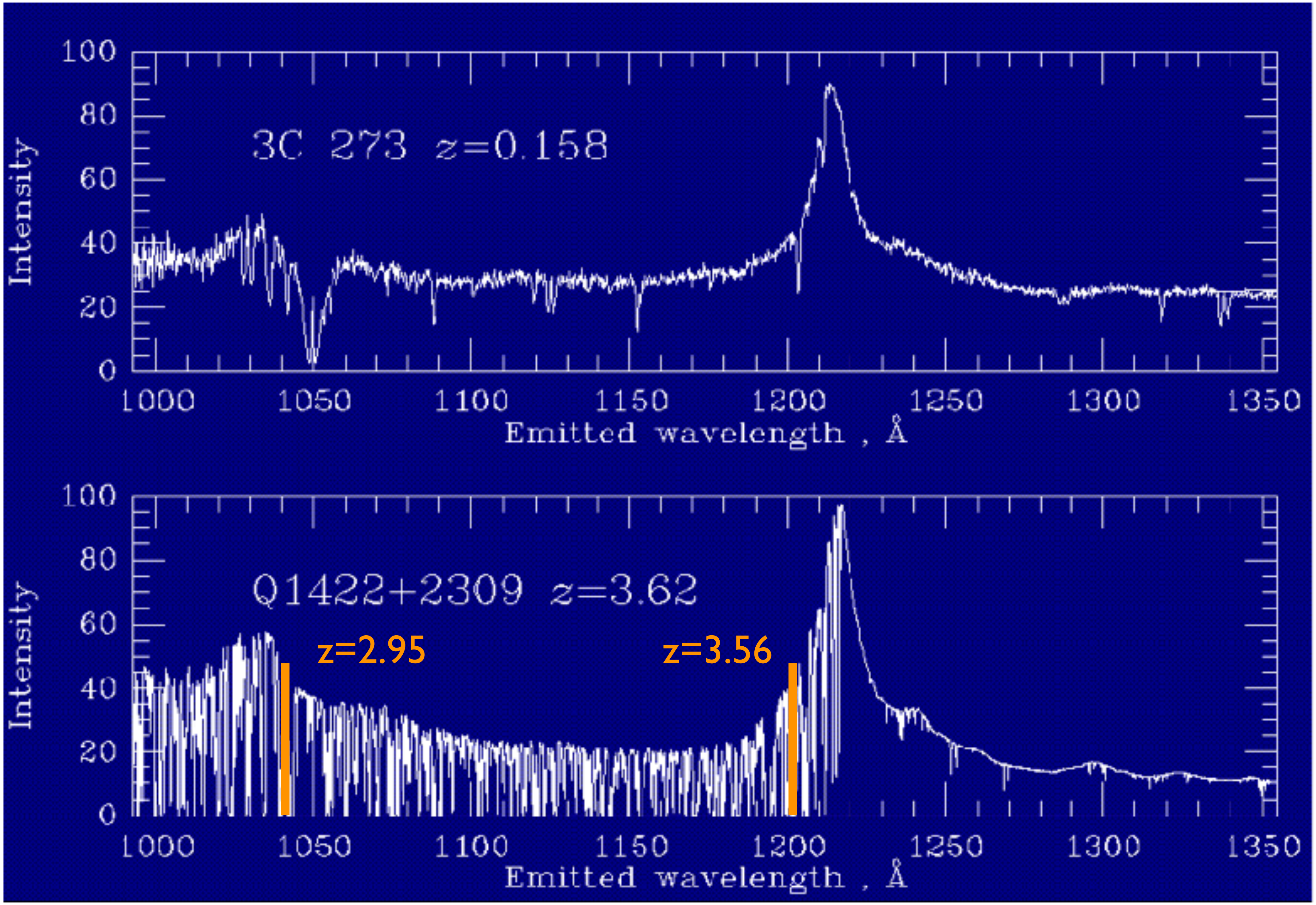

Figure from William C. Keel

Introducing the Lyman-α forest

Lyman-α video by Andrew Pontzen
https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

Introducing the Lyman-α forest

CLAMATO video by KG Lee
https://www.youtube.com/watch?v=TVHIGDxYIQk

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Physics of the Lyman-α forest

$$F(\lambda = \lambda_\alpha(1+z)) = e^{-\tau(z)} \qquad \tau(z) = \frac{c}{H(z)}\, n_{H_I}(z)\, \sigma_\alpha$$

$$n_{H_I} = n_H\, x_{H_I} \qquad n_H = \frac{\rho_b}{m_p}$$

Let us ignore Helium today

$$0 = -x_{H_I}\,\Gamma_{H_I} + (1 - x_{H_I})\; n_e\, \alpha(T) \qquad \alpha(T) \propto T^{-0.7}$$

$$x_{H_I} \ll 1 \text{ at } z \ll 6 \qquad n_e \approx n_H \qquad x_{H_I} \approx \frac{n_H\; \alpha(T)}{\Gamma_{H_I}}$$

$$n_{H_I} = \frac{\alpha(T)}{\Gamma_{H_I}}\, n_H^2 = \frac{\alpha(T)}{\Gamma_{H_I}\, m_p^2}\, \rho_b^2$$

Rauch 1998, Meiksin 2009, McQuinn 2015

Physics of the Lyman-α forest

$$n_{H_I} = \frac{\alpha(T)}{\Gamma_{H_I}}\, n_H^2 = \frac{\alpha(T)}{\Gamma_{H_I}\, m_p^2}\, \rho_b^2$$

Let us simplify the model to have a better intuition

We can describe the gas/baryons as a fluctuating field around its mean density

$$\rho_b = \bar{\rho}_b(z)\Delta_b = \bar{\rho}_b(1+z)^3\Delta_b = \Omega_b\rho_{\rm crit}(1+z)^3\Delta_b$$

Temperature - density relation (good approximation at low densities)

$$T = T_0\left(\frac{\rho_b}{\bar{\rho}_b}\right)^{\gamma-1}$$

$\gamma \approx 1.6$ equation of state of gas

$$\tau = \tau_0(z)\ \Delta_b^\alpha = 1.41\frac{(1+z)^6\ (\Omega_b h^2)^2}{T_4^{0.7}(z)\ h\ E(z)\ \Gamma_{12}(z)}\Delta_b^\alpha$$

$$\alpha = 2 - 0.7(\gamma - 1) \approx 1.6$$

McDonald 2003

Physics of the Lyman-α forest

Peculiar velocities of the gas change absorption features $\lambda_\alpha \left(1 + \frac{v_\parallel}{c}\right)$

Coherent velocities change absorption position

$$\tau_s(x) = \int dx' \; \tau(x') \; W\left(\frac{(x-x')}{H(z)} - v_\parallel(x'), T(x')\right)$$

Random velocities caused by gas temperature broaden lines

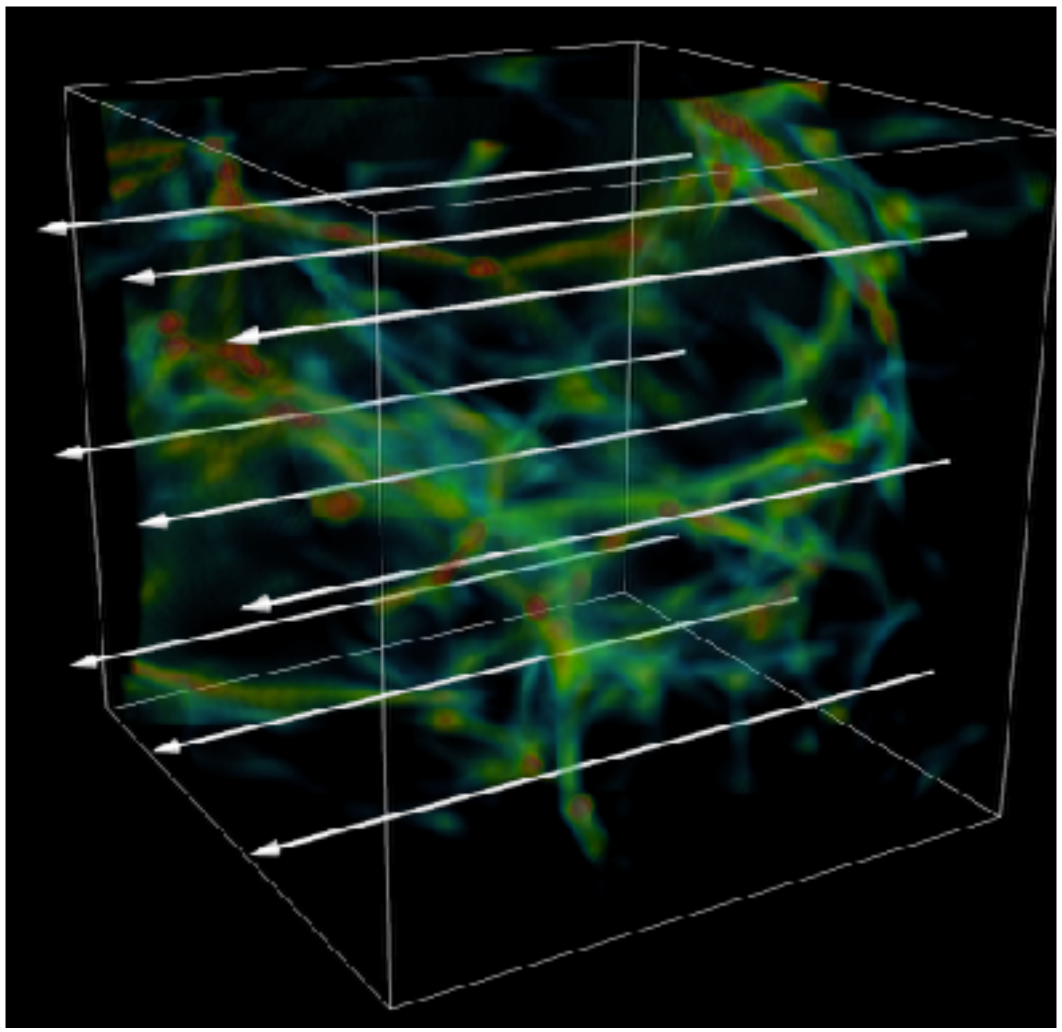
$$W(v,T) = \frac{1}{\sqrt{2\pi\sigma^2(T)}} e^{-v^2/2\sigma^2(T)}$$

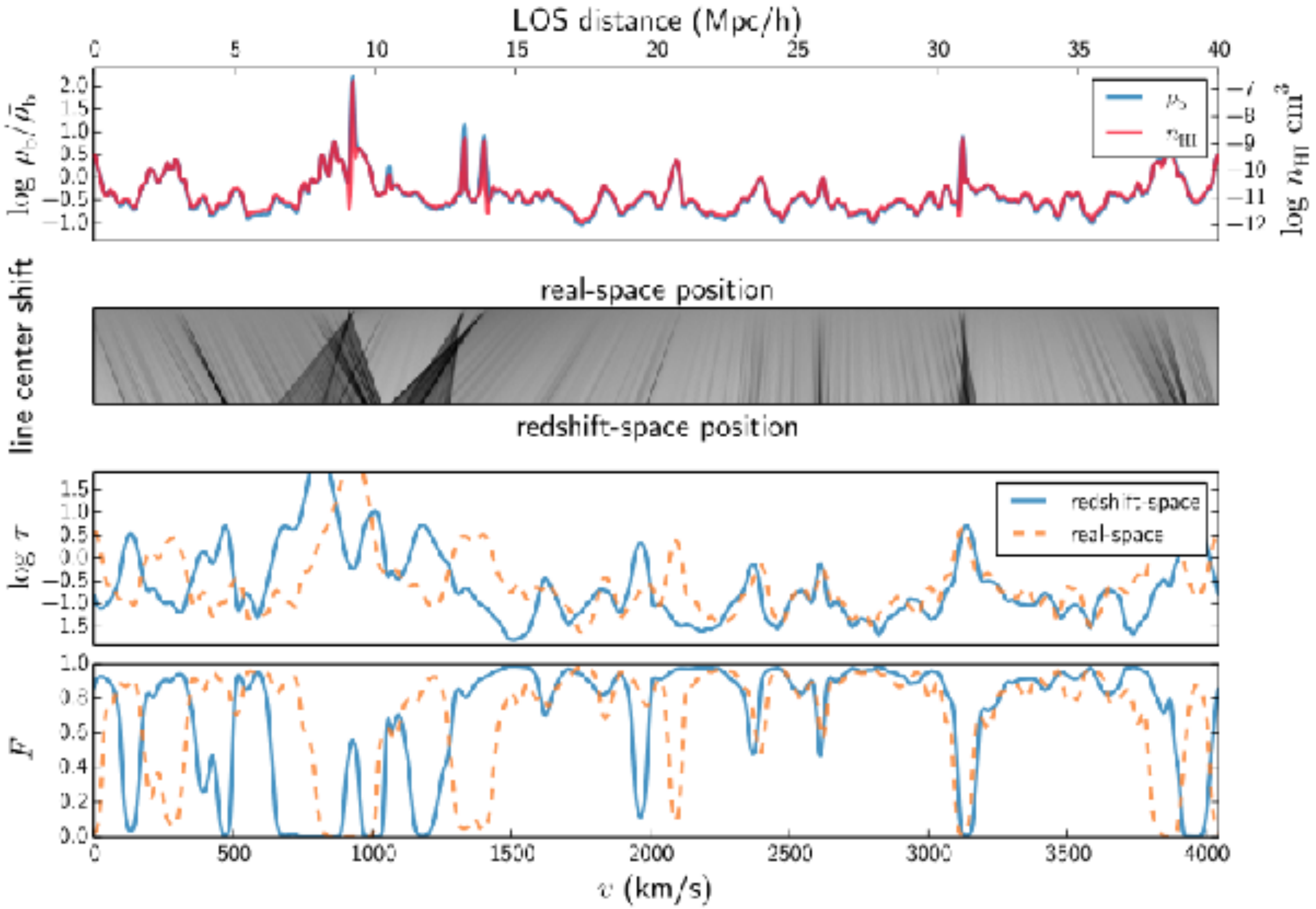
$$\sigma(T) = 9.1 \text{ km s}^{-1} \, (T/10000K)^{1/2}$$

McDonald 2003

Physics of the Lyman-α forest

We can simulate it very well using hydrodynamic simulations





Figures from Casey Stark (UC Berkeley)

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Lyman-α forest as a biased tracer

What do we mean by bias? It can get confusing…

Consider an observable τ tracing density fluctuations $\tau(\mathbf{x}) = \tau\left[\rho(\mathbf{x})\right]$

If you like configuration space

$$b_\tau = \lim_{R\to\infty} \frac{\delta_\tau(\mathbf{x})}{\delta(\mathbf{x}, R)} \qquad b_\tau^2 = \lim_{r\to\infty} \frac{\xi_{\tau\tau}(r)}{\xi_{\rho\rho}(r)} \qquad b_\tau = \lim_{r\to\infty} \frac{\xi_{\tau\rho}(r)}{\xi_{\rho\rho}(r)}$$

If you prefer Fourier space

$$b_\tau = \lim_{k\to 0} \frac{\delta_\tau(\mathbf{k})}{\delta(\mathbf{k})} \qquad b_\tau^2 = \lim_{k\to 0} \frac{P_{\tau\tau}(k)}{P_{\rho\rho}(k)} \qquad b_\tau = \lim_{k\to 0} \frac{P_{\tau\rho}(k)}{P_{\rho\rho}(k)}$$

Lyman-α forest as a biased tracer

Taylor expansion on powers of density fluctuations

$$\tau(\mathbf{x}) = \tau\left[\rho(\mathbf{x})\right] \qquad \rho(\mathbf{x}) = \bar{\rho}\,(1 + \delta(\mathbf{x})) \qquad \tau(\mathbf{x}) = \bar{\tau}\,(1 + \delta_\tau(\mathbf{x}))$$

$$\tau(\delta) = \tau|_{\delta=0} + \left.\frac{\partial \tau}{\partial \delta}\right|_{\delta=0} \delta + \frac{1}{2}\left.\frac{\partial^2 \tau}{\partial \delta^2}\right|_{\delta=0} \delta^2 + \mathcal{O}(\delta^3)$$

If $|\delta| \ll 1$

$$\tau(\delta) = \tau|_{\delta=0} + \left.\frac{\partial \tau}{\partial \delta}\right|_{\delta=0} \delta \qquad \bar{\tau} = \tau|_{\delta=0}$$

$$\delta_\tau(\mathbf{x}) = \frac{1}{\bar{\tau}}\left.\frac{\partial \tau}{\partial \delta}\right|_{\delta=0} \delta = b_\tau\ \delta \qquad \boxed{b_\tau = \frac{1}{\bar{\tau}}\left.\frac{\partial \tau}{\partial \delta}\right|_{\delta=0}}$$

McDonald 2006

Lyman-α forest as a biased tracer

EXAM: What is the bias of the following tracers?

$$\tau(\rho) = A\ \rho \qquad\qquad b_\tau = 1$$

$$\tau(\rho) = A\ \rho^\alpha \qquad\qquad b_\tau = \alpha$$

$$F = e^{-\tau(\rho)} = e^{-A\ \rho^\alpha} \qquad\qquad b_F = -\frac{\bar{\tau}}{\bar{F}}\ \alpha$$

$$F = e^{-\bar{\tau}(1+\delta_\tau)} = e^{-\bar{\tau}(1+\alpha\delta)} \approx \bar{F}\,(1 - \bar{\tau}\ \alpha\ \delta)$$

Remember: $b_\tau = \frac{1}{\bar{\tau}} \frac{\partial \tau}{\partial \delta}\Big|_{\delta=0}$

Lyman-α forest as a biased tracer

Linear redshift space distortions (RSD) in galaxy clustering

The volume is deformed in redshift space

$$V_s = \left(1 + \frac{1}{H(z)} \frac{\partial v_{\parallel}}{\partial r_{\parallel}}\right) V_r = (1-\eta)\, V_r \qquad \eta = -\frac{1}{H(z)} \frac{\partial v_{\parallel}}{\partial r_{\parallel}}$$

Density of galaxies is modified by velocity gradient

$$n_g^s = \frac{n_g^r}{1-\eta} = \bar{n}_g \frac{1+\delta_g^r}{1-\eta} \approx \bar{n}_g \left(1 + b_g \delta + \eta\right) \qquad \delta_g^s = b_g \delta + \eta$$

In Fourier space, and assuming linear perturbation theory

$$\eta(\mathbf{k}) = f\ \mu^2\ \delta(\mathbf{k}) \qquad f = \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^{0.6}$$

$$\boxed{\delta_g^s(\mathbf{k}) = \left(b_g + f\mu^2\right) \delta(\mathbf{k}) = b_g \left(1 + \beta\mu^2\right) \delta(\mathbf{k}) \qquad \beta = \frac{f}{b_g}}$$

Kaiser 1987, Hamilton 1997

Lyman-α forest as a biased tracer

Same applies for linear RSD in optical depth

$$\delta_\tau^s(\mathbf{k}) = \left(b_\tau + f\mu^2\right)\delta(\mathbf{k}) = b_\tau\left(1 + \beta_\tau \mu^2\right)\delta(\mathbf{k}) \qquad \beta_\tau = \frac{f}{b_\tau}$$

How about the Lyman-α forest?

$$F^s = e^{-\tau_s} \approx e^{-\bar{\tau}(1+b_\tau\delta+\eta)} \approx \bar{F}\left[1 - \bar{\tau}\, b_\tau\, \delta - \bar{\tau}\, \eta\right]$$

$$\delta_F^s = -\frac{\bar{\tau}\, b_\tau}{\bar{F}}\delta - \frac{\bar{\tau}}{\bar{F}}\eta = b_F^\delta\, \delta + b_F^\eta\, \eta \qquad b_F^\delta = -\frac{\bar{\tau}\, b_\tau}{\bar{F}} \qquad b_F^\eta = -\frac{\bar{\tau}}{\bar{F}}$$

And in Fourier space

$$\delta_F^s(\mathbf{k}) = \left(b_F^\delta + b_F^\eta\, f\mu^2\right)\delta(\mathbf{k}) = b_F^\delta\left(1 + \beta_F\mu^2\right)\delta(\mathbf{k}) \qquad \boxed{\beta_F = \frac{f\, b_F^\eta}{b_F^\delta}}$$

McDonald 2003, Seljak 2012

Lyman-α forest as a biased tracer

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

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

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

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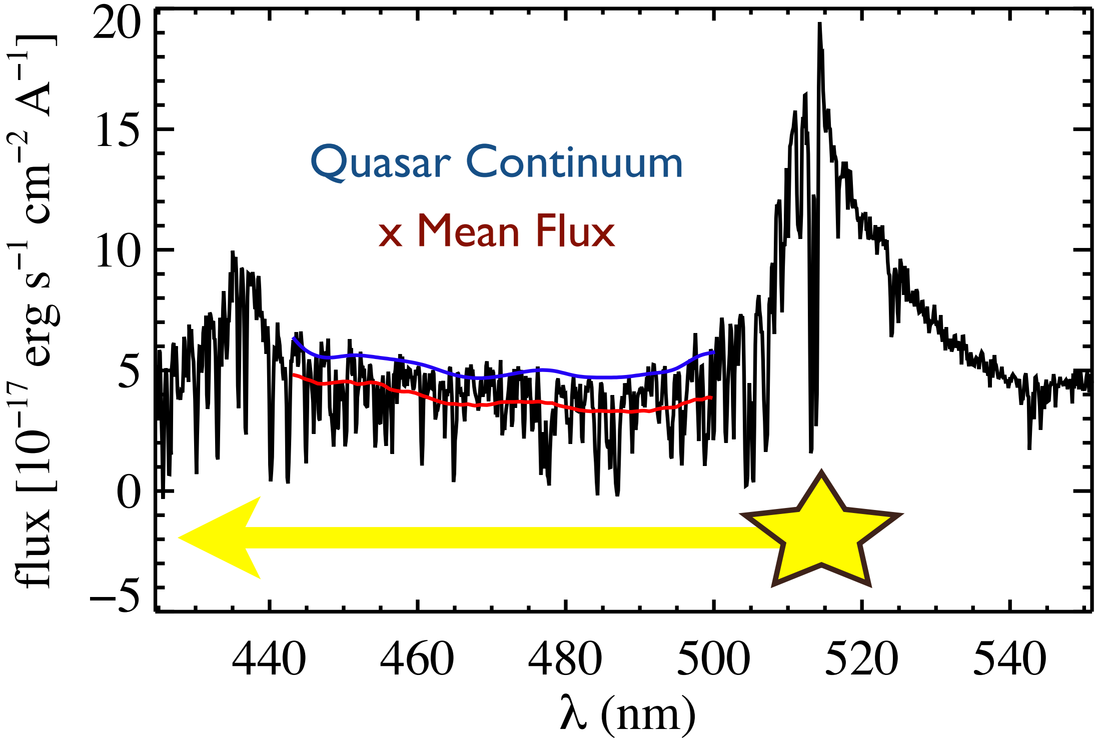
Analysing the Lyman-α forest



Observed flux   Transmitted fraction

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

Quasar continuum

Observed wavelength   Absorption redshift

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

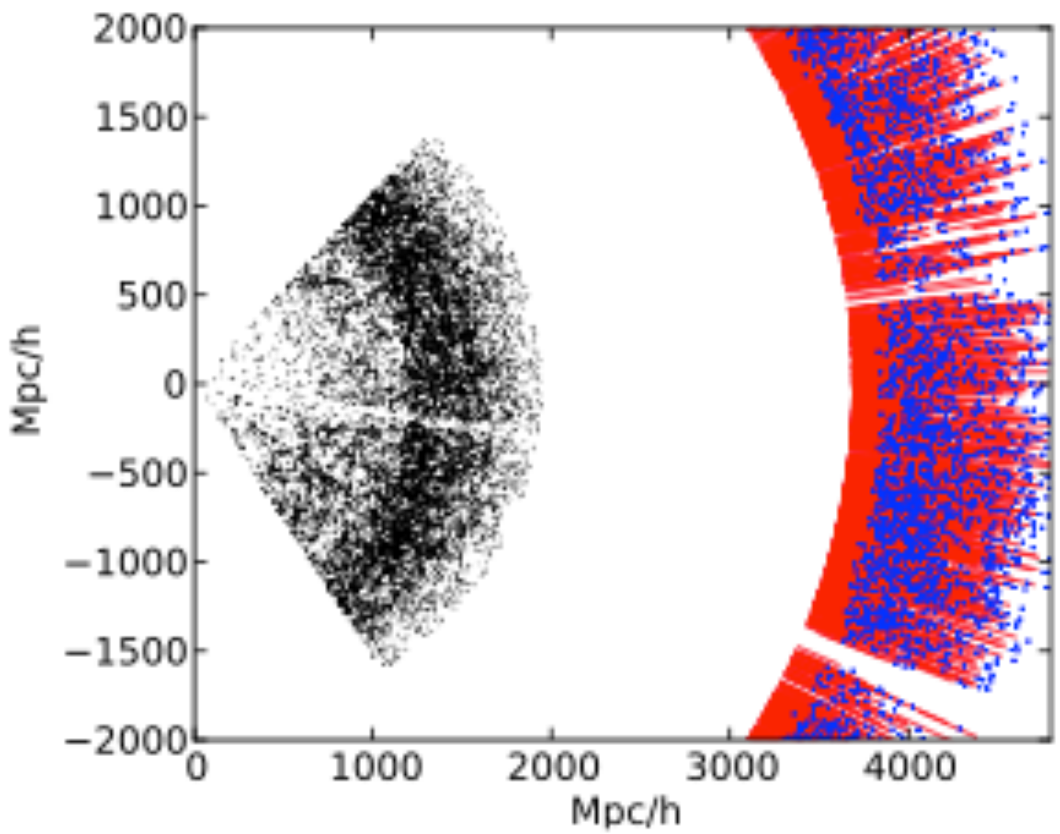
LyaF wavelength (121.6 nm)

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

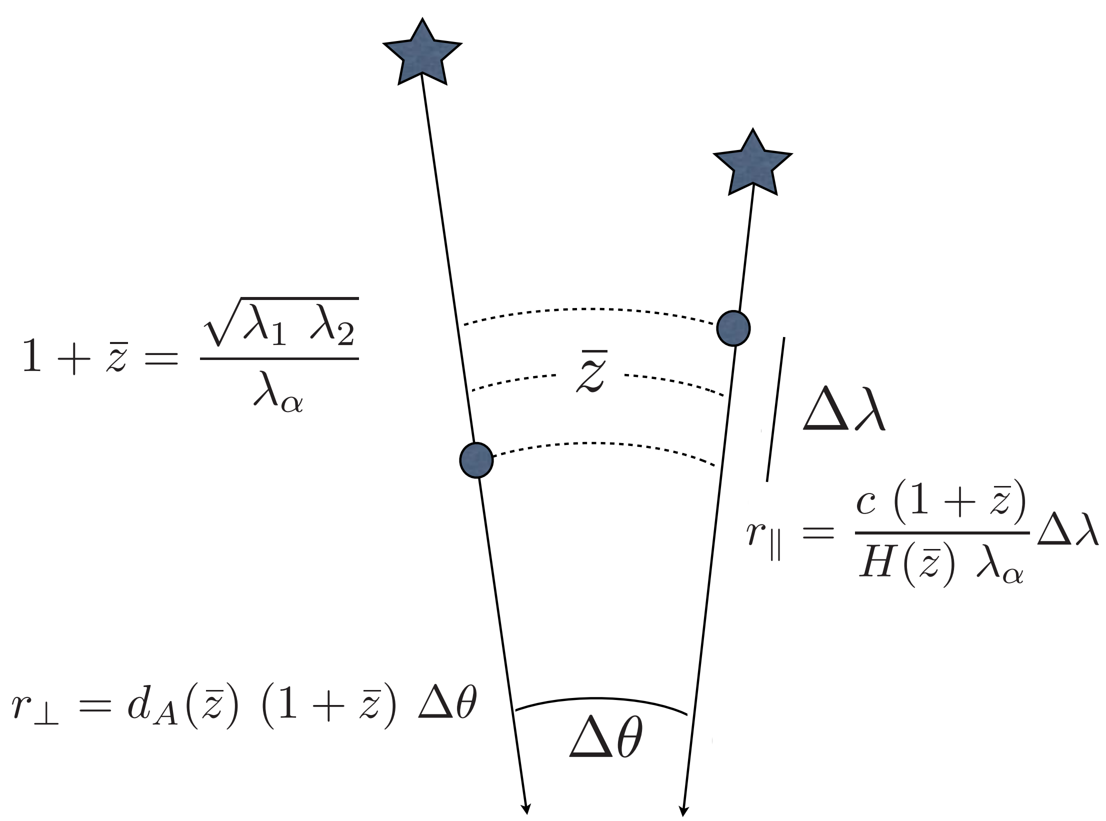
Flux fluctuations in pixels trace the density along the line of sight to the quasar

Analysing the Lyman-α forest

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



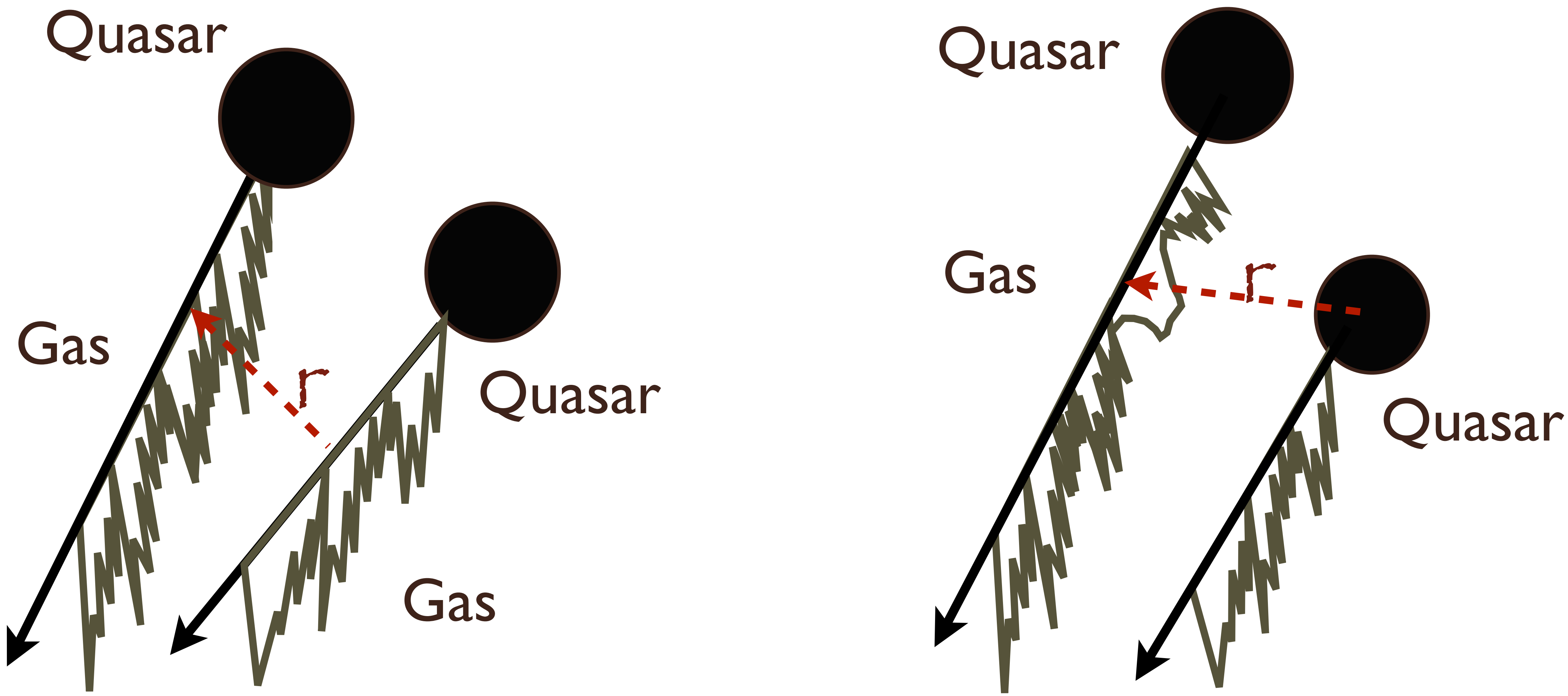
LyaF volume : 50 (Gpc/h)^3



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

Analysing the Lyman-α forest

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)

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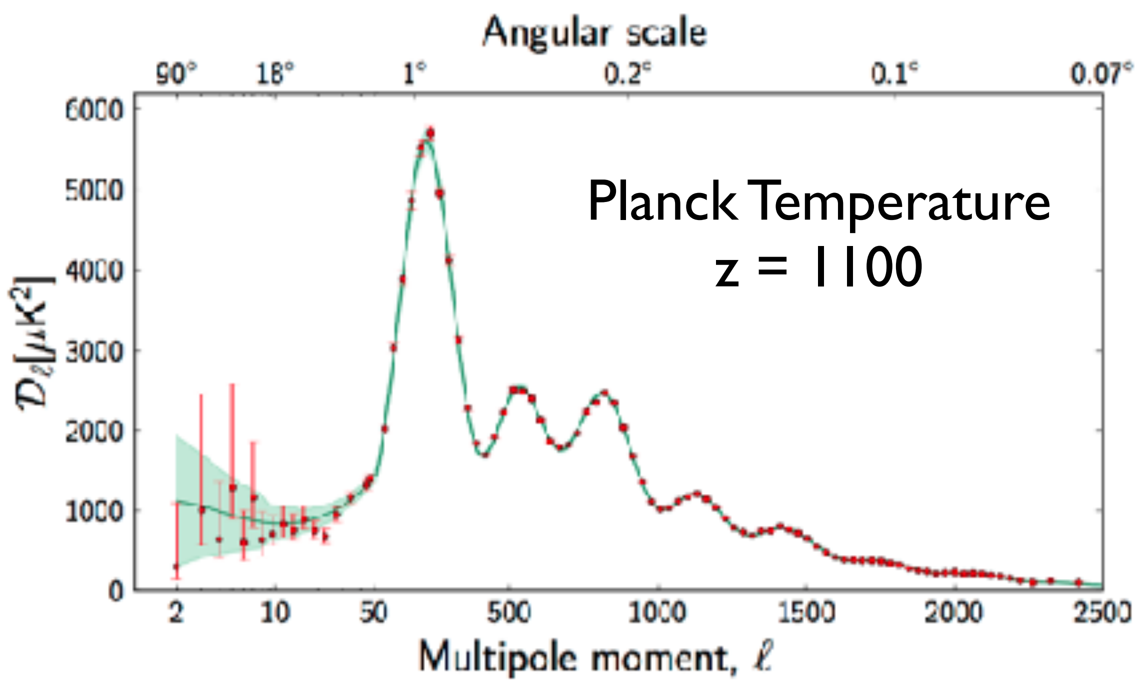
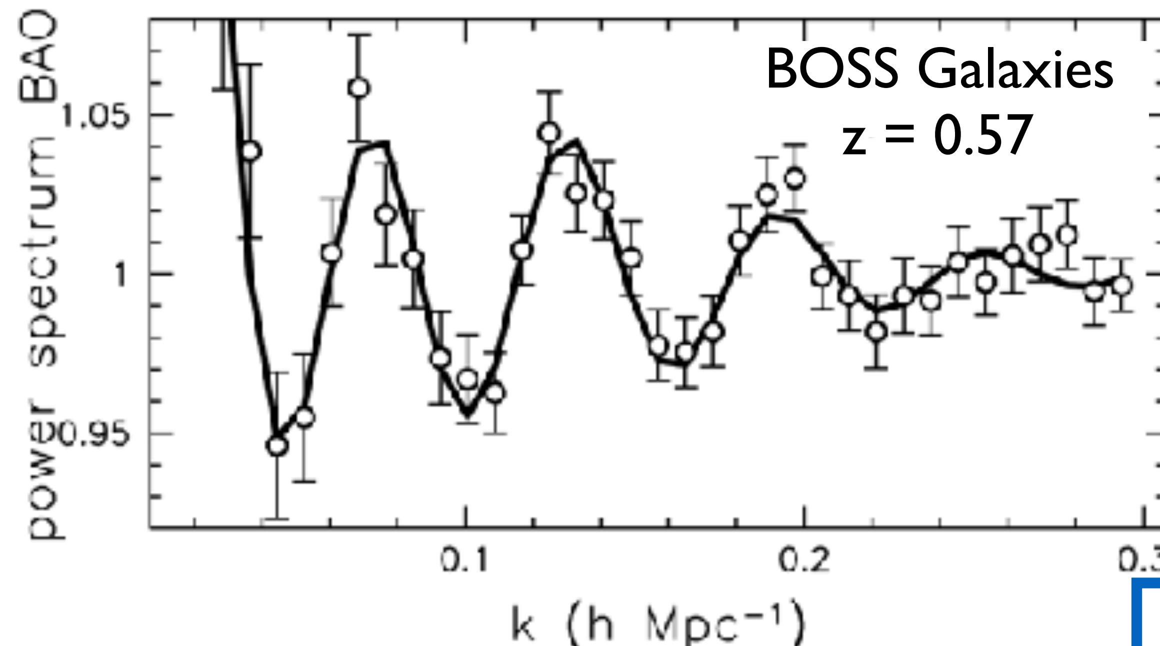
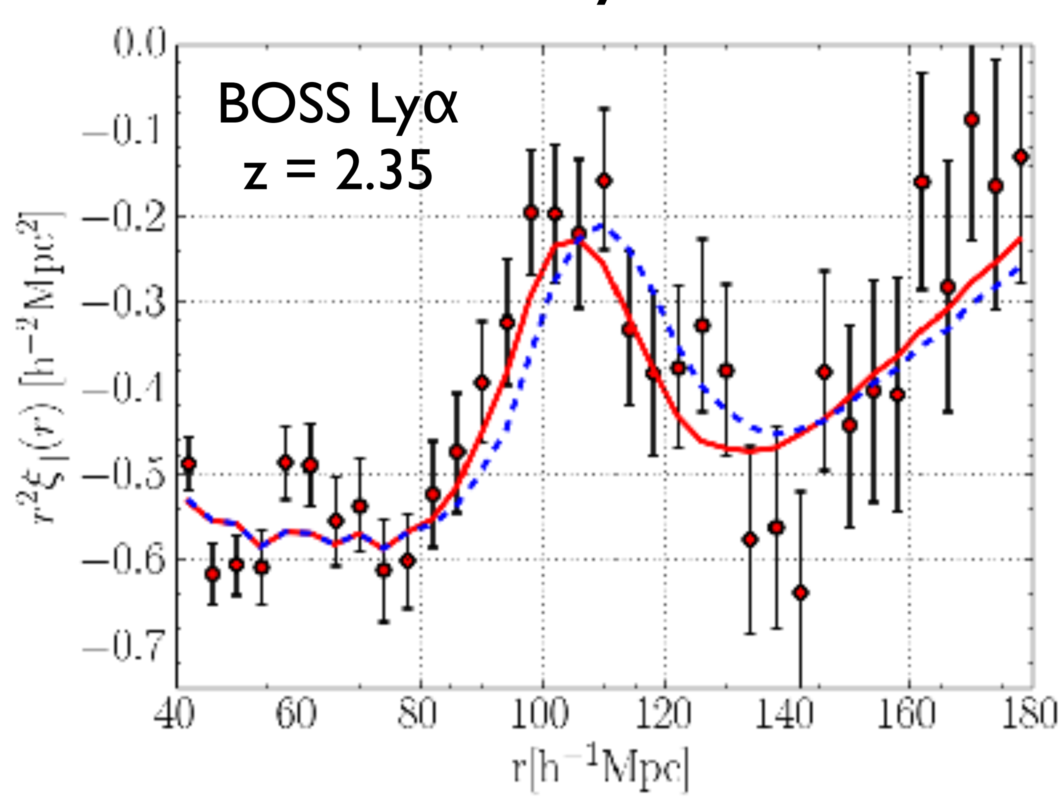
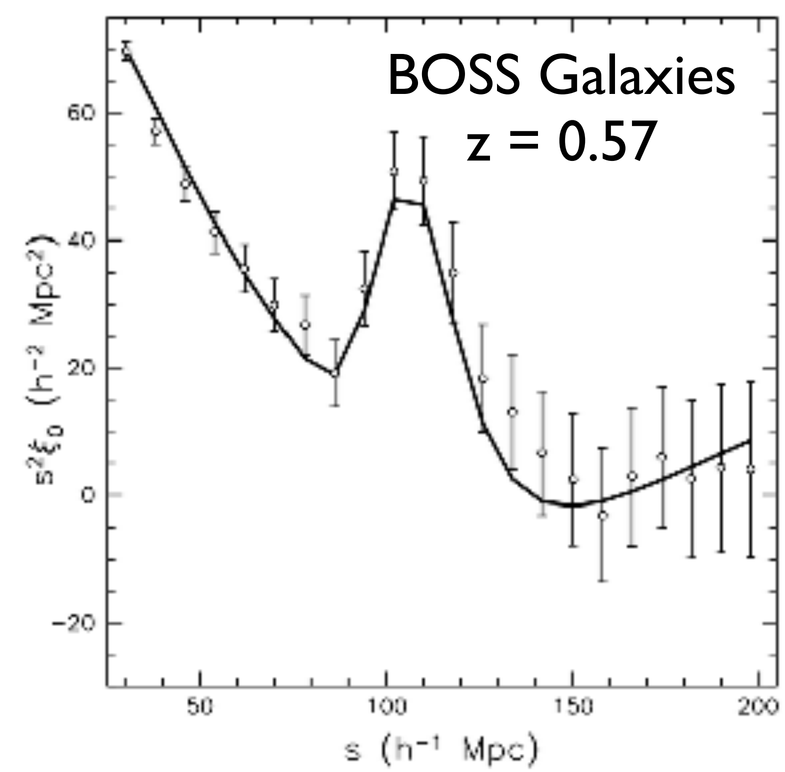
Recent results from BOSS

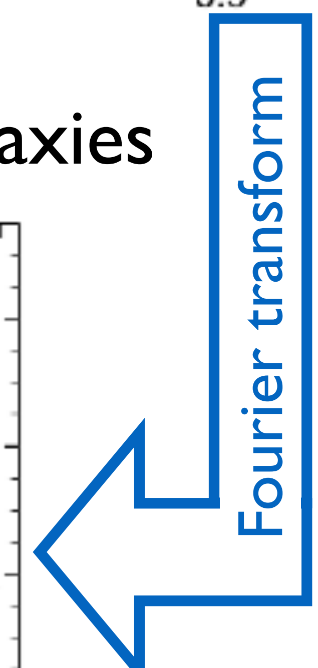




Oscillations clearly seen in CMB, but also in clustering of galaxies



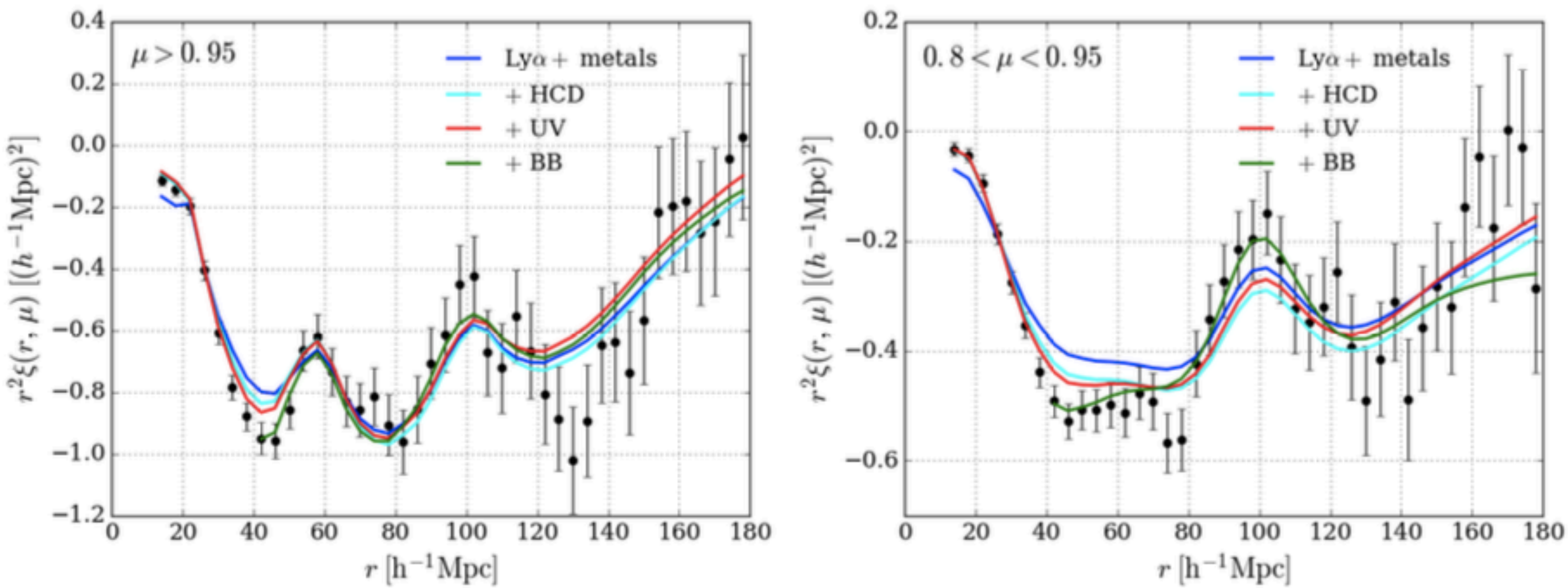




Recent results from BOSS

Julian Bautista
(Moving from Utah to Portsmouth)

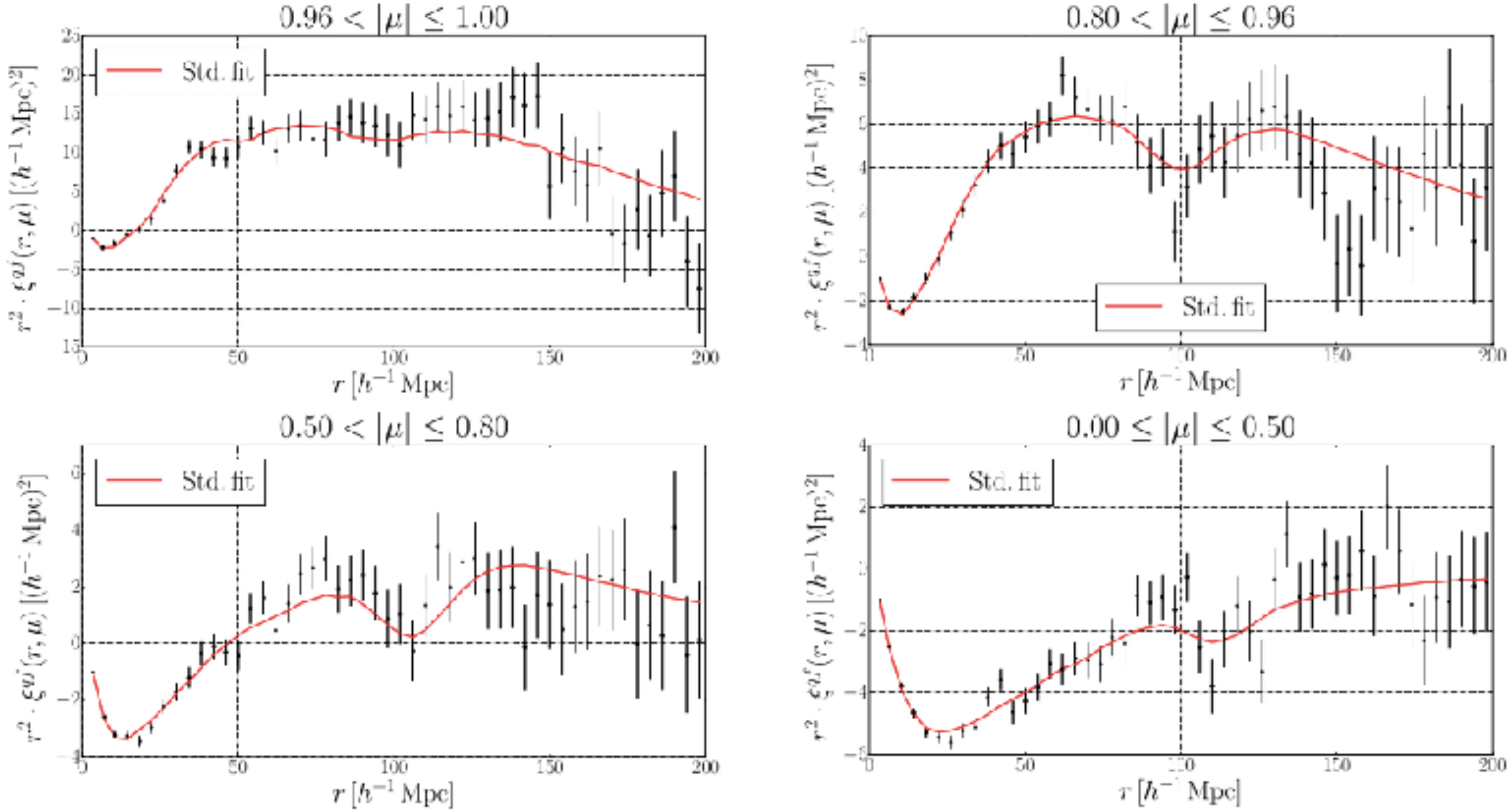
Bautista et al 2017
BAO from DR12
Lya auto-correlation



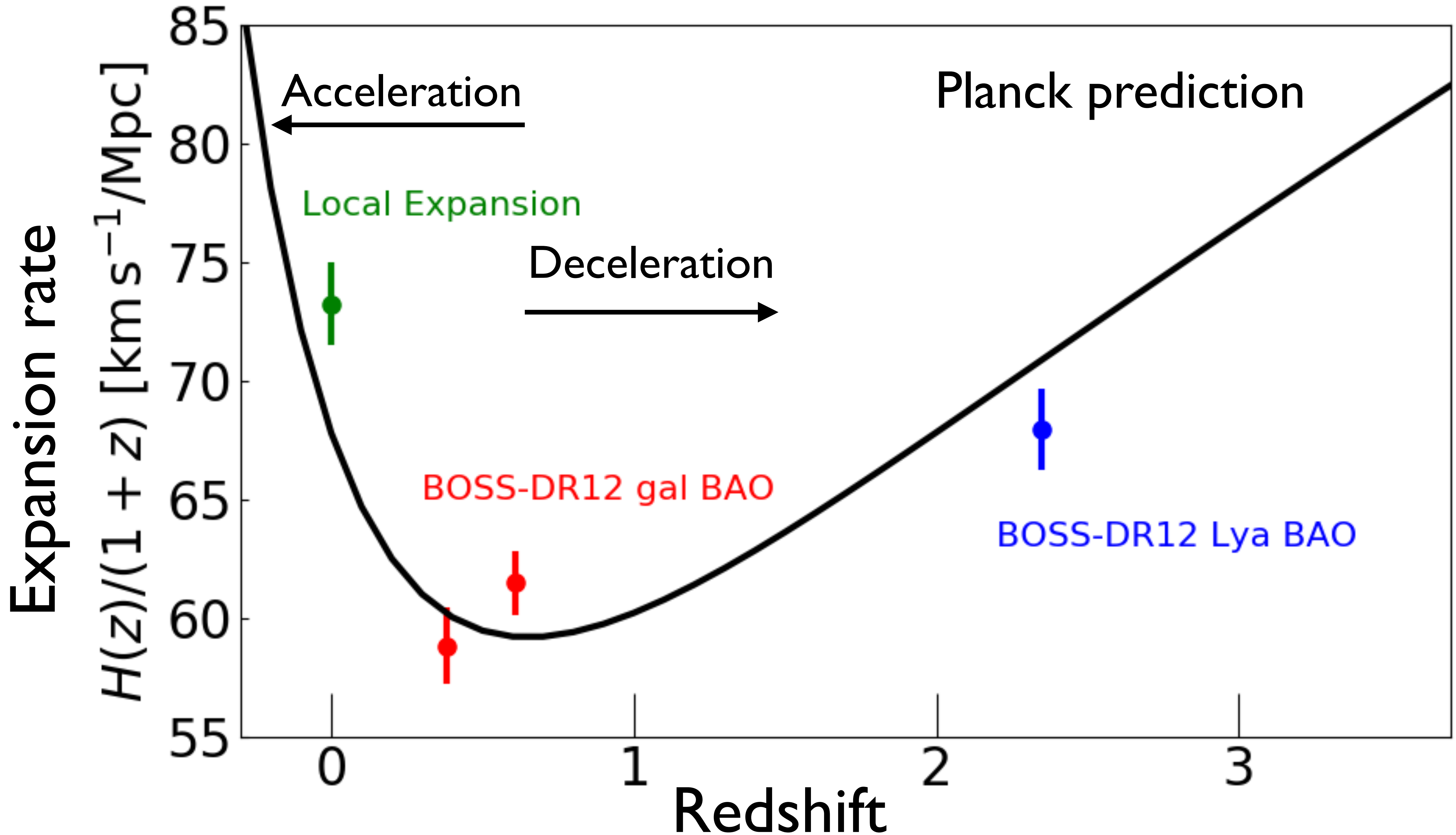
Recent results from BOSS

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

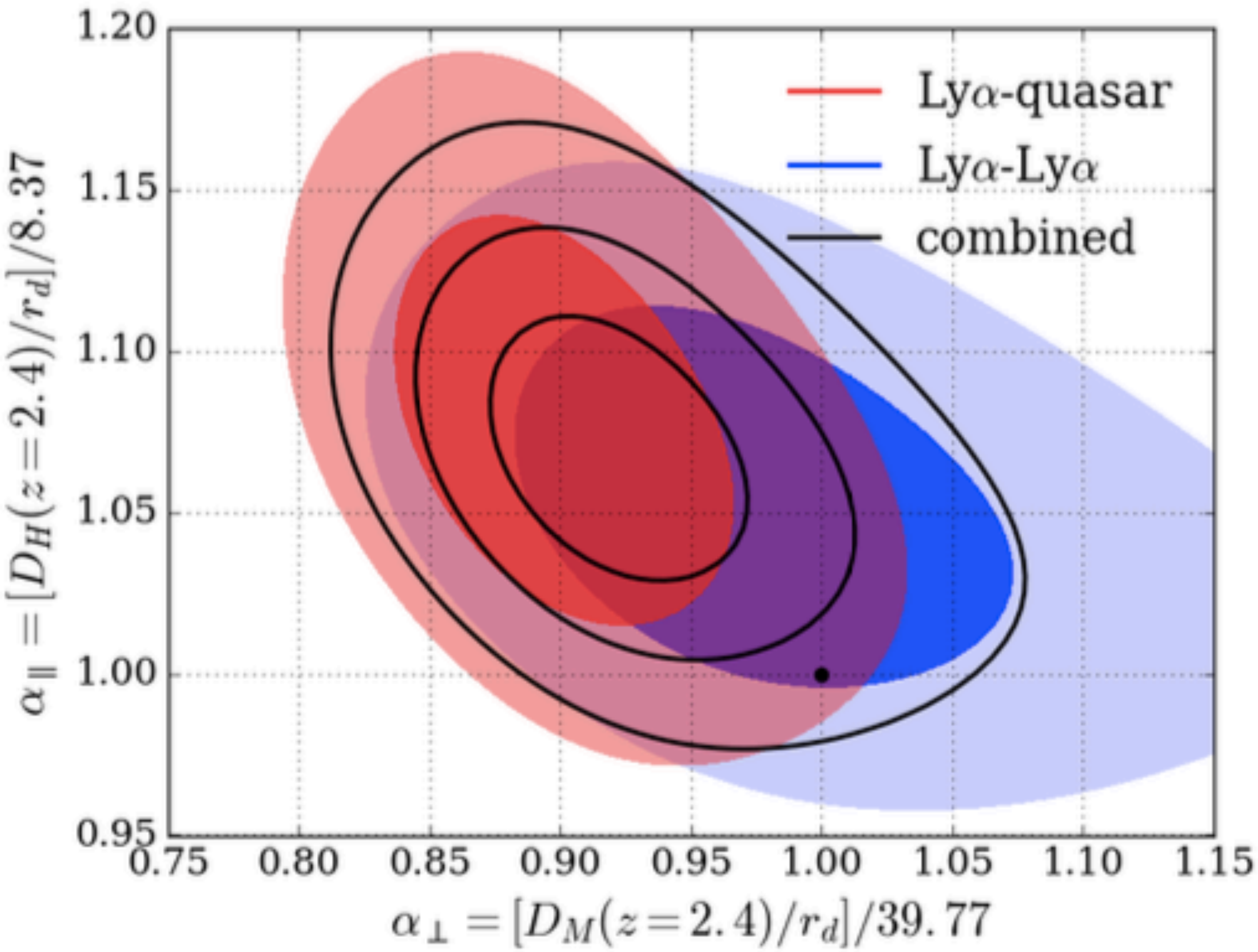
dMdB et al. 2017
BAO from DR12
Quasar-Lya cross

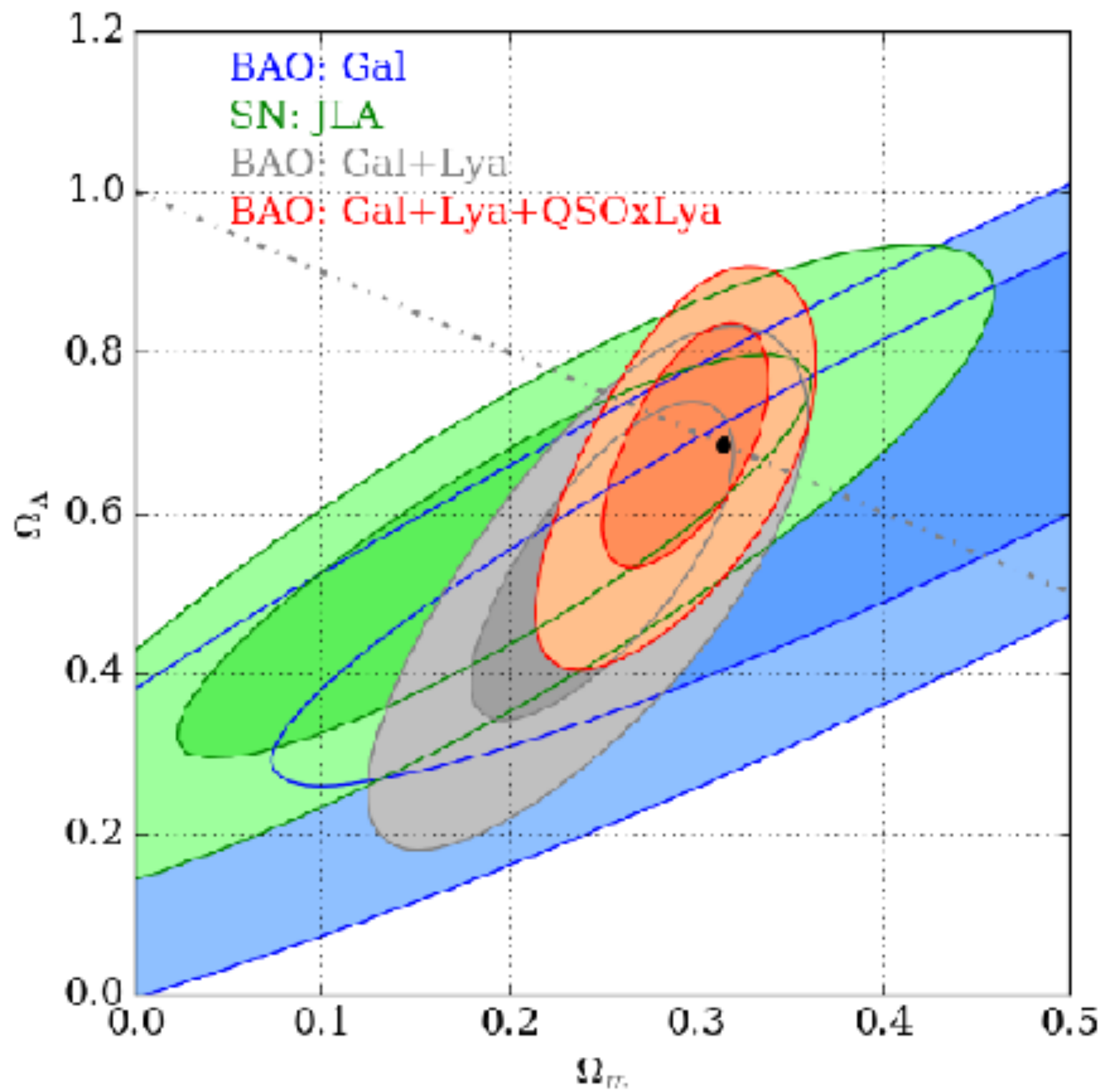


Recent results from BOSS



Recent results from BOSS





In a flat LCDM model

$$\Omega_m = 0.292 \pm 0.019 \quad \text{BAO}$$
$$\Omega_m = 0.315 \pm 0.017 \quad \text{Planck}$$

References

Reviews of InterGalactic Medium / Lyman-α forest
- Rauch (1999, astro-ph/9806286)
- McDonald (2003, astro-ph/0108064)
- Meiksin (2009, arXiv:0711.3358)
- McQuinn (2015, arXiv:1512.00086)

Latest Lyman-α measurements from BOSS
- Bautista et al. (2017, arXiv:1702.00176)
- du Mas des Bourboux et al. (2017, arXiv:1708.02225)

Other cosmology references
- Weinberg et al. (2013, arXiv:1201.2434): Review on dark energy experiments
- Hogg (1999, astro-ph/9905116): Cosmological distances
- McDonald (2006, astro-ph/0609413): Renormalizing the bias parameters
- Hamilton (1997, arXiv:astro-ph/9708102): Review on Redshift Space Distortions (RSD)
- Seljak (2012, arXiv:1201.0594): Bias and RSD in the Lyman-α forest

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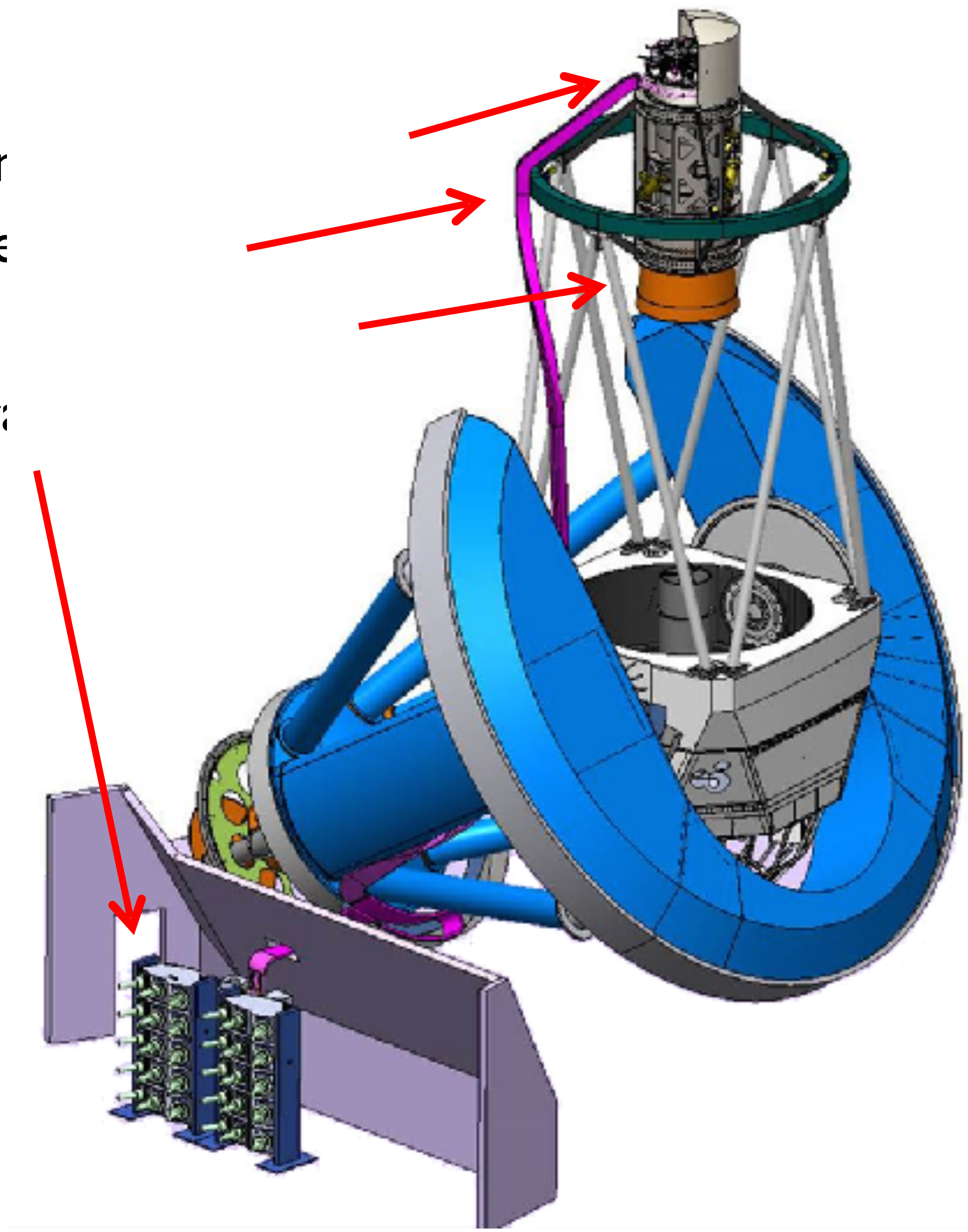
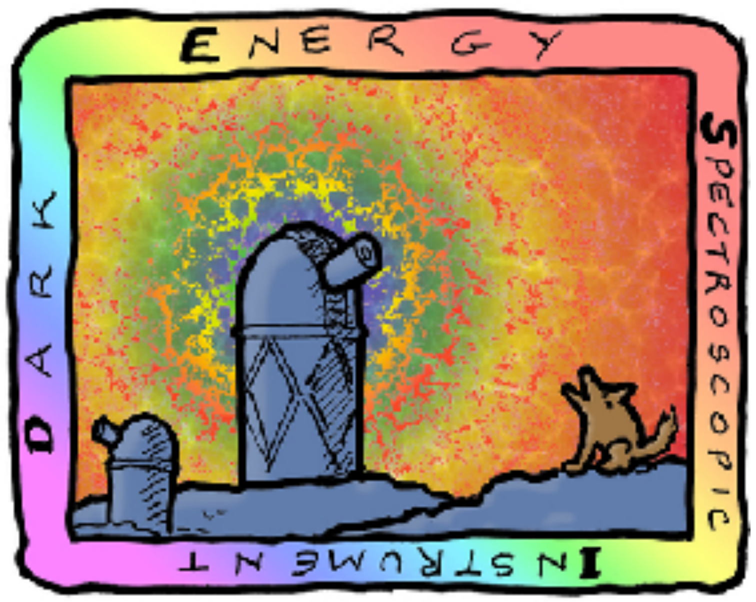
BONUS!

Dark Energy Spectroscopic Instrument

- 5000 fibers ir
- 10 fiber cable
- 3.2 deg. field
- 10 spectrogr



Readout
& Control

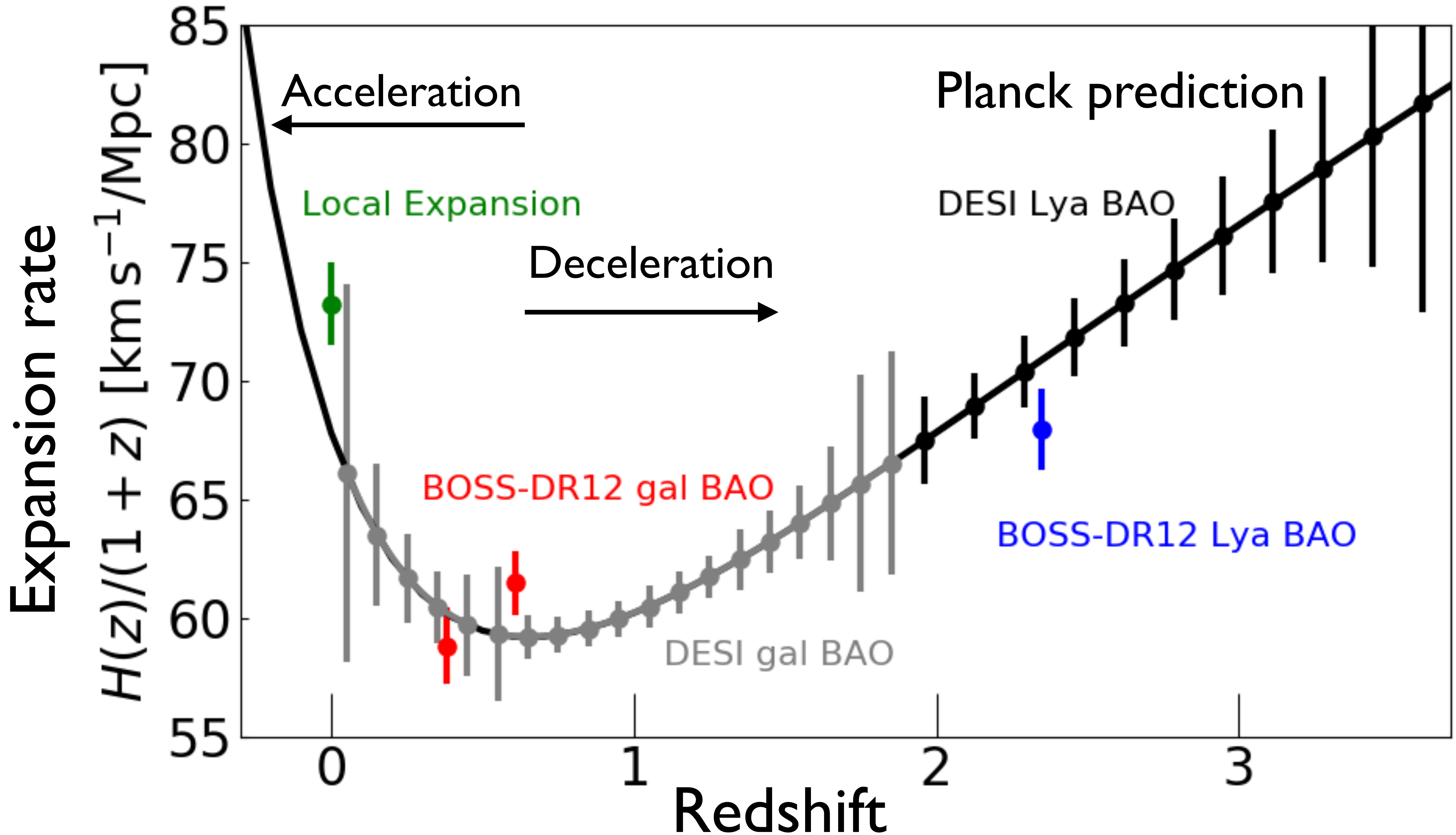


Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS dataset by an order of magnitude

Scheduled to start in 2019

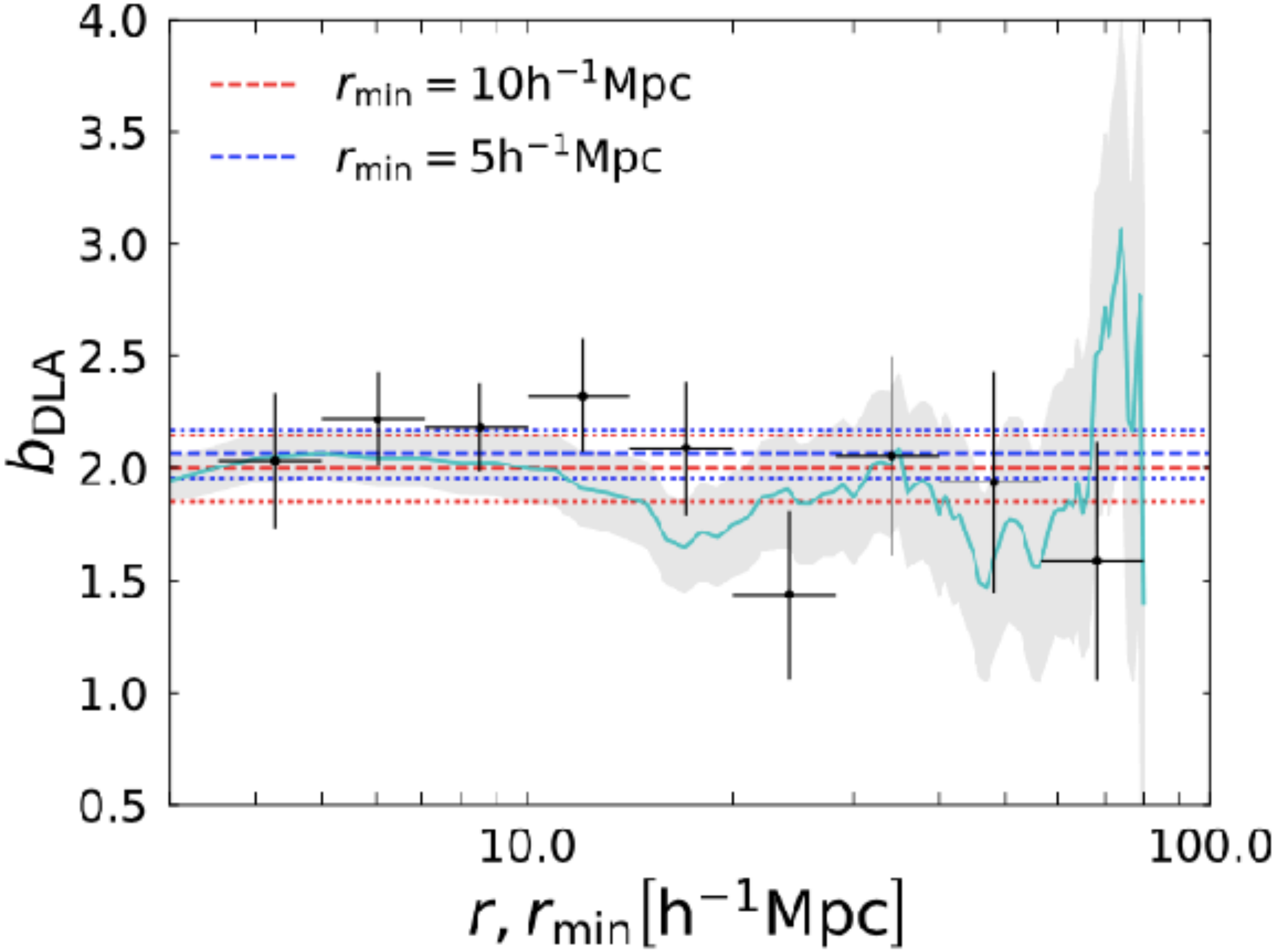
Dark Energy Spectroscopic Instrument



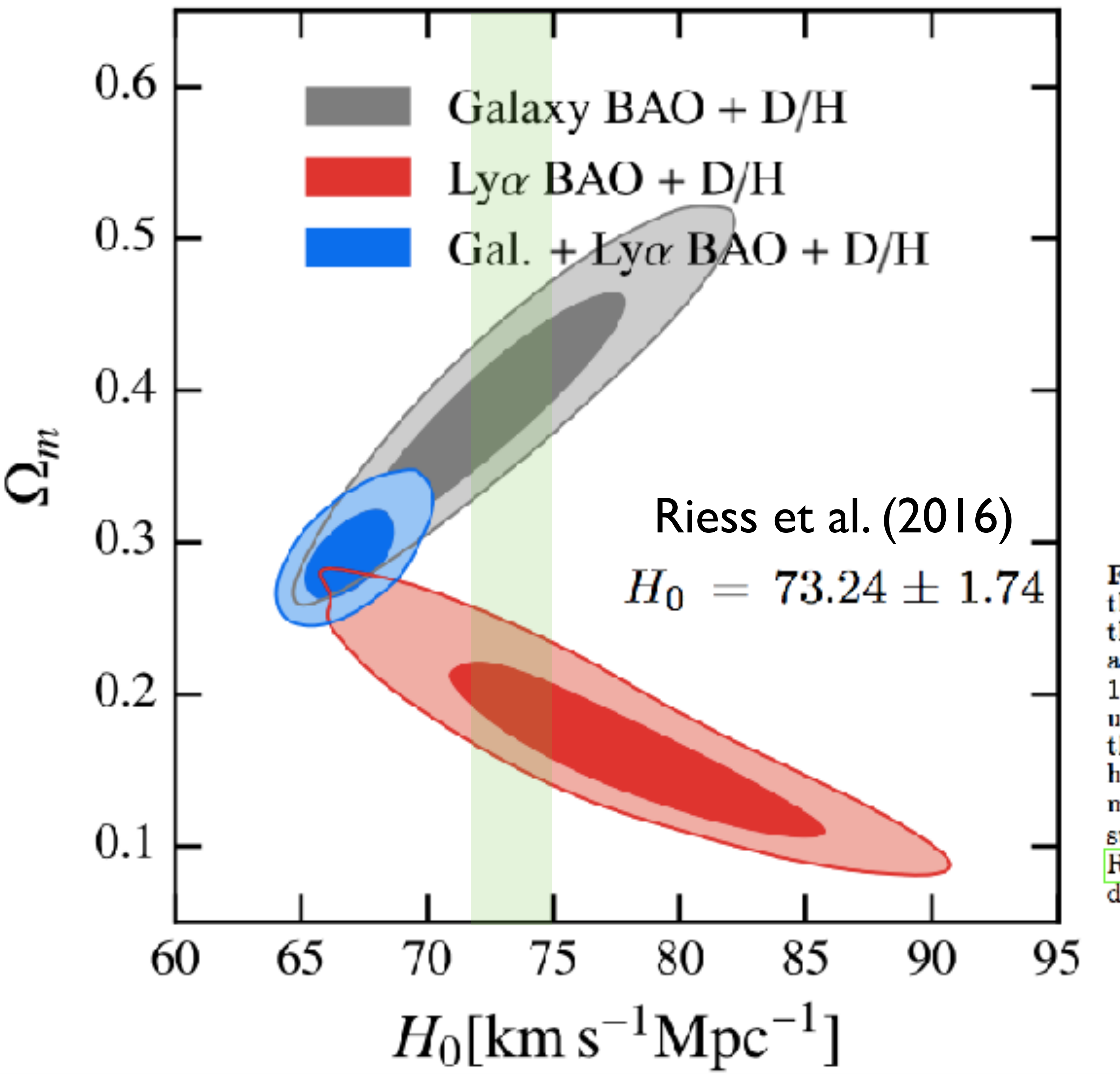
Recent results from BOSS

Ignasi Pérez-Ràfols
(moving from Barcelona
to Marseille)

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



Recent results from BOSS



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.