DESI Y1: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

中国物理学会高能物理分会第十四届全国粒子物理学术会议(2024)

Ting Tan (Postdoc at CEA Saclay)
On behalf of the DESI collaboration

References (arXiv): 2404.03002, 2404.03000, 2404.03001

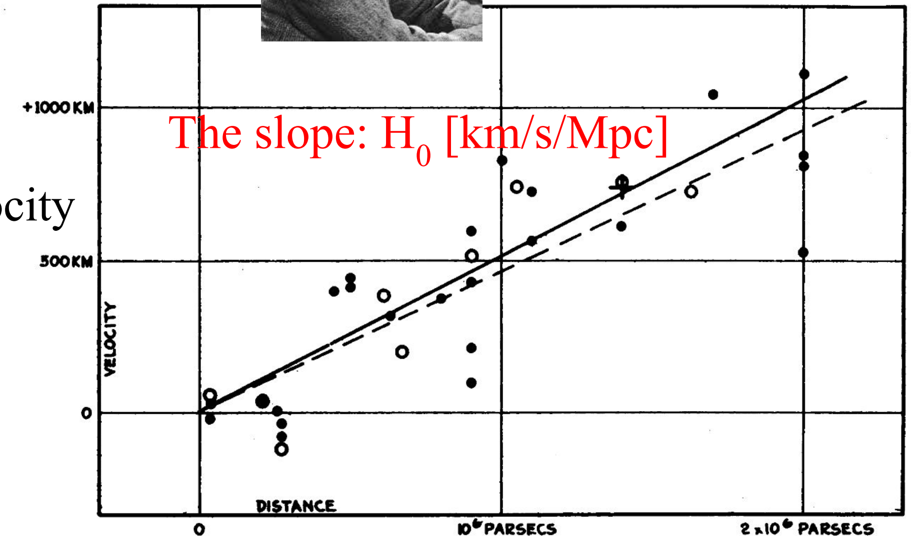
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The accelerated expanding universe

Edwin Hubble

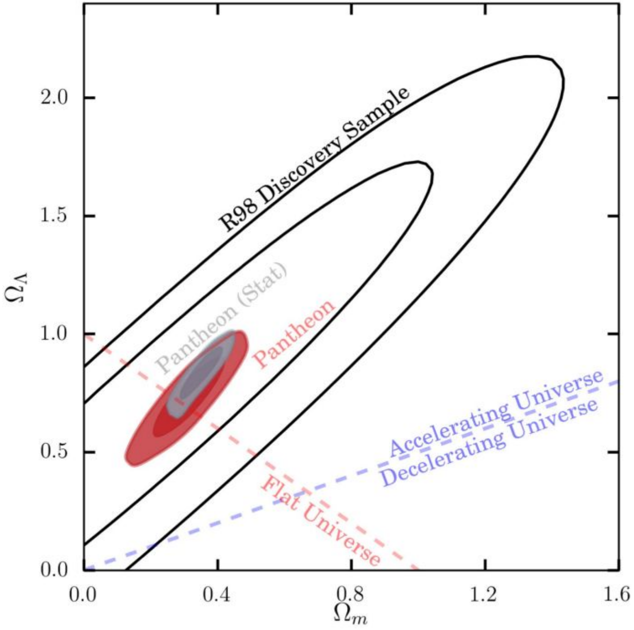
Velocity



Distance

1929 - expansion of the universe with nearby galaxies

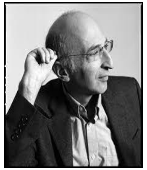
1998 - accelerated expansion of the universe with Type Ia supernovae



D. M. Scolnic et al. The Astrophysical Journal 859.2 (2018)

Adam Riess

Brian Schmidt

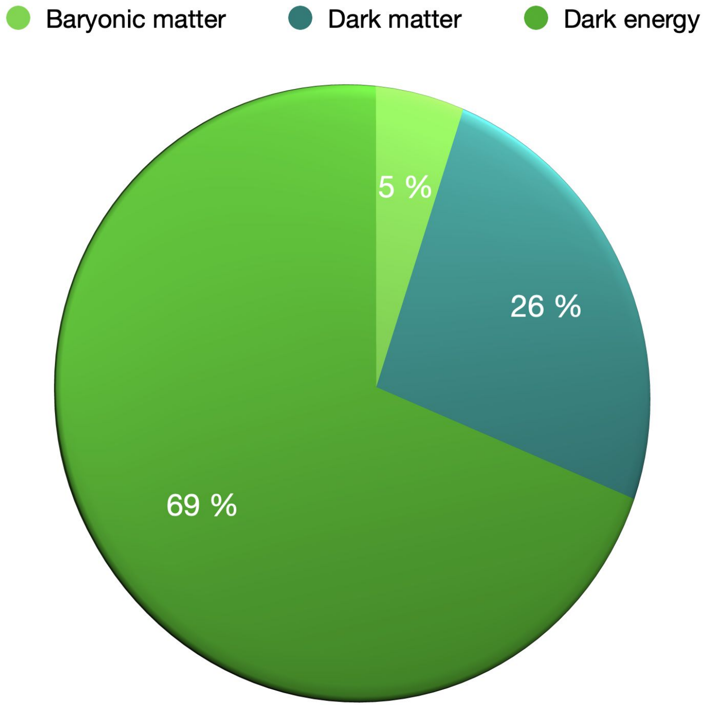


Saul Perlmutter

The accelerated expanding universe

ΛCDM model

- Dark matter (26.2%)
- Baryonic matter (4.9%)
- Dark energy (68.9%)
- Radiation (~0.01%)
- Curvature (flat)



Planck 2018 results

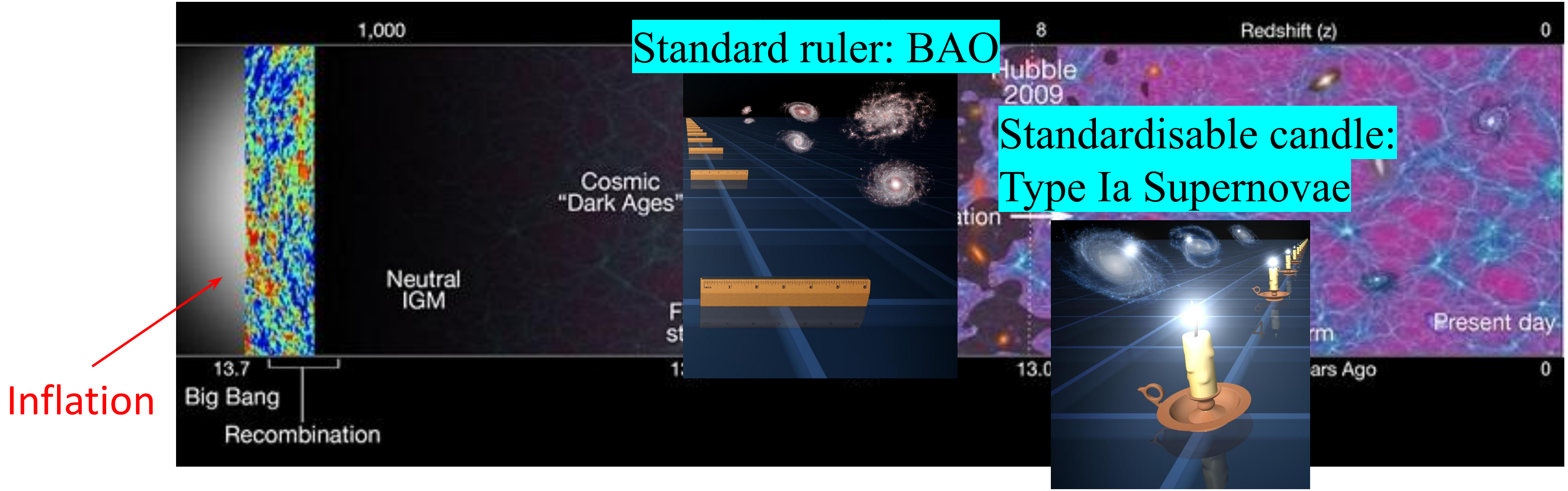
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The accelerated expanding universe

a: the scale factor of the universe (a_0 refers to the current time)

redshift z: expansion factor of the universe: $1 + z = \frac{a_0}{a}$

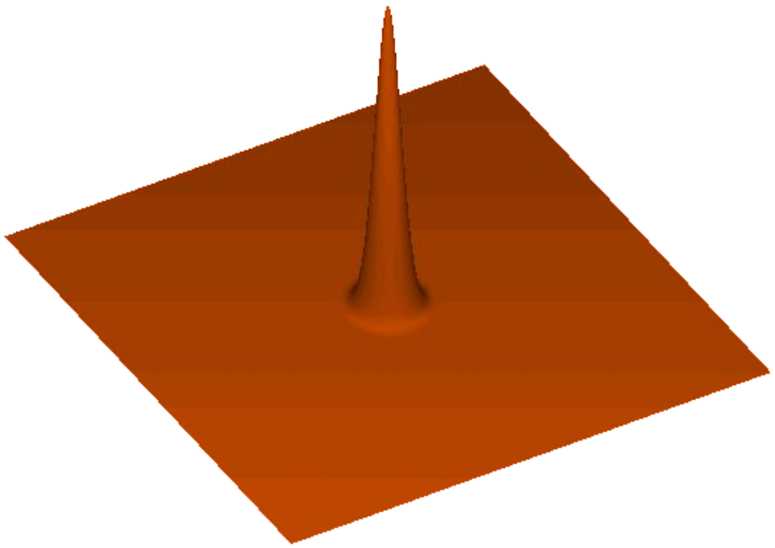


NASA/ESA

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

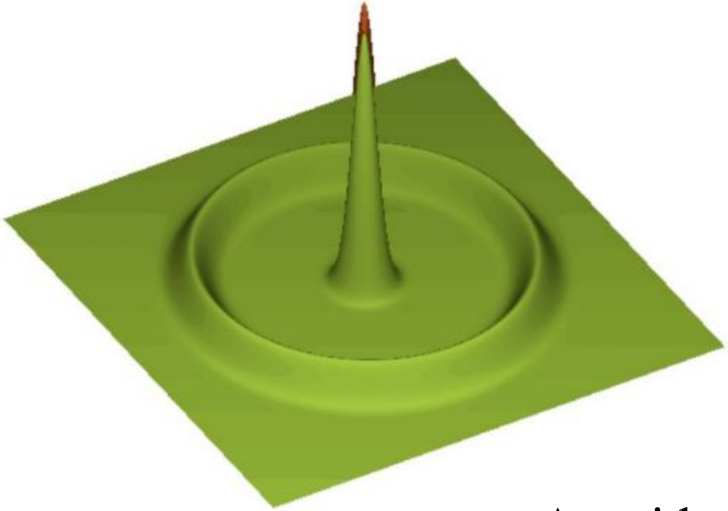
Baryon Acoustic Oscillations (BAO)

Sound waves in primordial plasma:



Eisenstein, Seo et al. 2007

Baryon Acoustic Oscillations (BAO)



Eisenstein, Seo et al. 2007

At recombination (z~1000),

• Plasma changes from optically thick to optically thin.

• Baryons decouple from photons.

• Sound speed of gas decreases.

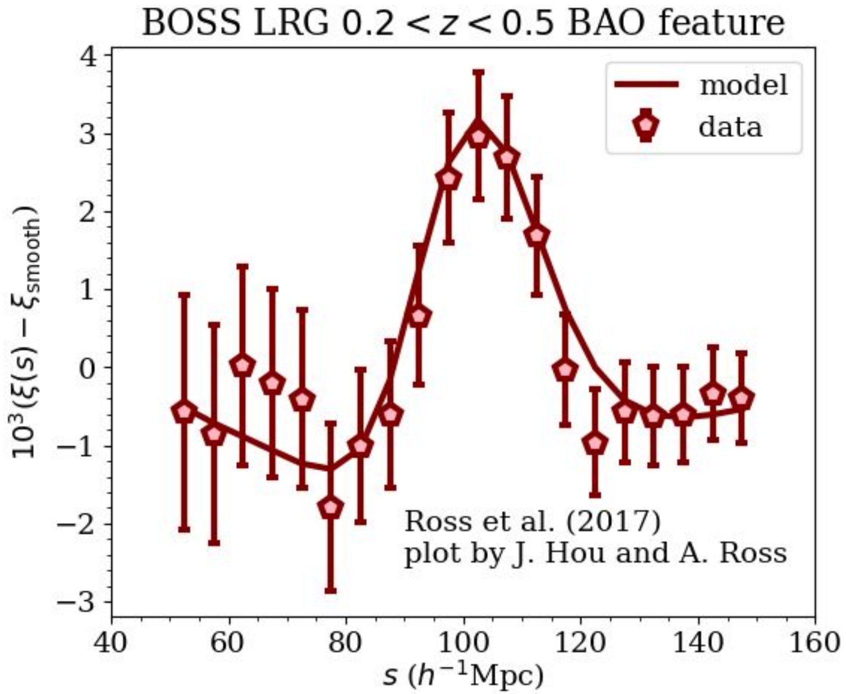
• The traveling wave stalls.

A residual spherical **peak in clustering of galaxies**

→ the wave has travelled before the recombination

→ the sound horizon scale at recombination (**~150 Mpc**).

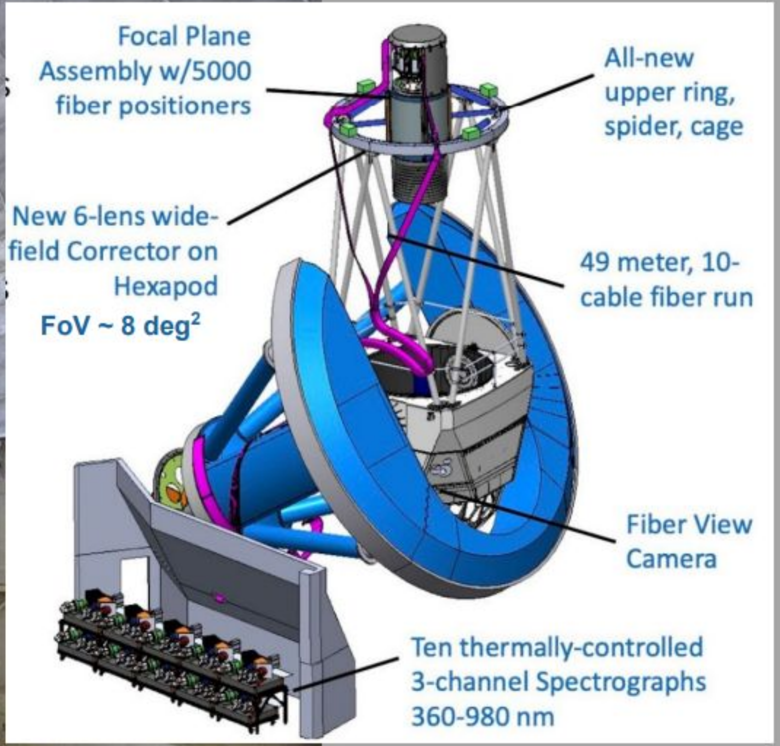
Measuring BAO using different tracers



Measurement of BAO: A peak in the two point correlation function (2PCF) of matter tracers, such as galaxies, quasars, voids, Lyα forests.

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

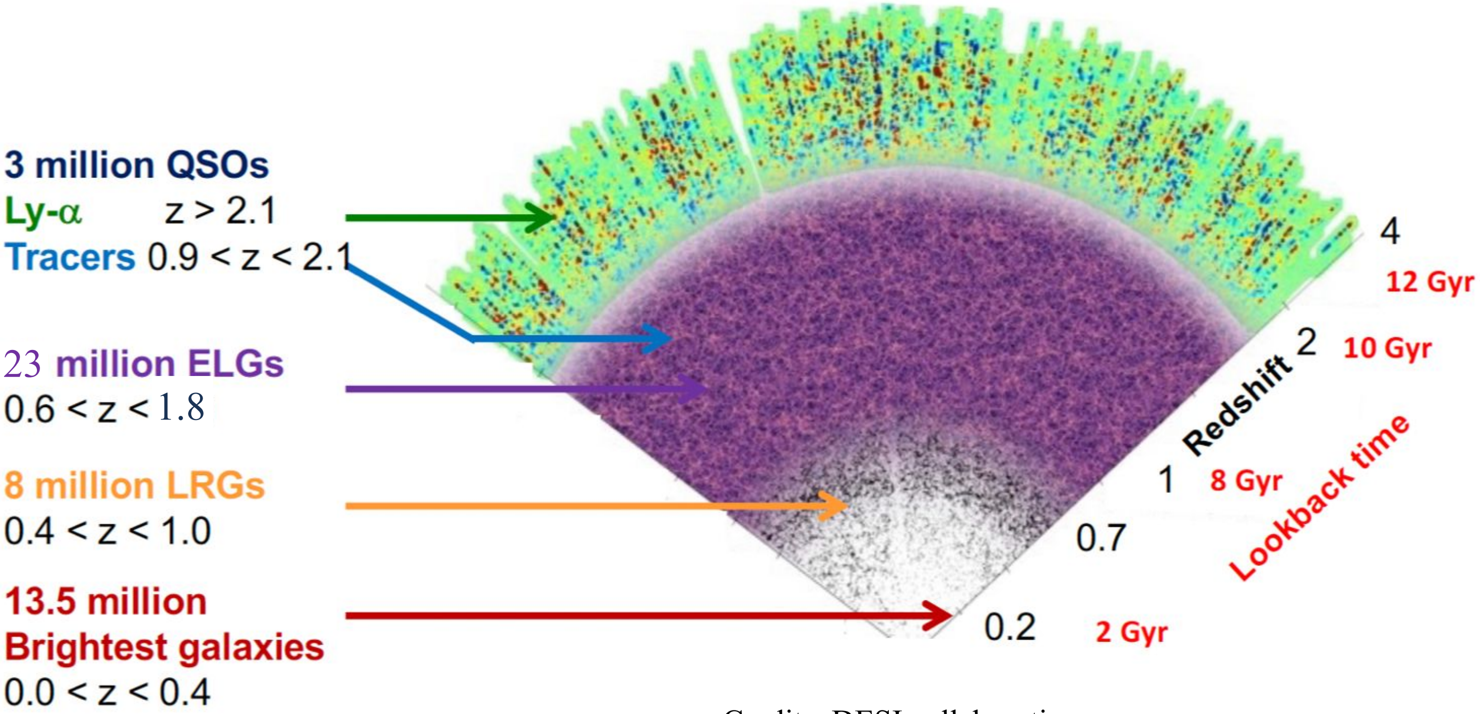
Mayall 4m telescope @ Kitt Peak (AZ)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

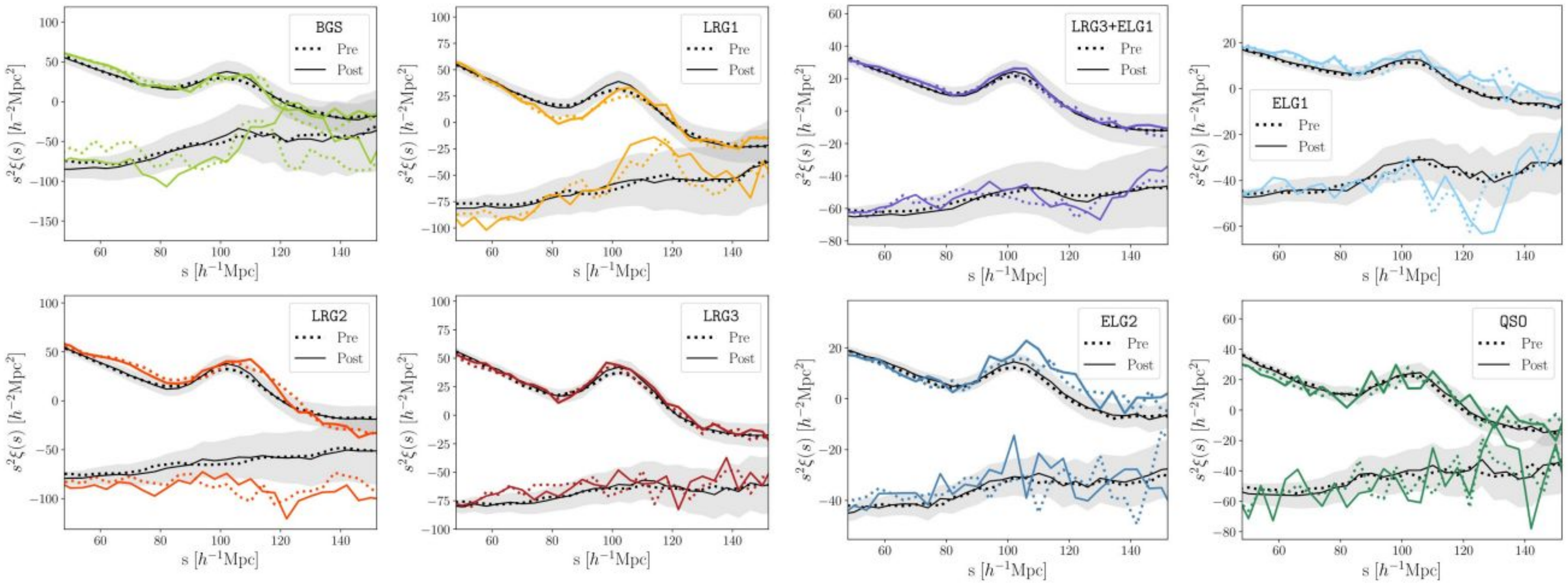
Dark Energy Spectroscopic Instrument

40 million galaxies and quasars



Credits: DESI collaboration

2-point correlation functions of DESI tracers

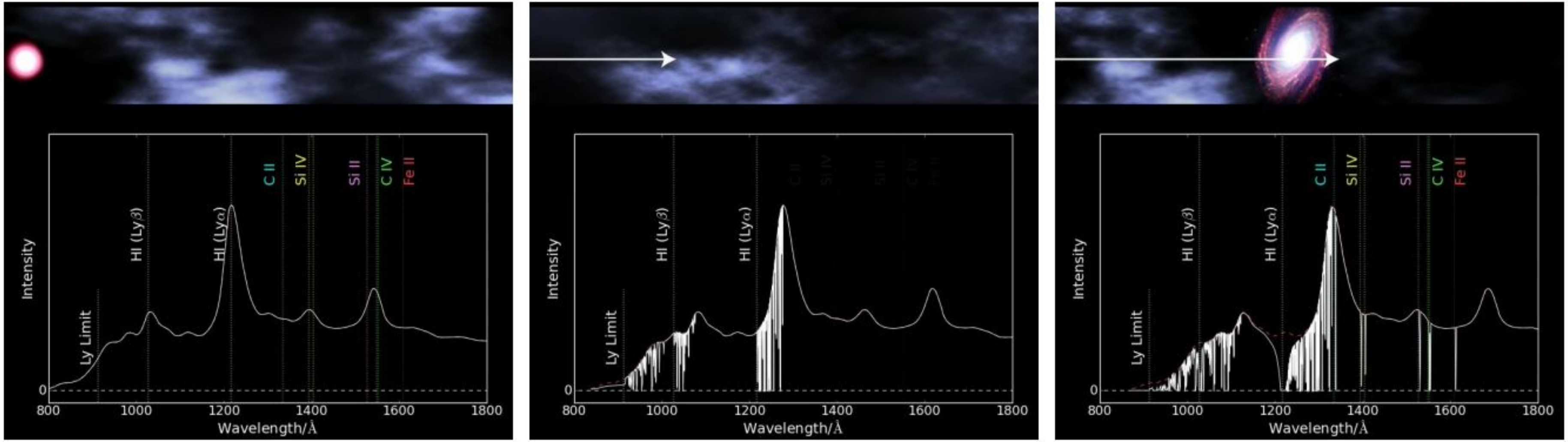


Credits: DESI collaboration

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

The Lyman-α Forest

credit: Andrew Pontzen



Background quasar —— Intervening gas ——→ Earth

- Absorption in QSO spectra by neutral hydrogen in the intergalactic medium
- The transmitted flux fraction F is a cosmological probe of the fluctuation in the neutral hydrogen density

$$F = e^{-\tau}$$

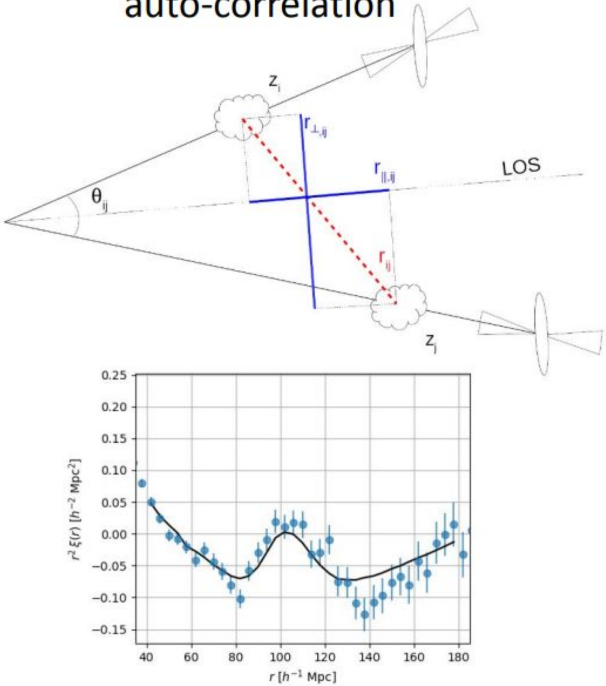
$$\tau \propto n_{HI}$$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

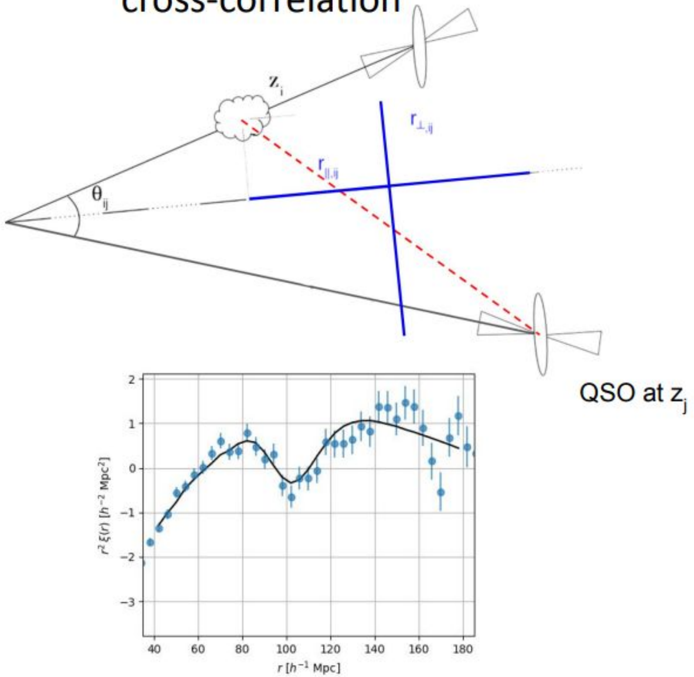
U.S. Department of Energy Office of Science

2-point correlation functions of DESI tracers

Lya-Lya auto-correlation



Lya-QSO cross-correlation

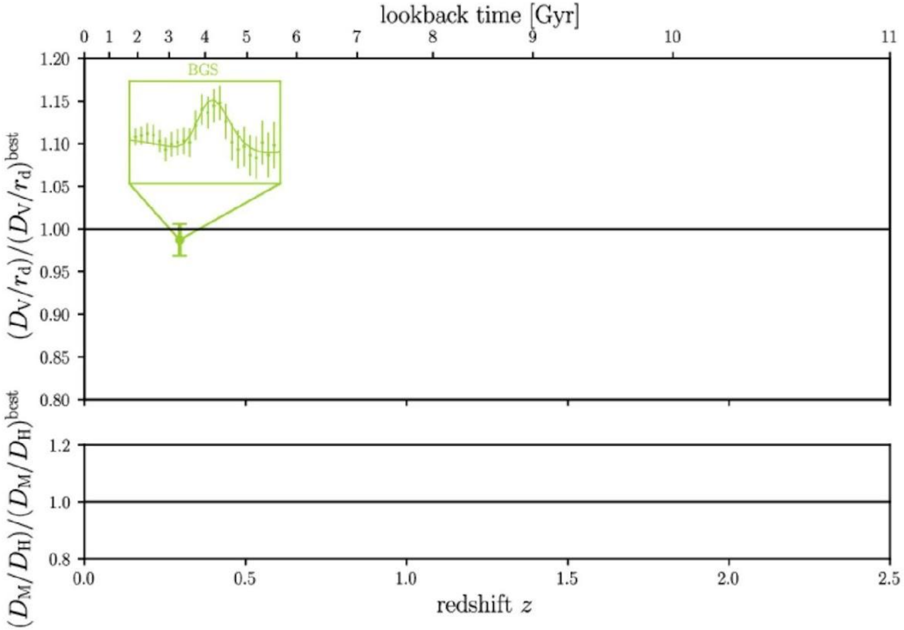


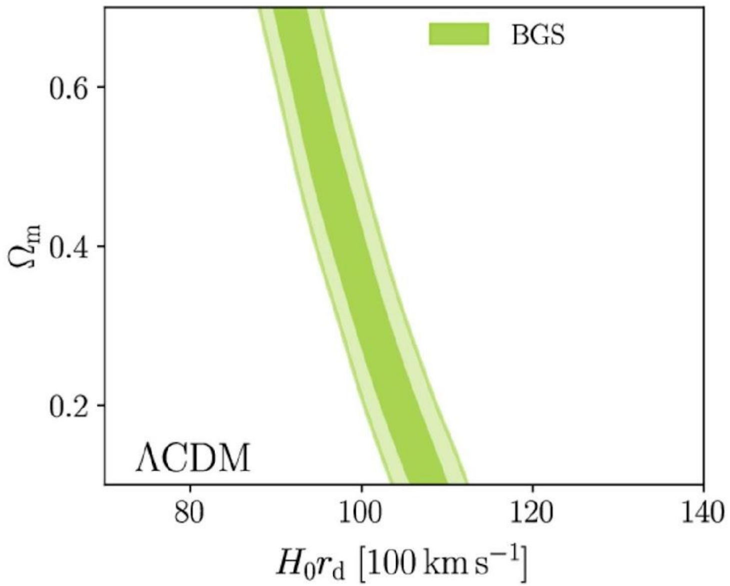
Credits: DESI collaboration

DESI Y1 BAO

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI BAO measurements

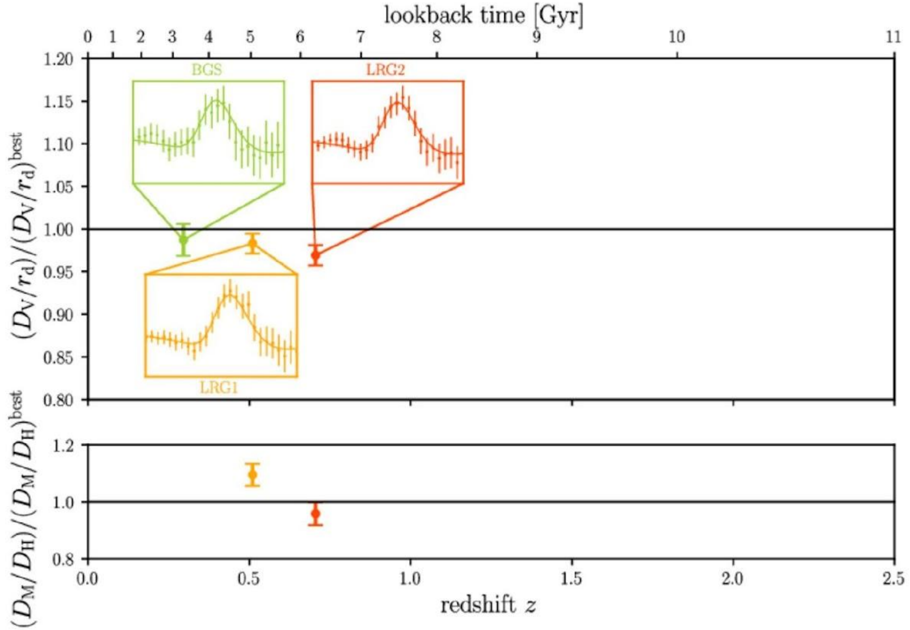


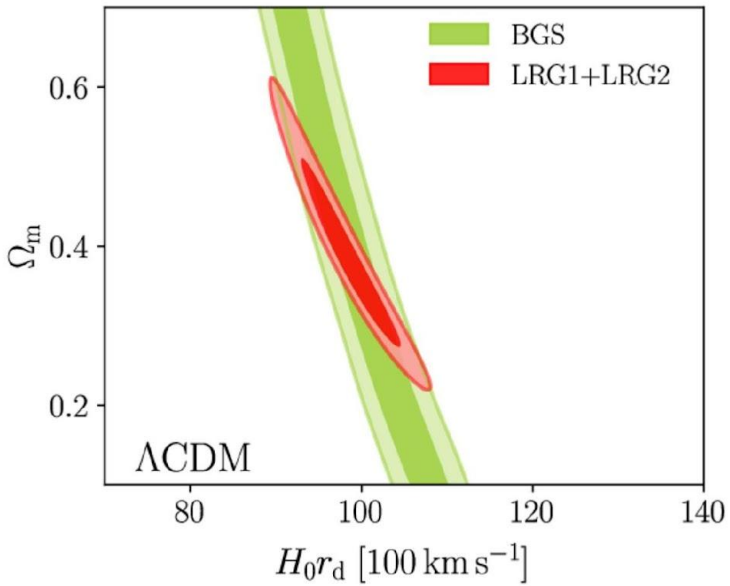


DESI Y1 BAO

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI BAO measurements



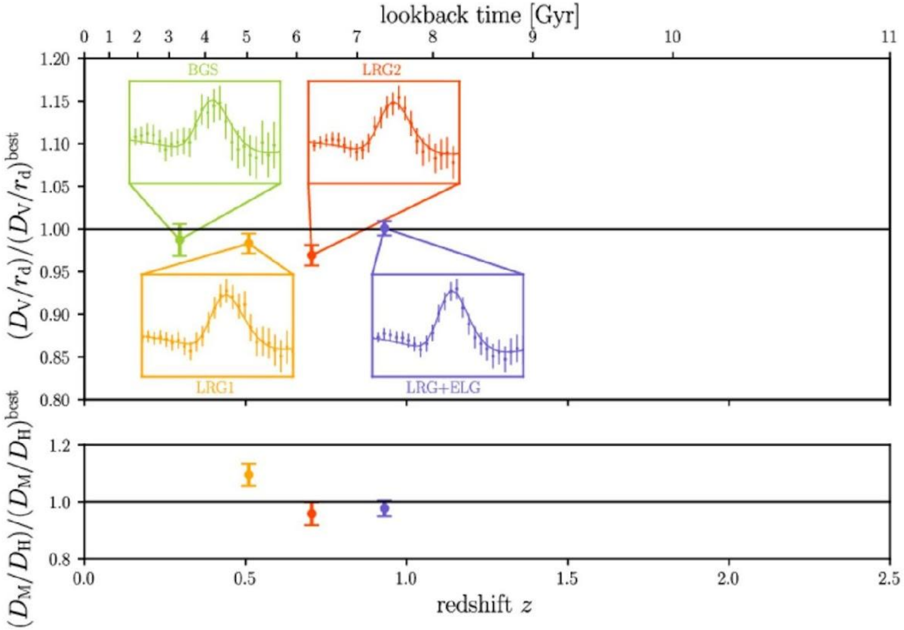


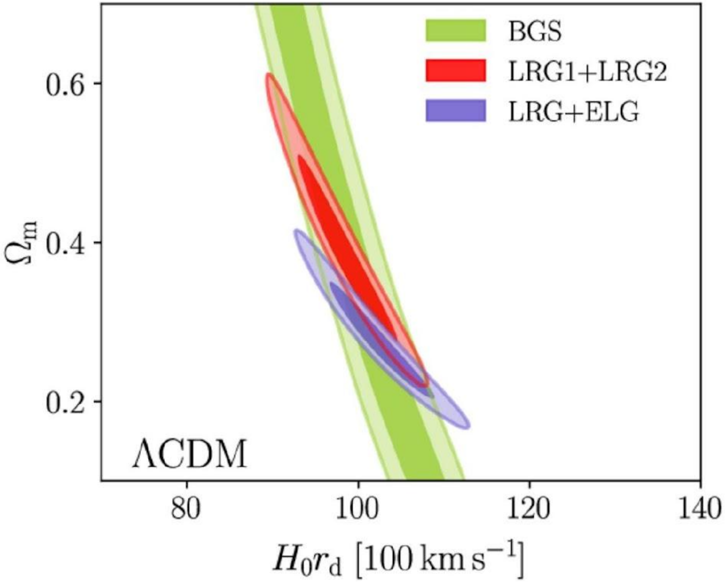
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

DESI BAO measurements



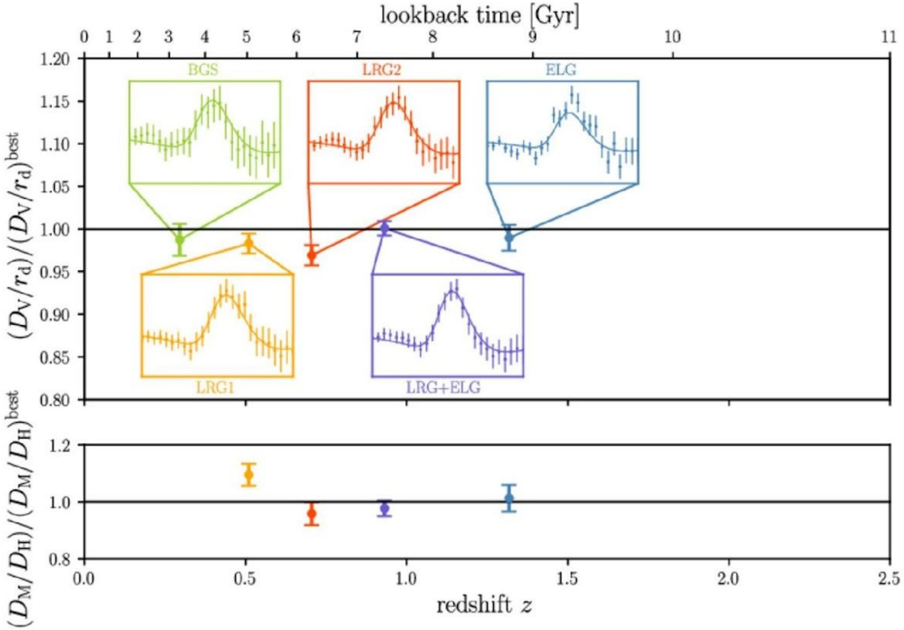


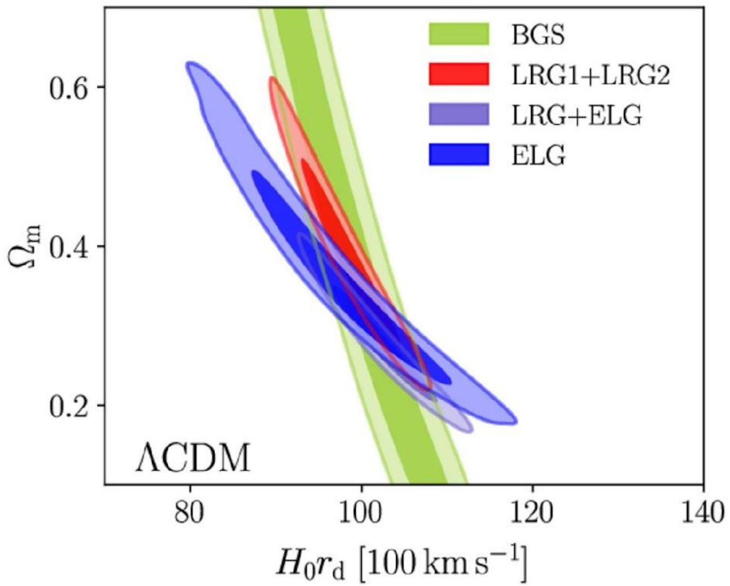
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

DESI BAO measurements



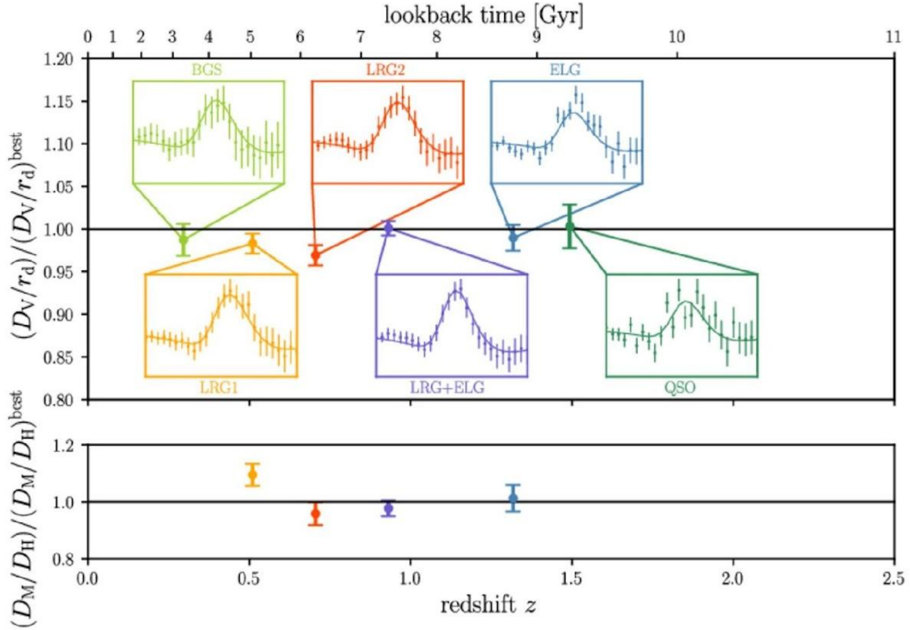


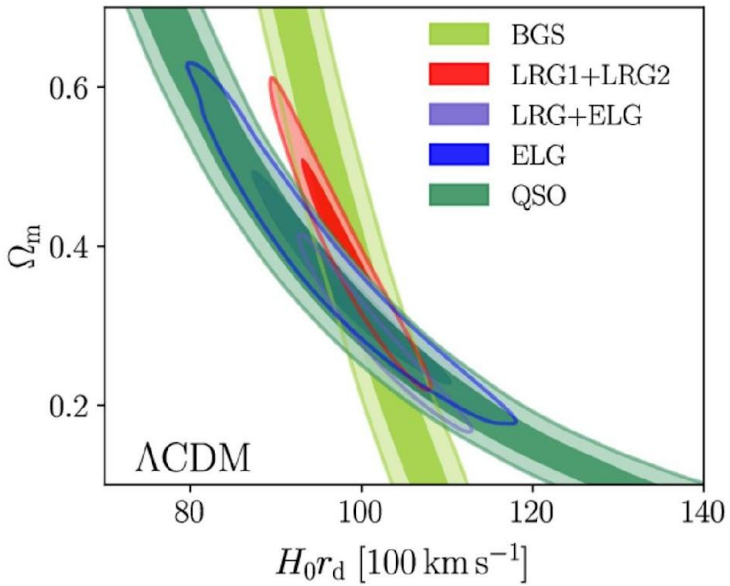
DESI Y1 BAO

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI BAO measurements



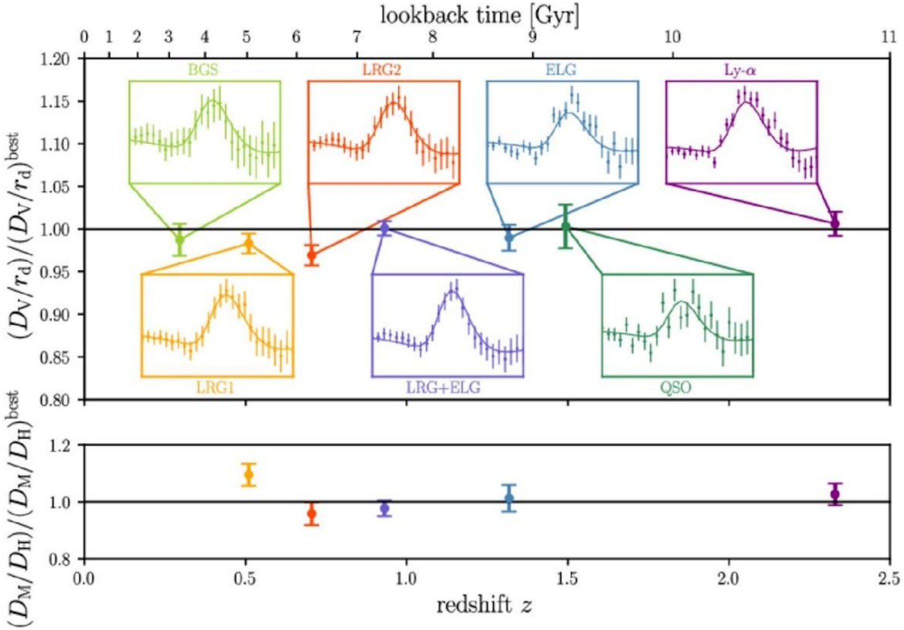


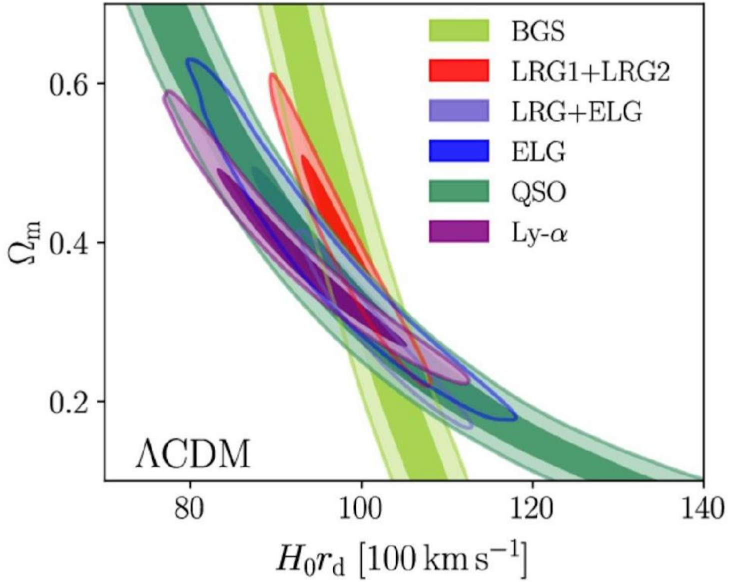
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

DESI BAO measurements





DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

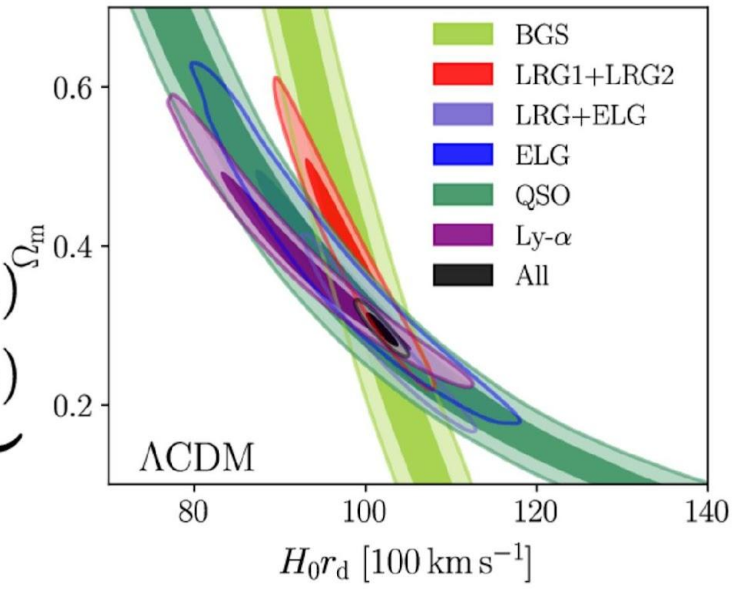
DESI BAO measurements

Consistent with each other, and complementary

$$\Omega_m = 0.295 \pm 0.015 \quad (\mathbf{5.1\%})$$

$$H_0 r_d = (101.8 \pm 1.3)\,[100\,\mathrm{km\,s^{-1}}] \quad (\mathbf{1.3\%})$$

$$\underbrace{\hspace{10em}}_{\text{DESI}}$$



Combined BAO result in ΛCDM

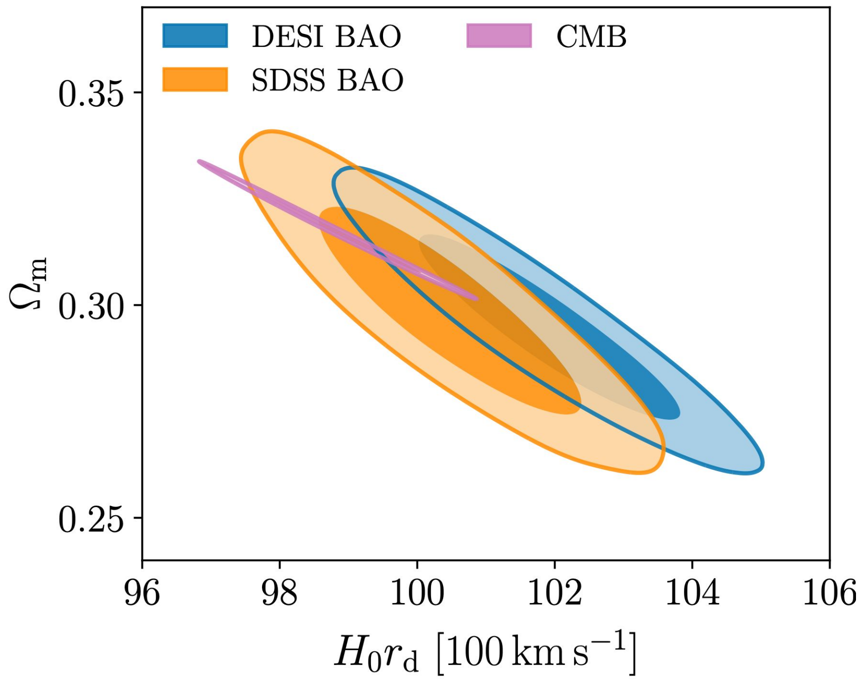
DESI Y1 BAO consistent with:

- SDSS BAO (eBOSS 2020)
- CMB (primary: Planck 2018; lensing: Planck PR4 + ACT DR6)

DESI and CMB are consistent at 1.9σ-level

Combined fit DESI + CMB:

$$\Omega_m = 0.3069 \pm 0.0050 \ (1.6\%)$$



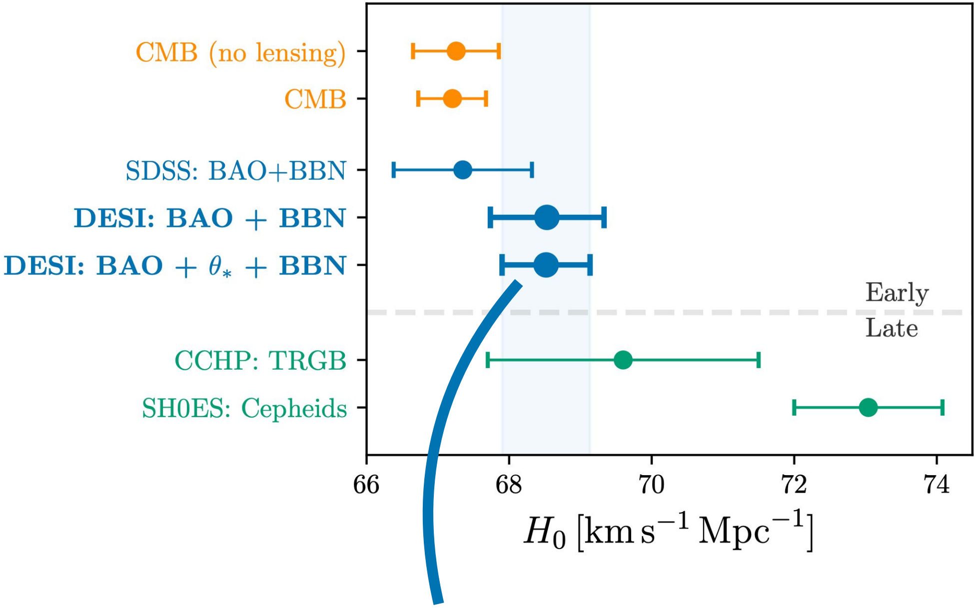
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Hubble constant in ΛCDM

$$H_0 r_d = h \times f(\Omega_m h^2, \Omega_b h^2)$$

- Can use BBN to measure Ω_b
- $\theta_\star$: measured acoustic peak position in CMB (expected to be more robust and model-independent than whole CMB fit outputs)

- Consistent with SDSS
- In agreement with CMB
- In 3.7σ tension with SH0ES



$H_0 = (68.53 \pm 0.62)$ km s^{-1} Mpc^{-1}

~2.1σ wrt CMB

DARK ENERGY SPECTROSCOPIC INSTRUMENT

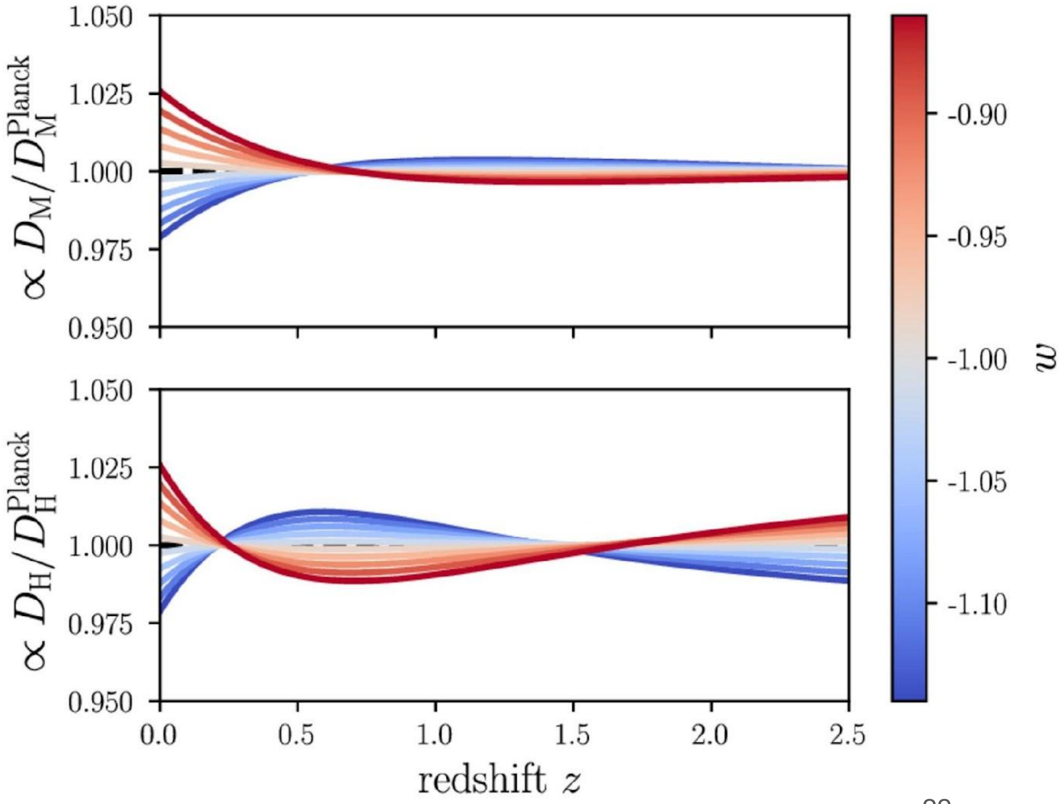
U.S. Department of Energy Office of Science

BAO measurements: dark energy

Dark energy equation of state:

$$P = w\rho$$

- w = constant



DARK ENERGY SPECTROSCOPIC INSTRUMENT

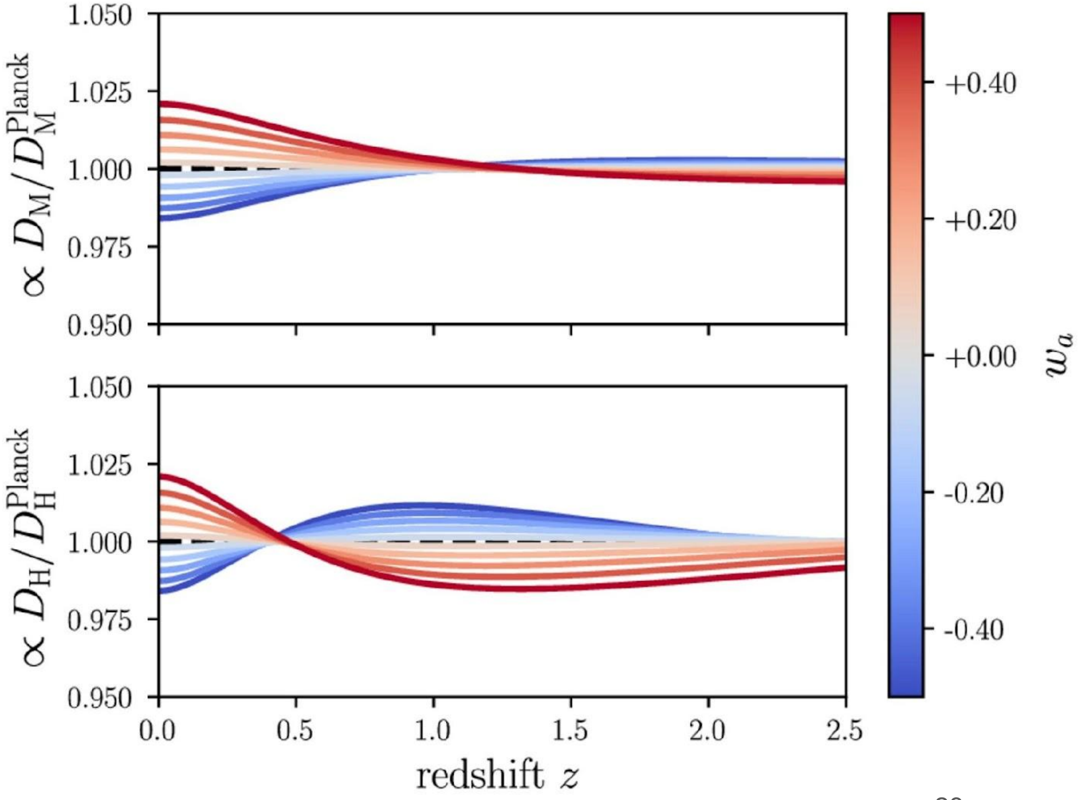
U.S. Department of Energy Office of Science

BAO measurements: dark energy

Dark energy equation of state:

$$P = w\rho$$

- CPL parameterization:
  $w(a) = w_0 + (1-a)w_a$



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Beyond ΛCDM: Dark Energy Equation of State

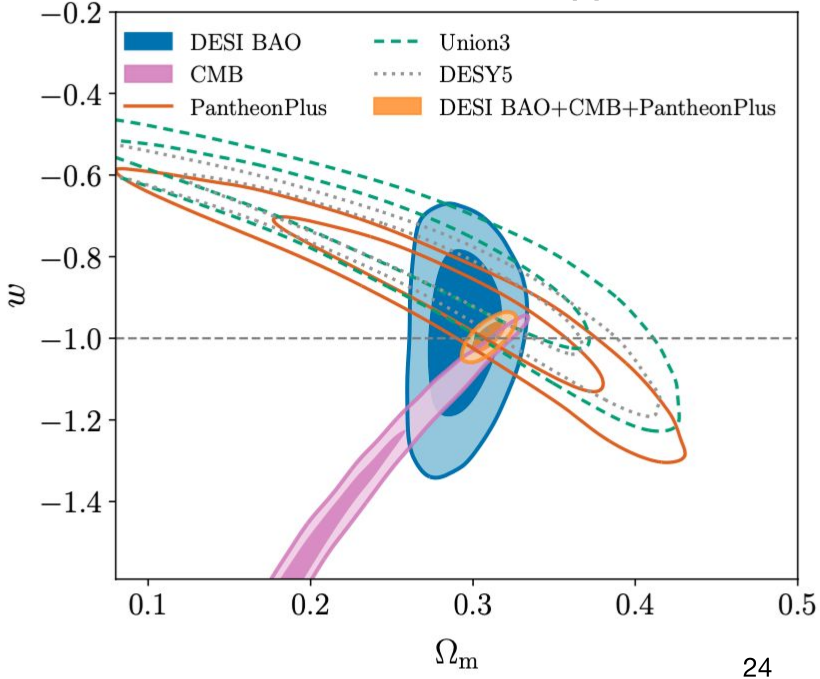
$f_{\rm DE}(z)$ depends on its equation of state: $w(z) = \dfrac{p(z)}{\rho(z)}$

ΛCDM: $w = -1$

Three **SN measurements** are available: Pantheon+ (2022), Union3 (2023), DES-Y5 (2024)

Assuming a constant EoS, DESI BAO is fully compatible with a cosmological constant

fit w(z) = constant



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

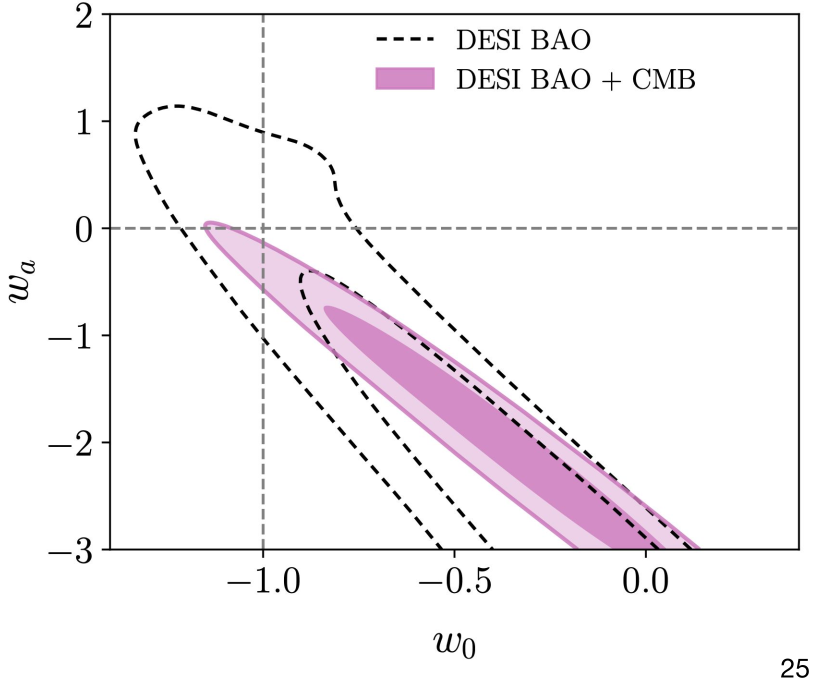
Beyond ΛCDM: Dark Energy Equation of State

The previous conclusion changes when considering a time-varying equation of state:

$$w(z) = w_0 + \frac{z}{1+z} w_a \qquad \text{(CPL parametrization)}$$

- DESI BAO alone has poor constraining power
- **DESI + CMB ⟹ 2.6 σ**

fit varying w(z)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Beyond ΛCDM: Dark Energy Equation of State

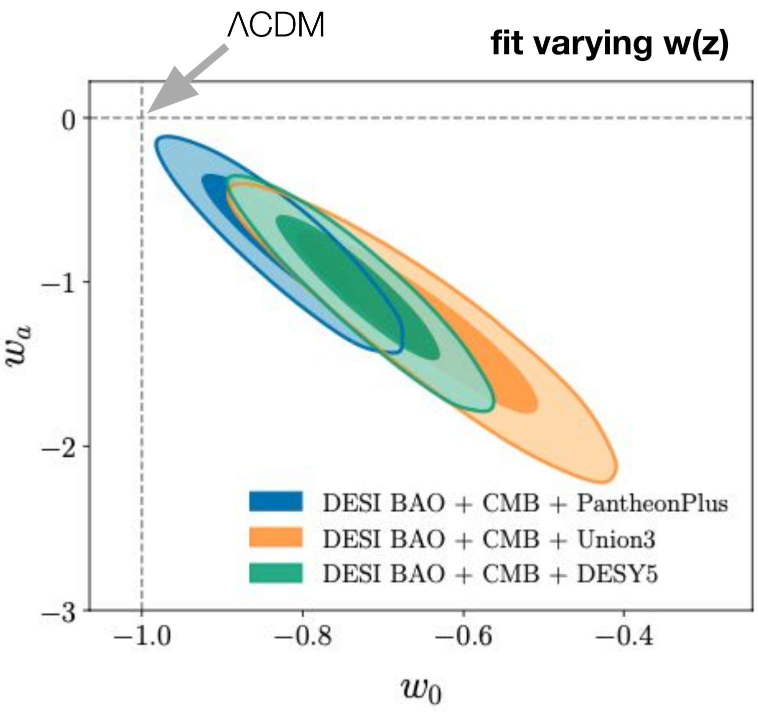
The previous conclusion changes when considering a time-varying equation of state:

$$w(z) = w_0 + \frac{z}{1+z} w_a$$ (CPL parametrization)

- DESI BAO alone has poor constraining power
- DESI + CMB $\Rightarrow$ 2.6 σ
- **DESI + CMB + supernovae $\Rightarrow$ from 2.5σ to 3.9σ, depending on the considered SN sample**

$w_0 > -1$, $w_a < 0$ favored

fit varying w(z)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

The sum of neutrino masses

CMB measurements are sensitive to Σm_ν

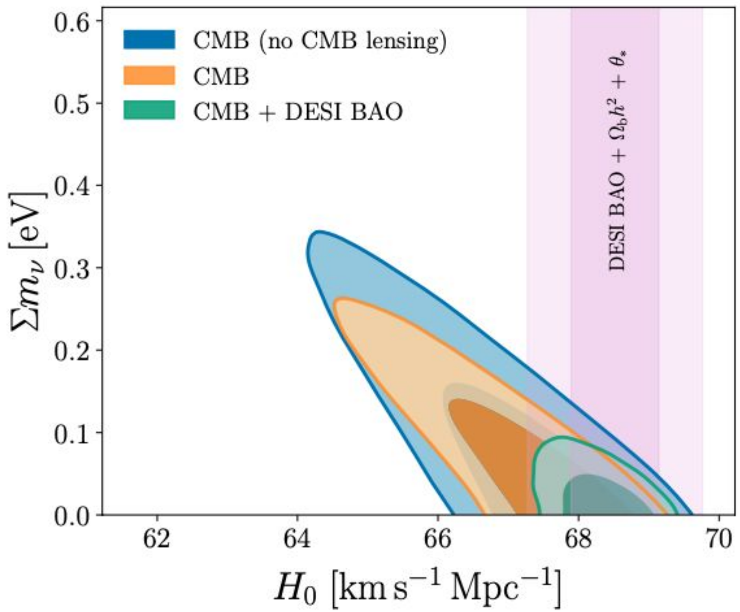
But internal degeneracies limiting its precision

BAO helps break degeneracies (through H_0 / Ω_m)

95% CI limits:

$$\sum m_\nu < 0.21\,\mathrm{eV}$$ CMB alone, ΛCDM

ΛCDM fit



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The sum of neutrino masses

CMB measurements are sensitive to Σm_ν

But internal degeneracies limiting its precision

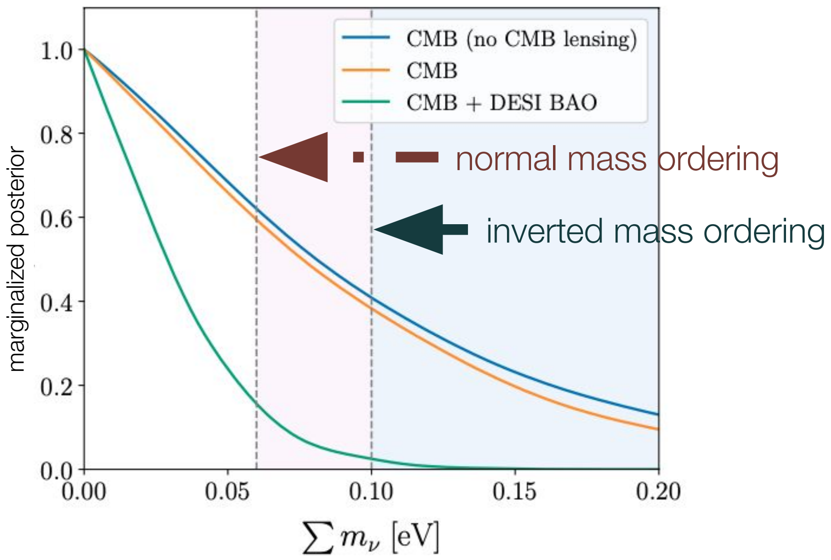
BAO helps break degeneracies (through H_0 / Ω_m)

95% CI limits:

$\sum m_\nu < 0.21\,\mathrm{eV}$ CMB alone, ΛCDM

$\sum m_\nu < 72\,\mathrm{meV}$ CMB + DESI BAO, **ΛCDM**

ΛCDM fit



Some preference for normal over inverted mass ordering at the 2σ level

Limit changes if adding a prior on mass ordering

The sum of neutrino masses

CMB measurements are sensitive to Σm_ν

But internal degeneracies limiting its precision

BAO helps break degeneracies (through H_0 / Ω_m)

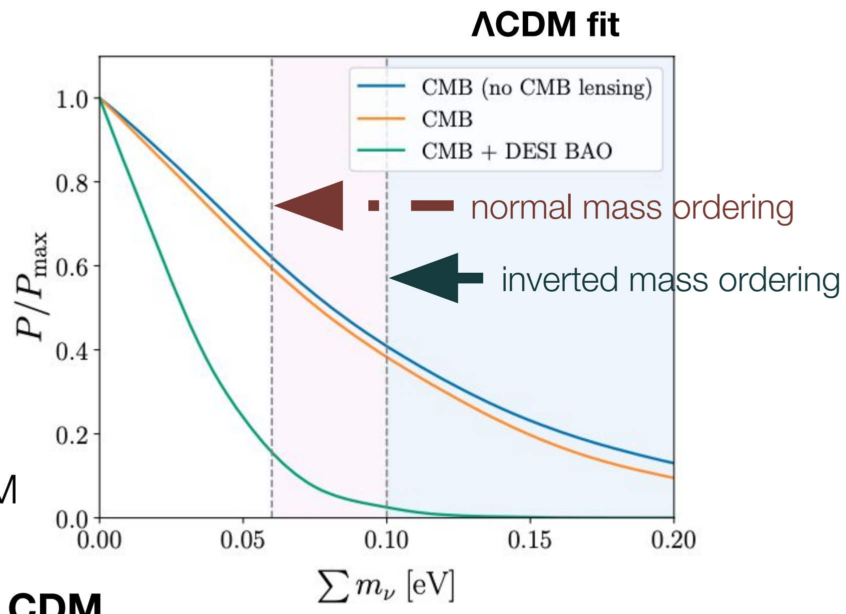
95% CI limits:

$\sum m_\nu < 0.21\,\mathrm{eV}$ CMB alone, ΛCDM

$\sum m_\nu < 72\,\mathrm{meV}$ CMB + DESI BAO, ΛCDM

$\sum m_\nu < 195\,\mathrm{meV}$ CMB + DESI BAO, **w_0w_aCDM**

certainly more robust at this stage



Summary: results from DESI BAO Y1

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

- DESI already has the **most precise BAO** measurements ever
- **DESI BAO is consistent (at the ~1.9σ level) with CMB in flat ΛCDM**
  - in flat ΛCDM, DESI prefers "small Ω_m, large H_0 (though 3.7σ away from SH0ES), $\Sigma m_\nu < 72$meV"
- Some hint of **time-varying Dark Energy equation of state**
  - especially when combined with supernovae measurements
  - $\Sigma m_\nu < 195$meV for wCDM

https://data.desi.lbl.gov/doc/papers/

What's next?

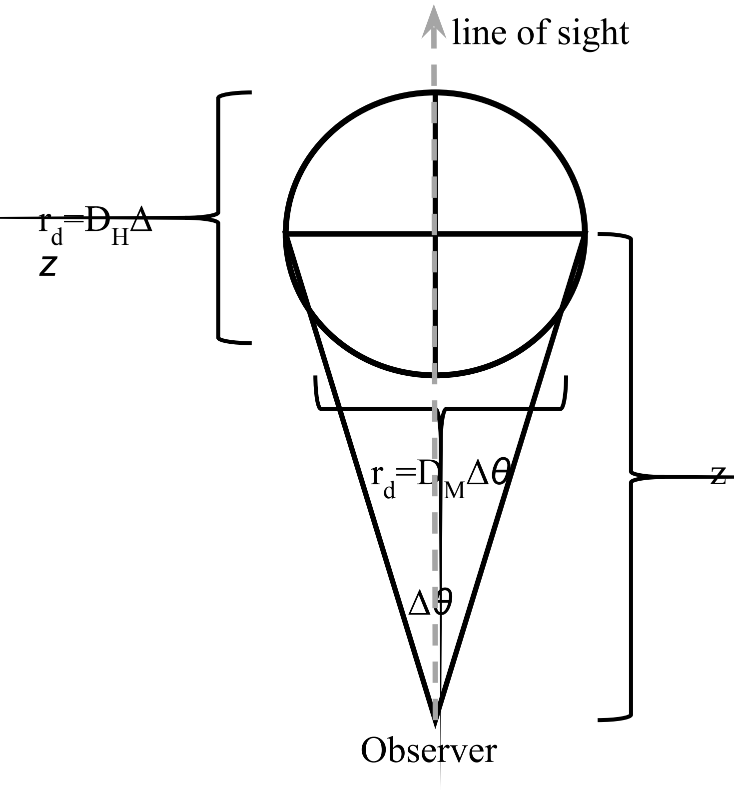
- Cosmology measurement beyond BAO: "full-shape" results soon
- Year-3 data: data collection completed

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Thanks to our sponsors and
72 Participating Institutions!

Linking the BAO scale to cosmology



The sound horizon r_d determines how far the sound wave of BAO traveled until recombination

We use two observables $\Delta\theta$ and Δz to measure the sound horizon: $r_d = \sqrt{D_M(z)^2 \Delta\theta^2 + D_H(z)^2 \Delta z^2}$

$$\Delta\theta = \frac{D_M(z)}{r_d} \qquad \Delta z = \frac{D_H(z)}{r_d}$$

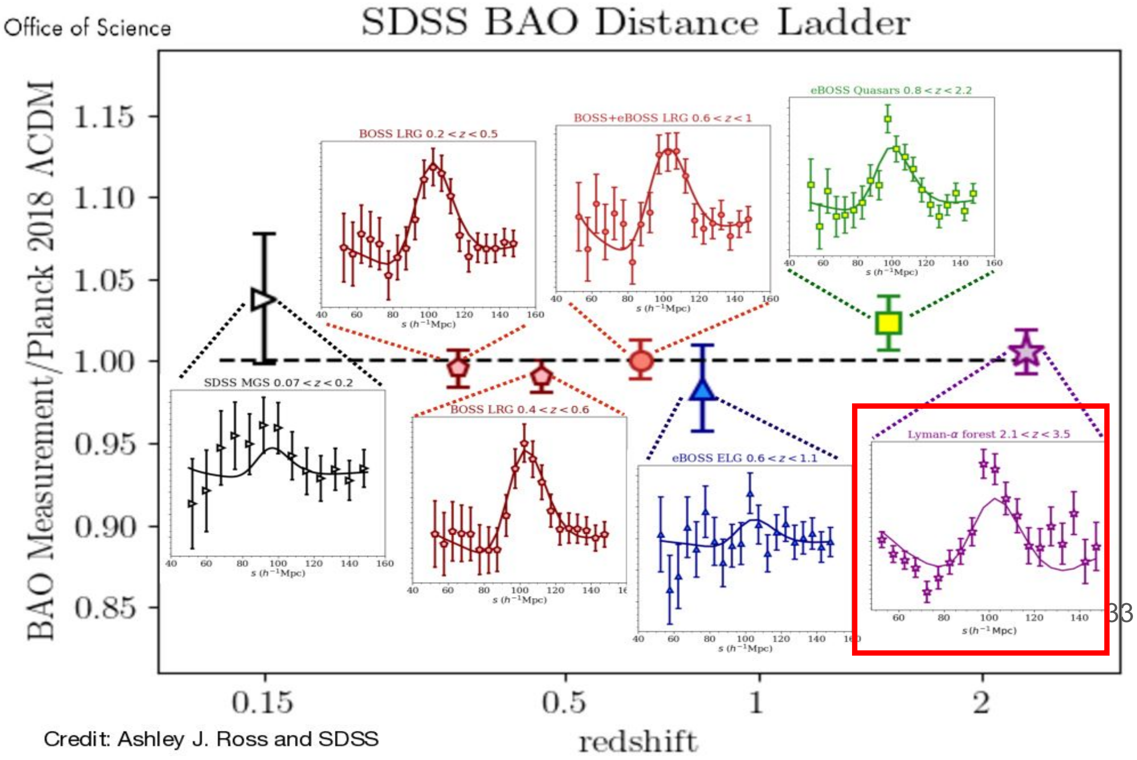
$$D_M(z) = \int_0^z \frac{c}{H(z')} dz'$$ Angular diameter distance (flat universe)

$$D_H(z) = \frac{c}{H(z)}$$ Hubble distance

BAO peak determines $D_M(z)/r_d$ and $D_H(z)/r_d$, thus giving constraints on $H(z)$

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Measuring BAO using different tracers



Credit: Ashley J. Ross and SDSS

Lyα forests provide high-redshift measurement of the BAO

Measurement of BAO: A peak in the two point correlation function (2PCF) of matter tracers, such as galaxies, quasars, voids, Lyα forests.

Beyond ΛCDM: Dark Energy Equation of State

The previous conclusion changes when considering a time-varying equation of state:

$$w(z) = w_0 + \frac{z}{1+z} w_a \qquad \text{(CPL parametrization)}$$

- DESI BAO alone has poor constraining power
- DESI + CMB $\Longrightarrow$ 2.6 σ
- **DESI + CMB + supernovae $\Longrightarrow$ from 2.5σ to 3.9σ, depending on the considered SN sample**

$w_0 > -1$, $w_a < 0$ favored