DESI shakes up the Dark Universe

Satya Gontcho A Gontcho (Berkeley Lab, University of Virginia)

On behalf of the DESI Collaboration

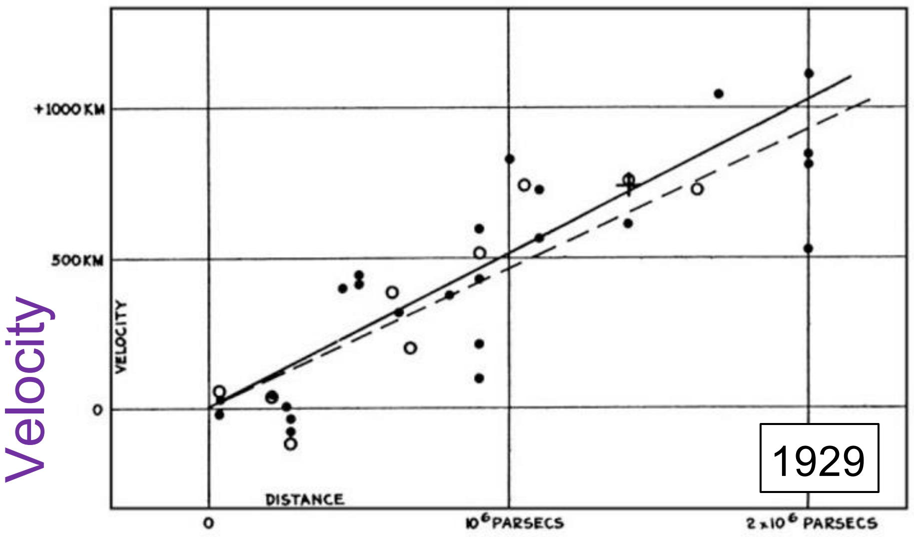
September 11, 2025
New Physics from Galaxy Clustering at GGI

The expanding universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Velocity increases with Distance



Velocity

Distance

Expanding Universe

Velocity = H x Distance

H ~ 70 km/s/Mpc*

(7% per Giga-year)

*current estimation

The expanding universe

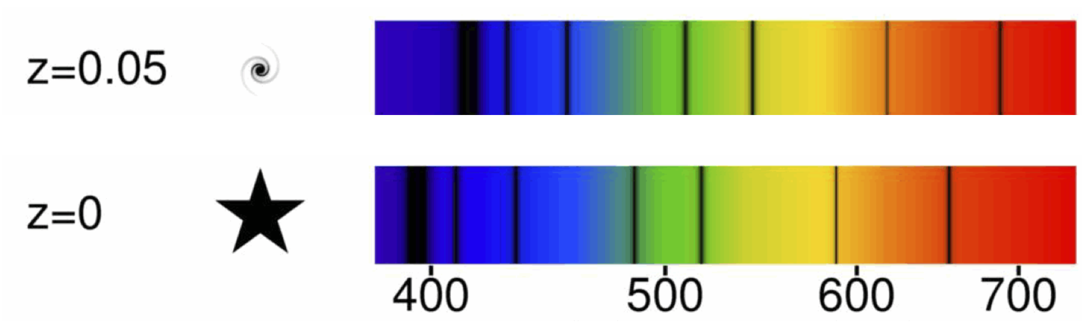
Hubble law

v = H . D

Spectroscopy

Redshift $z = \dfrac{\lambda - \lambda_0}{\lambda_0}$

(Doppler effect: $z = v/c$)



Photometry

Source of known luminosity

$$\mathcal{L}_{\mathrm{obs}} \propto \frac{\mathcal{L}_0}{D^2}$$

Cepheids (Period – luminosity)
Type Ia Supernovae (Peak luminosity)

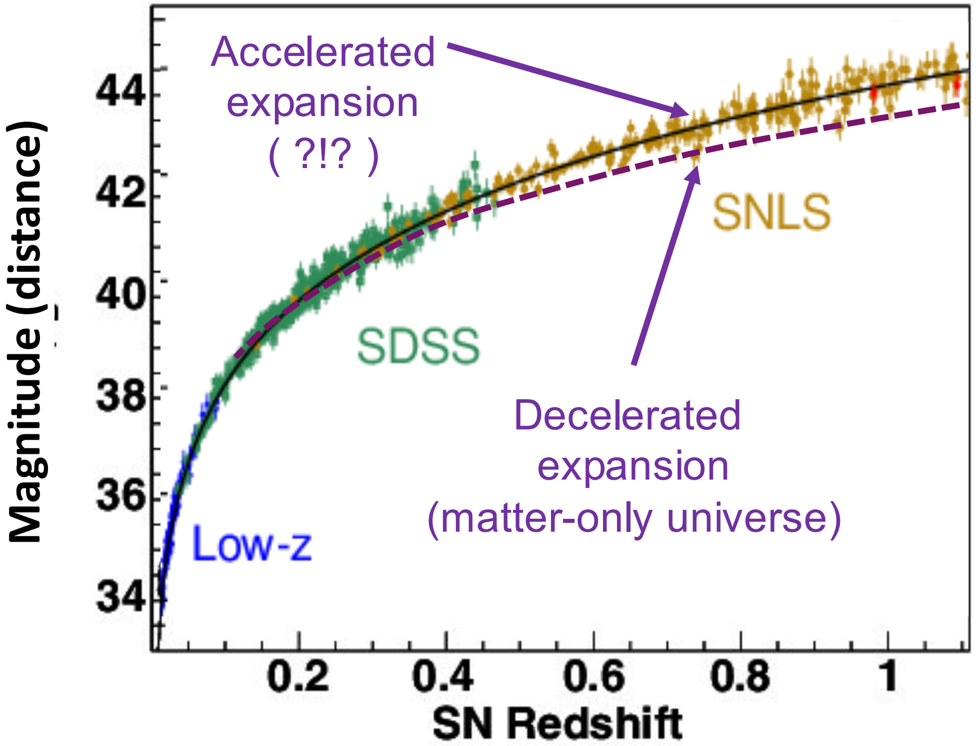
Variation of H? $\Longrightarrow$ Study at different epochs (= redshifts)

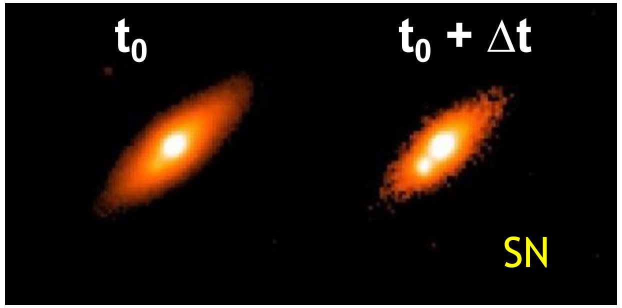
The expanding universe

2011 Nobel Prize

Perlmutter et al., 1998
Riess et al., 1998

Hubble diagram
distance – redshift relation





SN Ia
(known luminosity)

SNIa are weaker (~20%)
for a given redshift
Hence more distant (~10%)

Accelerated expansion

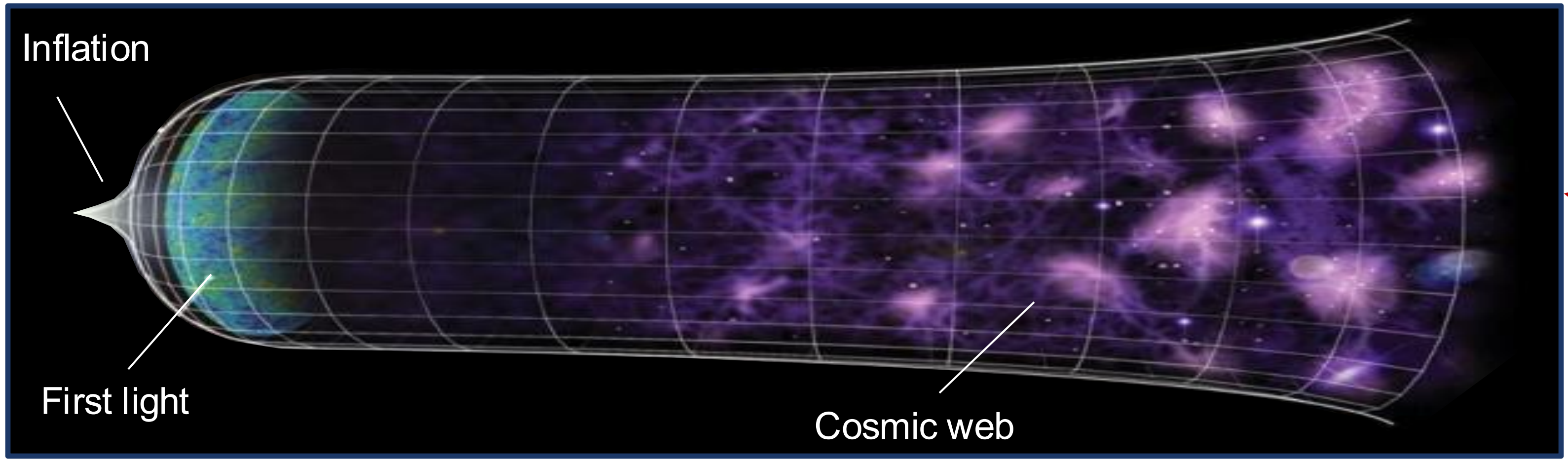
Incompatible with matter domination

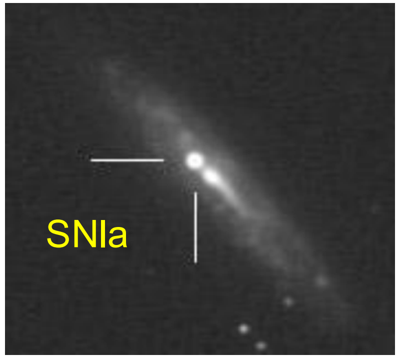
DARK ENERGY!

DARK ENERGY SPECTROSCOPIC INSTRUMENT

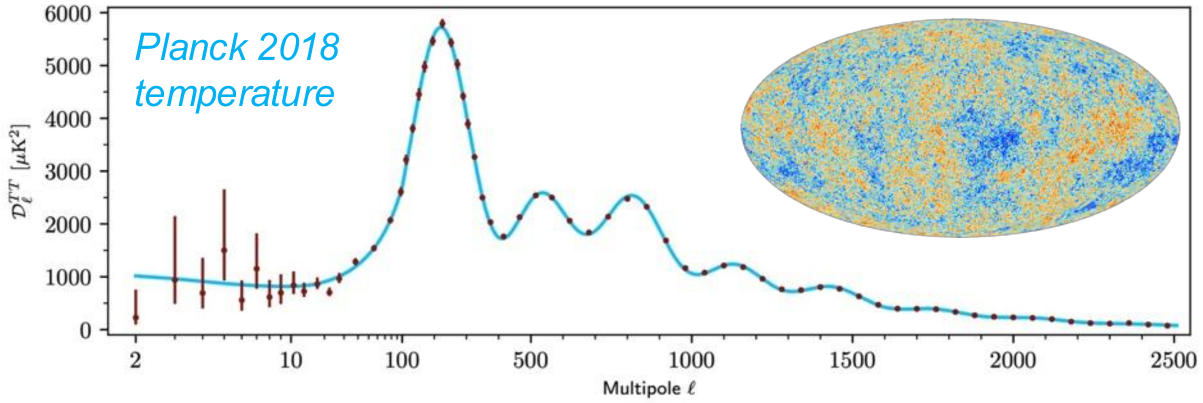
U.S. Department of Energy Office of Science

Standard model of cosmology





Accelerated expansion



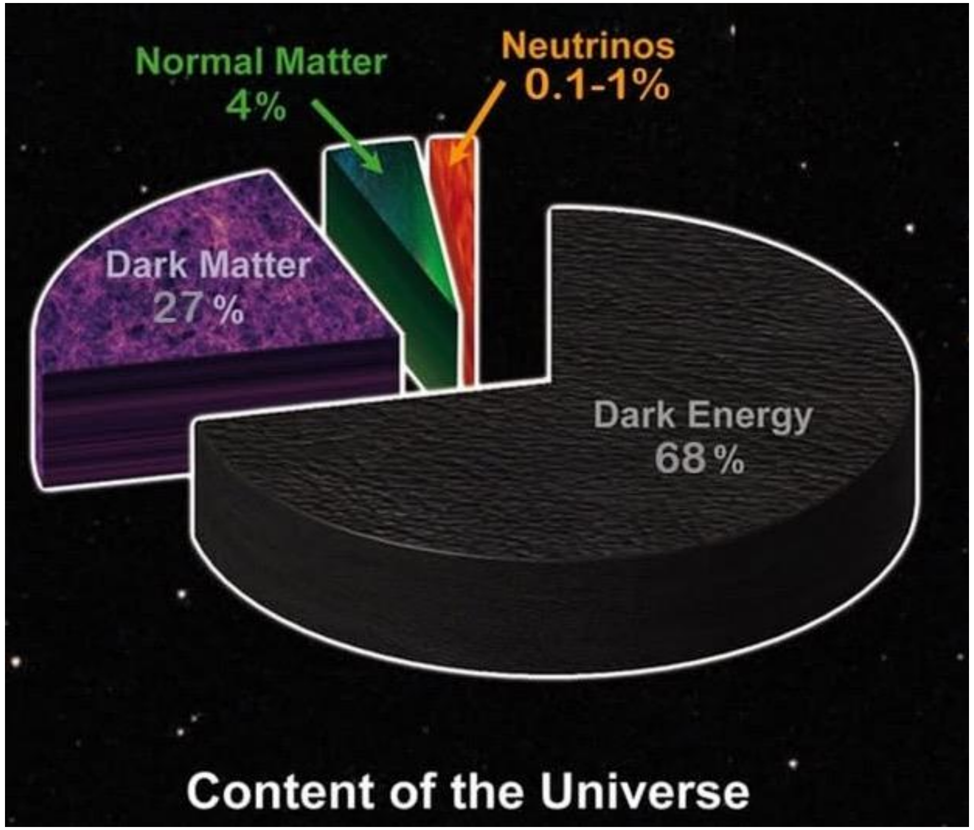
Cosmic Microwave Background

Physics we know
+ cosmological model

successfully predicts most observations of last 20 yrs

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

Standard model of cosmology – ΛCDM



Two main components of unknown nature

- **Dark Matter** (galaxy formation, gravitational lensing, rotation curves, …)
- **Dark Energy** (late-time acceleration)

Other missing information

- **Neutrino masses**

Dark Energy

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry ($G_{\mu\nu}$)?
Cosmological constant Λ

Energy content ($T_{\mu\nu}$)?
Additional component

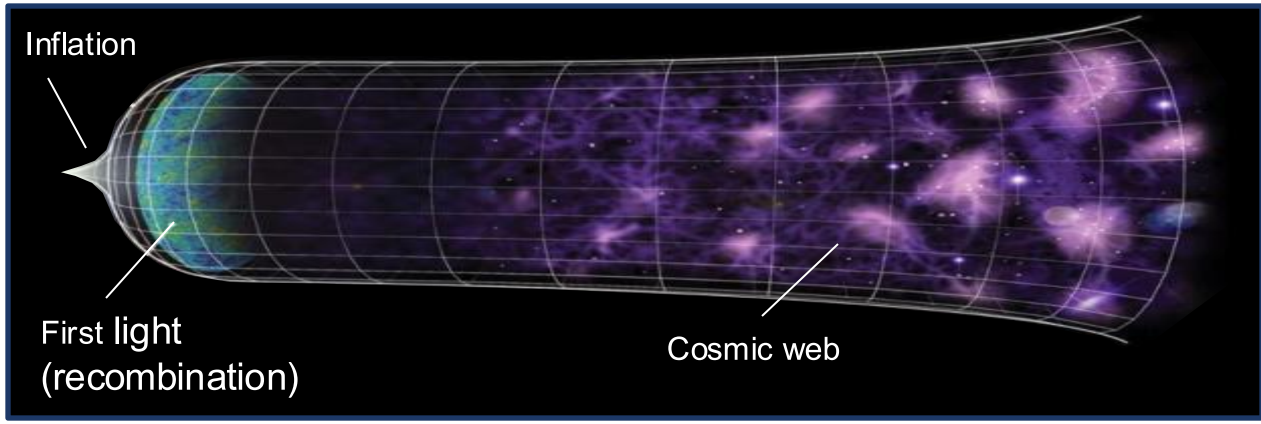
$$w = \frac{p}{\rho}$$

Accelerated expansion

Modified gravity?
Beyond general relativity

Baryon Acoustic Oscillations

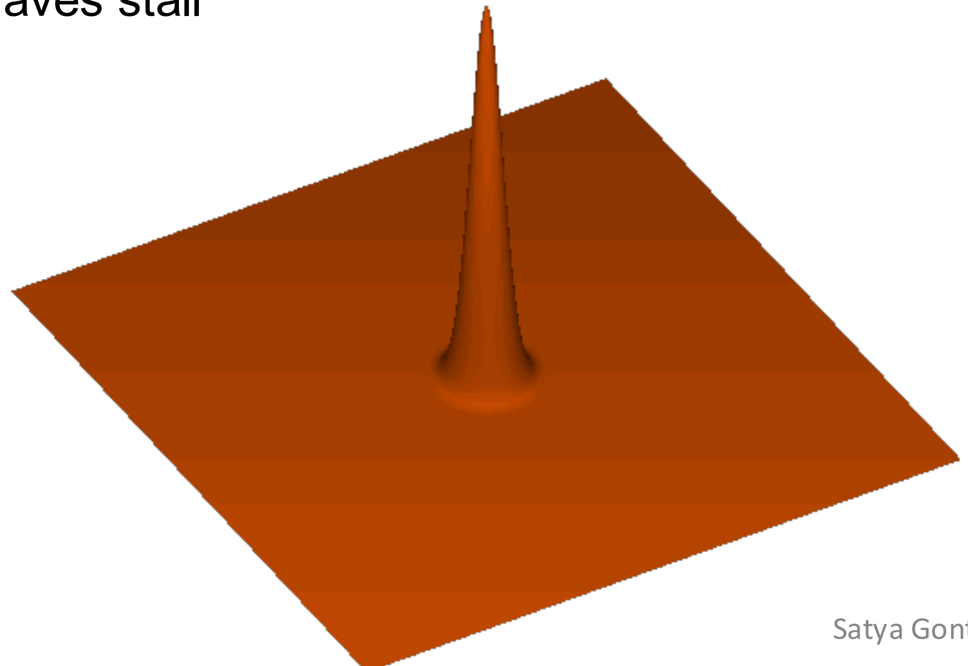
Baryon Acoustic Oscillations (BAO)



Propagation of baryon-photon over-density sound waves in primordial plasma

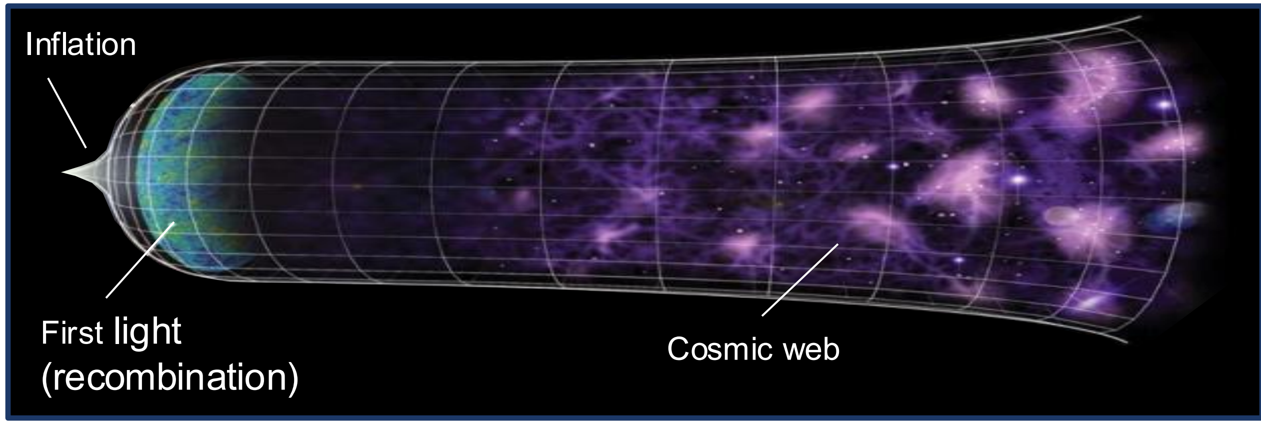
At recombination ($z \sim 1100$): $p + e^{-} \rightarrow H$

- Plasma evolves from optically thick to optically thin
- Baryons decouple from photons
- Waves stall



Residual spherical shell ⟶ Peak in clustering of matter

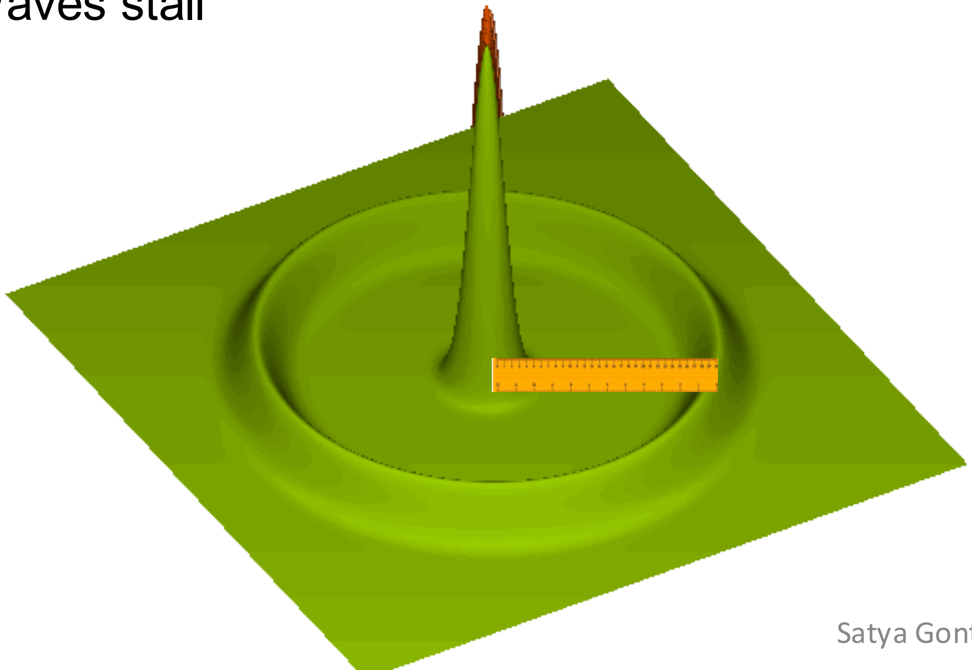
Baryon Acoustic Oscillations (BAO)



Propagation of baryon-photon over-density sound waves in primordial plasma

At recombination (z~1100): p + e^- → H

- Plasma evolves from optically thick to optically thin
- Baryons decouple from photons
- Waves stall



Residual spherical shell ⟶ Peak in clustering of matter

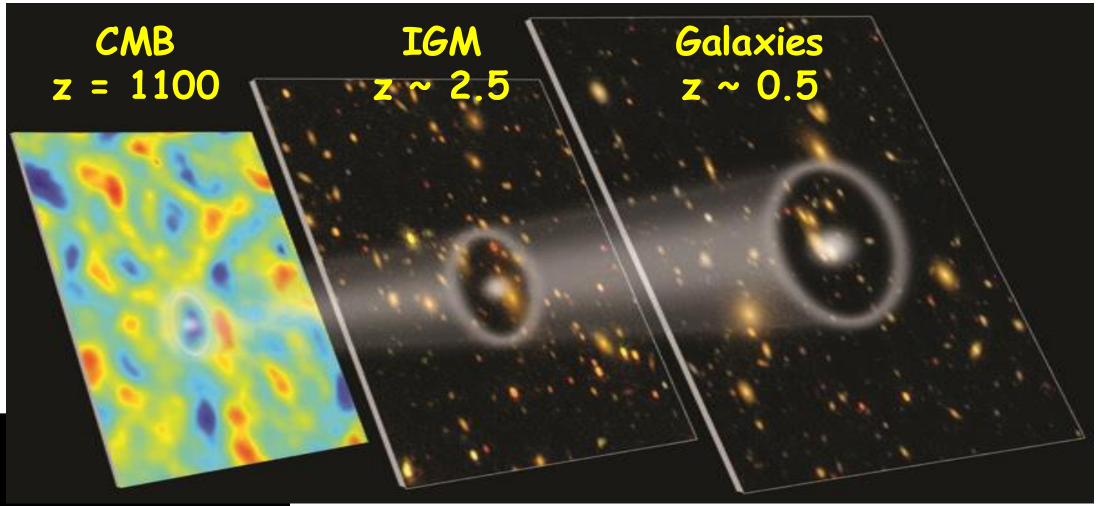
Size of feature = distance sound wave traveled

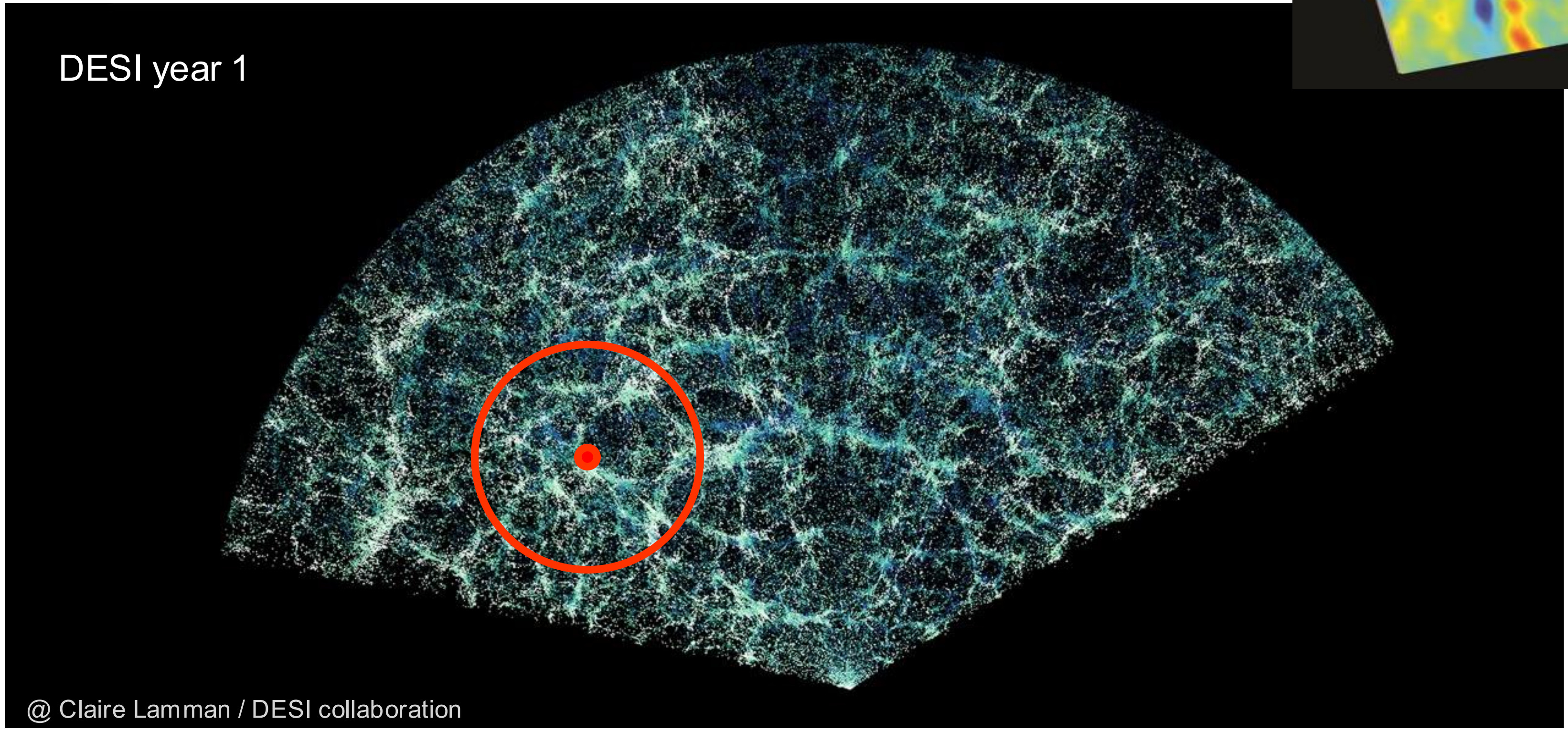
Preferred 3D scale r_s ~ 150 kpc (at recombination)
r_s ~ 150 Mpc (today)

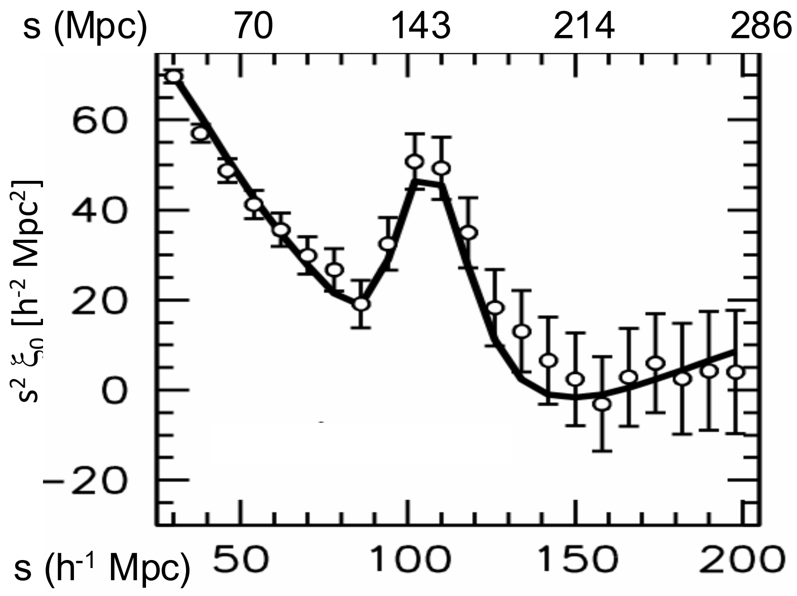
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Baryon Acoustic Oscillations (BAO)

Imprint of fluctuations in primordial plasma
→ Standard Ruler to measure distances





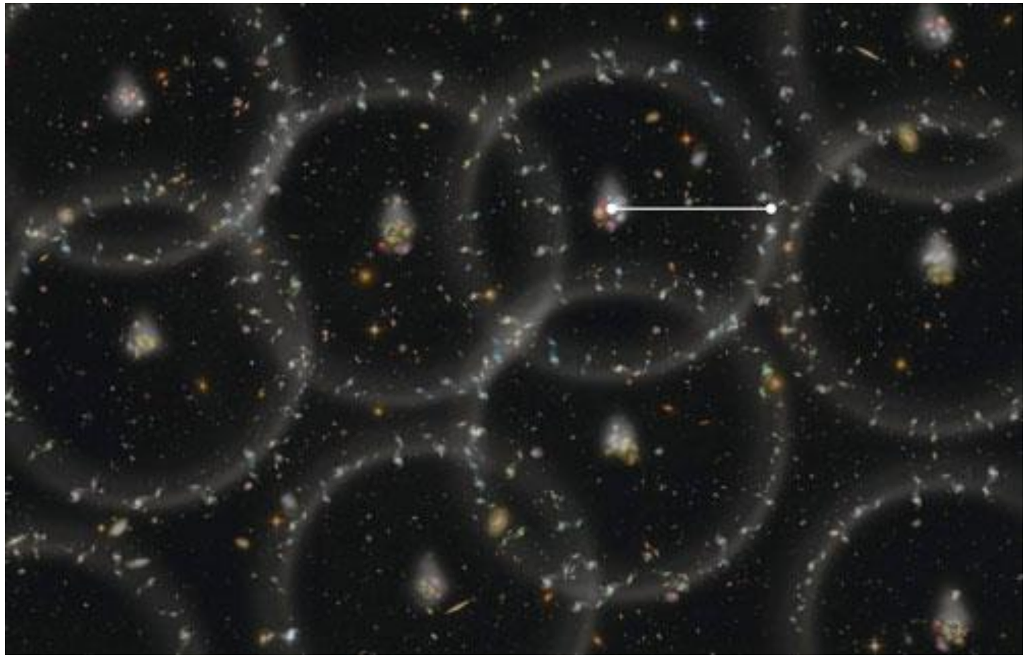


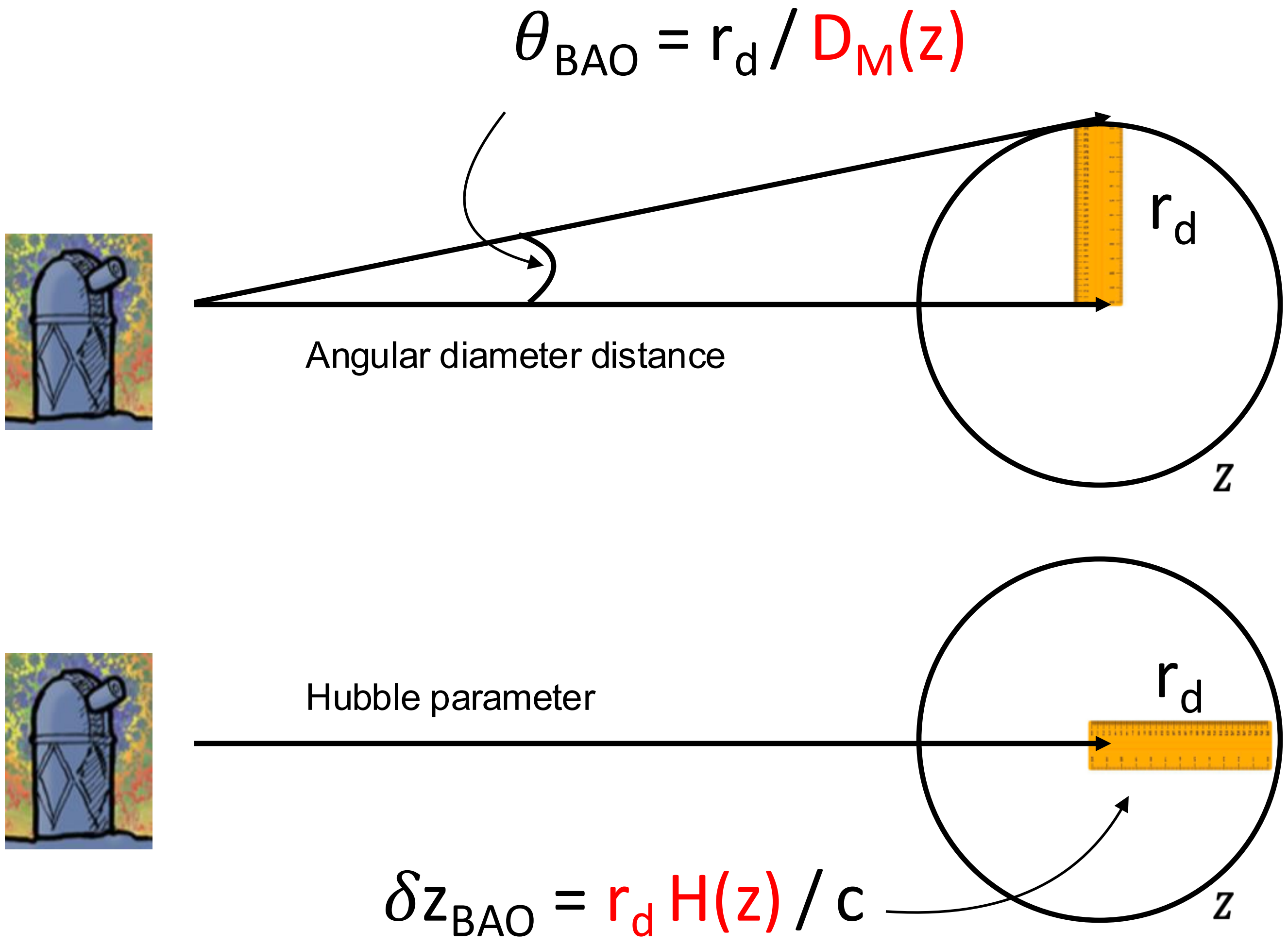
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The BAO standard ruler

Artist's view of BAO





$D_M(z)$ anf $H(z)$ encode expansion history of the Universe

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DESI

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

NERSC

FROM RESEARCH TO INDUSTRY cea

GOBIERNO DE ESPAÑA | MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

HEISING-SIMONS FOUNDATION

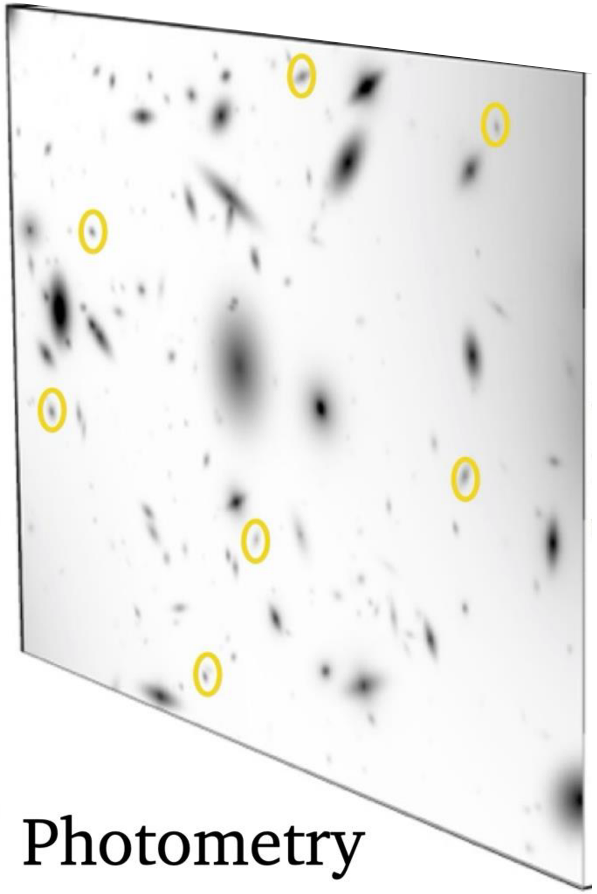
CONAHCYT

GORDON AND BETTY MOORE FOUNDATION

Science & Technology Facilities Council

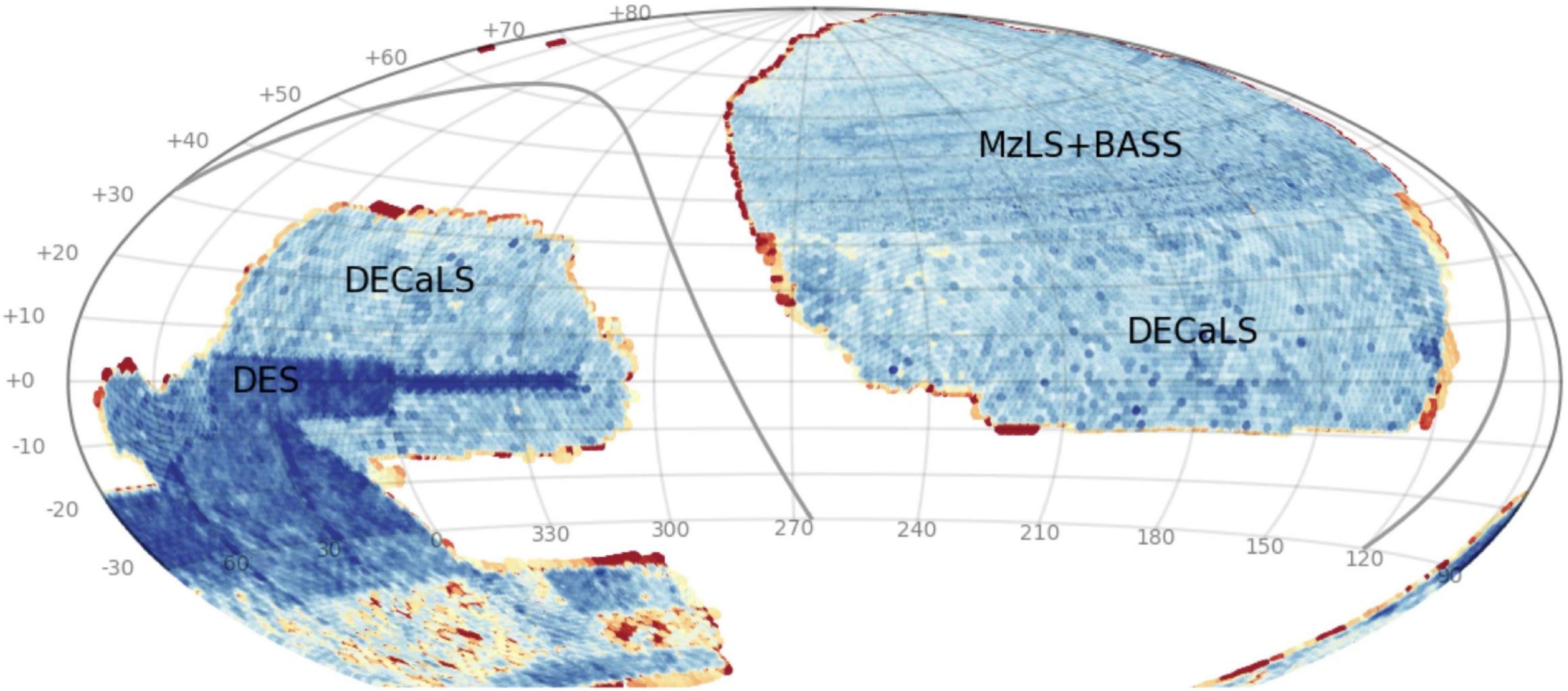
Thanks to our sponsors and
72 Participating Institutions!

Photometry before DESI



Photometry
of 1/3 of the Sky

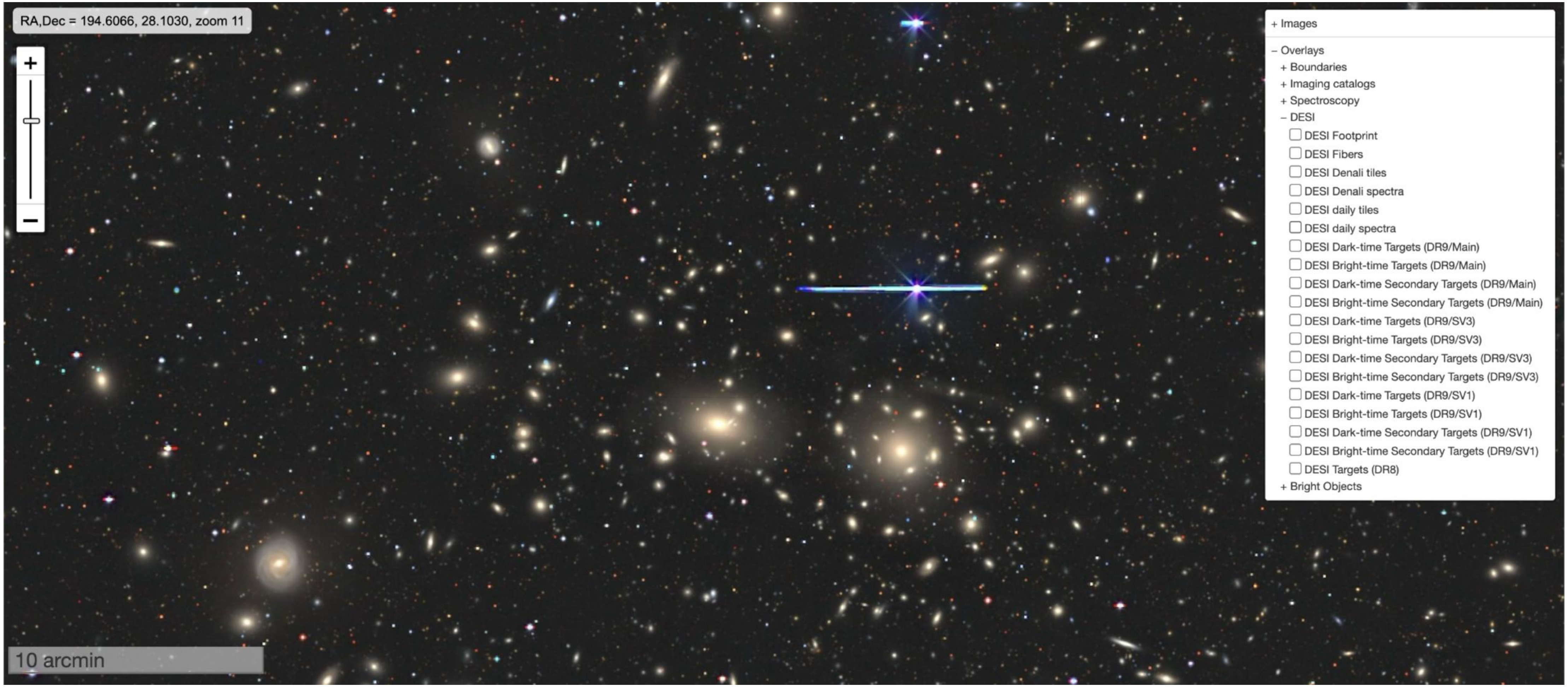
DESI Legacy Surveys



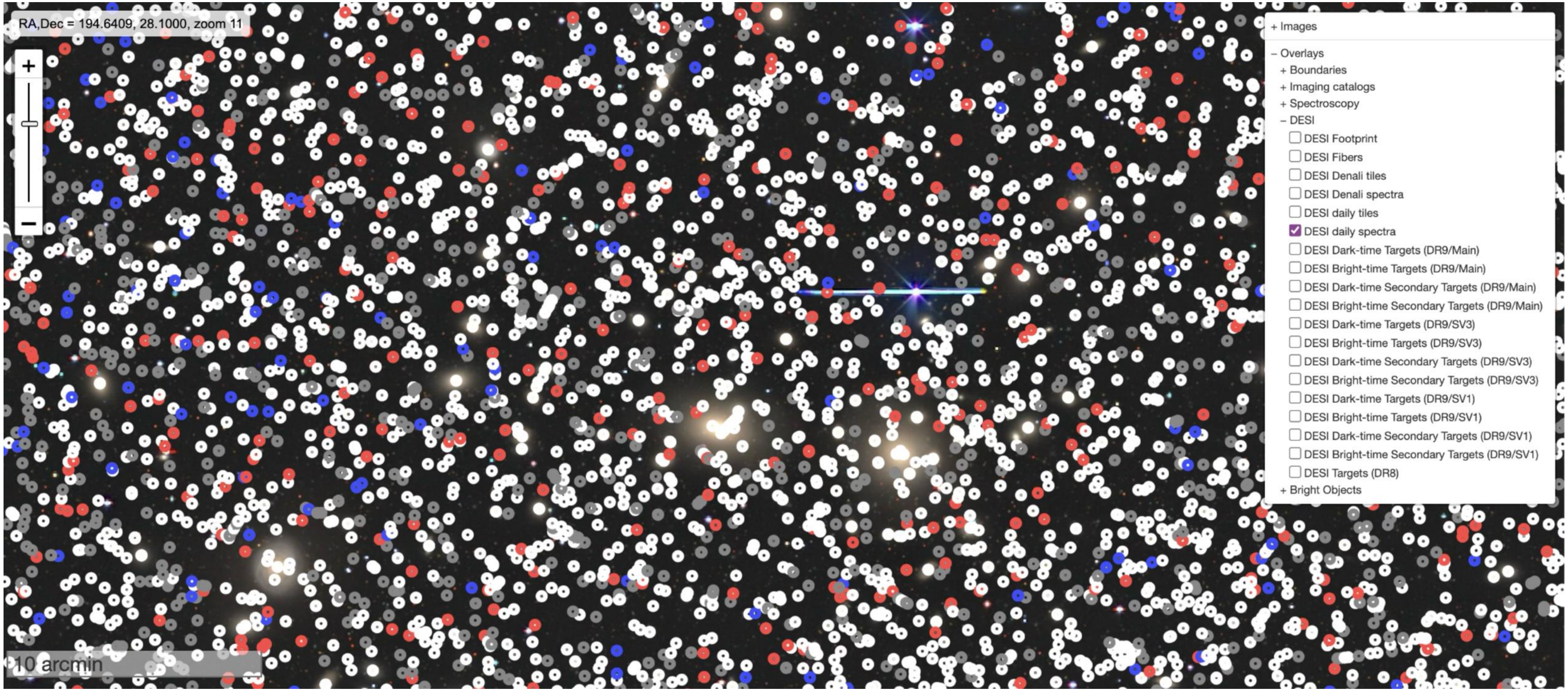
18k sq. deg. in *grz* using three telescopes (Bok, Mayall & Blanco)

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

Viewer: legacysurvey.org/viewer



Viewer: legacysurvey.org/viewer

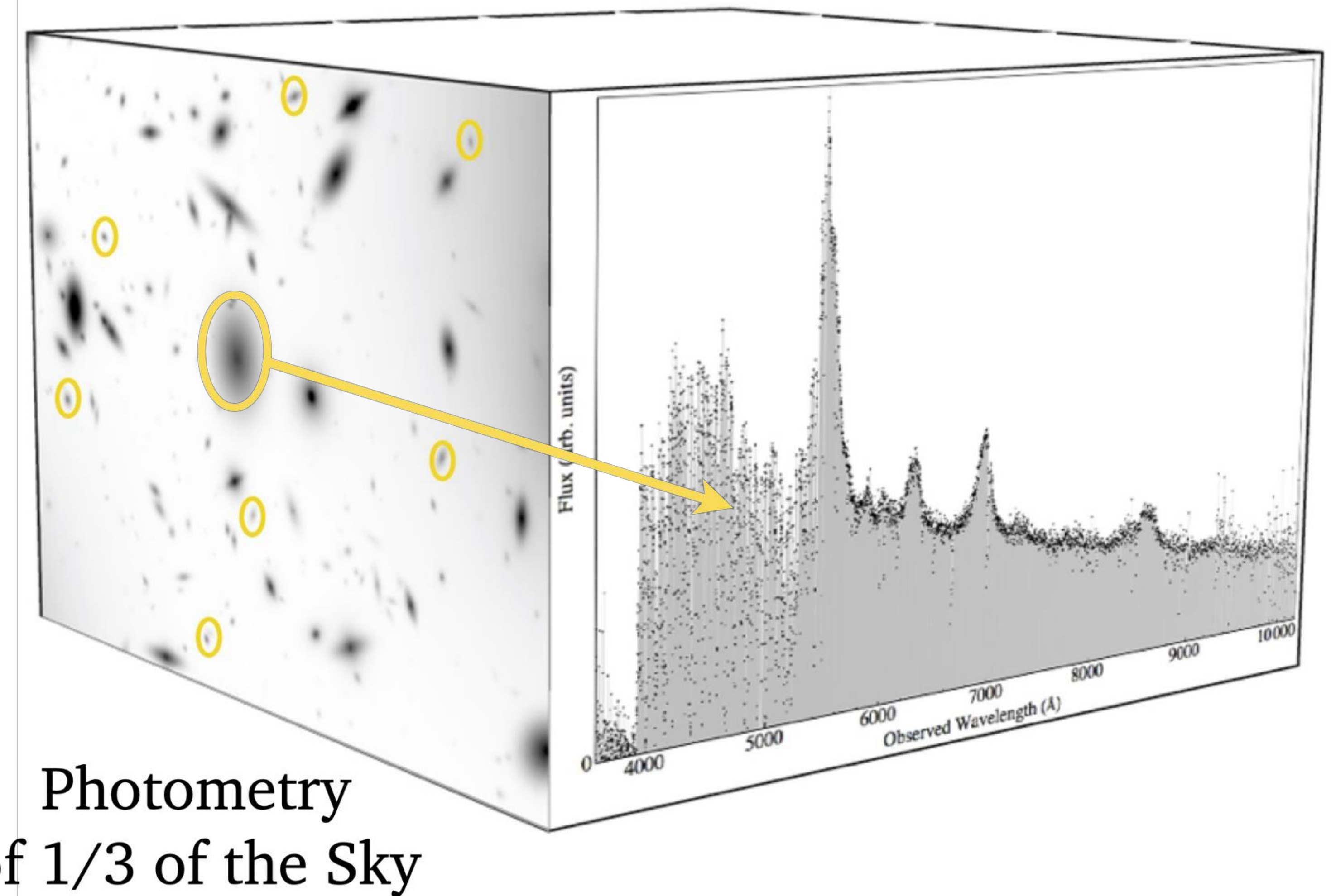


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Viewer: legacysurvey.org/viewer

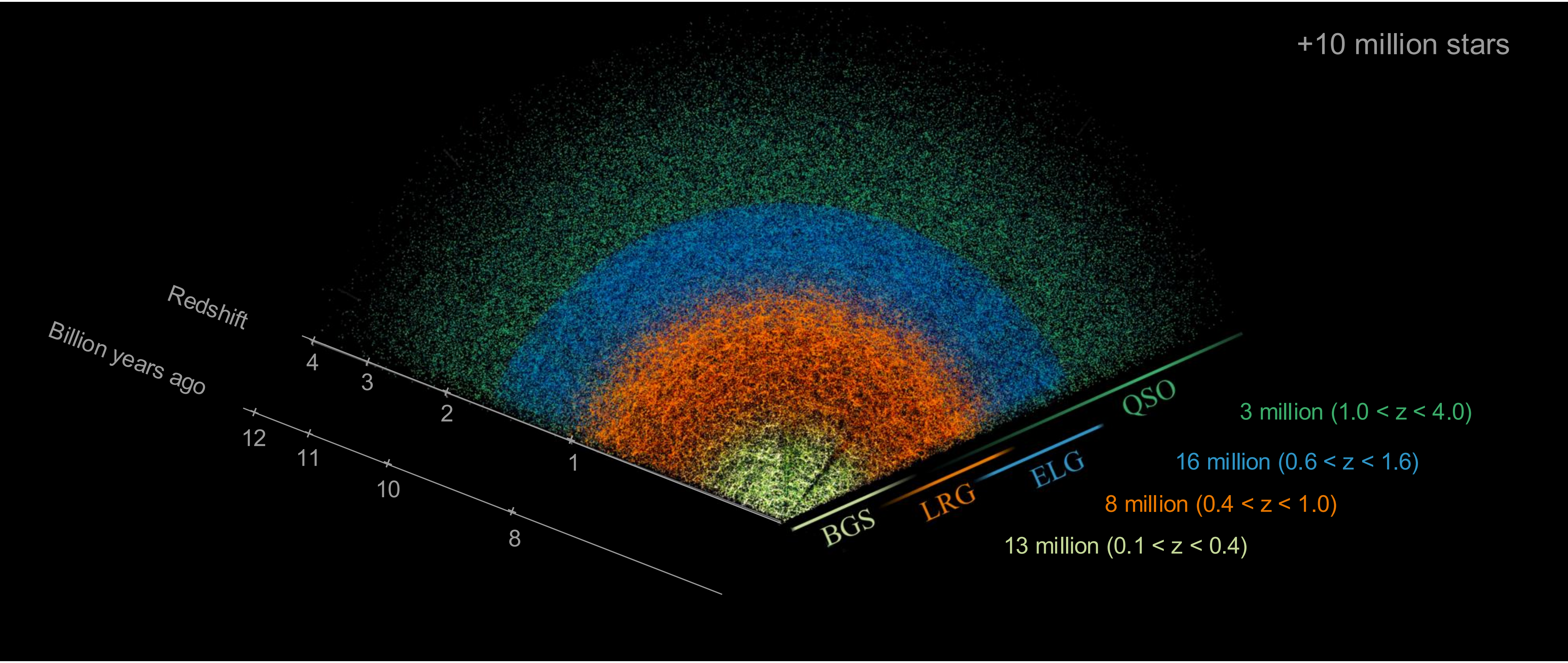
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI: spectroscopic galaxy survey

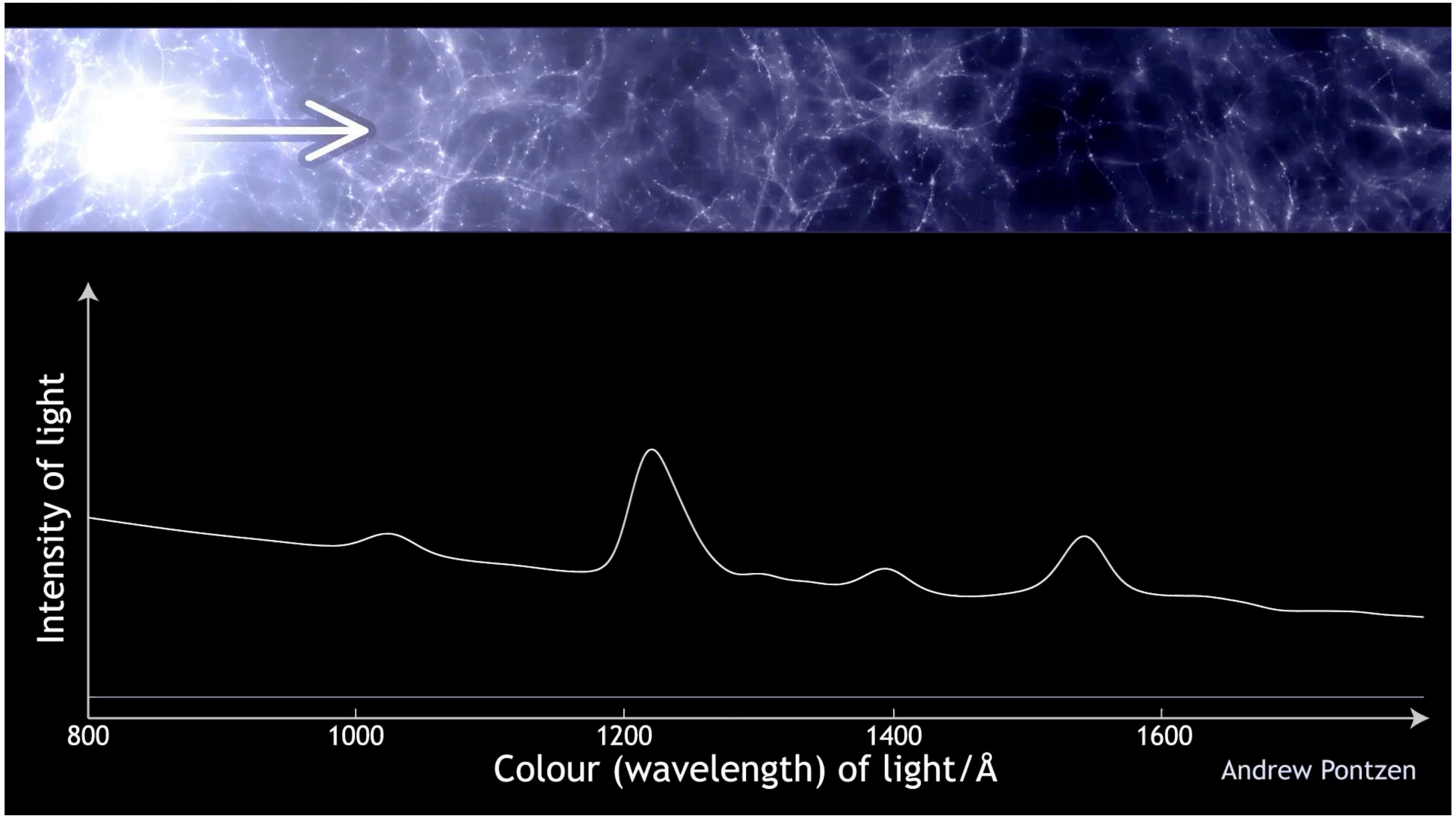


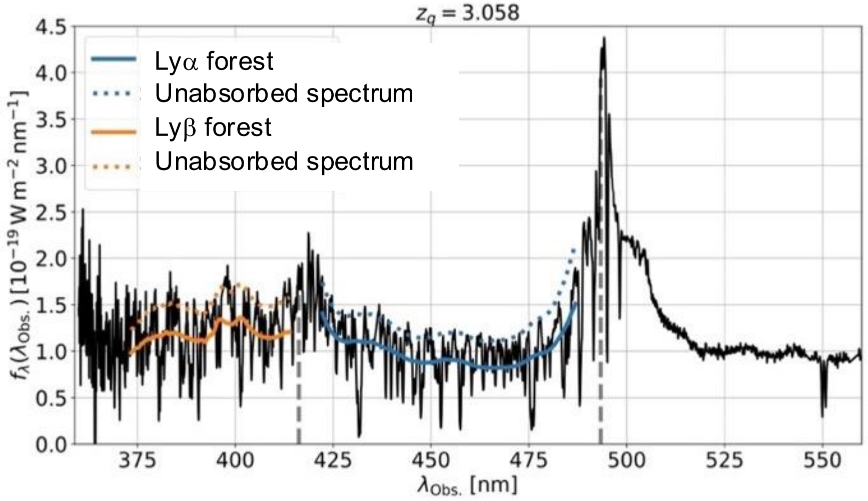
DESI targets: 40 million galaxies & quasars!

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



The Lyman-α Forest at z>2.1





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

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

- Quasars visible to high redshift (z ~ 5)
- Absorption of Quasar spectrum by neutral H in IGM
- Transmitted flux fraction F: proxy for neutral H density

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

DESI instrument

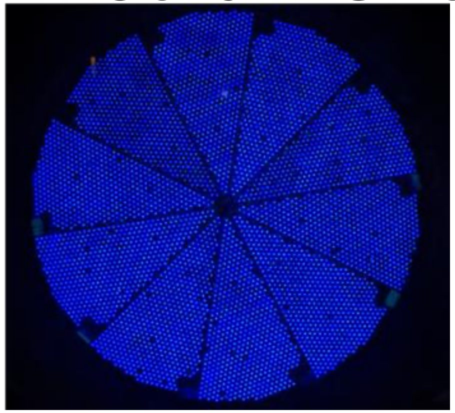
Mayall telescope
at Kitt Peak Observatory (AZ)

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

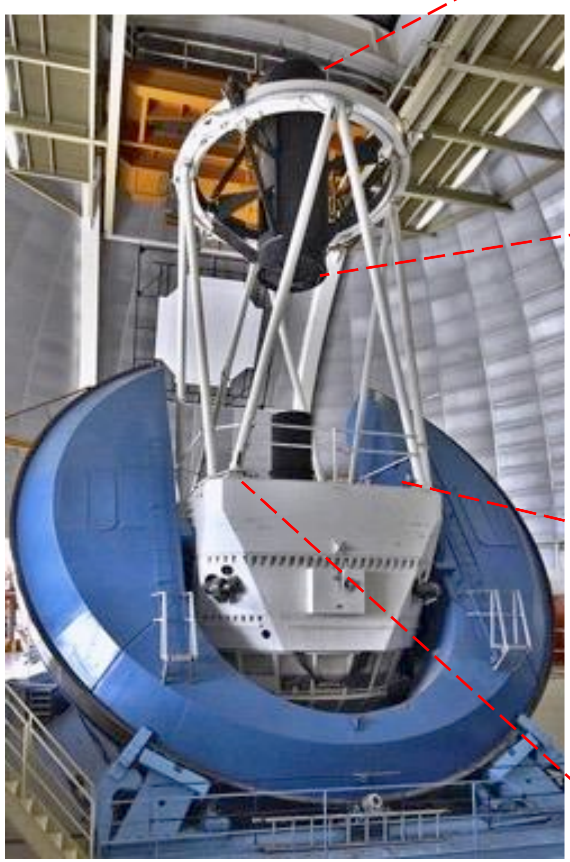
U.S. Department of Energy Office of Science

DESI instrument

Focal plane:
5000 fiber positioners
(high multiplexing)



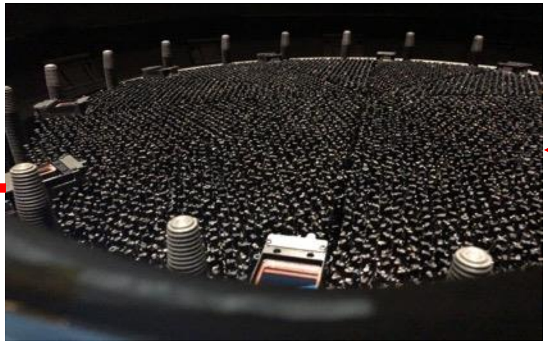
7 deg^2
field of view



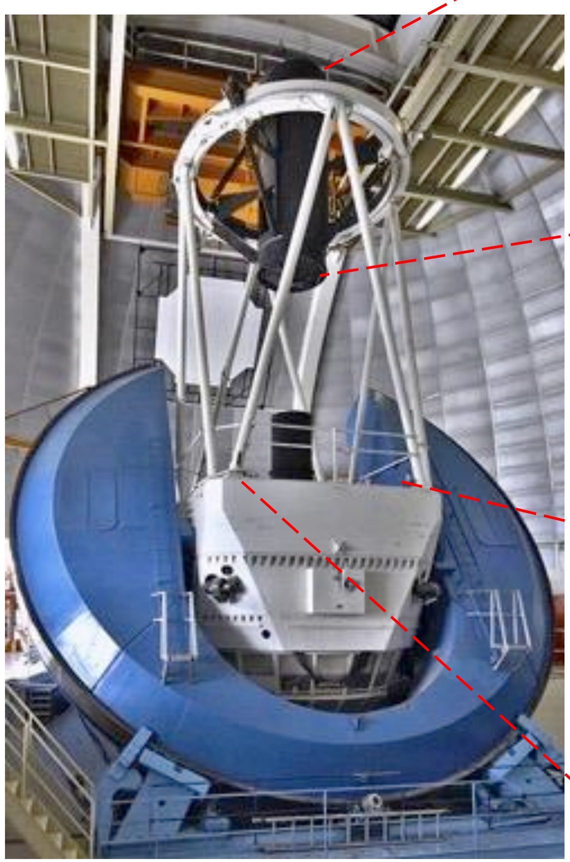
4m mirror
(large collecting area)

DESI instrument

7 deg^2
field of view



40m-long optical fibers



4m mirror
(large collecting area)

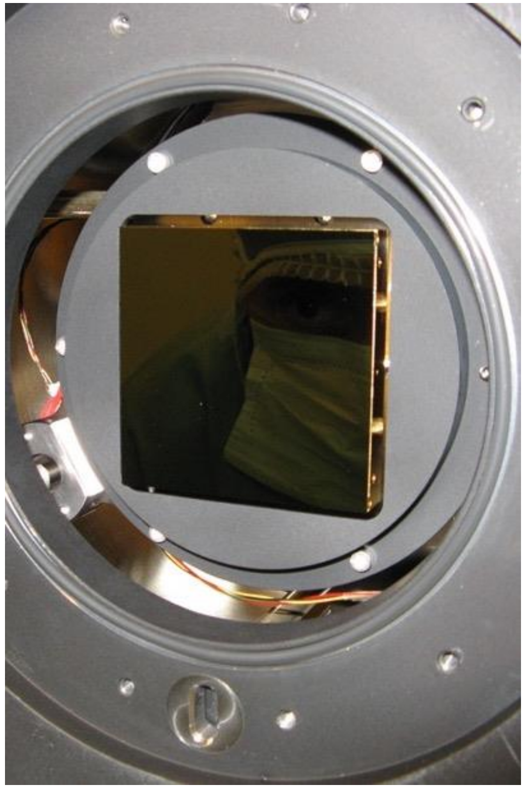
10 3-band spectrographs

DARK ENERGY SPECTROSCOPIC INSTRUMENT

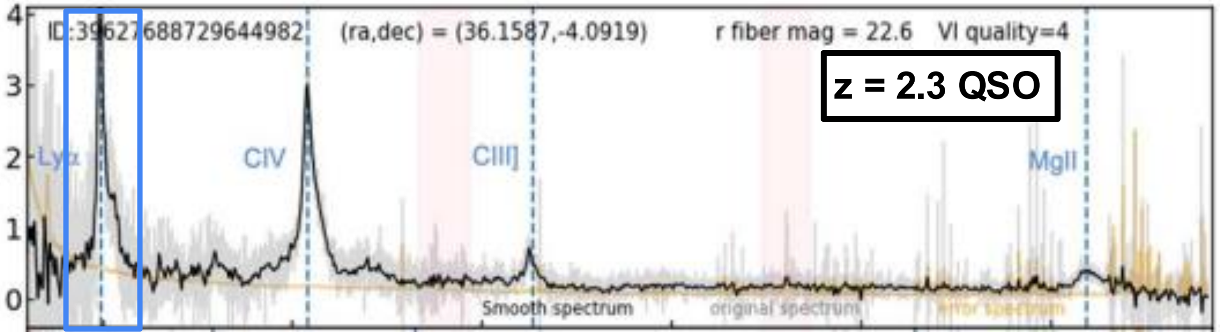
U.S. Department of Energy Office of Science

DESI instrument

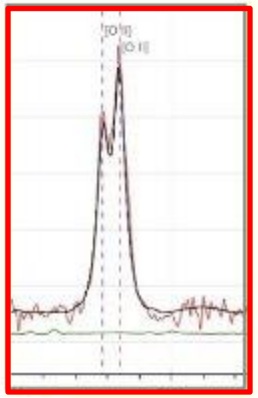
10 3-band spectrographs [360nm – 980nm]

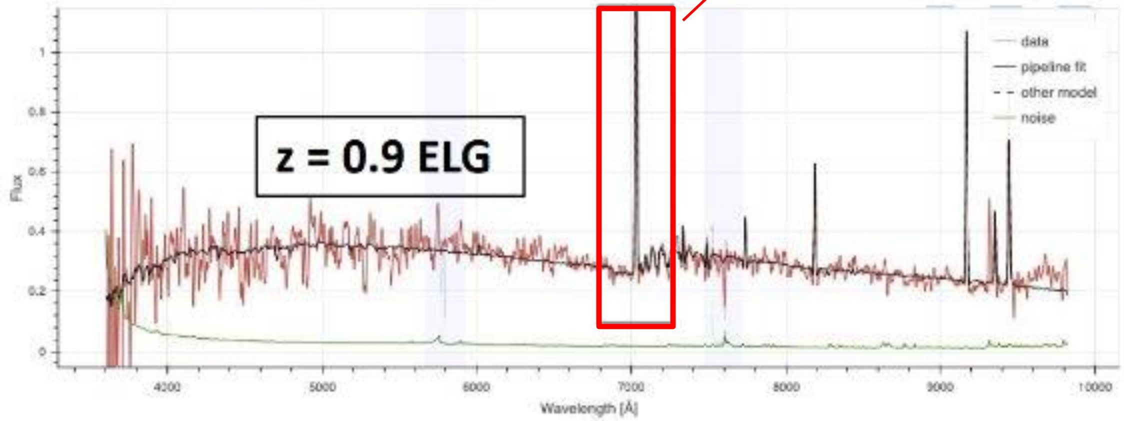


Lyα λ121.6 nm
down to z = 2.0



[OII] λ373 nm
up to z = 1.6





DESI DR2: data & analysis

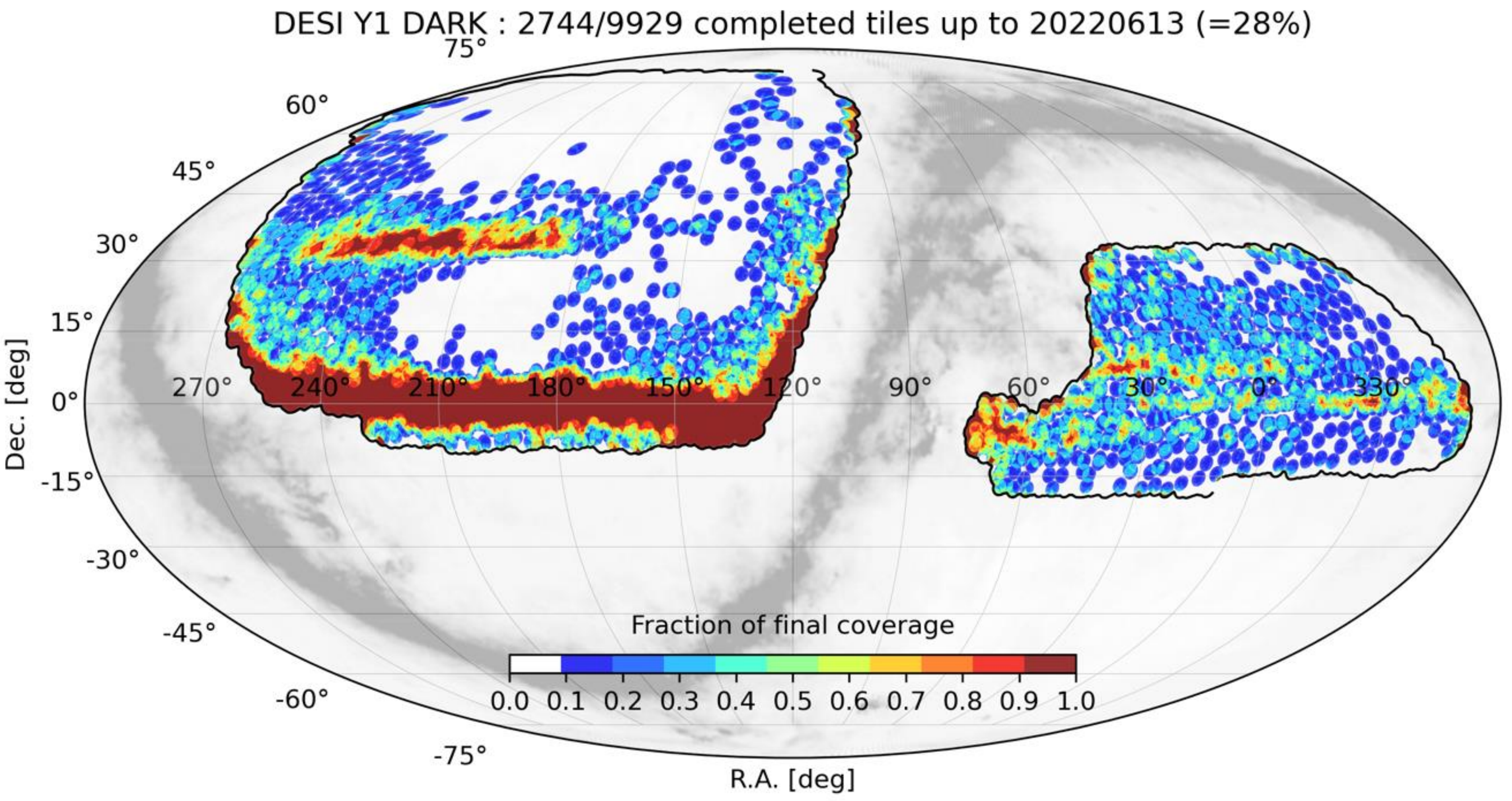
DESI Data Release 1 footprint

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

DR1 analysis sample

420,000 Lyman-α forests
5.7 million galaxies and quasars

2 to 3x larger than SDSS (20 years)



DESI 2024 II: Samples (*arXiv:2404.03002*)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Data Release 2 footprint

DR1 analysis sample

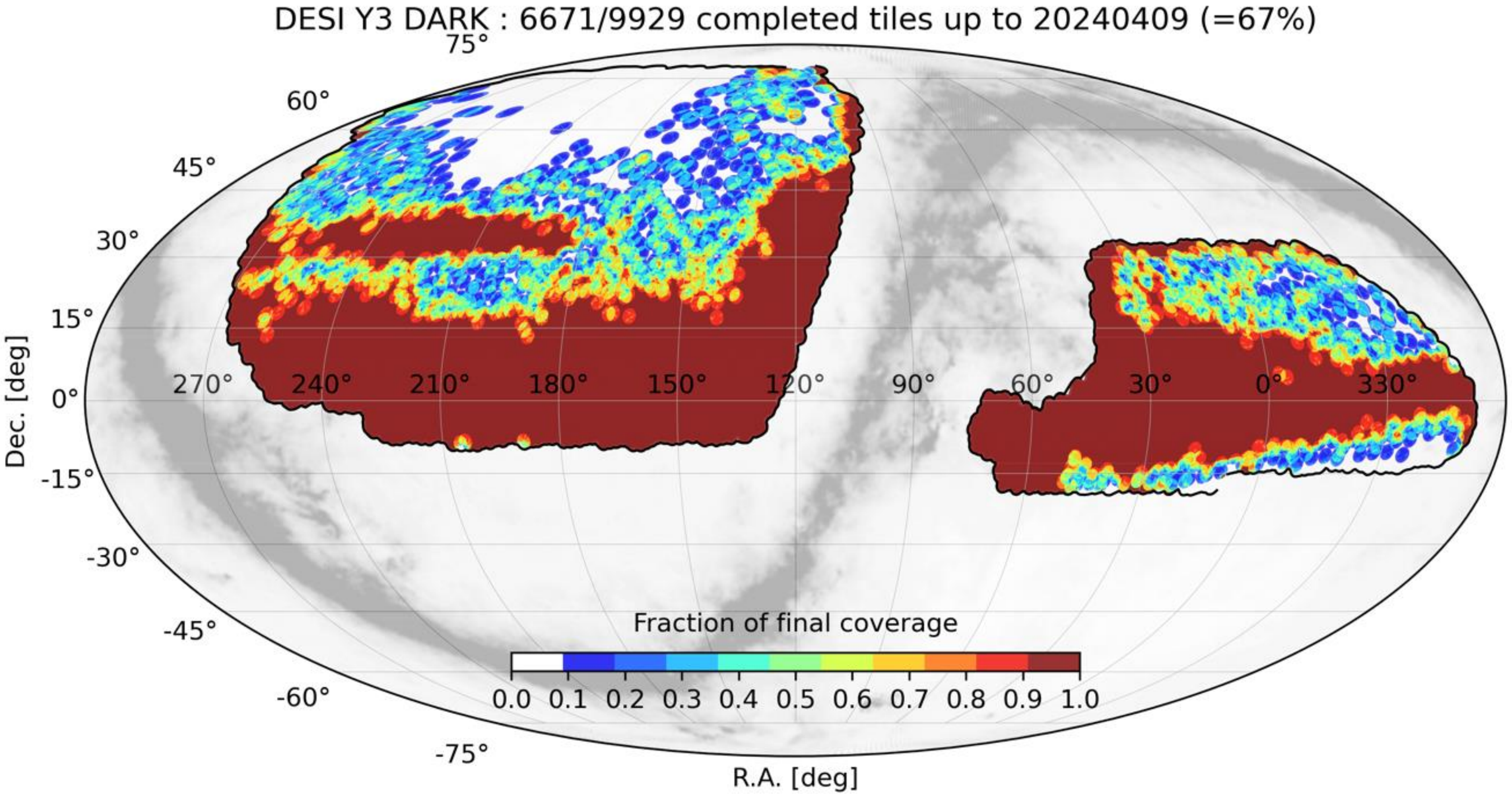
420,000 Lyman-α forests
5.7 million galaxies and quasars

2 to 3x larger than SDSS (20 years)

DR2 analysis sample

820,000 Lyman-α forests
14.3 million galaxies and quasars

2 (QSO) to 3 (ELG) x DR1



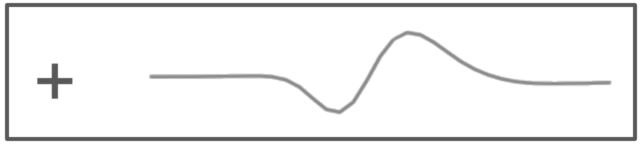
DESI DR2 results I: Lya (*arXiv:2503.14739*)
DESI DR2 results II: BAO (*arXiv:2503.14738*)

Blinding strategy

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

Blinded analysis to prevent confirmation bias

- Catalog-level for Galaxies & quasars: redshifts & weights
- Cosmology-level for Lyman-alpha forest: shift of BAO peak



Procedure

Determine analysis parameters
& validate choices based on
- Simulated data (*mocks*)
- Data splits (*blinded data*)

Robustness tests

- Variations in data vector
- Methods to compute correlations & covariances
- BAO modeling (priors, broadband, …)
- Imaging systematics
- Data splits

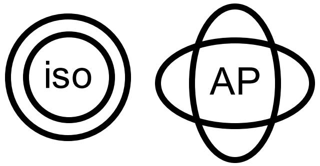
DESI DR2 results I: Lya (*arXiv:2503.14739*)
DESI DR2 results II: BAO (*arXiv:2503.14738*)

Systematics

DESI DR2 results I: Lya (*arXiv:2503.14739*)
DESI DR2 results II: BAO (*arXiv:2503.14738*)

Galaxy clustering

Dominant systematics
- Theoretical modeling
- Galaxy-halo connection
- Fiducial cosmology



Total systematic (tracer-dependent)

$$\Delta\alpha_{\mathrm{iso}} = 0.14\% \text{ to } 0.22\%$$
$$\Delta\alpha_{\mathrm{AP}} = 0.22\% \text{ to } 0.33\%$$

Induced increase of σ_{tot} over σ_{stat}

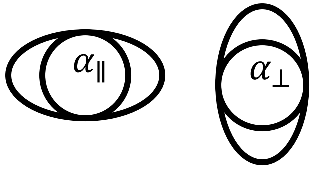
$\Delta\,\sigma(\alpha_{\mathrm{iso}}) = 1 - 9\%$ (BGS – LRG3+ELG1)
$\Delta\,\sigma(\alpha_{\mathrm{AP}}) = 0.1 - 2\%$ (QSO – LGR3+ELG1)

Lyα forest clustering

Dominant systematics
- non-linear evolution of BAO peak

Total systematic

$$\Delta\alpha_{\parallel} = 0.3\%$$
$$\Delta\alpha_{\perp} = 0.3\%$$



Induced increase of σ_{tot} over σ_{stat}

$\Delta\,\sigma(\alpha_{\mathrm{iso}}) = 9\%$ (Lyα)

Statistics-limited!

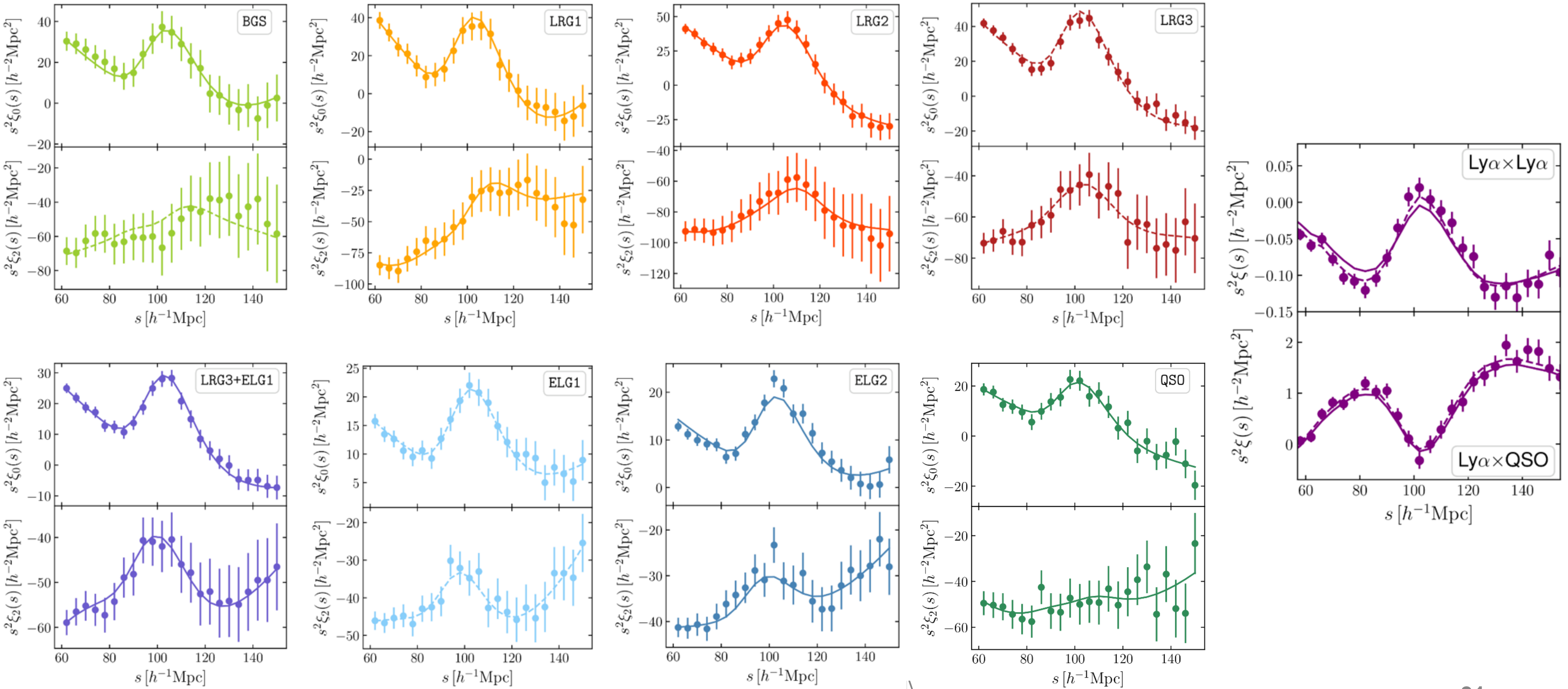
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DR2 clustering measurements

LRG+ELG (0.8<z<1.1)

15σ detection of BAO at z_{eff} = 0.93



DARK ENERGY SPECTROSCOPIC INSTRUMENT

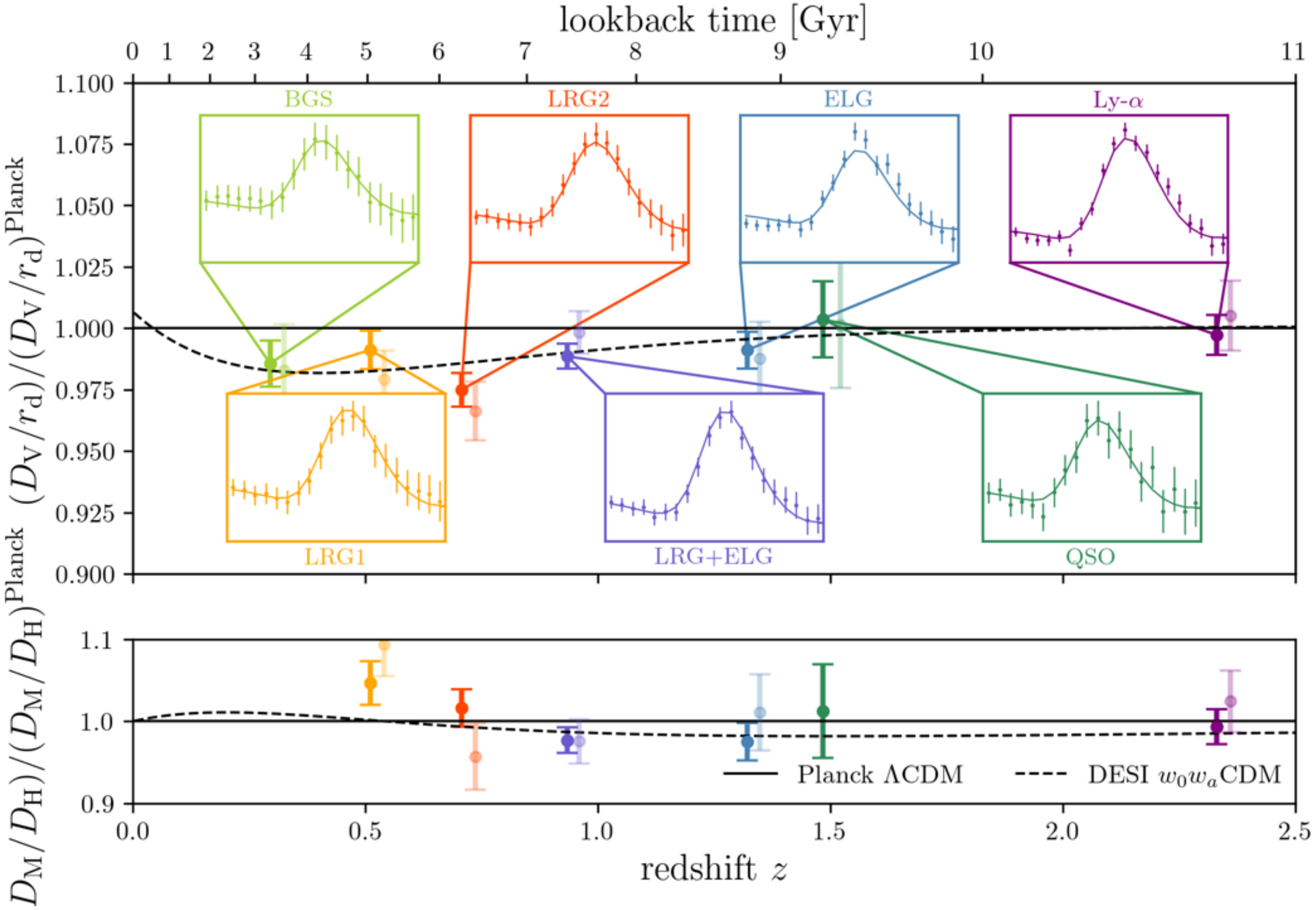
U.S. Department of Energy Office of Science

DESI DR2 BAO

BAO data: $\Delta\theta$ and Δz $\longrightarrow$ D_M / r_d and D_H / r_d

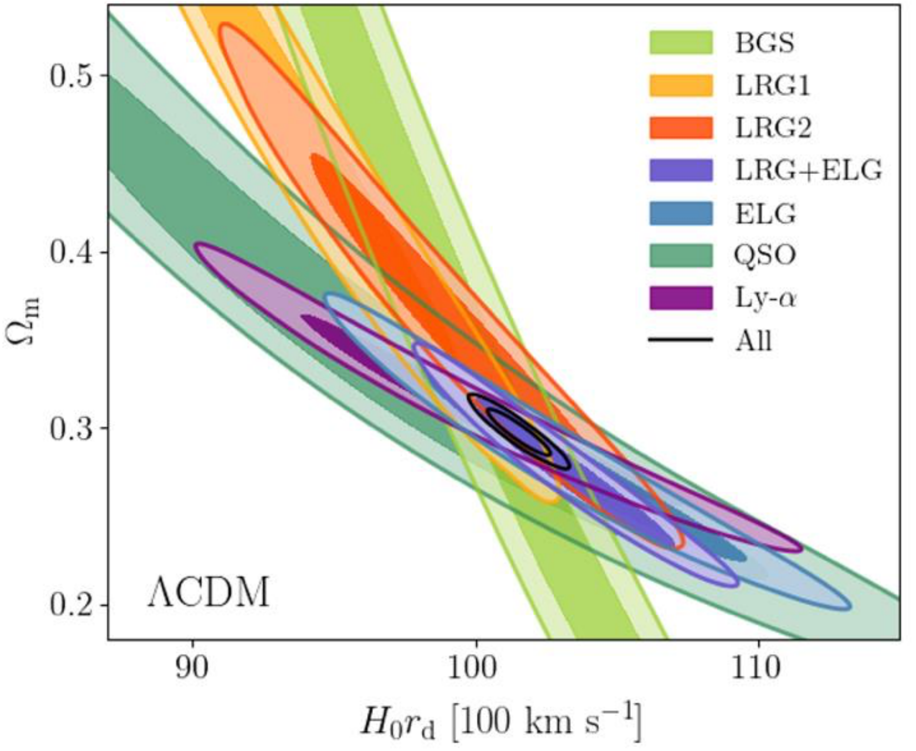
$$D_V = \left(zD_M(z)^2 D_H(z)\right)^{1/3}$$

Ω_M and $H_0 r_d$



Aggregated precision on BAO distance scale: 0.3%

(vs. 0.6% for final SDSS)



Agreement & complementarity between tracers

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

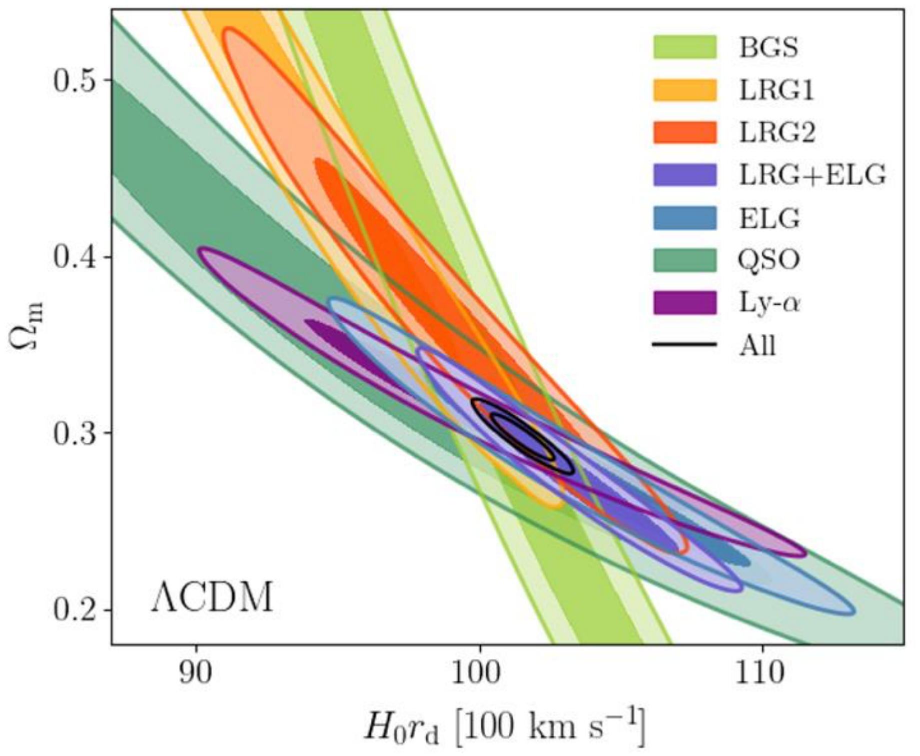
DESI DR2 BAO

BAO data: $\Delta\theta$ and Δz $\longrightarrow$ D_M / r_d and D_H / r_d

$$D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$

Ω_M and $H_0 r_d$

$$\underbrace{\begin{aligned} \Omega_m &= 0.298 \pm 0.0086 \qquad && (\mathbf{2.9\%}) \\ h r_d &= 101.54 \pm 0.73 \;\; \mathrm{Mpc} \qquad && (\mathbf{0.7\%}) \end{aligned}}_{\textbf{DESI}}$$



Agreement & complementarity between tracers

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

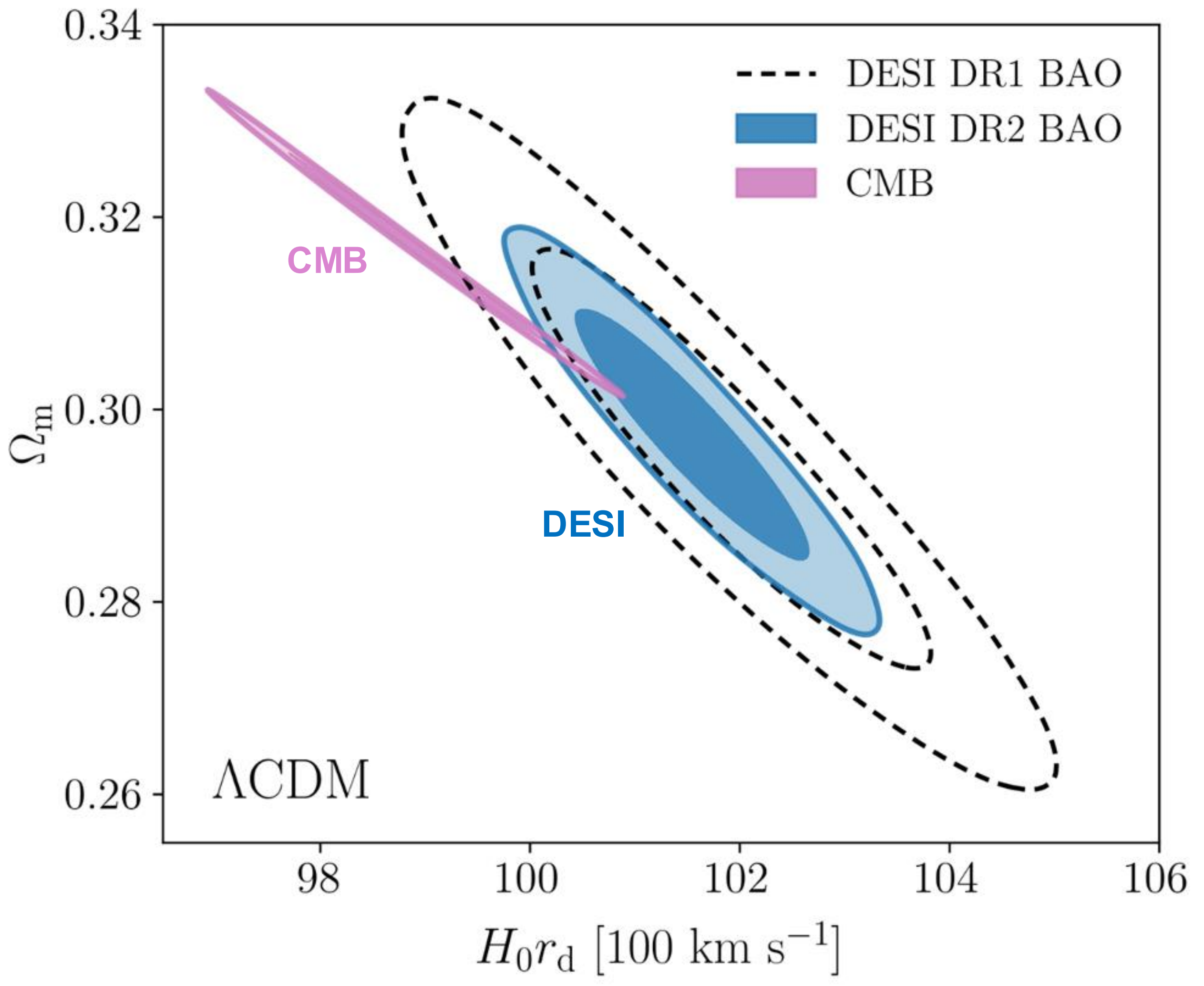
ΛCDM: DESI DR2 vs. CMB

DESI DR2 BAO is:

- Consistent with **DESI DR1**
- 2.3σ from the **CMB** (was 1.9σ with DESI DR1)

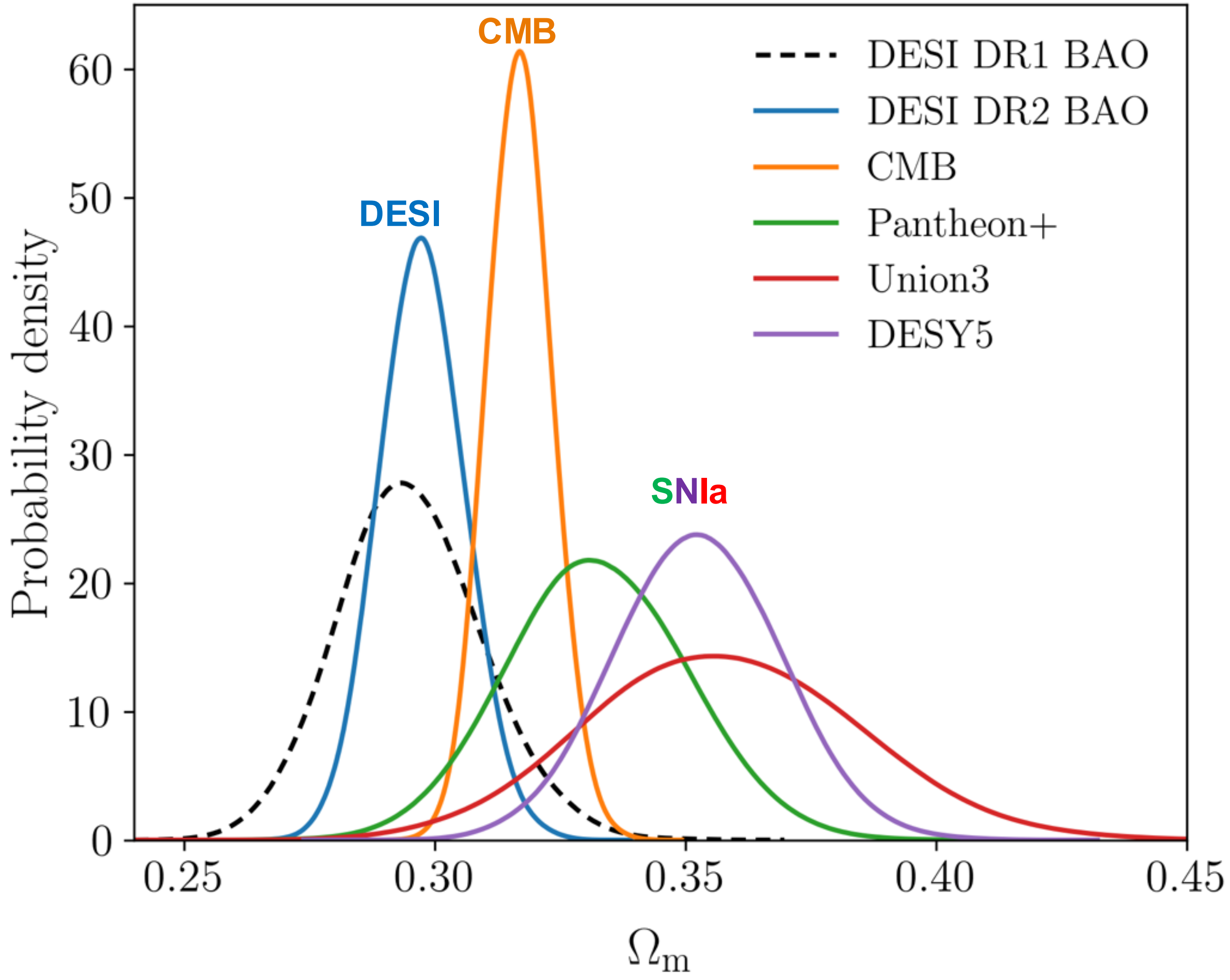
CMB:

- primary CMB from Planck PR4 (CamSpec)
- CMB lensing from Planck PR4 + ACT DR6



ΛCDM: DESI DR2 vs. Supernovae

- **DESI DR2** consistent with DESI DR1
- **DESI DR2** is lower than the CMB
- **DESI DR2** is lower than Supernovae:
  - 1.7σ lower than Pantheon+
  - 2.1σ lower than Union3
  - 2.9σ lower than DESY5

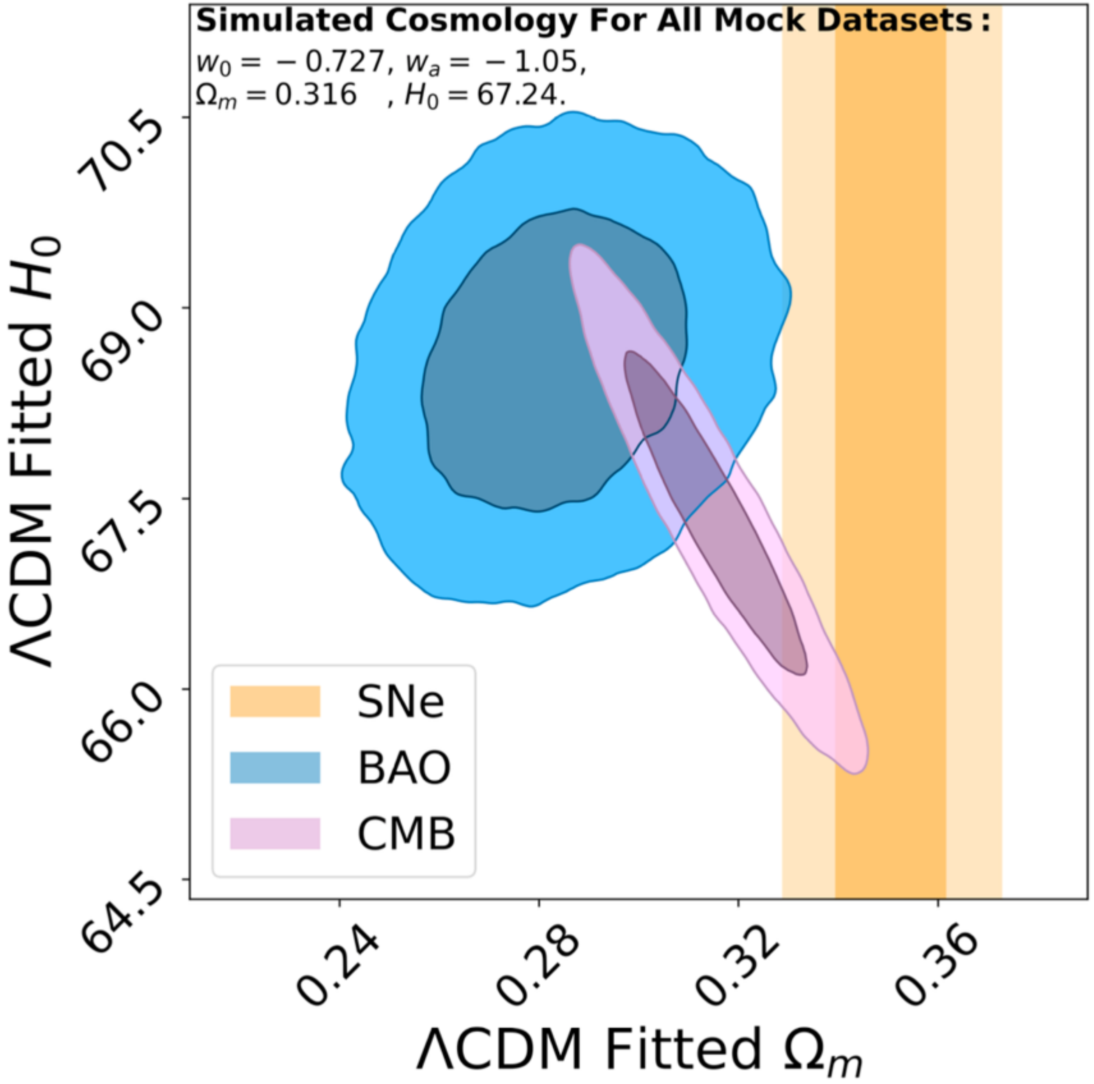


Data consistency

Differences in H_0 & Ω_m
between DESI BAO, CMB and SN

expected

when dynamic dark energy universe fitted assuming ΛCDM



Tang+ (arXiv:2412.04430)

Expansion rate of the Universe

H_0

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

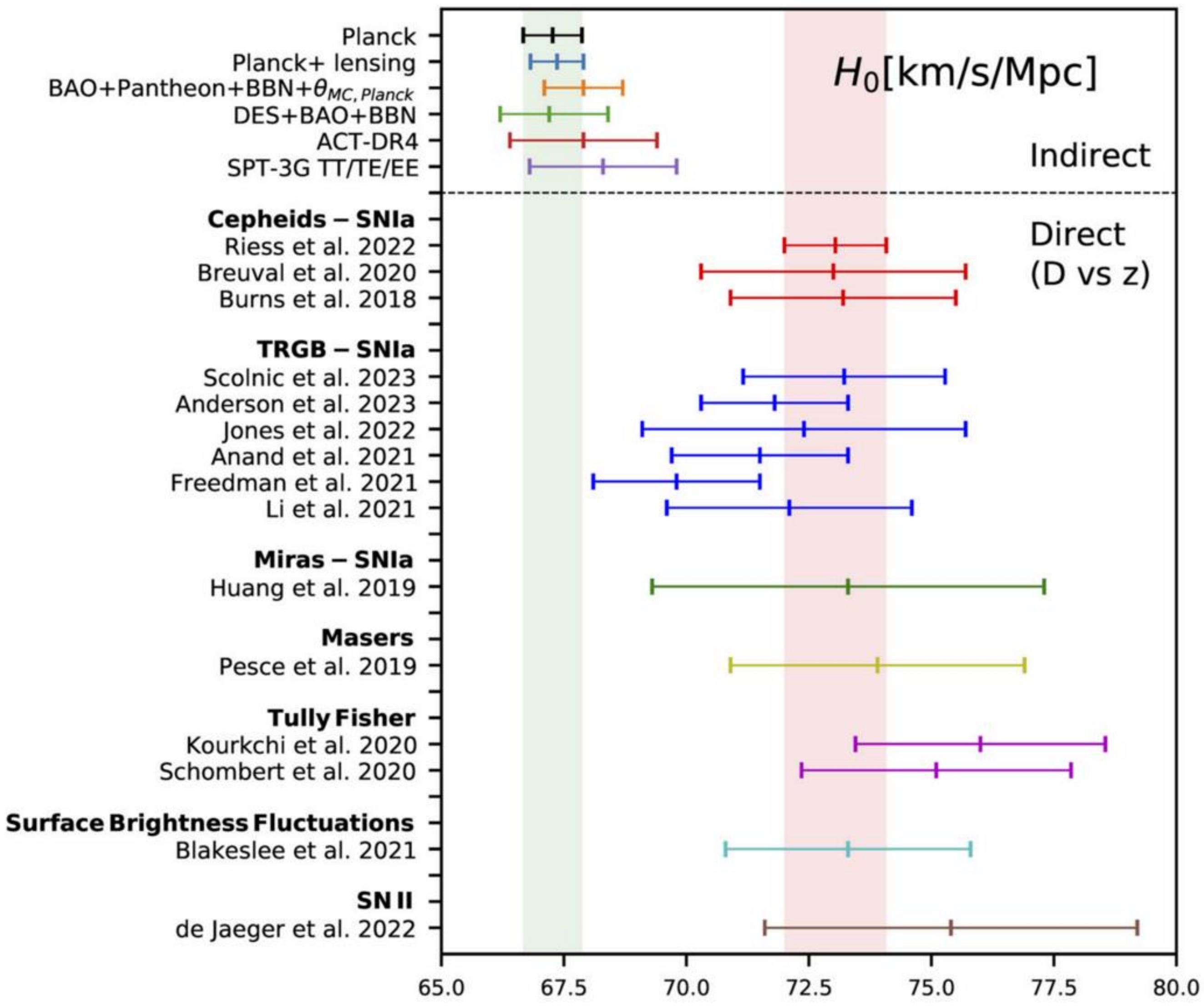
H_0

Extrapolation to z=0 (normalization) of **early-universe data**

Distance-ladder calibration approach in **late-time universe**

Early-time

Late-time Universe



Riess & Breuval 2023

H_0

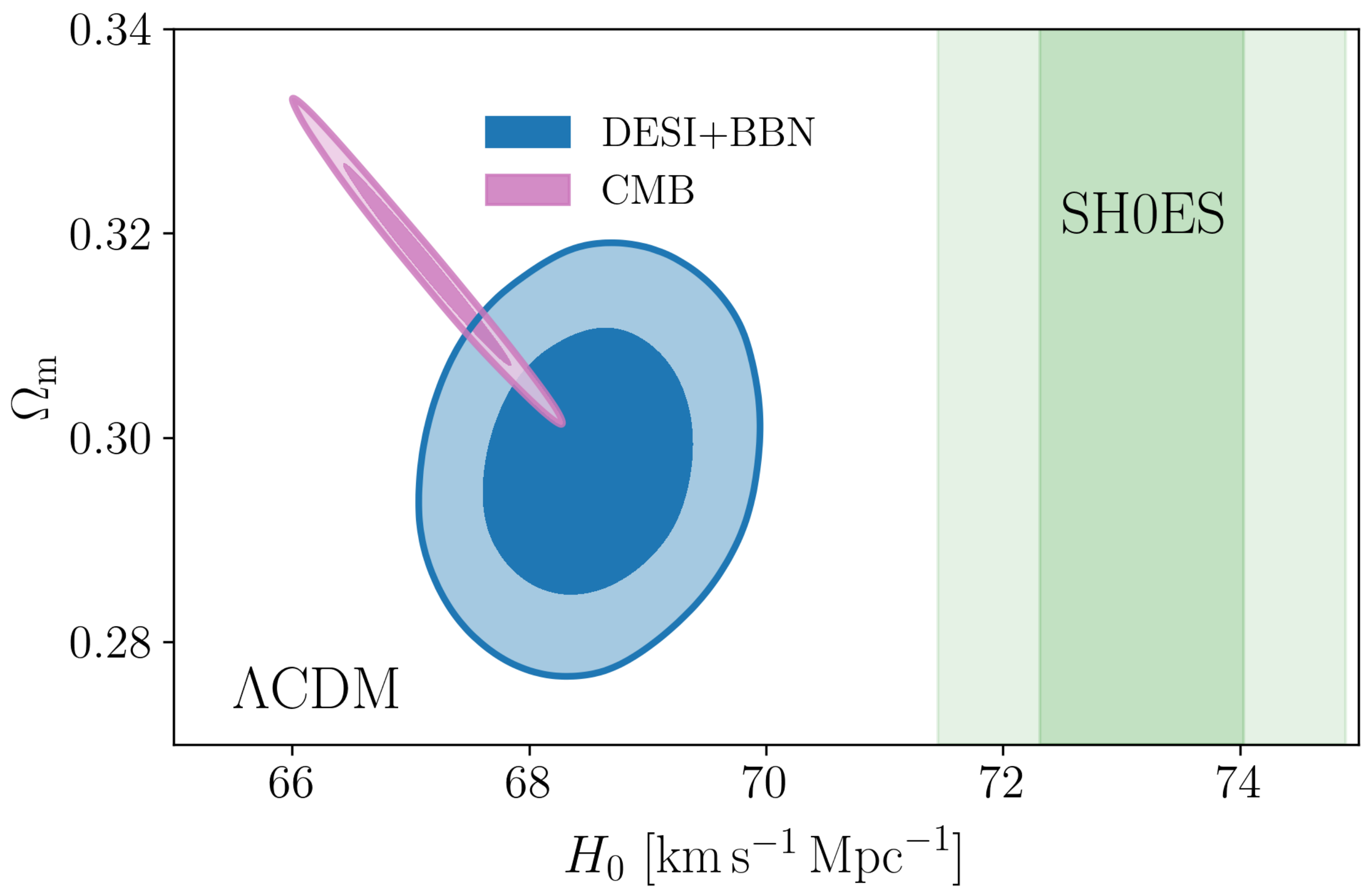
BAO data: $\Delta\theta$ and Δz ⟶ D_M / r_d and D_H / r_d ➡ Ω_M and $H_0 r_d$

Using r_d from BBN ($\Omega_b \to r_d$)

$$\underbrace{H_0 = 68.51 \pm 0.58 \ \ \mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\text{DESI + BBN}} \quad (\mathbf{0.8\%})$$

→ **0.8% precision on H_0, independent of CMB**

→ **4.5σ tension with SH$_0$ES**



Dark Energy

Dark Energy

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Equation of state $P = w\rho$

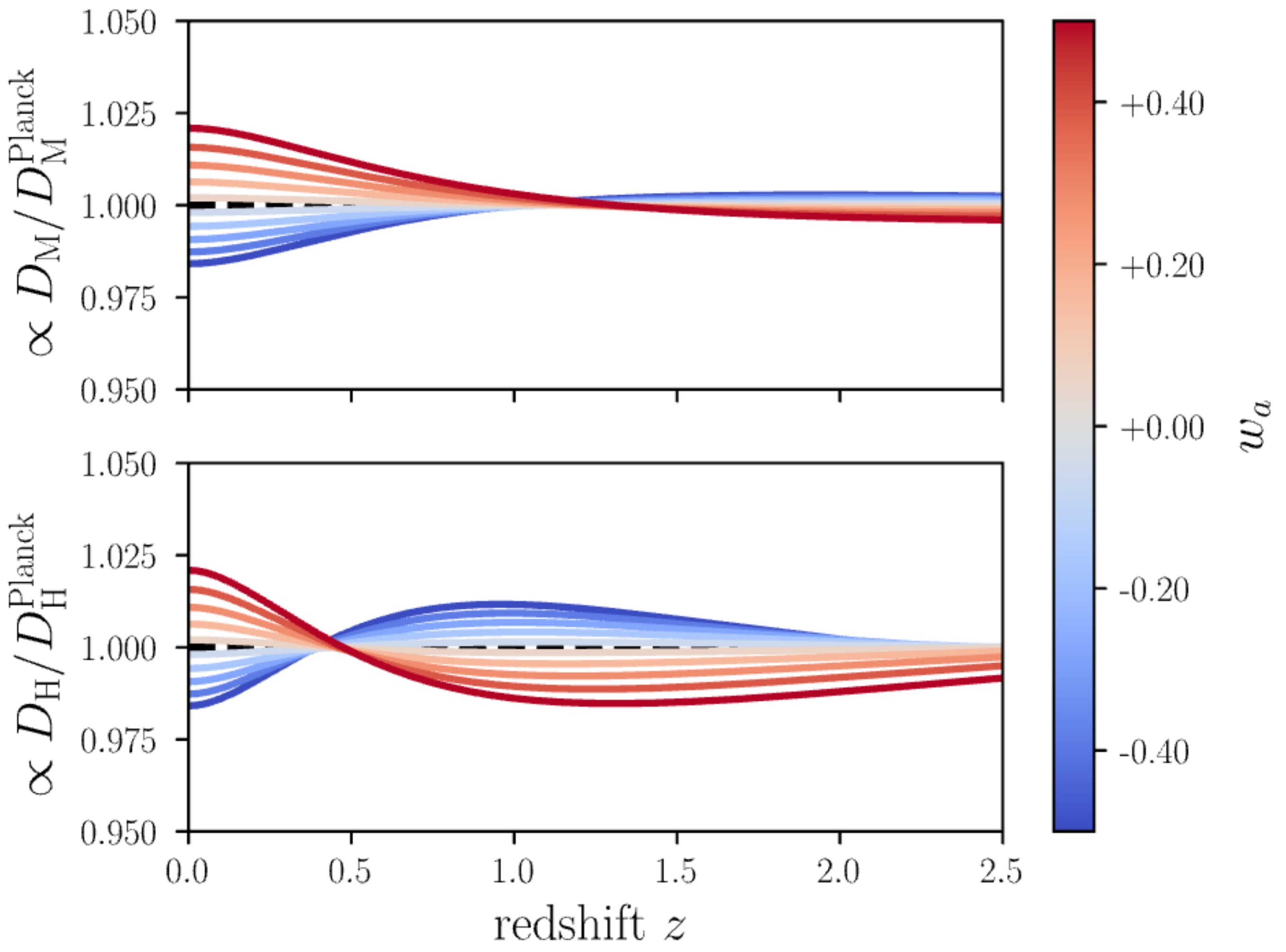
Dynamic dark energy

(Chevalier & Polarski 2001, Linder 2003)

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

Cosmological constant Λ

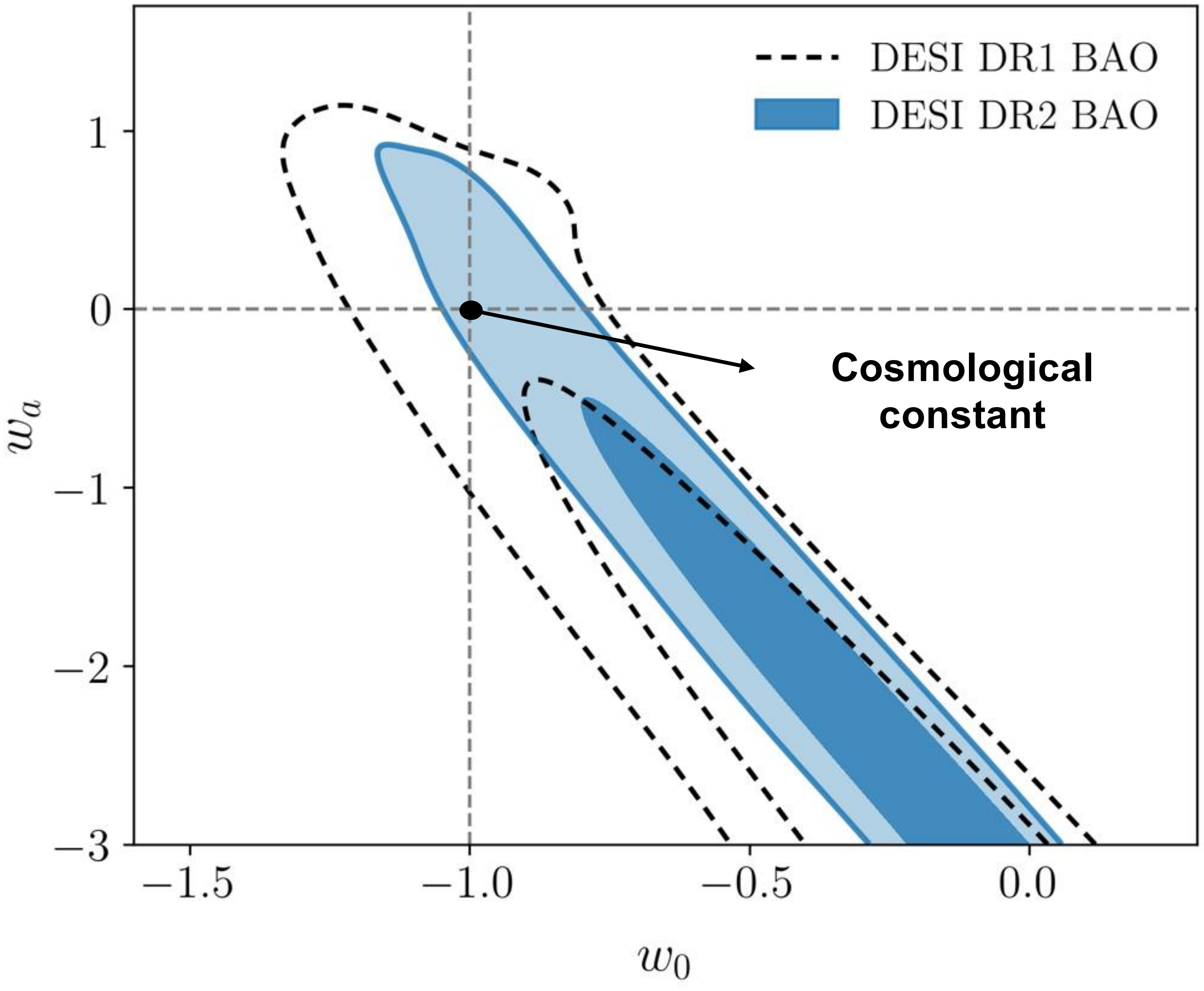
$w_0 = -1$ and $w_a = 0$



Evolving Dark Energy

$$w(a) = w_0 + (1 - a)w_a$$

- Degeneracy in $w_0 - w_a$ plane with BAO alone
- DESI DR2 within 2σ of ΛCDM

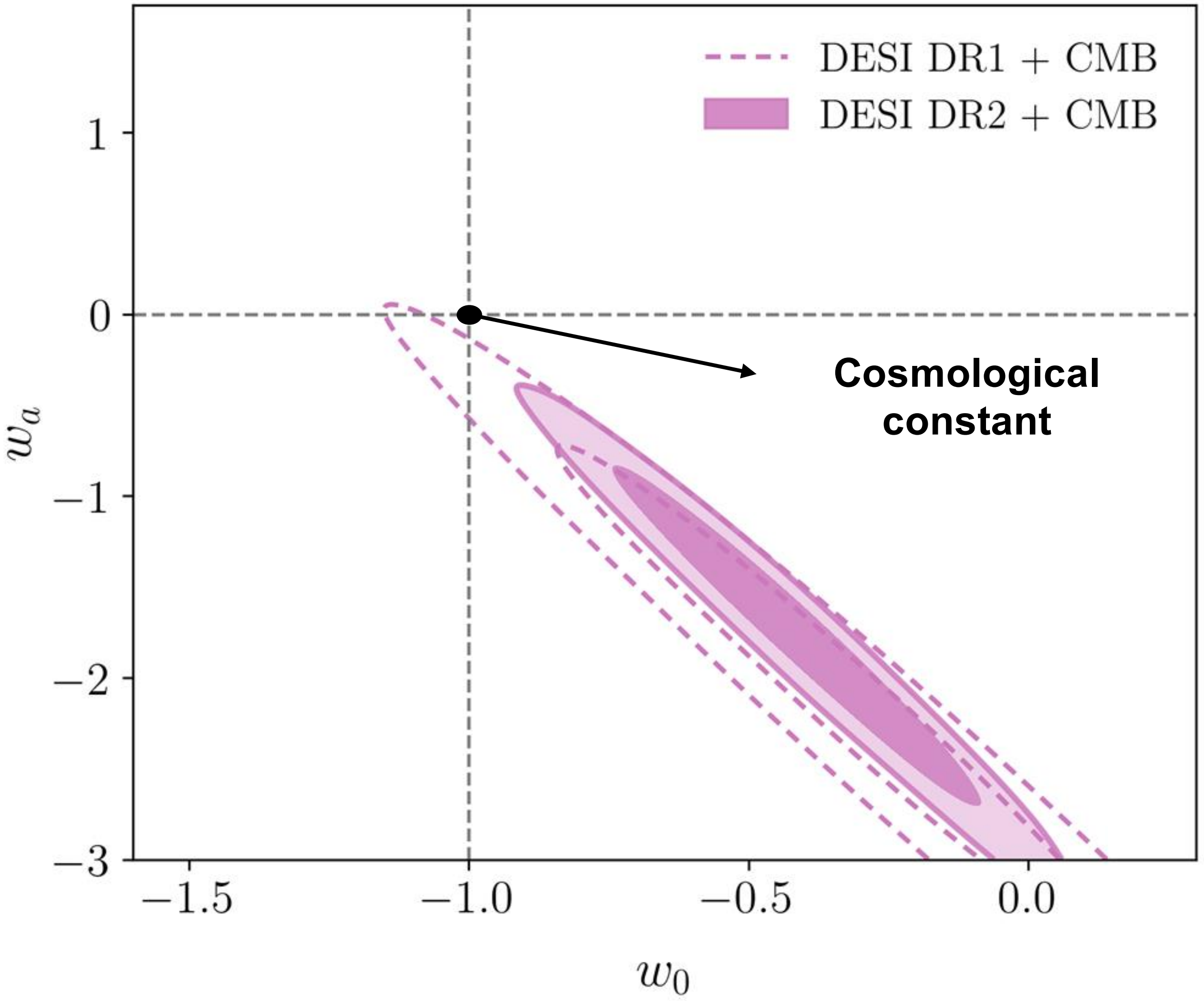


Evolving Dark Energy

$$w(a) = w_0 + (1-a)w_a$$

- **3.1σ** preference for evolving dark energy with DESI DR2 + CMB

$$\left.\begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned}\right\} \textbf{DESI + CMB}$$



Evolving Dark Energy

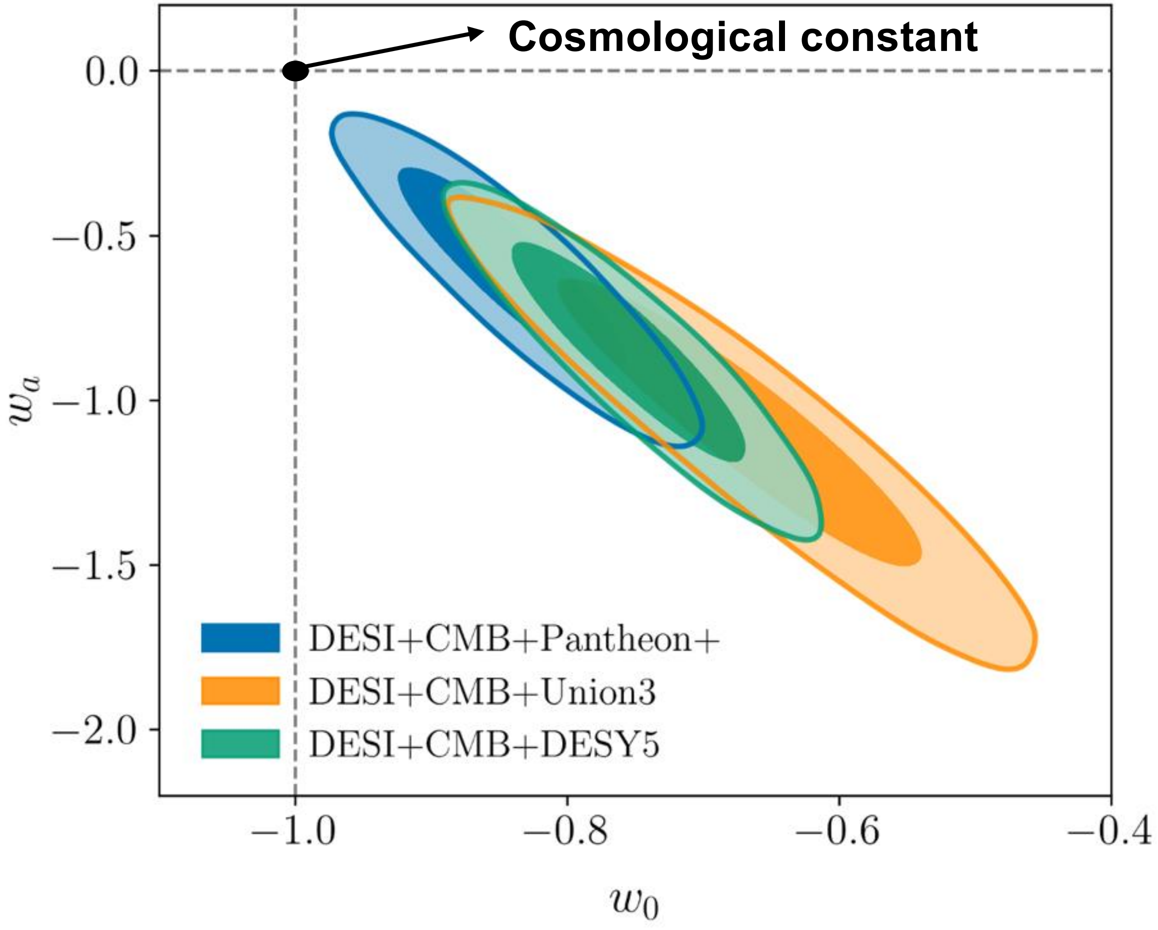
DESI DR2 results II: BAO (*arXiv:2503.14738*)

$$w(a) = w_0 + (1 - a)w_a$$

DESI + CMB + Pantheon+: 2.8σ

DESI + CMB + Union3: 3.8σ

DESI + CMB + DES-SN5Yr: 4.2σ

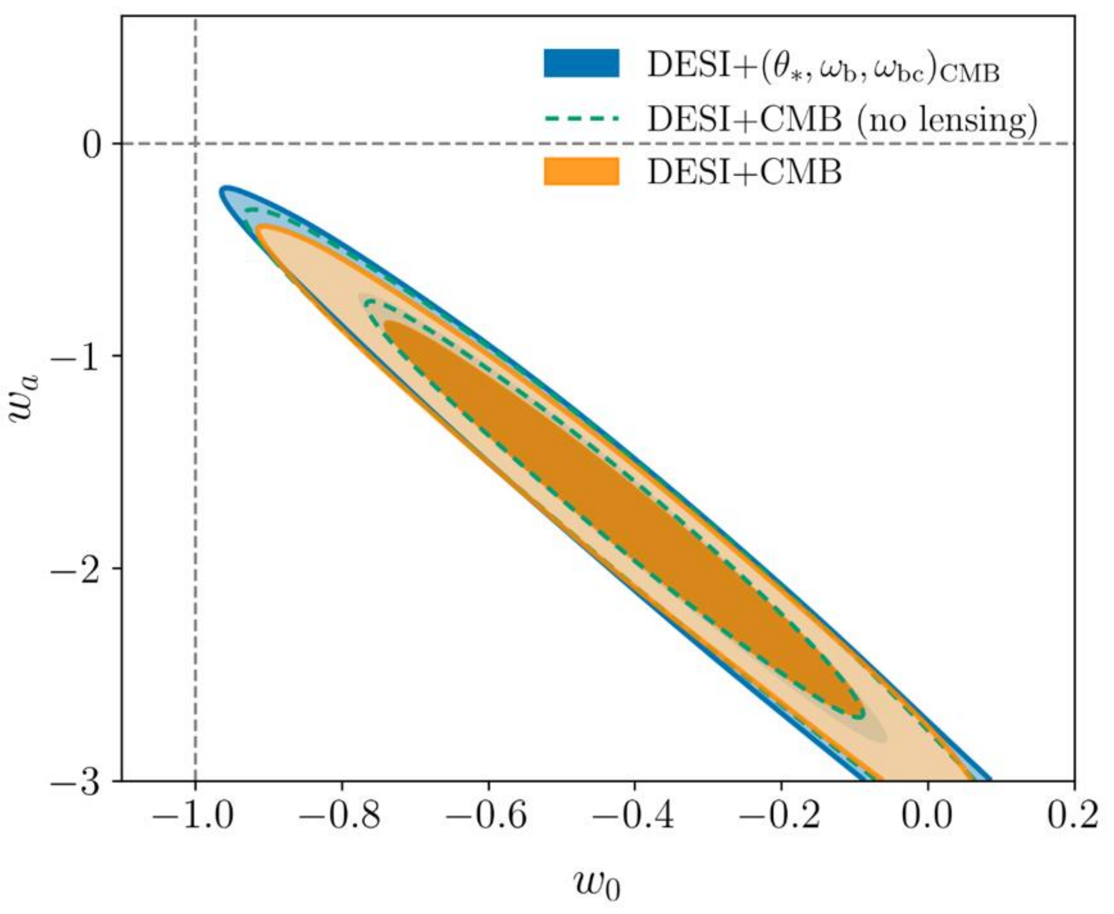


Result robustness

CMB alternatives limited to early-time information

- Early-Universe priors on $(\theta_*, \omega_b, \omega_{bc})$ derived from CMB:
  DESI + $(\theta_*, \omega_b, \omega_{bc})_{CMB} \Longrightarrow$ 2.4σ
- CMB without lensing:
  DESI + CMB (no lensing) $\Longrightarrow$ 2.7σ

Weaker preference (3.1σ for DESI + CMB) but similar posteriors

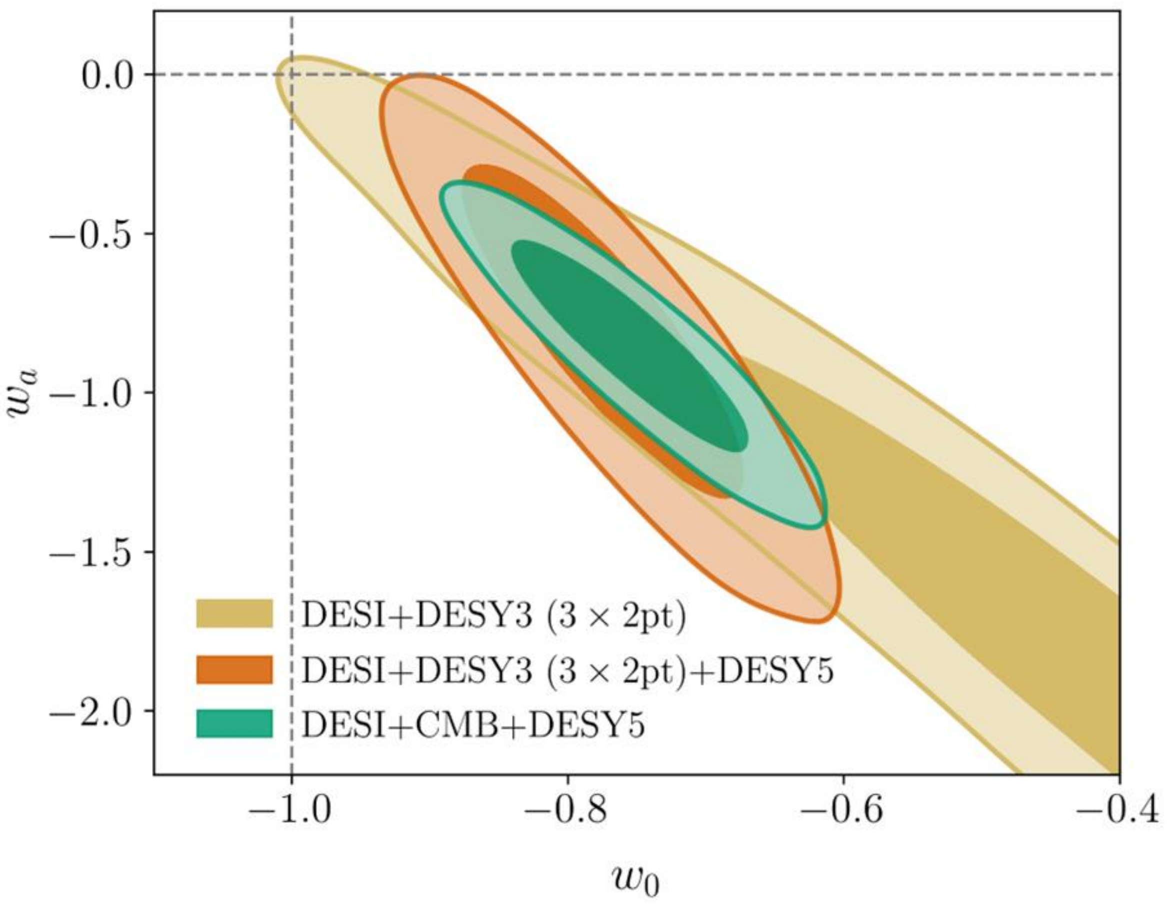


Result robustness

Constraint limited to low-redshift probes

- Replacing CMB with DESY3 $3 \times 2\text{pt}$ (weak lensing + galaxy clustering)
  DESI + DESY3 (3×2pt) $\Longrightarrow$ 2.2σ
  DESI + DESY3 (3×2pt) + DESY5 $\Longrightarrow$ 3.3σ

Preference for same region



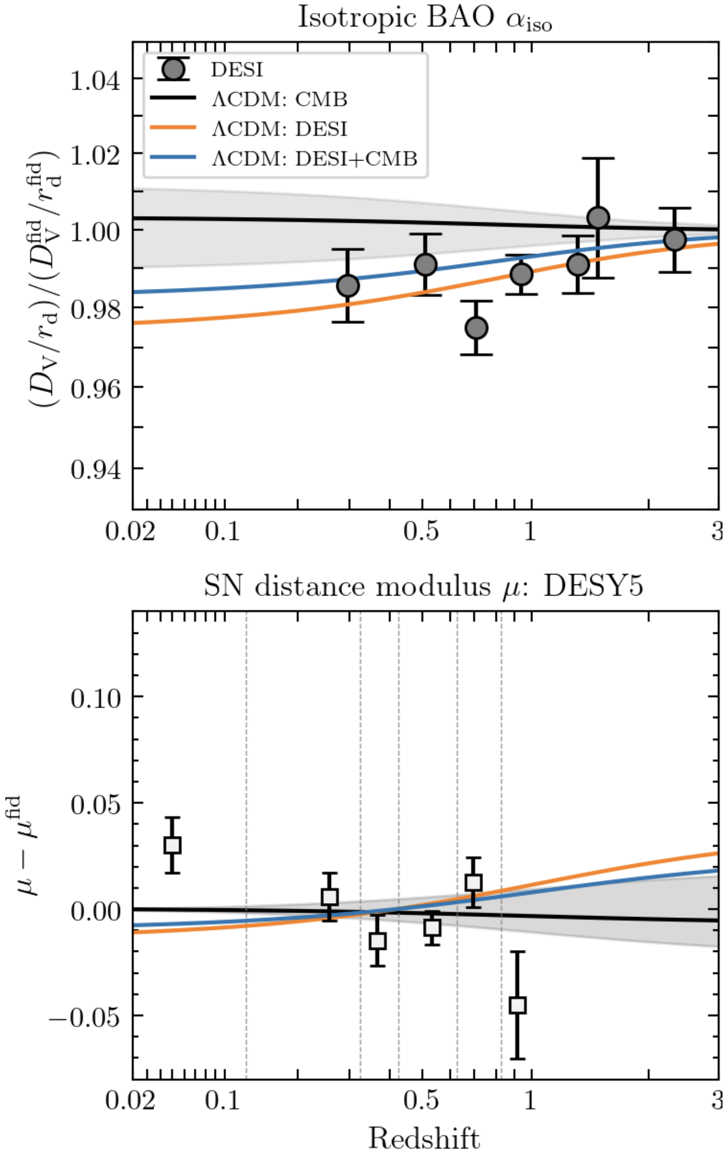
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The nature of the evidence

Isotropic BAO
distance measurement

Supernovae
distance modulus



- **ΛCDM** model can fit DESI BAO
- DESI at $z < 1$ prefer distances 1-2% lower than CMB prediction

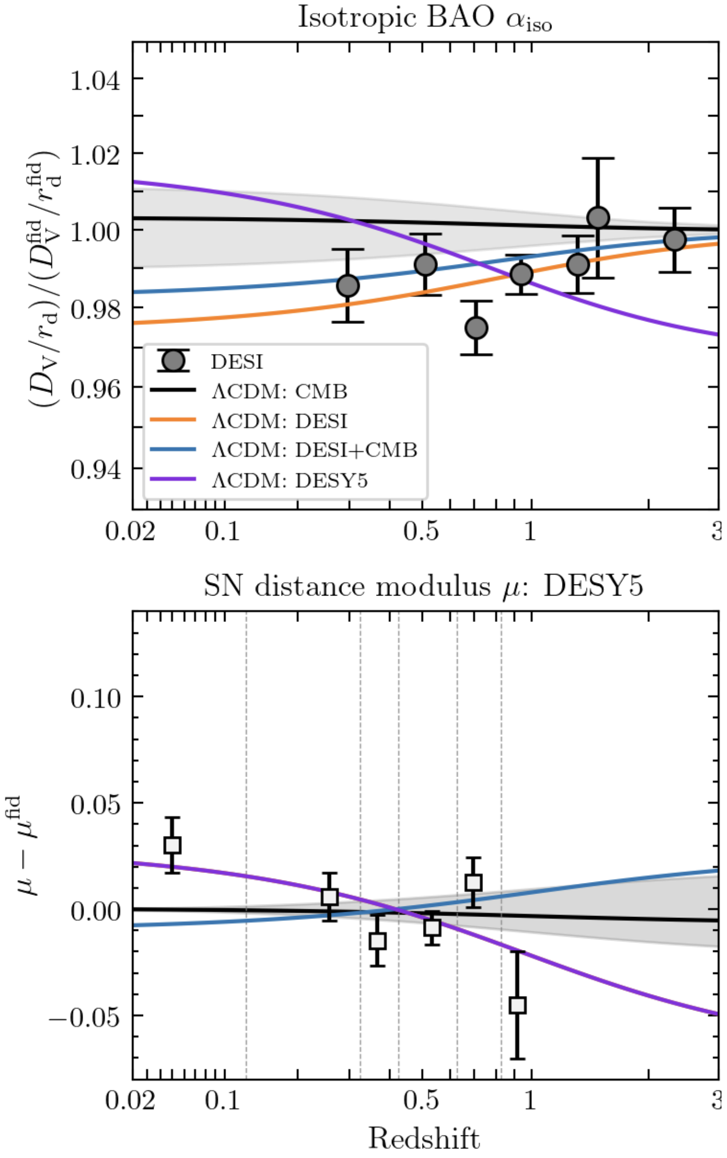
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus



- **ΛCDM** model can fit DESI BAO
- DESI at $z < 1$ prefer distances 1-2% lower than CMB prediction

- **ΛCDM** model can fit SNe
- Tension with DESI and CMB

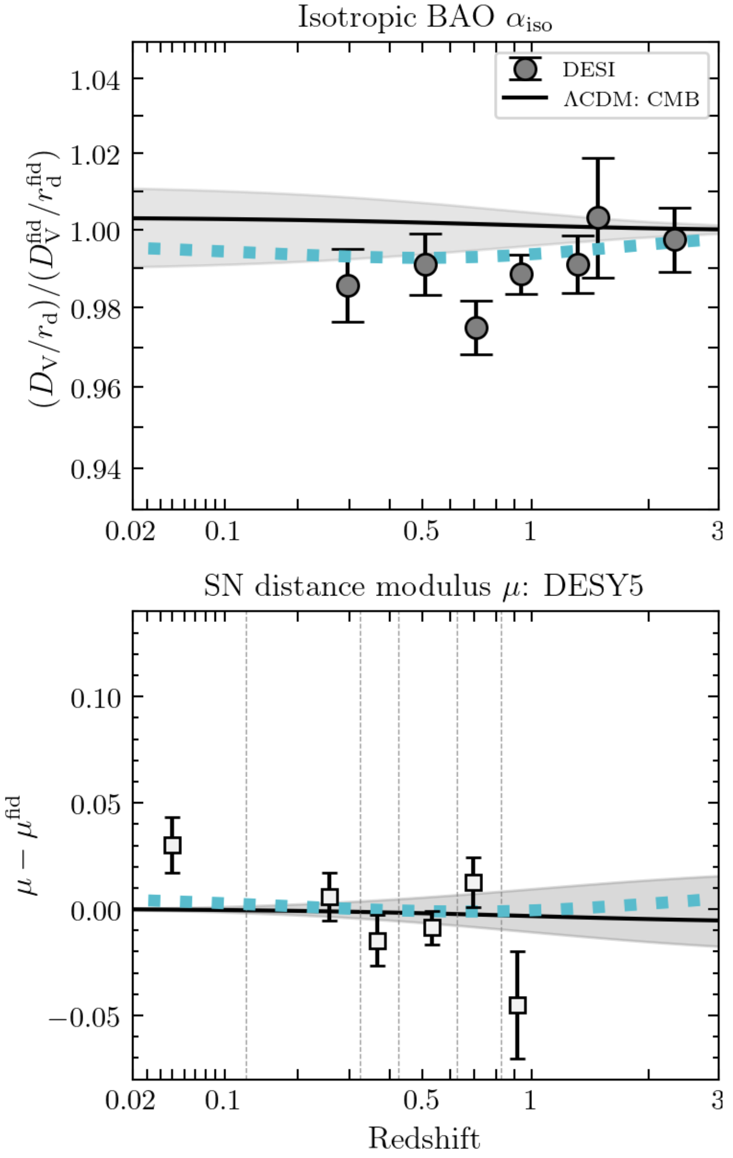
$\Longrightarrow$ No good **ΛCDM** fit to DESI BAO, CMB & SN simultaneously

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

The nature of the evidence

Isotropic BAO
distance measurement

Supernovae
distance modulus



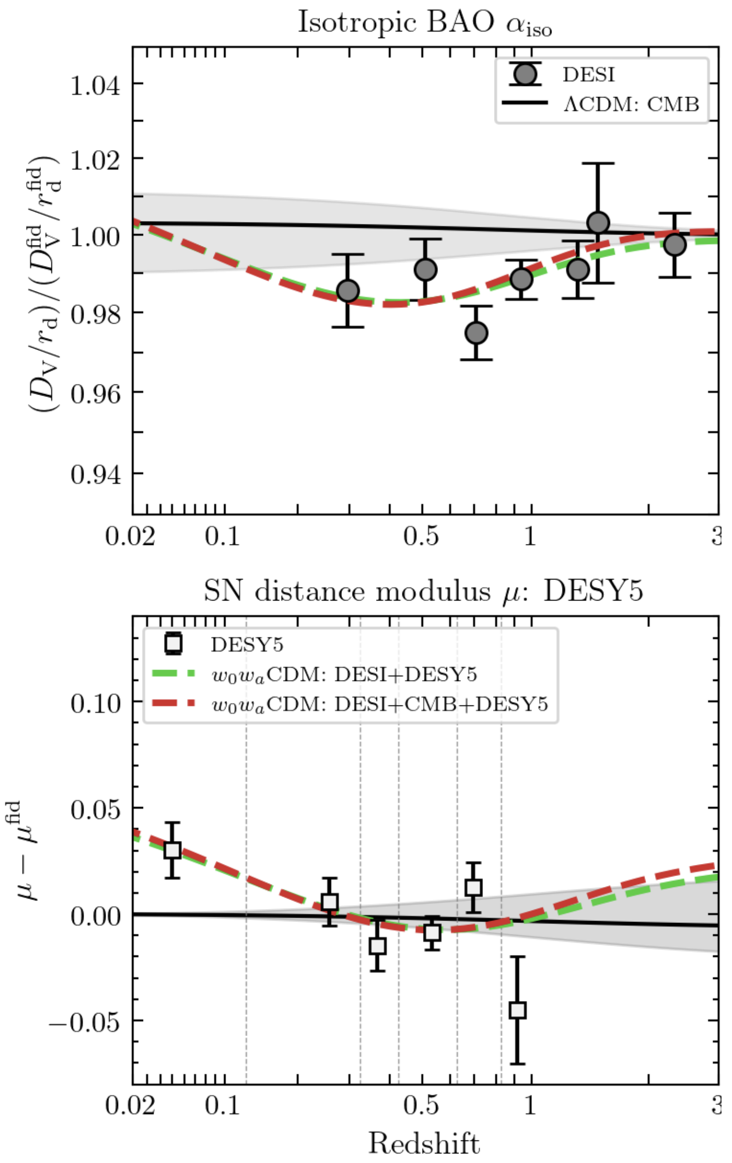
$\Longrightarrow$ Not have enough freedom in ***w*CDM** to fit BAO, CMB and SN simultaneously either

The nature of the evidence

DESI DR2 results II: BAO (*arXiv:2503.14738*)

Isotropic BAO
distance measurement

Supernovae
distance modulus



***w_0w_a*CDM** fit to BAO+SN

also a good fit to CMB

Dark Energy model

Observations = distance(z), not w(z)!

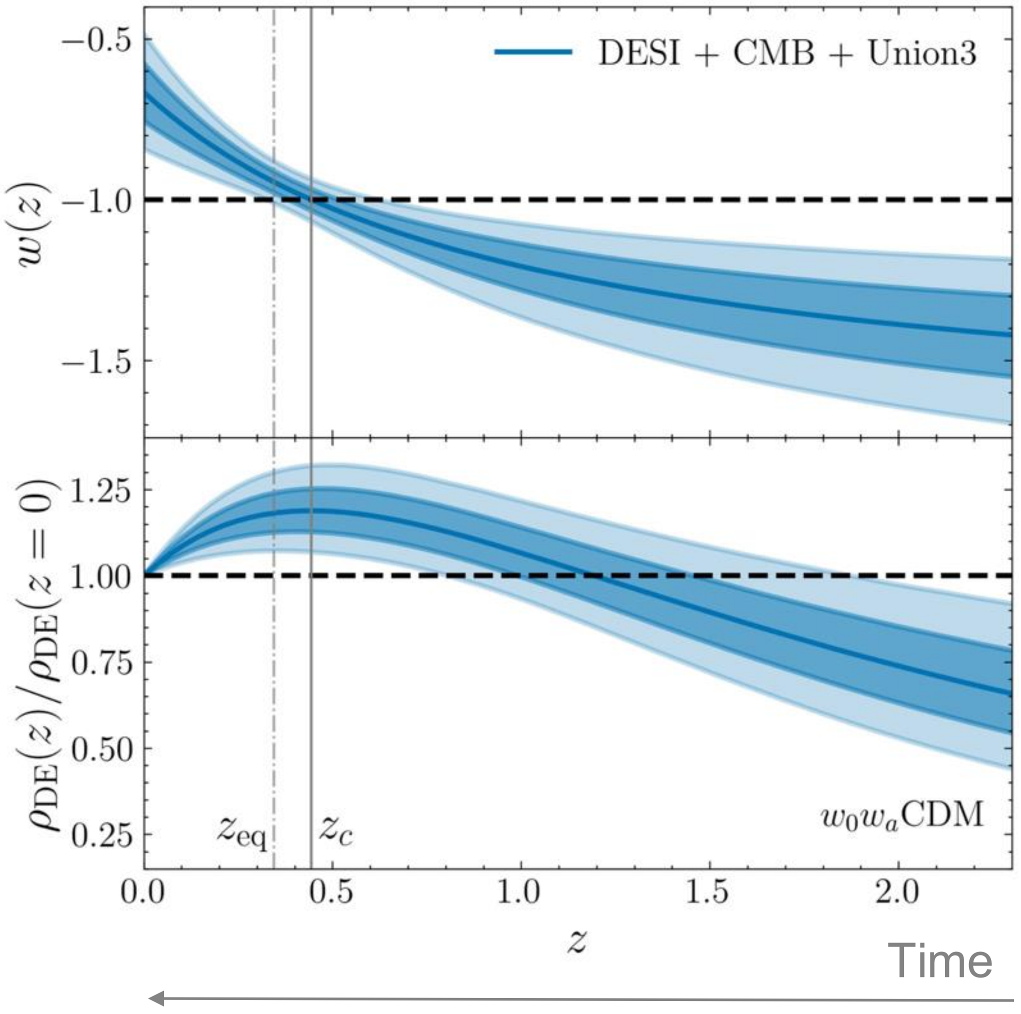
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Dark energy model

DESI DR2 results II: BAO (*arXiv:2503.14738*)

DESI supporting paper Lodha+ (*arXiv:2503.14743*)



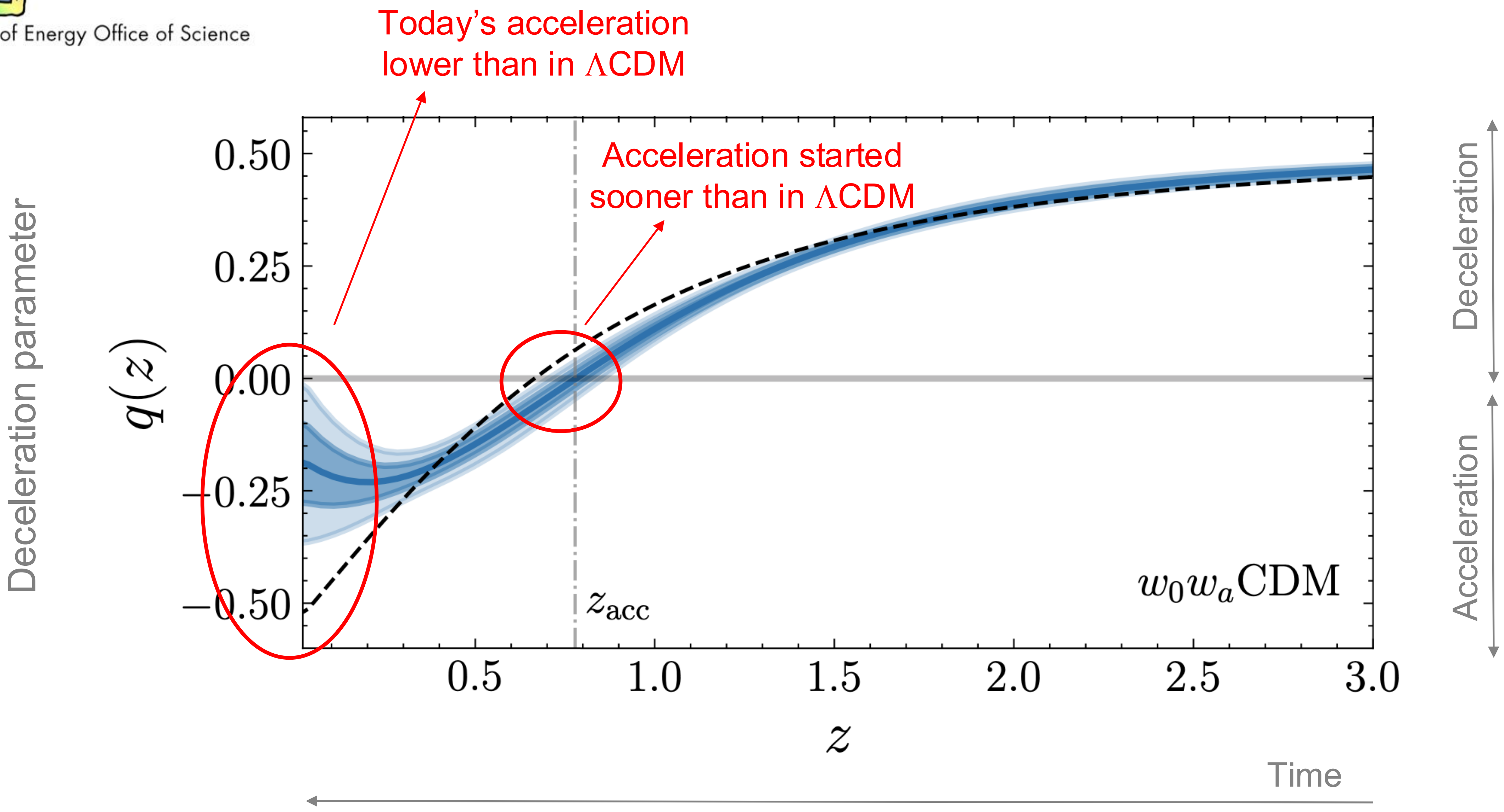
w < -1 at high z : increasing dark energy density with time !

Could indicate more complex dark sector

Maximum dark energy density reached at z ~ 0.45 (phantom crossing)

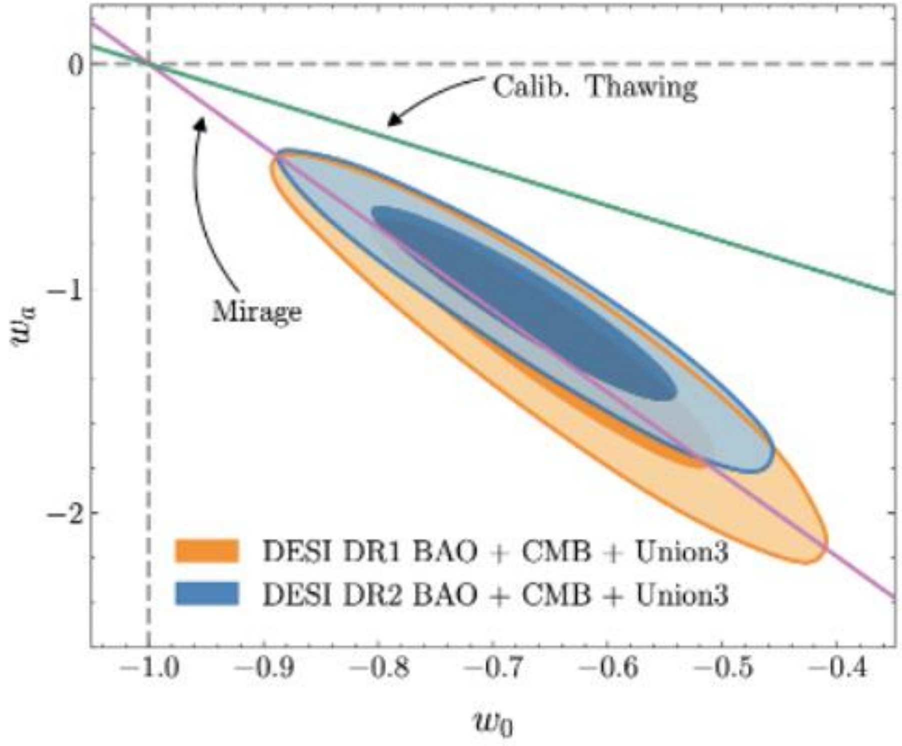
Weakening dark energy

DESI DR2 results II: BAO (*arXiv:2503.14738*)
DESI supporting paper Lodha+ (*arXiv:2503.14743*)



Dark energy model

DESI DR2 results II: BAO (*arXiv:2503.14738*)
DESI supporting paper Lodha+ (*arXiv:2503.14743*)



Three classes of dark energy

- Thawing (away from w = -1)
- Emergent (from ρ = 0, never crosses w = -1)
- Mirage ($\langle w \rangle$ = -1)

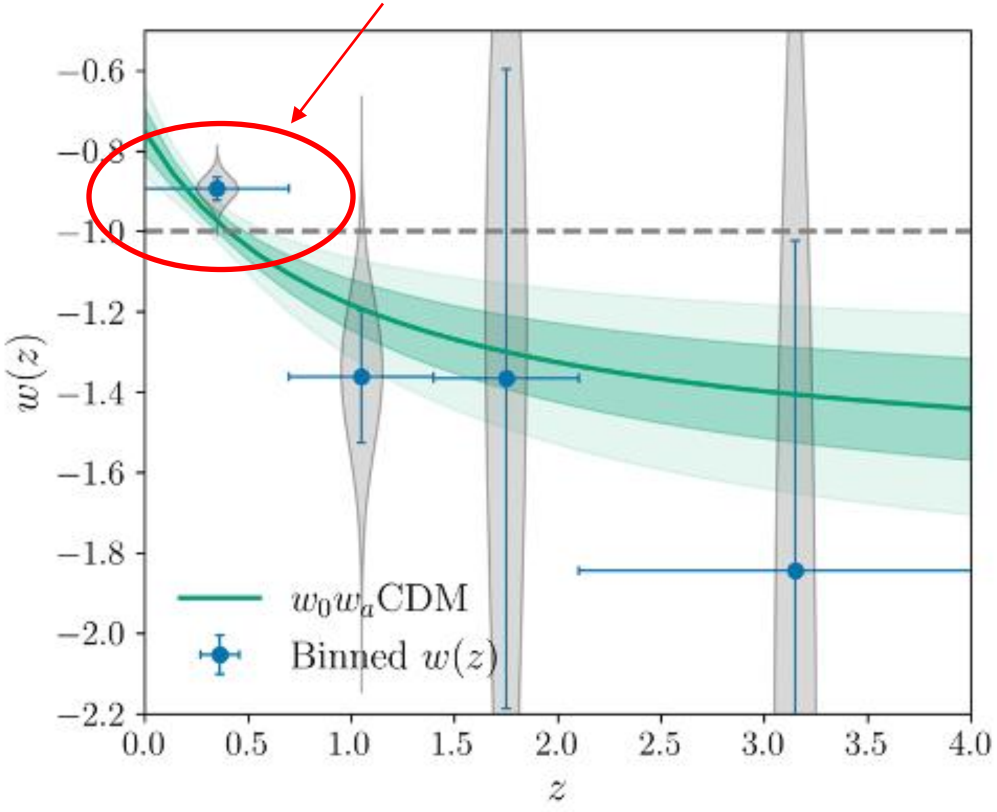
Improvement over LCDM
DESI BAO + CMB + SN (DESY5)

Dark Energy Model	$\Delta\chi^2$
Thawing	-12.0
Emergent	-3.9
Mirage	-21.3
$w_0 w_a$	-21.4

Dark energy model

DESI DR2 results II: BAO (*arXiv:2503.14738*)
DESI supporting paper Lodha+ (*arXiv:2503.14743*)

>3σ from ΛCDM



Binned reconstruction of $w(z)$

- Consistent with w_0w_aCDM
- Weaker than ΛCDM at small z (>3σ)
- Preference for ”phantom” at large z

Neutrino masses

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Upper bounds on neutrino masses

In ΛCDM, Σm_ν changes angular diameter distance to last scattering, degenerate with Ω_m, H_0 …

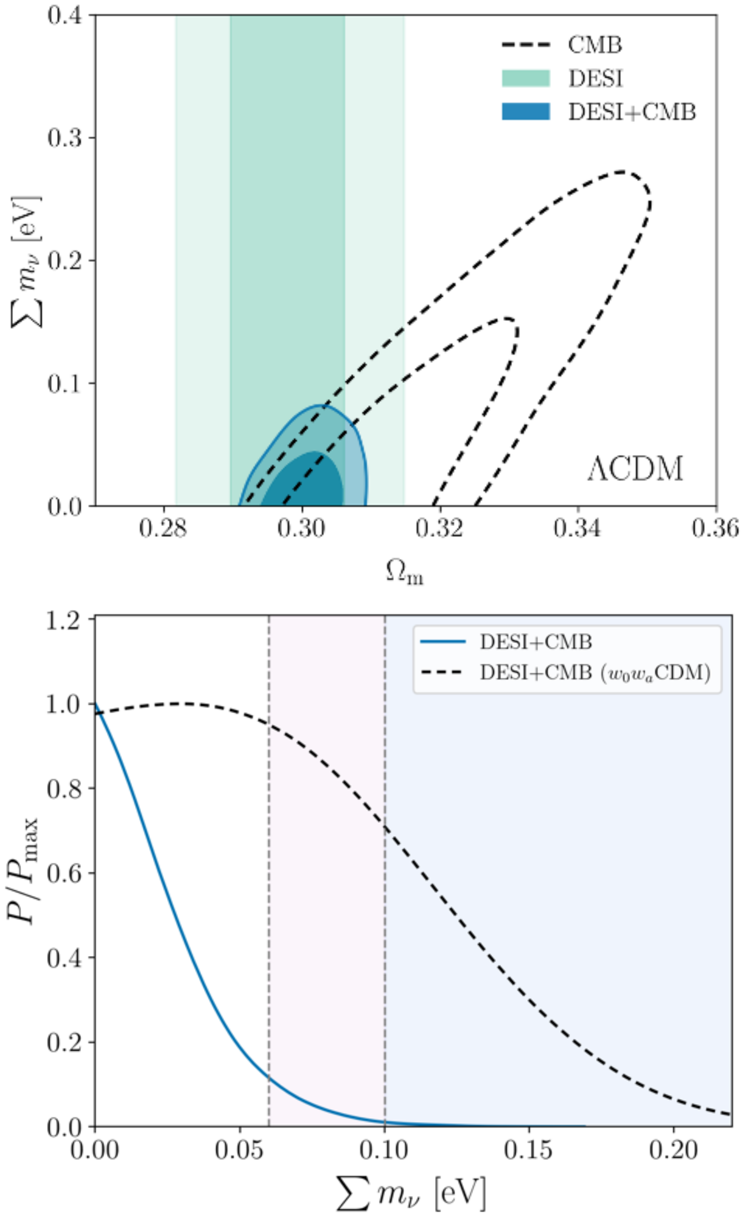
BAO breaks degeneracy

$$\sum m_\nu < 0.064 \text{ eV}$$ (95%, DESI (BAO)+CMB)

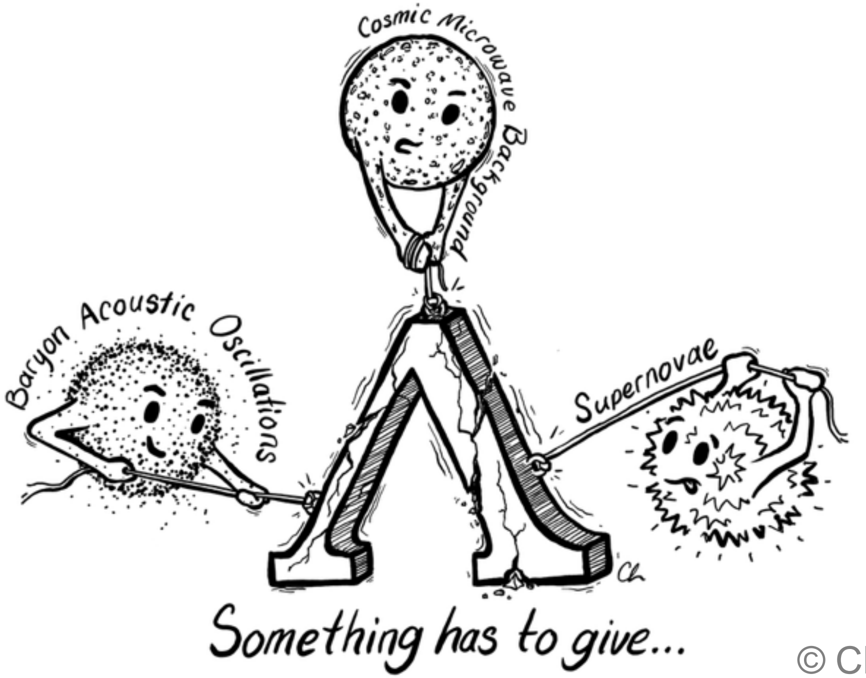
Tightest constraint to-date (in ΛCDM)

In w_0w_aCDM, relaxed to

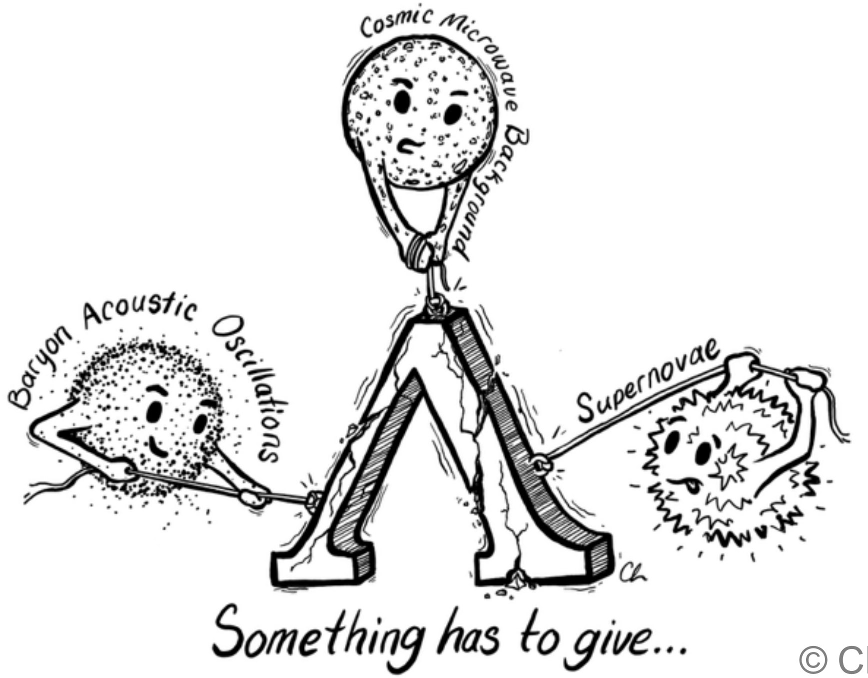
$$\sum m_\nu < 0.163 \text{ eV}$$ (95%, DESI (BAO)+CMB)



Thank you!


Cosmic Microwave Background
Baryon Acoustic Oscillations
Supernovae
Something has to give...

Thank you!



DESI will observe until 2029!

- extended southern footprint by ~20% (down to DEC -20)
- Increase overlap with LSST, Simons Observatory by ~50%