DESI
Year-1 Results

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35th Rencontres de Blois,

Blois, October 25, 2024

Dark Energy Spectroscopic Instrument

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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Introduction

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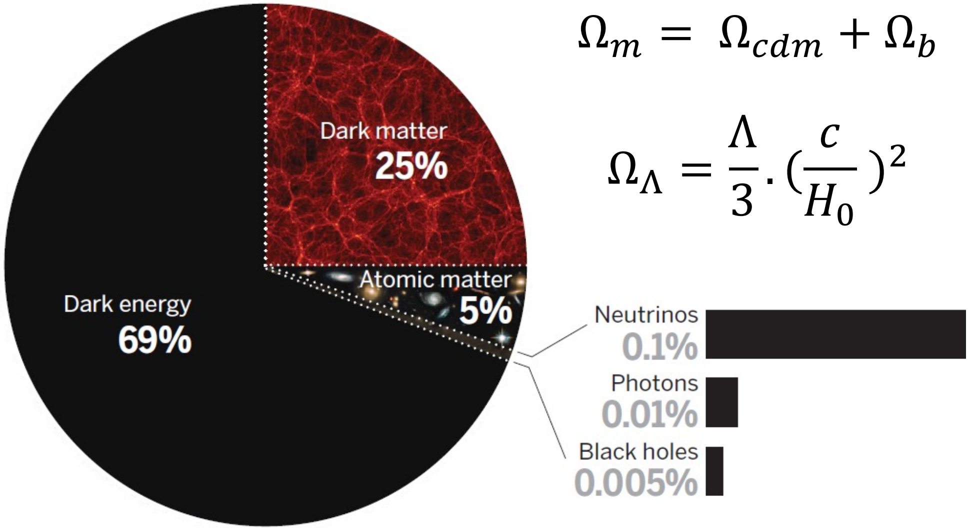
Baryonic Acoustic Oscillations (BAO)

Context in Cosmology: ΛCDM

ΛCDM

- "Standard Model" of cosmology
- General Relativity (GR)
- Cosmological constant (Λ)
- Flat Universe

$$\Omega_m + \Omega_\Lambda + \Omega_r = 1$$



$$\Omega_m = \Omega_{cdm} + \Omega_b$$

$$\Omega_\Lambda = \frac{\Lambda}{3} . (\frac{c}{H_0})^2$$

Extensions of ΛCDM

- Curvature of Universe

$$\Omega_K = 1 - (\Omega_m + \Omega_\Lambda + \Omega_r)$$

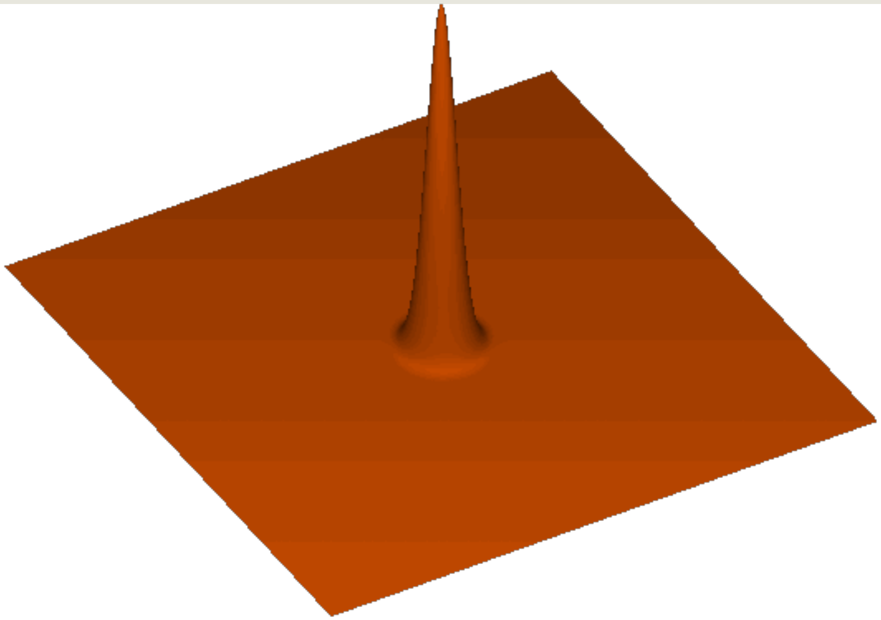
- Equation of state of Dark Energy

$$w(z) = \frac{p(z)}{\rho(z)}$$

Open questions

- H_0 tensions
- Ω_k tensions

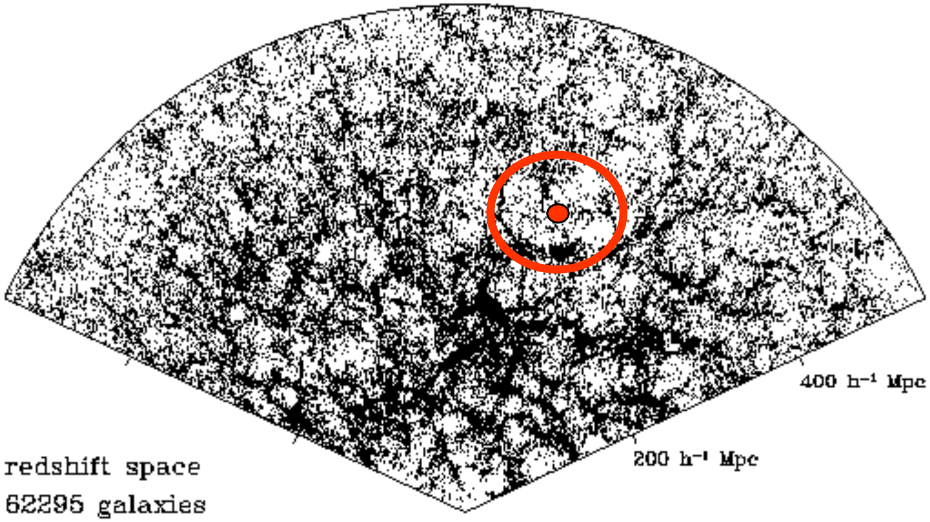
BAO, a probe for Dark Energy



Acoustic propagation of an over-density

- Sound waves propagates through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination (z~1100) with a speed $\sim c/\sqrt{3}$
- Then, the radius of the baryonic overdensity is frozen at r_d ~150 Mpc.

BAO, a standard ruler



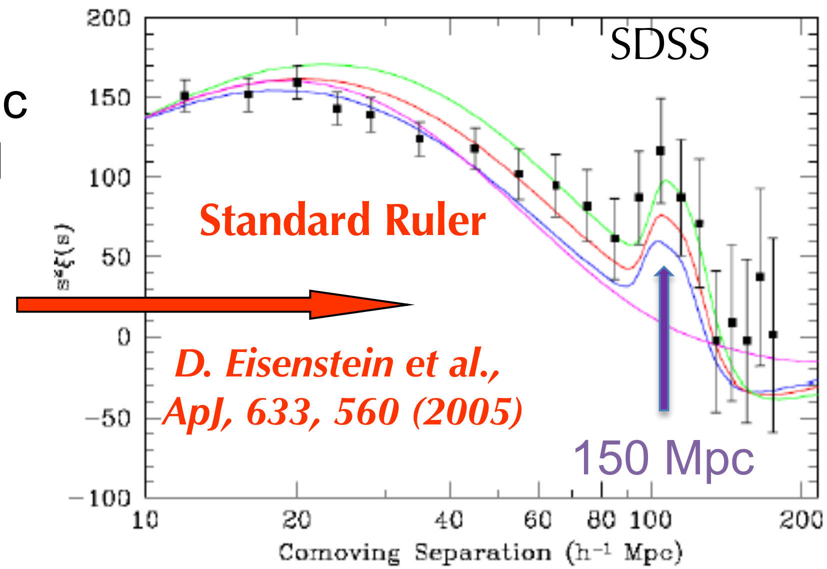
A special distance

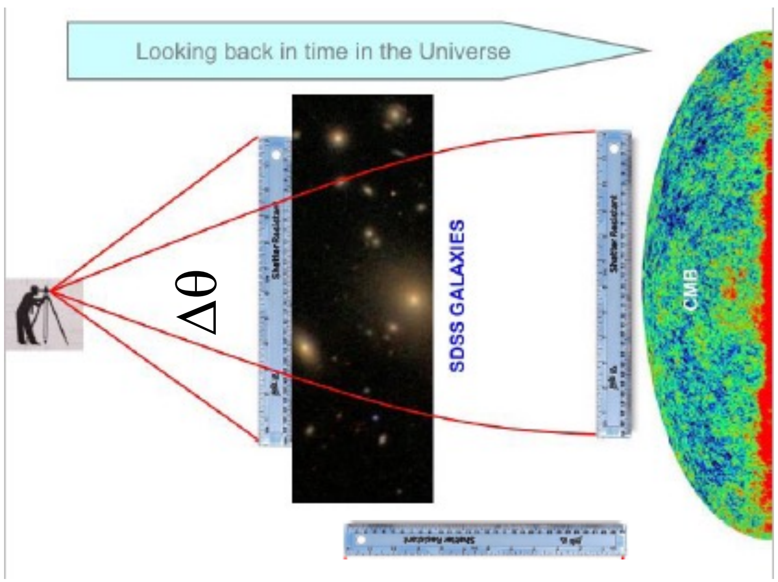
- Galaxies form in the overdense shells about 150 Mpc in radius.
- For all z, small excess of galaxies at r_d ~150 Mpc (in comoving coordinates) away from other galaxies.
- ⇒ **Standard Ruler**
- **BAO method:** we just assume that it is the same distance for all redshifts, we don't need to know its value!

Observation of baryonic acoustic peak

First observation

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs, <z> ~ 0.35
  "Luminous Red Galaxies"





A 3D measurements

- Position of acoustic peak
- **Transverse direction:**

$\Delta\theta = r_d/(1+z)/D_A(z) = r_d/D_M(z)$

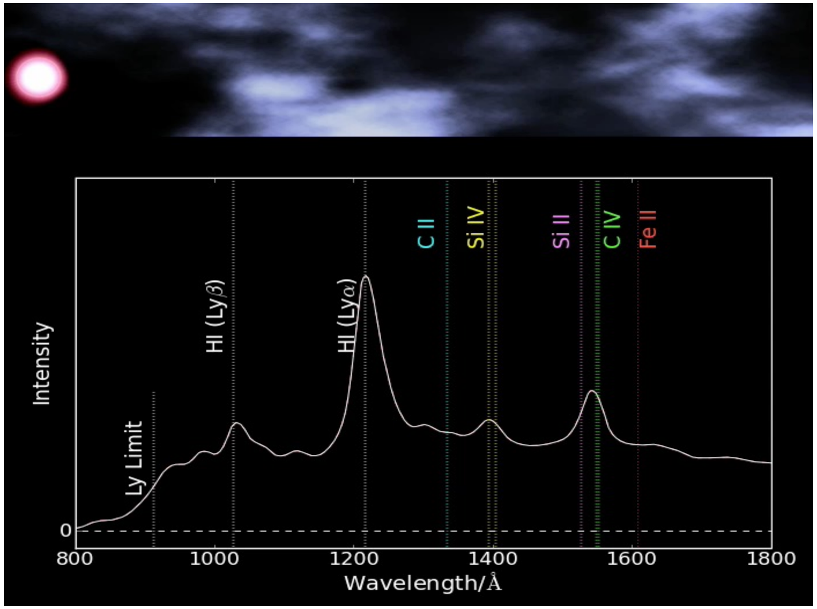
$\Rightarrow$ Sensitive to angular distance $D_A(z)$

- **Radial direction** (along the line of sight):

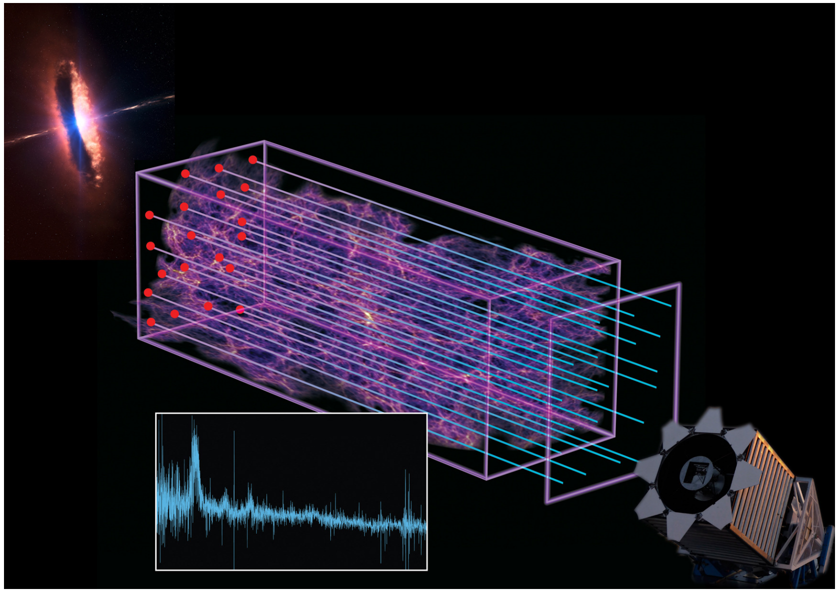
$\Delta z = r_d \cdot H(z)/c$

$\Rightarrow$ Sensitive to Hubble parameter H(z).

Another Tracer of Matter: Ly-α forest



- For z>2, no discrete tracer (galaxy) observable with DESI
- Use Ly-α forests of quasars (2.0<z<3.5)
- HI absorption in intergalactic medium (IGM) along the line of sight of quasars



- We expect low density gas (IGM) to follow the dark matter density
- Compute correlation function between HI 'clouds'
- Measure the location of BAO

Dark Energy Spectroscopic Instrument

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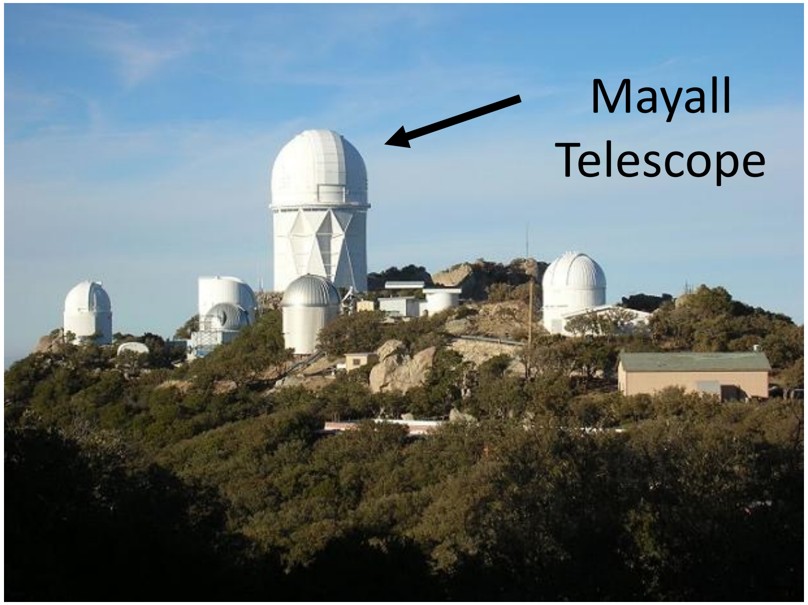
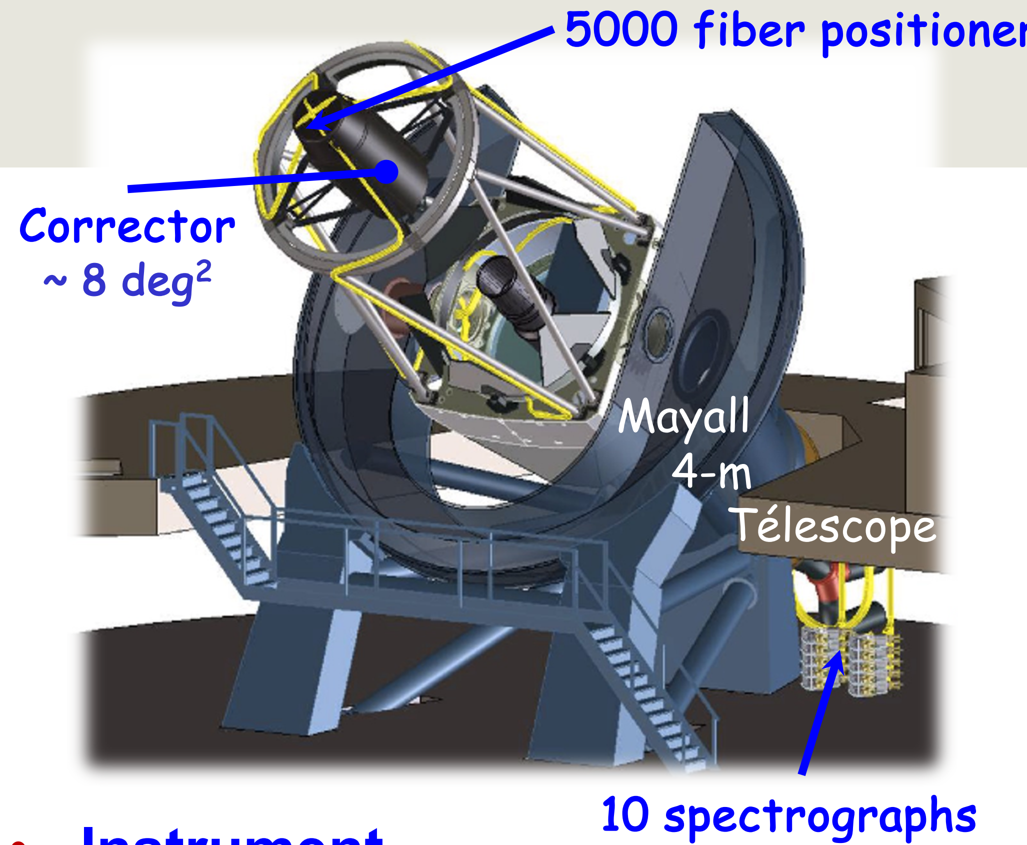
DESI

DESI Project

- **Scientific project**
  - 3D map for 0<z<4
  - Footprint ~14000 deg^2 (1/3 sky)
  - International collaboration
  - 72 institutions (46 non-US)
  - ~900 members





- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide FoV (~ 8 deg^2)
  - Robotic positioner with 5000 fibers
  - 10 spectrographs x 3 bands (blue, visible, red-NIR) →360-1020 nm

DESI tracers of the Matter

Five target classes

~40 million redshifts

in 5 years

3 million QSOs

Ly-α z > 2.1

Tracers 0.9 < z < 2.1

16 million ELGs

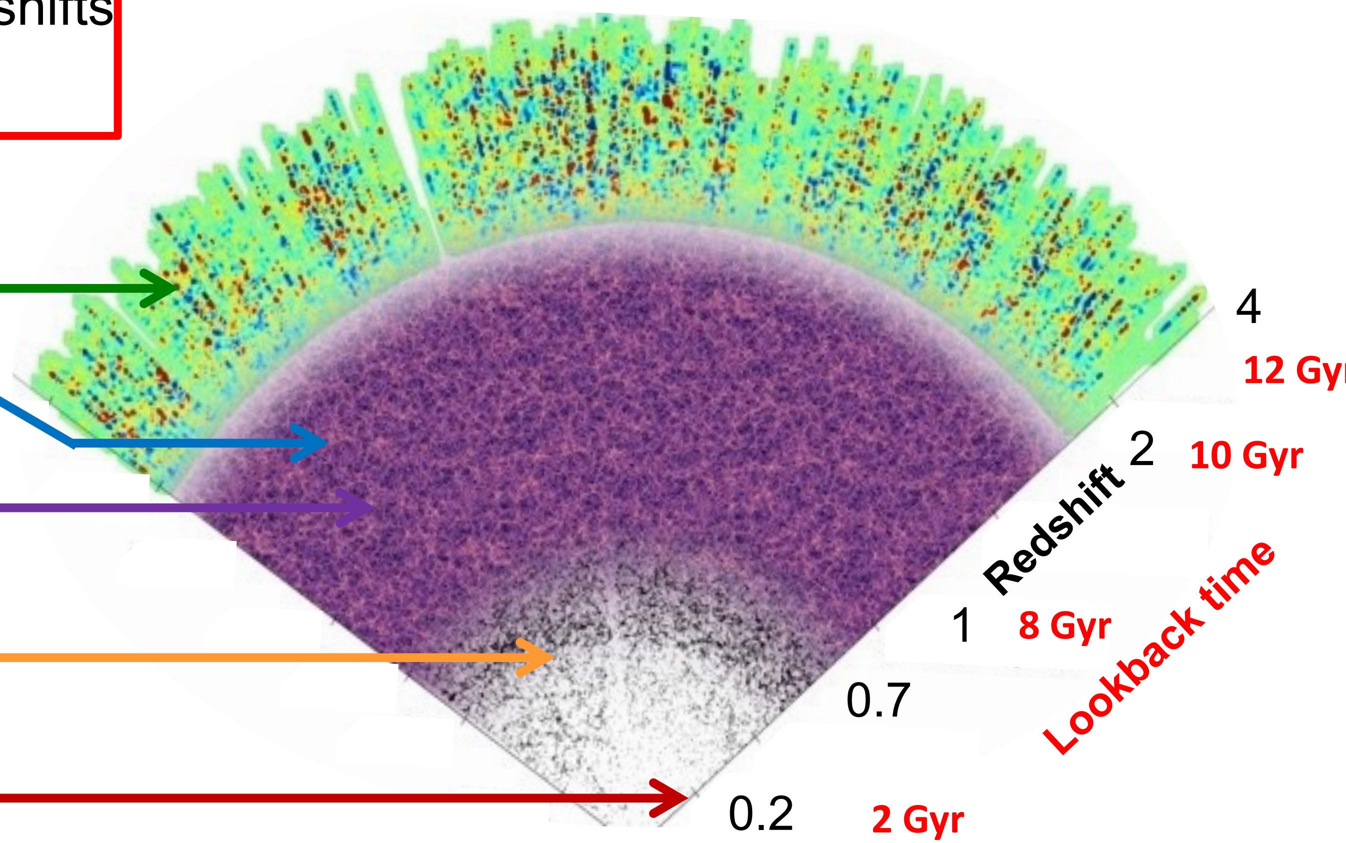
0.6 < z < 1.6

8 million LRGs

0.4 < z < 1.0

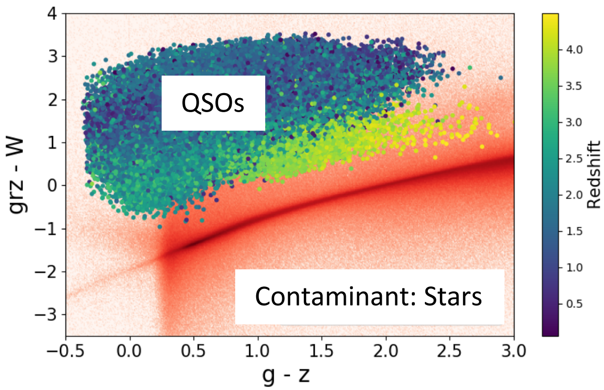
13.5 million Brightest galaxies

0.0 < z < 0.4

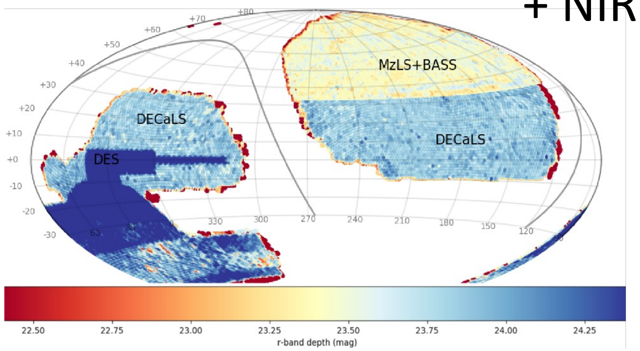


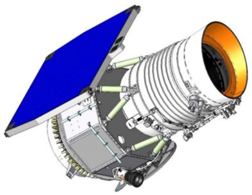
Rolling observations – Redshift factory

Target Selection



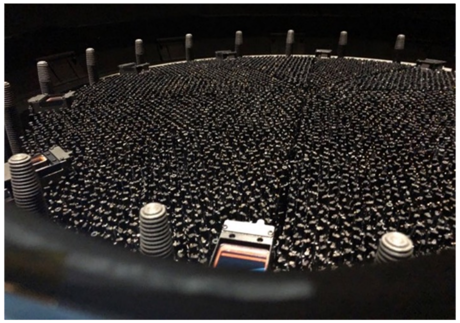
Imaging Surveys: optical grz bands + NIR with WISE



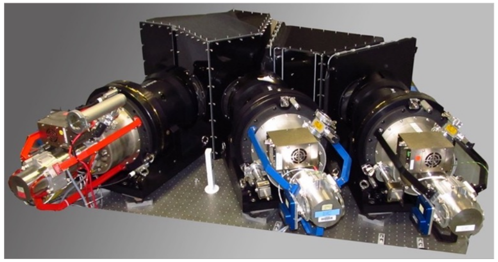


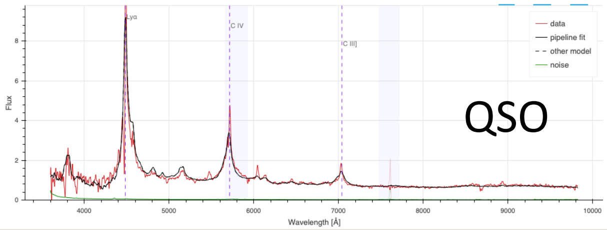
Observation…

…of 5000 objects every ~20mins…

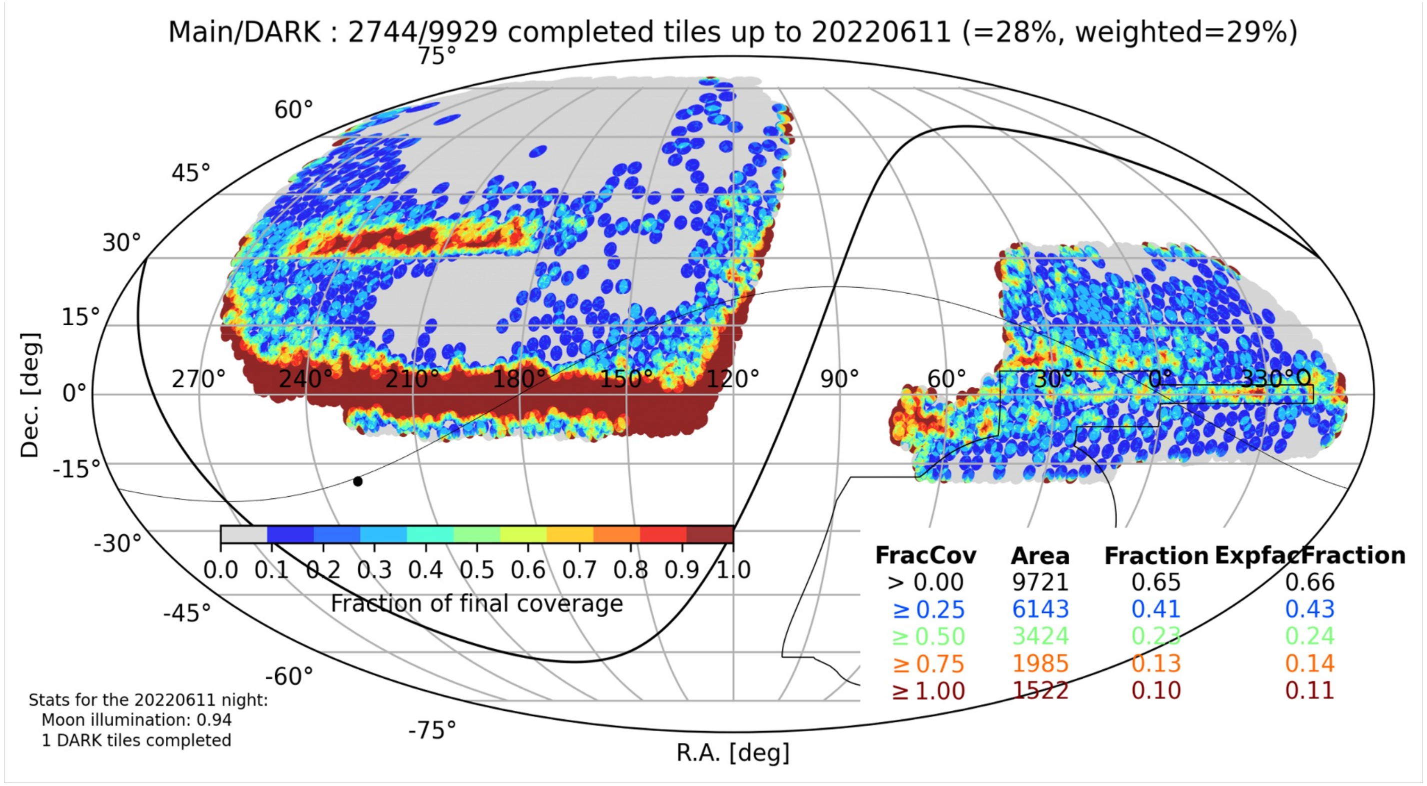


…and measure their redshift



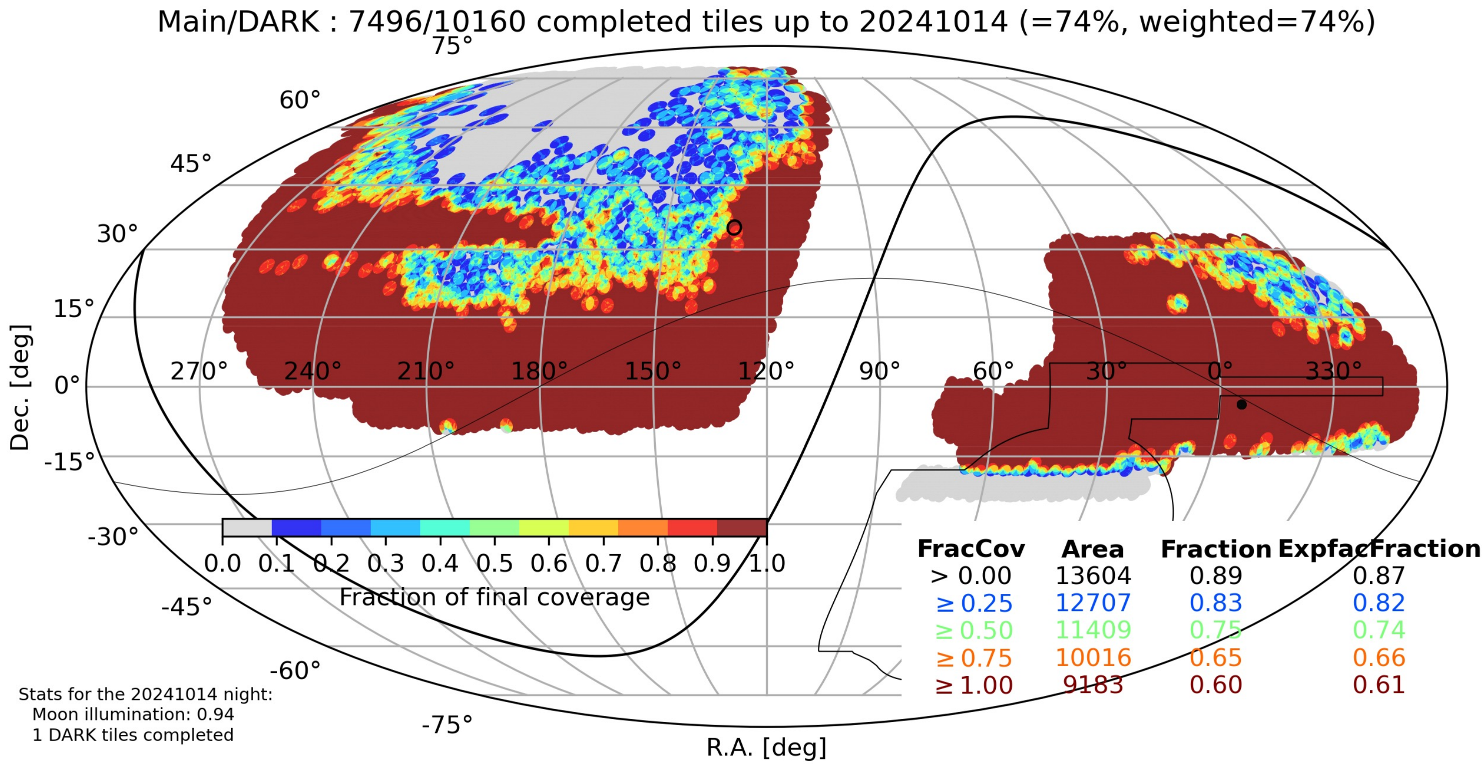


DESI Y1 footprint



- Grey area: DESI footprint over 5 years ~14000 deg^2
- On average 5 passes
- In Y1, only 1500 deg^2 with 5 passes

Current Status of Observing



– ~75% of the final dataset ⟹ Survey will be completed in Nov. 2025, 6 months ahead of schedule

– Already ~10,000 deg^2 with 5 passes

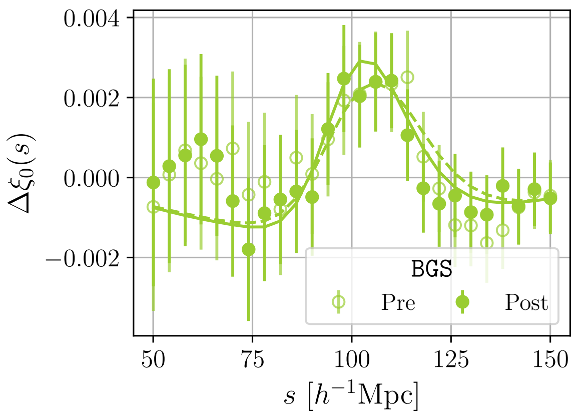
BAO Measurements

Methodology for DESI Y1

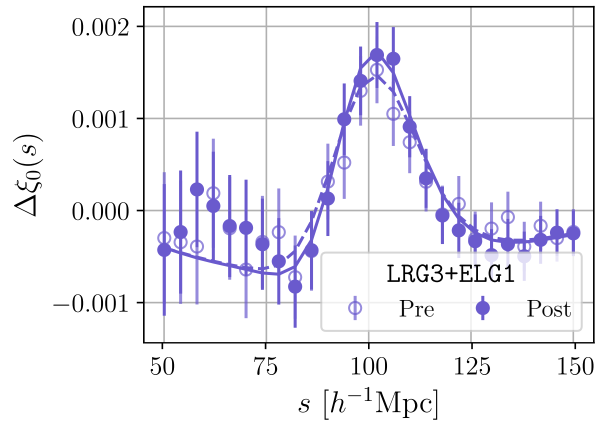
- **Blind analysis** to mitigate observer/confirmation biases (catalog-level blinding)
- **Unified BAO pipeline** applied to all (discrete) tracers/redshifts consistently
- Common modeling of BAO used for all tracers
- Reconstruction method applied to all tracers
- **Analytic covariance matrices** (validated with mocks)
- Wide-ranging tests of systematic errors, done before unblinding
- Results given for **6 redshift bins** over $0.1<z<2.1$
- Additional measurement at $z\sim2.3$ with Ly-α forest

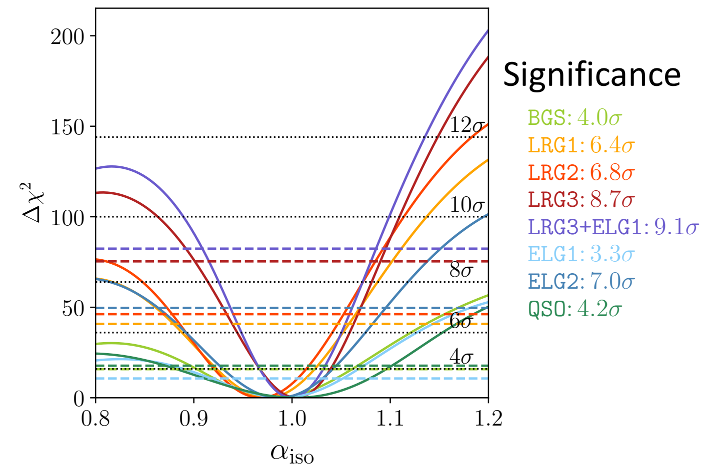
Results: a few examples

BGS z=0.30



LRG3+ELG1 z=0.93





Significance: 4.0σ
Precision: 1.85%

Significance: 9.1σ
Precision: 0.81%

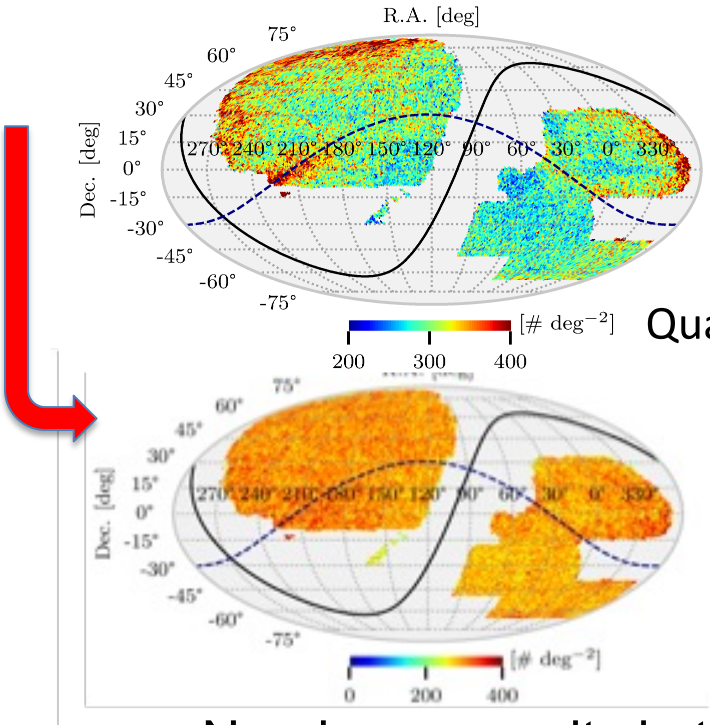
- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\rm iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest significance 4.0σ

Systematics Error Budget

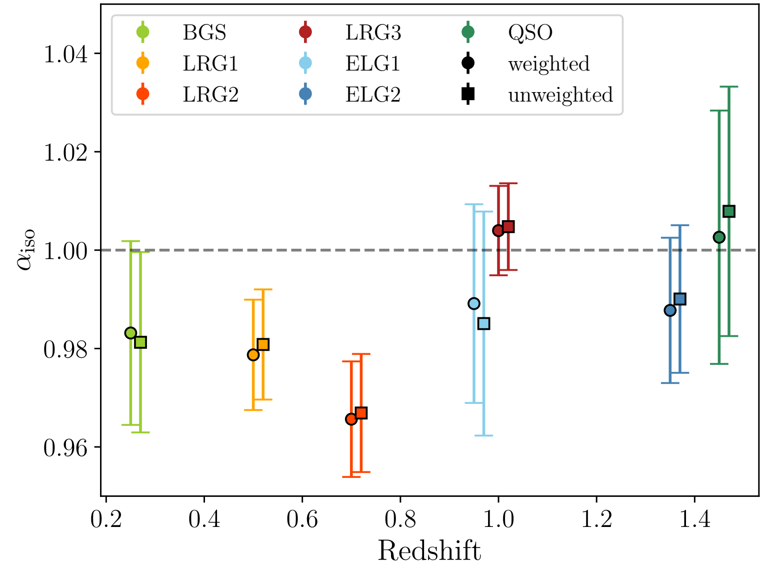
- Observational effects in data (**imaging**, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction

- Incomplete theory modelling
- Choice of fiducial cosmology
- Galaxy-halo (HOD) model uncertainties

Example of systematics: Imaging



Quasar target density



- Non-homogeneity in target selection due variations of imaging catalogs (depth, dust contaminants,…)
- Regression methods developed to correct those effect
- Same measurements of BAO with/without corrections
- **BAO almost insensitive to imaging effects**

Systematics Error Budget

– Observational effects in data (imaging, fiber assignment,…)
– Reconstruction algorithm
– Covariance matrix construction

No effect on BAO

– Incomplete theory modelling
– Choice of fiducial cosmology
– Galaxy-halo (HOD) model

Systematics Error Budget

- Observational effects in data (imaging, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction

No effect on BAO

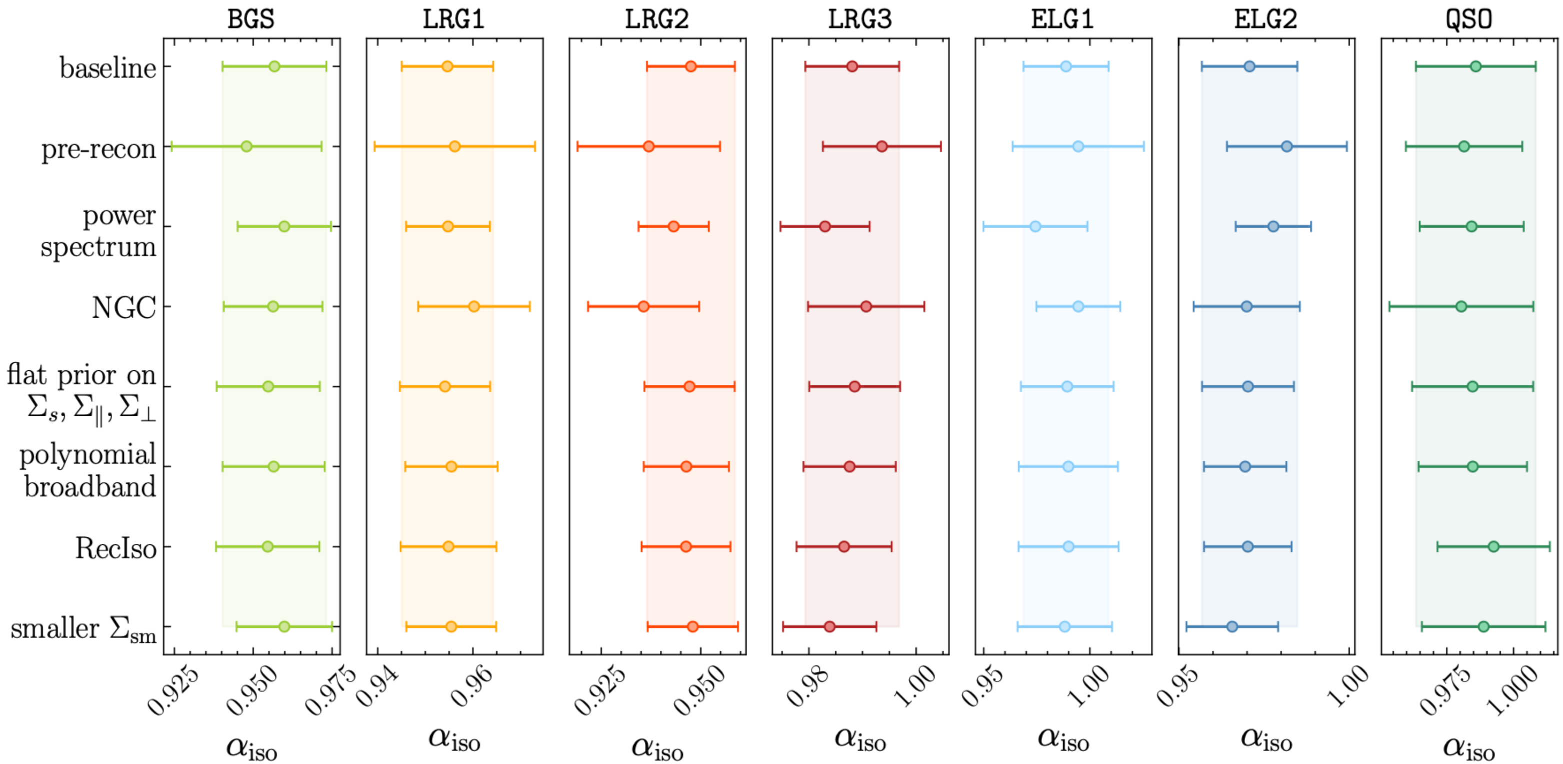
- Incomplete theory modelling $\boldsymbol{\sigma_{theo}} = 0.1\%$
- Choice of fiducial cosmology $\boldsymbol{\sigma_{fid}} = 0.1\%$
- Galaxy-halo (HOD) model $\boldsymbol{\sigma_{HOD}} = 0.2\%$

$\sigma_{sys} = 0.25\%$

All systematics much smaller than statistical errors

$$\boldsymbol{\sigma_{total} = 1.05\sigma_{stat.}}$$

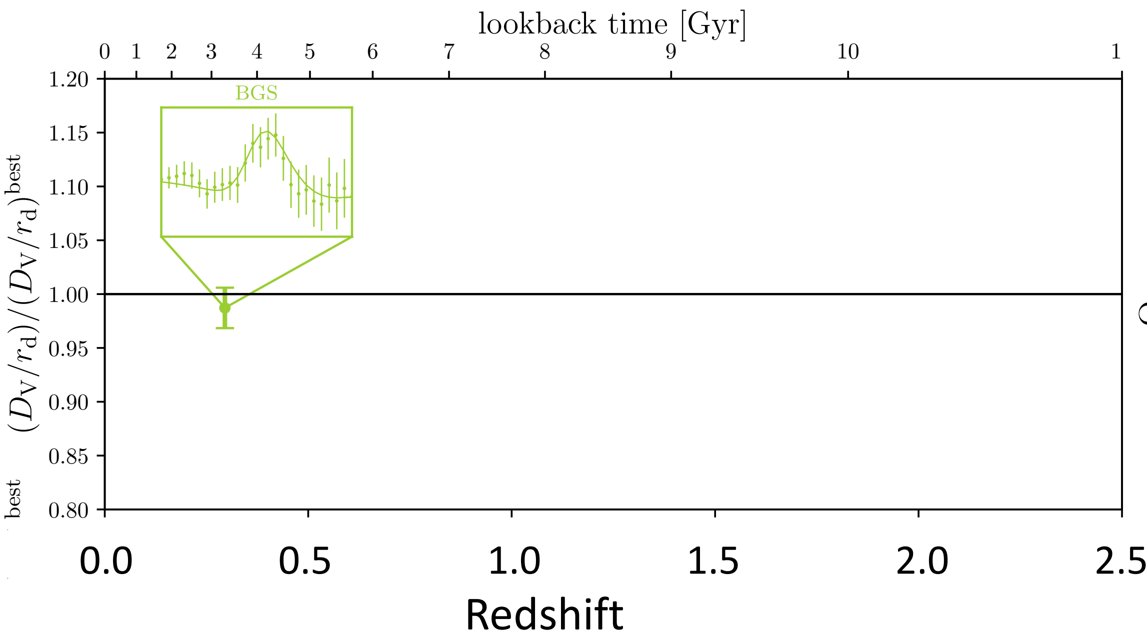
Stability of the results

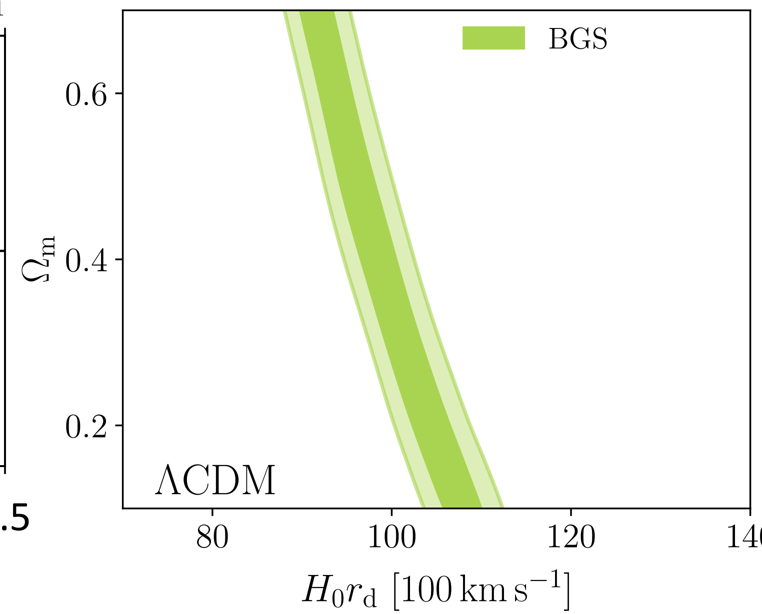


- Comparison with the baseline analysis for different configurations (with/without reconstruction, power-spectrum, without SGC, priors damping parameters, broadband modeling and reconstructions)
- **Extremely stable results**

DESI Year 1: BGS

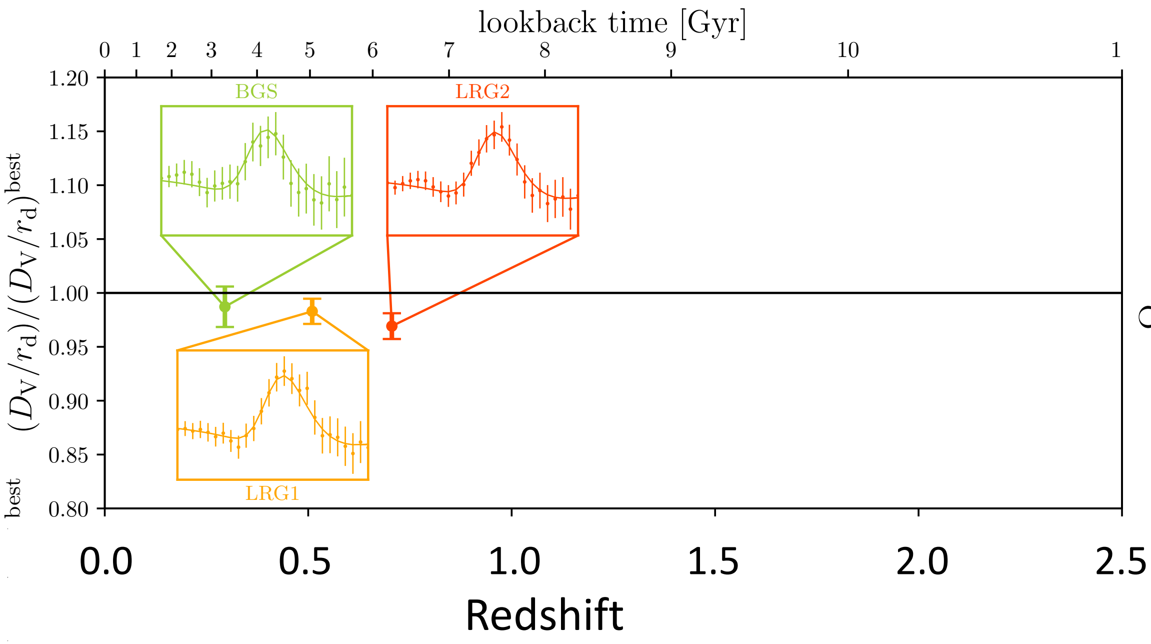
$$\alpha_\perp = \frac{D_\mathrm{M}}{r_\mathrm{d}}\frac{r_\mathrm{d}^\mathrm{fid}}{D_\mathrm{M}^\mathrm{fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_\mathrm{d}} \qquad \alpha_\mathrm{iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$$

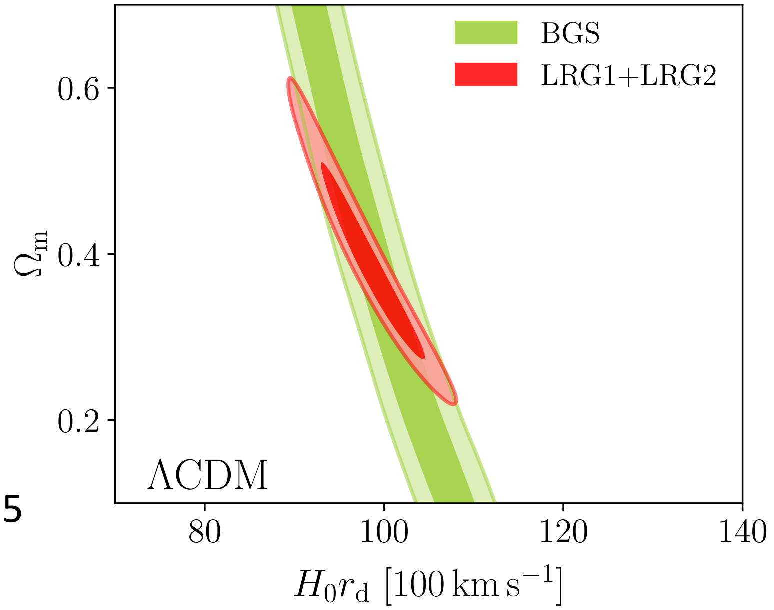




- Friedman equation for ΛCDM $H(z) \equiv H_0\sqrt{\Omega_m\,(1+z)^3 + (1-\Omega_m\,)}$
- Limitation due the cosmic variance (small part of the visible Universe)

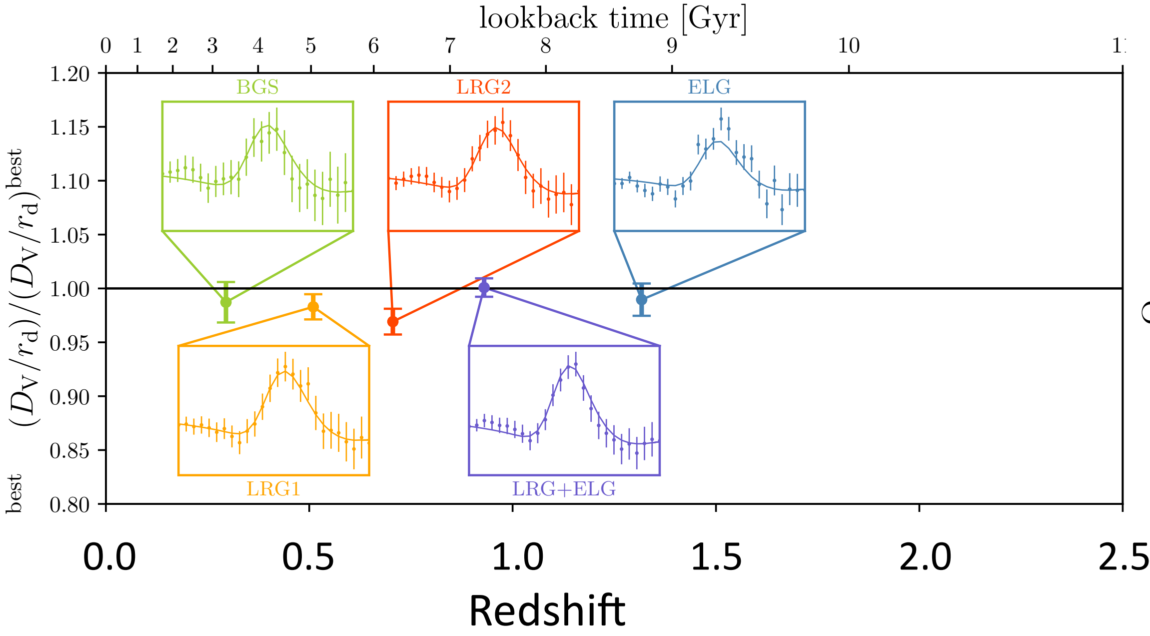
DESI Year 1: BGS + LRG

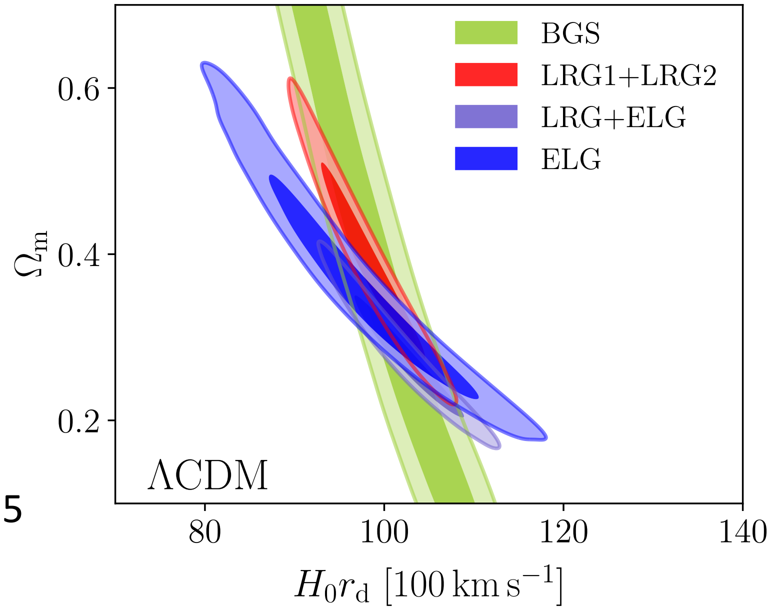




– LRG: Main tracer in SDSS, precise measurement

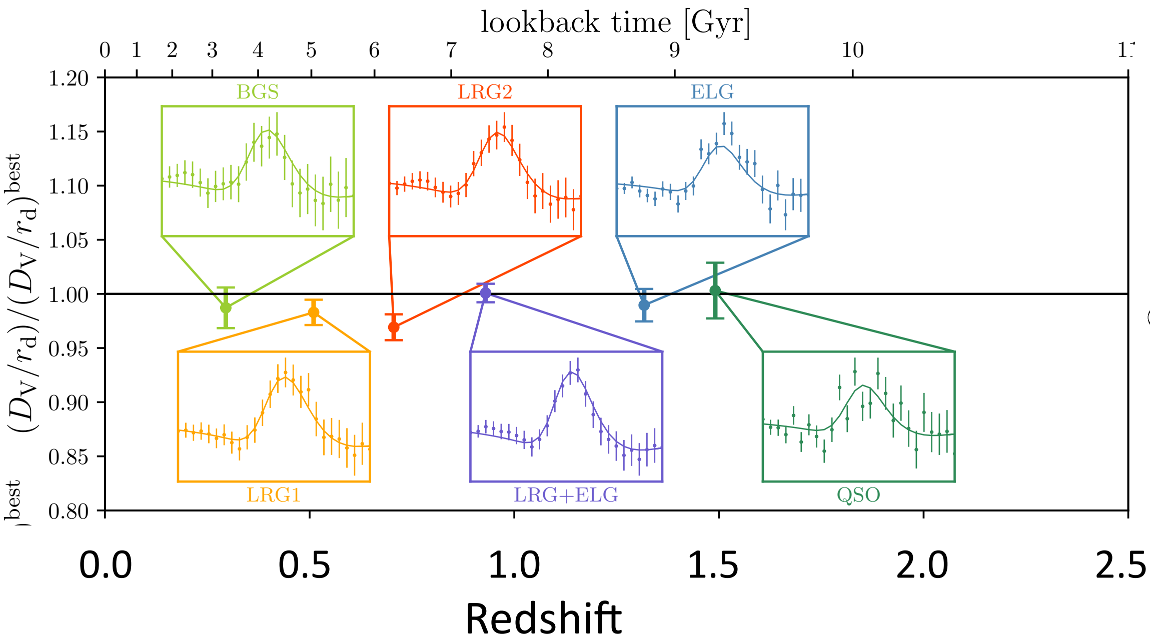
DESI Year 1: BGS + LRG + ELG

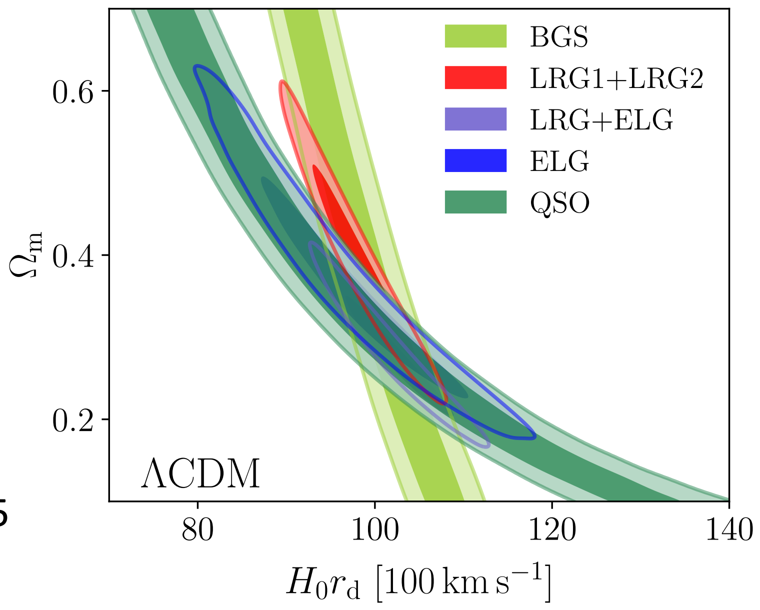




- ELG: Main tracer in DESI, precise measurement, but only a small fraction was observed in DESI Y1

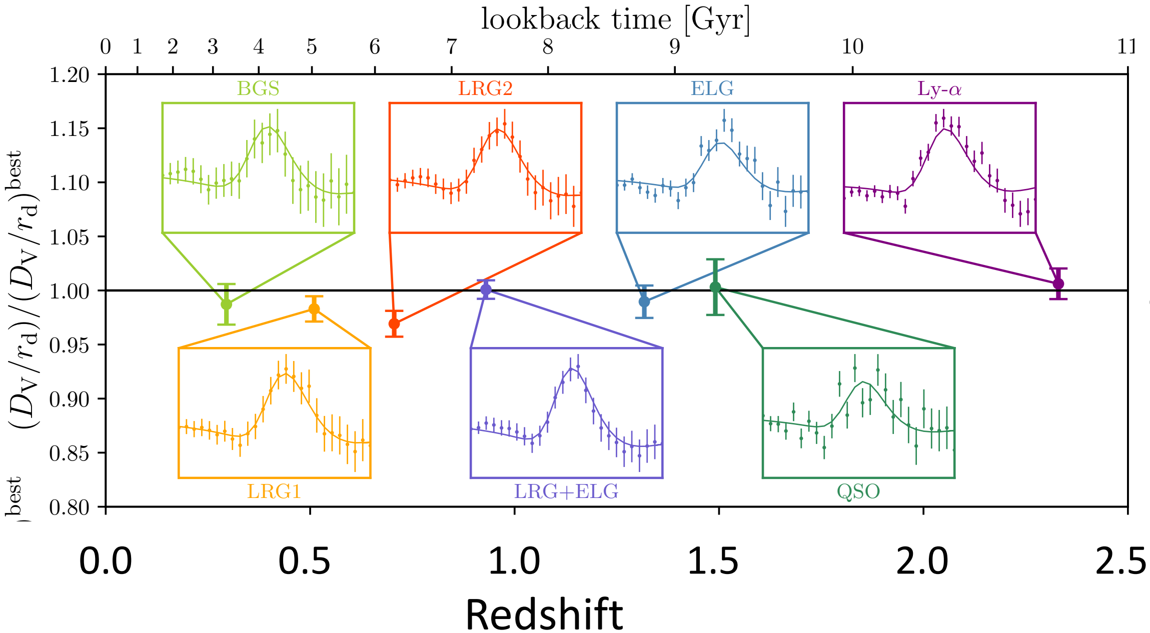
DESI Year 1: BGS + LRG + ELG + QSO

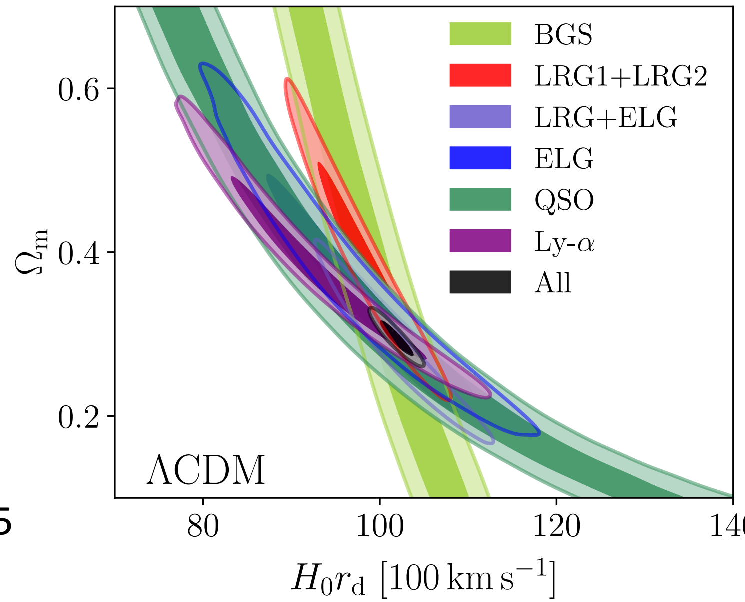




– QSO: huge volume but small density (shot noise limitation)

DESI Year 1: BGS + LRG + ELG + QSO + Ly-α

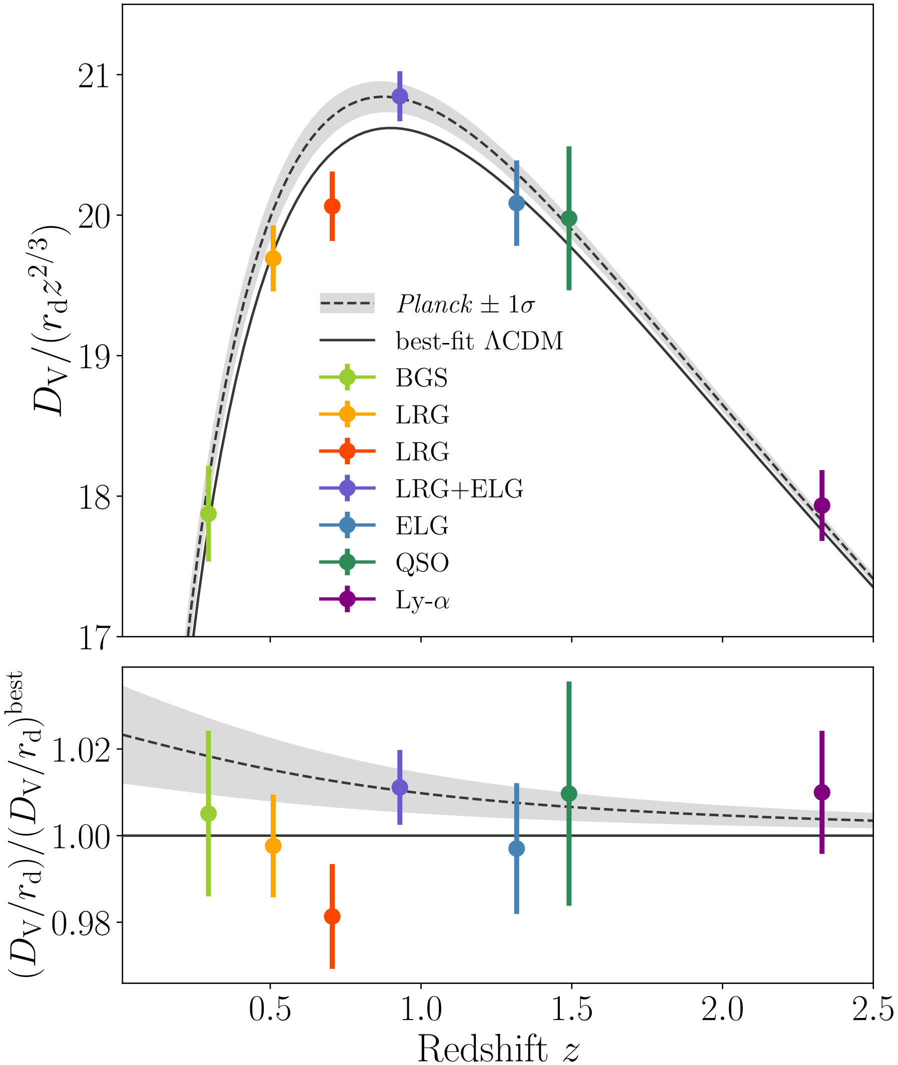




– Different dependence as a function of redshift (Ω_m,r_d)
– Break the degeneracy without knowing r_d

Cosmological Interpretation

DESI Year 1 - Hubble diagram

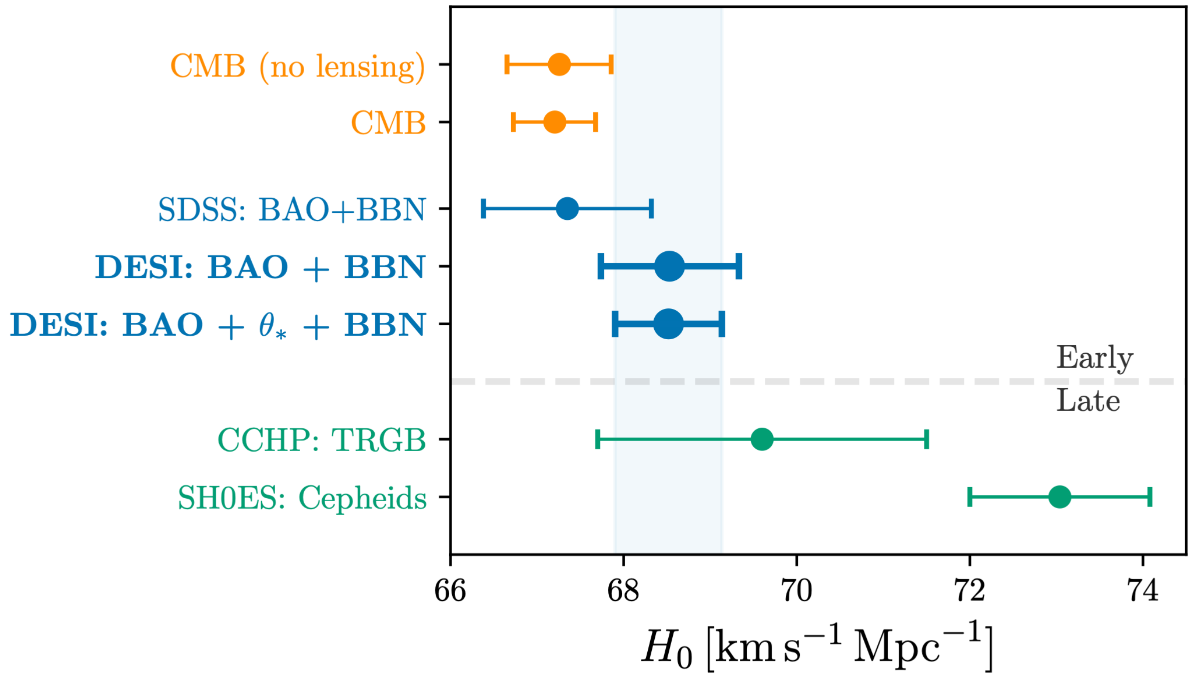


– ~6M discrete tracers
– 0.1<z<2.1
– 3 times bigger than SDSS
– Total precision on BAO: 0.52%

– With Ly-α forest of QSOs at z~2.3 : precision on BAO 1.1%

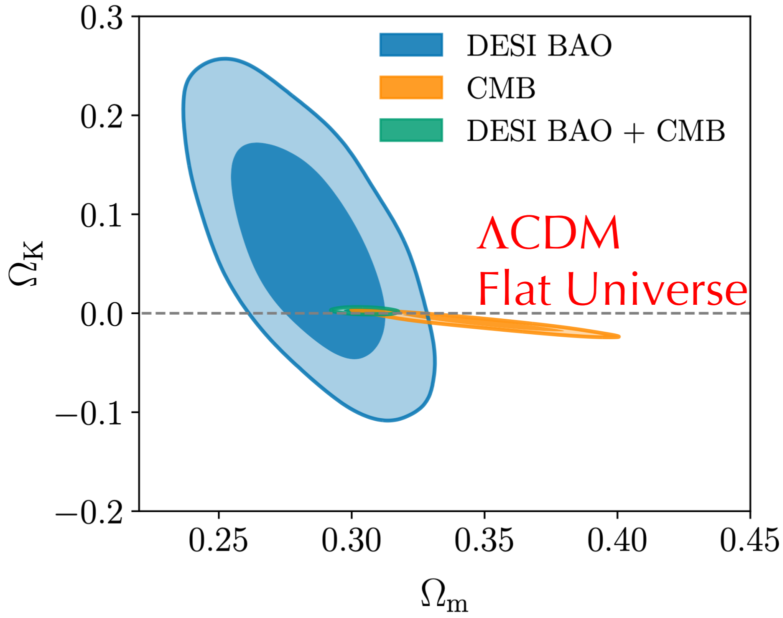
– Consistent with ΛCDM
– Agreement with Planck: 1.9σ
– BAO ~almost systematic free measurements

Hubble constant in ΛCDM



- **Main tension in cosmology**: 5σ discrepancy between CMB and late measurements (SNIa)
- Big Bang Nucleosynthesis (BBN) can be used to measure r_d
- Consistency with CMB: 2.1σ
- Consistency with SNIa (SH0ES): 3.7σ

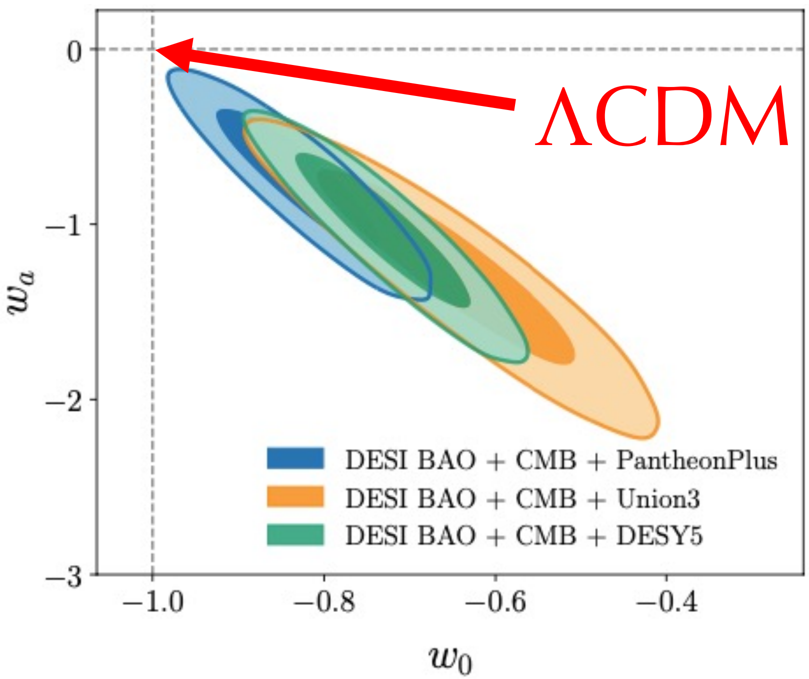
Beyond ΛCDM: Spatial Curvature



- With CMB alone, hints of non-null spatial curvature
- With CMB alone, ~ 2 to 3σ deviation from 0
- With CMB + DESI, flat Universe

$$\Omega_K = 0.0024 \pm 0.0016$$

Beyond ΛCDM: Dark Energy Equation of State



Dark Energy Equation of State

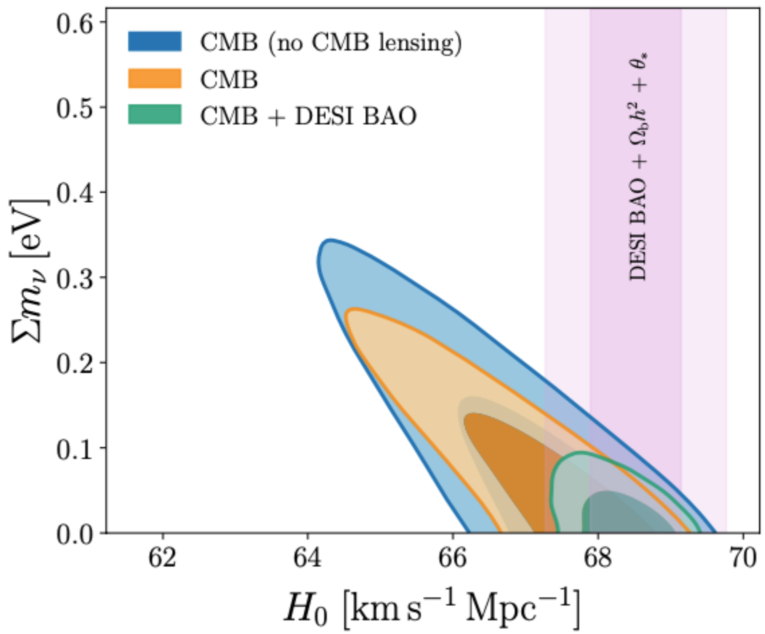
$$w(z) = \frac{p(z)}{\rho(z)}$$

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

- For ΛCDM, we expect w=-1, i.e. w_0=-1 and w_a=0
- Combining DESI+CMB+SN: 2.5σ to 3.9σ effect depending on the SN sample
- **Indication of dynamical dark energy with DESI???**

Sum of neutrino masses

- CMB is sensitive to $\sum m_\mu$
- Degeneracy with (Ω_m or H_0)
- BAO measures Ω_m and breaks the degeneracies



Limits at 95% CL:

- For ΛCDM with CMB alone: $\sum m_\nu < 0.21\,\mathrm{eV}$
- For ΛCDM with CMB + DESI: $\sum m_\nu < 72\,\mathrm{meV}$
- For w_0w_aCDM with CMB + DESI, it provides a conservative bound! $\sum m_\nu < 195\,\mathrm{meV}$

Summary: Results from DESI BAO Y1

– BAO results with Y1

- With only one year (Y1), DESI provides the most precise measurement of BAO over 0<z<2.5
- In ΛCDM DESI is consistent with CMB (~2σ), but DESI prefers lower Ω_m or higher H_0!
- Some hints of time-varying Dark Energy equation of state, especially when SNIa are added

  $\Longrightarrow$ a 2.5σ to 3.9σ effect

– Near Future for DESI

- Full shape analysis mid-November 2024

  $\Rightarrow$ Better constraint on $\sum m_\mu$ and test of GR.
- BAO with 3 years (~70% of the survey) in Spring 2025