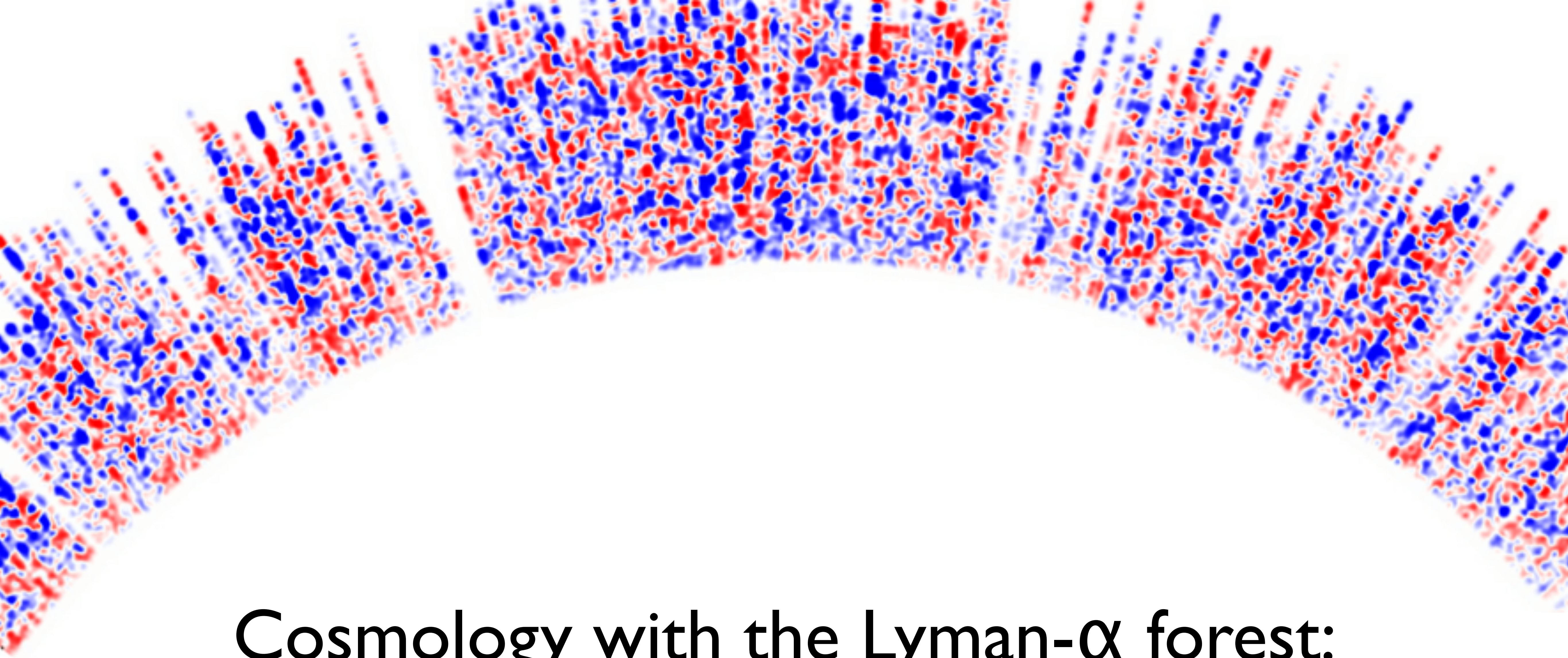


Cosmology with the Lyman-α forest: challenges and opportunities

Andreu Font-Ribera

STFC Ernest Rutherford Fellow at University College London

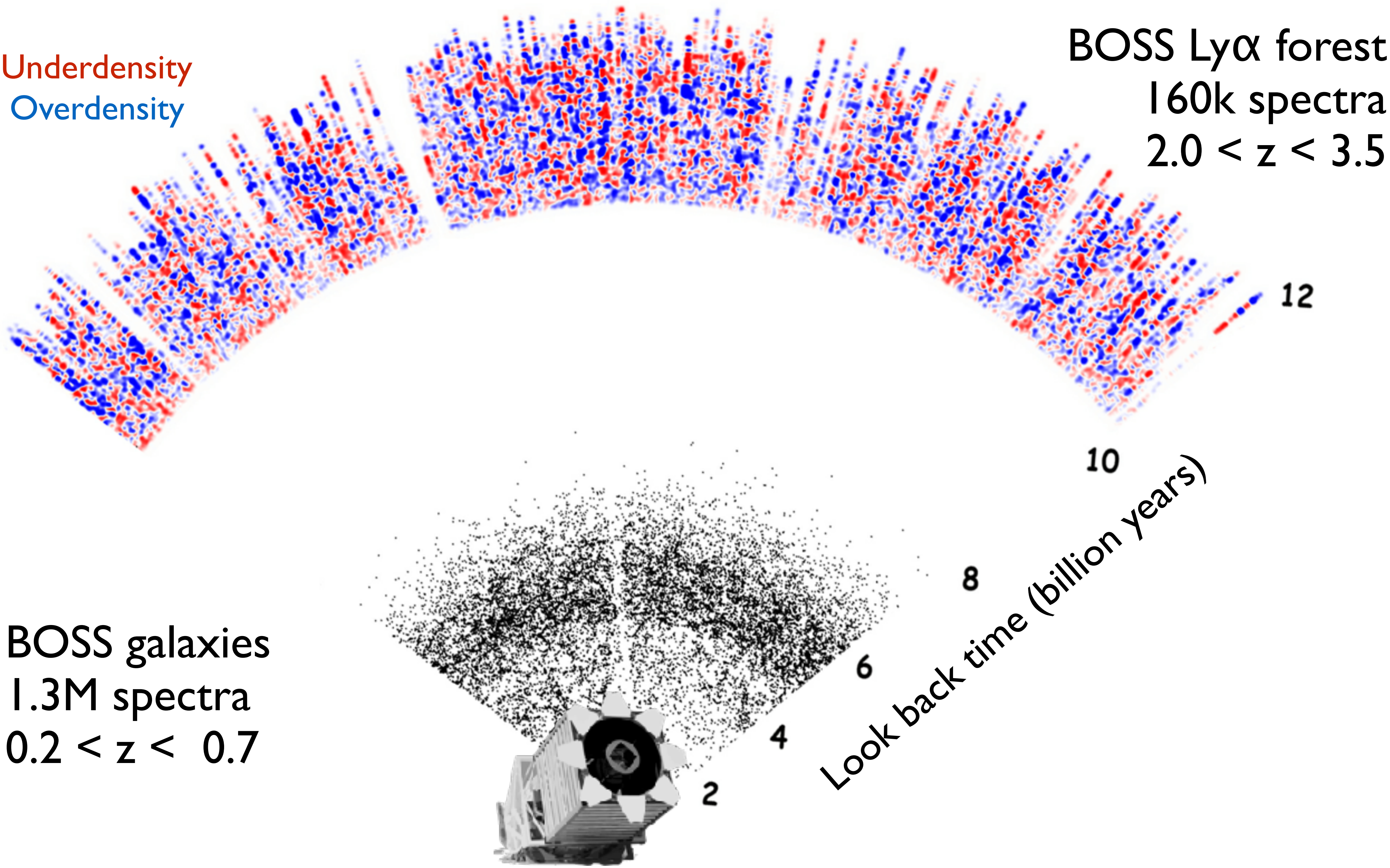
Large scale structure

The distribution of matter in the Universe tells us about:

- Accelerated expansion of the Universe / dark energy
- Tests of general relativity on cosmological scales
- Initial conditions of the Universe / inflation
- Particle physical properties of dark matter
- Mass and number of neutrino species

However, most of the matter in the Universe is in the form of dark matter and we need indirect tracers to study it

Redshift Surveys



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Baryon Acoustic Oscillations

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

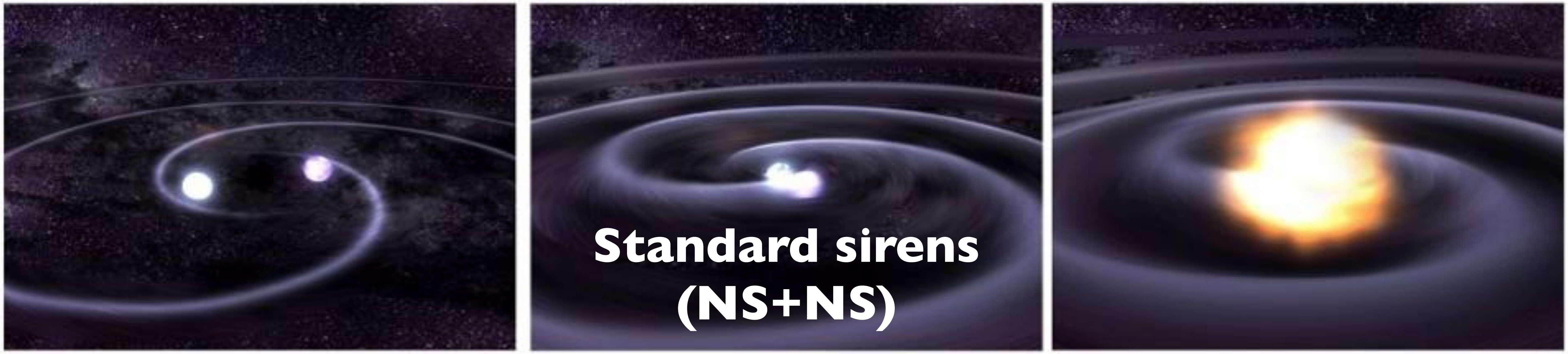
Standard candle (Supernovae)

known luminosity
+
measure flux
↓
distance

Standard ruler (BAO)

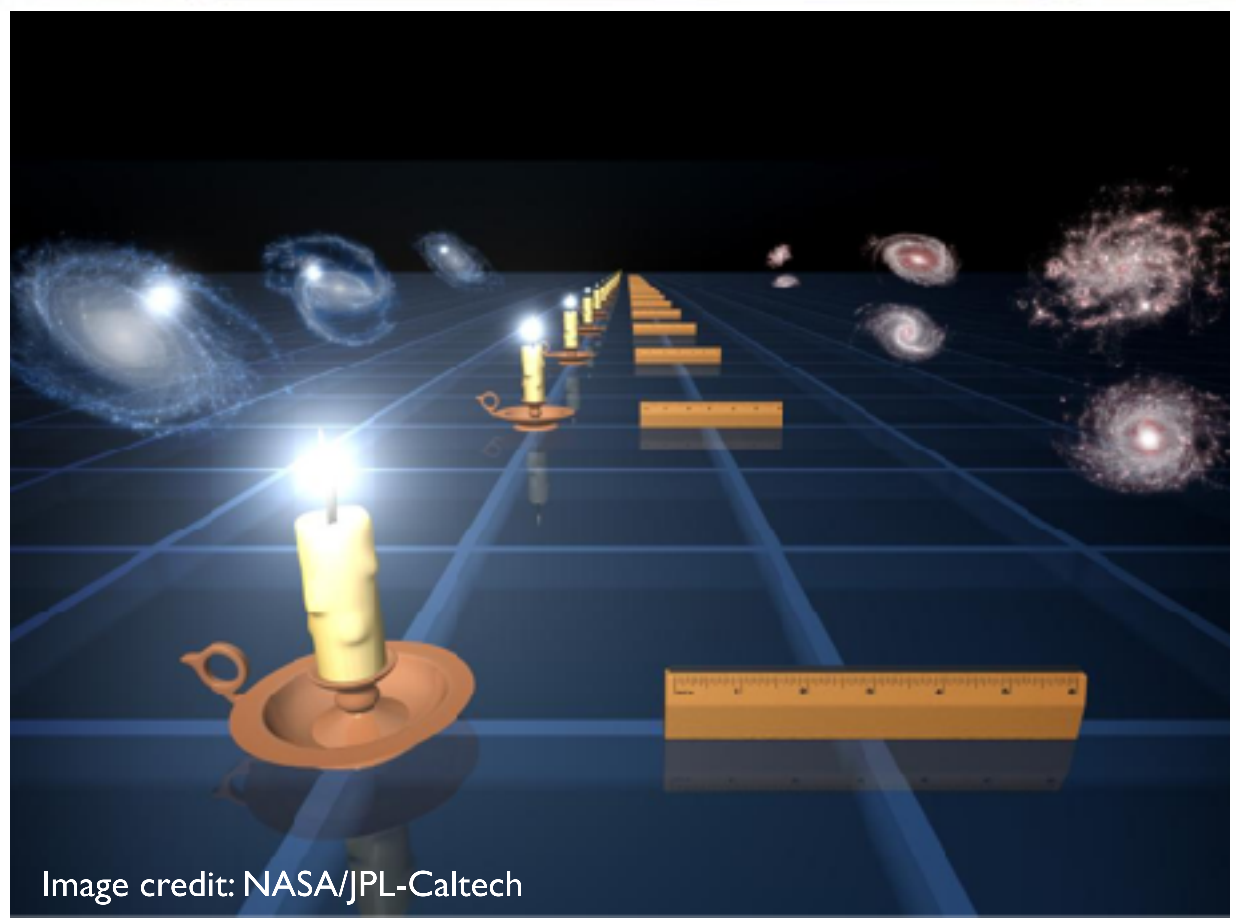
known size
+
measure apparent size
↓
distance

Baryon Acoustic Oscillations



Standard candle (Supernovae)

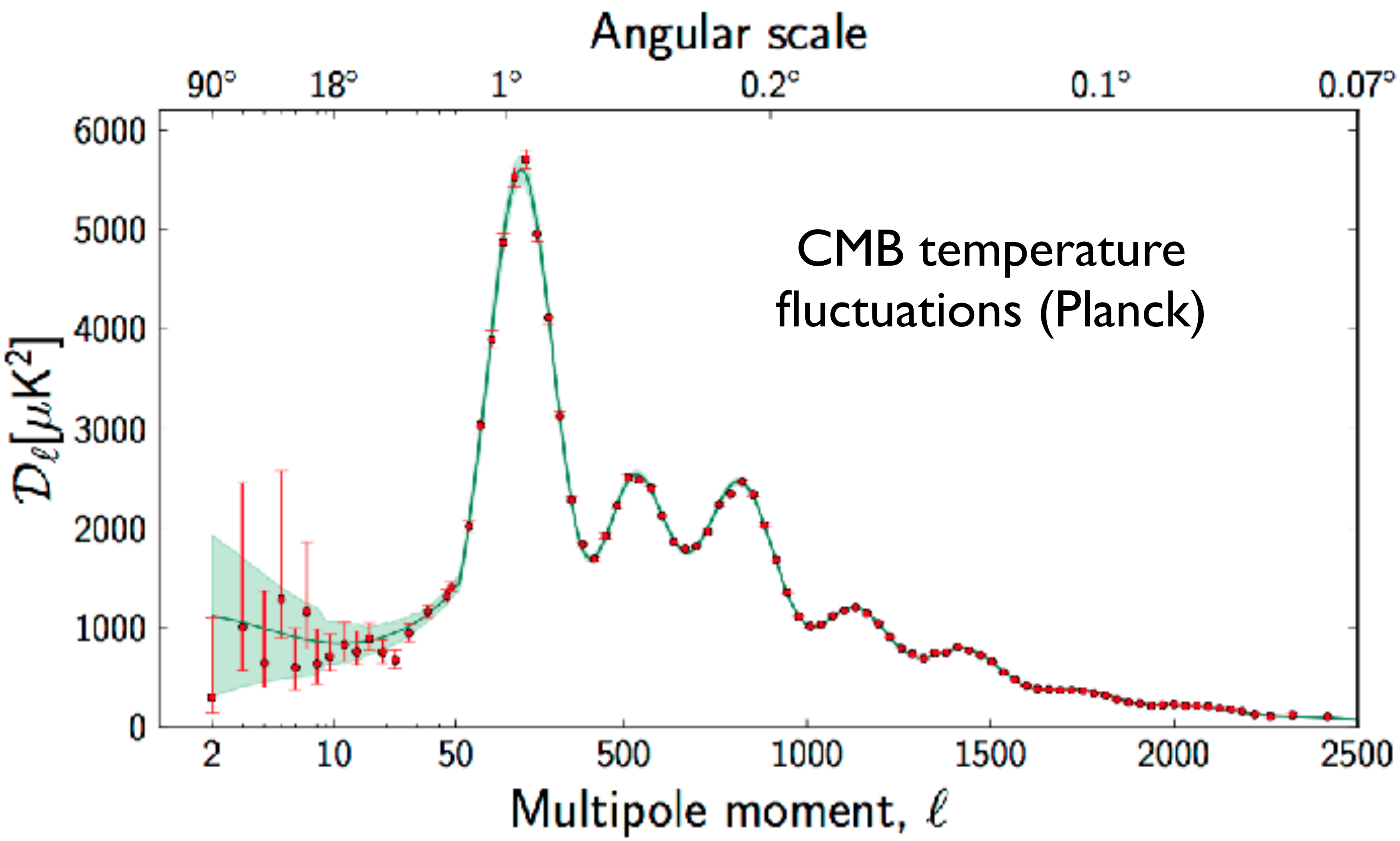
known luminosity
+
measure flux
↓
distance



Standard ruler (BAO)

known size
+
measure apparent size
↓
distance

Baryon Acoustic Oscillations



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

Sound horizon at recombination (from Planck): $r_d = 147.6 \pm 0.3 \text{ Mpc}$

Baryon Acoustic Oscillations

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

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

Sound horizon at recombination (from Planck): $r_d = 147.6 \pm 0.3 \text{ Mpc}$

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

We learn about the expansion!

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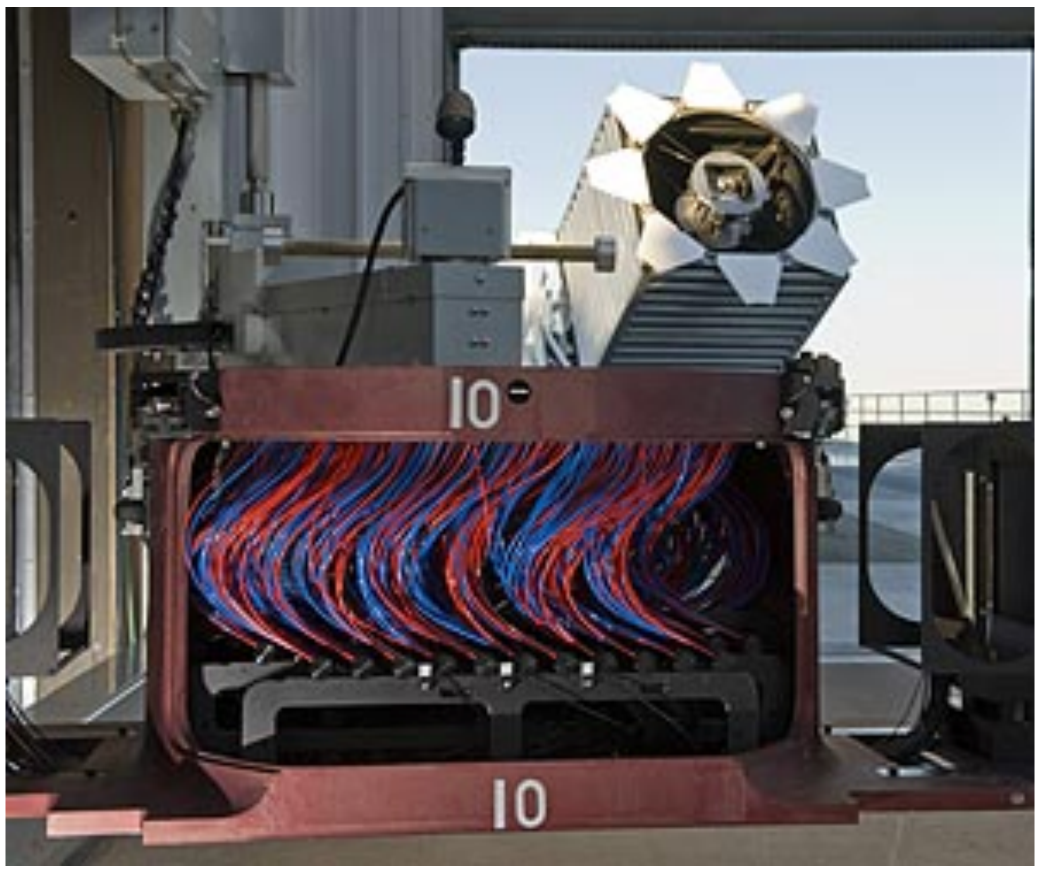
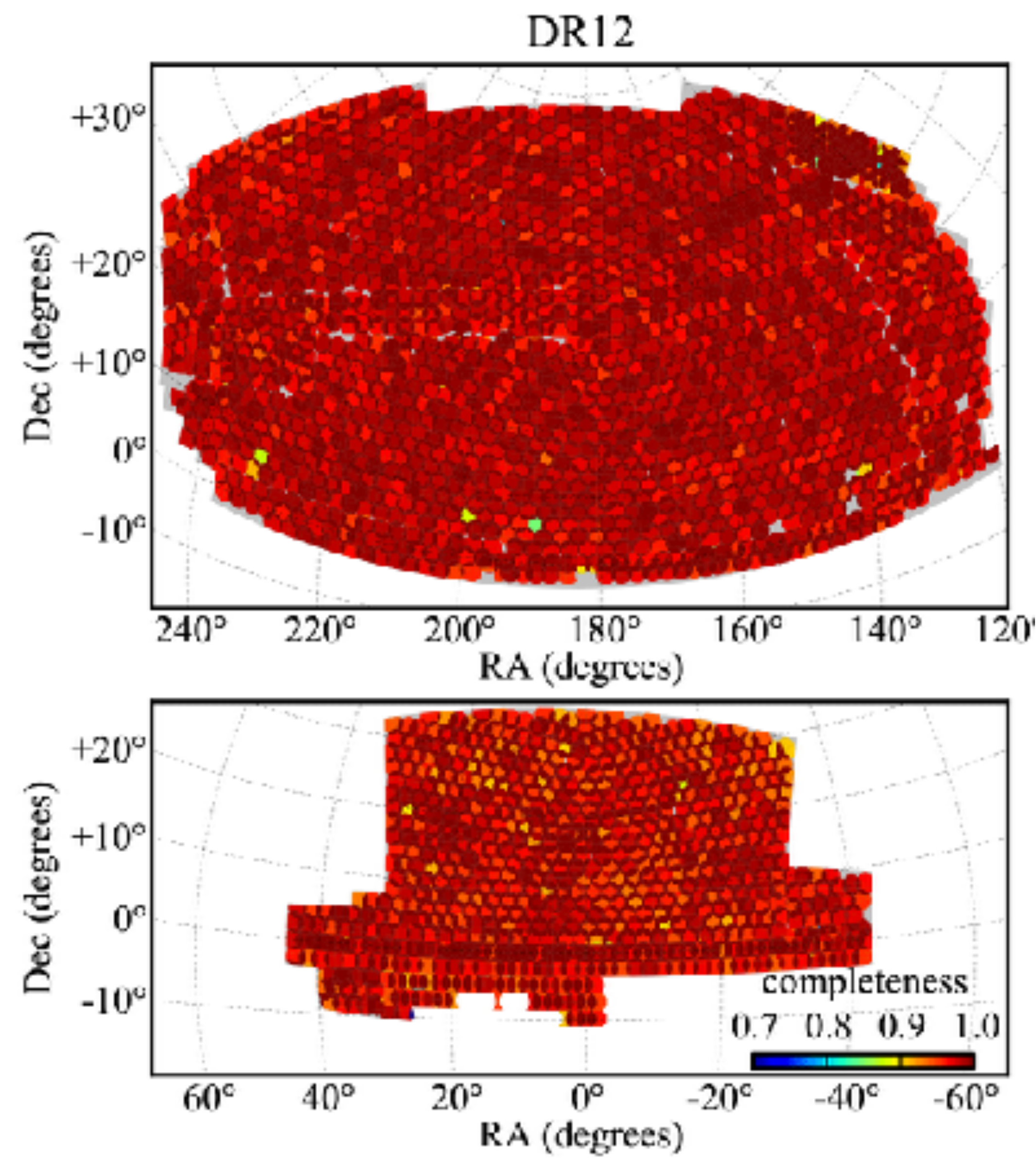
BOSS

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

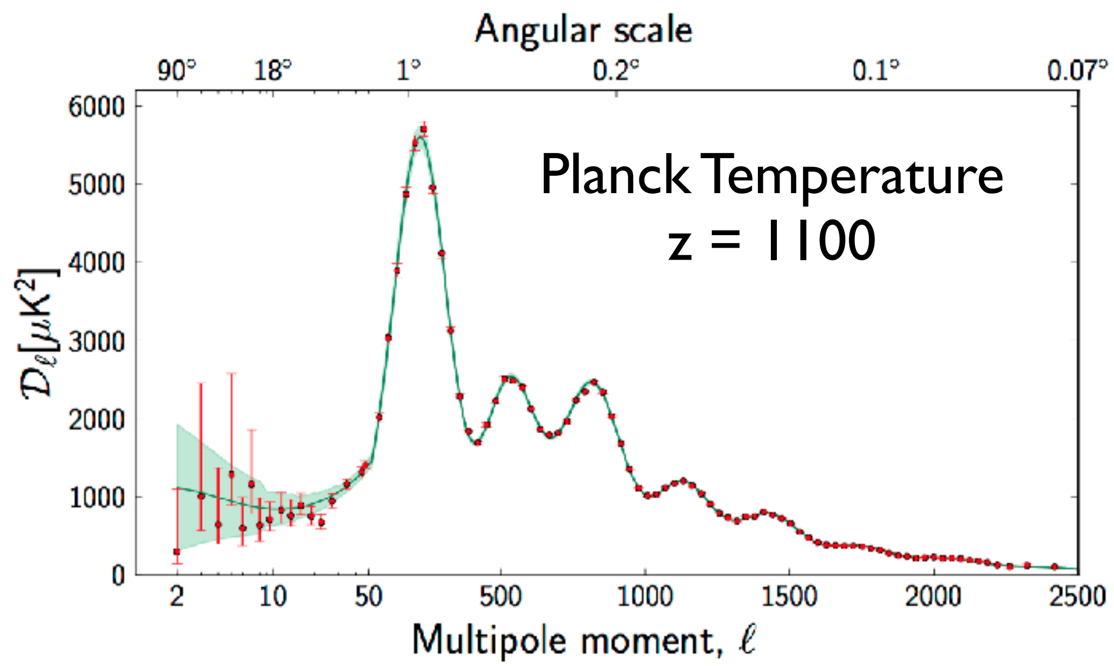


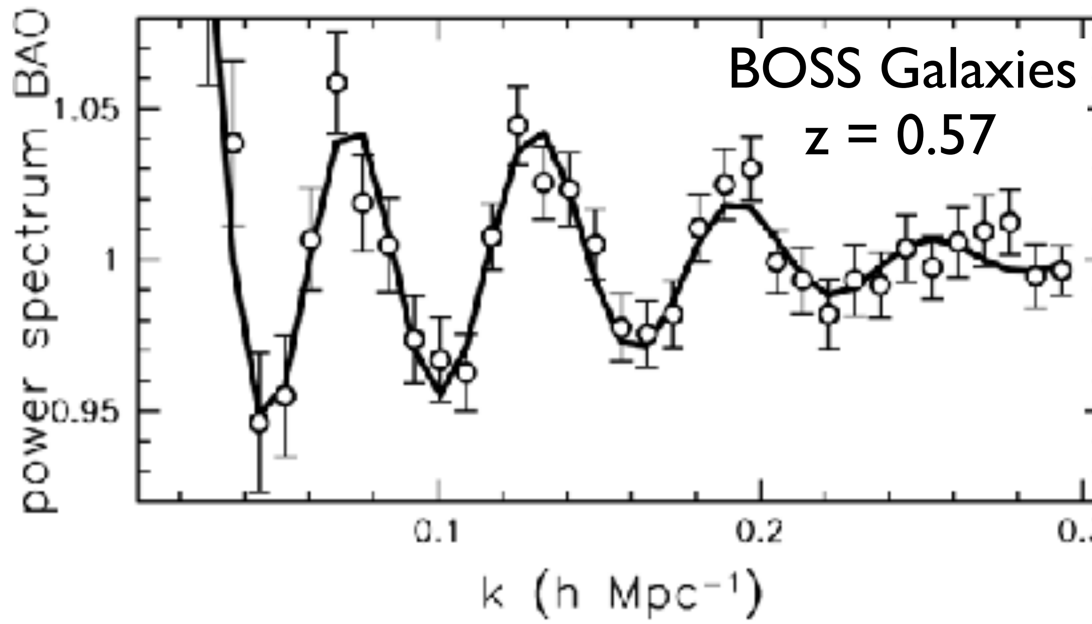
2 optical spectrographs
Mid resolution (R~2000)
1000 spectra at a time



10.000 sq. deg. (1/4 sky)
1.3M galaxies (0.2 < z < 0.7)
160k quasar (2.1 < z < 3.5)

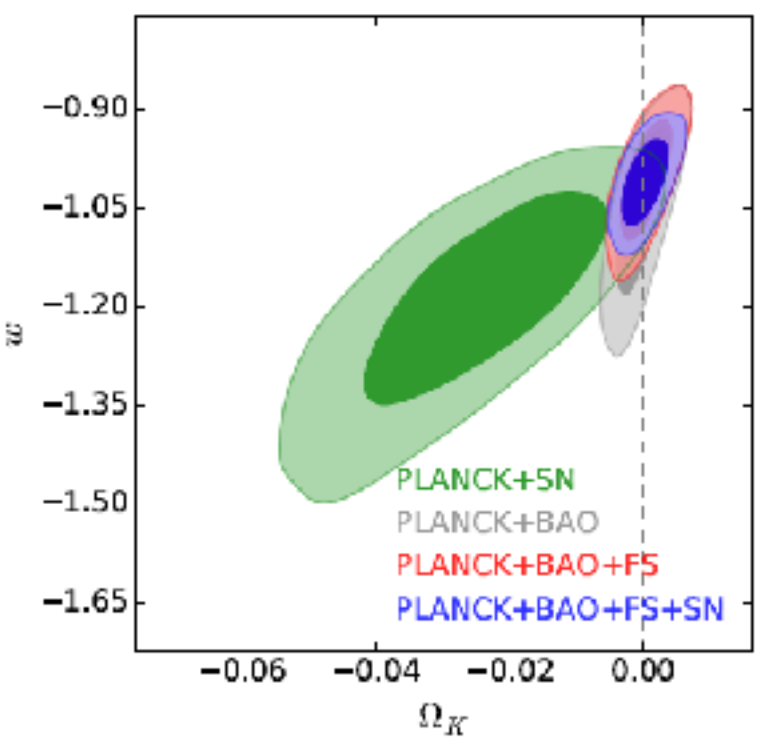
Baryon Acoustic Oscillations

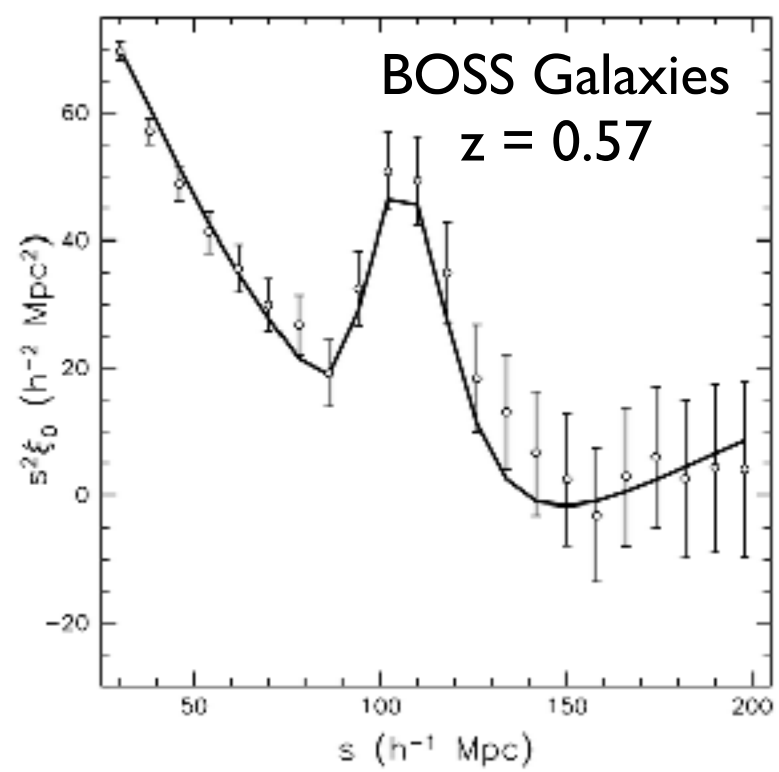




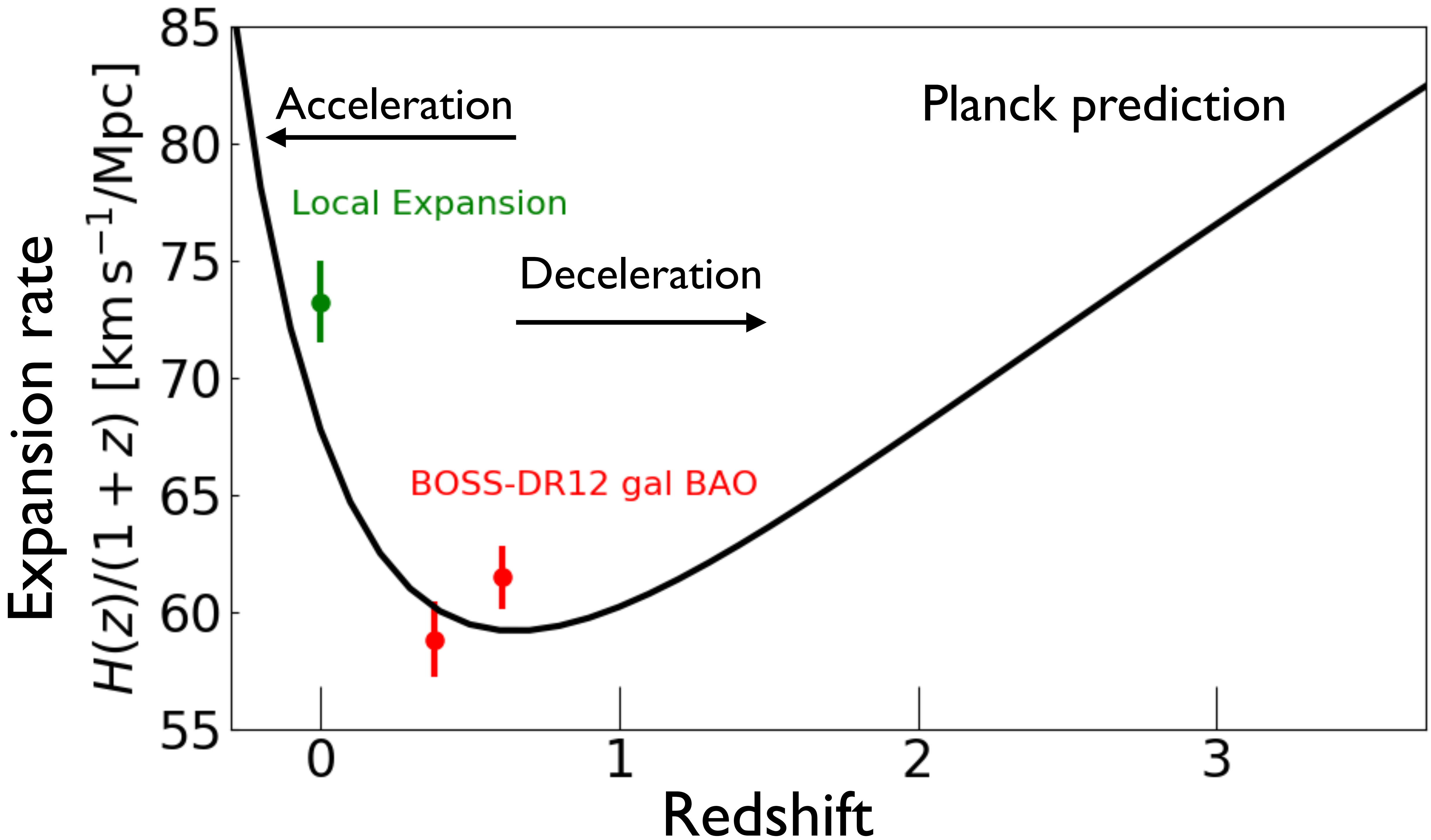
Oscillations clearly seen in CMB, but also in clustering of galaxies

Fourier transform





BOSS



Acceleration
Planck prediction
Local Expansion
Deceleration
BOSS-DR12 gal BAO
Expansion rate
$H(z)/(1+z)$ [km s^{-1}/Mpc]
85
80
75
70
65
60
55
0
1
2
3
Redshift

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The Lyman-α forest

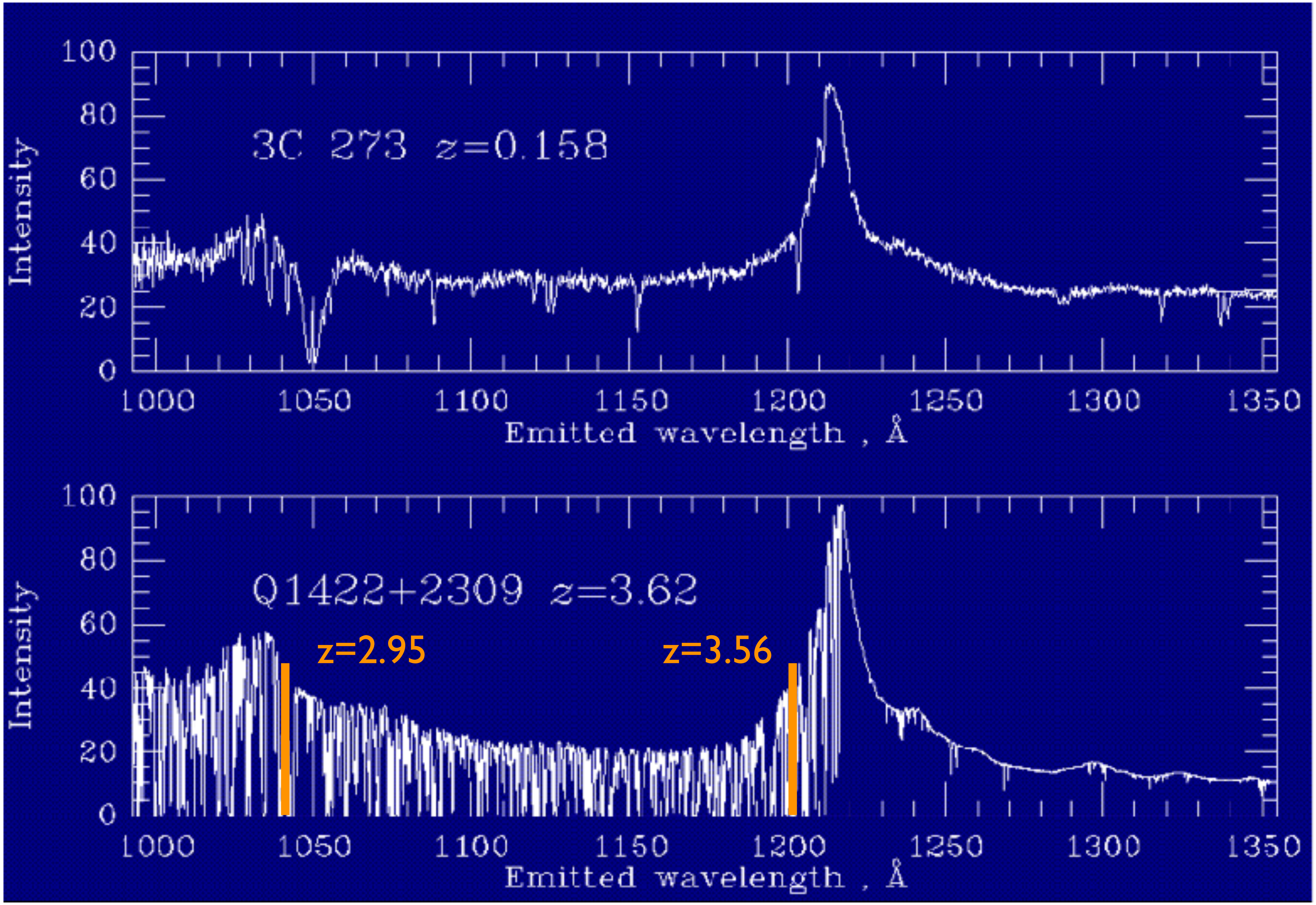
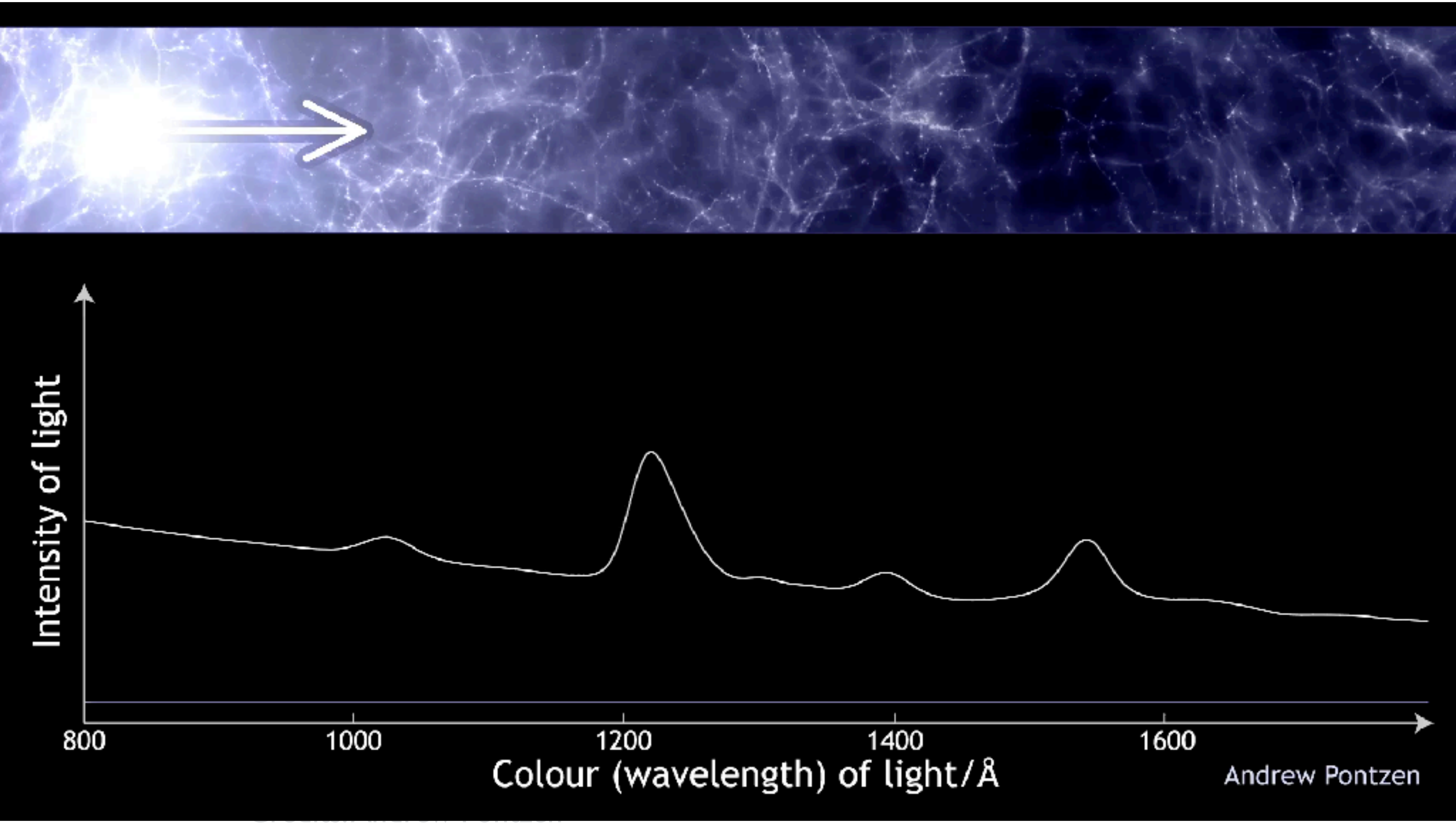
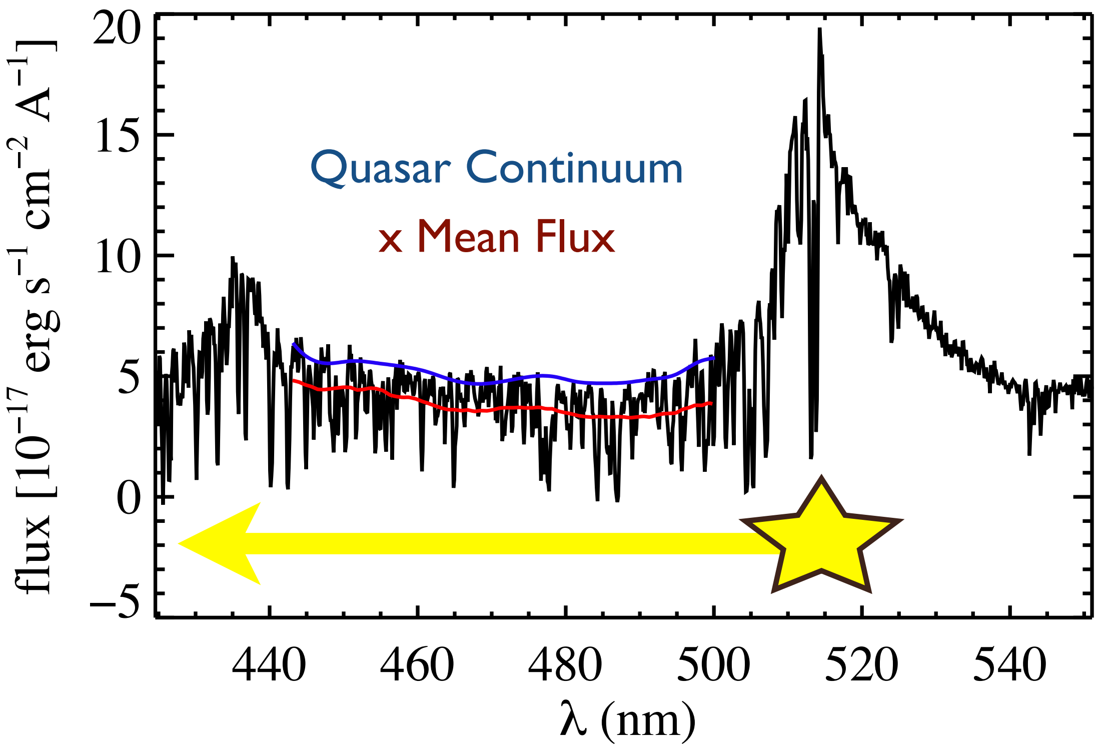


Figure from William C. Keel

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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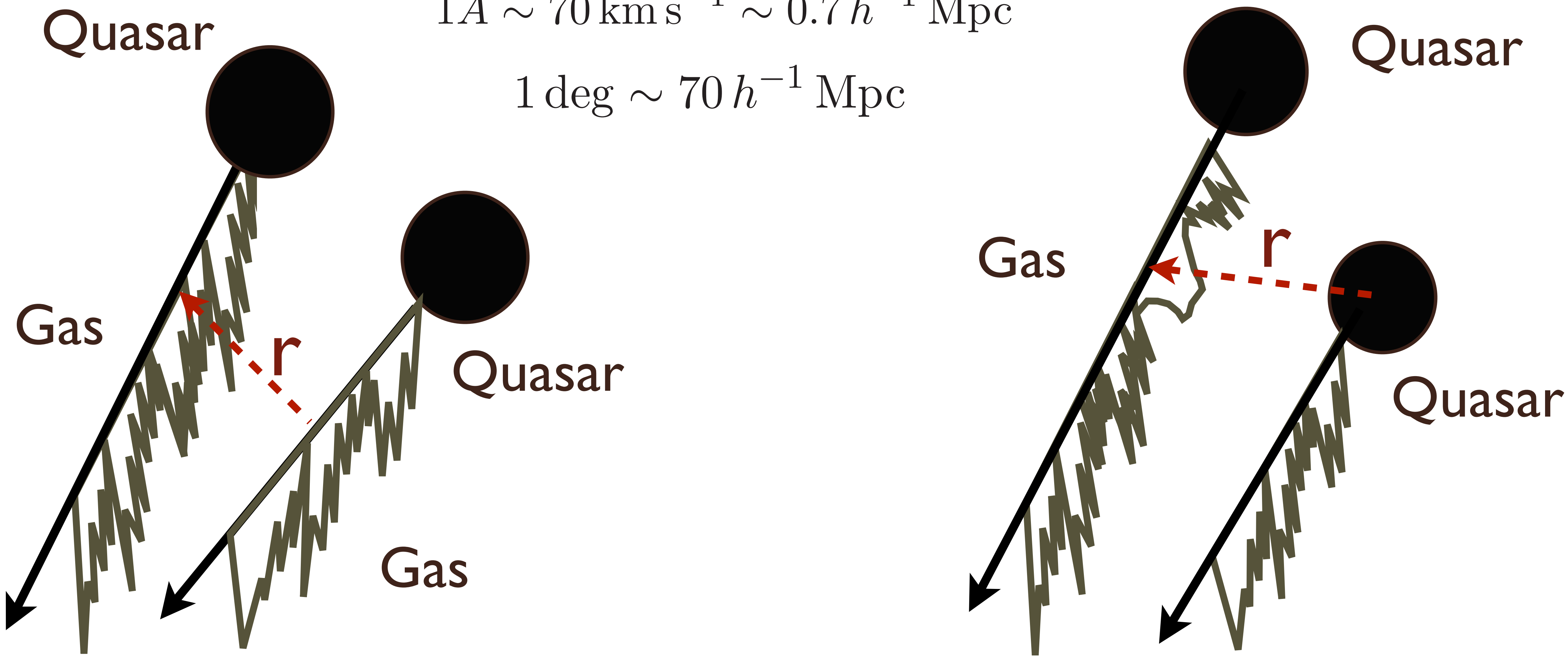
BOSS Lyman-α BAO

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 | Lyα-quasar cross-correlation

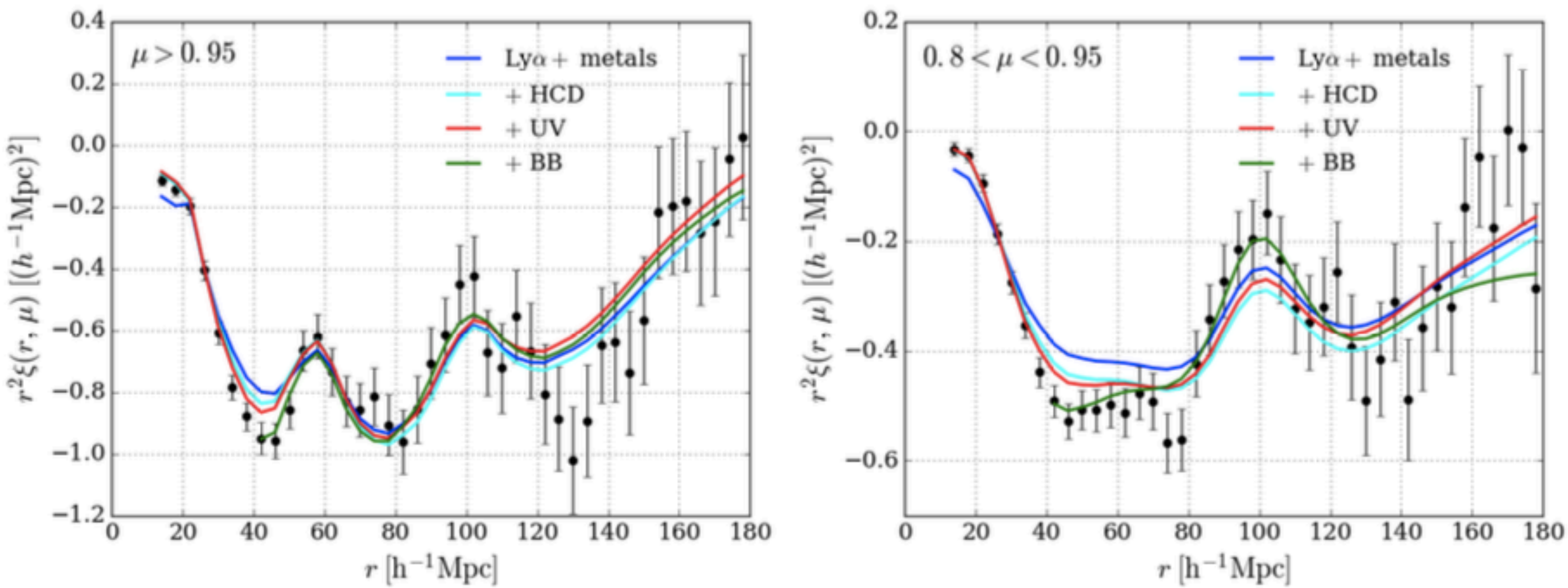
Delubac et al. (2015) —— DR11 —— Font-Ribera et al. (2014)

Bautista et al. (2017) —— DR12 —— du Mas des Bourboux (2017)

Lya auto-BAO

Julian Bautista
(Moved from Utah
to Portsmouth)

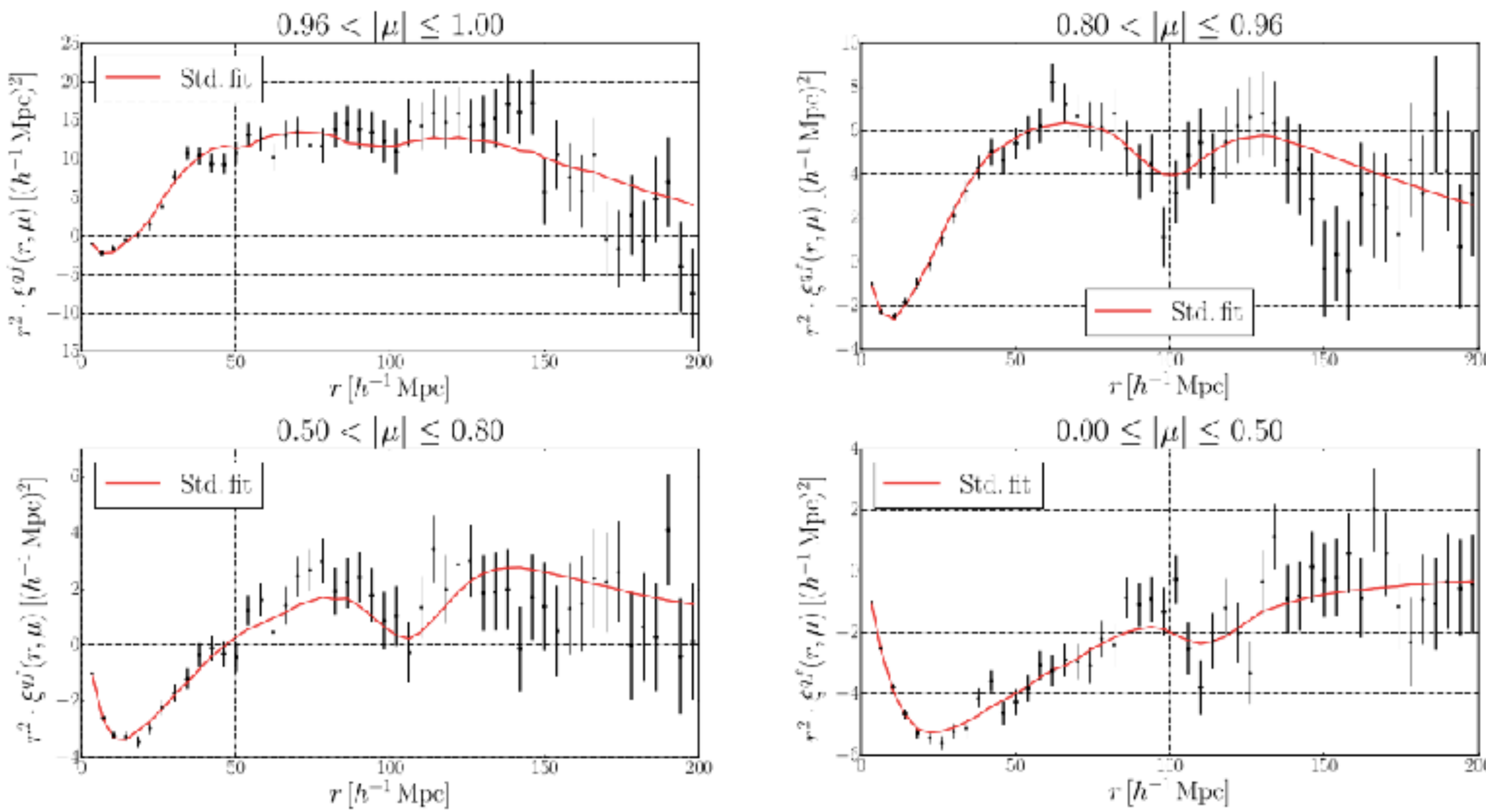
Bautista et al (2017)
BAO from DR12 Lyα
auto-correlation



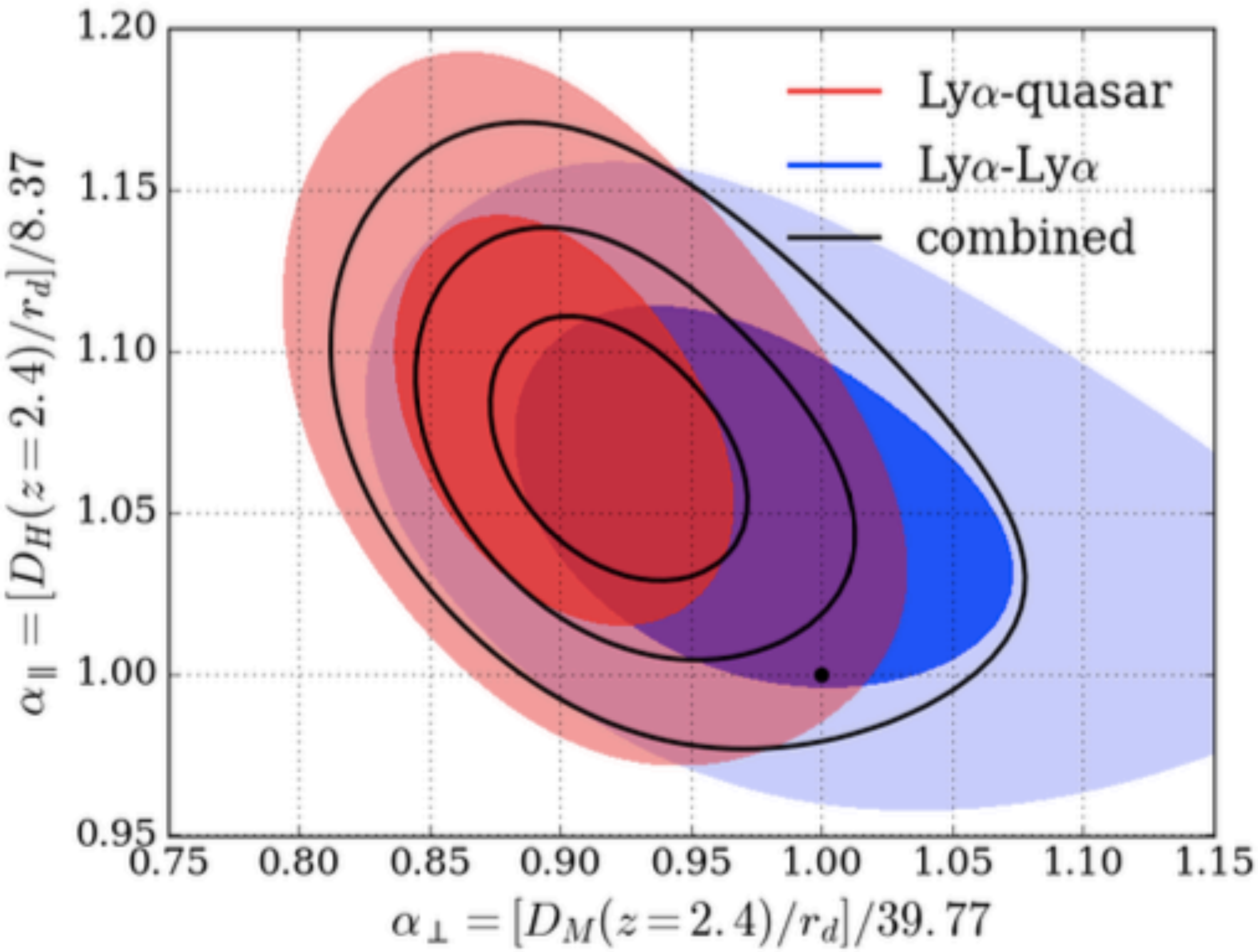
QSO-Lya cross-BAO

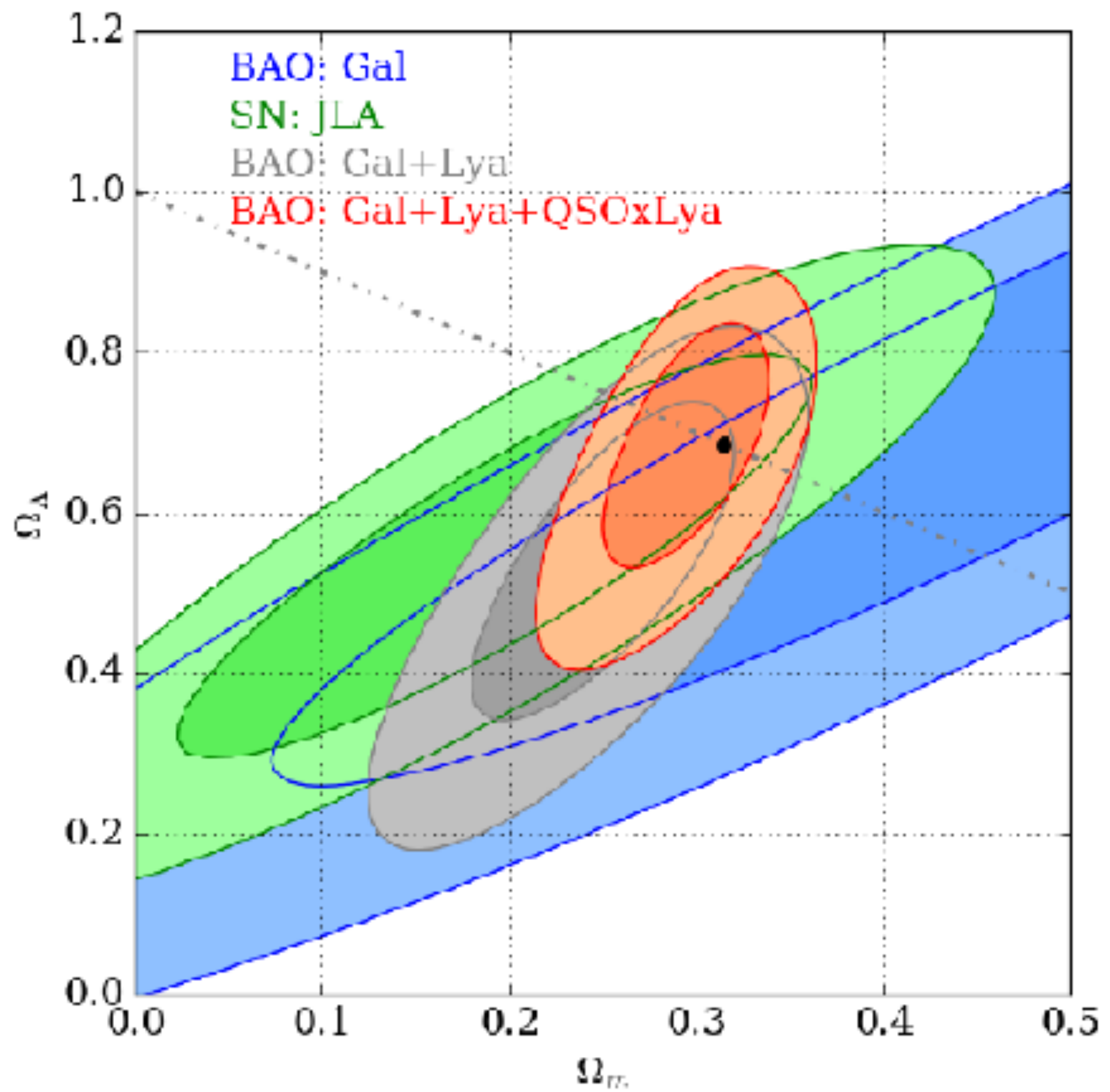
Helion du Mas des Bourboux
(Moved from Saclay to Utah)

dMdB et al. (2017) BAO
from DR12 QSO x Lyα



Combined BOSS BAO



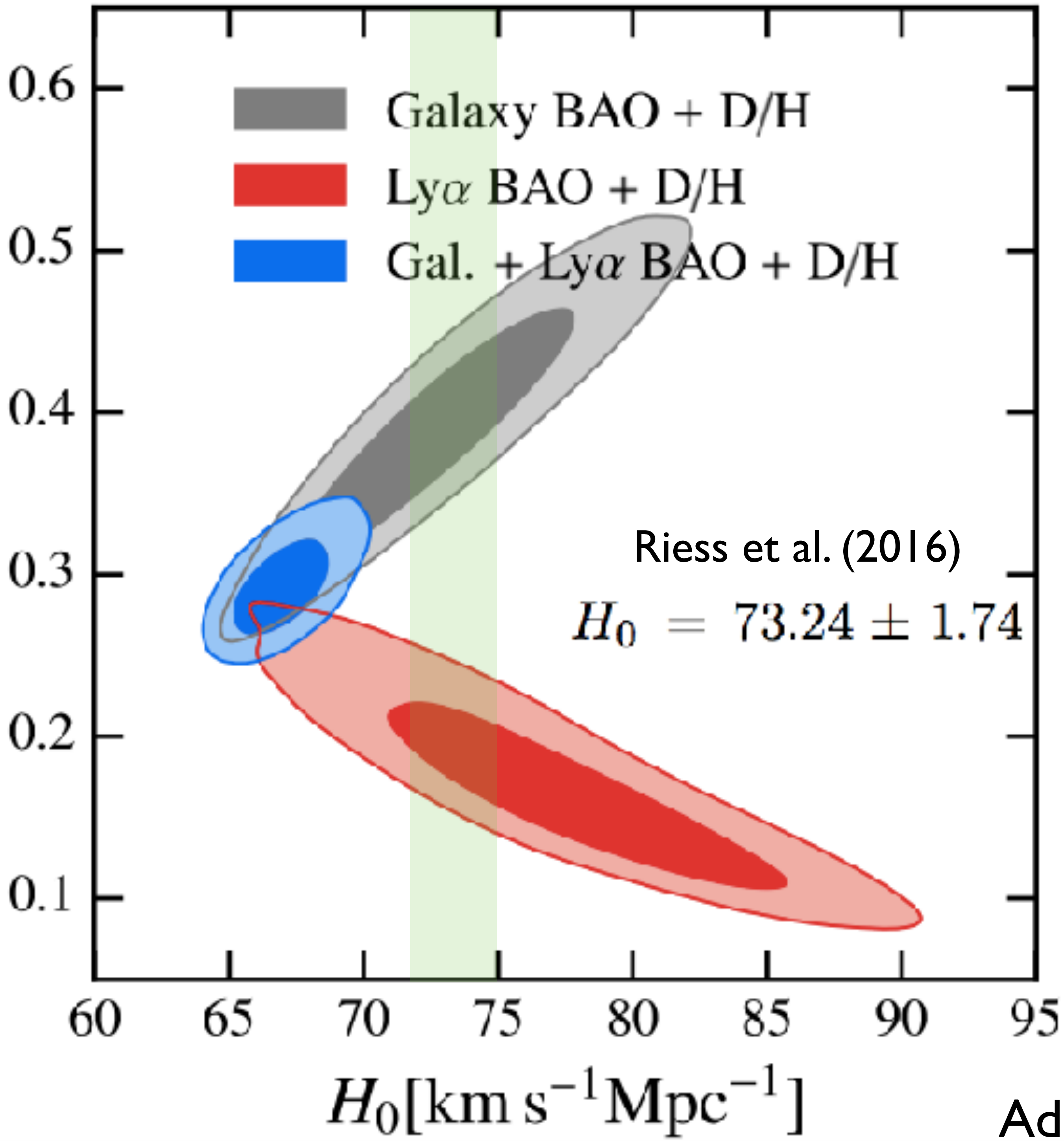


In a flat ΛCDM model

$\Omega_m = 0.292 \pm 0.019$ BAO

$\Omega_m = 0.315 \pm 0.017$ Planck

BAO and the H_0 tension



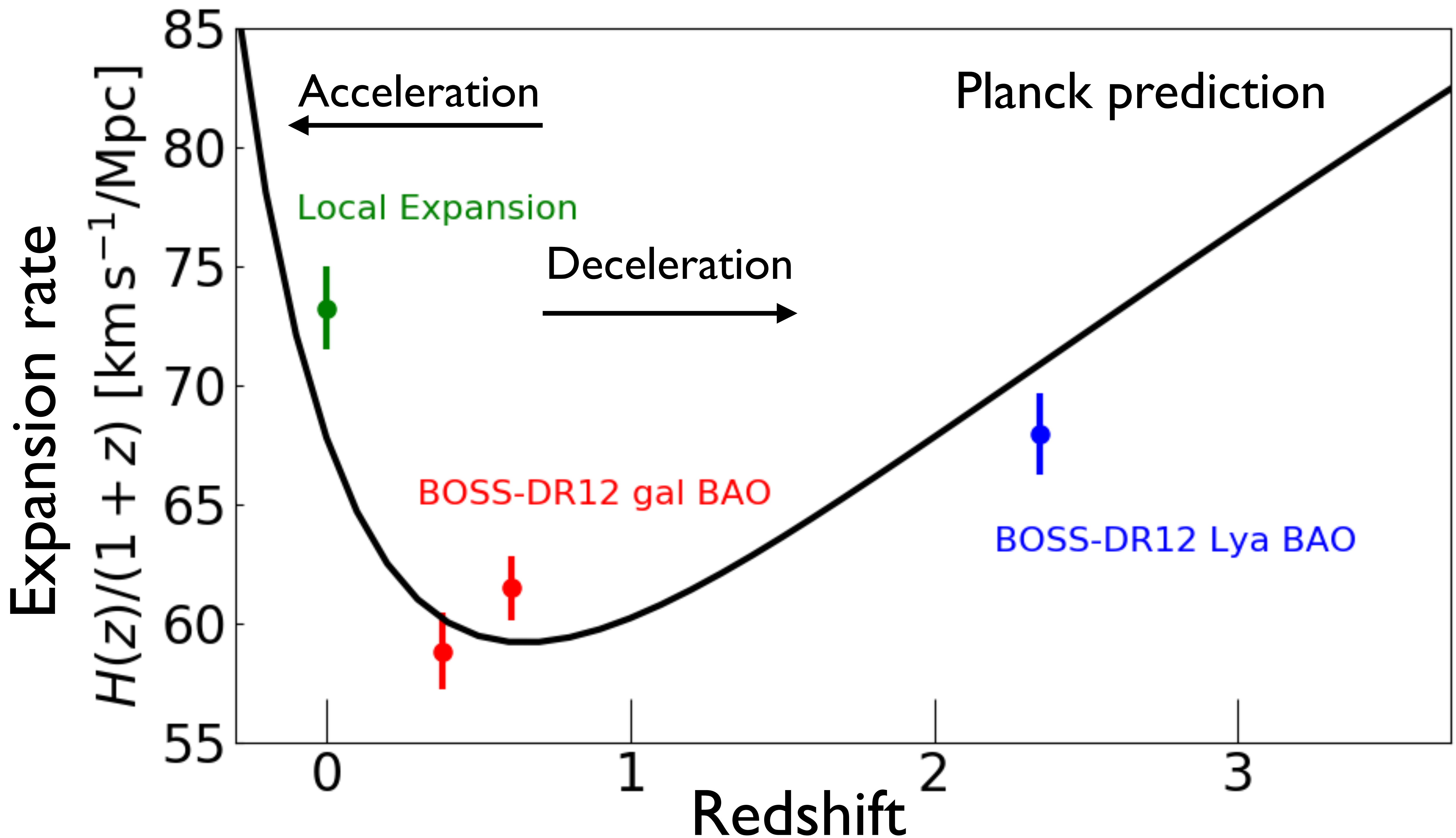
Addison et al. (2017)

Planck + LCDM predicts value of H_0 lower than that from local expansion (Riess et al. 2016)

BAO + LCDM constraint Ω_m and H_0 r_s (sound horizon, size of ruler)

With BBN prior on Ω_b we can break degeneracy and measure H_0 from BAO

BOSS Lyman-α BAO



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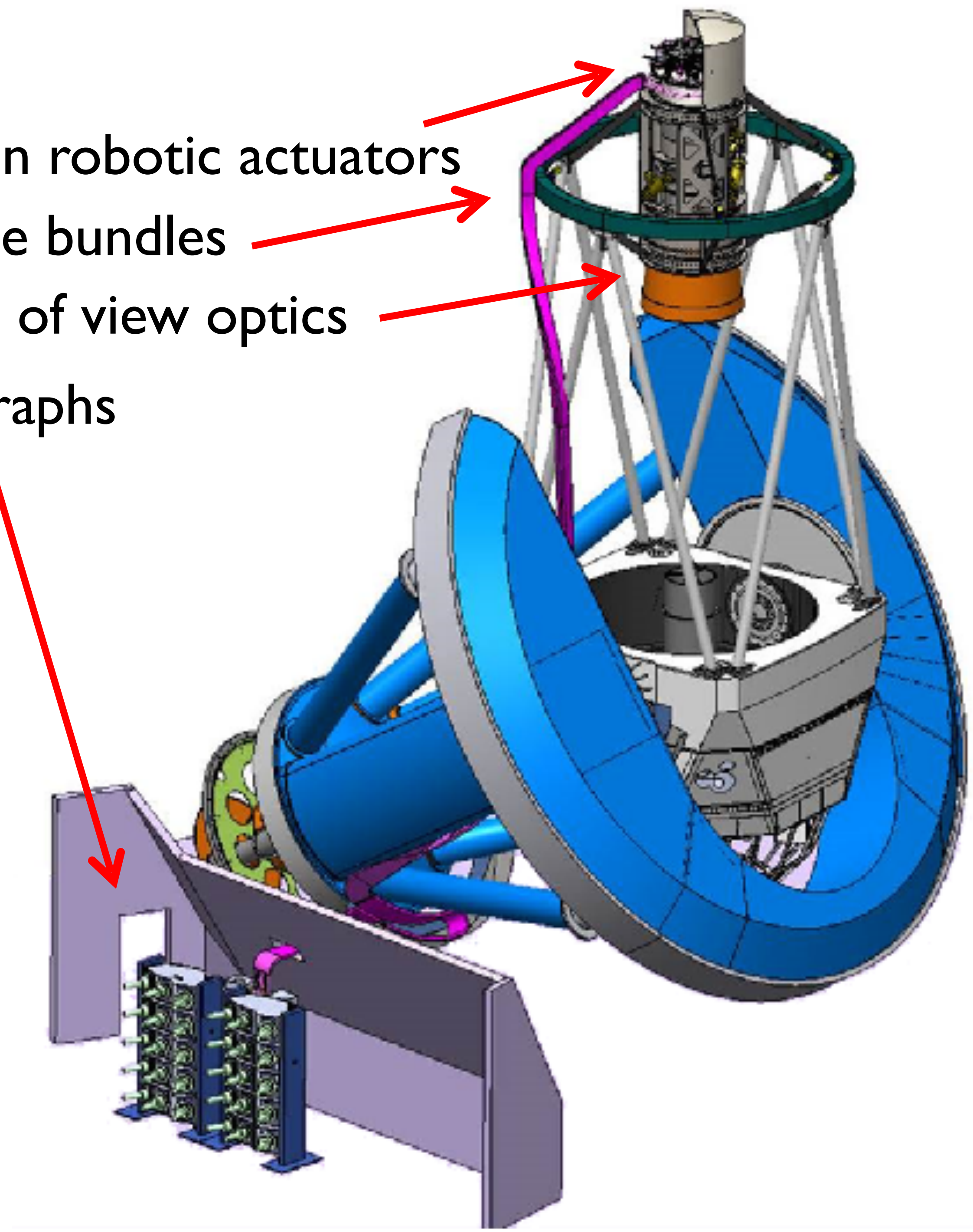
Dark Energy Spectroscopic Instrument

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



Readout
& Control

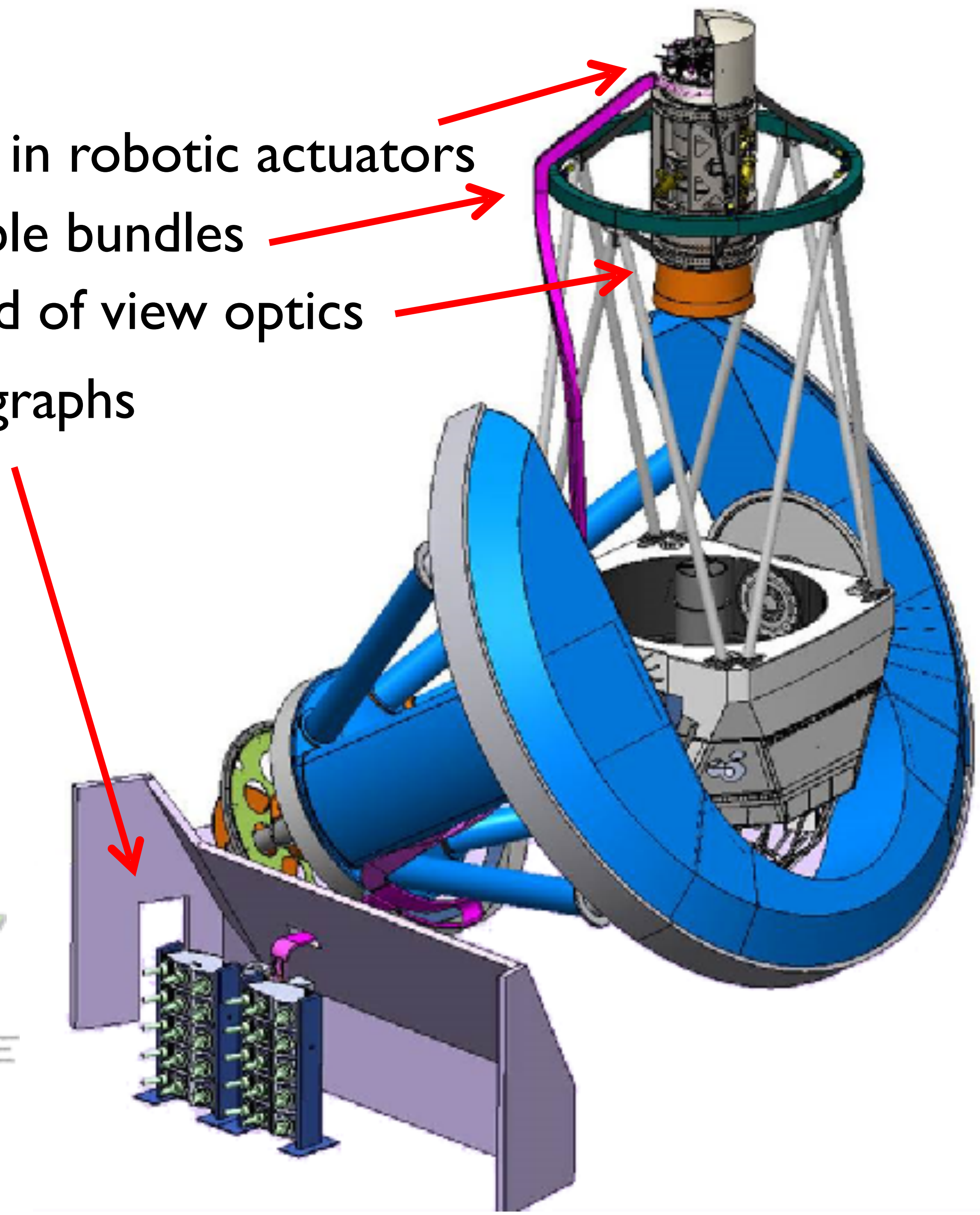
Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS dataset by an order of magnitude

Scheduled to start in 2019

Dark Energy Spectroscopic Instrument

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

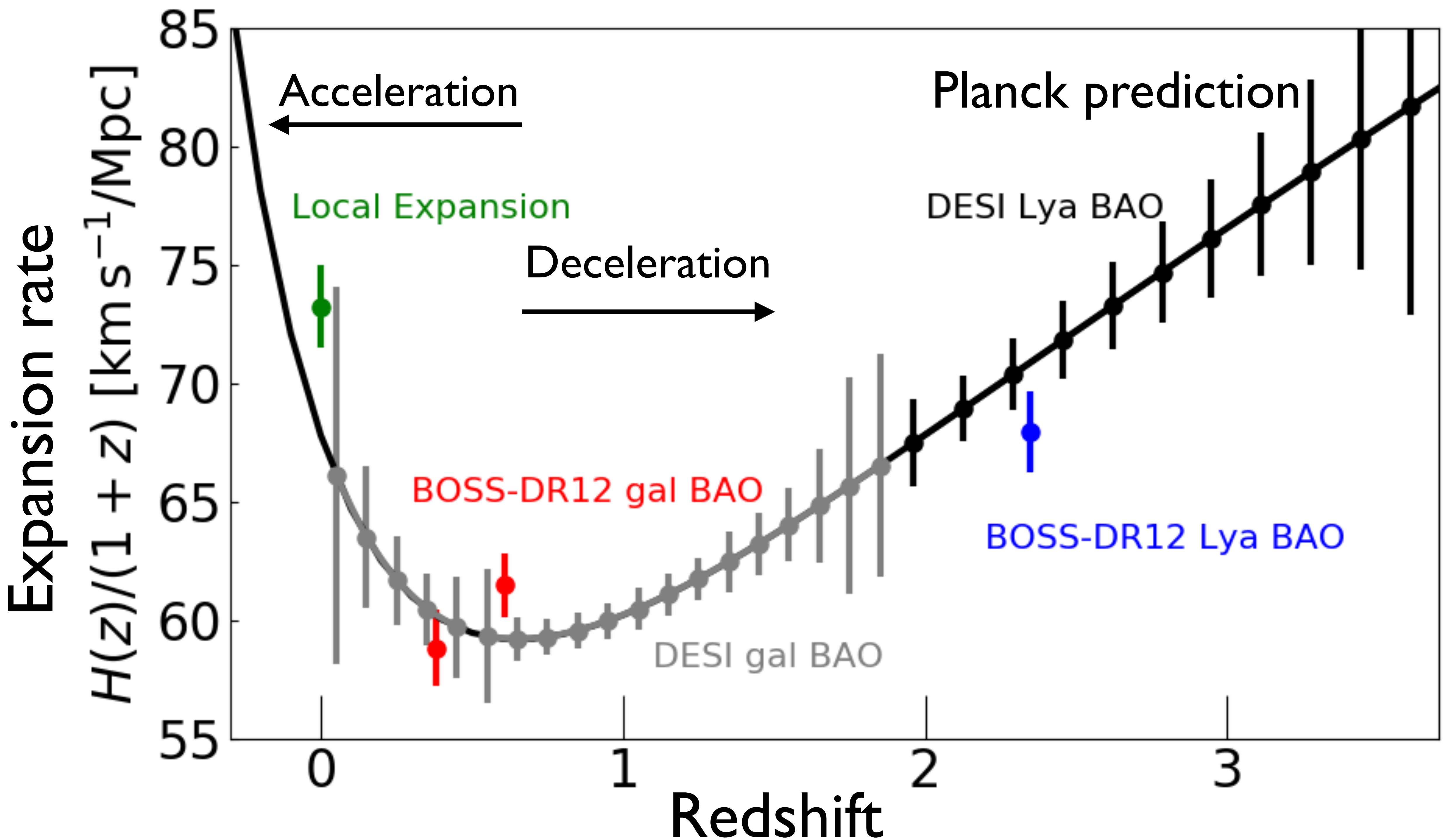


Readout & Control

Lens in cell, UCL, March 2018

Dark Energy Spectroscopic Instrument

DESI projections (Font-Ribera++ 2014b)



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White paper on BAO systematics

Led by: Nicolas Busca (LPNHE), Andreu Font-Ribera (UCL), Julien Guy (LBNL) and Anže Slosar (BNL)

Lessons learned from BOSS/eBOSS. Need to be ready for DESI!

4 type of simulations needed — DESI Ly-α mocks

9 astrophysics systematics

7 instrumental systematics

6 analysis systematics

Translating now into cosmological simulations requirements

DESI Lyα mocks with CoLoRe

Mock realisations of the survey are extremely valuable:

- Test analysis pipeline: continuum fitting, covariance matrix
- Test potential systematics: metals, DLAs, sky residuals
- Forecast survey performance: help vs depth?

All Lyα BAO analyses in BOSS used mocks using an algorithm developed in Font-Ribera et al. (2012)

… but they do not have correlated quasars

DESI needs mocks with correct cross-correlation with quasars!

DESI Lyα mocks with CoLoRe

CoLoRe: Cosmological Lognormal Realizations

- Developed by David Alonso (Oxford) for LSST
- Galaxy clustering, cosmic shear, intensity mapping…
- We have adapted it to also generate Lyα skewers


James Farr
(PhD @ UCL)

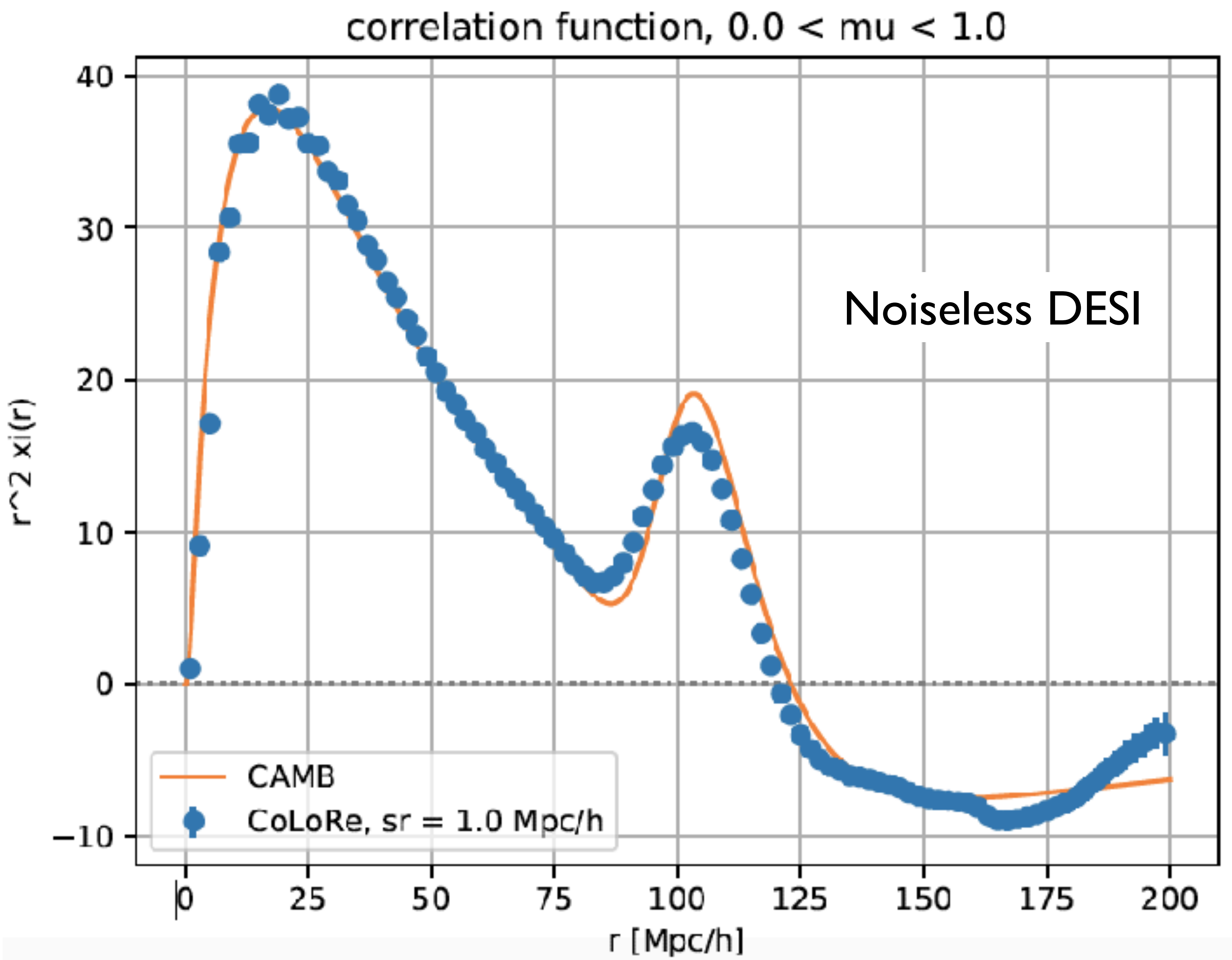
How does it work?

- Define a (really) large box covering all sky to z=4
- Generate a random Gaussian field using linear density P(k)
- Generate light-cone with linear growth
- Lognormal transformation + Poisson sampling to get halos
- Extract density and velocity towards each halo

Performance:

- MPI parallelised: can generate 8192^3 using 256 nodes at NERSC
- Cell sizes still too large, we need to add extra uncorrelated power

DESI Lyα mocks with CoLoRe



James Farr
(PhD @ UCL)

Work in progress:

- Model smoothing
- Add RSD
- Extra power
- Add contaminants

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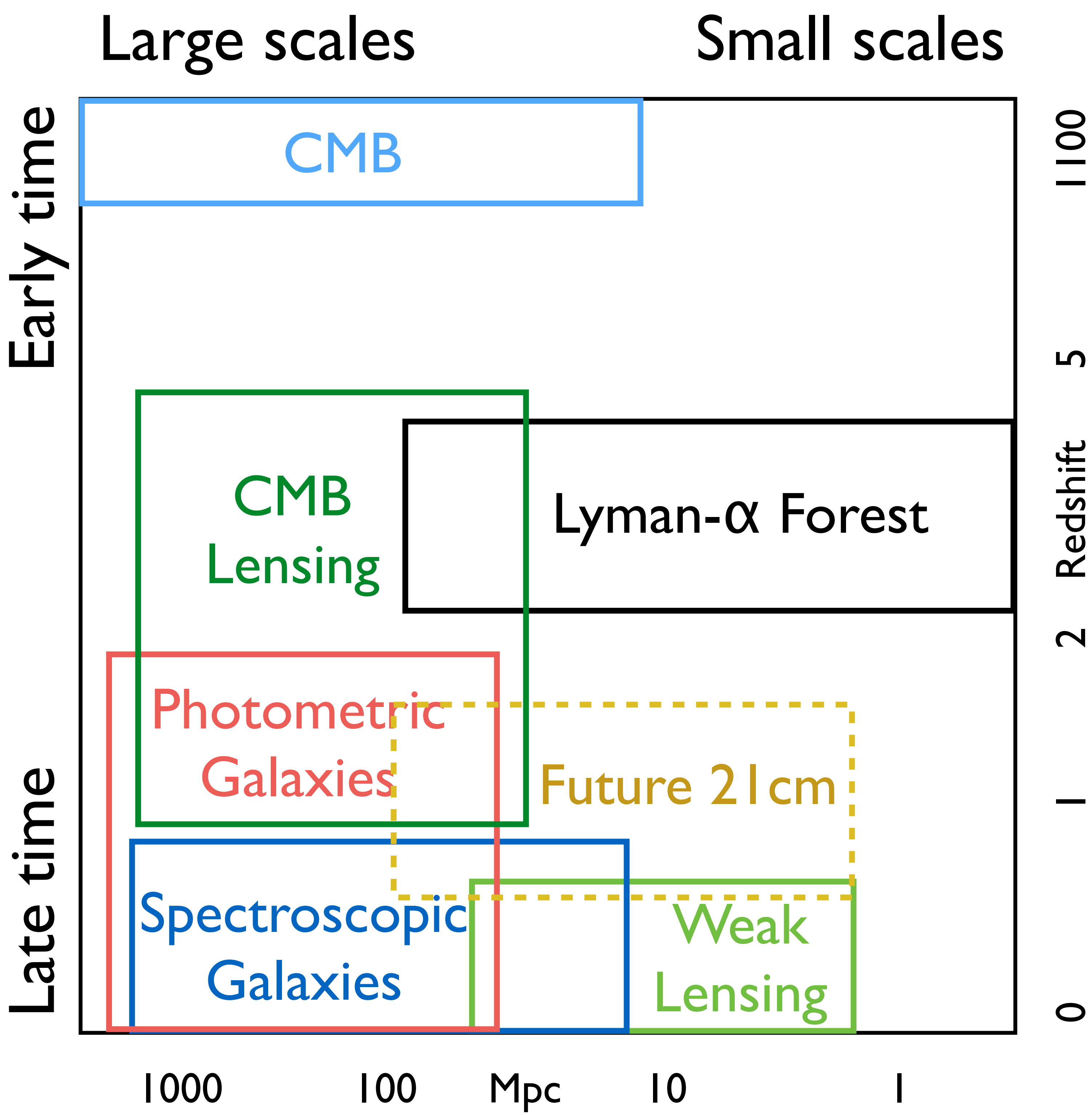
Small scale clustering

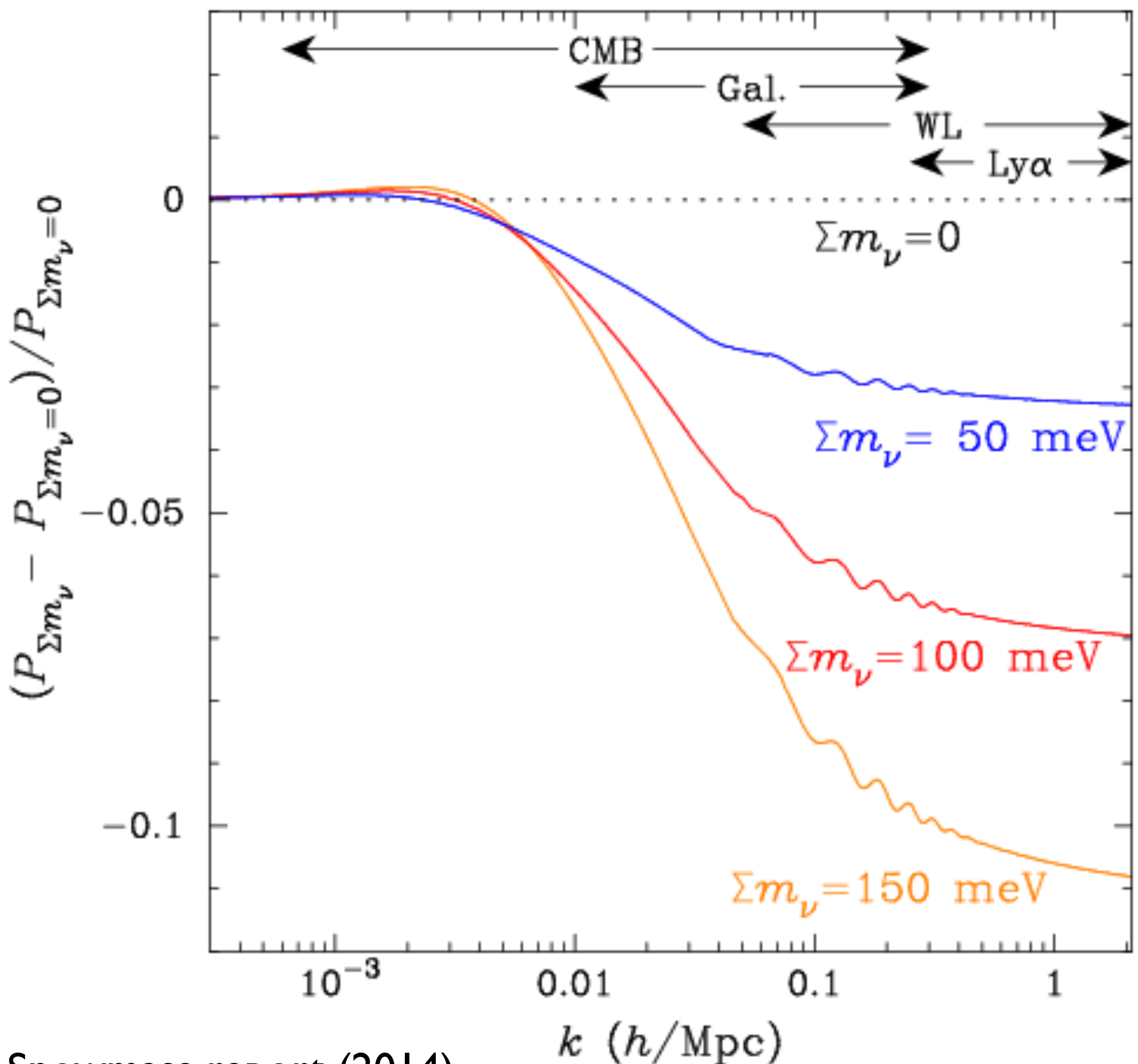


Lyman-α forest offers a unique window to study small scale clustering

Combined with CMB, it allows us to study:

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

Small scale clustering



Snowmass report (2014)

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

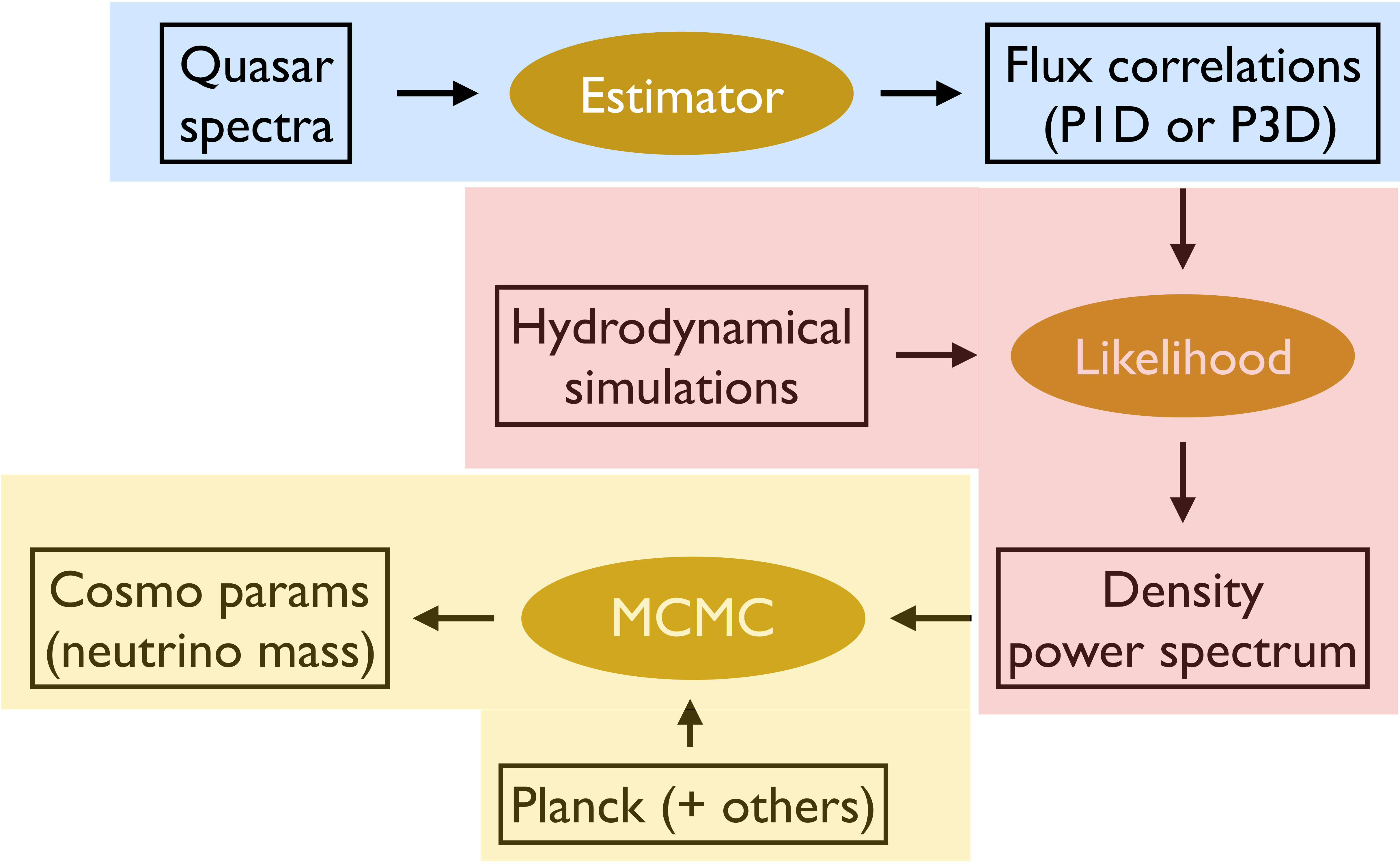
Comparing the power on large and small scales we can constraint neutrino masses

Best constraints from Planck + BOSS Lyα

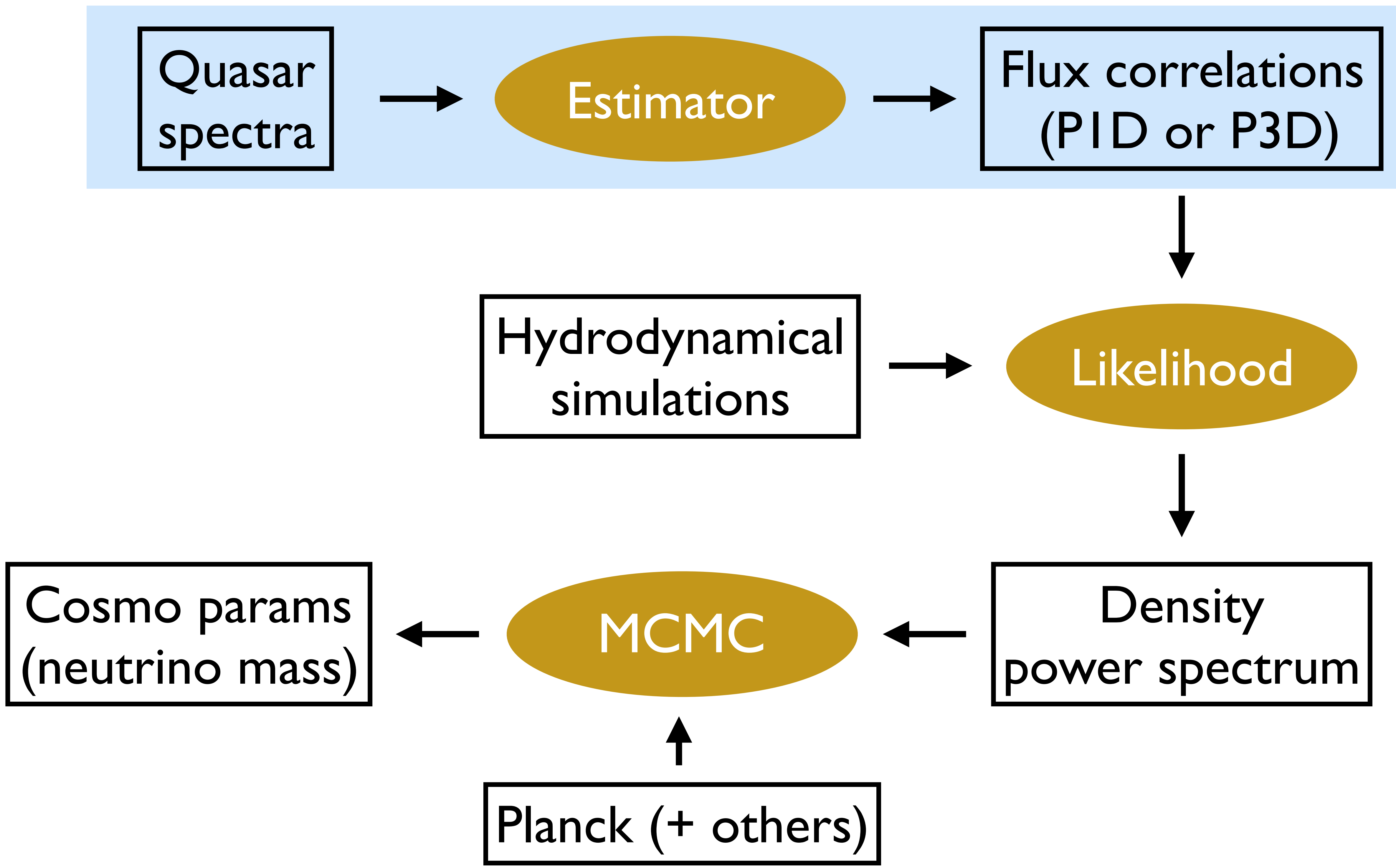
$\Sigma m_\nu < 0.12$ eV (95%)

(Palanque-Delabrouille++ 2015)

Small scale clustering

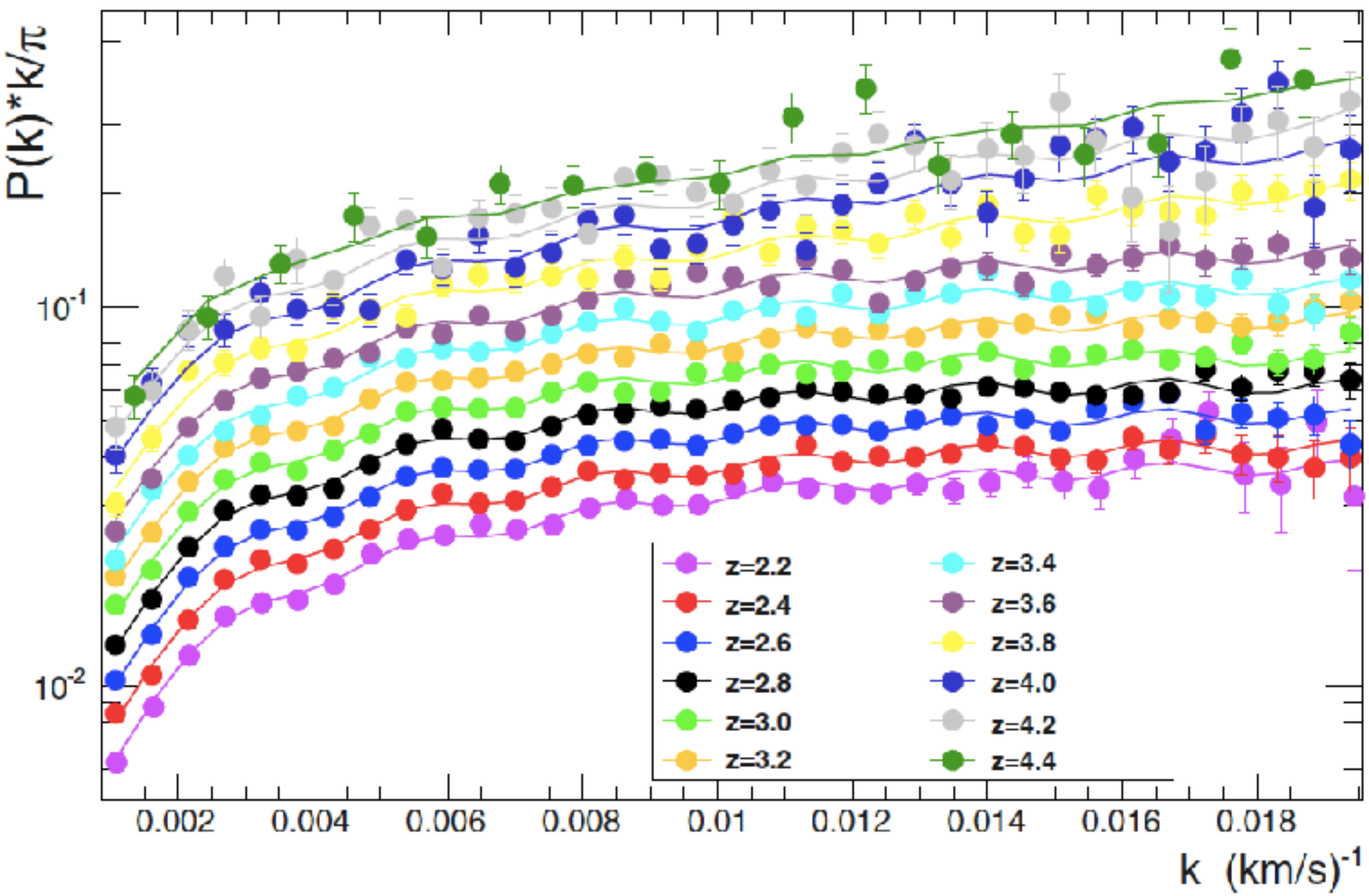


Small scale clustering



Estimators: 1D P(k)

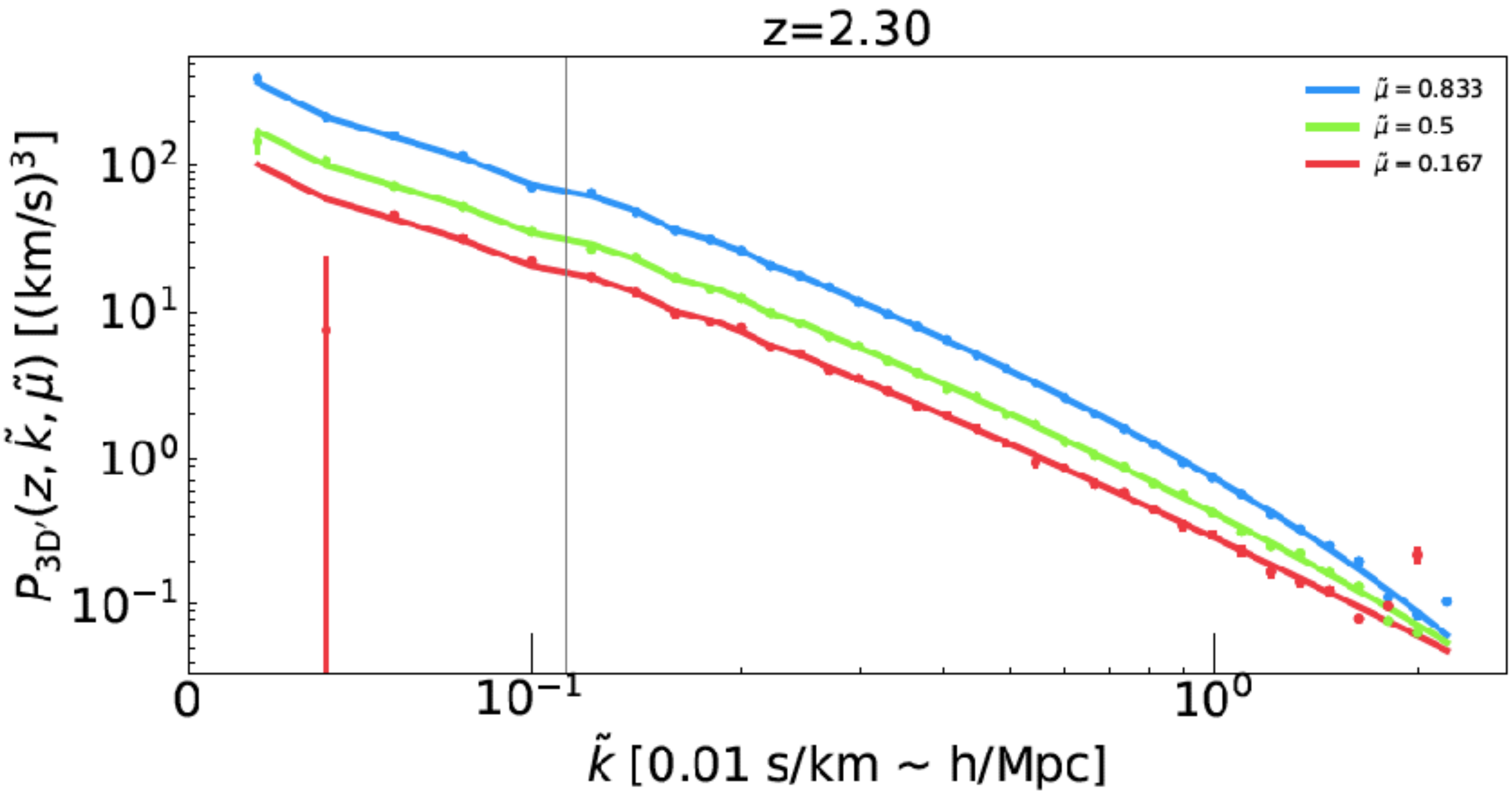
1D correlations, one skewer at a time (Palanque-Delabrouille et al. 2013)



~ 0.1 h/Mpc Line of sight (1D) wavenumber ~ 2 h/Mpc

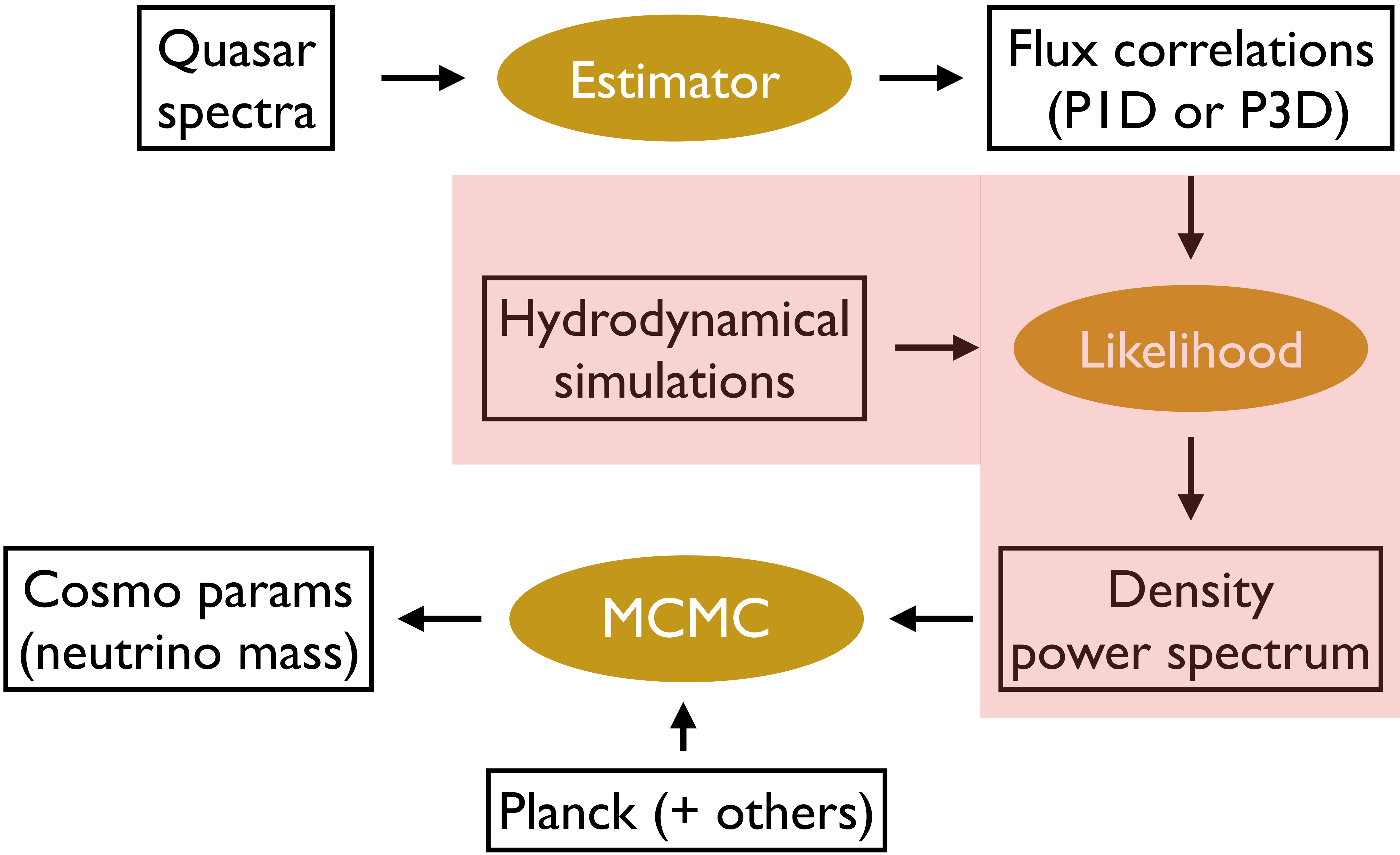
An efficient algorithm for estimating the 3D Lyα forest power spectrum

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



Measurement from 40 mock realisations of BOSS

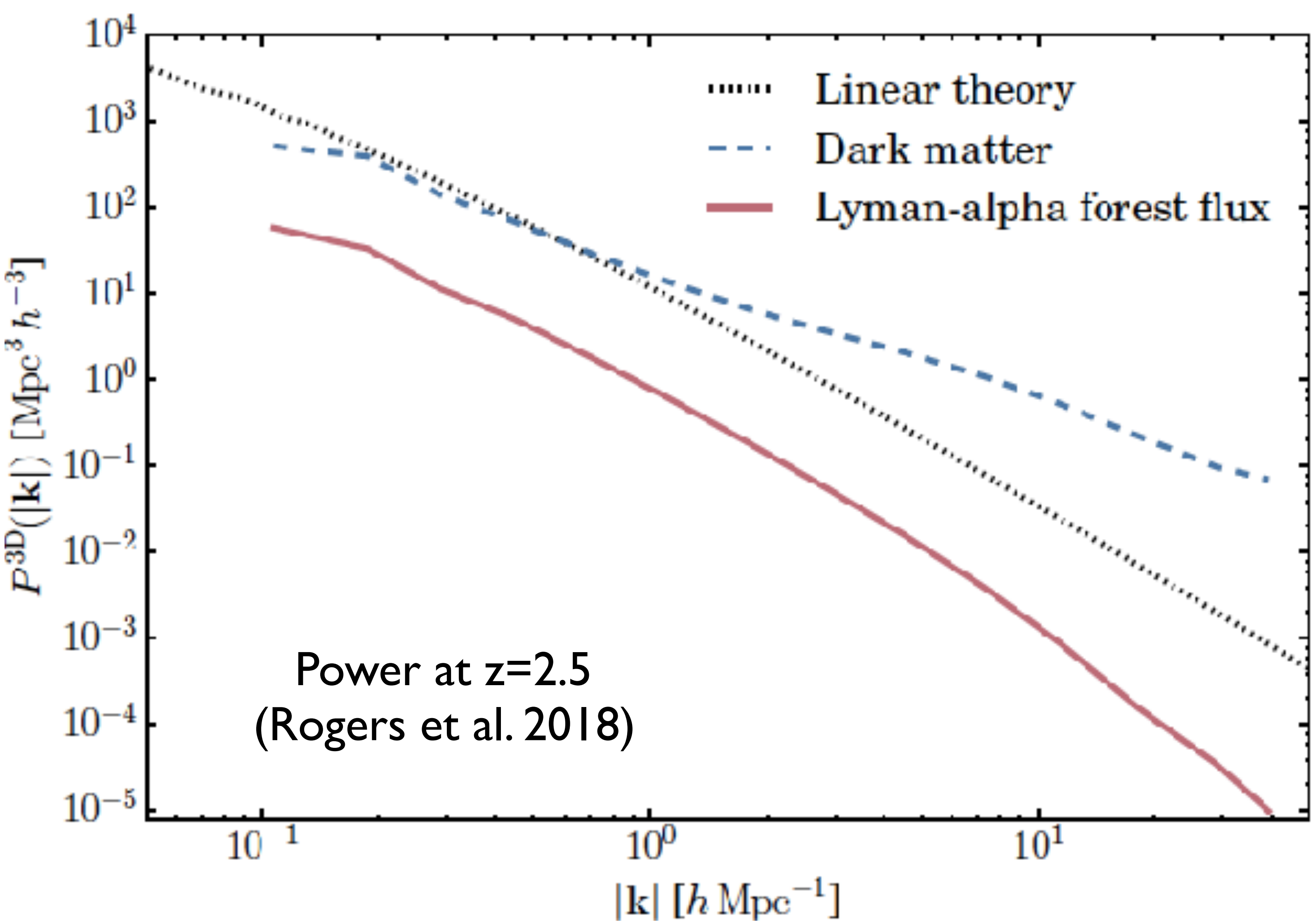
Small scale clustering

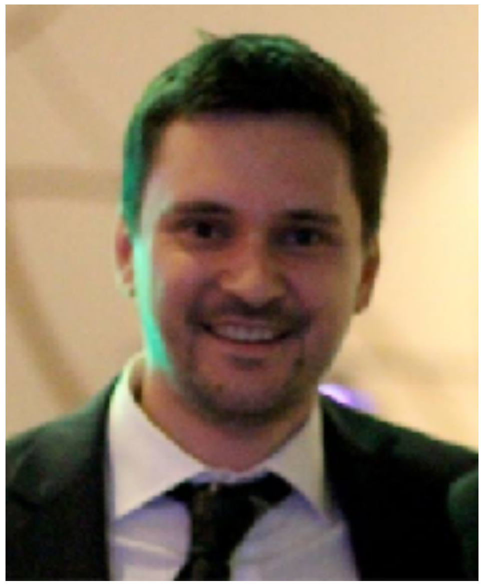


Hydro simulations of Lyα

New program at UCL to measure neutrino mass from Lyα

- MP-Gadget, by Yu Feng (Berkeley) & Simeon Bird (Riverside)
- Study effect of neutrinos on Lyα, and its degeneracies
- First proposal submitted to DiRAC (UK supercomputer)



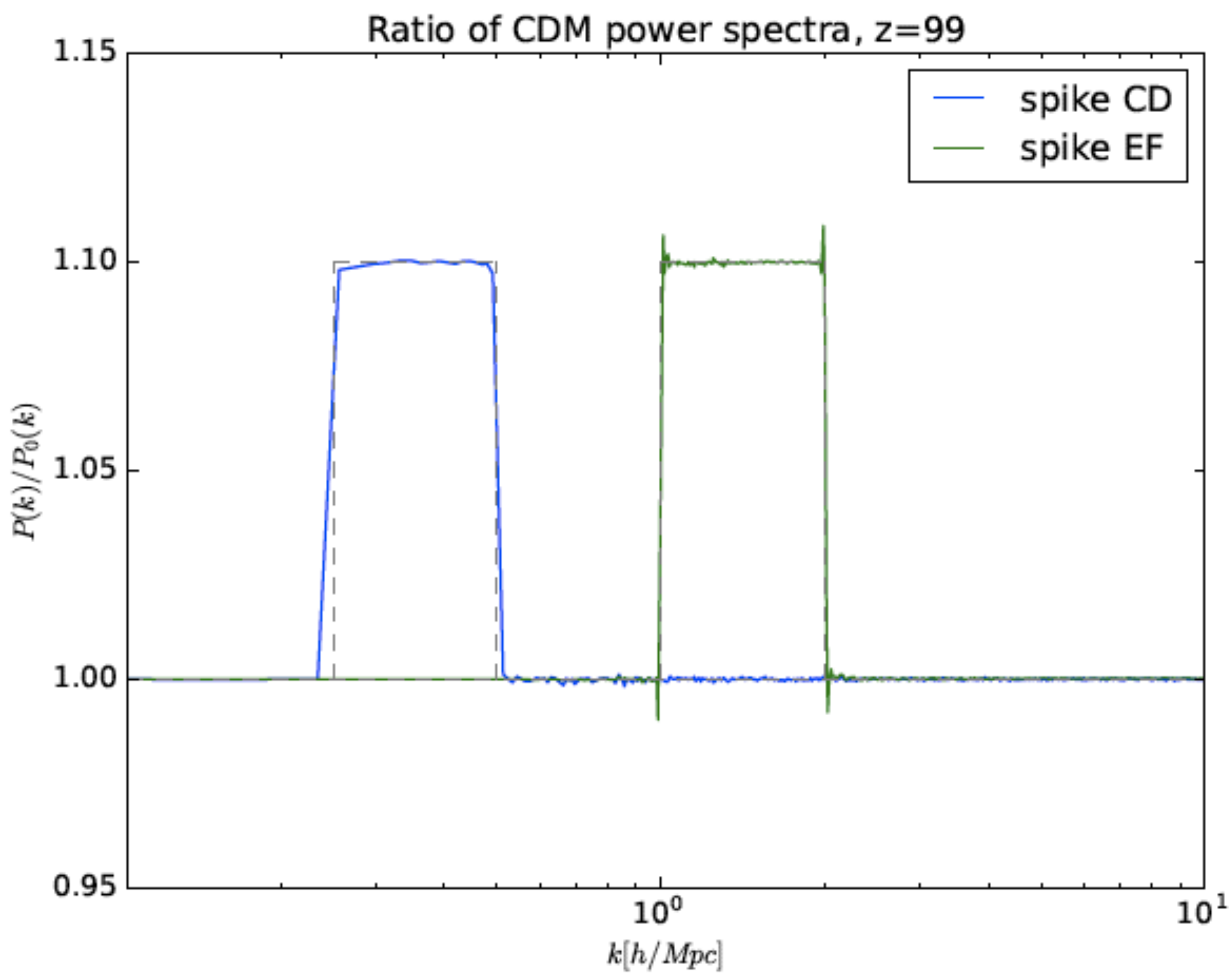


Chris Pedersen
(PhD @ UCL)

Why is the Lyα forest a good tracer of the linear density field?

Hydro simulations of Lyα

First project: why is the Lyα forest a good tracer of the linear density field?



Generate simulations with features in linear power

Hydro simulations of Lyα

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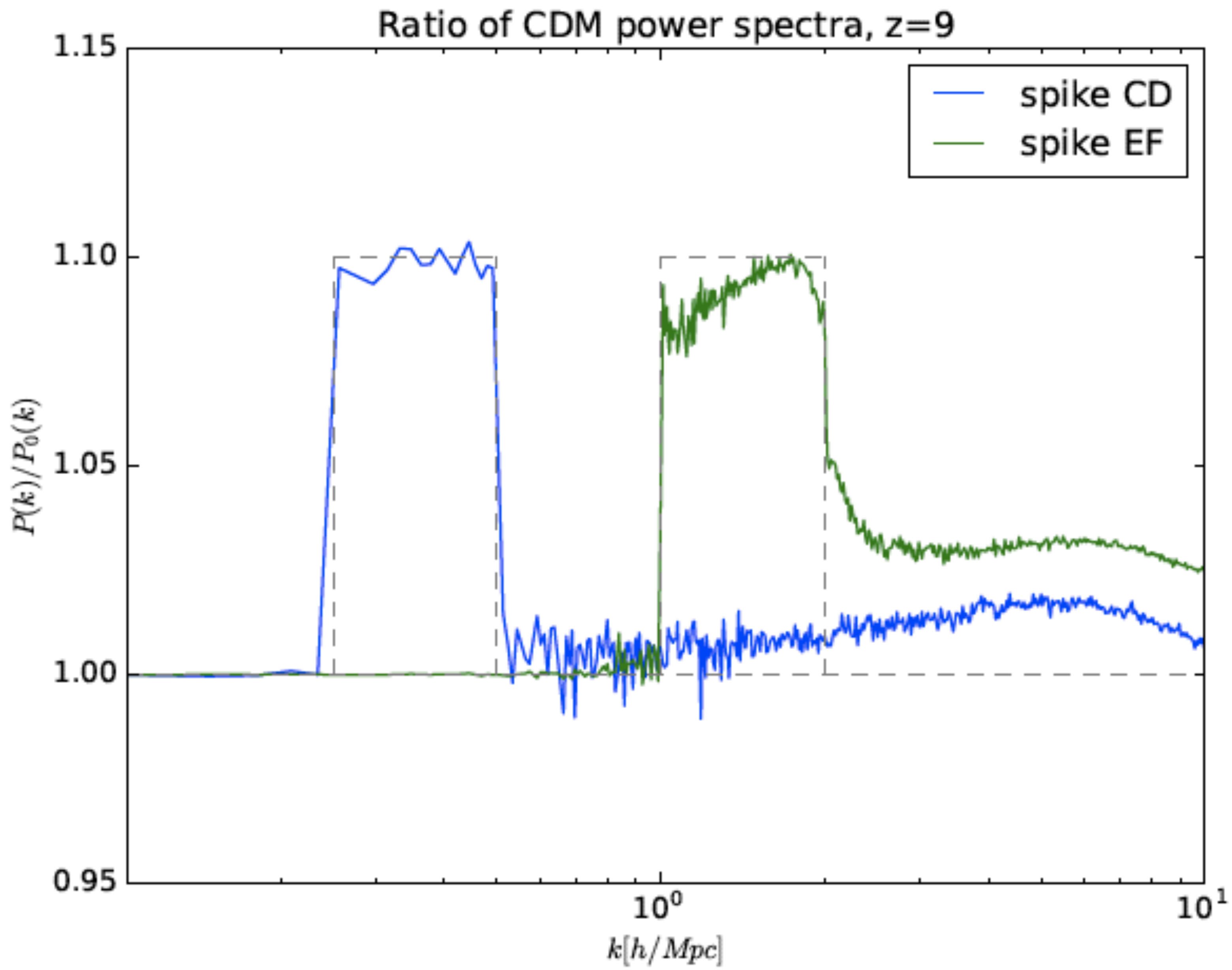

Generate simulations with features in linear power

Information is lost in the density power spectrum due to non-linearities (mode-coupling)

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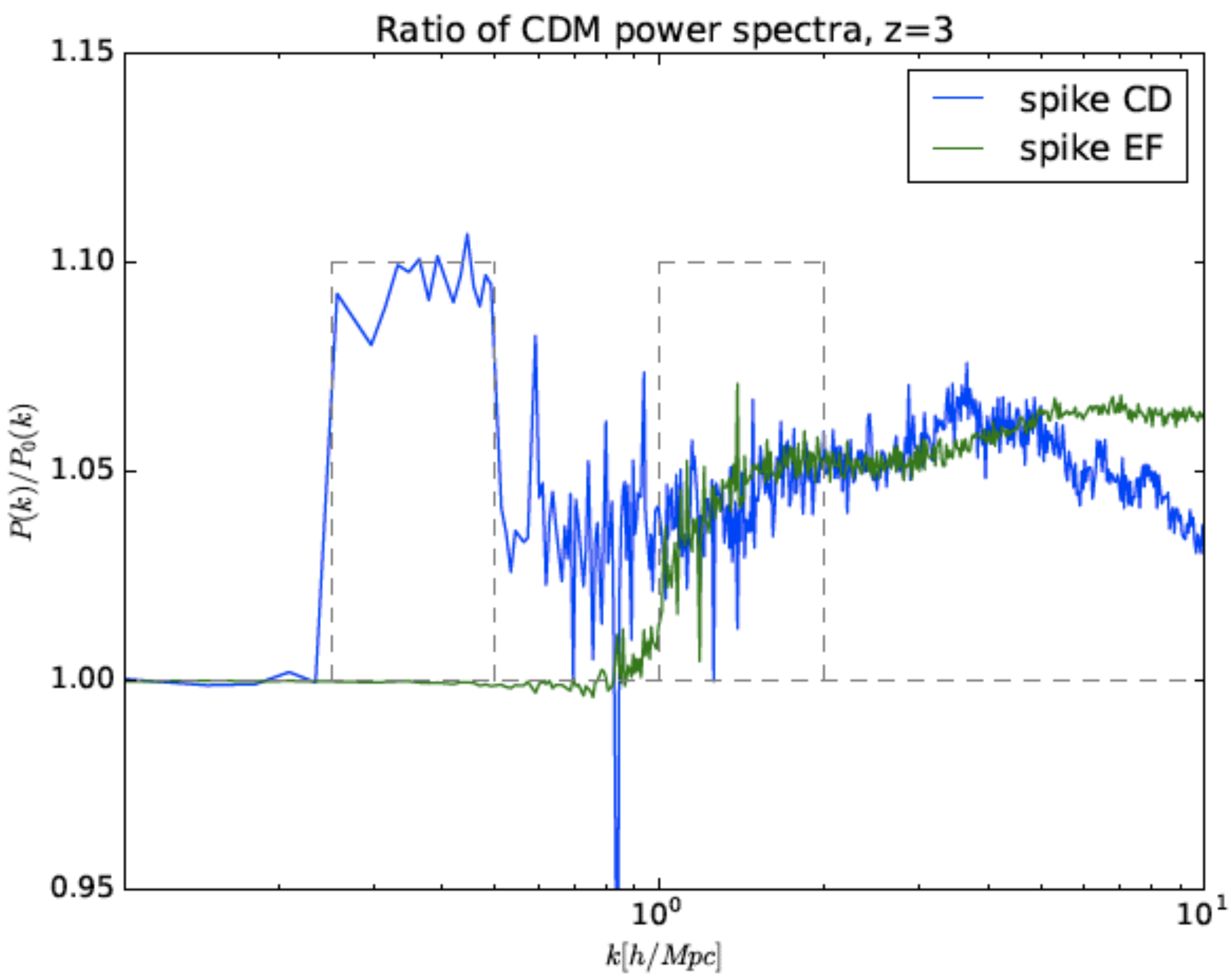

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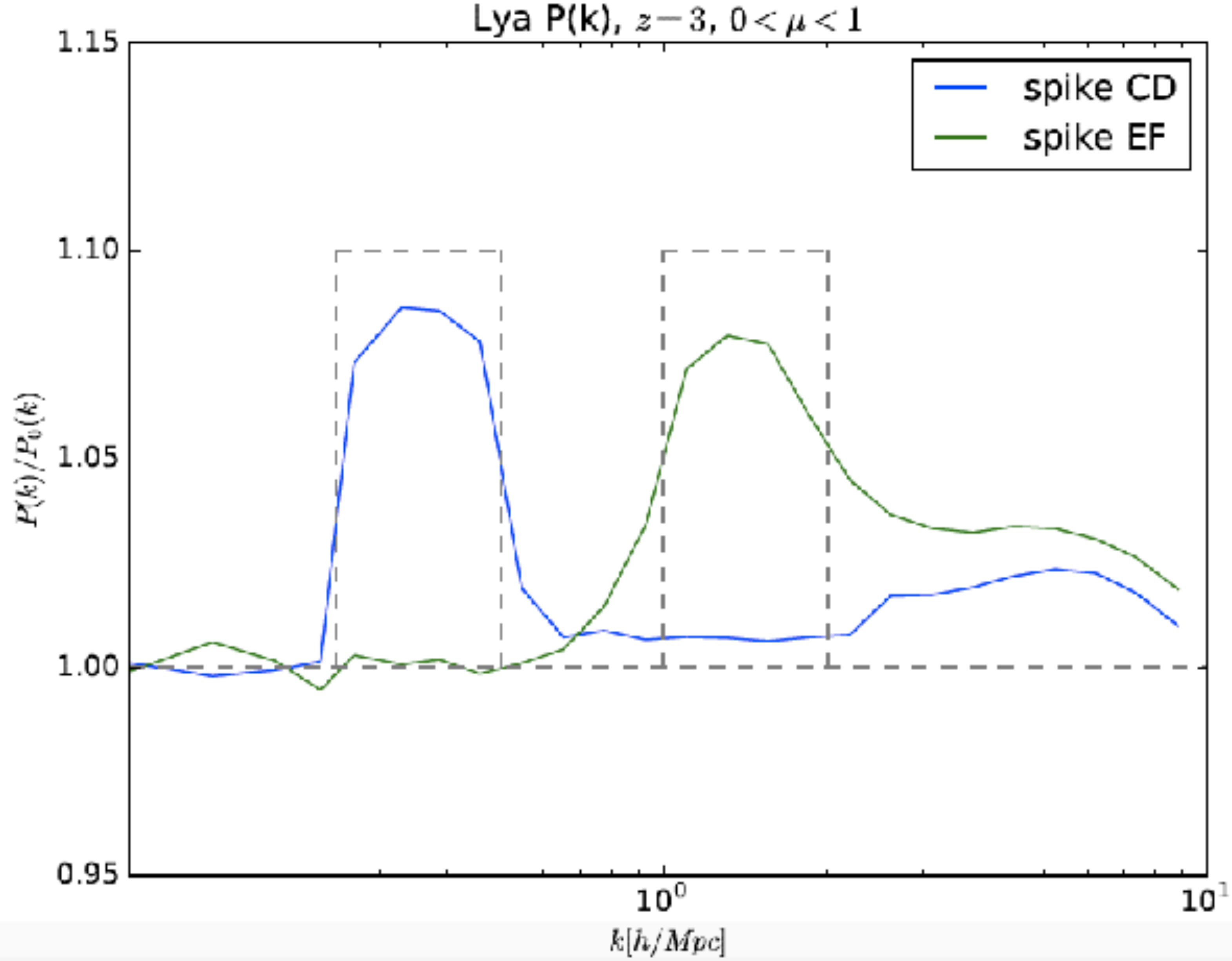


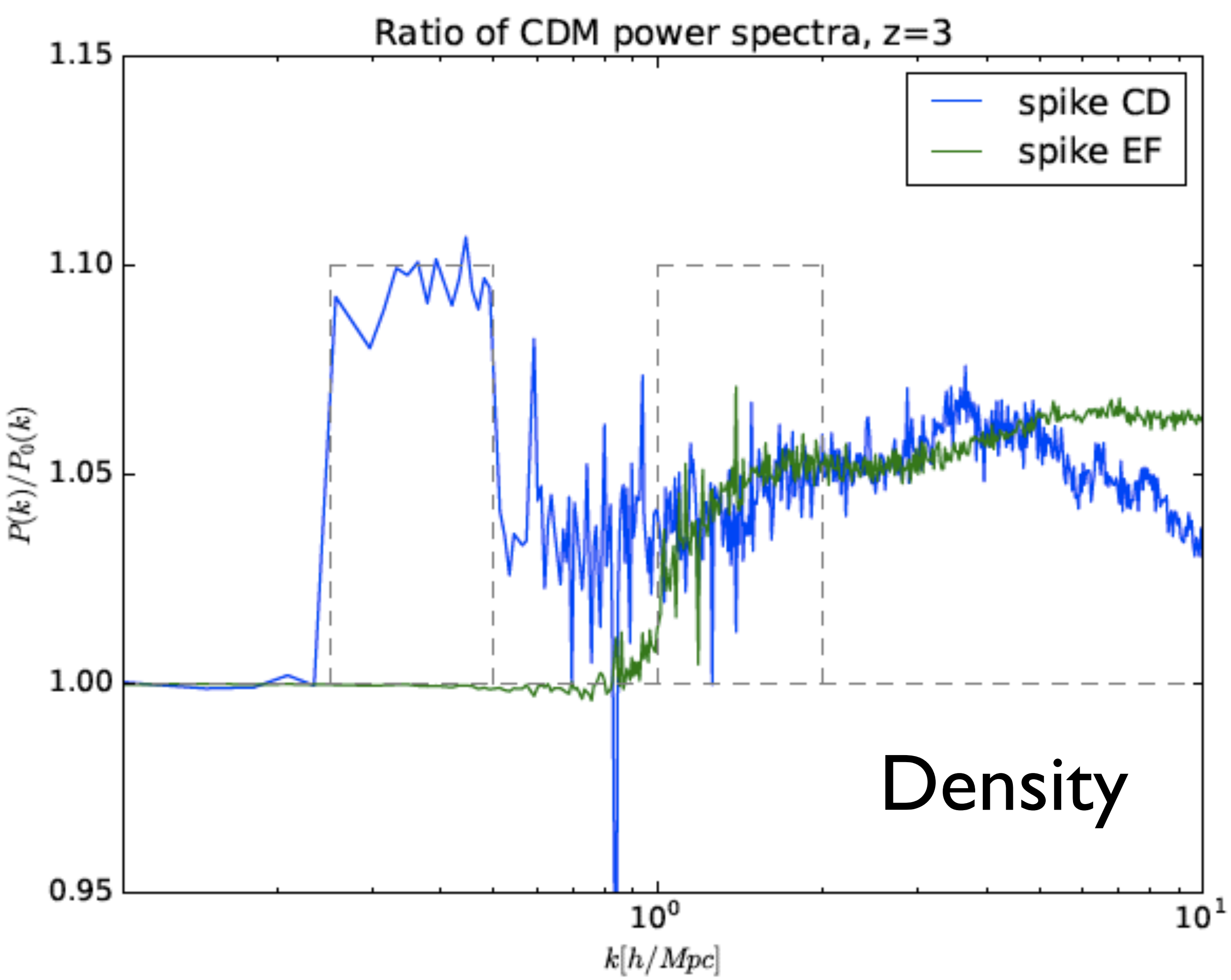
Generate simulations with features in linear power

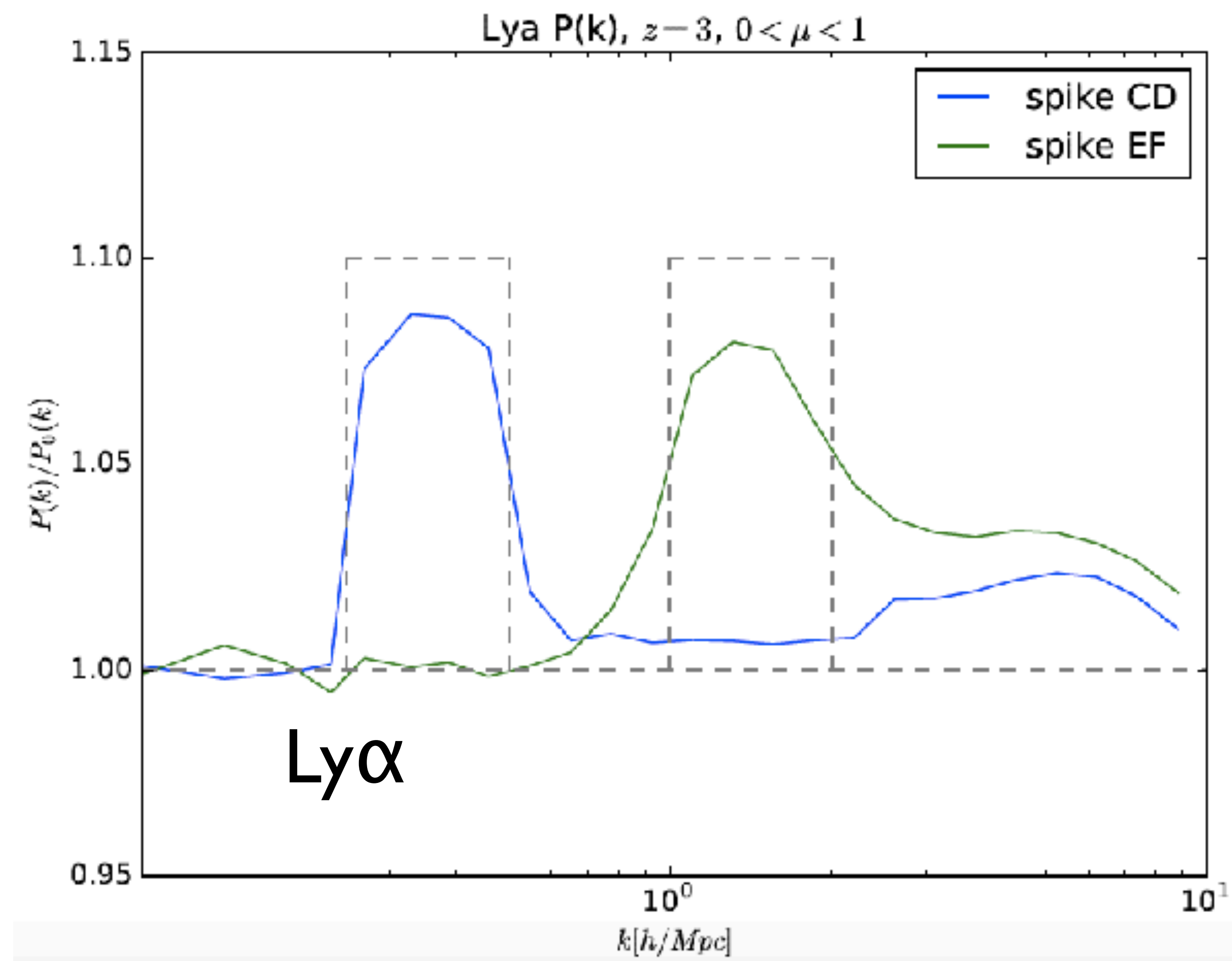
Information is lost in the density power spectrum due to non-linearities (mode-coupling)

Lyα 3D power is less affected by non-linearities

Hydro simulations of Lyα

First project: why is the Lyα forest a good tracer of the linear density field?





Lyα is a better tracer of initial conditions than density!

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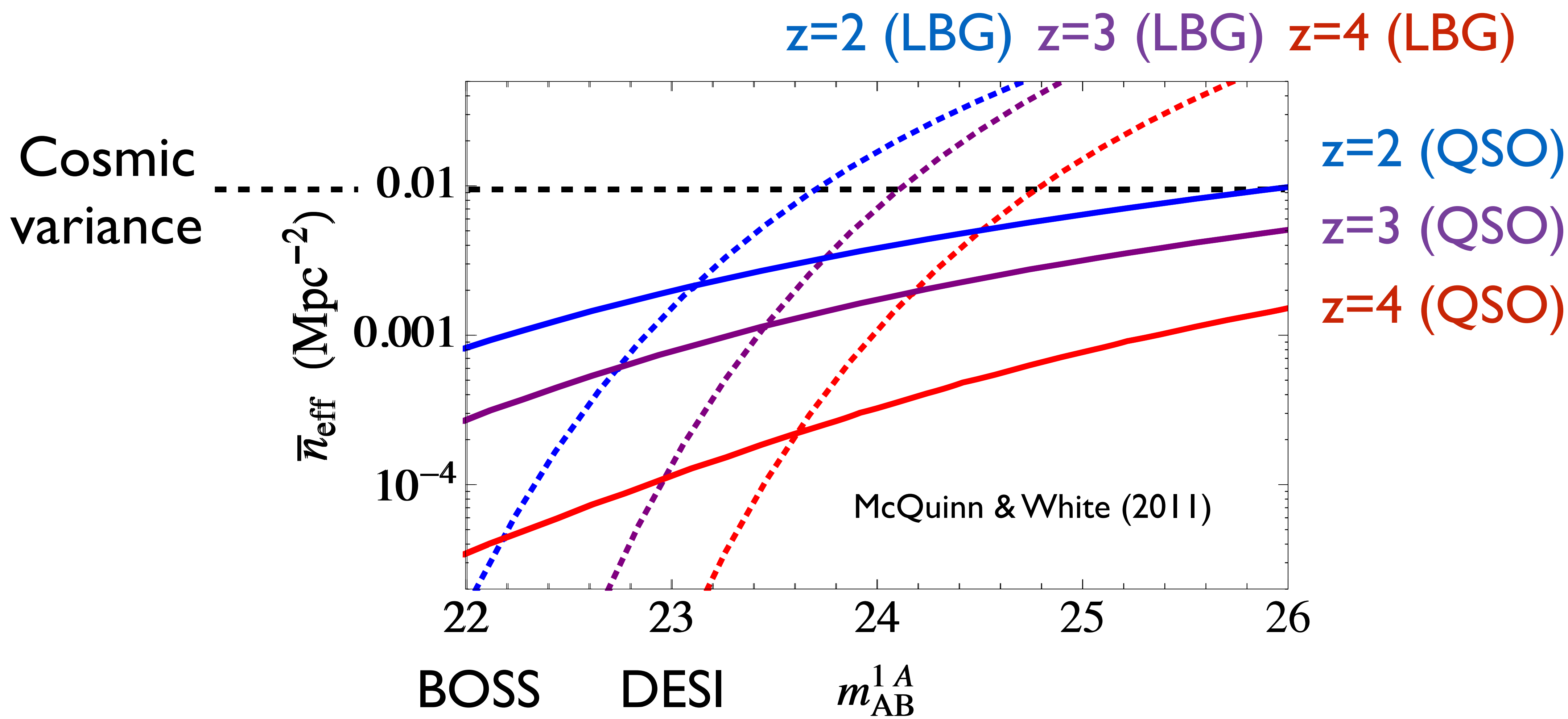
After-DESI (2025)

- Galaxy surveys running out of sky: DESI cosmic variance limited to z < 1.4
- Not the case for Ly-α surveys: errors limited by density of lines of sight
- Quasars are rare, but we can also use galaxies as backlight (see CLAMATO)



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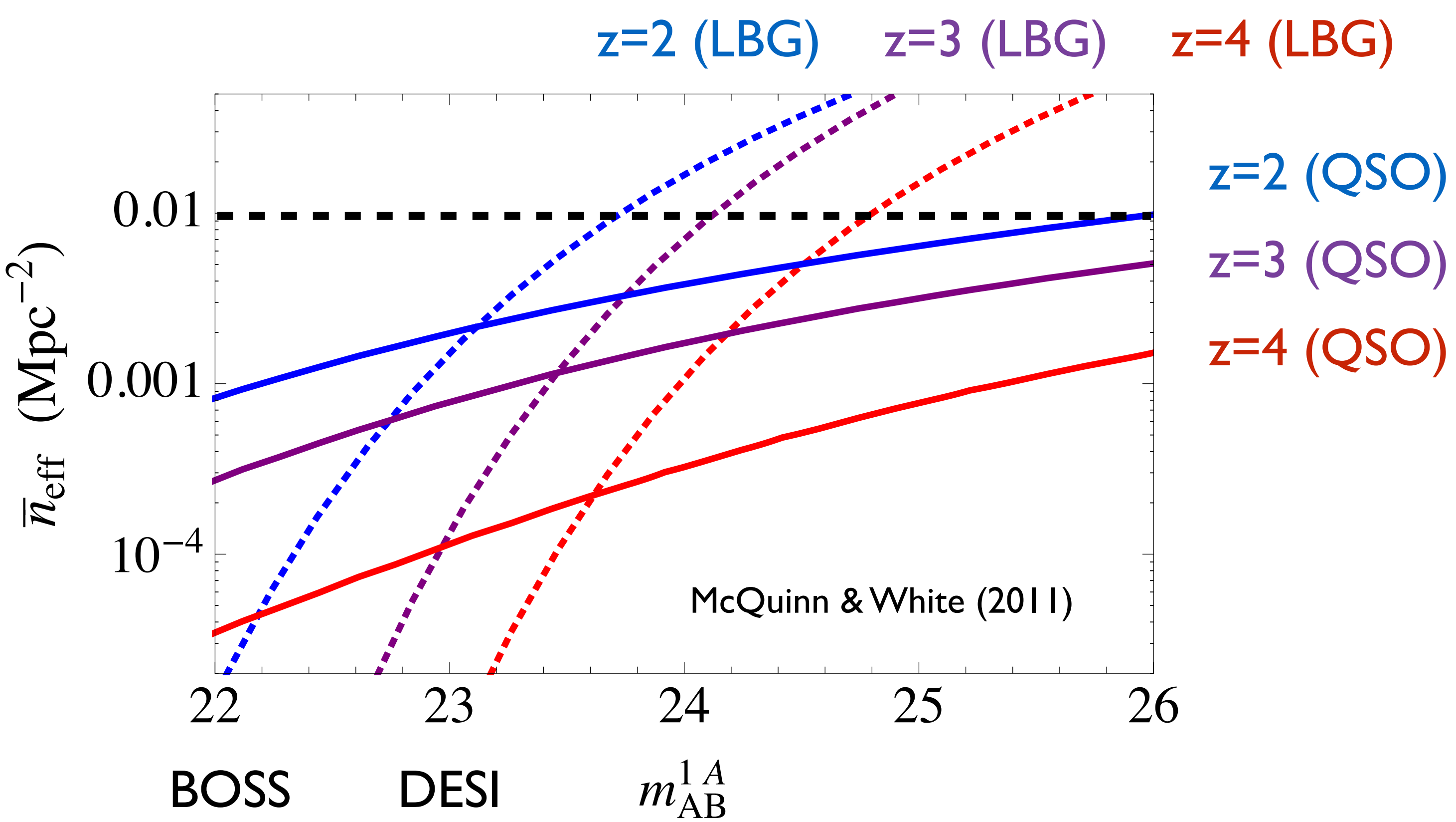
Lyman-α science is just starting!



- Still possible an order of magnitude increase
- LSST will solve target selection by 2025
- Complementary to WFIRST, Euclid and CMB-S4

Summary

Data analysis for BOSS (2009-2017)

- Co-chaired BOSS Lya working group (2012-2017)
- Novel method to generate mock Lya surveys (Font-Ribera++2012a)
- Pioneered Lya-QSO cross-correlation (Font-Ribera++ 2012b,2013)
- First BAO in correlations of different tracers (Font-Ribera++2014a)

Essential development for DESI (2017-2020)

- Co-chaired DESI Lya working group (2017-)
- Algorithm to measure Lyα power on all scales (Font-Ribera++ 2018)
- Transform theoretical models to reach sub-percent precision

Bright future: DESI (2020-2025) ...and more!

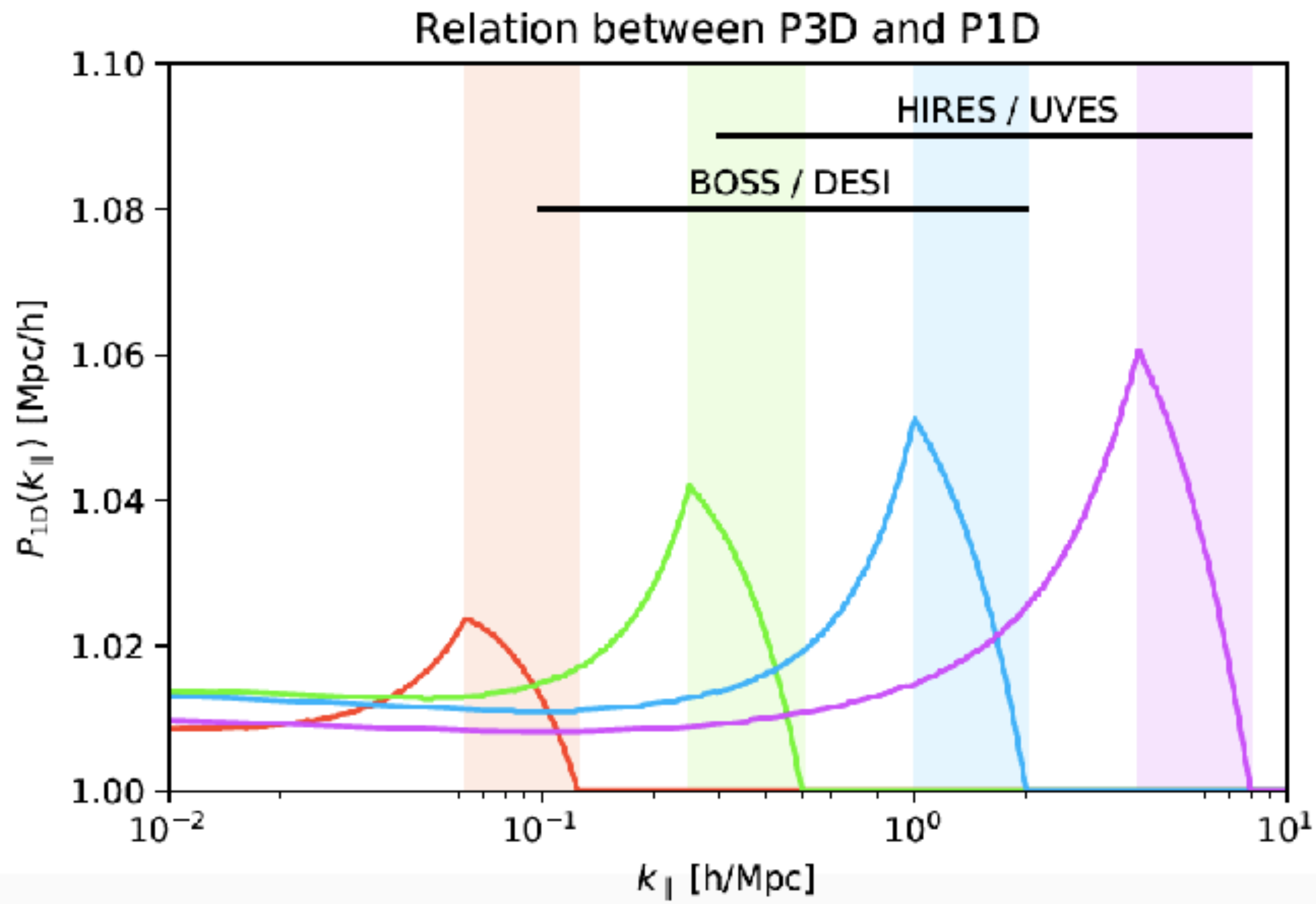
- Sub-percent measurement of expansion over cosmic time
- Detect effect of neutrino mass
- Best constraints on small scale primordial power spectrum
- Combination with WFIRST, Euclid, LSST and CMB-S4

Extra slides

Estimators: 1D P(k)

$P_{1\mathrm{D}}(k_\parallel)$ mixes several 3D modes into a single $k_\parallel$

$$P_{1\mathrm{D}}(k_\parallel) = \int dr_\parallel \, e^{ik_\parallel r_\parallel} \, \xi(r_\parallel, \mathbf{r}_\perp = 0) = \frac{1}{(2\pi)^2} \int d\mathbf{k}_\perp \, P_F(k_\parallel, \mathbf{k}_\perp)$$



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

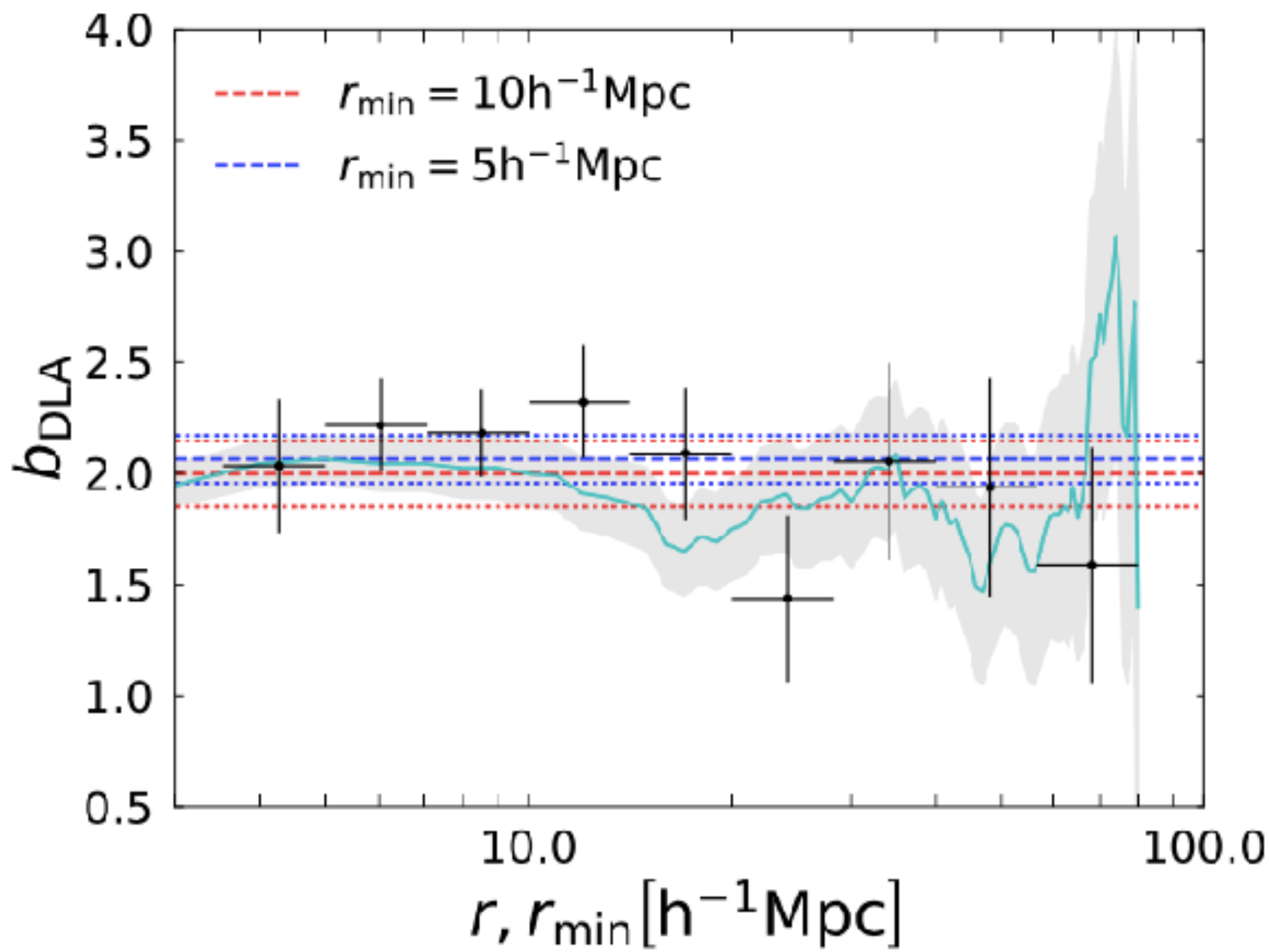
Cosmic variance

DLA-Lya cross-correlation

Ignasi Pérez-Ràfols
(moving from Barcelona
to Marseille)

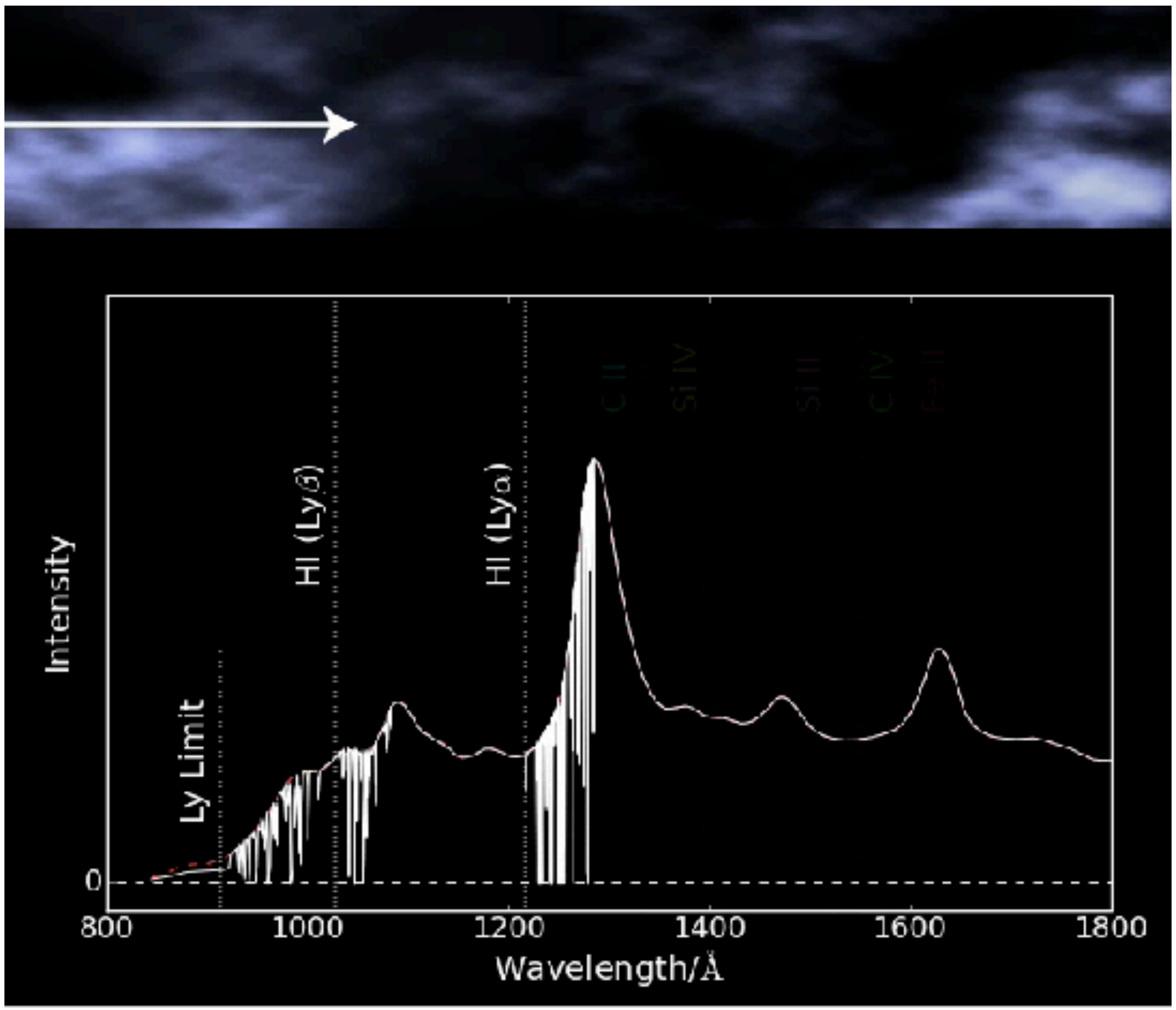
Very relevant for 21cm forecasts!

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

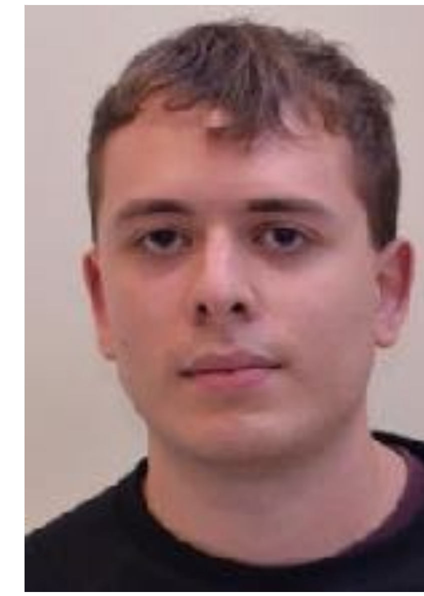


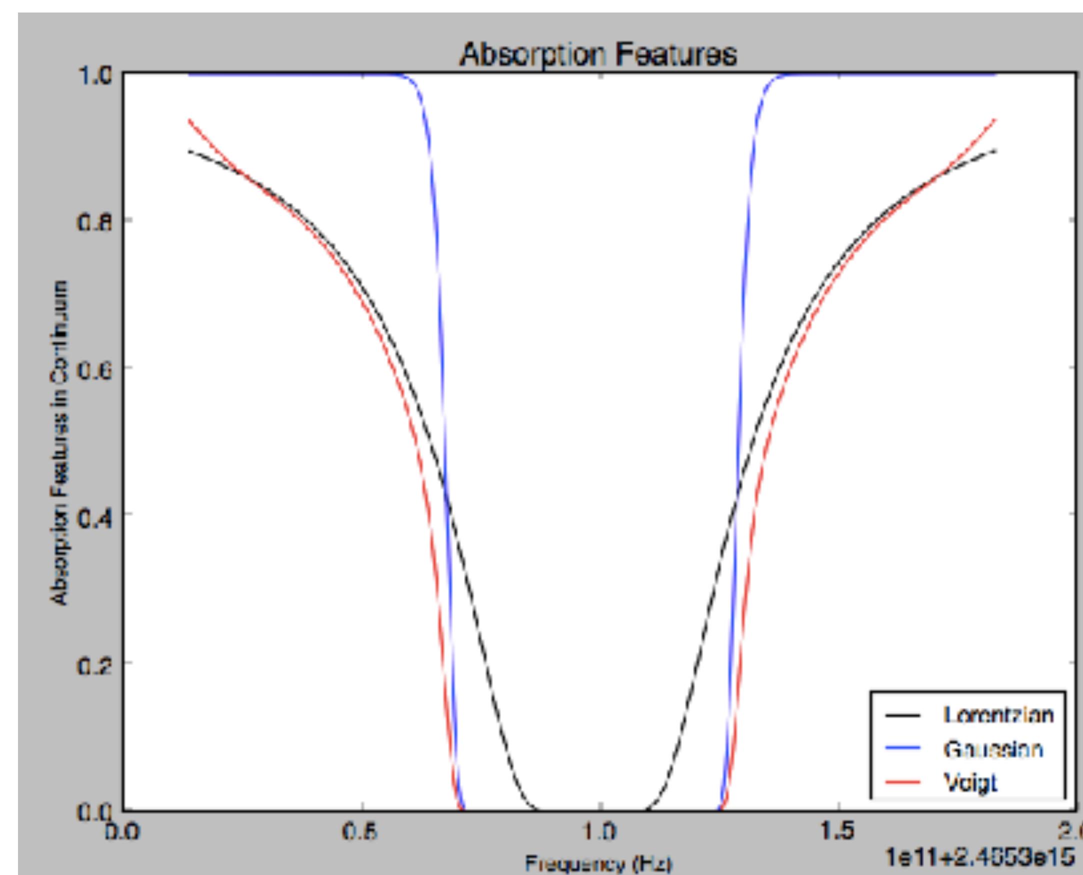
Contamination by high column densities

High column density (HCD) hydrogen absorbers are leading contaminants to the Lyman-α forest



Keir Rogers
(PhD @ UCL)
1D: 1711.06275
3D: 1706.08532



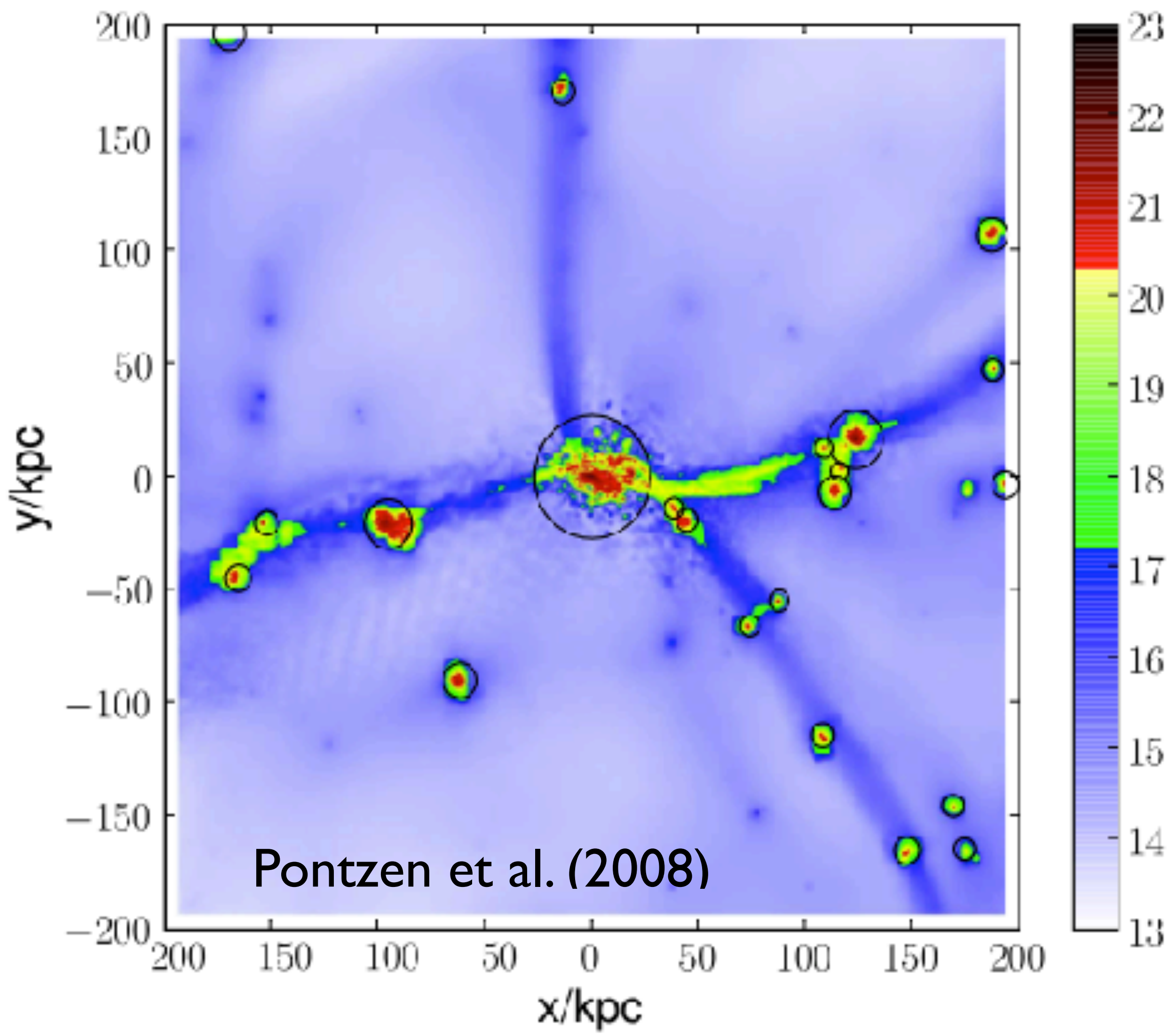


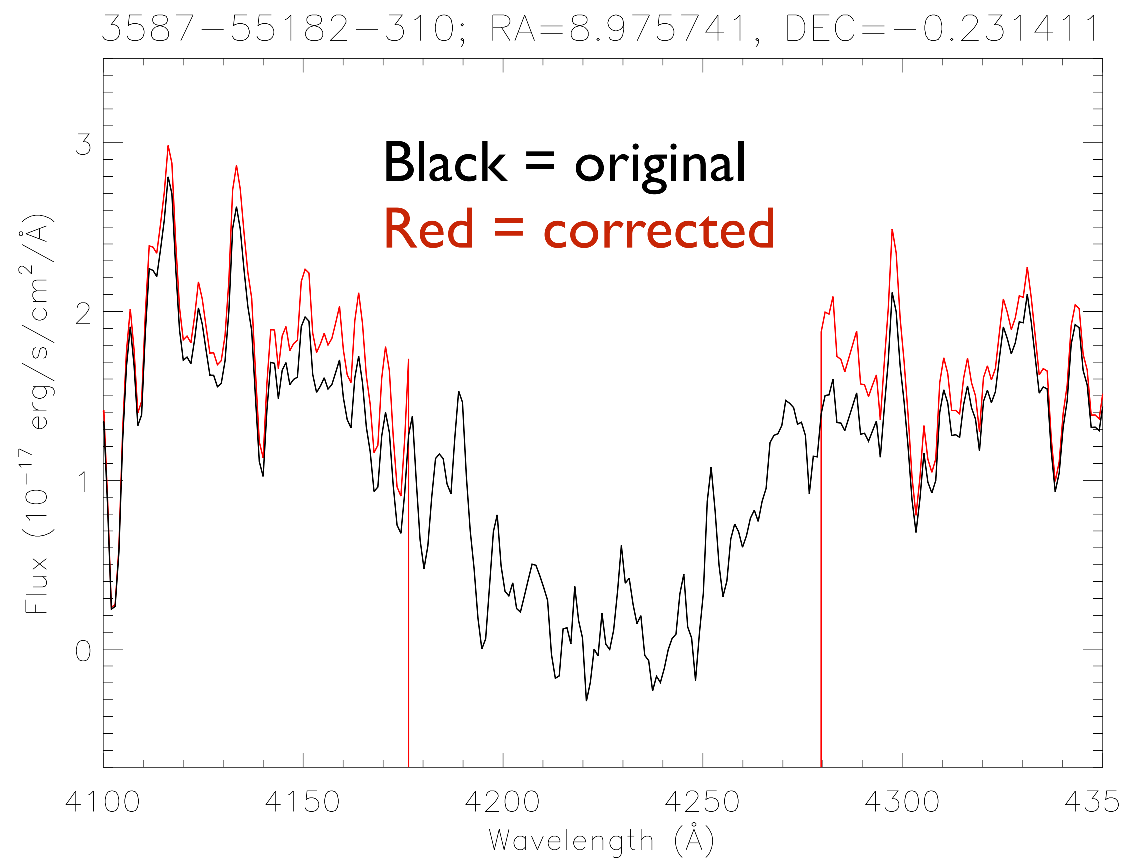
Contamination by high column densities

Lyman Limit System (LLS) are self-shielded against UV radiation

Damped Lyman-α (DLA) systems have Lorentzian tail

In BOSS we identified/masked the largest DLAs, but smaller systems where hidden in the noise





Absorber category	$N(\mathrm{H\,I})_{min}$ [atoms cm^{-2}]	$N(\mathrm{H\,I})_{max}$
Lyman-alpha forest	0	1.6×10^{17}
LLS	1.6×10^{17}	1×10^{19}
Sub-DLA	1×10^{19}	2×10^{20}
Small DLA	2×10^{20}	1×10^{21}
Large DLA	1×10^{21}	∞

Pure Ly-α model $P^{3D}_{\rm Forest}(|\boldsymbol{k}|,\mu,z) = b^2_{\rm Forest}(1+\beta_{\rm Forest}\mu^2)^2 P^{3D}_{\rm Linear}(|\boldsymbol{k}|,z) D_{\rm NL}(|\boldsymbol{k}|,\mu)$

Consider absorption is caused by two tracers (Font-Ribera et al. 2012)

$$P^{3D}_{\rm Contaminated}(|\boldsymbol{k}|,\mu,z) = P^{3D}_{\rm Linear}(|\boldsymbol{k}|,z)\,[\tilde{b}^2_{\rm Forest} D_{\rm NL}(|\boldsymbol{k}|,\mu) + 2\tilde{b}_{\rm Forest}\tilde{b}_{\rm HCD} + \tilde{b}^2_{\rm HCD}]$$

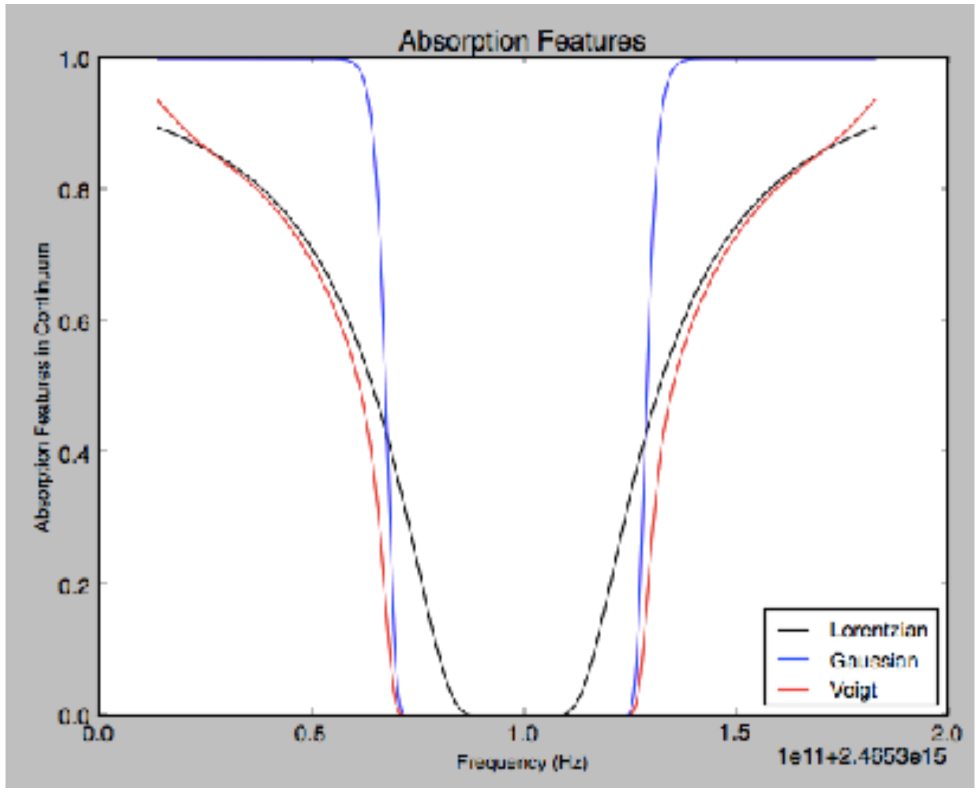
$$\tilde{b}_{\rm Forest} = b_{\rm Forest}(1 + \beta_{\rm Forest}\mu^2) \qquad \tilde{b}_{\rm HCD} = b_{\rm HCD}(1 + \beta_{\rm HCD}\mu^2) F_{\rm HCD}(k_{\parallel}, z)$$

Model used in BOSS DR12: top-hat absorption

$$F^{\rm BOSS}_{\rm HCD}(k_{\parallel}, z) = \frac{\sin(L_{\rm HCD} k_{\parallel})}{L_{\rm HCD} k_{\parallel}},$$

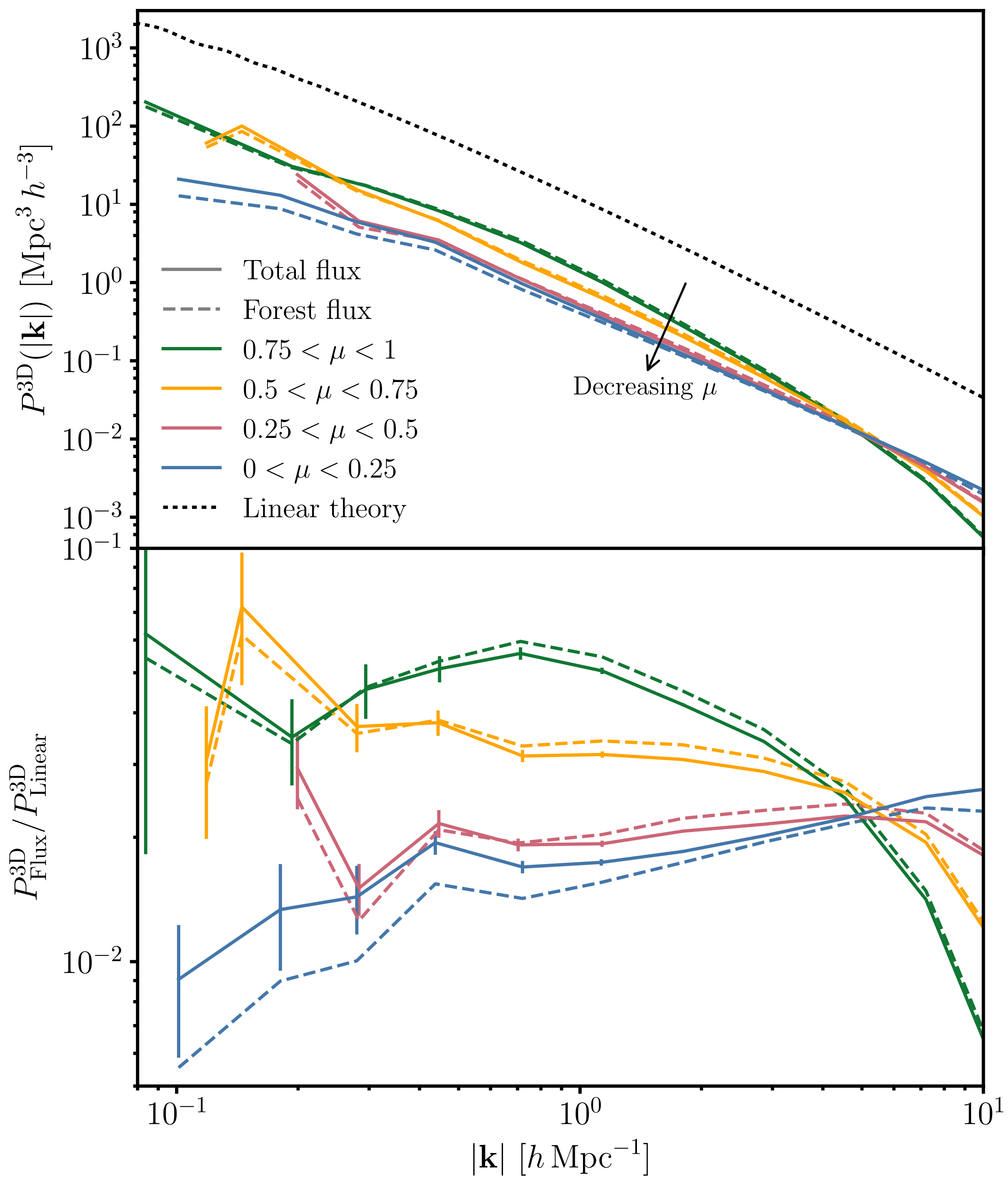
Rogers et al. (2018): use FT of Voigt profile

$$F^{\rm Voigt}_{\rm HCD}(k_{\parallel}, z) = \int_{N({\rm H\,I})_{\rm min}}^{N({\rm H\,I})_{\rm max}} {\rm d}N({\rm H\,I})\, f(N({\rm H\,I}), z)\, V(k_{\parallel}, N({\rm H\,I})).$$



Contamination by high column densities

Total power as measured in Illustris



Fractional effect as measured in Illustris