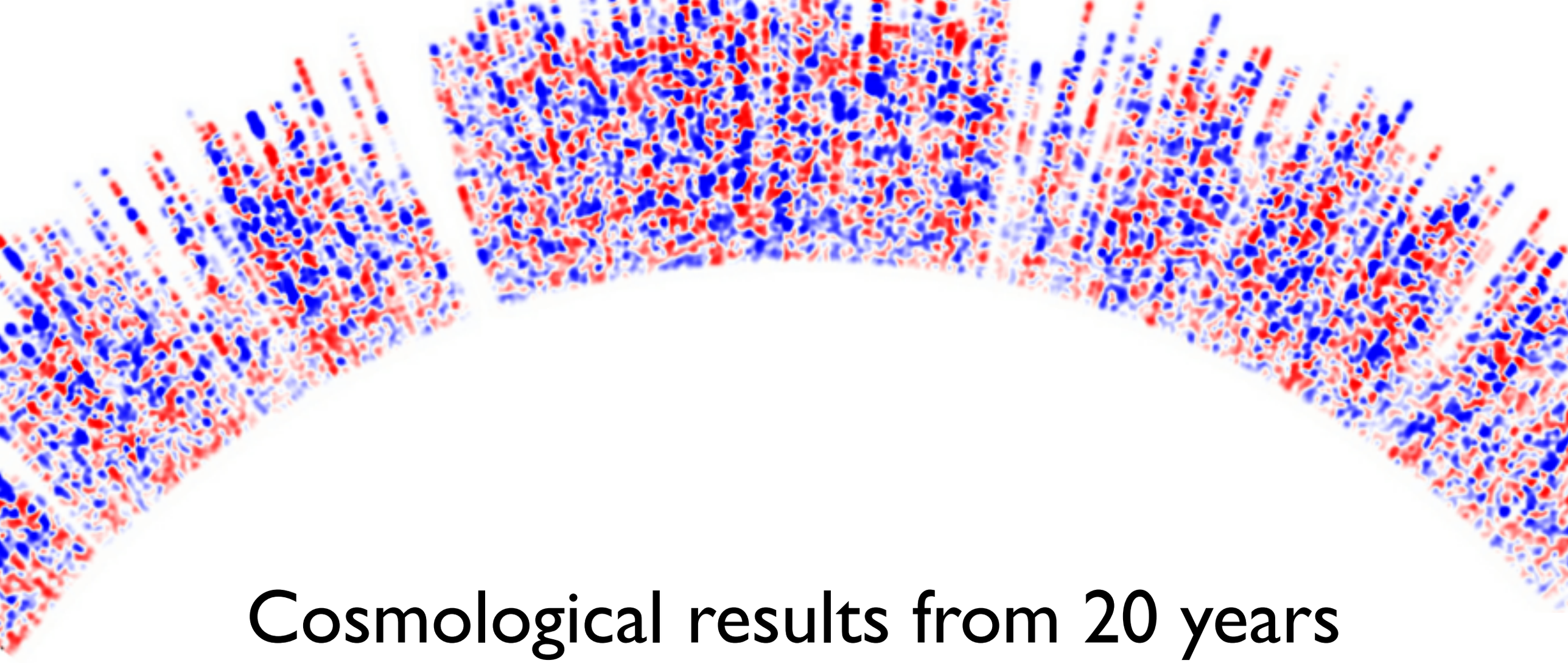


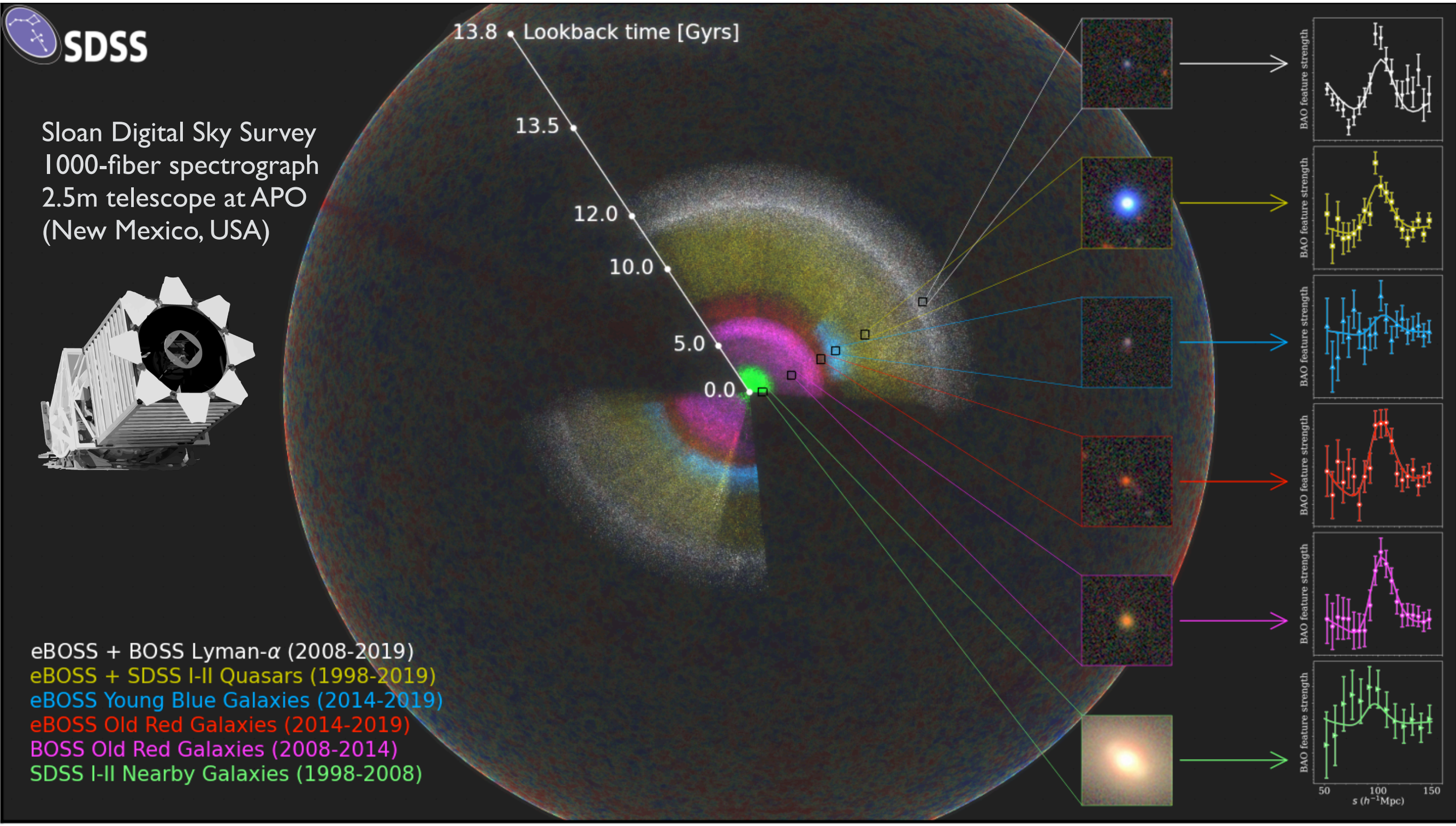
Cosmological results from 20 years of the Sloan Digital Sky Survey

Andreu Font-Ribera

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

On behalf of the eBOSS Collaboration

Mapping the Universe with SDSS

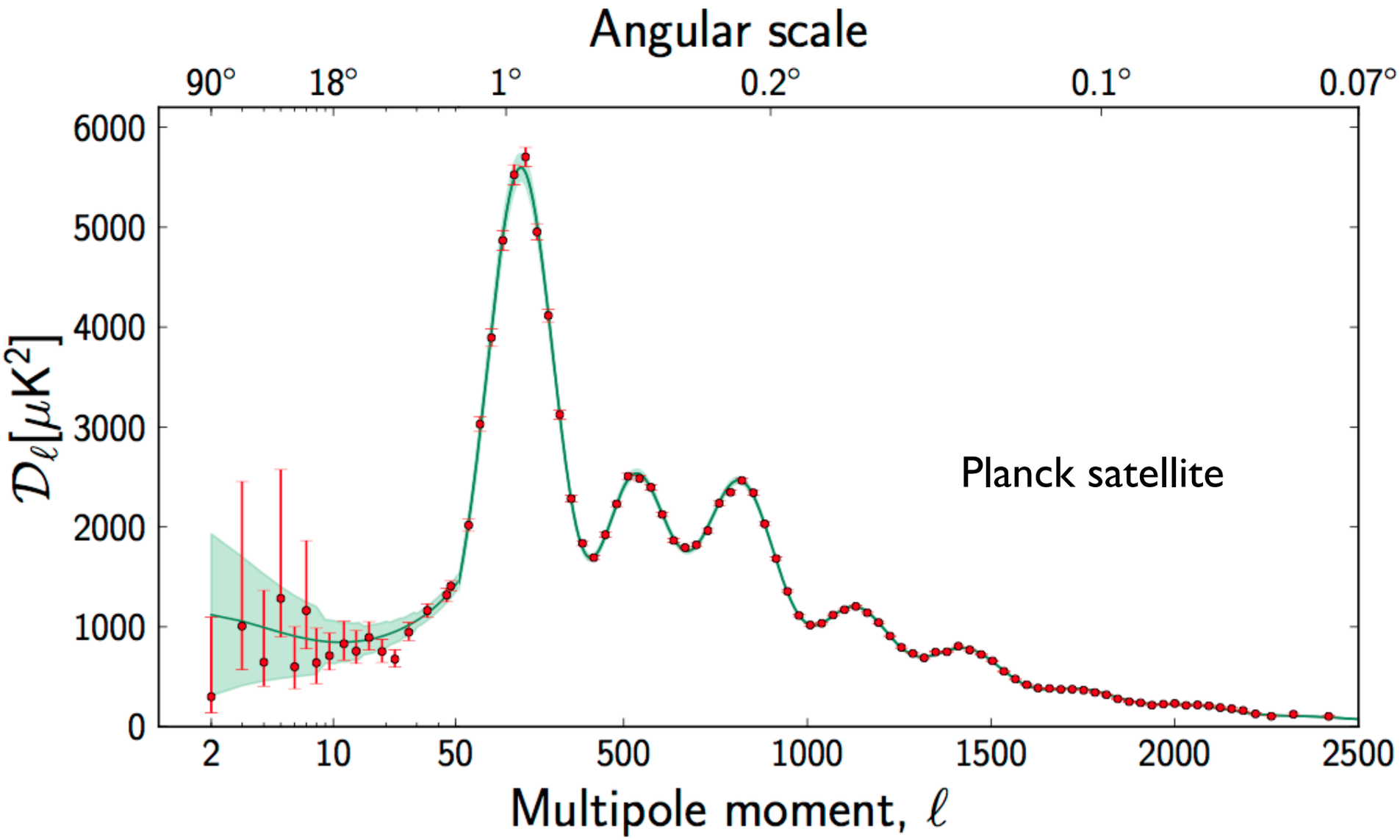


Outline

- Introduction to Baryon Acoustic Oscillations
- BOSS (2009-2014) and eBOSS (eBOSS, 2014-2019)
- Cosmology from 20 years of SDSS
  - Curvature, dark energy and neutrino masses
  - H_0 tension

Baryon Acoustic Oscillations

Oscillations clearly seen in the CMB temperature power spectrum



Baryon Acoustic Oscillations

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

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

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

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

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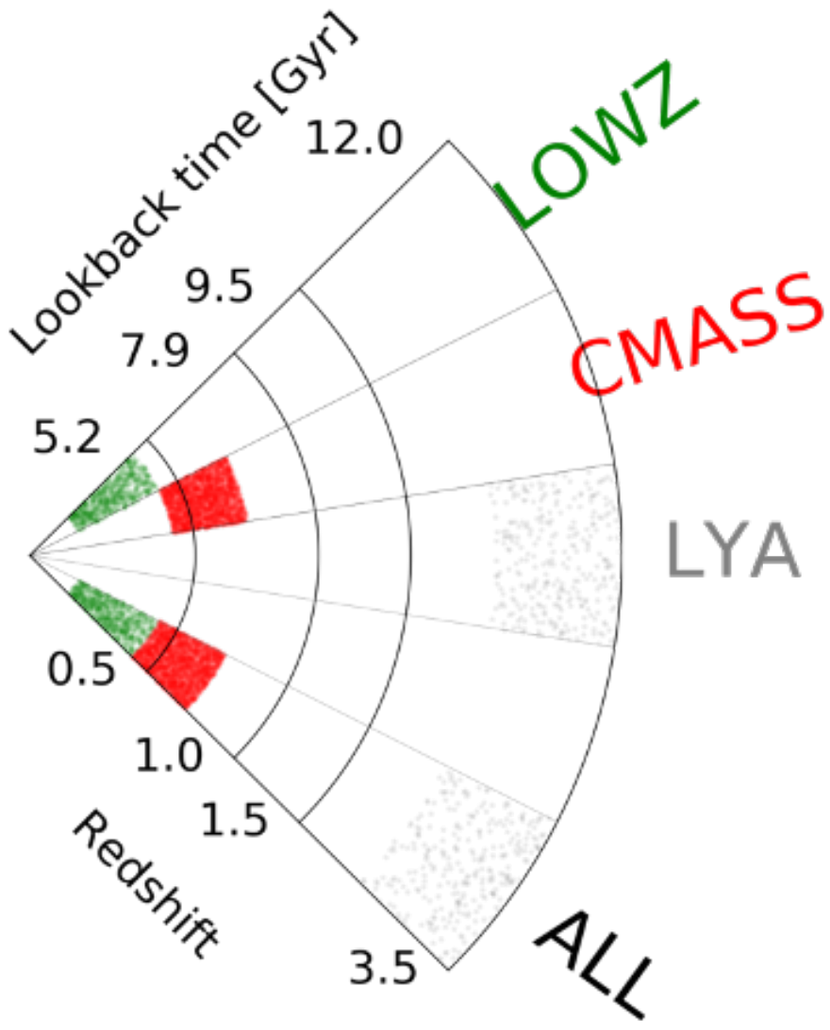
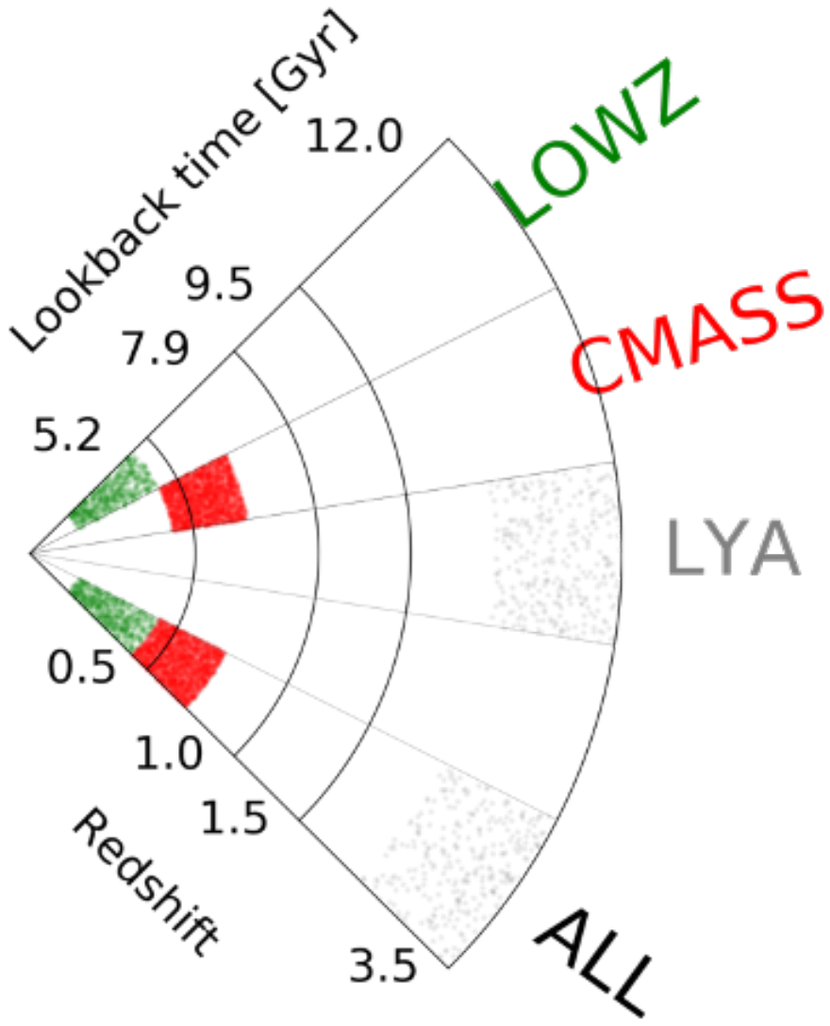
BAO from SDSS

Baryon Oscillation Spectroscopic Survey
(BOSS, SDSS III, 2009-2014)

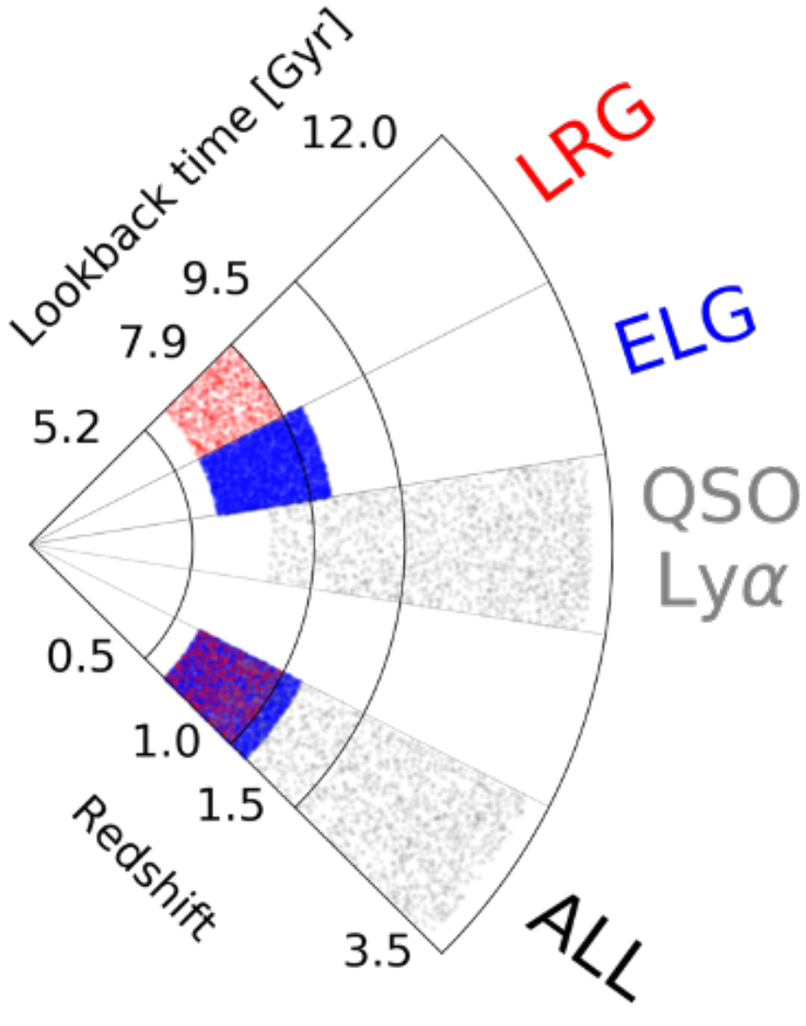


BAO from SDSS

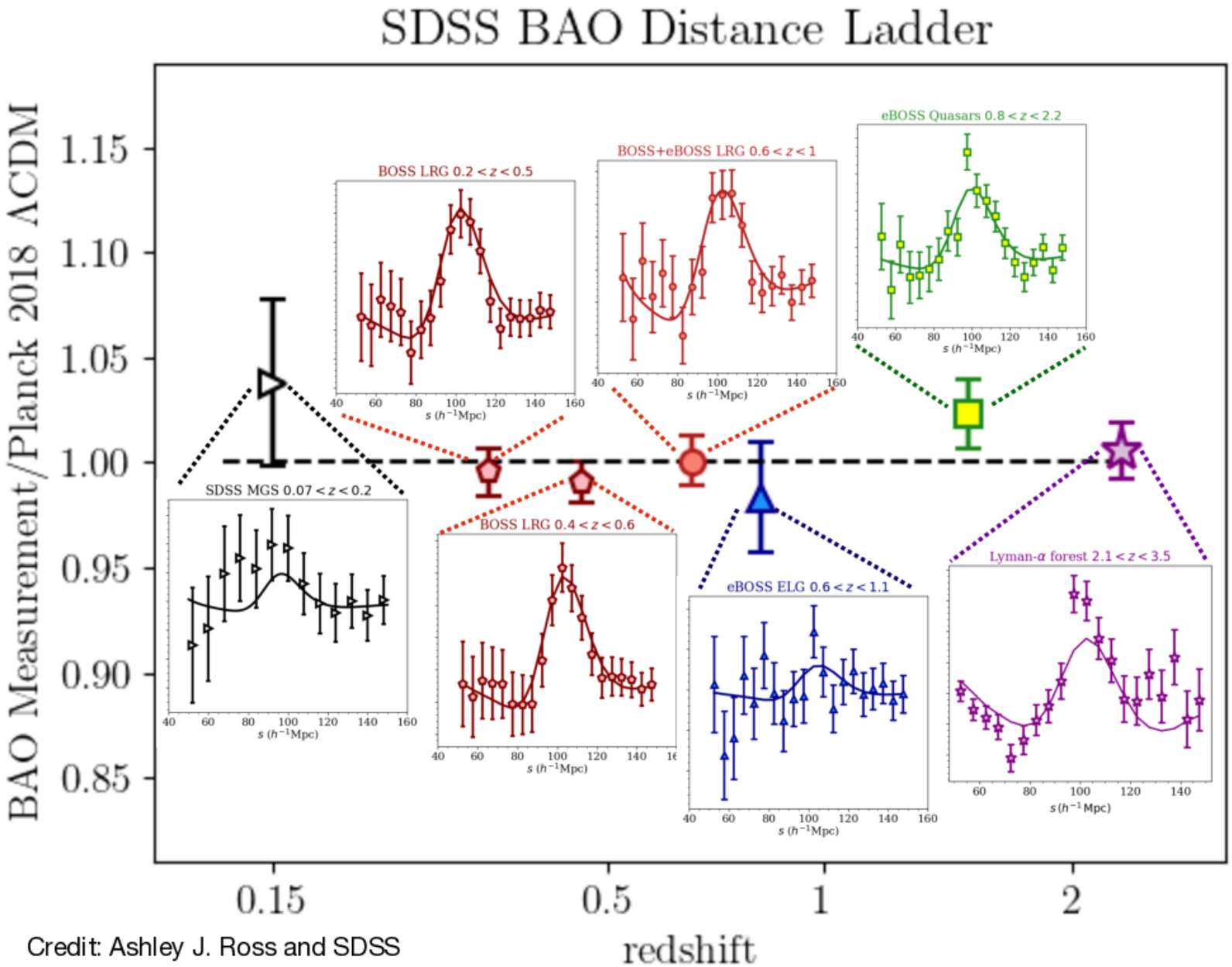
Baryon Oscillation Spectroscopic Survey
(BOSS, SDSS III, 2009-2014)



Extended BOSS
(eBOSS, SDSS IV, 2014-2019)

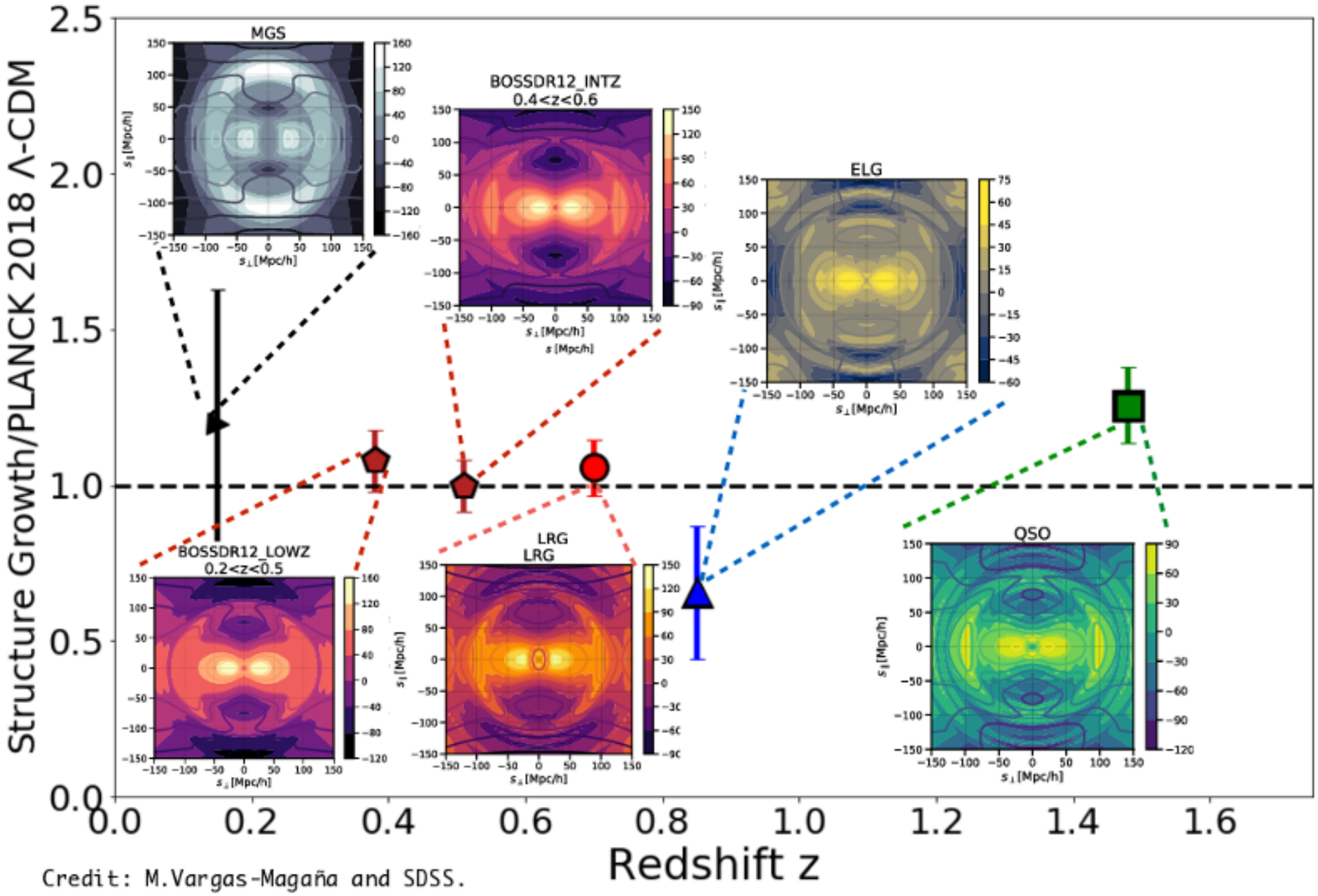


BAO from SDSS



BAO from BOSS/eBOSS provide accurate distances over wide redshift range

RSD from SDSS



RSD from BOSS/eBOSS provide accurate measurements of growth of structure

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Cosmology from SDSS

eBOSS Collaboration 2021 (arXiv:2007.08991)

"The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory"

Interpretation of 23-paper arXiv submission from July 20, 2020

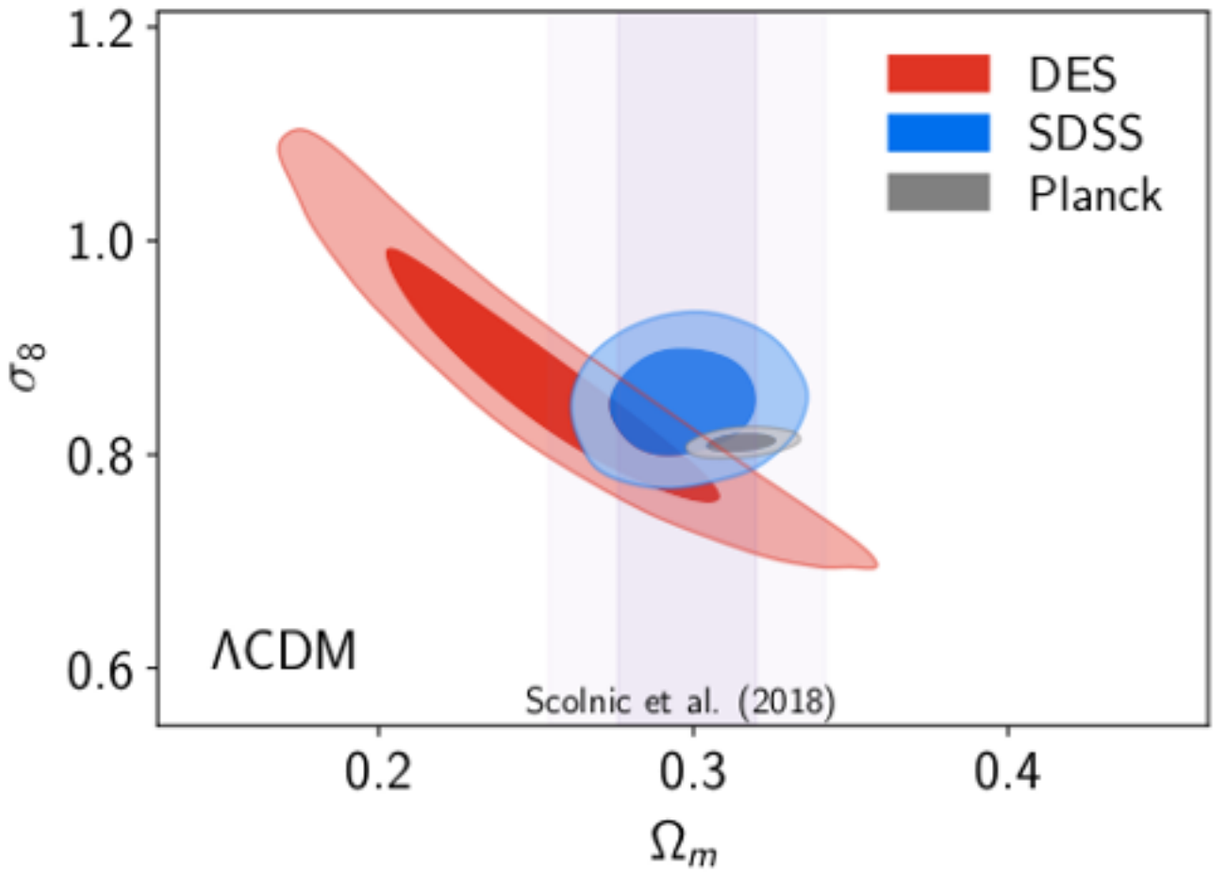
Collaboration paper co-led by (left to right): Eva-Maria Mueller (Oxford), Kyle Dawson (Utah), Andreu Font-Ribera (IFAE), Zheng Zheng (Utah) and Anze Slosar (BNL)

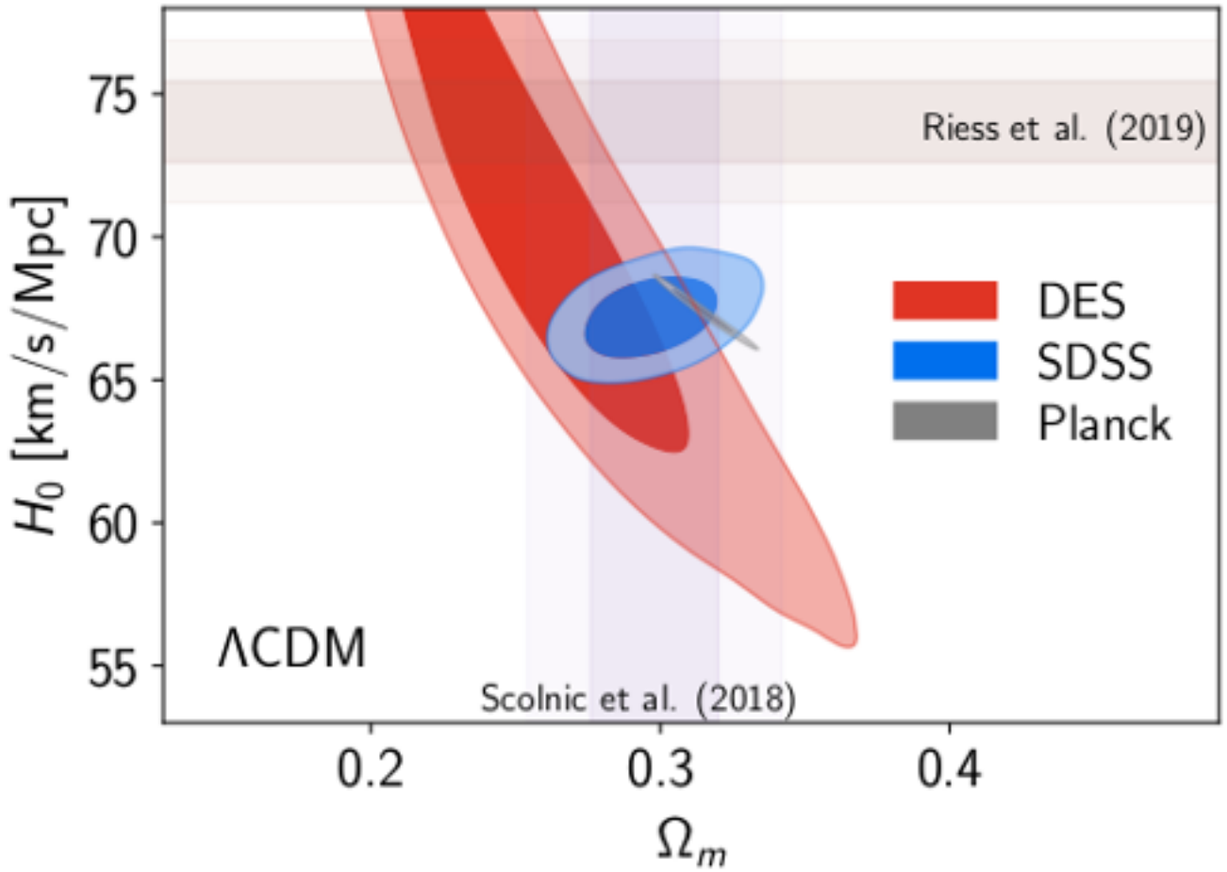




Cosmological tensions

- SDSS fully consistent with Planck CMB, Pantheon SNe and DES 3x2
- Clear H_0 tension with SHOES distance ladder (more latter)





DES and SDSS results have BBN prior and weak prior on n_s

Outline

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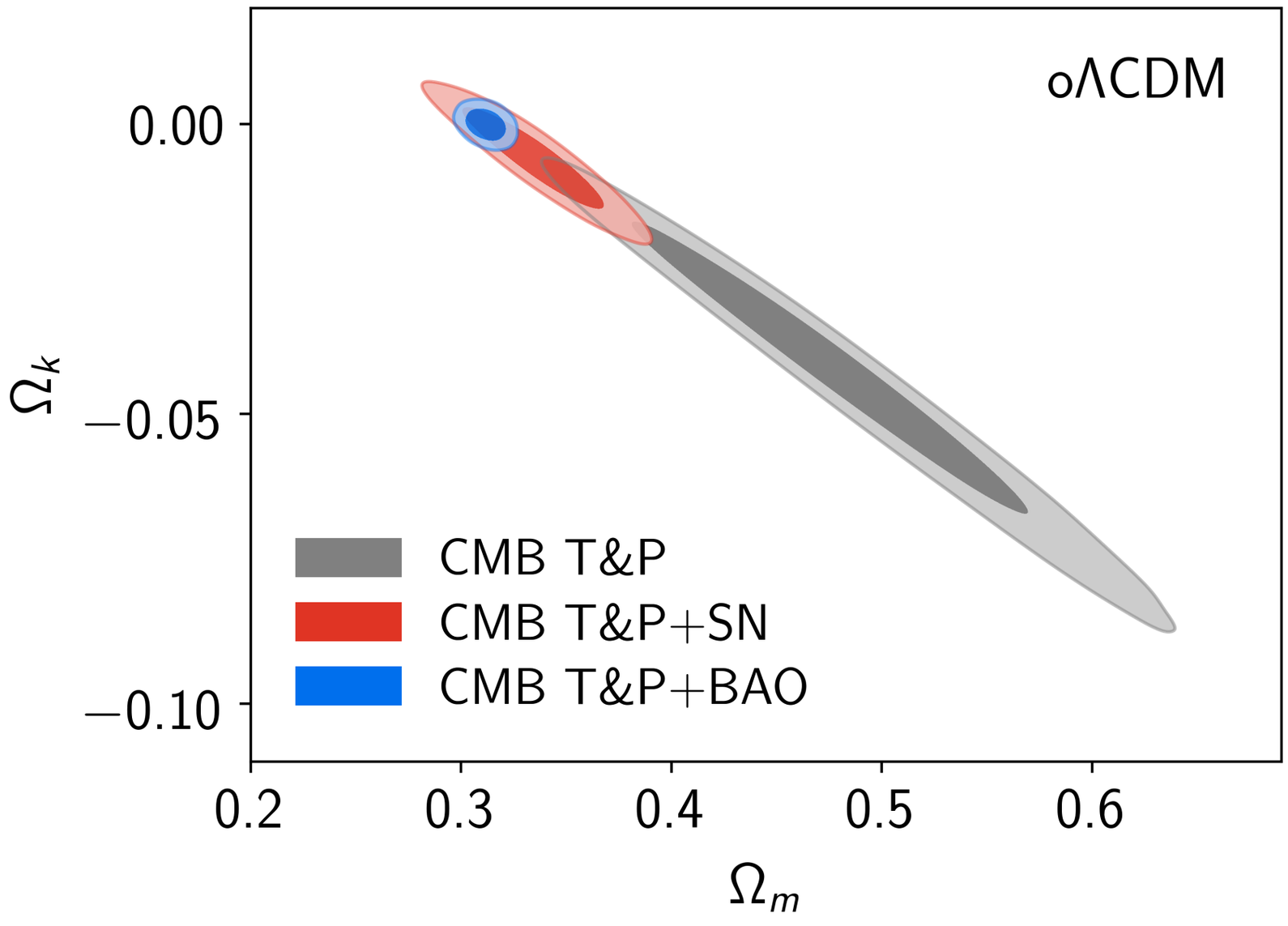
  - Extensions: curvature, dark energy and neutrino masses
  - H_0 tension

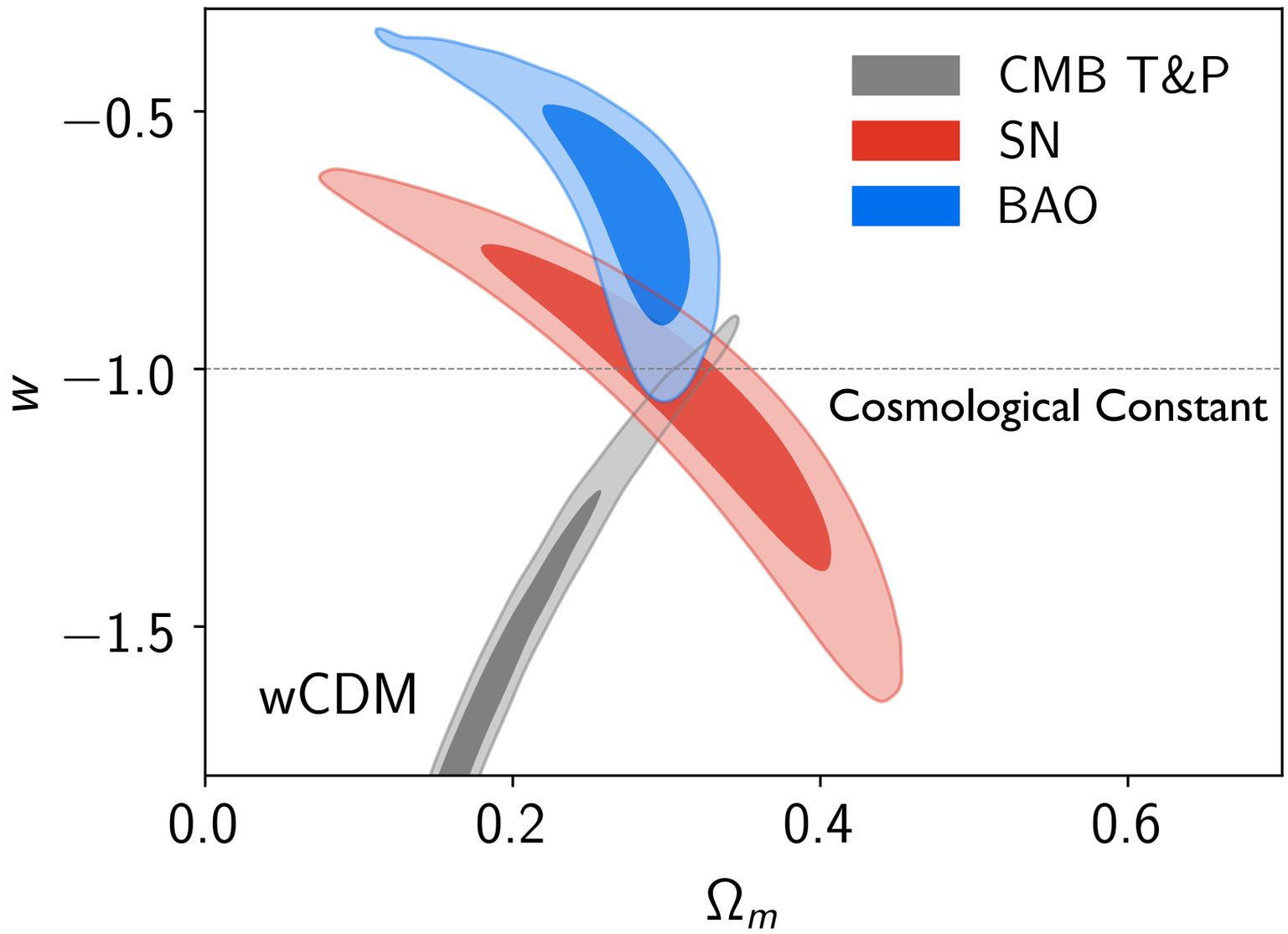
Curvature



BAO + CMB has a clear preference for a flat Universe

Dark Energy

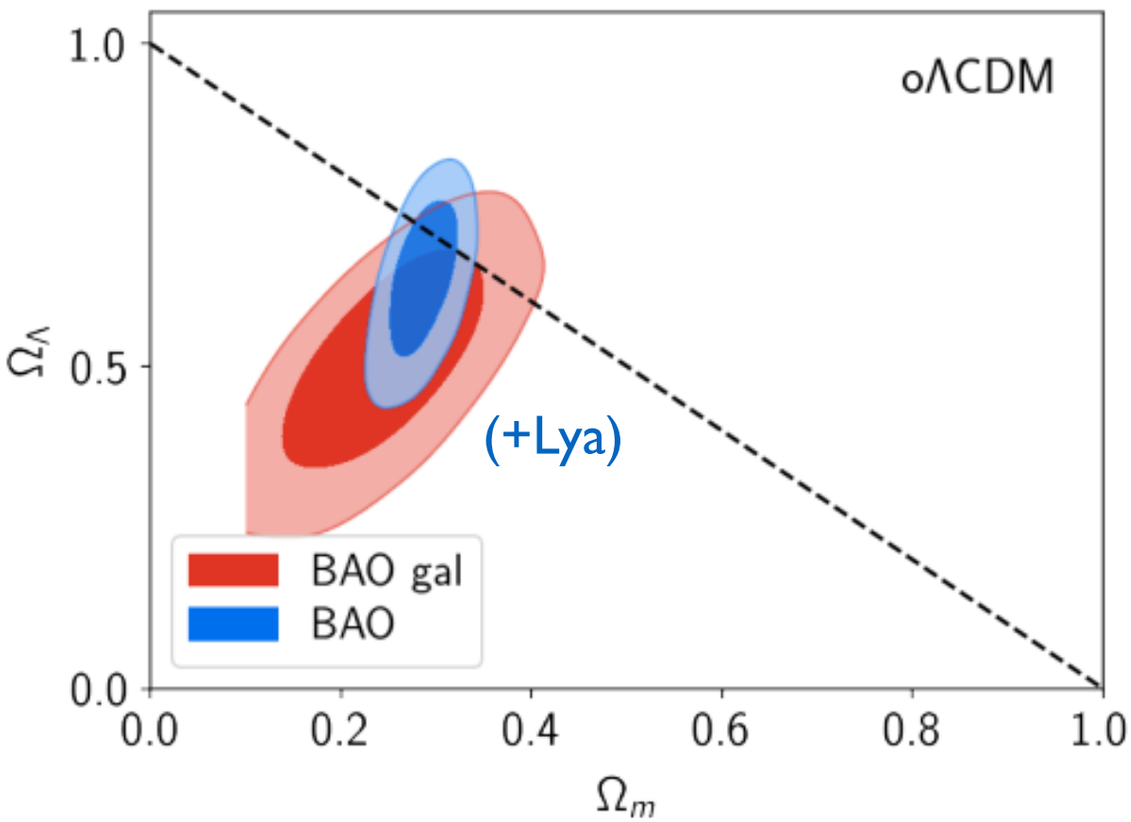
Equation of state of dark energy $w = p_{\rm DE}/\rho_{\rm DE}$

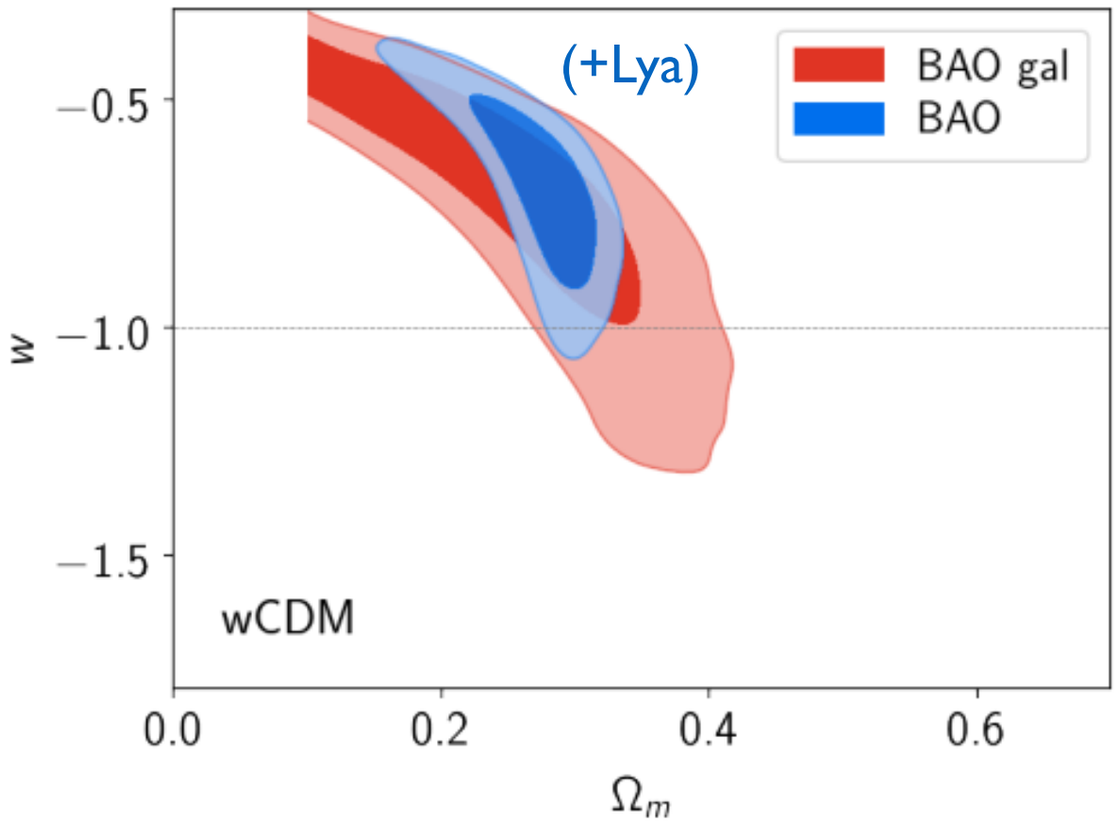


Dark energy consistent with cosmological constant

Role of Lyman-α BAO

SDSS measures galaxy and quasar BAO at z<=1.5 (BAO gal)
along with Lyman-α forest BAO at z=2.33



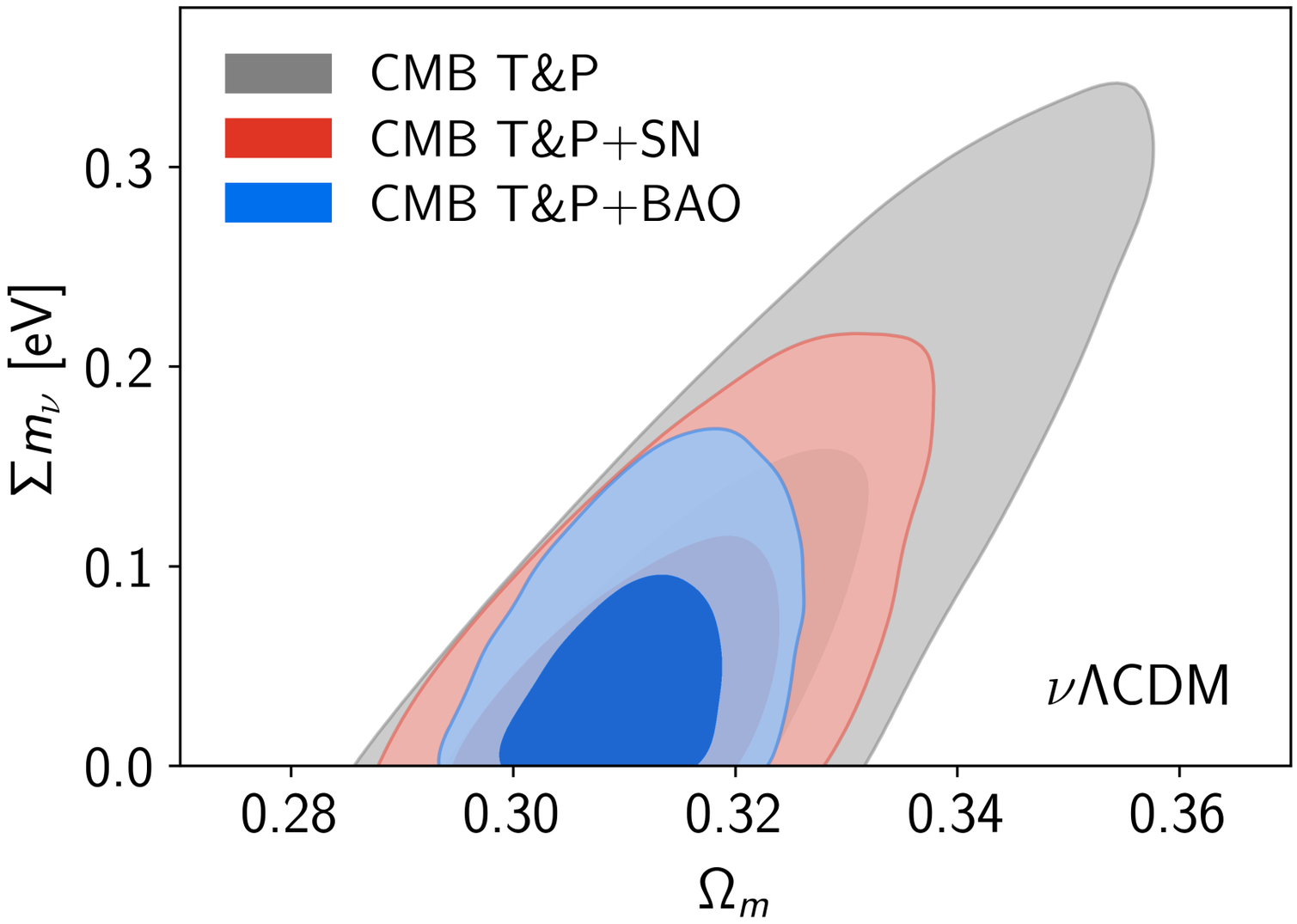


Combined they allow precise constraints on curvature and dark energy

Massive neutrinos

Lower limits from neutrino oscillation experiments

$$\sum m_\nu > 0.0588\,\mathrm{eV} \quad \text{normal hierarchy,}$$
$$\sum m_\nu > 0.0995\,\mathrm{eV} \quad \text{inverted hierarchy.}$$



BAO breaks degeneracy with matter density in CMB

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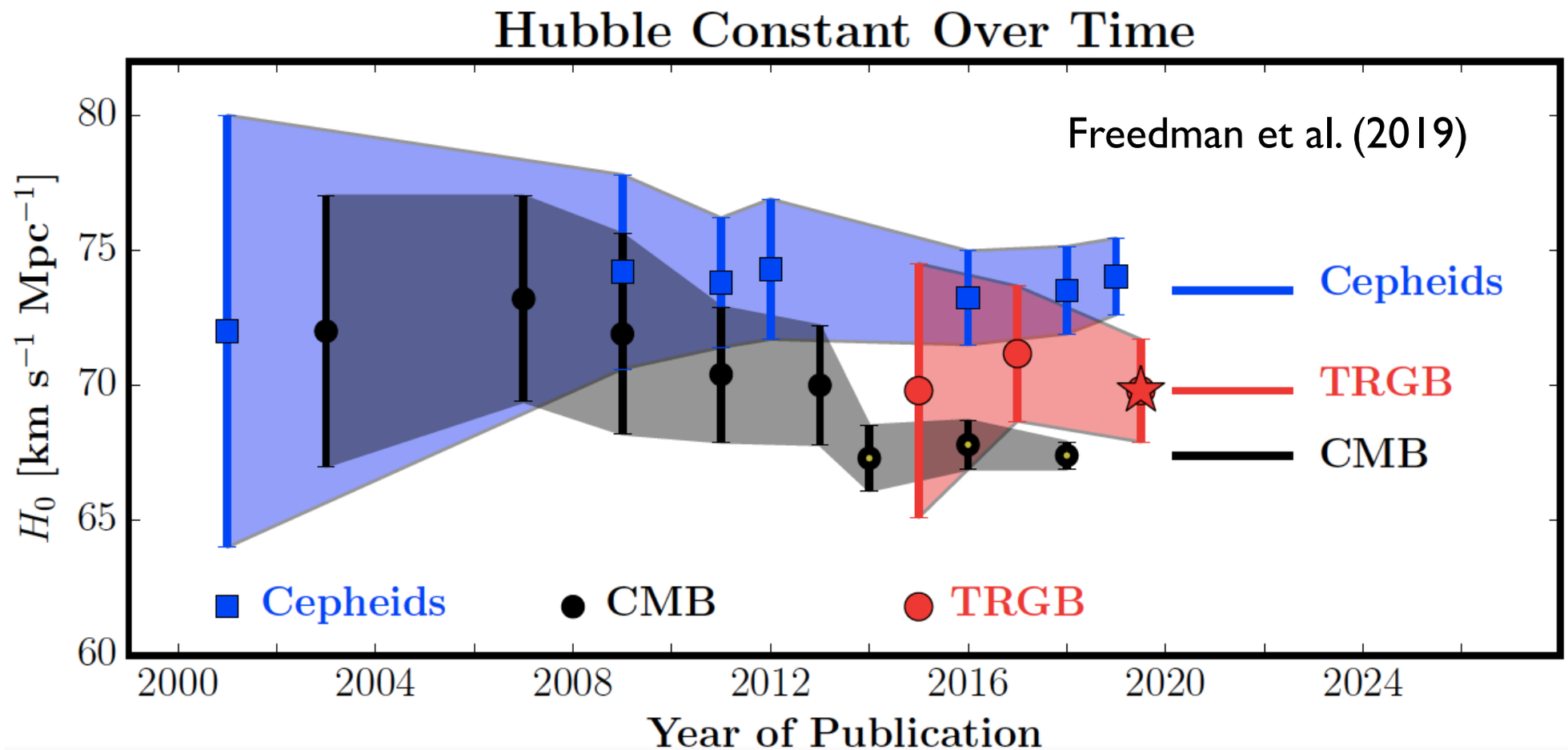
BAO and the H_0 tension

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 + SDSS

WMAP + SDSS

SPT + SDSS

ACT + SDSS

r_d + SN + SDSS

BBN + SDSS

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

Prefer low H_0

Planck

Planck + **SPT**

Planck + **SDSS**

WMAP + **SDSS**

SPT + **SDSS**

ACT + **SDSS**

r_d + **SN** + **SDSS** → This does not assume Λ

BBN + **SDSS** → This does not use CMB

Consistent with both

SPT

TRGB

LIGO GW

Prefer high H_0

SHOES

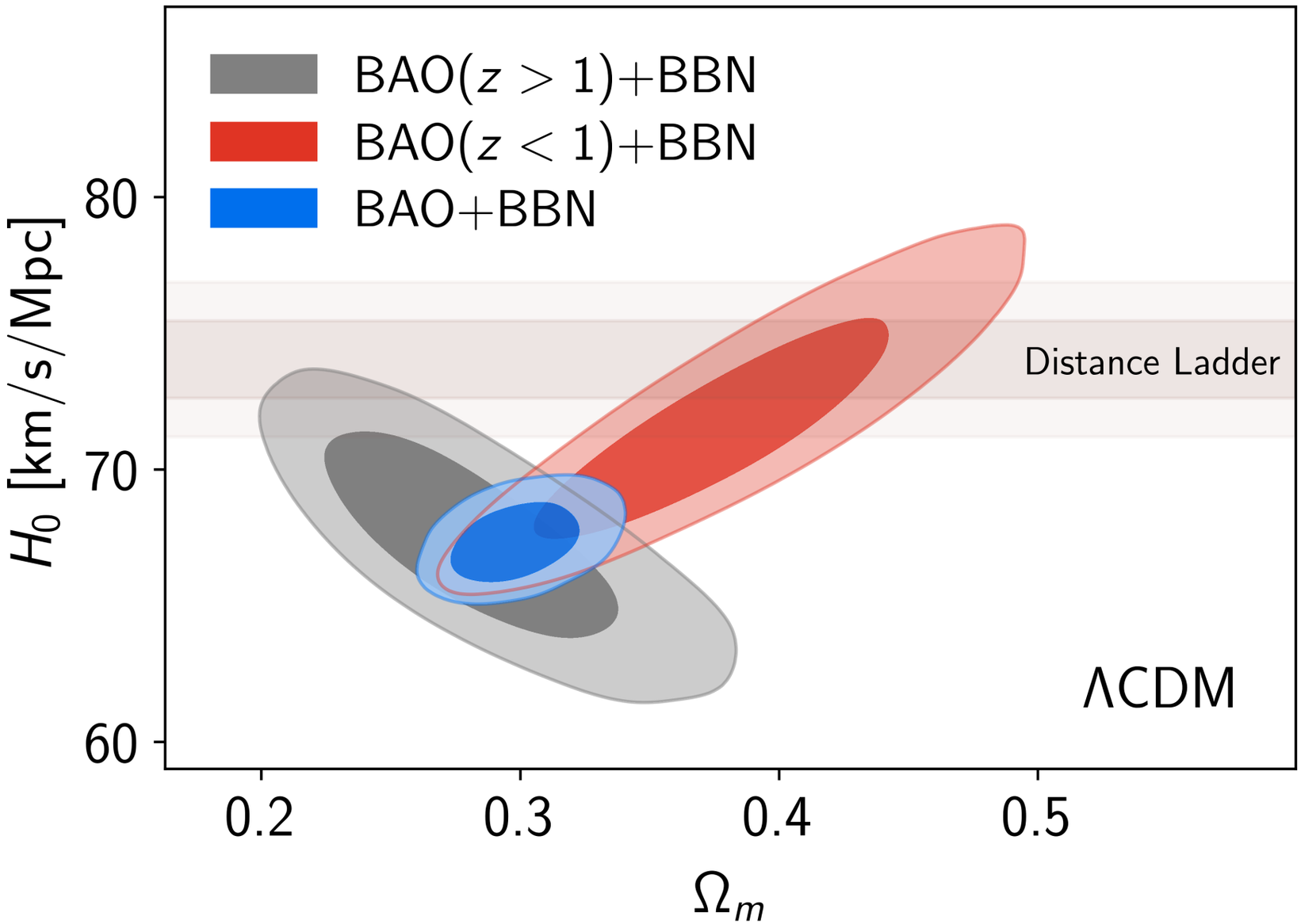
HoLICOW

Systematics on either side? Problems with flat ΛCDM?

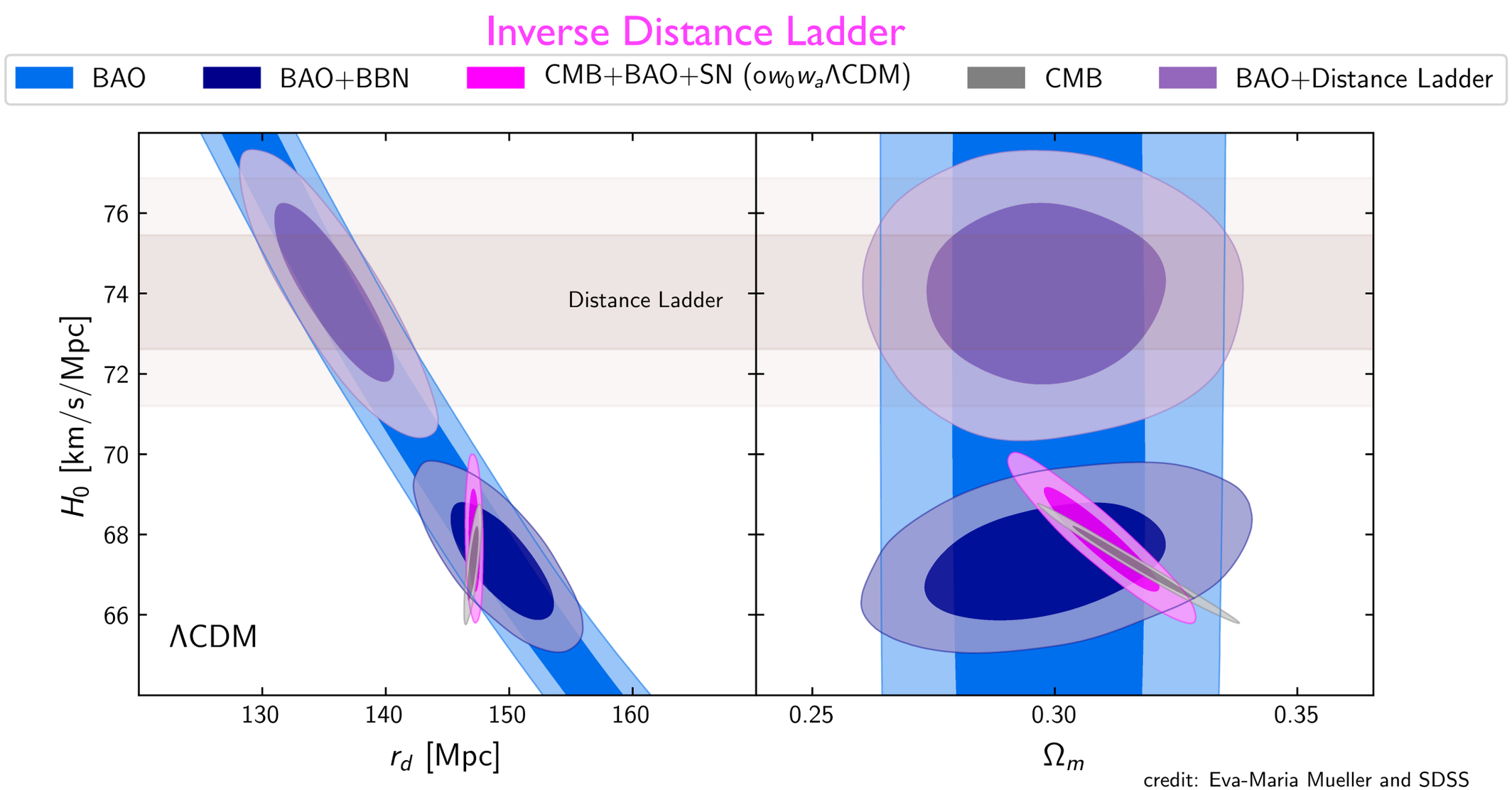
BAO and the H_0 tension

BAO + LCDM constraint Ω_m and H_0 r_d (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



credit: Eva-Maria Mueller and SDSS

BAO constraints Ω_m and product H_0 r_d (sound horizon, size of ruler)

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

BAO and the H_0 tension

Prefer low H_0

Planck

Planck + SPT

Planck + SDSS

WMAP + SDSS

SPT + SDSS

ACT + SDSS

r_d + SN + SDSS

BBN + SDSS

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

- BOSS/eBOSS measured BAO at <1% accuracy using galaxies
- 1.4% measurement at z=2.3 using quasars and Ly-α forest
- Independent (8-σ) detection of Dark Energy
- Order-of-magnitude better constraint on spatial curvature
- Tightest constraints on neutrino mass (CMB+BAO)
- Alternative H_0 measurements consistent with CMB ones

Extra slides