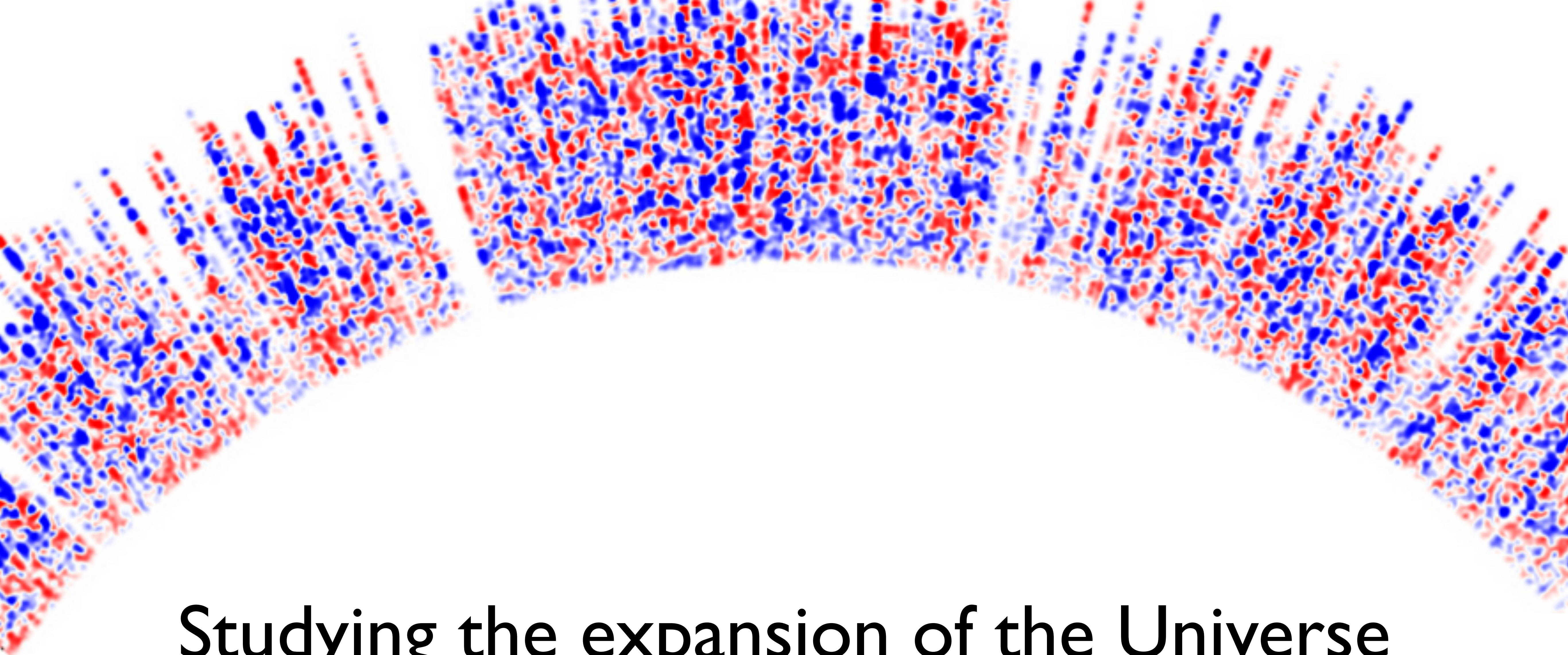


Studying the expansion of the Universe with quasar spectra

Andreu Font-Ribera

University College London (UCL)

Institut de Fisica d'Altes Energies (IFAE, Barcelona)

Redshift Surveys

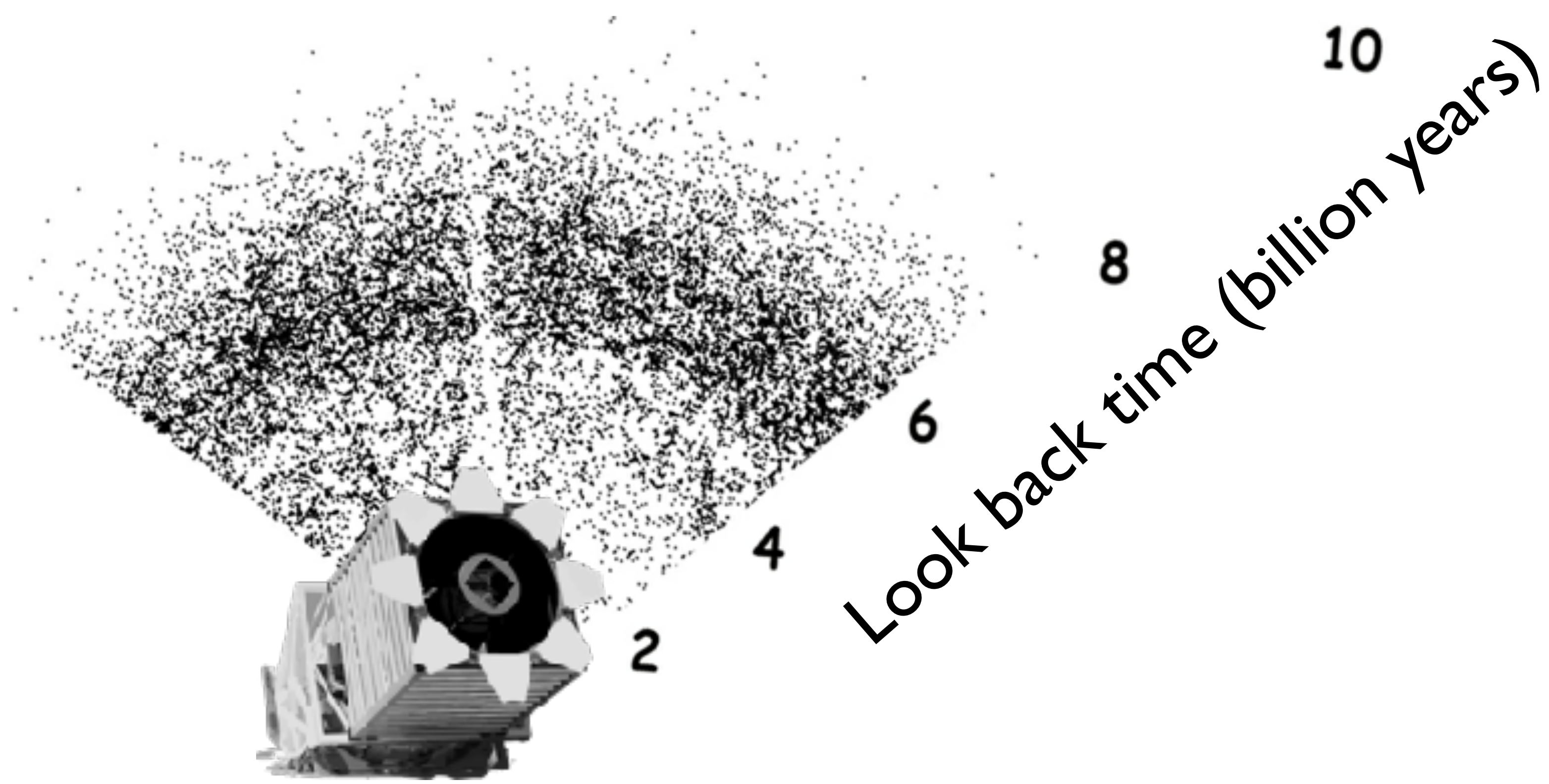
The distribution of matter in the Universe tells us about:

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

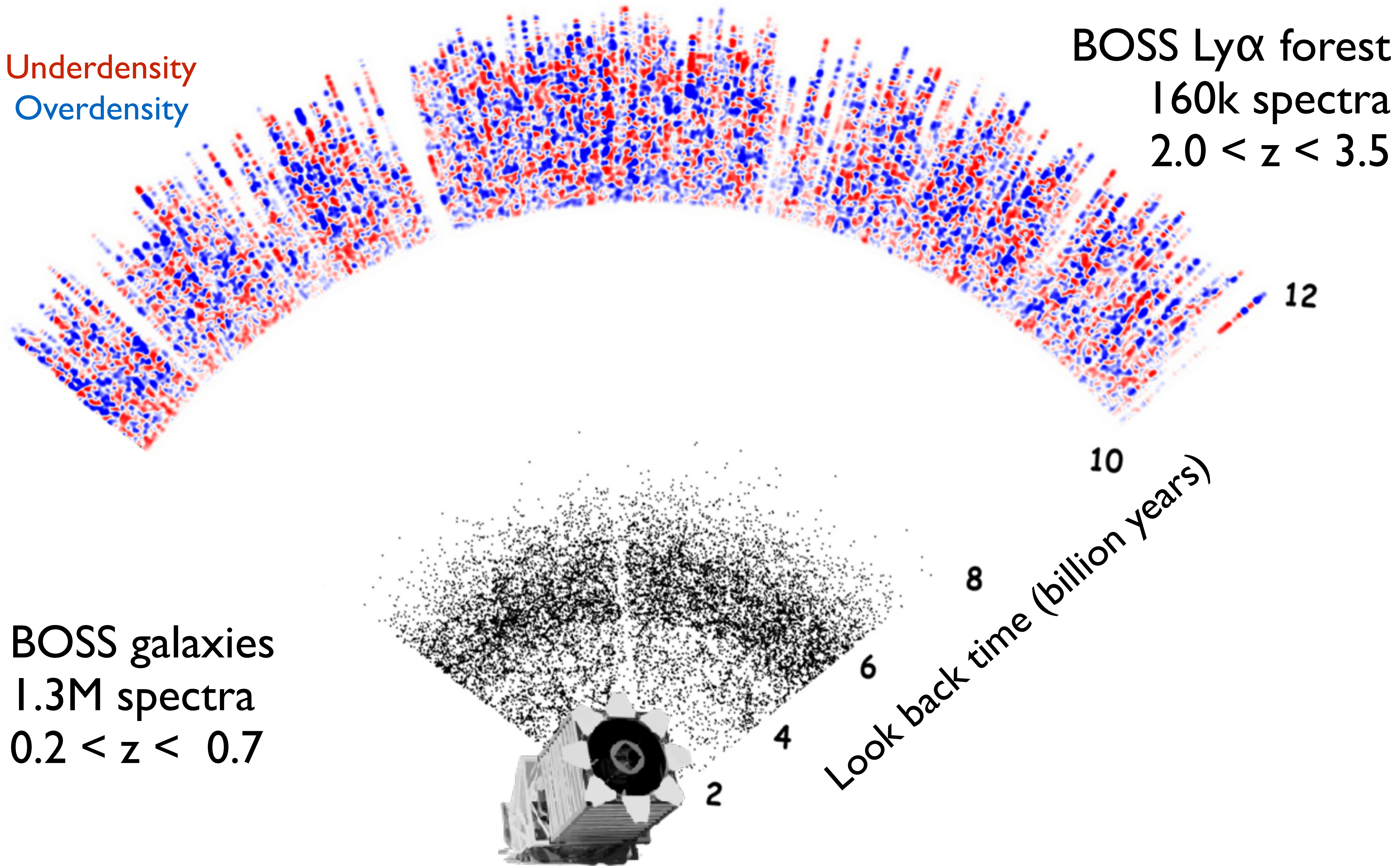
However, most of the matter in the Universe is in the form of dark matter and we need indirect tracers to study it

Redshift Surveys

BOSS galaxies
1.3M spectra
0.2 < z < 0.7



Redshift Surveys



Outline

- Introduction to Baryon Acoustic Oscillations
- Past: Baryon Oscillation Spectroscopic Survey (BOSS, 2009-2014)
    - Going to high-z: BAO with the Lyman-α forest
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    - BAO and the H_0 tension
- Future: Dark Energy Spectroscopic Instrument (DESI, 2020-2025)

Studying the Expansion

We can relate redshift to distance if we have a cosmological model

Comoving distance

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

Hubble constant (current expansion rate)

Hubble parameter (expansion rate)

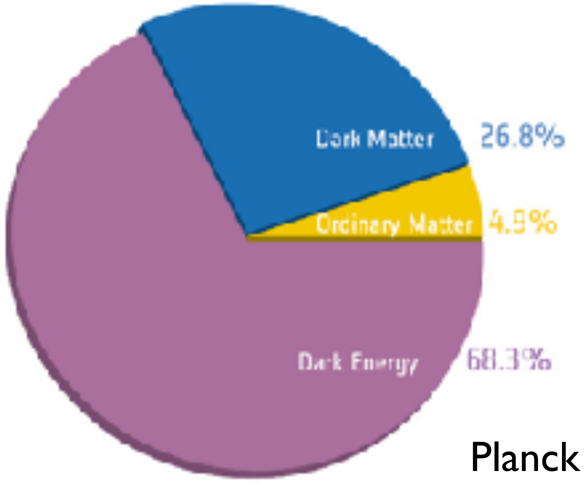
$$\frac{H^2(z)}{H_0^2} = \boxed{\Omega_r}(1+z)^4 + \boxed{\Omega_m}(1+z)^3 + \boxed{\Omega_\Lambda} + \boxed{\Omega_k}(1+z)^2$$

Radiation

Dark Energy

Matter (baryonic or dark)

Curvature



Planck satellite

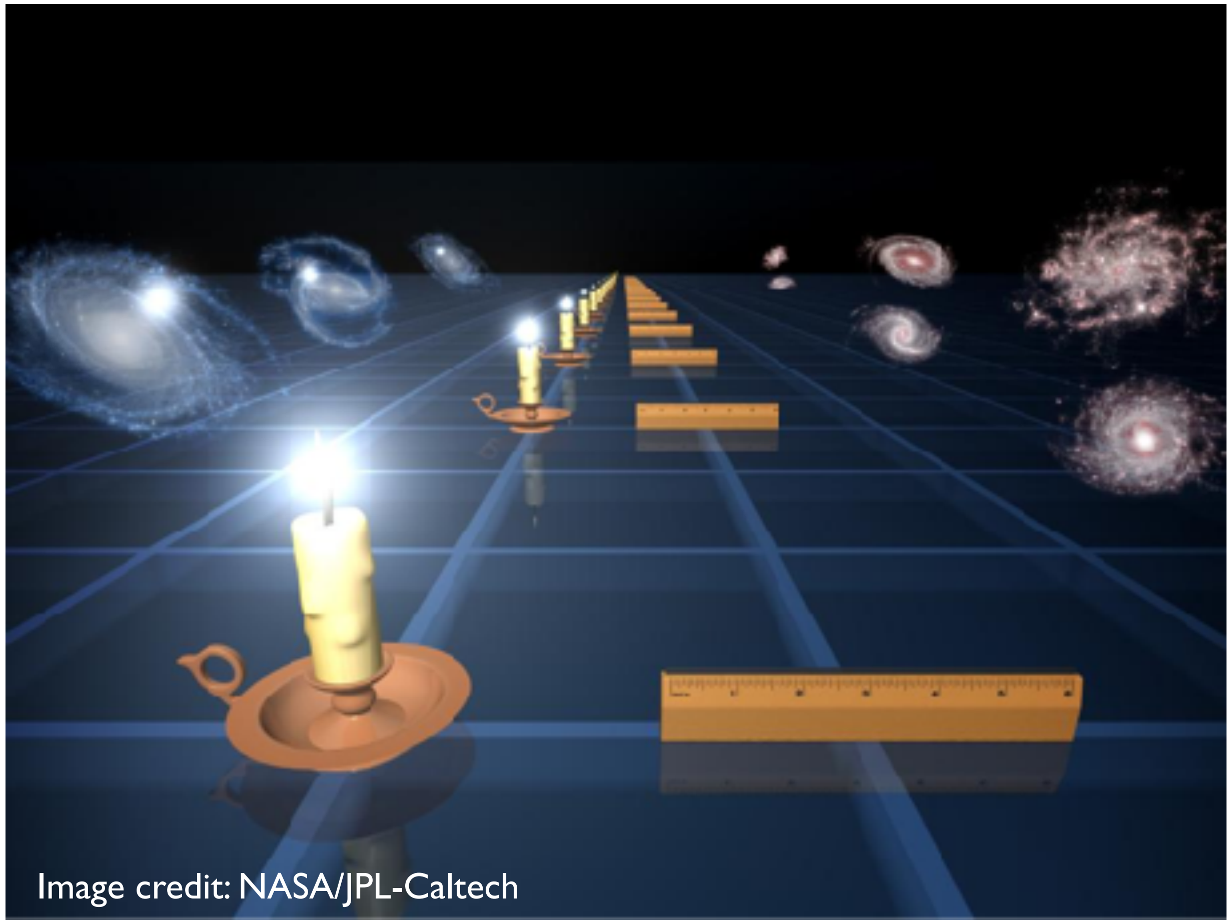
We can learn about the Dark Energy if we can measure distances!

Studying the Expansion

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

Standard candle (Supernovae)

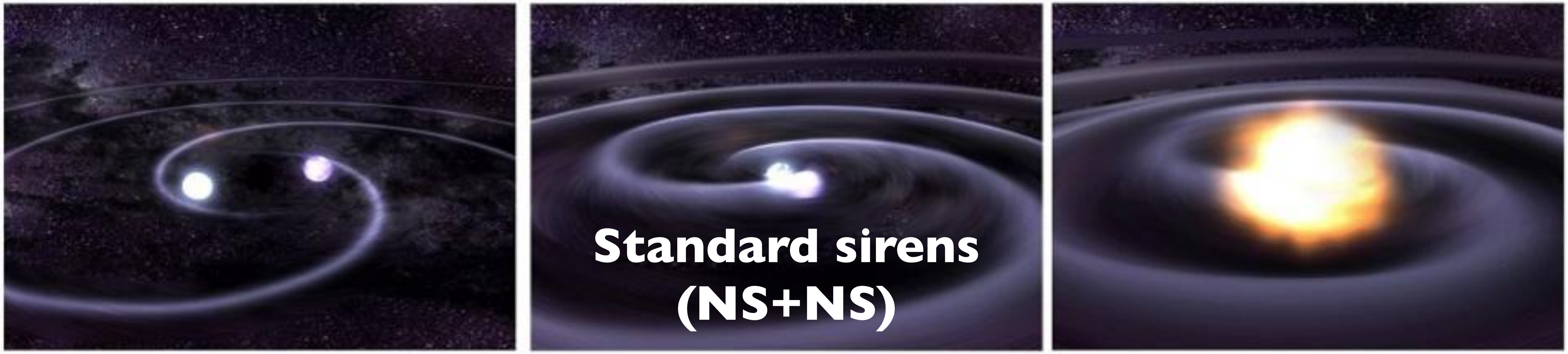
known luminosity
+
measure flux
↓
distance



Standard ruler (BAO)

known size
+
measure apparent size
↓
distance

Studying the Expansion



Standard candle (Supernovae)

known luminosity
+
measure flux
↓
distance

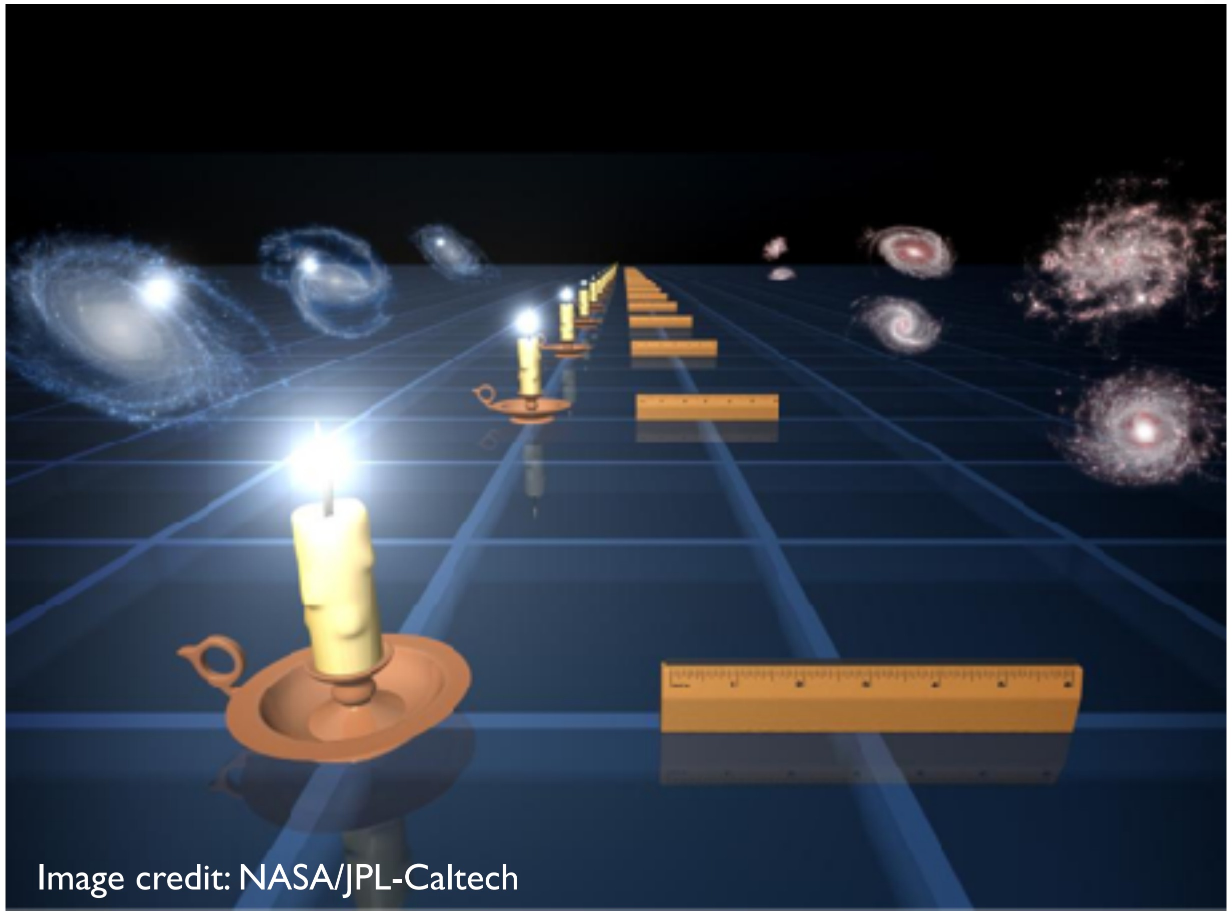


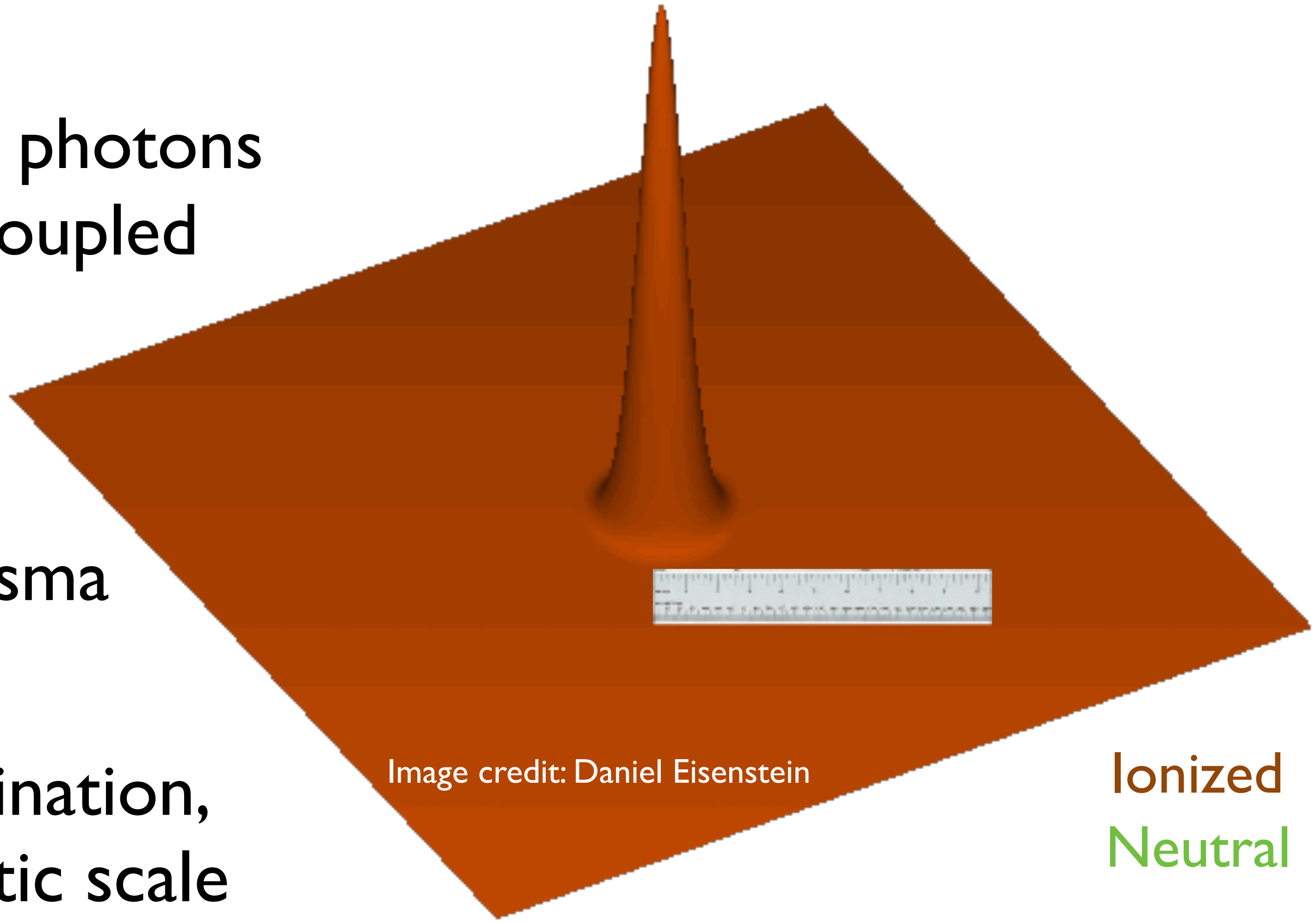
Image credit: NASA/JPL-Caltech

Standard ruler (BAO)

known size
+
measure apparent size
↓
distance

Baryon Acoustic Oscillations

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



Ionized

Neutral

Primordial density fluctuations generated sound waves in the plasma

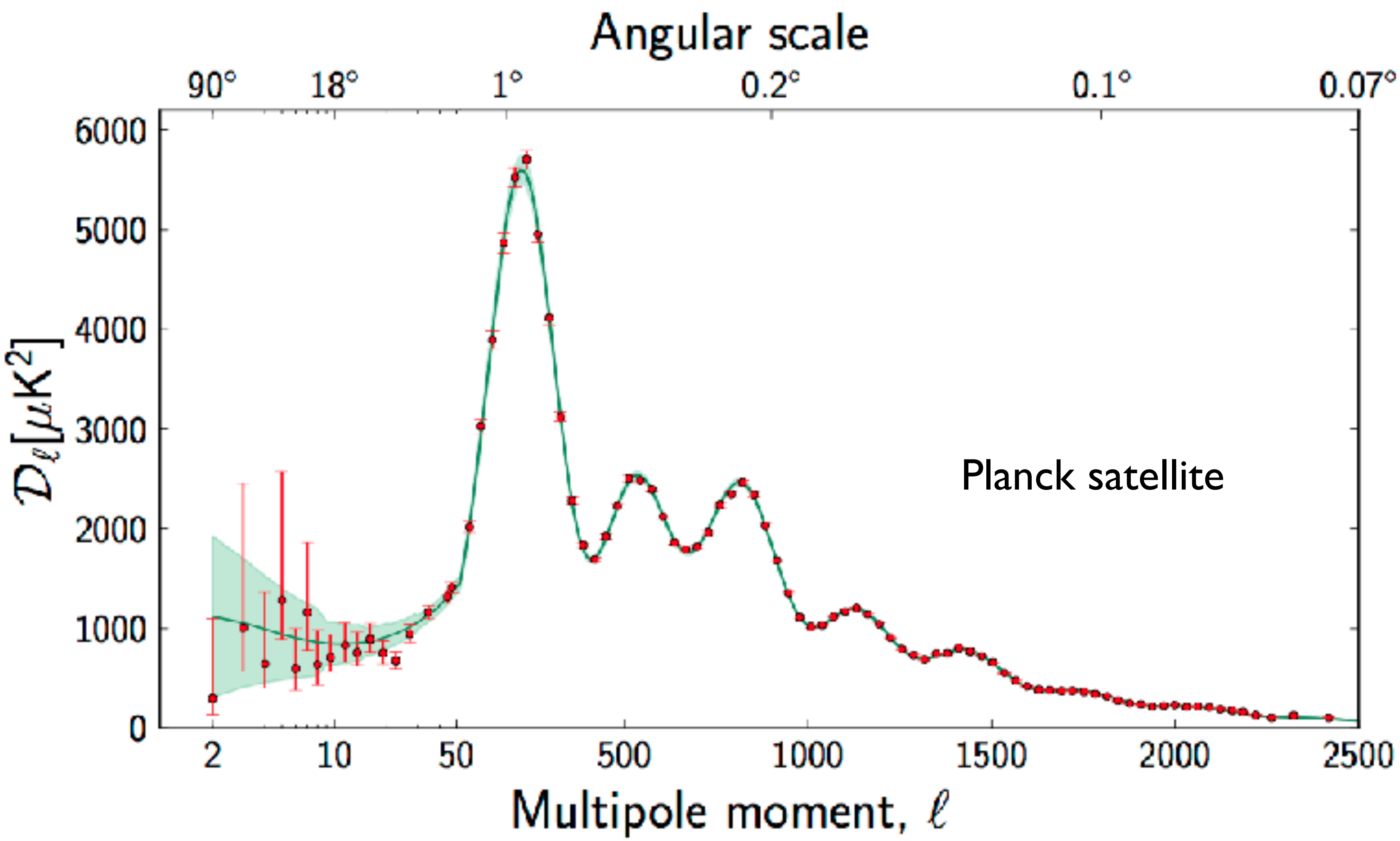
These waves froze out at recombination, leaving an imprint at a characteristic scale

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

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

Baryon Acoustic Oscillations

Oscillations clearly seen in the CMB temperature power spectrum



Baryon Acoustic Oscillations

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

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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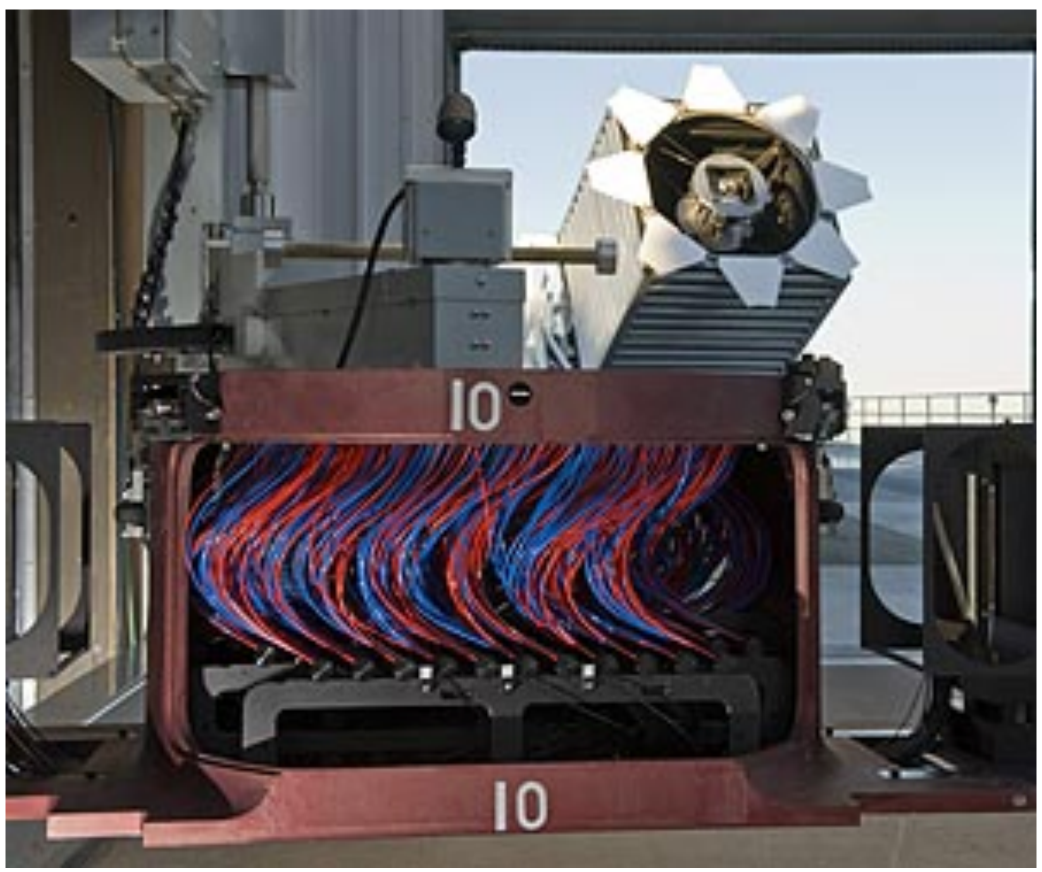
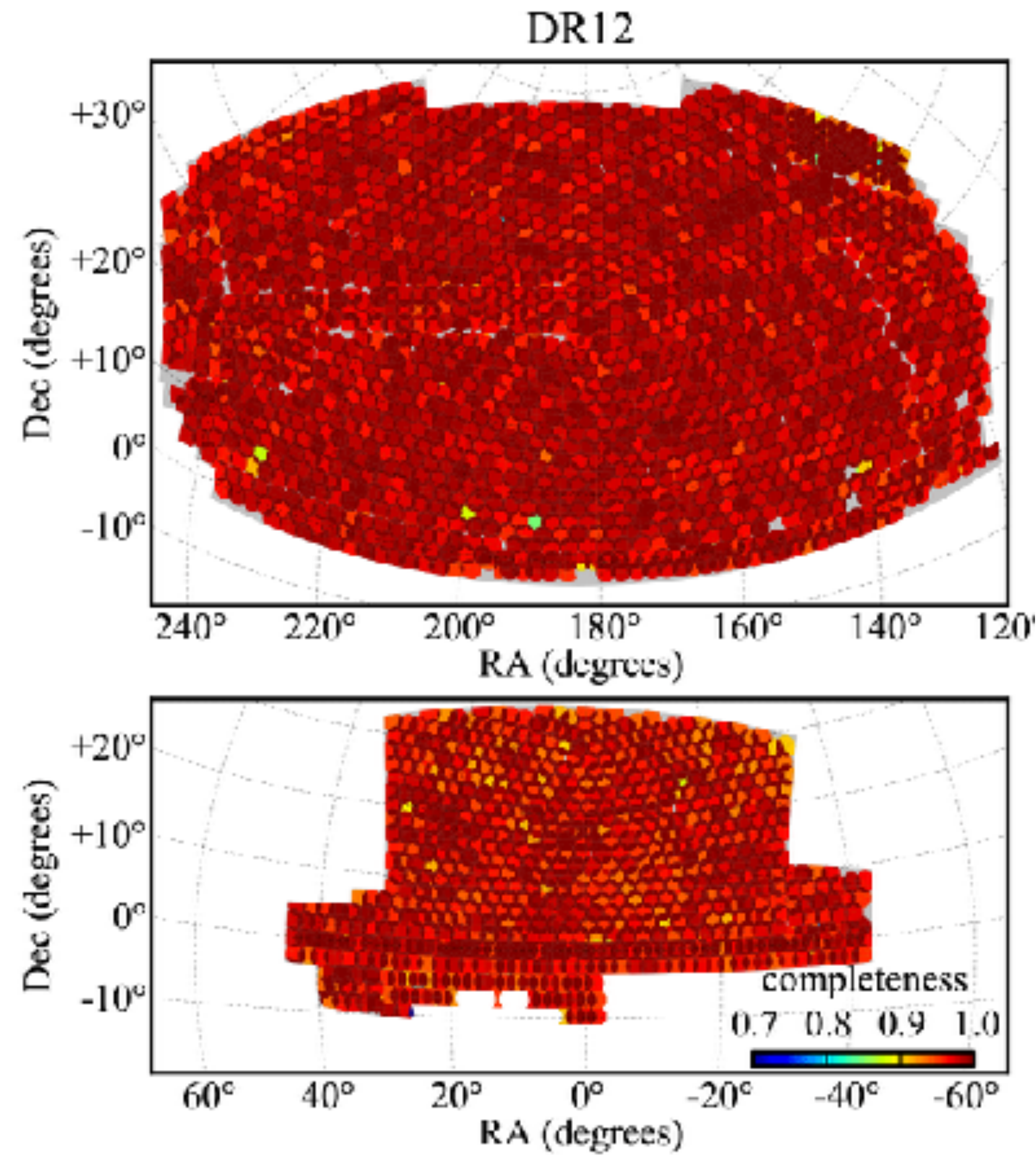
BOSS (2009-2014)

Baryon Oscillation Spectroscopic Survey (BOSS)

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

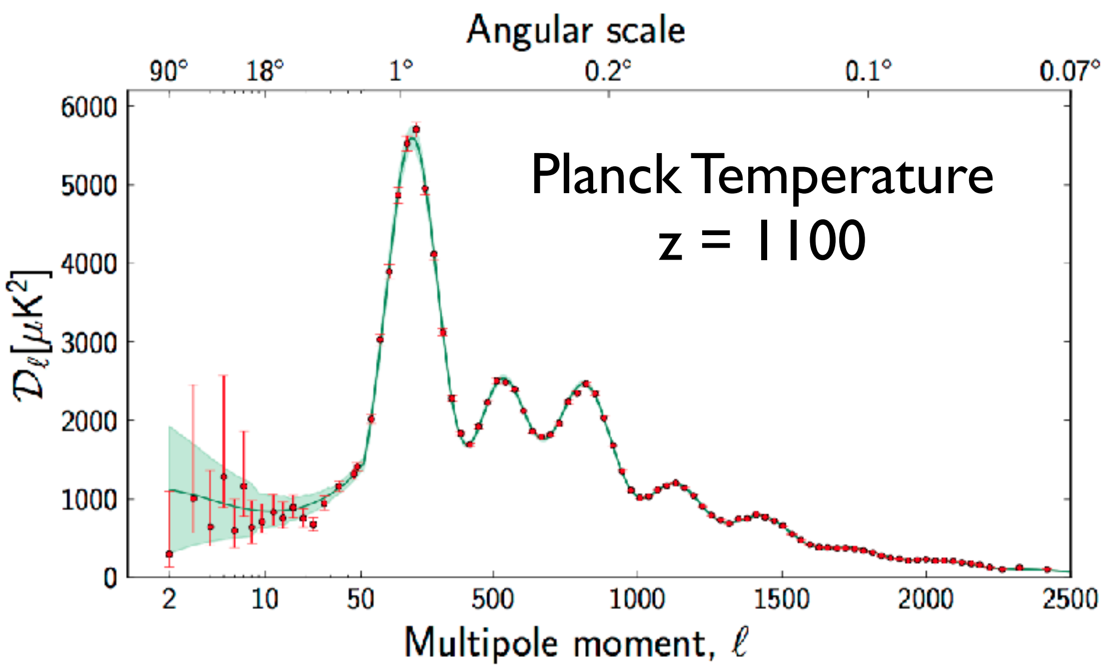


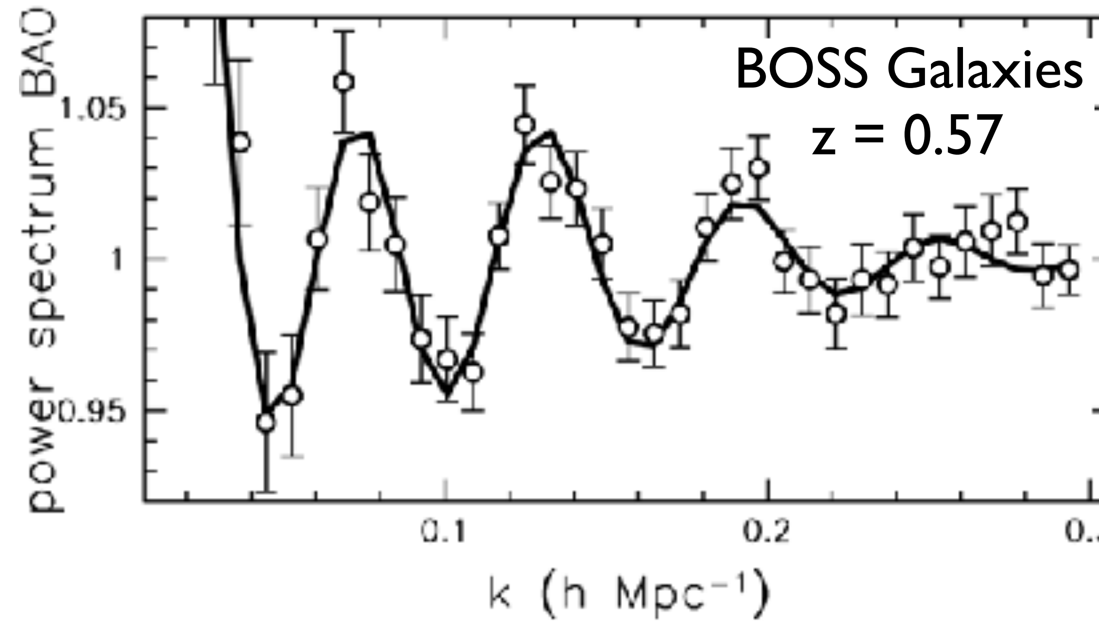
1000 spectra at a time
10.000 sq. deg. (1/4 sky)



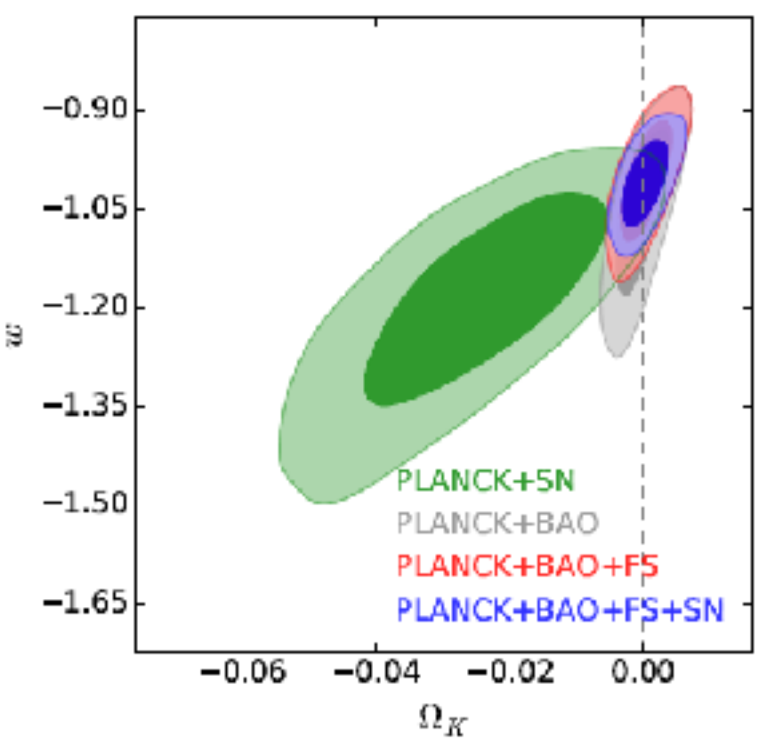
1.3M galaxies (0.2 < z < 0.7)
160k quasar (2.1 < z < 3.5)

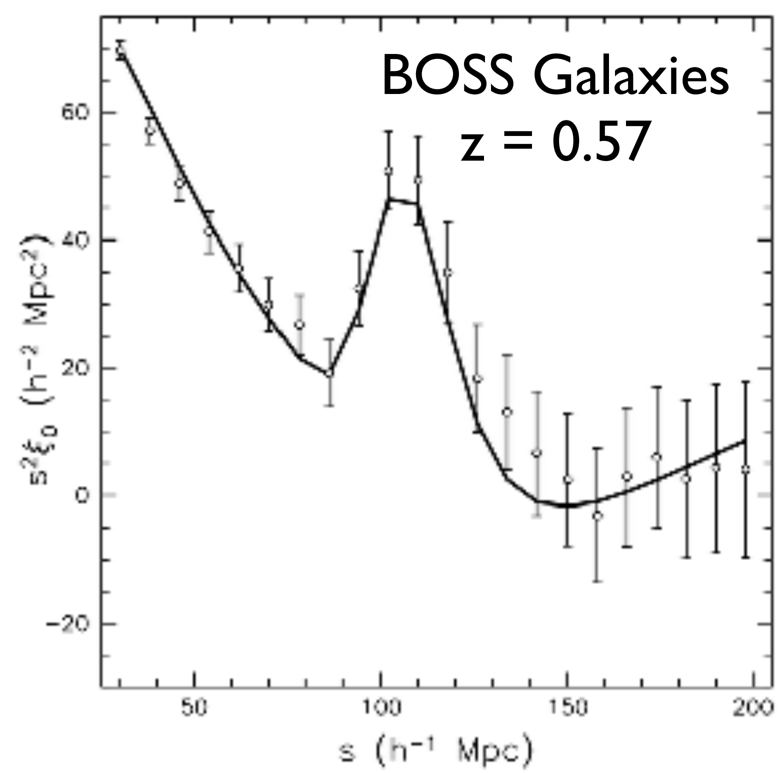
BOSS (2009-2014)





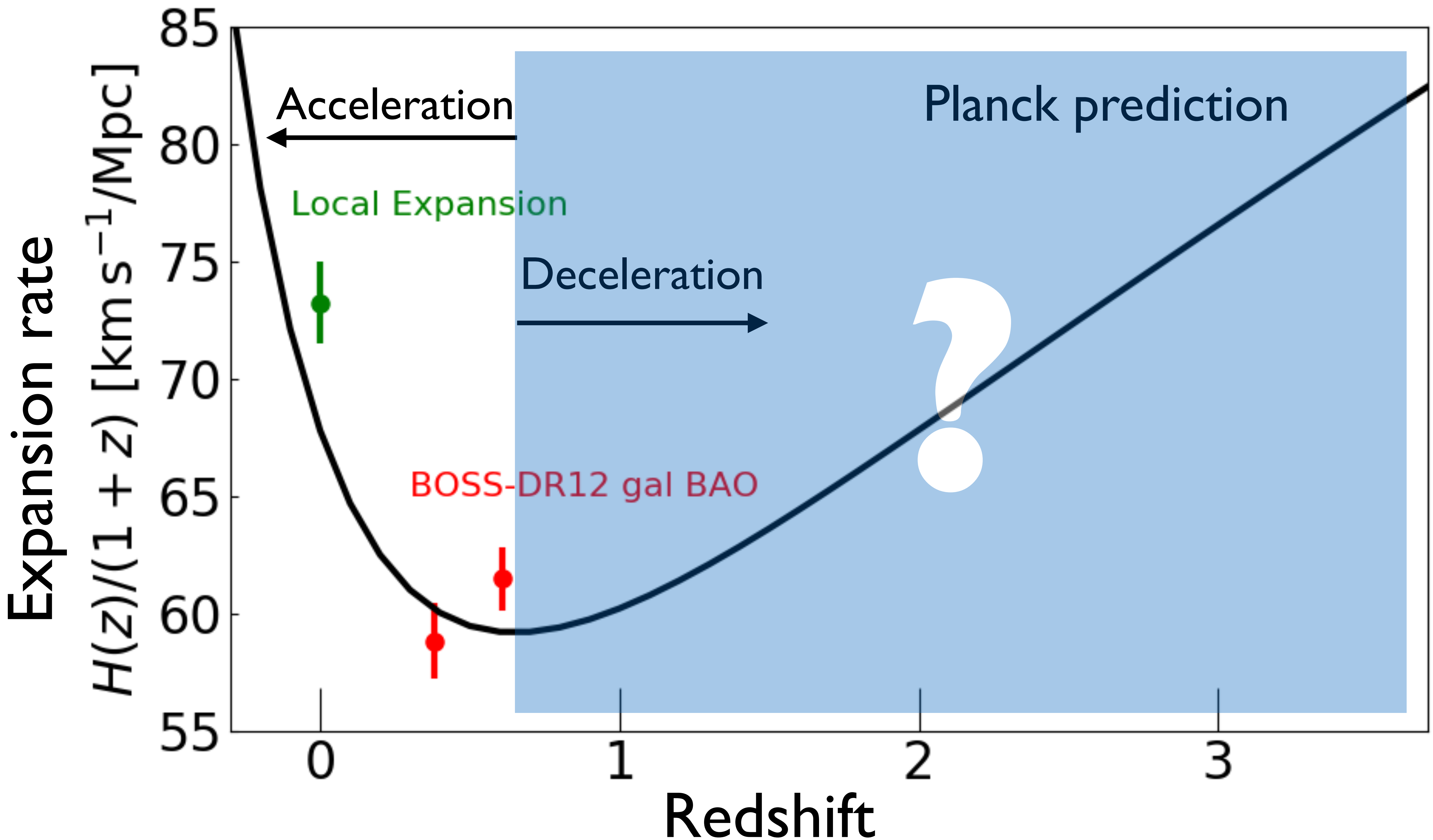
Oscillations clearly seen in CMB, but also in clustering of galaxies





Fourier transform

BOSS (2009-2014)



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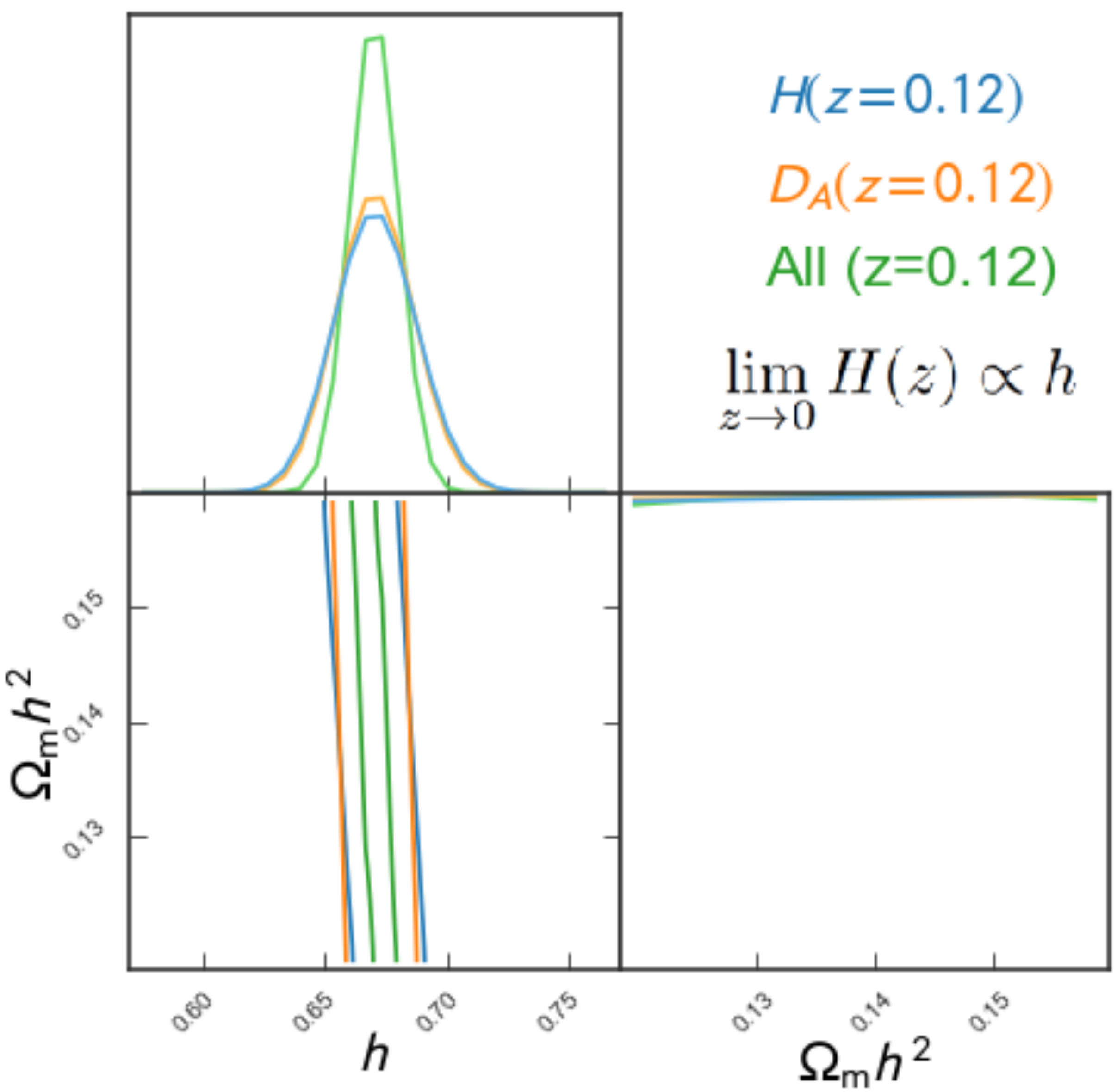
Why high-z BAO?

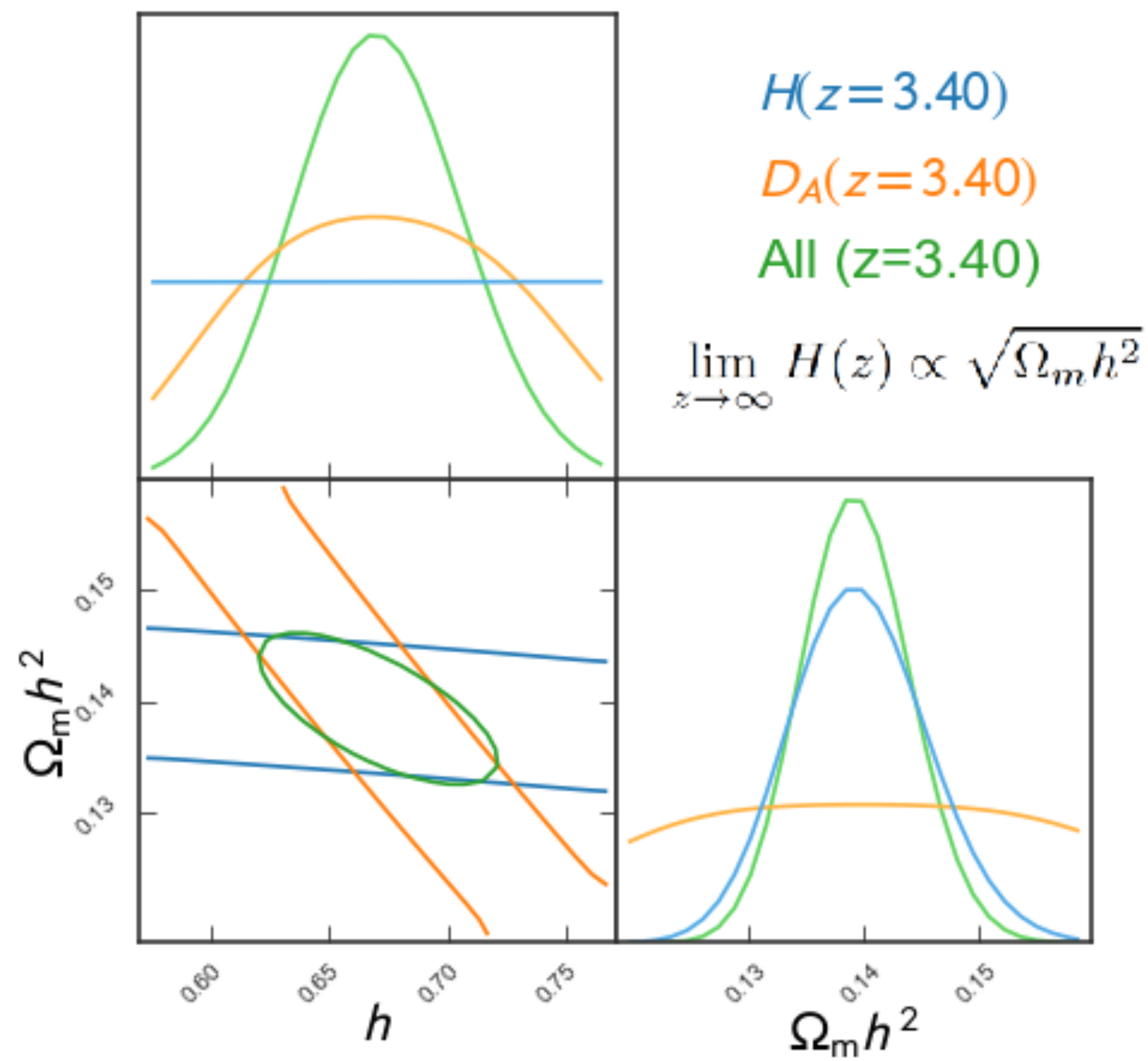
Flat LCDM - fixed r_d

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

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

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





The Lyman-α forest

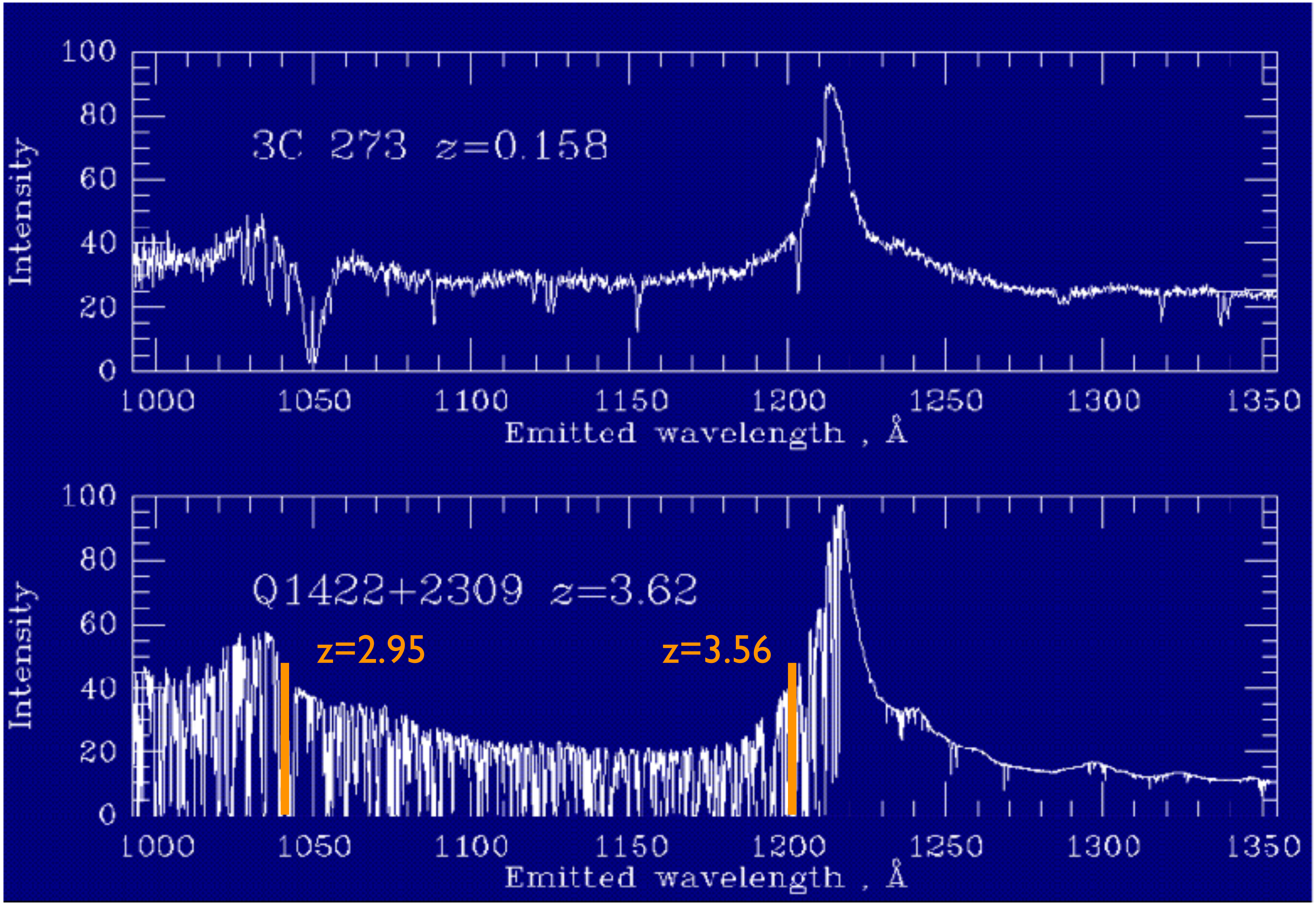
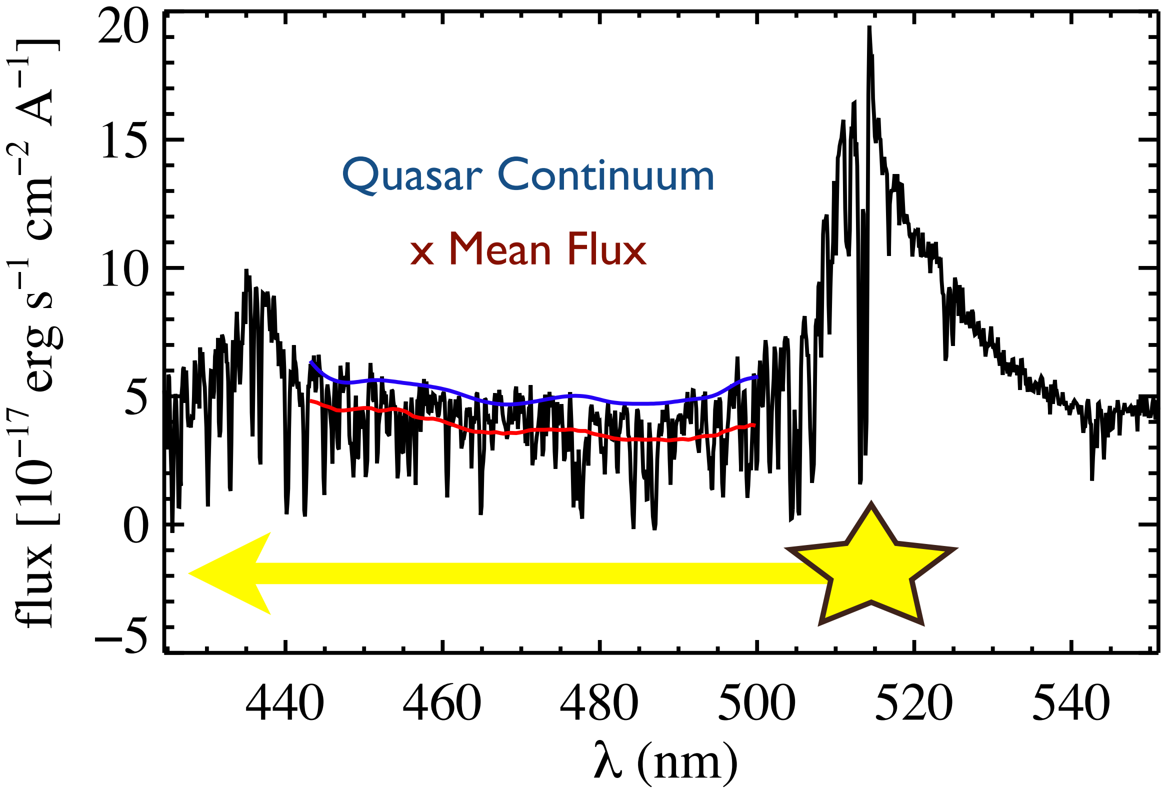


Figure from William C. Keel

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)

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

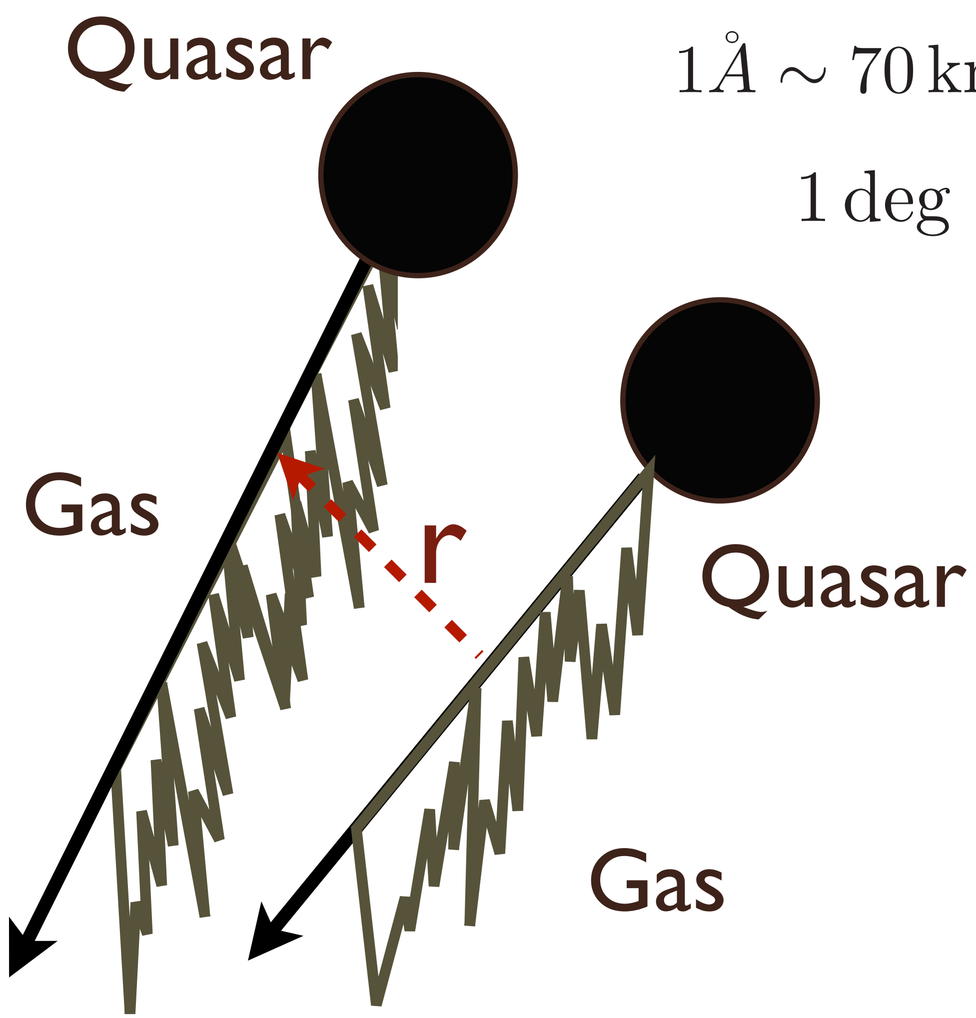
Flux fluctuations in pixels trace the density along the line of sight to the quasar

BOSS Lyman-α BAO

Two independent ways of measuring the BAO scale

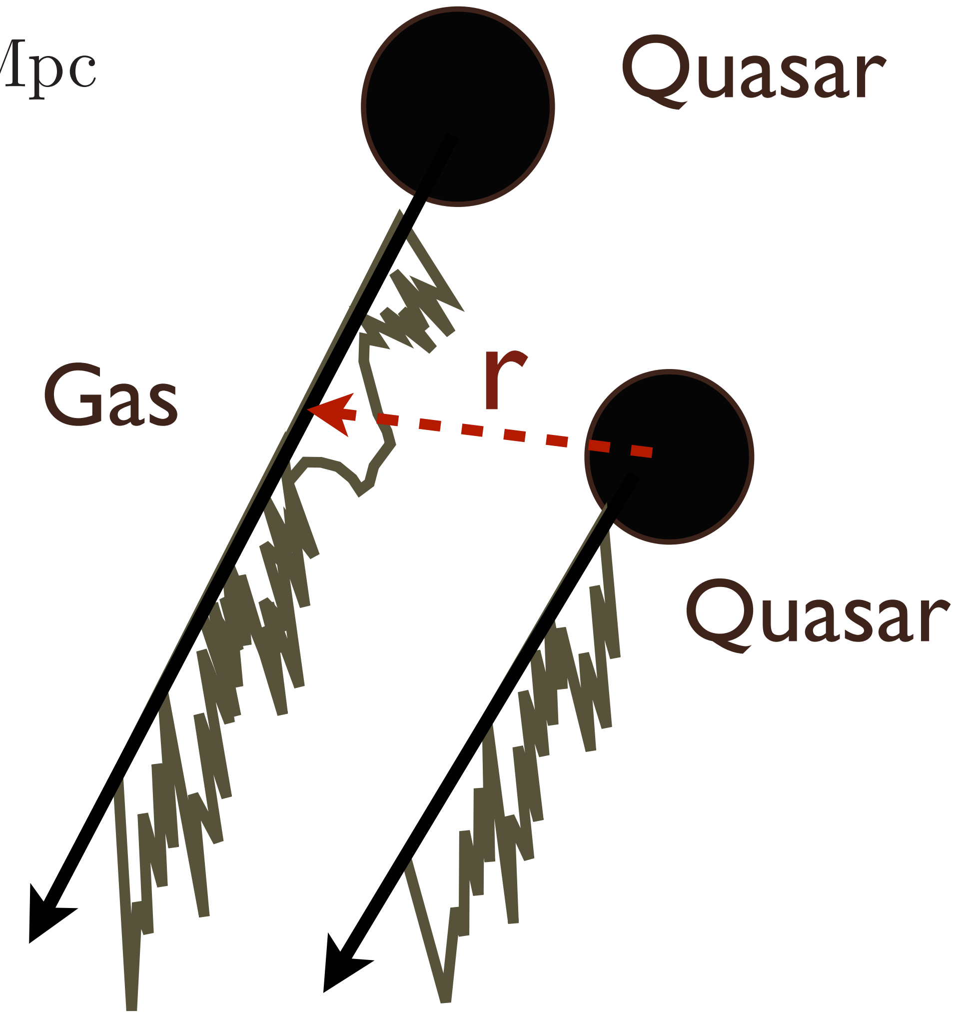
$$1\,\mathring{A} \sim 70\,\mathrm{km\,s^{-1}} \sim 0.7\,h^{-1}\,\mathrm{Mpc}$$

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



Lyα auto-correlation

Bautista et al. (2017)

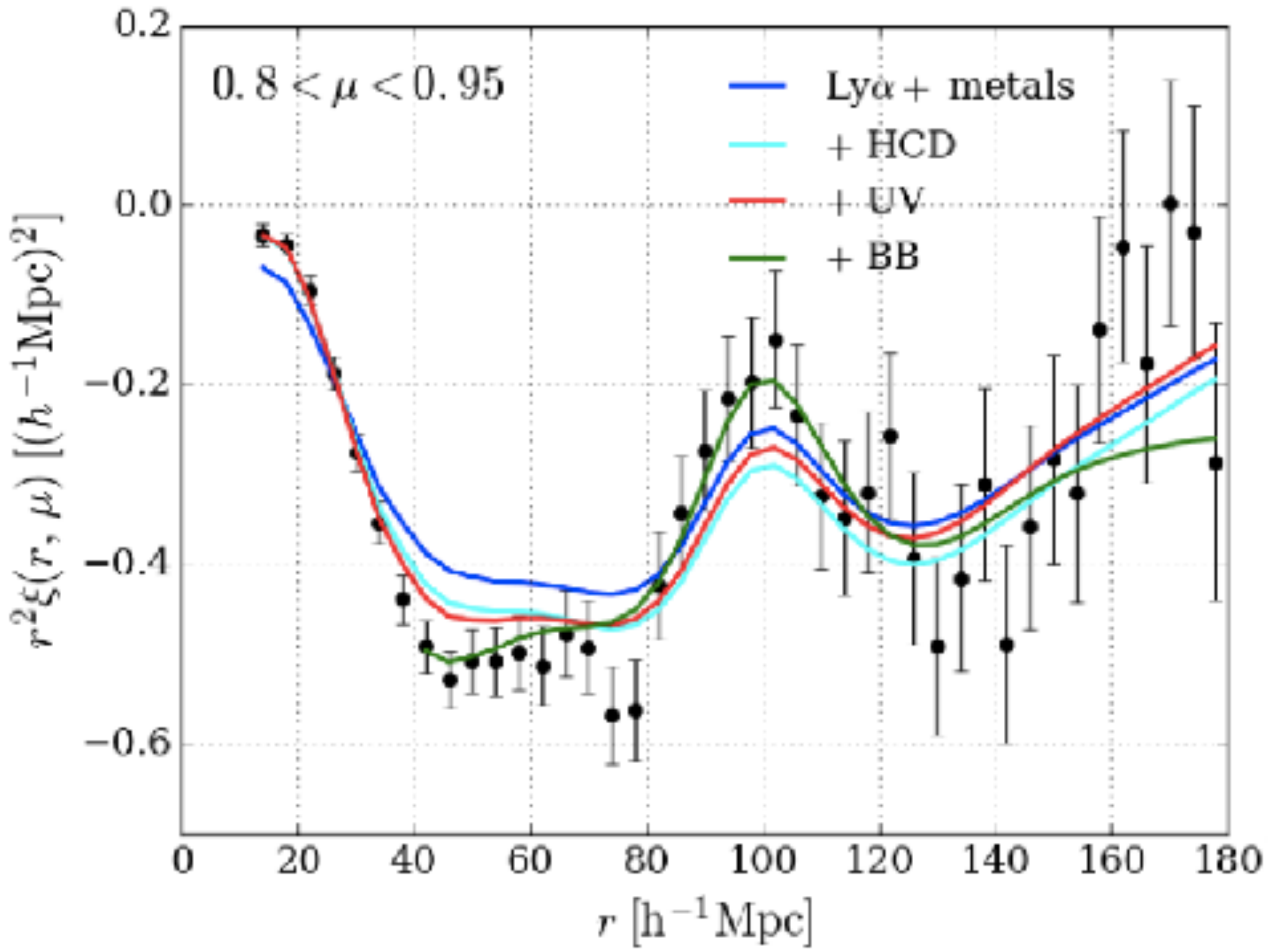


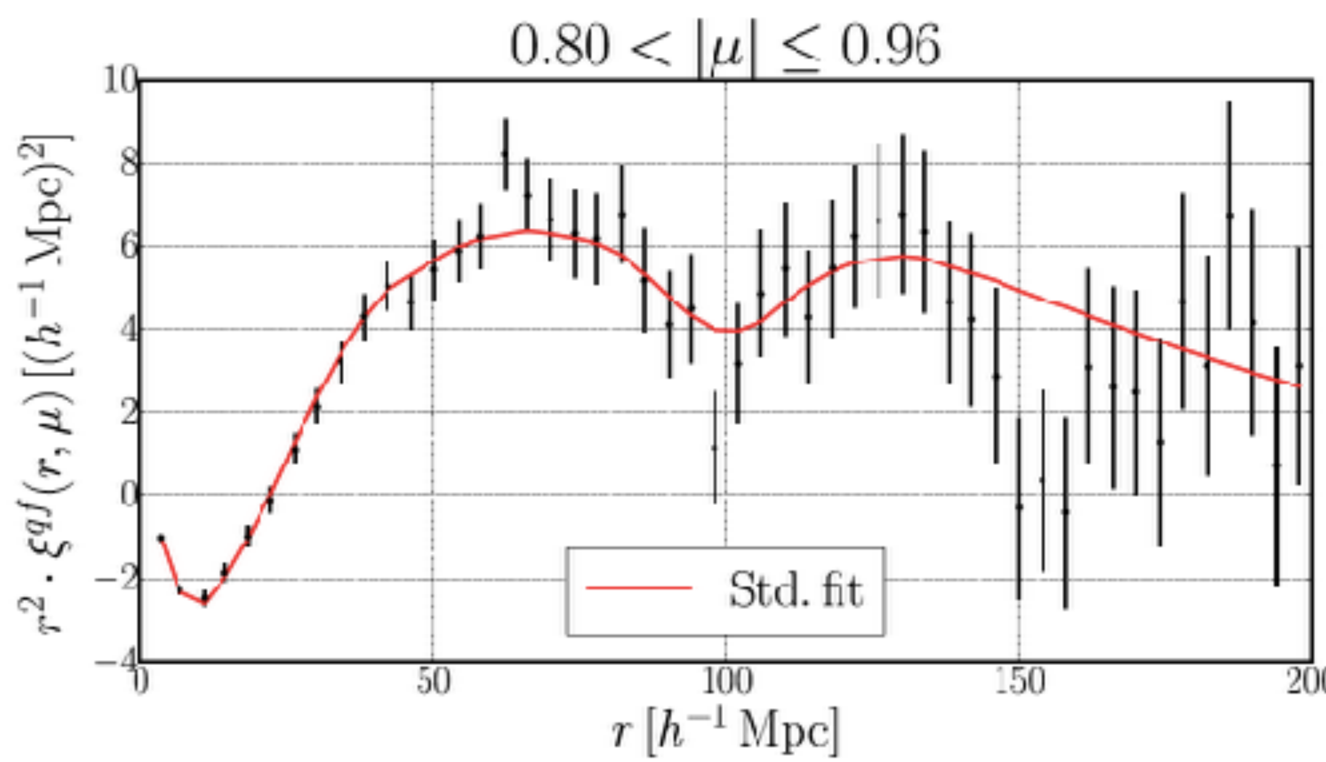
Lyα-quasar cross-correlation

du Mas des Bourboux (2017)

BOSS Lyman-α BAO

Two independent ways of measuring the BAO scale



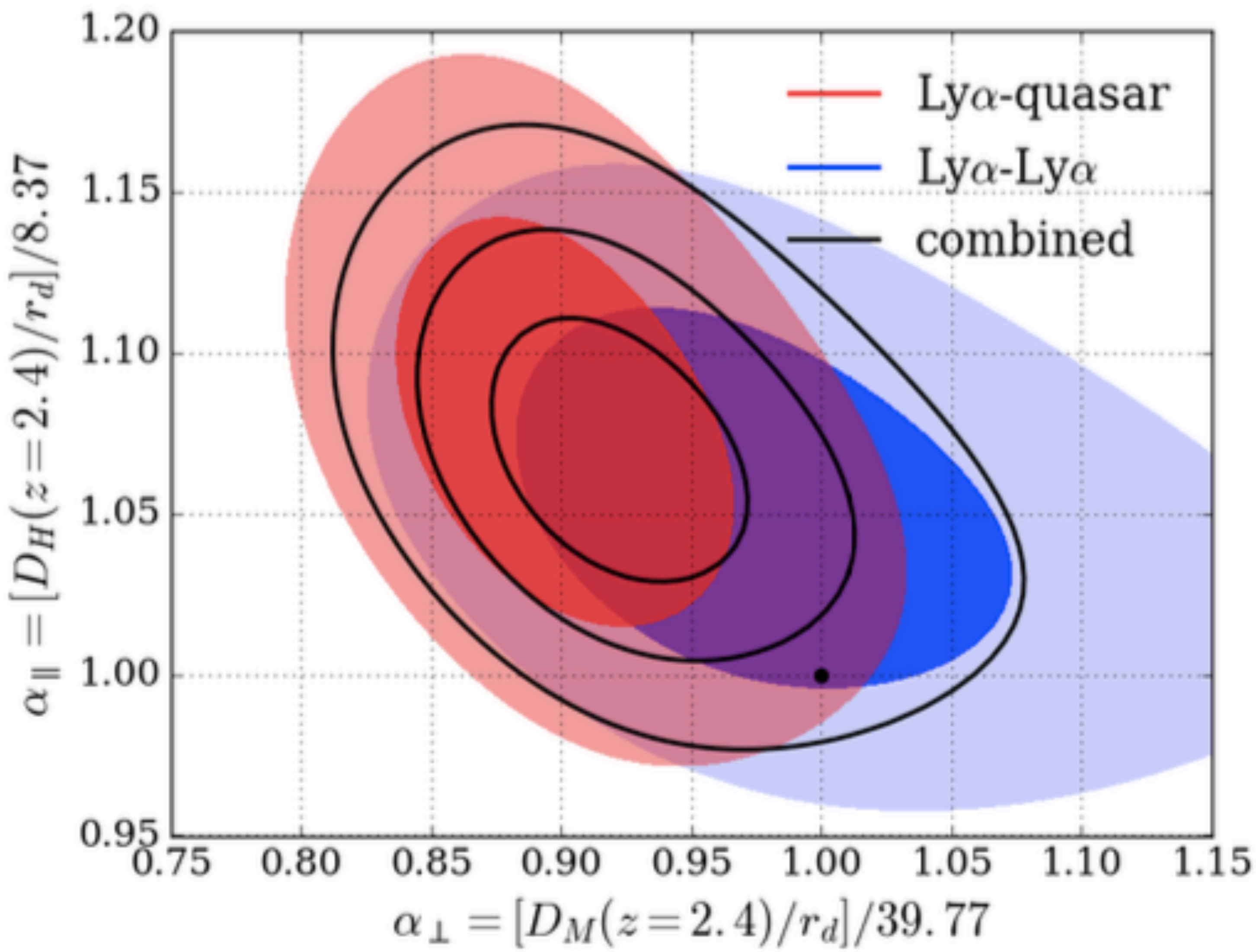


Lyα auto-correlation

Lyα-quasar cross-correlation

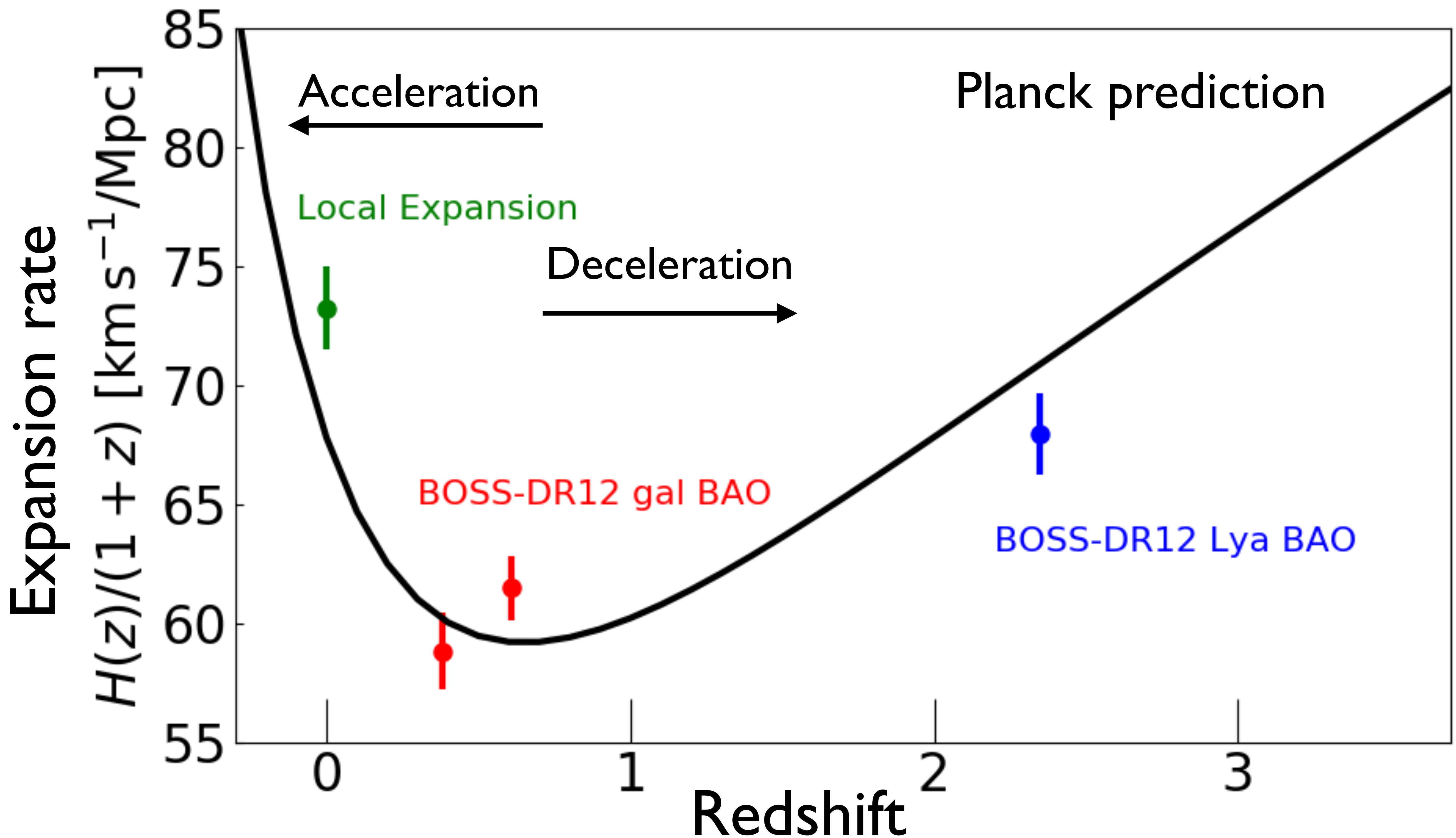
Bautista et al. (2017) Final BOSS DR12 du Mas des Bourboux (2017)

BOSS Lyman-α BAO



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

BOSS Lyman-α BAO



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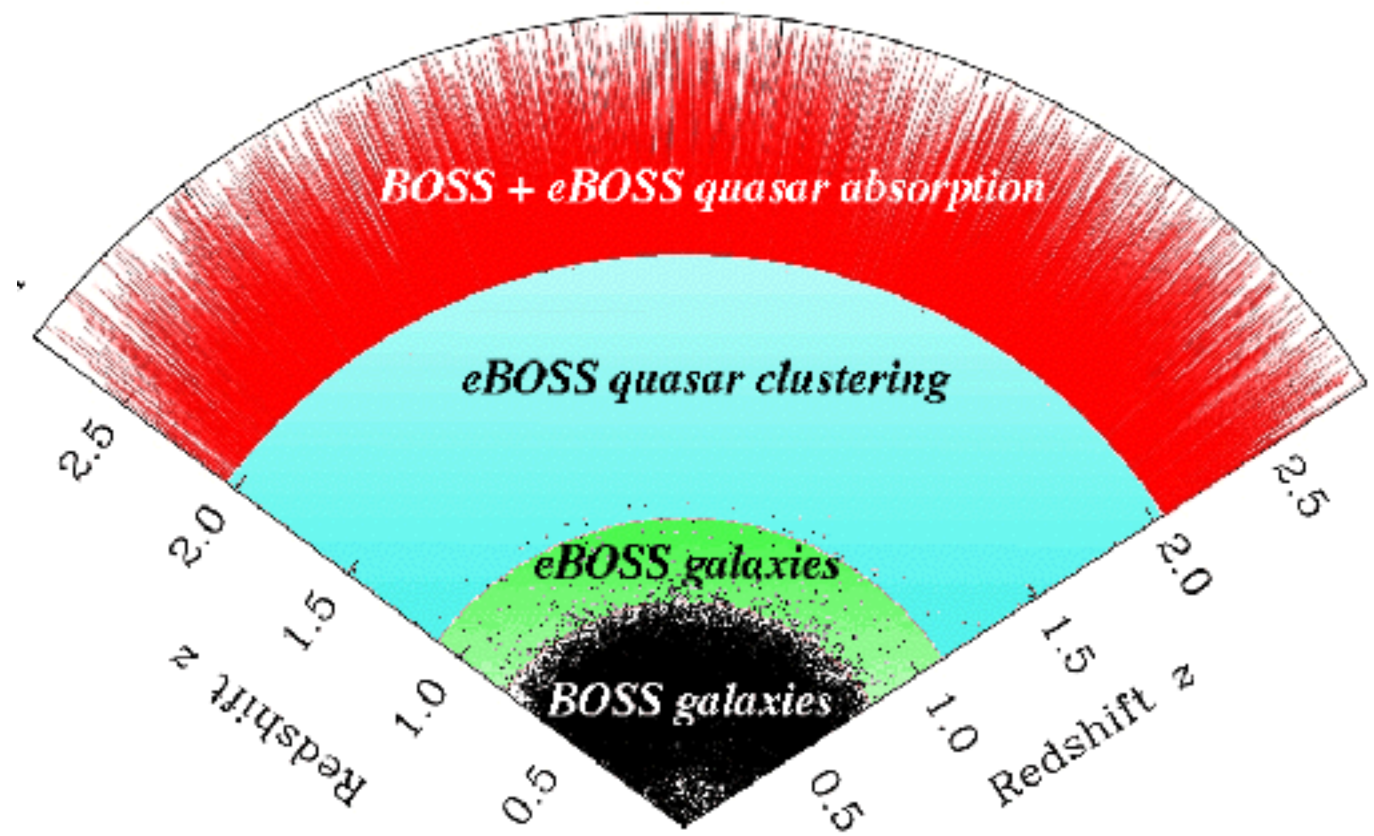
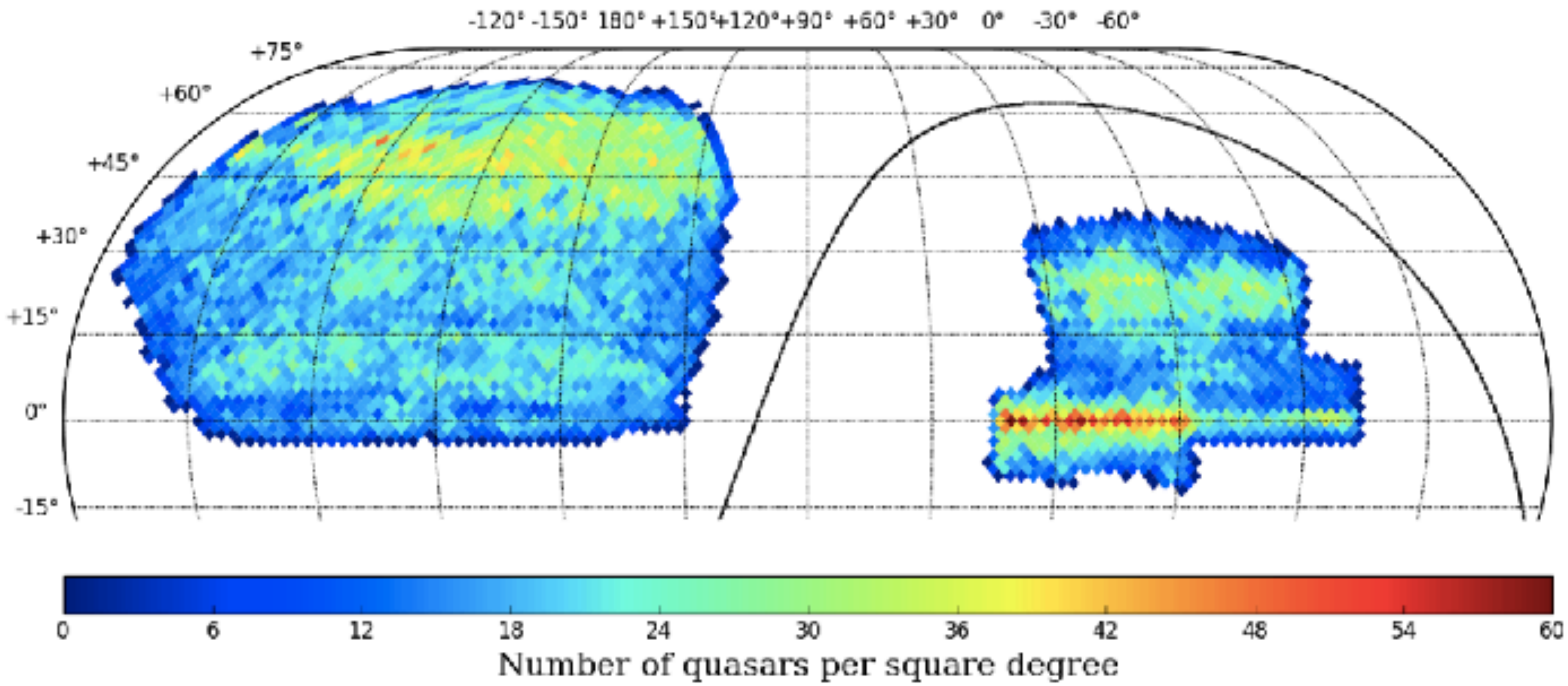
eBOSS (2014-2019)

Extended Baryon Oscillation Spectroscopic Survey (eBOSS)

- One of the surveys in SDSS-IV
- Same instrument than BOSS
- Fill gap in $1 < z < 2$
- Prototype for DESI
- DR14 already public
- Final DR16 public end of 2019



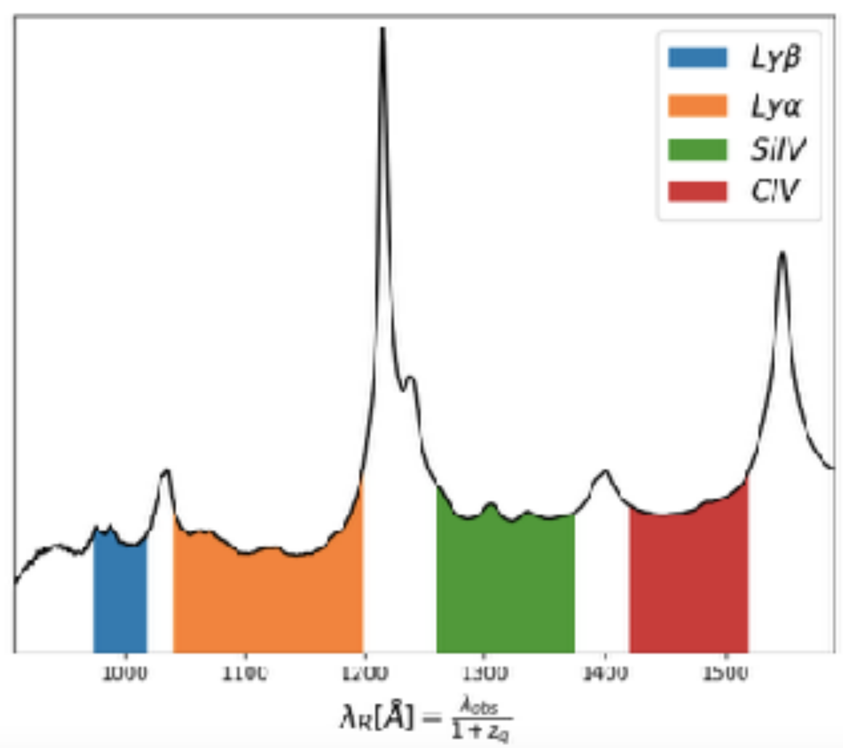
eBOSS Lyα DR14



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

20% more quasars than BOSS

New in eBOSS analyses: use also the LyB region!

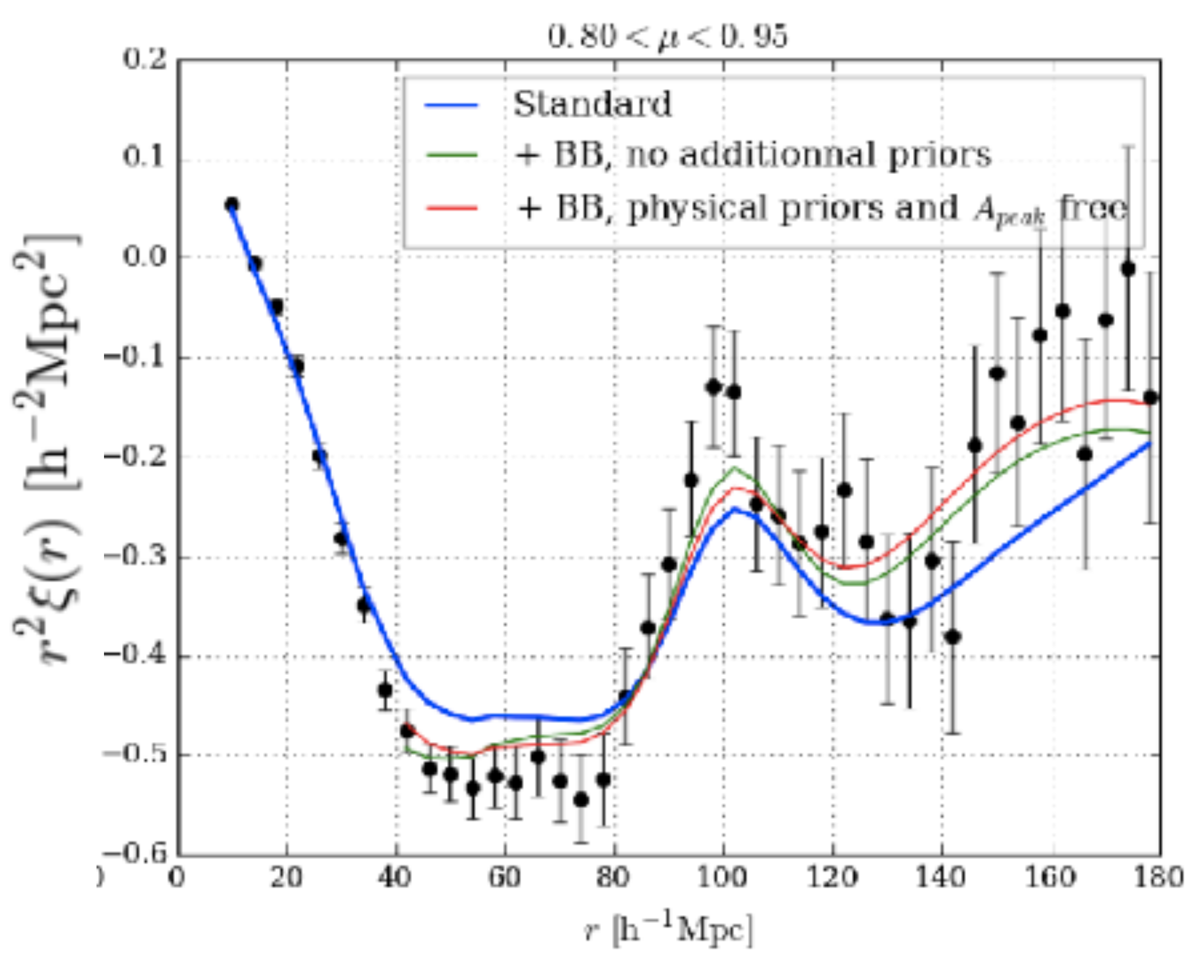


eBOSS Lyα DR14

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

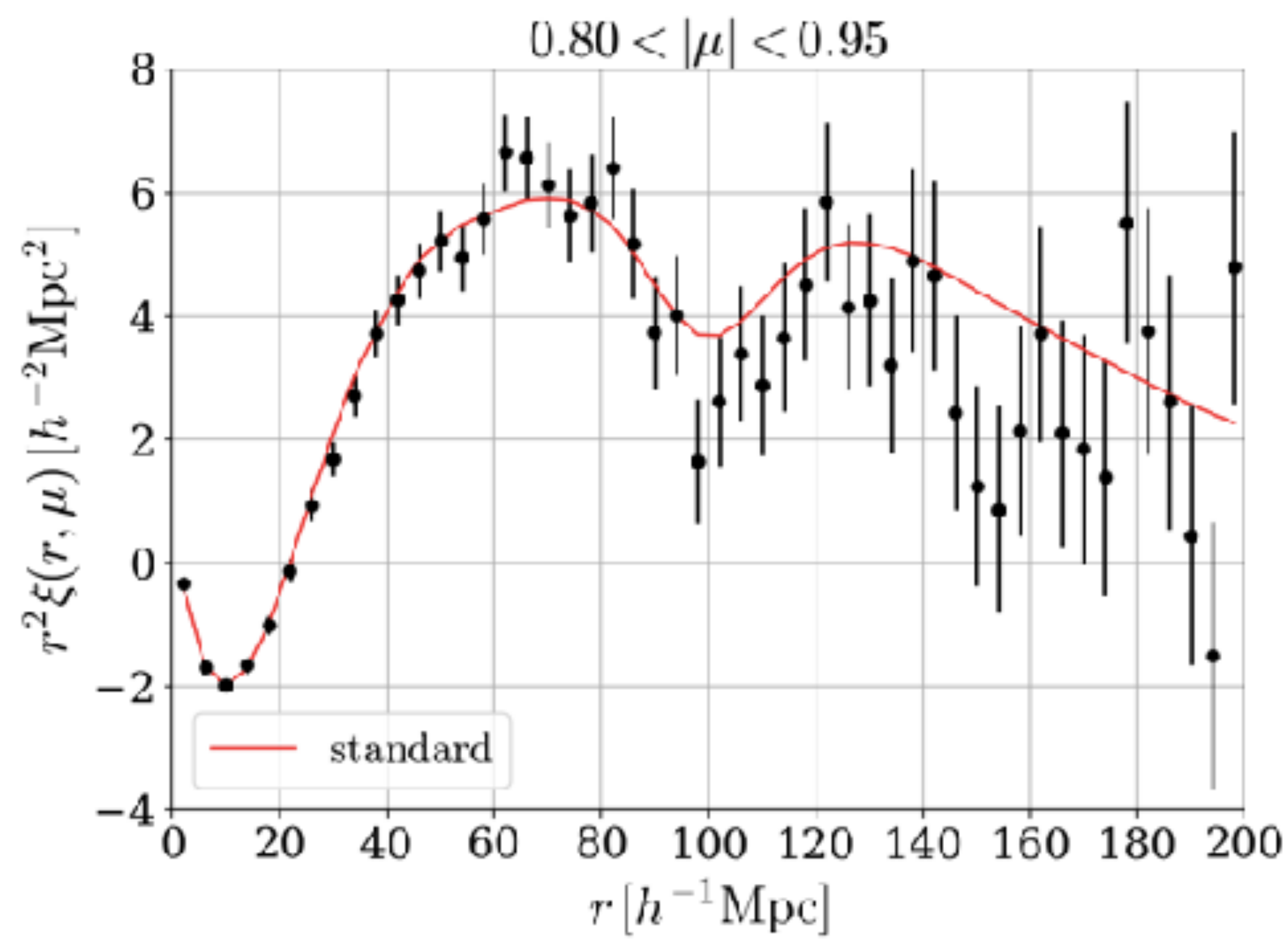
Errorbars 20% smaller than BOSS DR12

Lyα auto-correlation



Sainte Agathe et al. (2019)

QSO-Lyα cross-correlation



Blomqvist et al. (2019)

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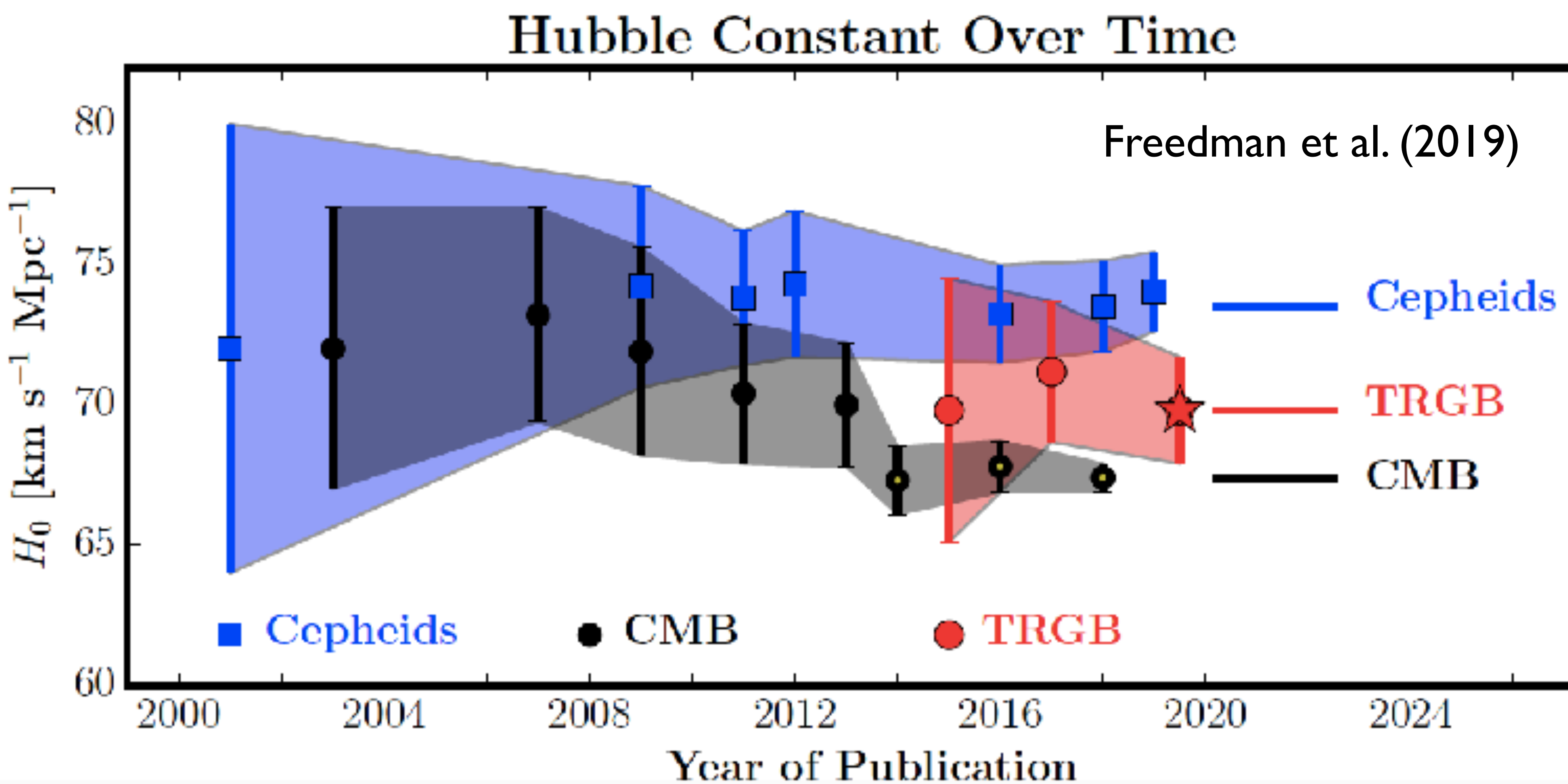
BAO and the H_0 tension

How fast is the Universe currently expanding?

One of the key cosmological parameters has been historically controversial



Early Universe physics —> low H_0

Local distances —> high H_0

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 → These do not use CMB

Consistent with both

SPT

TRGB

LIGO GW

Prefer high H_0

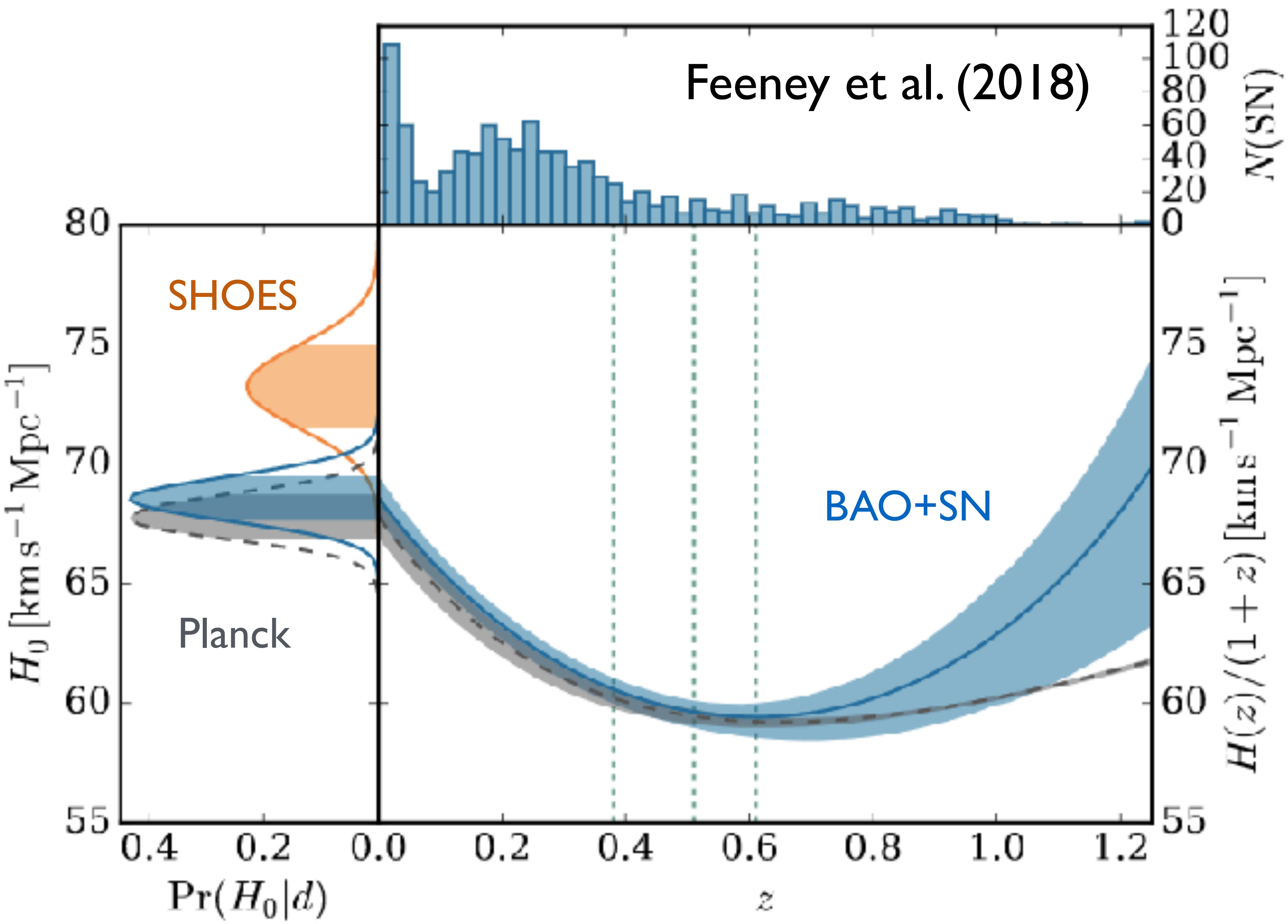
SHOES

HoLICOW

Systematics on either side? Problems with flat ΛCDM?

BAO and the H_0 tension

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

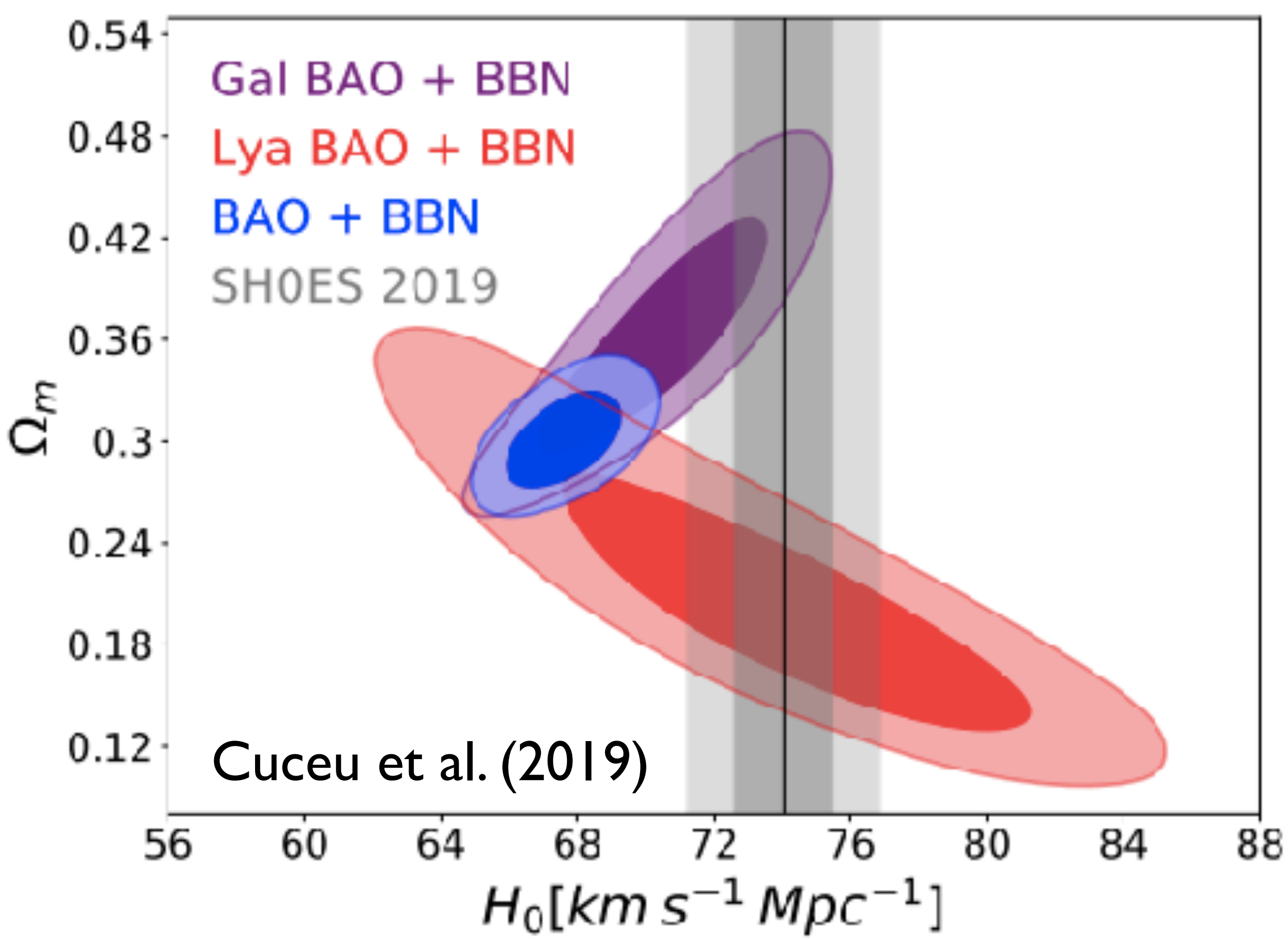


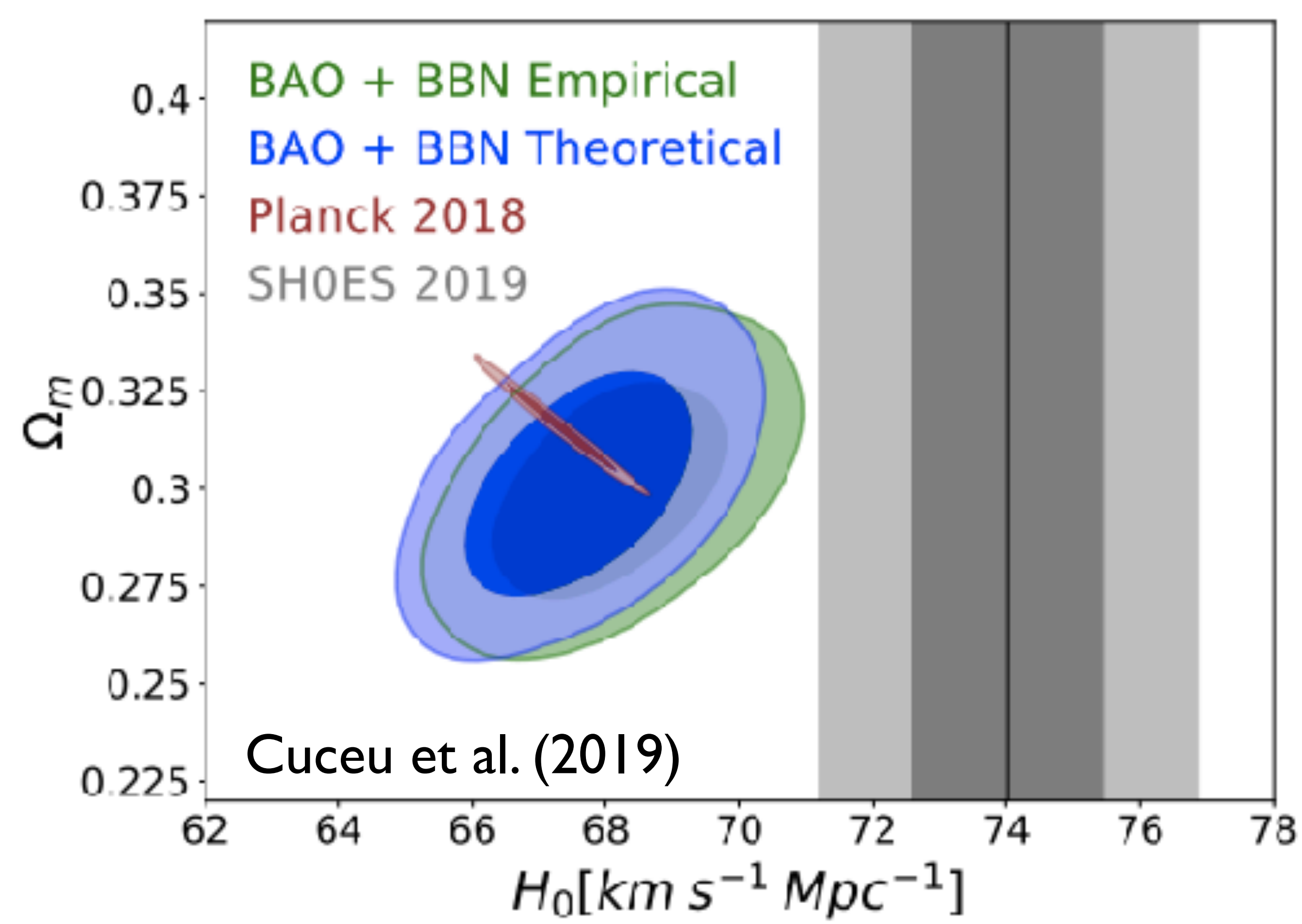
- BAO (SDSS/BOSS + 6dF)
- Pantheon SN
- r_d from CMB
- Free dark energy model

BAO and the H_0 tension

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

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





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)

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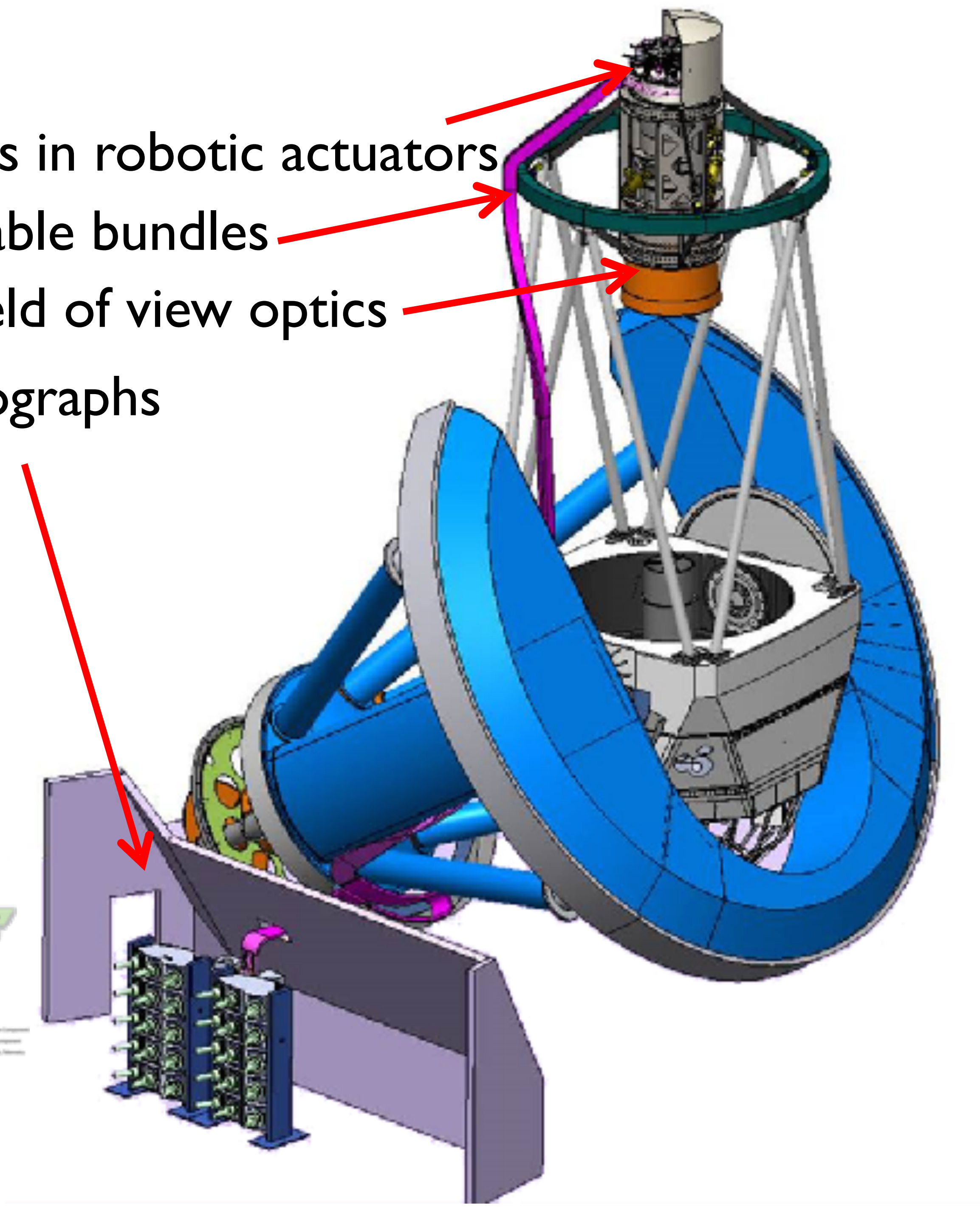
Dark Energy Spectroscopic Instrument

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



Readout & Control

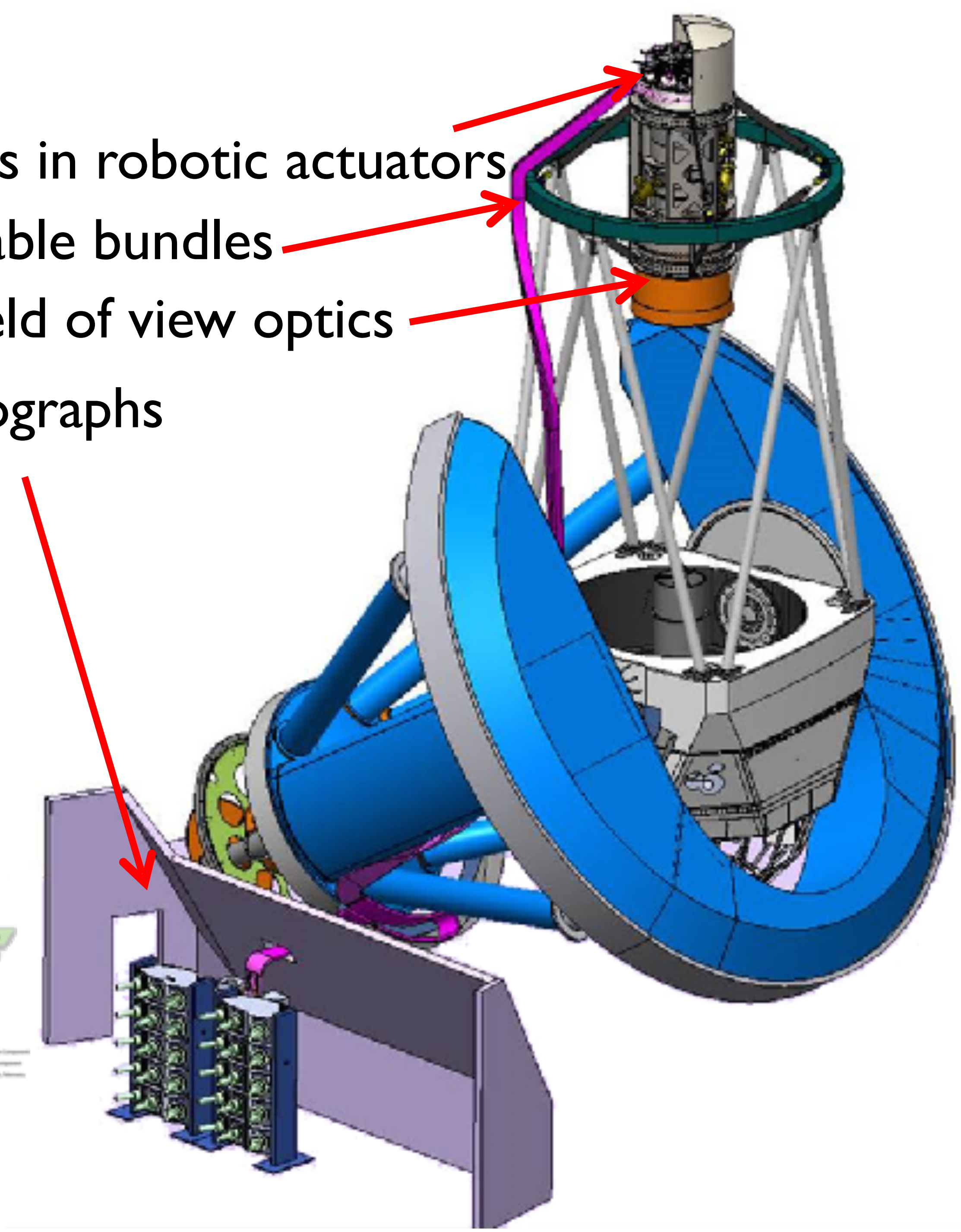
Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS dataset by an order of magnitude

Scheduled to start in 2020

Dark Energy Spectroscopic Instrument

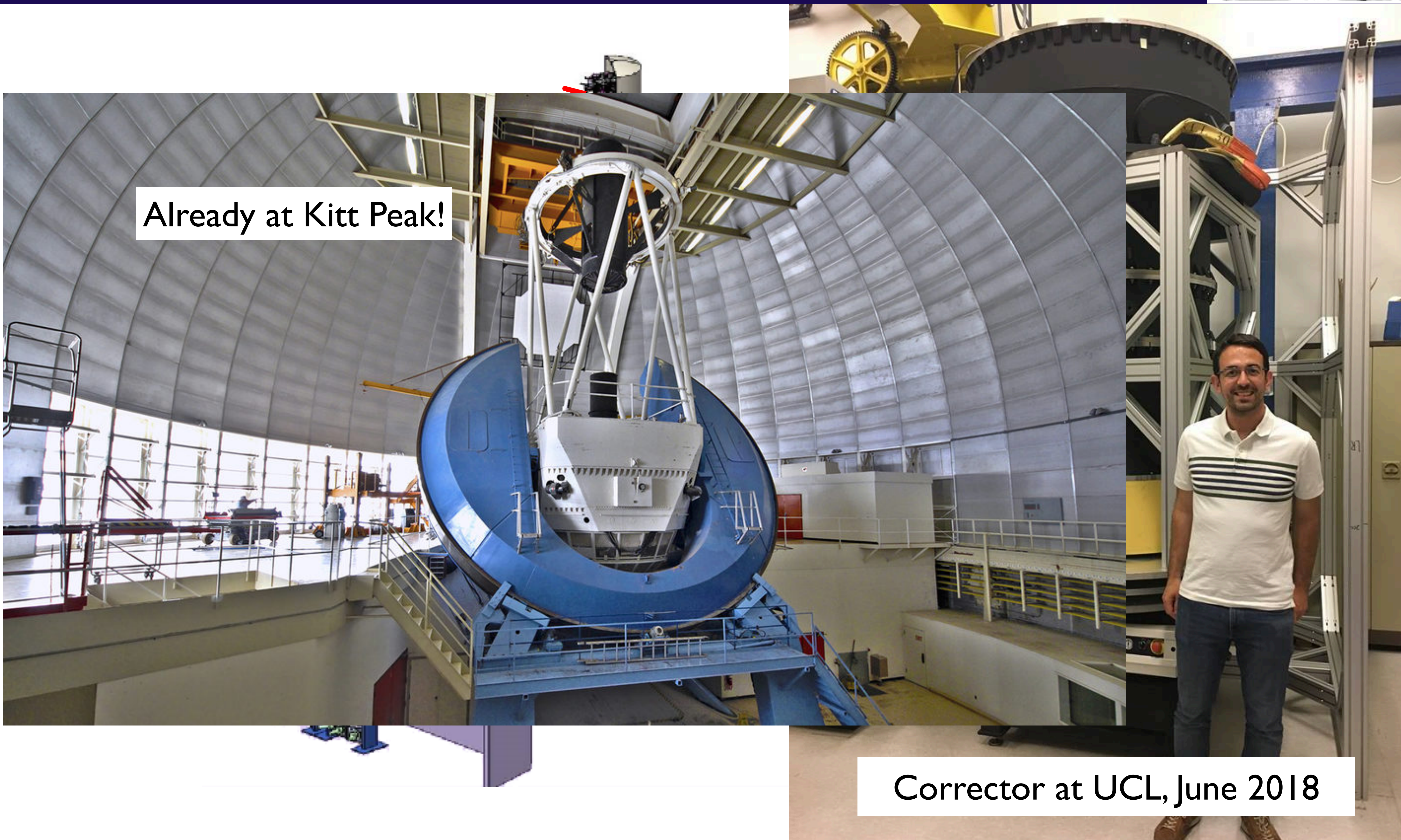
- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



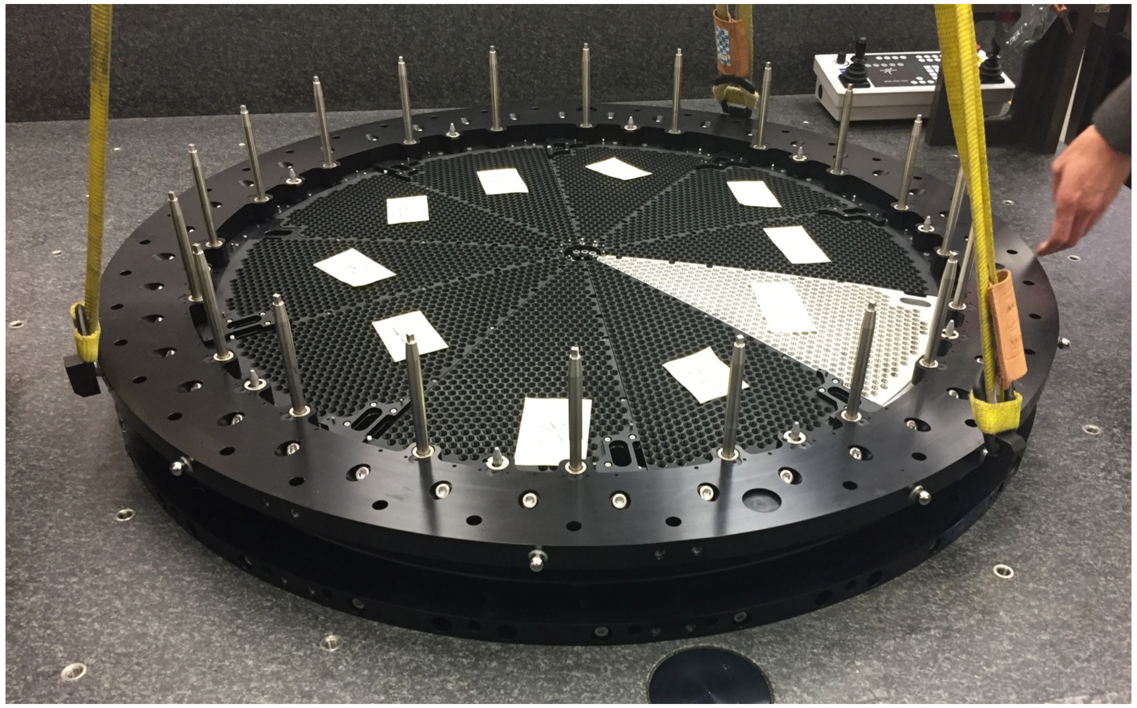
Readout & Control

Corrector at UCL, June 2018

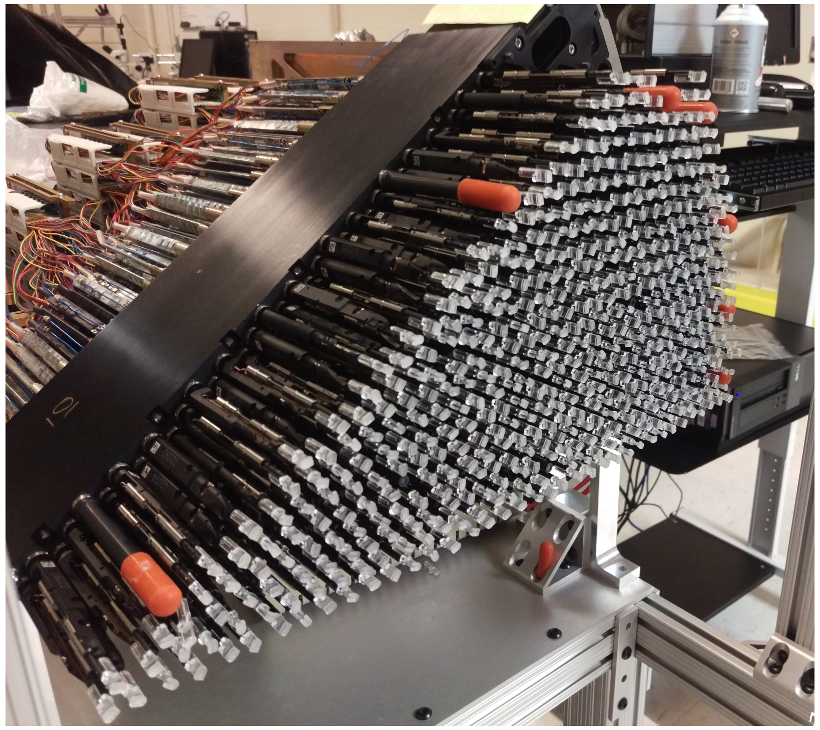
Dark Energy Spectroscopic Instrument



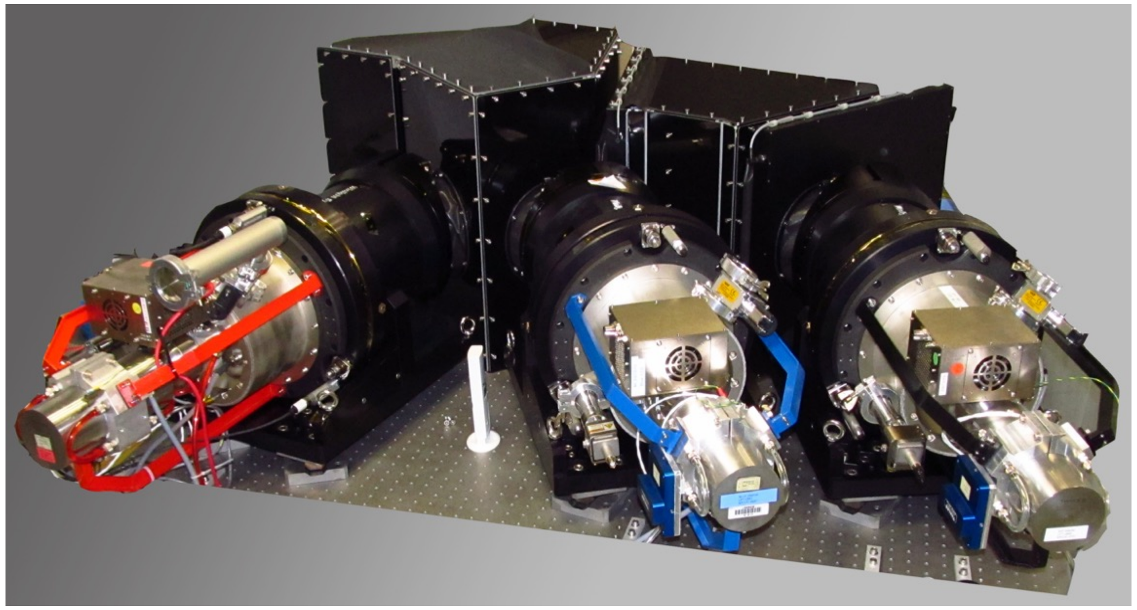
Dark Energy Spectroscopic Instrument



Focal plane and ring completed



All 10 petals populated with positioners

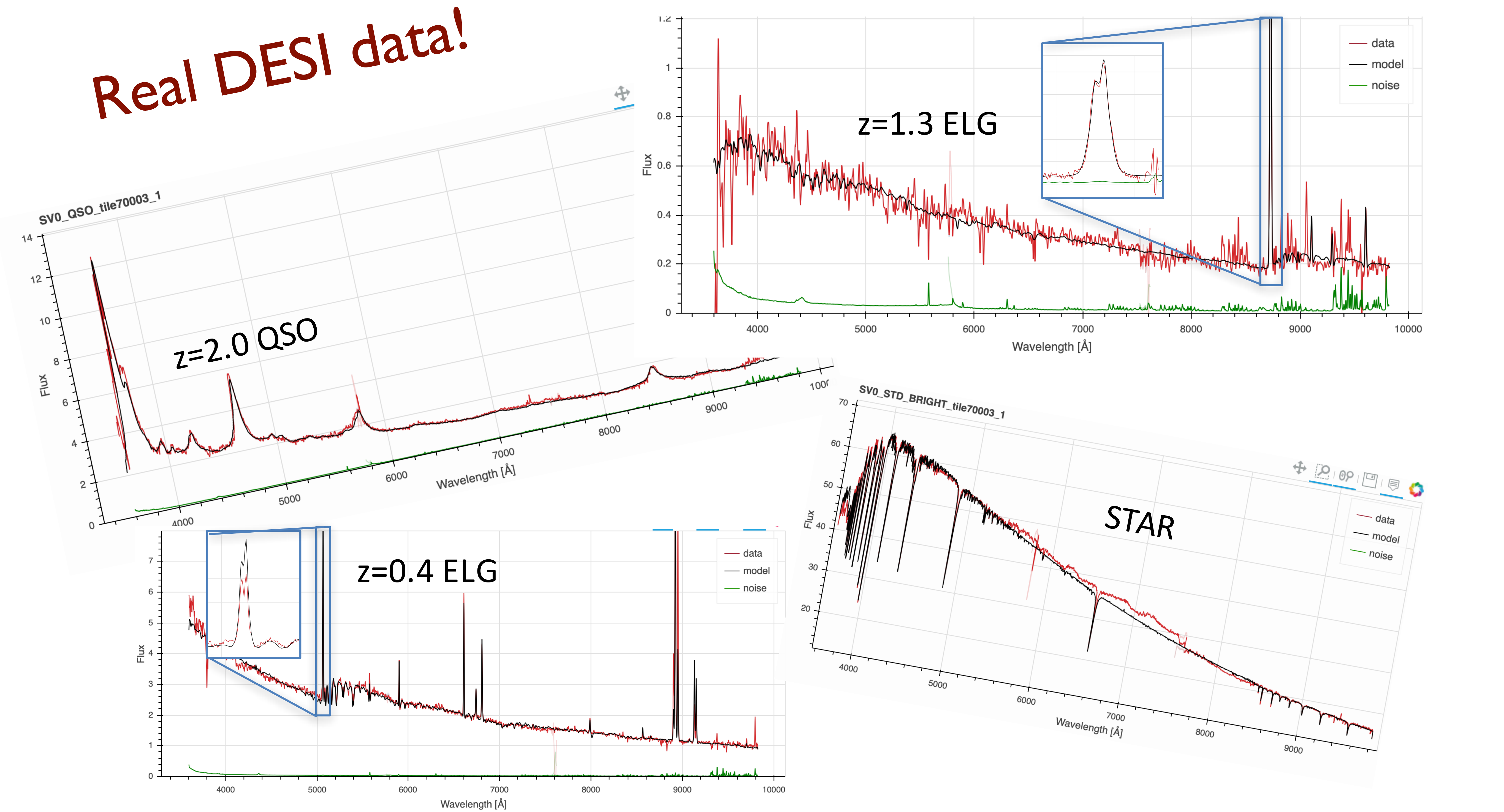


All spectrographs verified and at Kitt Peak

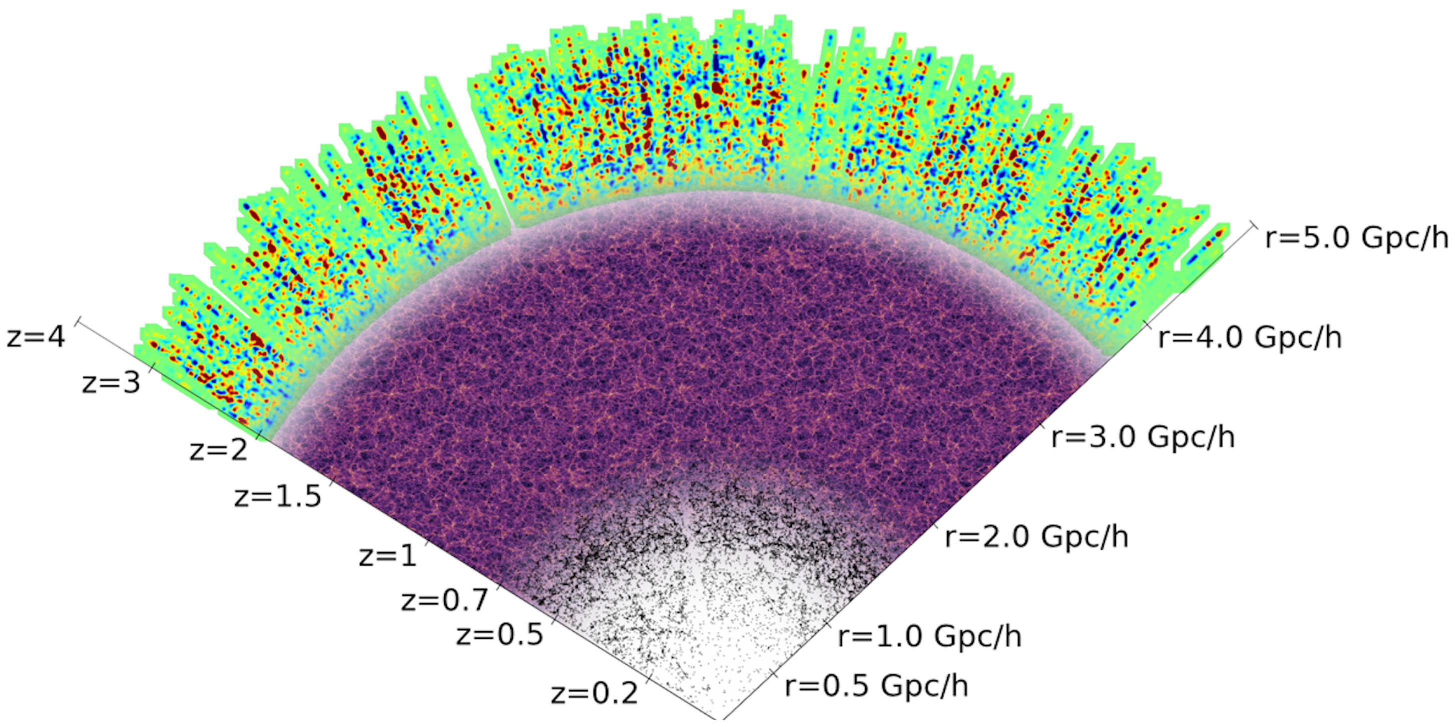
DESI timeline:

- Corrector installed August 2018
- Commissioning ongoing
- Survey Validation Spring 2020
- Science starts in the Fall!

Dark Energy Spectroscopic Instrument



Dark Energy Spectroscopic Instrument



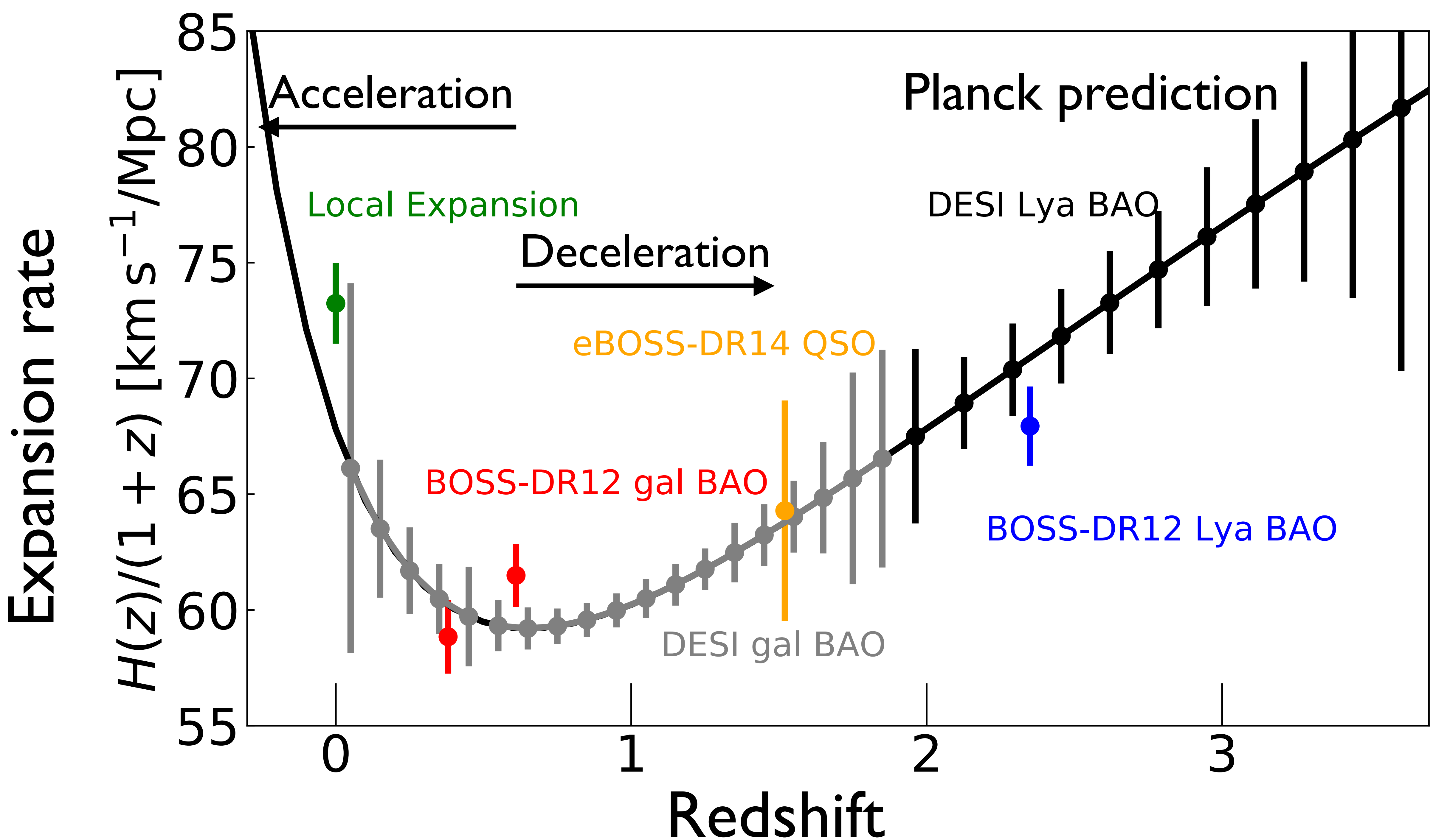
Two surveys

- 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 Instrument

DESI projections (Font-Ribera++ 2014b)



Summary

- Baryon Acoustic Oscillations can shed light on dark energy
- BOSS measured BAO at 1% accuracy using galaxies
  - 2% measurement at $z \sim 2.3$ using quasars and Ly-α forest
- In 2020, DESI will start collecting a x10 larger dataset
- Not only dark energy: neutrino masses, inflationary models…