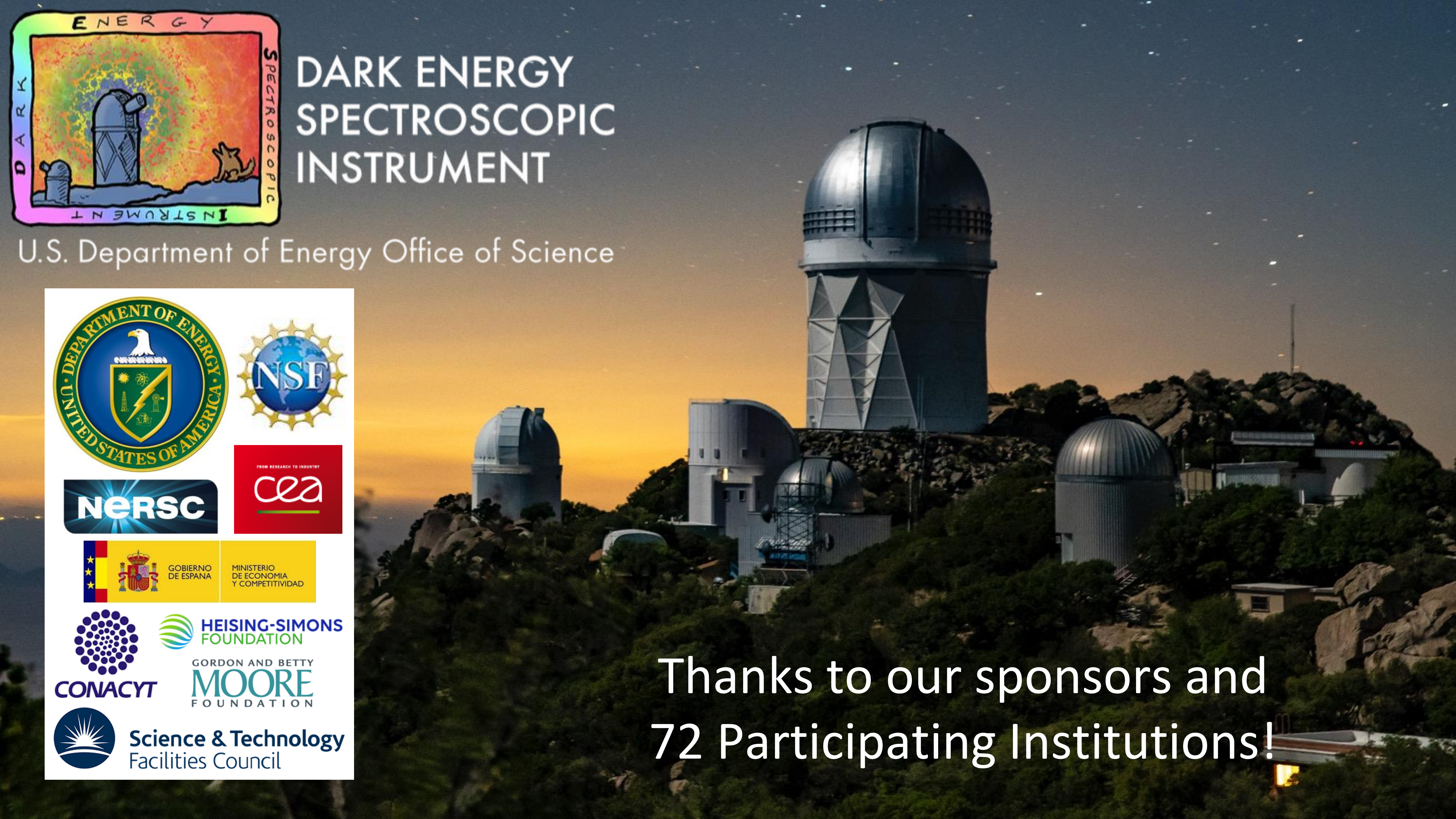
DESI DR2 Results: From Baryon Acoustic Oscillations to Dark Energy

Andrei Cuceu
NHFP Fellow
Berkeley Lab

On behalf of the DESI Collaboration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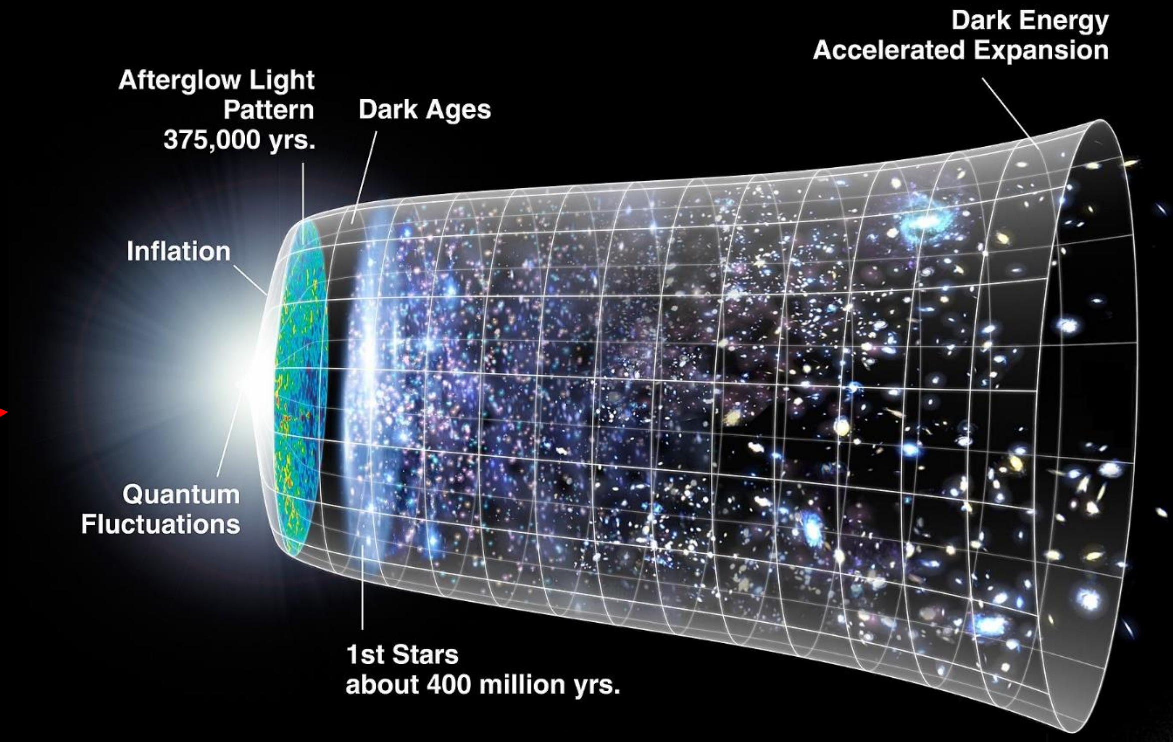
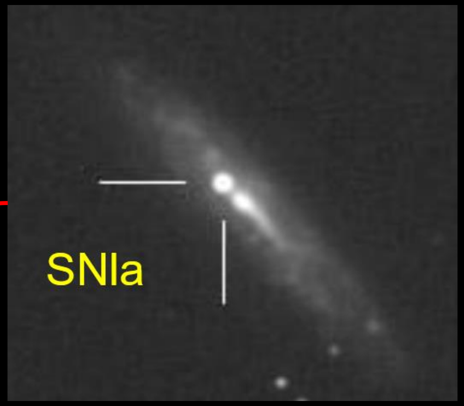
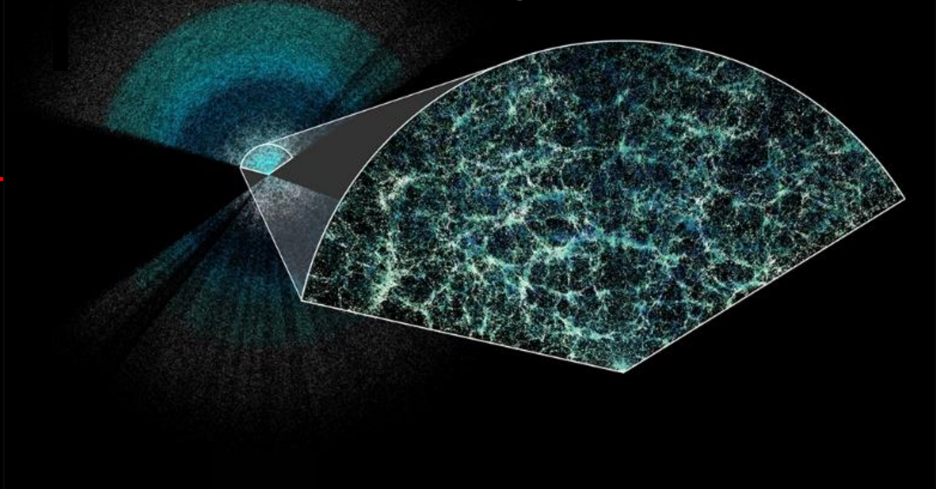
Standard model of cosmology



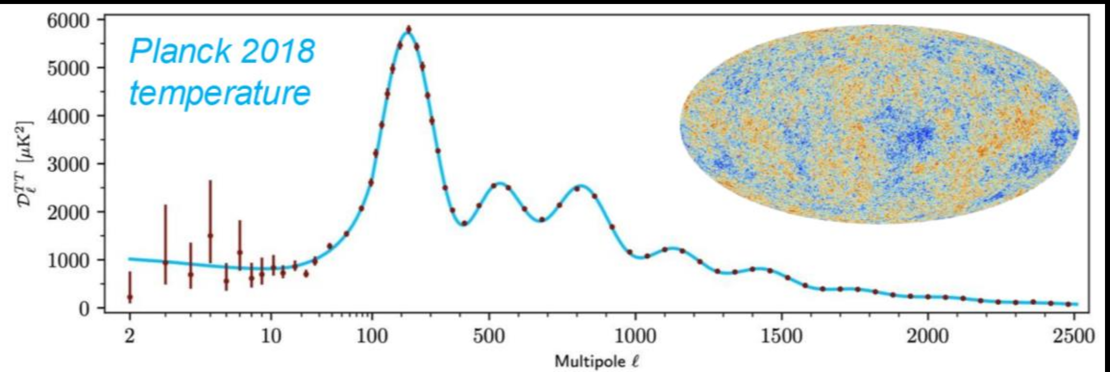
Supernovae



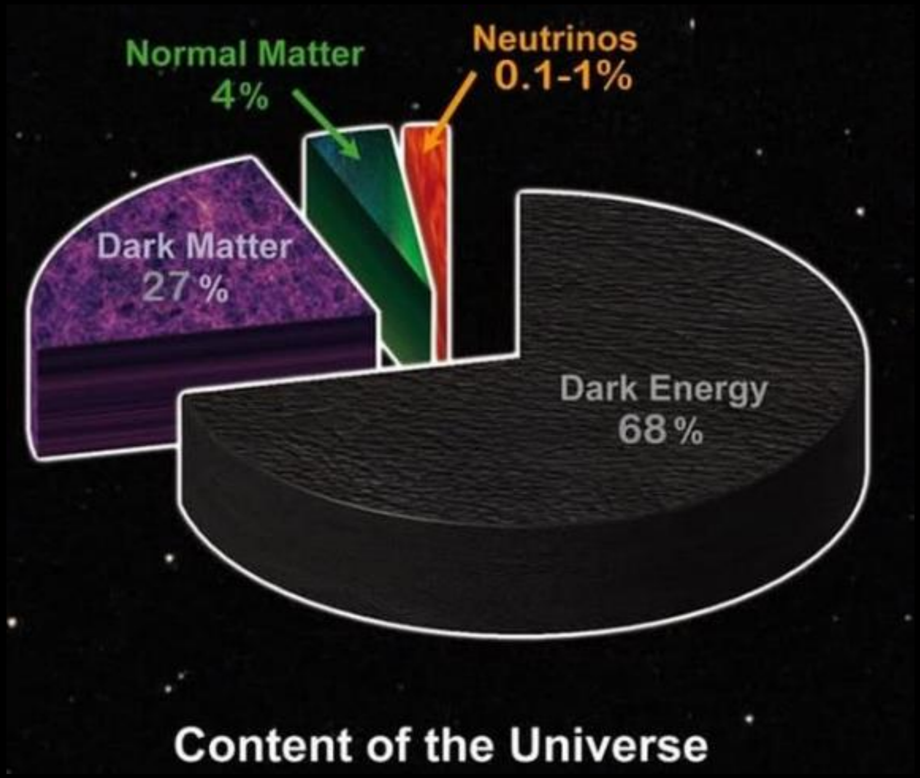
Large-scale structure



Cosmic Microwave Background (CMB)



Standard model of cosmology - ΛCDM



Components we will discuss today

- **Dark Energy** (late-time acceleration):
  - Cosmological constant (Λ)?
  - Evolving equation of state?
- **Neutrinos** (cosmology, laboratory experiments):
  - Neutrino mass constraints
  - Close to ruling out inverted hierarchy?

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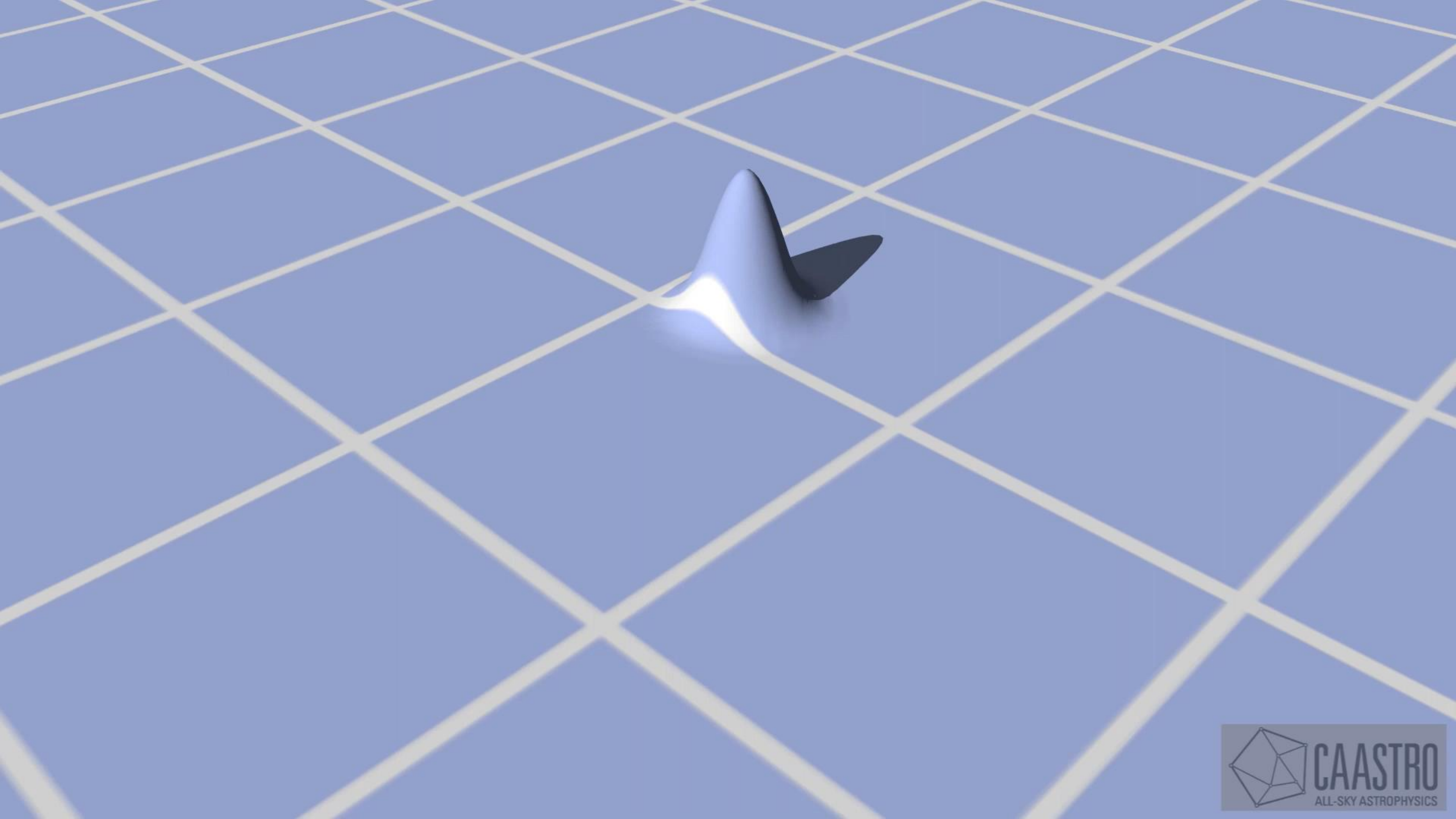
Baryon Acoustic Oscillations (BAO)


CAASTRO
ALL-SKY ASTROPHYSICS

Baryon Acoustic Oscillations (BAO)

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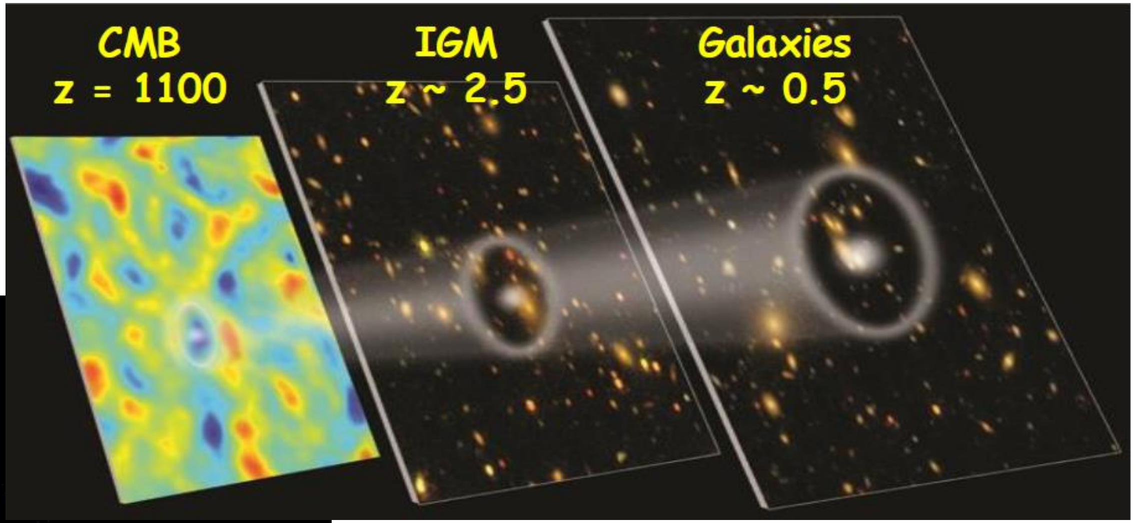
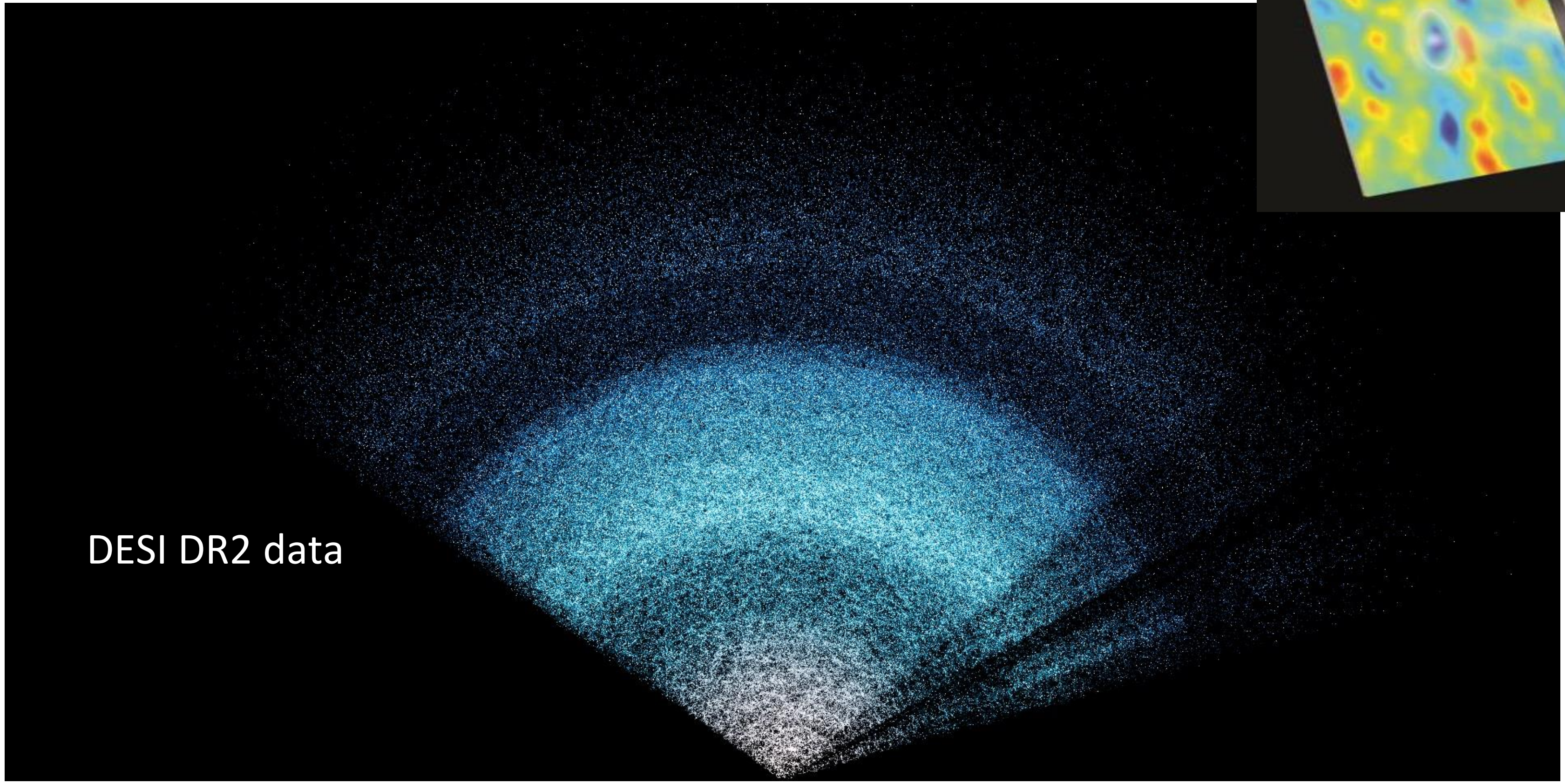
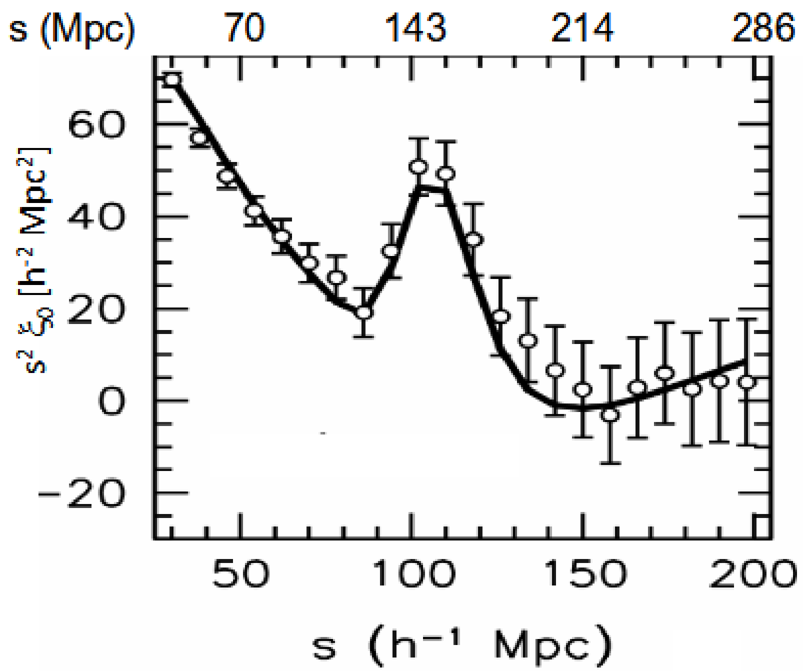
Imprint of fluctuations in primordial plasma
→ Standard Ruler to measure distances

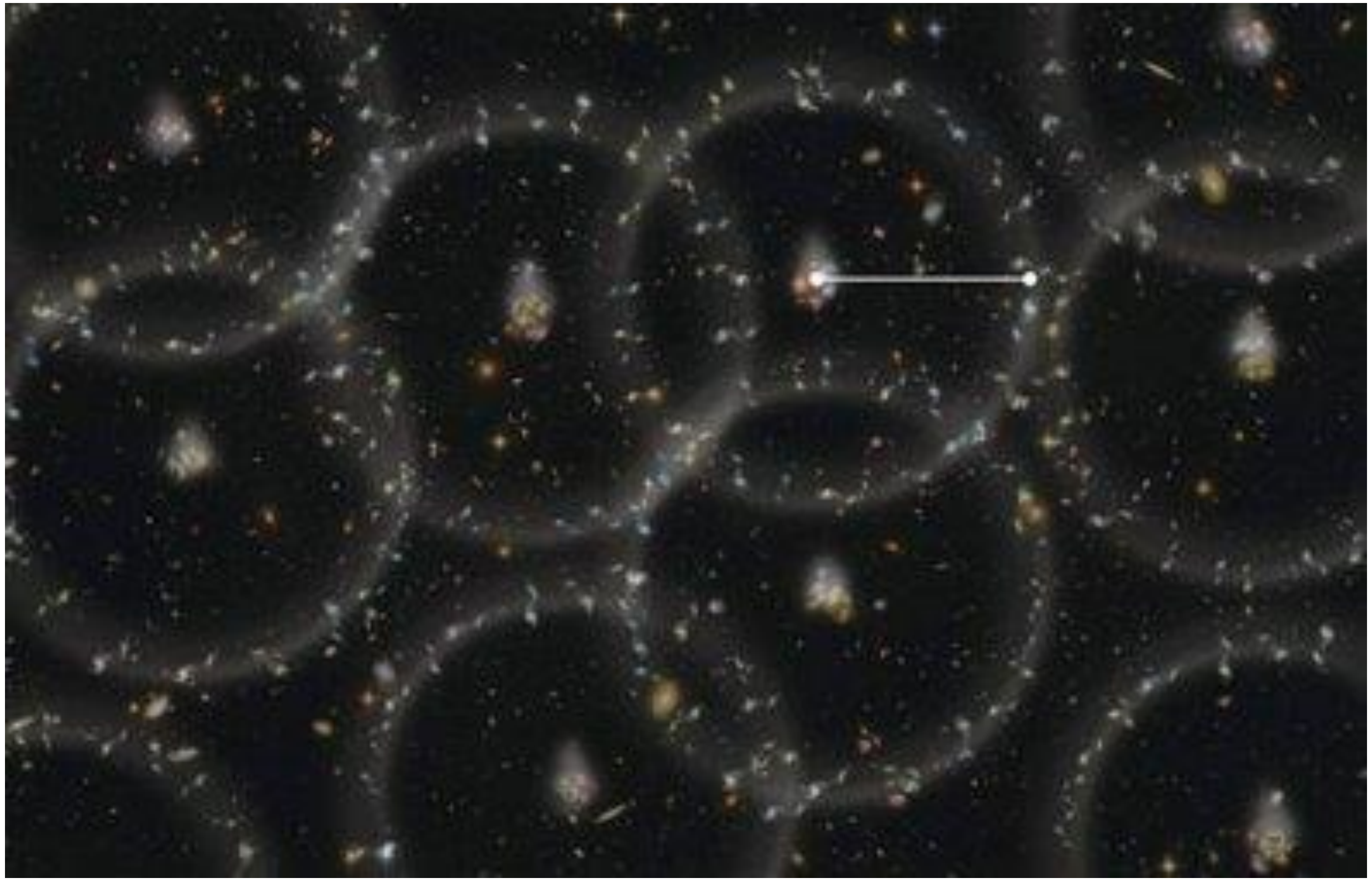


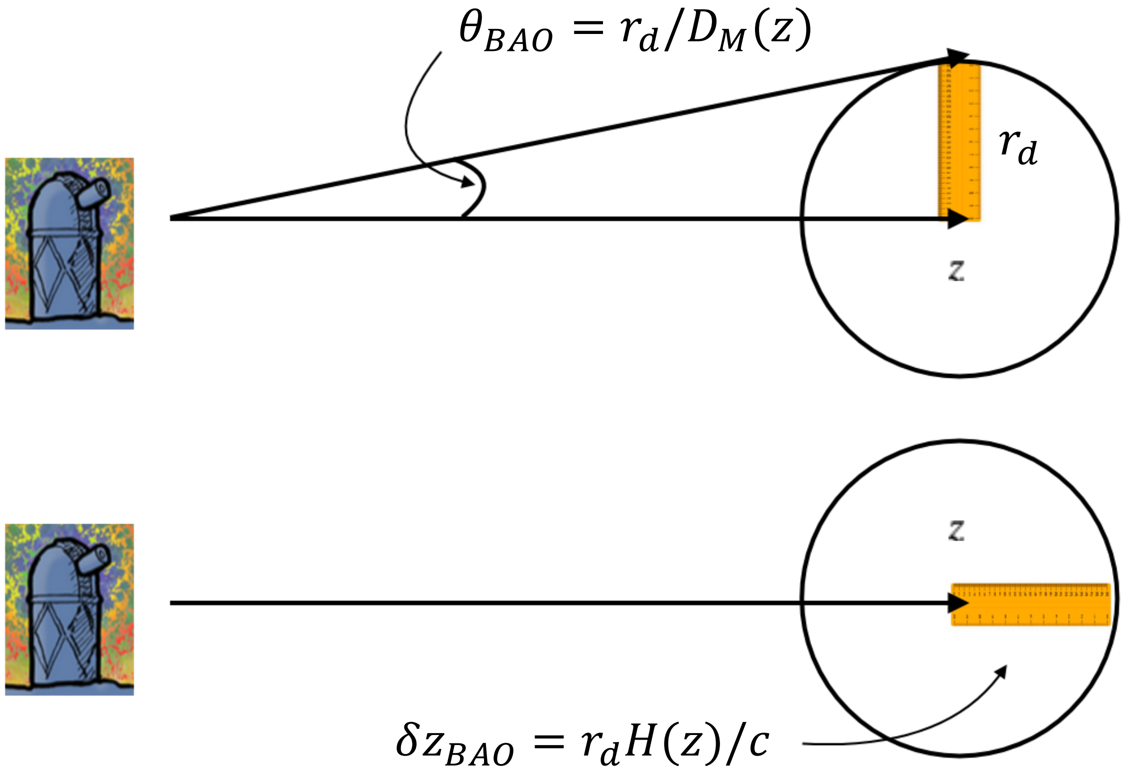




Credit: DESI collaboration

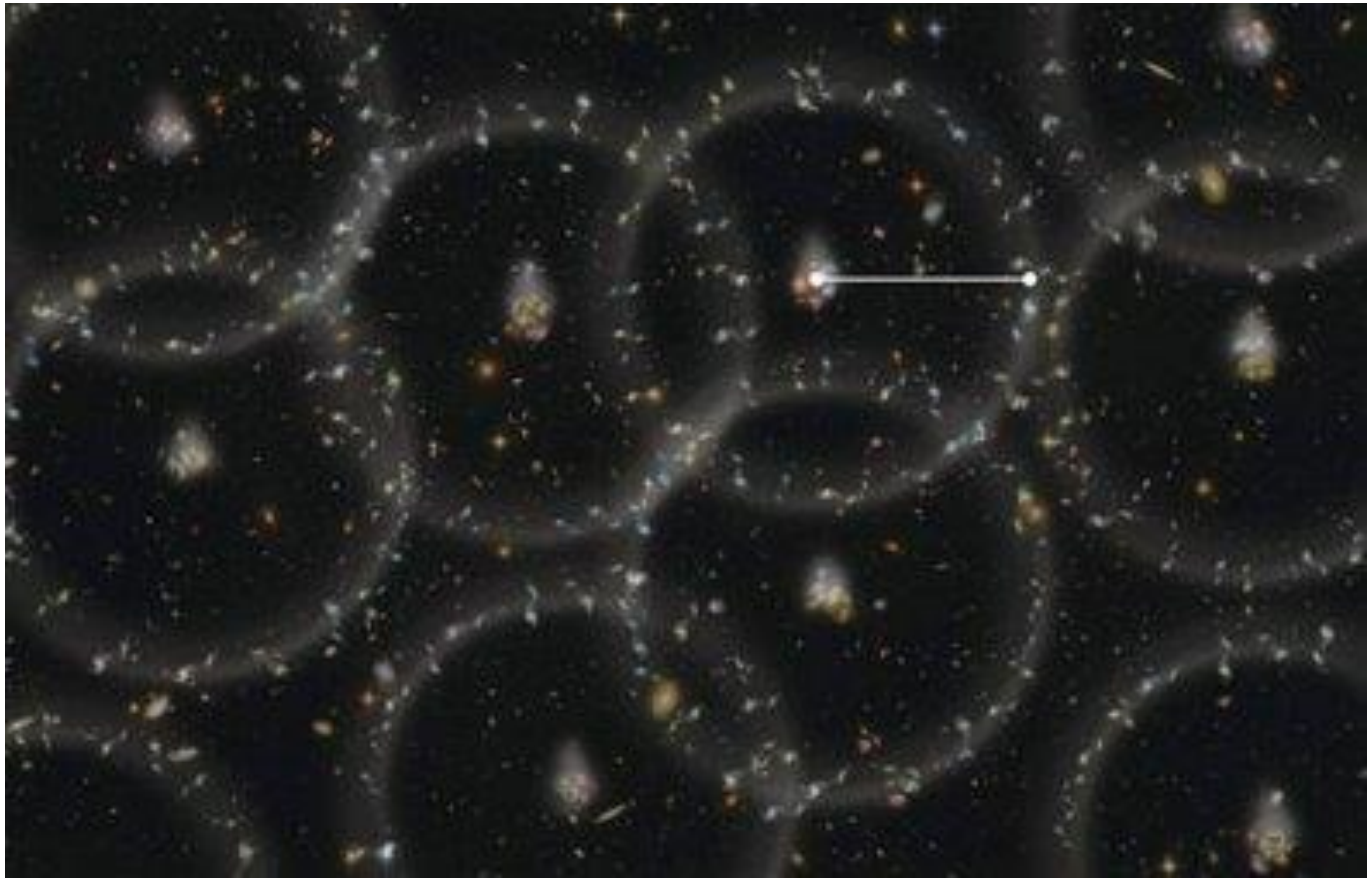
BAO → standard ruler

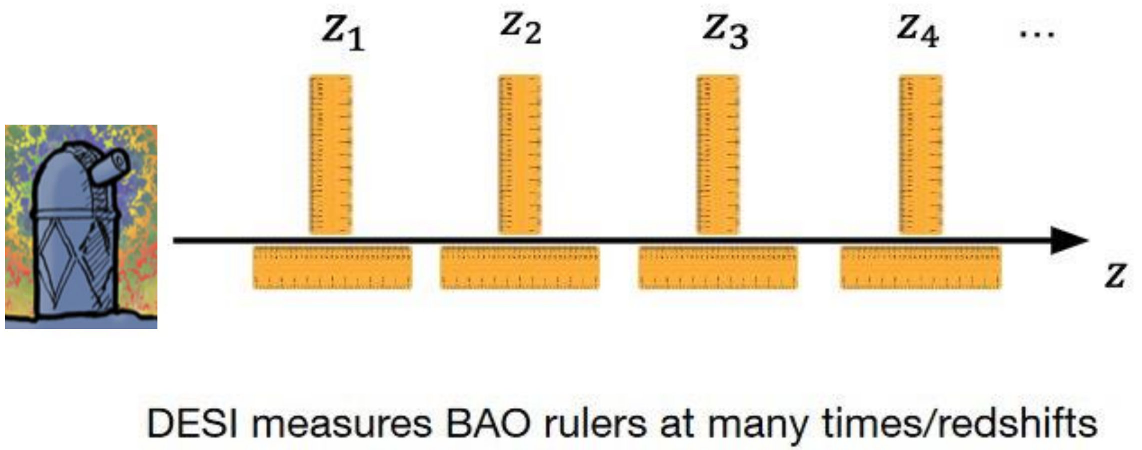




$D_M(z)$ and $H(z)$ encode **expansion history** of the Universe

BAO → standard ruler





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

Dark Energy Spectroscopic Instrument (DESI)

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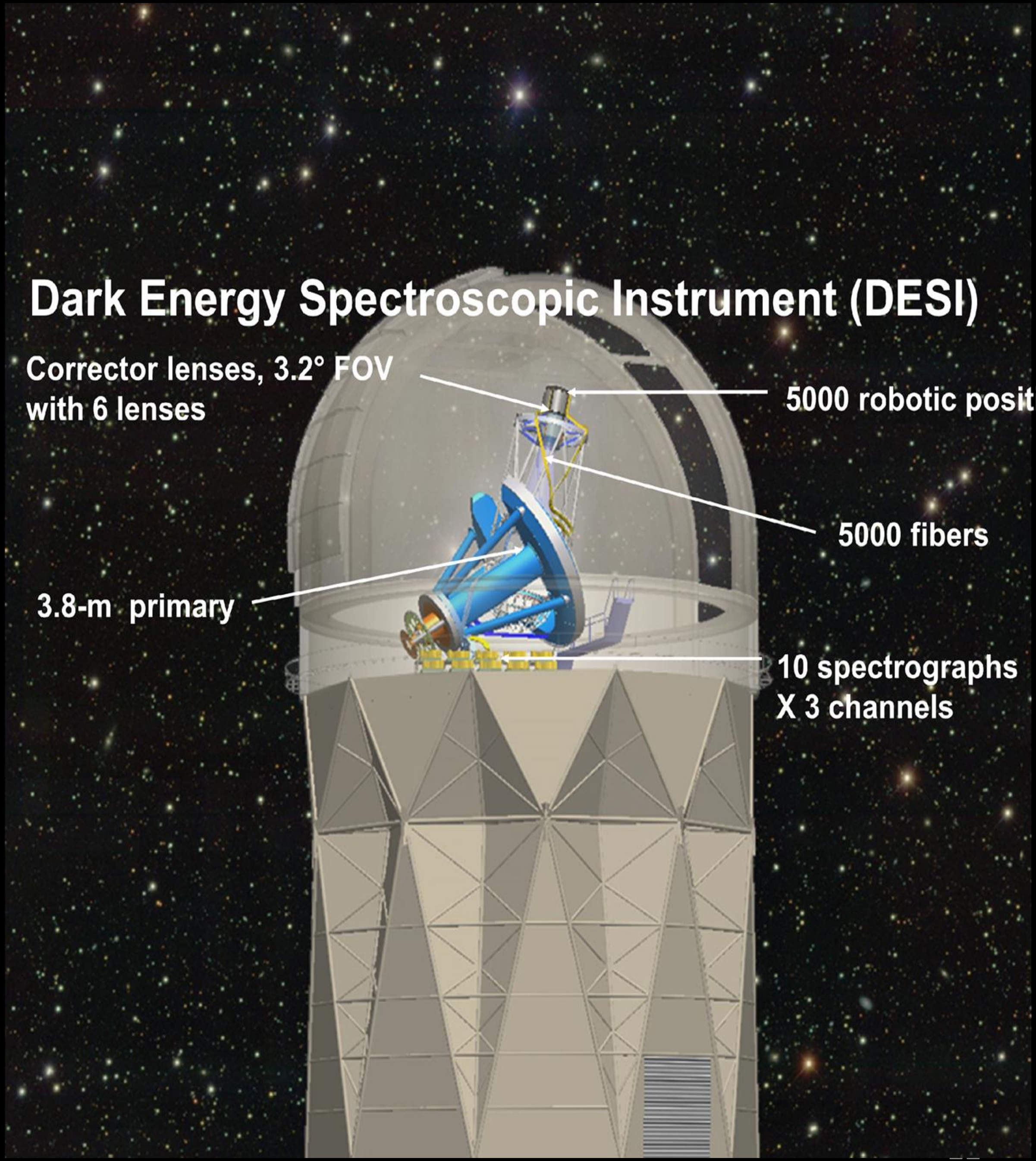
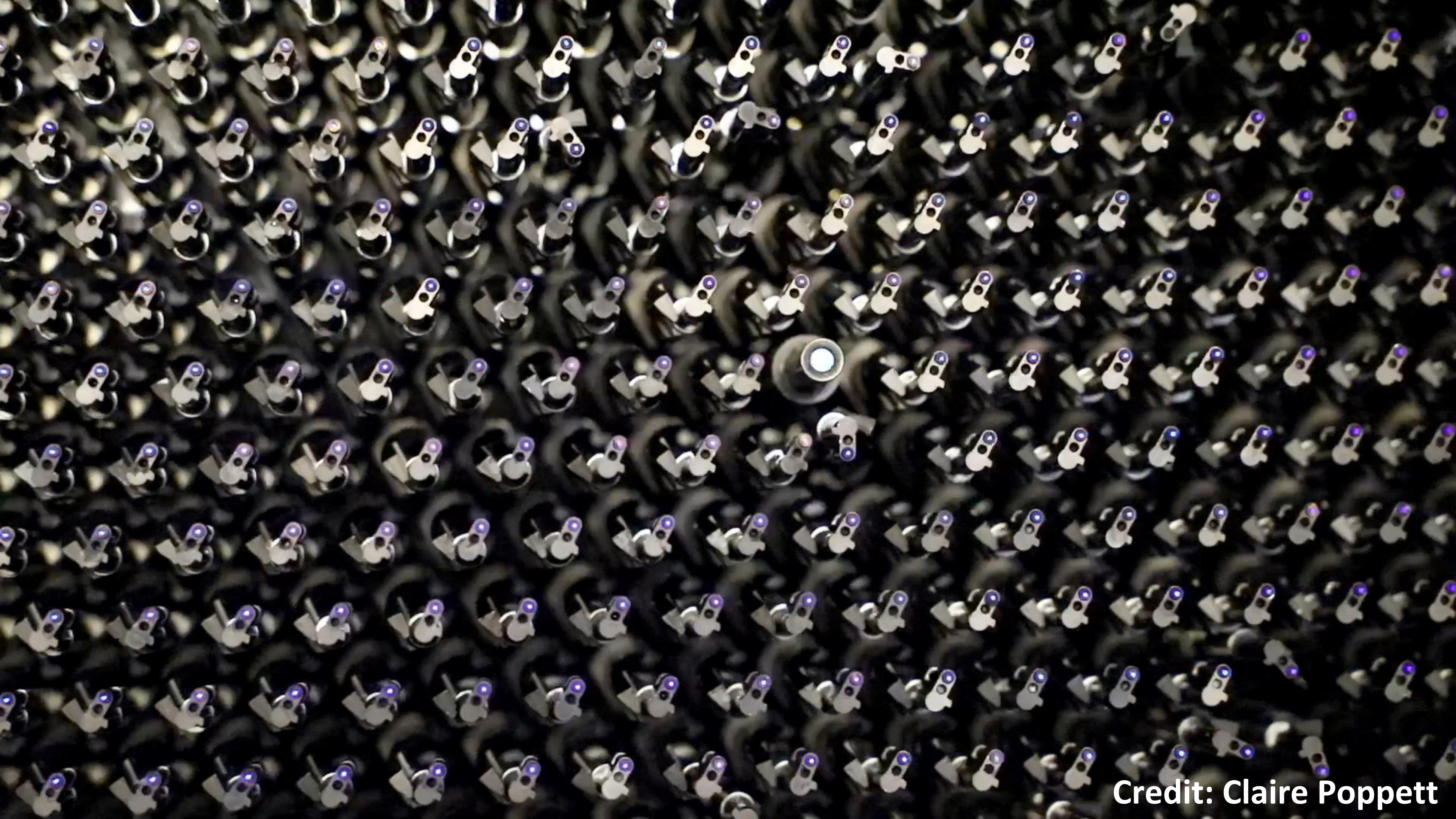
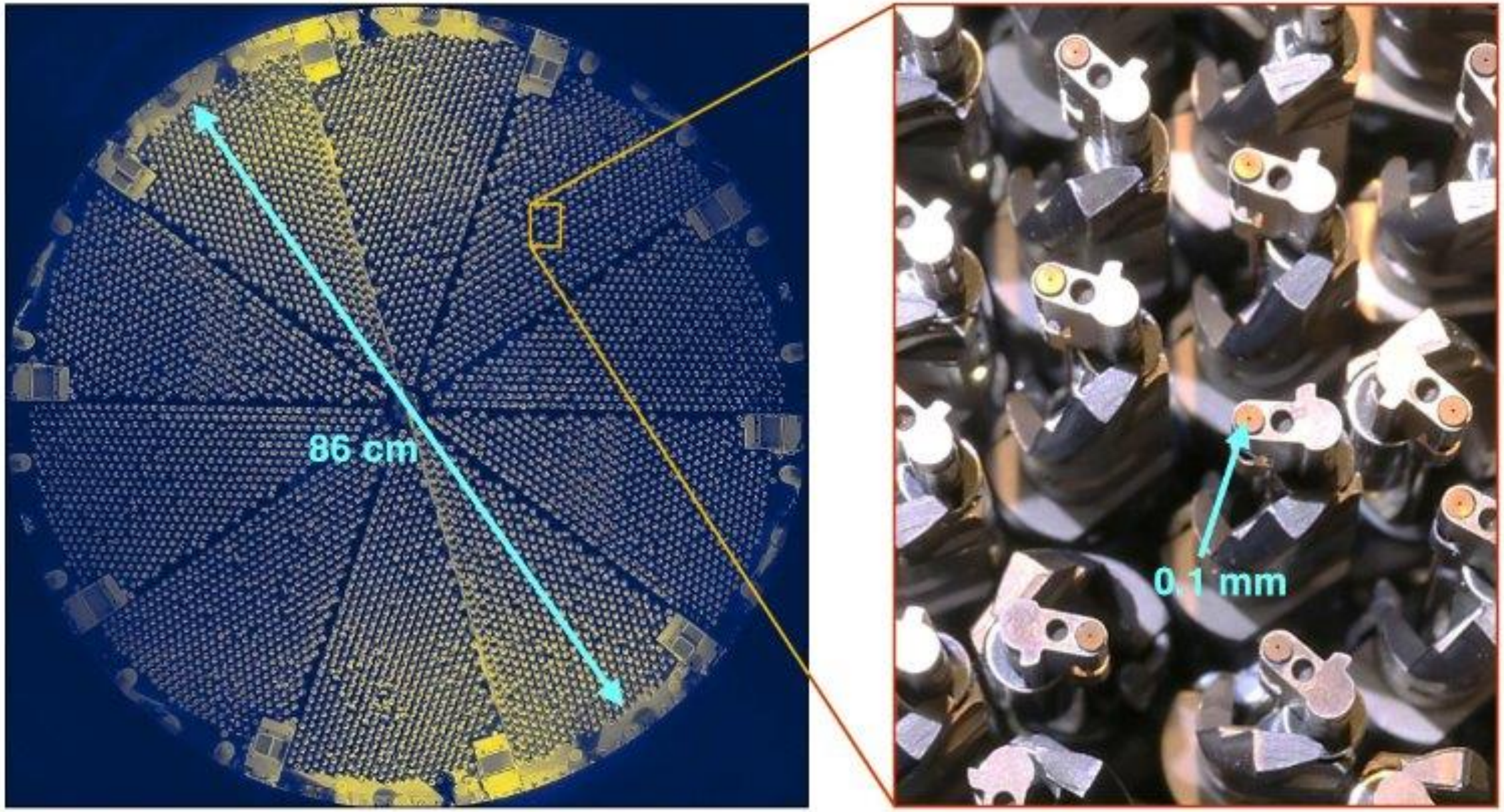
Dark Energy Spectroscopic Instrument (DESI)

- Designed for precision dark energy from z = 0 → 3
- First Stage 4 experiment
- Nominal 5-year Survey: 2021 → 2026
- 5000-robot army → 5000 fibers → 10 spectrographs
- 5000 spectra every ~ 15 min




Credit: Claire Poppett

The focal plane



All 5000 fibres can be positioned to accuracy of <5 μm RMS in <120s

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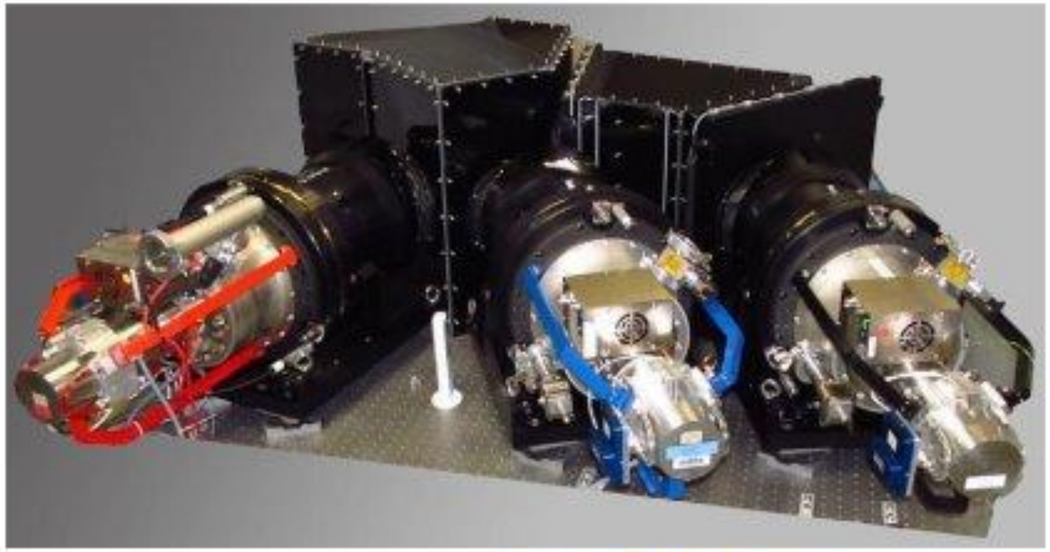
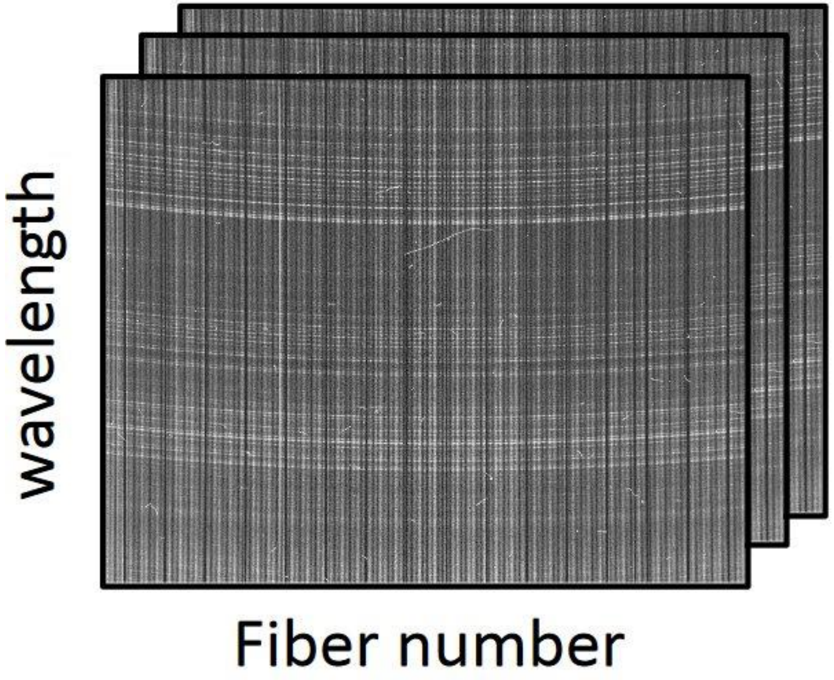
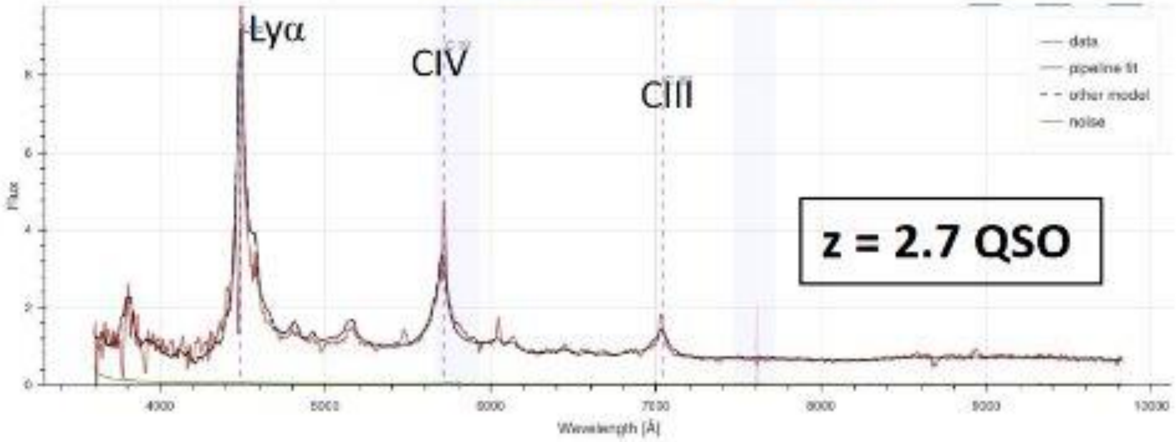
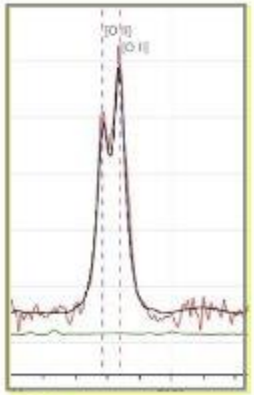
DESI spectra



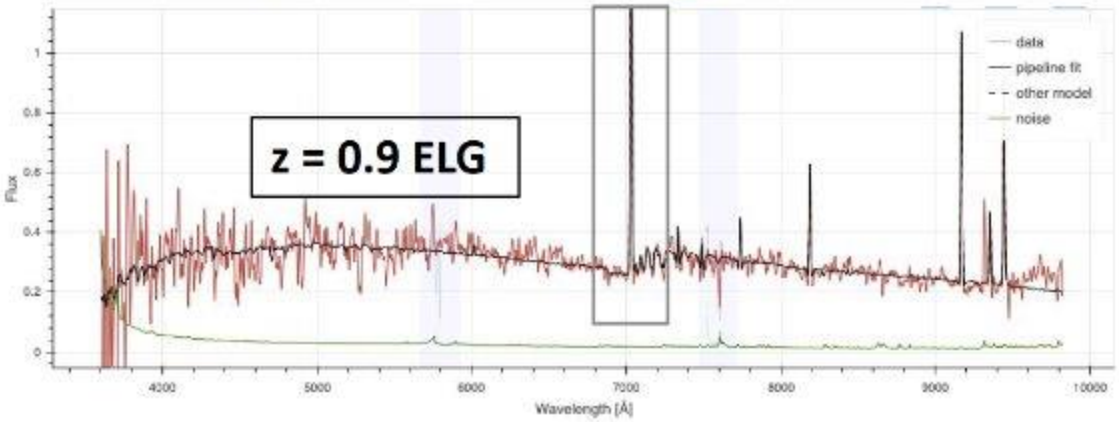


Lyα 121.6 nm
down to z = 2.0





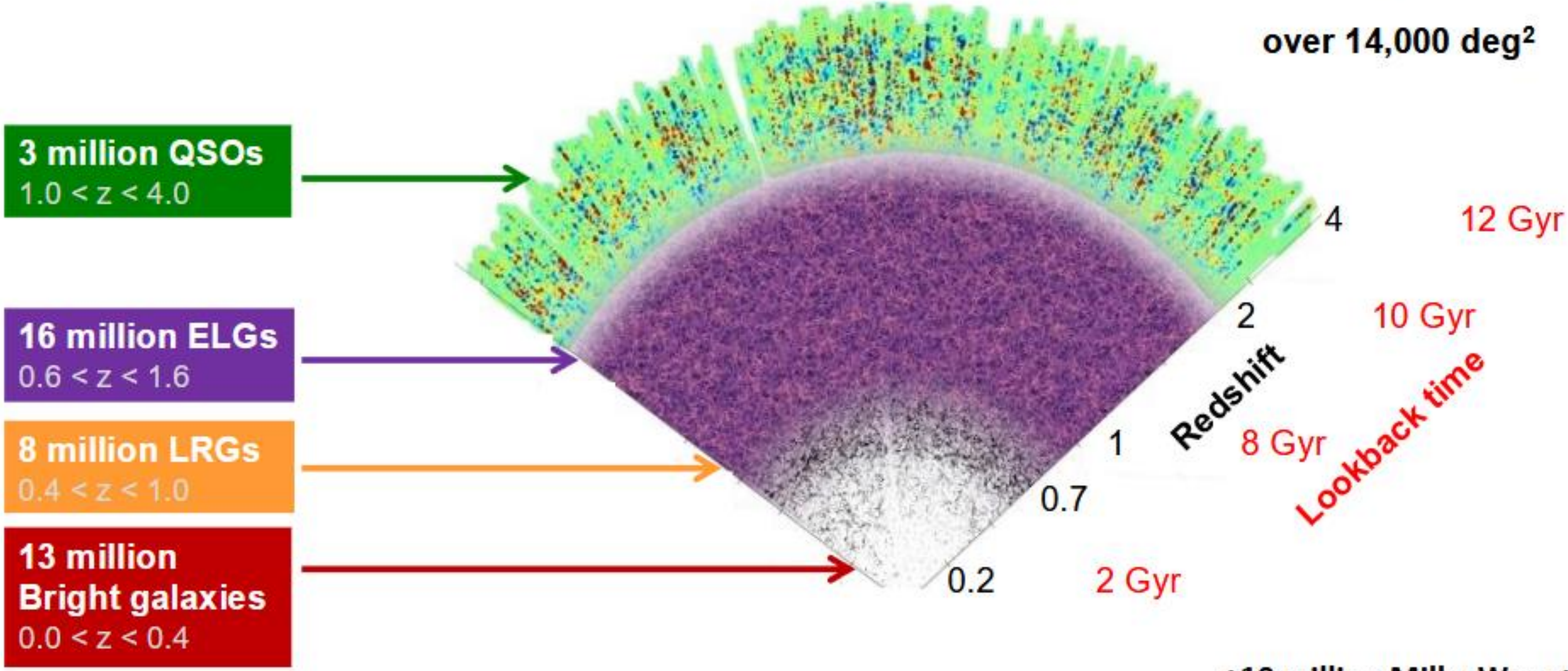
[OII] doublet at 373 nm
up to z = 1.6



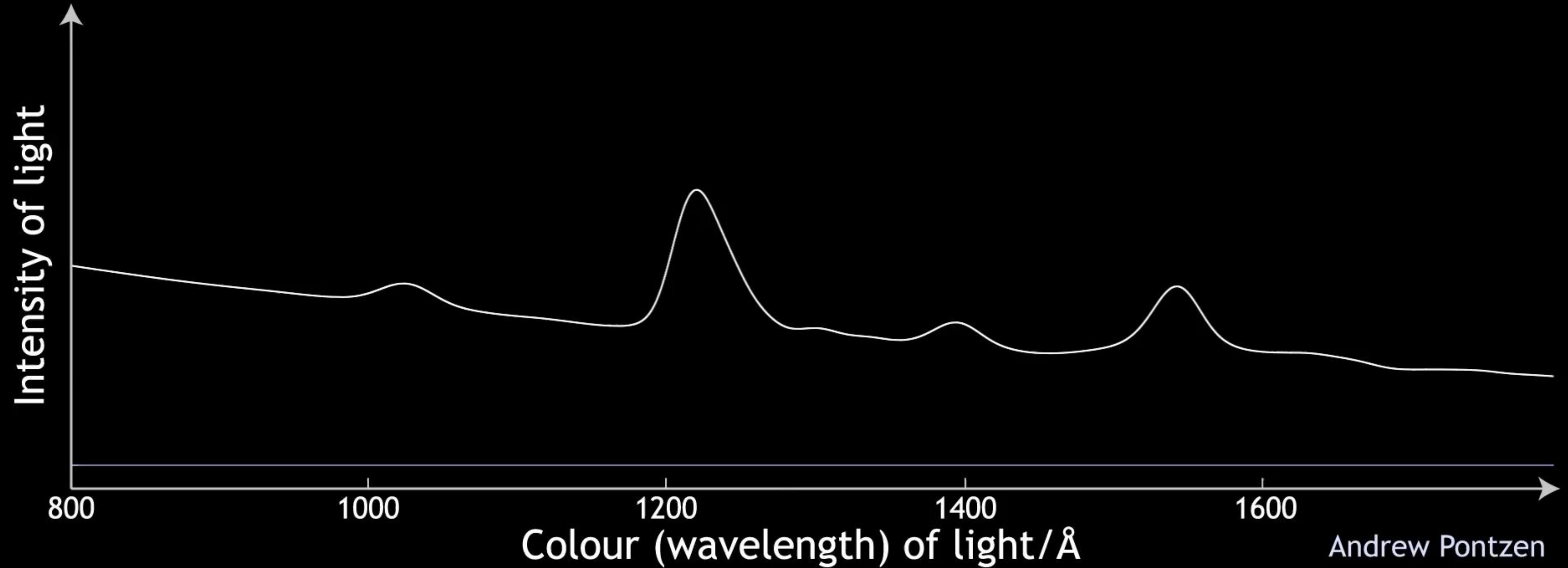
DESI targets

40 million
galaxies and quasars covering $0 < z < 4$

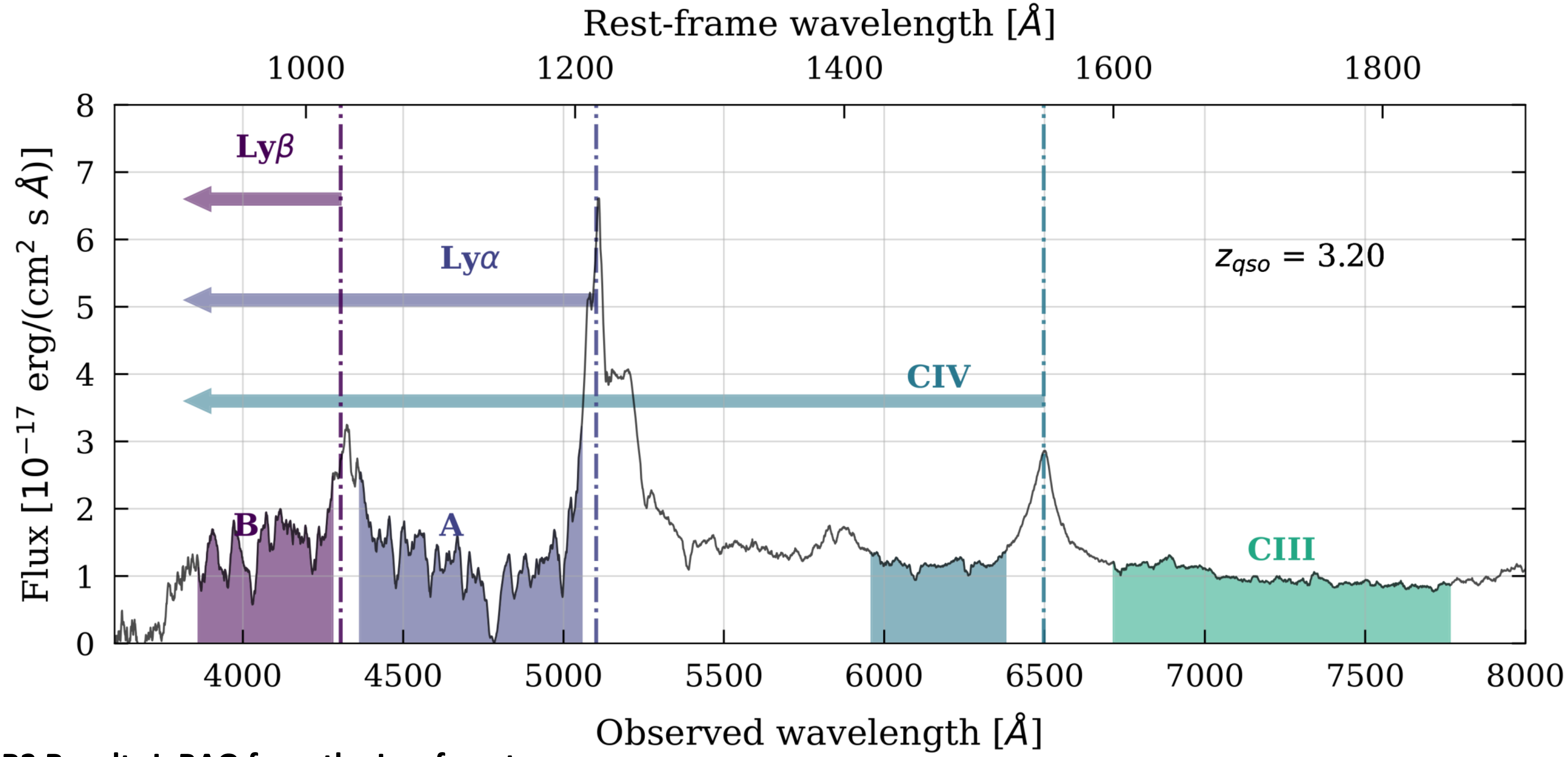
over 14,000 deg²



+10 million Milky Way stars

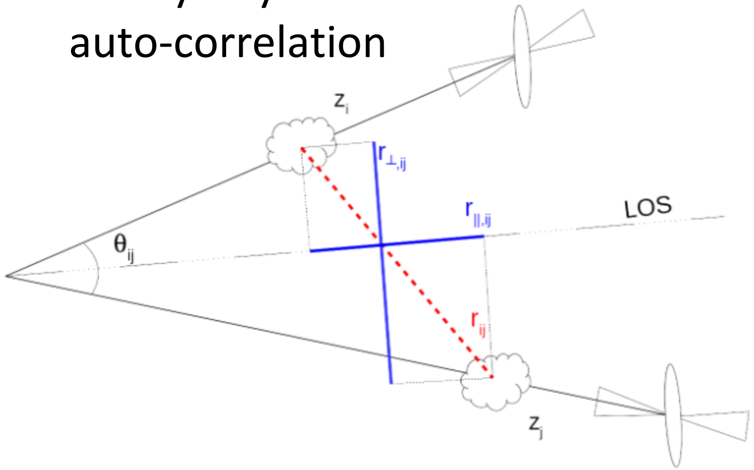

Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen

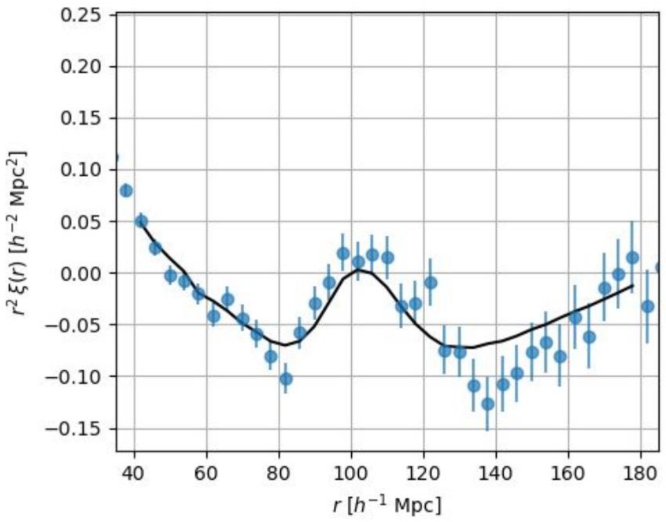
DESI spectrum of a quasar at $z = 3.20$



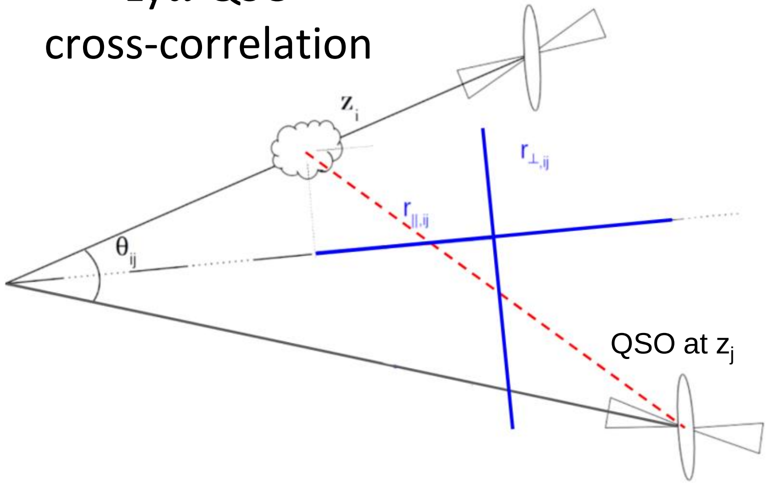
Lyα forest analysis

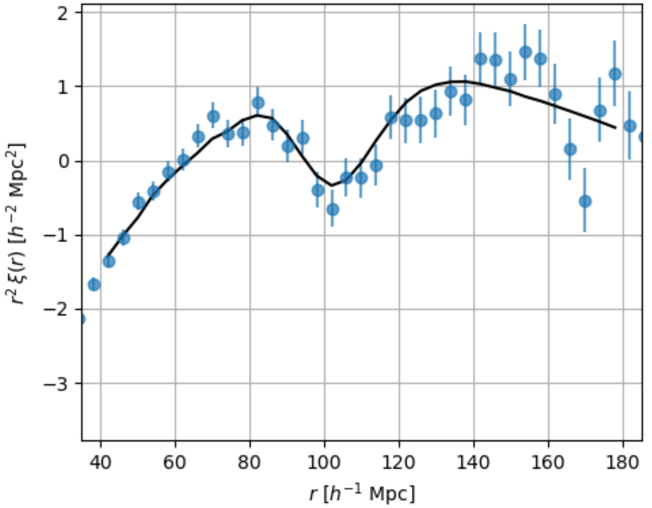
Lyα-Lyα
auto-correlation





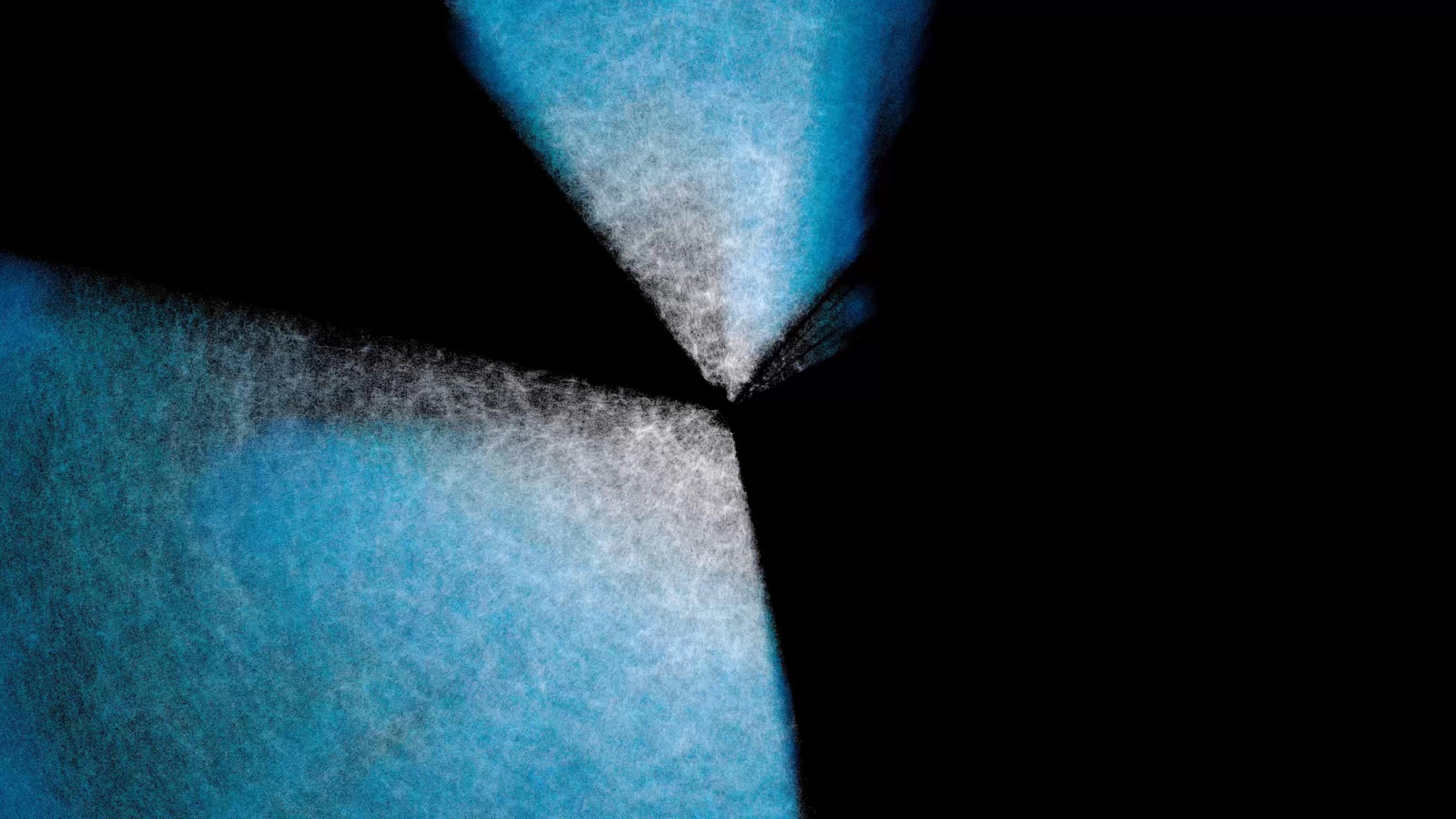
Lyα-QSO
cross-correlation





DESI DATA RELEASE 2 (DR2)

Data collected during the first 3 years of observations



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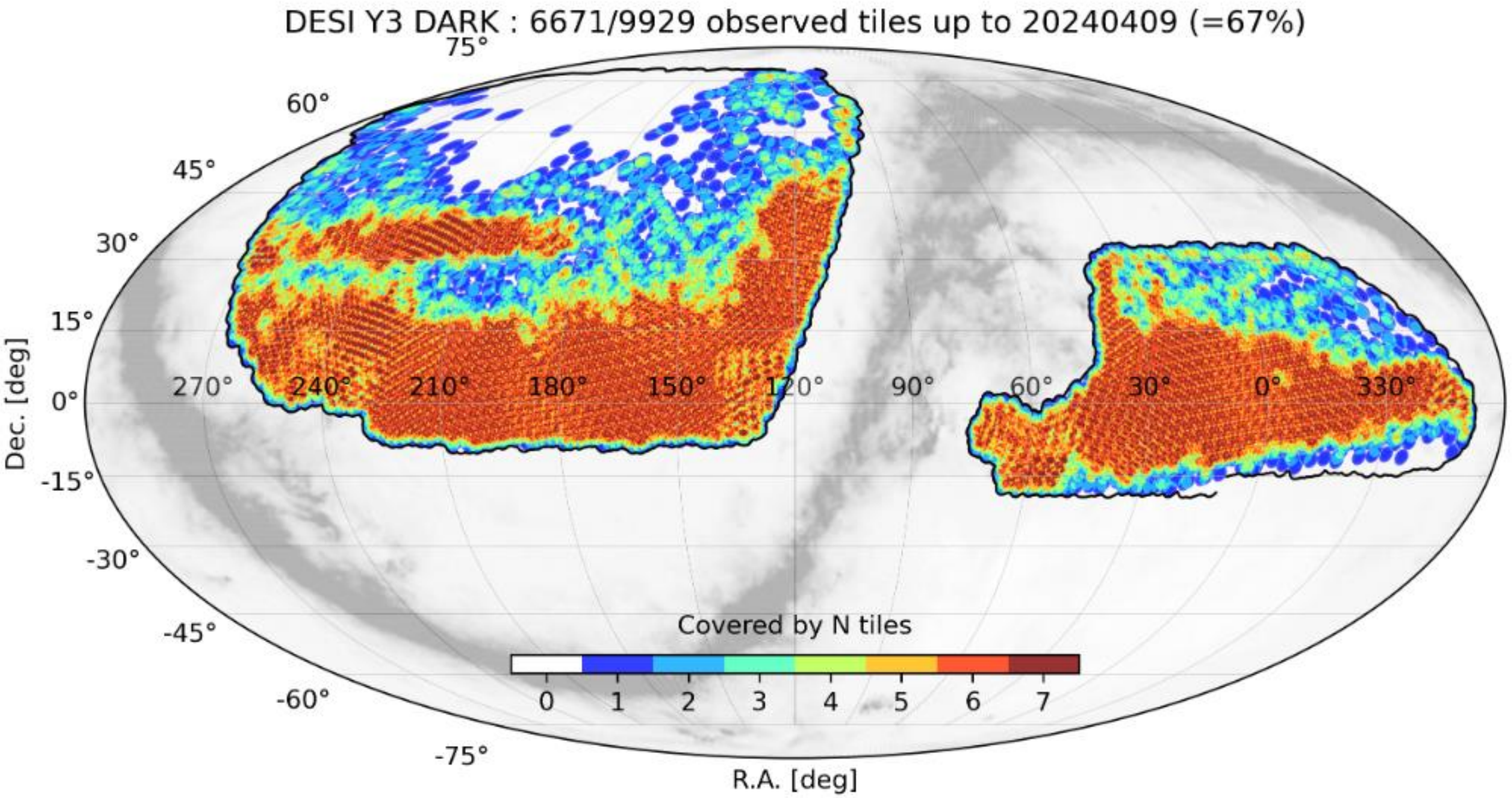
The DESI DR2 sample



The DESI DR2 sample

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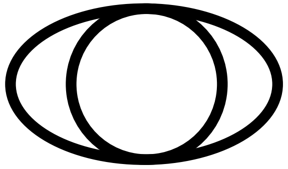
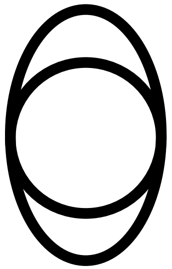
- Over 14 million galaxies and quasars in the sample used in this analysis
- Compared to DR1, this represents a factor of ~2.4 improvement in data volume

Tracer	DR1	DR2
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**

BAO scaling parameters



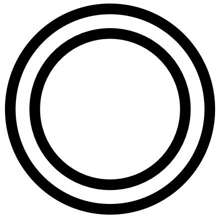
$$\alpha_\perp = \frac{D_M/r_d}{[D_M/r_d]_{fid}} \quad \text{and} \quad \alpha_{||} = \frac{D_H/r_d}{[D_H/r_d]_{fid}}$$



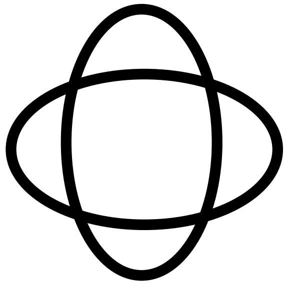
perpendicular ruler size

line-of-sight ruler size

OR



$$\alpha_{iso} = (\alpha_\perp^2 \alpha_{||})^{1/3} \quad \text{and} \quad \alpha_{AP} = \frac{D_H/D_M}{[D_H/D_M]_{fid}}$$



Isotropic BAO scale

anisotropy of BAO (Alcock-Paczynski effect)

DESI DR2 blinding

- BAO measurements were kept blinded during the validation process
- For galaxies and quasars: Catalog-level blinding that modifies galaxy redshifts and weights
- For Lyα forest: Data-vector blinding that shifts the BAO peak location

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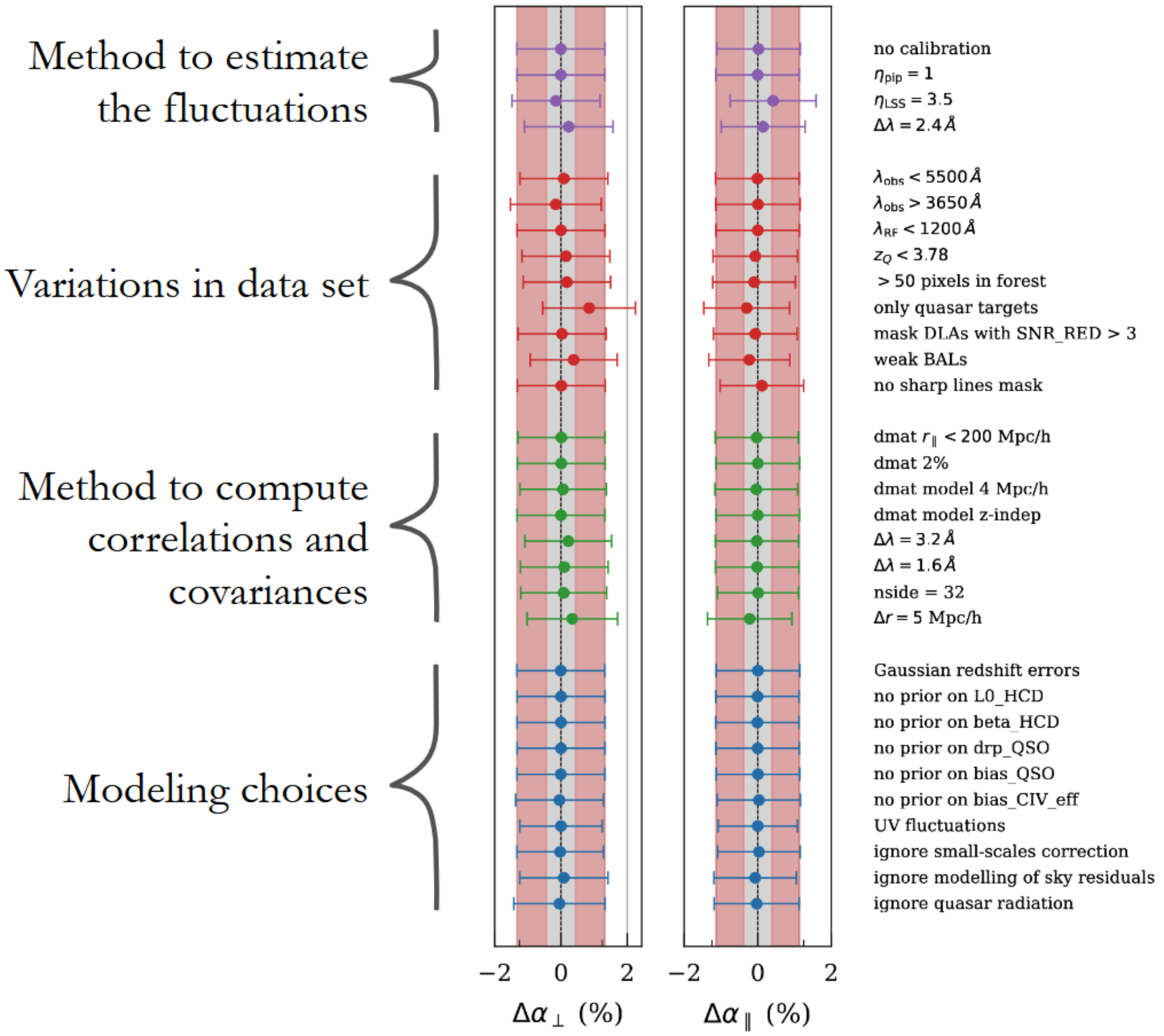
DR2 Lyα BAO robustness tests

DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest

Supporting paper: Validation of the DESI DR2 Lyα BAO analysis using synthetic datasets (Casas++ 2025)

Supporting paper: Construction of the Damped Lyα Absorber Catalog for DESI DR2 Lyα BAO (Brodzeller++ 2025)



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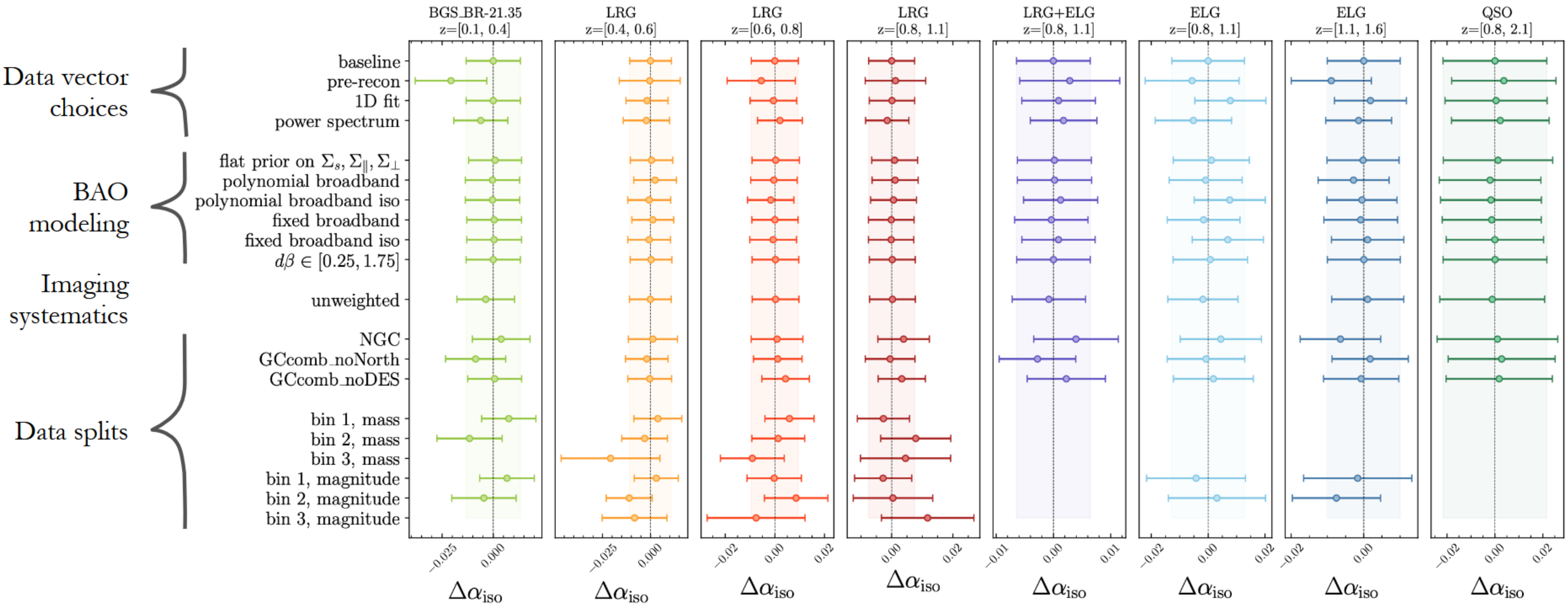
DR2 Galaxy BAO robustness tests



Differences in the isotropic BAO dilation

Supporting paper: Validation of DESI DR2 BAO from Galaxies and Quasars (Andrade++ 2025)

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Systematics – folded in the final results

Galaxy clustering

Tracer	Parameter	Theory (%)	HOD (%)	Fiducial (%)	Total (%)
BGS	α_{iso}	0.1	No detection	0.1	0.141
LRG1	α_{iso}	0.1	No detection	0.1	0.141
	α_{AP}	0.2	0.19	0.18	0.329
LRG2	α_{iso}	0.1	No detection	0.1	0.141
	α_{AP}	0.2	0.19	0.18	0.329
LRG3	α_{iso}	0.1	0.17	0.1	0.221
	α_{AP}	0.2	0.19	0.18	0.329
LRG3+ELG1	α_{iso}	0.1	0.17	0.1	0.221
	α_{AP}	0.2	0.19	0.18	0.329
ELG1	α_{iso}	0.1	0.17	0.1	0.221
	α_{AP}	0.2	No detection	0.1	0.224
ELG2	α_{iso}	0.1	0.17	0.1	0.221
	α_{AP}	0.2	No detection	0.1	0.224
QSO	α_{iso}	0.1	0.17	0.1	0.221
	α_{AP}	0.2	0.19	0.18	0.329

Lyα forest

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

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

(due to non-linear evolution of the BAO peak)

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Unblinding – December 2024

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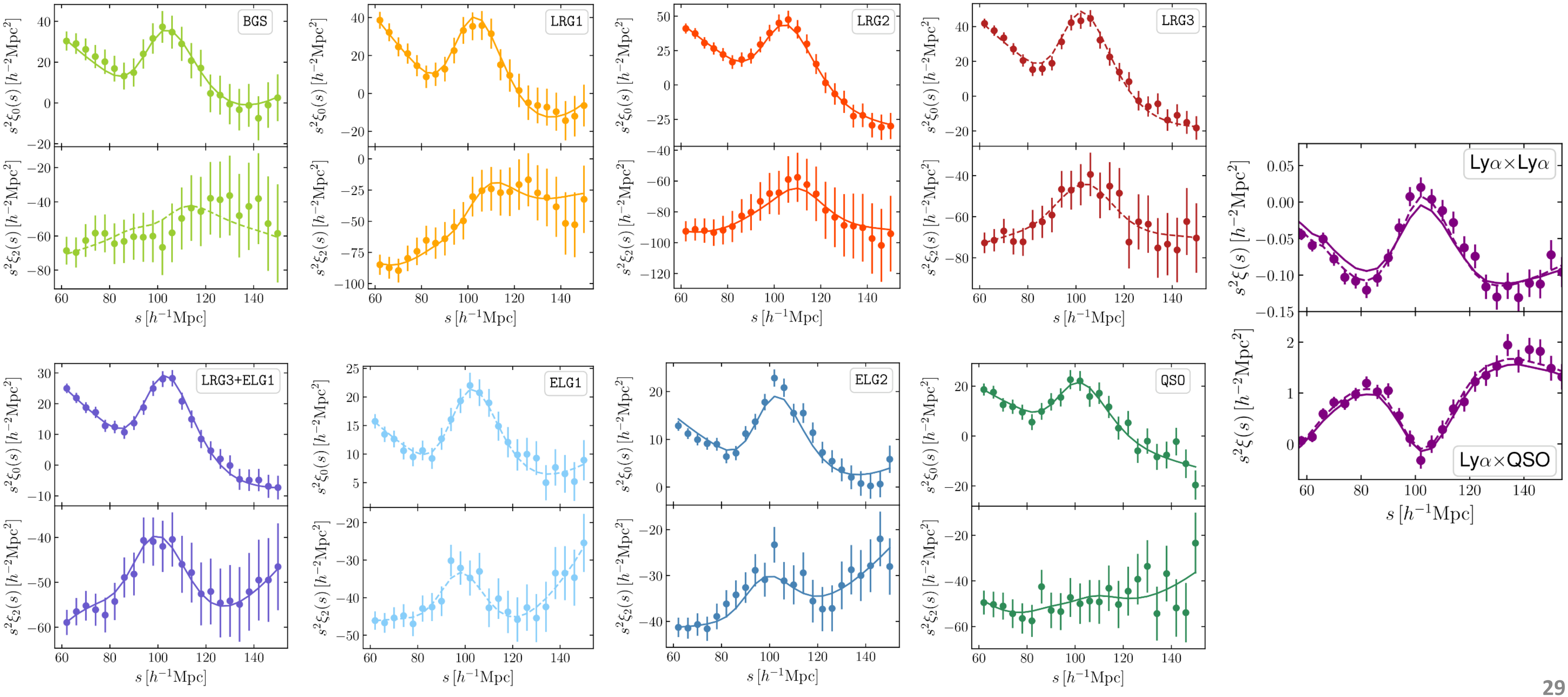
DESI DR2 clustering measurements



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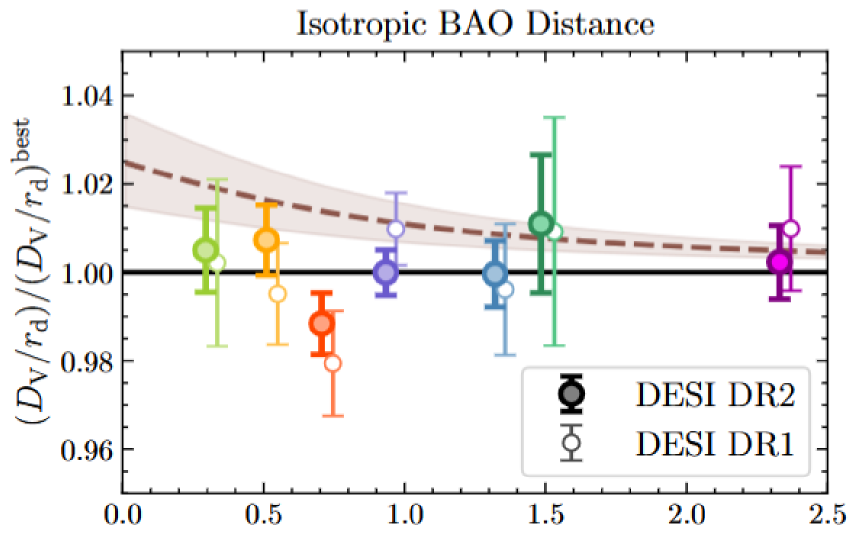
BAO Distance measurements



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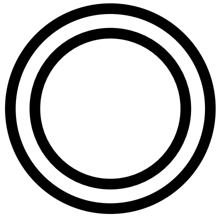
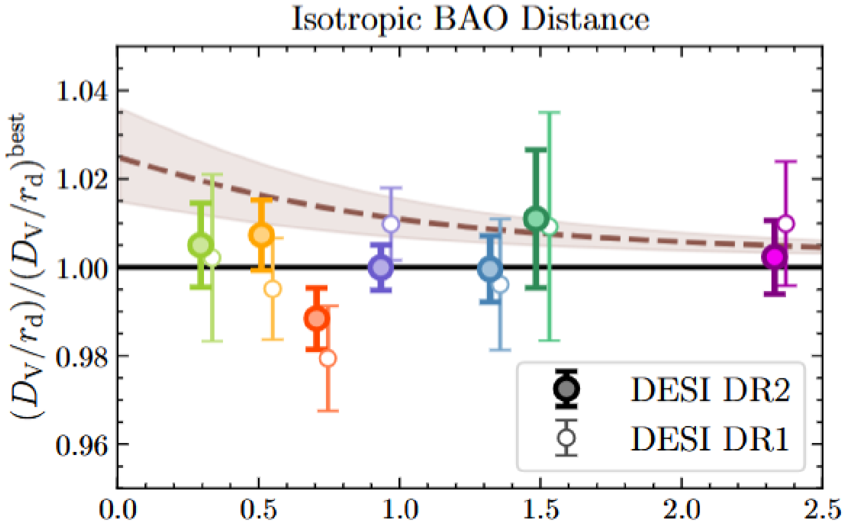
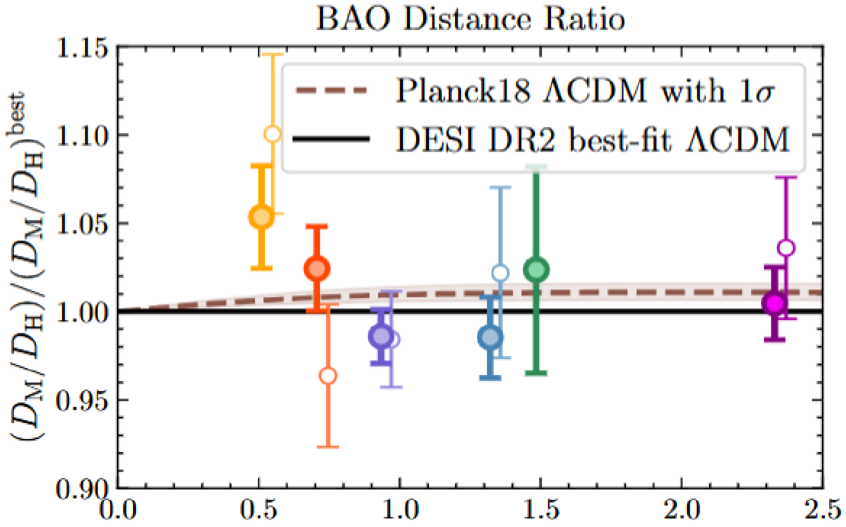
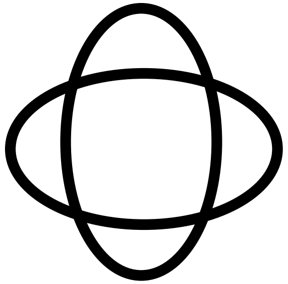
BAO Distance measurements









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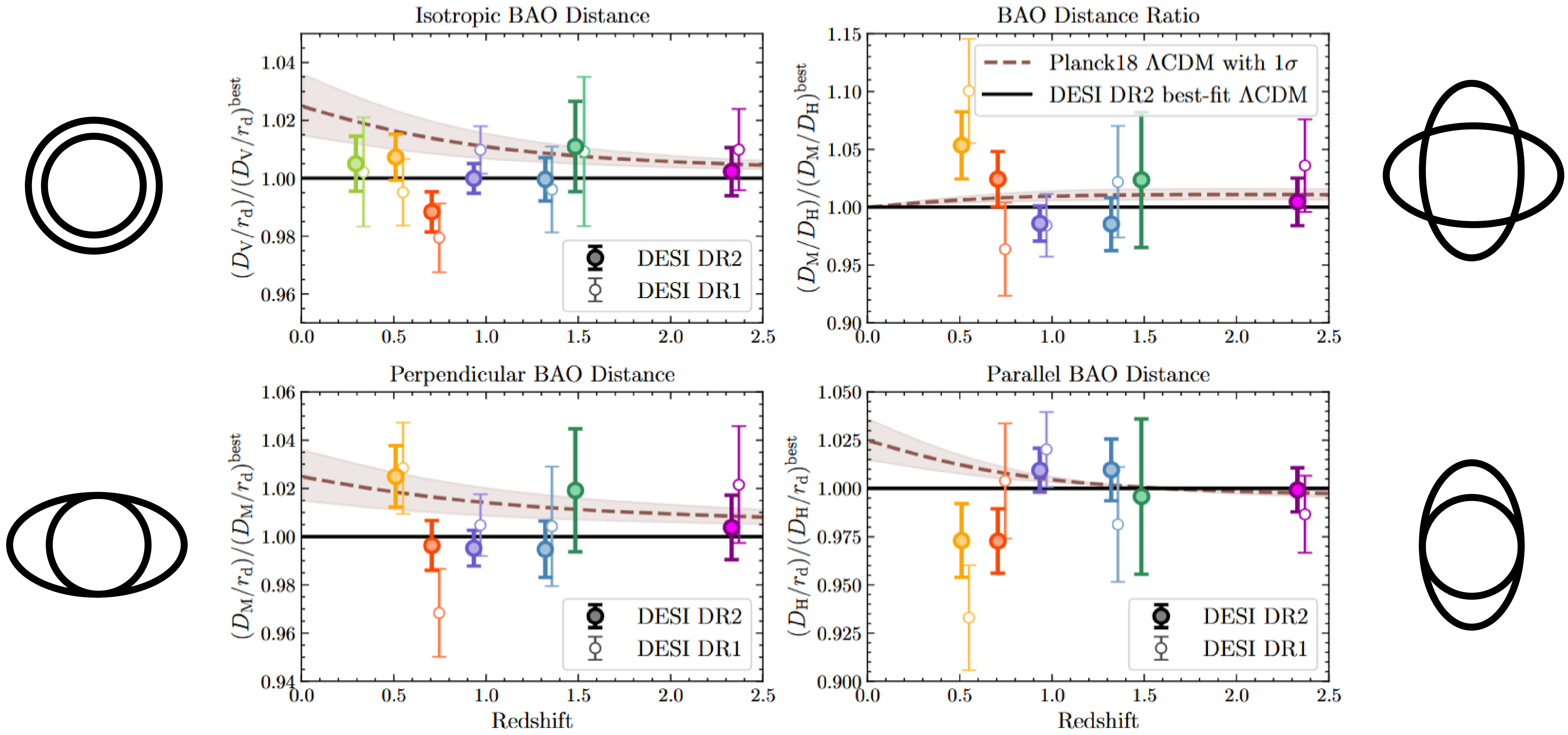
BAO Distance measurements

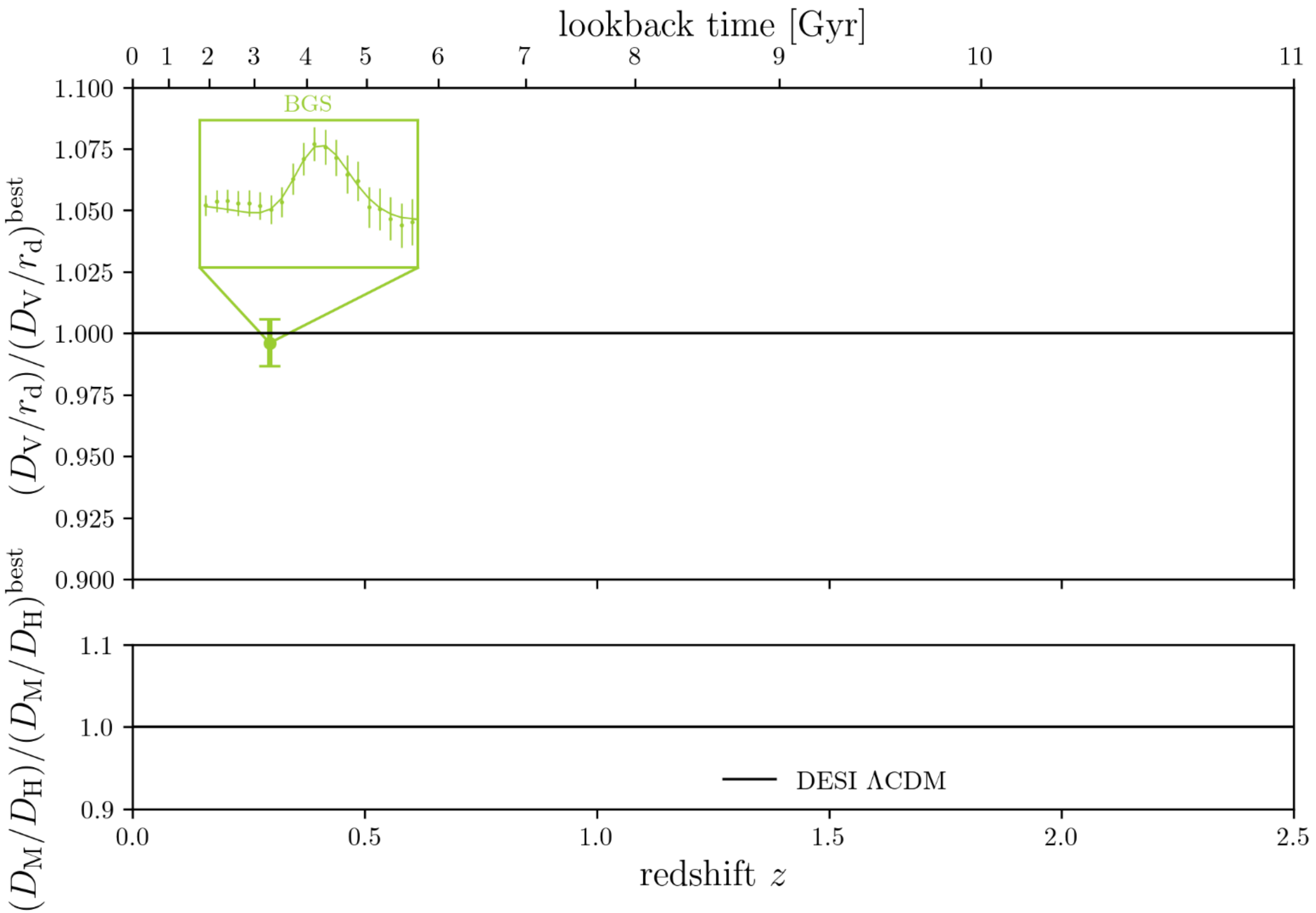


Main Results

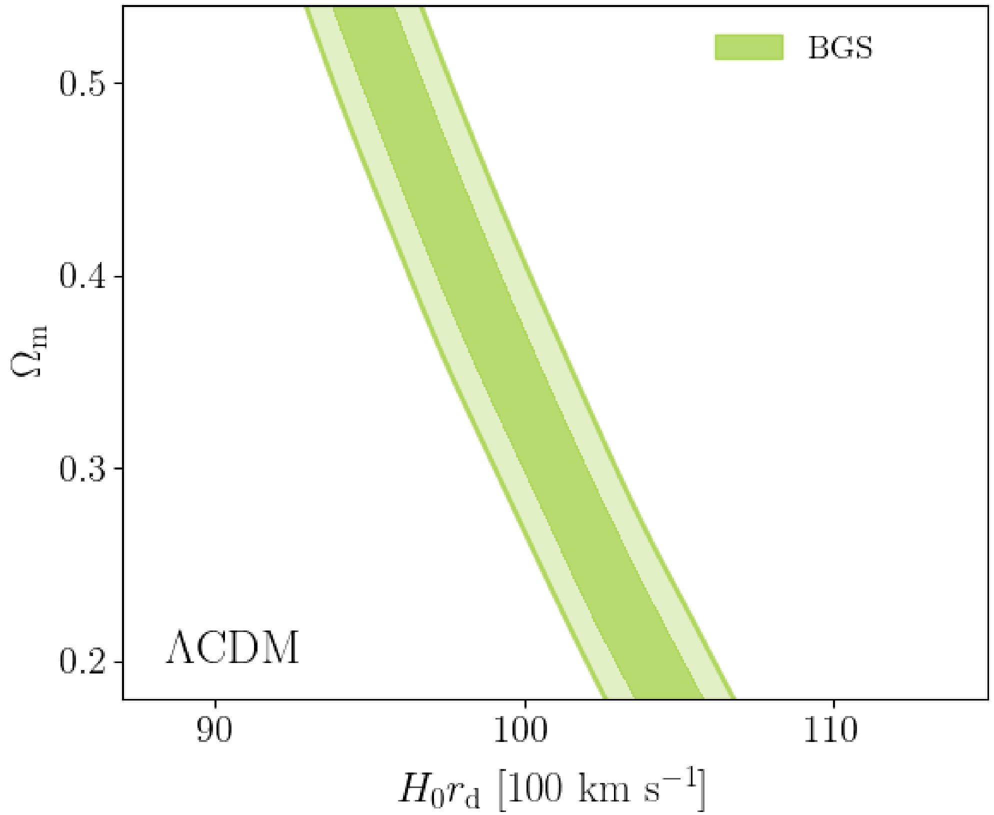
I. ΛCDM constraints

DESI DR2 BAO

DESI BAO measurements



Flat ΛCDM results



DESI DR2 BAO

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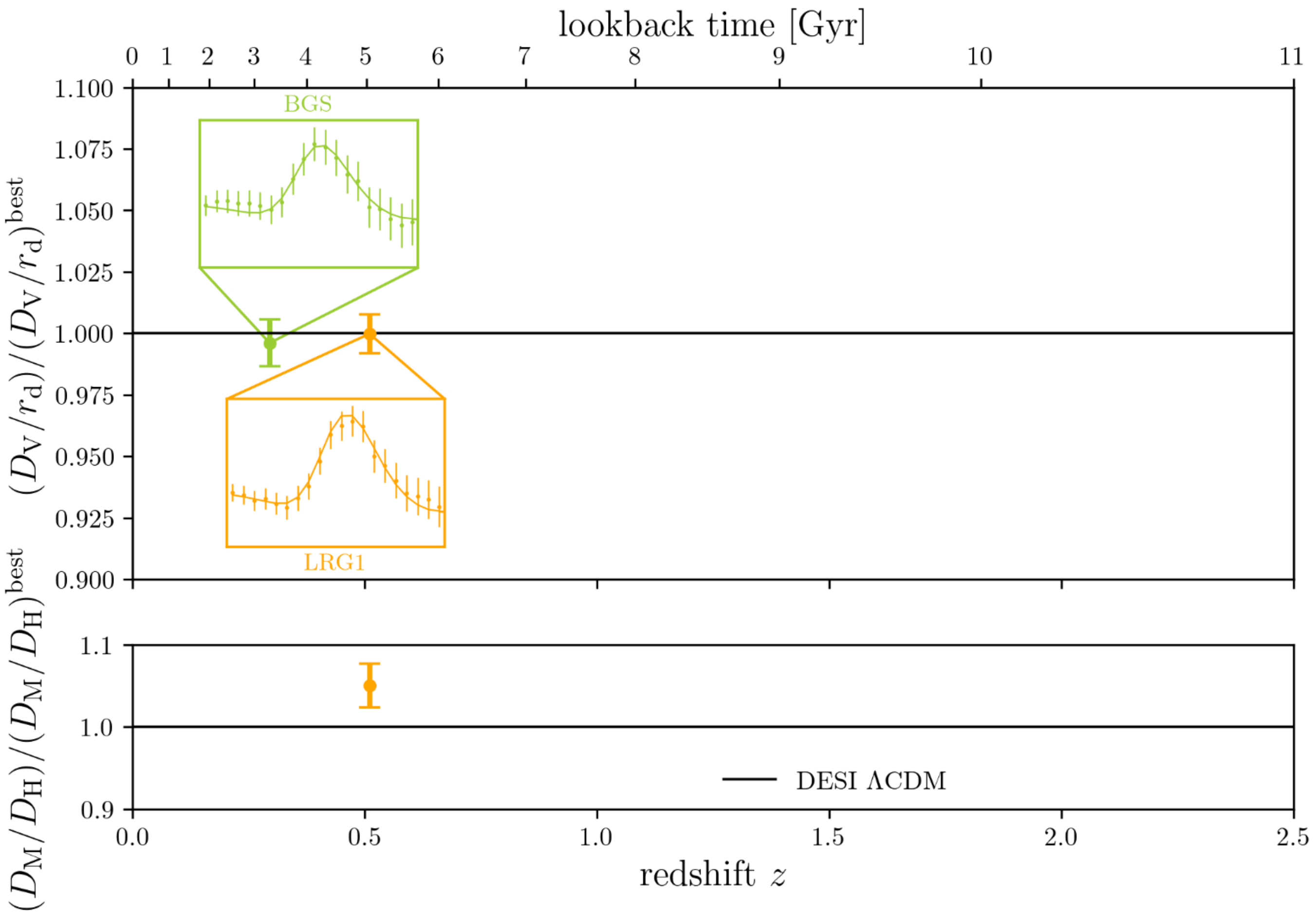
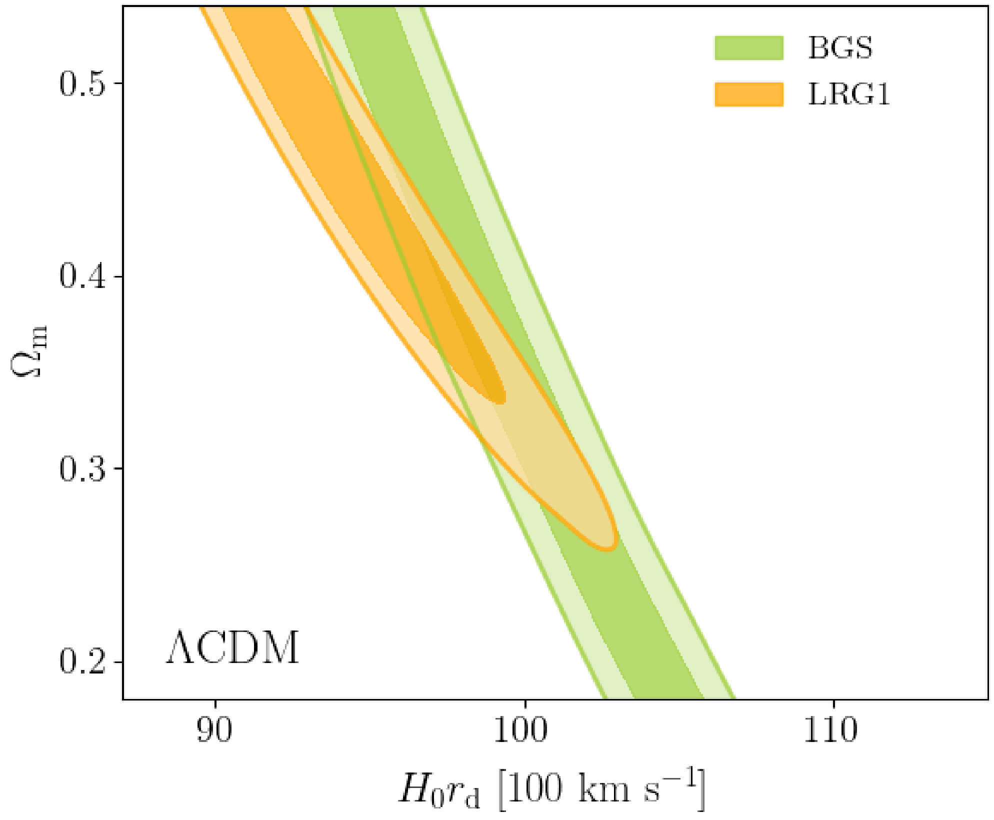
DESI BAO measurements

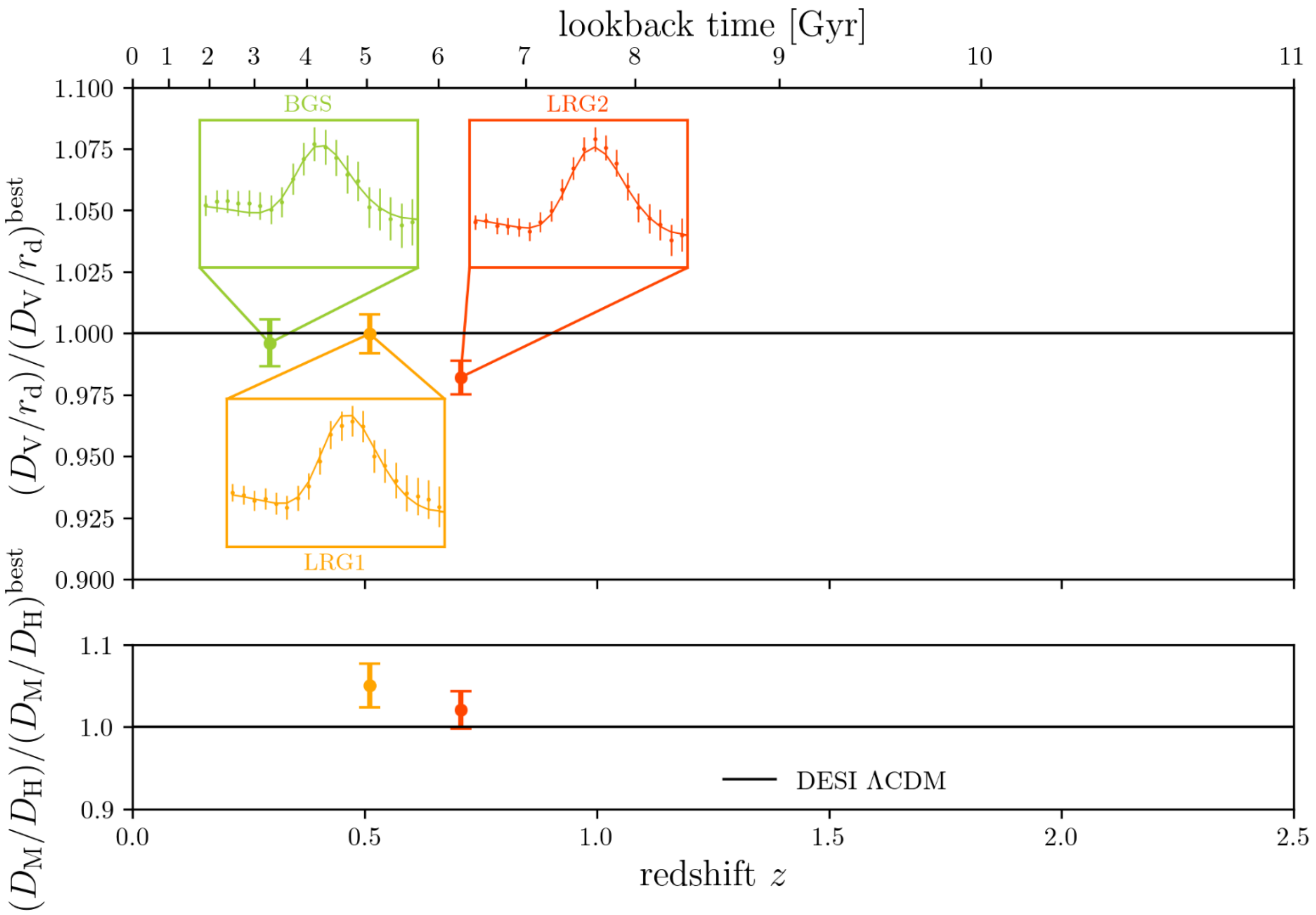


Flat ΛCDM results



DESI DR2 BAO

DESI BAO measurements



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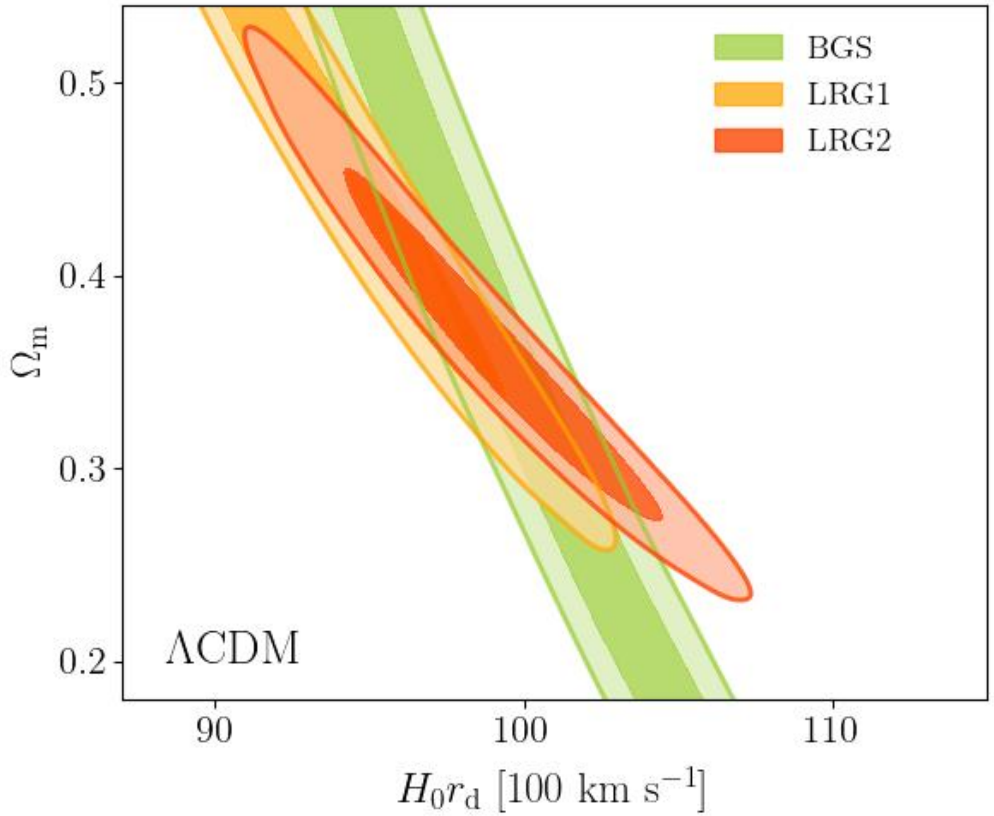

DESI DR2 Results II: BAO measurements and Cosmology

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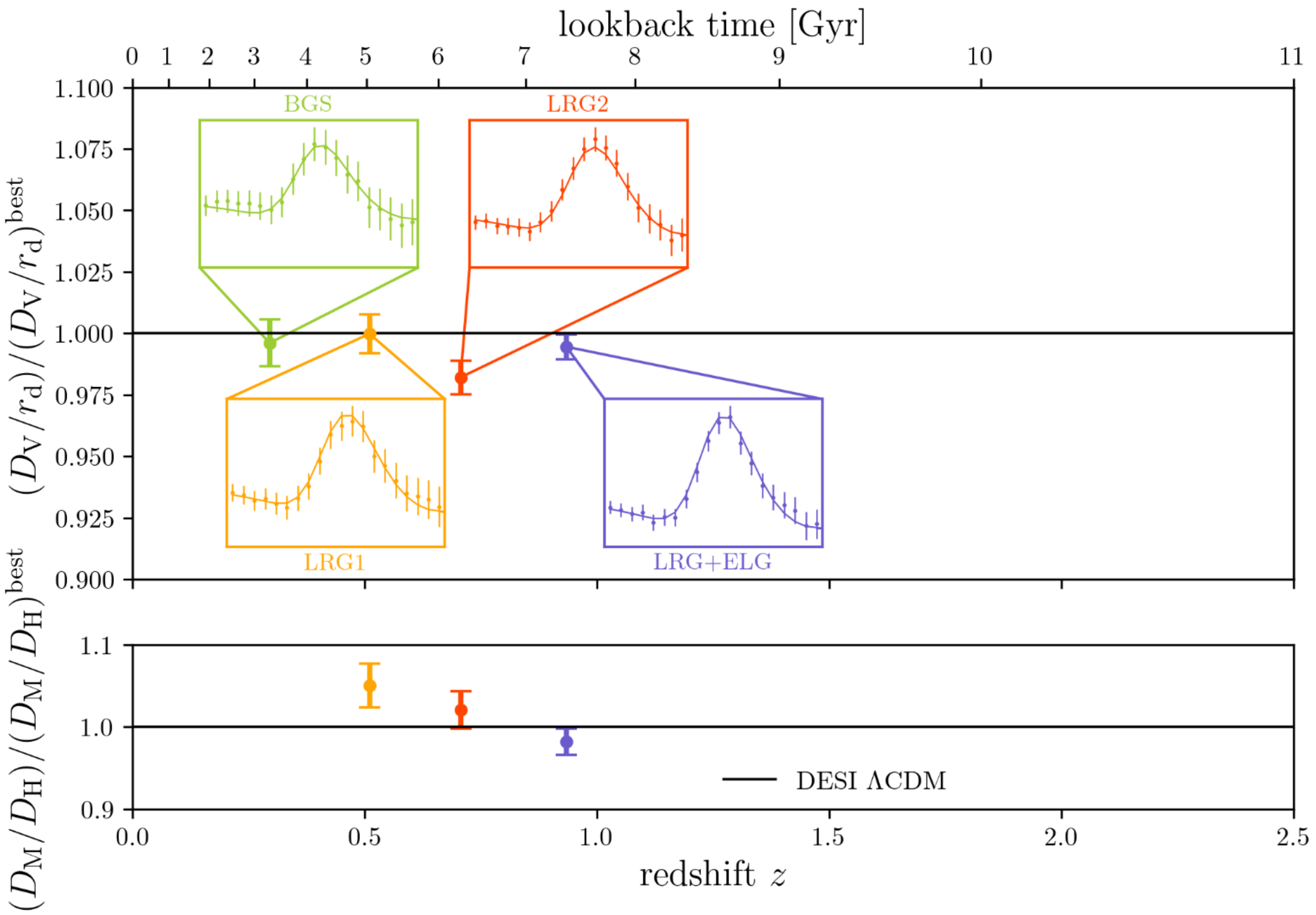
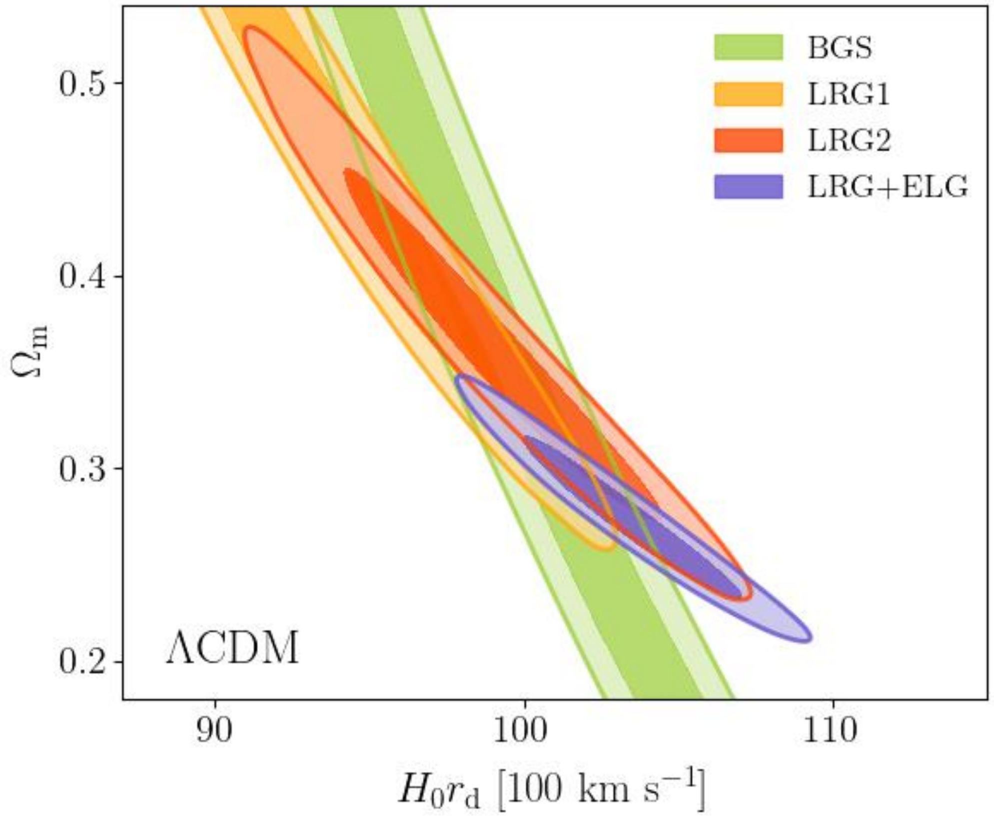
DESI DR2 BAO

DESI BAO measurements



Flat ΛCDM results



DESI DR2 BAO

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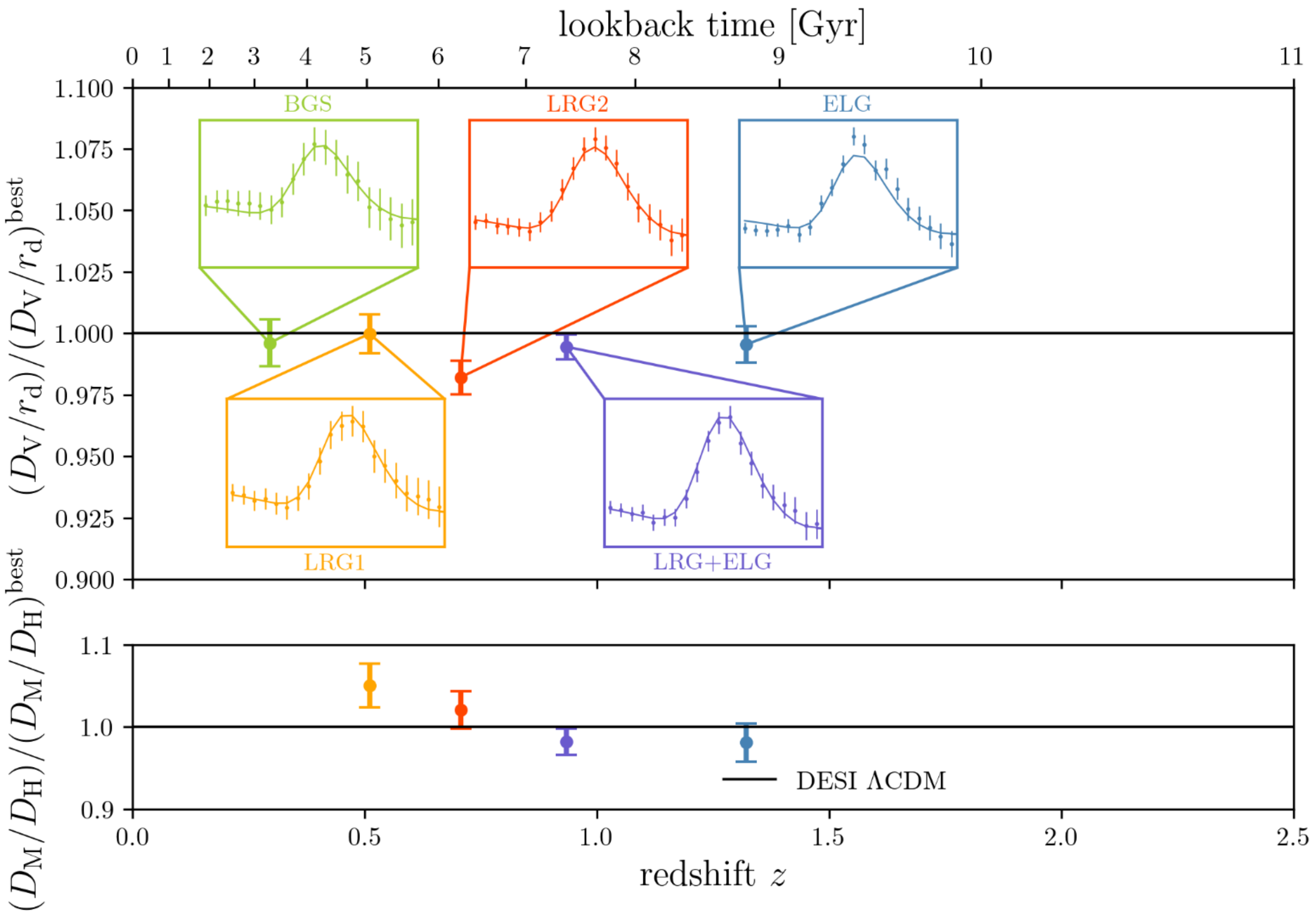
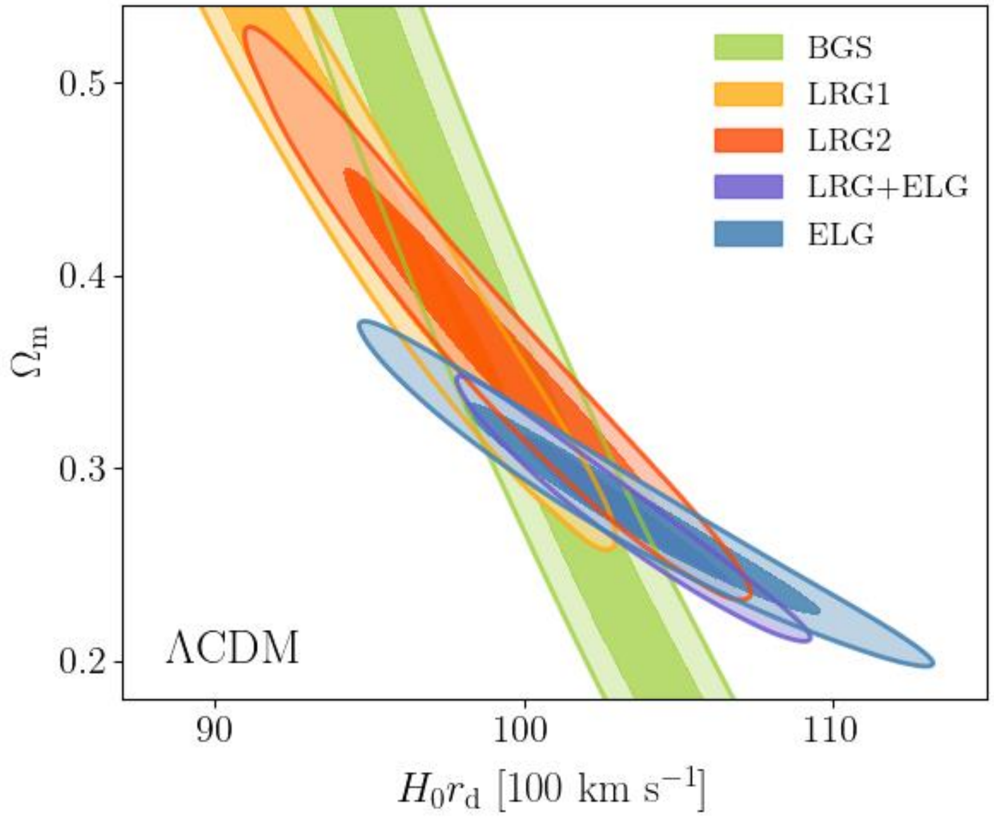
DESI BAO measurements



Flat ΛCDM results



DESI DR2 Results II: BAO measurements and Cosmology

DESI DR2 BAO

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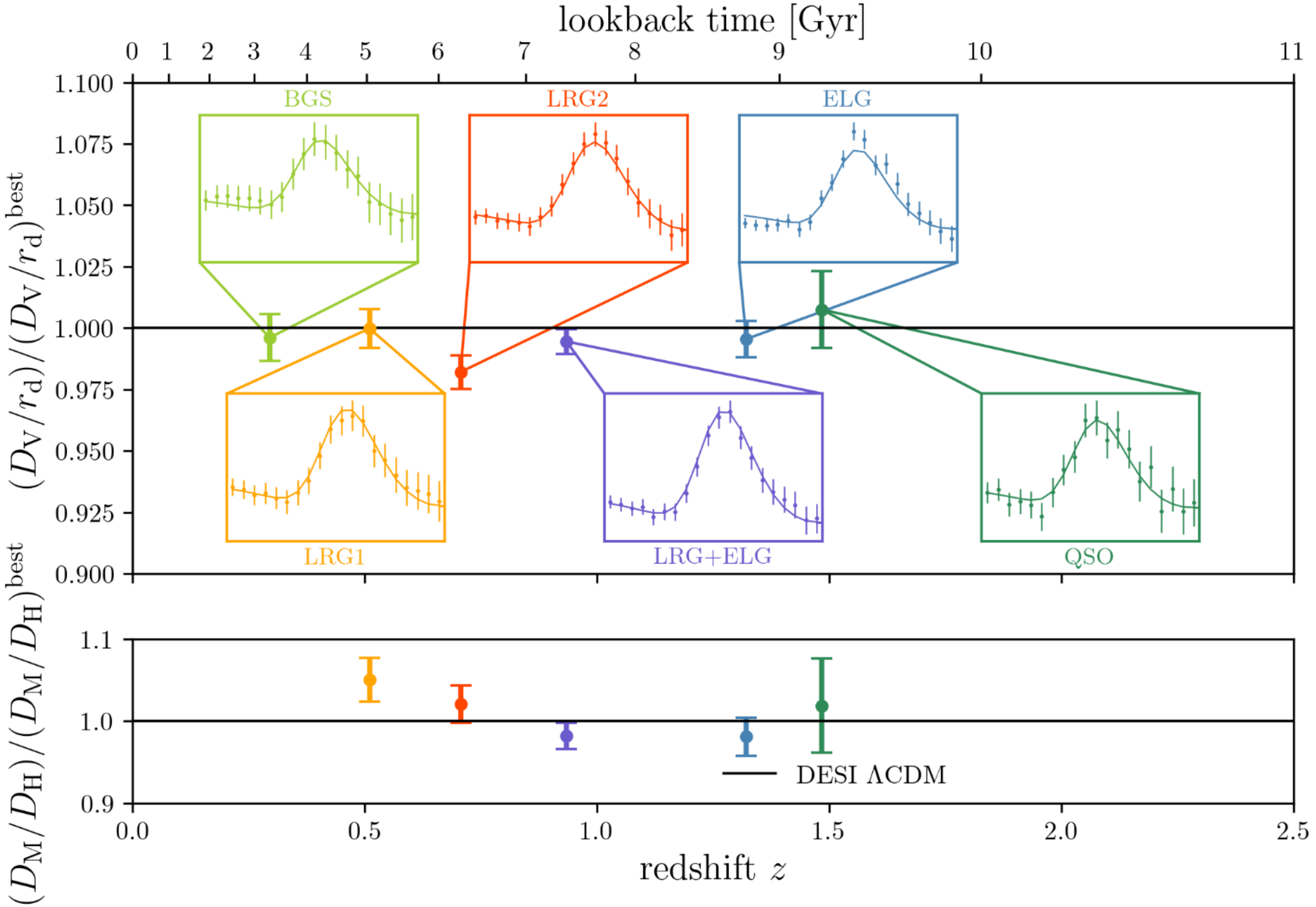
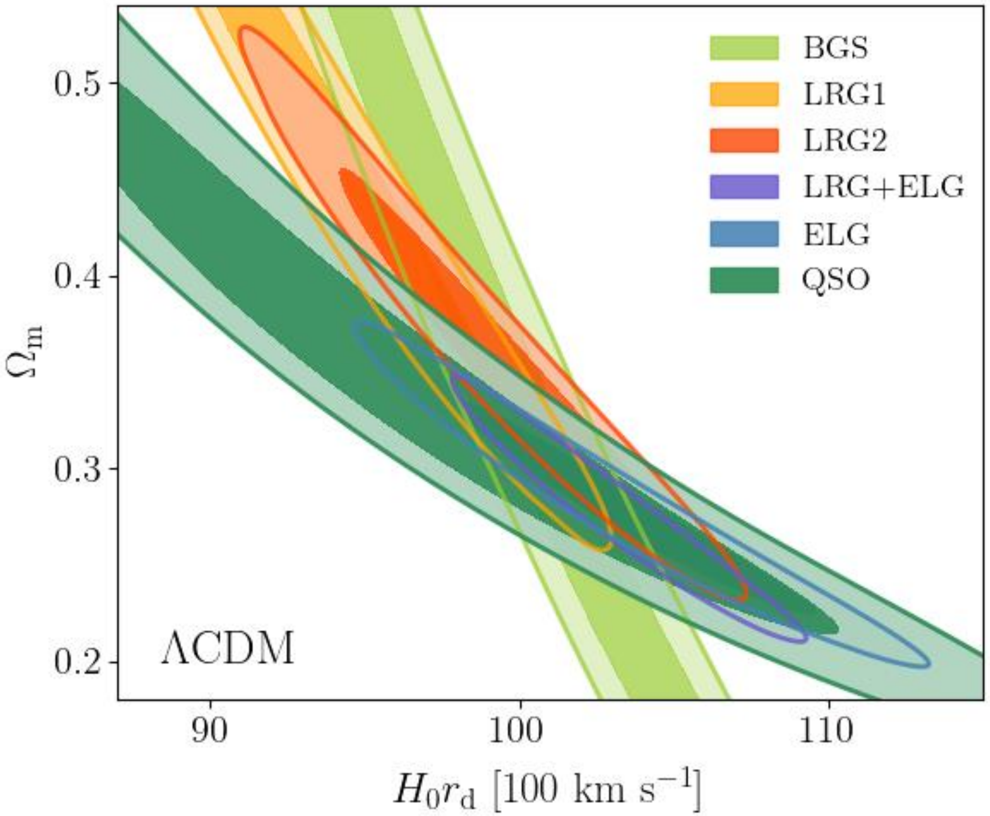


Flat ΛCDM results



DESI DR2 BAO

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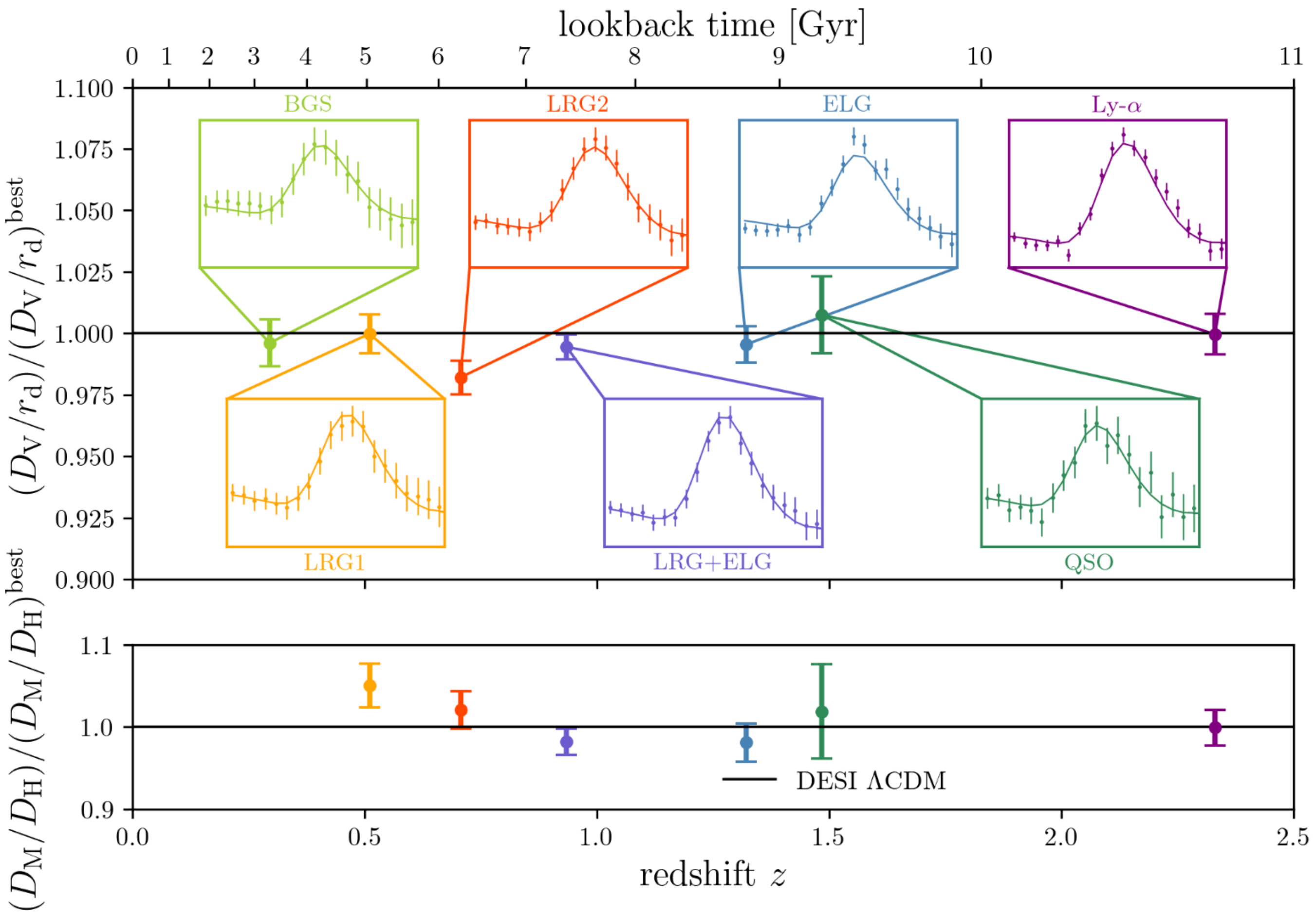
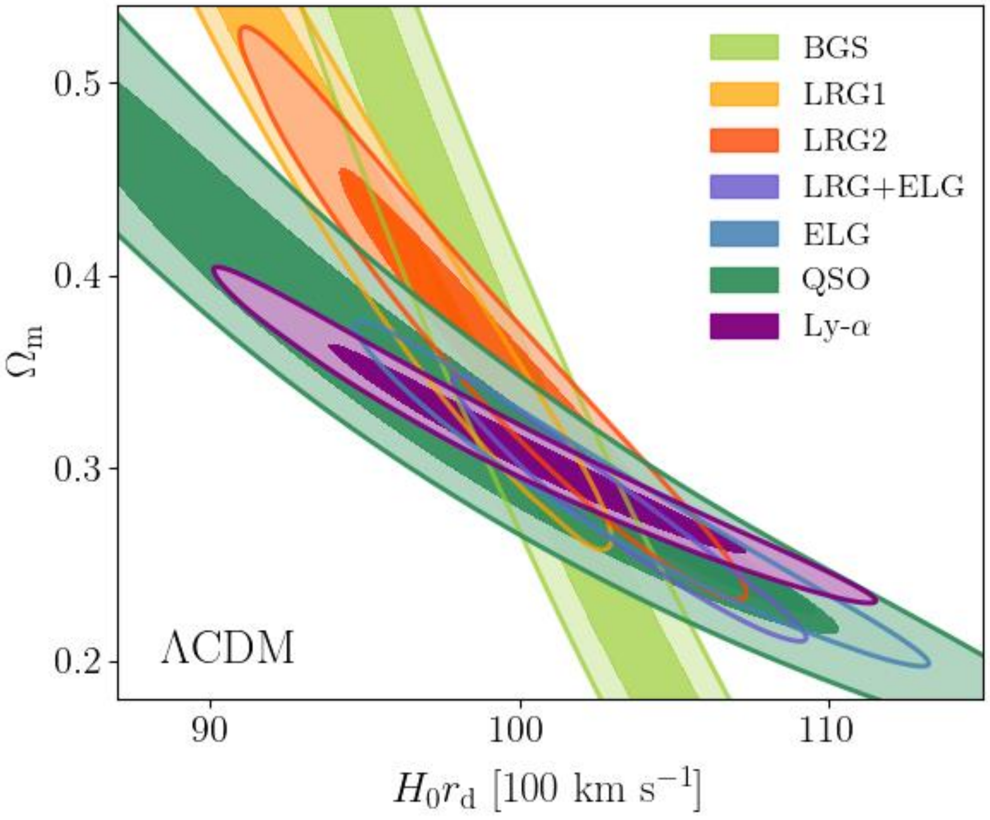
DESI BAO measurements



Flat ΛCDM results



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DESI DR2 BAO

DESI BAO measurements

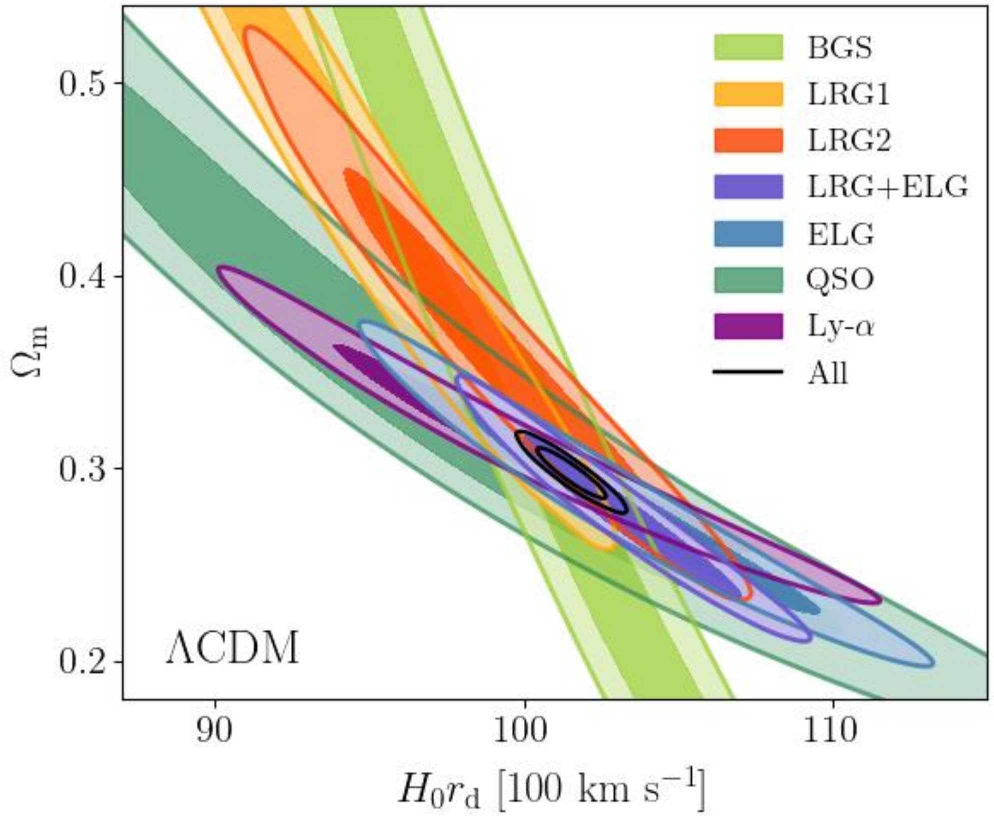
Consistent with each other,
and complementary

Ω_m=0.2975 ± 0.0086 **(2.9%)**

$H_0 r_d$=(101.54 ± 0.73) [100 km/s] **(0.7%)**

DESI

Flat ΛCDM results

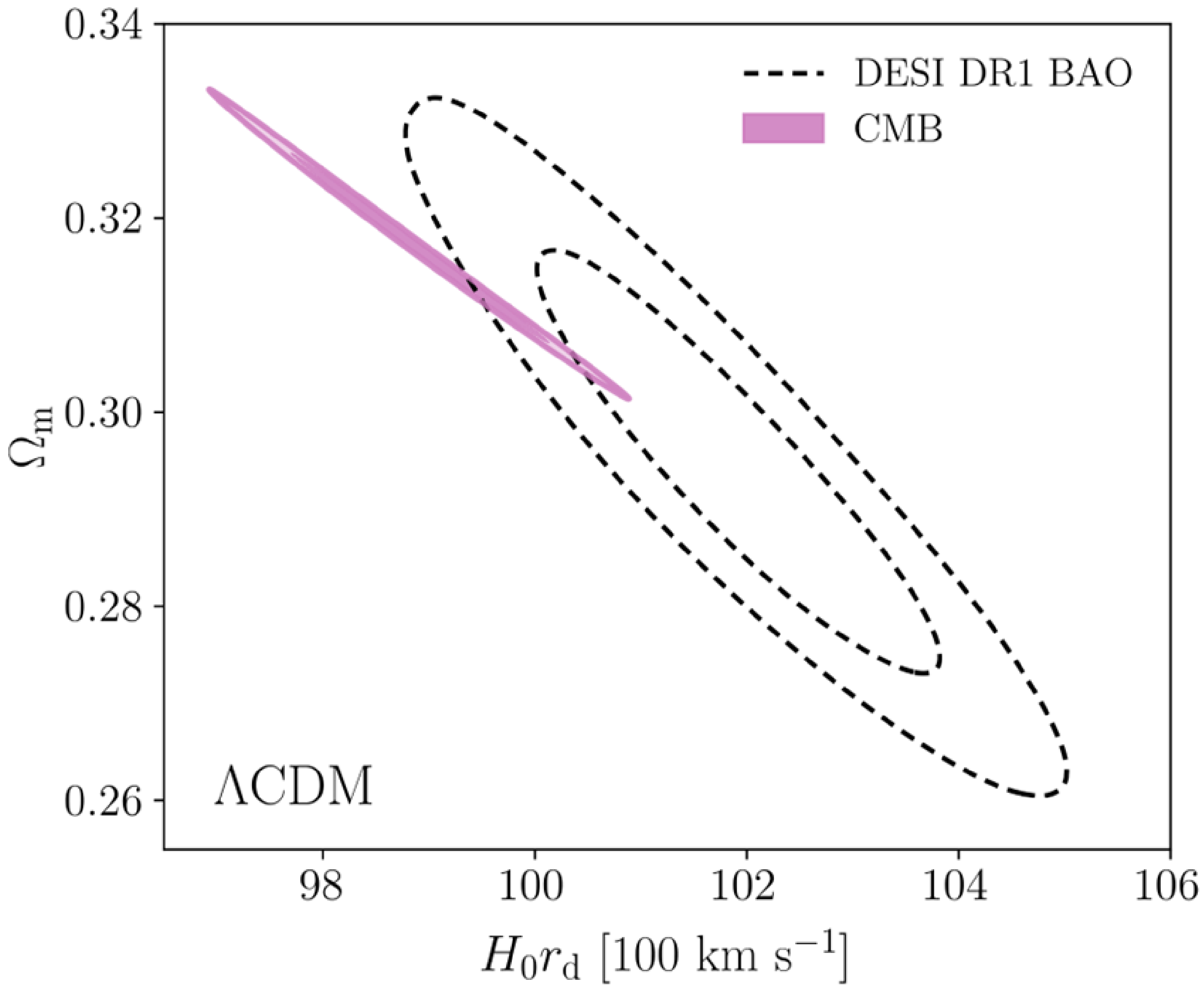


ΛCDM: Consistency with the CMB

DESI DR1 BAO was 1.9σ from the **CMB**

CMB includes:

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



ΛCDM: Consistency with the CMB

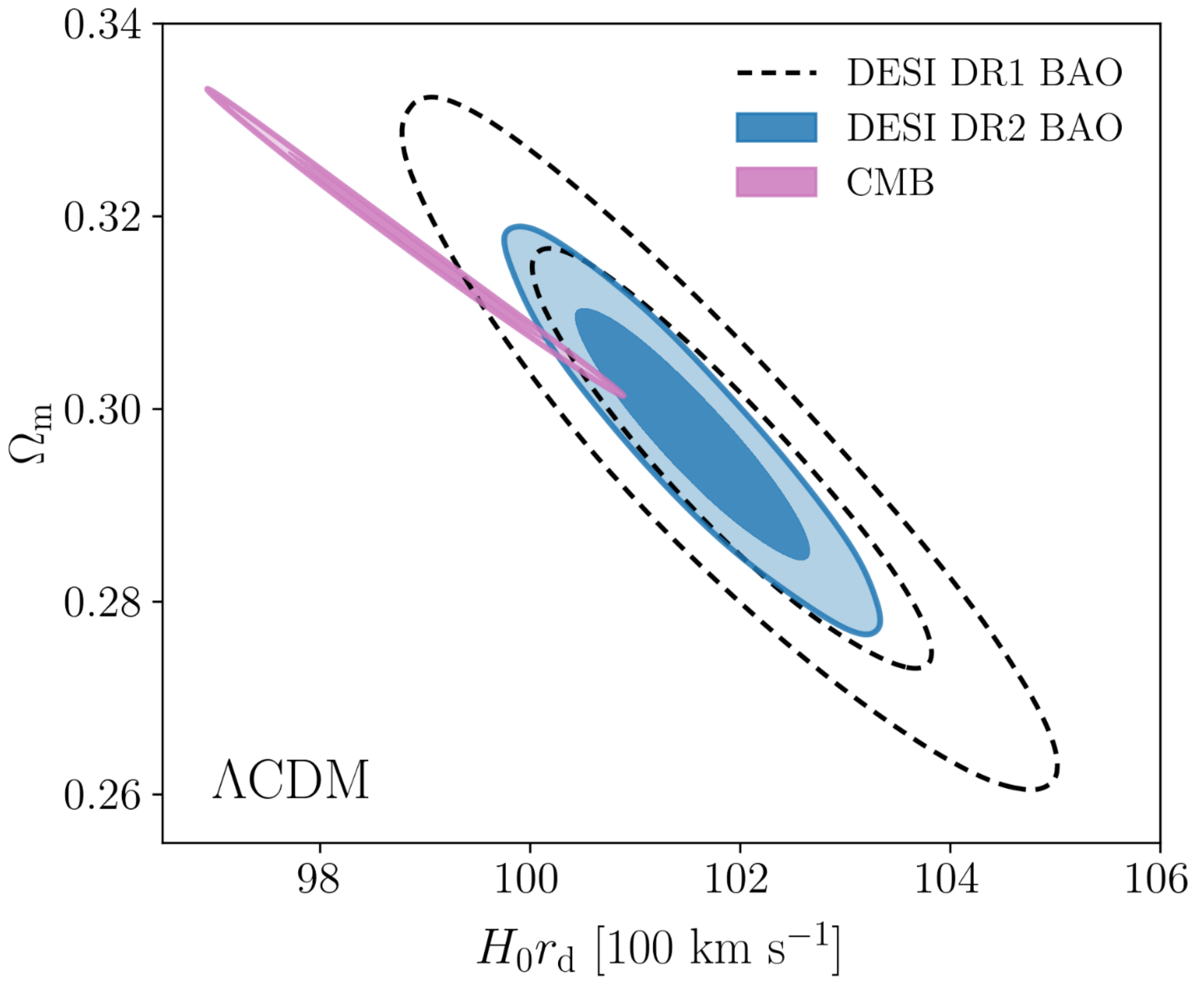
DESI DR1 BAO was 1.9σ from the CMB

CMB includes:

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

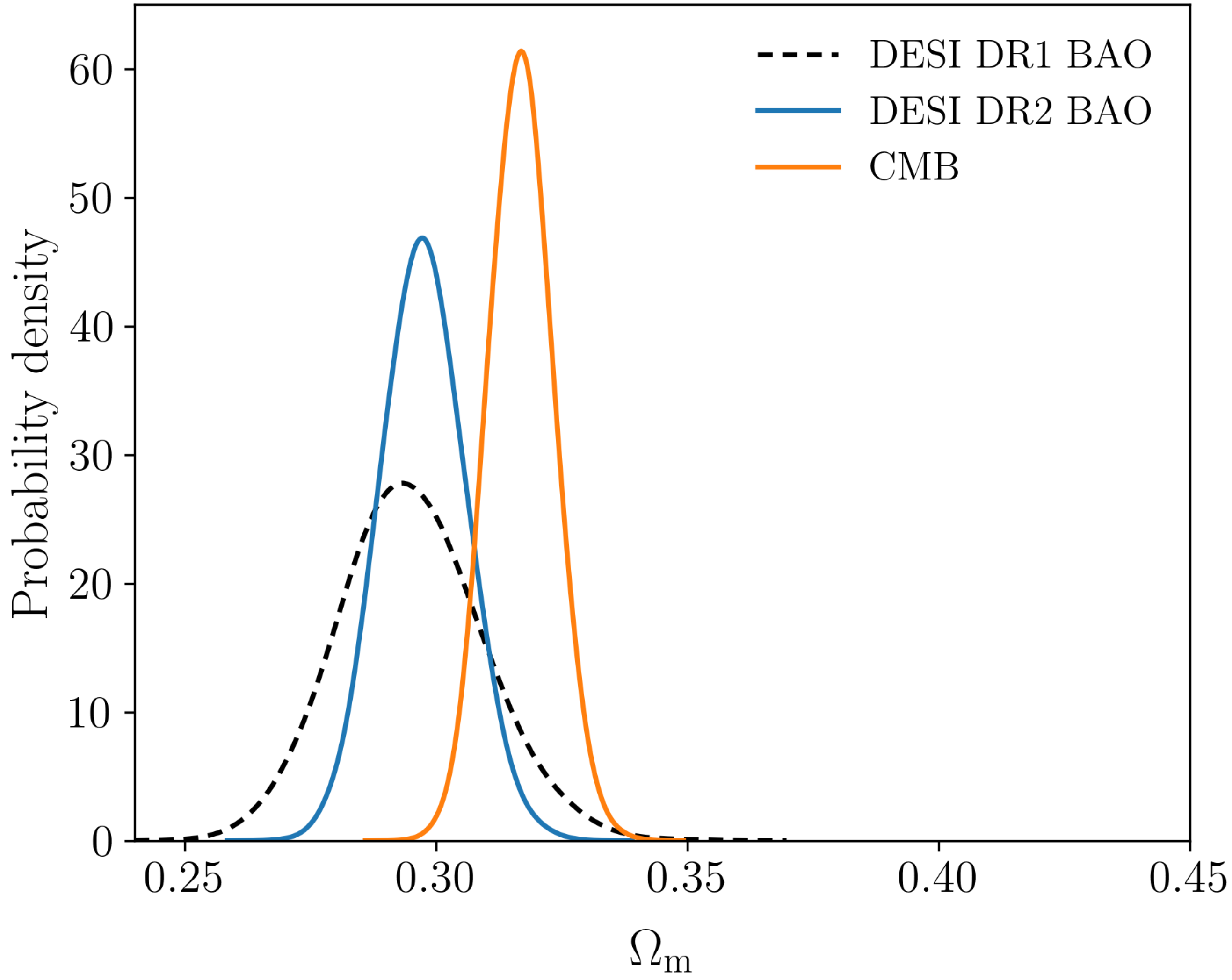
DESI DR2 BAO is:

- Consistent with **DESI DR1**
- 2.3σ from the CMB



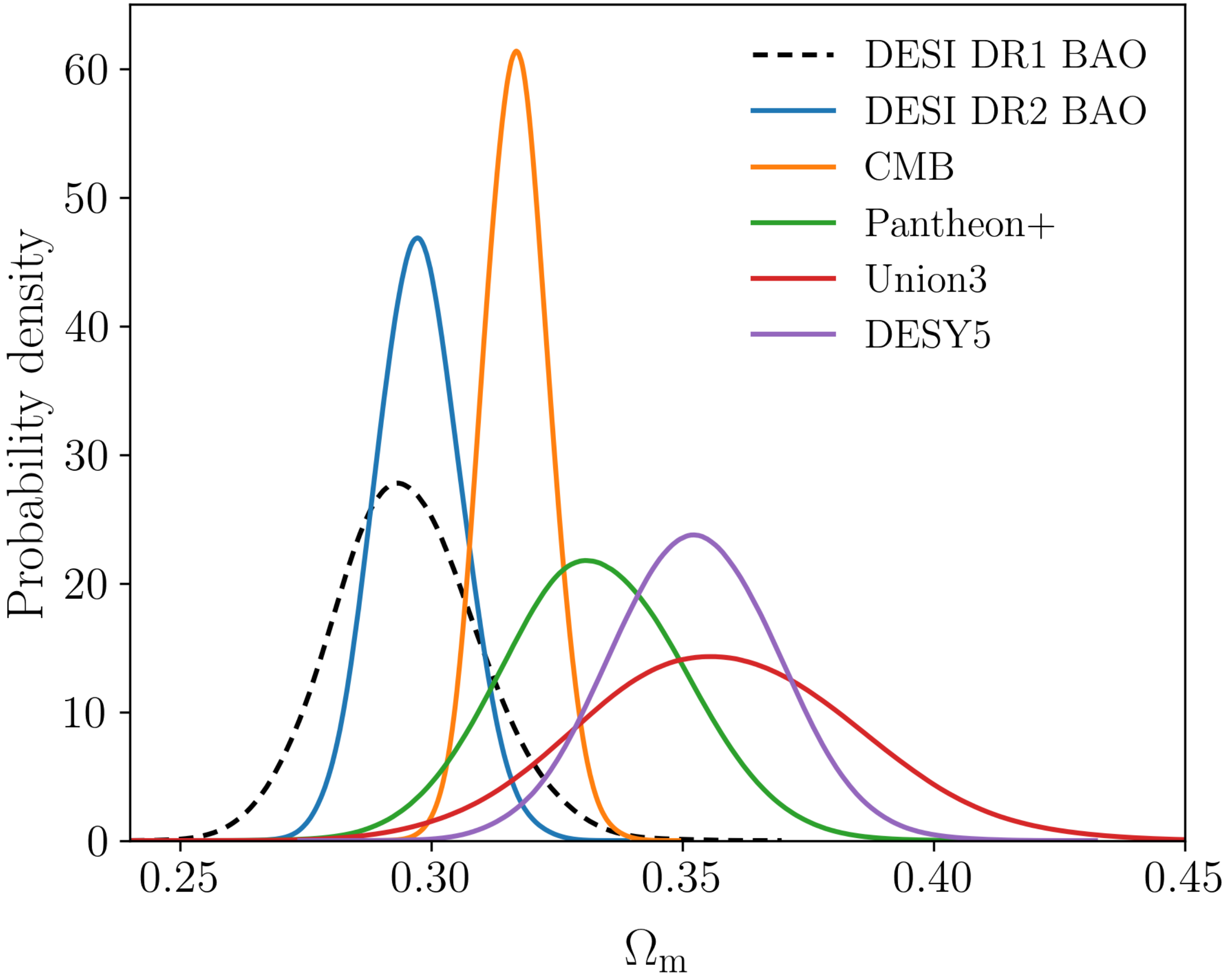
ΛCDM: Consistency with Supernovae

- **DESI DR2** consistent with DESI DR1
- **DESI DR2** is lower than the CMB



ΛCDM: Consistency with 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



Hubble constant

- **Isotropic BAO** → $H_0 r_d$

Hubble constant

- **Isotropic BAO** $\rightarrow H_0 r_d(\Omega_m h^2, \Omega_b h^2)$

Hubble constant

- **Isotropic BAO** → $H_0 r_d(\Omega_m h^2, \Omega_b h^2)$
- **Anisotropic BAO** → Alcock-Paczynski → Ω_m

Hubble constant

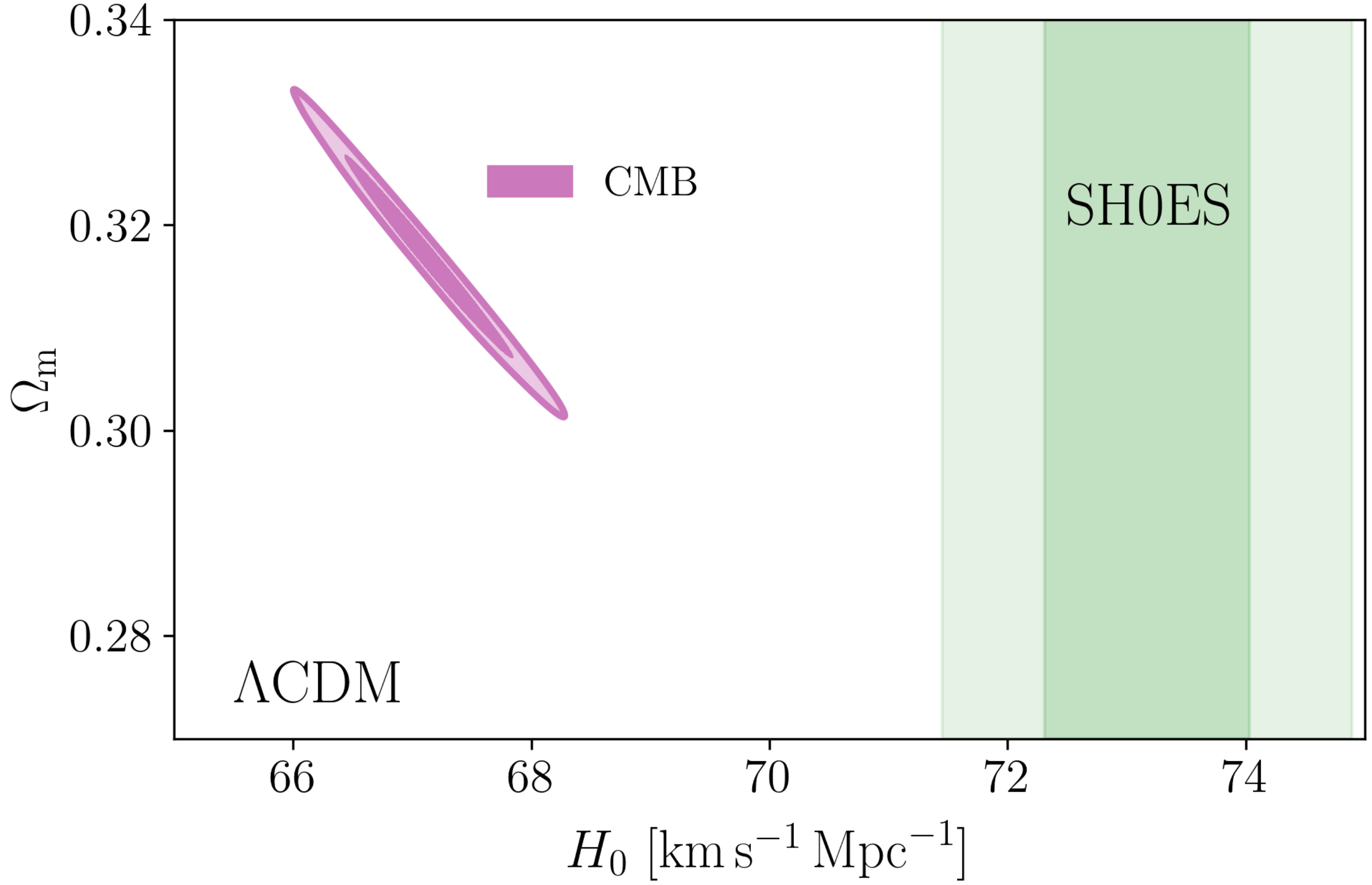
- **Isotropic BAO** → $H_0 r_d(\Omega_m h^2, \Omega_b h^2)$
- **Anisotropic BAO** → Alcock-Paczynski → Ω_m
- $\Omega_b h^2$ measured from **Big Bang Nucleosynthesis (BBN):** Schöneberg et al., 2024

Hubble constant

- **Isotropic BAO** → $H_0 r_d(\Omega_m h^2, \Omega_b h^2)$
- **Anisotropic BAO** → Alcock-Paczynski → Ω_m
- $\Omega_b h^2$ measured from **Big Bang Nucleosynthesis (BBN):** Schöneberg et al., 2024

⟹ constraints on H_0

Hubble constant

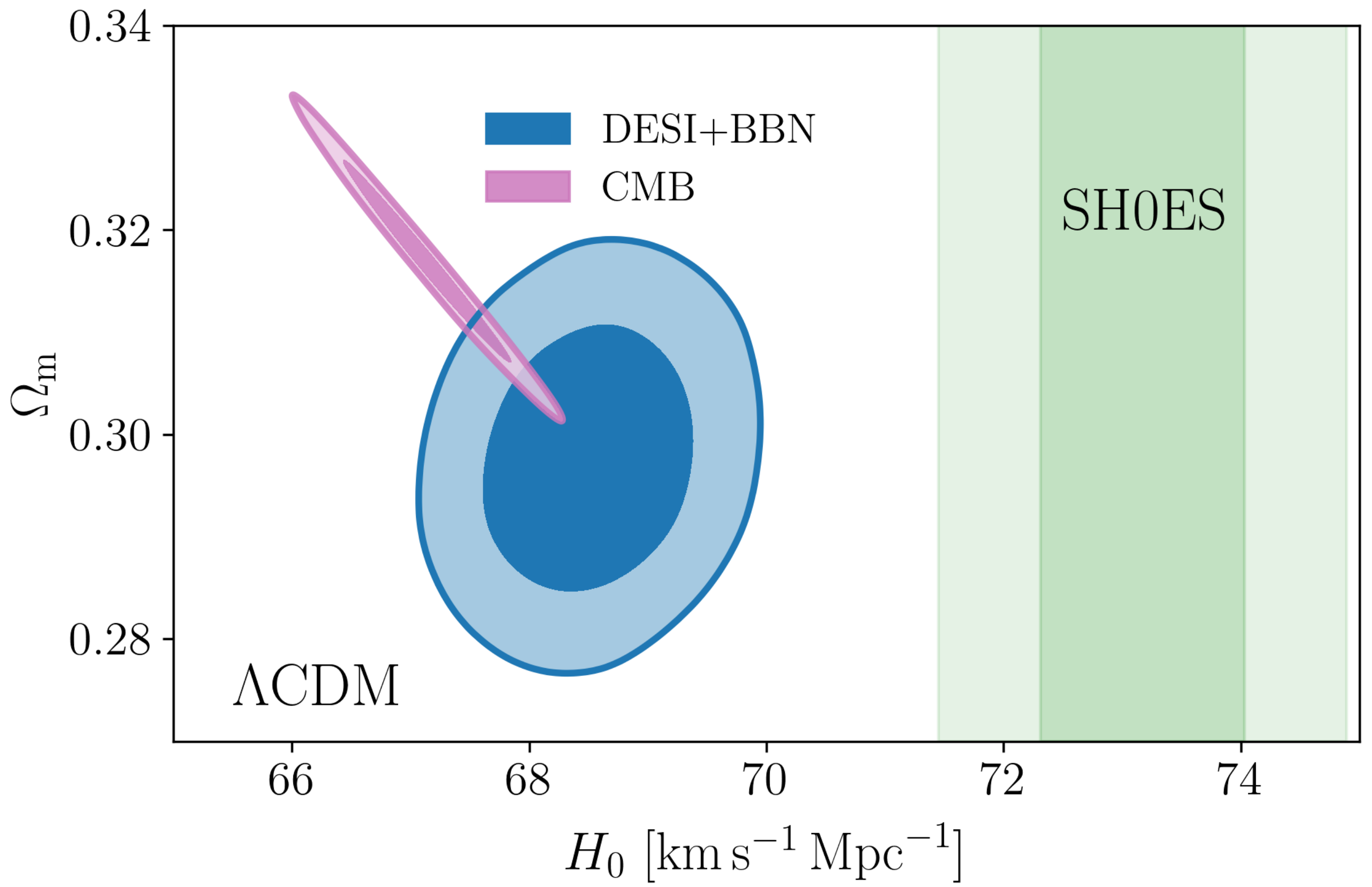


Hubble constant

$$H_0 = (68.51 \pm 0.58)\ \text{km/s/Mpc}$$

DESI + BBN

- In 4.5σ tension with SH0ES



Hubble constant

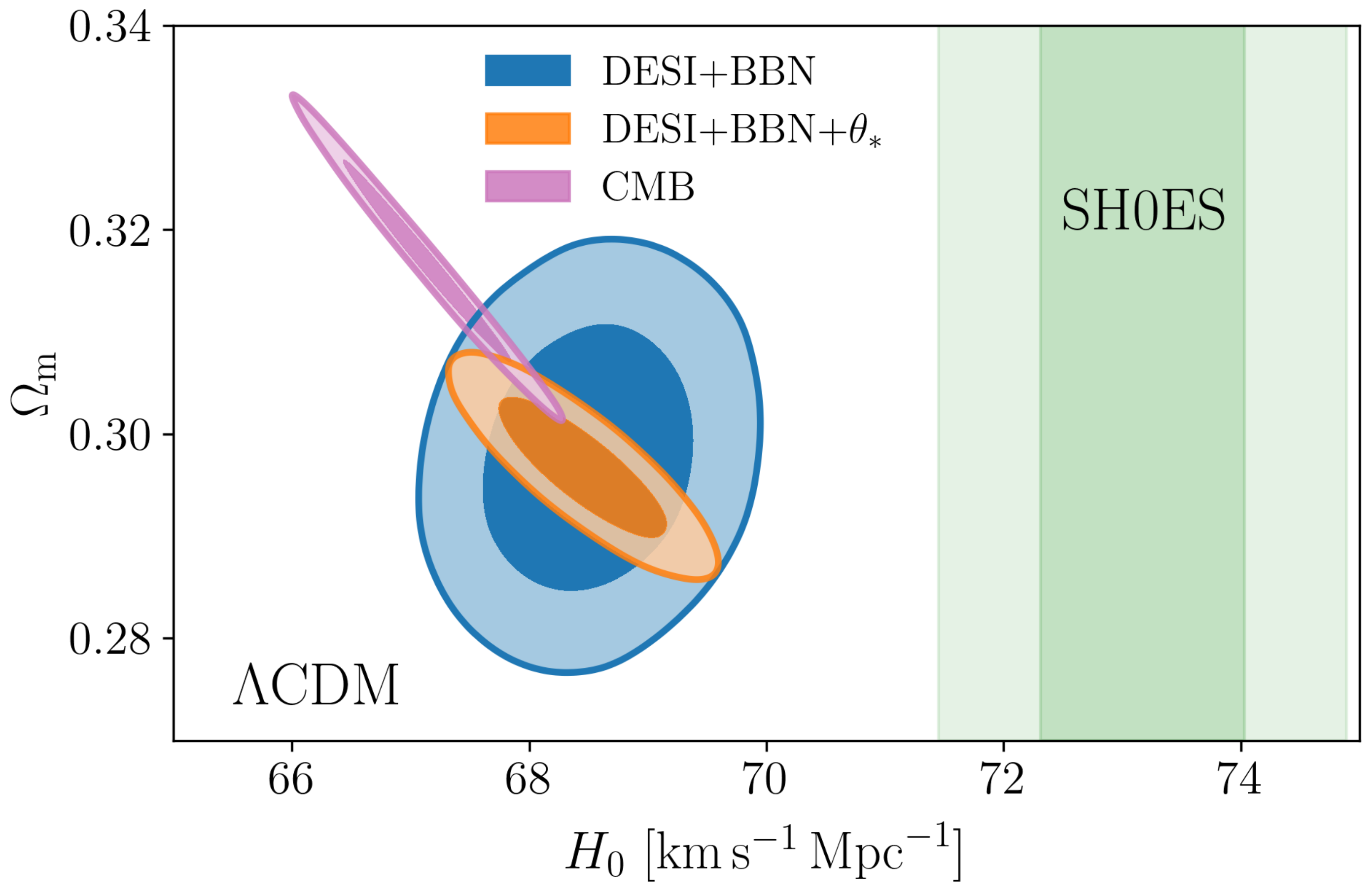
$H_0 = (68.51 \pm 0.58)$ km/s/Mpc

DESI + BBN

$H_0 = (68.45 \pm 0.47)$ km/s/Mpc

DESI + θ_* + BBN

- In 4.5σ tension with SH0ES
- θ_* - CMB angular acoustic scale



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Hubble constant

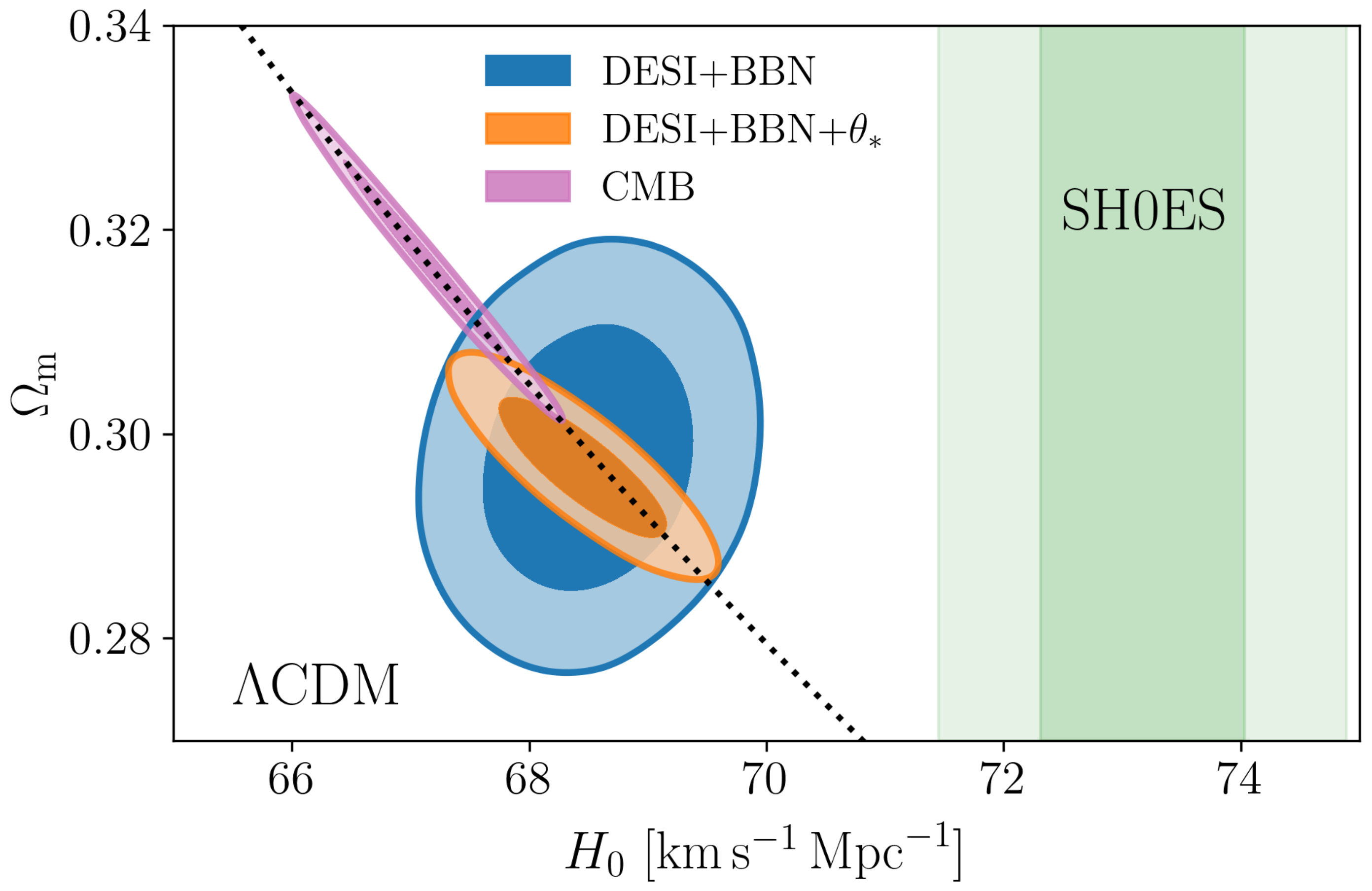
$$\underbrace{H_0 = (68.51 \pm 0.58)\ \mathrm{km/s/Mpc}}_{\text{DESI + BBN}}$$

DESI + BBN

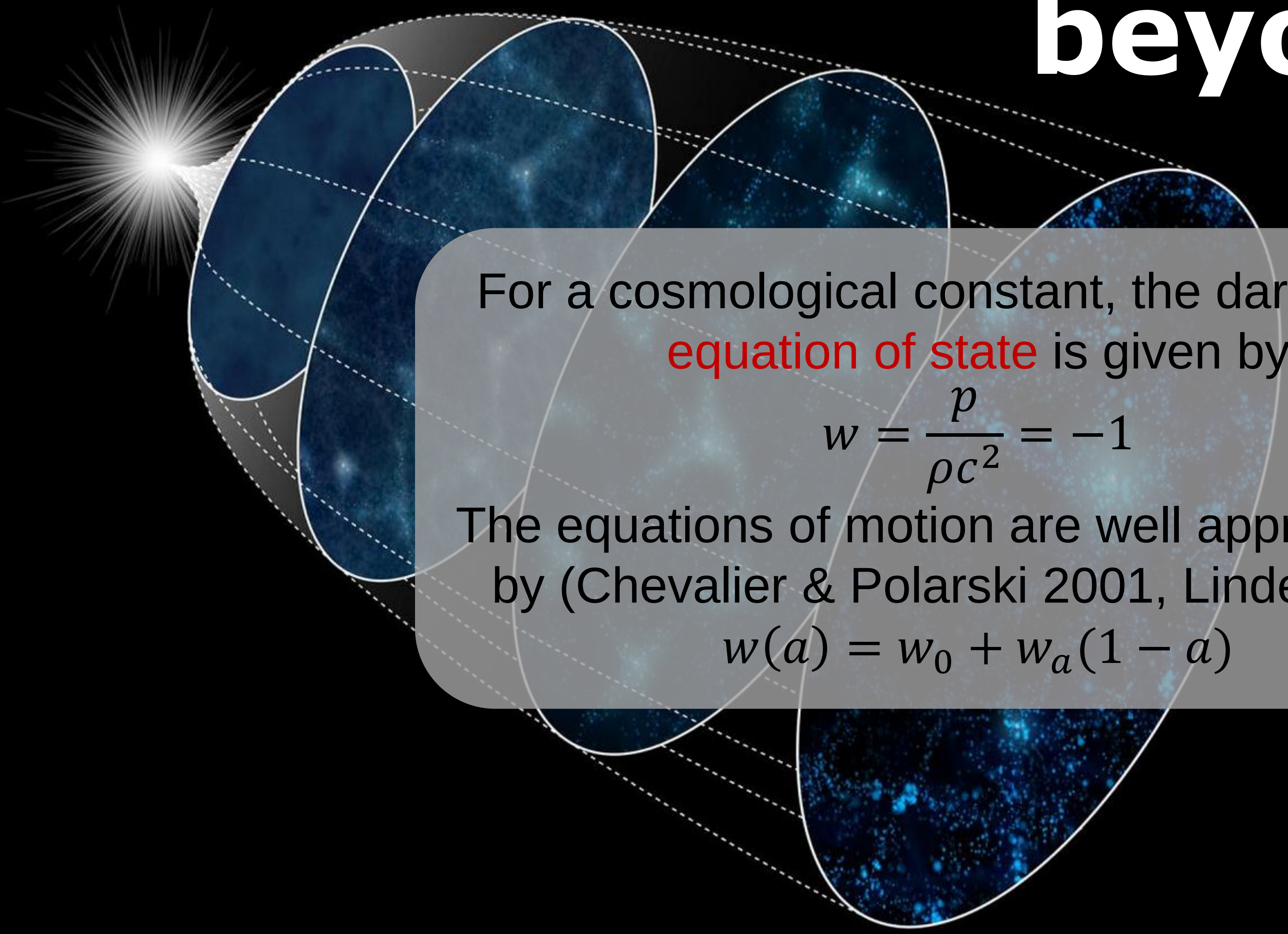
$$\underbrace{H_0 = (68.45 \pm 0.47)\ \mathrm{km/s/Mpc}}_{\text{DESI} + \theta_* + \text{BBN}}$$

DESI + θ_* + BBN

- In 4.5σ tension with SH0ES
- θ_* - CMB angular acoustic scale
- Close to CMB, but still higher
- CMB degeneracy direction points to our result (dotted line)



II. Dark Energy beyond ΛCDM



For a cosmological constant, the dark energy equation of state is given by

$$w = \frac{p}{\rho c^2} = -1$$

The equations of motion are well approximated by (Chevalier & Polarski 2001, Linder 2003)

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

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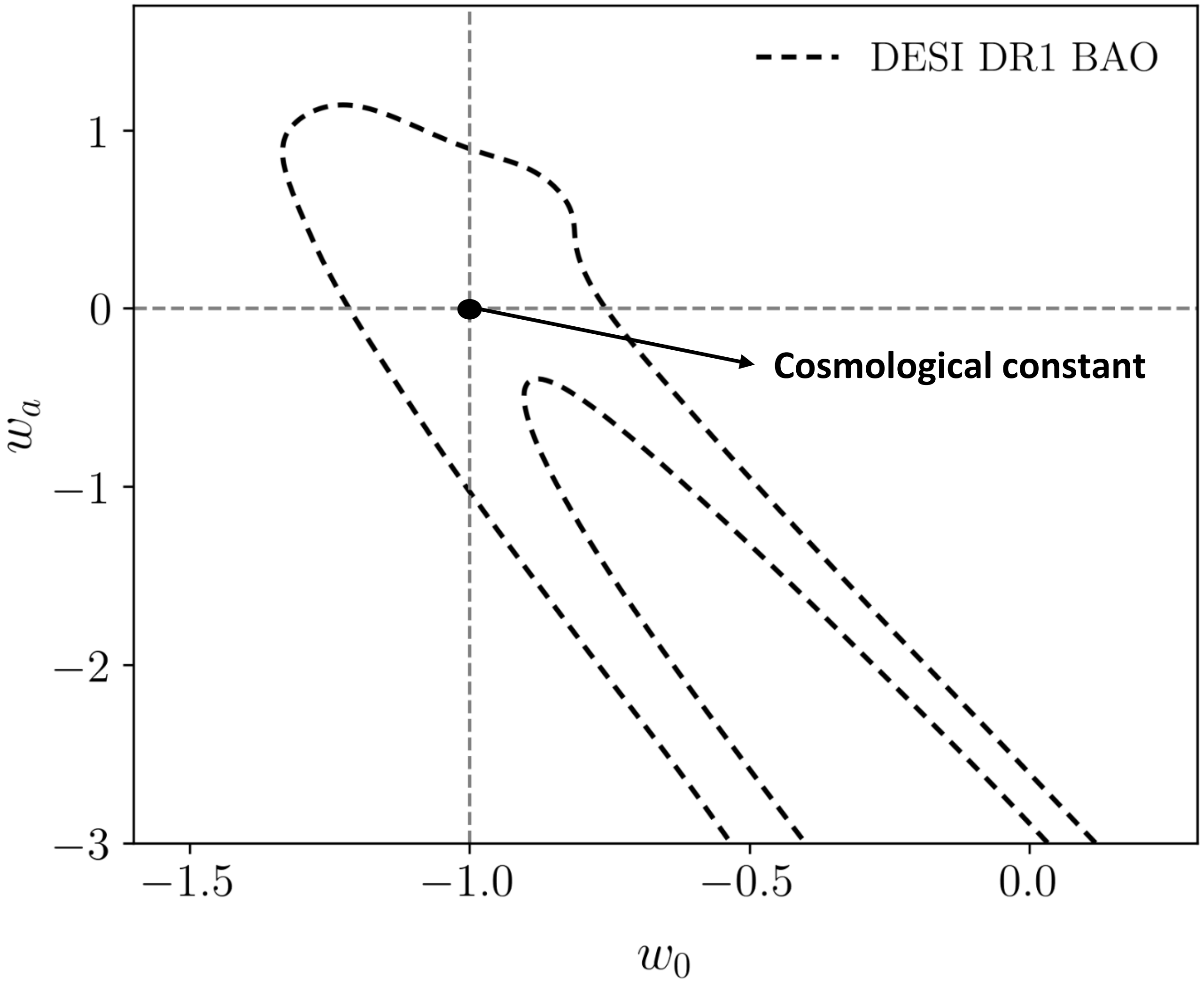
Evolving Dark Energy

- BAO data define a degeneracy direction in the $w_0 - w_a$ plane



DESI DR2 Results II: BAO measurements and Cosmology

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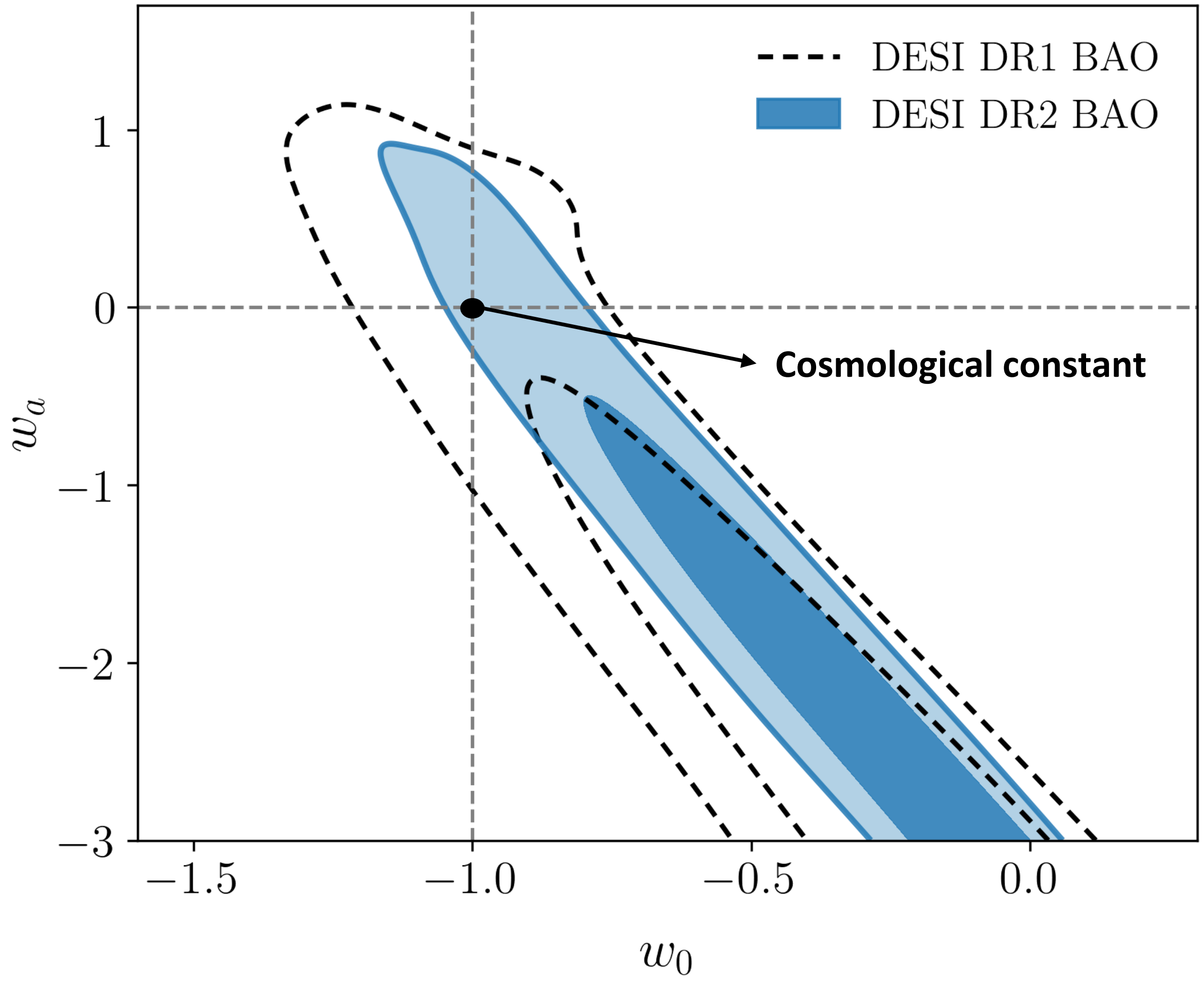
Evolving Dark Energy

- BAO data define a degeneracy direction in the $w_0 - w_a$ plane

- DESI DR2 still within 2σ of ΛCDM

- Need to combine with other probes to break this degeneracy



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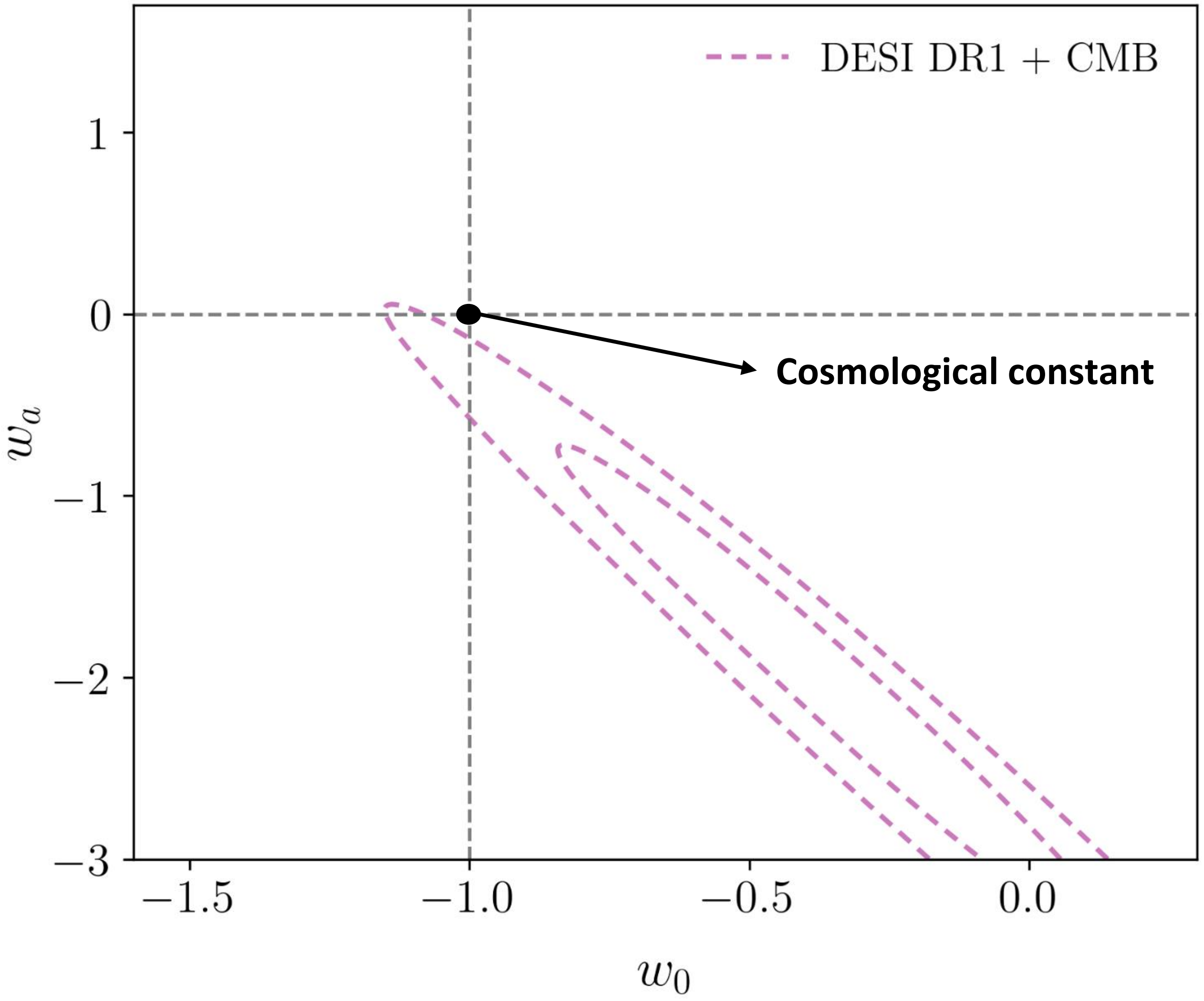
Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from ΛCDM



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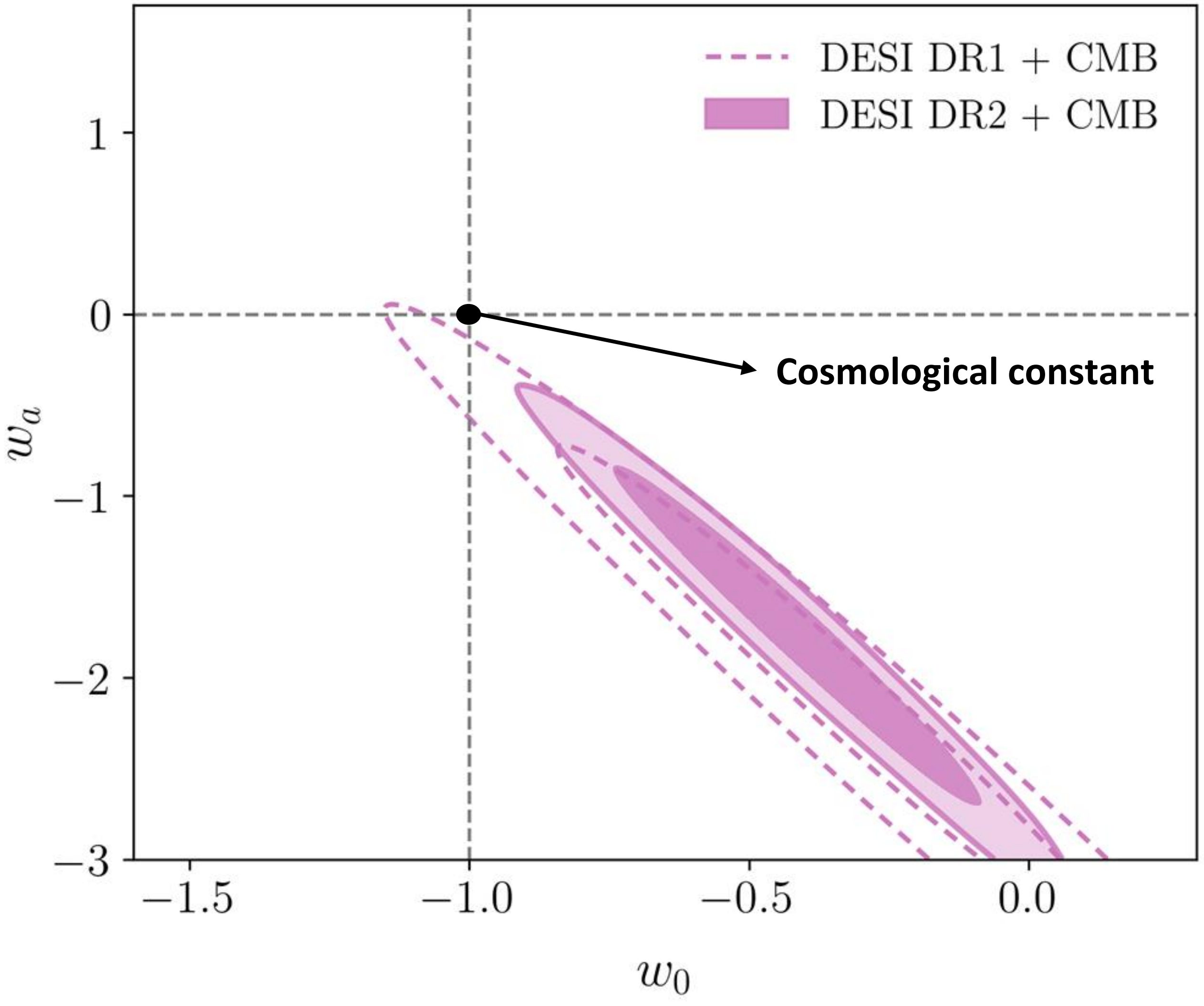
Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from ΛCDM
- **3.1σ** preference for evolving dark energy with DESI DR2 + CMB

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



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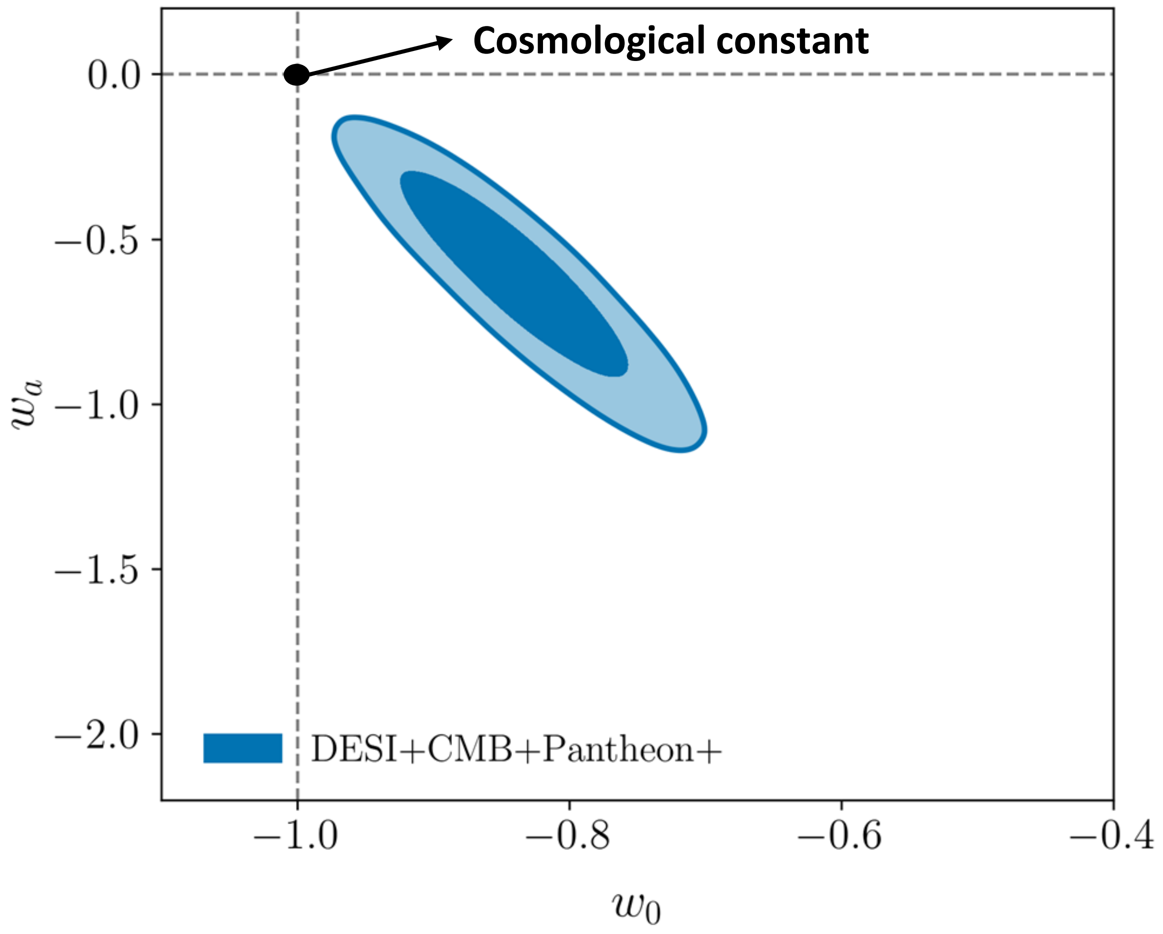
Evolving Dark Energy

Combining all DESI + CMB + SN

$w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}$

DESI + CMB + Pantheon+ $\Longrightarrow$ 2.8σ



DESI DR2 Results II: BAO measurements and Cosmology

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Evolving Dark Energy

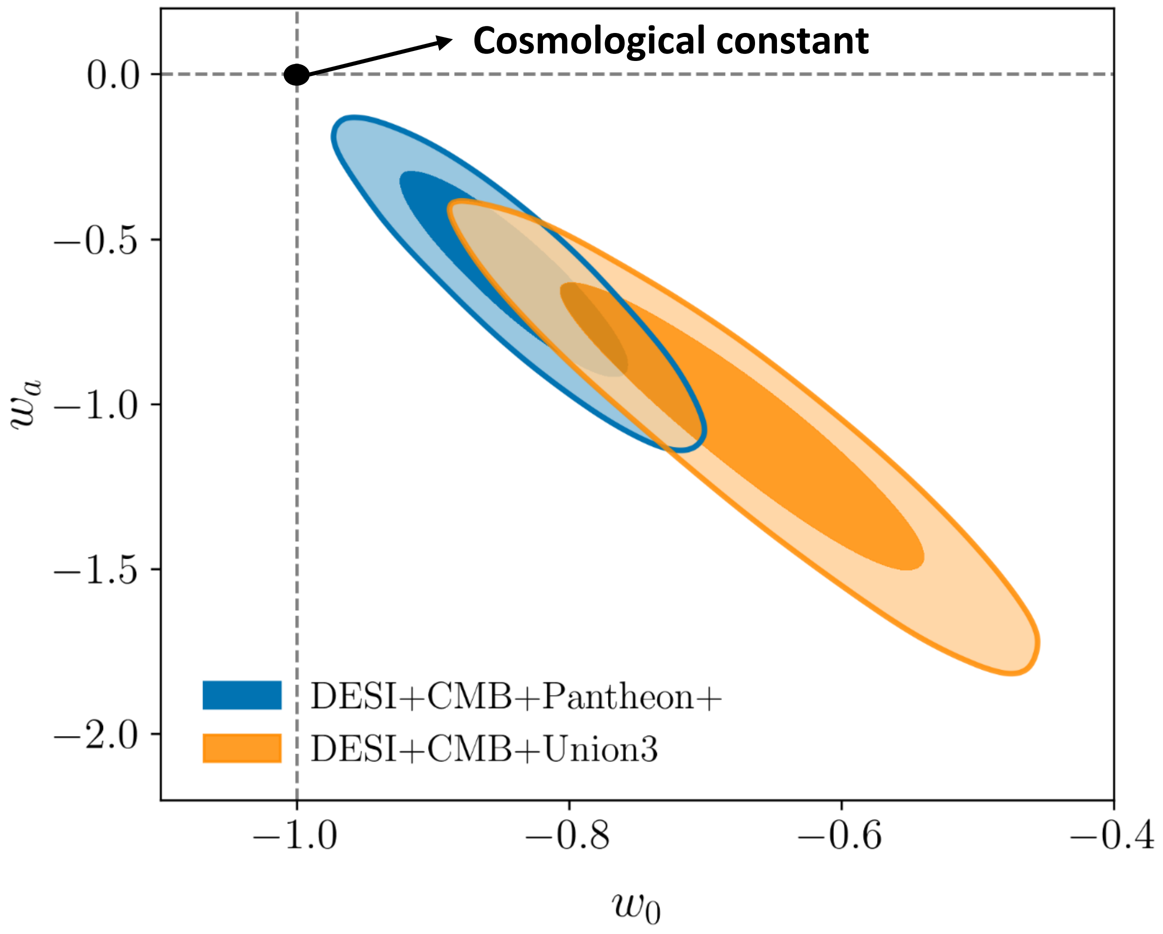
Combining all DESI + CMB + SN

$w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}$

DESI + CMB + Pantheon+ $\Longrightarrow$ 2.8σ

$w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}$

DESI + CMB + Union3 $\Longrightarrow$ 3.8σ



Evolving Dark Energy

Combining all DESI + CMB + SN

$$w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}$$

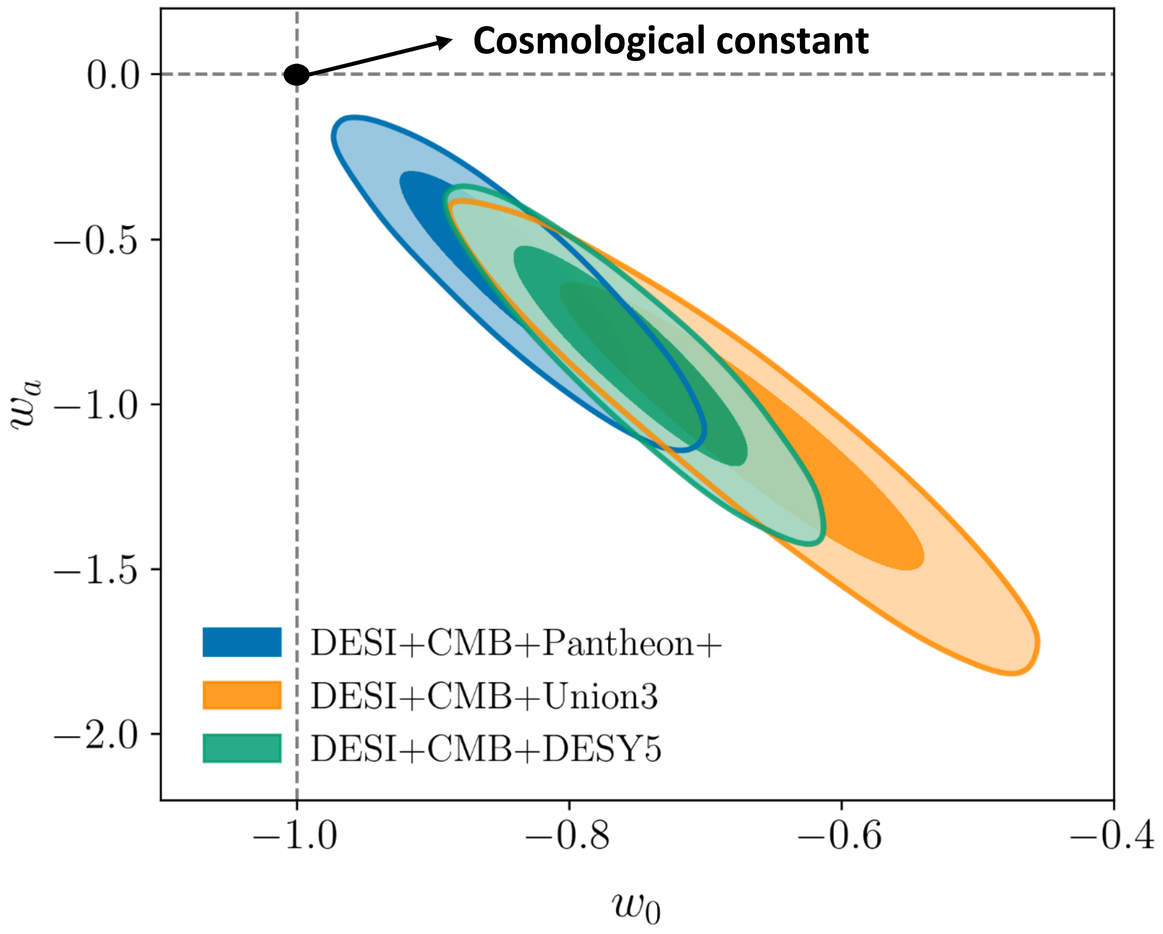
DESI + CMB + Pantheon+ $\Longrightarrow$ 2.8σ

$$w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}$$

DESI + CMB + Union3 $\Longrightarrow$ 3.8σ

$$w_0 = -0.752 \pm 0.057 \qquad w_a = -0.86^{+0.23}_{-0.20}$$

DESI + CMB + DESY5 $\Longrightarrow$ 4.2σ



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III. Massive Neutrinos

Image: Super Kamiokande Neutrino Observatory
Credit: Jordy Meow

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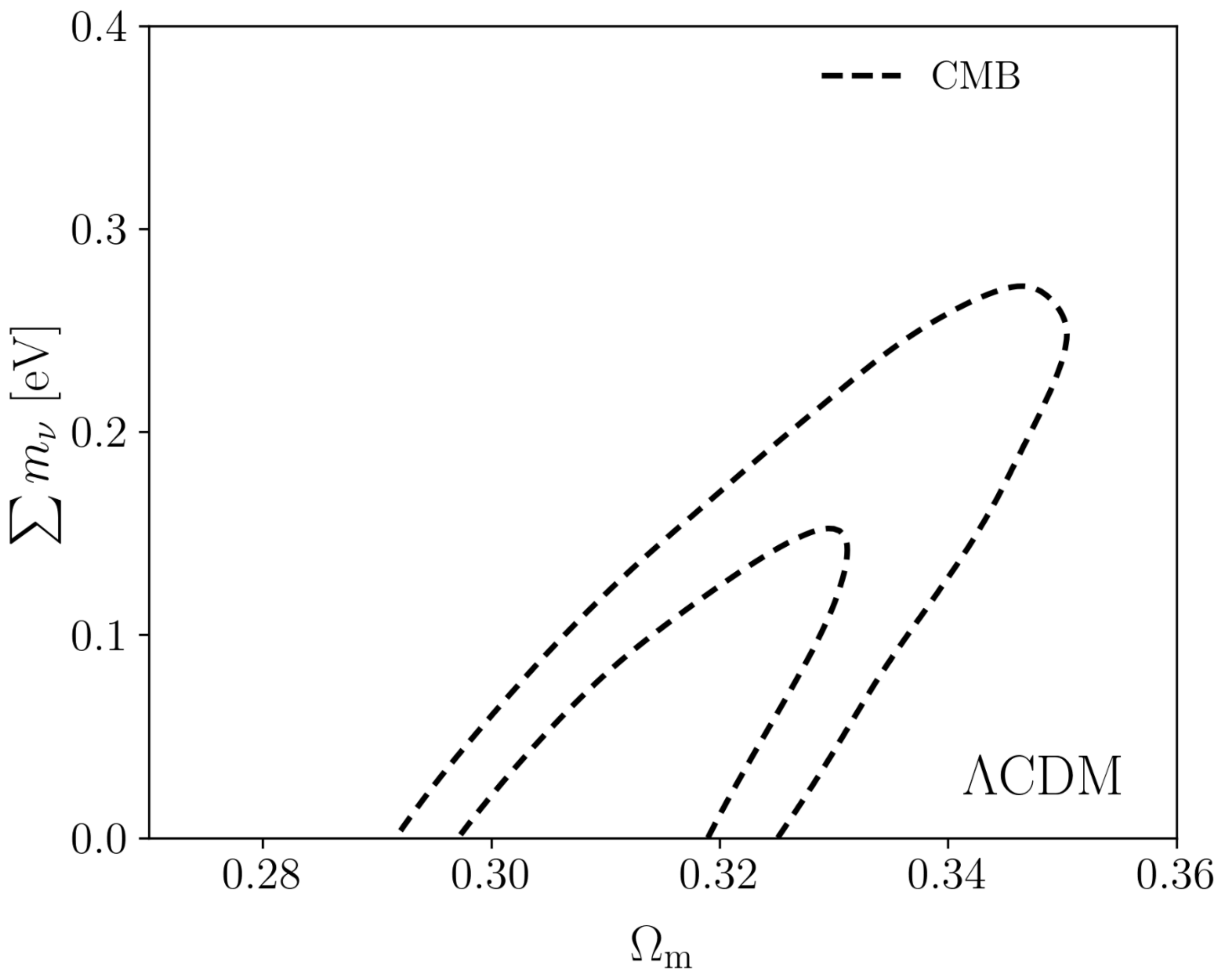
Neutrinos



- Massive neutrinos change the angular diameter distance to last scattering
- This is degenerate with the effects of other parameters, such as Ω_m and H_0

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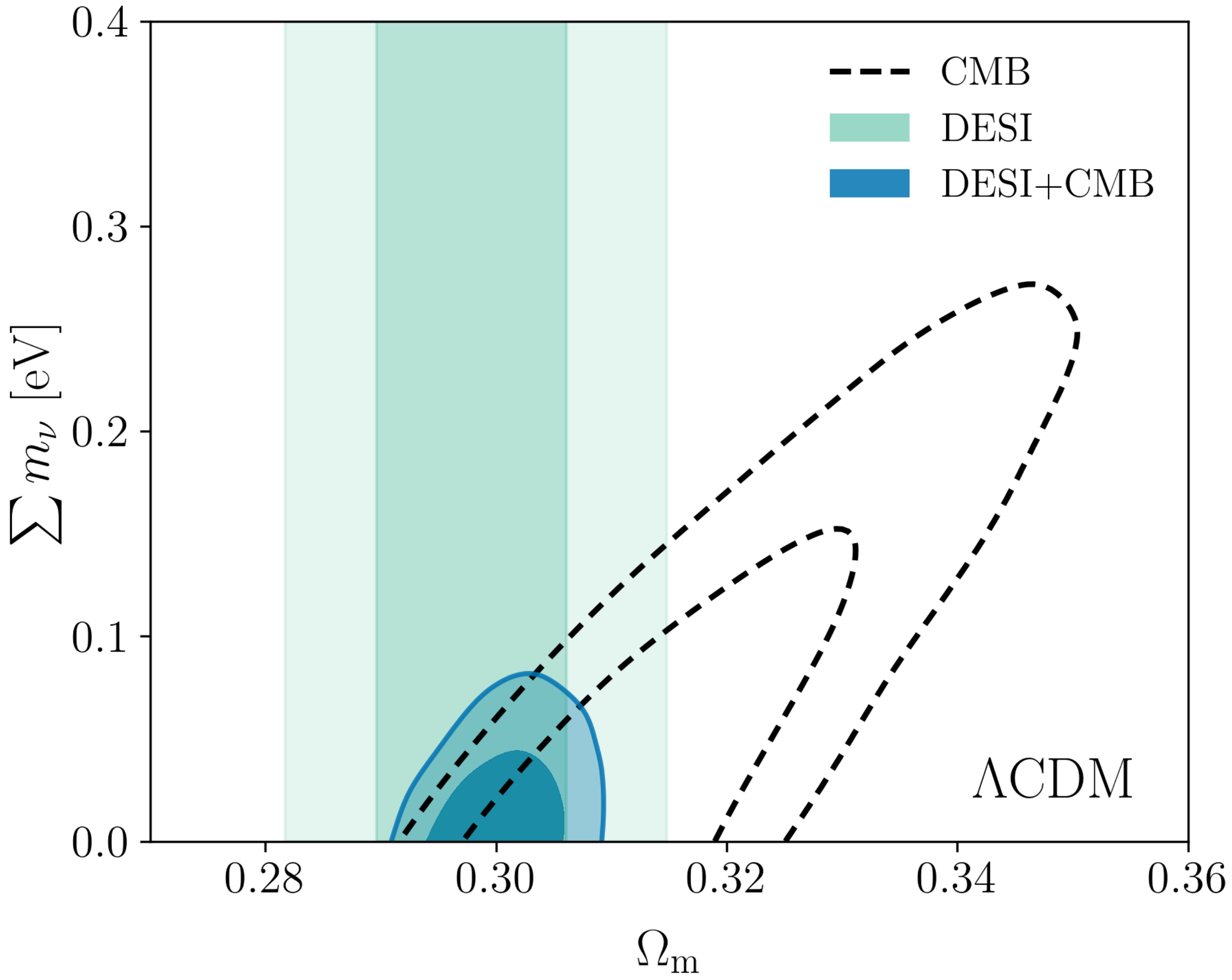
Neutrinos



- Massive neutrinos change the angular diameter distance to last scattering
- This is degenerate with the effects of other parameters, such as Ω_m and H_0
- DESI BAO helps to break this geometric degeneracy

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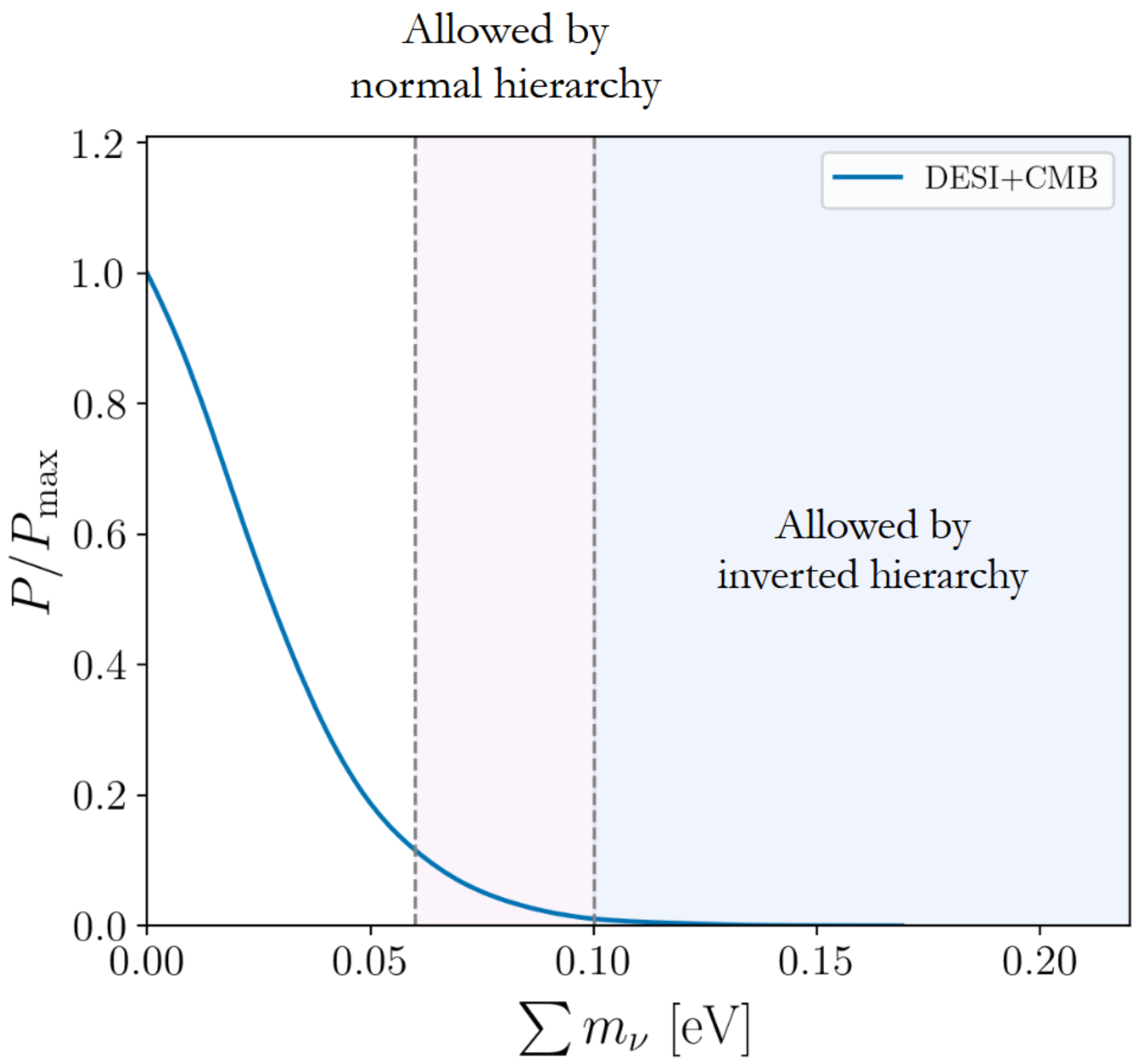
Neutrinos

- Assuming **a ΛCDM background**:

  $\sum m_\nu < 0.0642$ eV (95% CI)

- Close to the lower limit allowed by terrestrial experiments ($\sum m_\nu > 0.059$ eV)



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Neutrinos

Supporting paper on neutrinos: Elbers++ 2025

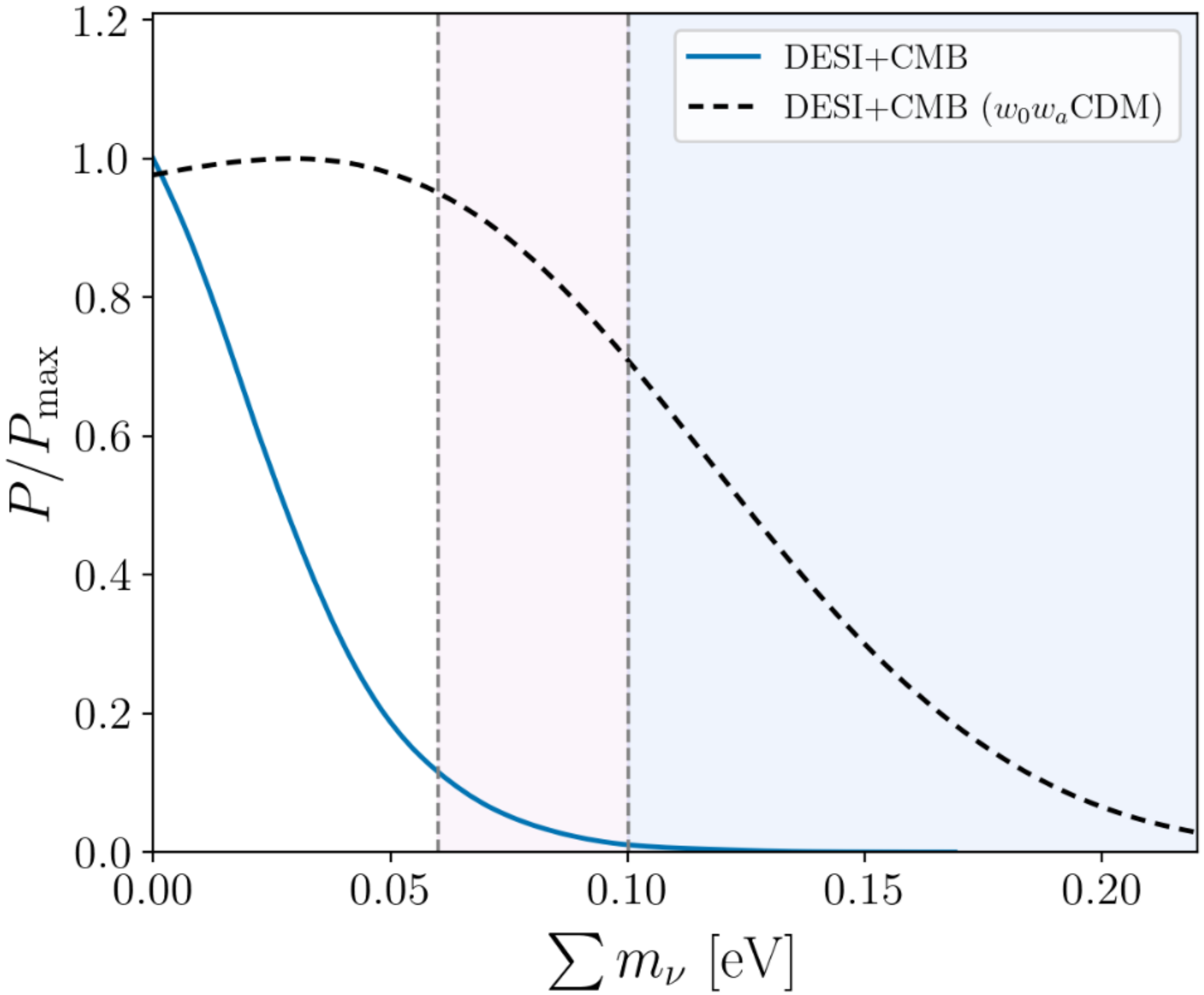
- Assuming **a ΛCDM background**:

  $$\sum m_\nu < 0.0642 \text{ eV (95\% CI)}$$

- Close to the lower limit allowed by terrestrial experiments ($\sum m_\nu > 0.059$ eV)

- Constraint significantly relaxed for **a w_0w_aCDM model**:

  $$\sum m_\nu < 0.163 \text{ eV (95\% CI)}$$



IV. The evidence for evolving dark energy

Are alternative explanations possible?

CMB alternatives where we marginalize over information dependent on late-time models

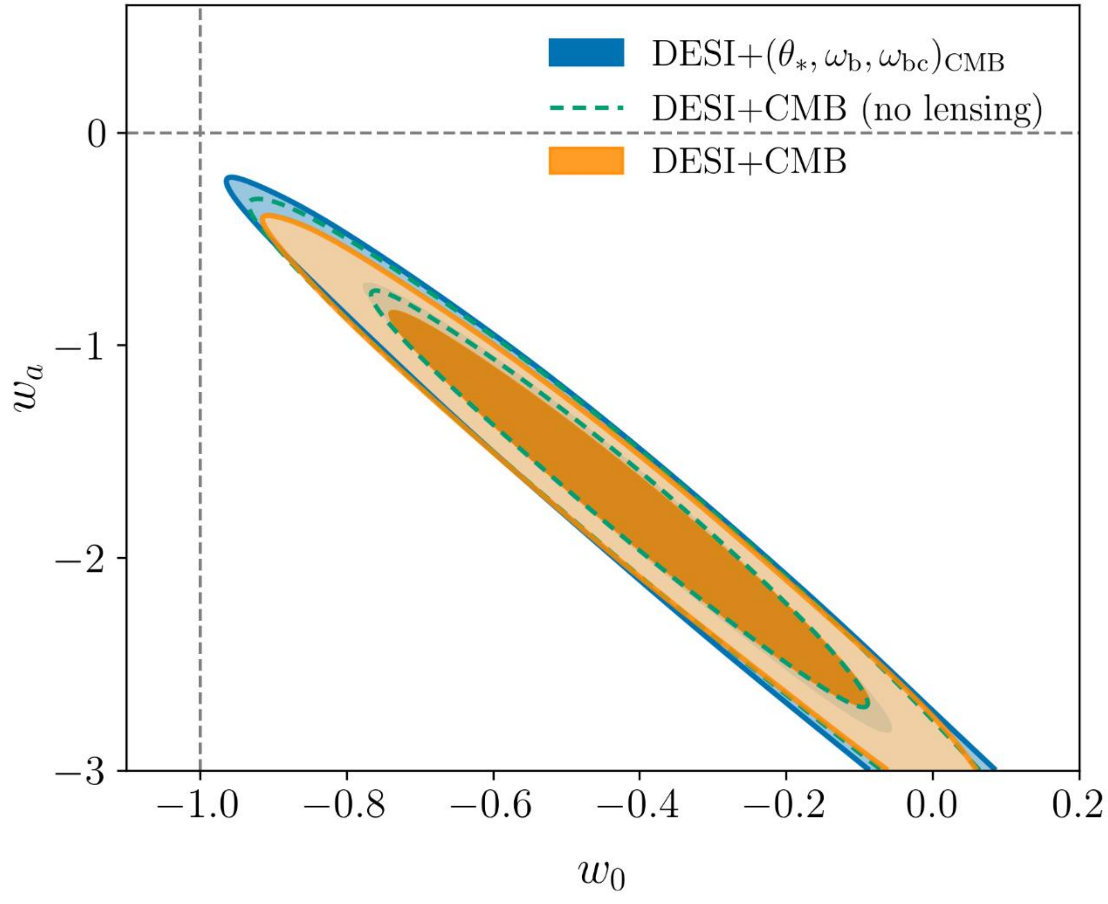
- Using early-Universe priors on $(\theta_*, \omega_b, \omega_{bc})$ derived from the CMB:

  DESI + $(\theta_*, \omega_b, \omega_{bc})_{CMB} \Longrightarrow$ 2.4σ

- Using CMB without lensing:

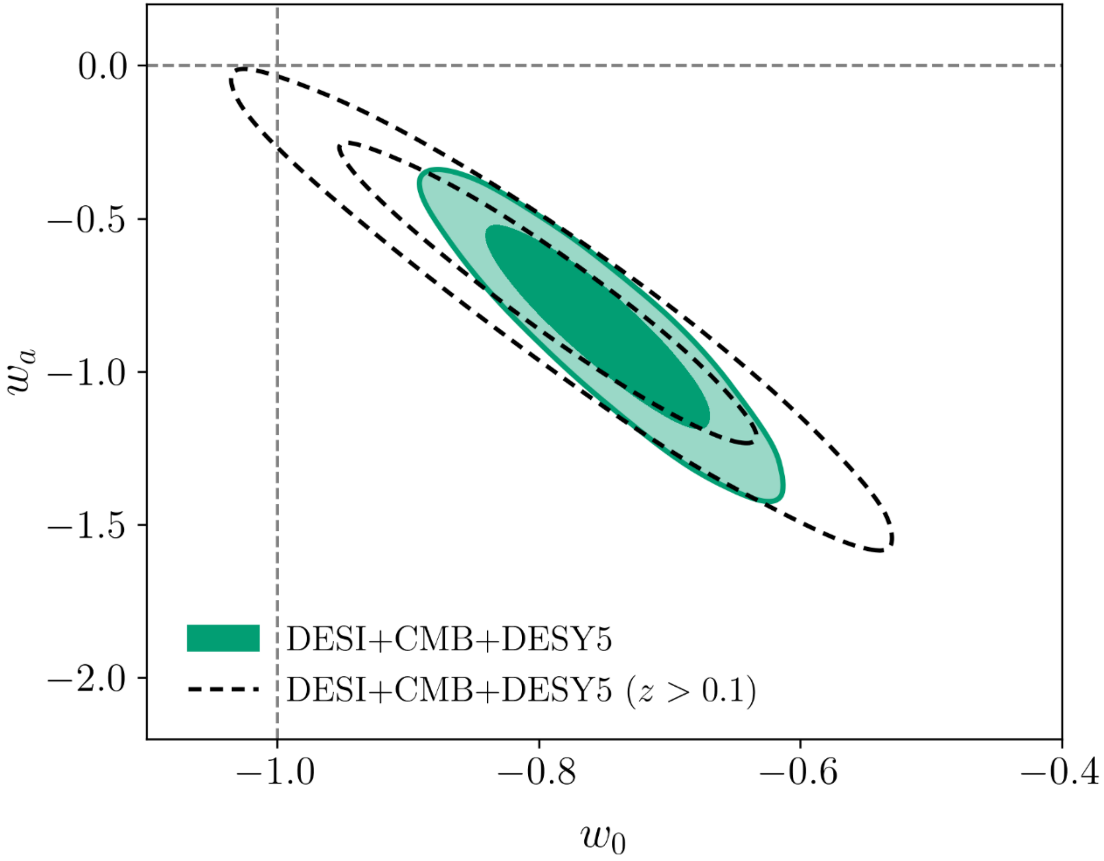
  DESI + CMB (no lensing) $\Longrightarrow$ 2.7σ

Preference for dynamic dark energy weakens (from 3.1σ), but posteriors remain very similar



Are alternative explanations possible?

- Constraining power of SNe primarily from comparison of $z < 0.1$ and $z > 0.1$ SNe
- No SNe compilation has uniformly observed objects from both regimes
- Removing the $z < 0.1$ SNe weakens the preference for evolving dark energy

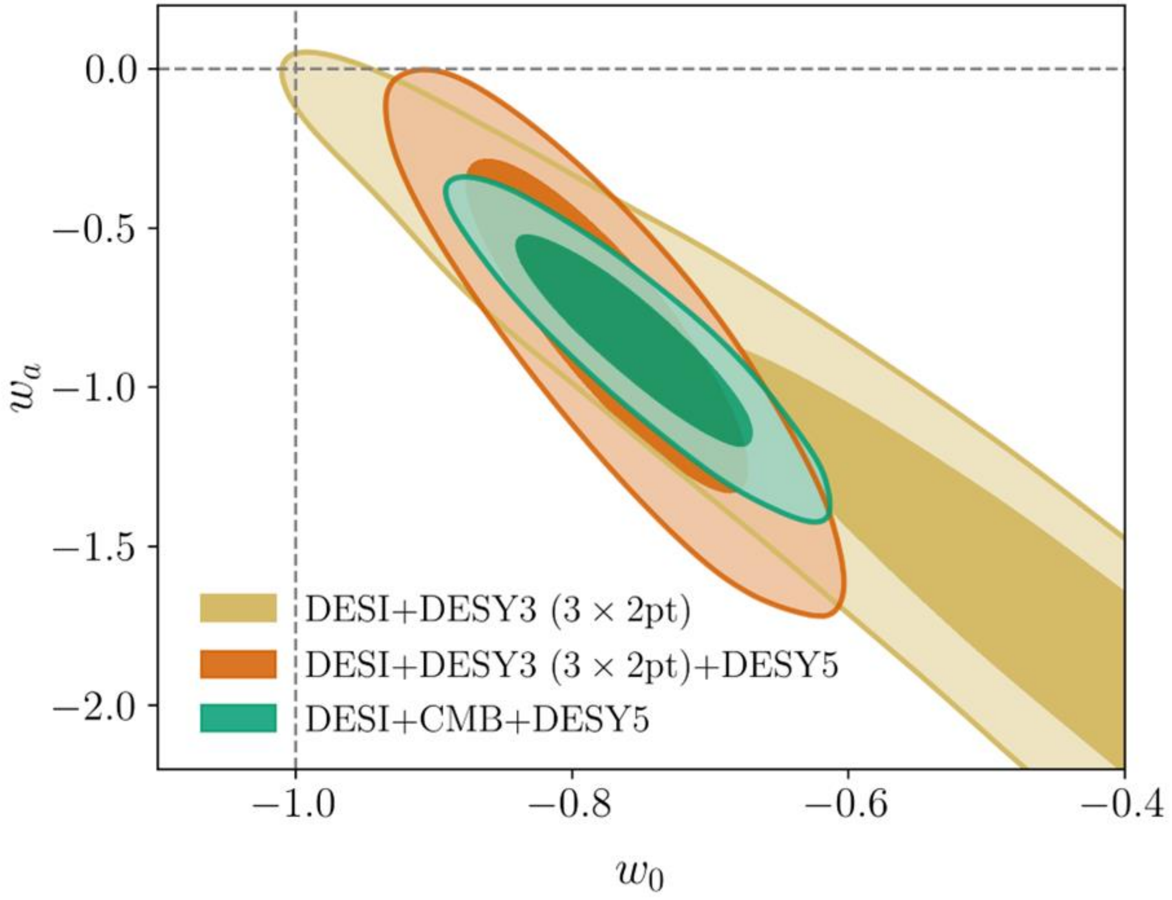


Are alternative explanations possible?

- Replacing the CMB with DESY3 3 × 2pt (weak lensing + galaxy clustering)
- Constraint coming entirely from low-redshift probes
- Still see preference for the same region:

DESI + DESY3 (3 × 2pt) ⟹ 2.2σ

DESI + DESY3 (3 × 2pt) + DESY5 ⟹ 3.3σ



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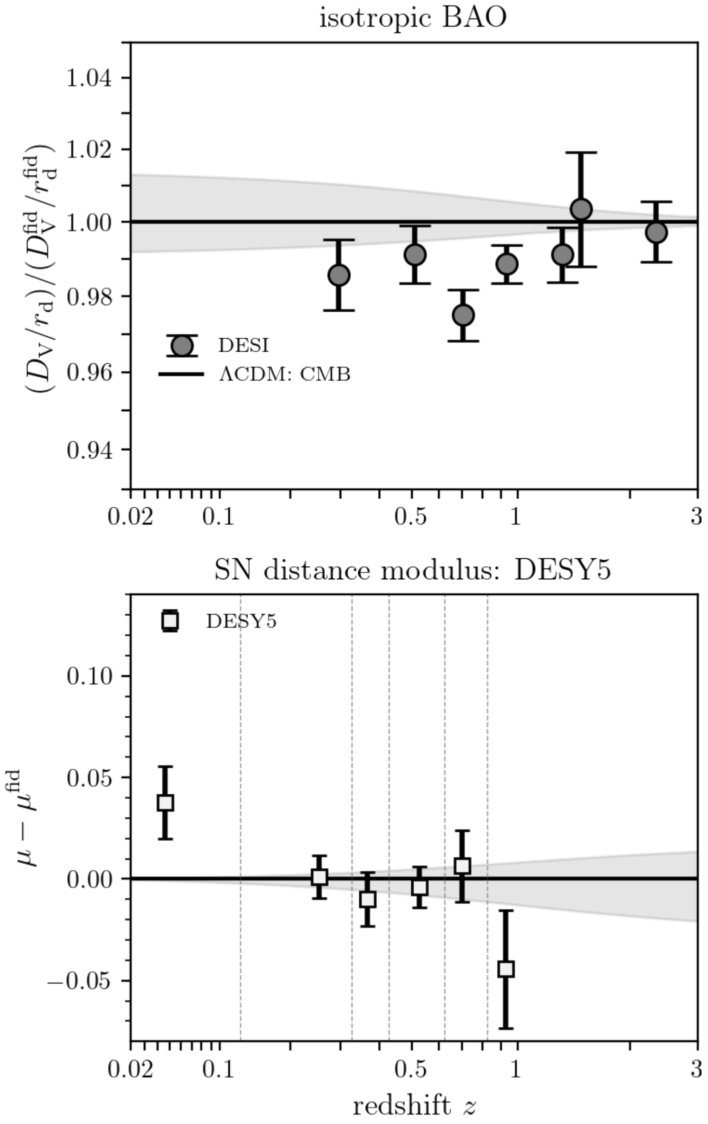
The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus



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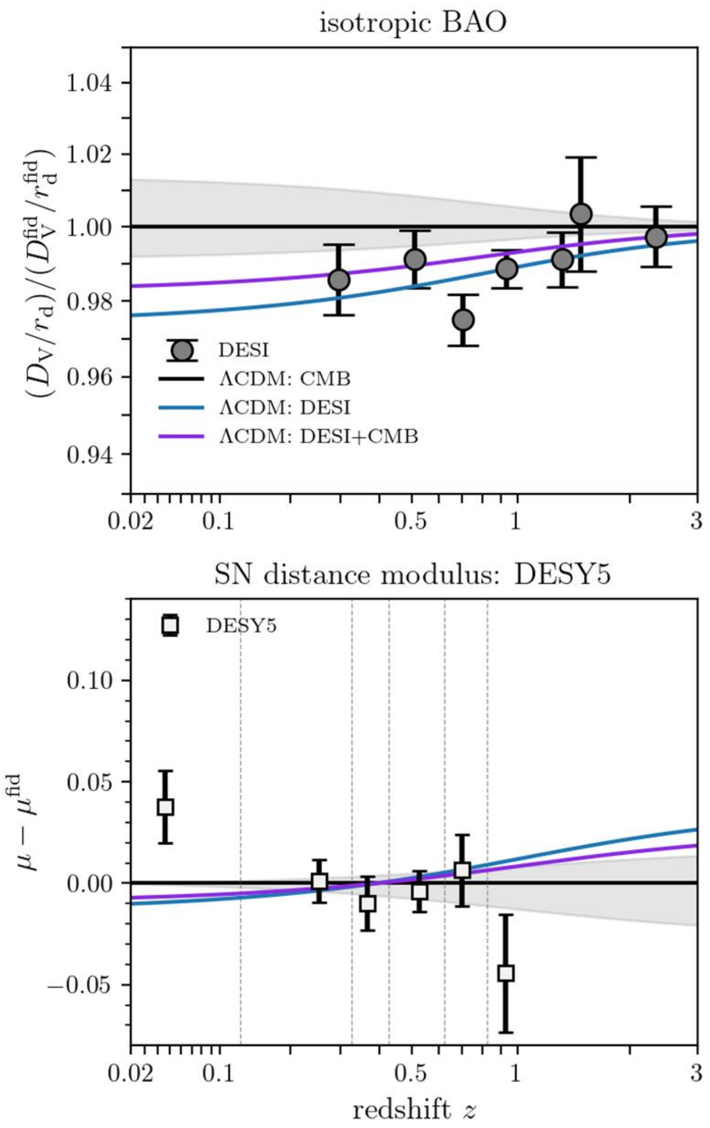
The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus



- There is a **ΛCDM** model that fits DESI BAO well
- DESI points at $z < 1$ prefer distances 1-2% lower than the CMB prediction

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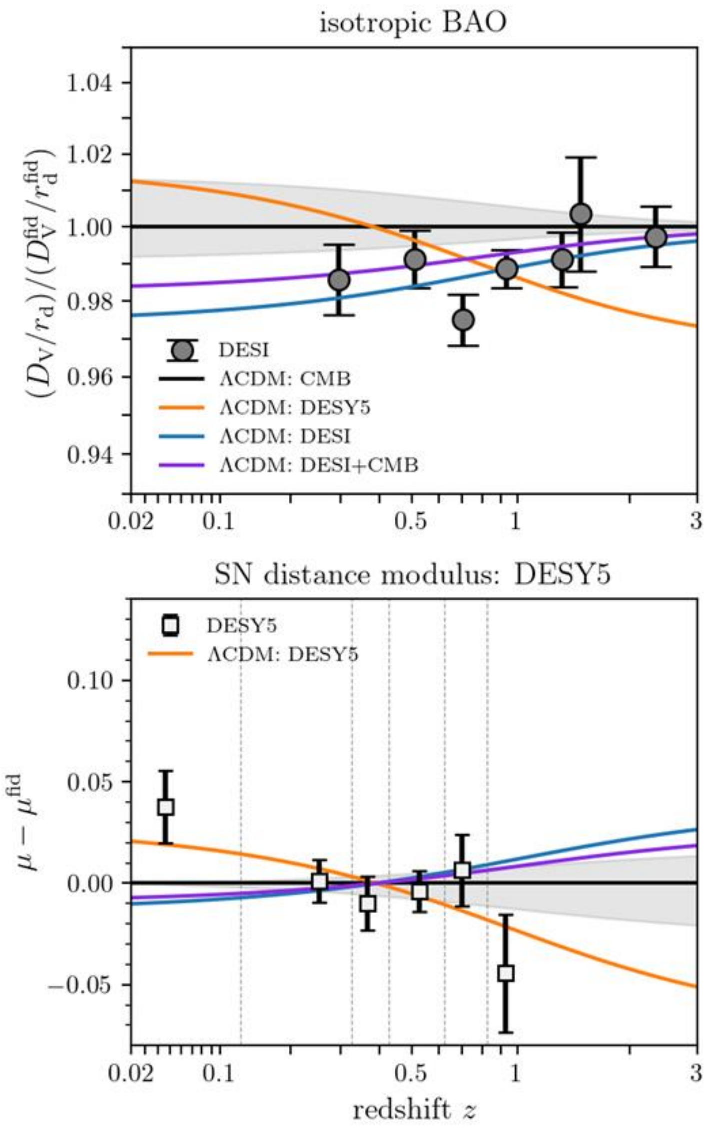
The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus



- There is a **ΛCDM** model that fits DESI BAO well
- DESI points at $z < 1$ prefer distances 1-2% lower than the CMB prediction
- There is a **ΛCDM** model that fits SNe well
- Tension with DESI and CMB due to the contrast between $z < 0.1$ and $z > 0.1$ SNe

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The nature of the evidence

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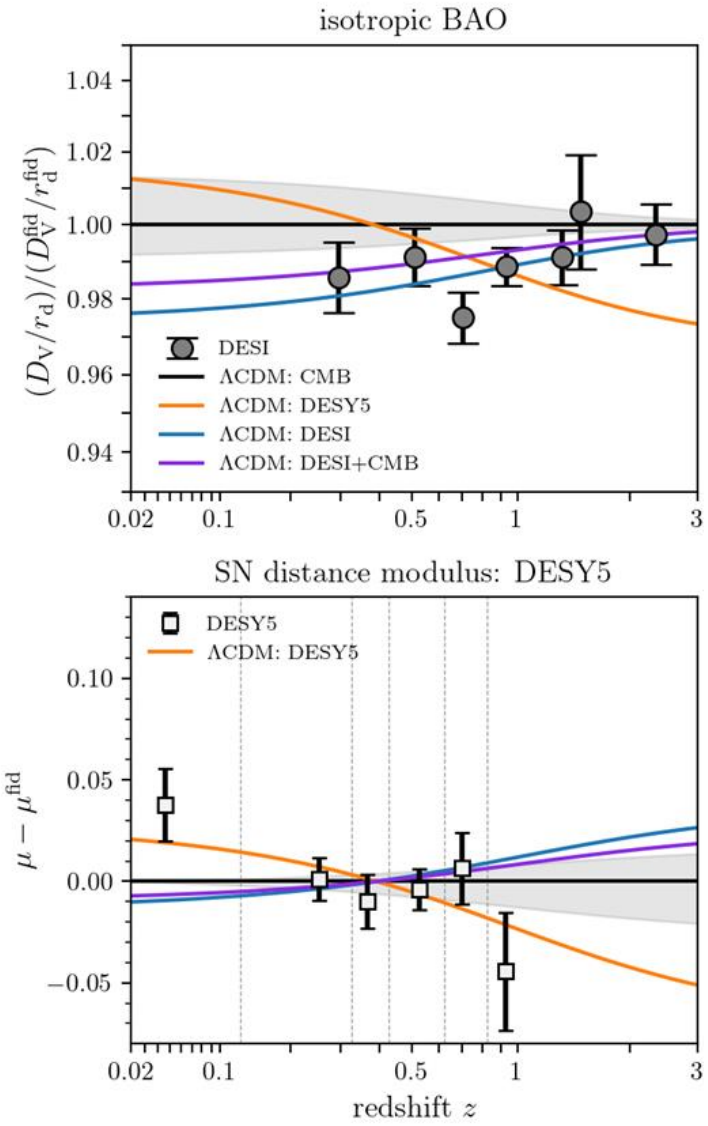
Isotropic BAO distance measurement

Supernovae distance modulus



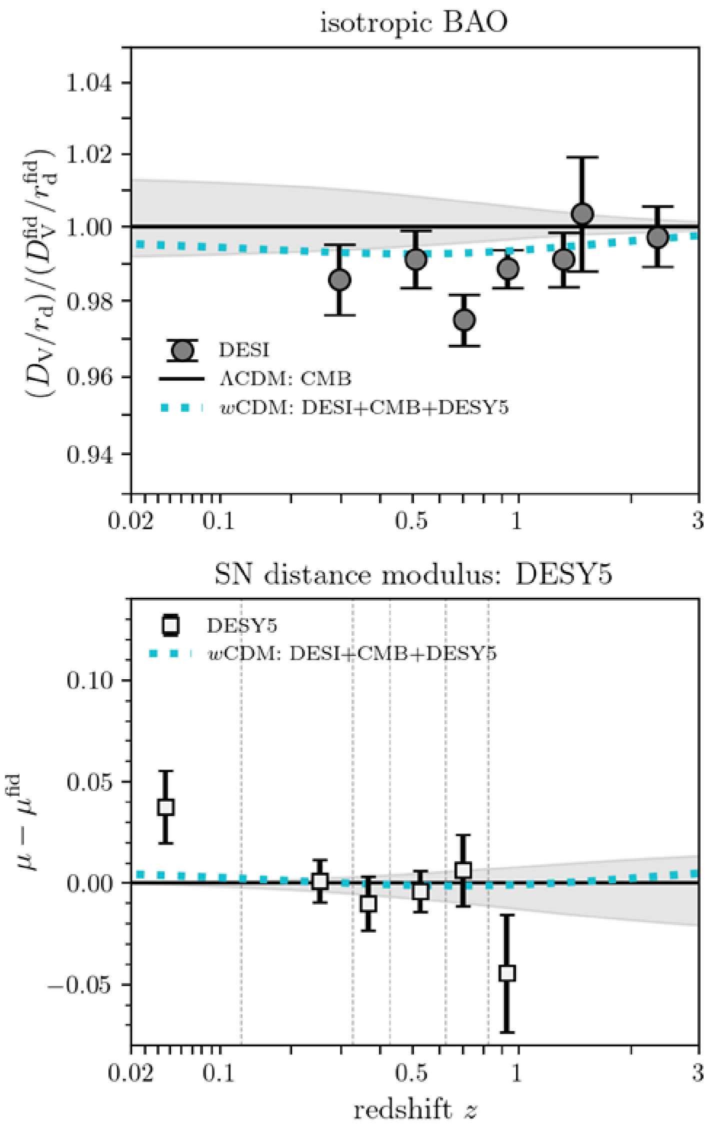
⟹ **ΛCDM** does not provide a good fit to all data simultaneously

DESI DR2 Results II: BAO measurements and Cosmology

The nature of the evidence

Isotropic BAO distance measurement

Supernovae distance modulus



$\Longrightarrow$ ***w*CDM** does not have enough freedom to fit everything either

DESI DR2 Results II: BAO measurements and Cosmology

The nature of the evidence

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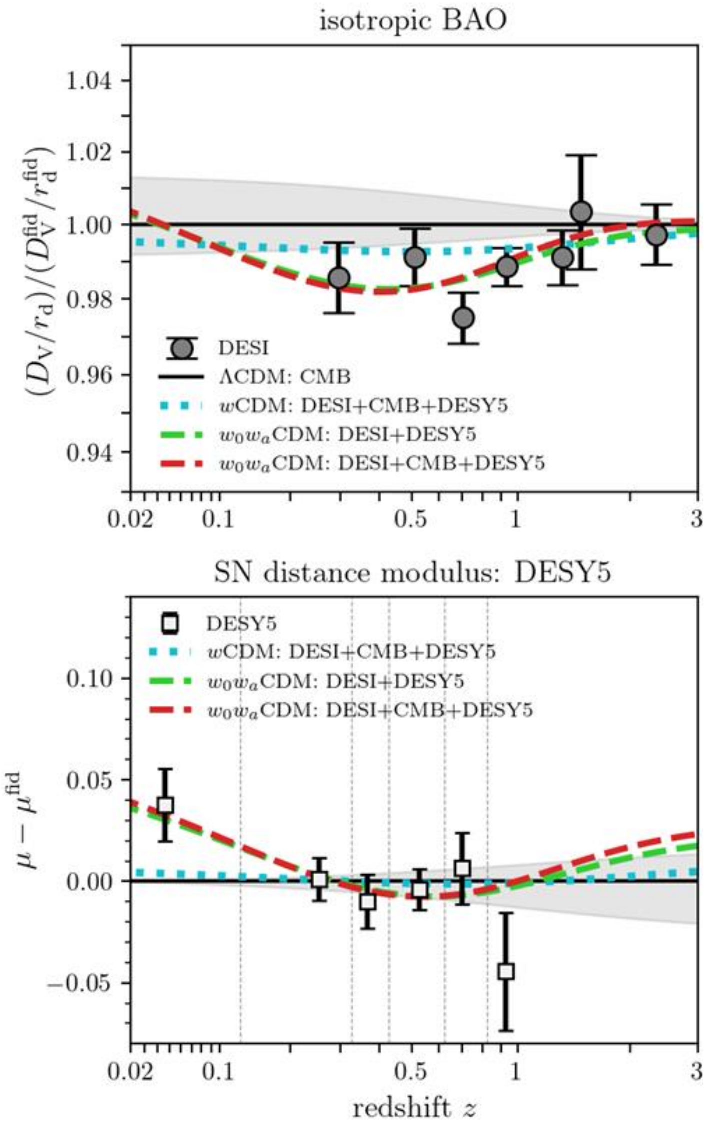
Isotropic BAO distance measurement

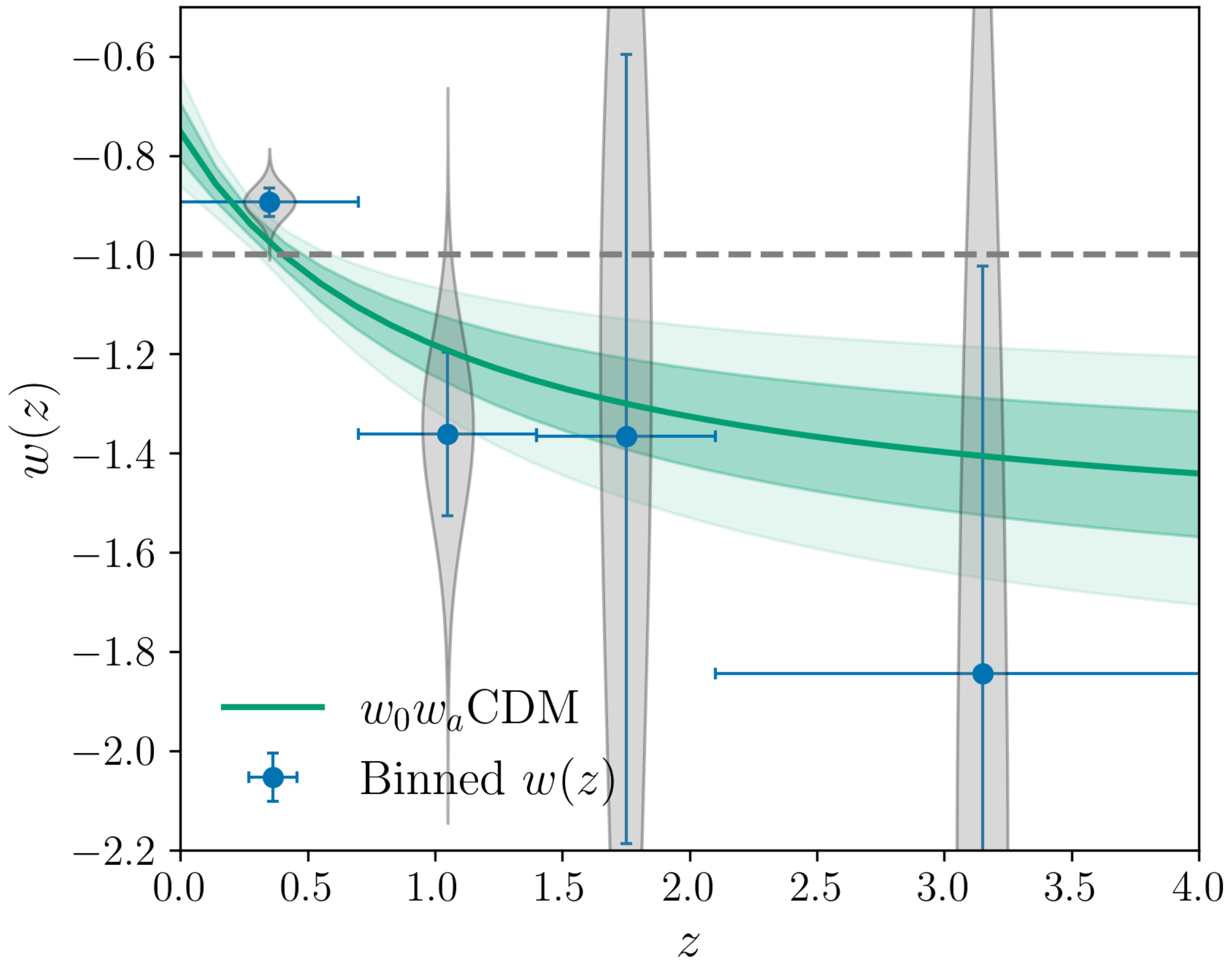
Supernovae distance modulus



$\Longrightarrow$ $\boldsymbol{w_0 w_a}$**CDM** has sufficient flexibility to simultaneously achieve good fits to all three datasets

DESI DR2 Results II: BAO measurements and Cosmology

Does $w_0 w_a$CDM capture the whole picture?



- Binned reconstruction of $w(z)$ consistent with $w_0 w_a$CDM
- Many more models tested in Lodha et al. (2025)

Supporting paper on dark energy: Lodha++ 2025

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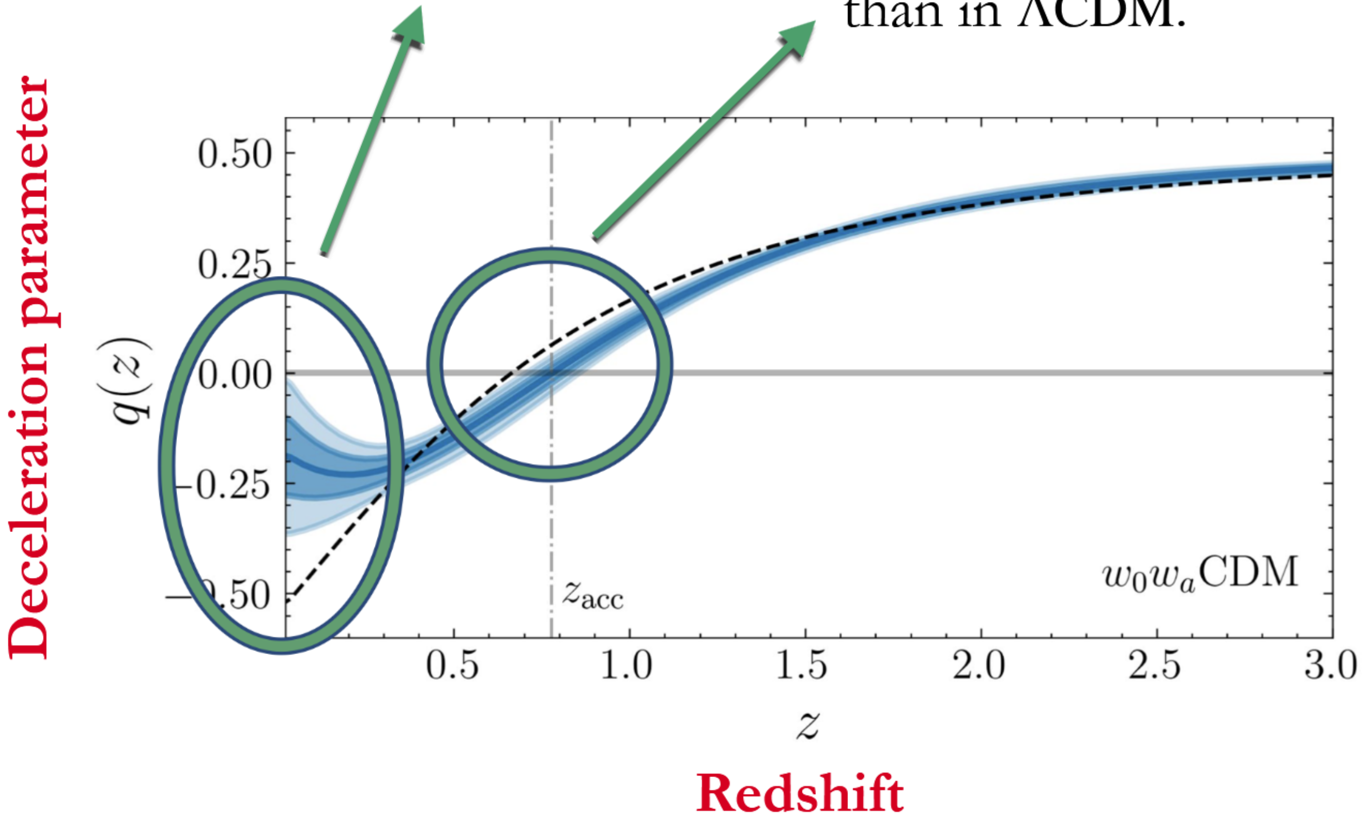
Implications

Acceleration is lower than ΛCDM at present.

Acceleration started earlier than in ΛCDM.



Supporting paper: Lodha++ 2025

Conclusions

- DESI prefers smaller values of Ω_m compared to the CMB within ΛCDM, while SNe prefer larger values than the CMB

- Assuming ΛCDM, DESI + CMB give the tightest constraints on the sum of neutrino masses to date, in increasing tension with lower bounds from terrestrial experiments

- These points hint at growing incompatibility between different datasets when interpreted using the ΛCDM model

- Evidence for evolving dark energy has increased with DESI DR2 BAO to 3.1σ from DESI+CMB alone, and to between 2.8σ and 4.2σ when including SNe

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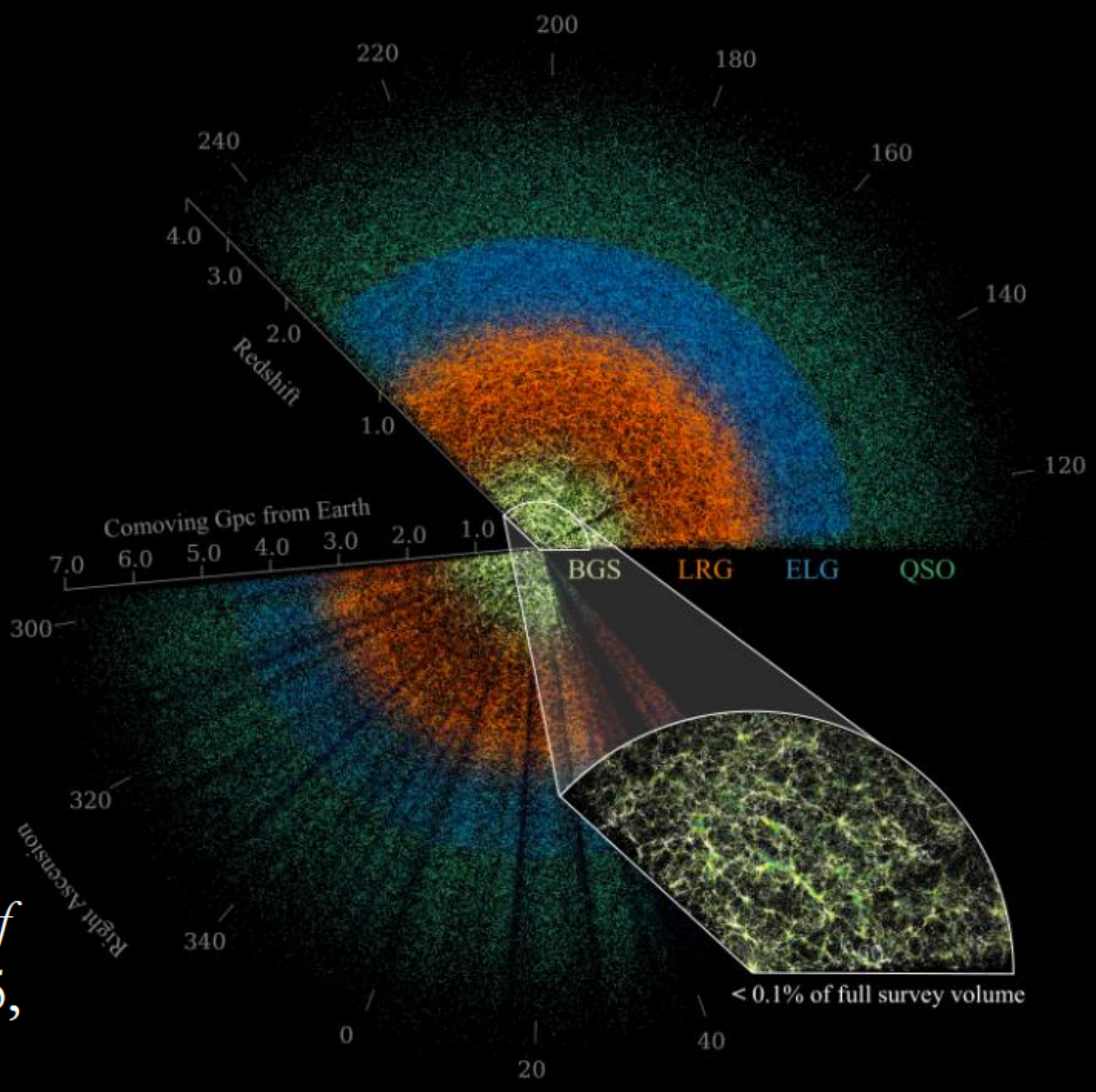
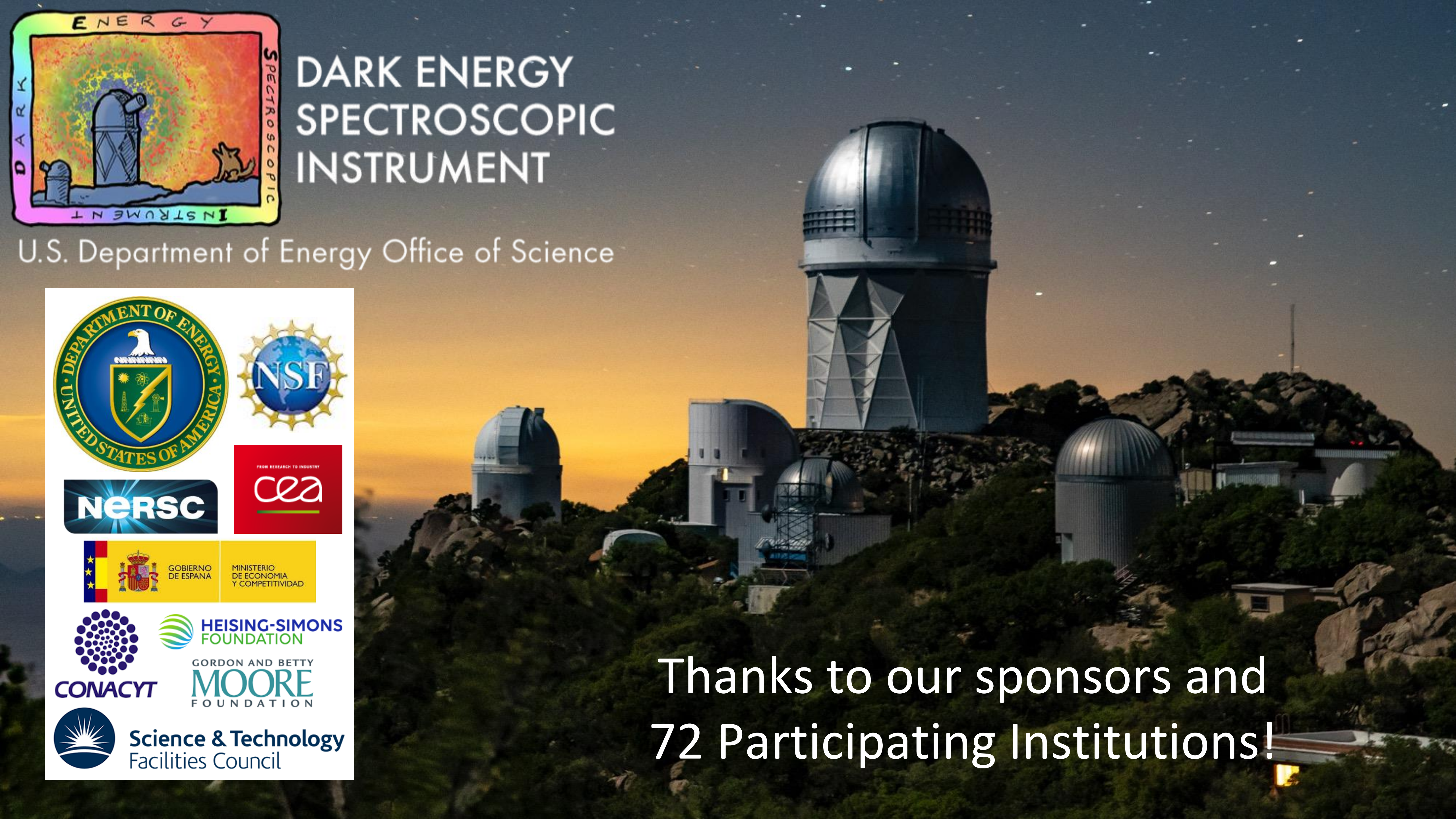
Getting started with DESI Data Release 1

- Multiple access points to redshifts, spectra, photometry, and much more.
- Tutorials (Python/Jupyter notebooks)
- Access to all large-scale catalogs used for DESI cosmological inference.
- More than 20 value-added catalogs spanning a wide range of samples and scales.



DESI Collaboration et al., *Data Release 1 of the Dark Energy Spectroscopic Instrument* 2025, AJ, submitted (arXiv:XX)

https://data.desi.lbl.gov/doc/releases/dr1



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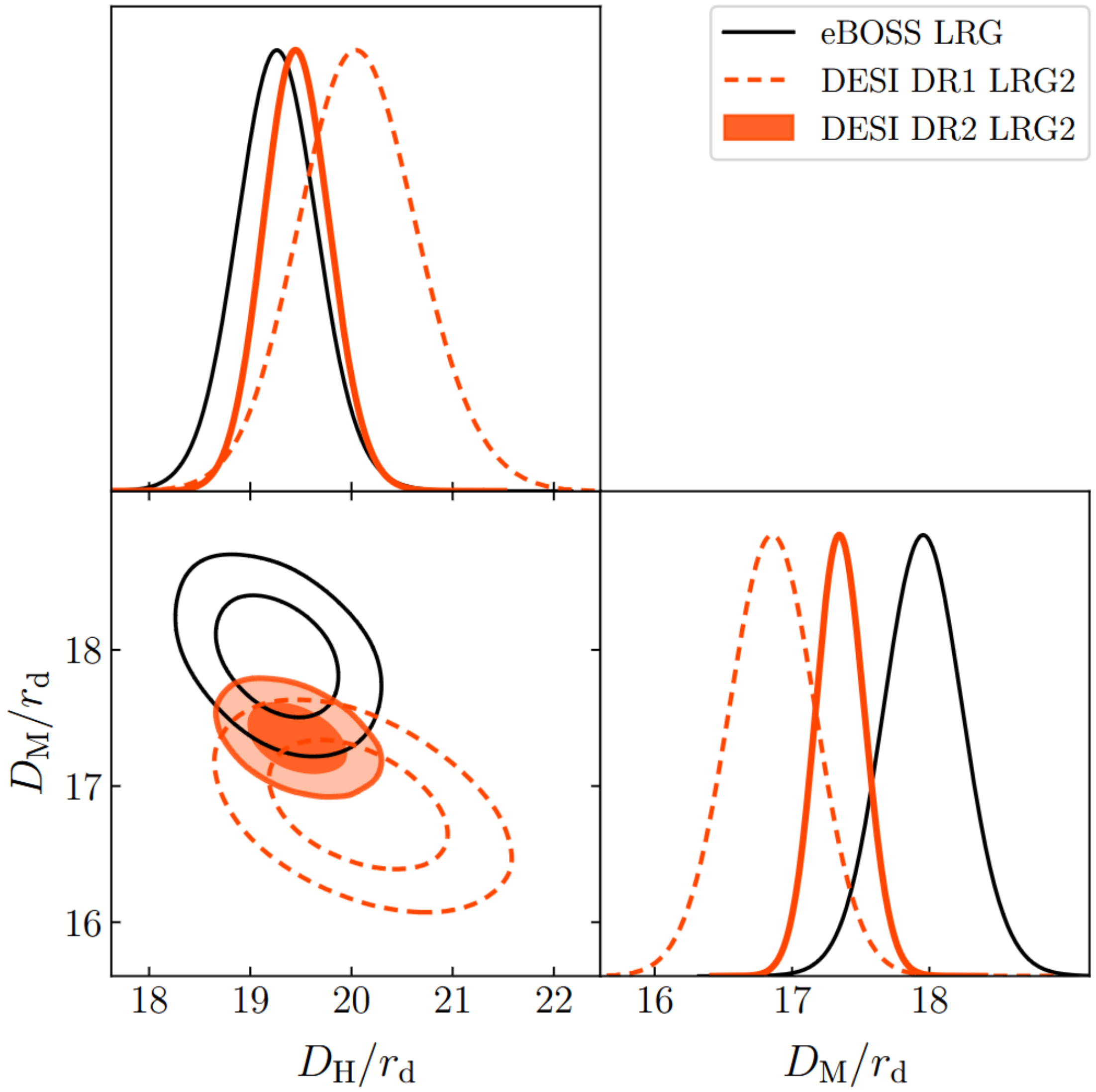
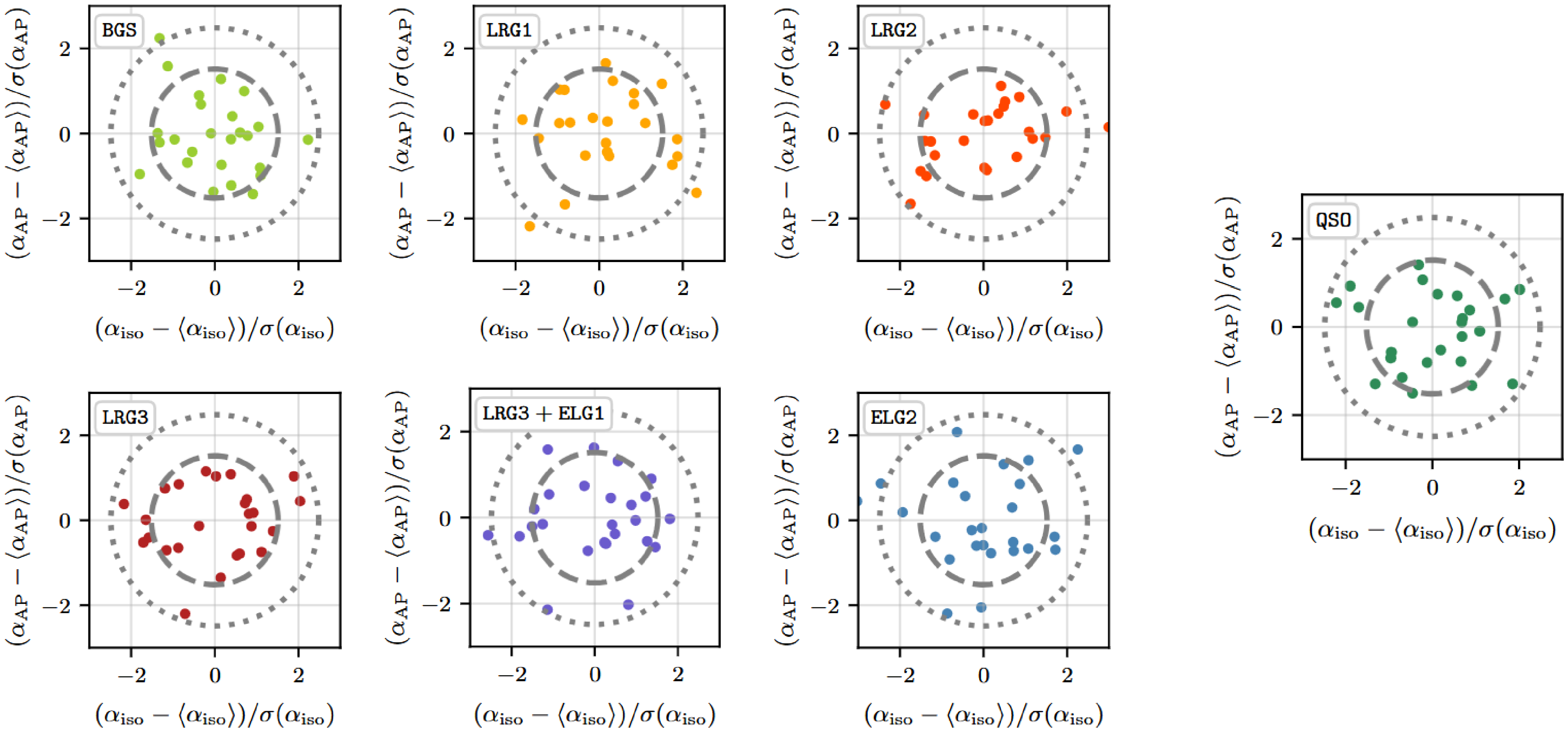
Tension with eBOSS?



Mocks tests


BGS
LRG1
LRG2
QSO
LRG3
LRG3 + ELG1
ELG2
$(\alpha_{AP} - \langle\alpha_{AP}\rangle)/\sigma(\alpha_{AP})$
$(\alpha_{iso} - \langle\alpha_{iso}\rangle)/\sigma(\alpha_{iso})$

DES Collaboration (2025)

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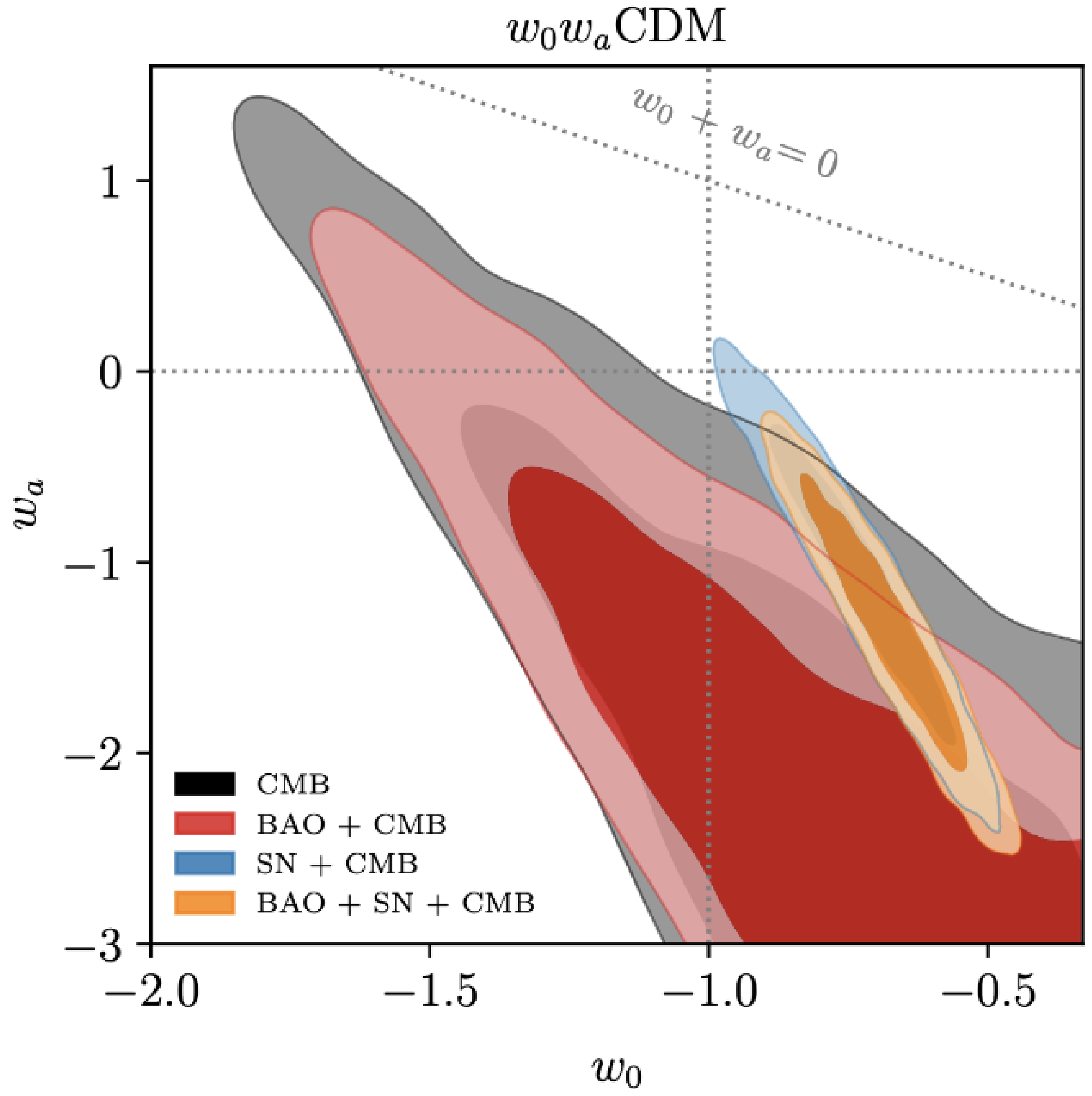

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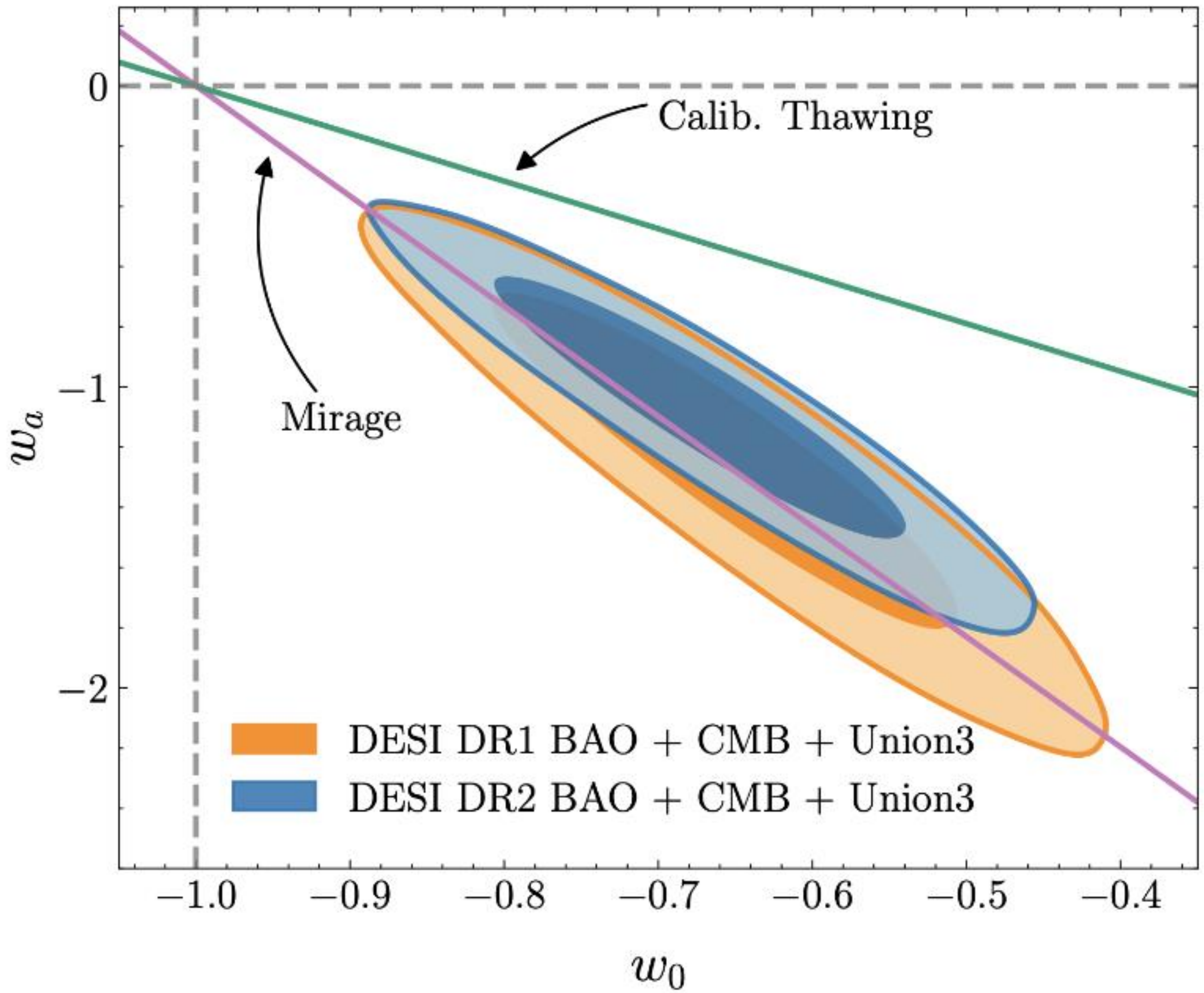
Lodha++ 2025



Implications

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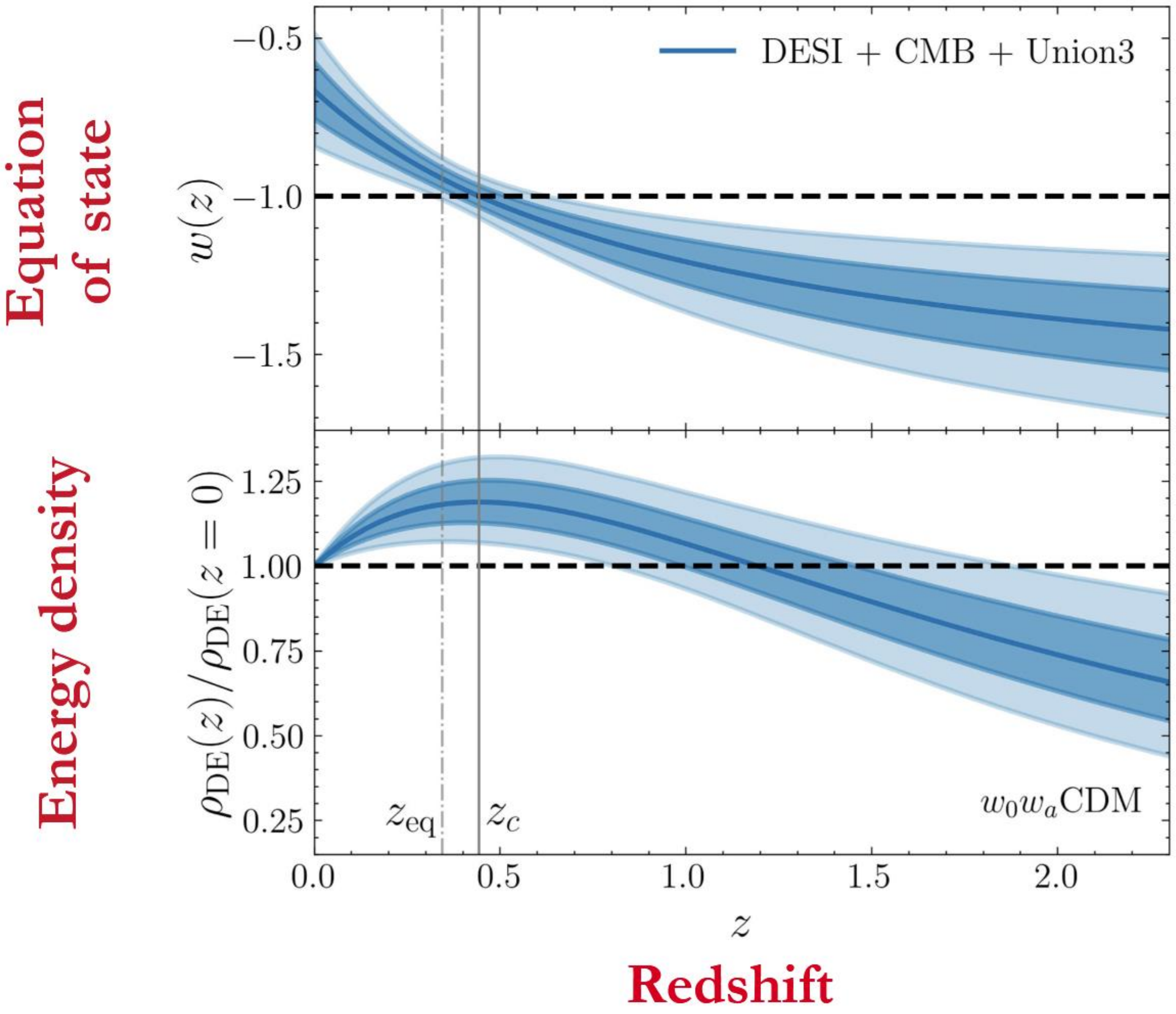

- Maximum dark energy density reached at $z \approx 0.45$ (phantom crossing)
- The phantom crossing could indicate a significantly more complex dark sector than previously assumed

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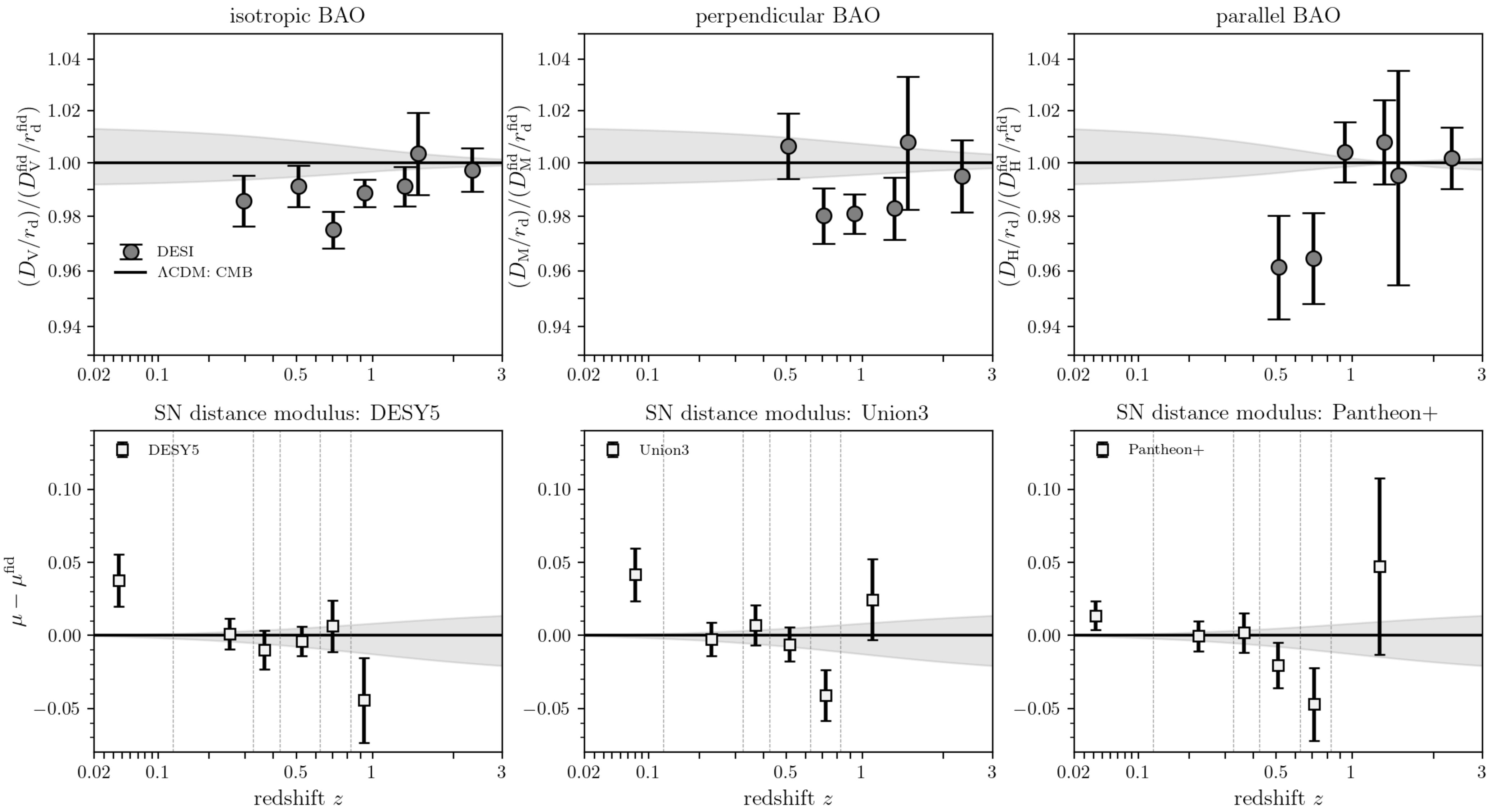
The nature of the evidence



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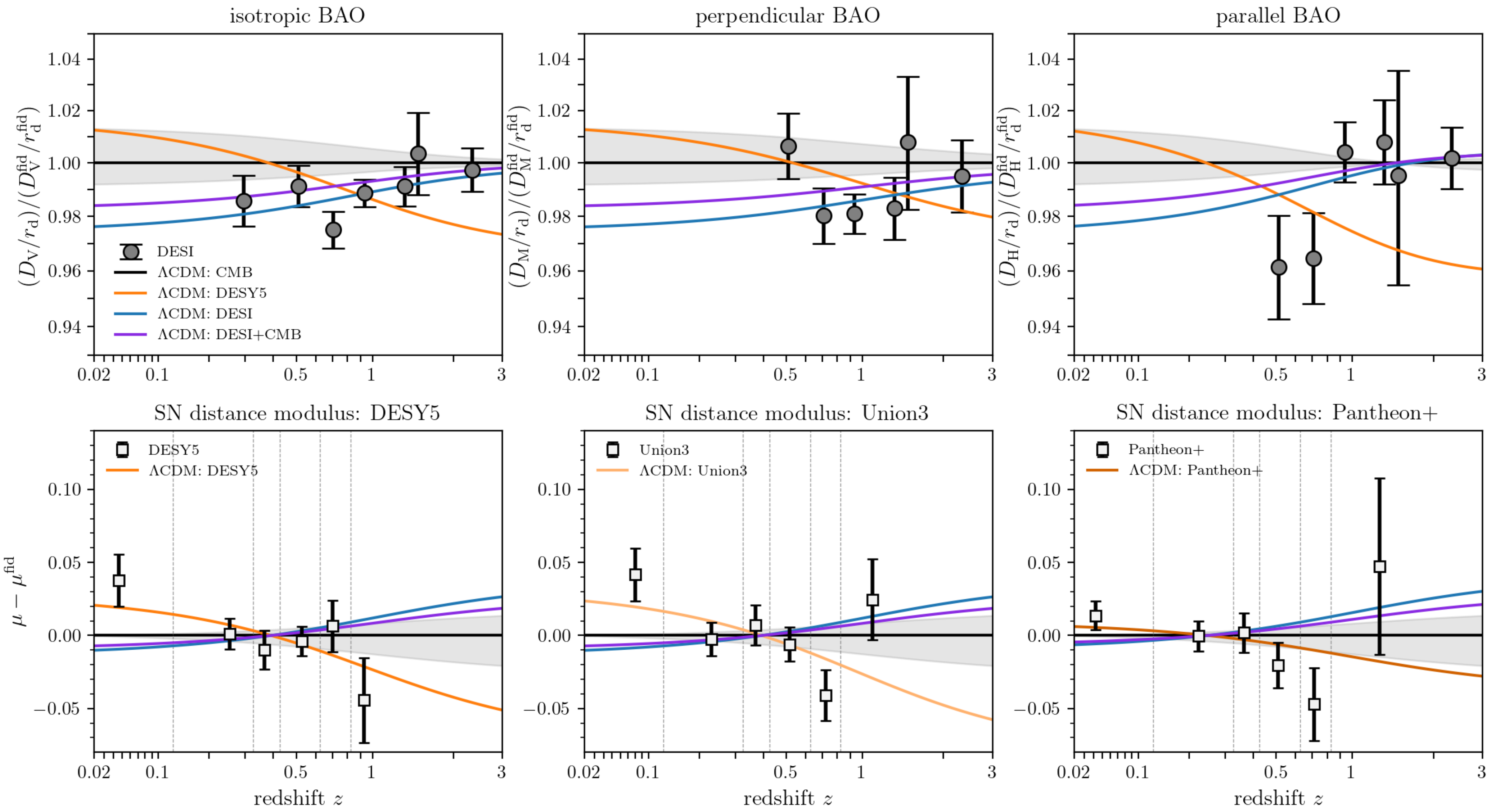
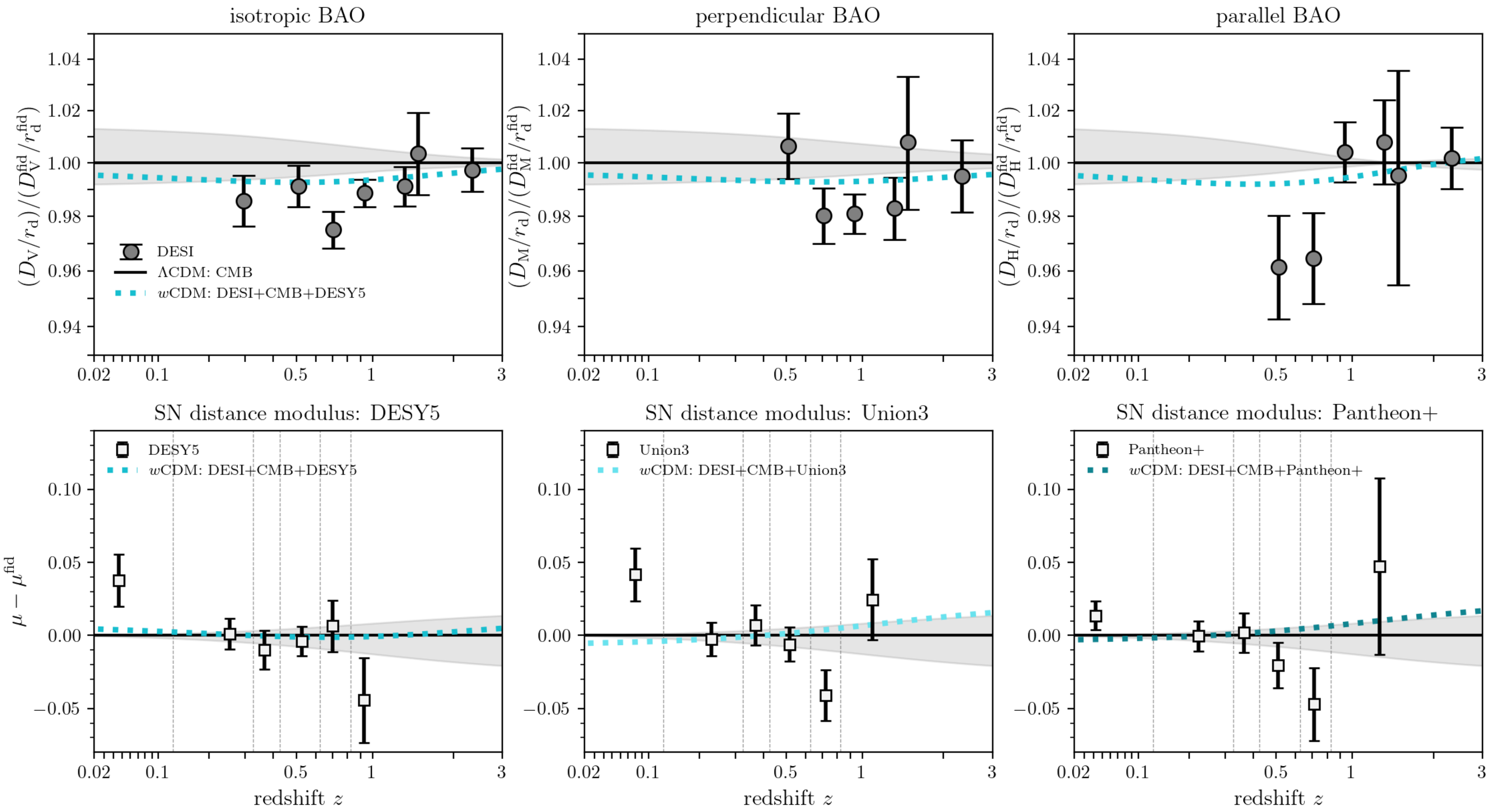
The nature of the evidence



The nature of the evidence



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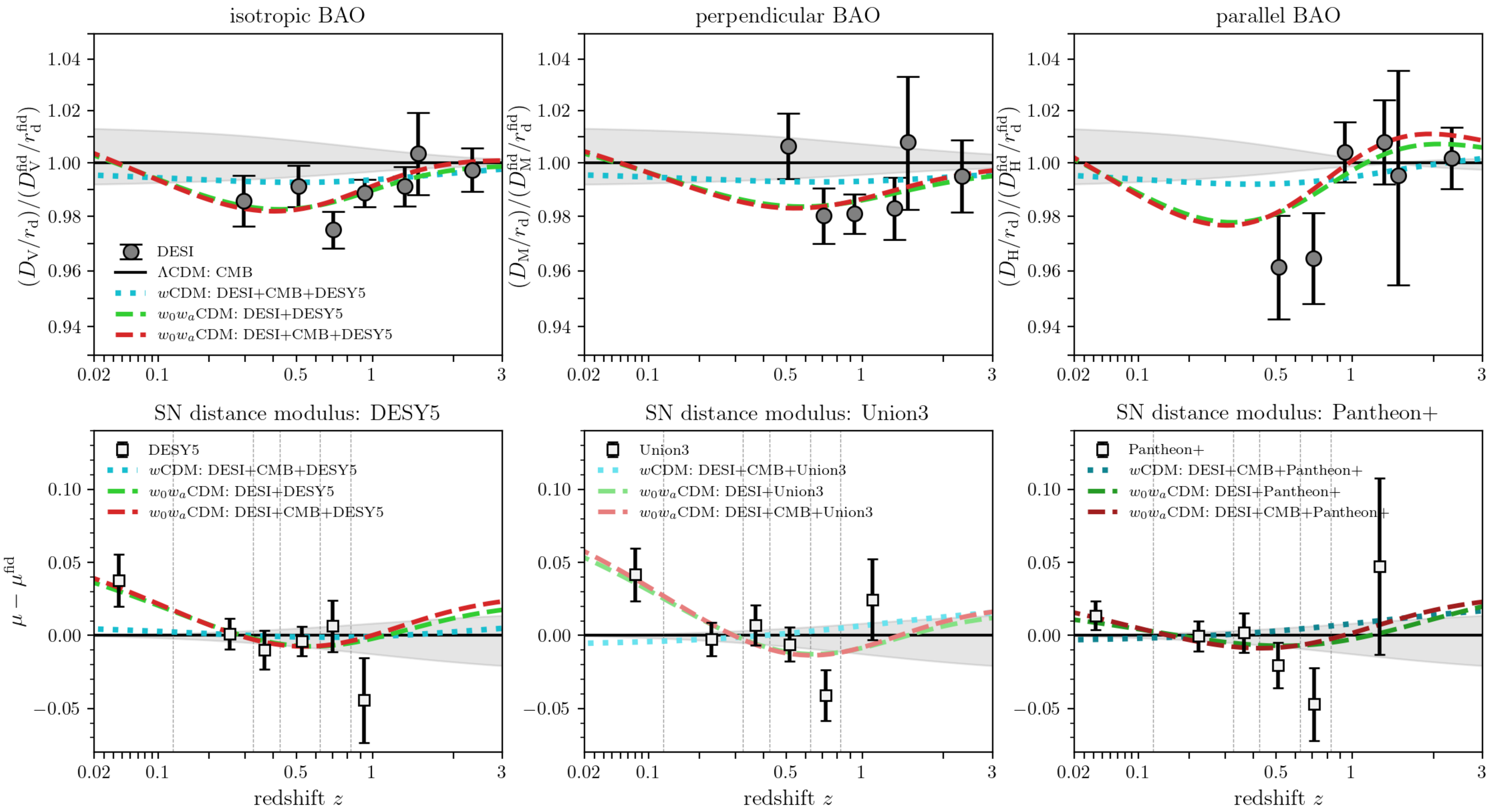
The nature of the evidence



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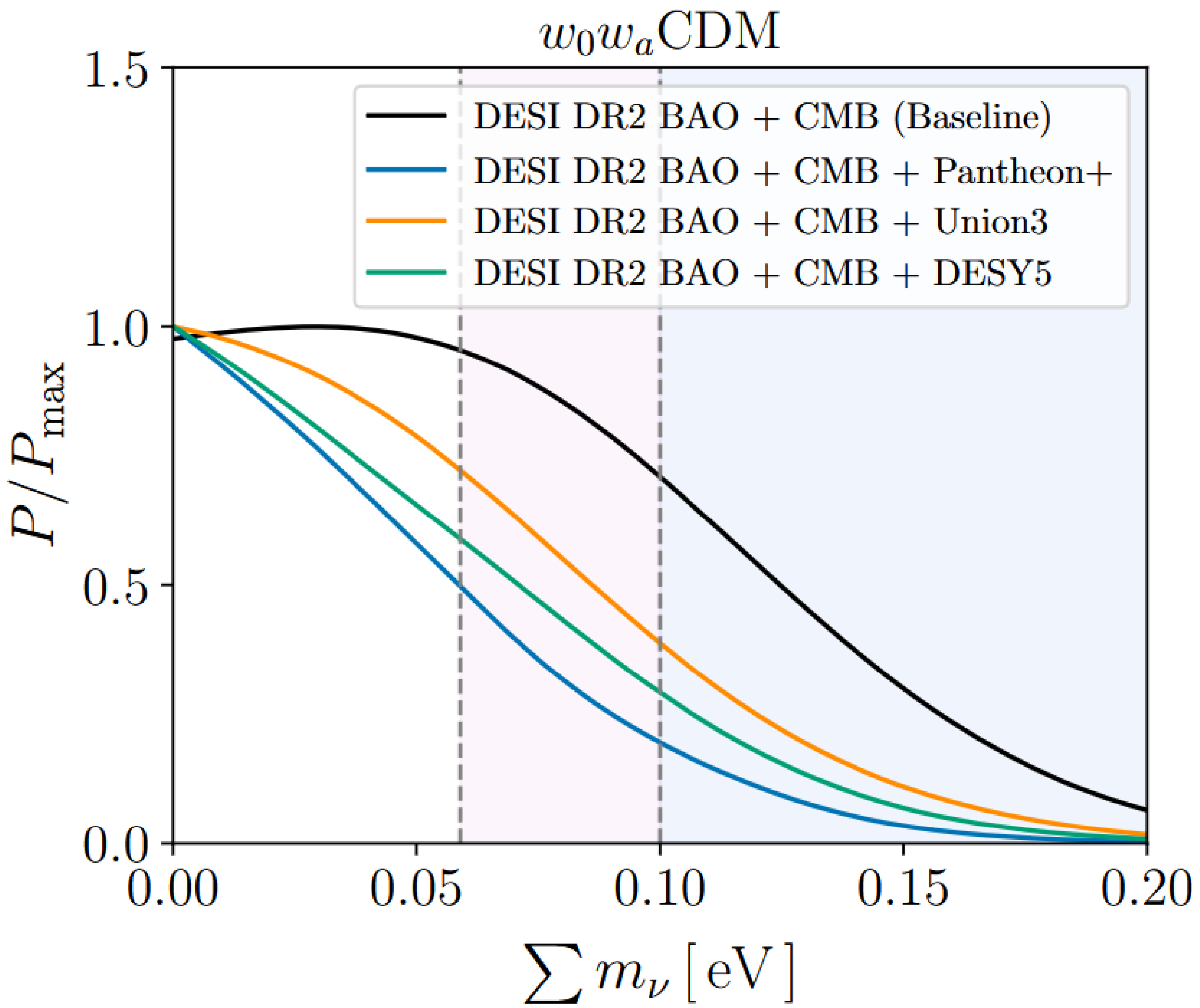
Neutrino constraints with SNe



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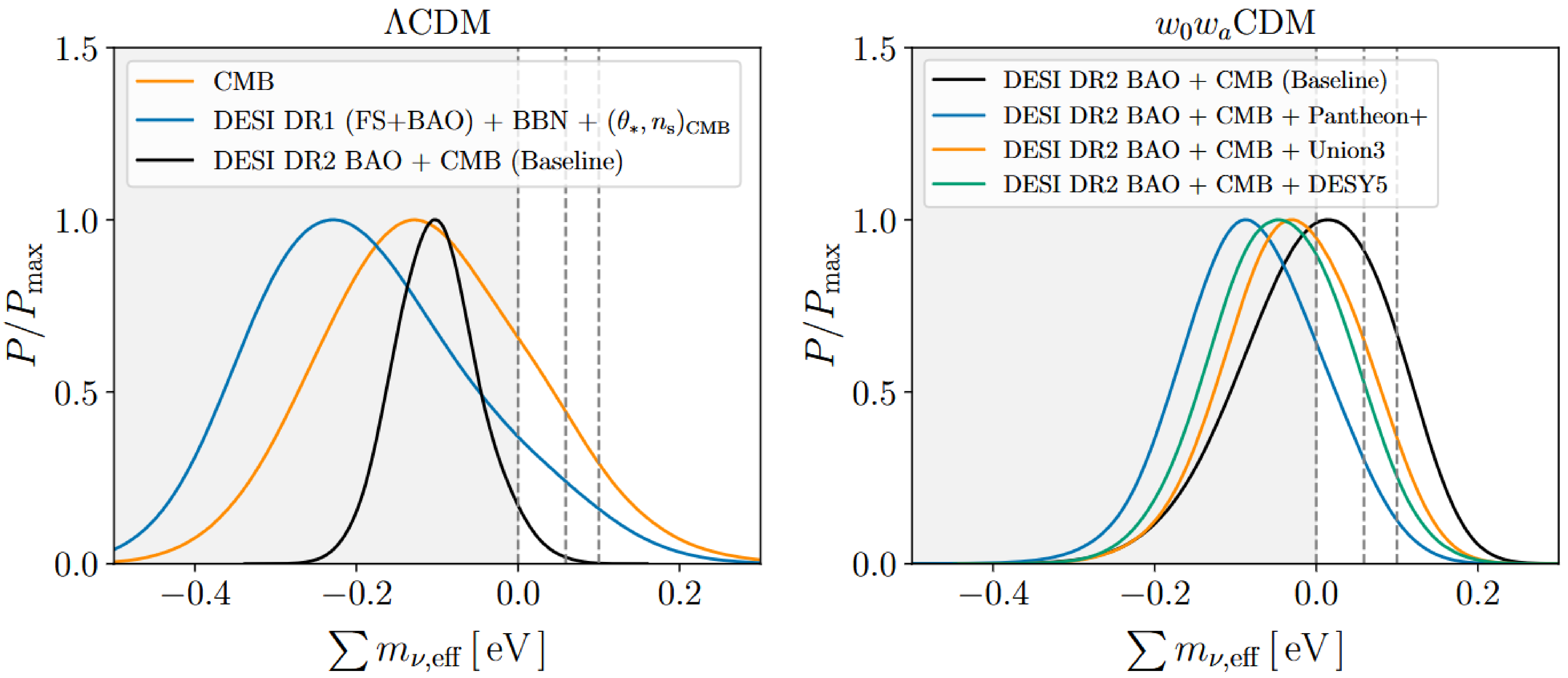
Extrapolating to negative neutrino mass



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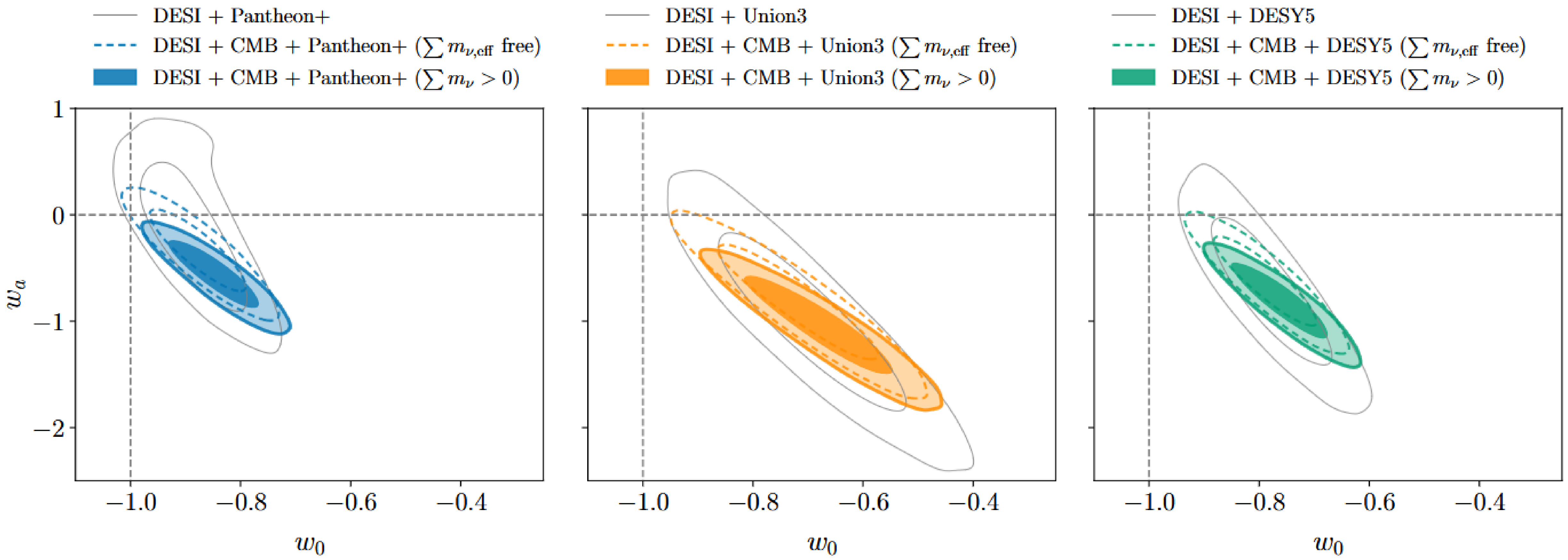
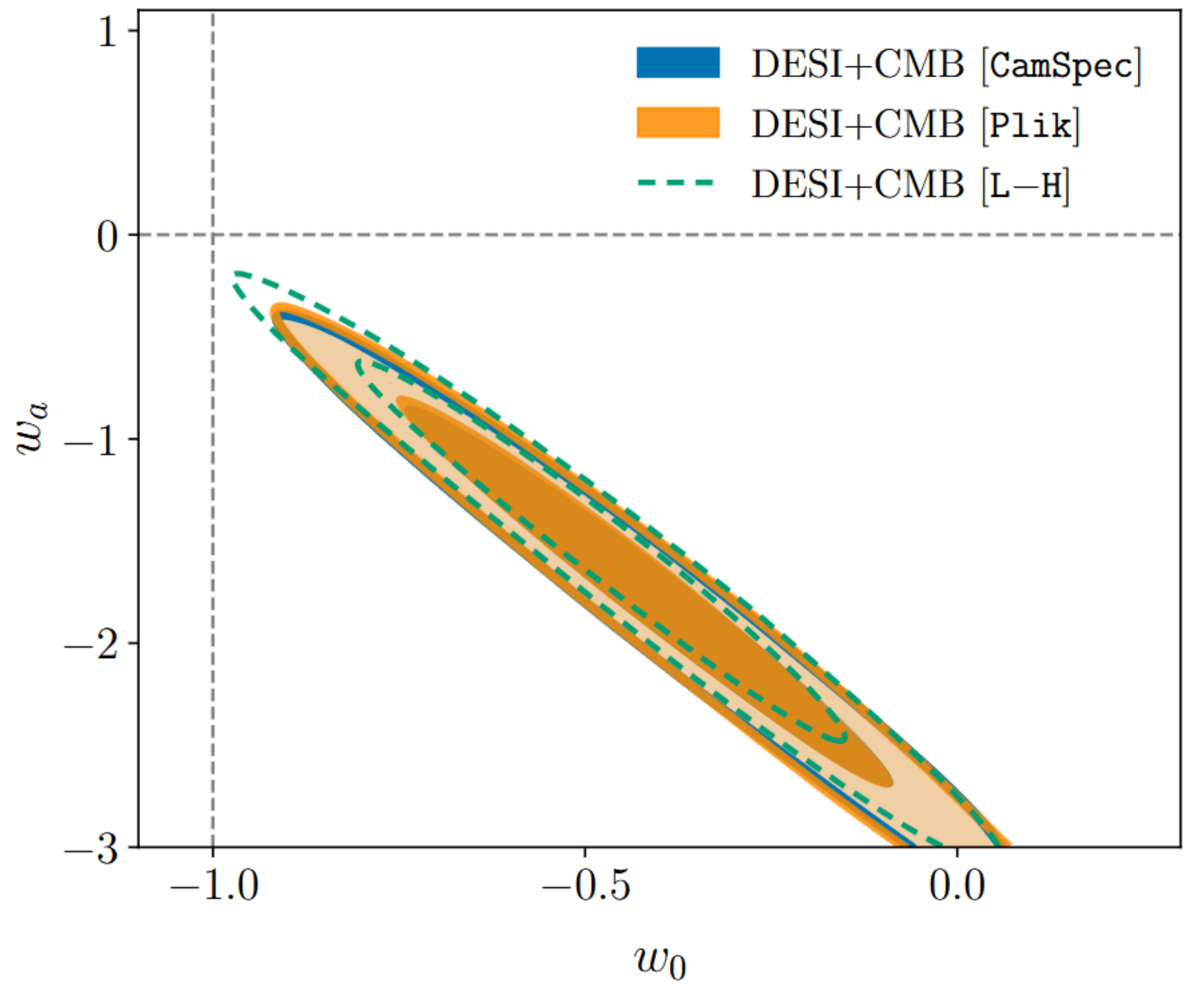
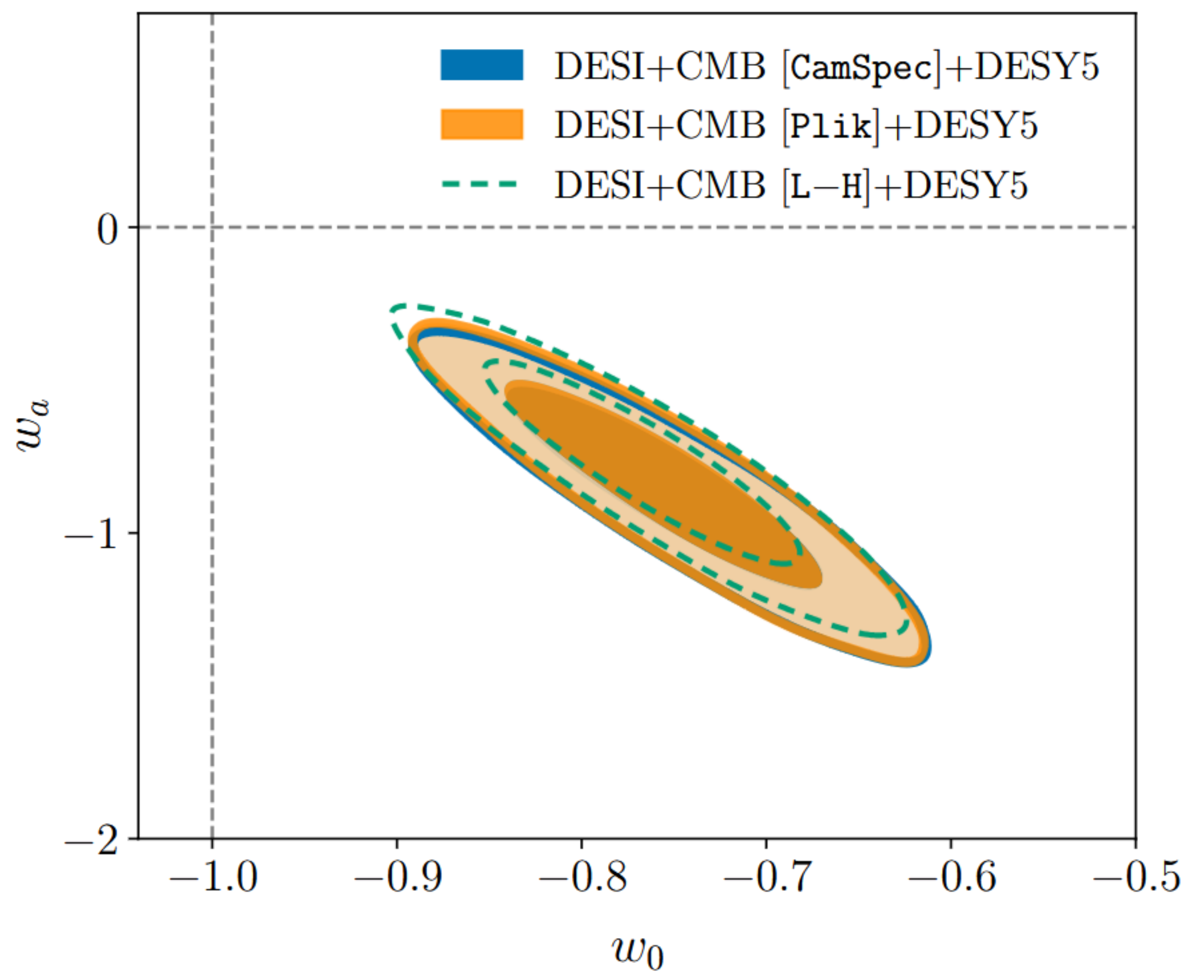
$w_0 w_a$CDM with free neutrino mass



Impact of CMB likelihood





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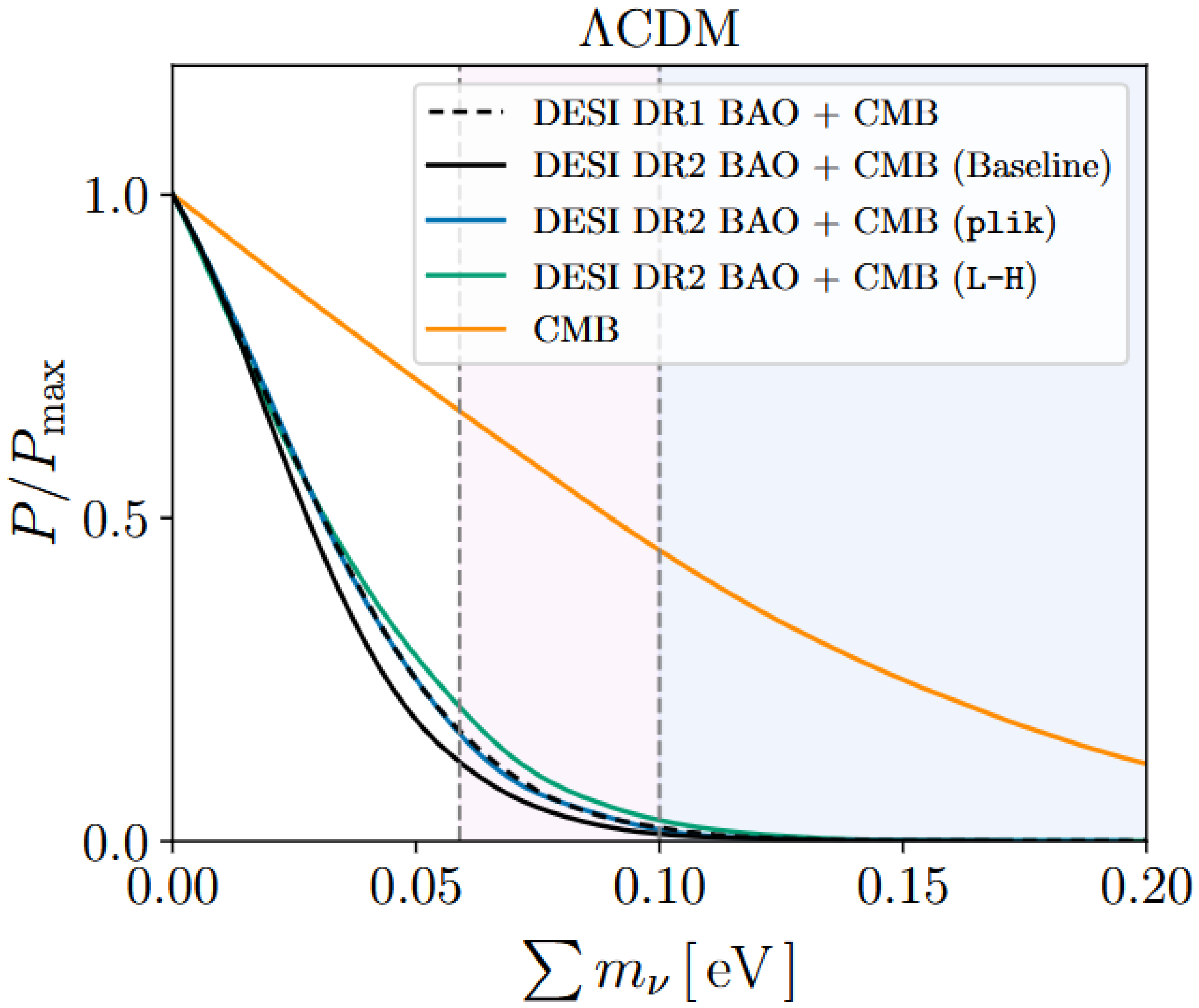
Impact of CMB likelihood



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The DESI DR2 BAO analysis

- BAO measured in 7 redshift bins
- One bin contains both LRGs and ELG due to overlap
- We measure 2D BAO in all bins except for BGS

Tracer	Redshift range	Effective redshift	N_{tracer}
BGS	0.1 – 0.4	0.295	1,188,526
LRG1	0.4 – 0.6	0.510	1,052,151
LRG2	0.6 – 0.8	0.706	1,613,562
LRG3 + ELG1	0.8 – 1.1	0.934	4,540,343
ELG2	1.1 – 1.6	1.321	3,797,271
QSO	0.8 – 2.1	1.484	1,461,588
Lyα	1.8 – 4.2	2.330	1,289,874