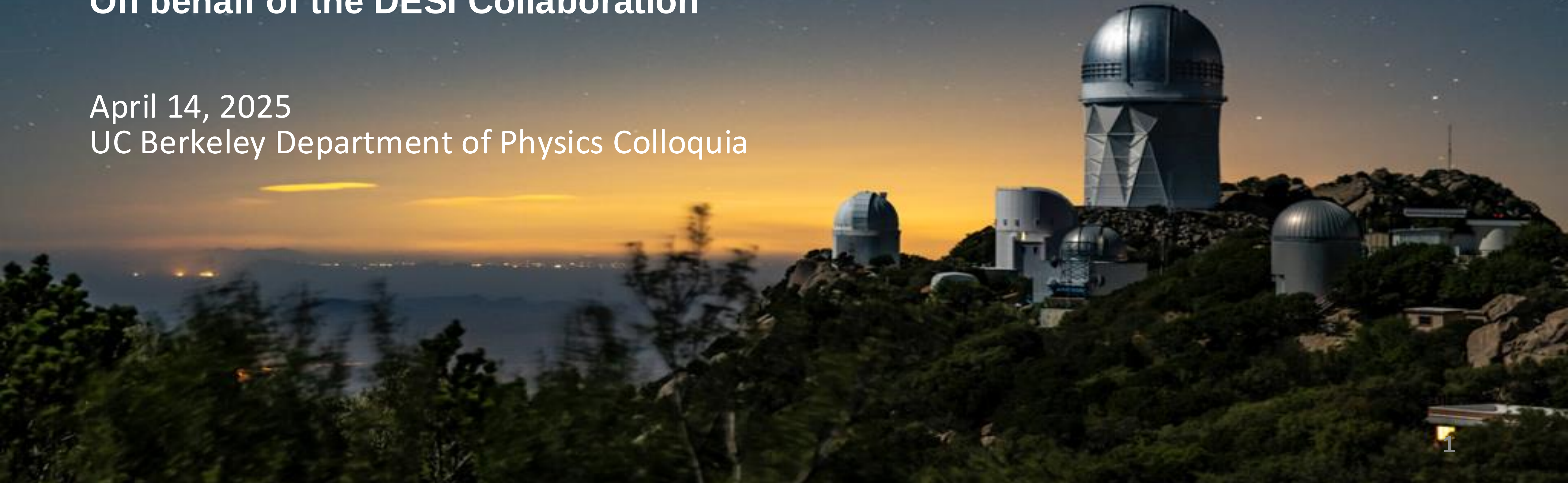
DESI shakes up the Dark Universe

Nathalie Palanque-Delabrouille (Berkeley Lab)

On behalf of the DESI Collaboration

April 14, 2025
UC Berkeley Department of Physics Colloquia



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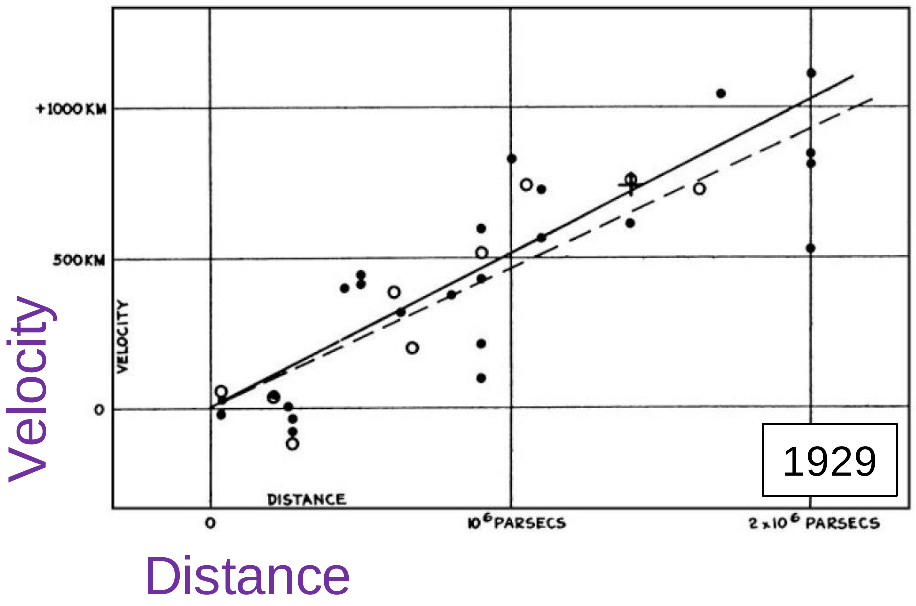
The expanding universe

Velocity increases with Distance



Expanding Universe

Velocity = H x Distance

H ~ 70 km/s/Mpc*
(7% per Giga-year)
*current estimation

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The expanding universe

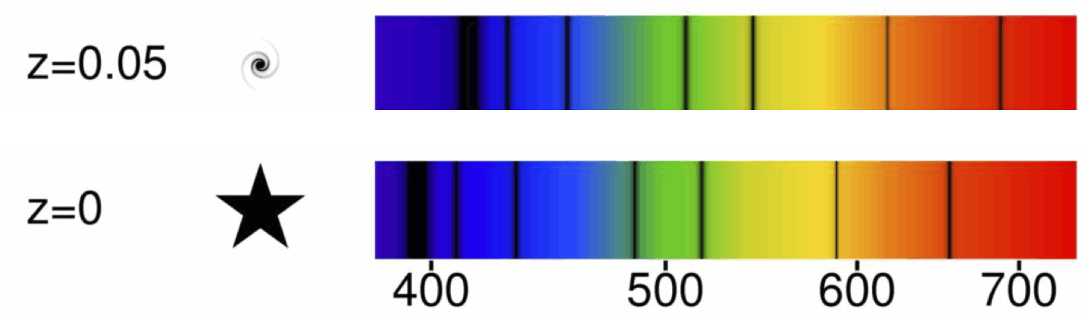
Hubble law

v = H . D

Spectroscopy

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

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



Photometry

Source of known luminosity

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

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

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

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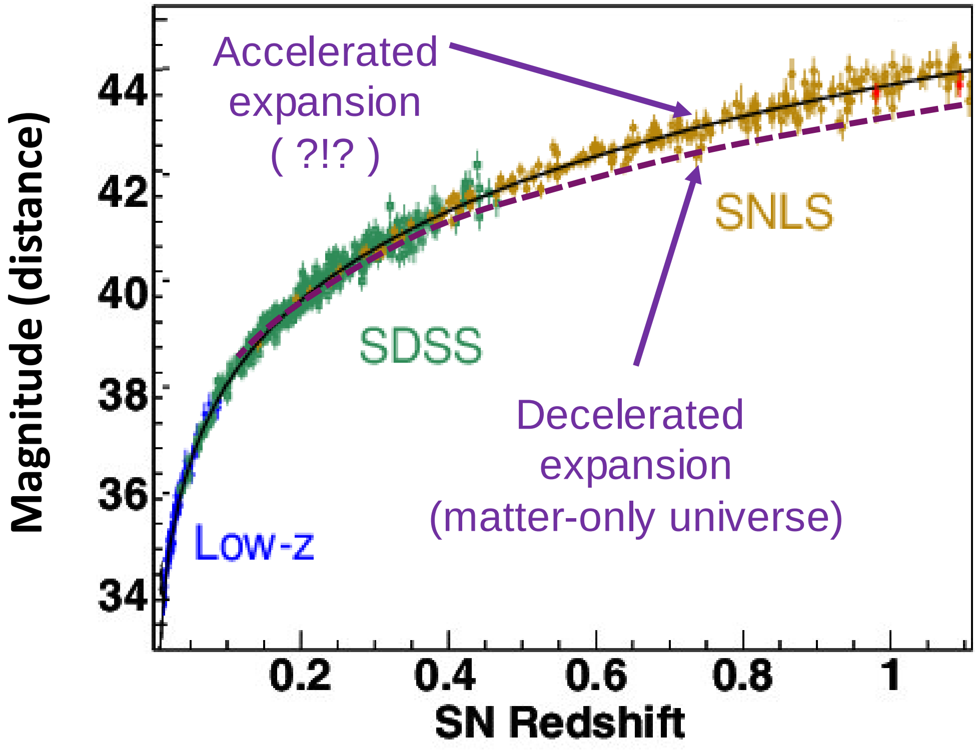
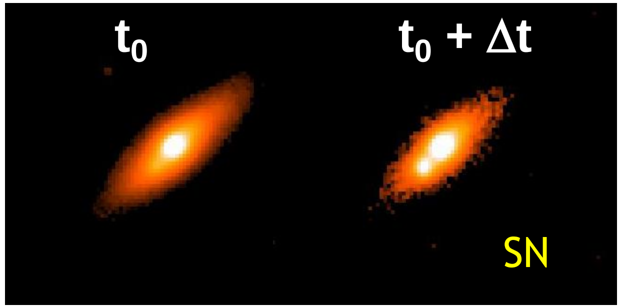
The expanding universe

2011 Nobel Prize

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

Hubble diagram
distance – redshift relation





SN Ia
(known luminosity)

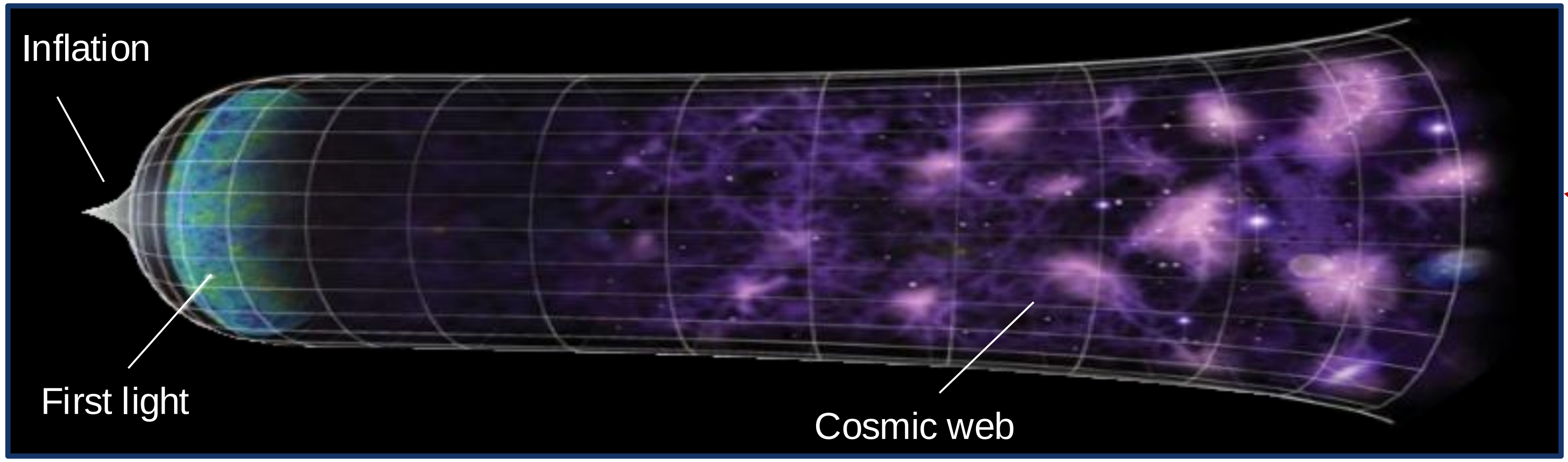
SNIa are weaker (~20%)
for a given redshift
Hence more distant (~10%)

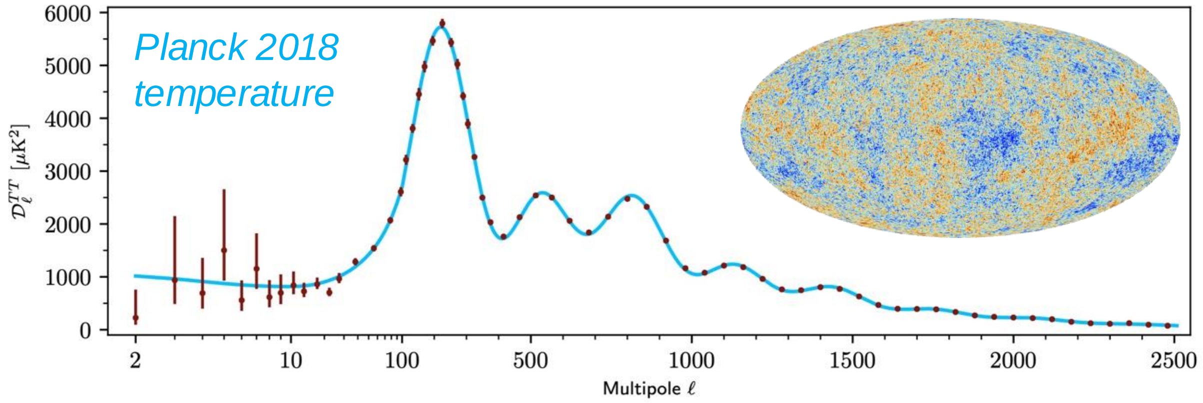
Accelerated expansion

Incompatible with matter domination

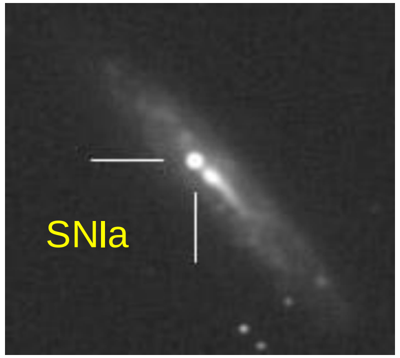
DARK ENERGY!

Standard model of cosmology





Cosmic Microwave Background



Accelerated expansion

Physics we know
+ cosmological model

successfully predicts most observations of last 20 yrs

Standard model of cosmology – ΛCDM

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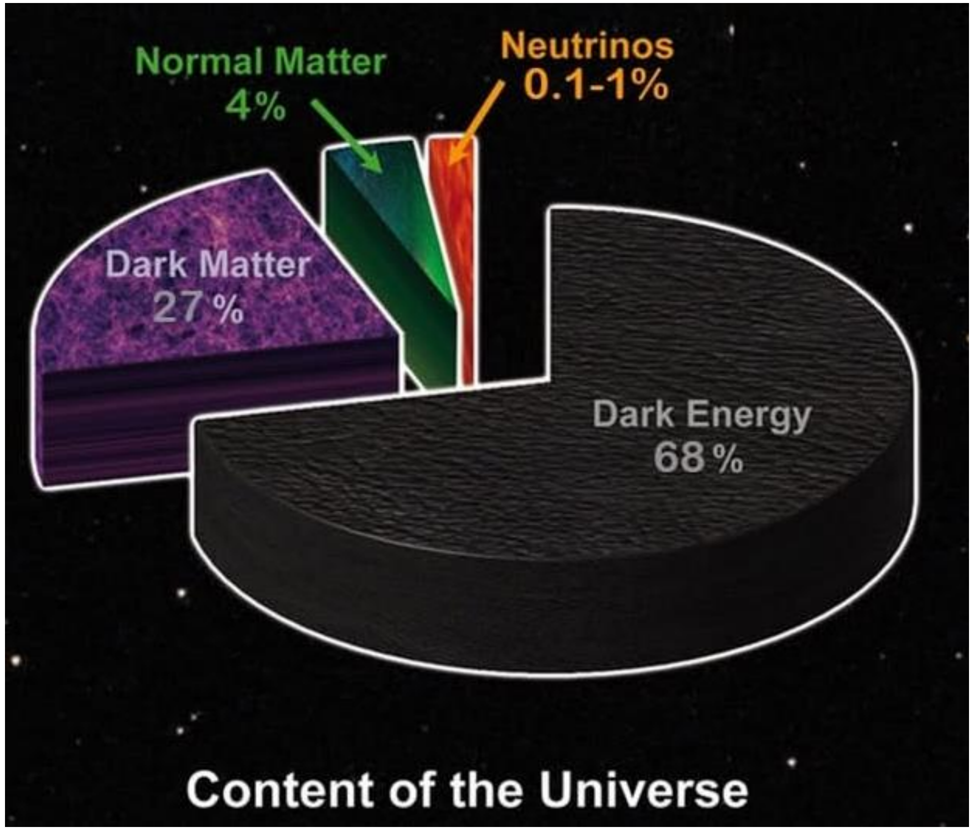


Two main two components of unknown nature

- **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

Accelerated expansion

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

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

Modified gravity?
Beyond general relativity

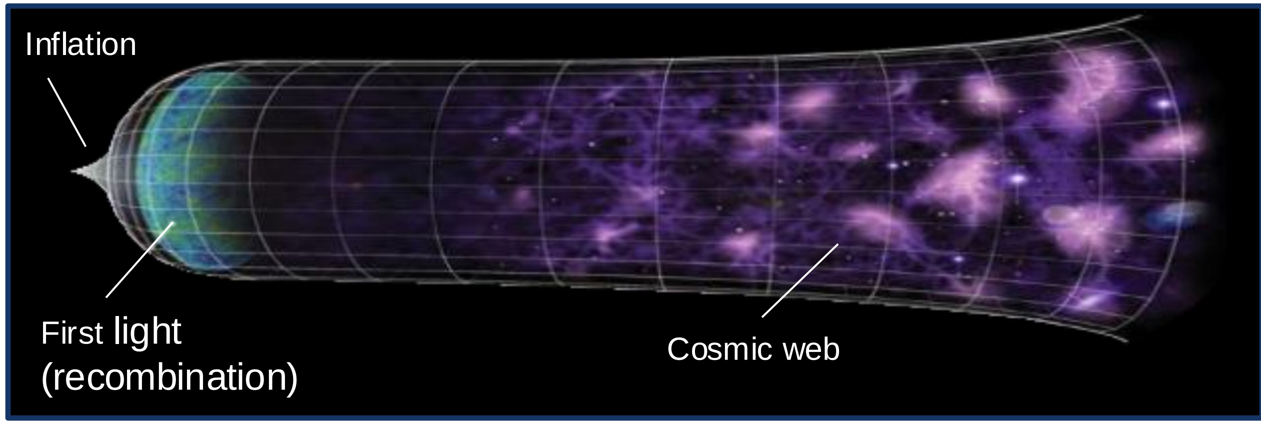
Baryon Acoustic Oscillations

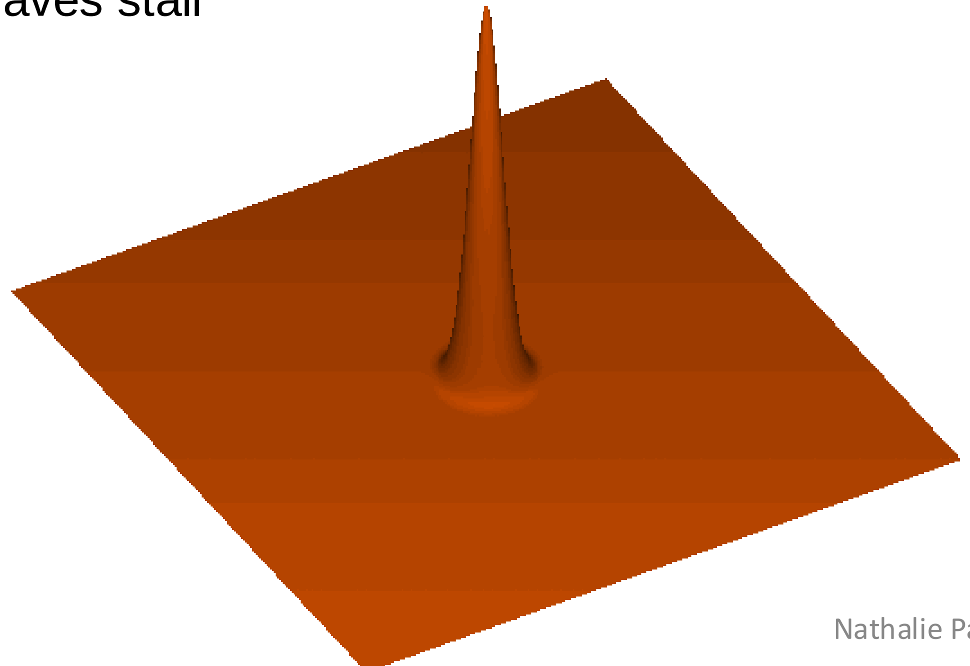
Baryon Acoustic Oscillations (BAO)

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

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

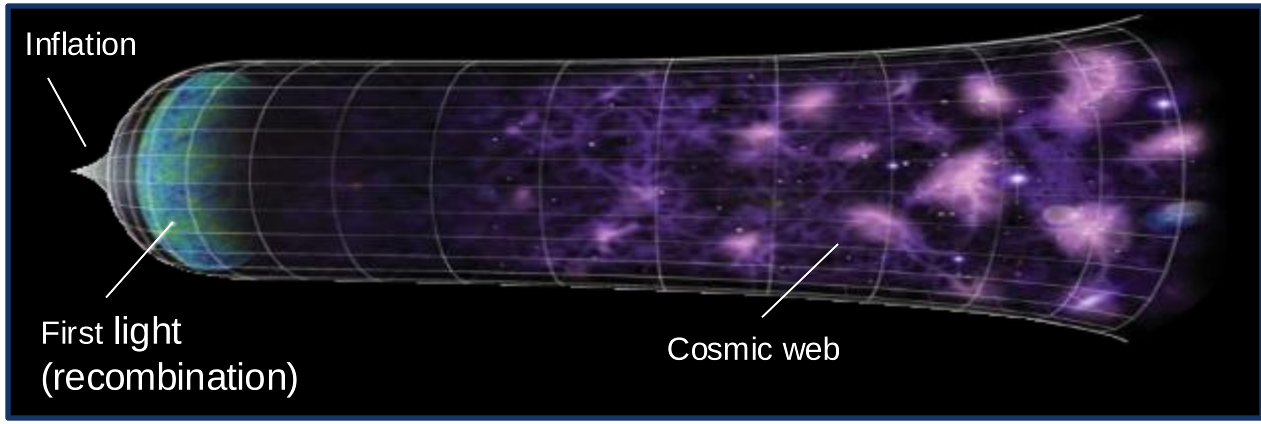
- Plasma evolves from optically thick to optically thin
- Baryons decouple from photons
- Waves stall





Residual spherical shell ⟶ Peak in clustering of matter

Baryon Acoustic Oscillations (BAO)



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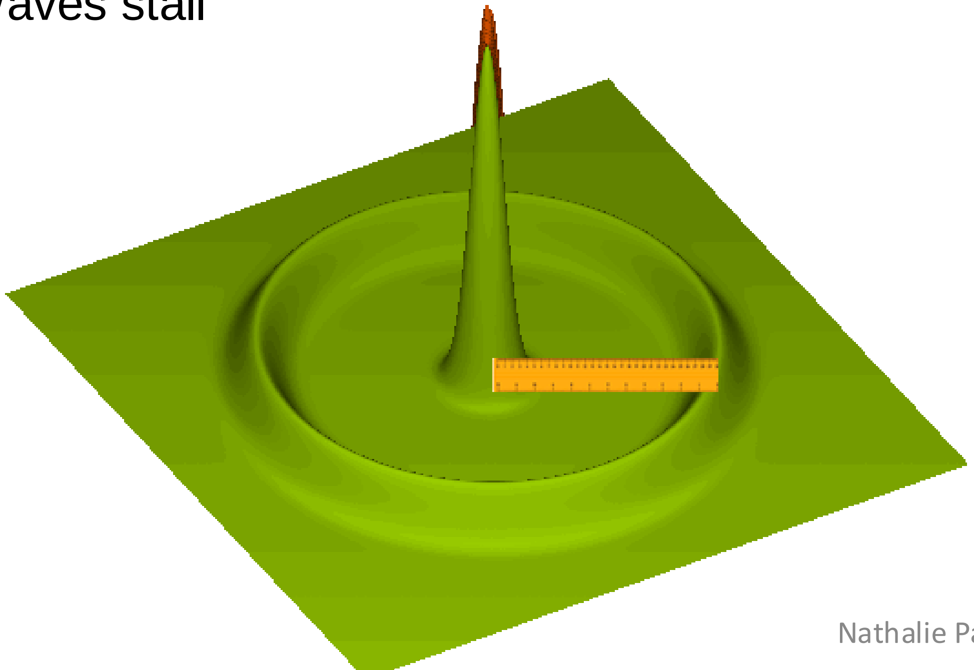

Residual spherical shell ⟶ Peak in clustering of matter

Size of feature = distance sound wave traveled

Preferred 3D scale $r_s \sim 150$ kpc (at recombination)
$r_s \sim 150$ Mpc (today)

Baryon Acoustic Oscillations (BAO)

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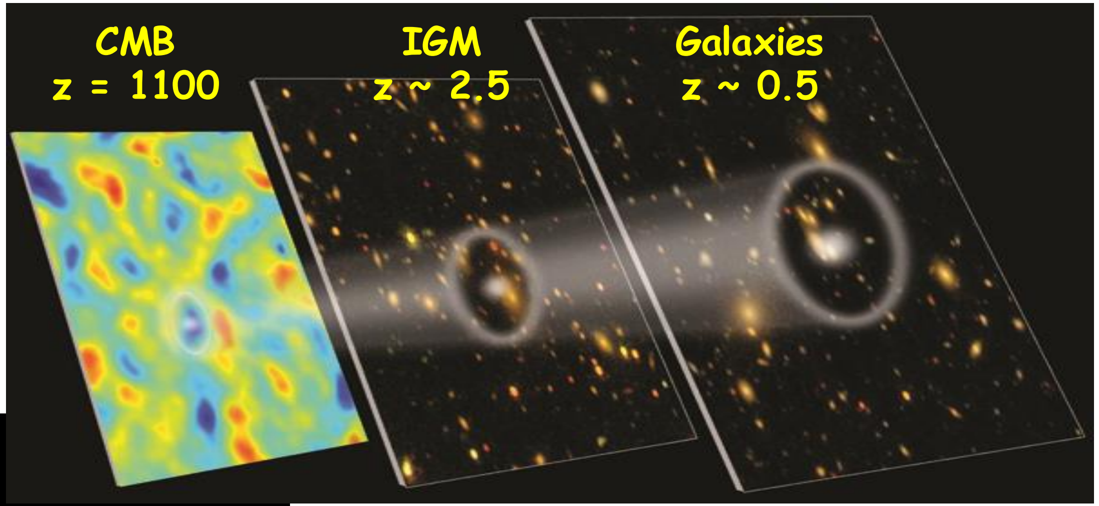
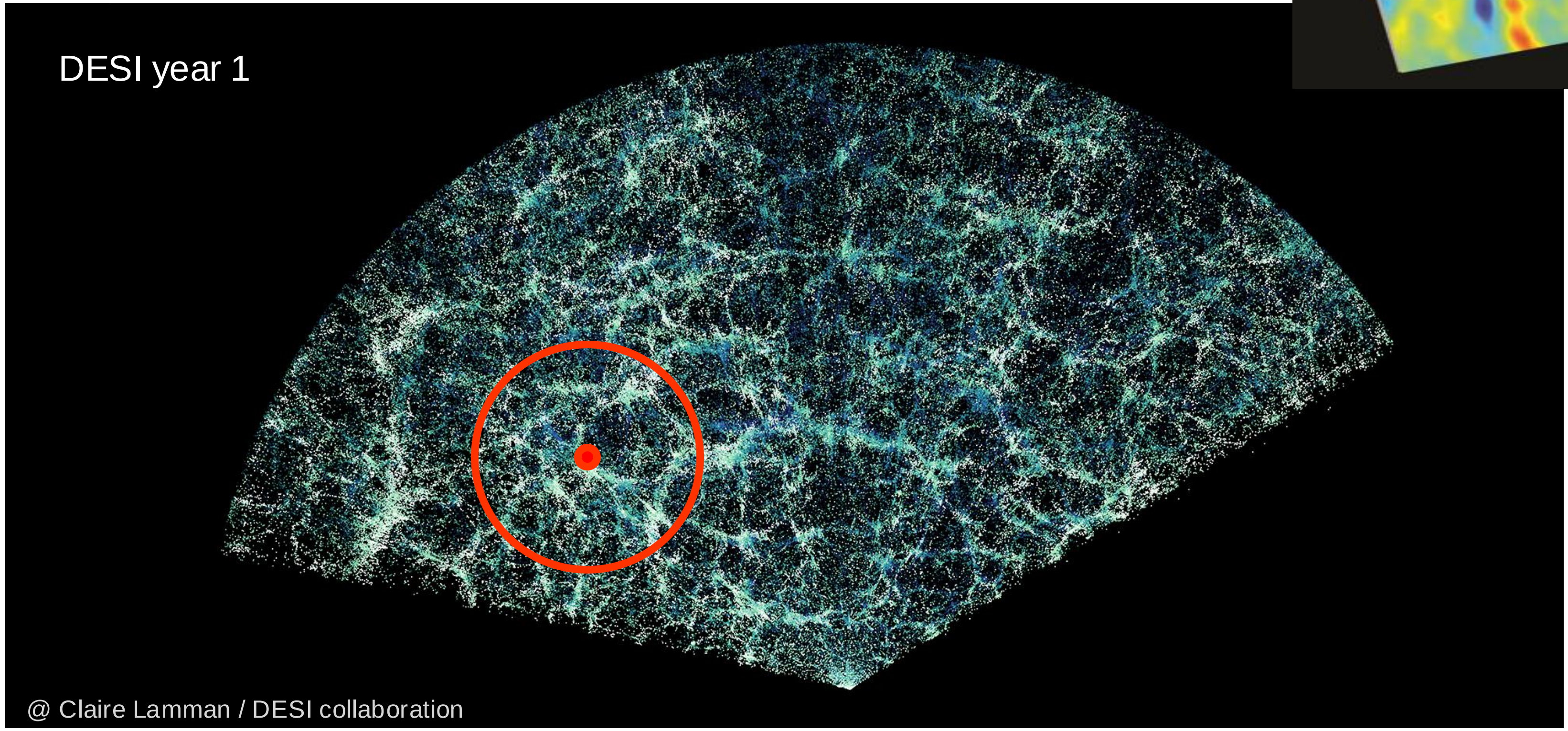
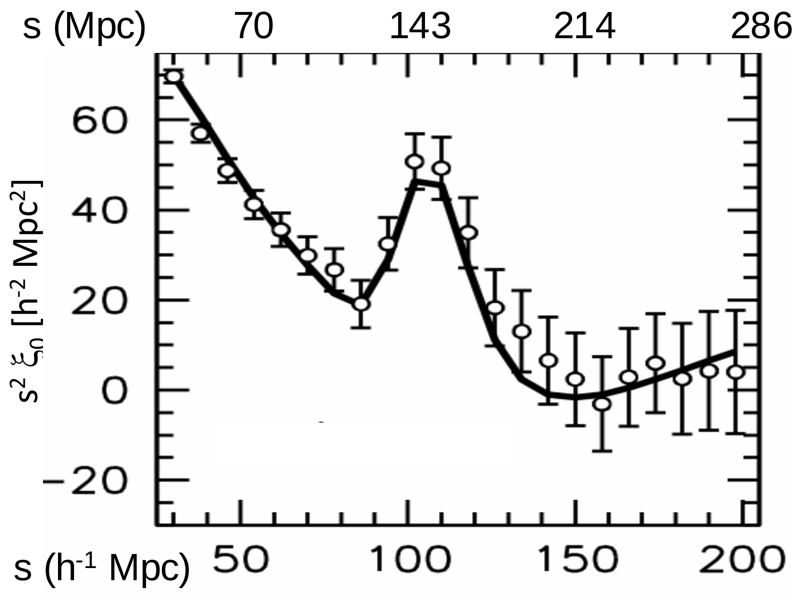
Imprint of fluctuations in primordial plasma
→ Standard Ruler to measure distances







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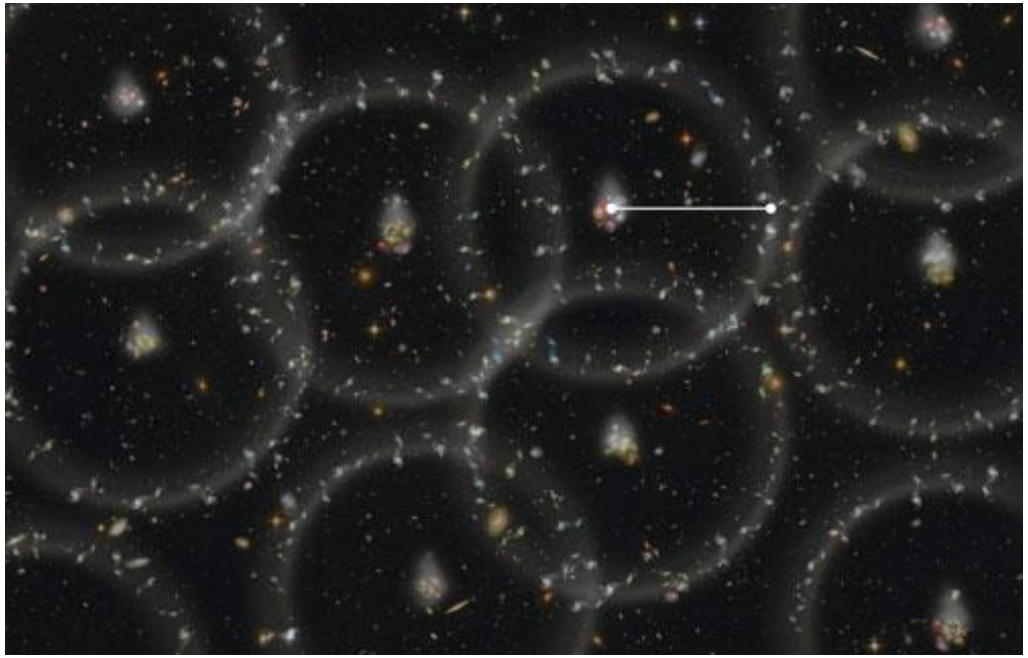
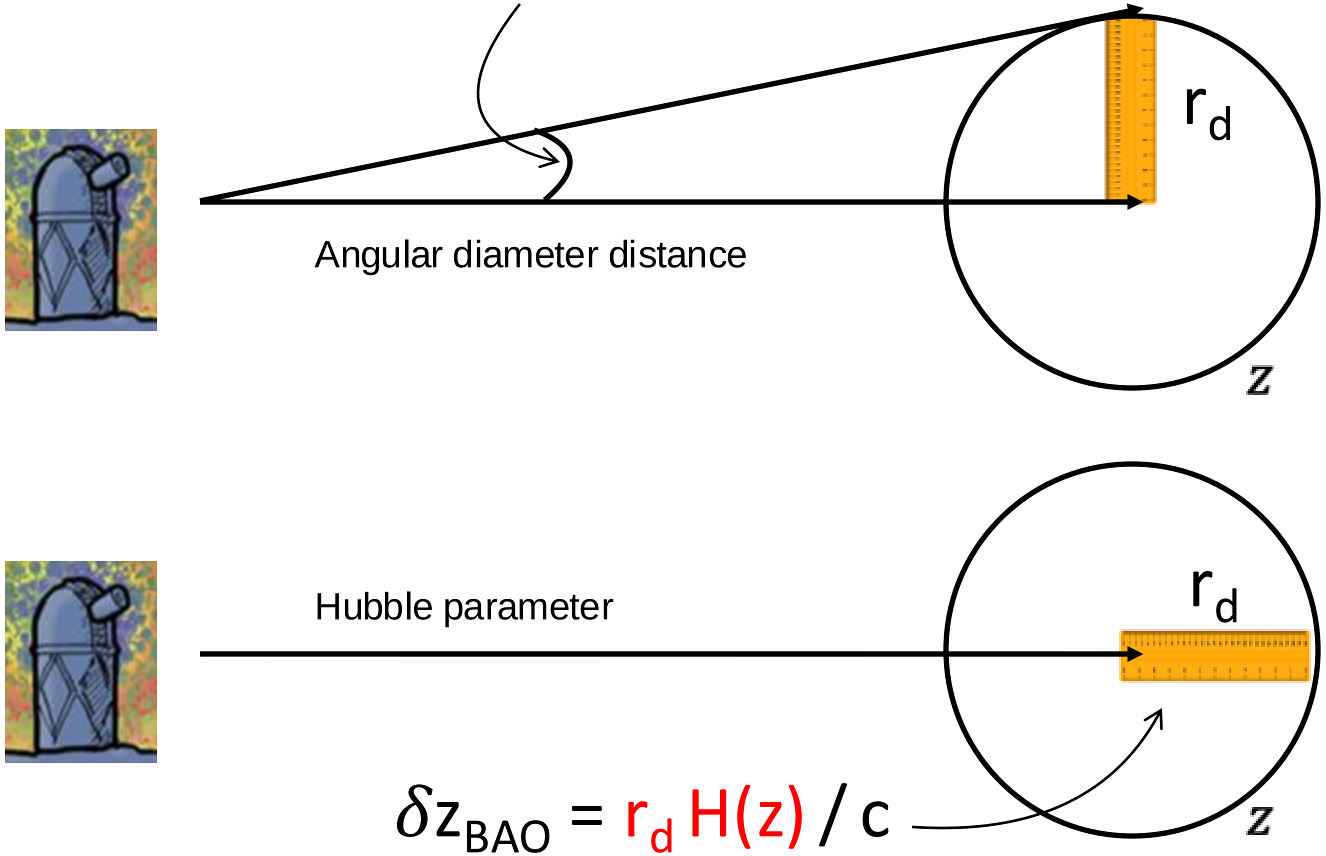
The BAO standard ruler

$$\theta_{BAO} = r_d \,/\, D_M(z)$$

Artist's view of BAO





$$\delta z_{BAO} = r_d\, H(z) \,/\, c$$

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

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DESI

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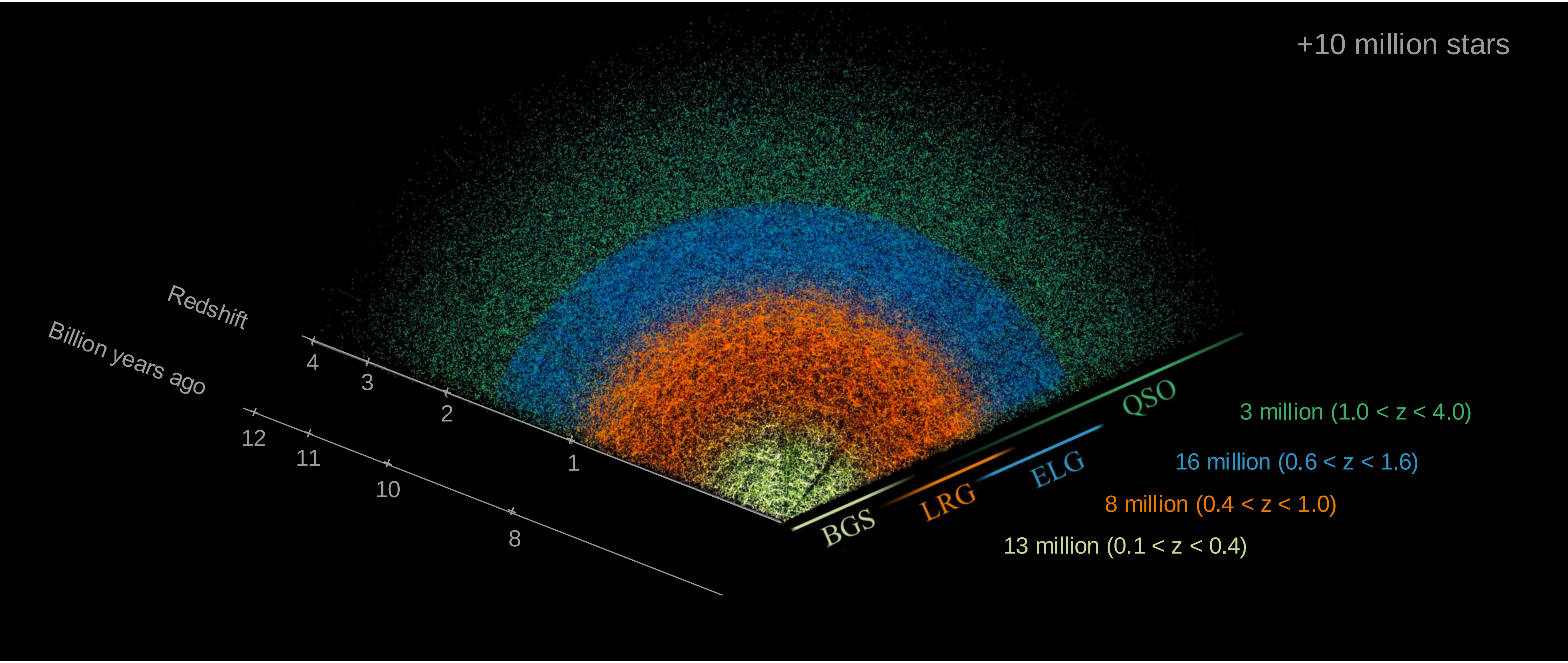
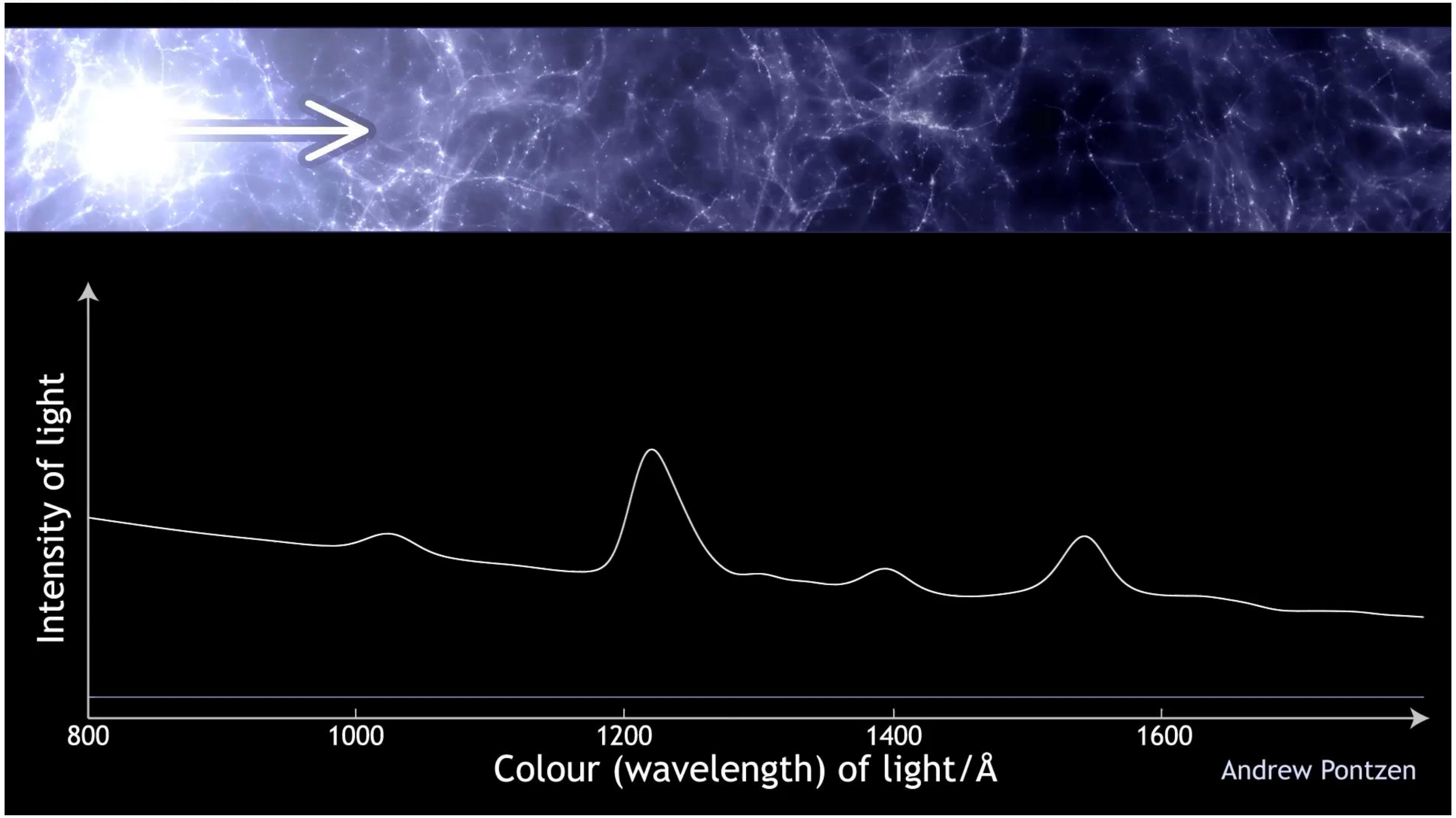
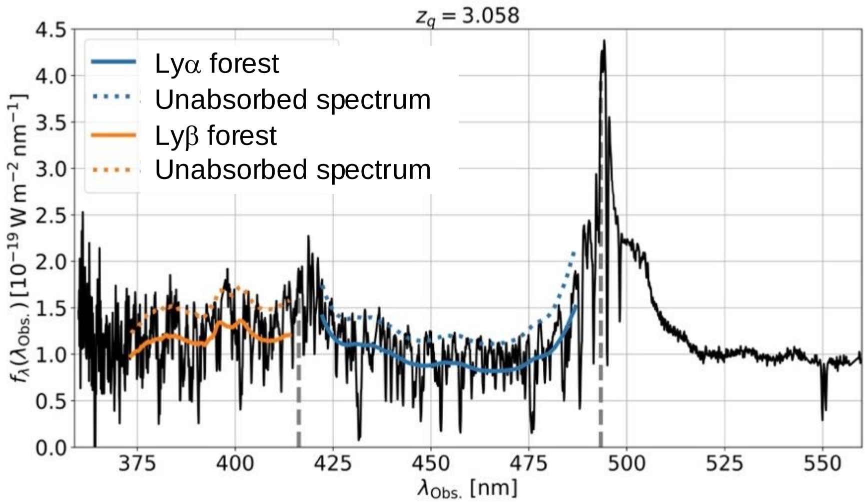
72 Participating Institutions!

DESI targets: 40 million galaxies & quasars!



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

DESI instrument

Mayall telescope
at Kitt Peak Observatory (AZ)

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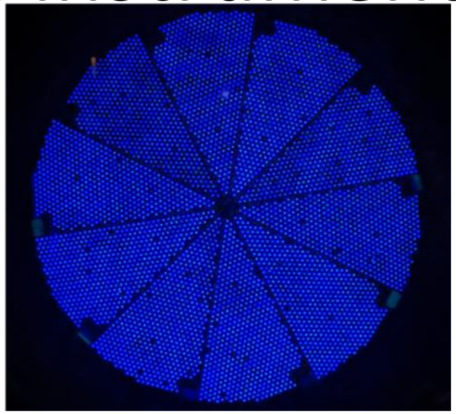
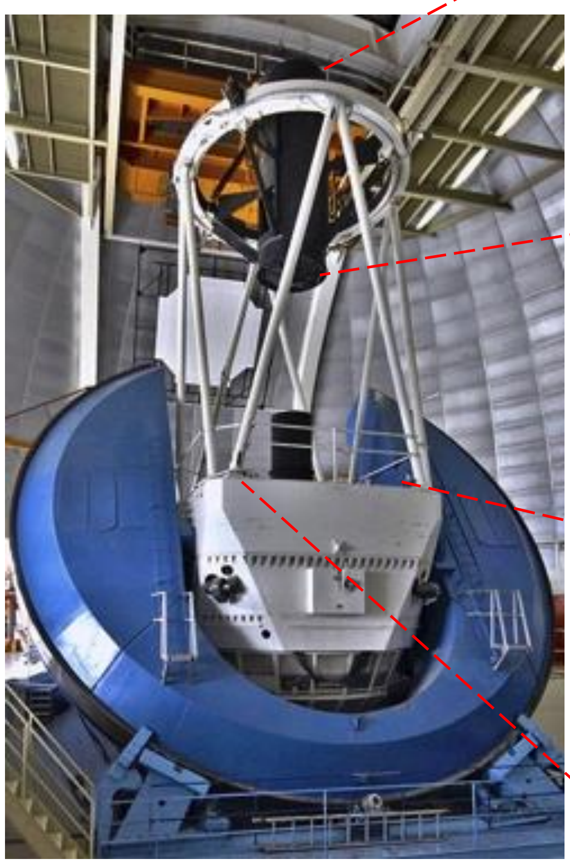
DESI instrument



Focal plane:
5000 fiber positioners
(high multiplexing)

7 deg^2
field of view



4m mirror
(large collecting area)

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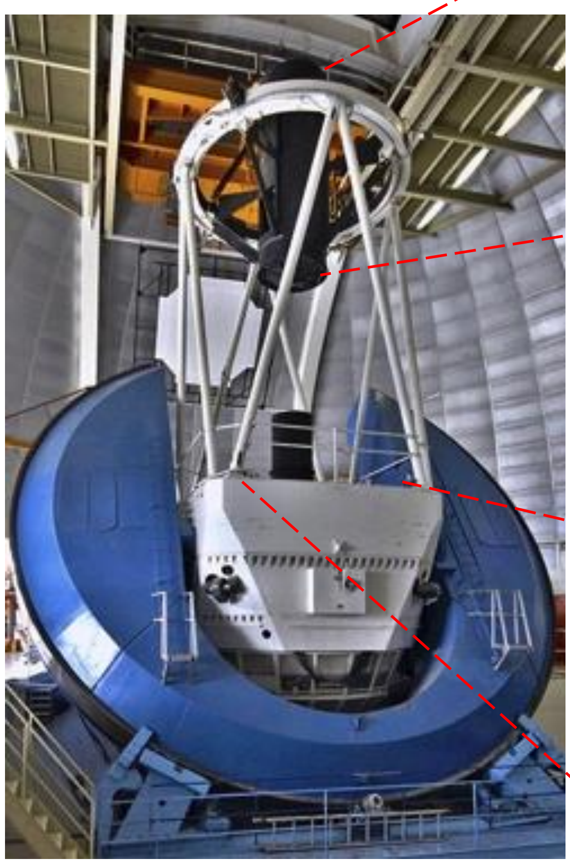
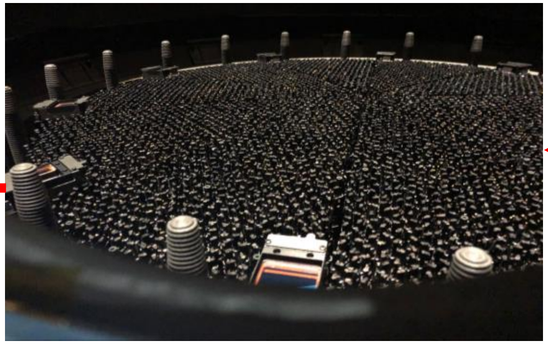
DESI instrument

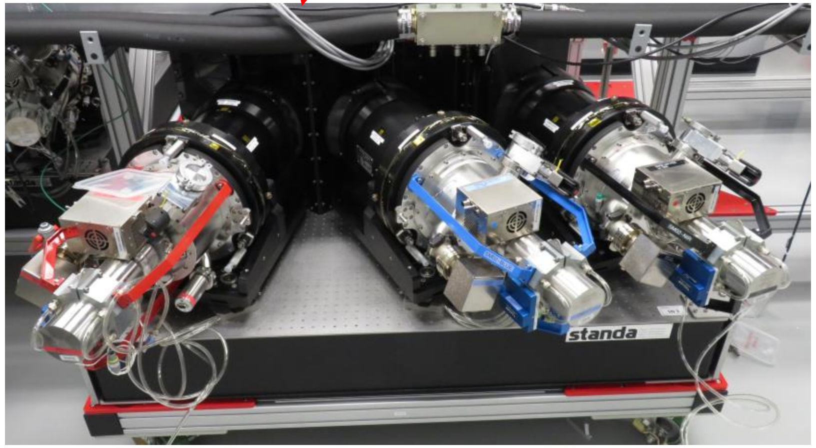


7 deg^2
field of view

40m-long optical fibers



10 3-band spectrographs



4m mirror
(large collecting area)

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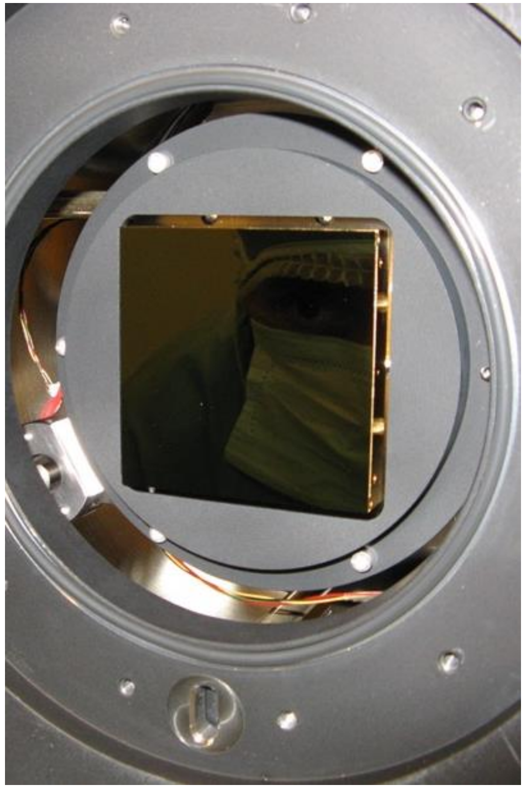
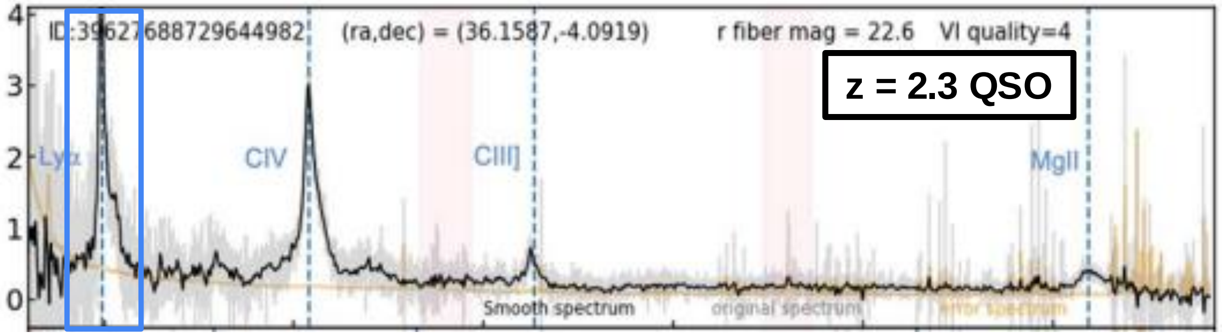
DESI instrument

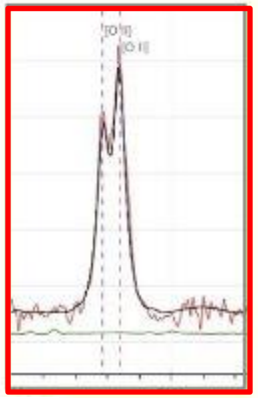
10 3-band spectrographs [360nm – 980nm]

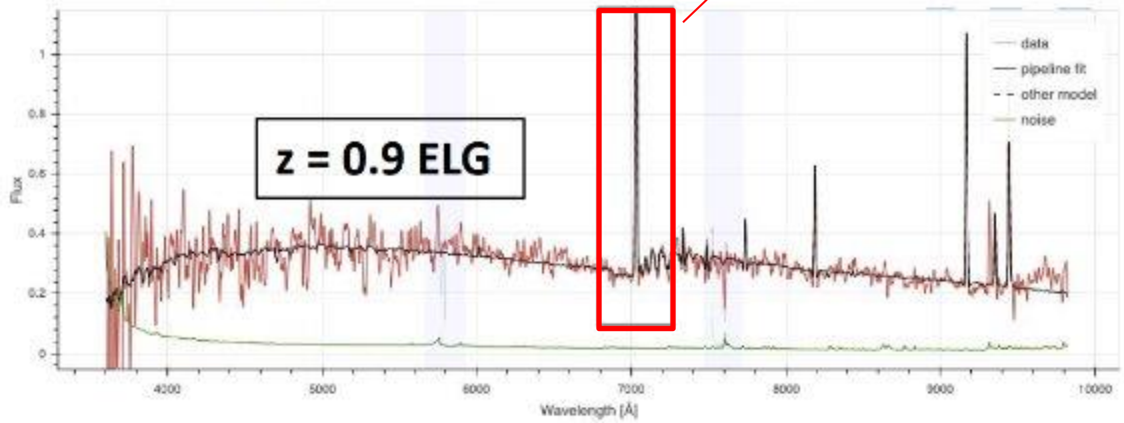


Lyα λ121.6 nm
down to z = 2.0



[OII] λ373 nm
up to z = 1.6





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DESI DR2: data & analysis

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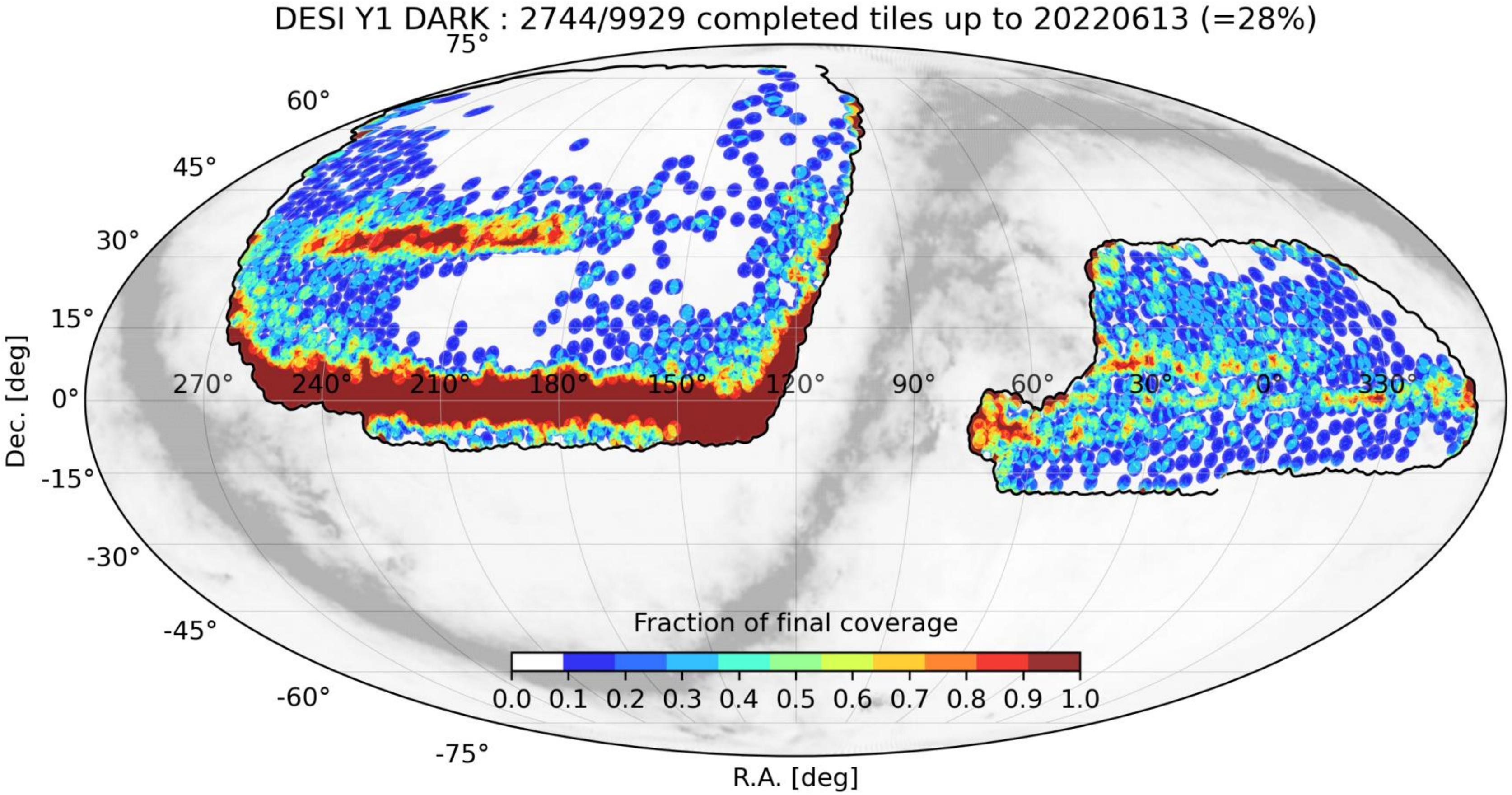
DESI Data Release 1 footprint

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*)

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DESI Data Release 2 footprint

DR1 analysis sample

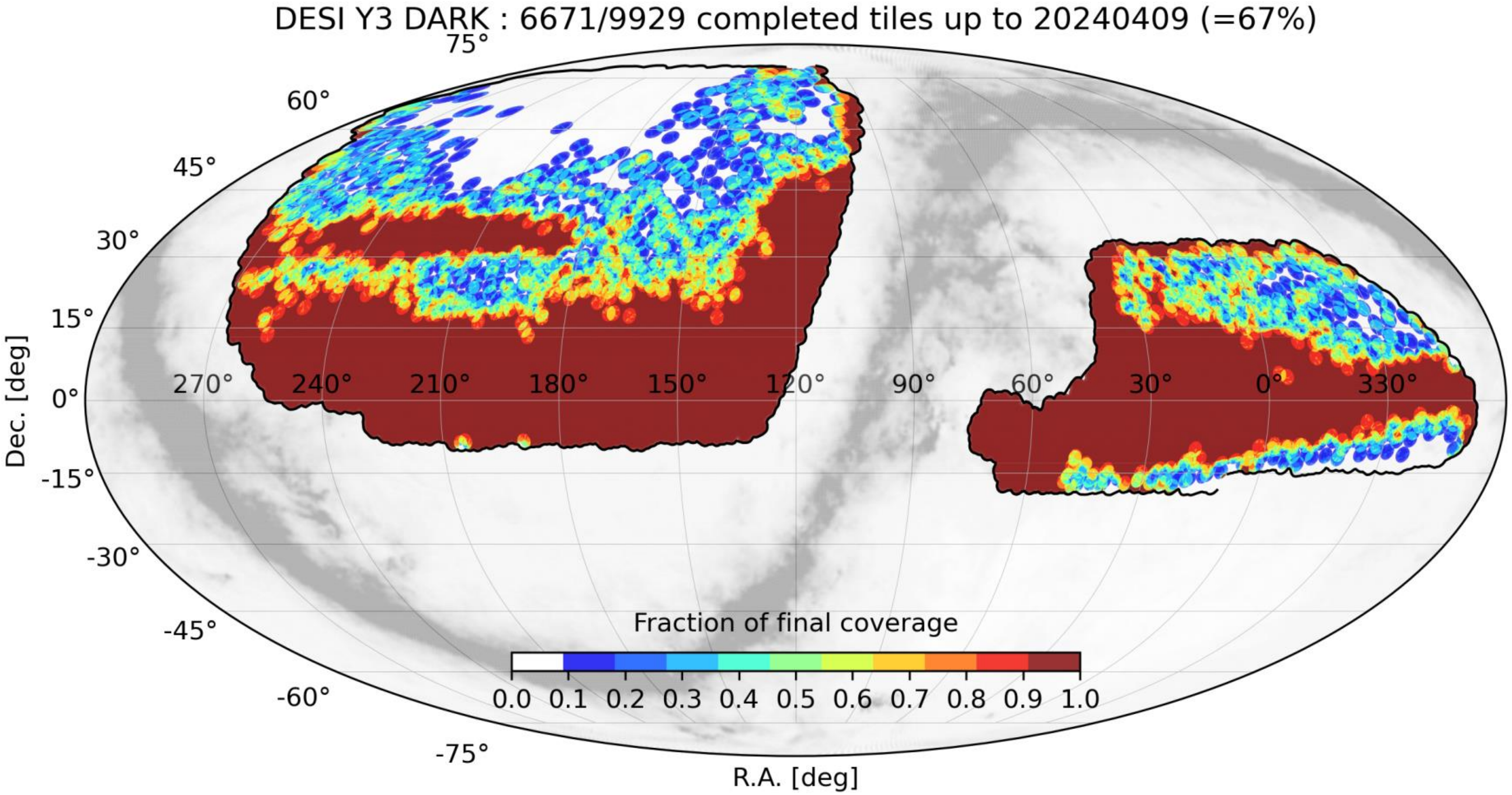
420,000 Lyman-α forests
5.7 million galaxies and quasars

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*)

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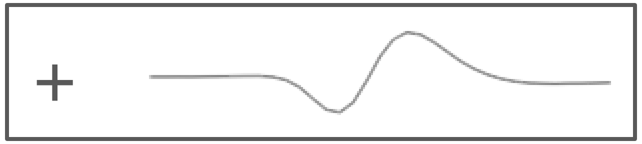
Blinding strategy

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*)

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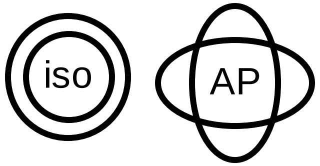
Systematics

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}

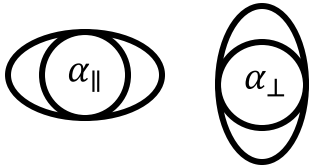
$\Delta\,\sigma(\alpha_{\mathrm{iso}}) = 1 - 9\%$ (BGS – LRG3+ELG1)
$\Delta\,\sigma(\alpha_{\mathrm{AP}}) = 0.1 - 2\%$ (QSO – LGR3+ELG1)

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!

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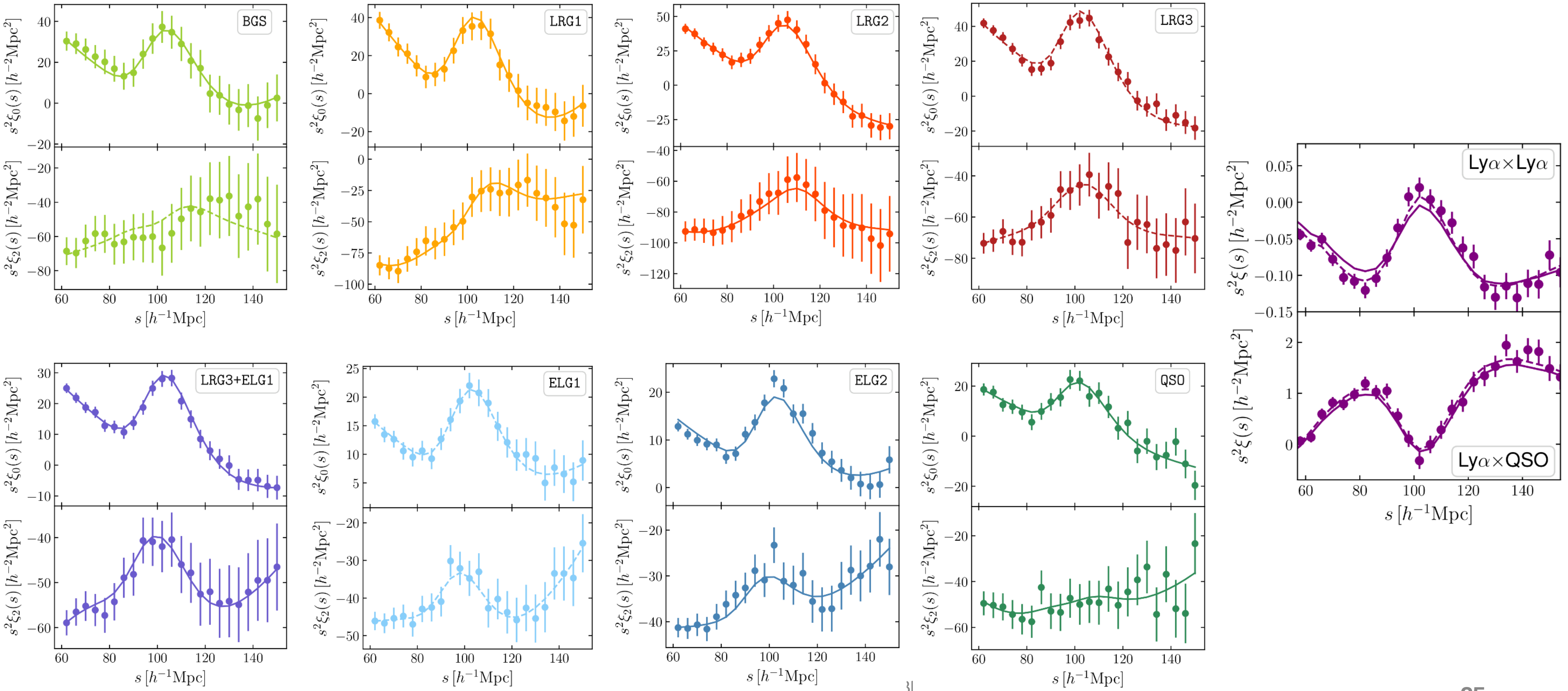
DR2 clustering measurements

LRG+ELG (0.8<z<1.1)

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



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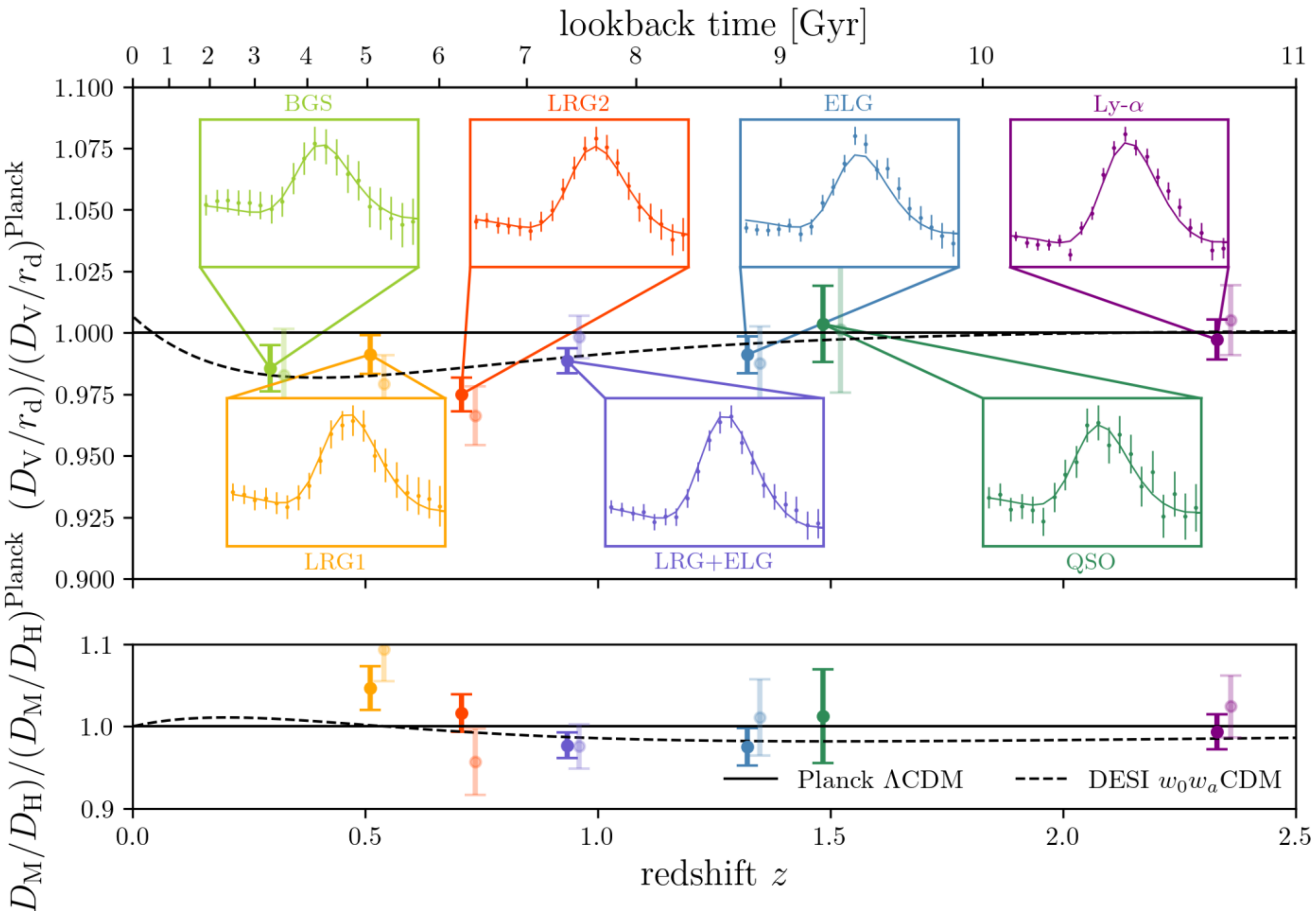
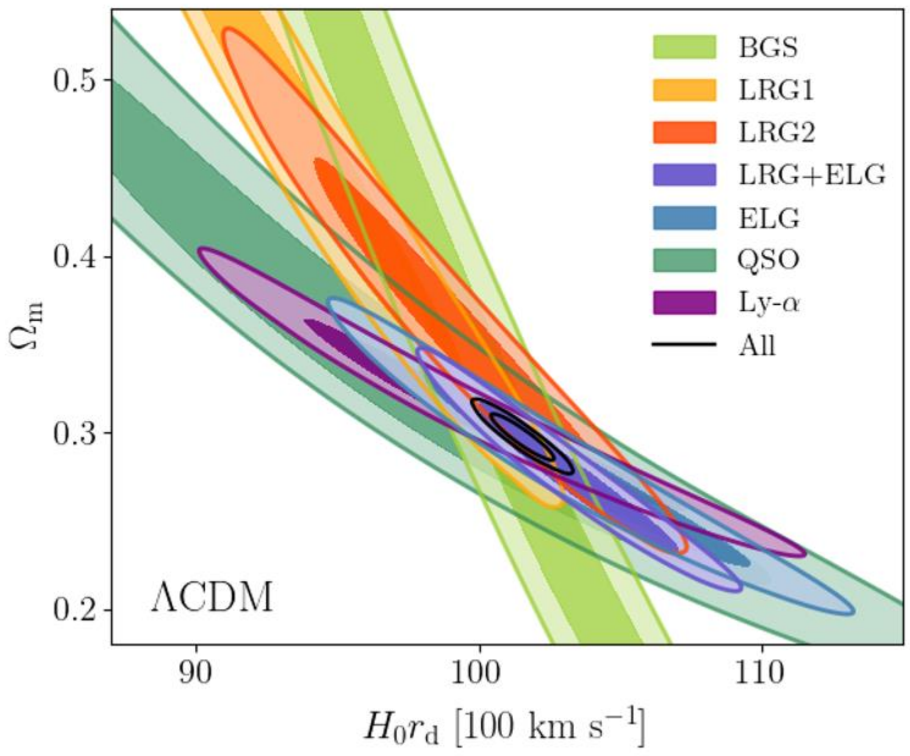
DESI DR2 BAO

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 $H_0 r_d$





Aggregated precision on BAO distance scale: 0.3%

(vs. 0.6% for final SDSS)

Agreement & complementarity between tracers

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DESI DR2 BAO

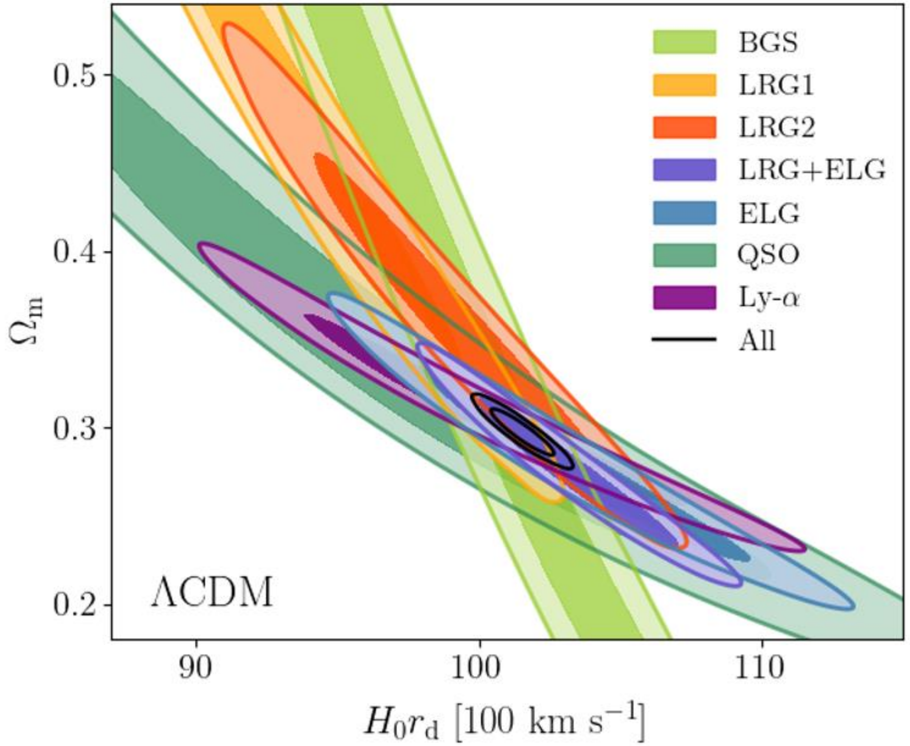
BAO data: $\Delta\theta$ and Δz $\longrightarrow$ D_M / r_d and D_H / r_d

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

Ω_M and H_0r_d

$$\underbrace{\begin{array}{ll}\Omega_m = 0.298 \pm 0.0086 & (\mathbf{2.9\%}) \\ hr_d = 101.54 \pm 0.73\ \ \mathrm{Mpc} & (\mathbf{0.7\%})\end{array}}_{}$$

DESI

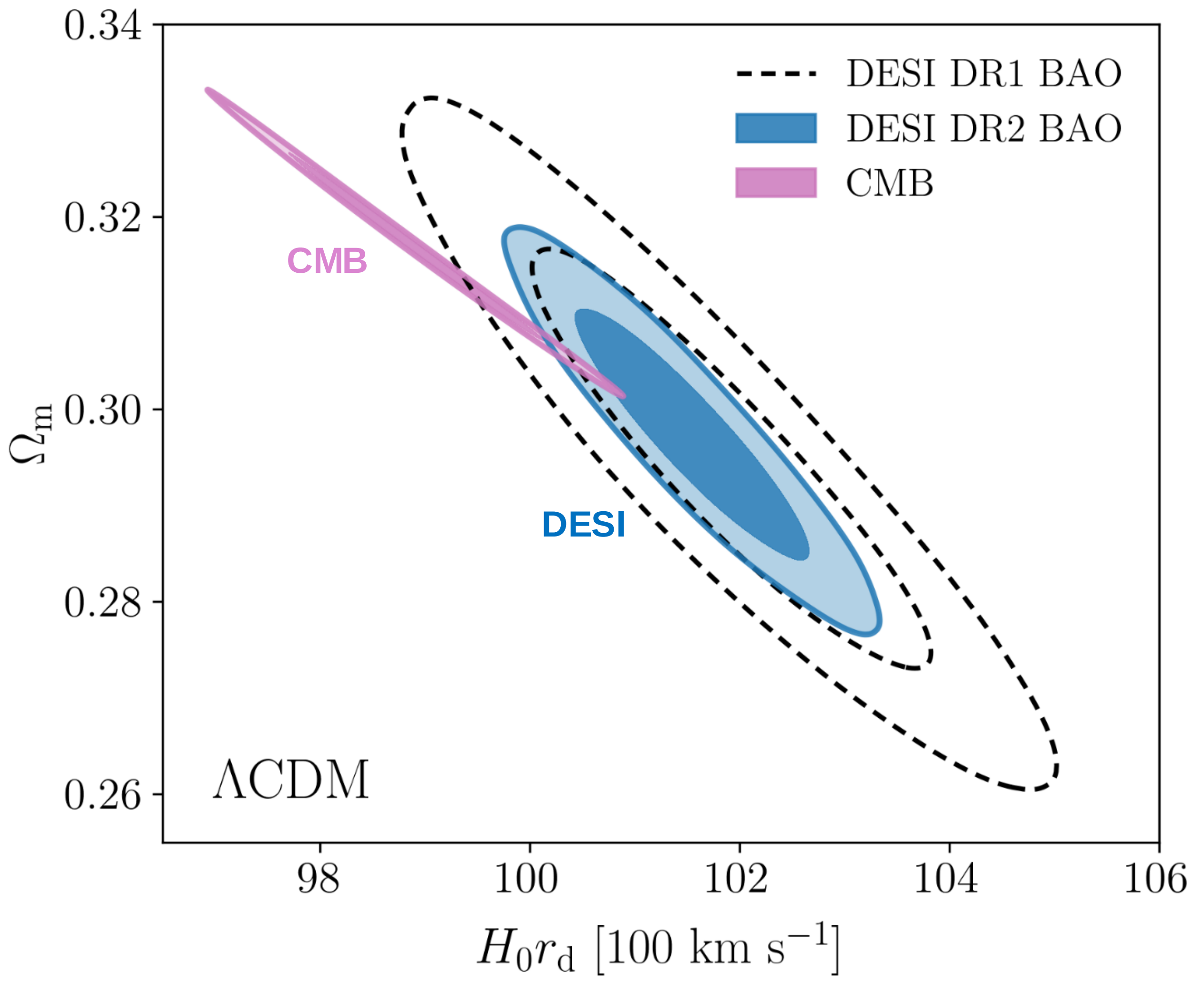


Agreement & complementarity between tracers

ΛCDM: DESI DR2 vs. CMB

DESI DR2 BAO is:
- Consistent with **DESI DR1**
- 2.3σ from the **CMB** (was 1.9σ with DESI DR1)

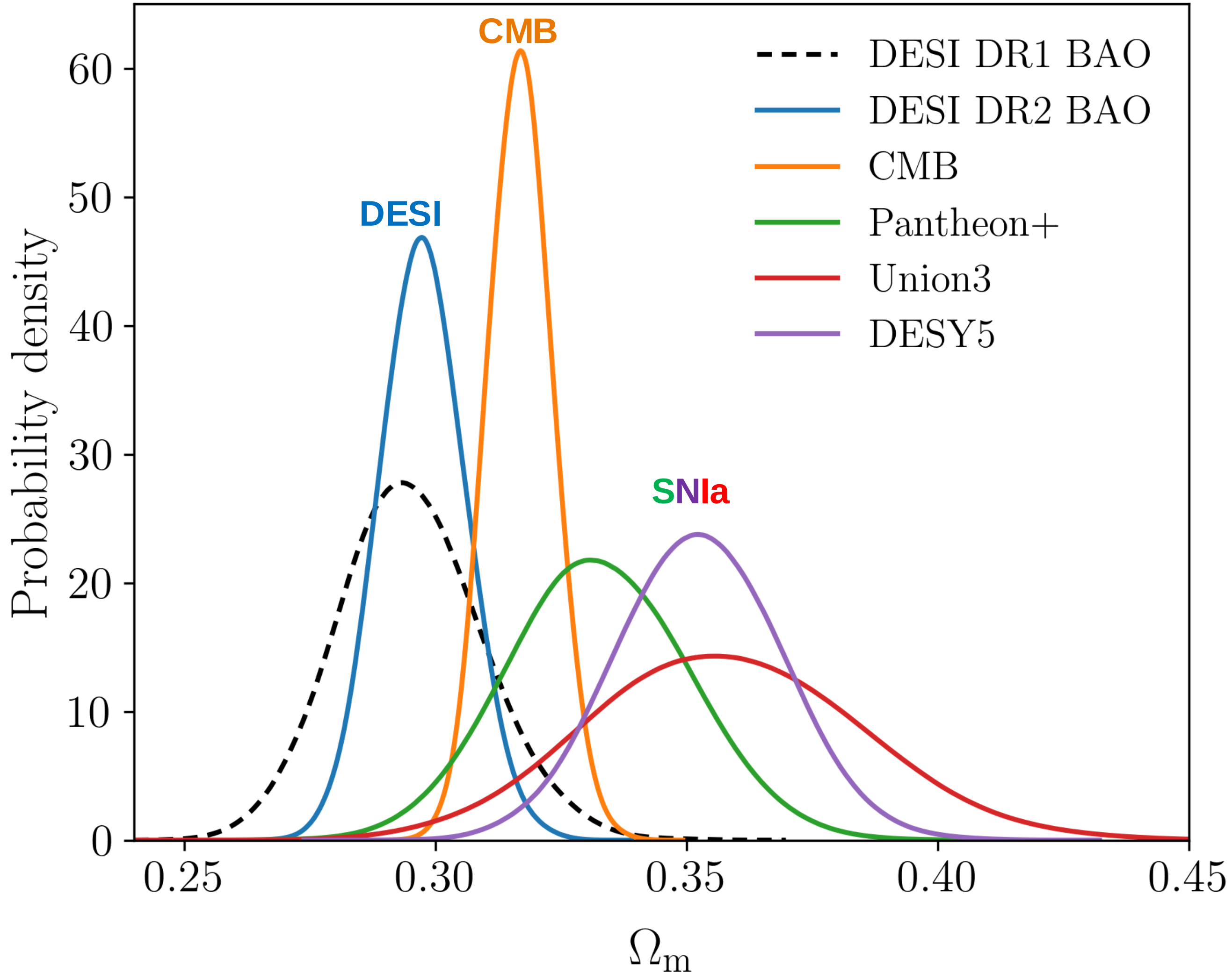
CMB:
- primary CMB from Planck PR4 (CamSpec)
- CMB lensing from Planck PR4 + ACT DR6



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

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

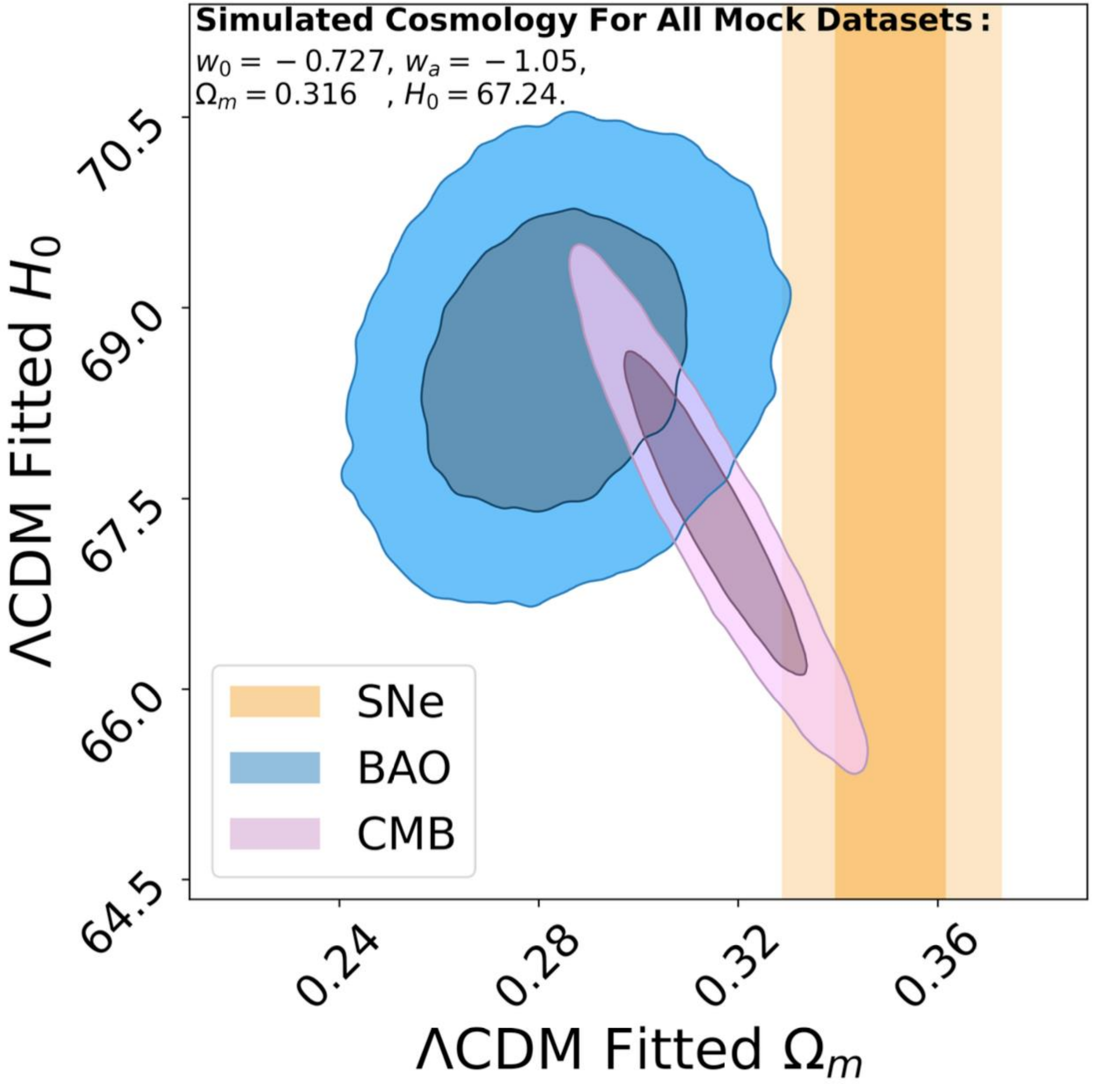


Data consistency

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

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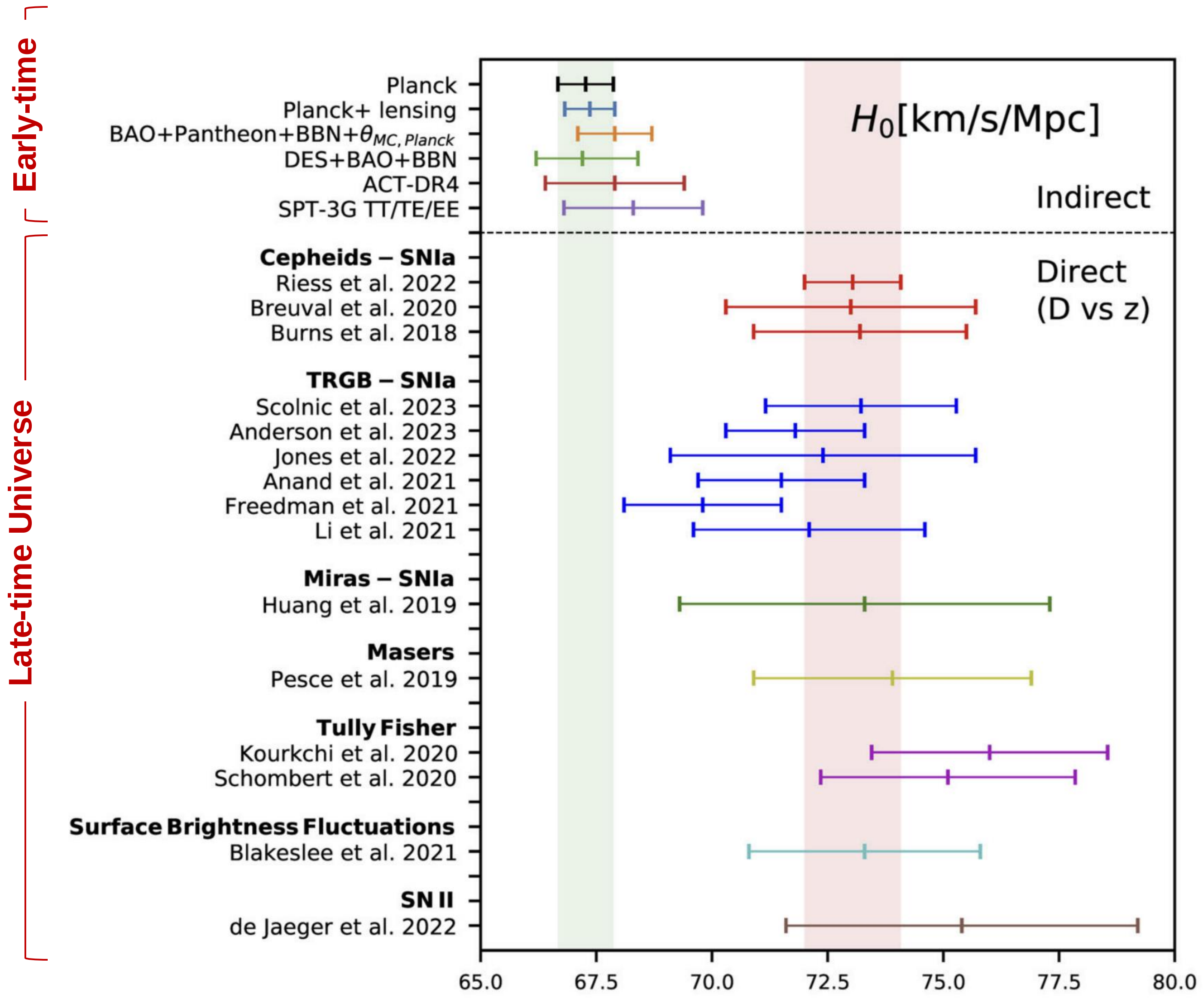
H_0

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

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



Riess & Breuval 2023

H_0

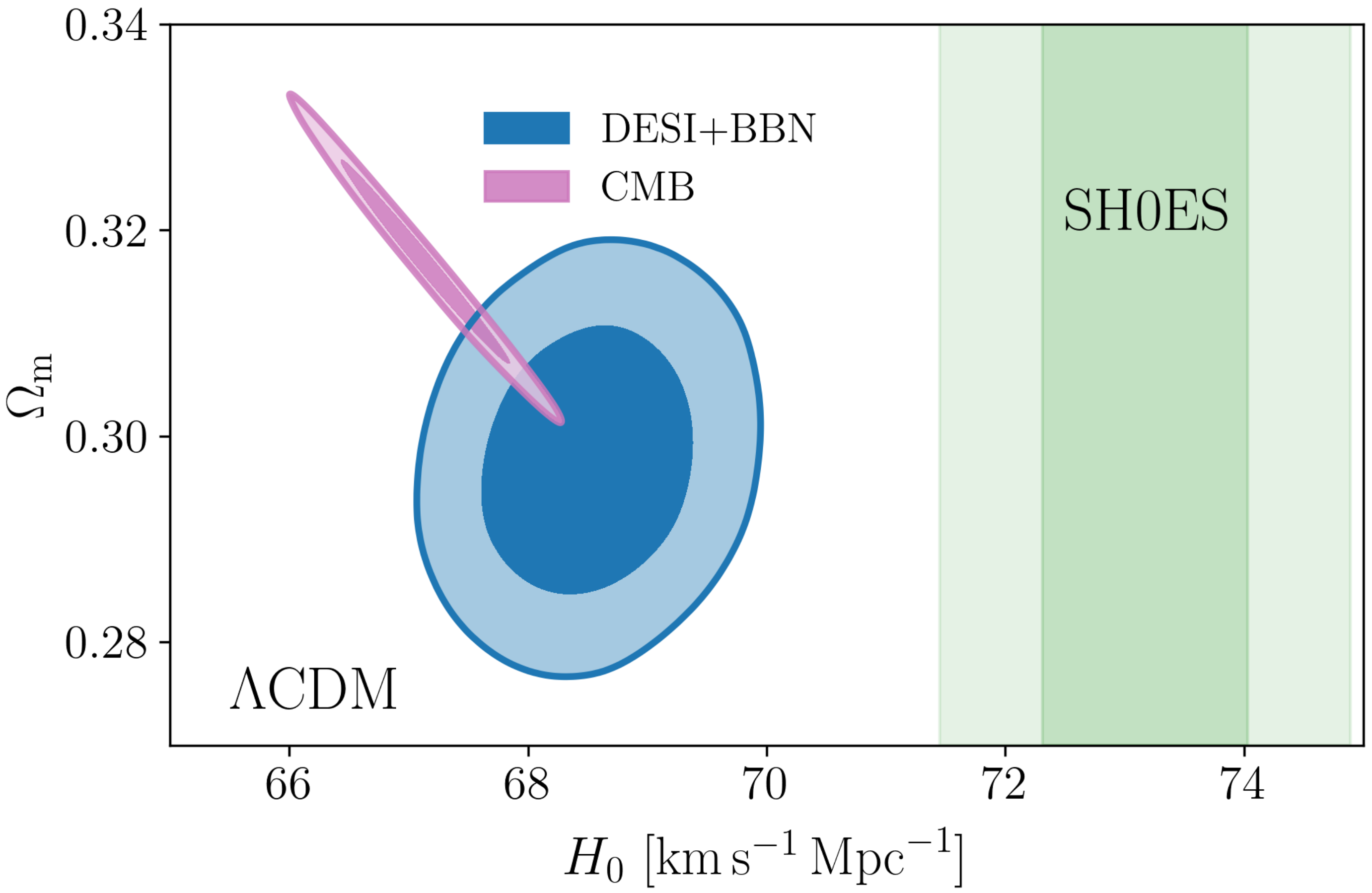
BAO data: $\Delta\theta$ and Δz $\longrightarrow$ D_M / r_d and D_H / r_d $\Rightarrow$ Ω_M and $H_0 r_d$

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

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

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

→ **4.5σ tension with SH$_0$ES**



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Dark Energy

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Dark Energy

Equation of state $P = w\rho$

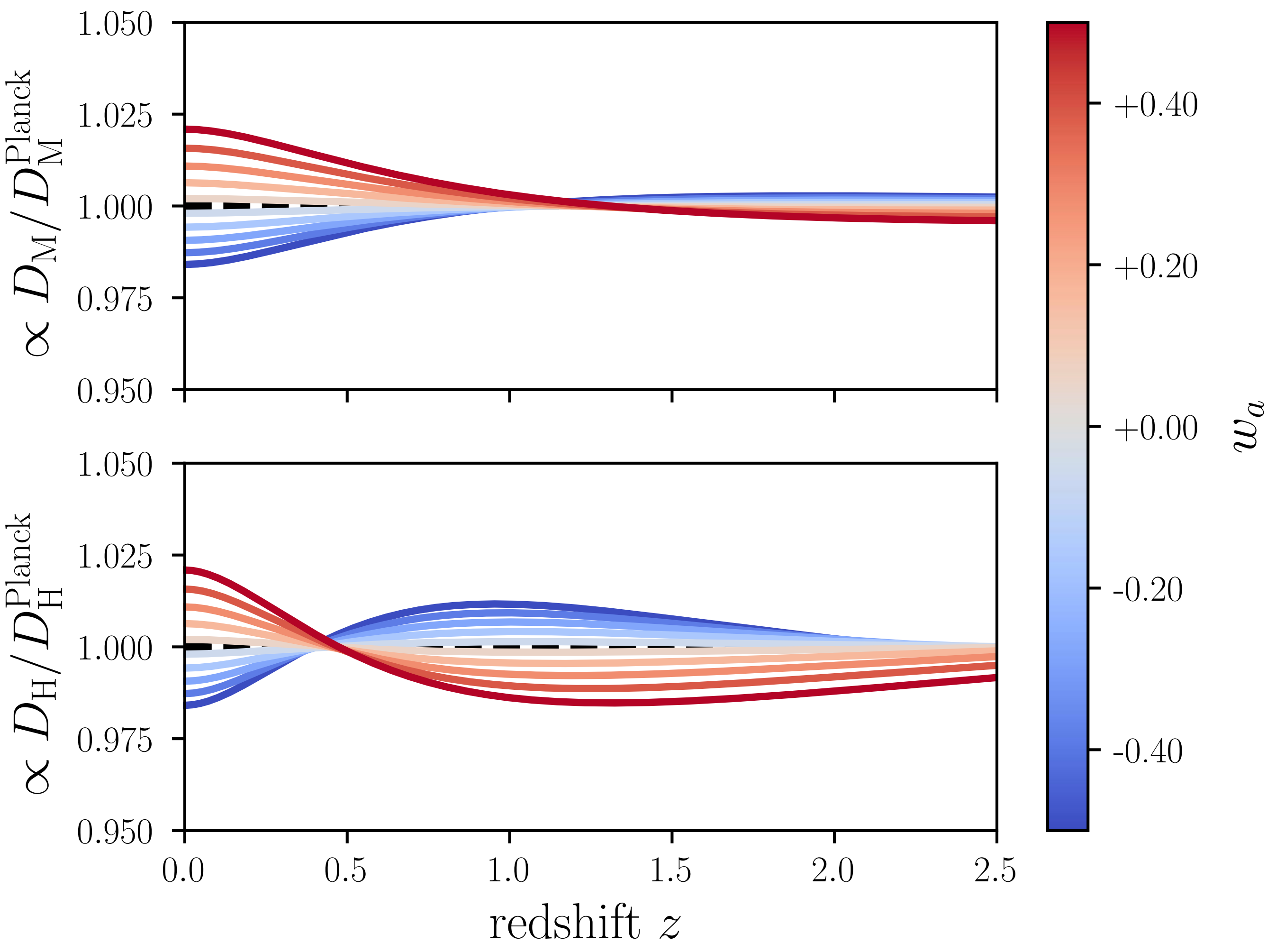
Dynamic dark energy

(Chevalier & Polarski 2001, Linder 2003)

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

Cosmological constant Λ

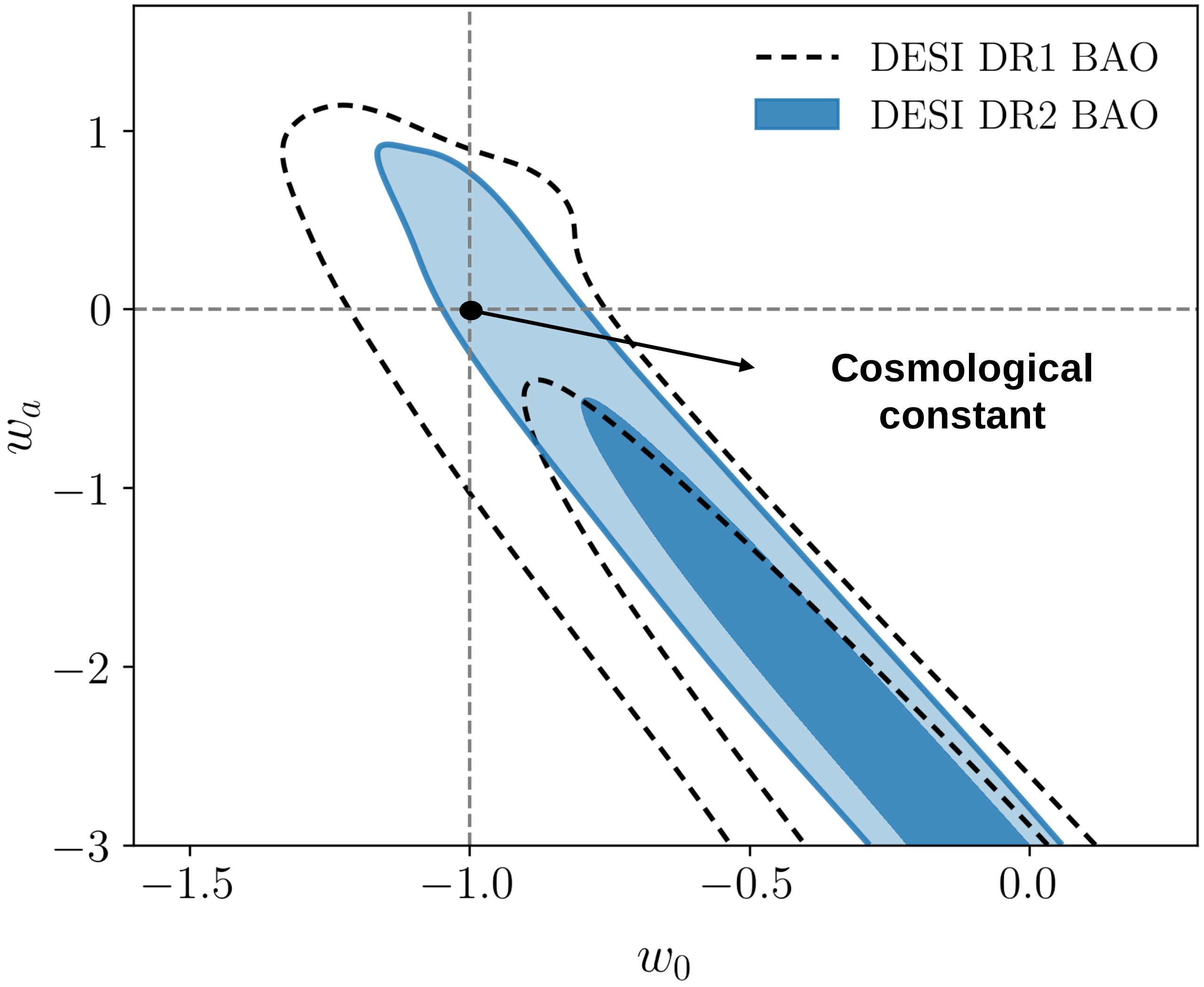
$$w_0 = -1 \text{ and } w_a = 0$$



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



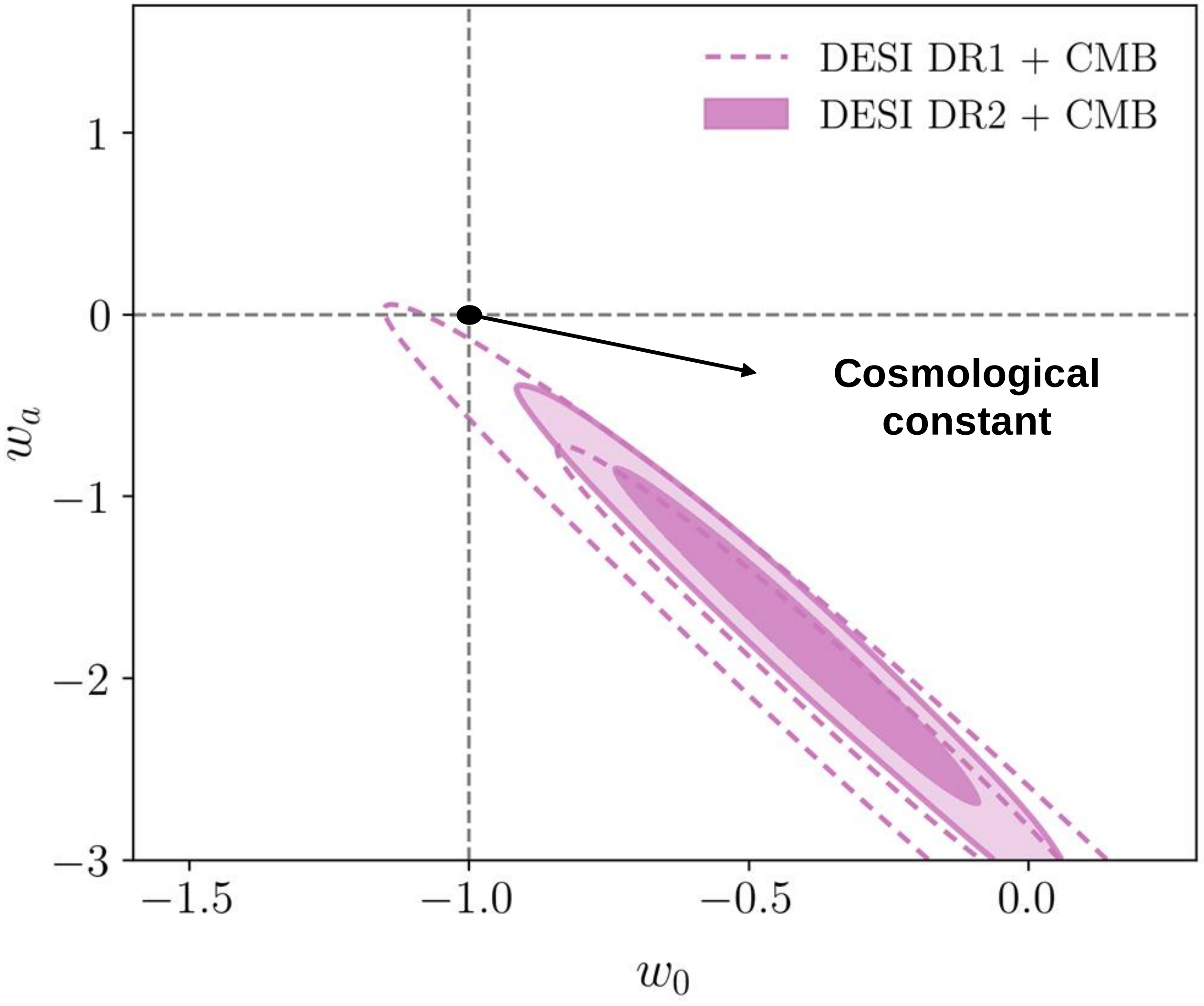
Evolving Dark Energy

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

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

- **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

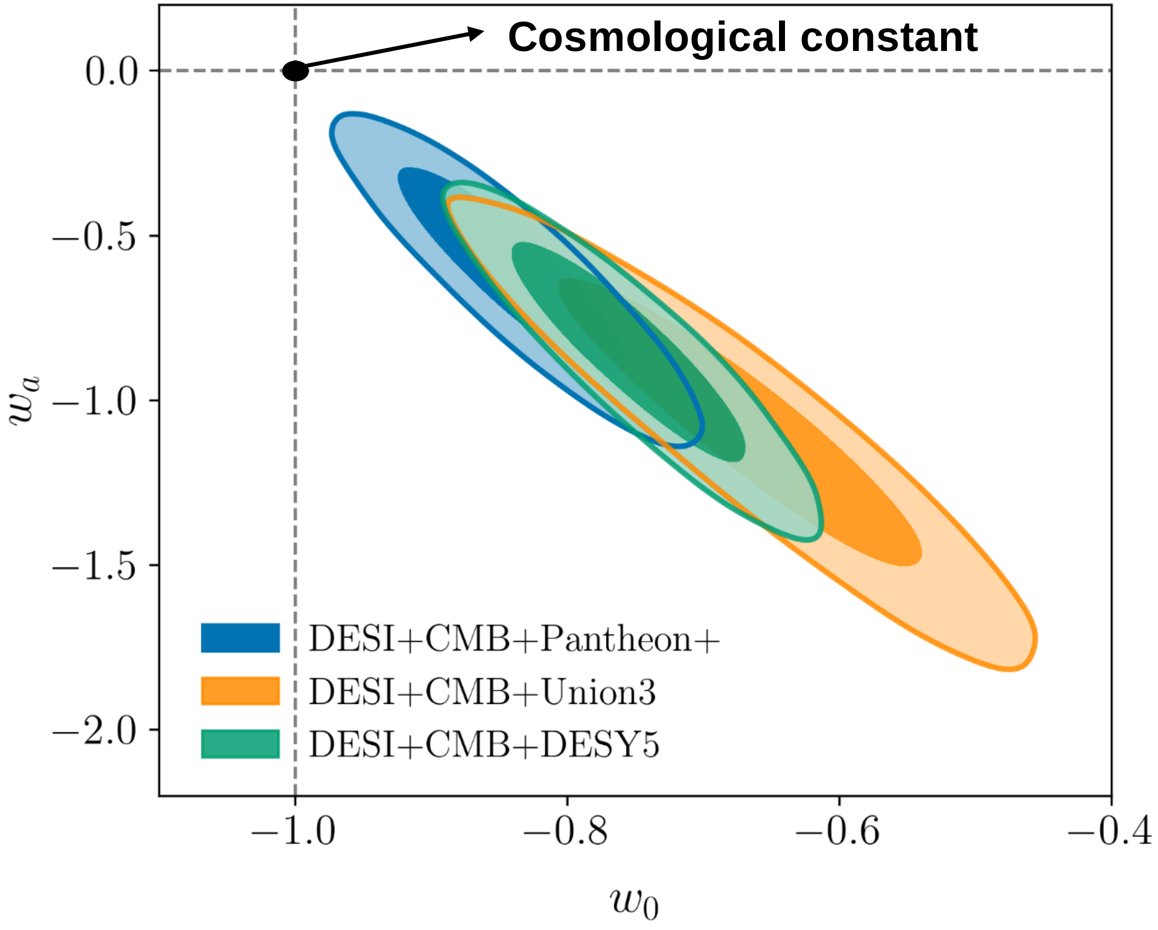
DESI DR2 results II: BAO (*arXiv:2503.14738*)

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

DESI + CMB + Pantheon+: 2.8σ

DESI + CMB + Union3: 3.8σ

DESI + CMB + DES-SN5Yr: 4.2σ

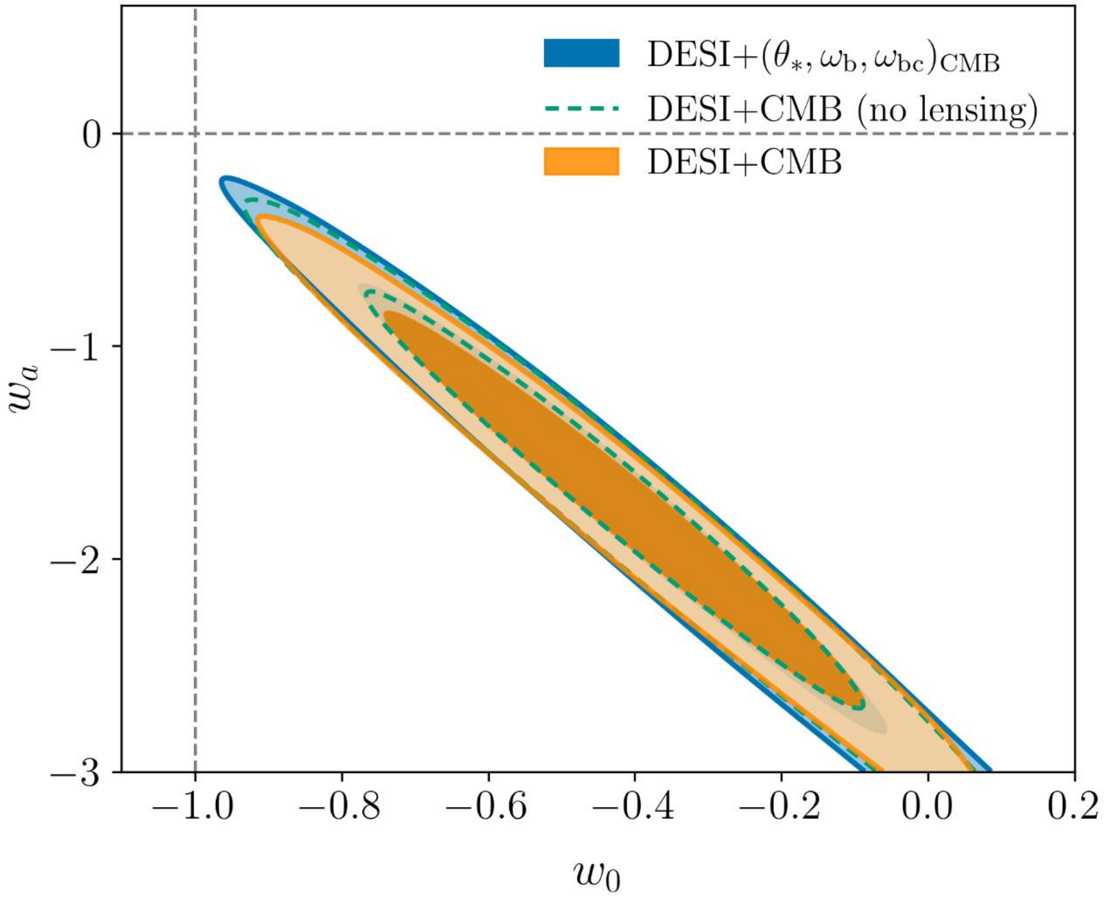


Result robustness

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

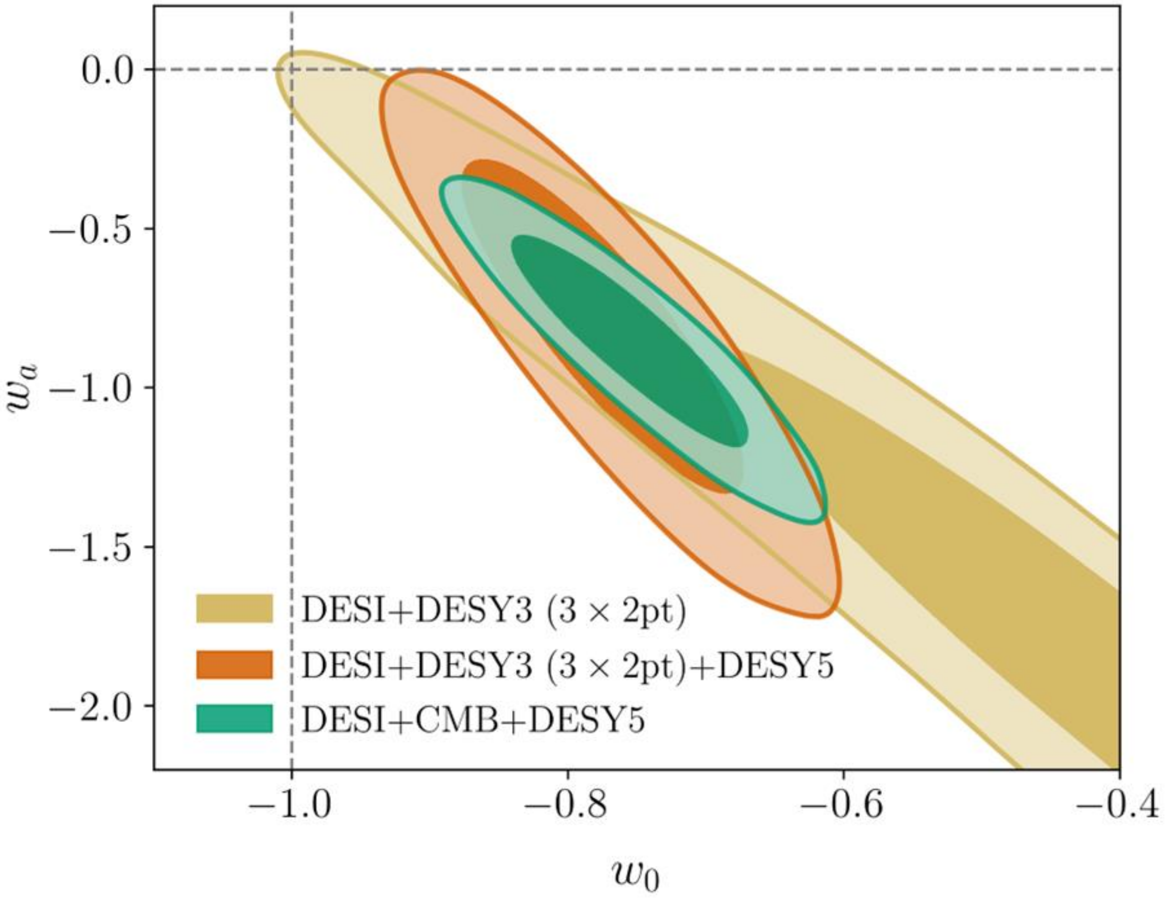


Result robustness

Constraint limited to low-redshift probes

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

Preference for same region



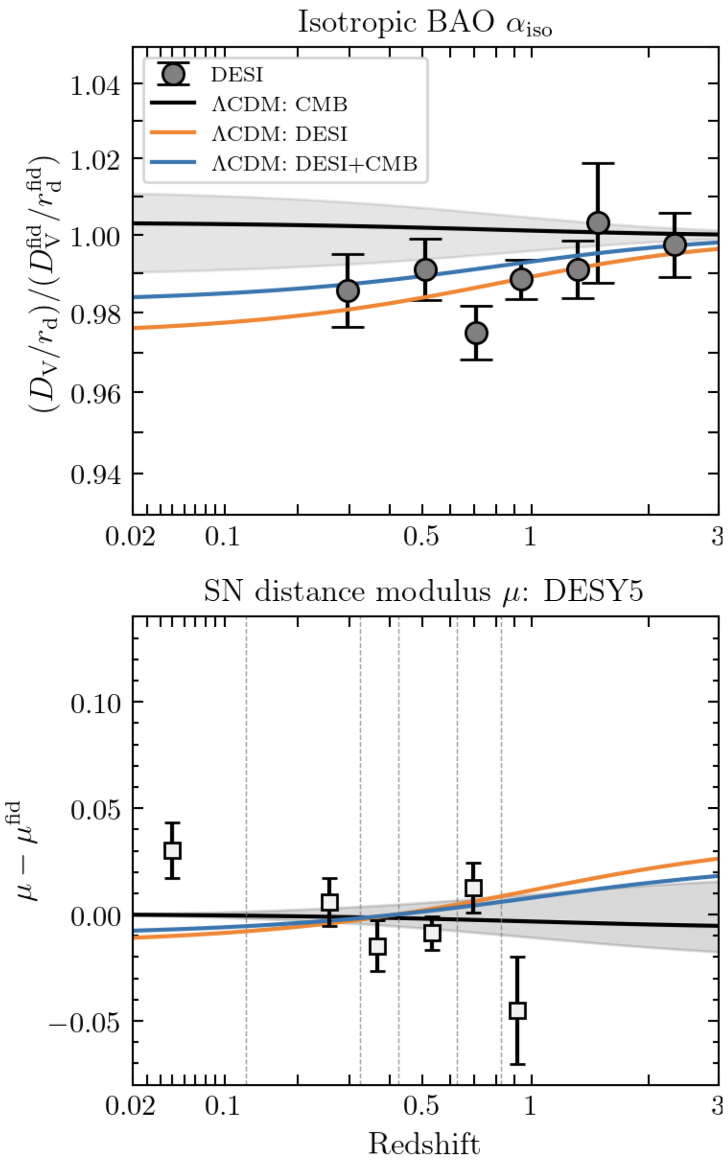
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus

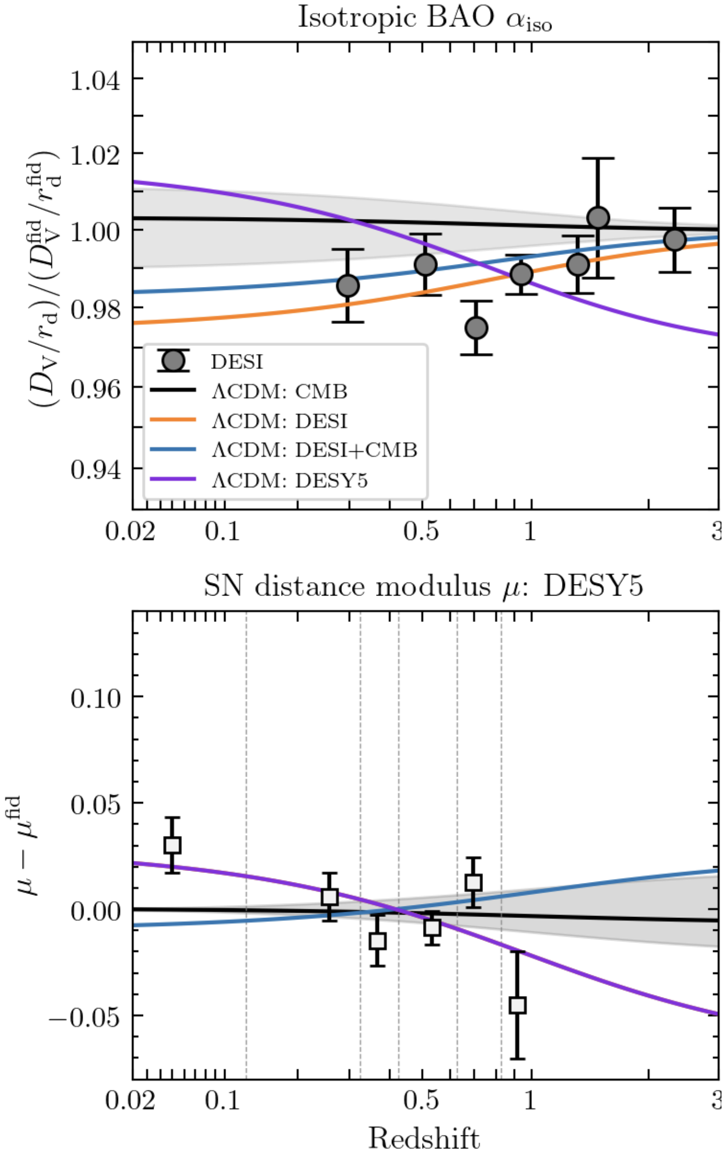


- **ΛCDM** model can fit DESI BAO
- DESI at $z < 1$ prefer distances 1-2% lower than CMB prediction

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

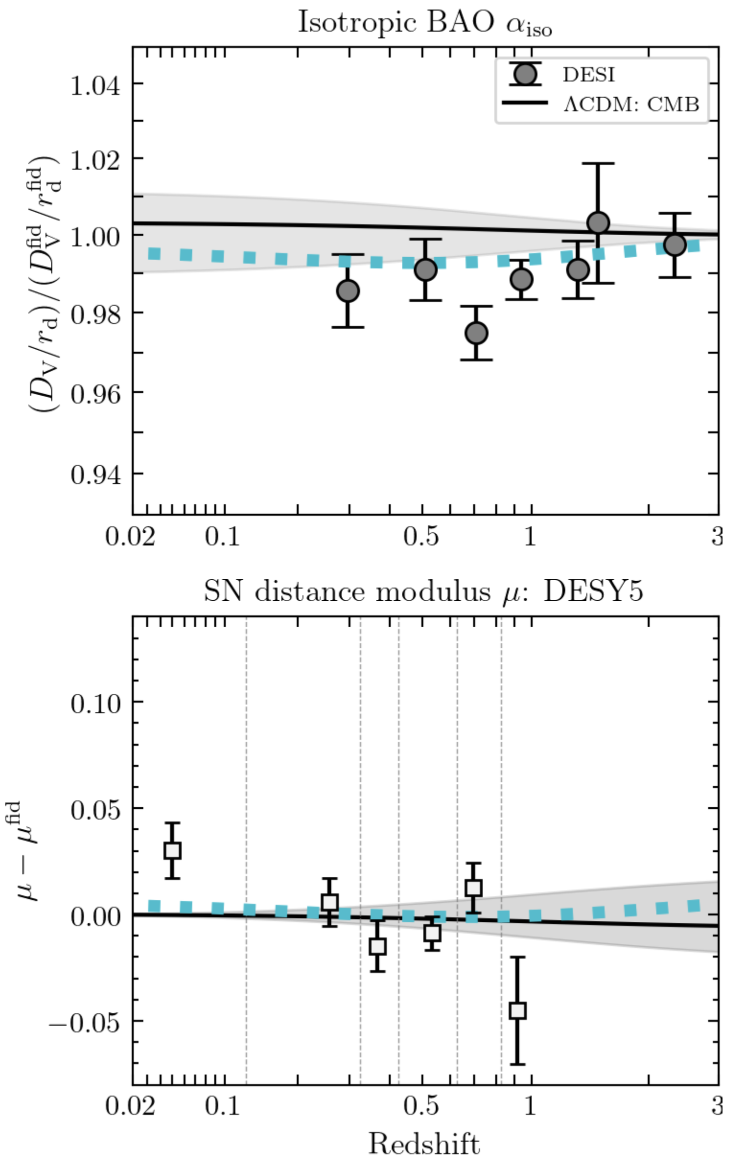
⟹ No good **ΛCDM** fit to DESI BAO, CMB & SN simultaneously

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

The nature of the evidence

Isotropic BAO
distance measurement

Supernovae
distance modulus



$\Longrightarrow$

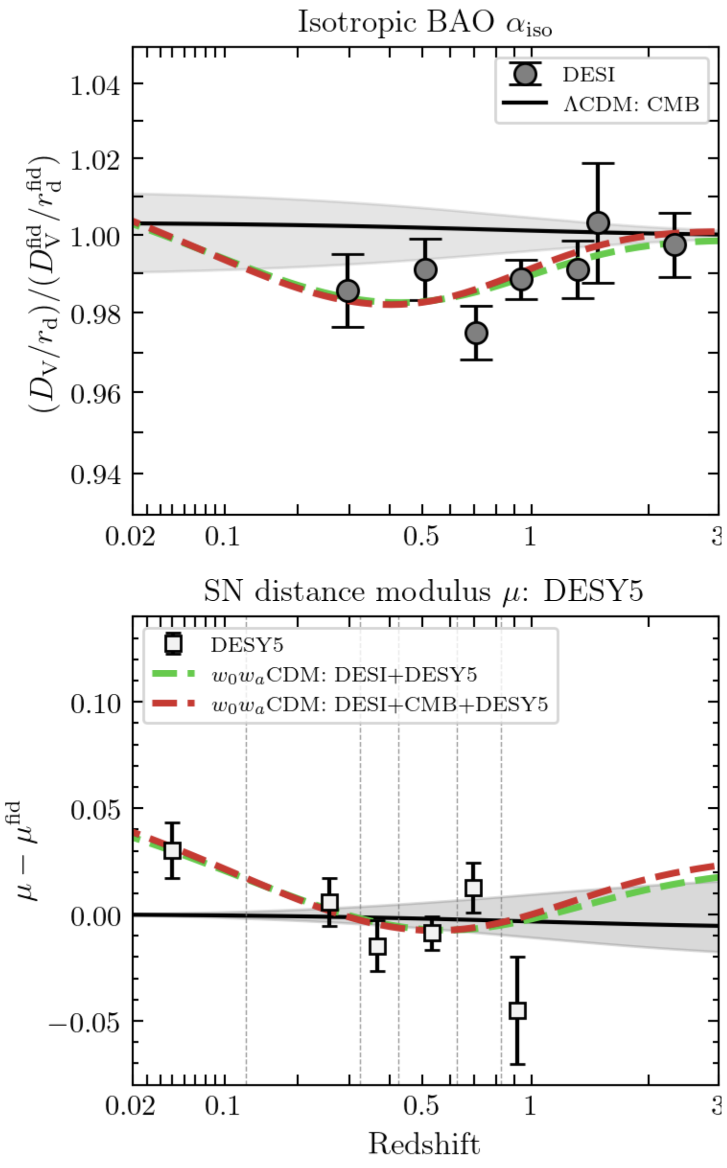
Not have enough freedom in ***w*CDM** to fit BAO, CMB and SN simultaneously either

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

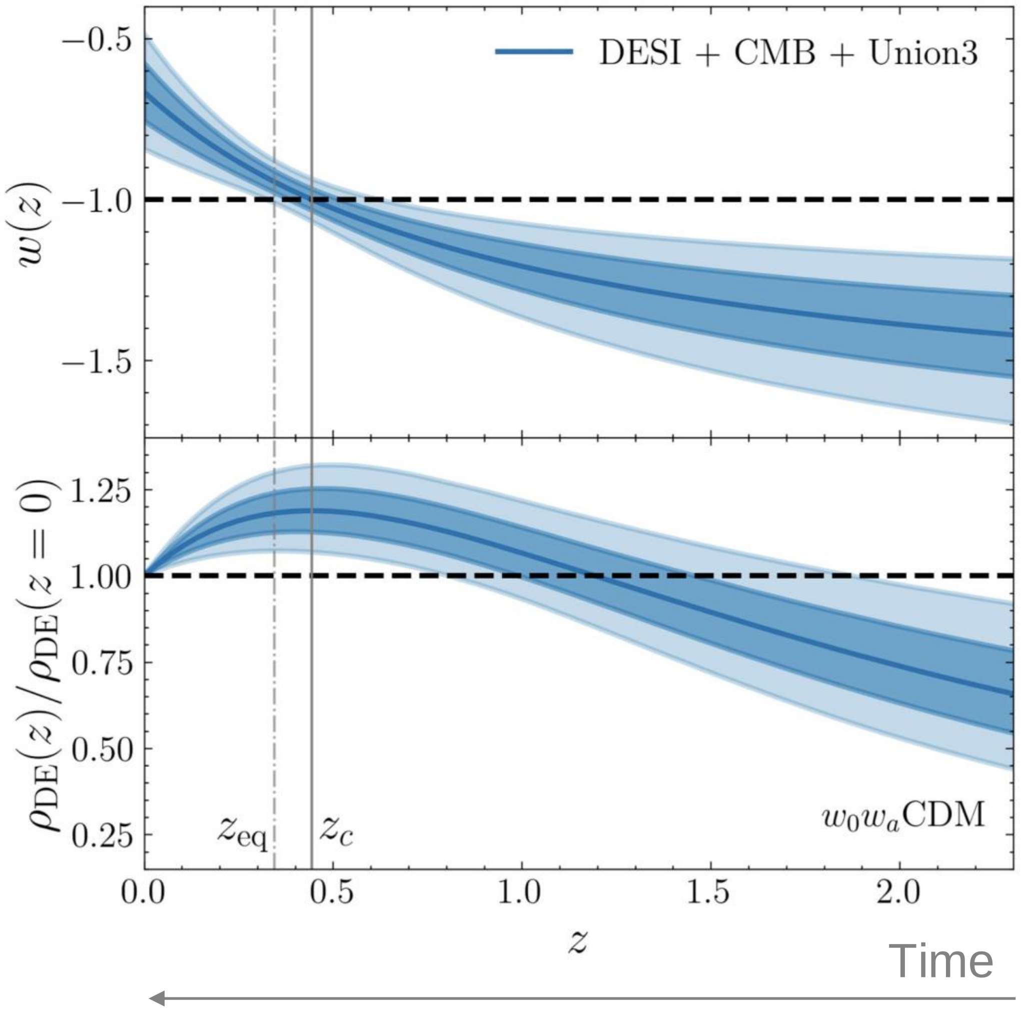
also a good fit to CMB

Dark Energy model

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

Dark energy 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)

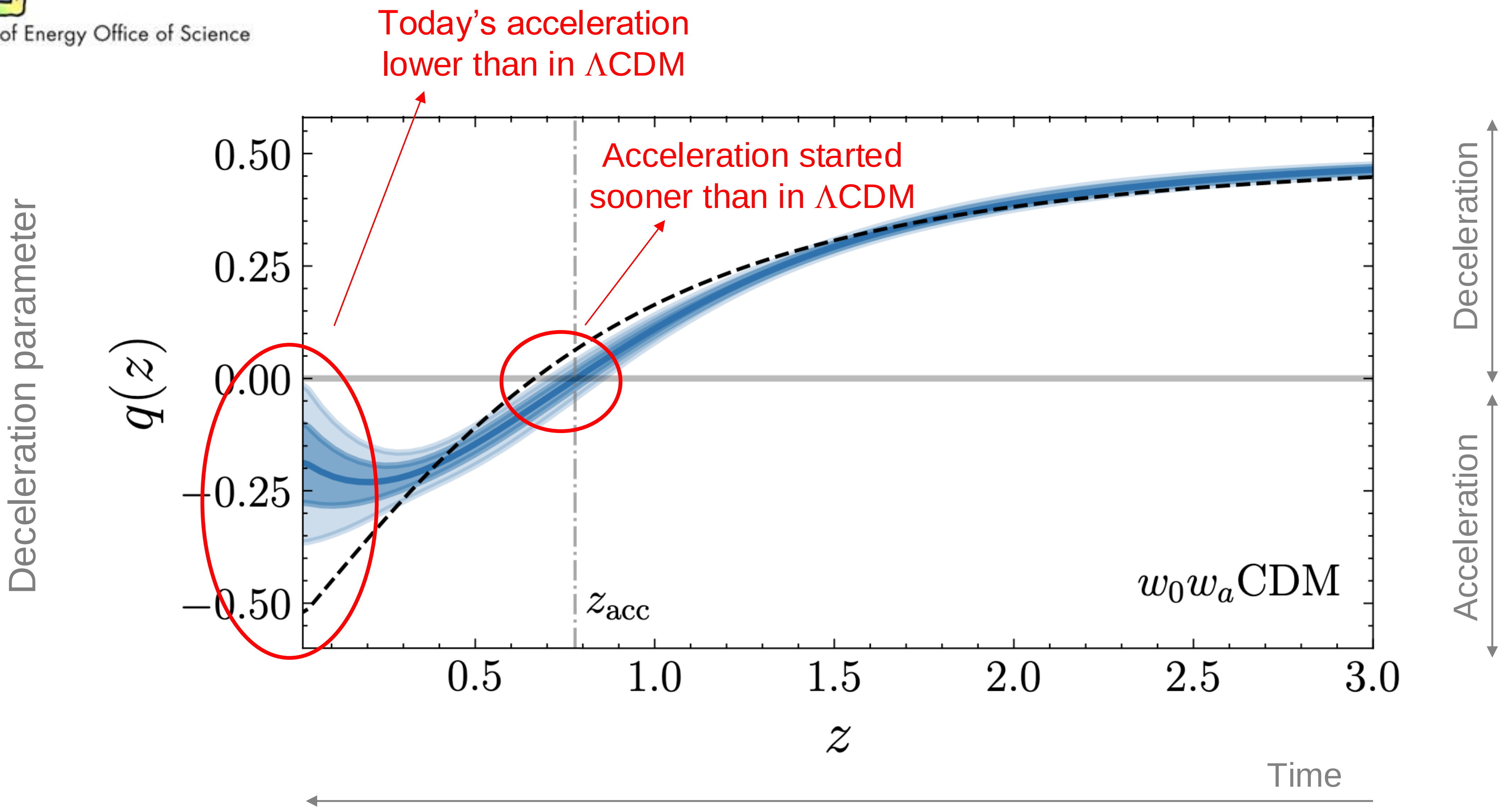
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Weakening dark energy

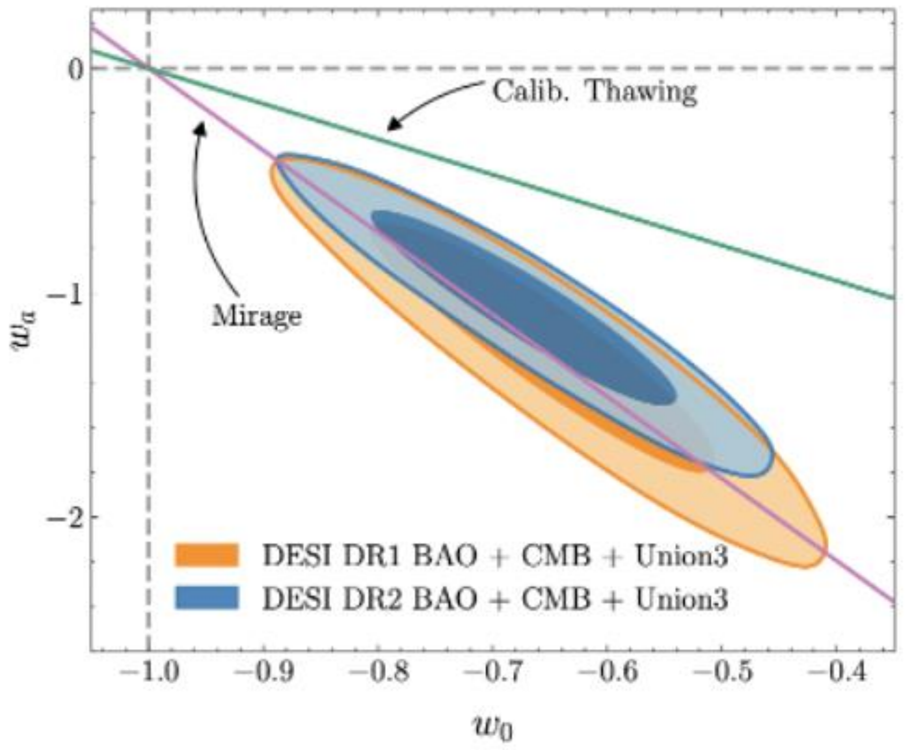
DESI DR2 results II: BAO (*arXiv:2503.14738*)

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 $\rho = 0$, never crosses $w = -1$)
- Mirage ($\langle w \rangle = -1$)

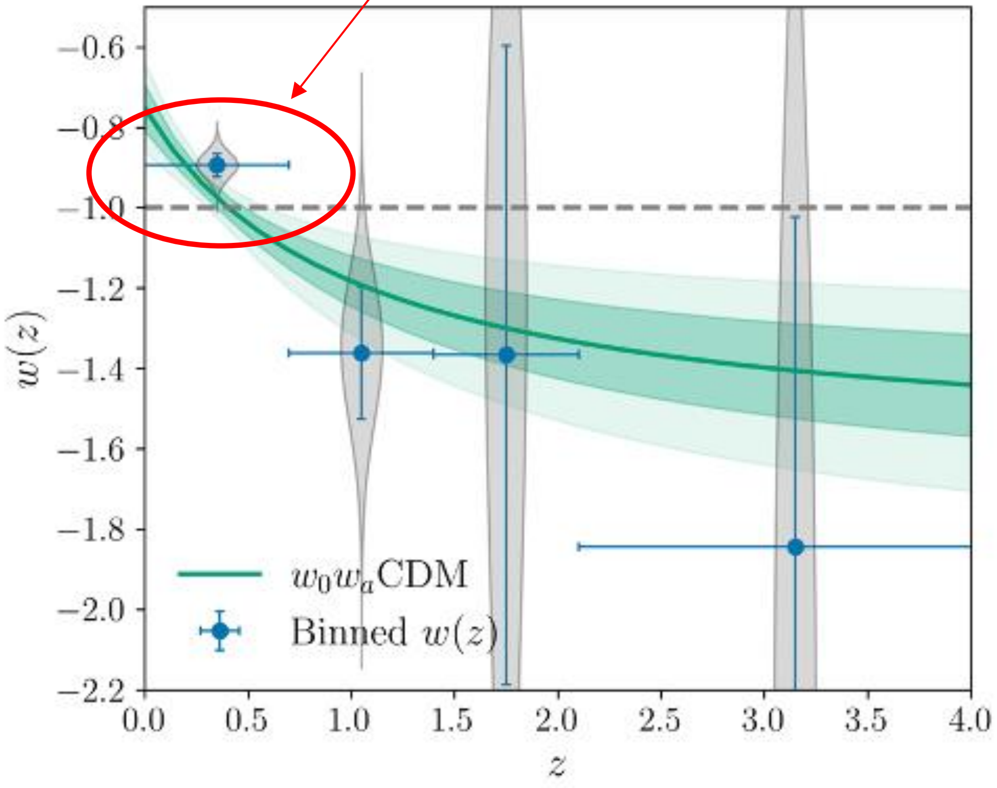
Improvement over LCDM
DESI BAO + CMB + SN (DESY5)

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
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Upper bounds on neutrino masses

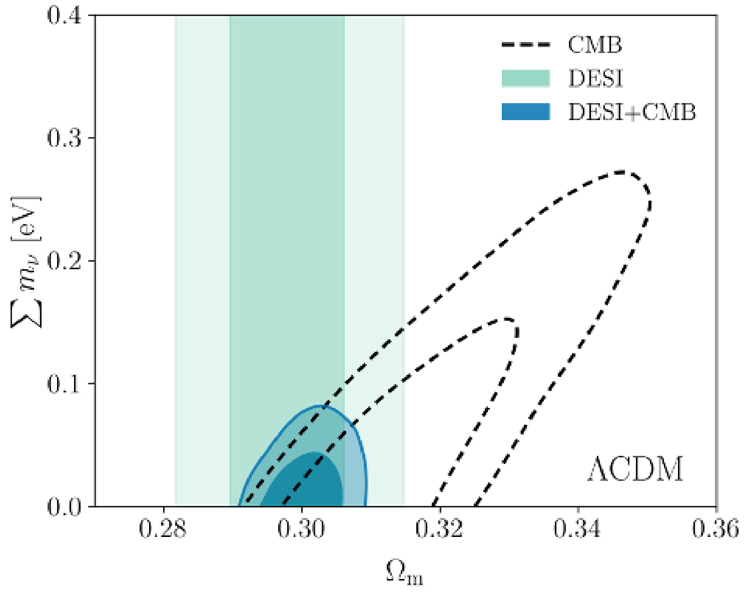
In ΛCDM, Σm_ν changes angular diameter distance to last scattering, degenerate with Ω_m, H_0 …
BAO breaks degeneracy

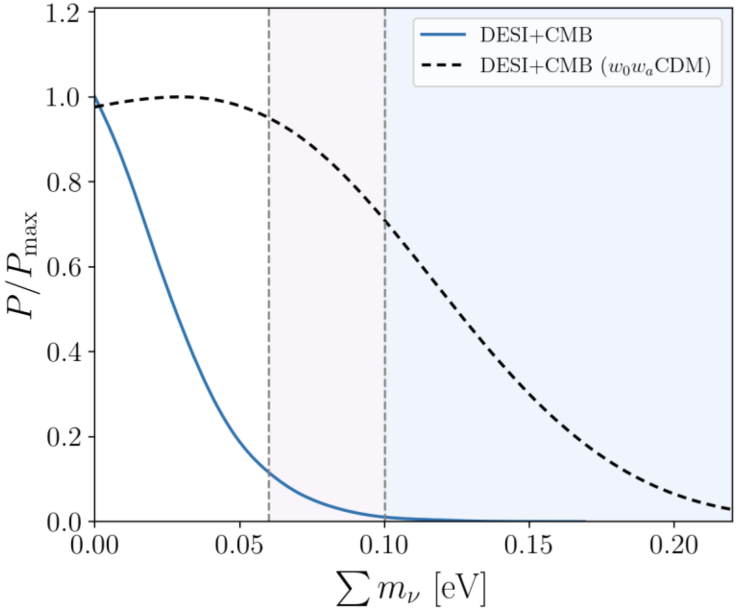
$$\sum m_\nu < 0.064 \text{ eV}$$ (95%, DESI (BAO)+CMB)

→ Tightest constraint to-date (in ΛCDM)

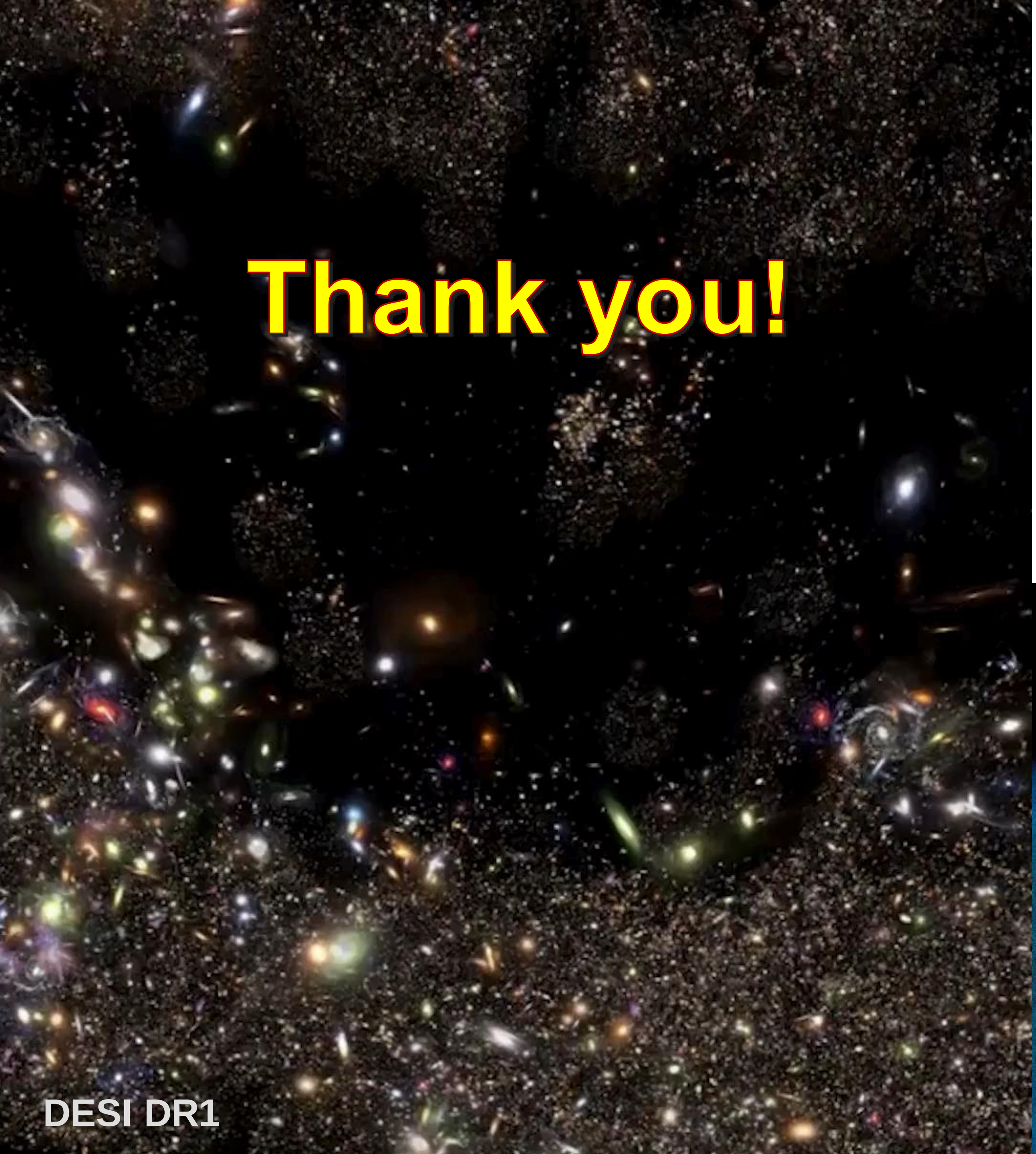
In w_0w_aCDM, relaxed to

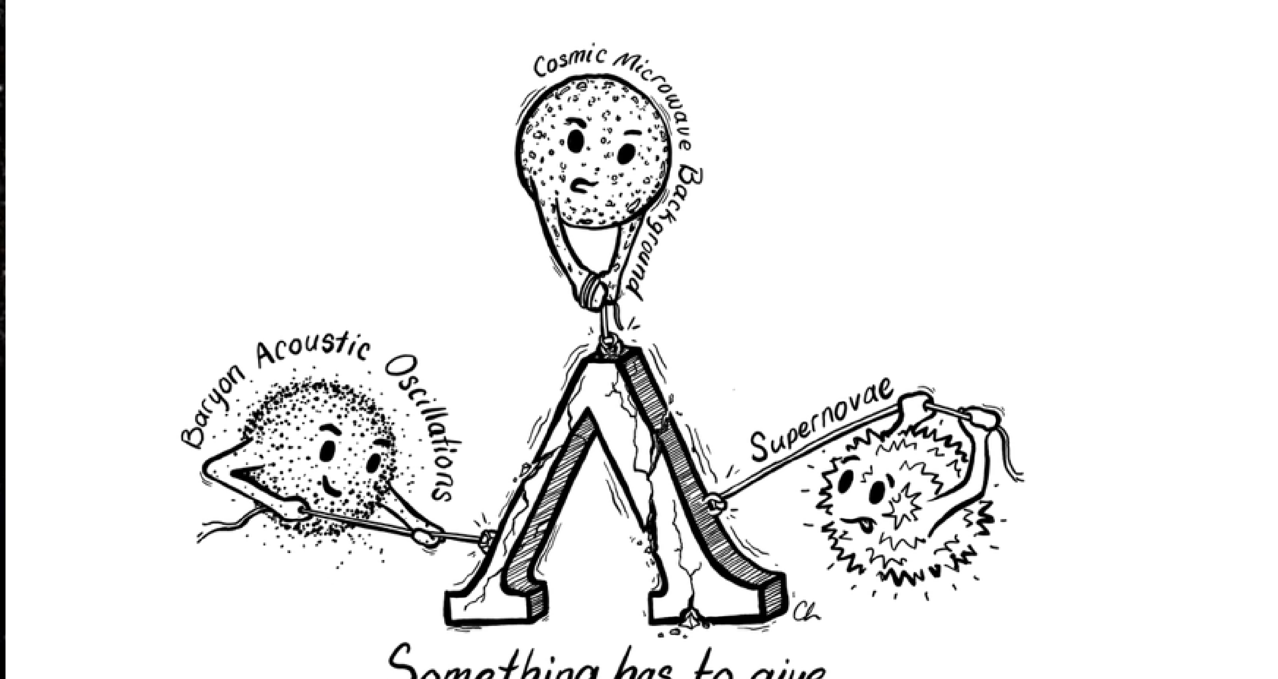
$$\sum m_\nu < 0.163 \text{ eV}$$ (95%, DESI (BAO)+CMB)





DESI supporting paper Elbers+ (*arXiv:2503.14744*)





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