Cosmological constraints from the first-year BAO measurements of the Dark Energy Spectroscopic Instrument (DESI)

Ramon Miquel (ICREA / IFAE Barcelona)
on behalf of the DESI Collaboration

PPC2024, Hyderabad, October 16th 2024

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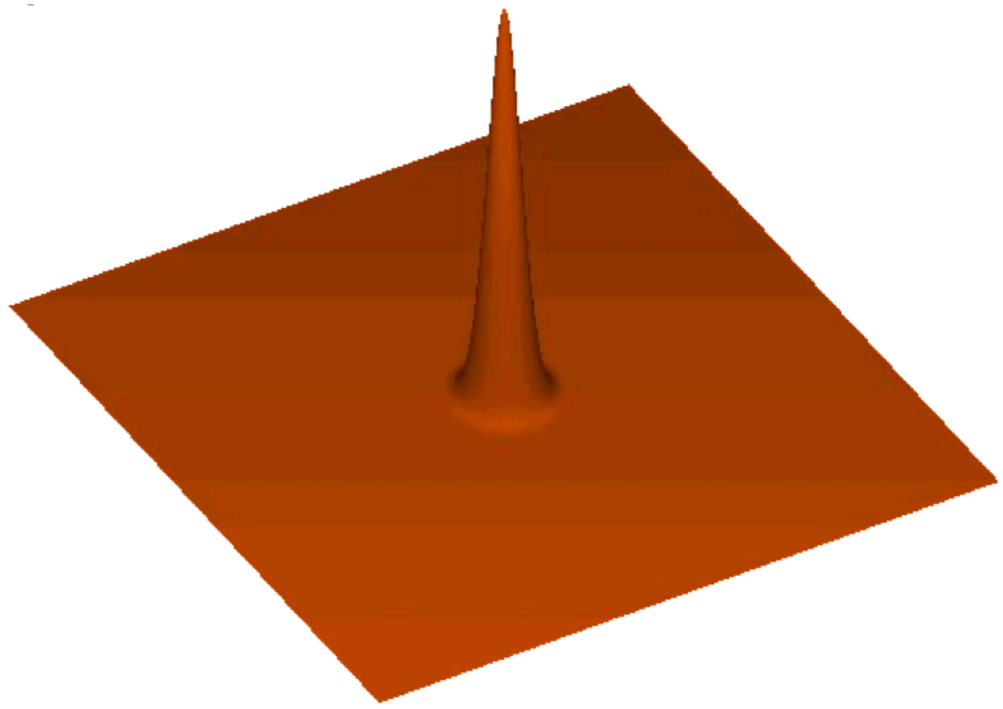
Baryon Acoustic Oscillations (BAO)

Gravity and pressure generated sound waves traveling from the initial density perturbations in the primordial plasma



Credit: Daniel Eisenstein

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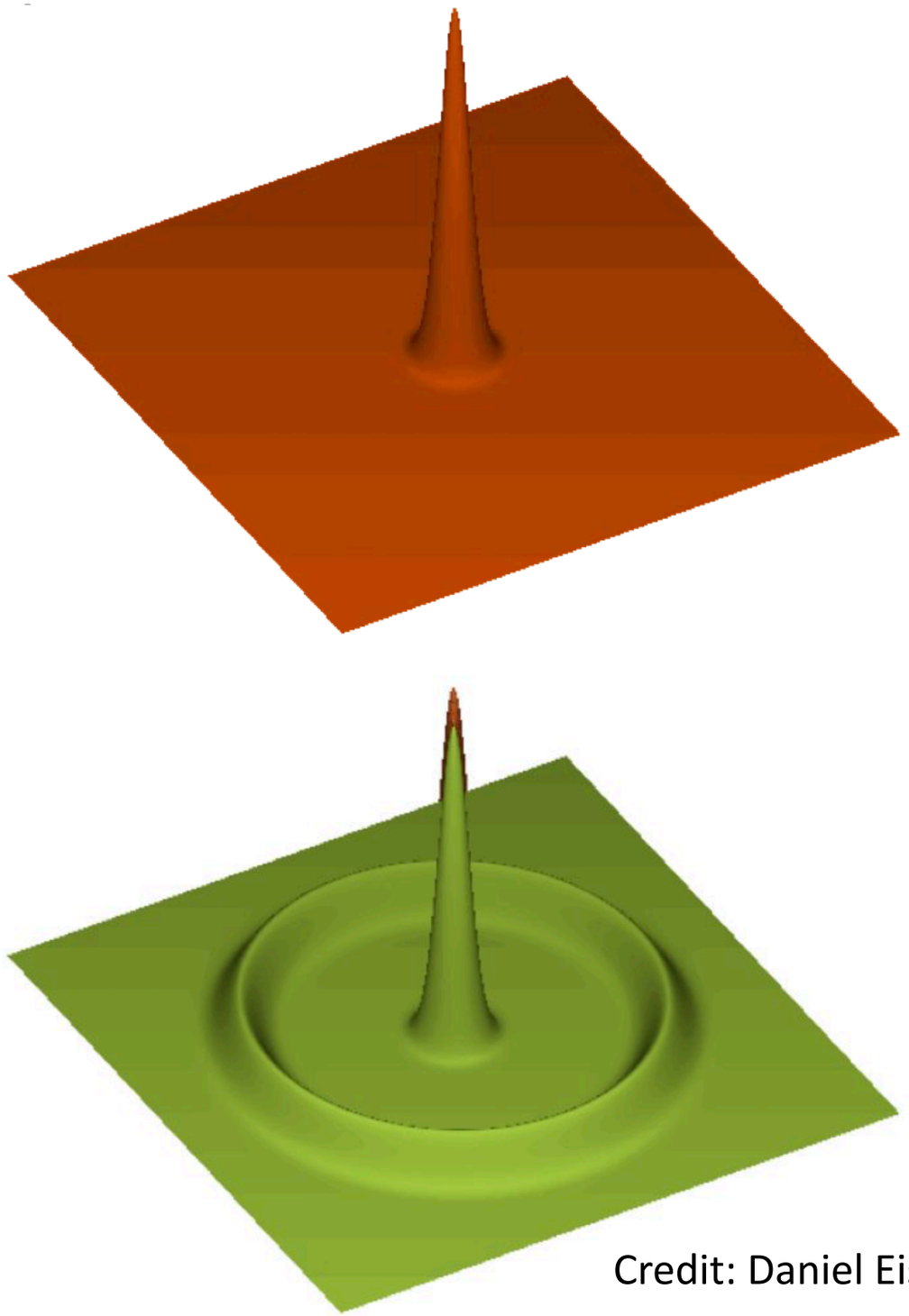
Baryon Acoustic Oscillations (BAO)

Gravity and pressure generated sound waves traveling from the initial density perturbations in the primordial plasma

When baryons and photons decoupled ($z \sim 1100$), pressure ended and waves stopped

Matter, then, tends to accumulate at the initial perturbation and at the replicas



Credit: Daniel Eisenstein

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Baryon Acoustic Oscillations (BAO)

Gravity and pressure generated sound waves traveling from the initial density perturbations in the primordial plasma

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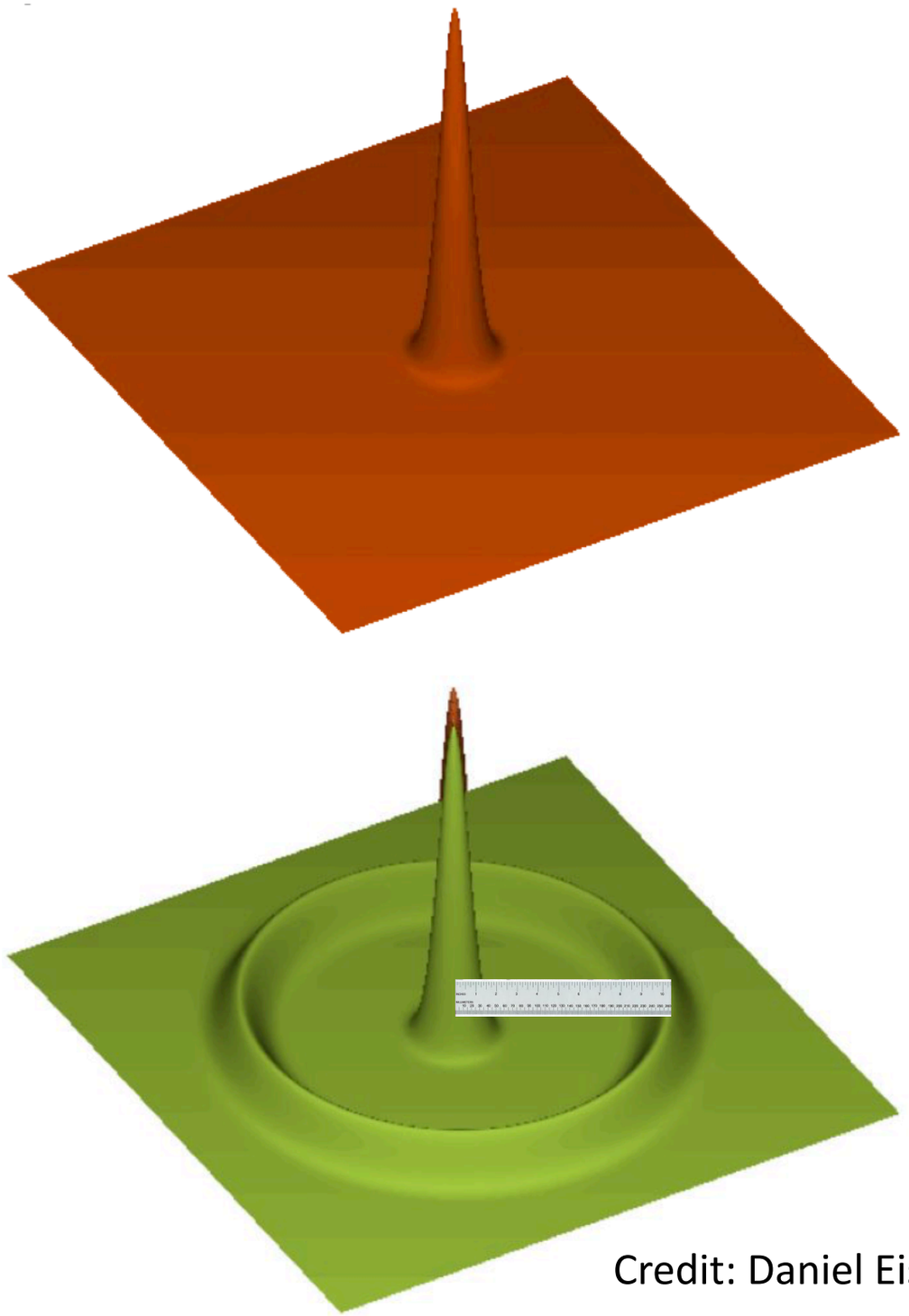
Matter, then, tends to accumulate at the initial perturbation and at the replicas

A characteristic scale is imprinted in the matter distribution at the sound horizon at decoupling, $r_d \sim 150$ Mpc



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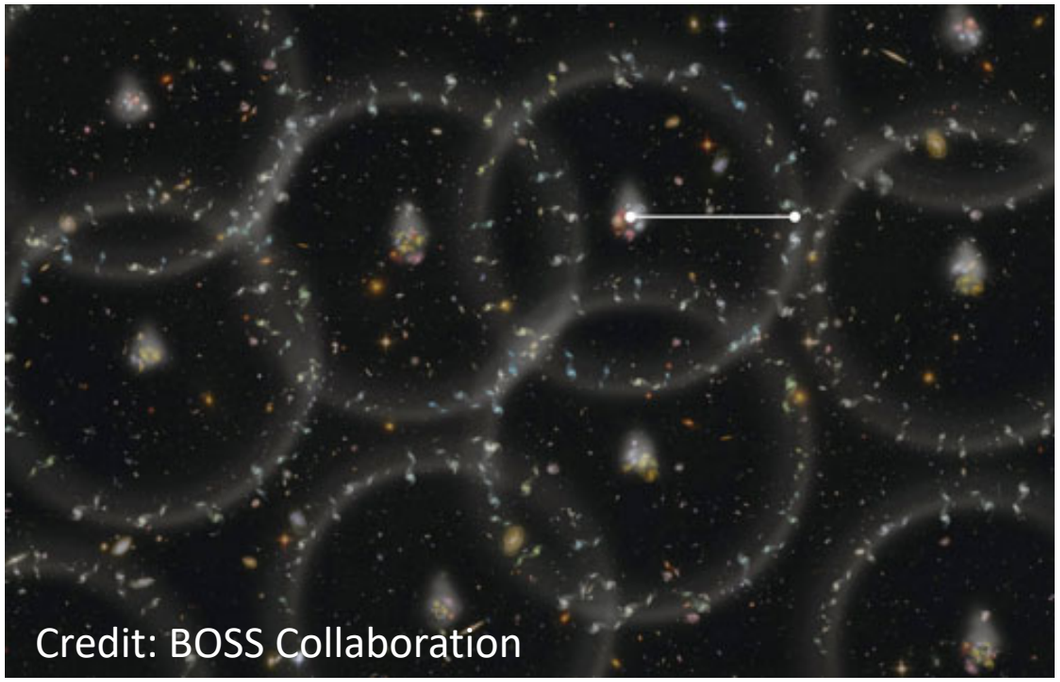
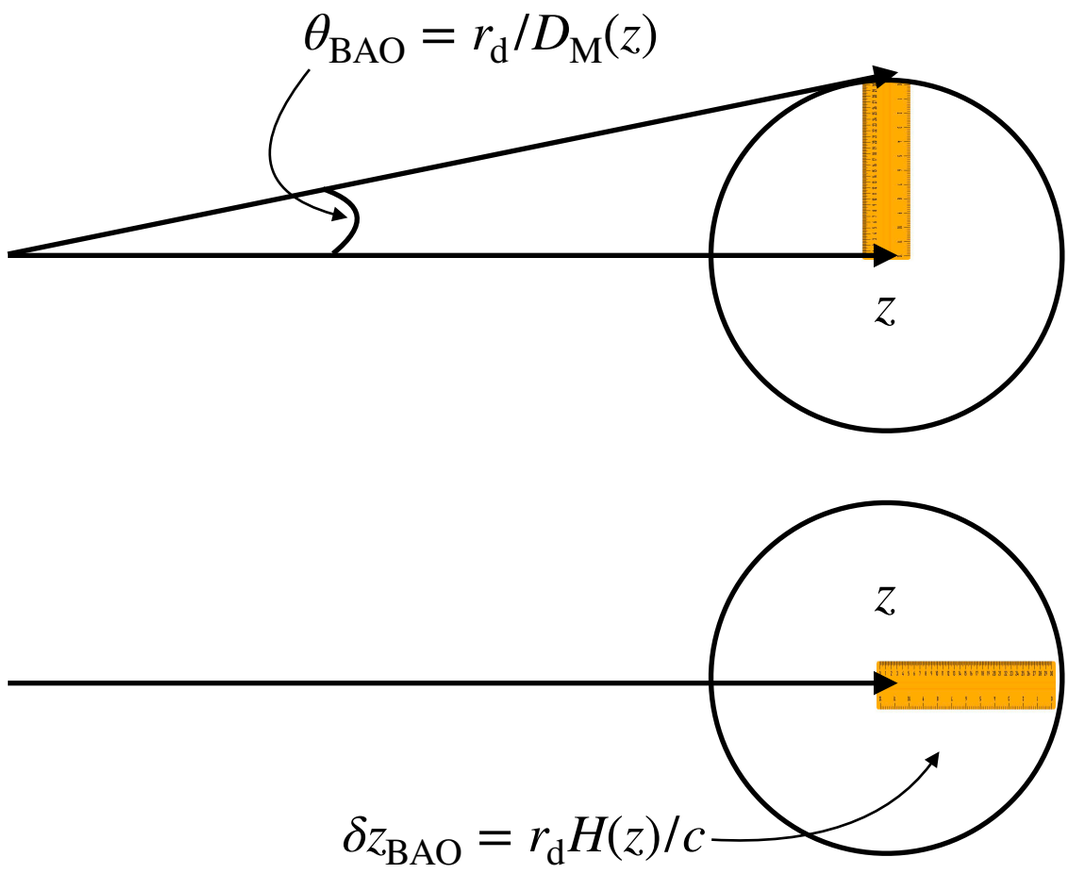
Baryon Acoustic Oscillations (BAO)





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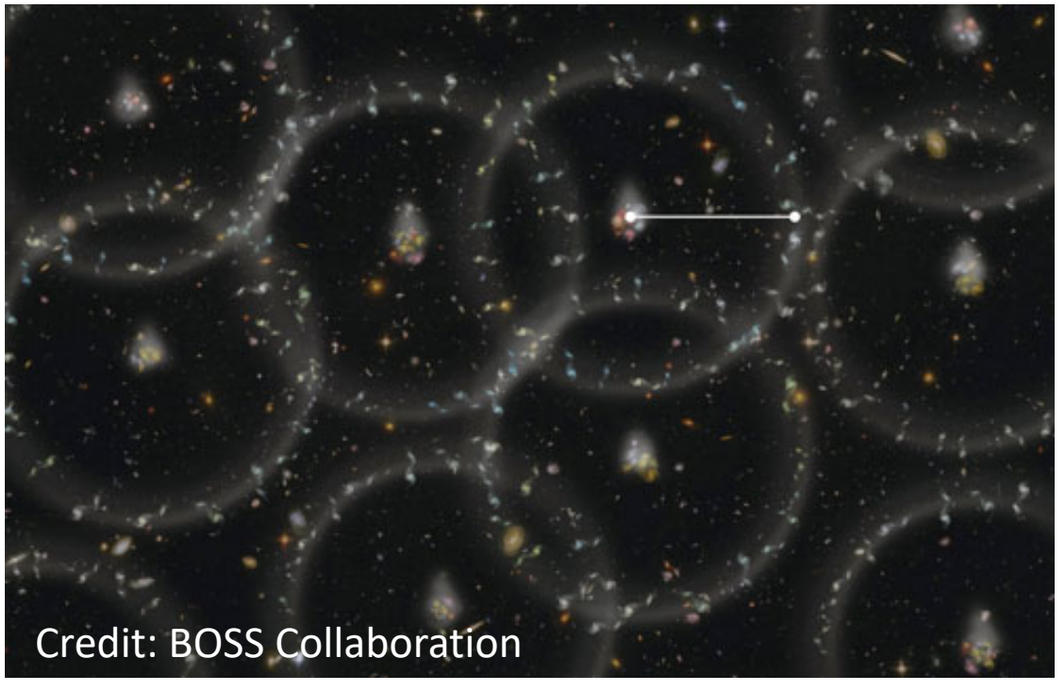
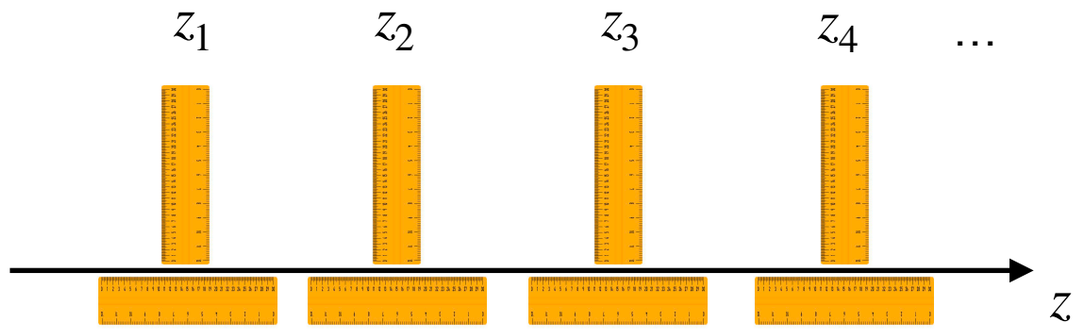
Baryon Acoustic Oscillations (BAO)





$D_{\mathrm{M}}(z)$ and $H(z)$ encode the **expansion history** of the Universe

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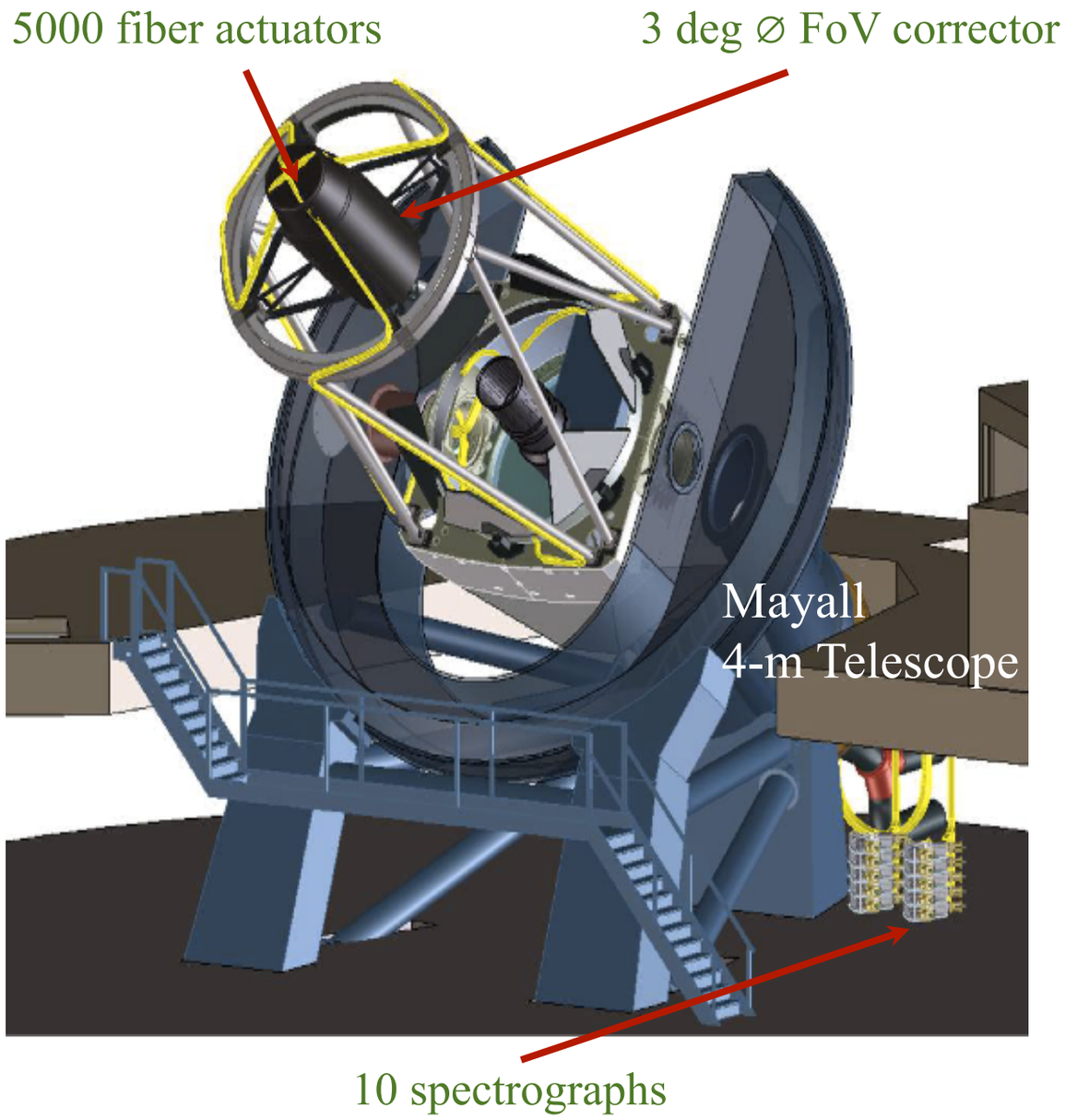
DESI: The project

- Stage-IV galaxy-redshift survey, built upon experience with BOSS, eBOSS
- Massively parallel fiber-fed spectrograph at the 4-meter Mayall telescope (AZ, USA)
- Automated fiber system with 5000 fibers
- Sky coverage: 14,000+ sq. deg.
- Number of galaxy and QSO redshifts: 40 M
- Started data taking in May 2021



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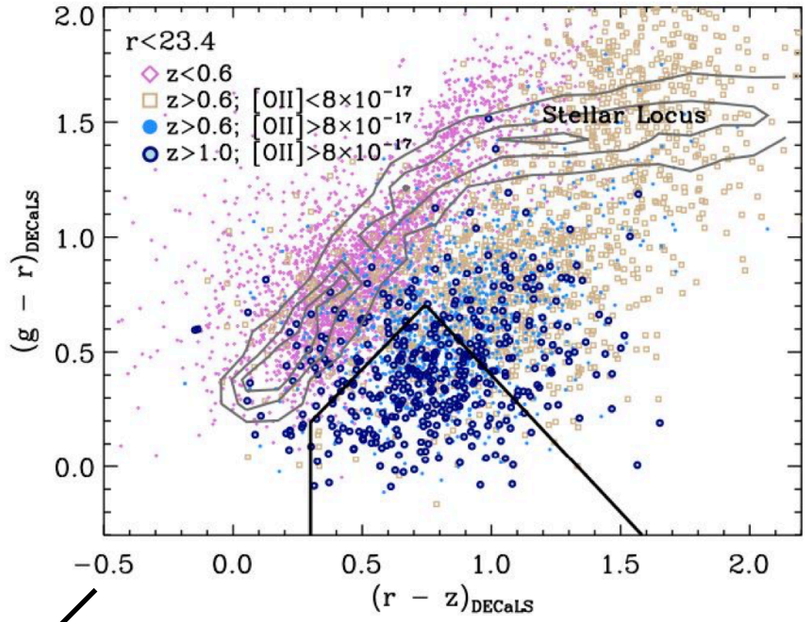
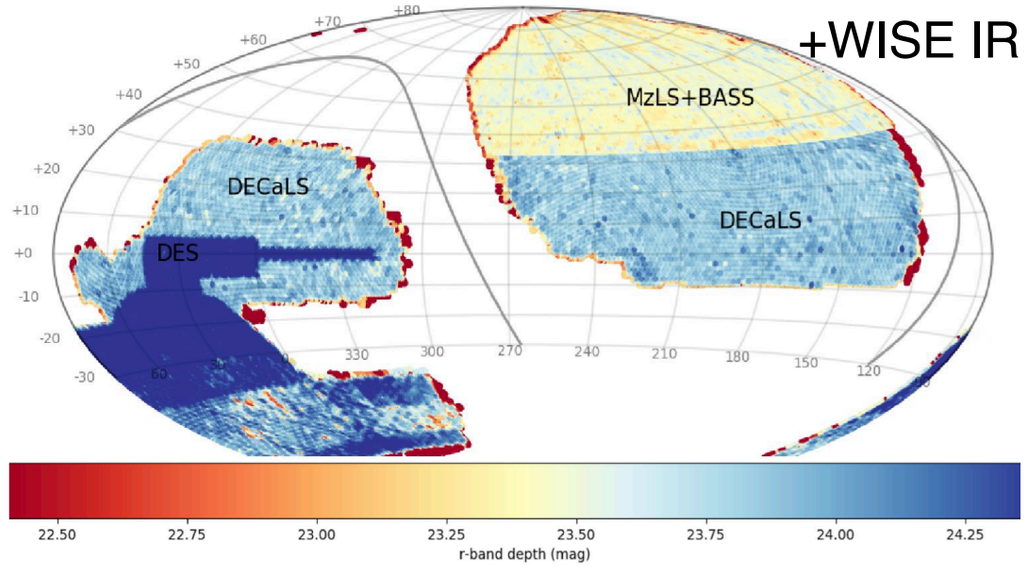
DESI: Multi-object spectroscopy

Target selection

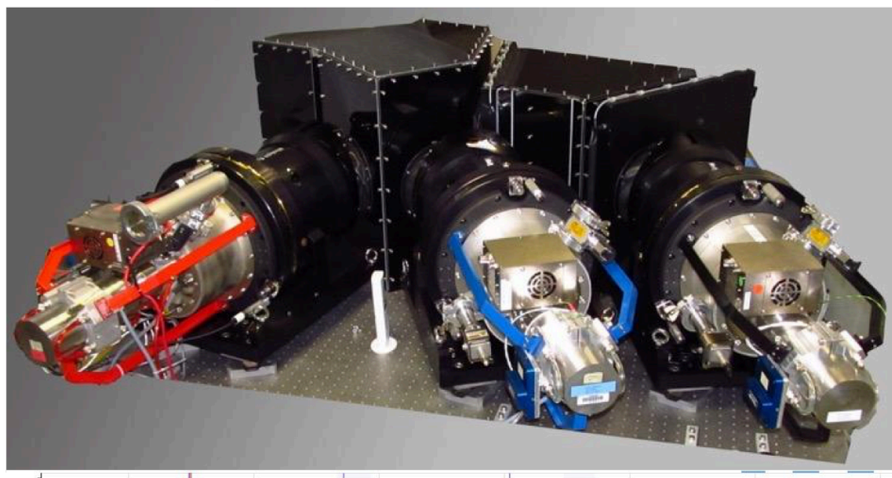


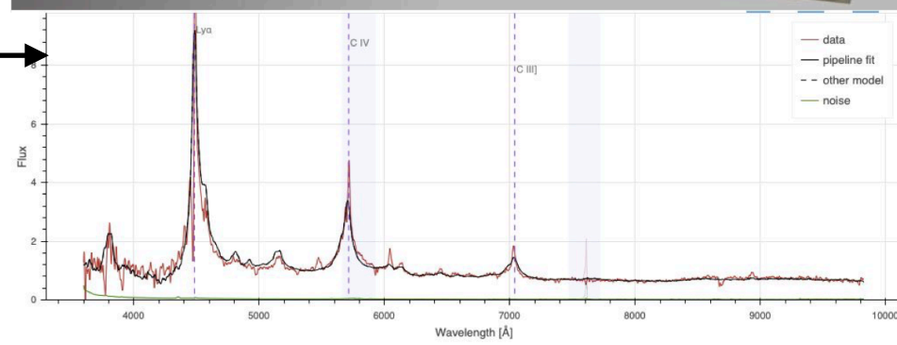
Imaging surveys (2014-2019)

+WISE IR all-sky sat.

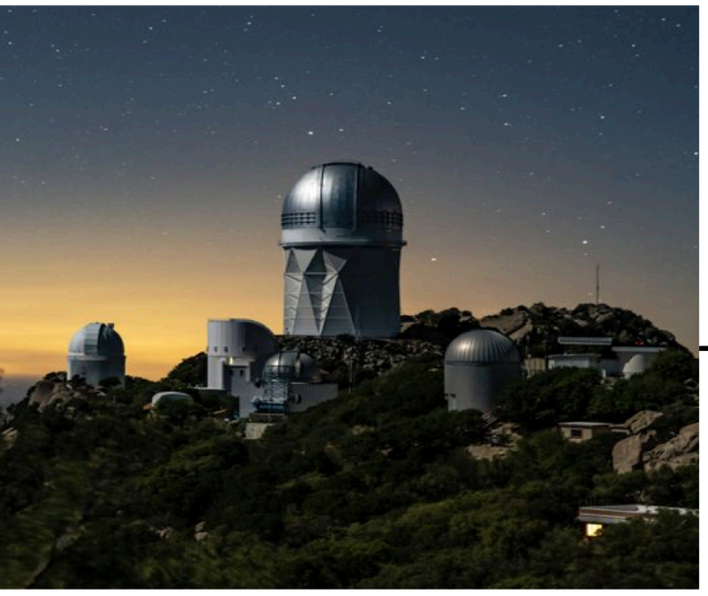


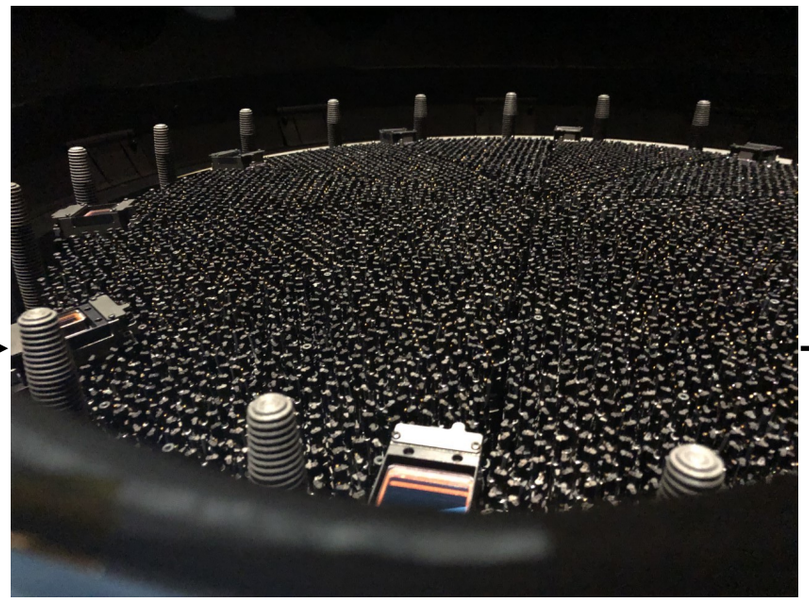
Obtain spectra, measure redshifts





Observation of 5000 objects every ~20 min





Credit: Etienne Burtin

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DESI: The survey

Five target classes

40 million redshifts

in 5 years

3 million QSOs

Lya $z > 2.1$

Tracers $0.9 < z < 2.1$

16 million ELGs

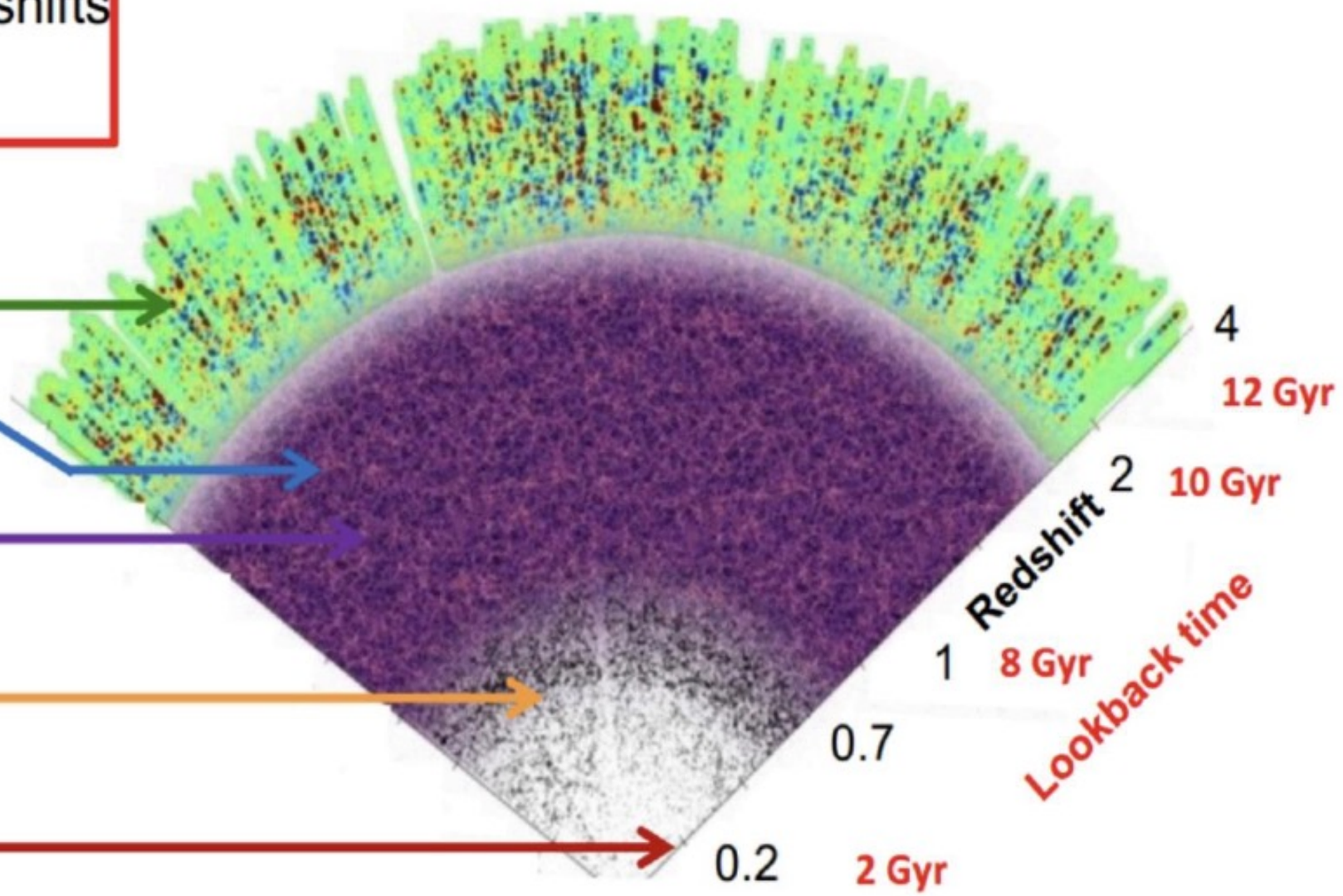
$0.6 < z < 1.6$

8 million LRGs

$0.4 < z < 1.0$

13.5 million Brightest galaxies

$0.0 < z < 0.4$



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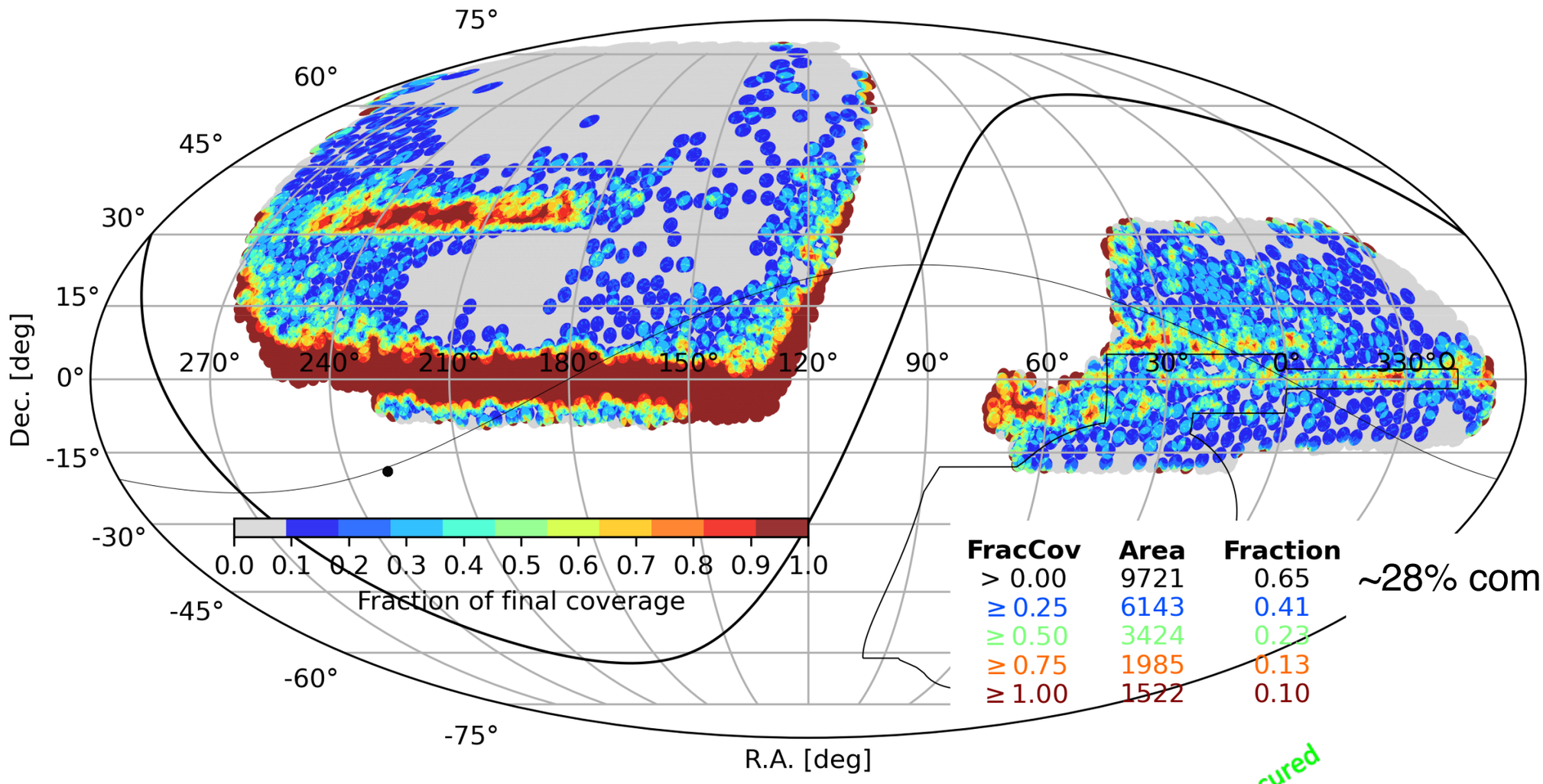
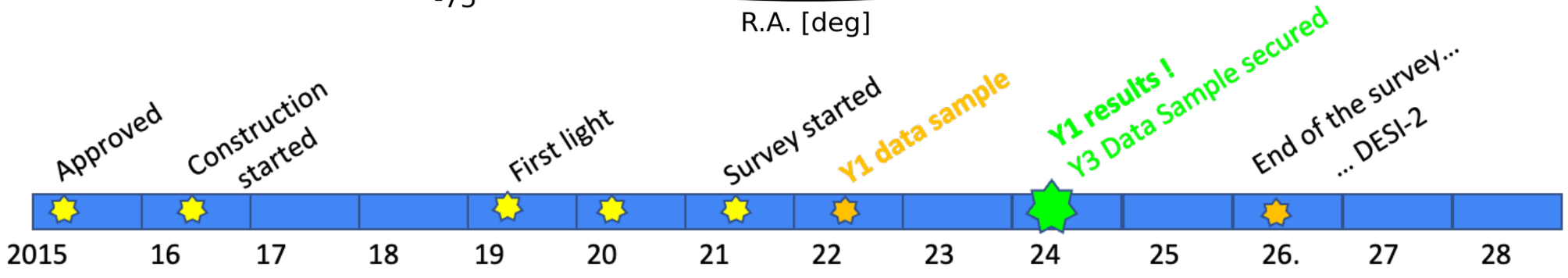
DESI: Year 1 dataset

DESI Y1 includes data taken from May 14th, 2021 to June 12th, 2022



FracCov	Area	Fraction
> 0.00	9721	0.65
≥ 0.25	6143	0.41
≥ 0.50	3424	0.23
≥ 0.75	1985	0.13
≥ 1.00	1522	0.10

~28% completed



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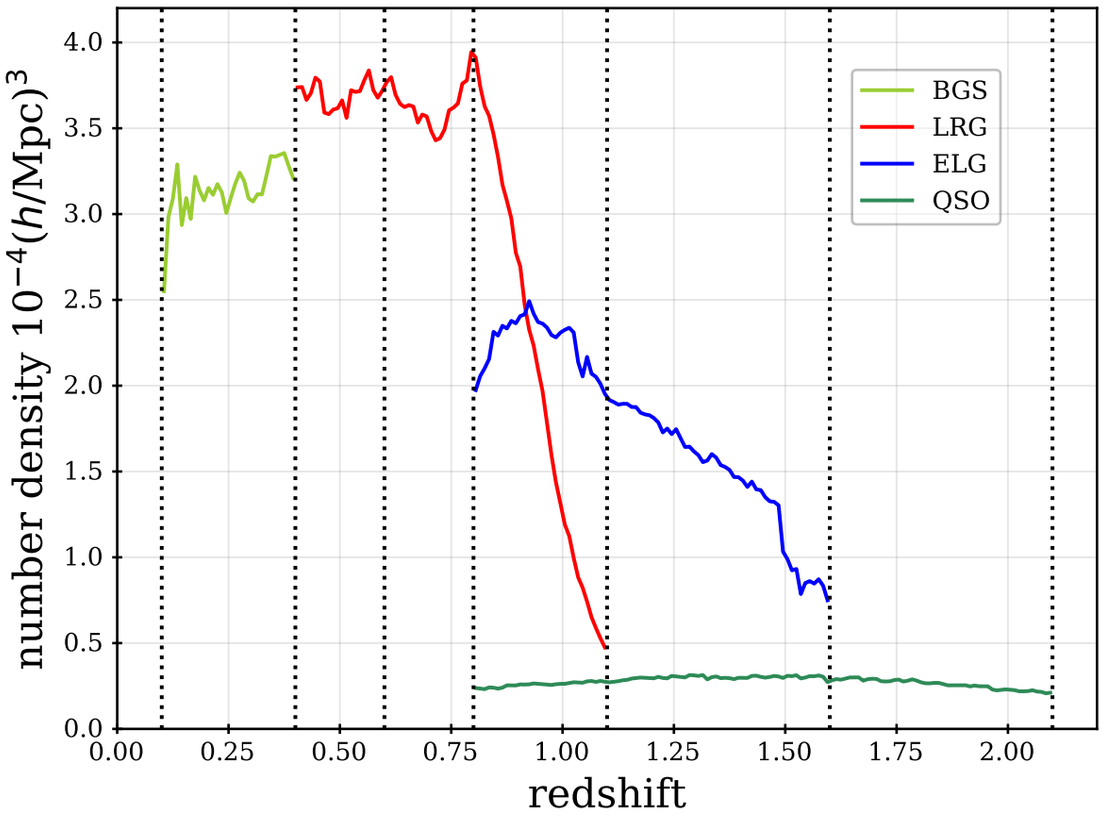
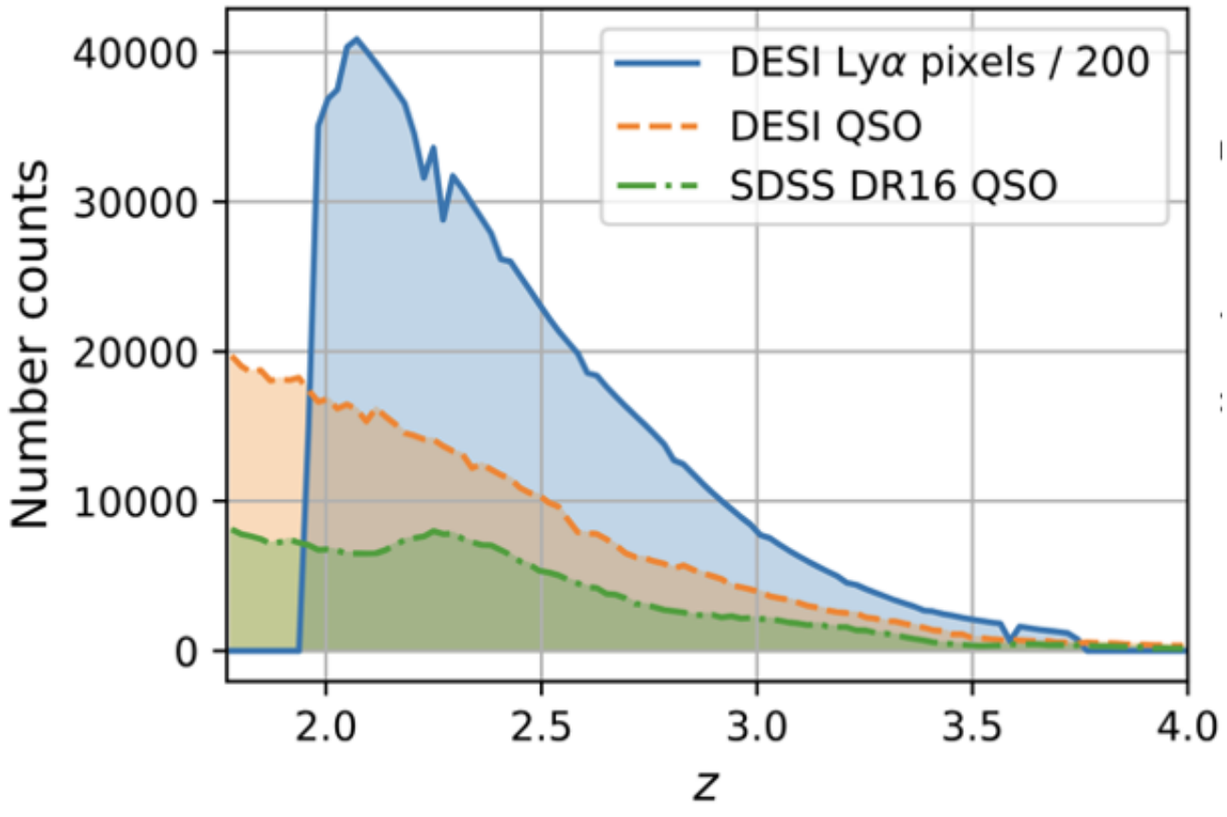
DESI: Year 1 dataset

DESI Y1 includes data taken from May 14th, 2021 to June 12th, 2022

5.7 million unique redshifts at z < 2.1



420,000 Lyman-α QSOs at z > 2.1



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DESI: Year 1 results

First batch of DESI Y1 cosmological analysis papers **released in April 2024**

https://data.desi.lbl.gov/doc/papers/

- DESI 2024 I: First year data release
- DESI 2024 II: DR1 catalogs
- **DESI 2024 III: BAO from Galaxies and Quasars at z < 2** — N. Padmanabhan, H.-J. Seo
- **DESI 2024 IV: BAO from the Lyman-α Forest at z > 2** — A. Font-Ribera, A. González-Morales, J. Guy
- DESI 2024 V: RSD from Galaxies and Quasars at z < 2
- **DESI 2024 VI: Cosmological constraints from BAO measurements** — D. Huterer, E. Mueller
- DESI 2024 VII: Cosmological constraints from RSD measurements

+ 15 companion papers

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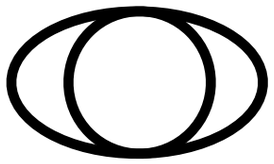
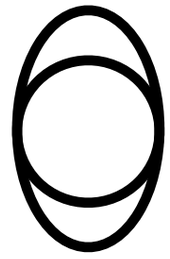
Galaxy BAO at z<2

"Scaling parameters":



$$\alpha_{\perp} = \frac{D_{\mathrm{M}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{M}}^{\mathrm{fid}}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\mathrm{H}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{H}}^{\mathrm{fid}}}$$



perpendicular std ruler size

line-of-sight std ruler size

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Galaxy BAO at z<2

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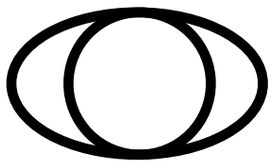
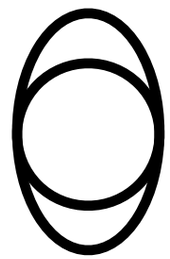


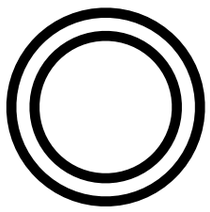
$$\alpha_{\perp} = \frac{D_{\rm M}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm M}^{\rm fid}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\rm H}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$



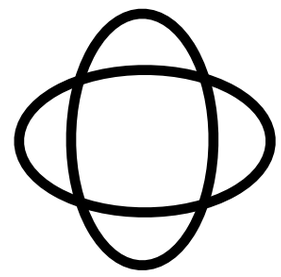
perpendicular std ruler size

line-of-sight std ruler size

OR



$$\alpha_{\rm iso} = \left(\alpha_{\perp}^2 \alpha_{||}\right)^{1/3} \quad \text{and} \quad \alpha_{\rm AP} = \frac{D_{\rm H}}{D_{\rm M}} \frac{D_{\rm M}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$



overall scale of std ruler

anisotropy of std ruler

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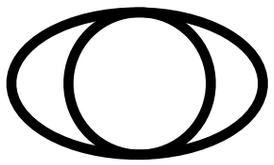

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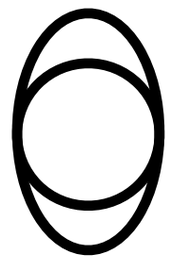
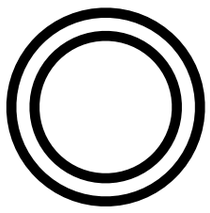


perpendicular std ruler size

line-of-sight std ruler size

OR



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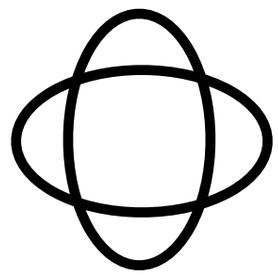

overall scale of std ruler

anisotropy of std ruler

OR

just $\alpha_{\rm iso} = \left(\alpha_{\perp}^2 \alpha_{||}\right)^{1/3}$ (if SNR is low)

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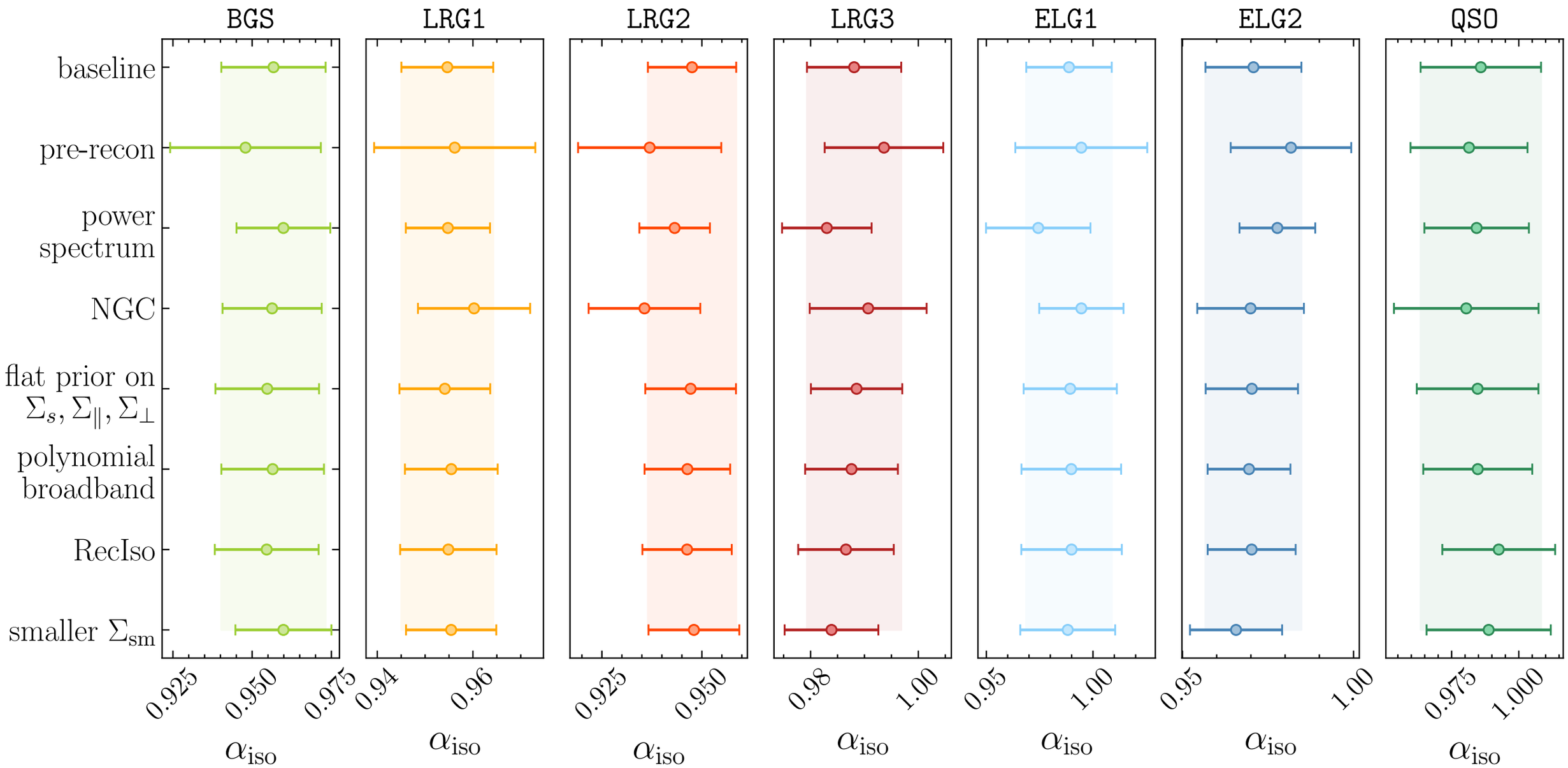
Tests before unblinding



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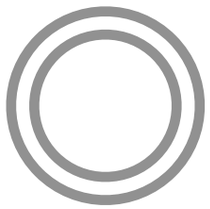
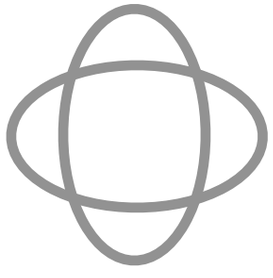
Unblinded data results

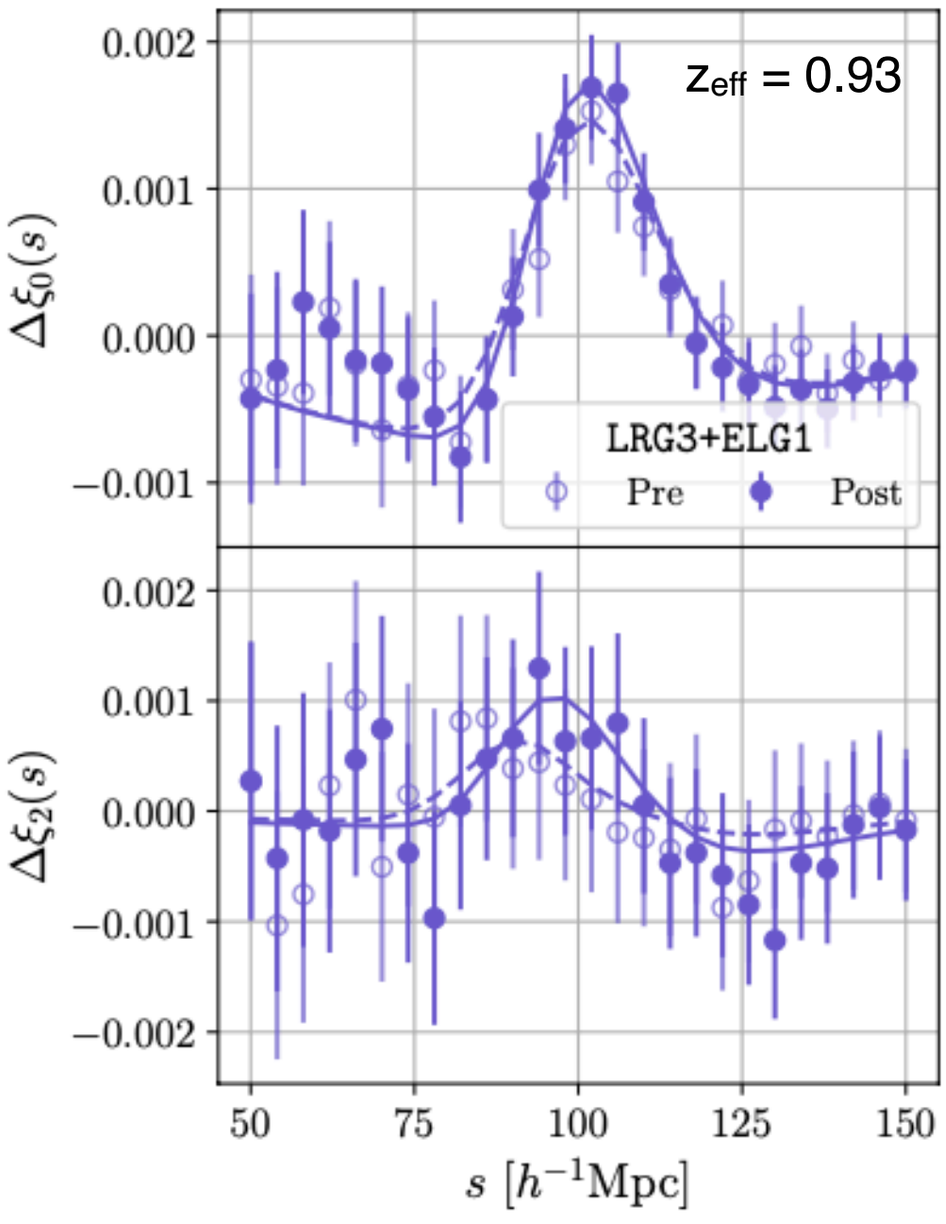
For example (in configuration space):

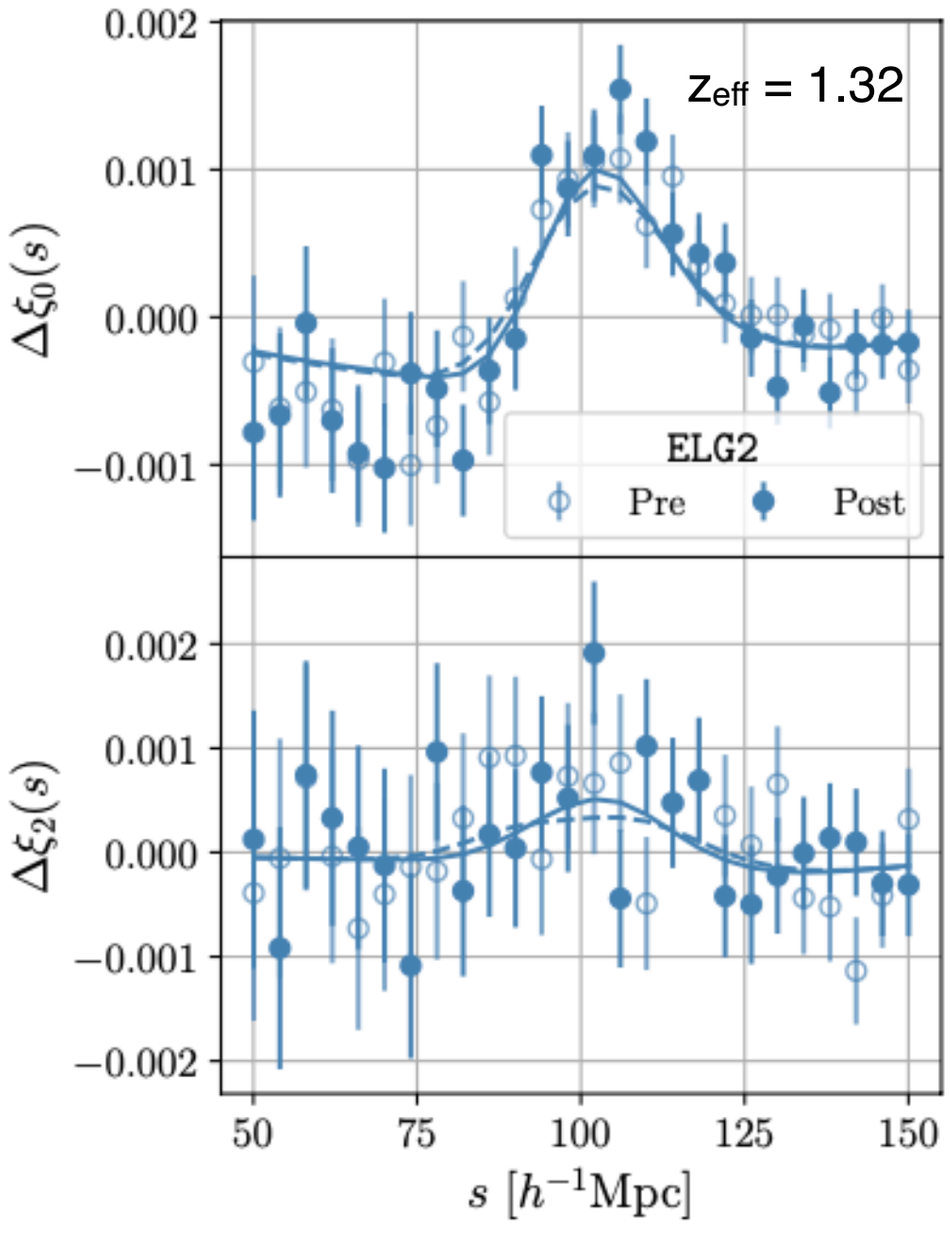


overall scale of ruler



anisotropy of ruler





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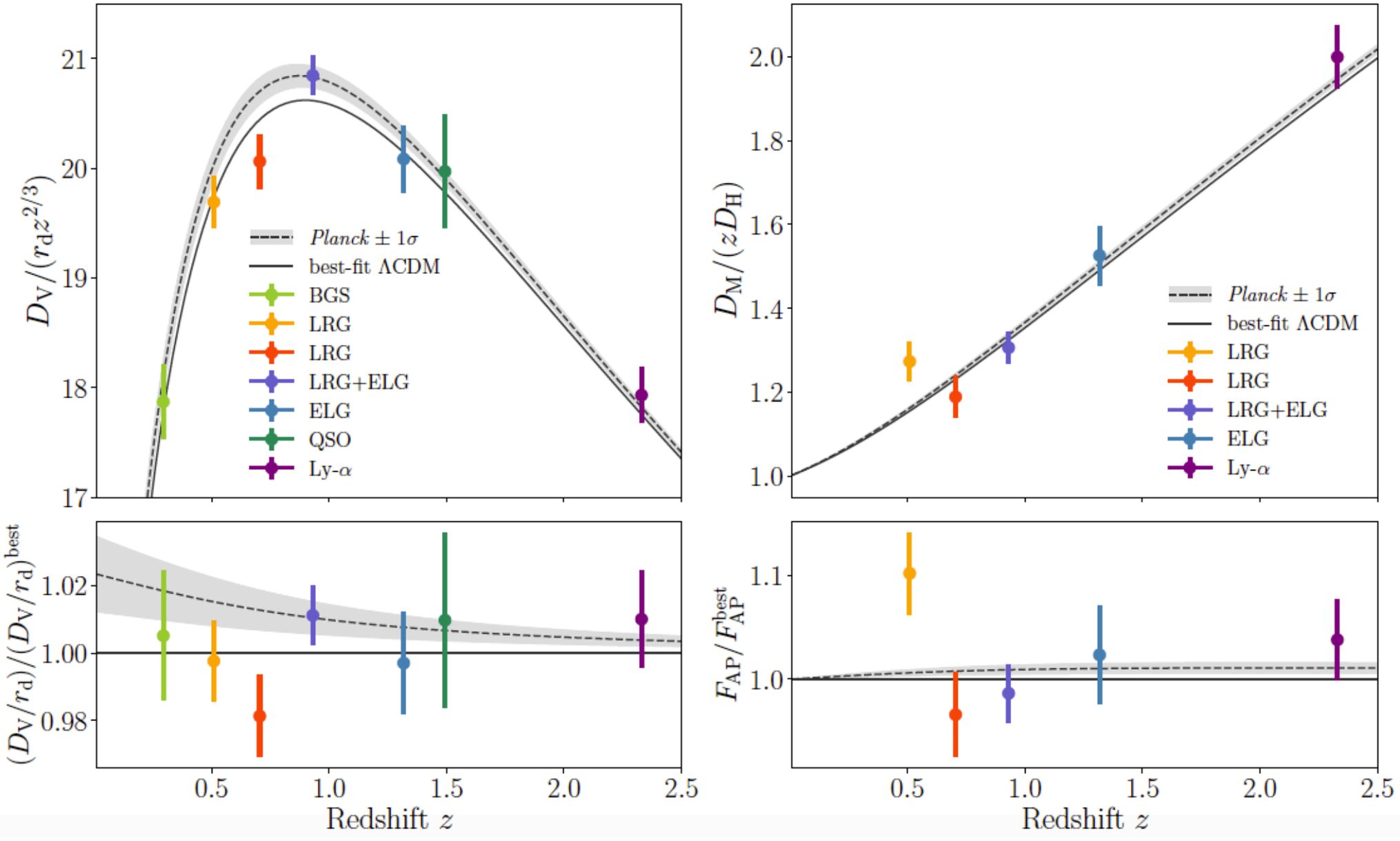
Unblinded data results



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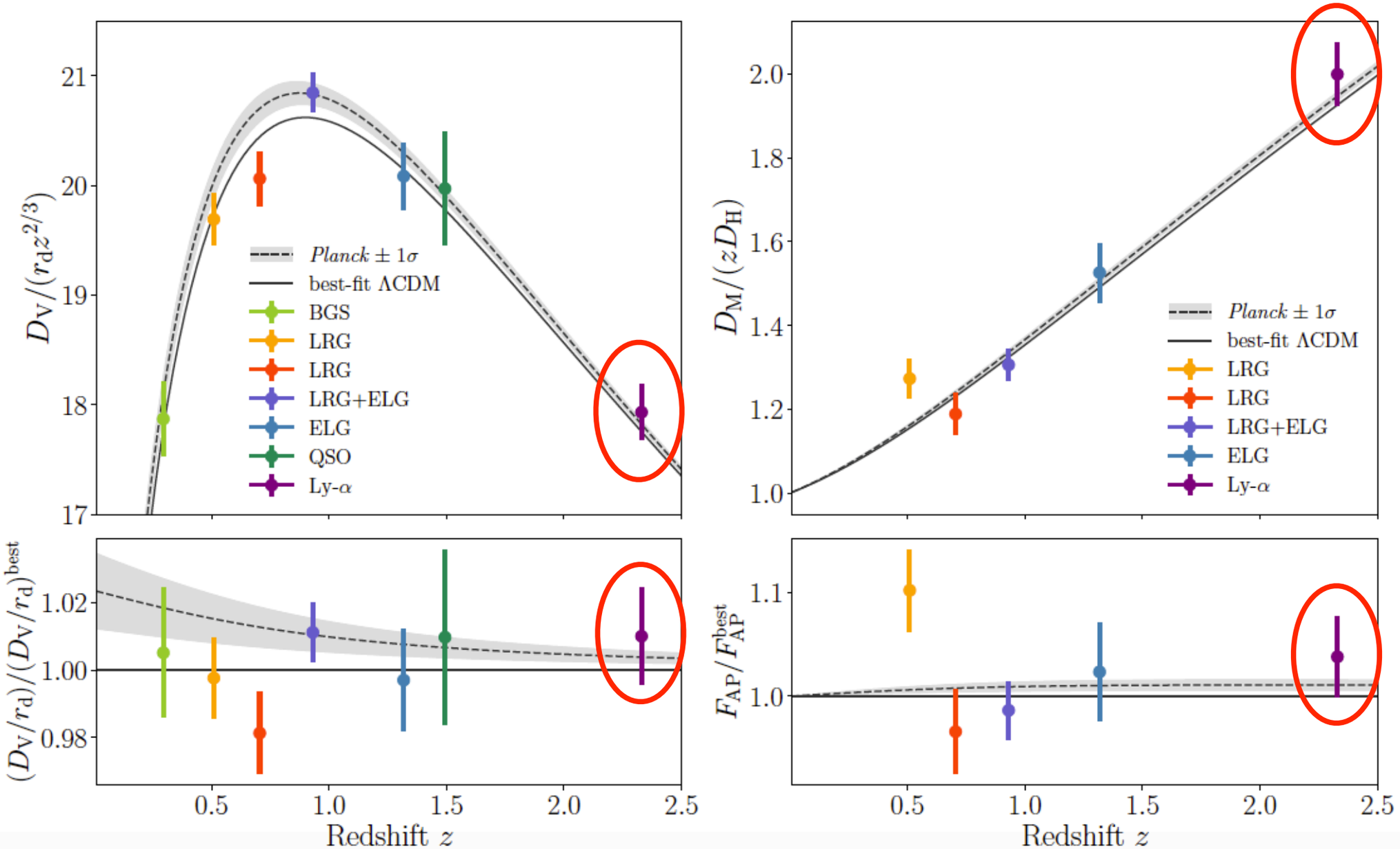

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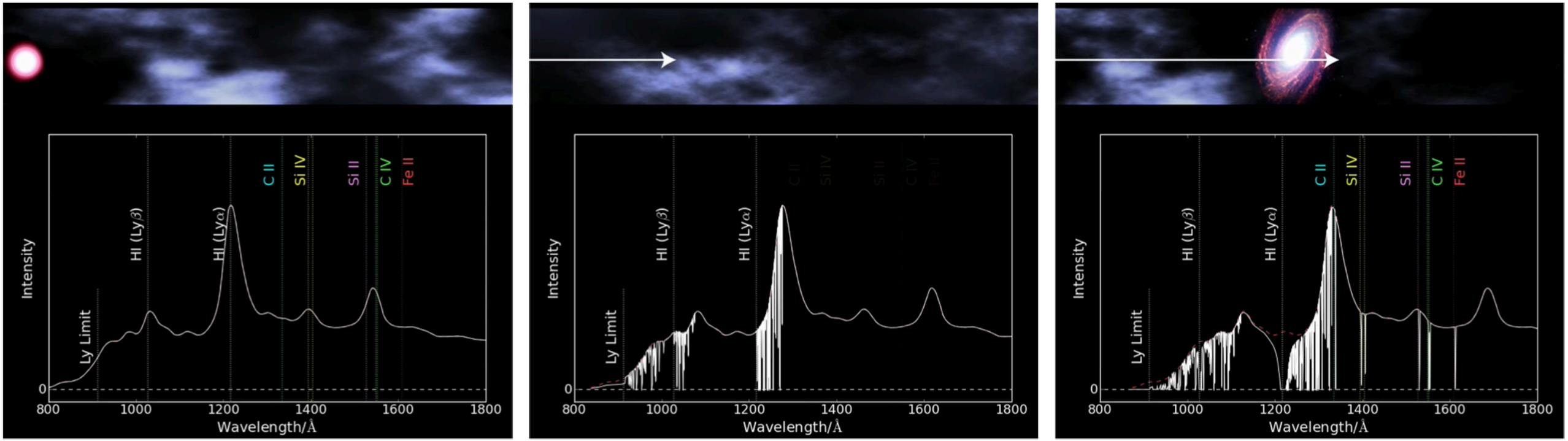
The Lyman-α (Lyα) forest

credit: Andrew Pontzen



Background quasar → Intervening gas → Earth

- Absorption in QSO spectra by neutral hydrogen in the intergalactic medium

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

- The transmitted flux fraction F is a cosmological probe of the fluctuation in the neutral hydrogen density

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

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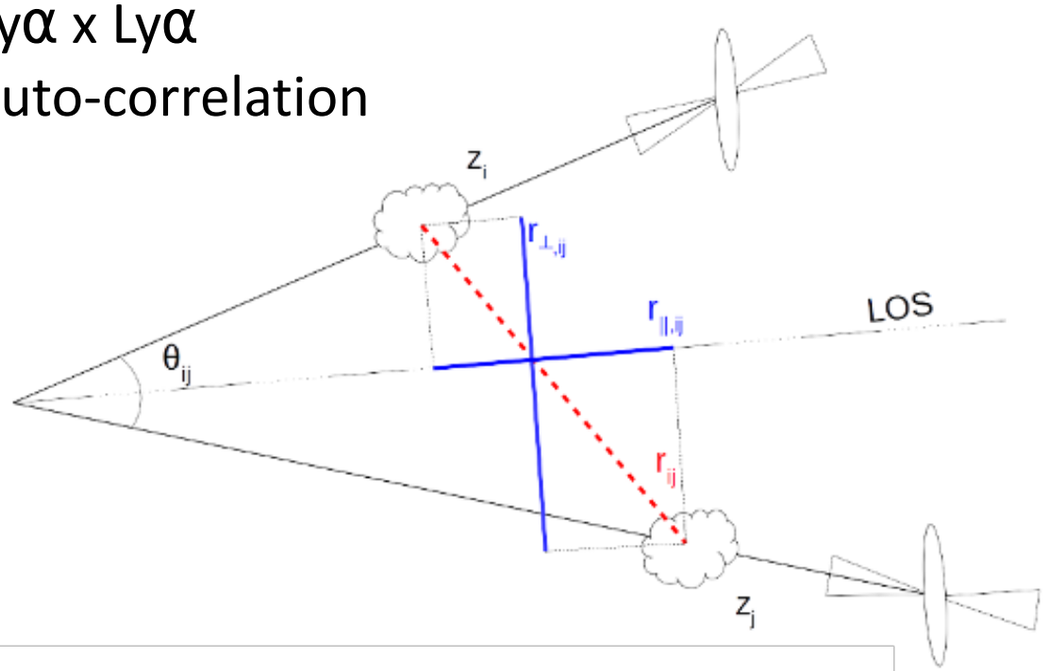
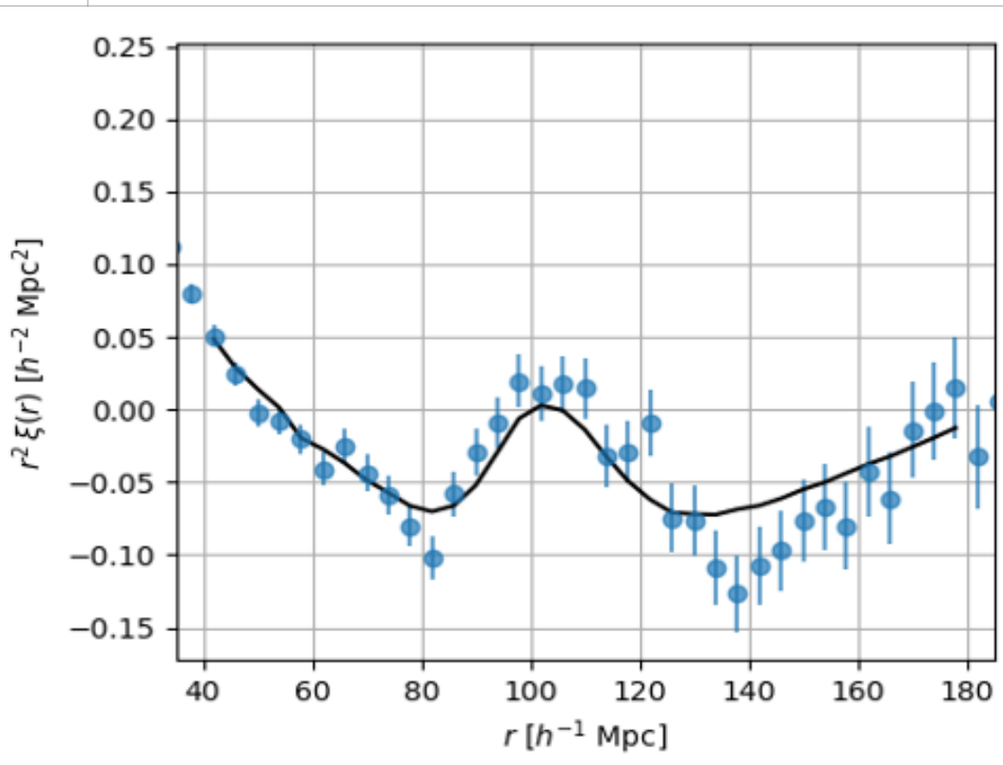
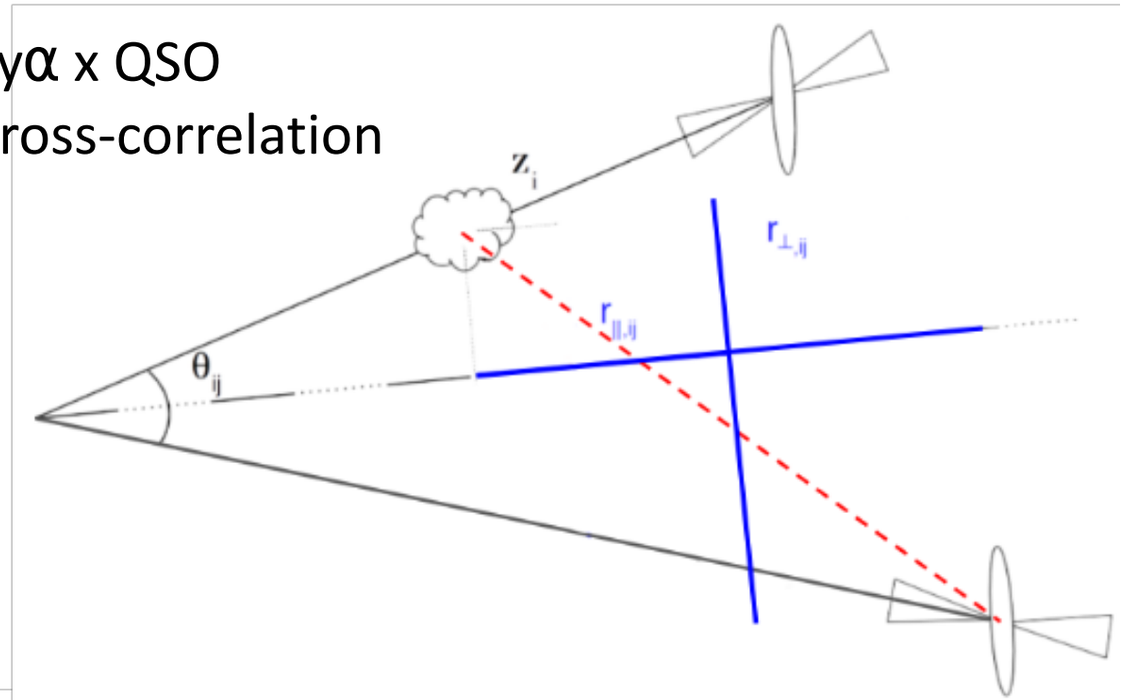
Lyα correlations in DESI Y1

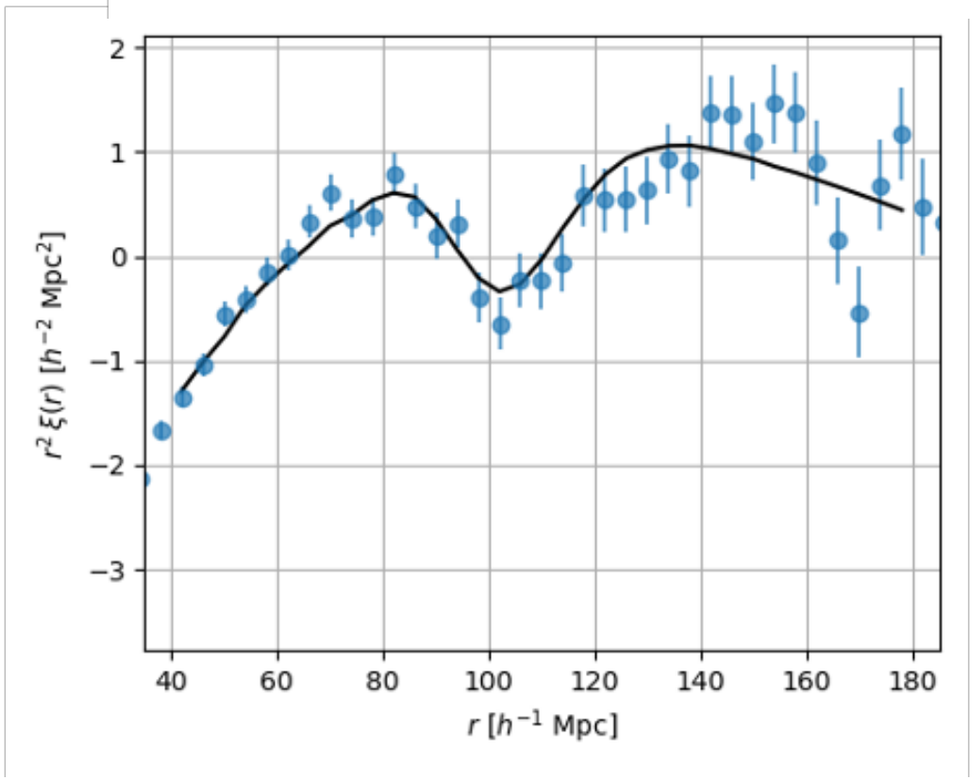
Lyα x Lyα
auto-correlation





Lyα x QSO
cross-correlation





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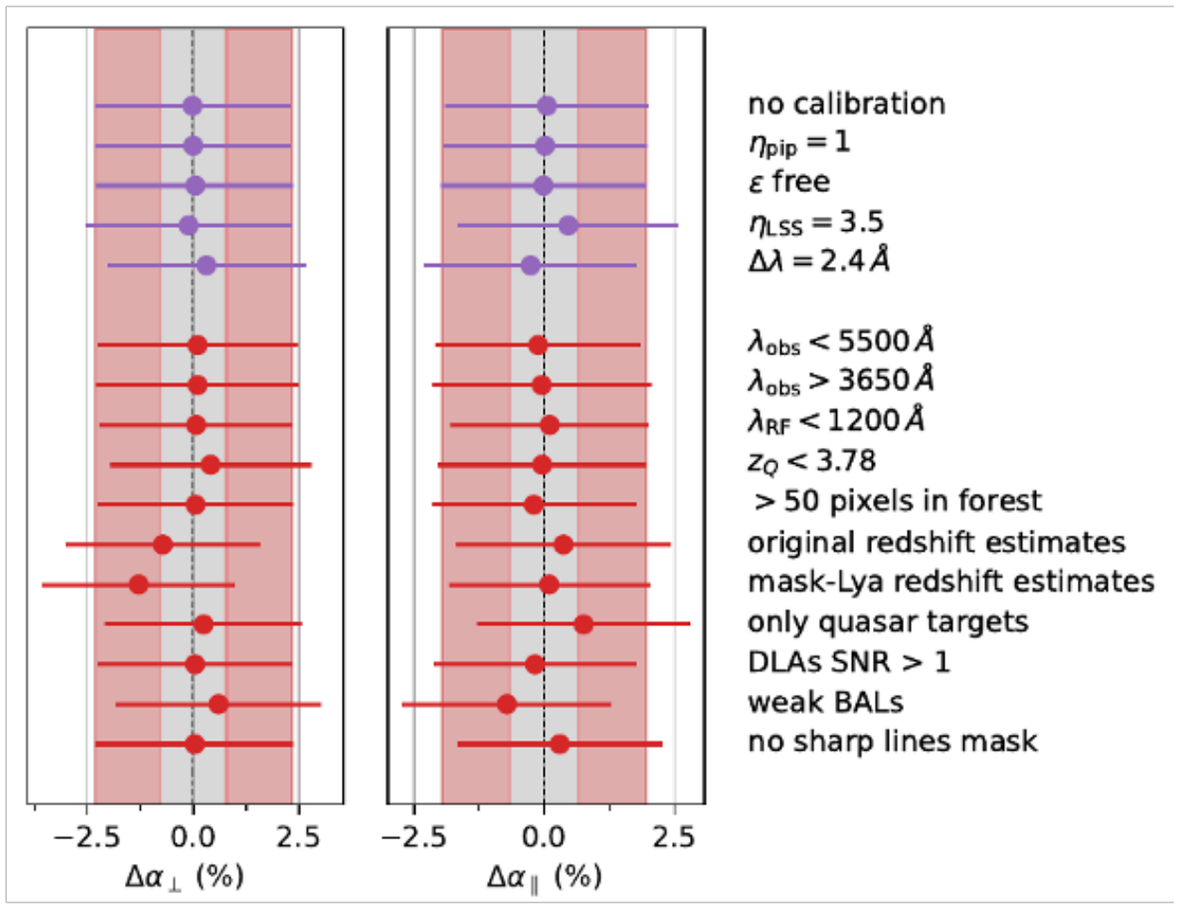
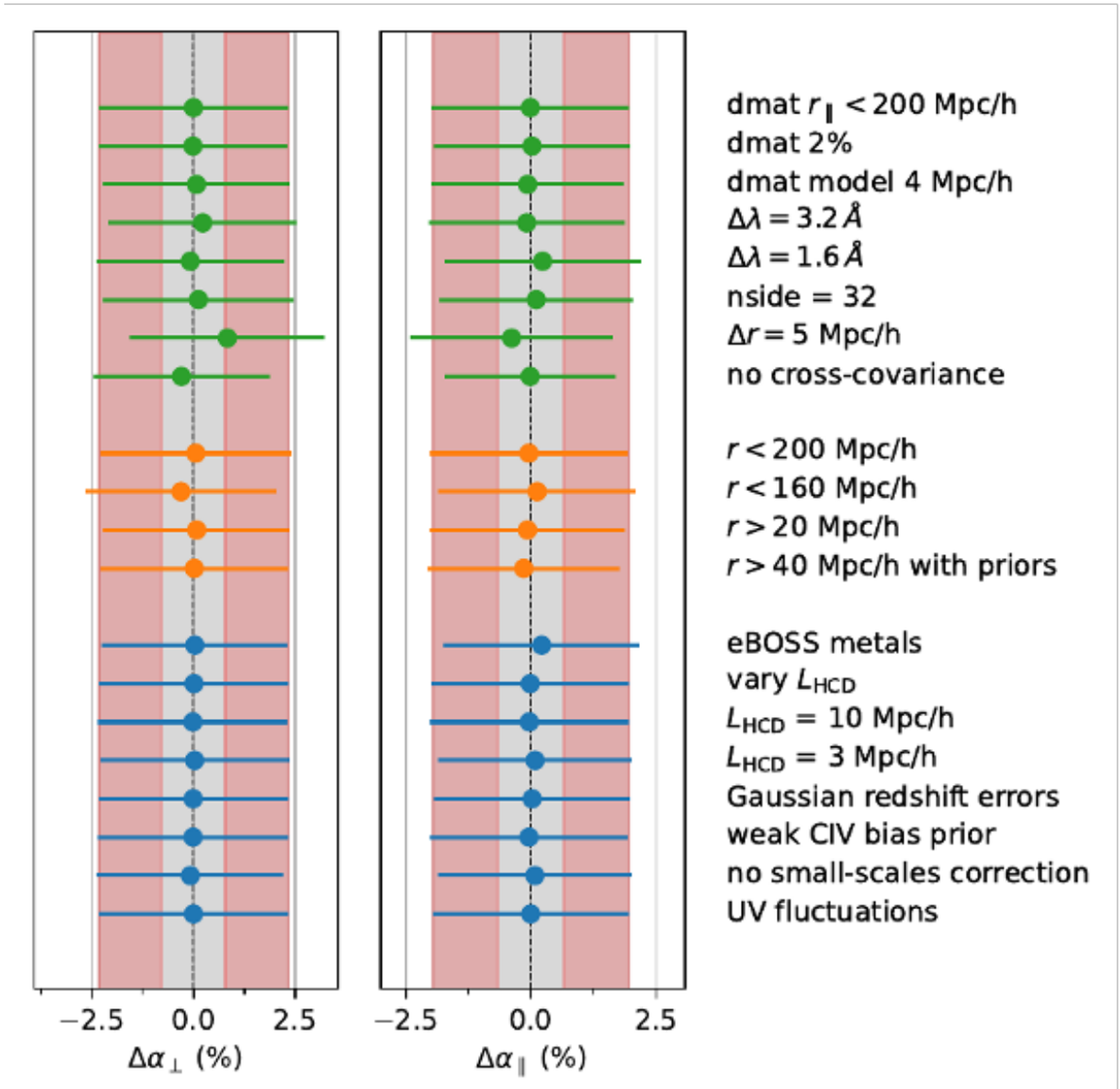
Lyα BAO: analysis validation

Robustness under variations of the (blinded) analysis





- Tests with same data set (purple, green, orange, blue):
  BAO shifts < ⅓ stat (gray band)
- Tests with varying data sets (red):
  BAO shifts consistent with statistical fluctuations

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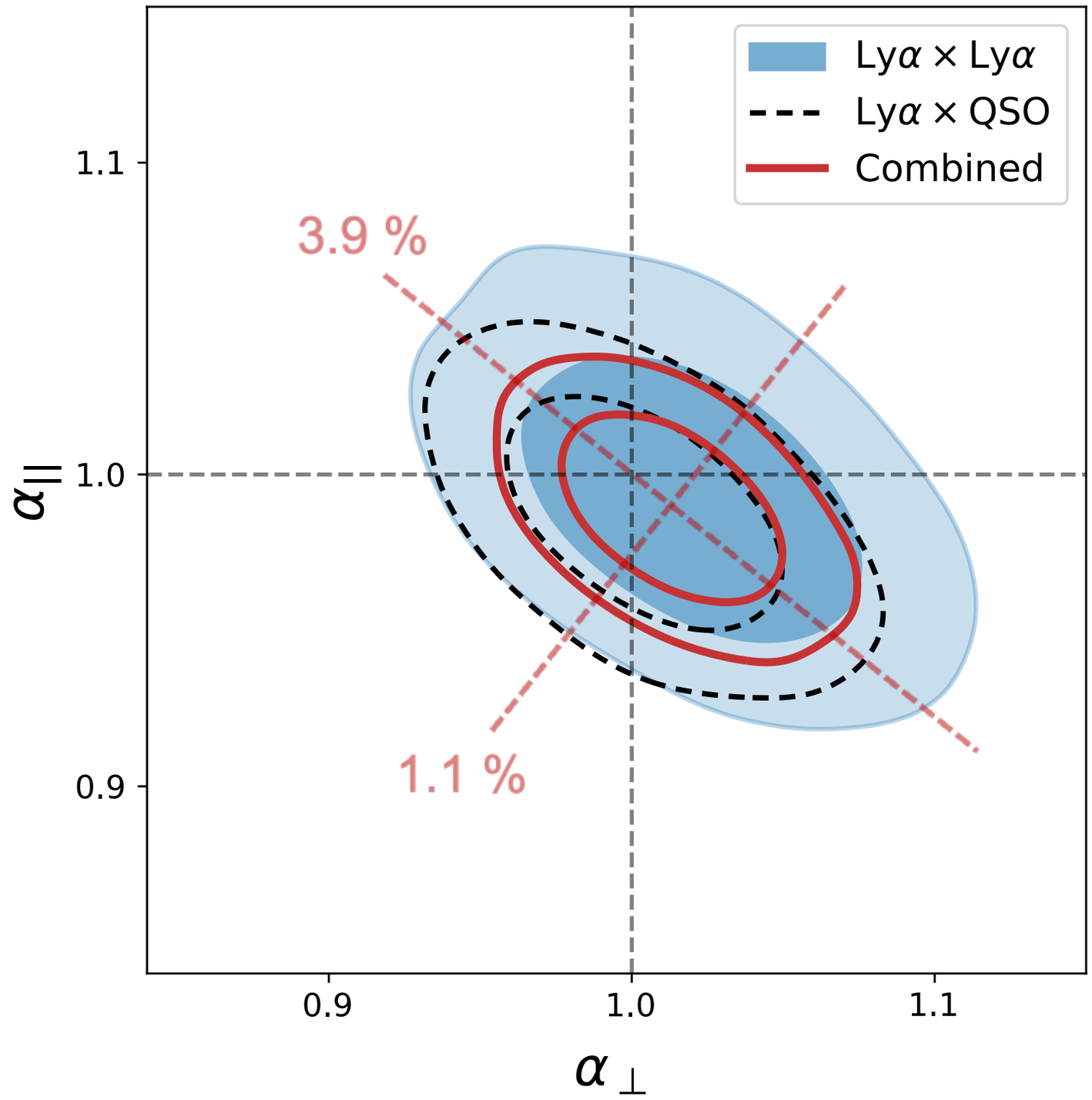
Lyα BAO: unblinded data results

$$\alpha_{\parallel} = \frac{D_H(z_{\rm eff})/r_d}{[D_H(z_{\rm eff})/r_d]_{\rm fid}}$$

$$\alpha_{\perp} = \frac{D_M(z_{\rm eff})/r_d}{[(D_M(z_{\rm eff})/r_d]_{\rm fid}}$$

$$\alpha_{\parallel} = 0.989 \pm 0.020$$

$$\alpha_{\perp} = 1.013 \pm 0.024$$



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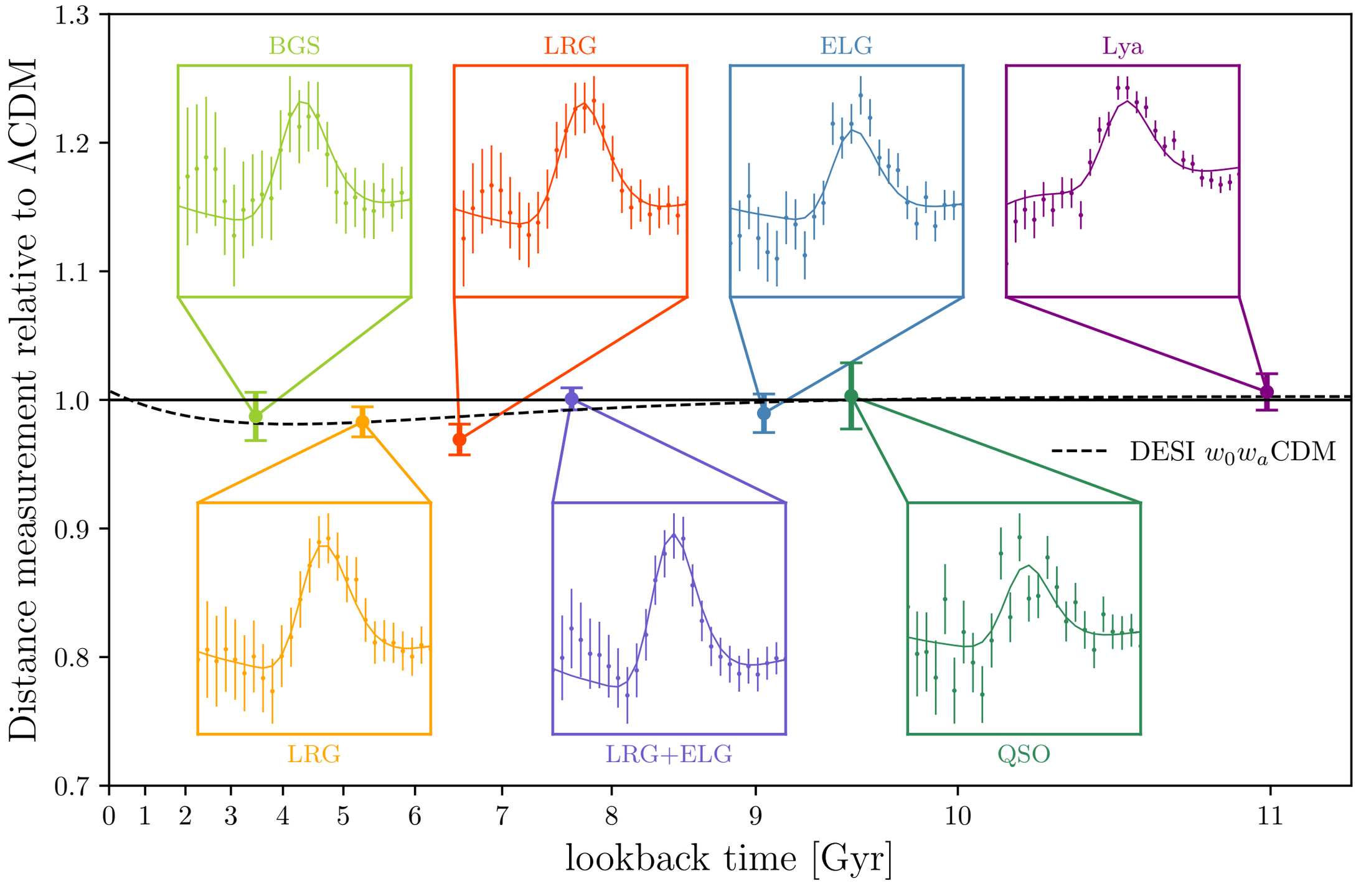
BAO from DESI Y1



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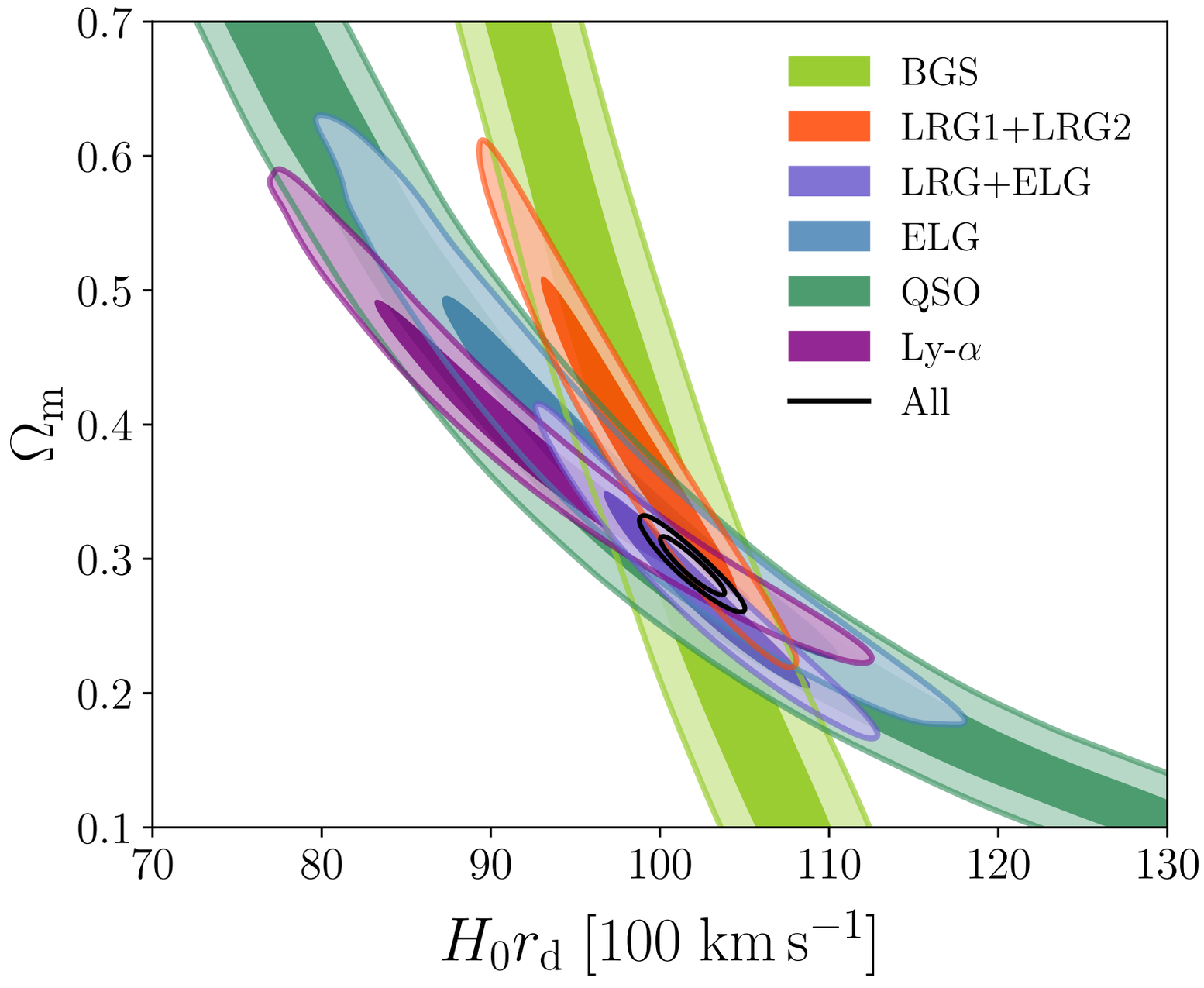
Flat ΛCDM from DESI Y1 BAO

$$\Omega_{\rm m} = 0.295 \pm 0.015$$

$$H_0 r_{\rm d} = 101.8 \pm 1.3 \ [10^2 \ {\rm km\,s^{-1}}]$$



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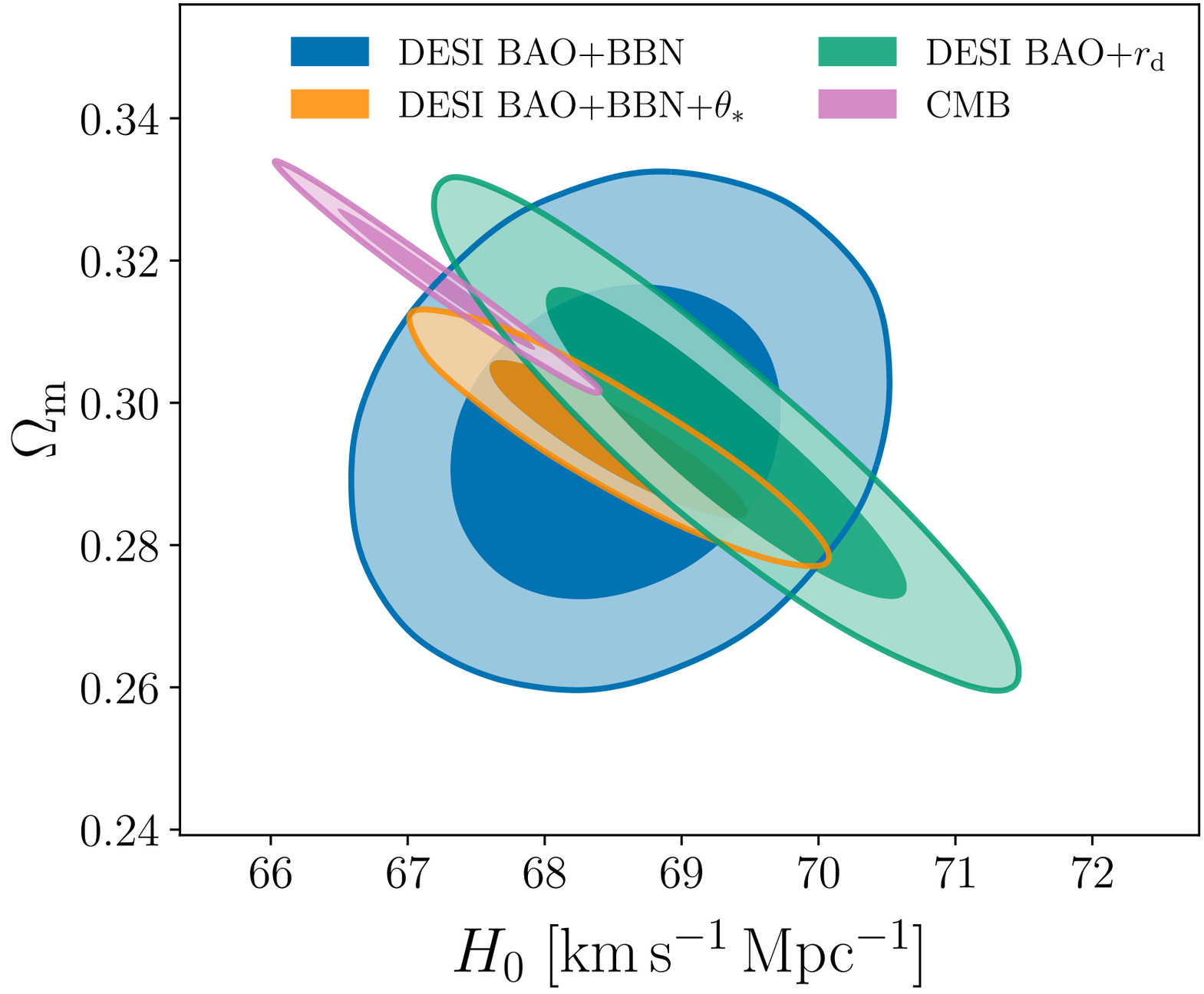
Breaking the H_0-r_d degeneracy

External information can calibrate r_d

DESI BAO + external info prefers slightly larger H_0

(but still consistent with CMB)



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DESI Y1 BAO and the Hubble tension

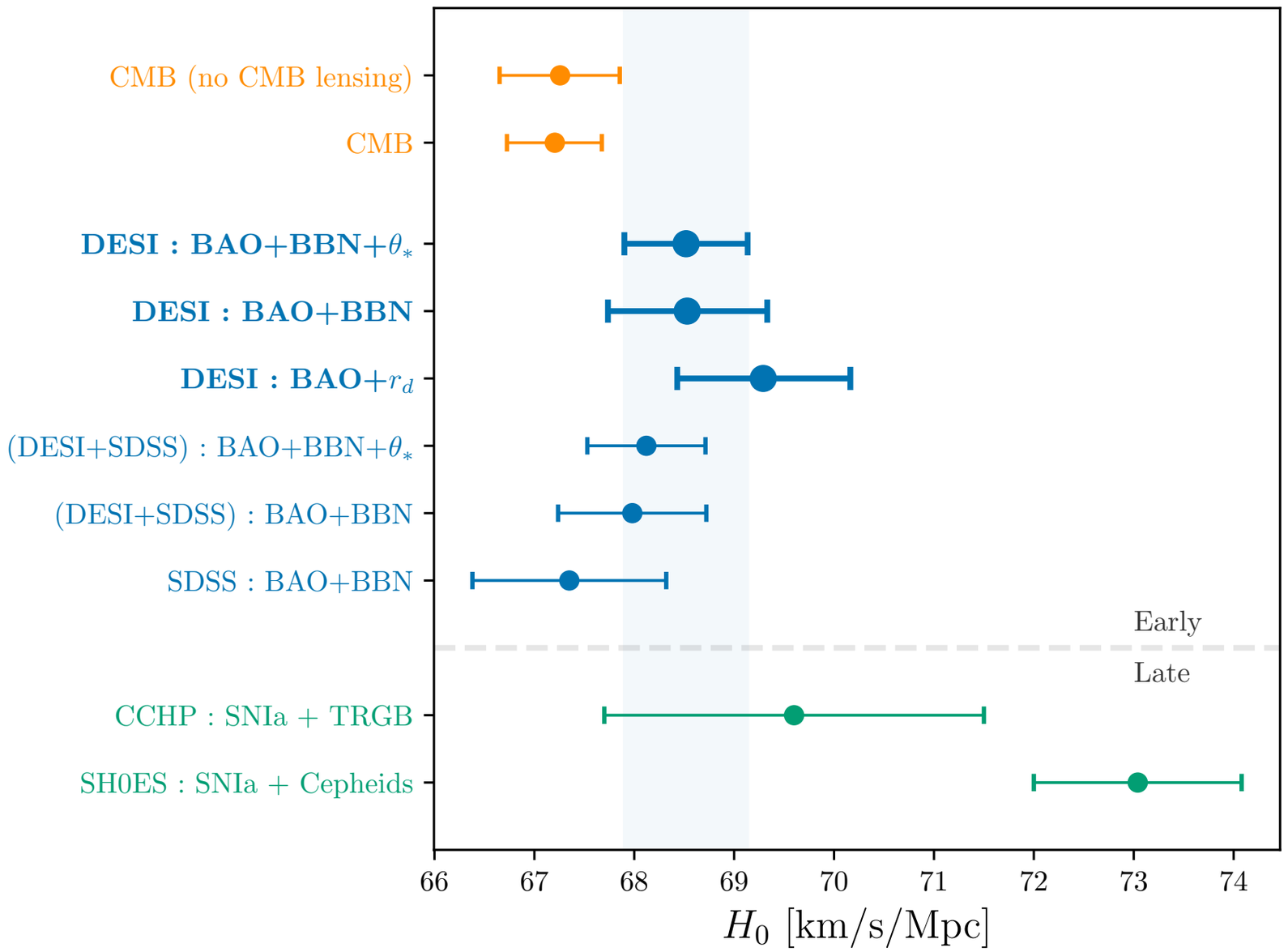
External information can calibrate $r_{\rm d}$

DESI BAO + external info prefers slightly larger H_0

(but still consistent with CMB)

DESI + CMB:

$H_0 = 67.97 \pm 0.38\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$



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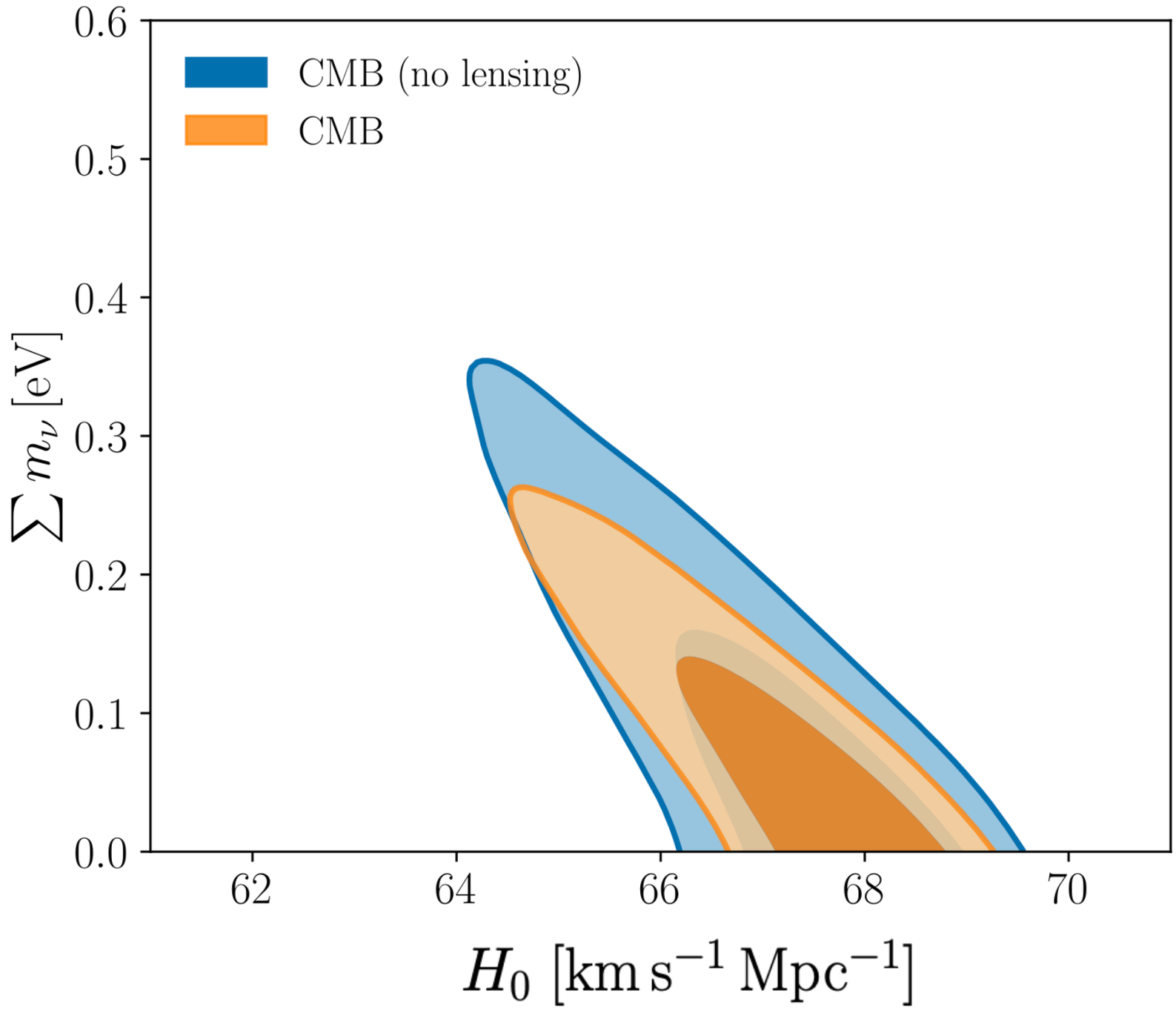
DESI Y1 BAO and neutrino masses



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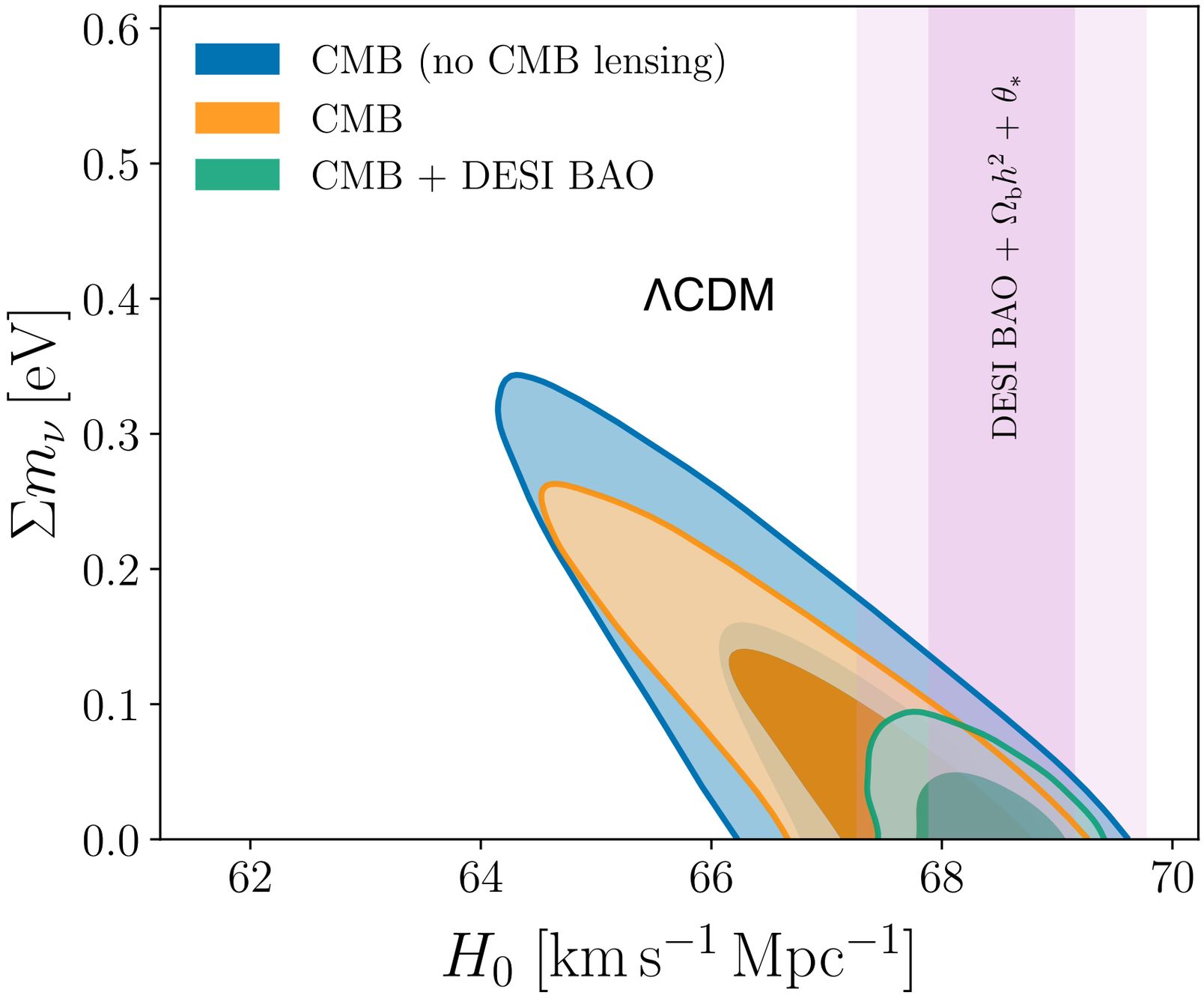
DESI Y1 BAO and neutrino masses

BAO breaks CMB degeneracy between H_0 and Σm_ν

DESI + CMB:
$\Sigma m_\nu < 0.072$ eV (95%)



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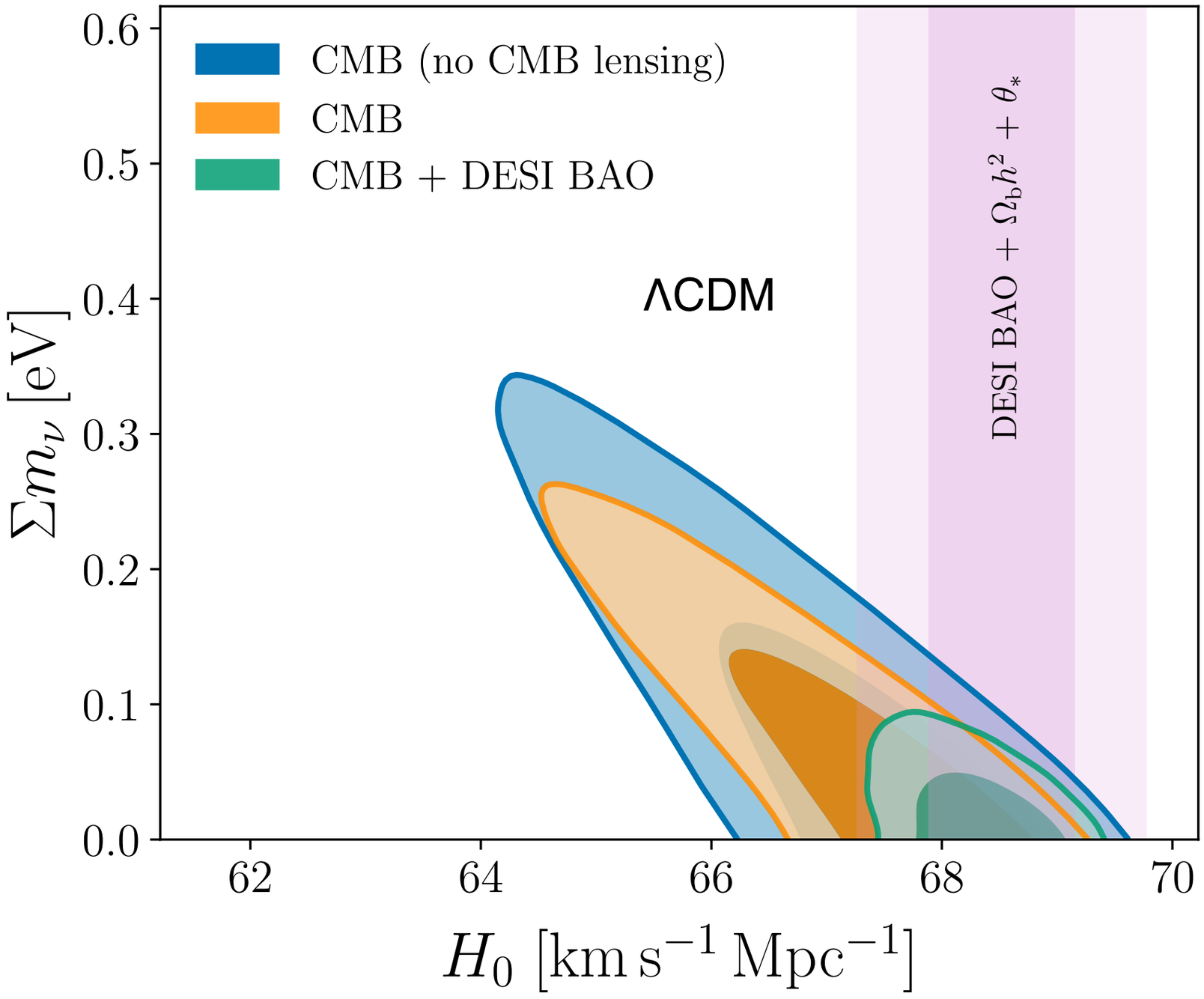
DESI Y1 BAO and neutrino masses

BAO breaks CMB degeneracy between H_0 and Σm_ν

DESI + CMB:
$\Sigma m_\nu < 0.072$ eV (95%)

But this limit is **cosmology-dependent!**

Allowing for $w(a)$:
$\Sigma m_\nu < 0.195$ eV (95%)



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DESI Y1 BAO and dark energy

Model with time-varying equation of state parameter:

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

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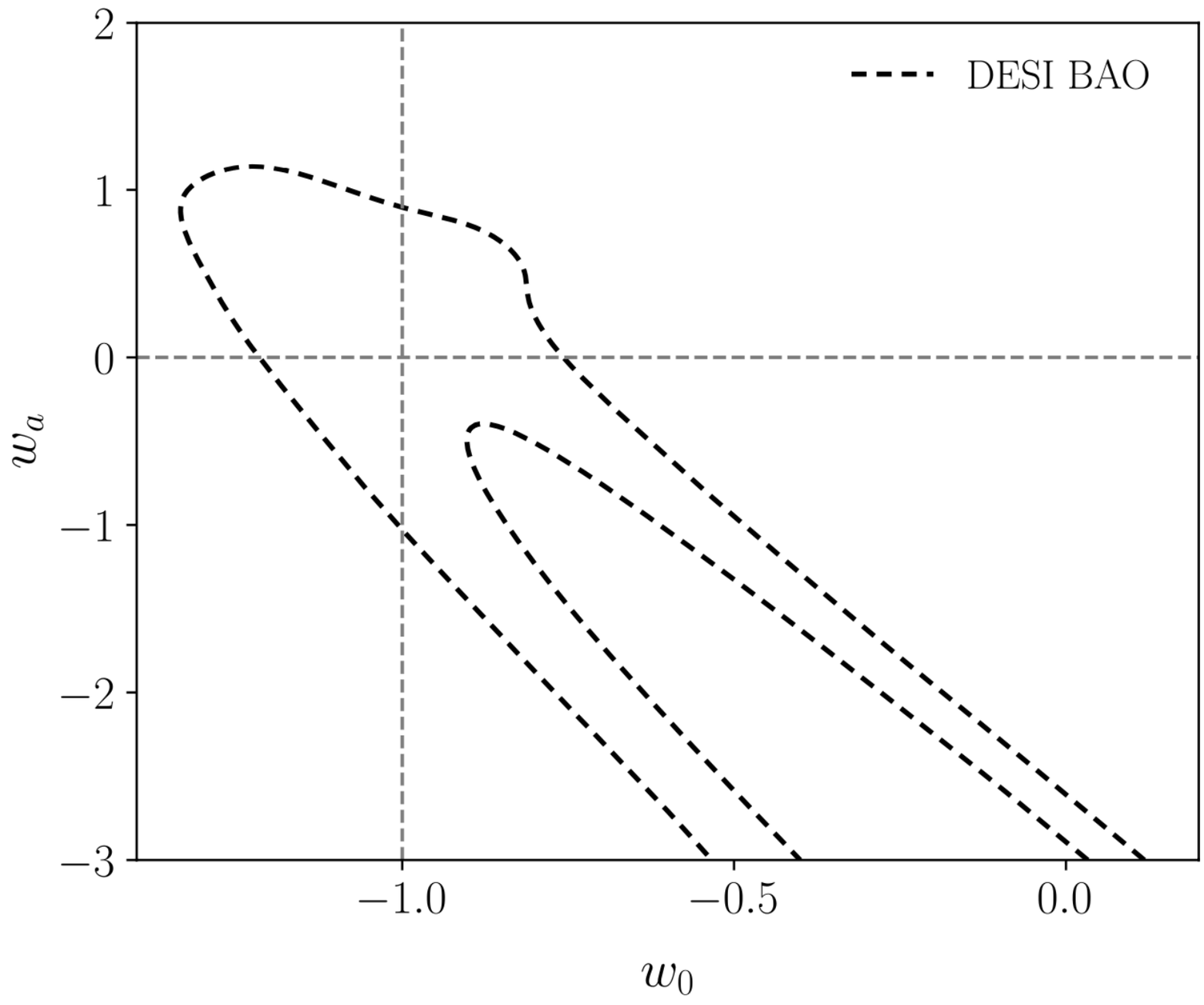

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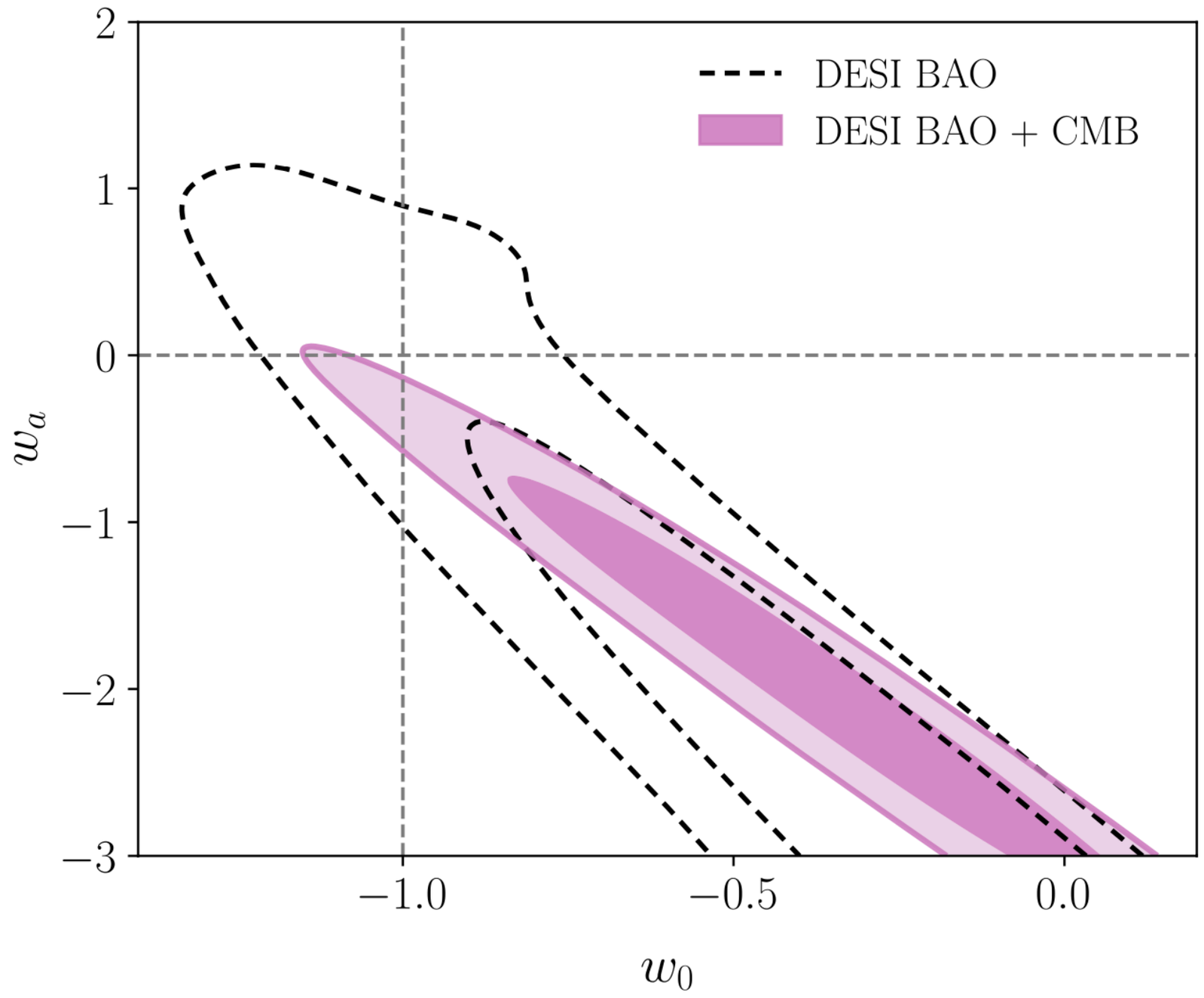

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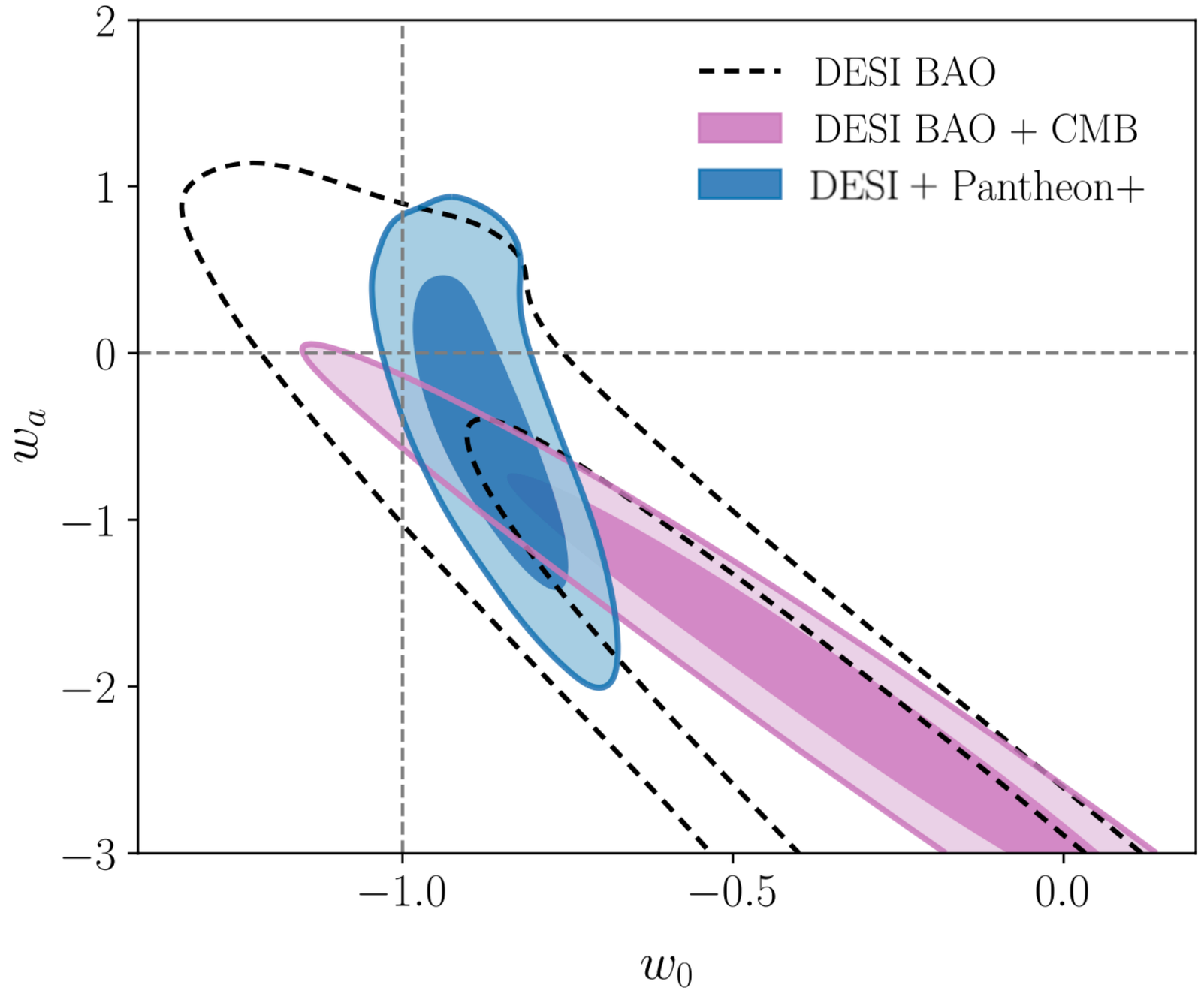
DESI Y1 BAO and dark energy

Model with time-varying equation of state parameter:

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

Pantheon+ SNIa

Scolnic et al 2022



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DESI Y1 BAO and dark energy

Model with time-varying equation of state parameter:

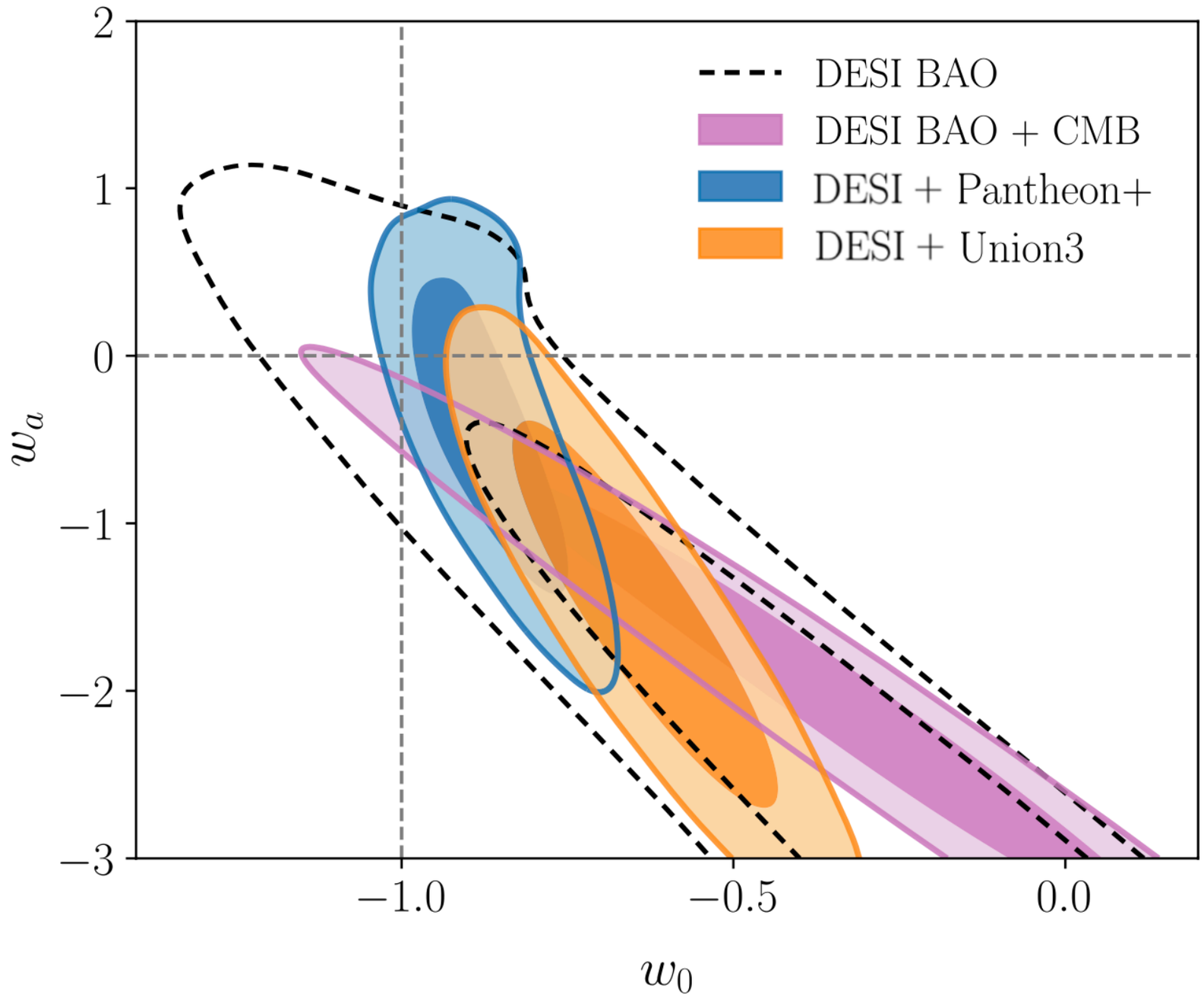
$$w(a) = w_0 + w_a(1 - a)$$

Pantheon+ SNIa

Scolnic et al 2022

Union3 SNIa

Rubin et al 2024



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DESI Y1 BAO and dark energy

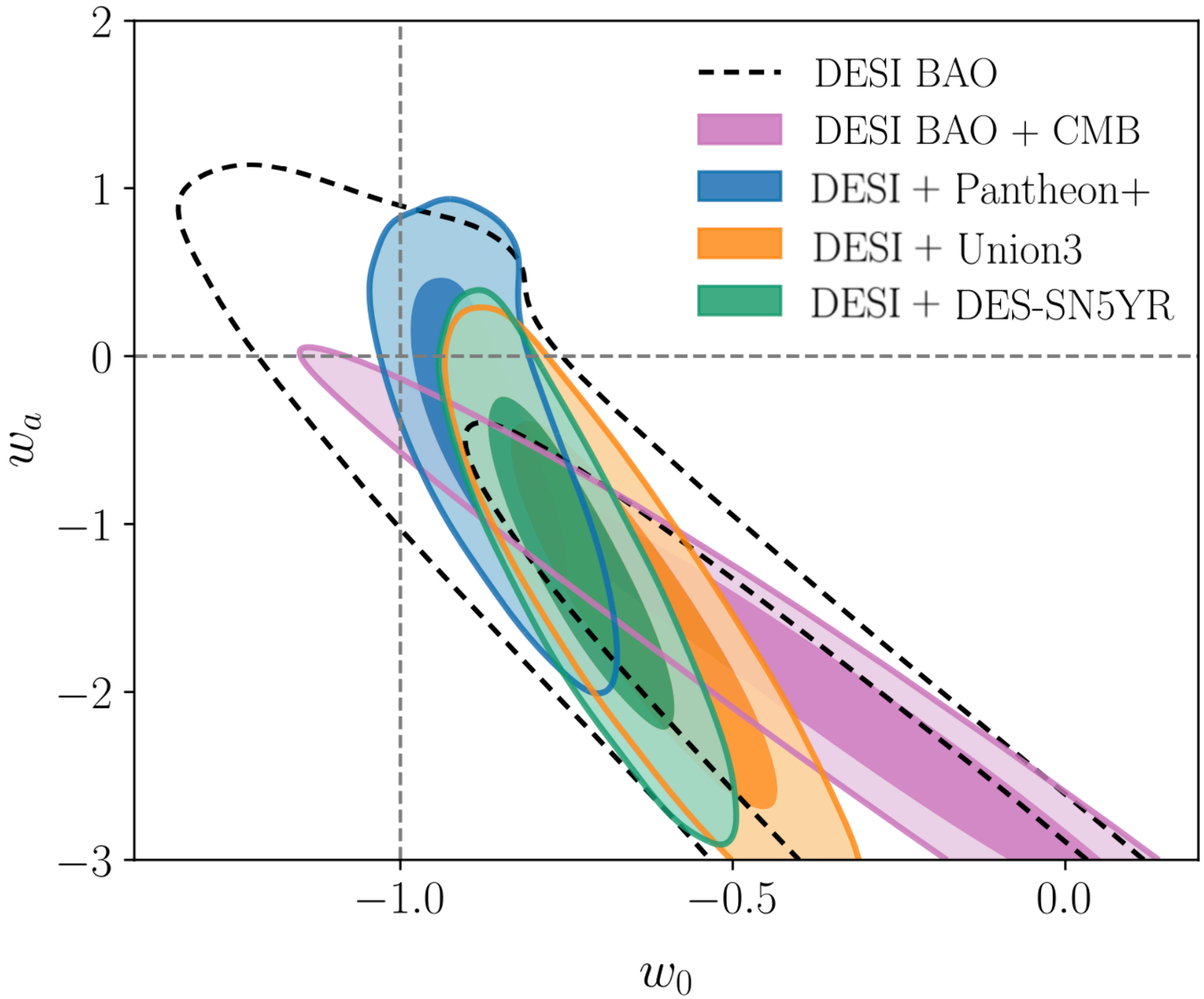
Model with time-varying equation of state parameter:

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

Pantheon+ SNIa
Scolnic et al 2022

Union3 SNIa
Rubin et al 2024

DES-SN5YR SNIa
Davis et al 2024



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DESI Y1 BAO and dark energy

Level of discrepancy with ΛCDM from

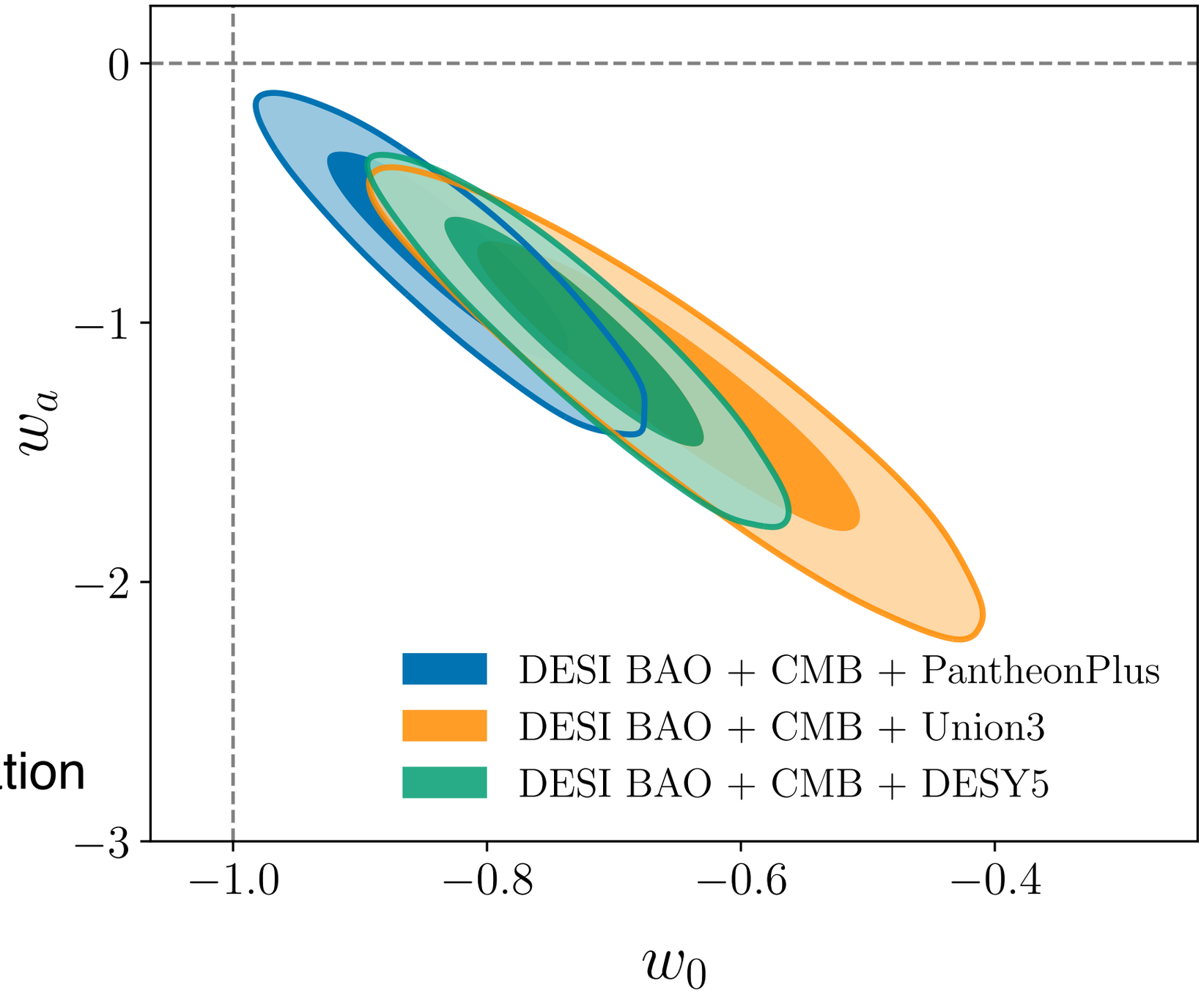
DESI Y1 BAO + CMB +

PantheonPlus: 2.5σ

Union3: 3.5σ

DES-SN5YR: 3.9σ

Hints of a time-varying equation of state of dark energy



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Summary and outlook

- DESI Y1 already has the **most precise BAO** measurements ever **(~0.5%)**
- DESI Y1 BAO + external priors give **~1% precision** on H_0
- Consistent with CMB in flat ΛCDM
- Very tight neutrino mass constraints in flat ΛCDM
- Hints of **time-varying DE equation of state**
- Check out the papers! https://data.desi.lbl.gov/doc/papers/

What's next?

- "Full-shape" $P(k)$ Y1 analysis – results very soon!
- Y3 data collection completed in spring 2024 – new BAO results expected in spring 2025
- Final Y5 DESI dataset will be ~4xY1 – results 2026+
- Then DESI-II, Spec-S5,…

Thanks a lot to Andreu Font-Ribera, whose slides I have extensively used for this talk

Extra Slides

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Galaxy BAO: Tests of systematic errors

We tested for many possible sources of systematic error using mocks and data:

- observational effects in data (imaging, fiber assignment etc)
- reconstruction algorithm
- covariance matrix construction

no BAO error detected

- incomplete theory modelling
- choice of fiducial cosmology
- galaxy-halo (HOD) model uncertainties

Systematic errors << statistical

Max. effect: $\sigma_{\rm total} = 1.05\sigma_{\rm stat.}$