Massively Parallel Large Area Spectroscopy from Space II
21-23 June 2021

Cosmology with spectroscopic galaxy surveys

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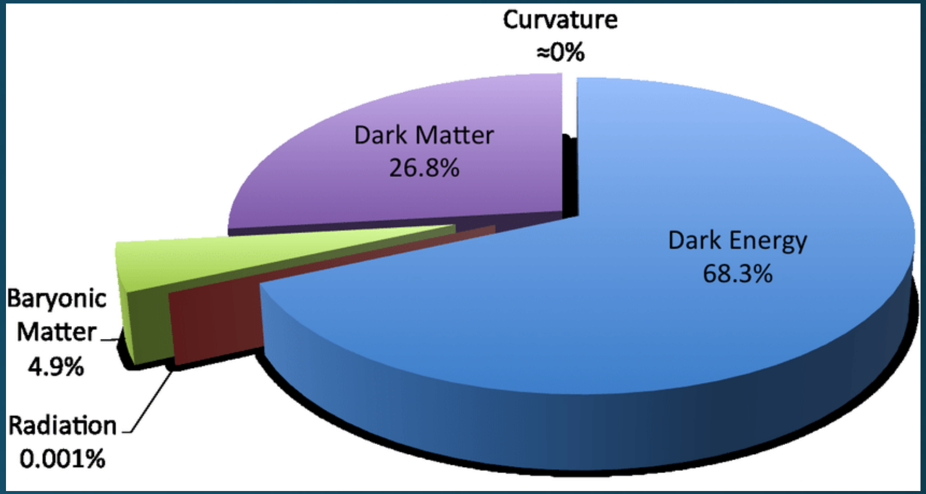
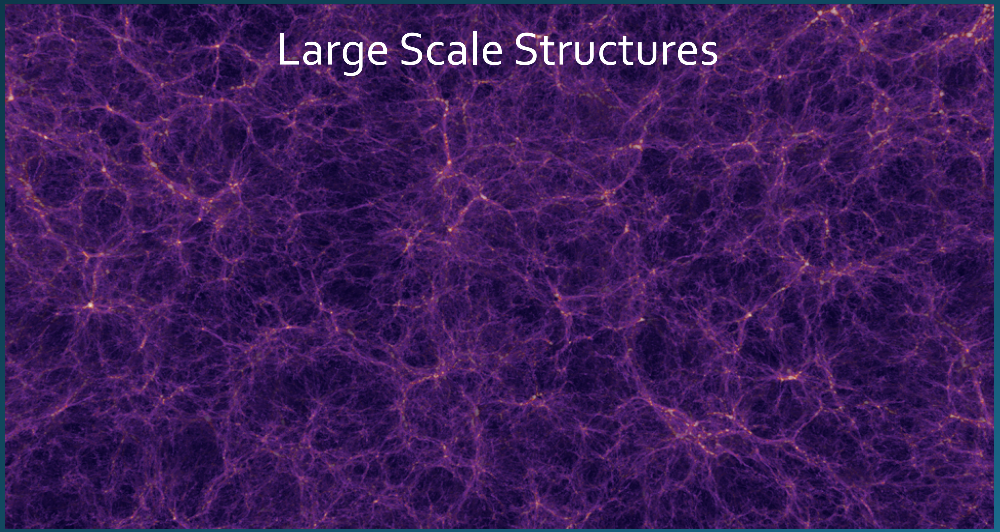
Questions in cosmology

- How did the Universe begin?
- Why Is the Universe accelerating?
- What is dark matter?
- What are the properties of neutrinos?





Evolving distribution of matter in Universe

- Cosmic expansion and growth of structure

Derived Measurements: $H(z)$, $D_M(z)$, $f\sigma_8(z)$

History of galaxy surveys

- **1989:** The CfA galaxy survey was the first systematic survey of 2,400 galaxies over about 20% of the sky that revealed the existence of large structures.
- **1996:** Las Campanas Redshift Survey observed 25,000 galaxies over 1.7% of the sky
- **2005**: The 2dFGRS measured 250,000 galaxies on 1500 deg2 (5% of the sky)
- **2009**: The 6dFGS measured the spectrum of 100,000 new galaxies **on** 17 000 deg2 (50% of the sky)
- **2010-2019**: The SDSS (BOSS, eBOSS) measured 2 million galaxies over 25% of the sky.

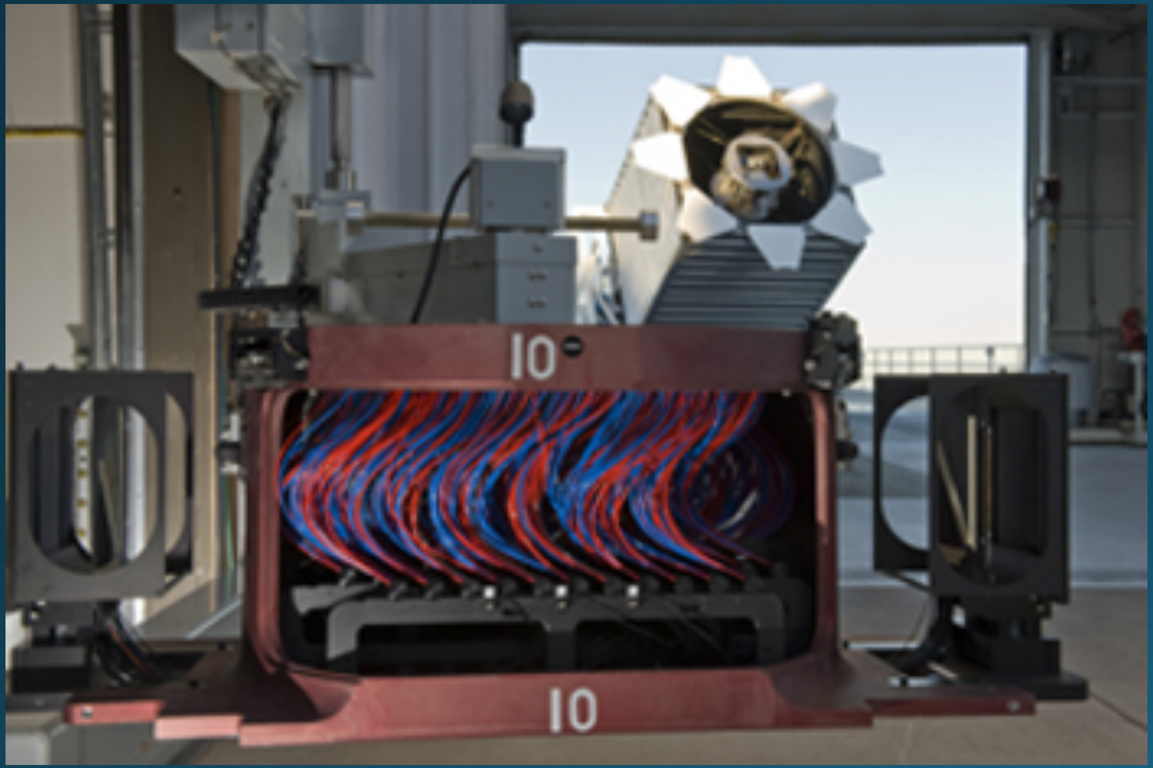
x10 galaxies

x10 galaxies

x10 Area

x10 galaxies

eBOSS, part of the SDSS-IV



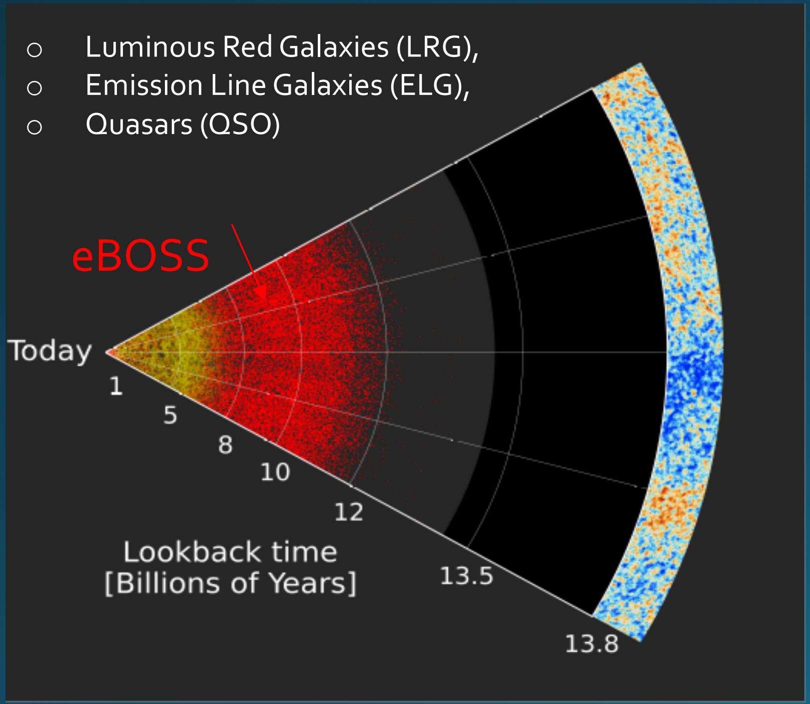
Optical fibers plugged by hand!

- eBOSS proposal submitted in 2011
- eBOSS data taking in 2014-2019
  - 2.5 m Sloan Telescope
  - 1,000 spectra simultaneously
  - 1.5 million galaxies and quasars over a wide redshift range $0.6 < z < 3.5$
- DR16 is the Final Data Release in 2020

eBOSS clustering techniques

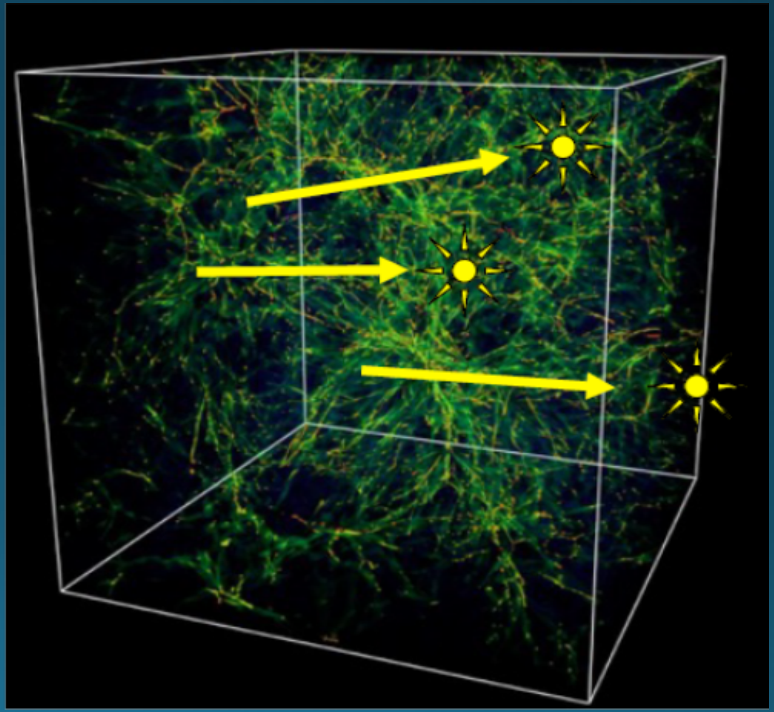
Direct tracers: galaxies and "core" quasars

- Intermediate redshift, z < 2
- trace high density regions
- traditional method



Indirect tracers: Lyman-alpha forest

- high redshift, z > 2
- trace low density in the line-of-sight
- recent method

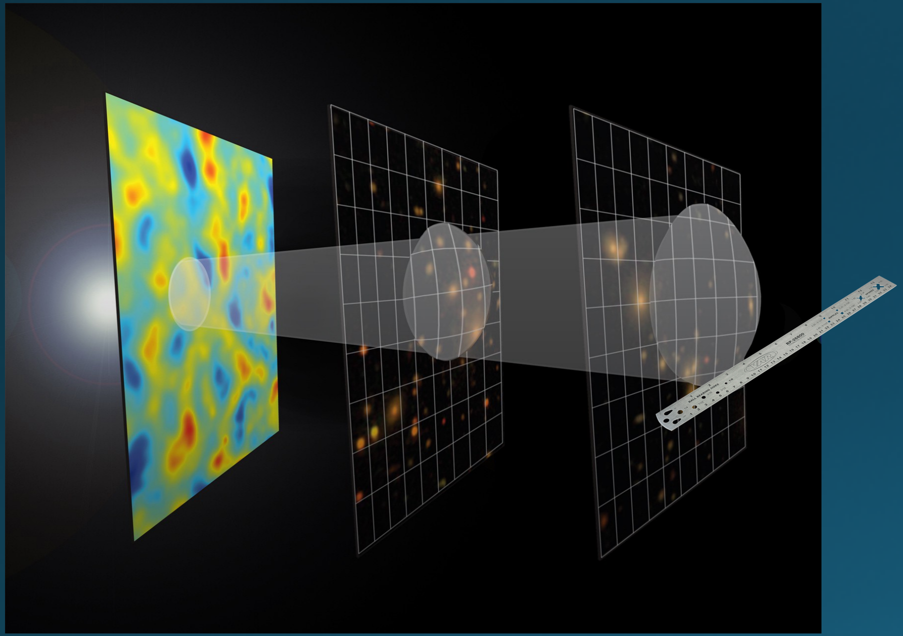


Measuring the Expansion History of the Universe between 6 and 11 billions of light years

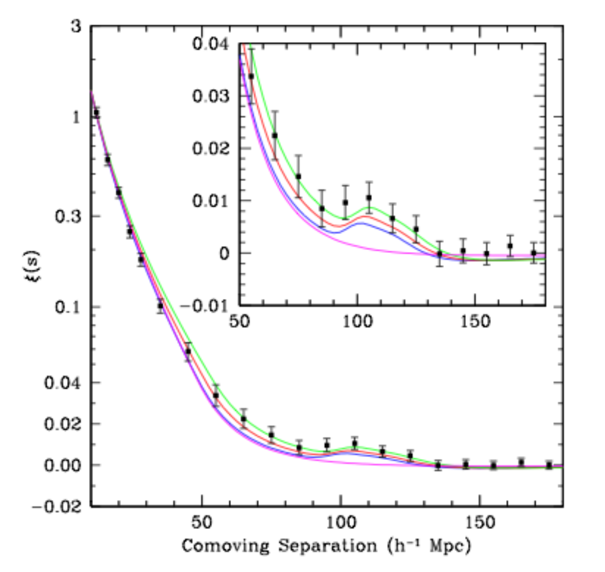
Constraints from galaxy clustering

Baryon Acoustic Oscillation (BAO)

BAO provide a characteristic scale "frozen" in the galaxy distribution: standard ruler



Position of the BAO peak (wiggles) can be measured in the correlation function (power spectrum) of the matter density field at different epochs (redshifts)



Eisenstein 2005

BAO provide measurement of :

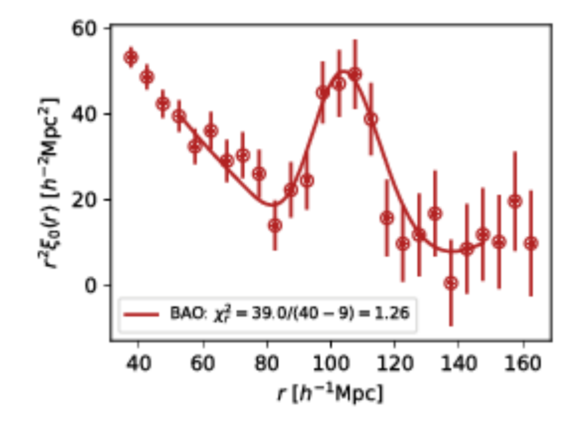
- the expansion rate H(z) (line-of-sight)
- the angular diameter distance $D_M(z)$ (transverse)

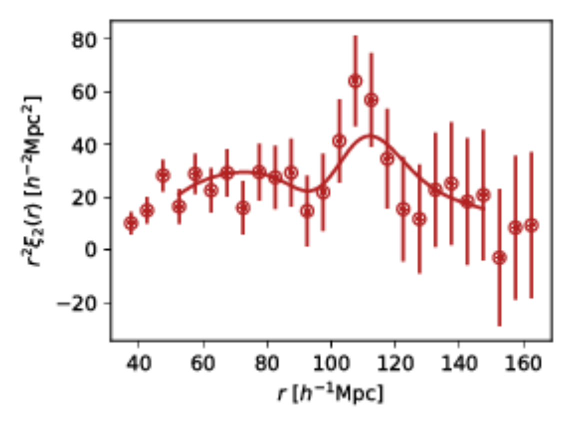
BAO measurements in eBOSS

Done with the three tracers: Luminous Red Galaxies (LRG), Emission Line Galaxies (ELG) and quasar (QSO)

eBOSS LRG sample at 0.6 < z < 1.0

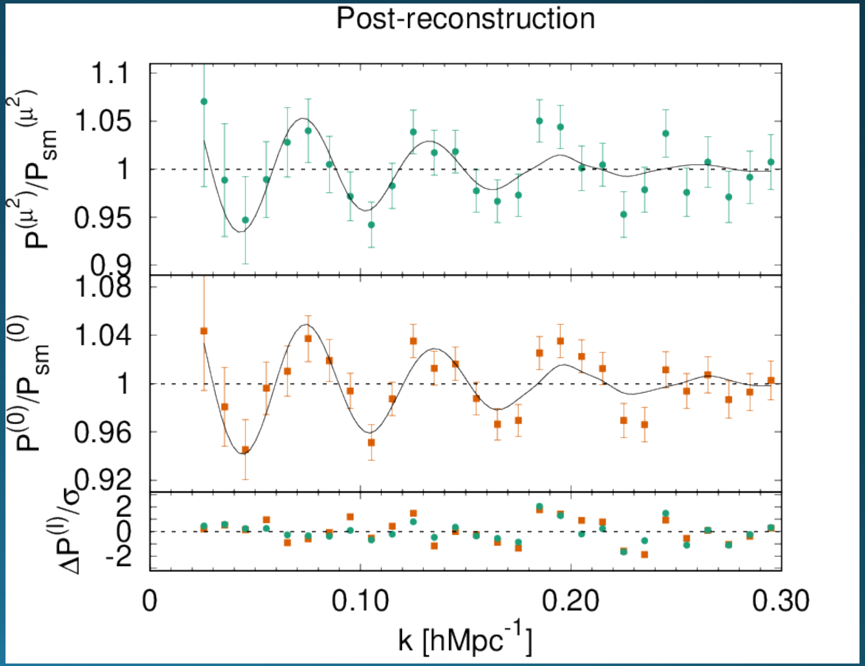
Measured in the correlation function





Bautista et al. 2020

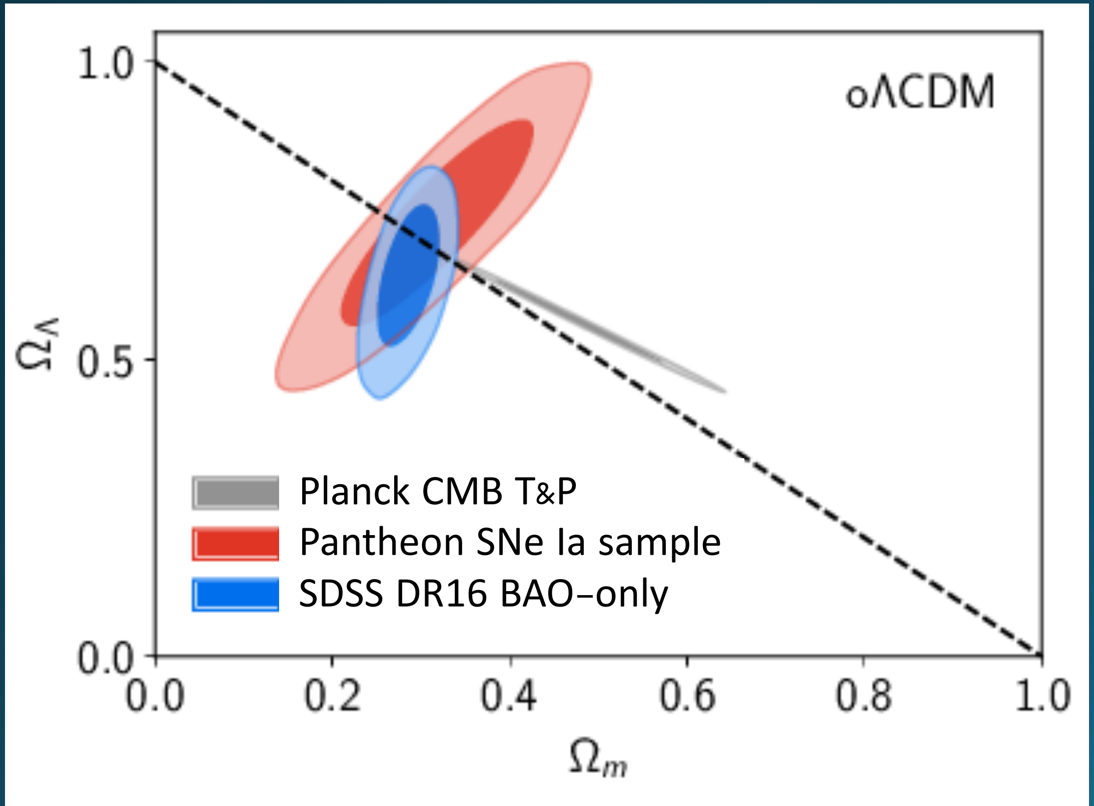
...and in the power spectrum



Gil-Marin et al. 2020

eBOSS DR16 results – BAO only

eBOSS Collaboration 2020



Alam et al. 2020

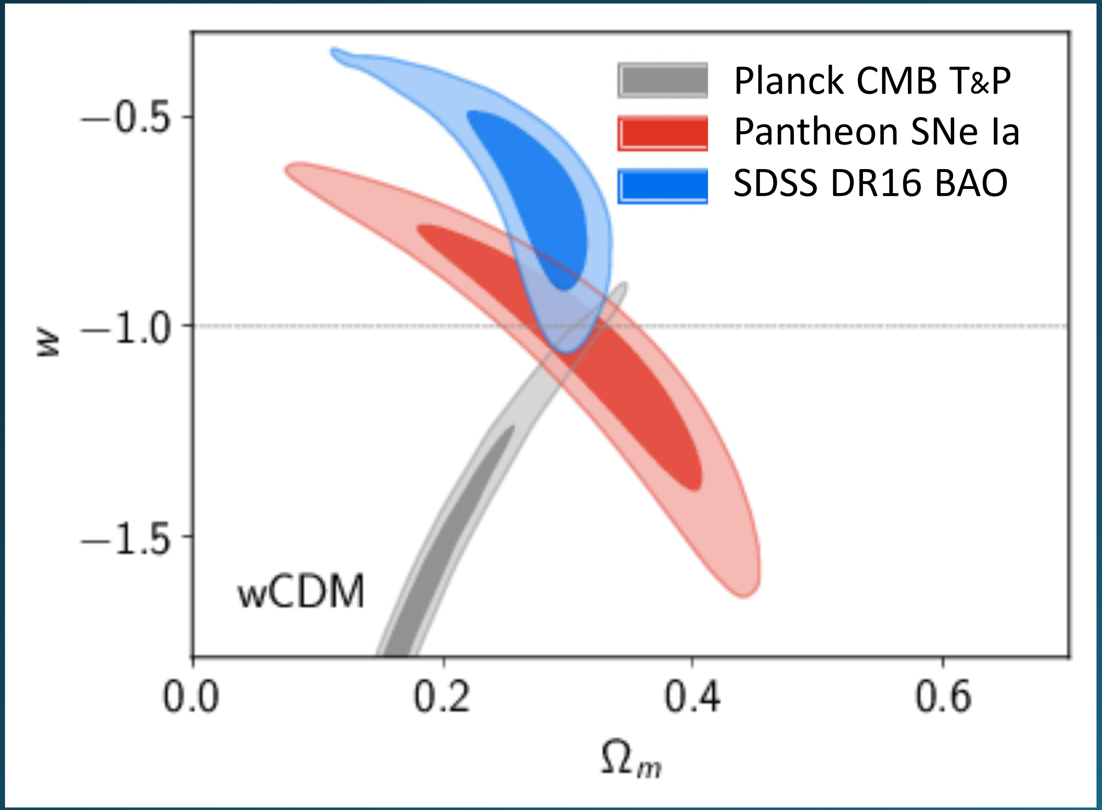
Assumption of a w=-1 cosmological constant model with free curvature (oΛCDM)

- BAO measurements alone lead to $\Omega_\Lambda = 0.637 +/- 0.084$, an 8σ confidence detection of a cosmological constant without any information from the CMB or SNe Ia data.
- The combination of BAO and CMB data favors a flat universe with $\Omega_k = -0.0001 +/- 0.0018$.

Independent probes confirm cosmic acceleration

eBOSS DR16 results – BAO only

eBOSS Collaboration 2020



Alam et al. 2020

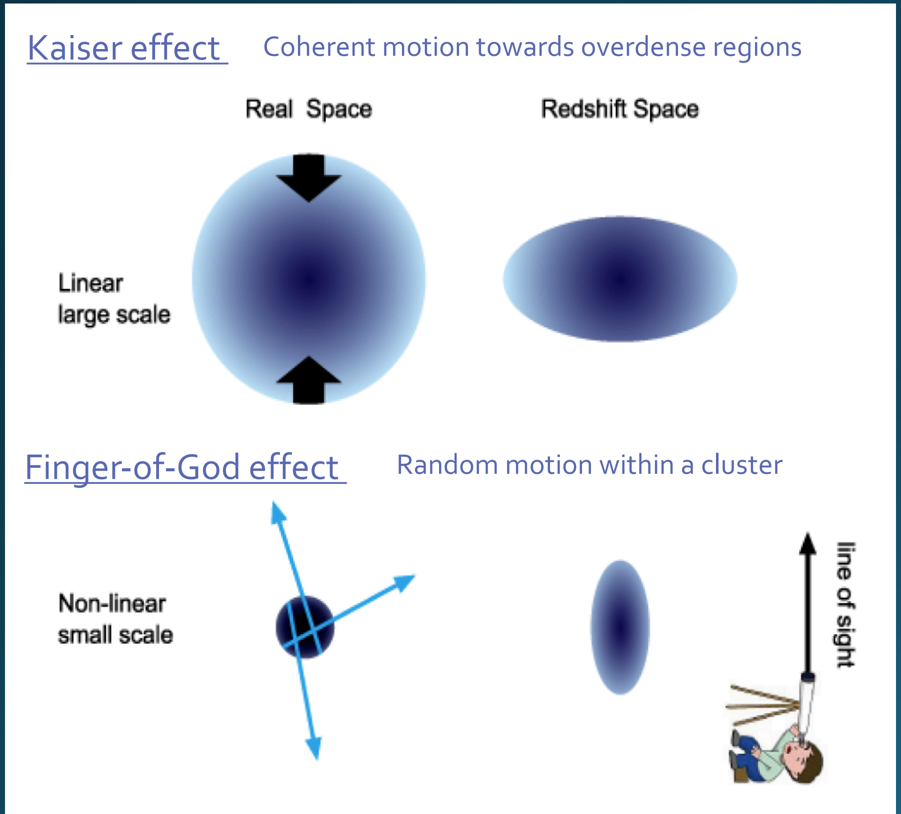
Assumption of a flat wCDM model

- Very tight constraints on the wCDM model when combining CMB+BAO, SN+BAO or CMB+SN.
- BAO excludes models with w < -1 favored by the CMB
- The combination of all three datasets favor a model with a cosmological constant, leading to an equation of state of dark energy of w = –1.026 +/– 0.033

… consistent with a cosmological constant.

Redshift Space Distortions (RSD)

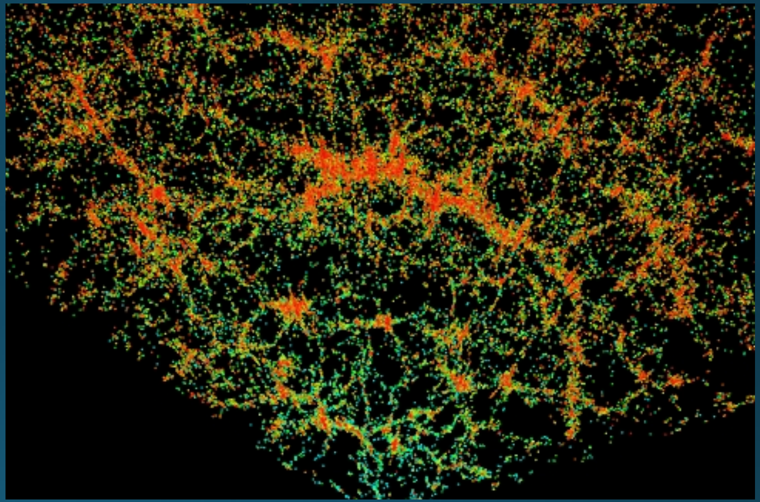
Effect along the line of sight due to peculiar velocities (Doppler effect)



Courtesy of K. Saito

Related to the linear growth rate of structure (in linear theory)

Due to the gravitational infall of galaxies onto massive forming structures, the strength of the signature depends on Ω_m.



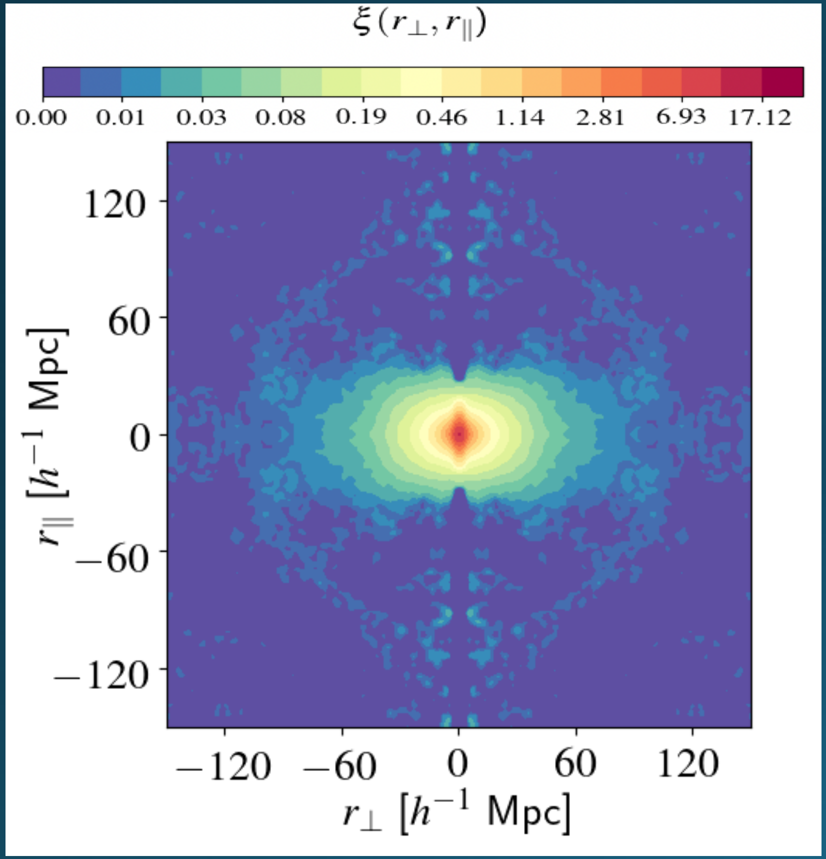
Growth rate of structures f(z),

$$f \equiv \frac{d \ln G}{d \ln a} \approx \Omega_m(z)^\gamma$$

$\gamma = 0.55$ in GR

Powerful tool to constrain possible deviations from GR

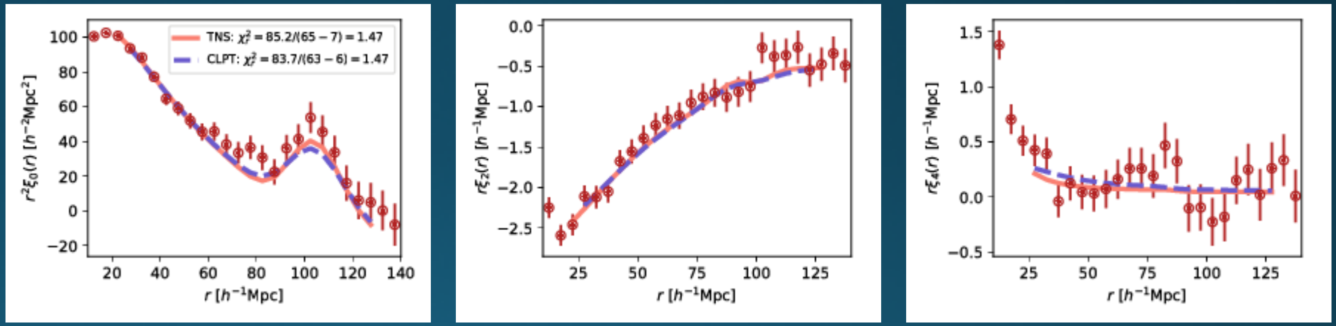
RSD measurements in eBOSS



Bautista et al. 2020

Anisotropic two-point correlation function ("Full-shape analysis")

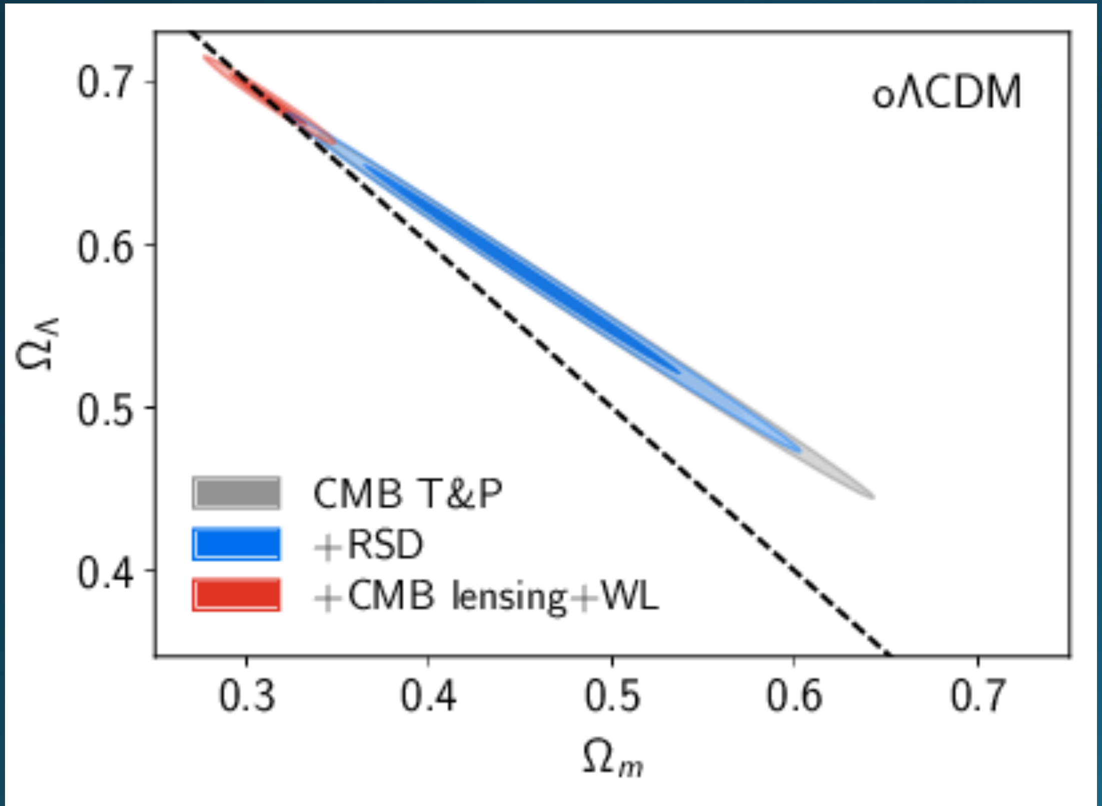
where the galaxy separation vector **r** has been decomposed into line-of-sight and transverse separations $(r_\perp, r_\parallel)$



Best-fit full-shape models accounting for RSD non-linearities to the eBOSS (LRG) multipoles.

eBOSS DR16 results – RSD

eBOSS Collaboration 2020



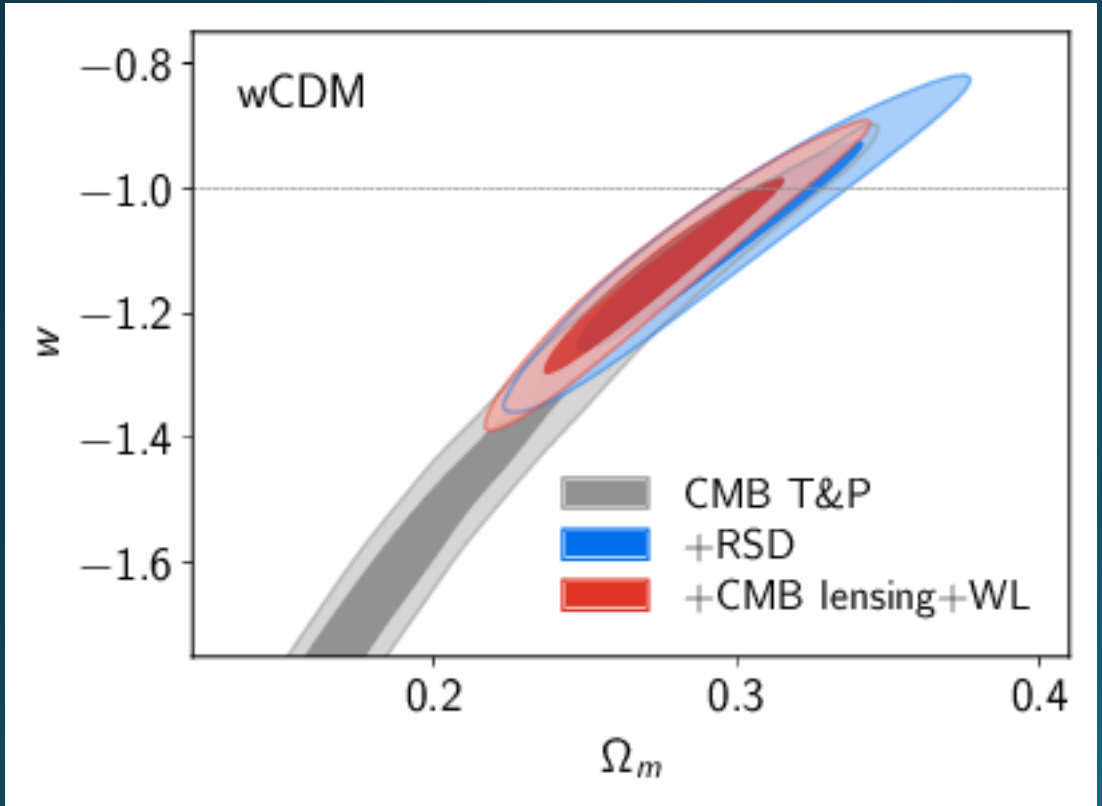
Alam et al. 2020

Assumption of a w=-1 cosmological constant model with free curvature (oΛCDM)

- While the Planck CMB data alone favor a model with negative curvature, the combination with all growth measurements (RSD, WL, and CMB lensing) leads to a model consistent with zero curvature Ω_k = -0.0010 +/- 0.0043.
- The constraining power is from CMB + CMB lensing (Ω_k = -0.0011 +/- 0.006), not RSD

eBOSS DR16 results – RSD

eBOSS Collaboration 2020



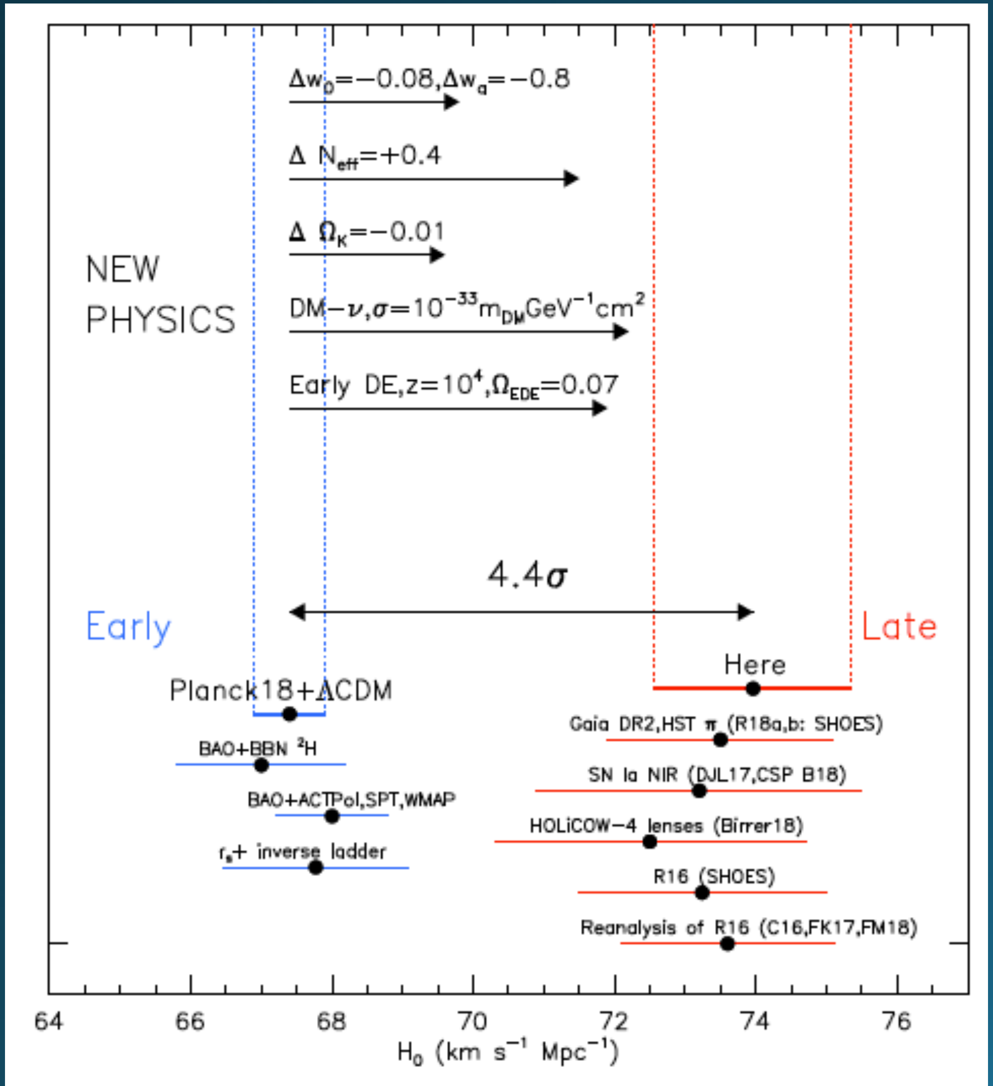
Alam et al. 2020

Assumption of a flat wCDM model

- Here, the largest impact on CMB contours comes from RSD data.
- Moreover, the CMB+RSD data are able to rule out the formal central value of w = –1.585 preferred by CMB alone.

Hints to new physics ?

Hubble tension



Riess et al. 2019

- **Early:** Predictions from the early Universe

Planck CMB: $H_0 = 67.4 \pm 0.5\ km/s/Mpc$

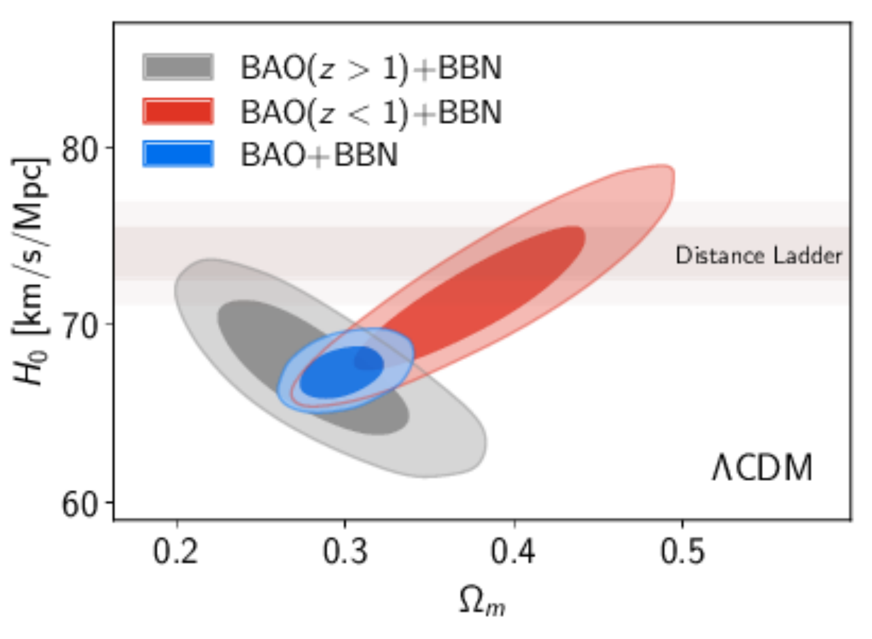
A 4σ discrepancy

- **Late:** Local measurements from "modern" distance ladders

Cepheid calibration of SNe, Tully-Fisher relation, strong gravitational lensing, gravitational waves from NS-NS mergers,…

$$H_0 = 73.2 \pm 1.3\ km/s/Mpc$$

Galaxy clustering constraints on H_o

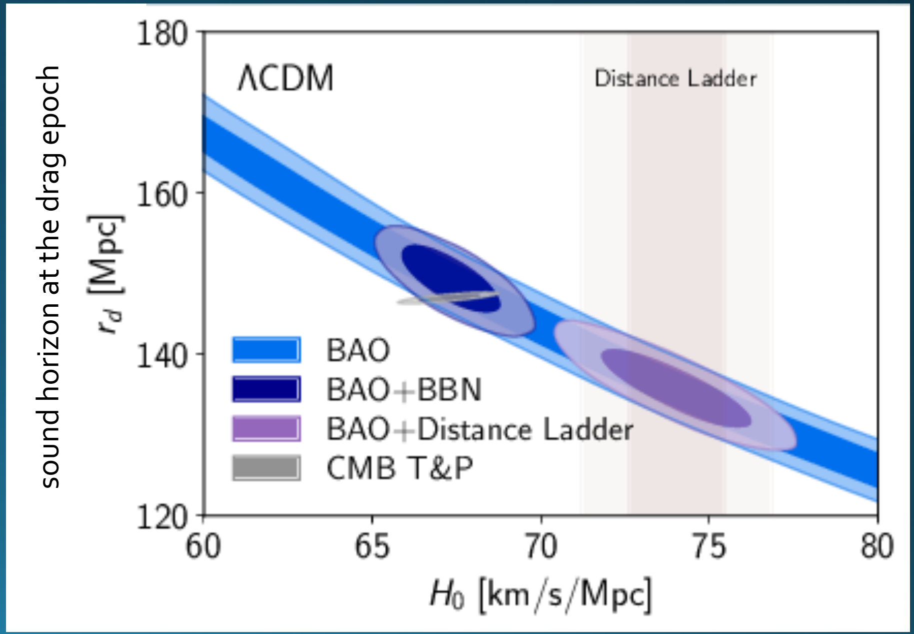


Alam et al. 2020 (eBOSS Collaboration)

The combination of BAO measurements at different z provide measurement of the quantity $r_d H_o$=c.

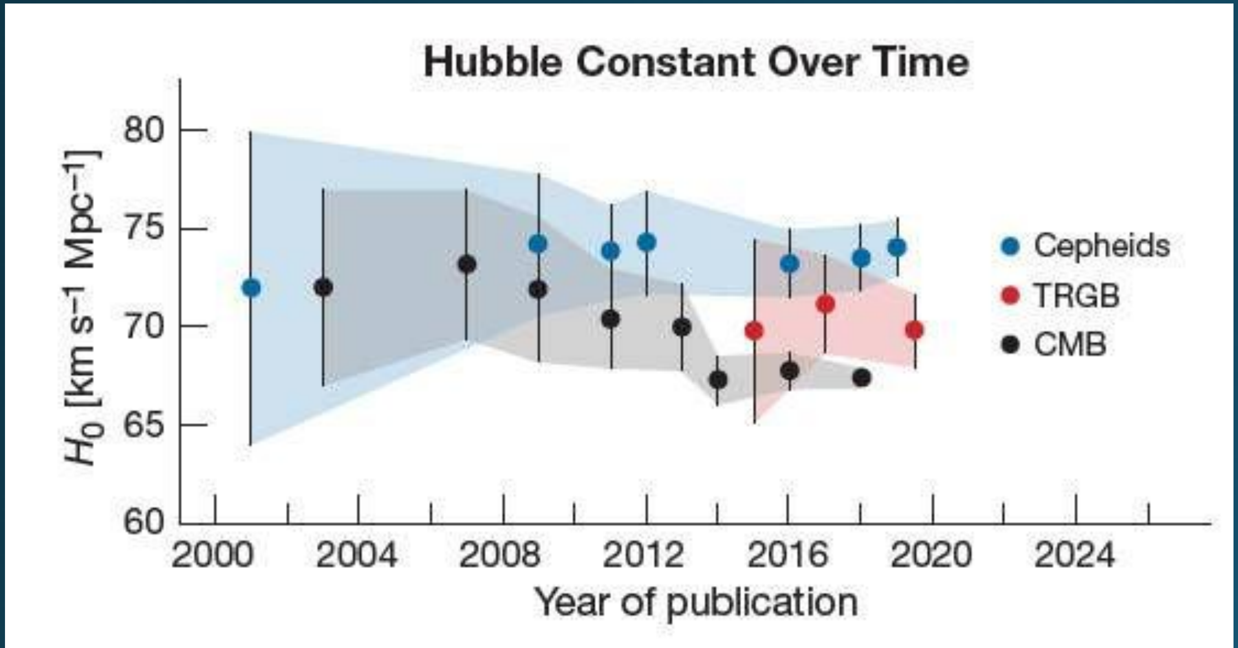
If added to BBN constraints, able to extract a measurement of H_o

$$H_0 = 67.35 \pm 1.0\ km/s/Mpc$$



"Ho tension" not restricted to systematic errors in Planck or to the strict assumptions of the ΛCDM model

Hubble tension



Freedman et al. 2019

- Recently, Hubble constant based on a calibration of the Tip of the Red Giant Branch (TRGB) applied to SNe

$$H_0 = 69.8 \pm 1.9\ km/s/Mpc$$

Freedman et al. 1907.05922

- Revisiting dust extinction corrections: the Hubble tension can be resolved given the large systematic uncertainties related to the choice of Cepheid color-luminosity calibration method

$$H_0 = 66.9 \pm 2.5\ km/s/Mpc$$
$$H_0 = 71.8 \pm 1.6\ km/s/Mpc$$

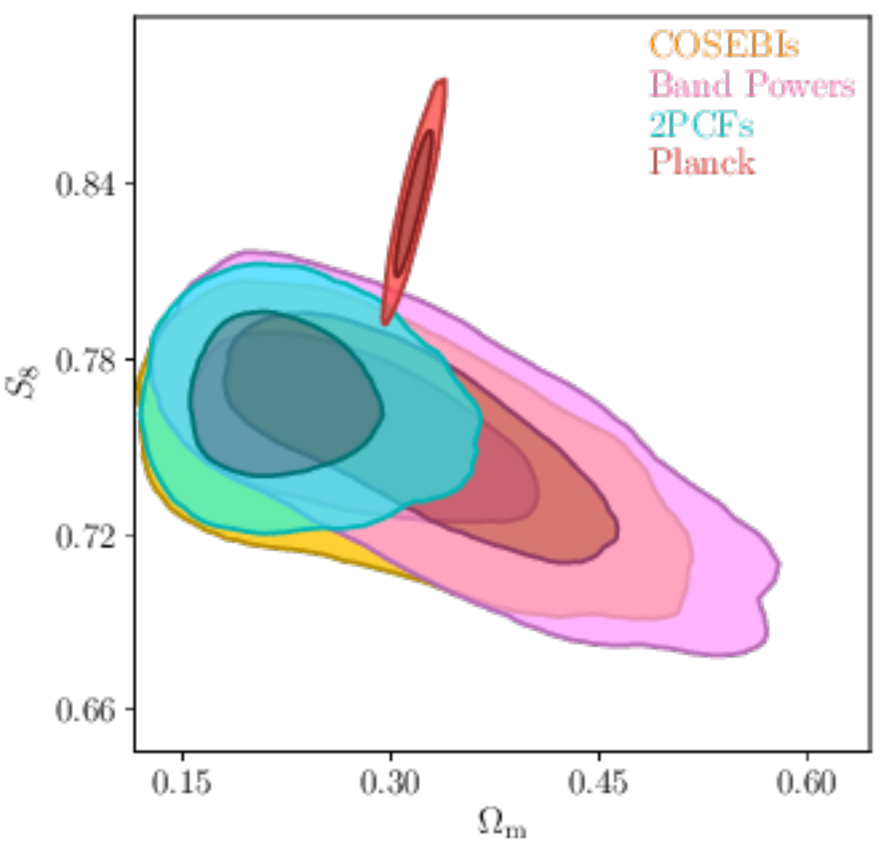
Mortsell et al. 2105.11461

New physics, or systematics?

S_8 tension

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

Amplitude of density perturbations



Asgari et al. 2021 (KiDS Coll.)

Discrepancy at the level of 2-3σ between value measured by CMB anisotropy and that from lensing, galaxy clustering or clusters abundance.

Planck CMB: $S_8 = 0.827 \pm 0.018$

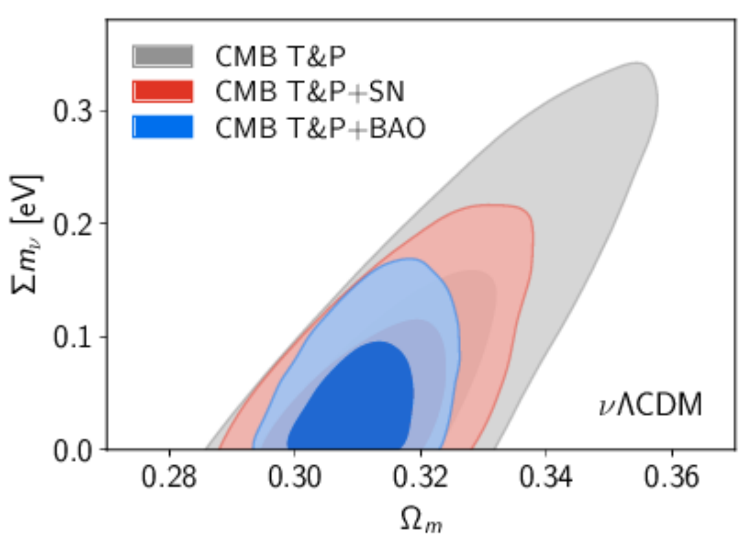
ACTPol+WMAP CMB: $S_8 = 0.840 \pm 0.030$

DES Y3 (3x2pt): $S_8 = 0.776 \pm 0.017$

KiDS 1000: $S_8 = 0.759 \pm 0.022$

Unknown astrophysical systematics?
Statistical fluke ?
New physics?

Beyond Standard Model: Massive neutrinos



Alam et al. 2020

Neutrino mass constraints from the CMB are degenerate with other cosmological parameters such as Ω_m or H_o.

$$\sum m_\nu < 0.268\ eV$$ Planck CMB only

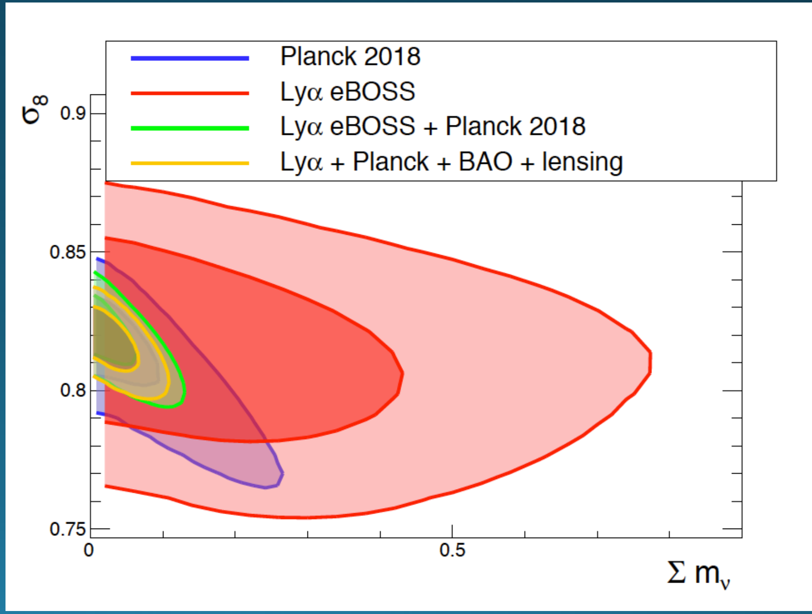
Galaxy clustering is a powerful tool:

$$\sum m_\nu < 0.125\ eV$$ CMB + SN + BAO

Including constraints from Lyman-α:

$$\sum m_\nu < 0.09\ eV$$

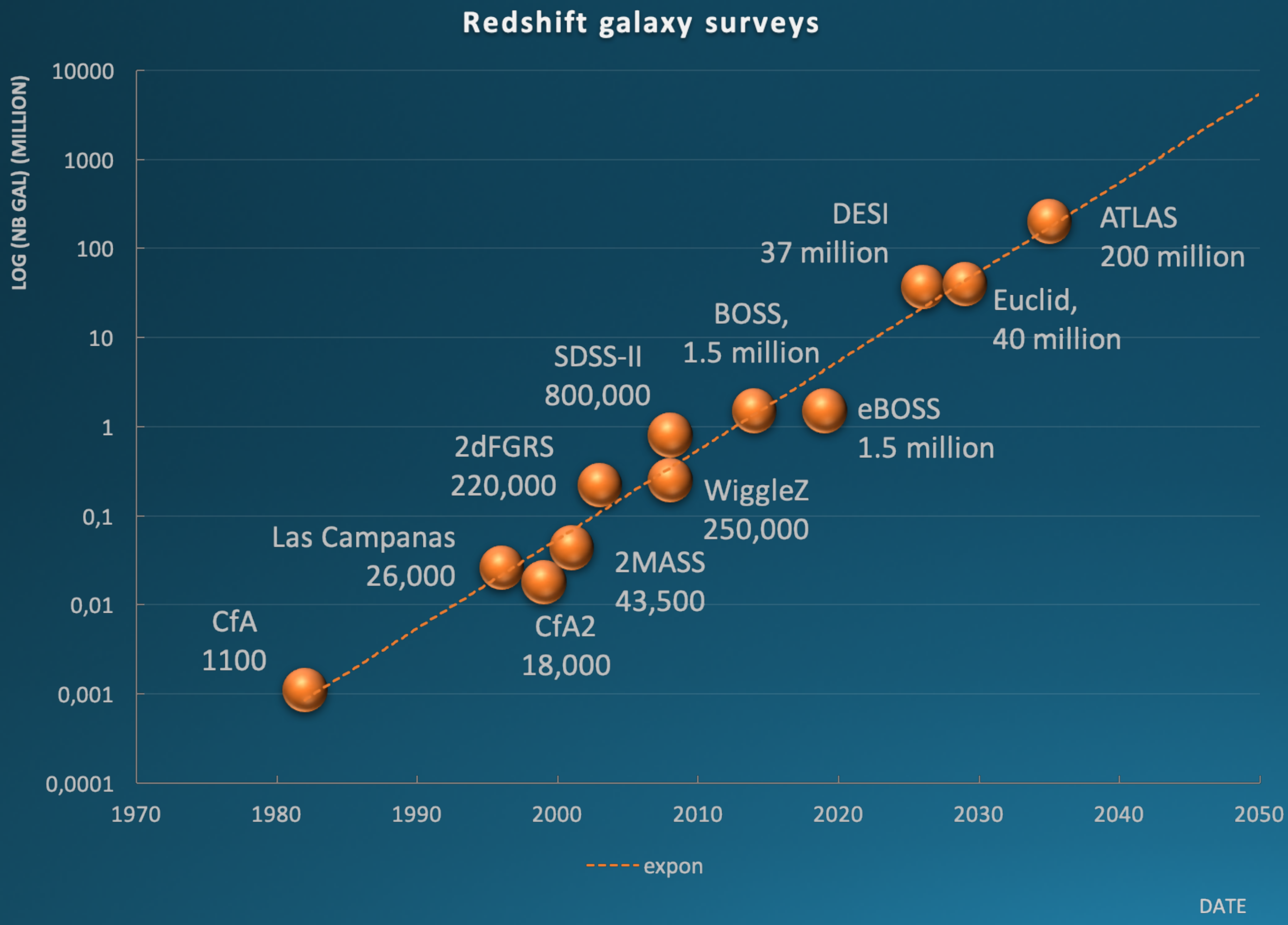
CMB + BAO + Lyman-α



Palanque-Delabrouille et al. 2020

Next generation of galaxy surveys

Galaxy surveys: the era of massive surveys



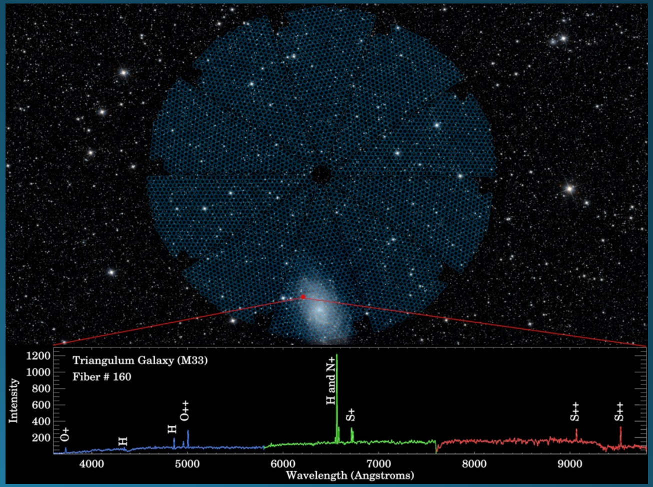
Redshift galaxy surveys increase 10X every 10 years !

Future spectroscopic galaxy surveys: DESI

The Dark Energy Spectroscopic Instrument (DESI) survey (2021-2026)

The DESIsurvey is conducted on the Mayall 4-meter telescope at Kitt Peak Observatory, AZ

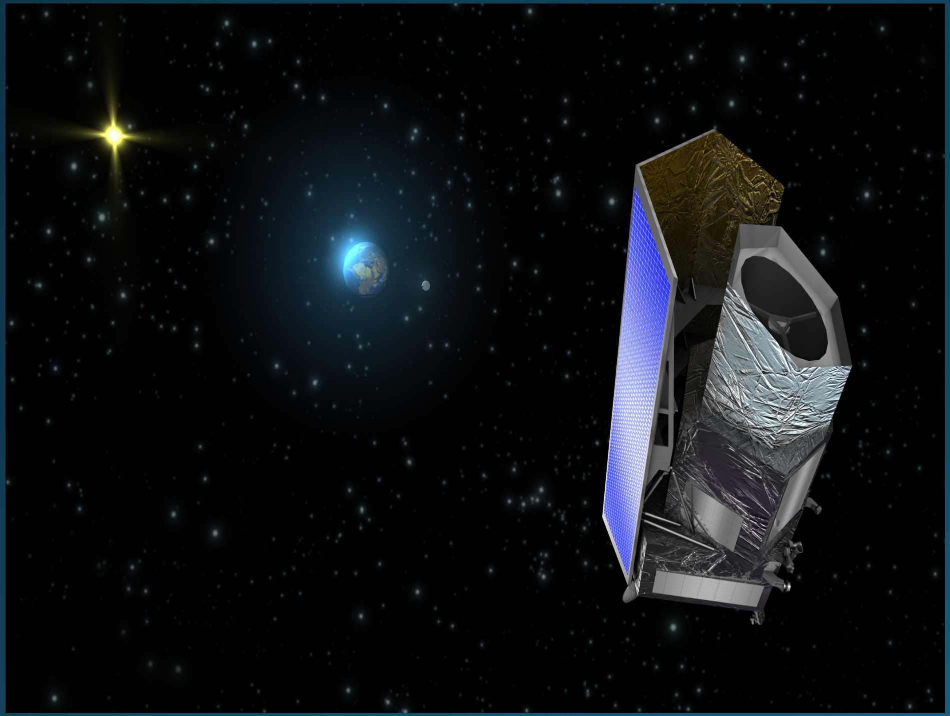
- 4 m telescope
- 14,000 deg² survey
- focal plane with 5,000 robotic positioners
- 37 million spectra for $0.05 < z < 3.5$



The DESI survey has just started, for a 5-year observation period

Future spectroscopic galaxy surveys: Euclid

The Euclid space mission (2022-2029)



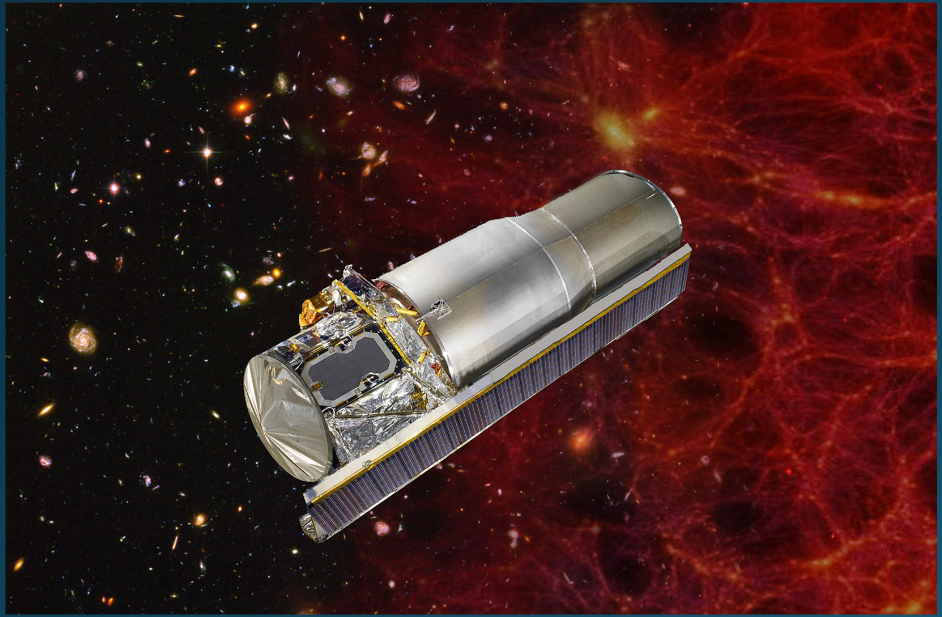
Euclid is a mission of the European Space Agency (ESA) selected in 2011.

- 1.2 m telescope
- 15,000 deg² survey
- 40 million spectra for $0.9 < z < 2.0$
- imaging of 2 billion galaxy

Launch in September 2022

Future spectroscopic galaxy surveys: ATLAS probe

The ATLAS probe (2030-2035)



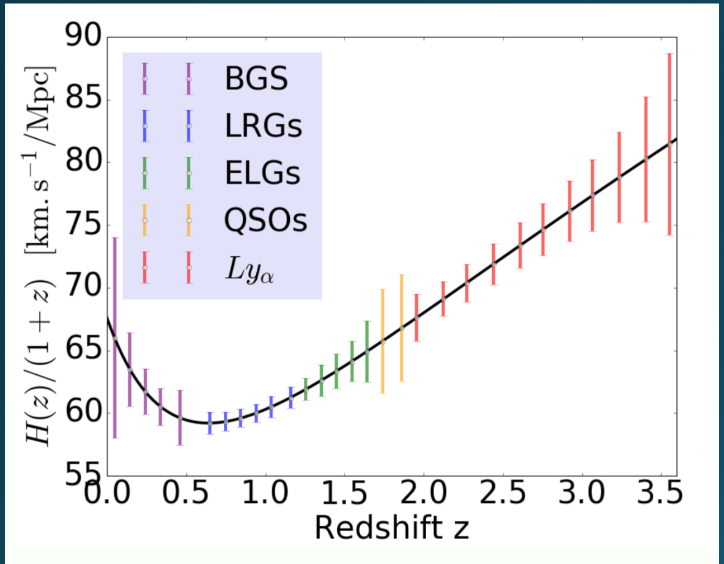
ATLAS (Astrophysics Telescope for Large Area Spectroscopy) Probe is a concept for a NASA probe-class space mission, spectroscopic follow-up to the Nancy Grace Roman Space Telescope.

- 1.5 m telescope
- 2,000 deg² survey
- 6,000 spectra at the same time
- 200 million spectra for $0.5 < z < 7$

Launch date before 2030

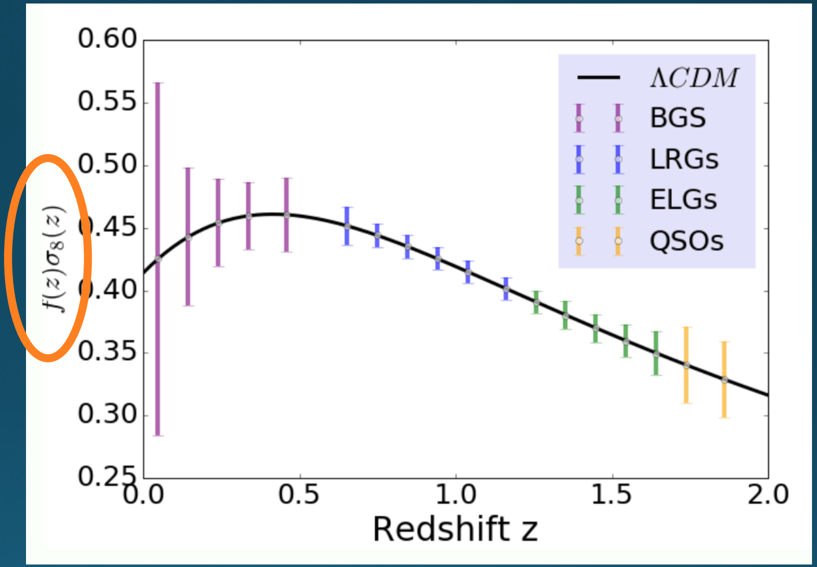
Expected constraints from DESI

Expansion history



sensitive to dark energy

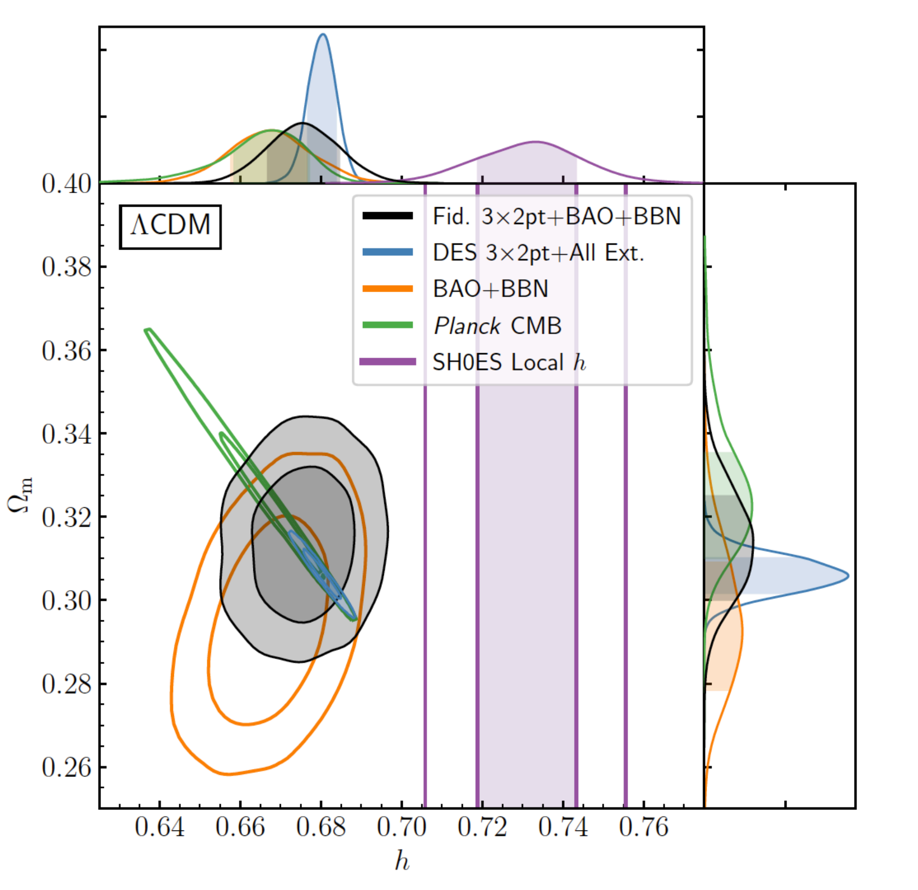
Growth of structure



sensitive to modified gravity

Using galaxy clustering alone, degeneracy between f(z) and $\sigma_8(z)$

Joint analysis with z-surveys



DES Y3 2021

- Joint analysis of Weak lensing and galaxy clustering with photometric surveys (DES, LSST, WFIRST WL).
  Combination of (3x2pt analysis) :
    - cosmic shear
    - galaxy clustering
    - galaxy-galaxy lensing (cross-correlation of source galaxy shapes with lens galaxy positions)
- Combination with other LSS probes (clusters, voids,..)
- Cross-correlation with future CMB surveys (Litebird, SO, CMB-S4)
  J. Bartlett's talk: Cross-Correlations of ATLAS Galaxies with the CMB
- Joint effort with SNe (host galaxy redshifts) and GW data (H_0)
  M. Moresco's talk: Cosmic Chronometers

Need to check the consistency of all probes

Conclusion

- Current observations agree with ΛCDM, but there are some tensions between all these observables. These discrepancies are possibly only artifacts, or hints of a new physics.

  Lord Kelvin is reported to have said to the Royal Institution of London in 1900 :

  The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds.

  These "two clouds" were a) problem with EM waves in moving media and b) atomic theory of matter, whose resolution would give rise to ...General Relativity (1915) and Quantum Mechanics (1925).

- The coming years will be exciting, with new Stage-IV experiments about to start, and future Stage-V experiments, which may answer the fundamental question:

What is the nature of dark energy?

Thank you