Studying Dark Energy with DESI Lyman Alpha Forests

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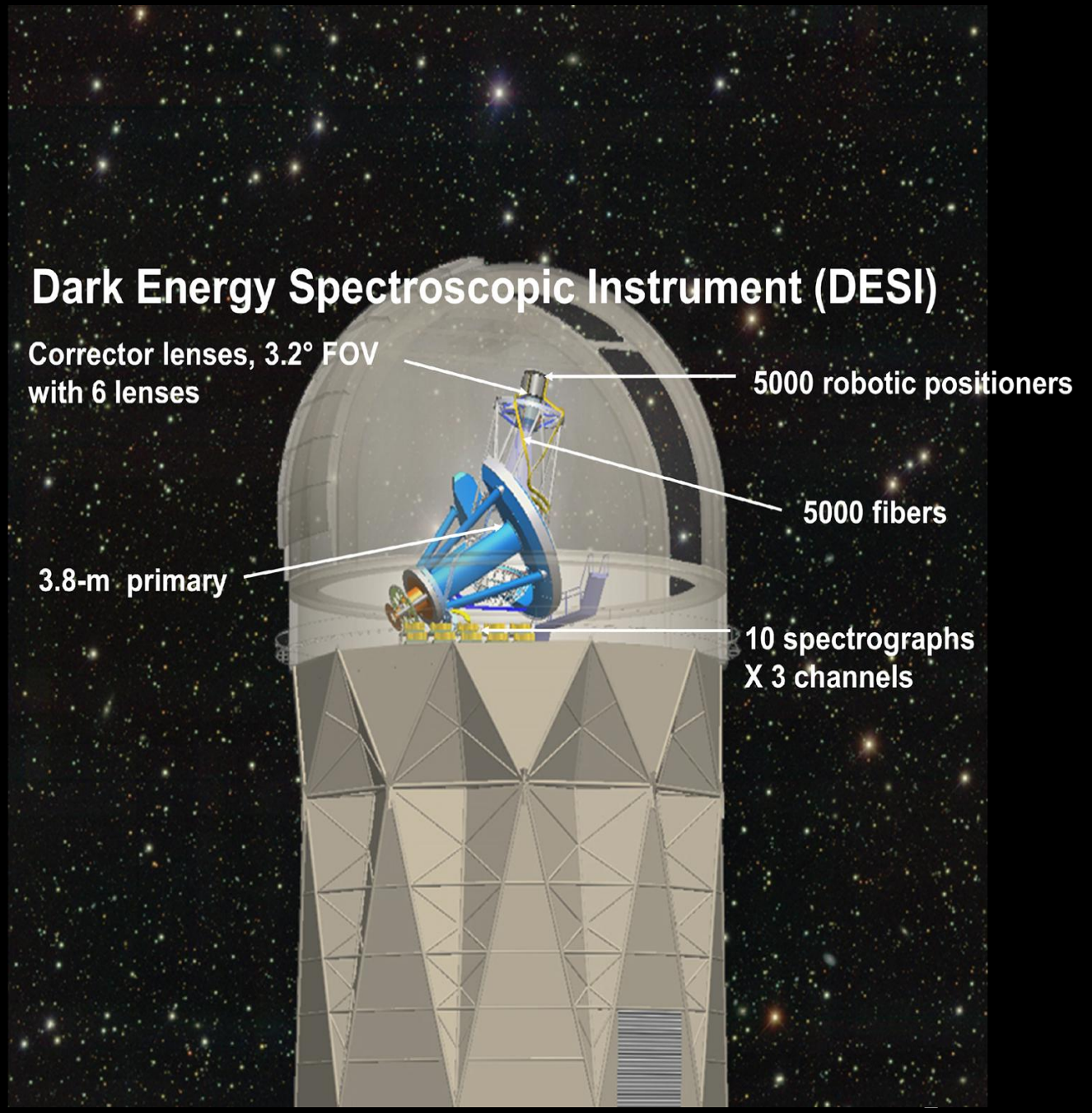
CCAPP Fellow 2021 - 2024

Dark Energy Spectroscopic Instrument (DESI)

- Designed for precision dark energy from z = 0 → 3
- Nominal 5-year Survey: 2021 → 2026
- 5000-robot army → 5000 fibers → 10 spectrographs
- 5000 spectra every ~ 15 min
- Large OSU contribution in every aspect of instrument development / operations / data analysis
- See talk by Ashley Ross for more details



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DESI targets

40 million
galaxies and quasars
covering 0 < z < 4

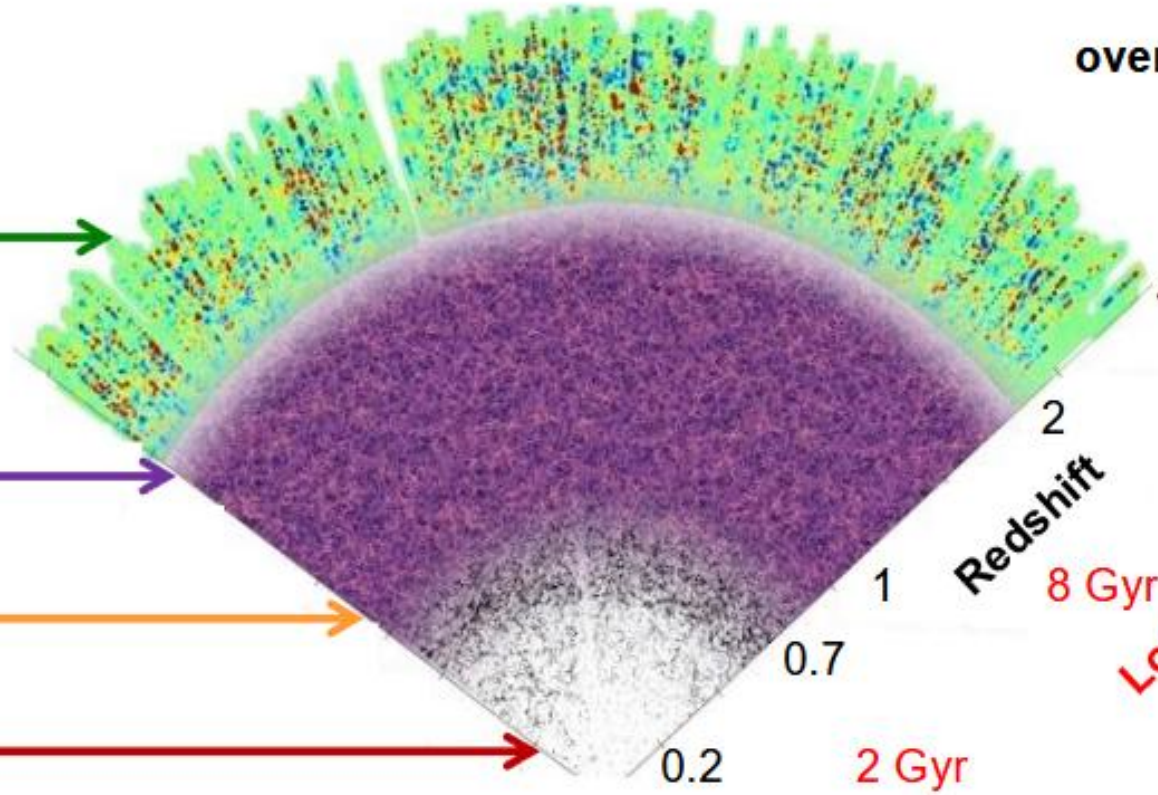
over 14,000 deg²

3 million QSOs
1.0 < z < 4.0

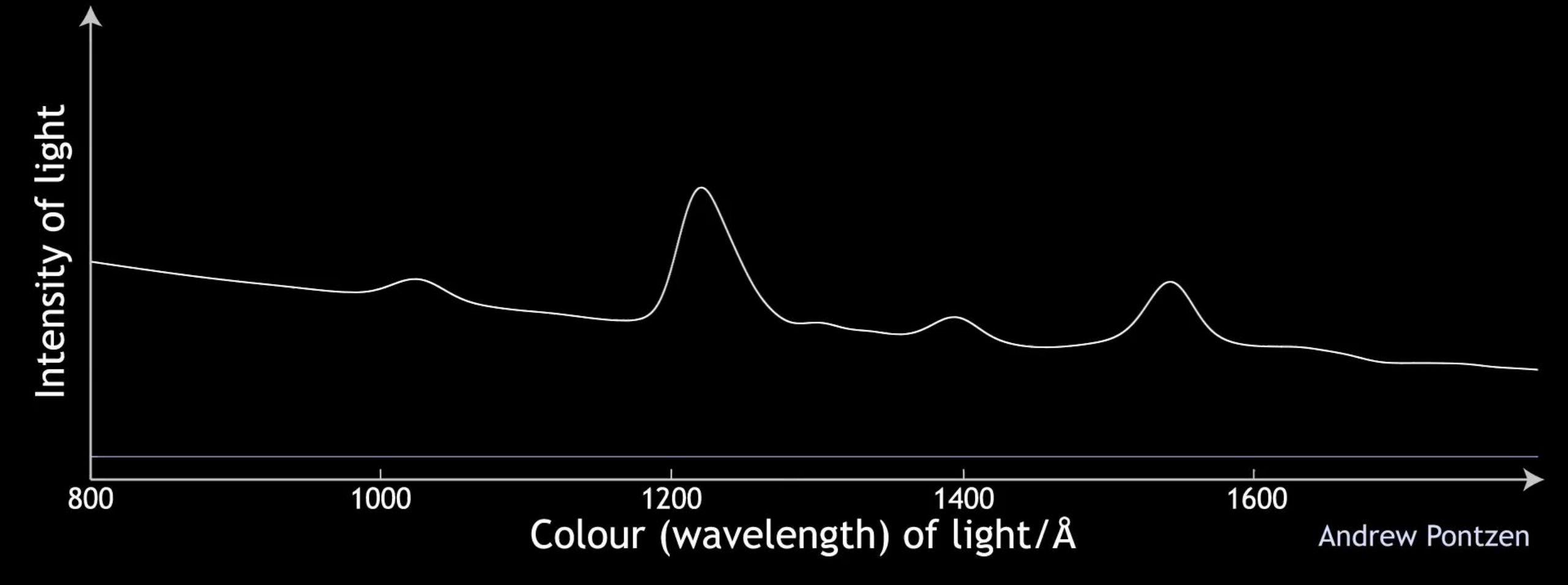
16 million ELGs
0.6 < z < 1.6

8 million LRGs
0.4 < z < 1.0

13 million Bright galaxies
0.0 < z < 0.4



+10 million Milky Way stars


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

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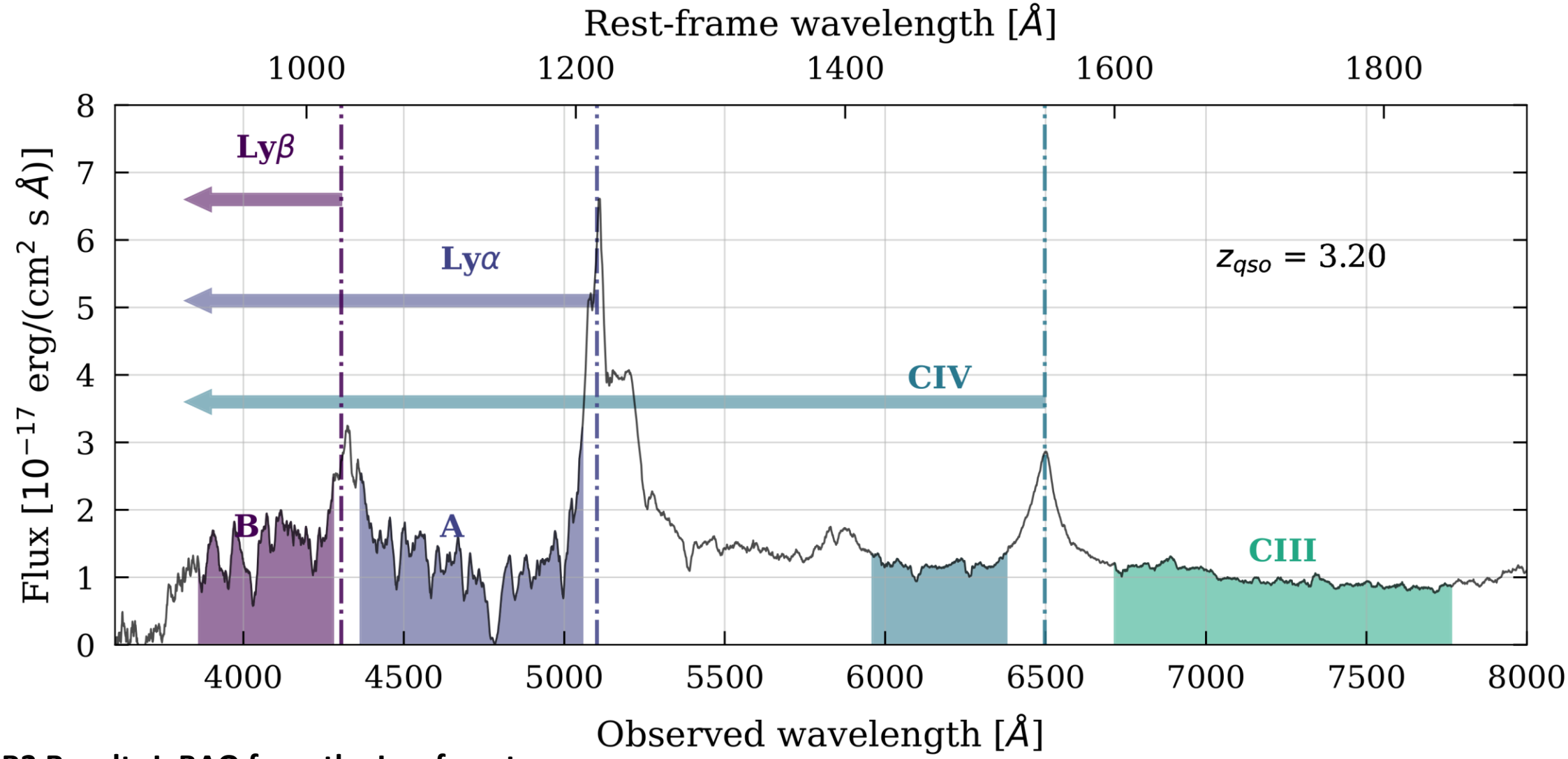
DESI spectrum of a quasar at $z = 3.20$



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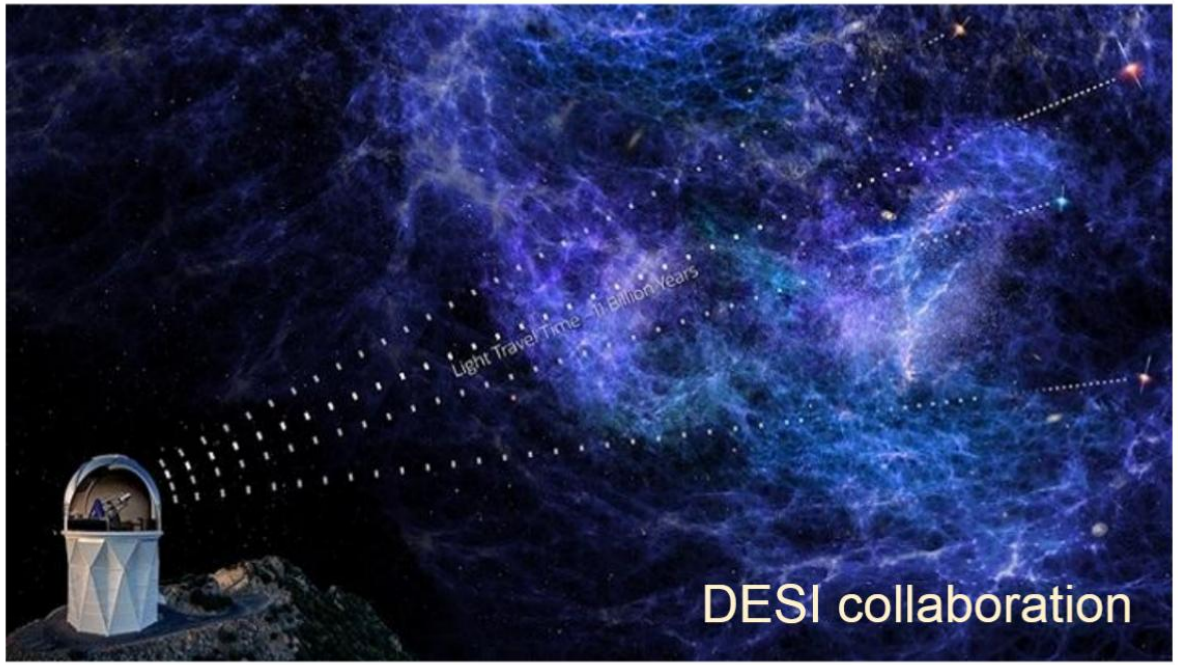
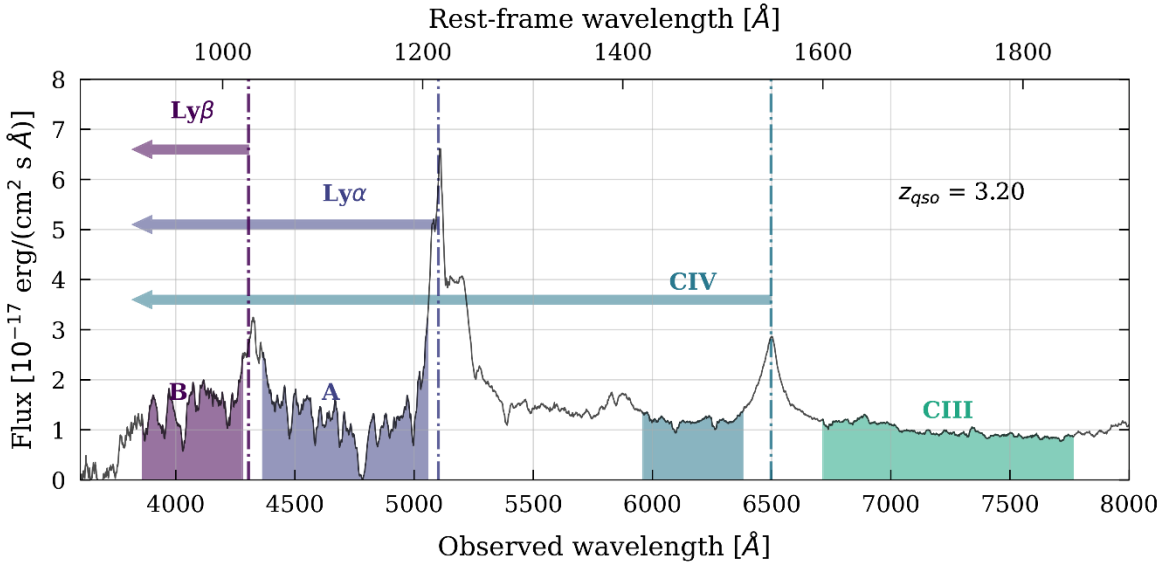
Lyα forest cosmology

Three main cosmological analyses:

1. **1D Power-Spectrum** (P1D; small scales)
2. **BAO** (3D; large scales)
3. **Full-shape** (3D; large to intermediate scales)





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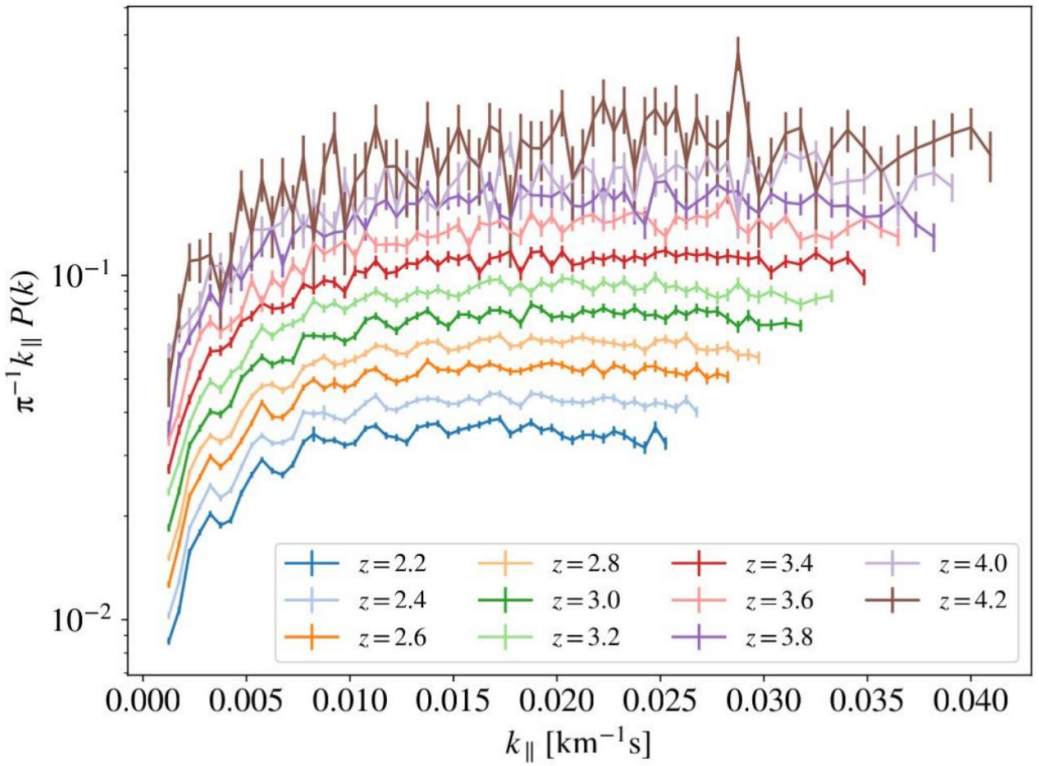
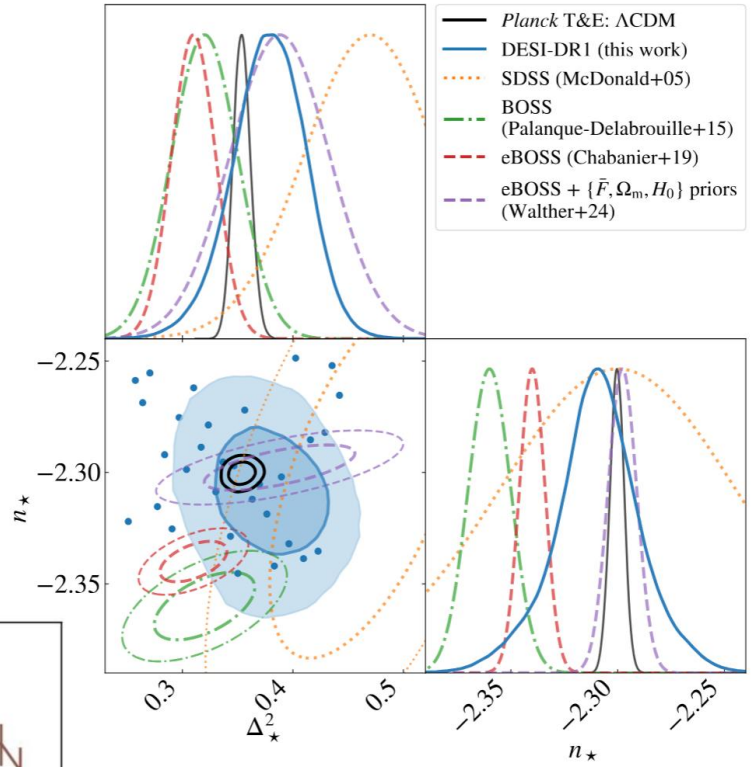
DESI DR1 Lyman-α P1D

CCAPP involvement:

- 1D power-spectrum measurement: Karacayli et al (2025; arxiv: 2505.07974)
- Validation: Karacayli et al (2025; arxiv: 2509.13593)
- Herbold et al (2025: arxiv: 2509.04405)

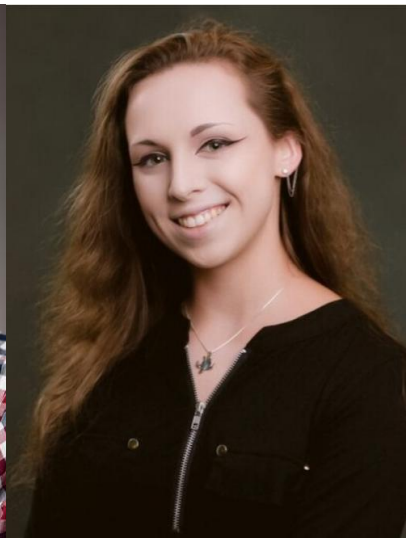




DR1 cosmology results: Chaves-Montero et al (2026; arxiv: 2601.21432)

Naim Karacayli

Meagan Herbold



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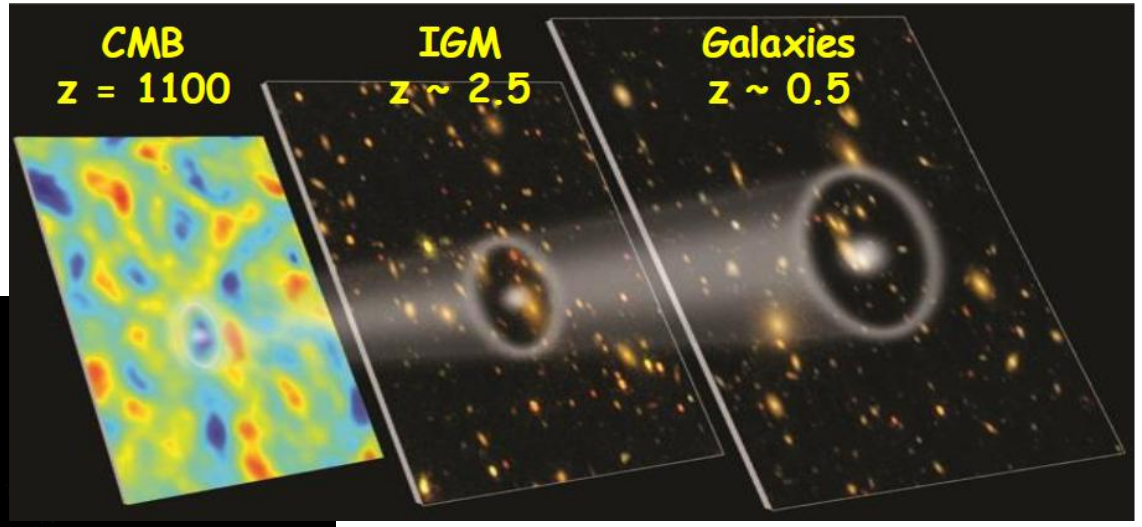
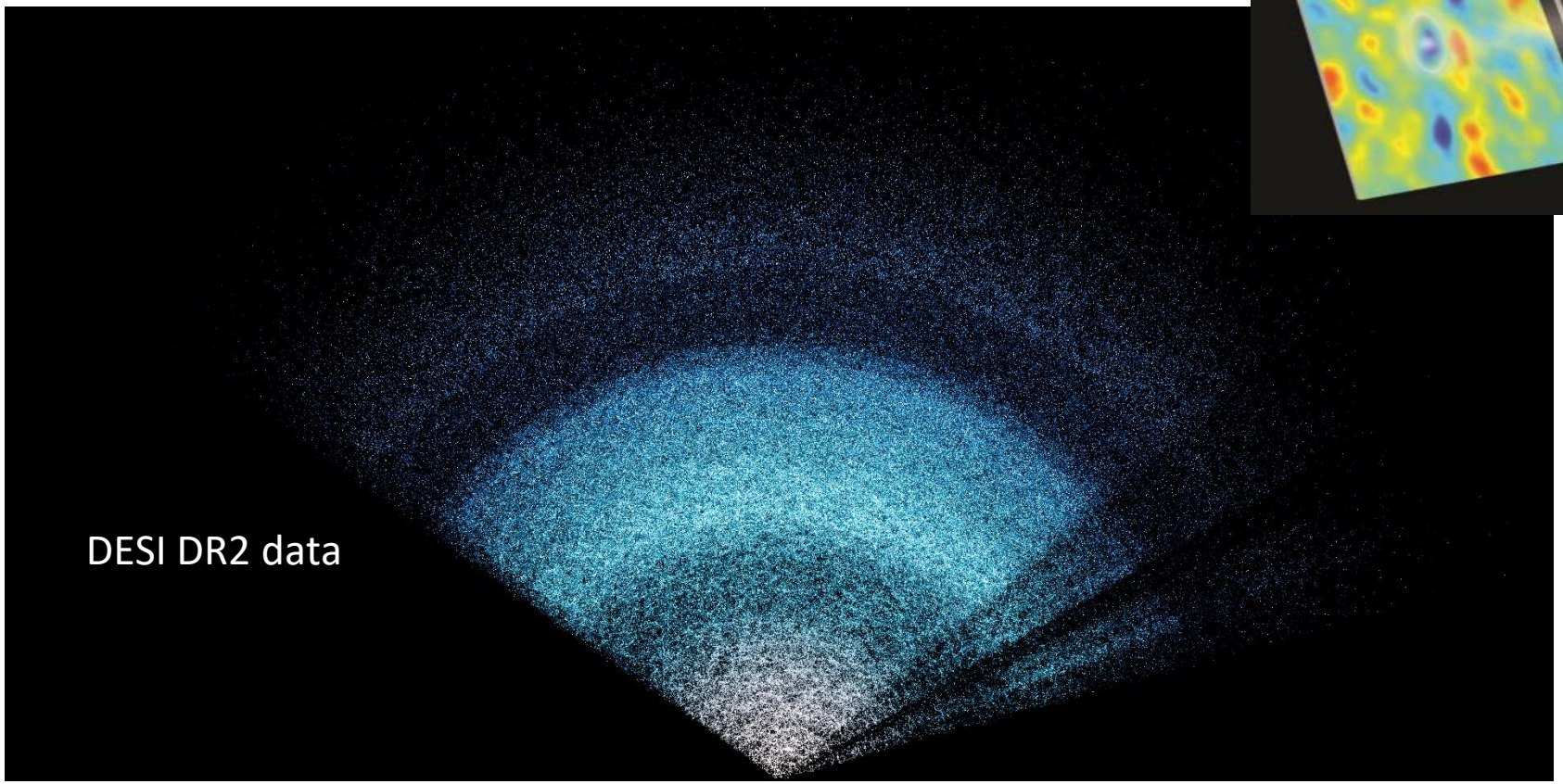
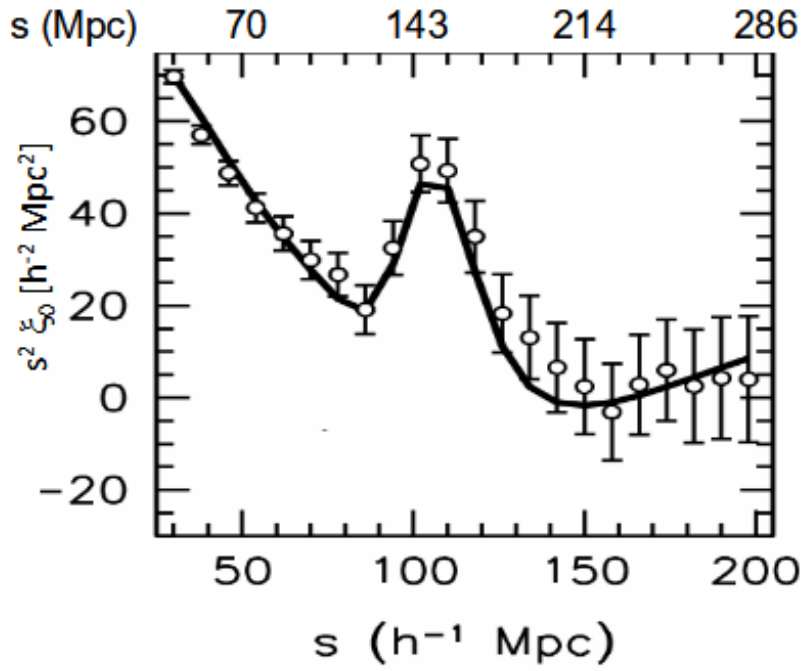
Baryon Acoustic Oscillations (BAO)

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







Credit: DESI collaboration

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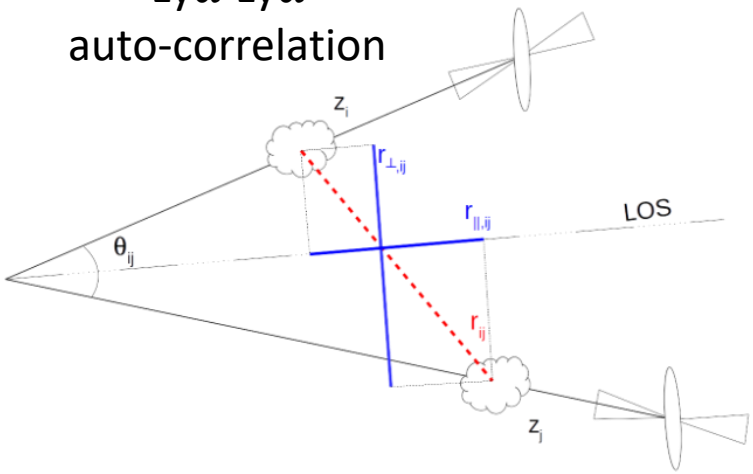
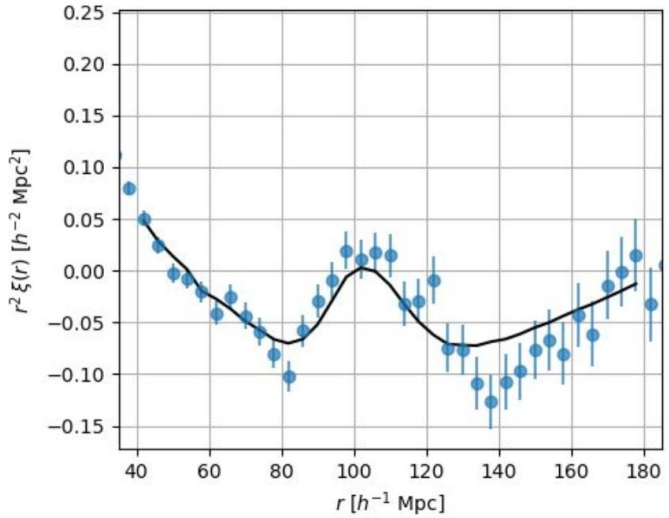
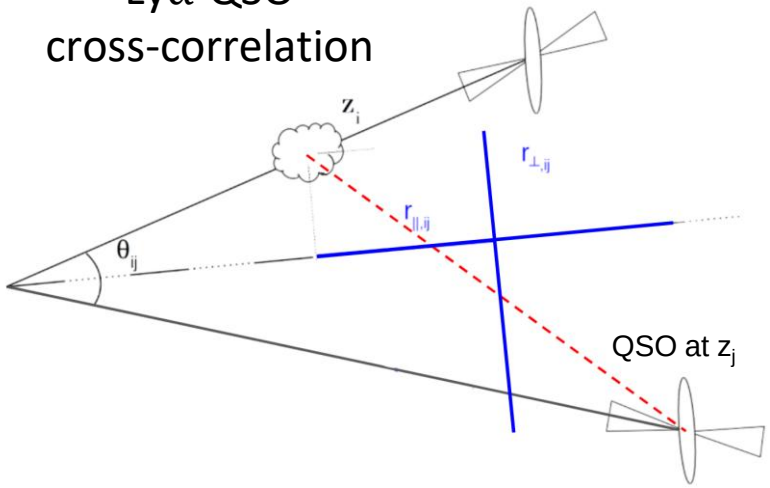
Lyα forest correlation functions

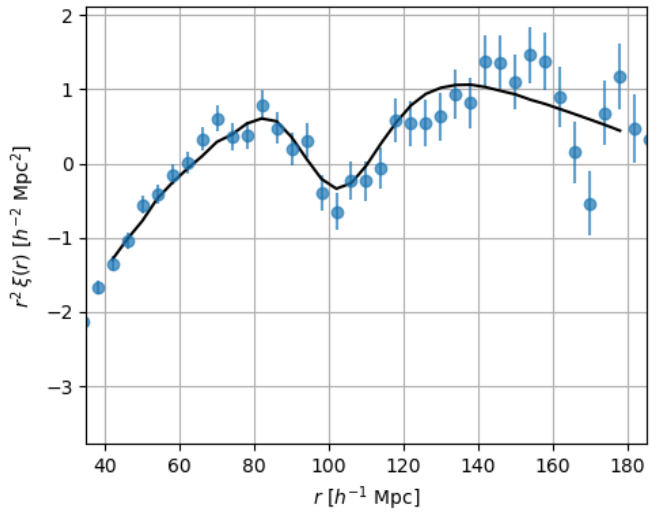
Lyα-Lyα auto-correlation





Lyα-QSO cross-correlation





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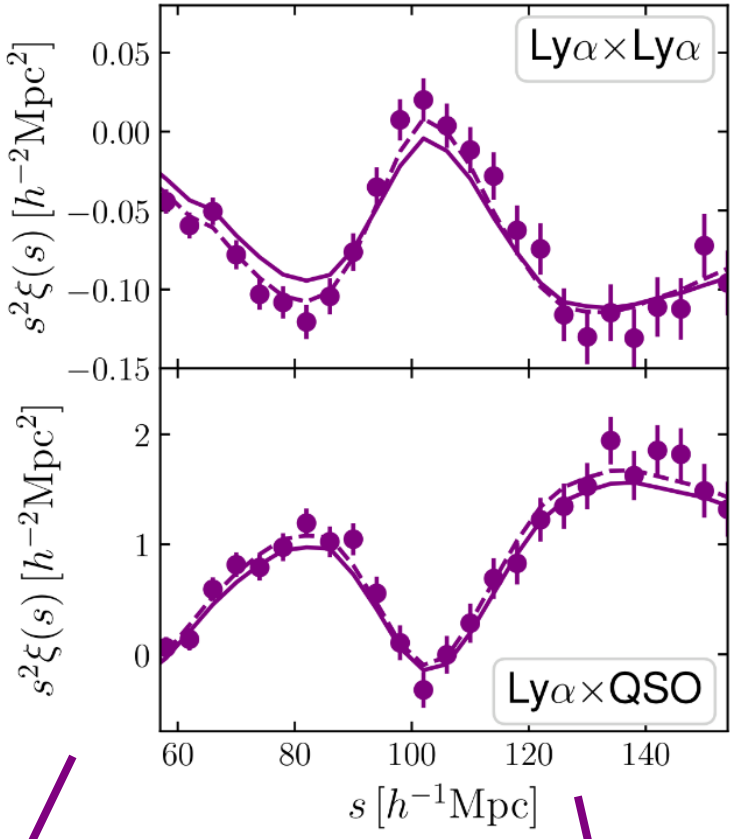
DESI DR2 Lyman-α BAO

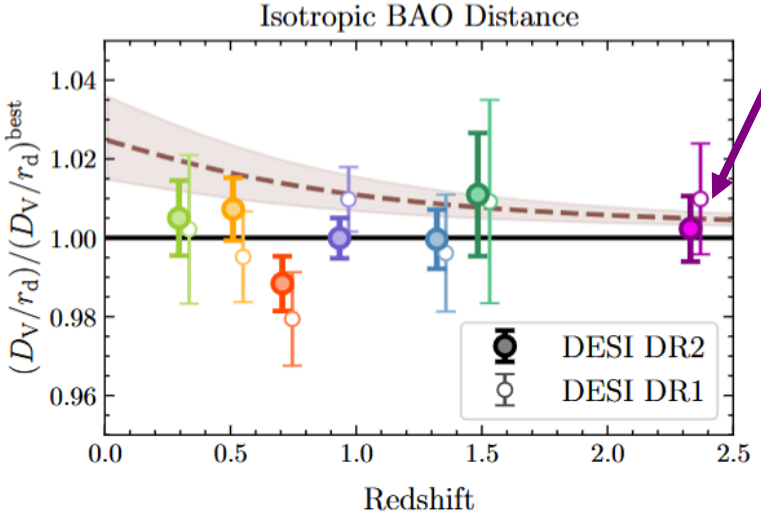
DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest (DESI++ 2025; arxiv: 2503.14739)

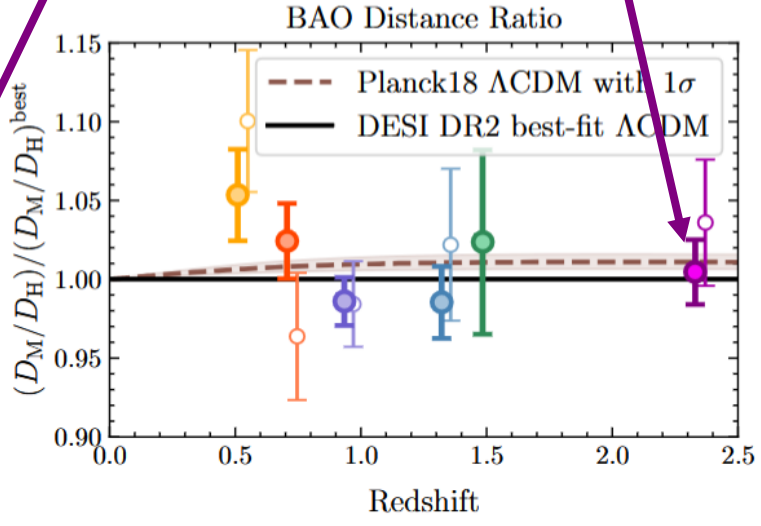
Molly Wolfson

Validation supporting paper: Casas++ 2025; arxiv: 2503.14741

Damped Lyα Absorbers supporting paper: Brodzeller, **Wolfson**, ++ 2025; arxiv: 2503.14740







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Lyman-α forest

Galaxies

DESI DR2 BAO Unblinding – December 2024

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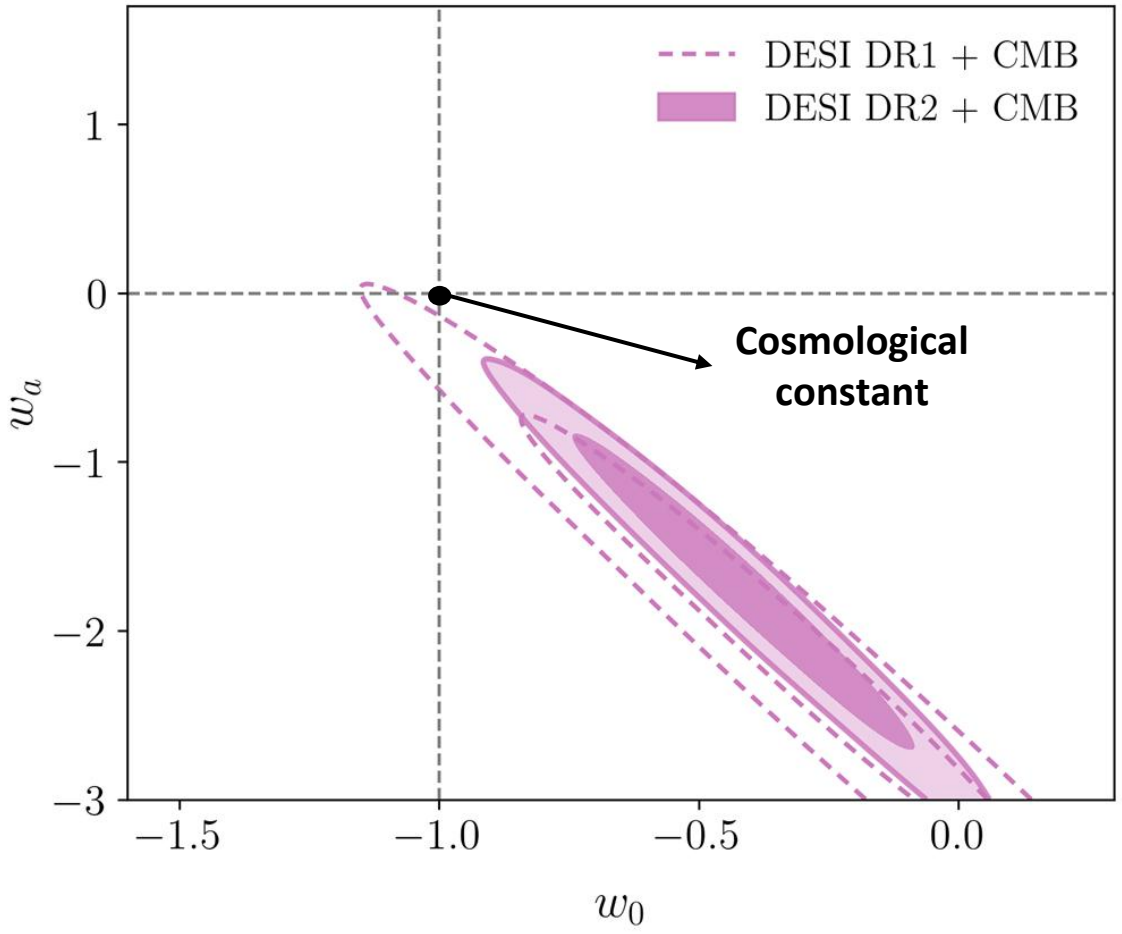
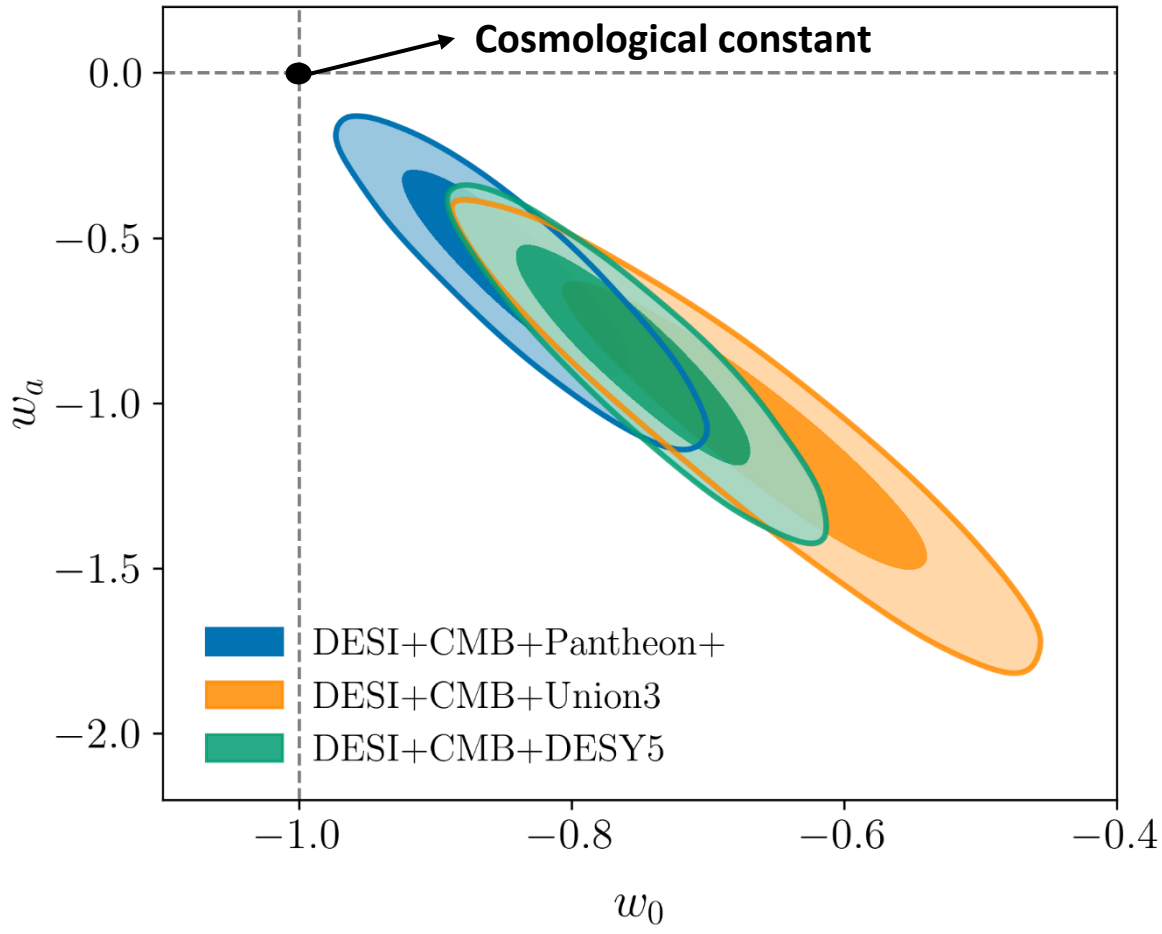
Evolving Dark Energy?

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



2.8σ – 4.2σ preference for evolving dark energy with DESI DR2 + CMB + SNe



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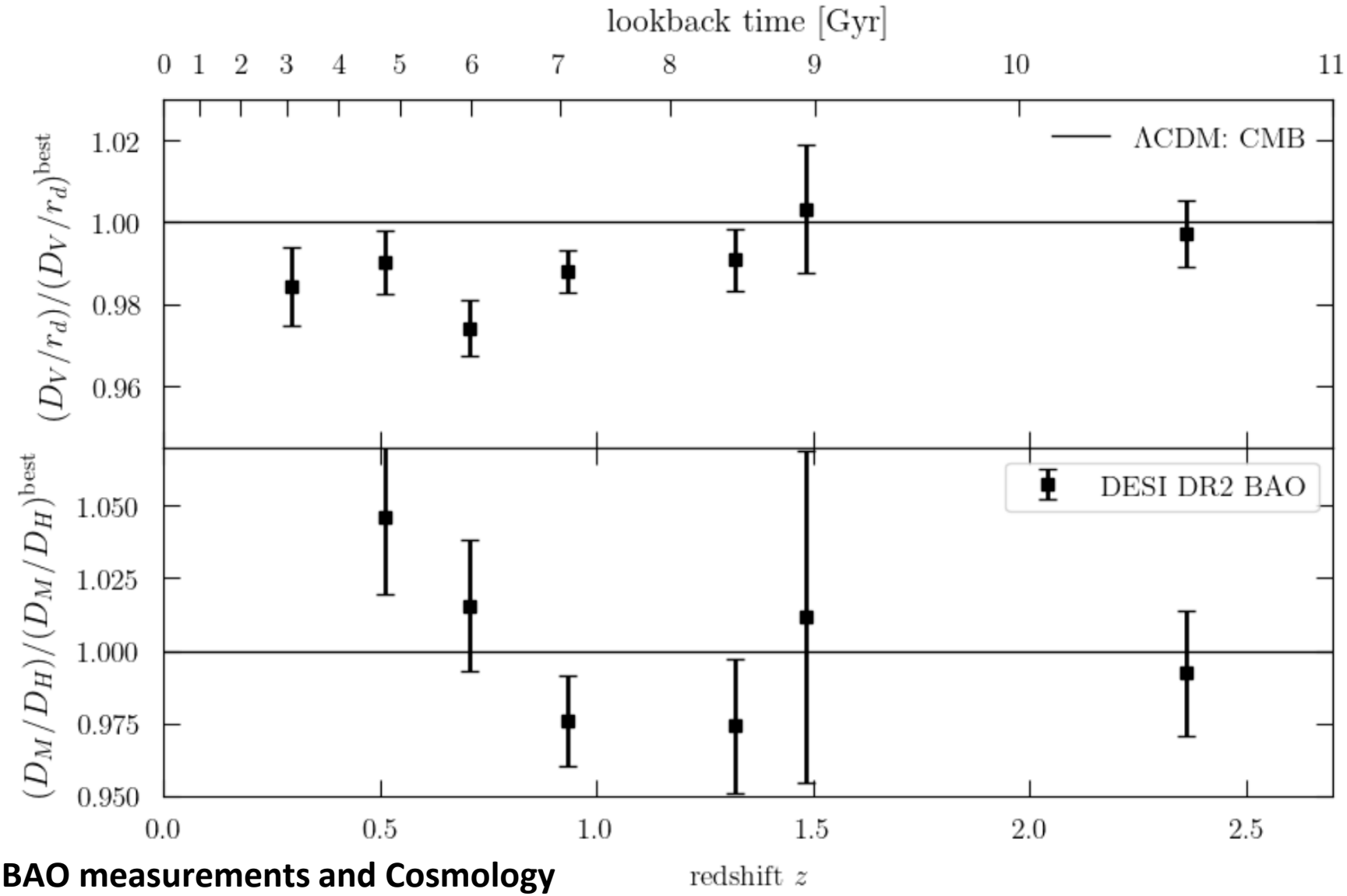
Improving dark energy constraints



DESI DR2 Results II: BAO measurements and Cosmology

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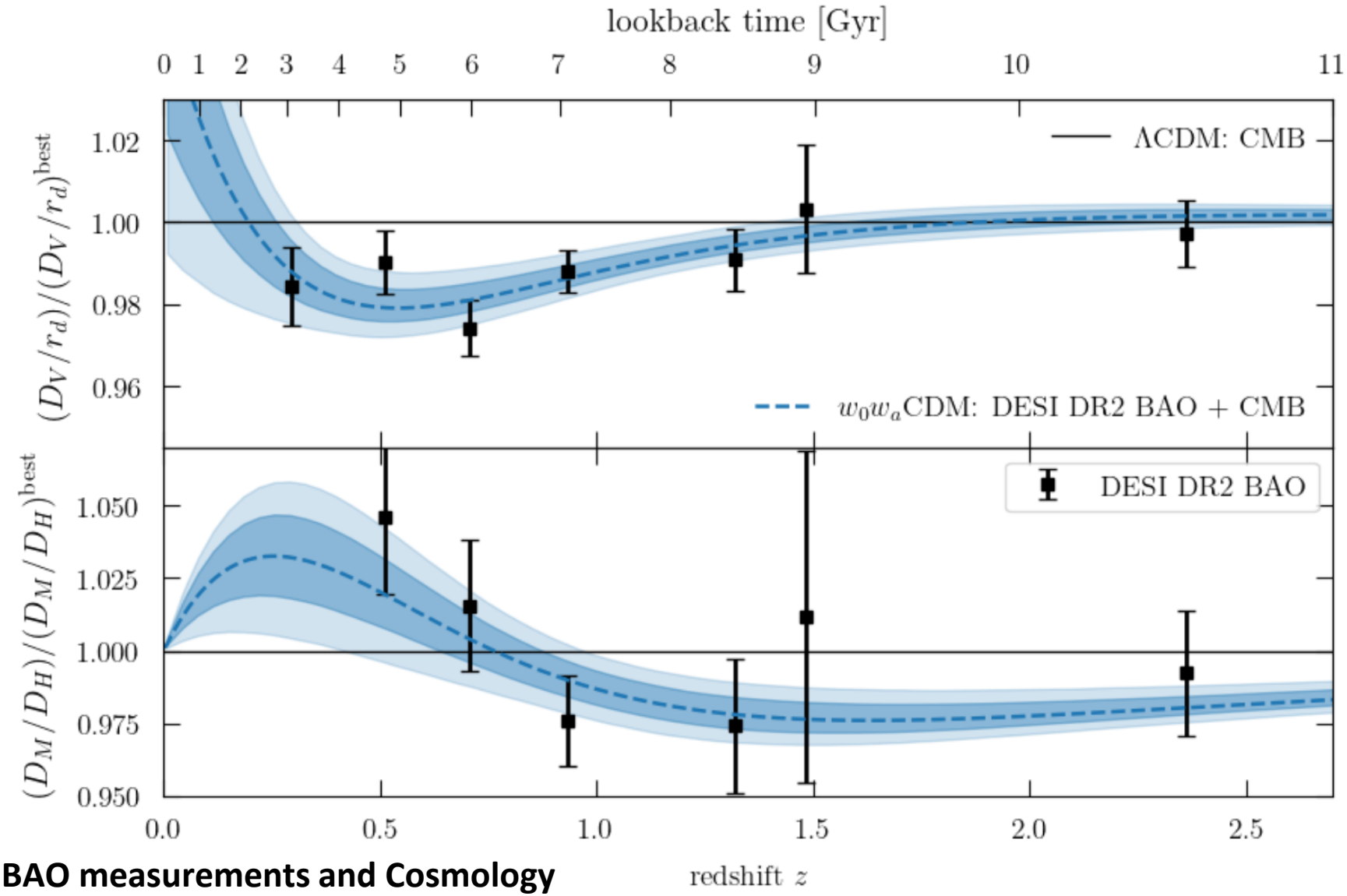
Improving dark energy constraints



DESI DR2 Results II: BAO measurements and Cosmology

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Alcock-Paczynski from full-shape

- Angles and redshifts $(\Delta\theta, \Delta z)$

  ↓ Fiducial cosmology

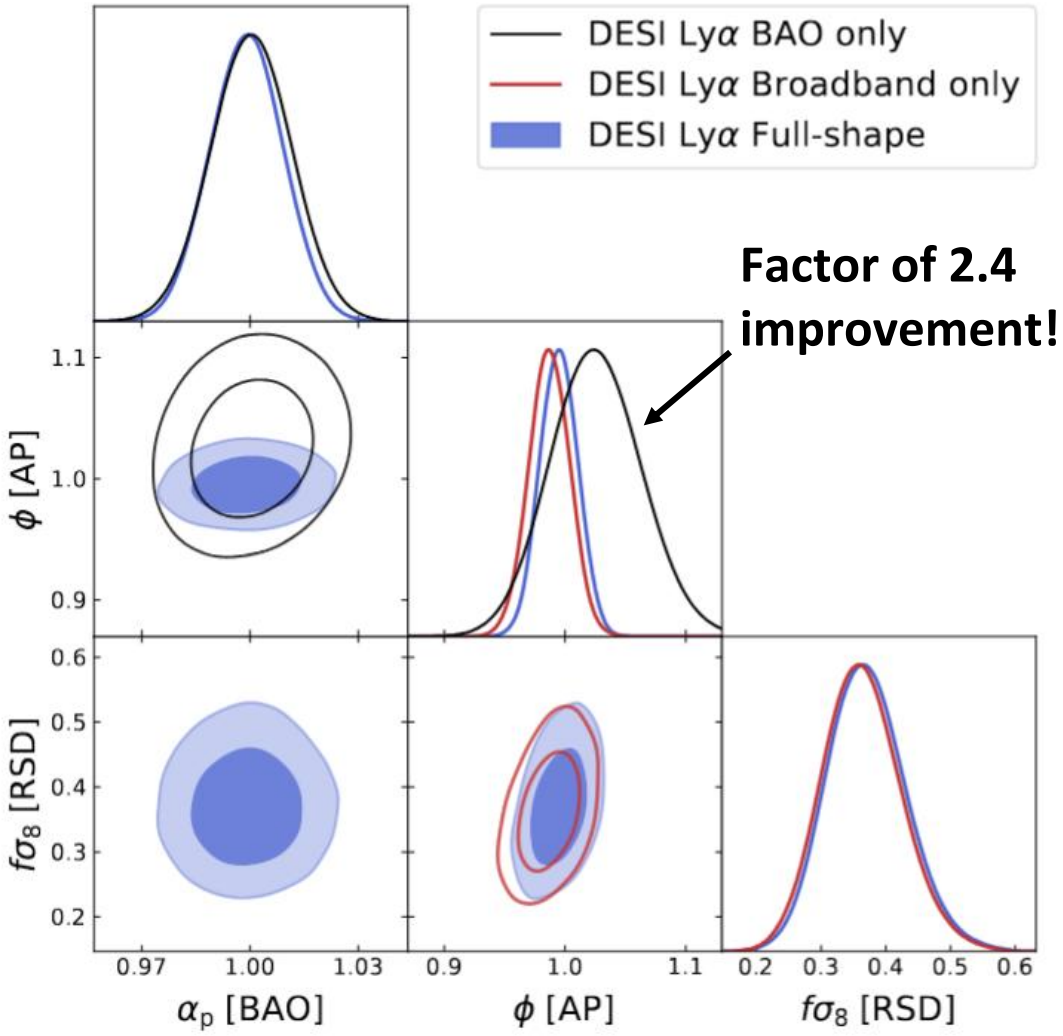
- Comoving distances $(r_\parallel, r_\perp)$.

- Wrong fiducial cosmology → characteristic anisotropy known as Alcock-Paczynski effect

- Very strong measurement with the Lyα forest

Improvement in distance constraints:

- Galaxies: ~15% to 30% better than BAO
- Lyα: factor of ~2 better than BAO



Cuceu++ 2025 (arxiv:2509.15308)

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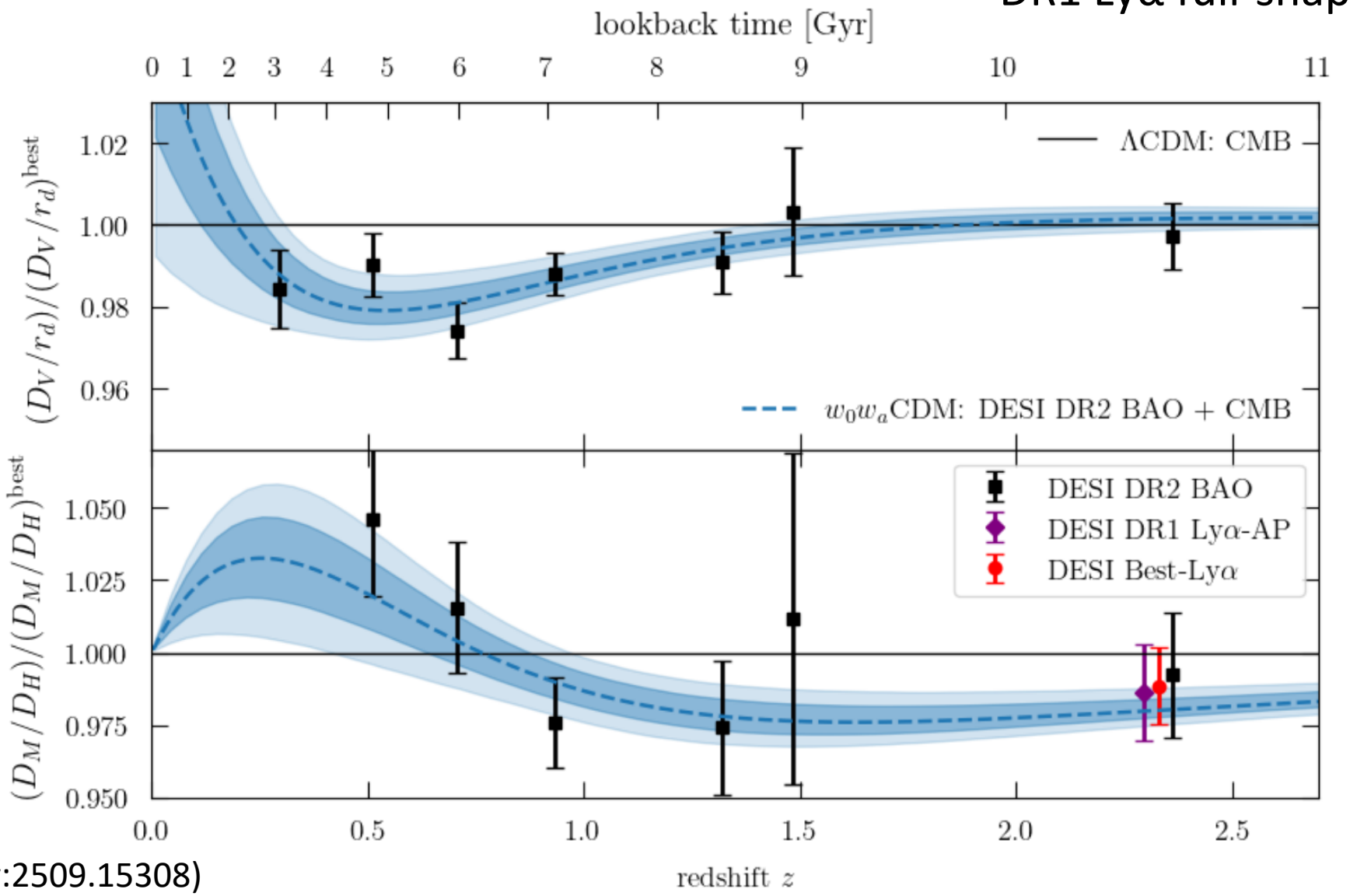
Improving dark energy constraints

DR1 Lyα full-shape analysis



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Improving dark energy constraints

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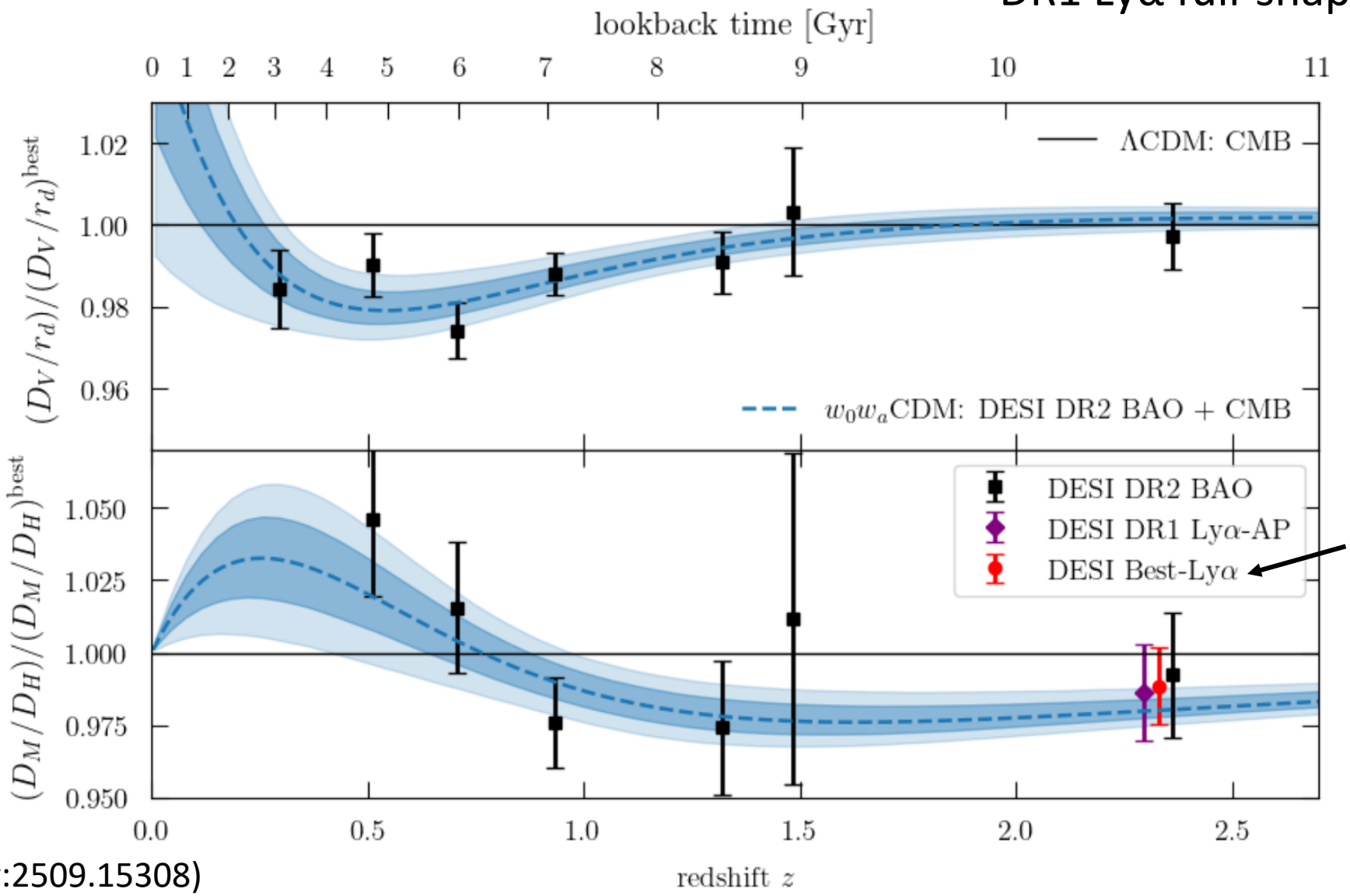

1.3% constraint!

Cuceu++ 2025 (arxiv:2509.15308)

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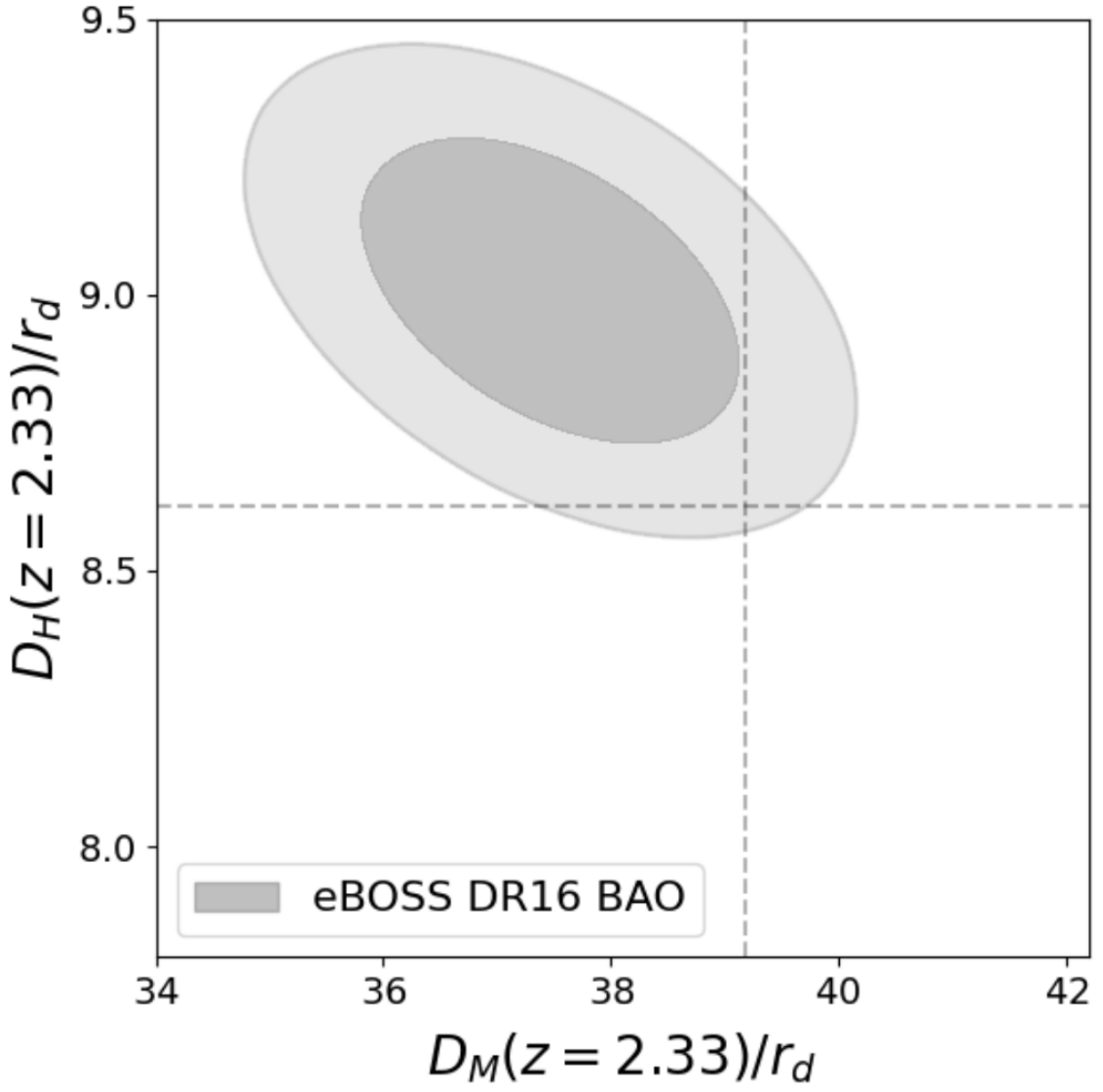
Lyα constraints in 2021



Isotropic BAO: 1.2%

Alcock-Paczynski: 4.0%

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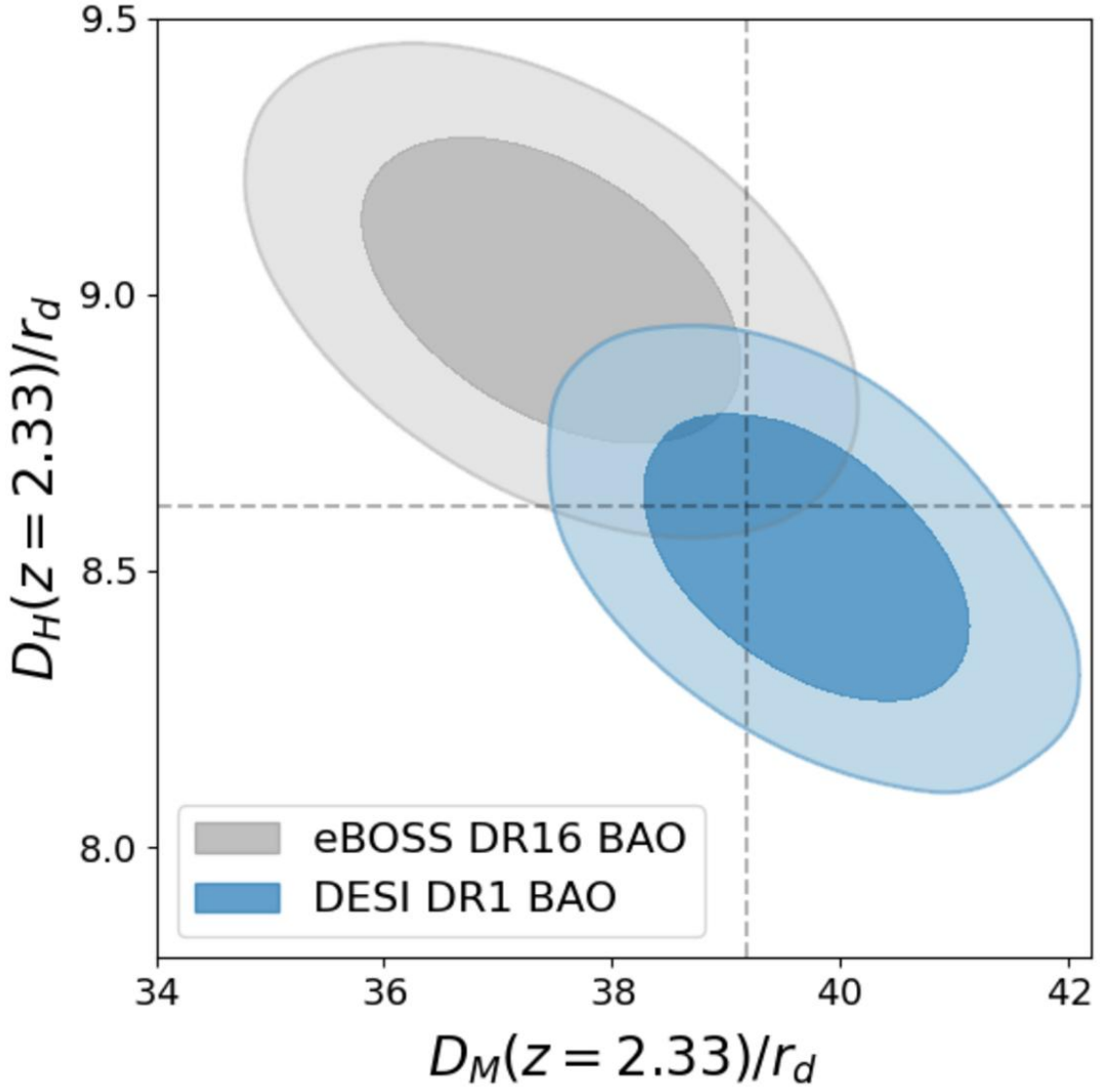
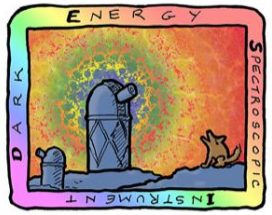
Lyα constraints in 2024



Isotropic BAO: 1.0%

Alcock-Paczynski: 3.4%



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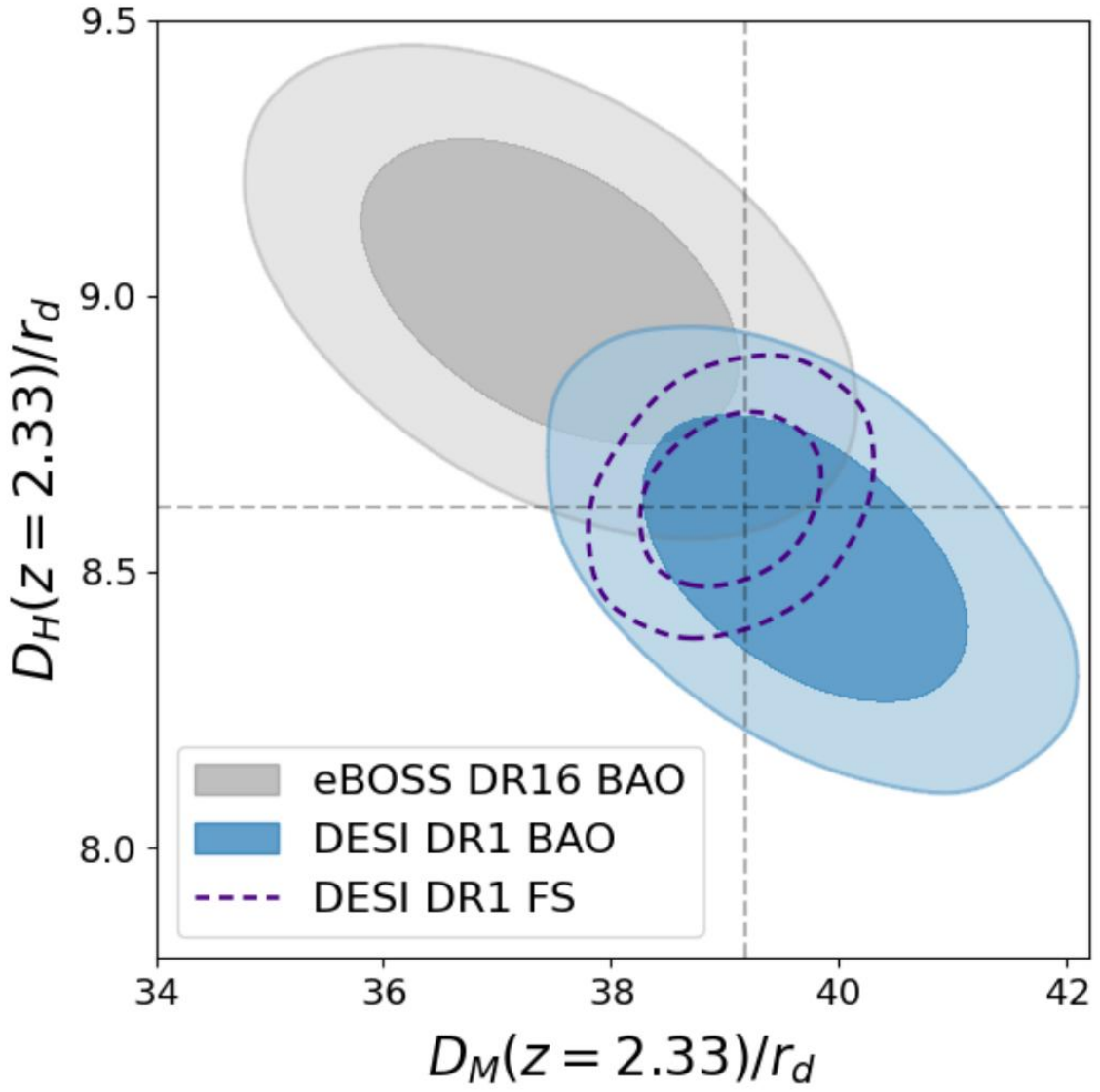
Lyα constraints in 2025



Isotropic BAO: 1.0%

Alcock-Paczynski: 1.6%

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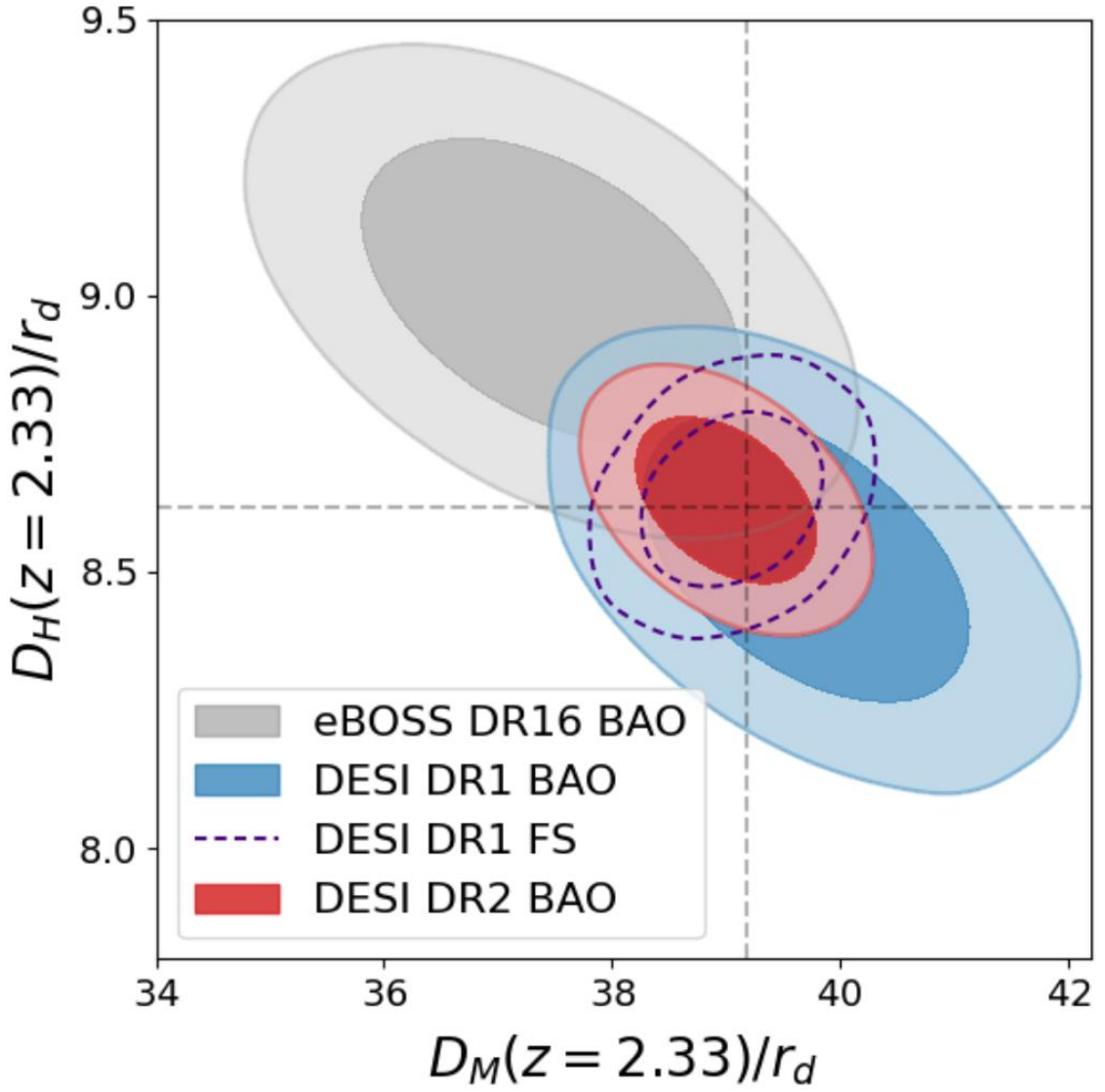
Lyα constraints now



Isotropic BAO: 0.7%

Alcock-Paczynski: 1.3%

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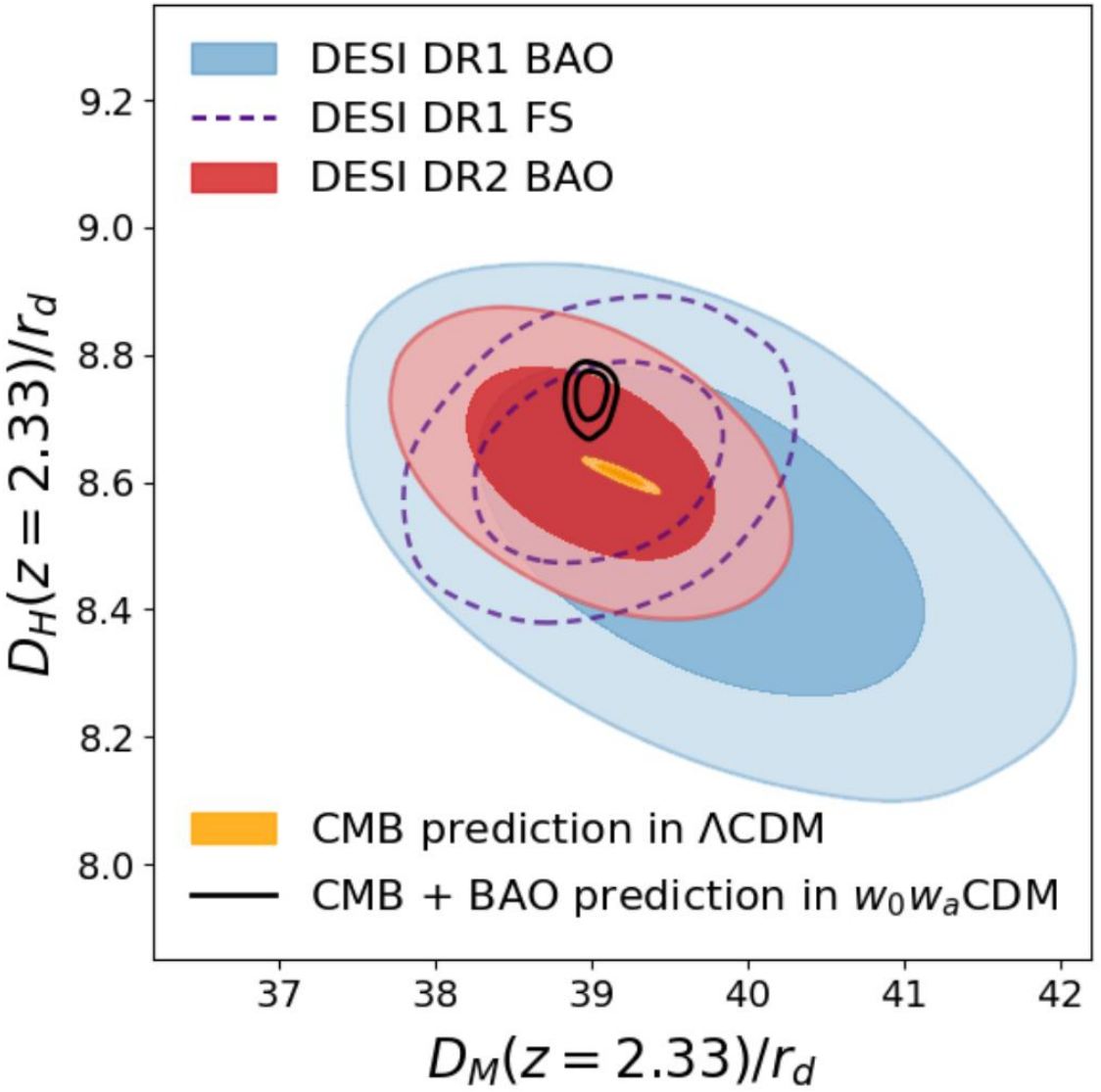
Lyα constraints in the near future



- Current ΛCDM and w0waCDM constraints about 2% apart in AP direction
- Current constraints are wide and agree with both predictions
- DESI DR2 full-shape unblinded!
- Significant improvement with respect to DR2 BAO (still around a factor of 2)
- Results coming soon!

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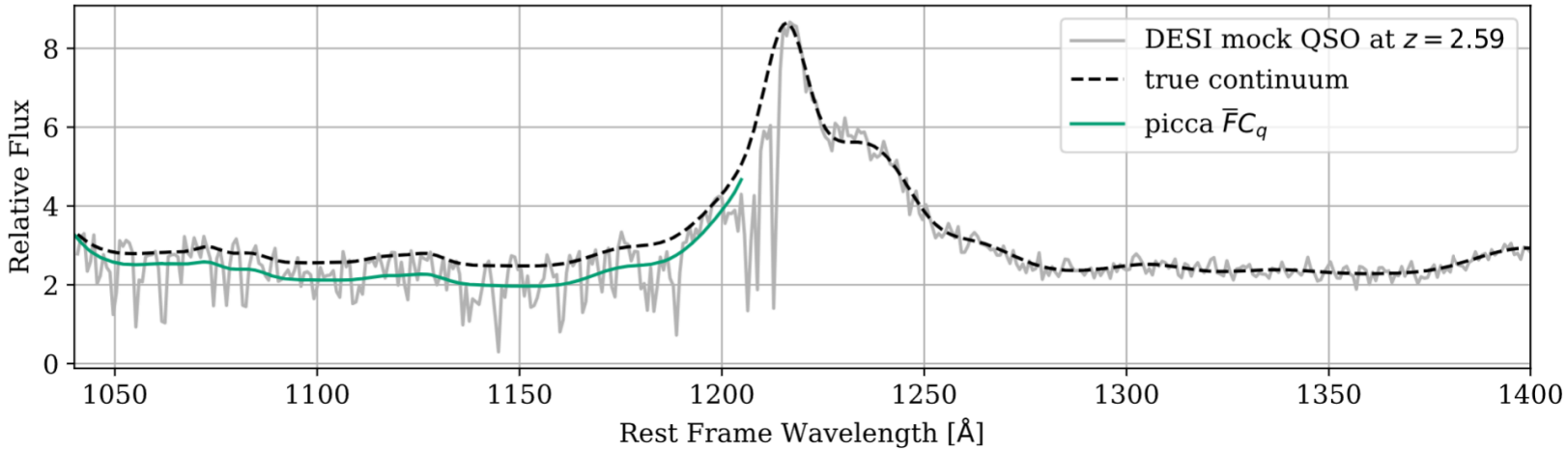
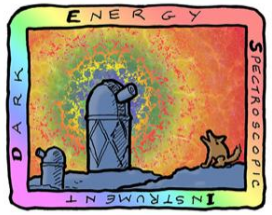
Conclusions

- Lyα forest → powerful cosmology tracer in unique regime ($2 < z < 4$)
- CCAPP plays a pivotal role in DESI Lyα analyses
- Work by Wynne Turner promises even better constraints!

Wynne Turner

Turner, Martini, ++ 2024 (arxiv: 2405.06743)
Turner, Cuceu, Martini, ++ 2025 (arxiv: 2509.14322)





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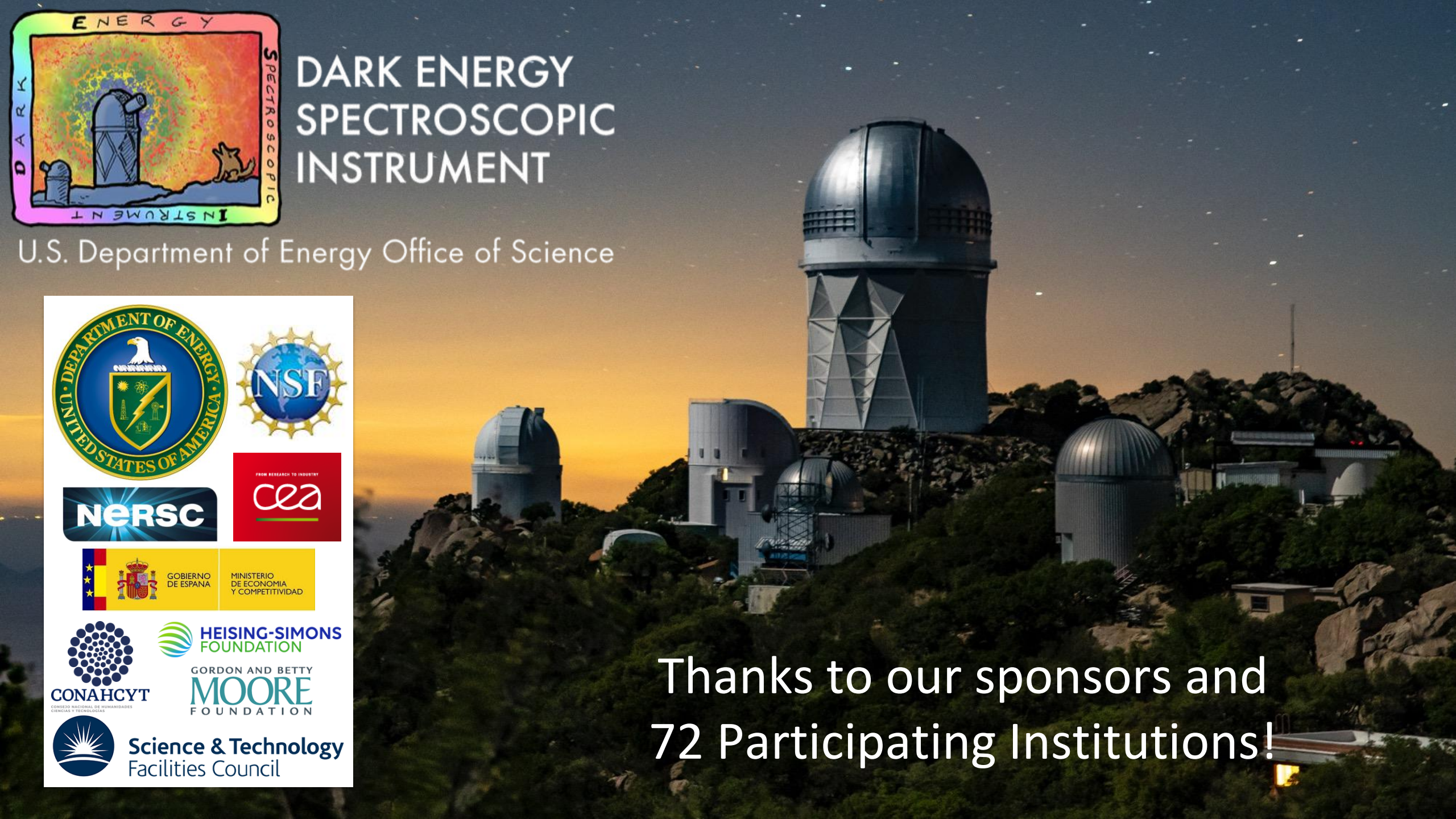
Conclusions

- Lyα forest → powerful cosmology tracer in unique regime ($2 < z < 4$)
- Factor of 2-3 improvements in distance measurements over the last few years
- Near-future results expected to distinguish ΛCDM and w0waCDM at $\sim 2\sigma$ with Lyα alone!
- Keep an eye out for DESI DR2 full-shape!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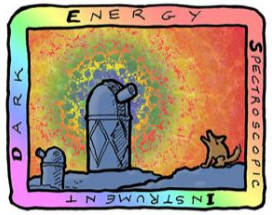

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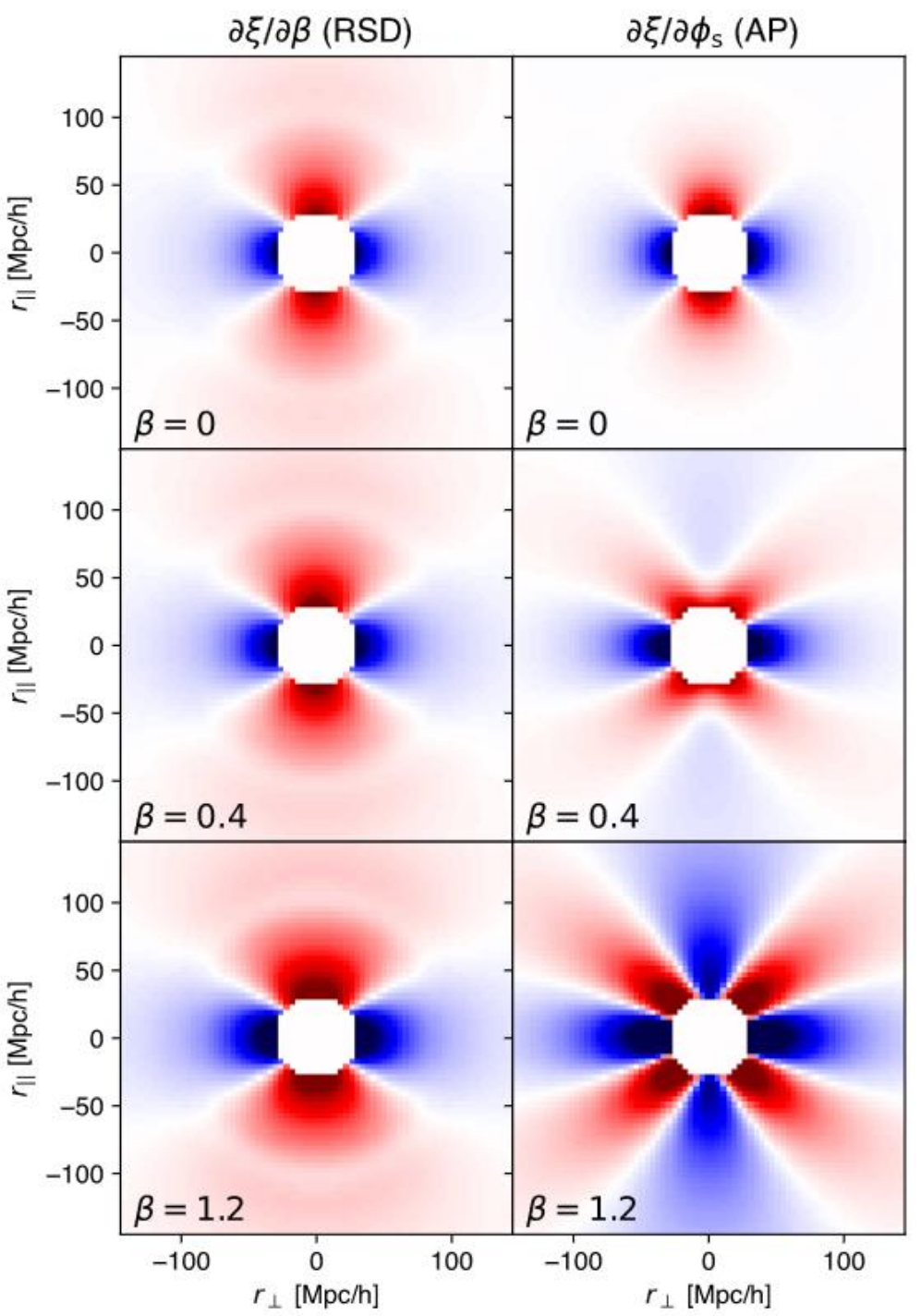
RSD vs AP

- Derivatives of the correlation function of a biased tracer in linear theory (no BAO)
- No RSD: AP degenerate with RSD
- Small RSD (galaxies): AP and RSD highly correlated
- Large RSD (Lyα): AP and RSD quite distinct
- Larger RSD → stronger AP signal



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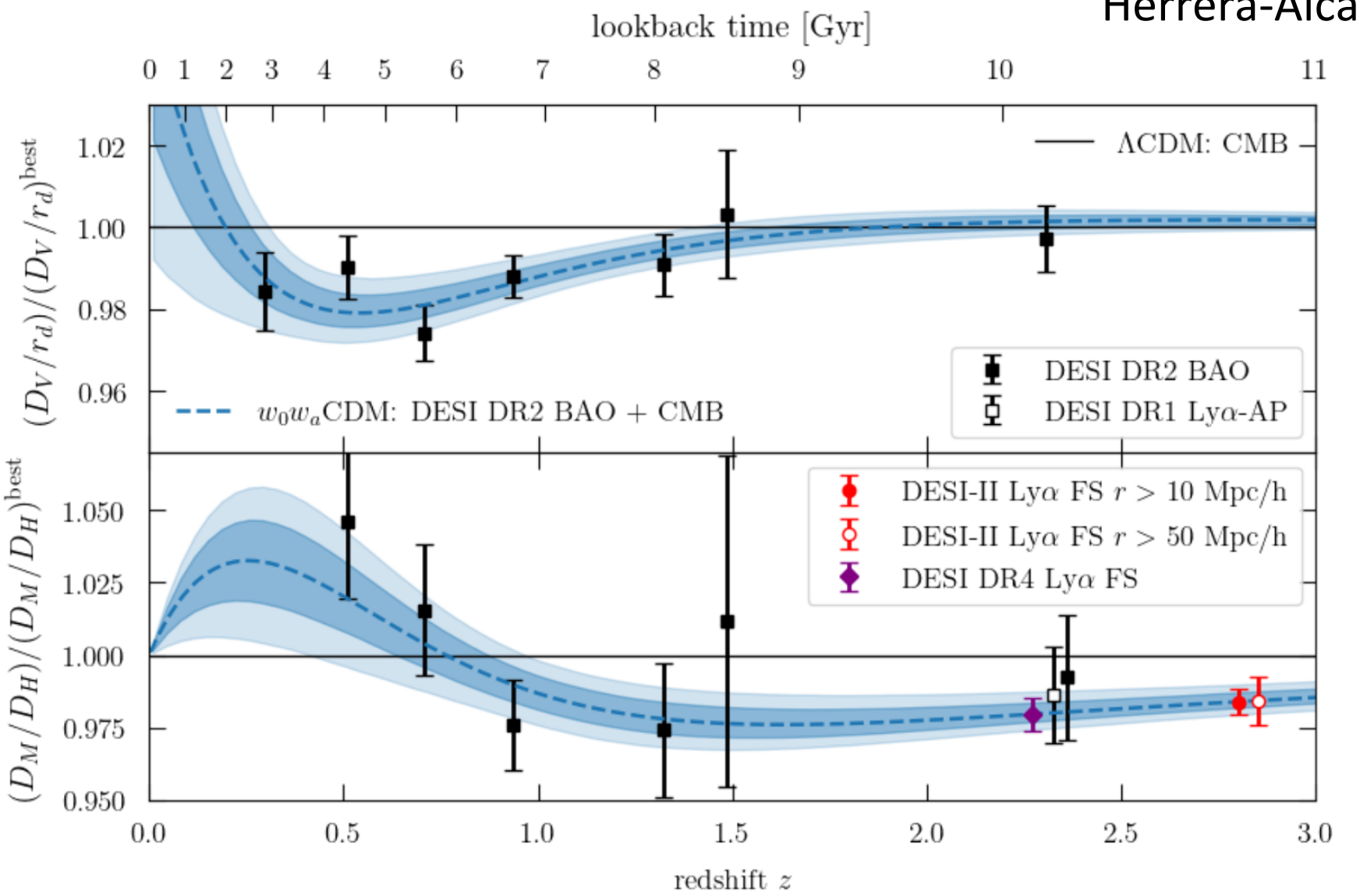
The future with DESI Lyα forest

Based on Cuceu++ 2021 and Herrera-Alcantar++ 2025



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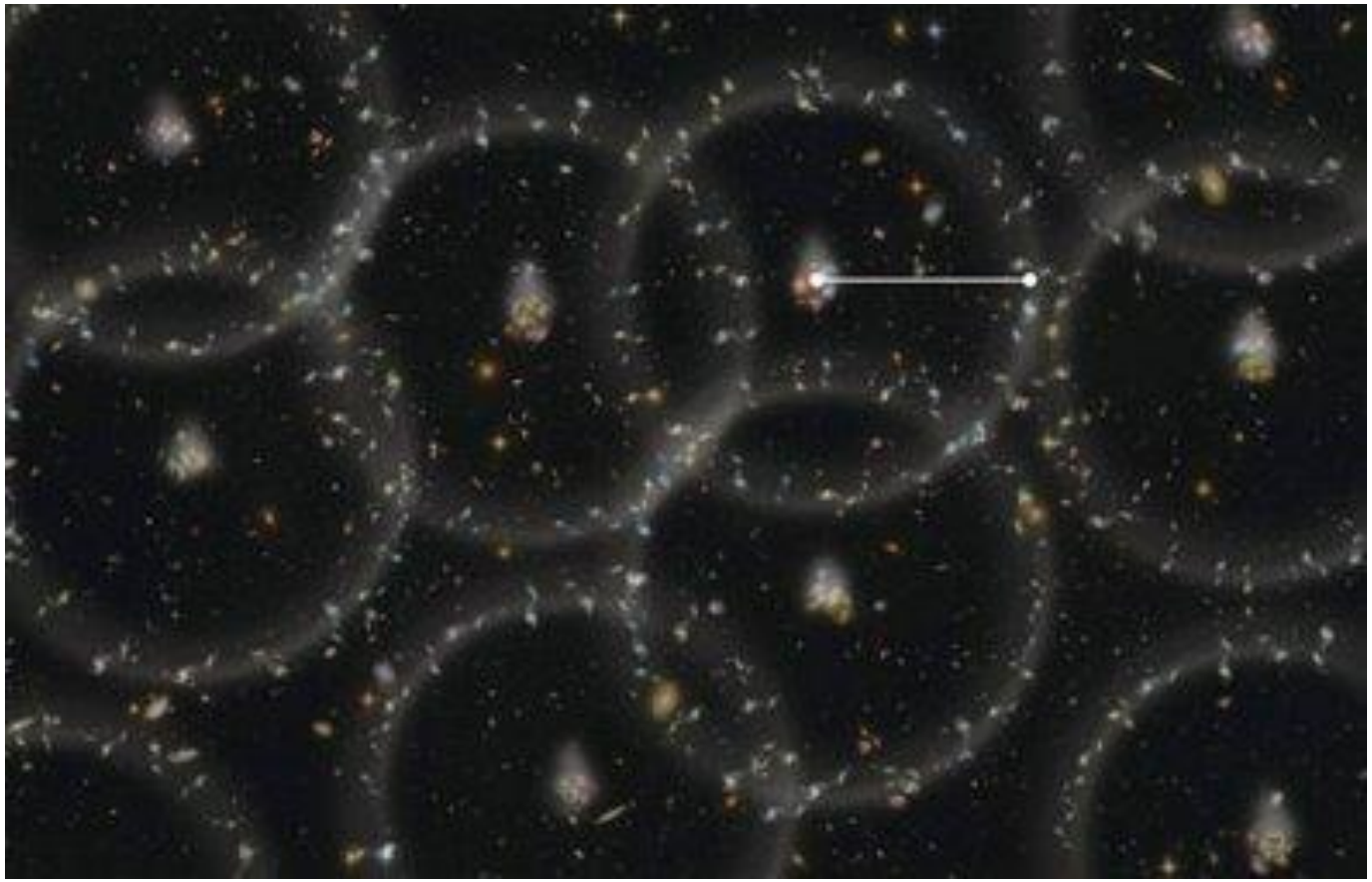
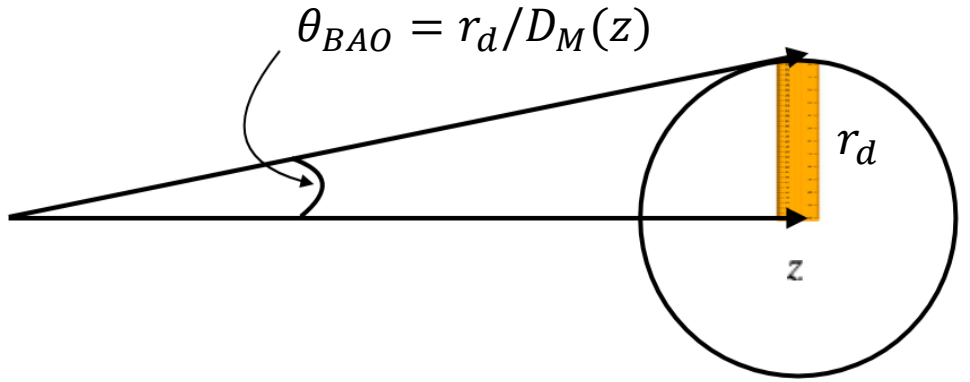
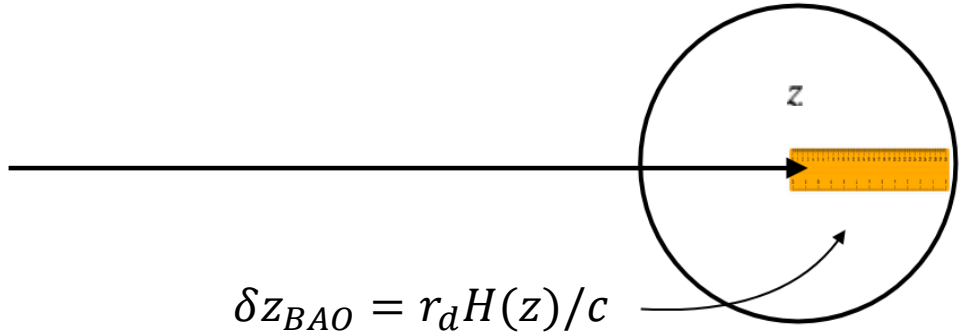
BAO → standard ruler







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

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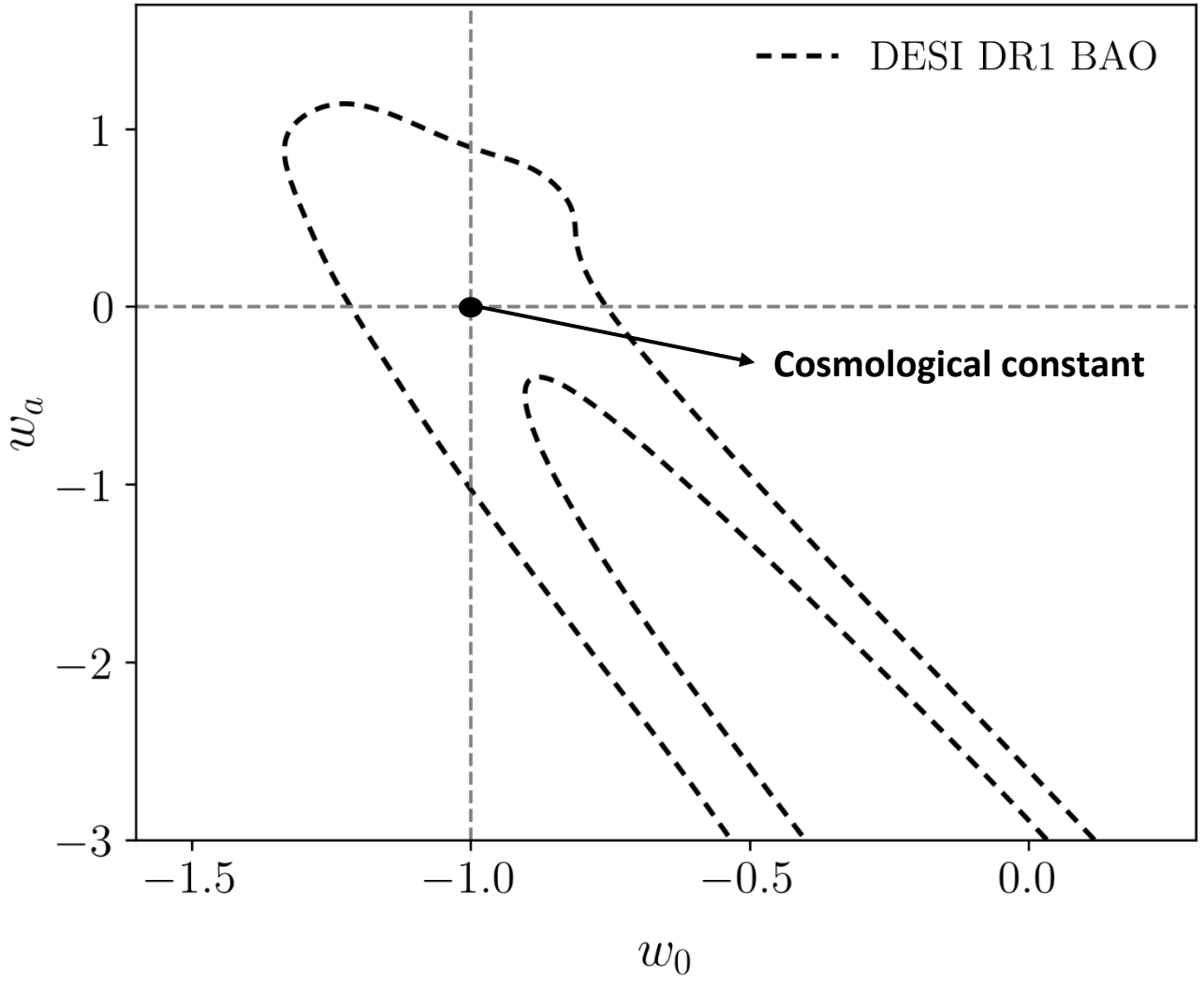
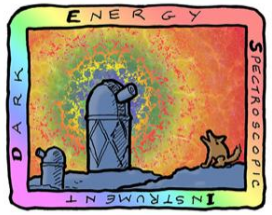
Evolving Dark Energy

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





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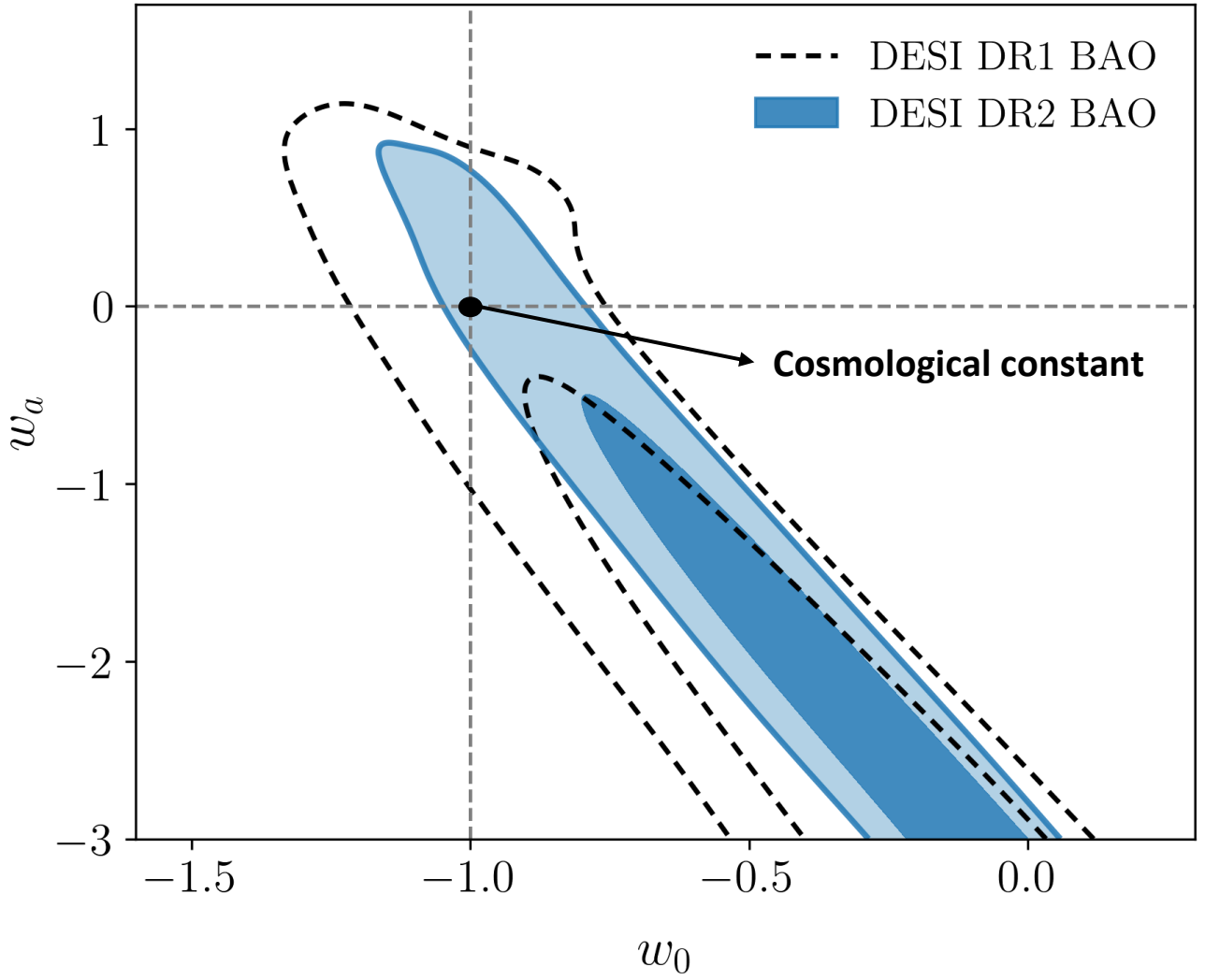
Evolving Dark Energy

- 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



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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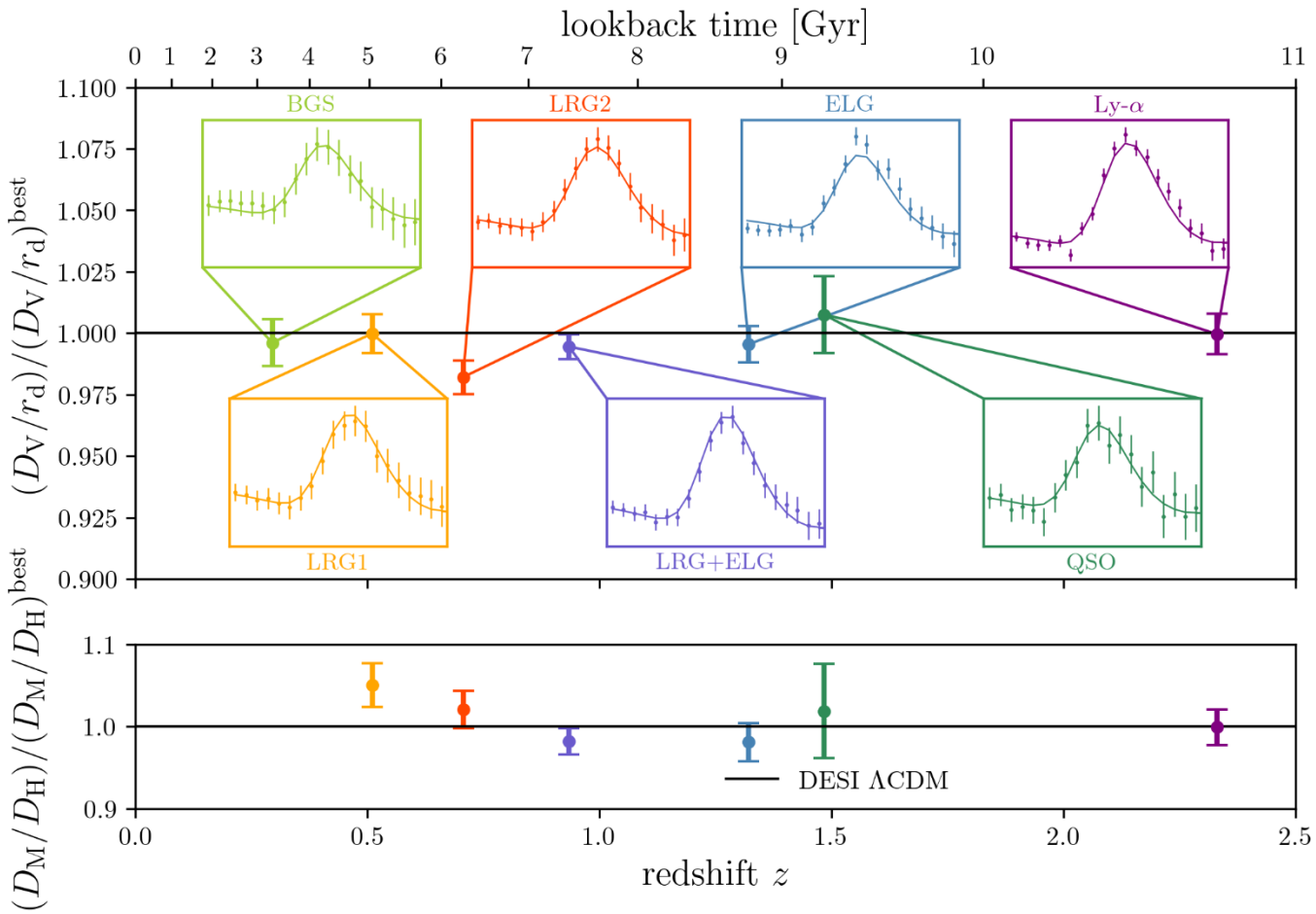
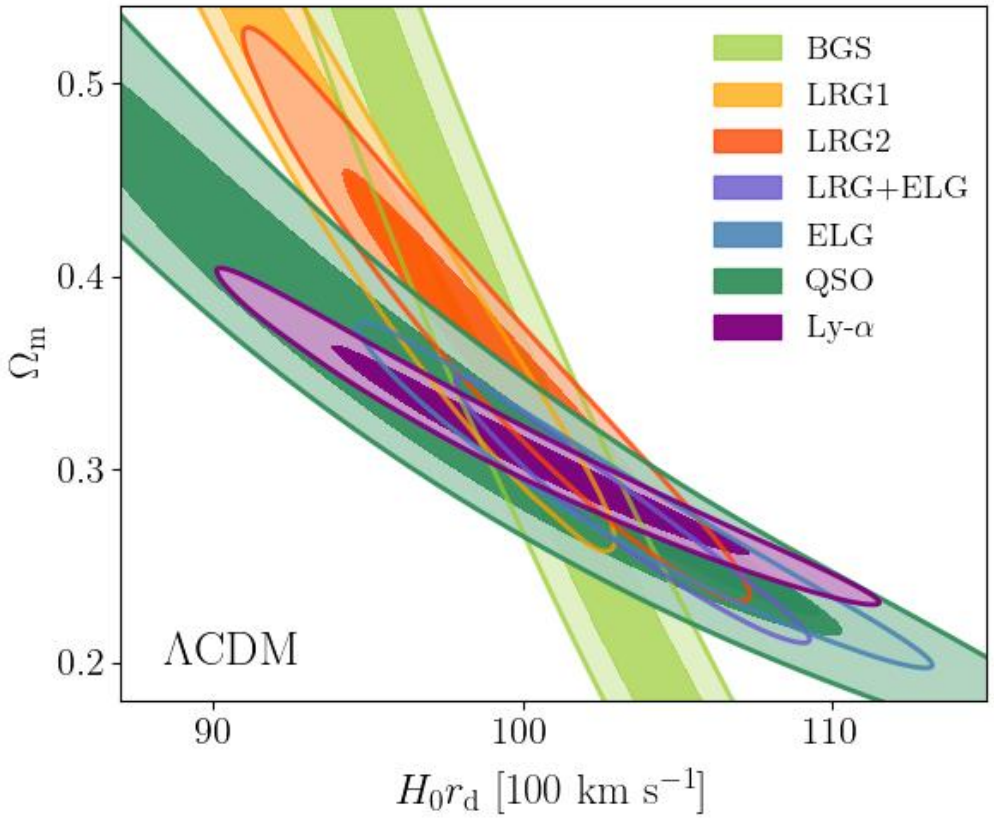
DESI DR2 BAO

DESI BAO measurements



Flat ΛCDM results



DESI DR2 Results II: BAO measurements and Cosmology

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DESI DR2 BAO

DESI BAO measurements

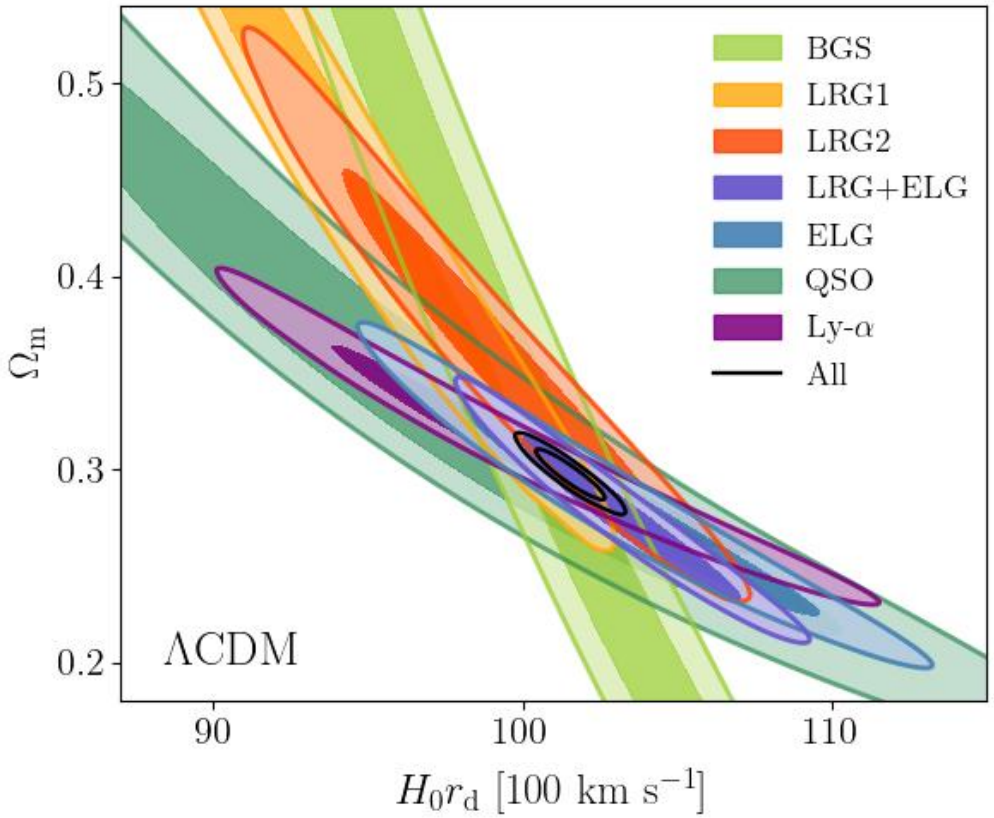
Consistent with each other,
and complementary

$\Omega_m = 0.2975 \pm 0.0086$ **(2.9%)**

$H_0 r_d = (101.54 \pm 0.73)\ [100\ \mathrm{km/s}]$ **(0.7%)**

DESI

Flat ΛCDM results



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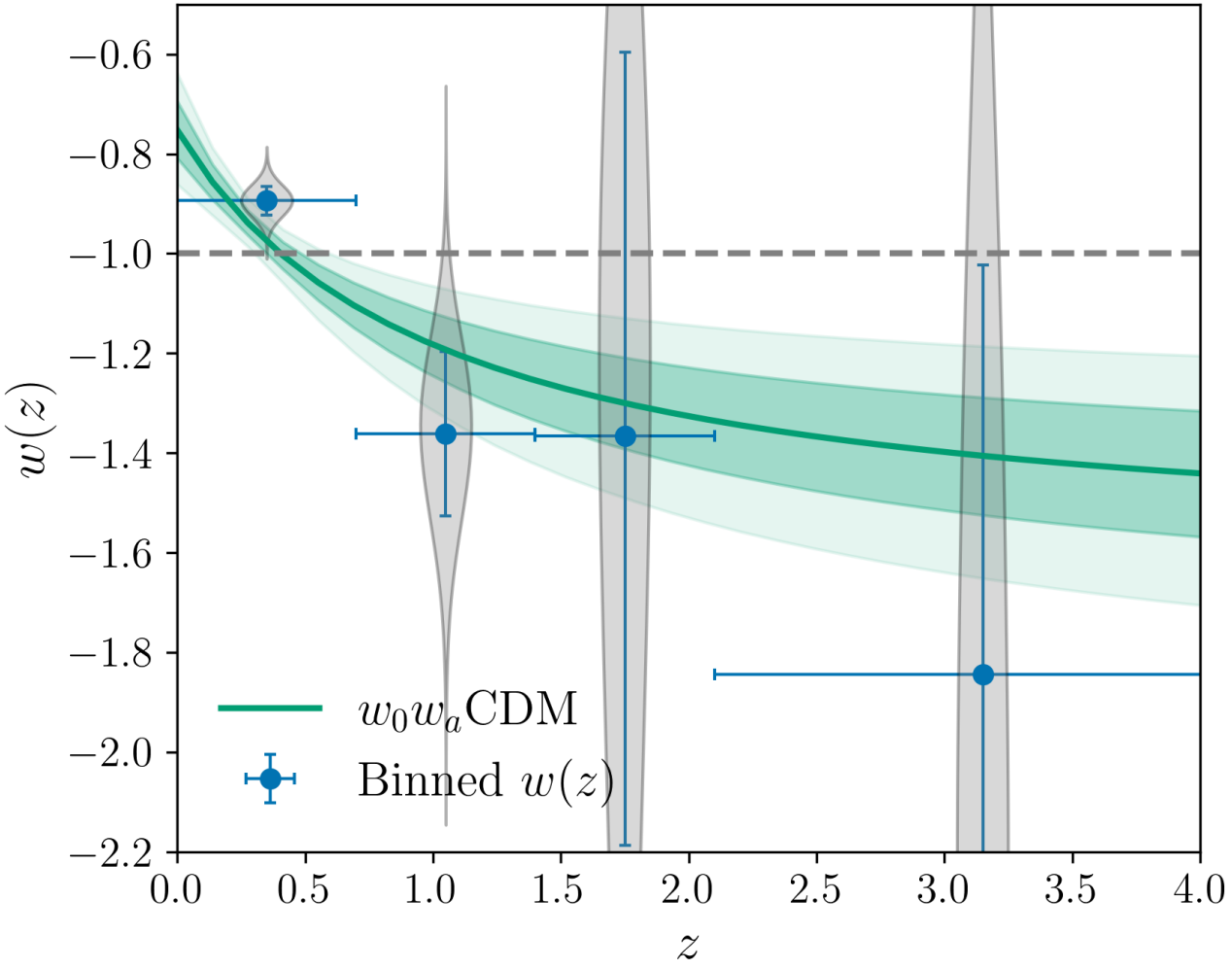
Does $w_0 w_a$CDM capture the whole picture?



- 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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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