Cosmology from the DESI Year 1 Baryon Acoustic Oscillations Measurements

Uendert Andrade

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On behalf of the DESI collaboration

XIII The International Conference on New Frontiers in Physics @ Crete, Greece - Aug 28, 2024

Outline

- The Dark Energy Spectroscopic Instrument (DESI) Overview
  - What is DESI? What does it do? How does it do it?
- DESI observables
  - BAO measurements
  - ~~Full Shape measurements~~
- Blind Watchers of the Sky
- Cosmological Constraints from DESI BAO

The Dark Energy Spectroscopic Instrument (DESI)

For over six decades, the Kitt Peak National Observatory has resided on the **Tohono O'odham Nation** upon the Quinlan Mountains, also known to the O'odham as **I'ilogam Du'ag** (manzanita bush mountain). [Ramon-Sauberan, J. (2021)]

DESI Survey: Making the Largest 3D Map of the Universe

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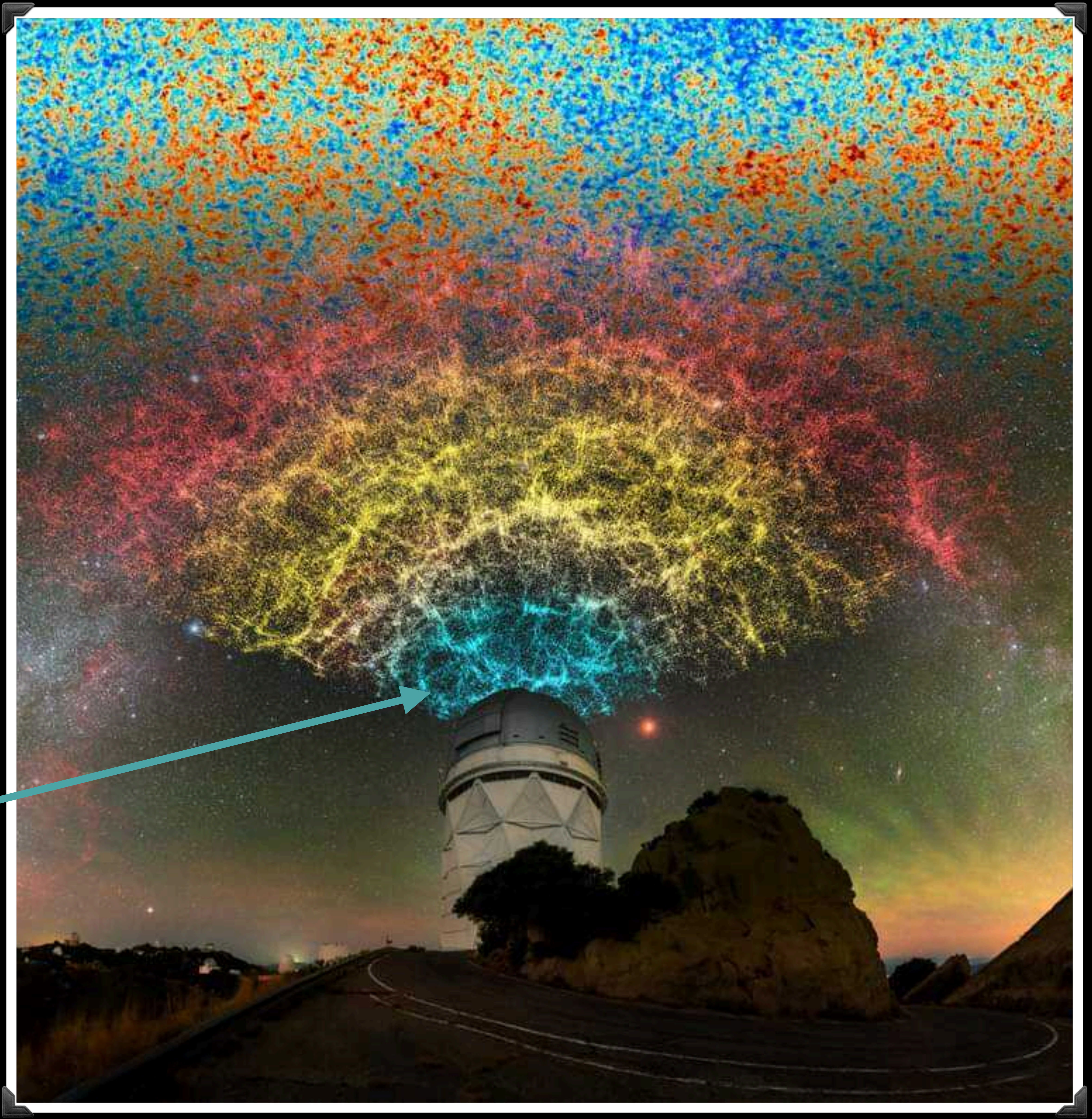

13.5 million Bright Galaxies
(0.0 < z < 0.4)

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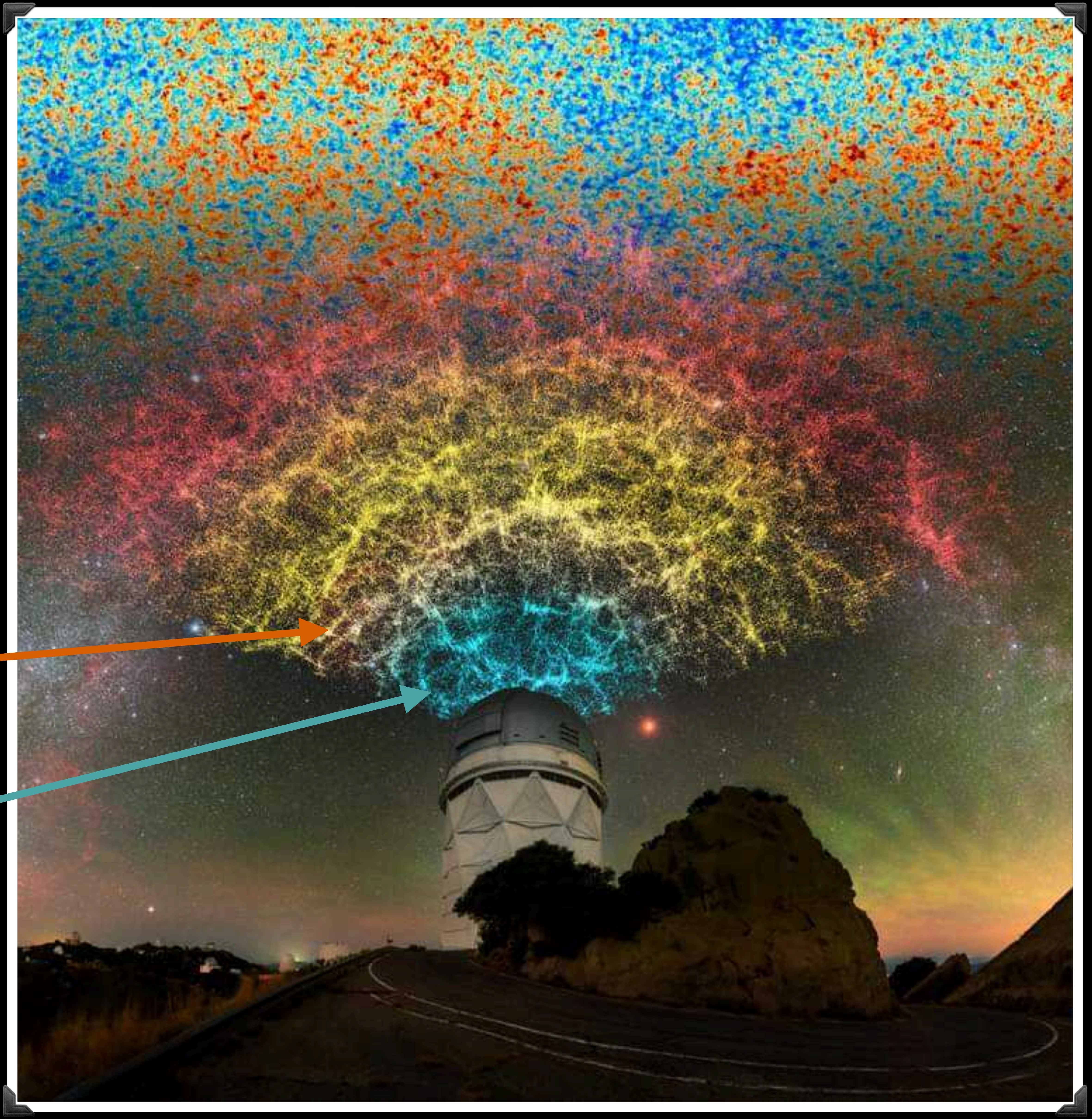

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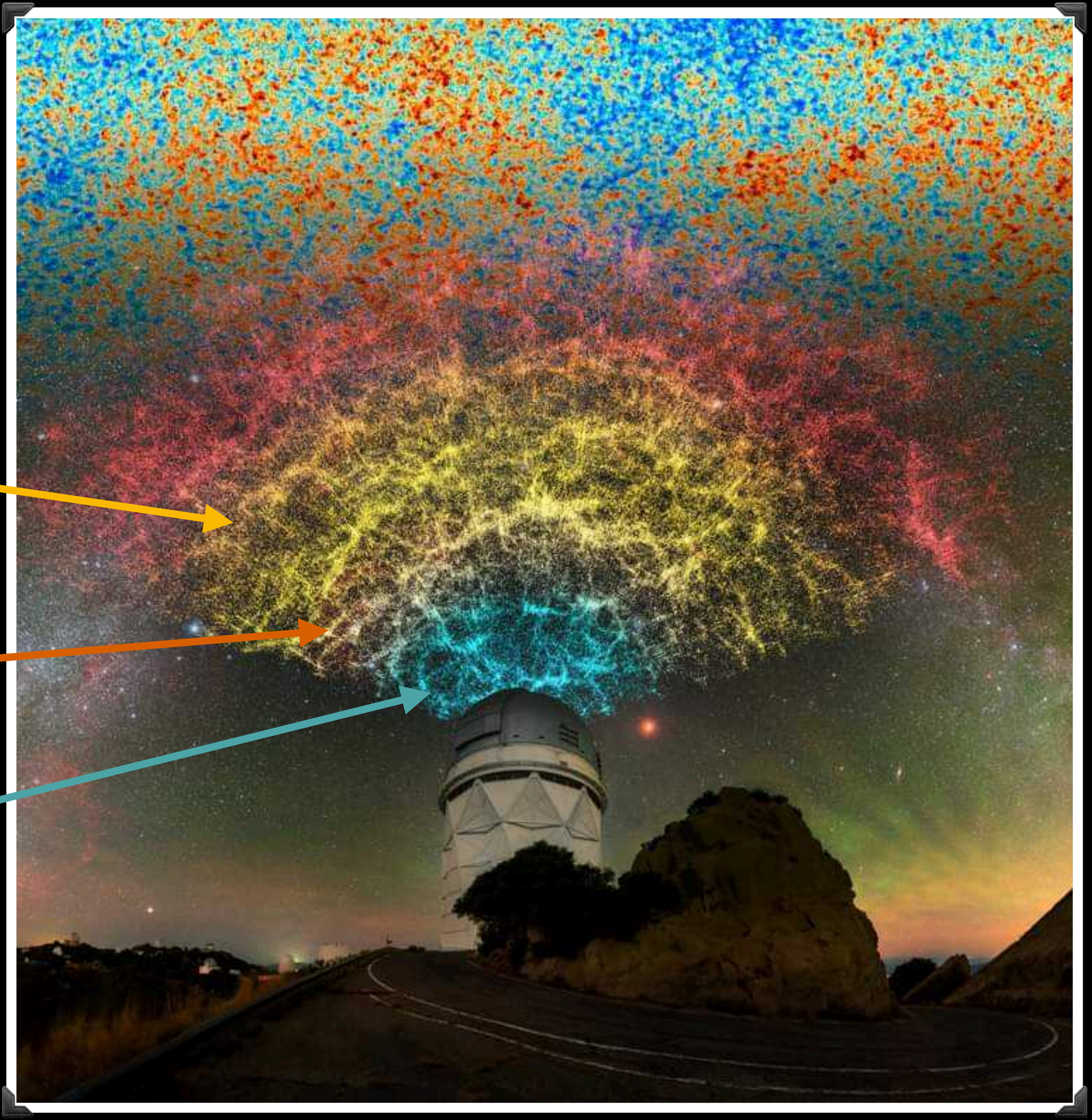

16 million Emission Line Galaxies
(0.6 < z < 1.6)

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DESI Survey: Making the Largest 3D Map of the Universe

3 million
Quasars ($0.9 < z < 2.1$)
+ Ly-a forest ($2.1 < z$)

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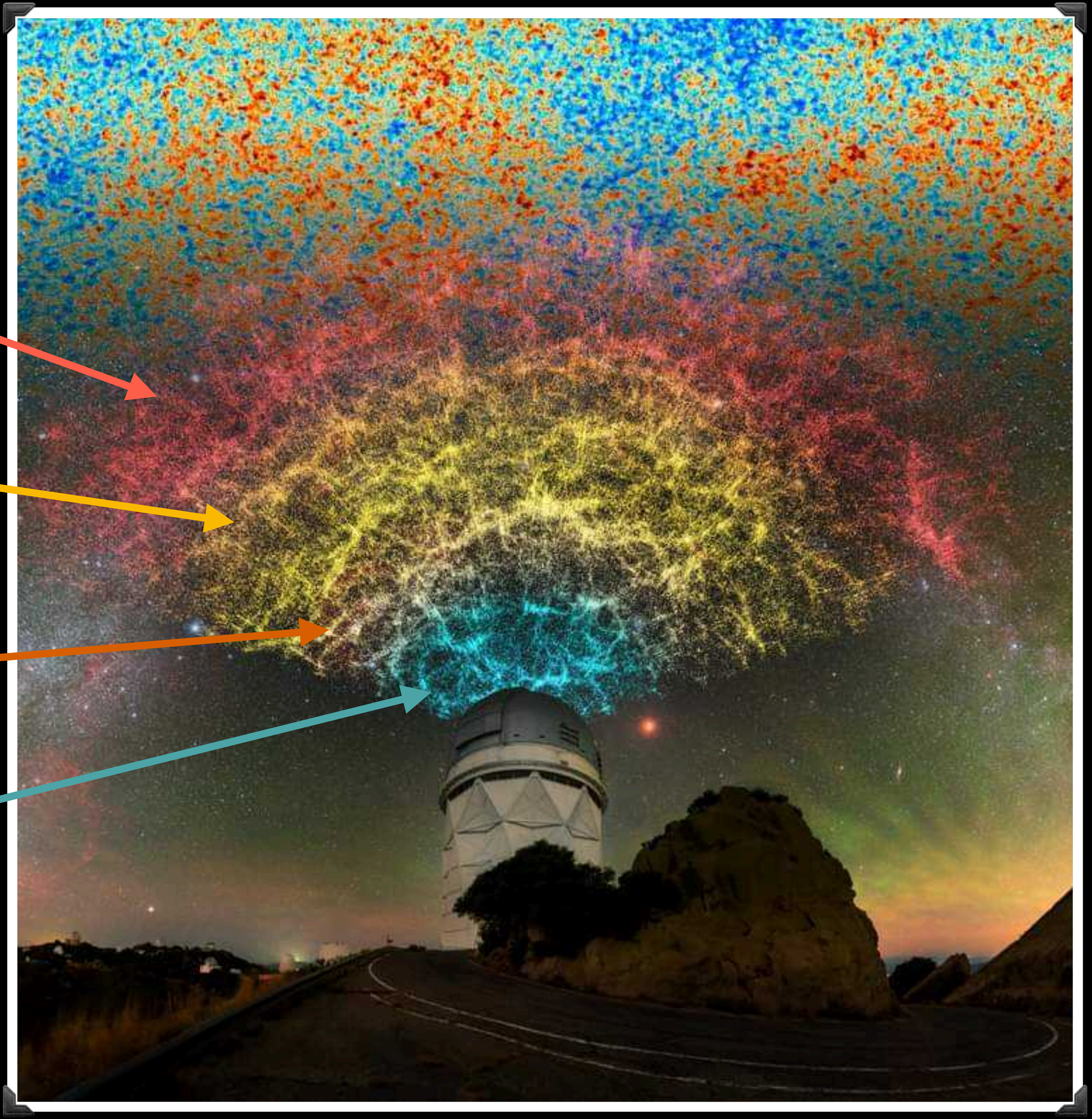

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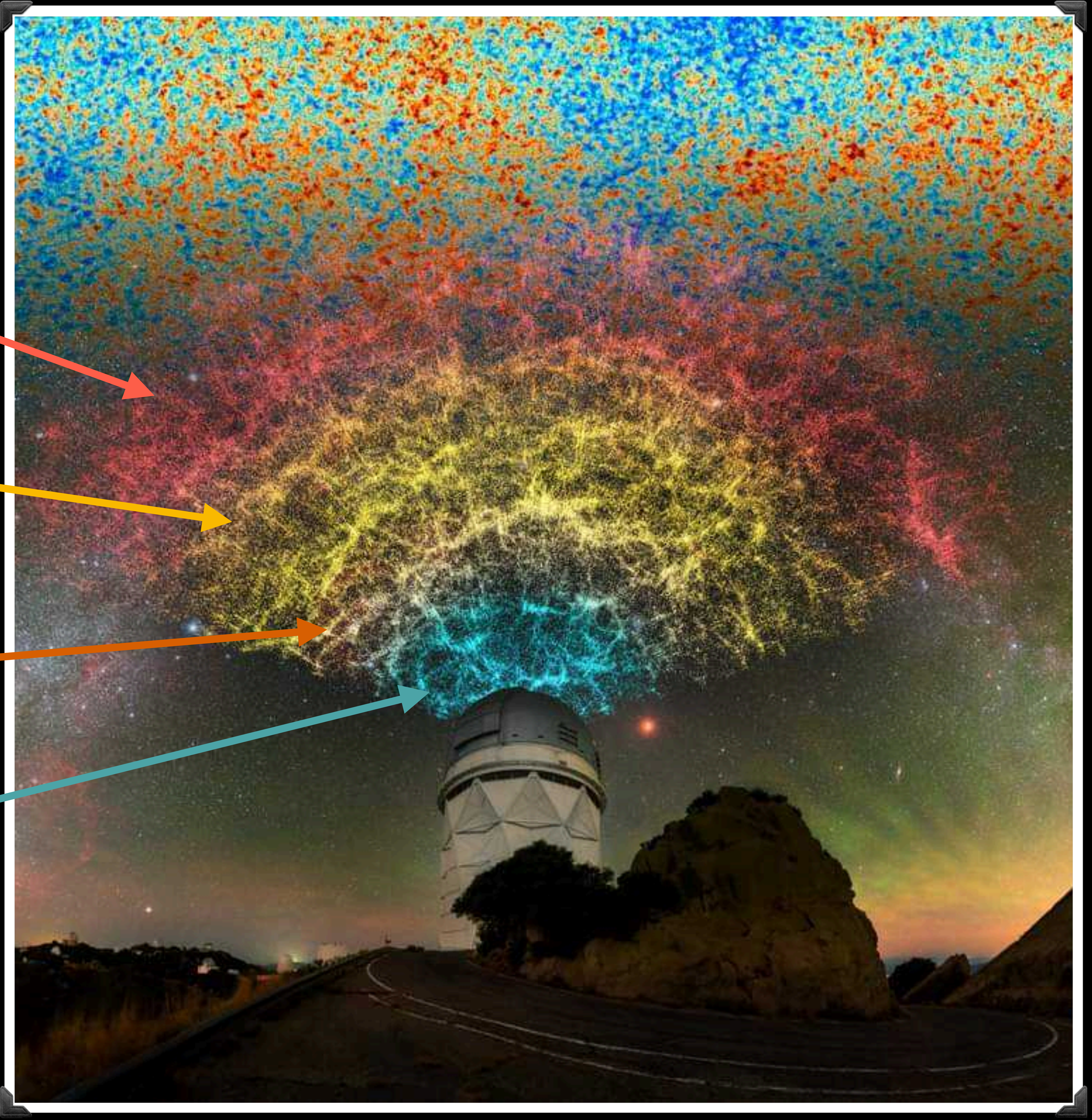

From 2021-2026 DESI will measure precise redshifts to ~40 million galaxies over 14,000 deg2 .

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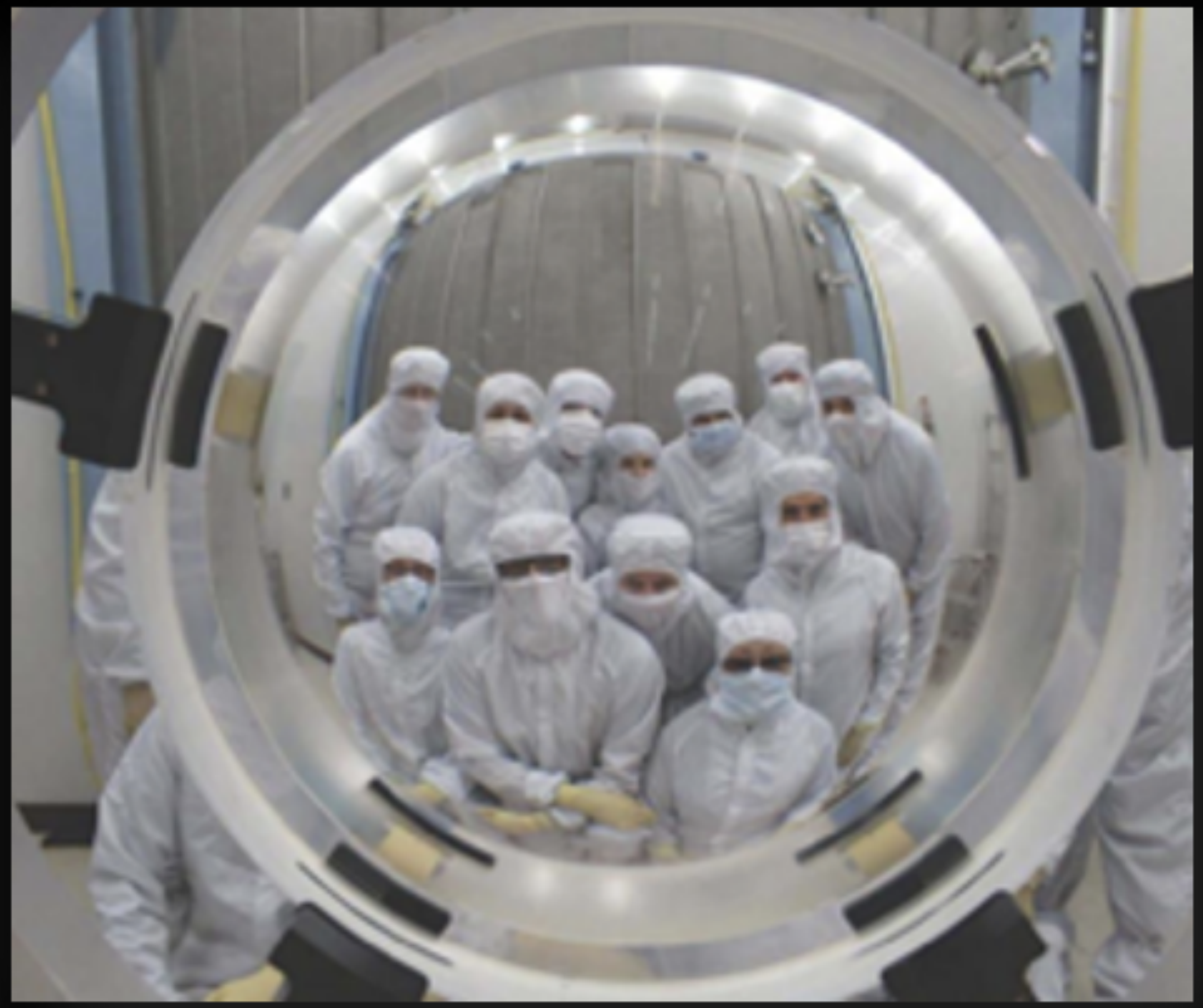
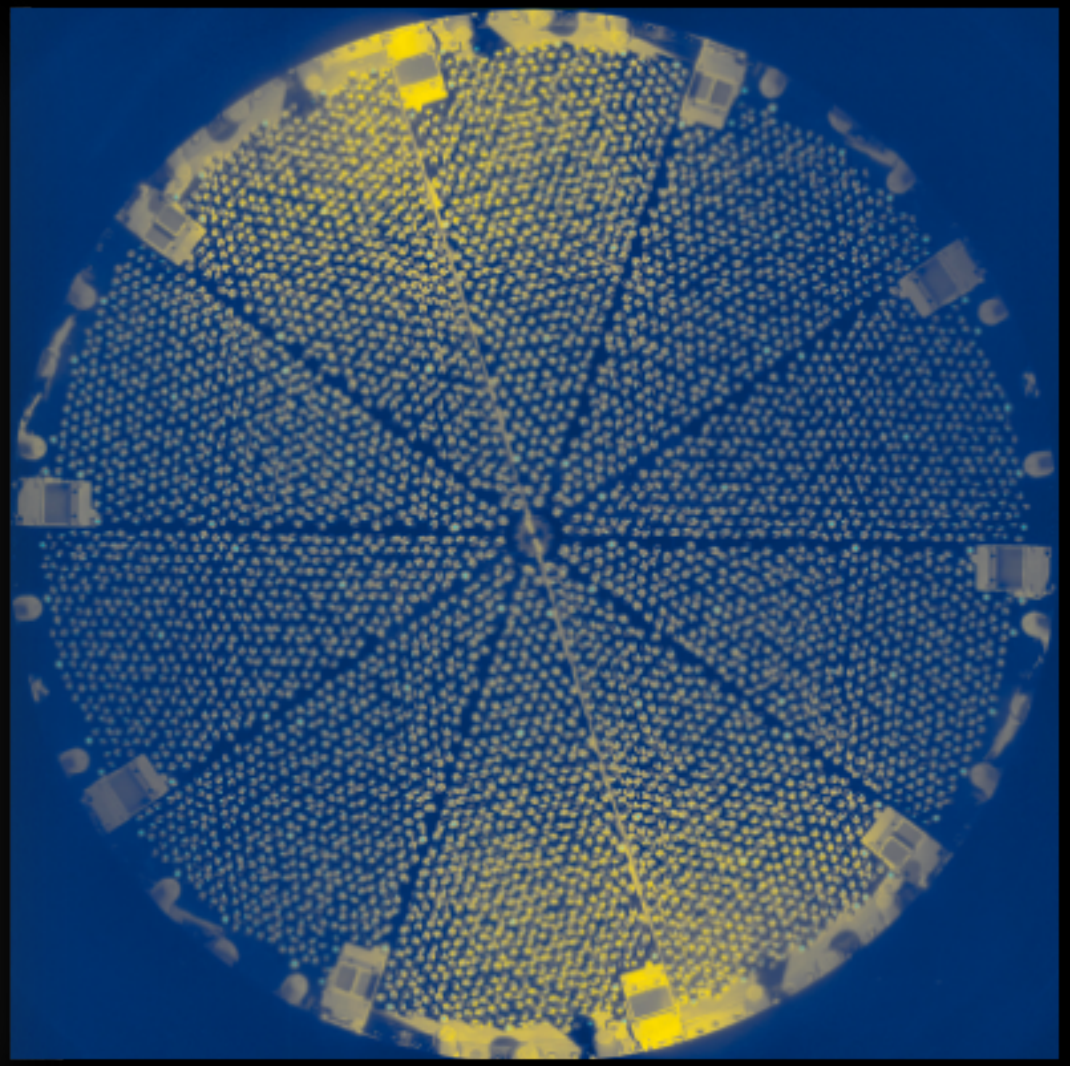
Key DESI Components

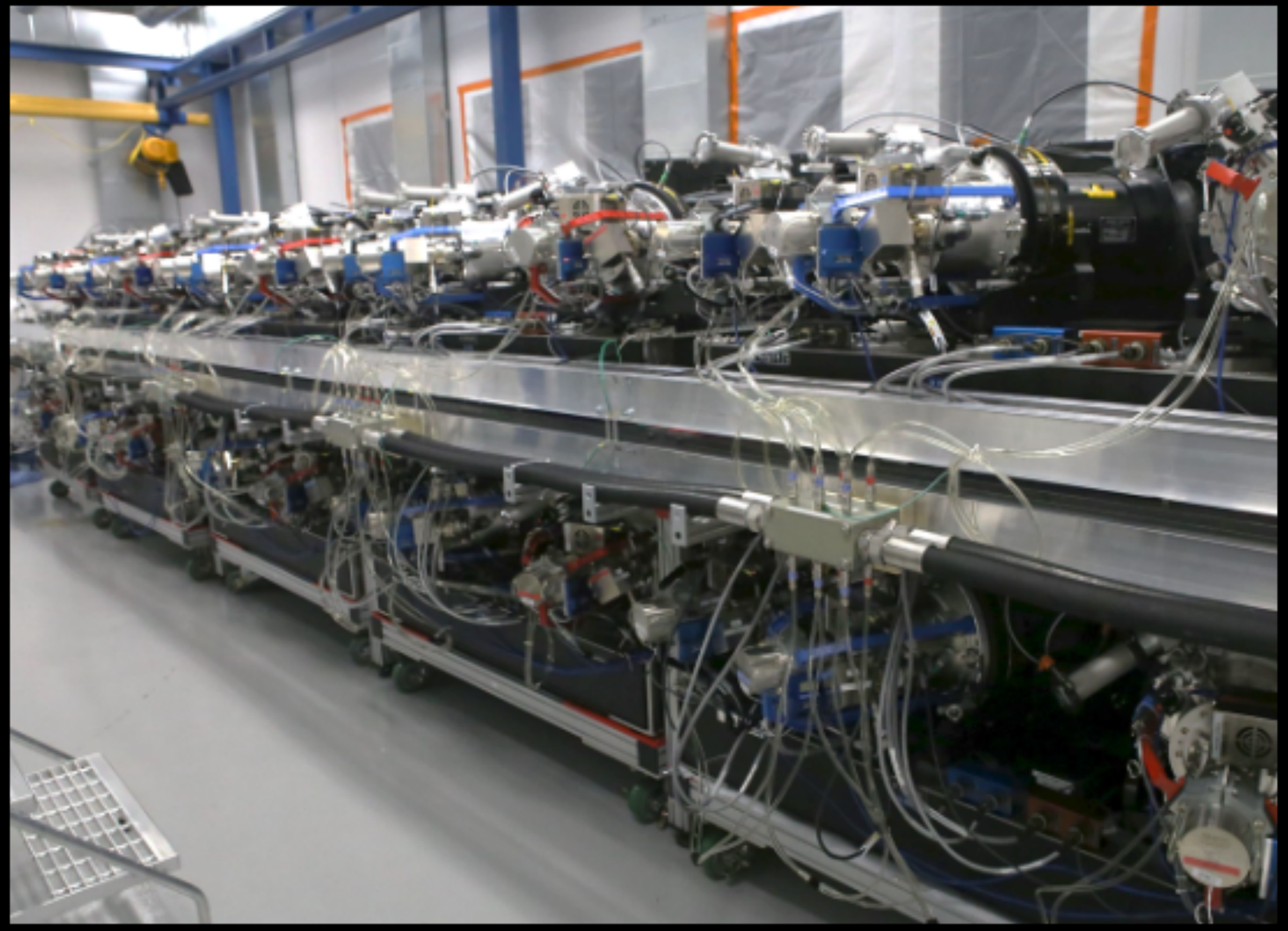
4m Mayall Telescope, KPNO, Arizona, USA



Wide Field Corrector 8 sq. deg. Field of View



Focal Plane with 5,000 Fiber Positioners

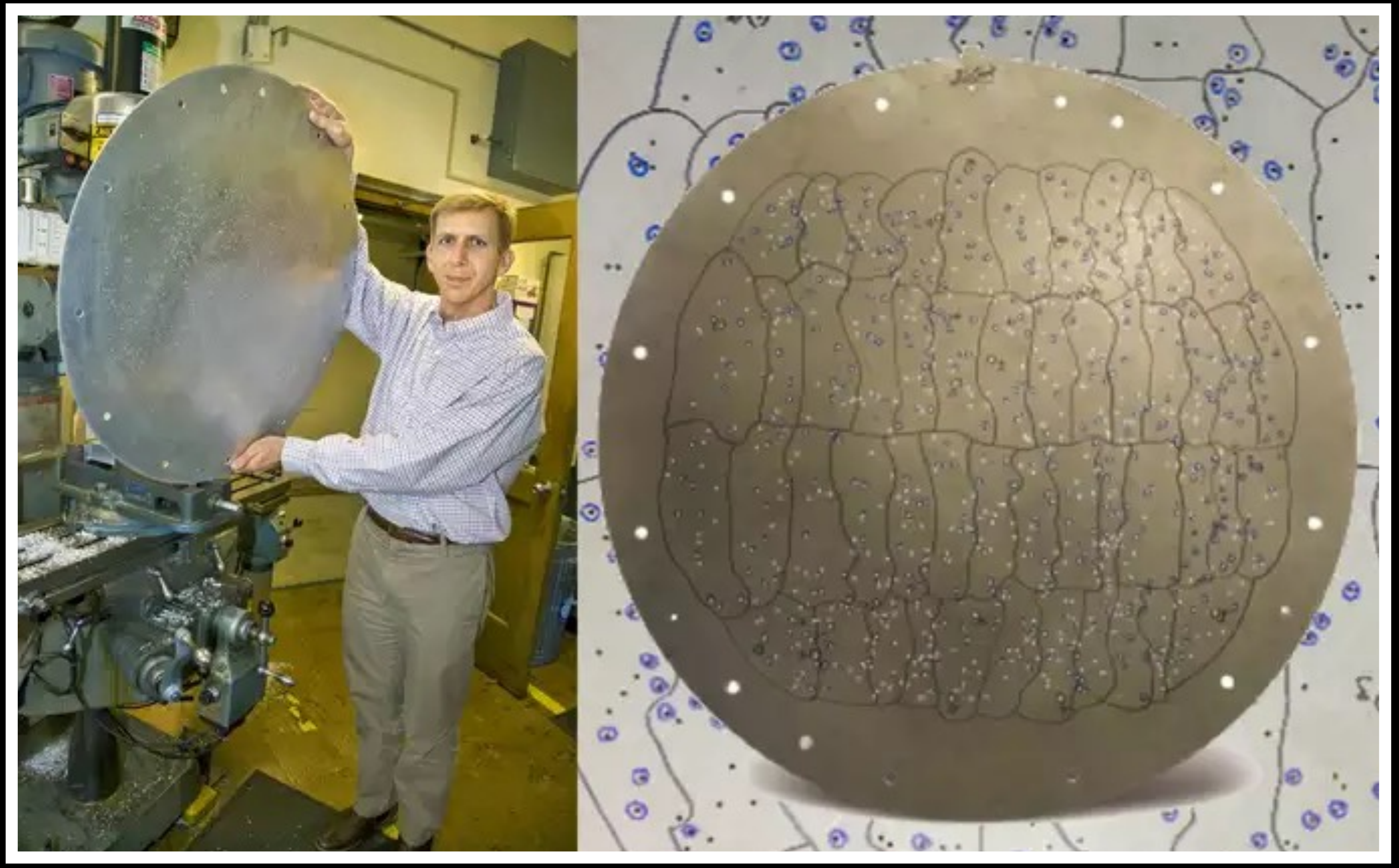


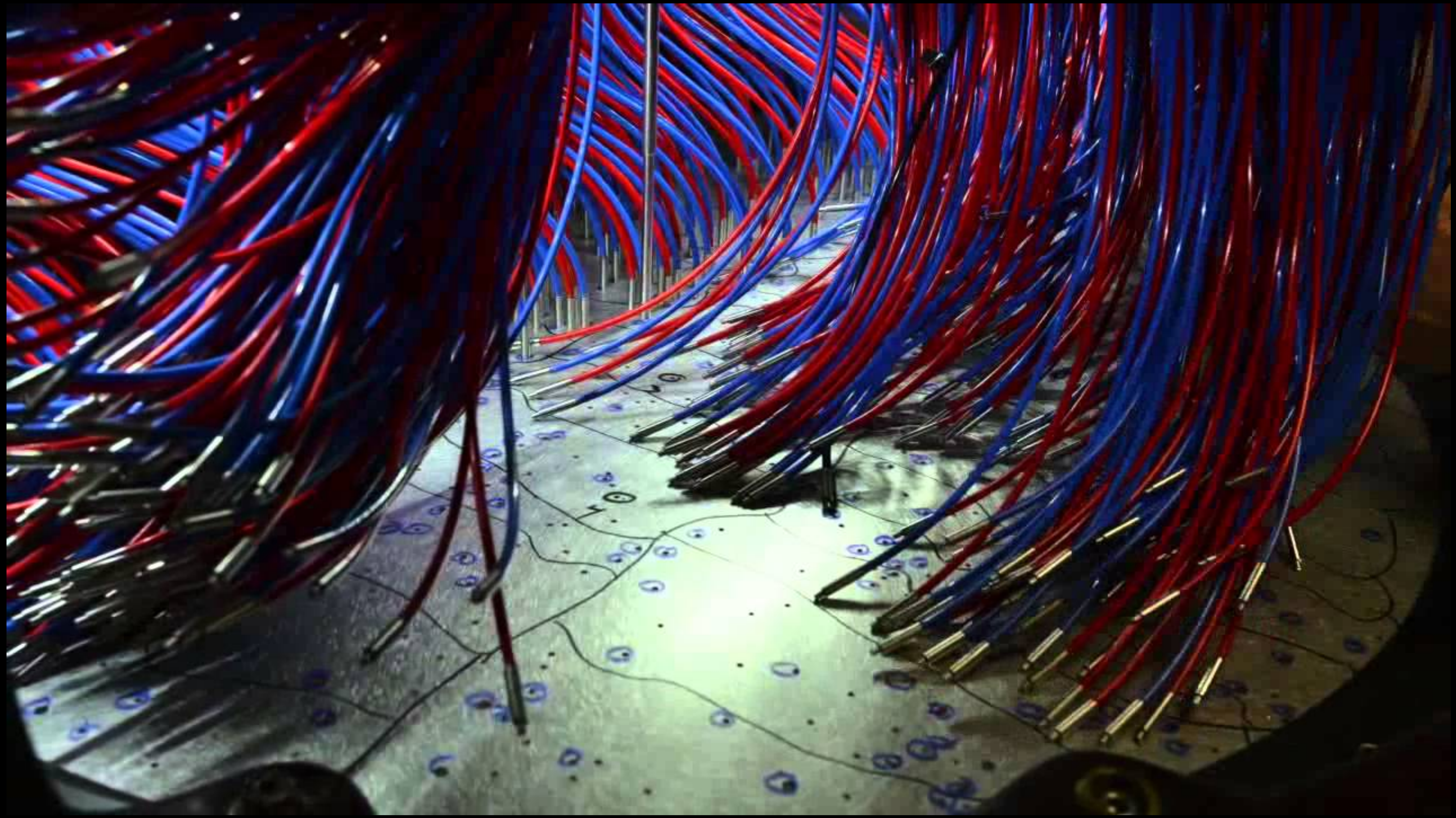
10 Multi-Object Spectrographs

Designed to optimize survey throughput:

- 5,000 fibers, wide field corrector, 10 spectrographs → maximum number of simultaneous targets
- remotely controlled fiber positioners; align, position, readout in parallel → minimum reconfiguration time
- dynamic field selection, exposure time calculator, autofocus → maximum operational efficiency

Fiber assignment before DESI





**Process of plugging optical fibers into plates
for observations for the Sloan Digital Sky Survey (SDSS)**

**Each plate can take anything from 30 mins to several hours
to be plugged by the expert SDSS Plate Pluggers.**

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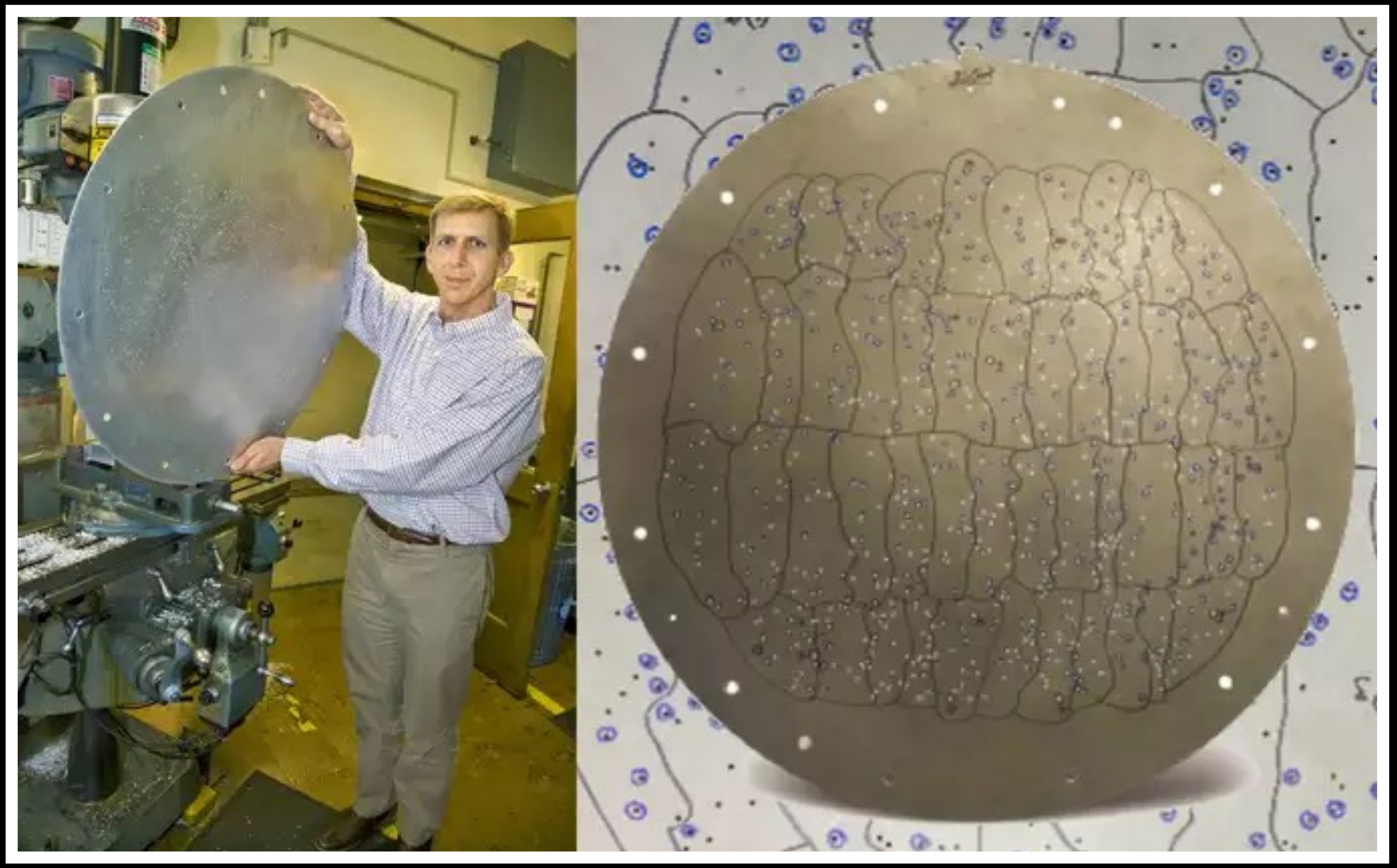

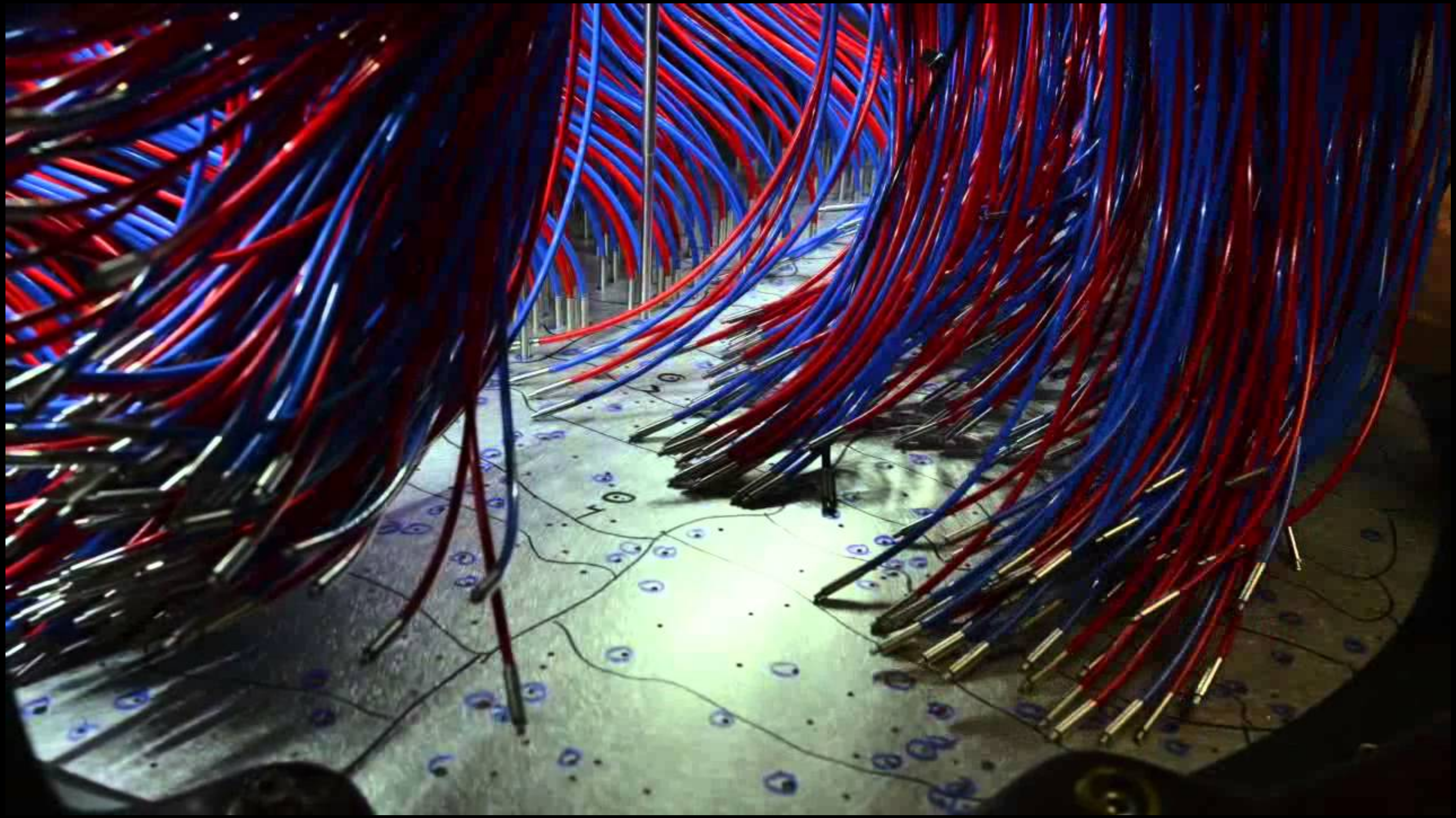

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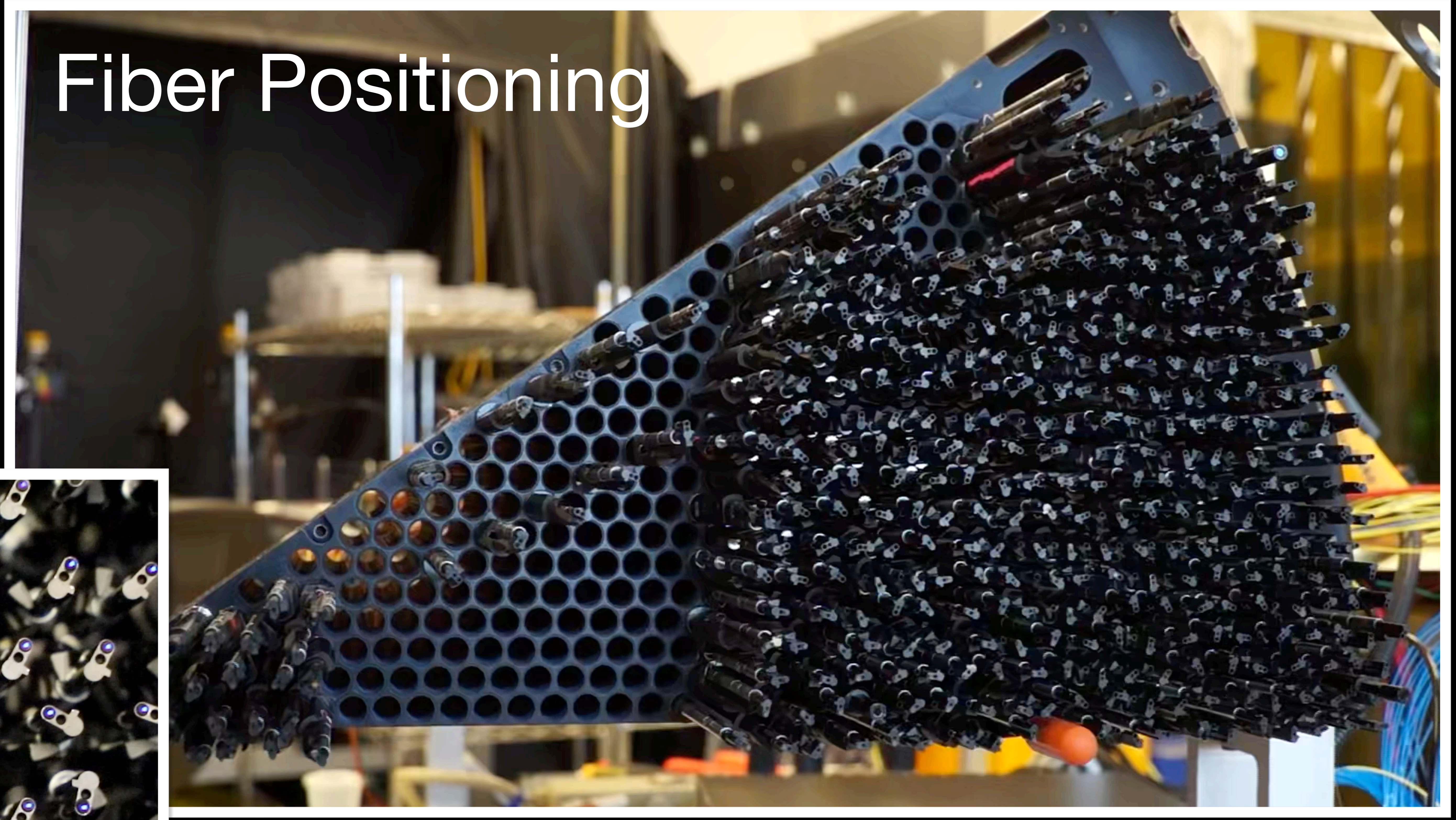
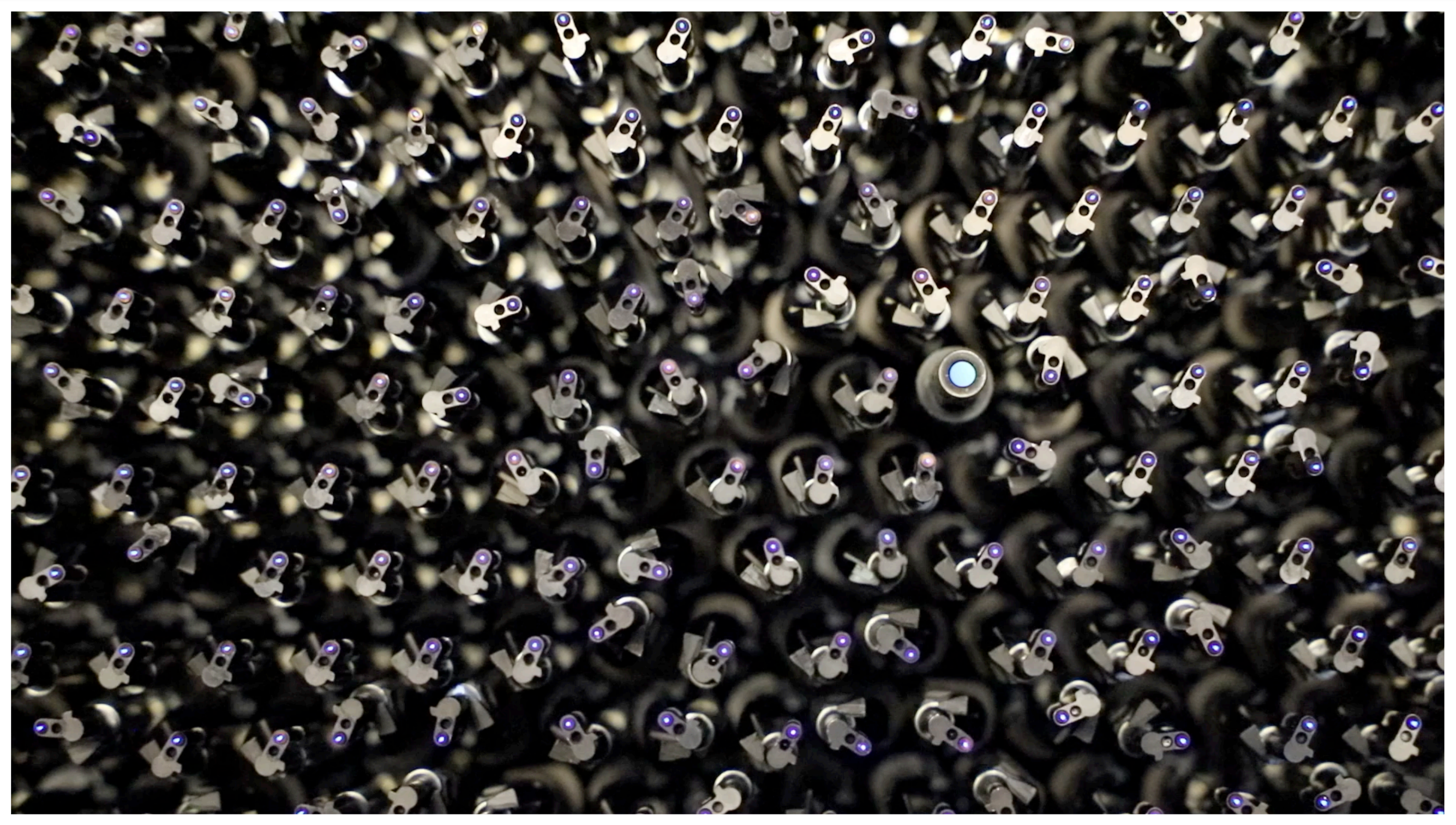
Automated dance of 5000 robotic positioners



Fiber Positioning



University of Michigan
undergraduate Clara Mateju
doing a stage 1 assembly.
Image credit: Curtis Weaverdyck

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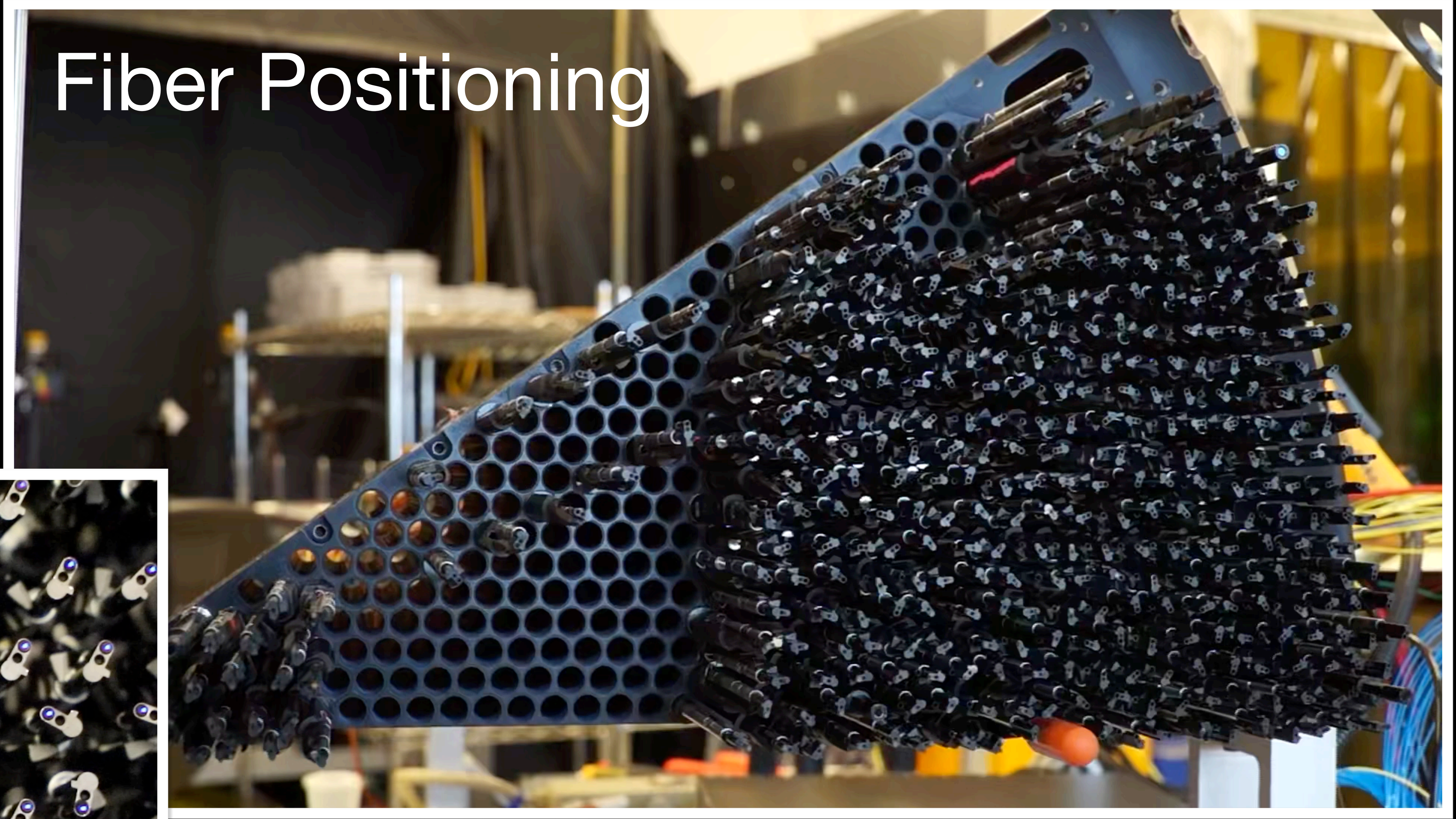

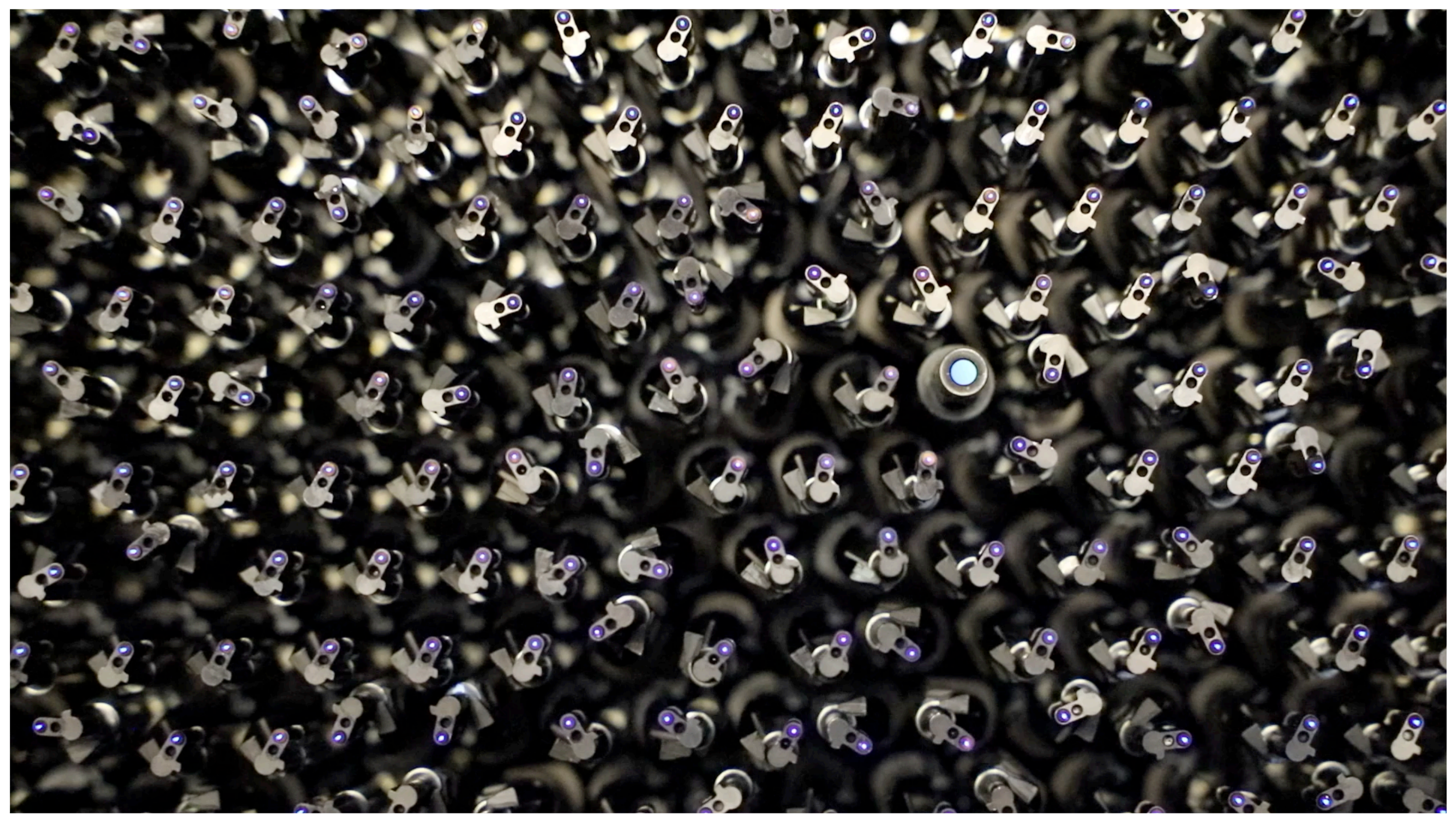

University of Michigan undergraduate Clara Mateju doing a stage 1 assembly.
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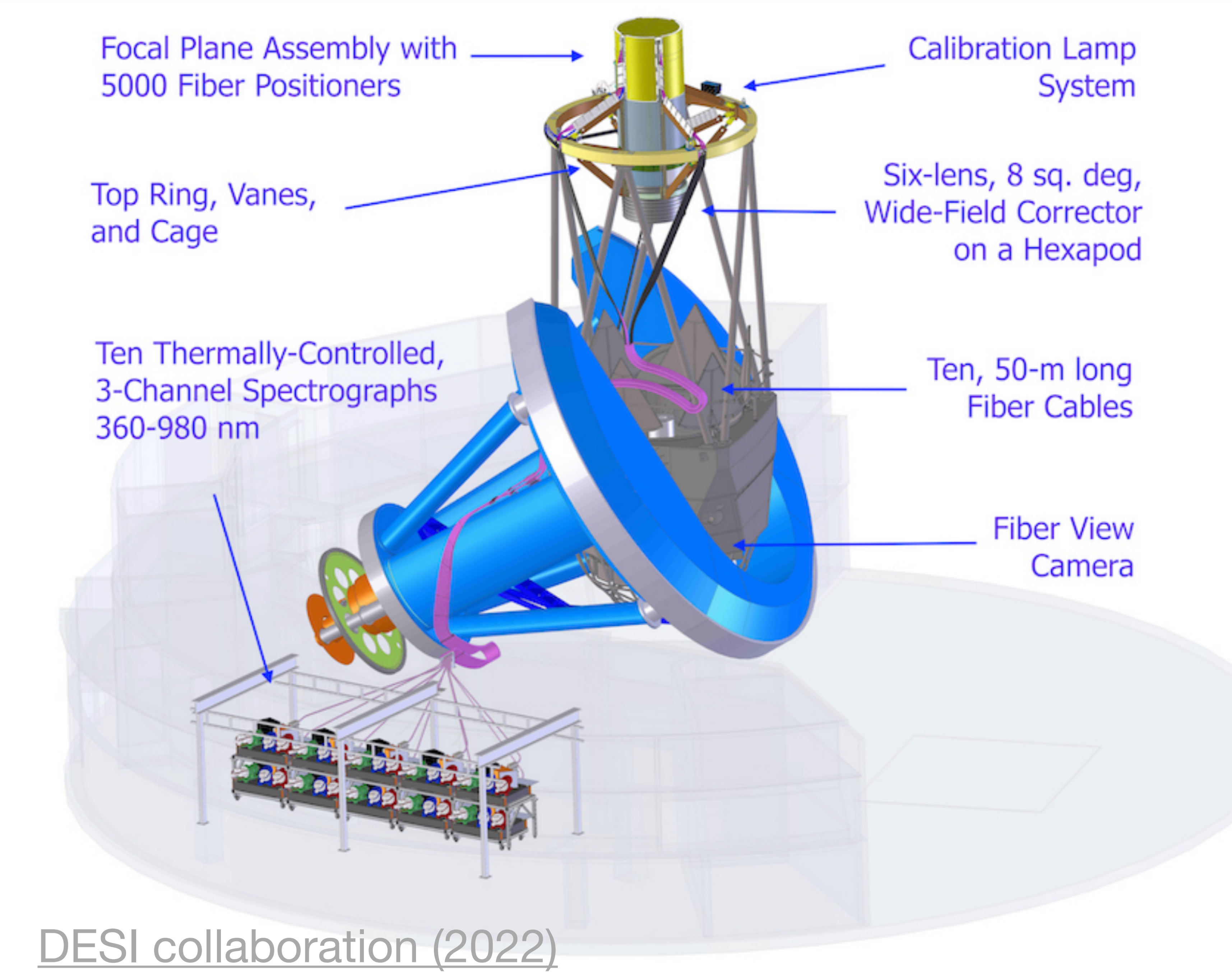
Instrument design

Credit: LBL/KPNO/NOIRLab/NSF/AURA



DESI collaboration (2022)

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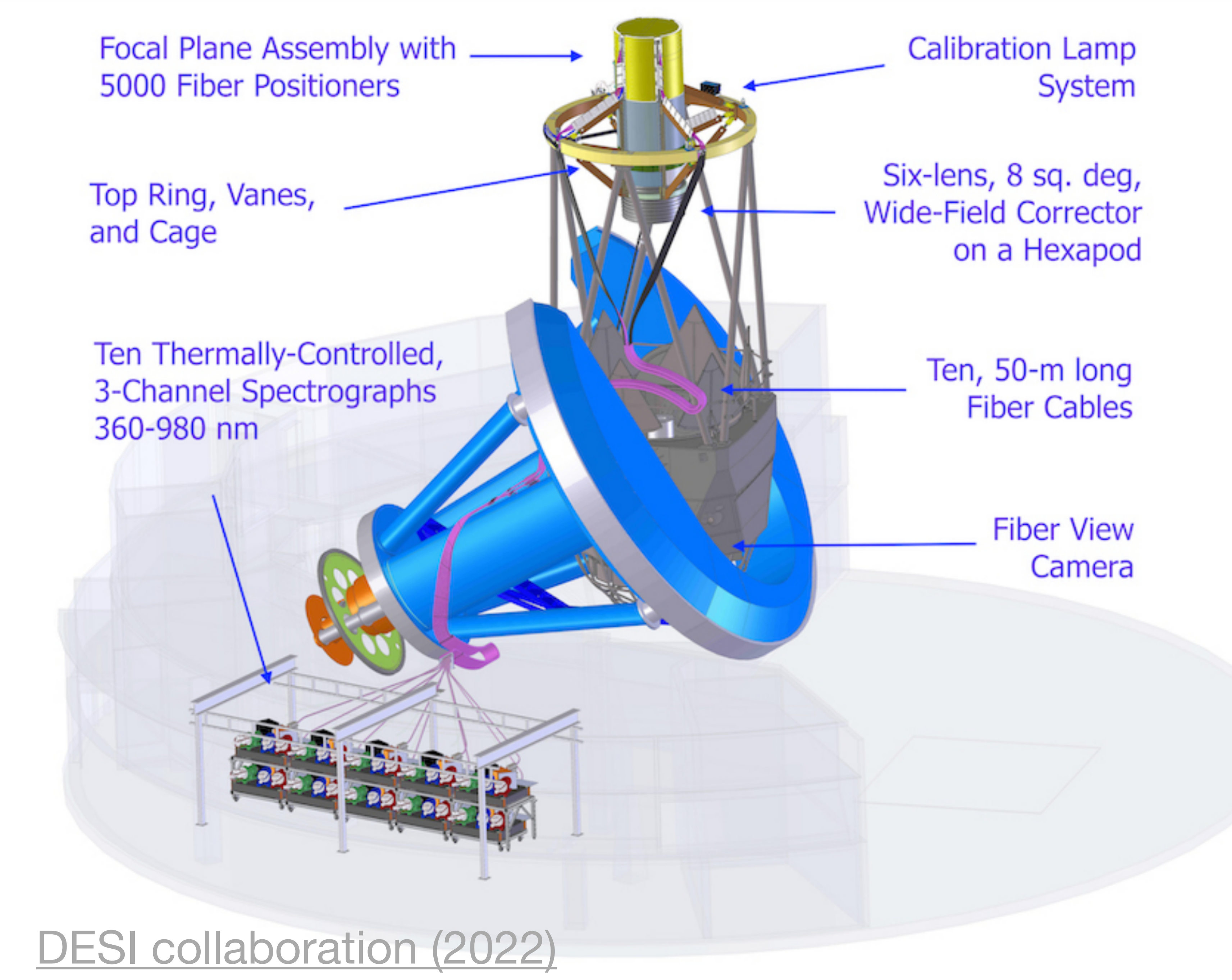
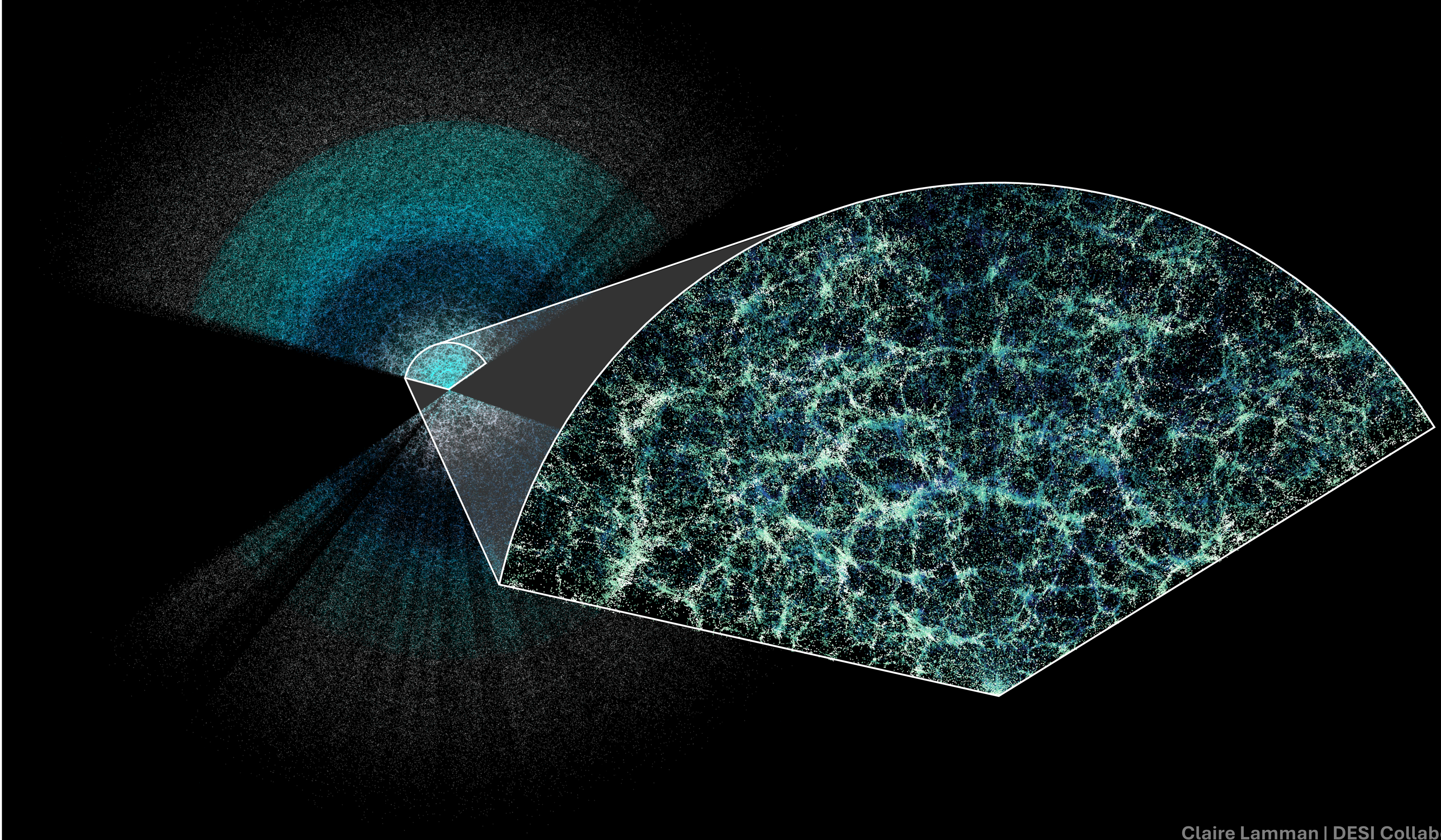


DESI collaboration (2022)

Overall, DESI surpasses its predecessors in terms of speed and quality of data:

- **One single night** collects **200,000 extragalactic redshifts** (same order as the entire 6dF Galaxy Survey (6dFGS), which operated between 2001 and 2006)
- **Ten times faster** to collect photos than SDSS

The largest 3D map of our Universe to date, constructed by DESI

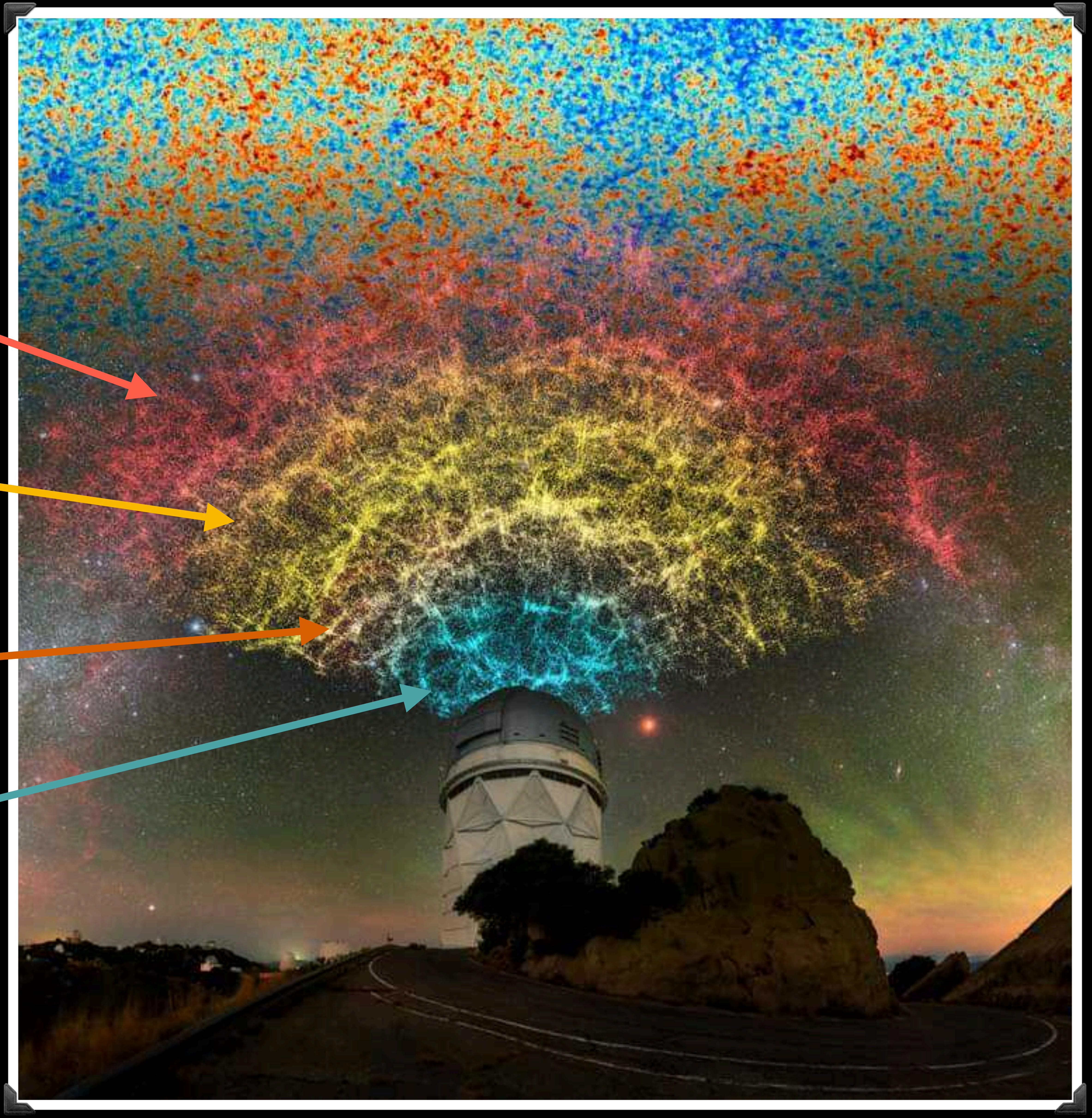


Claire Lamman | DESI Collaboration

A slice of galaxy positions from DESI's Year One data, colored by galaxy type. The magnified section is colored by declination, which spans 14 degrees. Colormap from cmastro.

DESI observables

DESI Survey: Making the Largest 3D Map of the Universe



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Science drivers:

- Baryon Acoustic Oscillations
- Redshift Space Distortions

(0.4 < z < 1)

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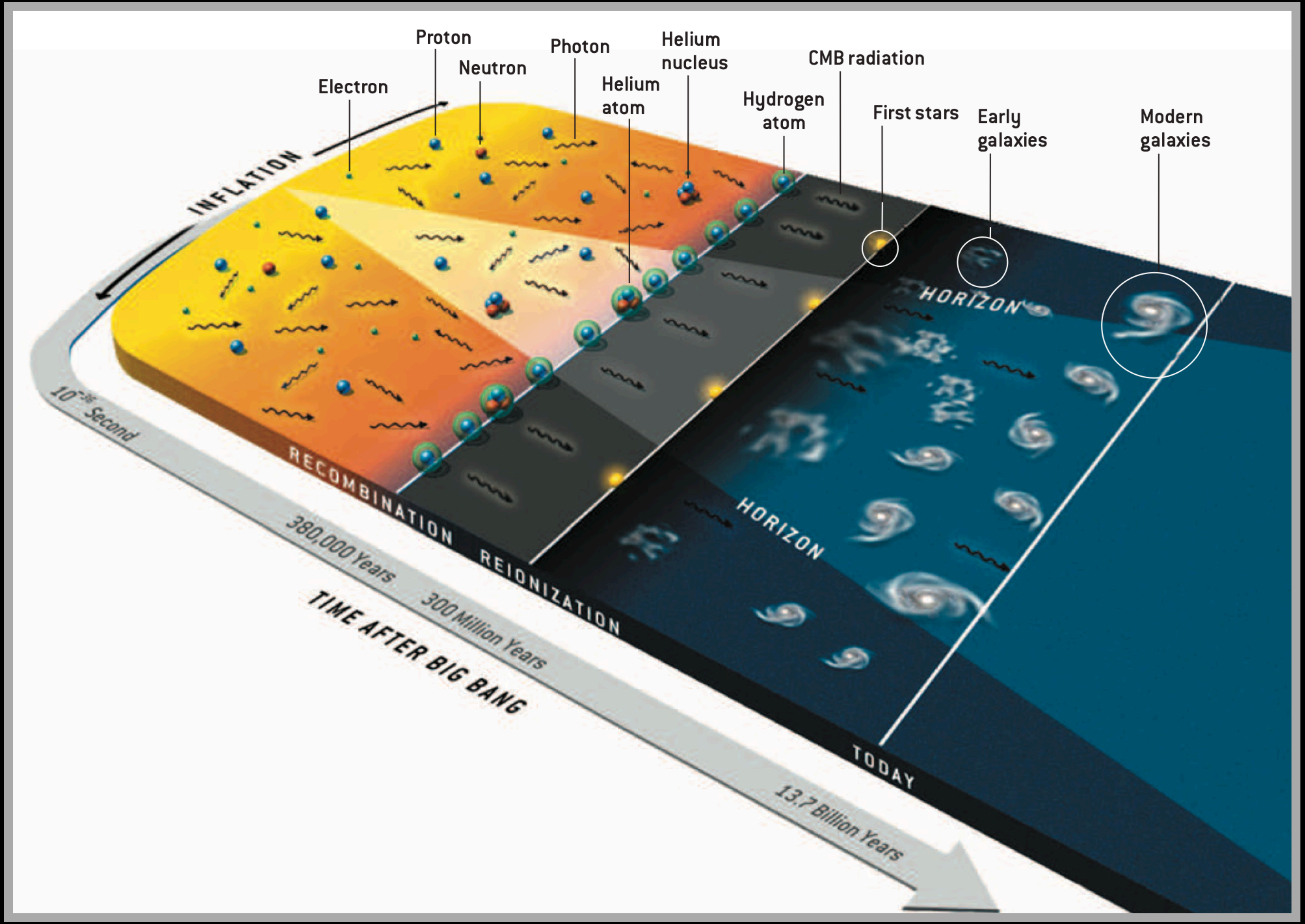
Baryon Acoustic Oscillations (BAO)

- Gravity and pressure generated sound waves in the primordial plasma
- When baryons and photons decoupled, the sound waves stopped



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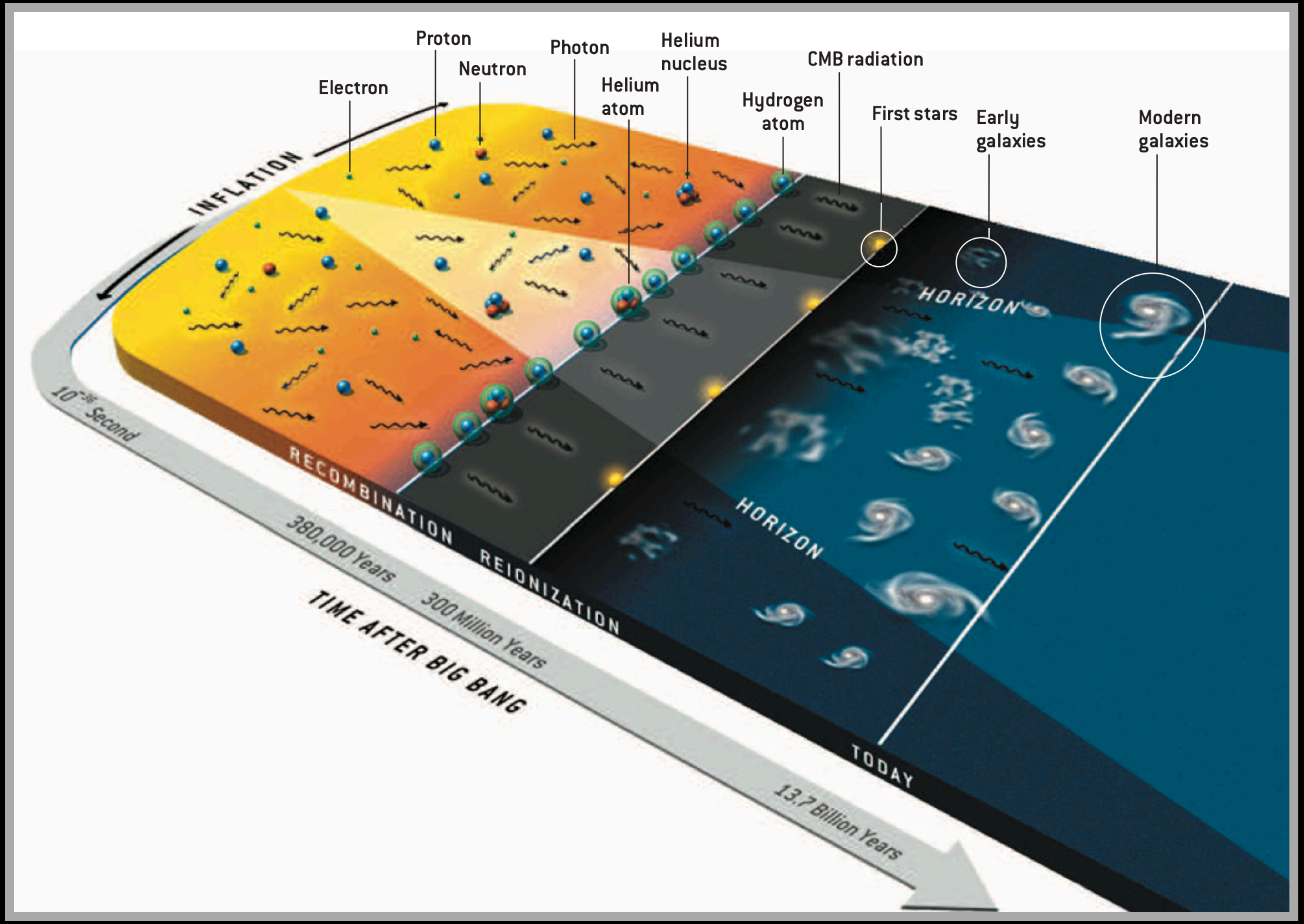

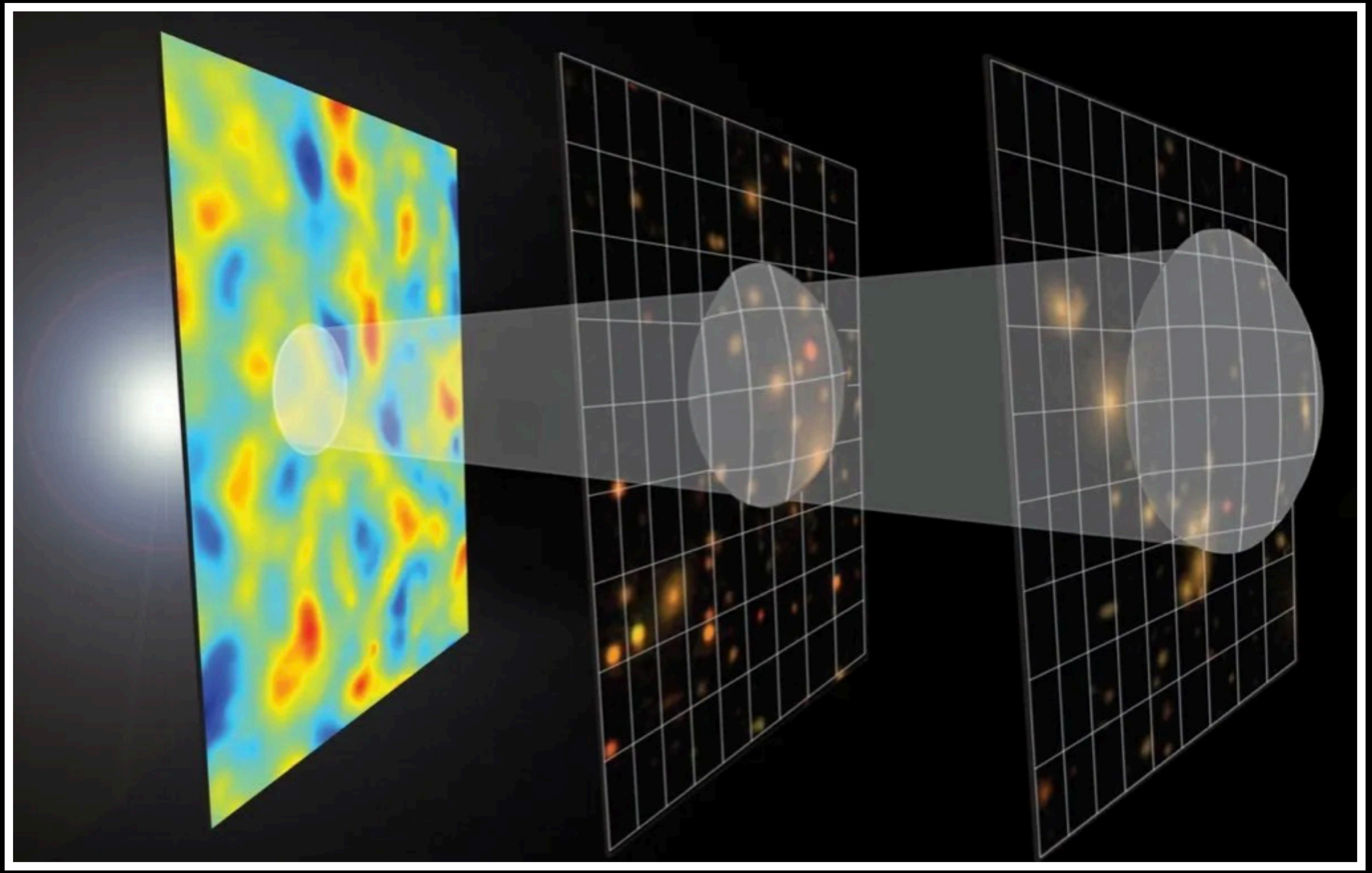

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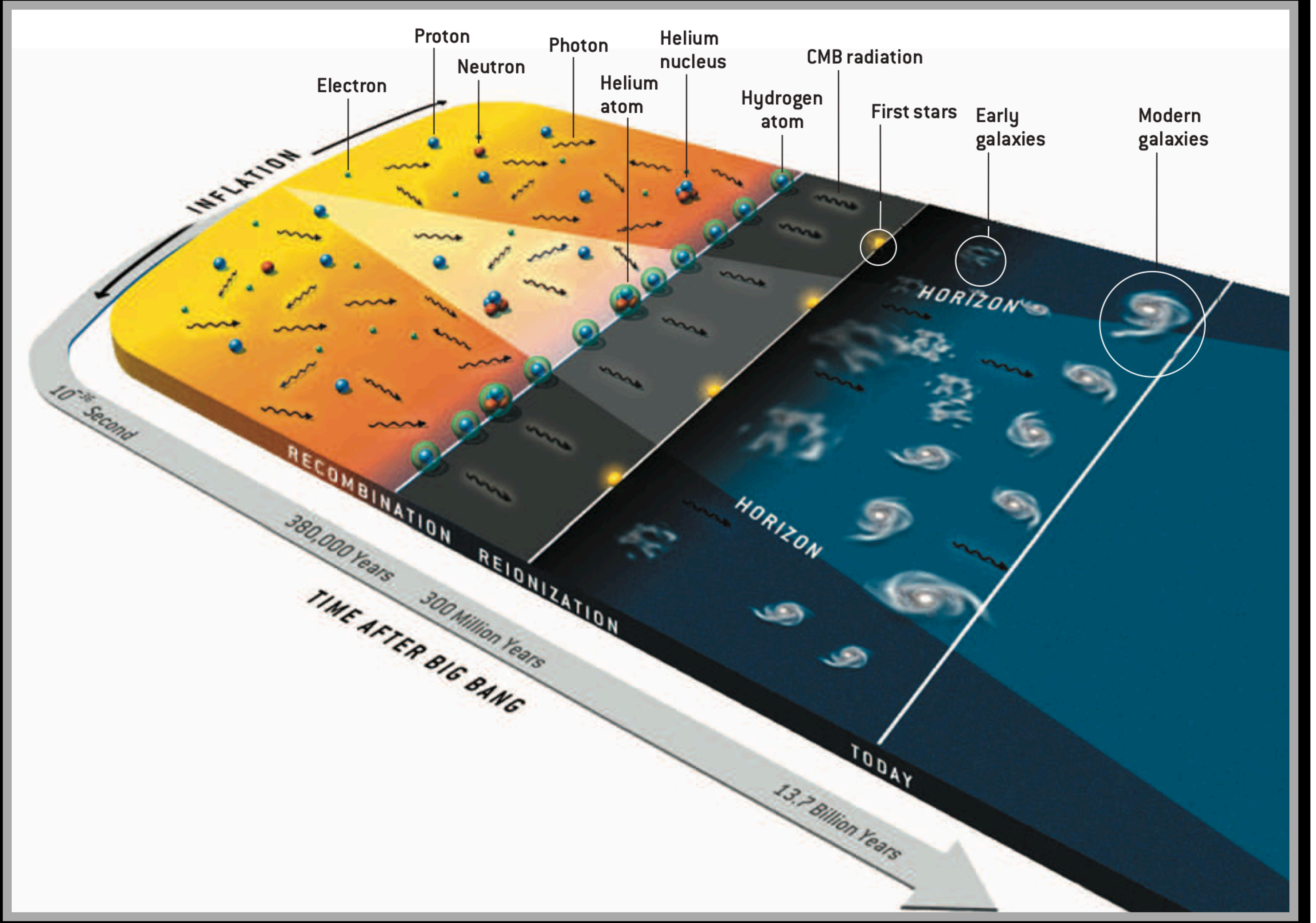

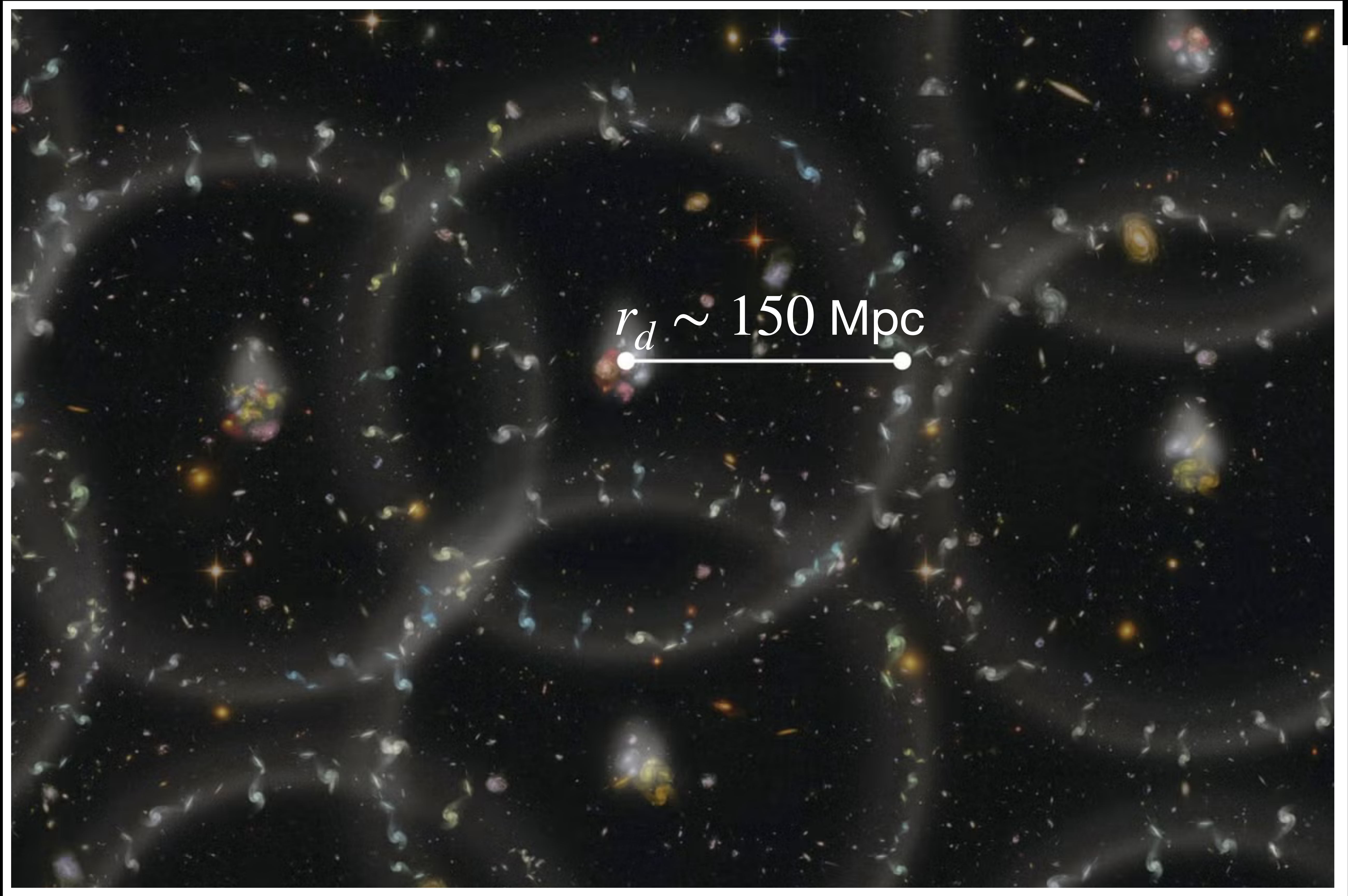

How do we learn cosmology from BAO?

- Measure angular positions, and redshifts of tracers (of the underlying matter density field, e.g., BGS, LRG, ELG, QSO, Lya)

- Work out distances to the tracers.

➡ If we know the characteristic scale from r_d early physics probes such as CMB or BBN, we measure absolute distances.

➡ Otherwise, we measure distances in units of r_d.

- Infer cosmology

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Calibrated BAO

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Un-Calibrated BAO

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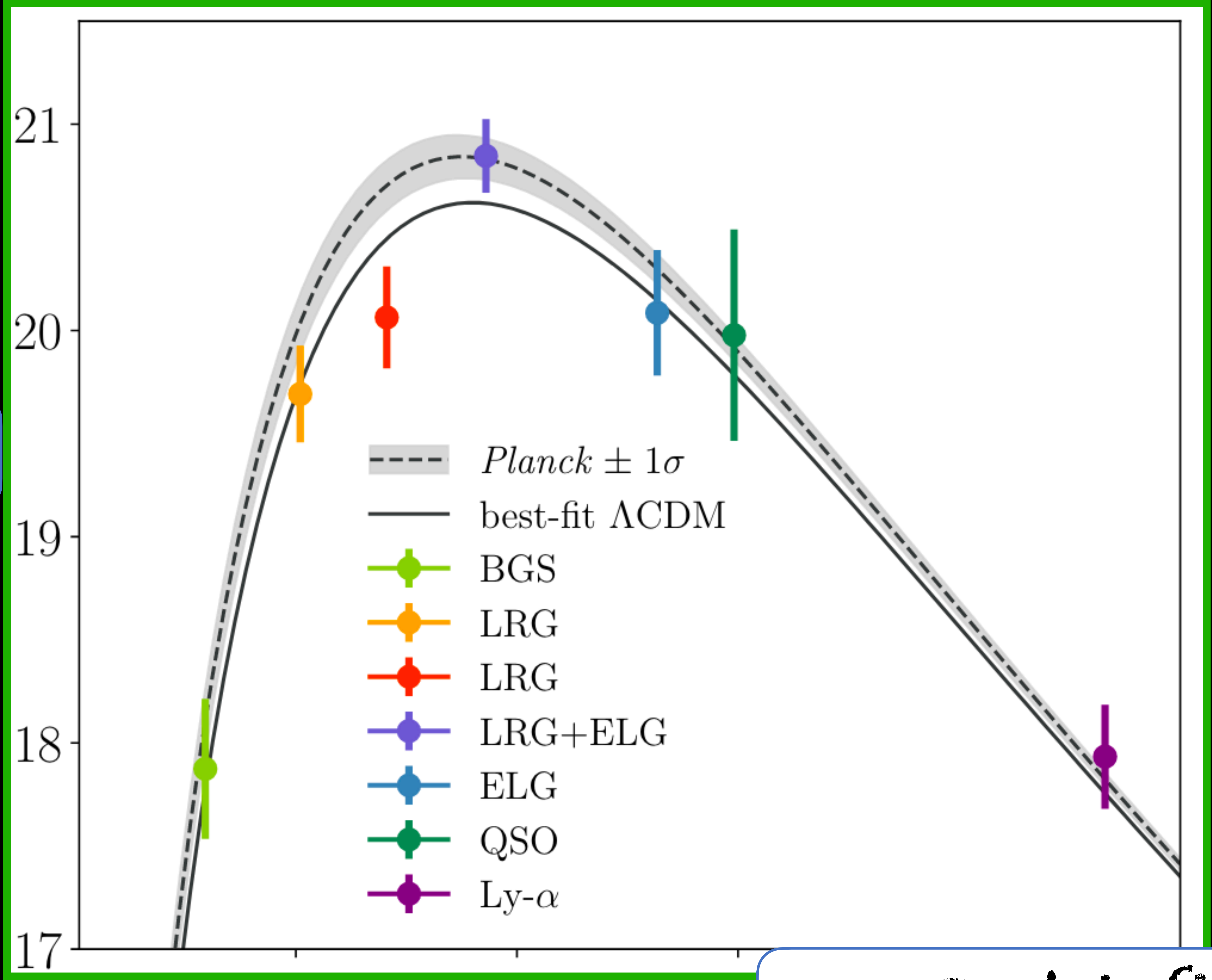
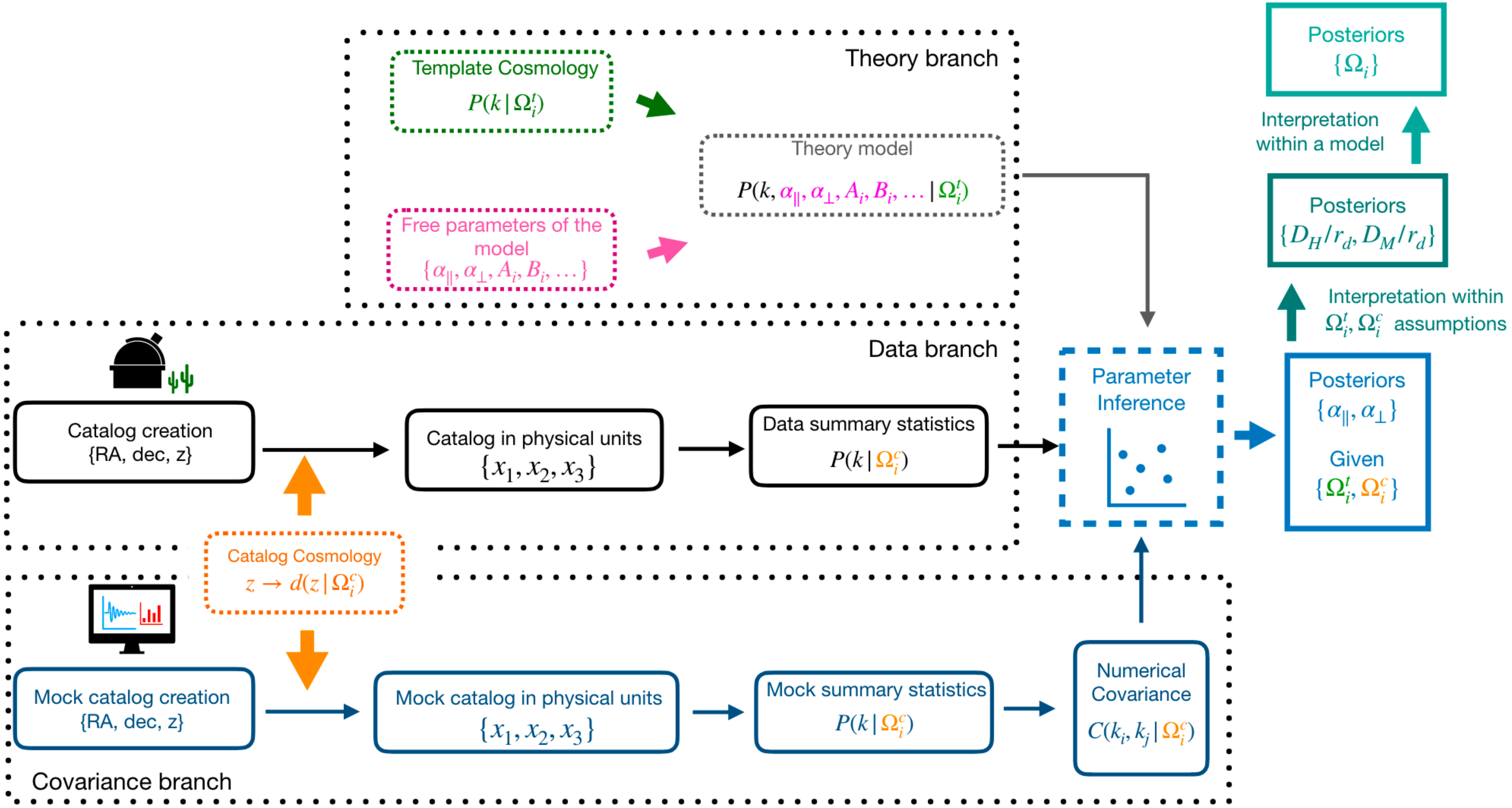


Distance

Redshift

From $(\mathrm{ra}, \mathrm{dec}, z)$ to Ω_i — Cosmo parameters

Santiago Sanz-Wuhl et al (2024): arXiv:2402.03427



Theory branch

Template Cosmology
$P(k \mid \Omega_i^t)$

Free parameters of the model
$\{\alpha_{\parallel}, \alpha_{\perp}, A_i, B_i, \dots\}$

Theory model
$P(k, \alpha_{\parallel}, \alpha_{\perp}, A_i, B_i, \dots \mid \Omega_i^t)$

Data branch

Catalog creation
{RA, dec, z}

Catalog in physical units
$\{x_1, x_2, x_3\}$

Data summary statistics
$P(k \mid \Omega_i^c)$

Catalog Cosmology
$z \rightarrow d(z \mid \Omega_i^c)$

Mock catalog creation
{RA, dec, z}

Mock catalog in physical units
$\{x_1, x_2, x_3\}$

Mock summary statistics
$P(k \mid \Omega_i^c)$

Numerical Covariance
$C(k_i, k_j \mid \Omega_i^c)$

Covariance branch

Parameter Inference

Posteriors
$\{\alpha_{\parallel}, \alpha_{\perp}\}$
Given
$\{\Omega_i^t, \Omega_i^c\}$

Interpretation within Ω_i^t, Ω_i^c assumptions

Posteriors
$\{D_H/r_d, D_M/r_d\}$

Interpretation within a model

Posteriors
$\{\Omega_i\}$

From $(\mathrm{ra}, \mathrm{dec}, z)$ to Ω_i — Cosmo parameters

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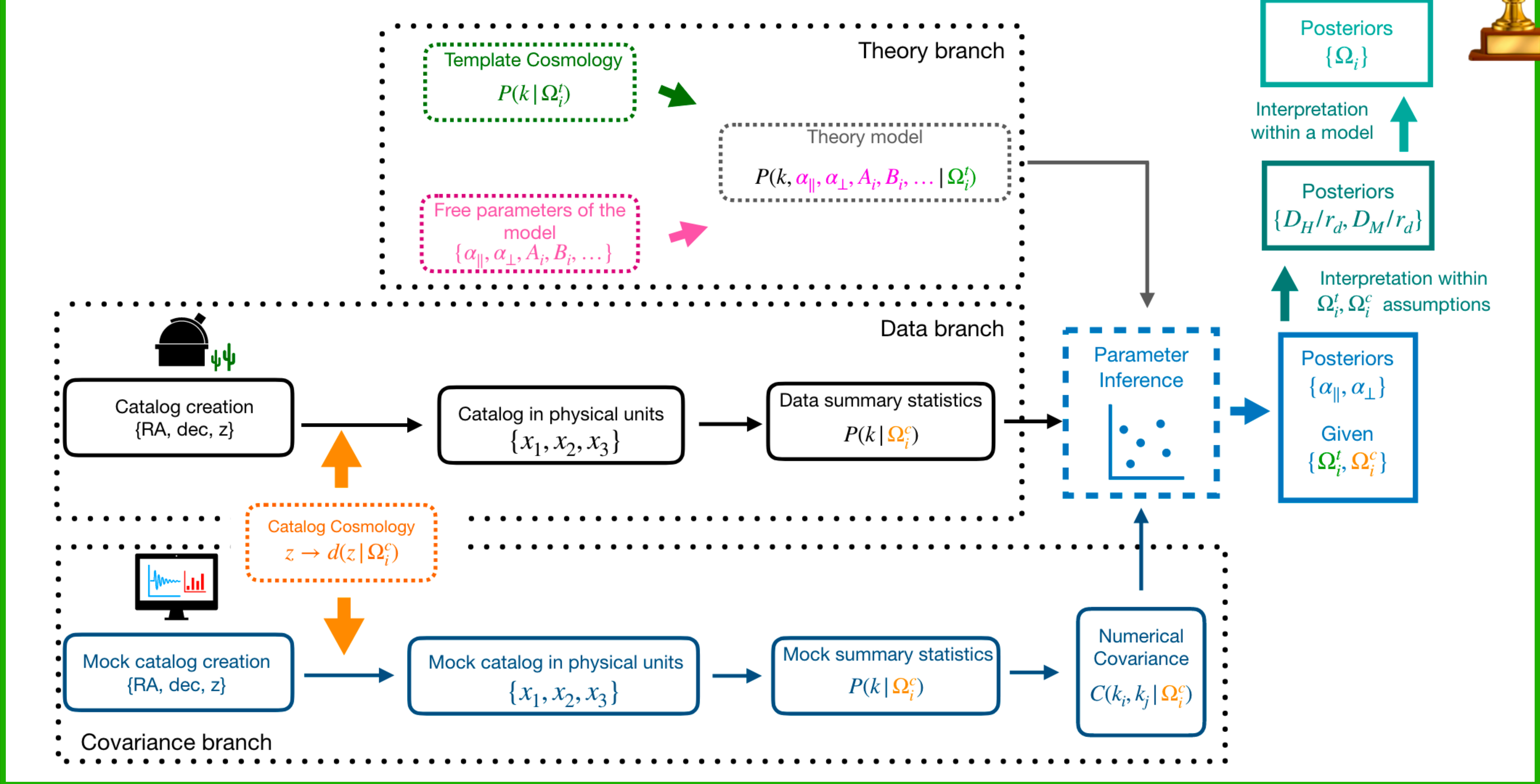

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Catalog Cosmology
$z \to d(z | \Omega_i^c)$

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$\{D_H/r_d, D_M/r_d\}$

Interpretation within a model

Posteriors
$\{\Omega_i\}$

Blind Watchers of the Sky

Blinding? In cosmology?

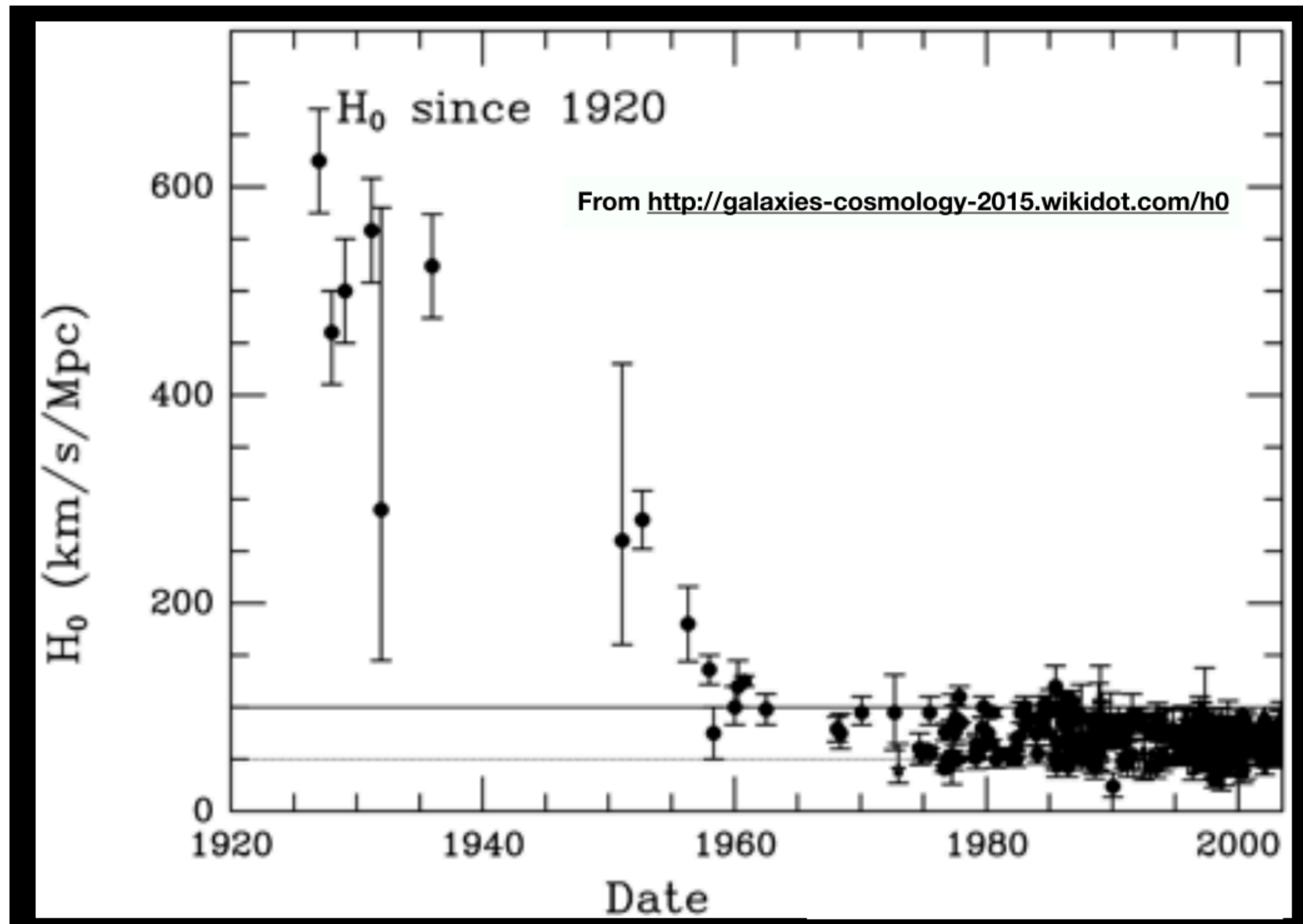

… what's the point ???

Credit slide: Samuel Brieden

Bandwagon effect

The bandwagon effect is a **psychological phenomenon** where people adopt certain behaviors, styles, or attitudes simply because others are doing so. More specifically, it is a **cognitive bias** by which public opinion or behaviors can alter due to particular actions and **beliefs** rallying amongst the public. [Wikipedia]

Credit slide: Samuel Brieden



> “The question of when to stop the search for sources of error is then very important. One psychologically plausible end point is when the result ‘seems’ right”
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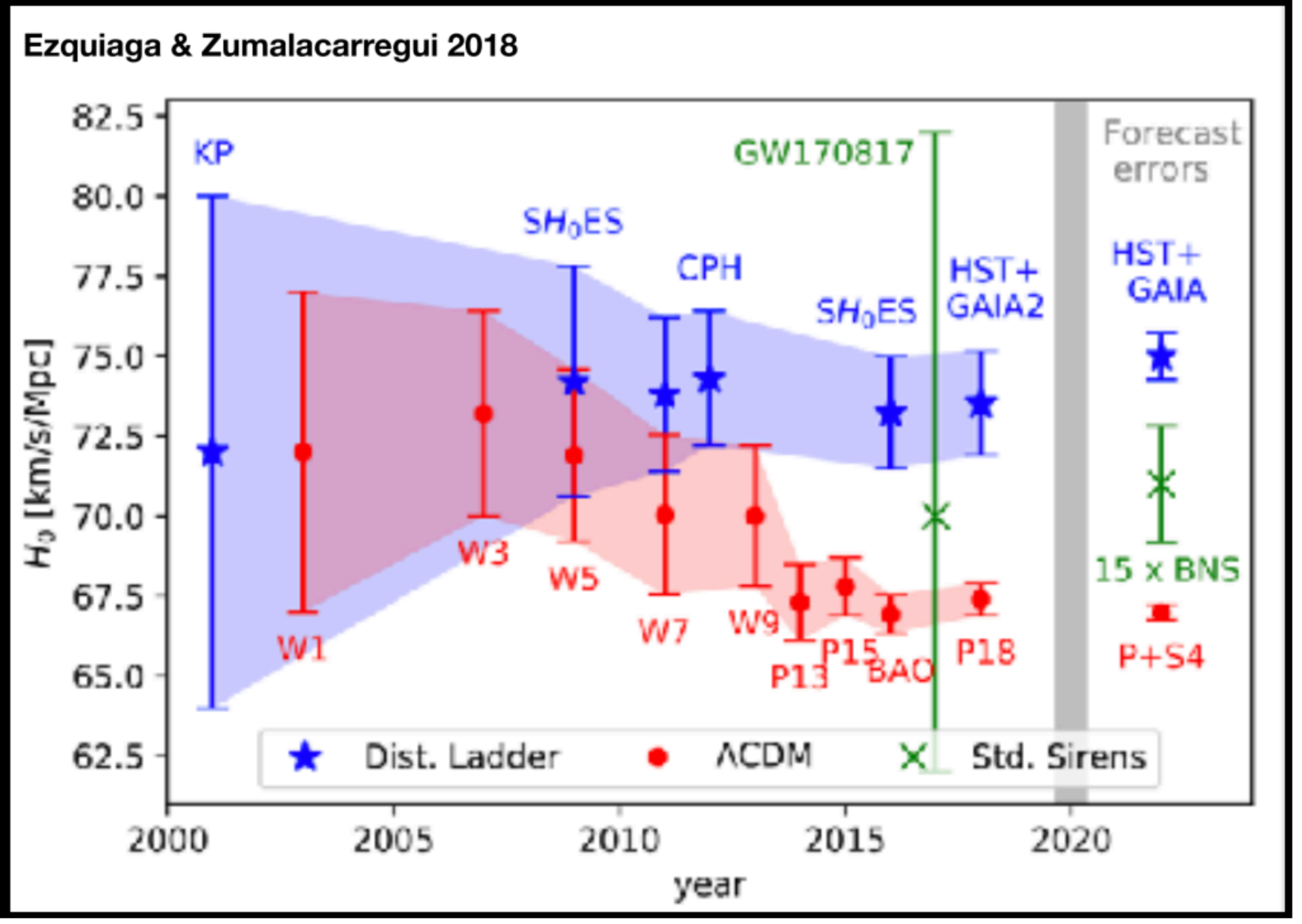
Ezquiaga & Zumalacarregui 2018

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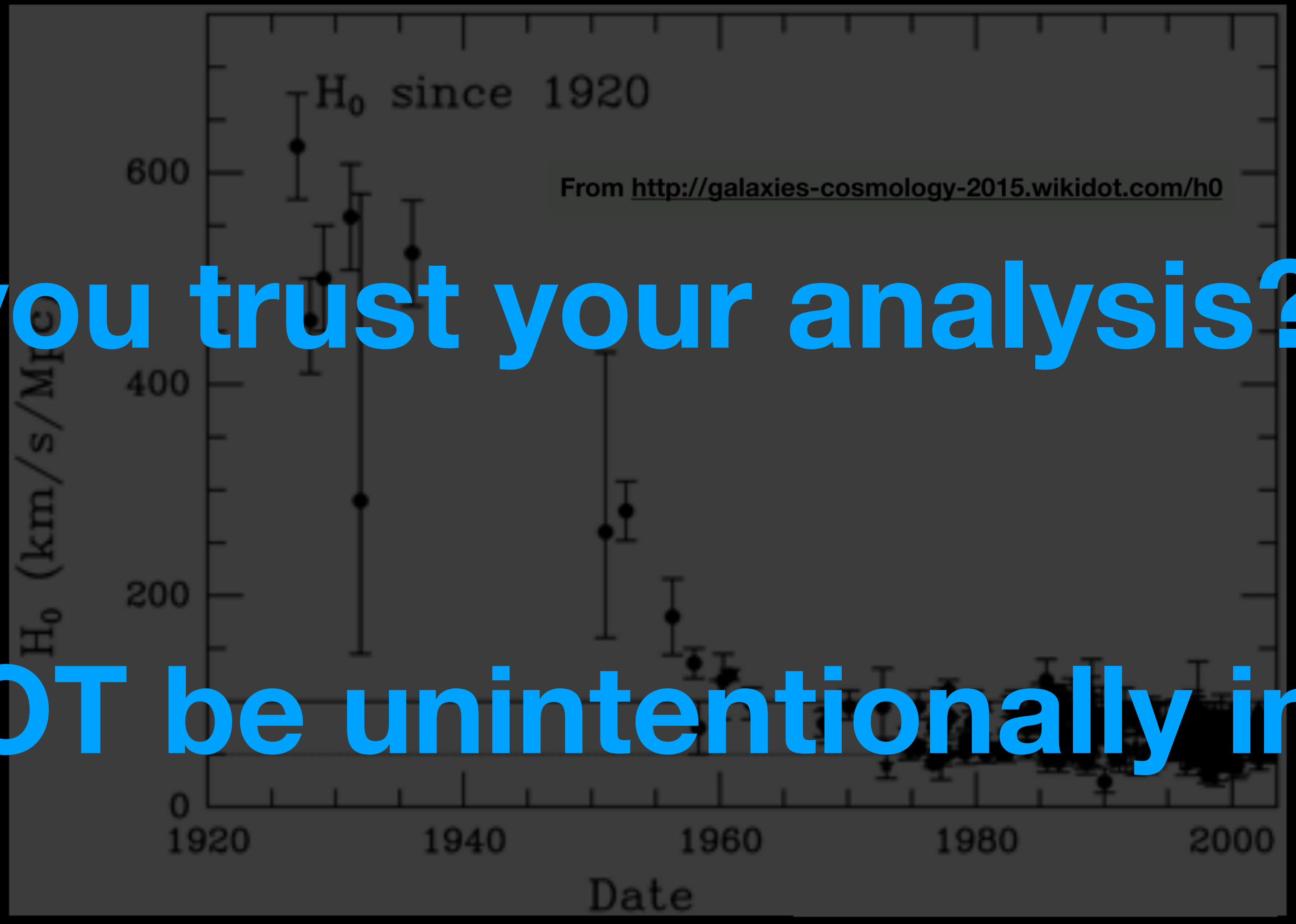
- **When do you trust your analysis? When do you say your analysis is validated?**
- **Can we NOT be unintentionally influenced by what we already know?**



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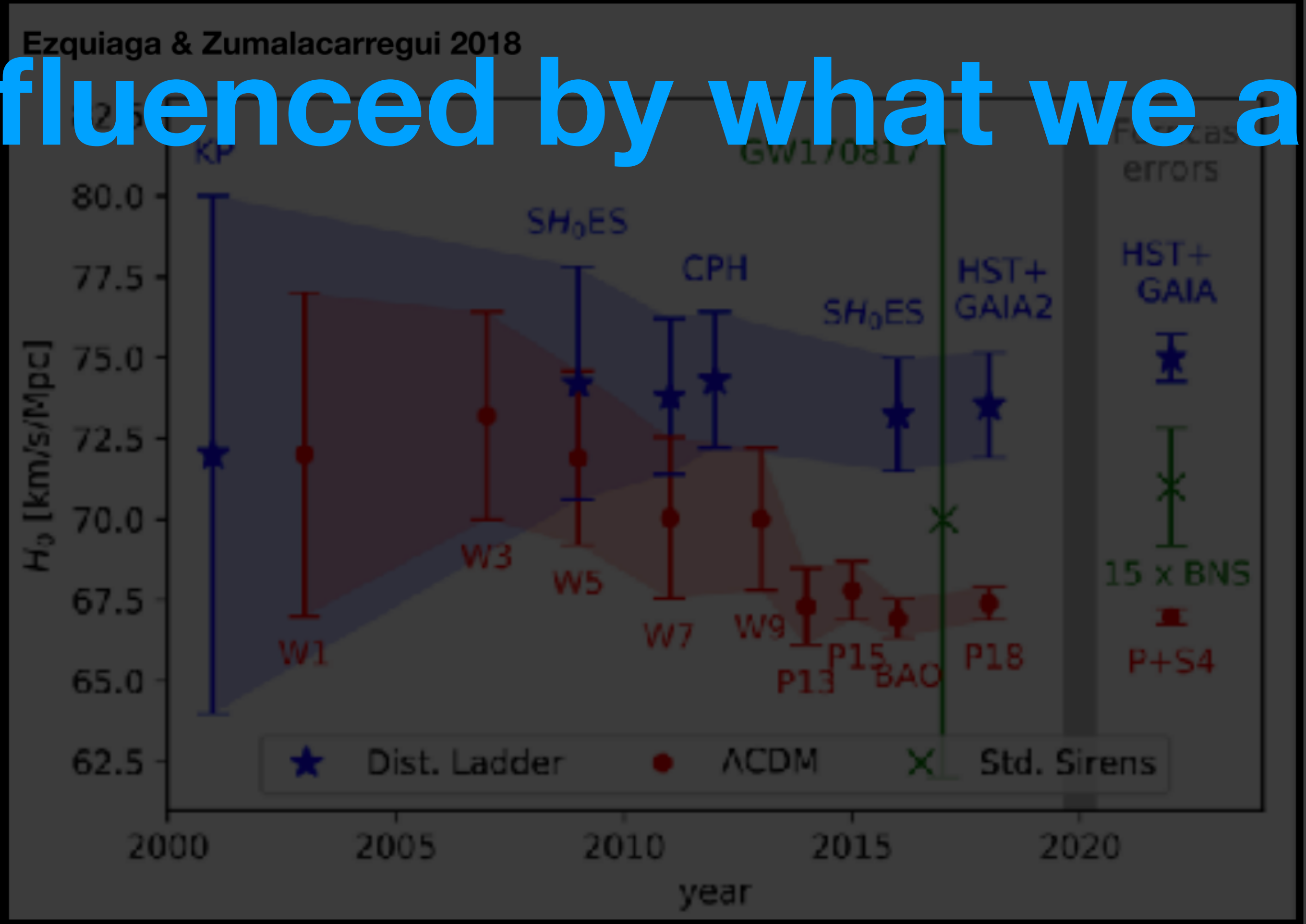

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How is the DESI BAO analysis different?

- The data! – already **the biggest ever BAO dataset** (both in and volume)
- **Blind analysis** to mitigate observer/confirmation biases (catalogue-level blinding)
- Theory developments in BAO fitting procedure
- New and improved reconstruction methods
- **Unified BAO pipeline** applied to all tracers/redshifts consistently
- Wide-ranging tests of systematic errors, done before unblinding
- New combined tracer method used for overlapping galaxy samples (LRG and ELG in $0.8 < z < 1.1$)

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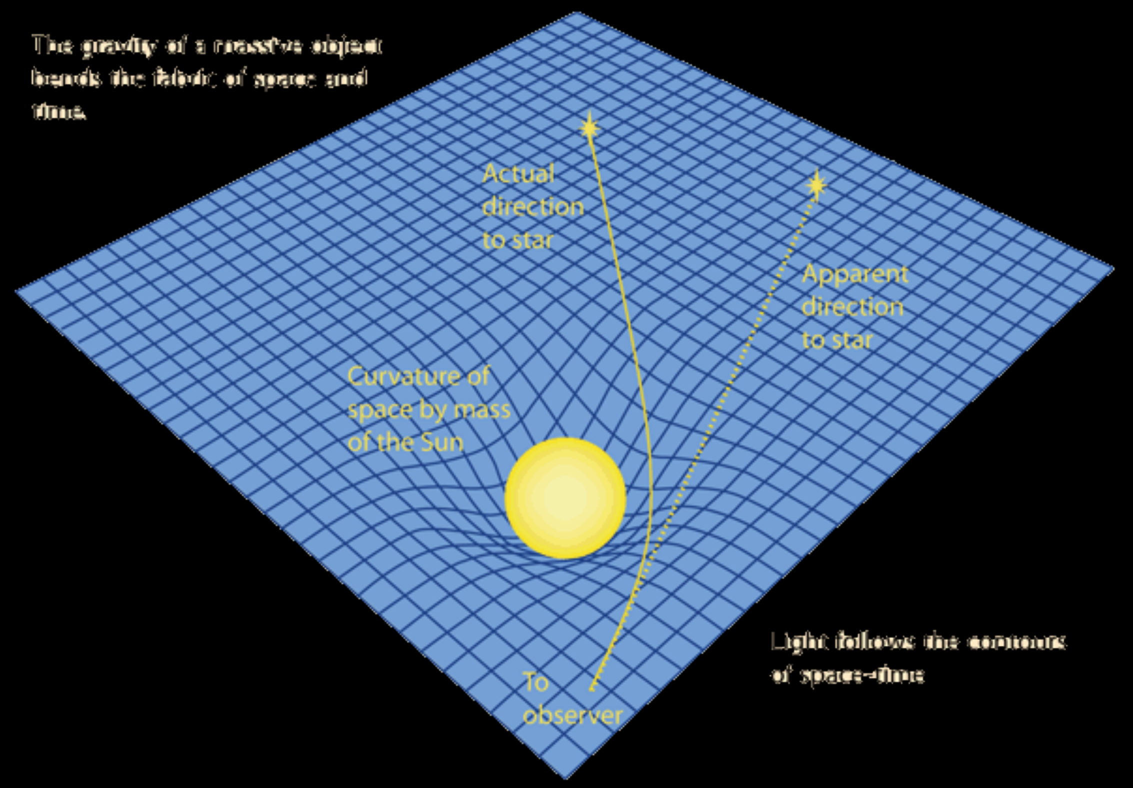
Validating the Galaxy and Quasar Catalog-Level Blinding Scheme for the DESI 2024 analysis: U. Andrade et al (2024): arXiv:2404.07282

Cosmological Constraints from DESI BAO

Standard Cosmological Model

GR and FLRW metric



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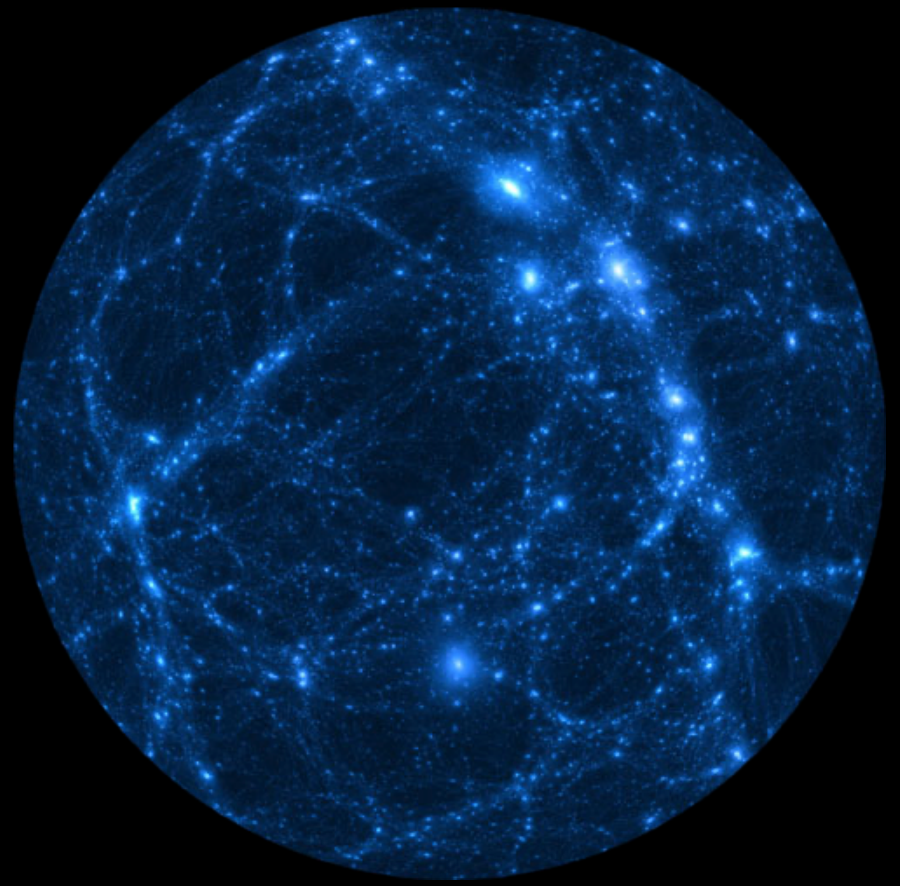
CDM



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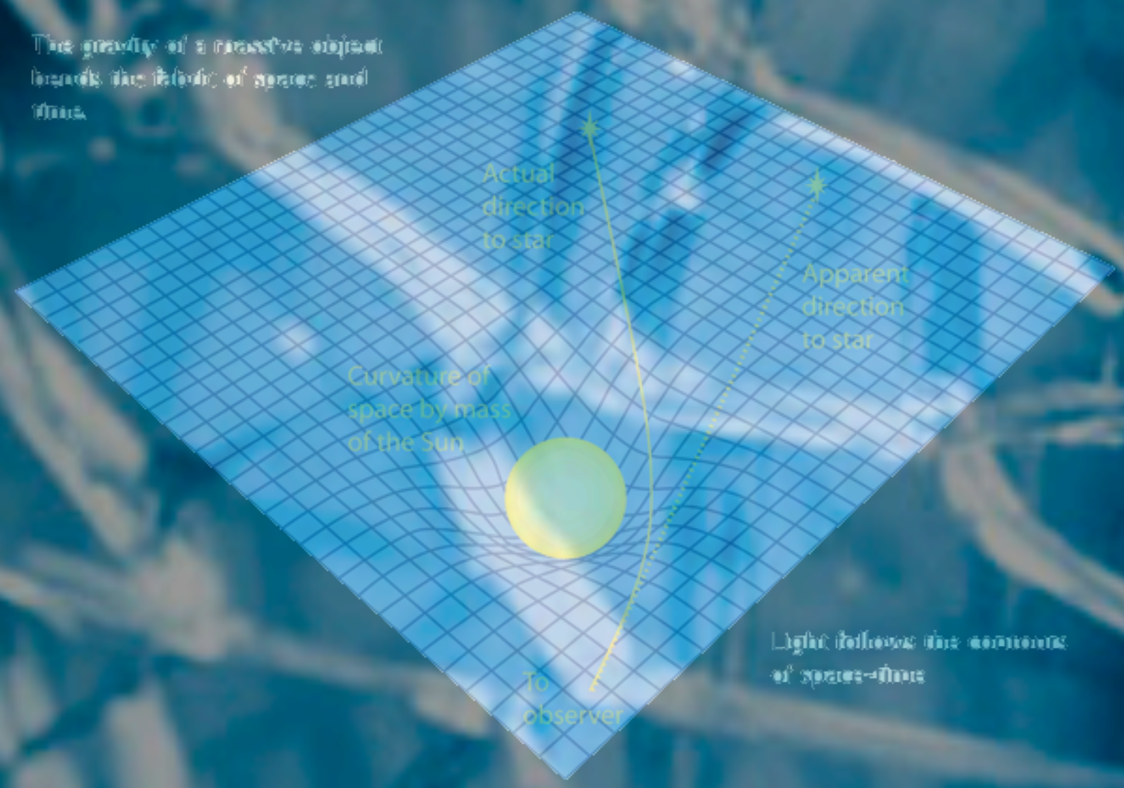
Cosmological Constant

Λ

ΛCDM model

Standard Cosmological Model

GR and FLRW metric + **CDM** + **Cosmological Constant**



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ΛCDM model

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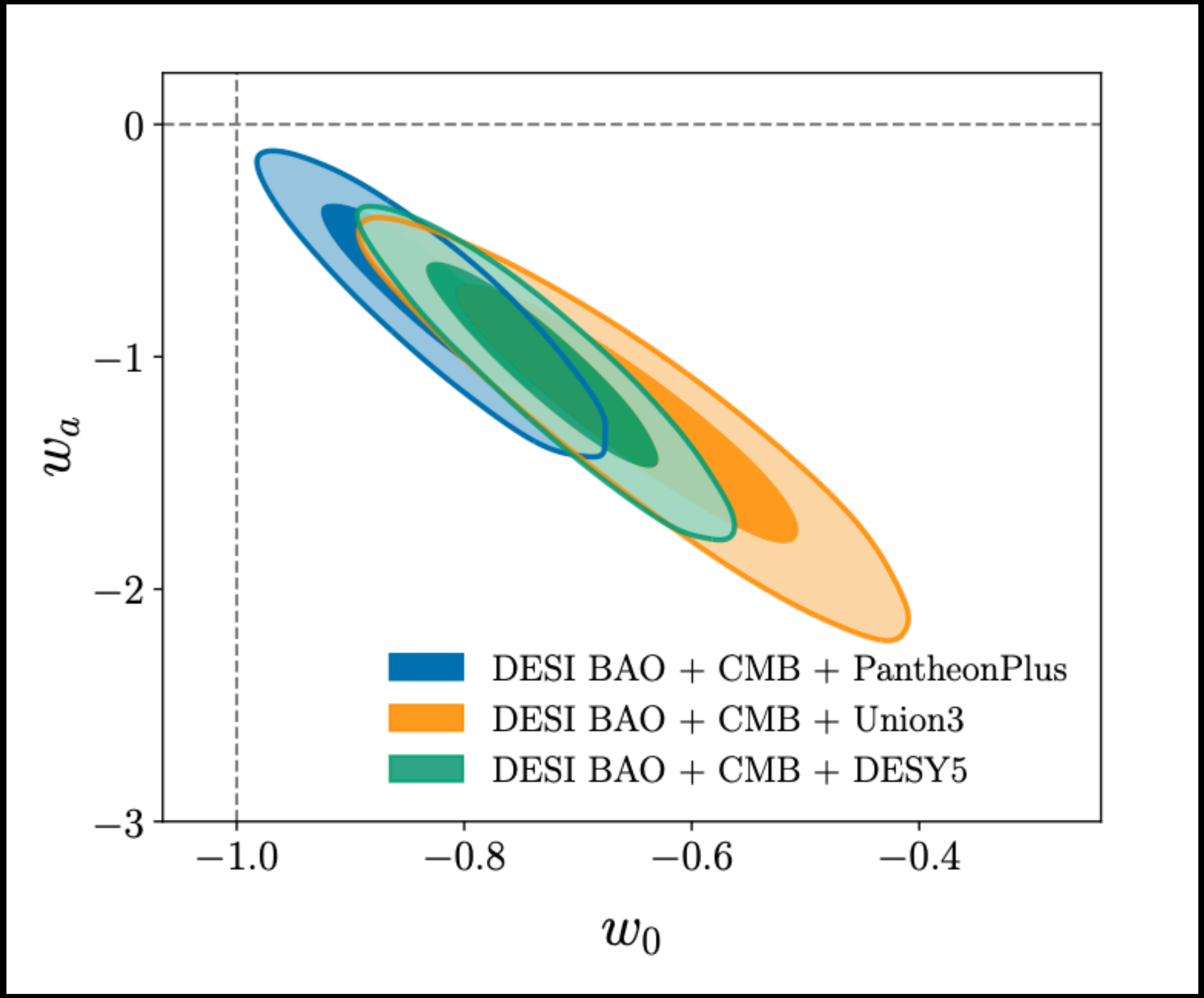
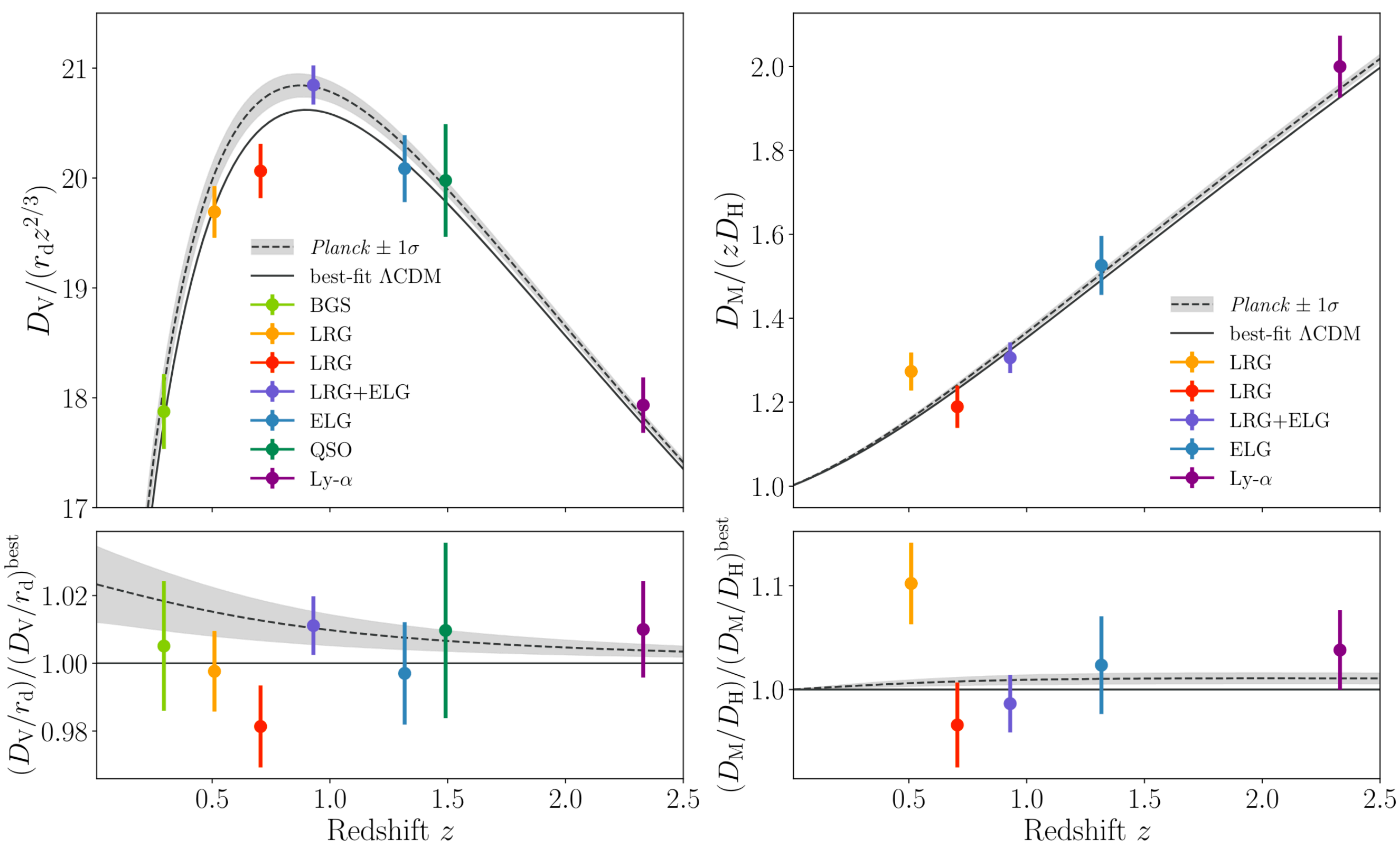
DESI: Breaking the Habit …

3.9σ tantalizing suggestion of deviations from the standard cosmological model



Distance Measurements



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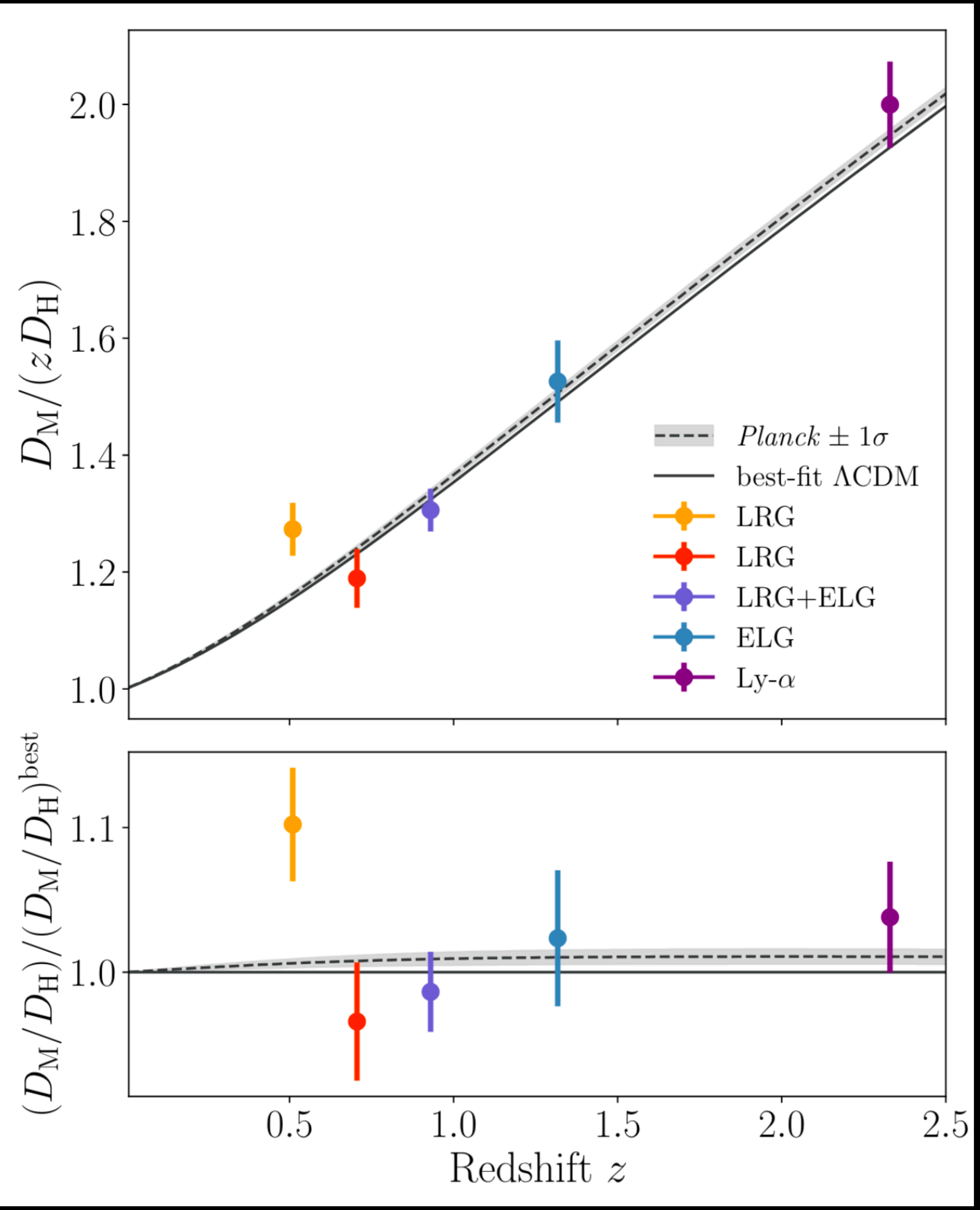

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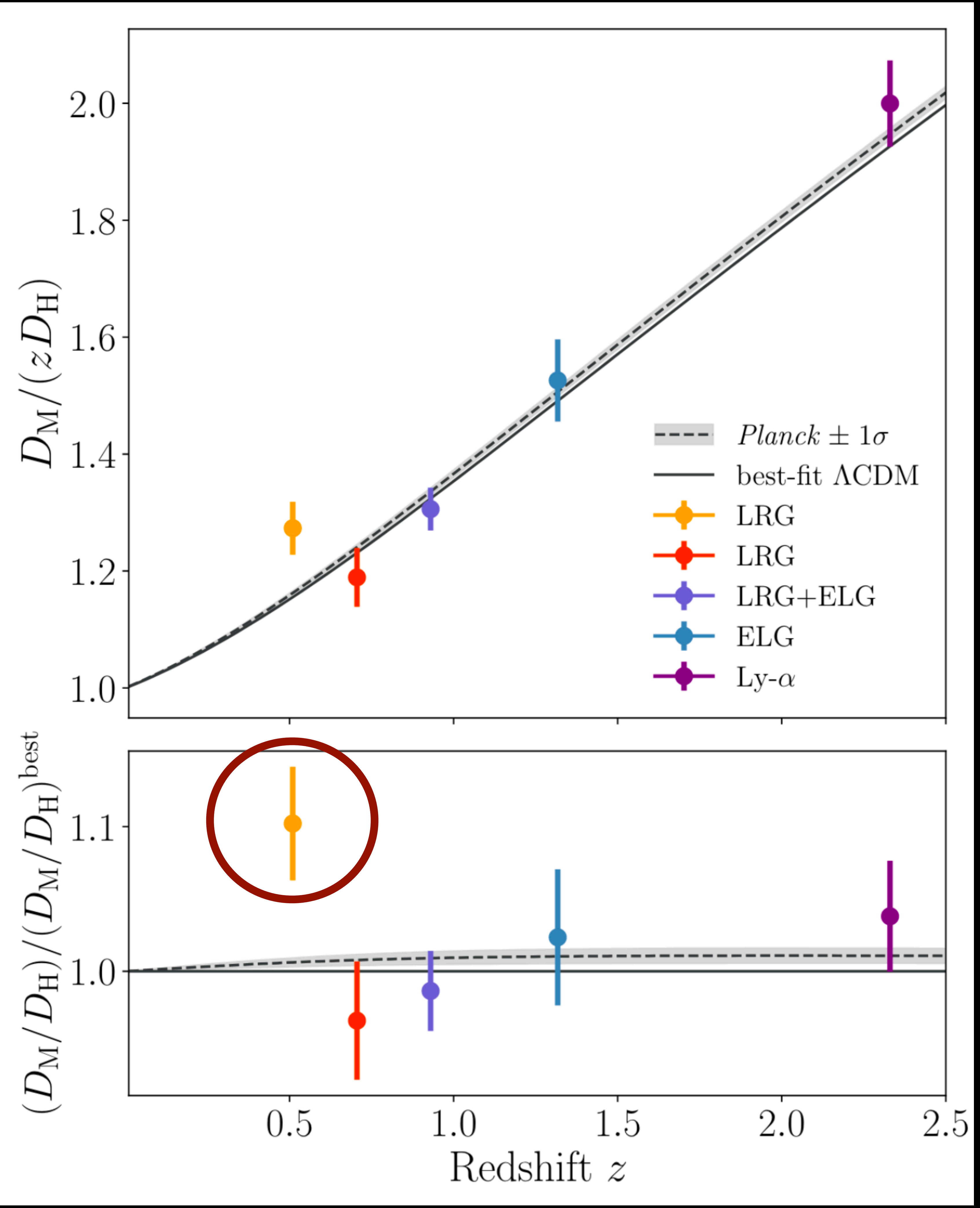

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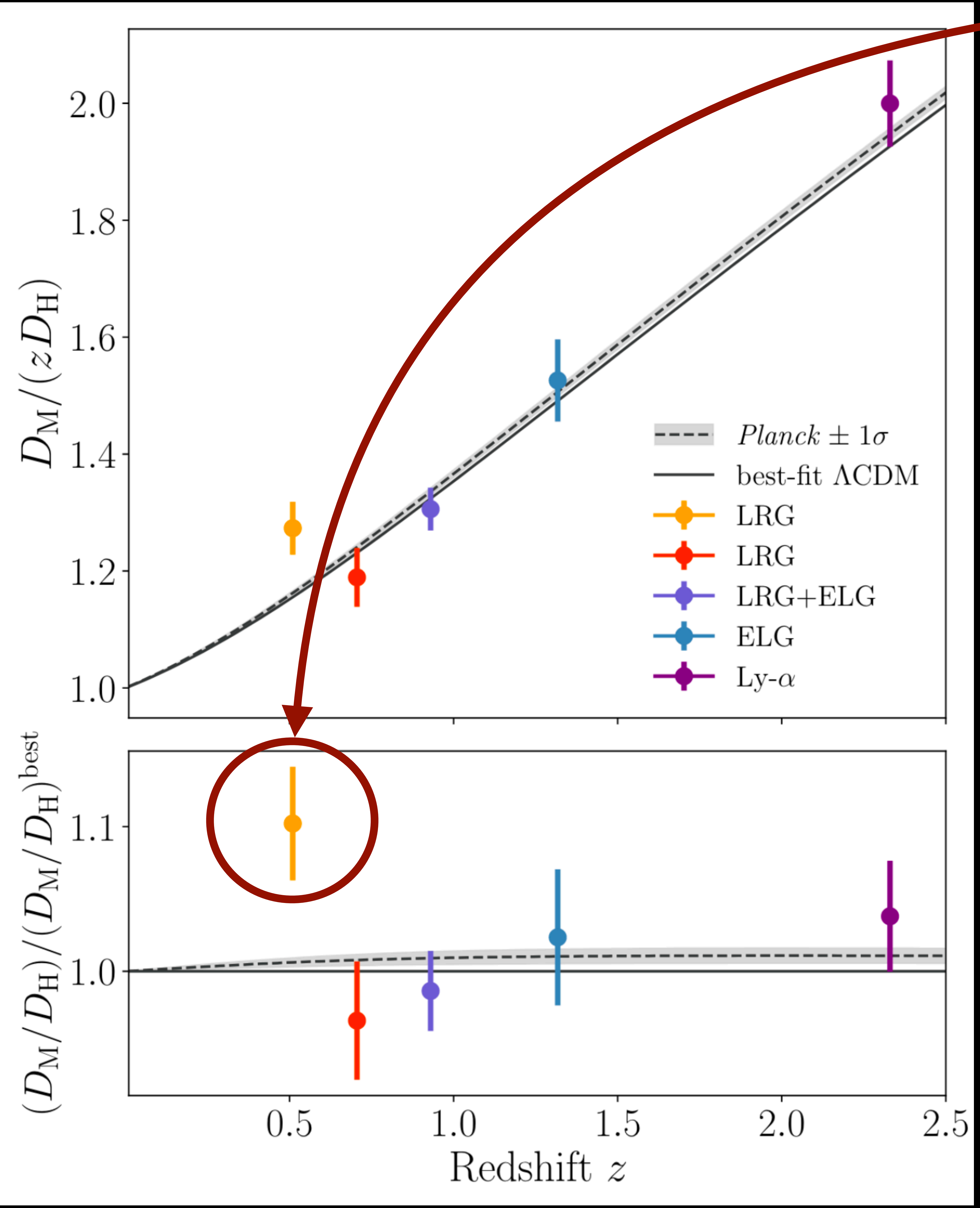
Distance Measurements

Most anomalous @ $z = 0.51$;offset at $\sim 2\sigma$ from ΛCDM.



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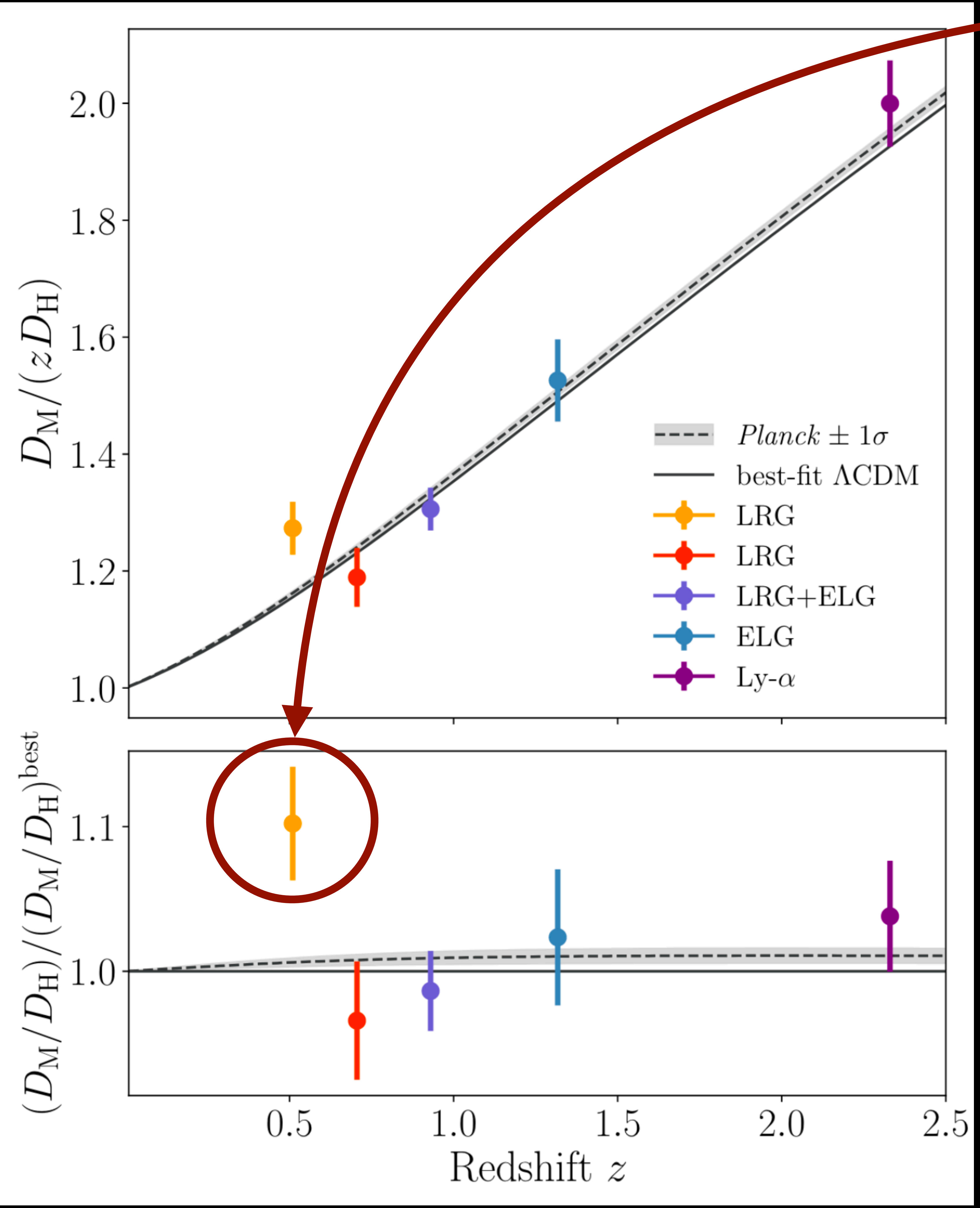

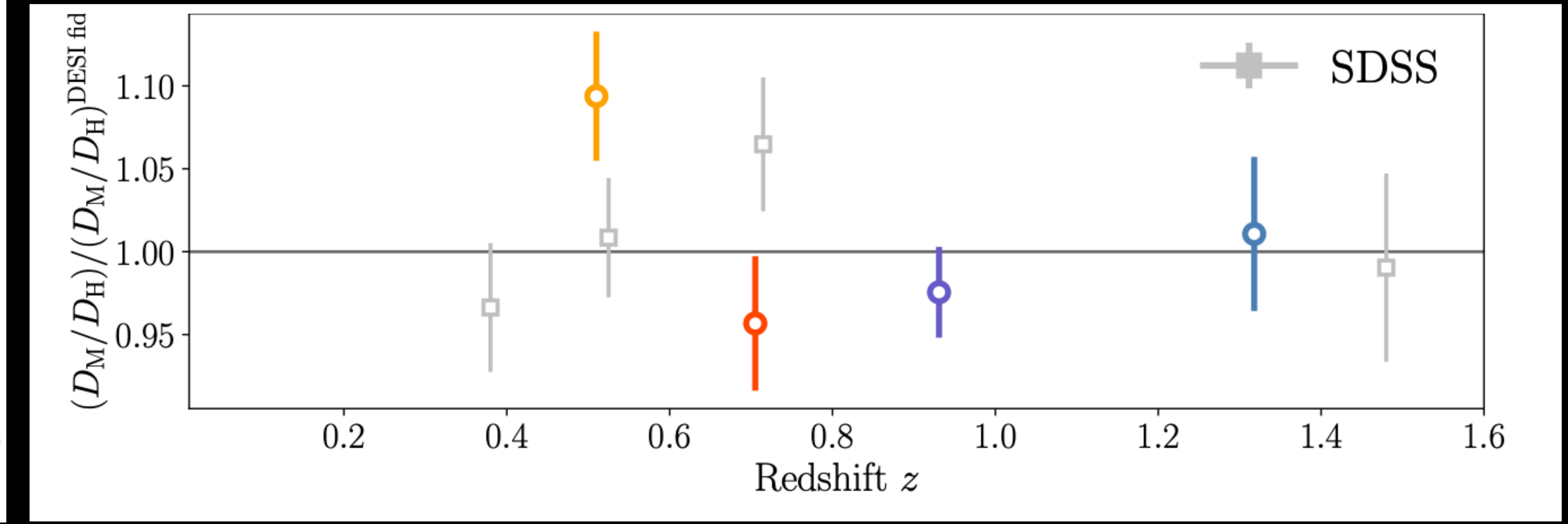

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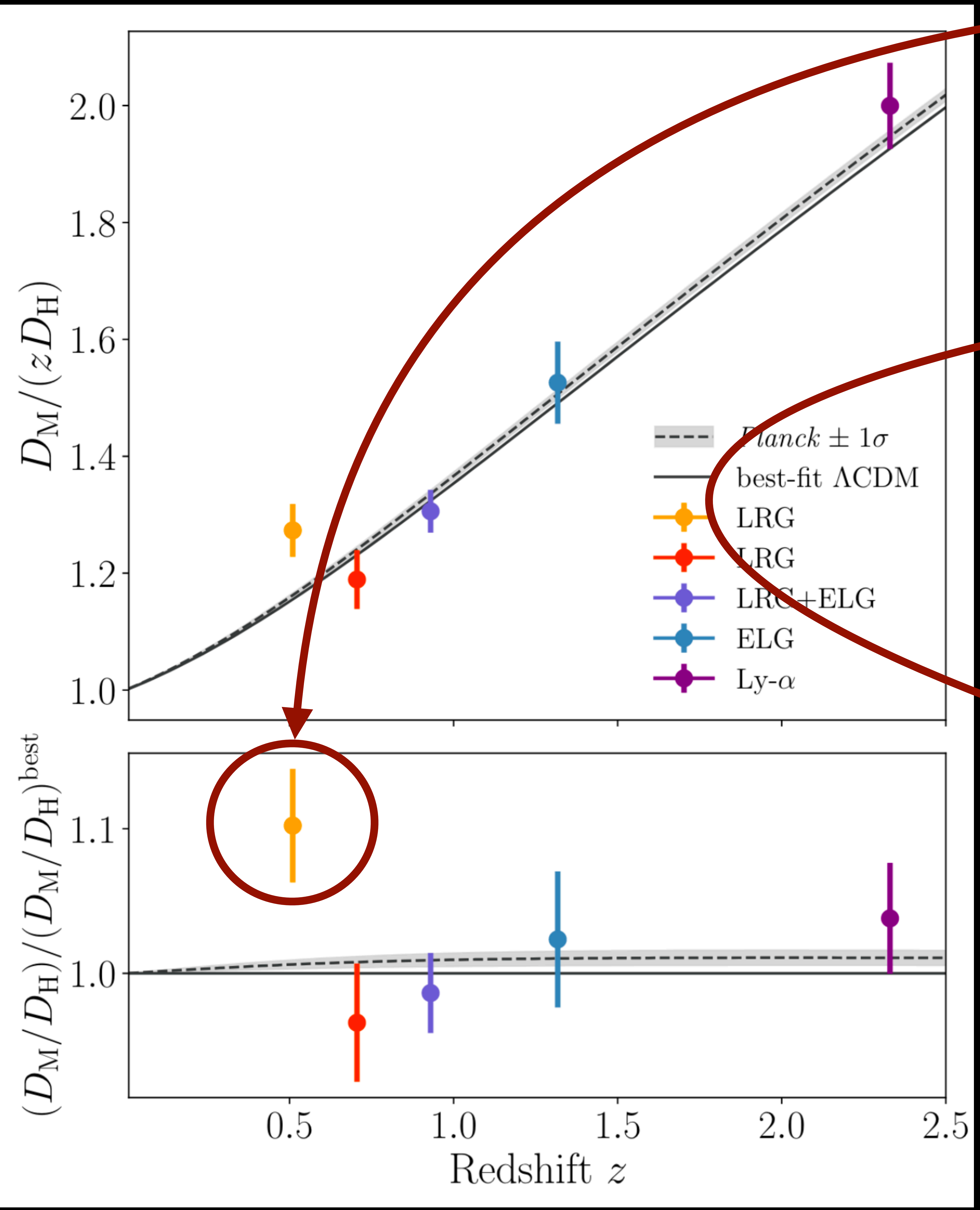
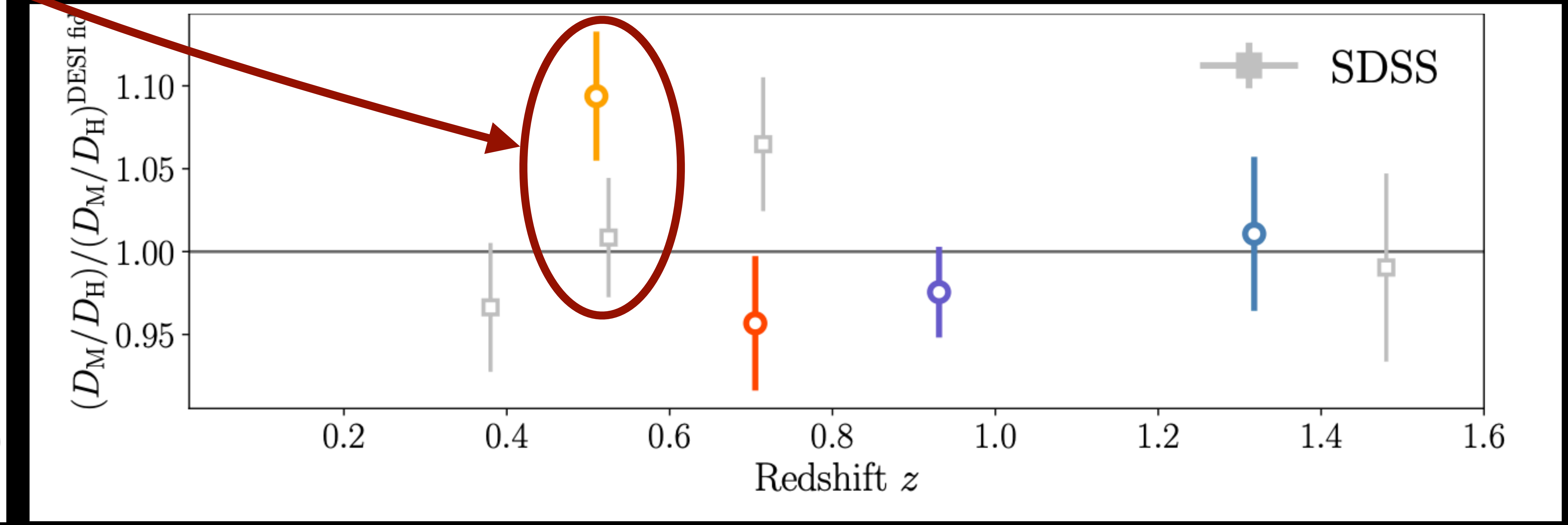
Results @ $z = 0.51$ from DESI and SDSS **agrees** $\sim 1\sigma$**.**





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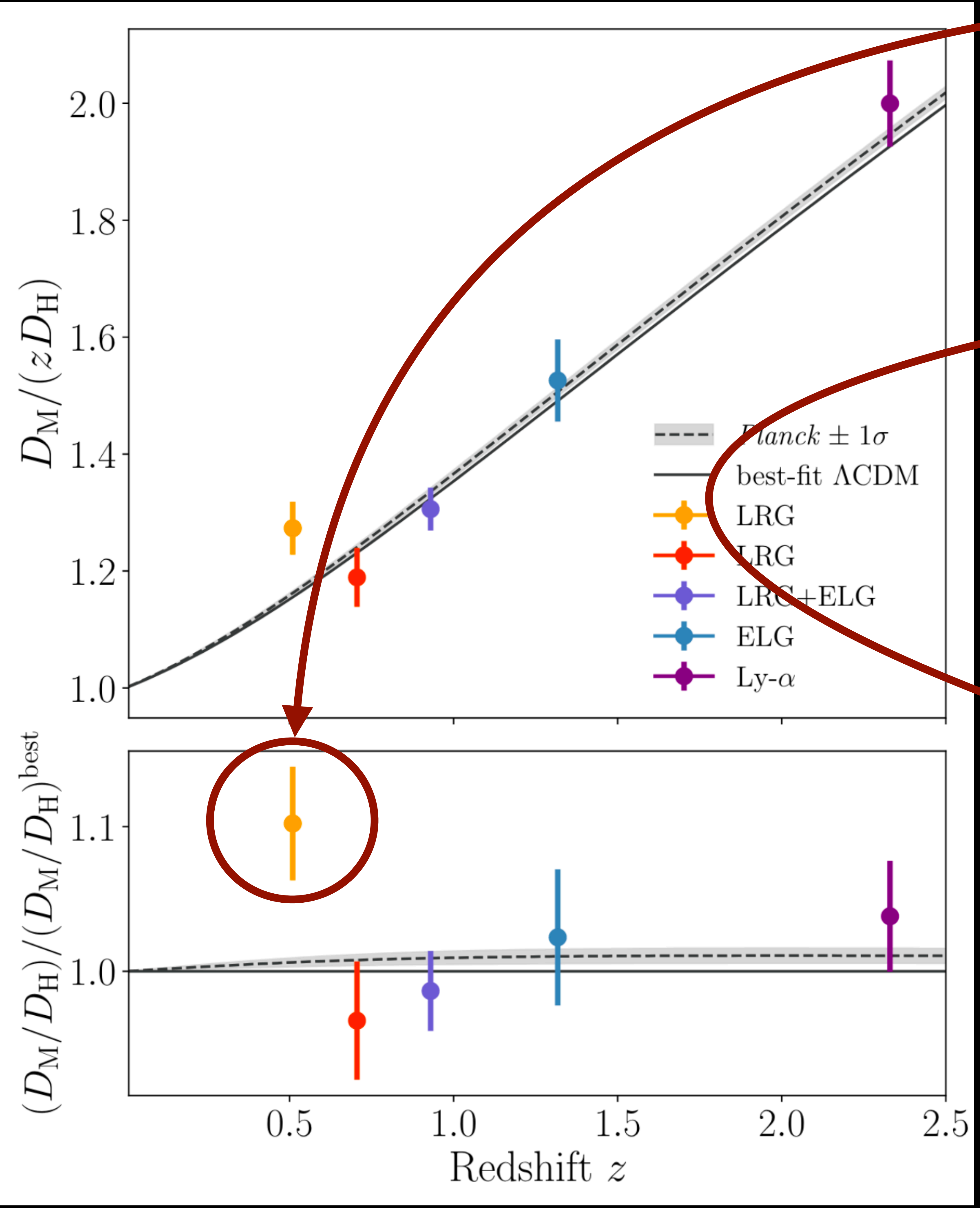
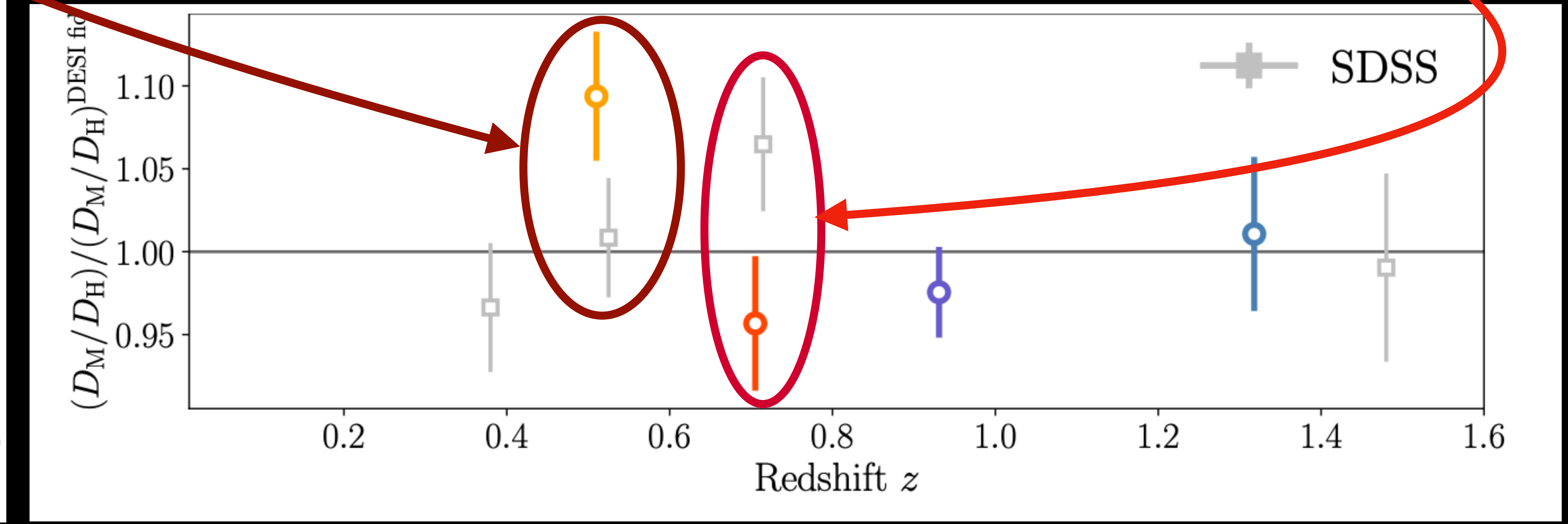
Although LRG2 $0.6 < z < 0.8$ is $\sim 2.7 - 3\sigma$ discrepant.

Cause of this difference unclear. Might be due to an unlucky sample variance fluctuation.





BAO dataset from DESI + SDSS

Combing DESI and SDSS to get the most precise BAO measurements ever made.

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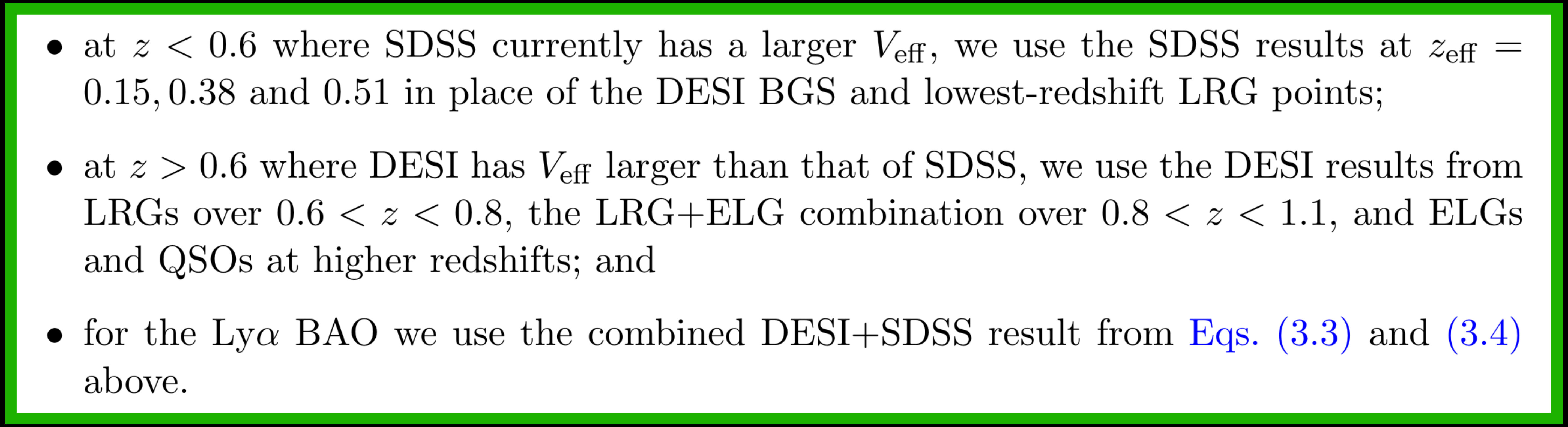
The composite BAO dataset:



- at $z < 0.6$ where SDSS currently has a larger $V_{\rm eff}$, we use the SDSS results at $z_{\rm eff} = 0.15, 0.38$ and 0.51 in place of the DESI BGS and lowest-redshift LRG points;
- at $z > 0.6$ where DESI has $V_{\rm eff}$ larger than that of SDSS, we use the DESI results from LRGs over $0.6 < z < 0.8$, the LRG+ELG combination over $0.8 < z < 1.1$, and ELGs and QSOs at higher redshifts; and
- for the Lyα BAO we use the combined DESI+SDSS result from Eqs. (3.3) and (3.4) above.

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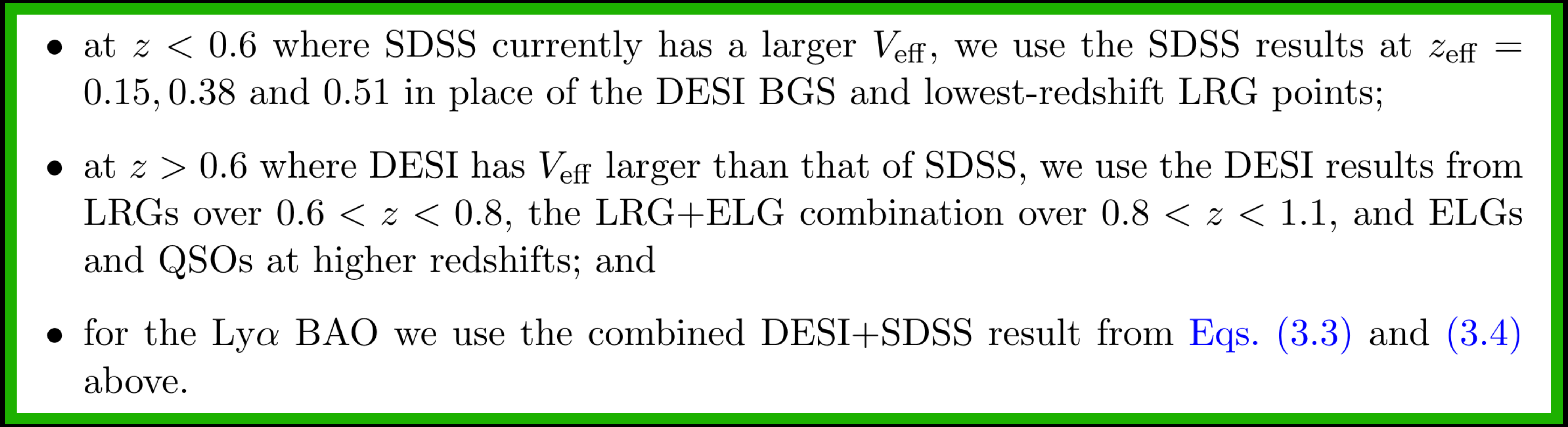

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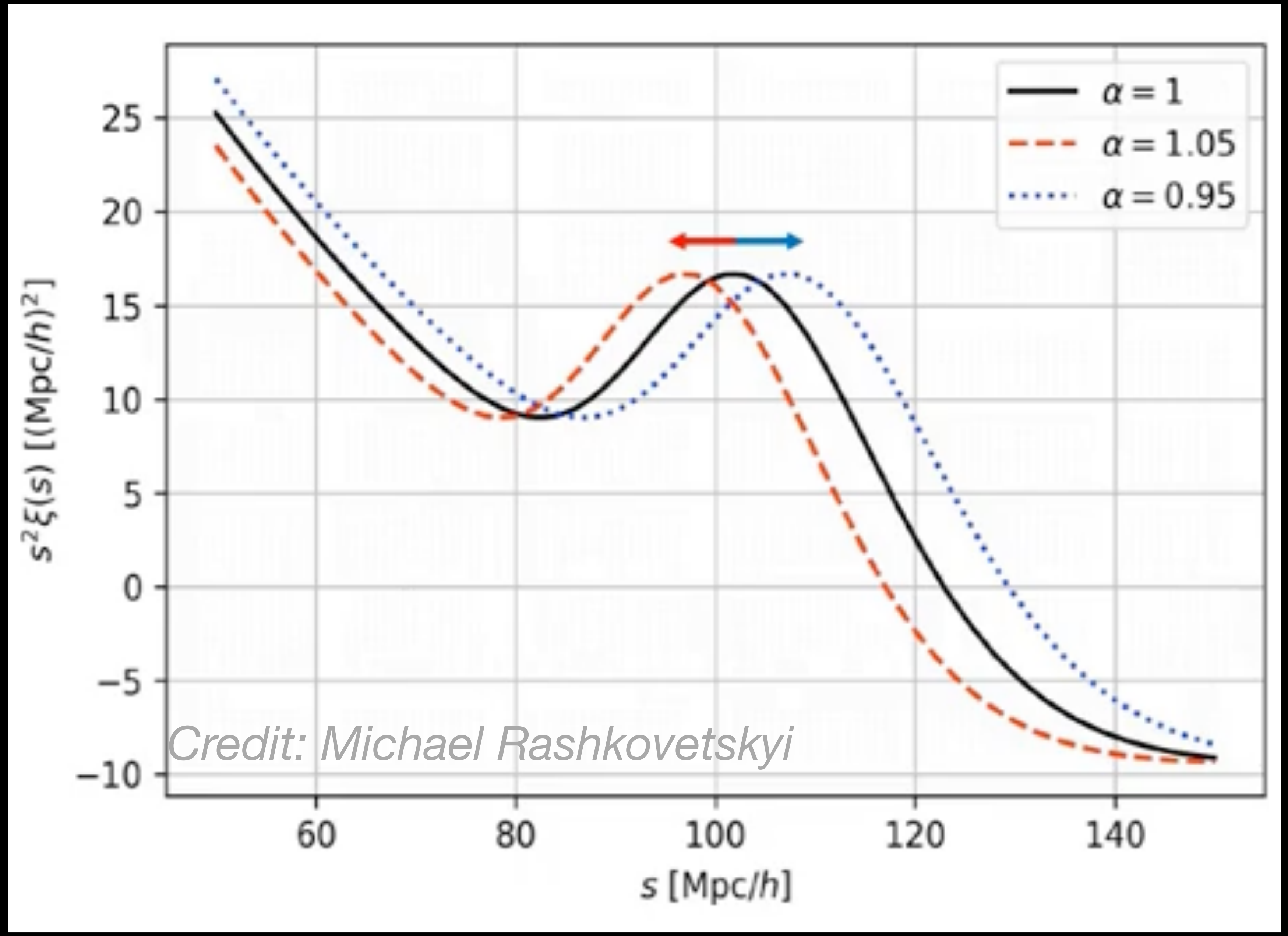
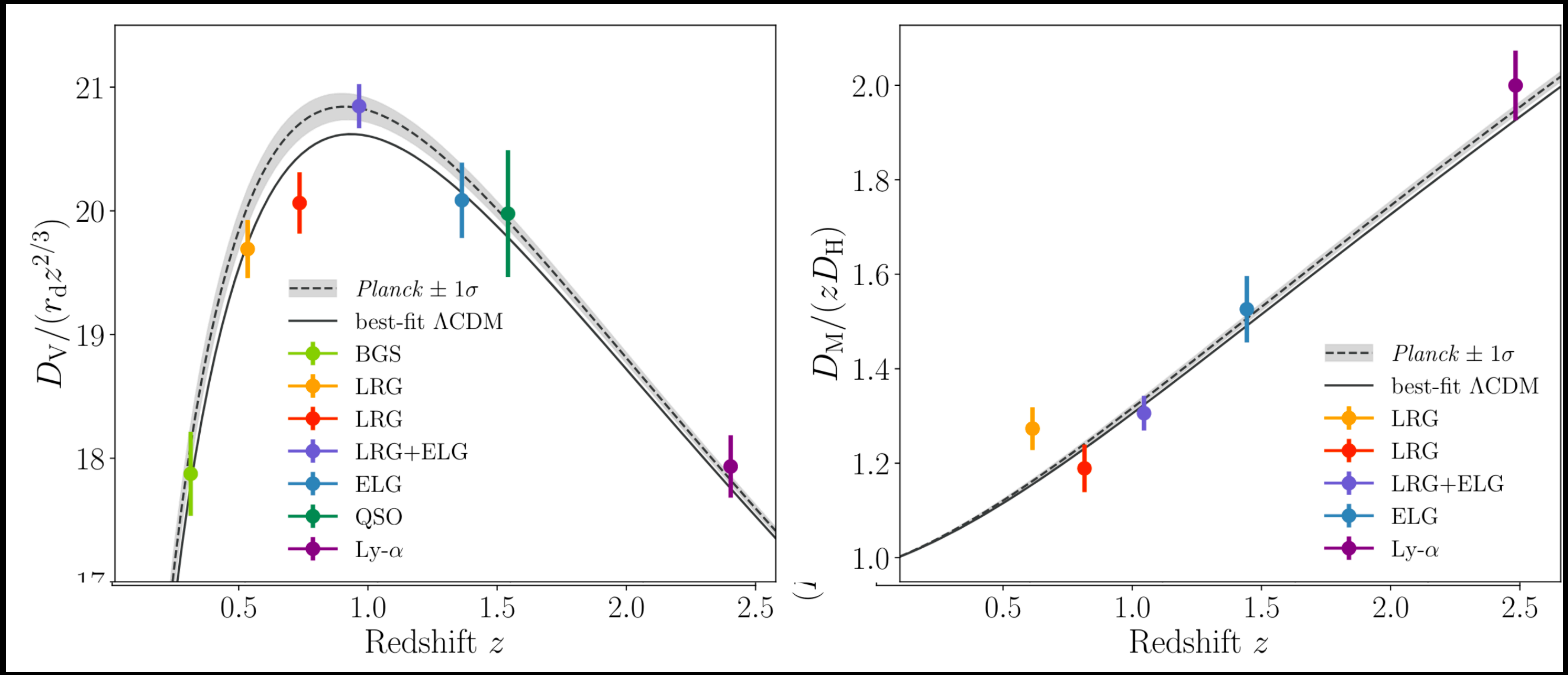
Distance Measurements

Relation between BAO parameters, e.g., $(\alpha_{\parallel}, \alpha_{\perp})$ and distances (D_M, D_H, D_V)



Credit: Michael Rashkovetskyi



$$\frac{D_M(z)}{r_d} \equiv \frac{D_A(z)\,(1+z)}{r_d} = \alpha_{\perp}\frac{D_M^{\mathrm{fid}}(z)}{r_d^{\mathrm{fid}}}$$

→ comoving angular diameter distance $D_M(z)$

$$\frac{D_H(z)}{r_d} \equiv \frac{c}{H(z) r_d} = \alpha_{\parallel}\frac{D_H^{\mathrm{fid}}(z)}{r_d^{\mathrm{fid}}}$$

→ Hubble distance $D_H(z)$

$$\frac{D_V(z)}{r_d} \equiv \frac{[z D_M^2(z) D_H(z)]^{1/3}}{r_d} = \alpha_{\mathrm{iso}}\frac{D_V^{\mathrm{fid}}(z)}{r_d^{\mathrm{fid}}}$$

→ spherically-averaged distance $D_V(z)$

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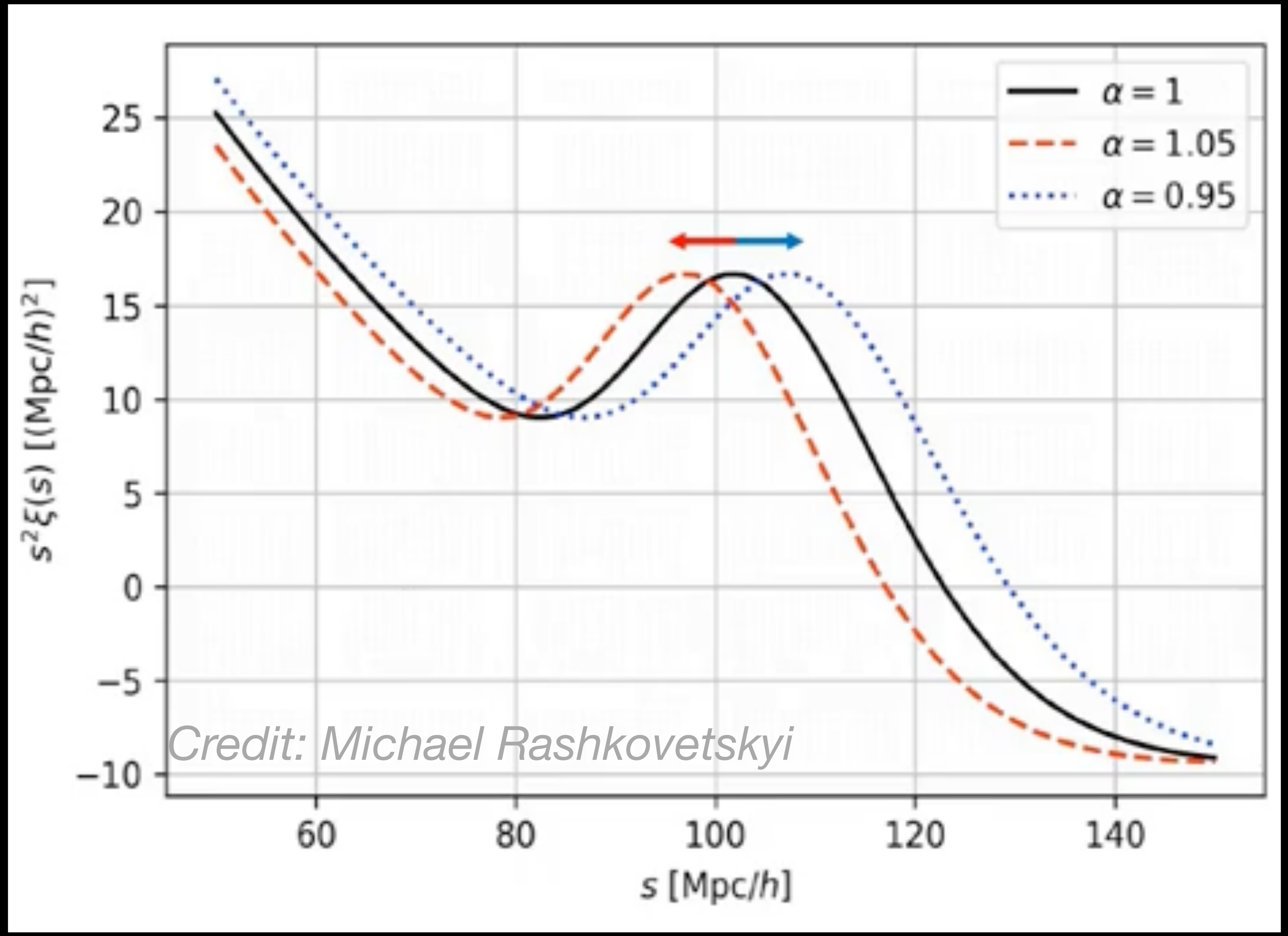

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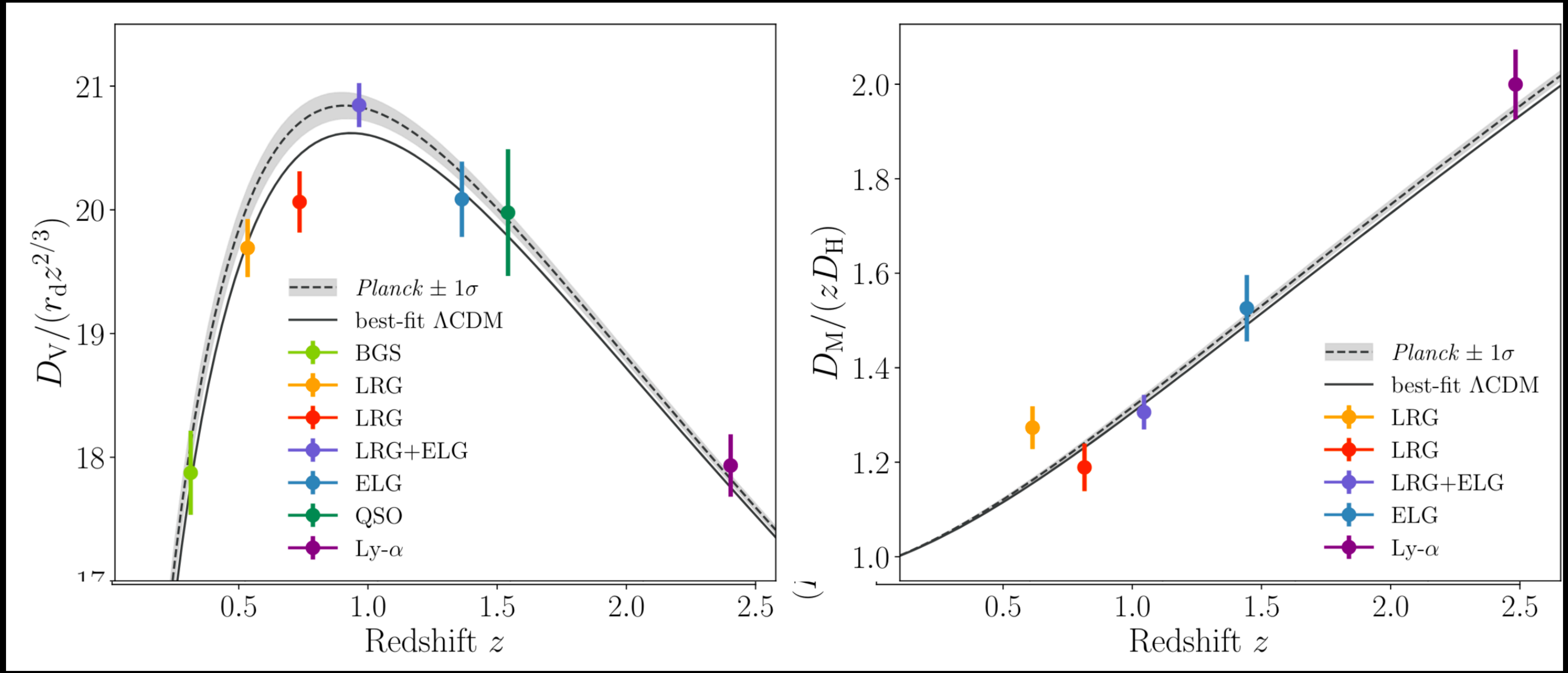

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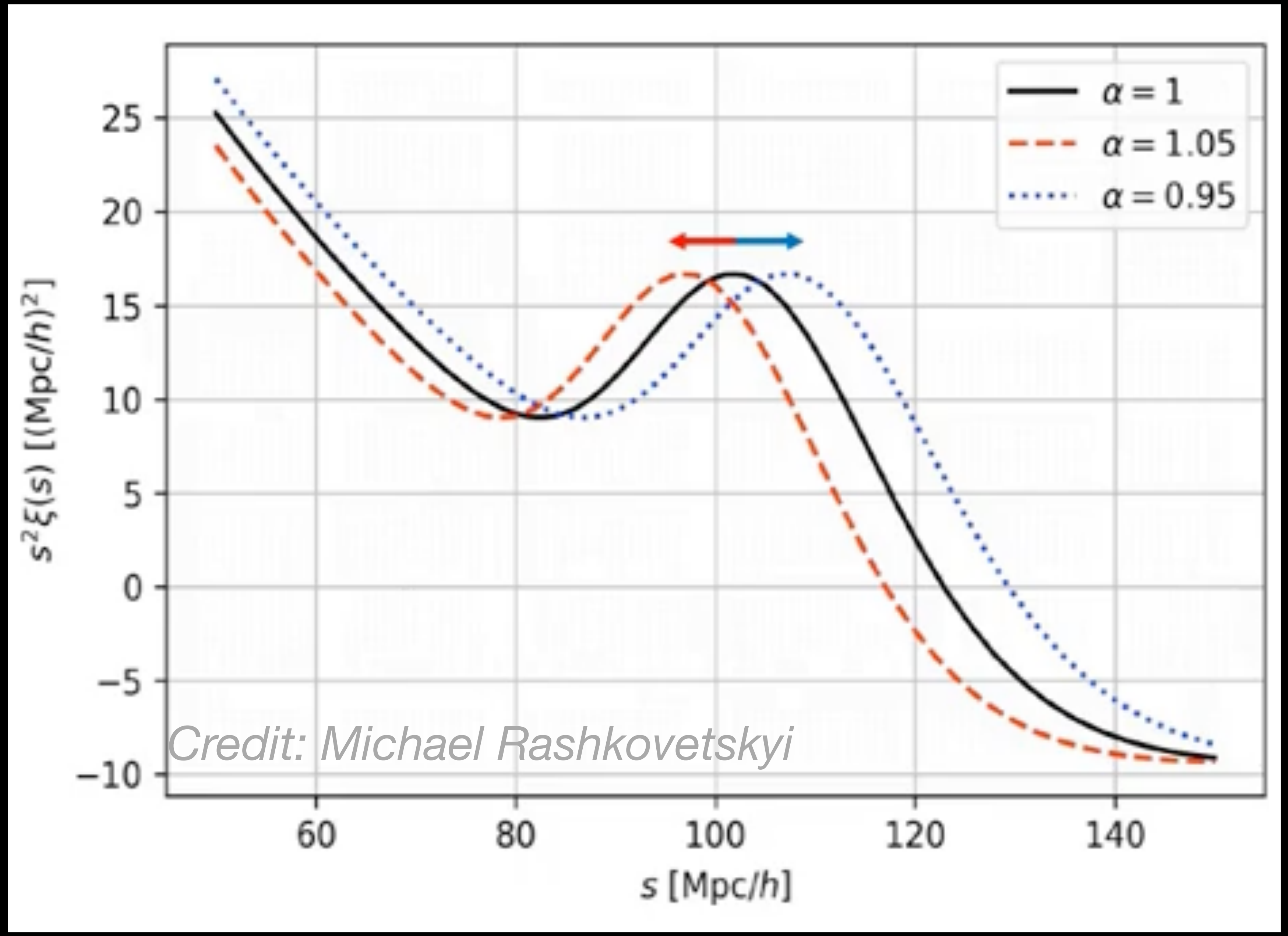

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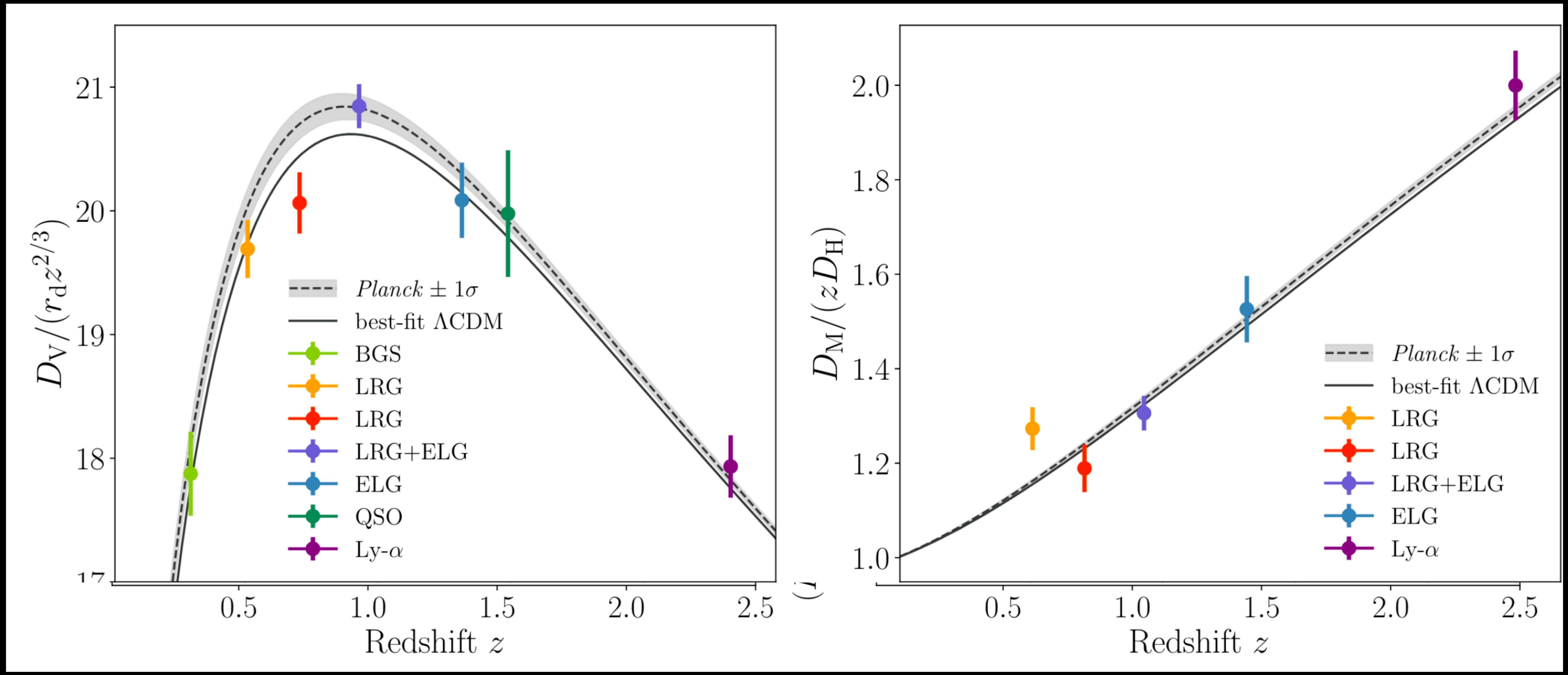

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→ Hubble distance $D_H(z)$

$$\boxed{\alpha_{\rm iso} = (\alpha_{\parallel}\alpha_{\perp}^2)^{1/3}\ ,\ \ \alpha_{AP} = \alpha_{\perp}/\alpha_{\parallel}}$$

$$\frac{D_V(z)}{r_d} \equiv \frac{[zD_M^2(z)D_H(z)]^{1/3}}{r_d} = \alpha_{\rm iso}\frac{D_V^{\rm fid}(z)}{r_d^{\rm fid}}$$

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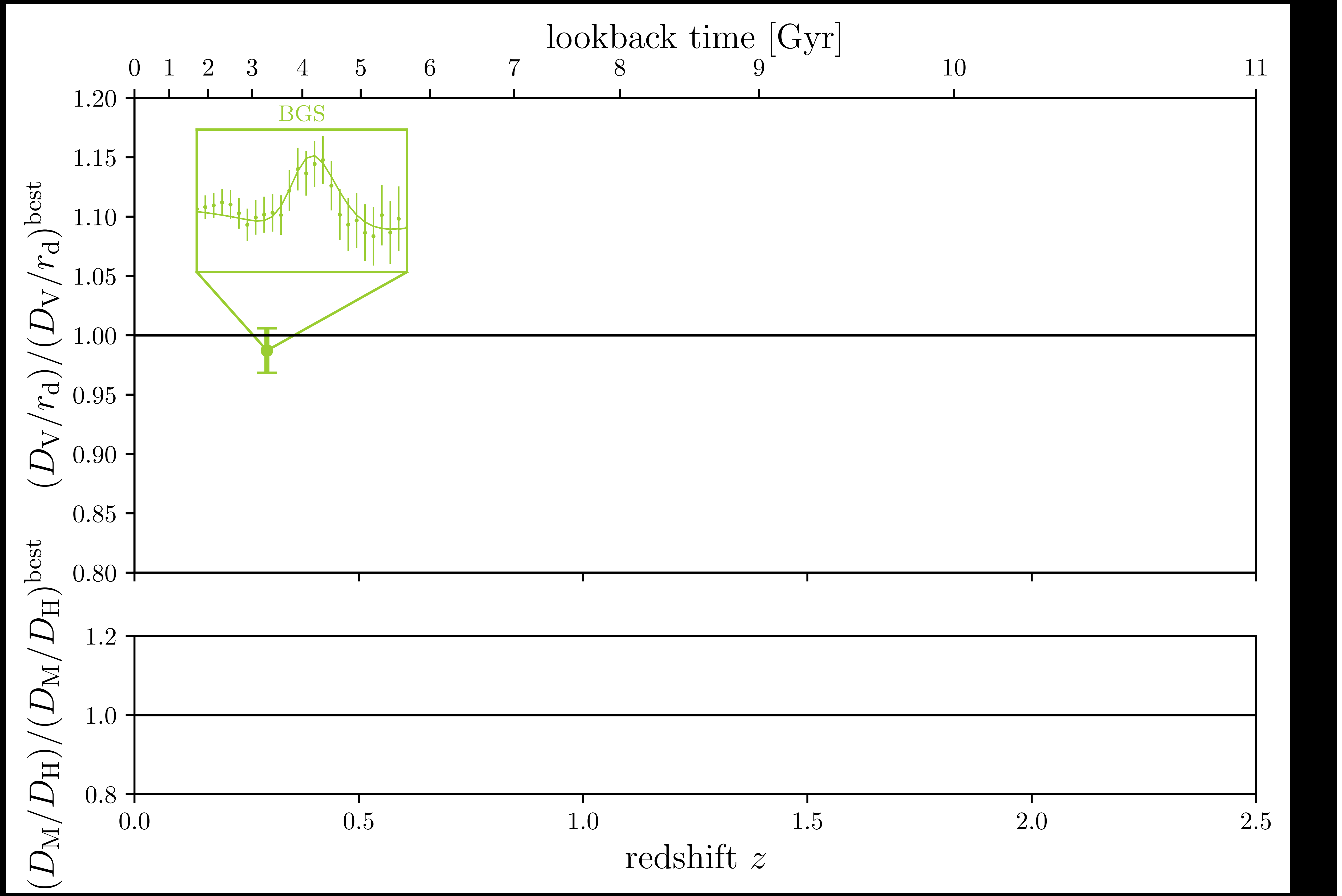
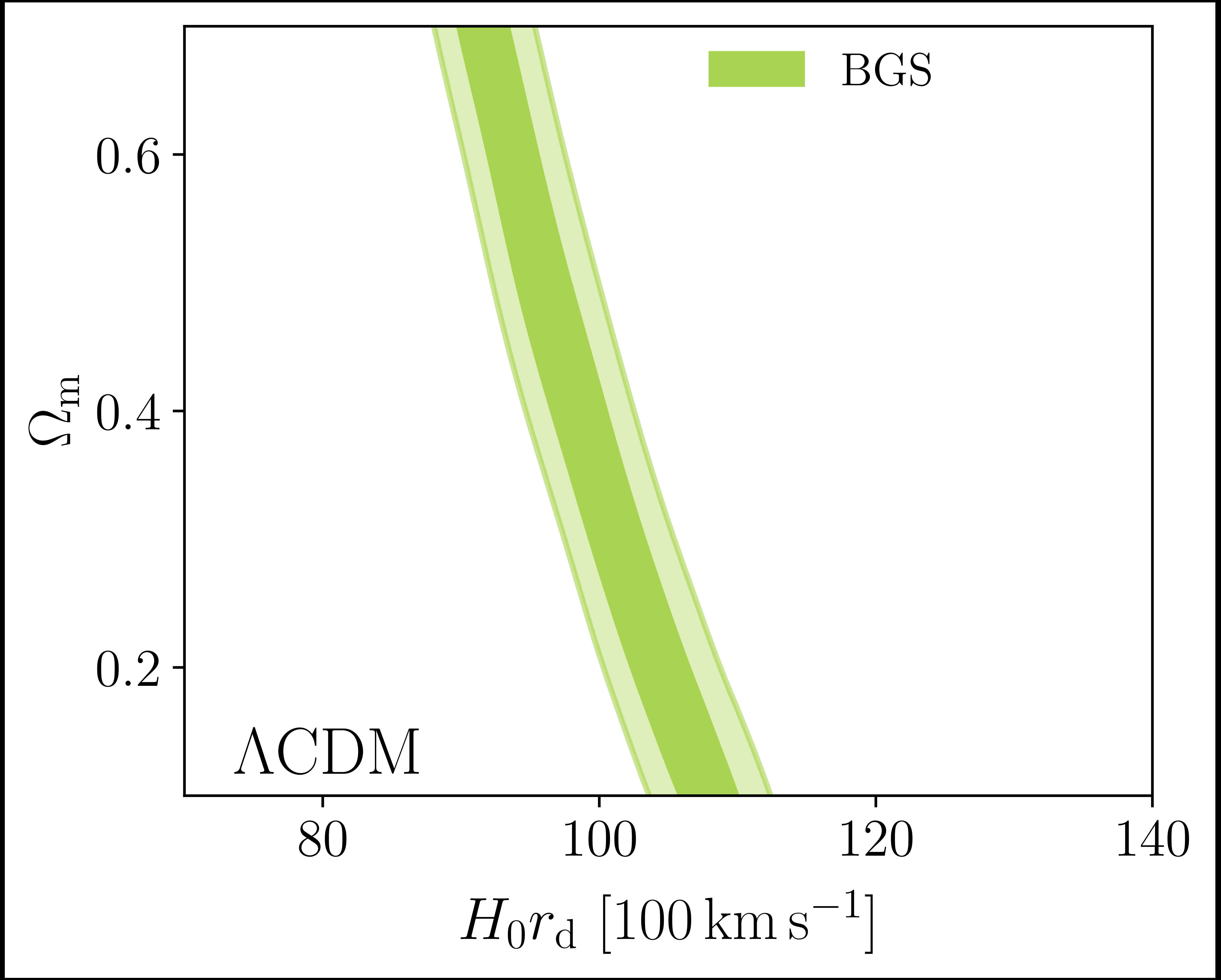
Internal consistency of DESI results





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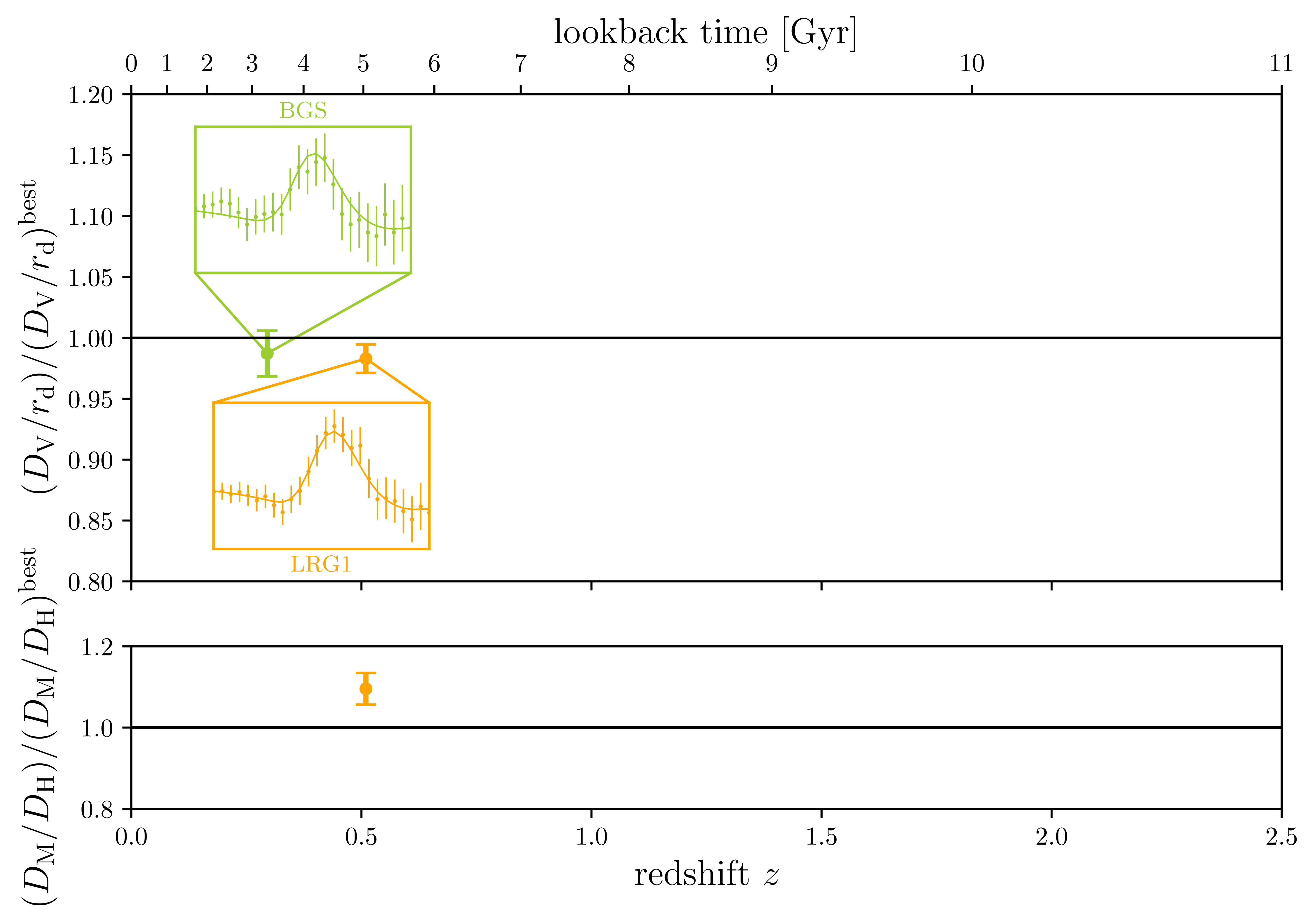

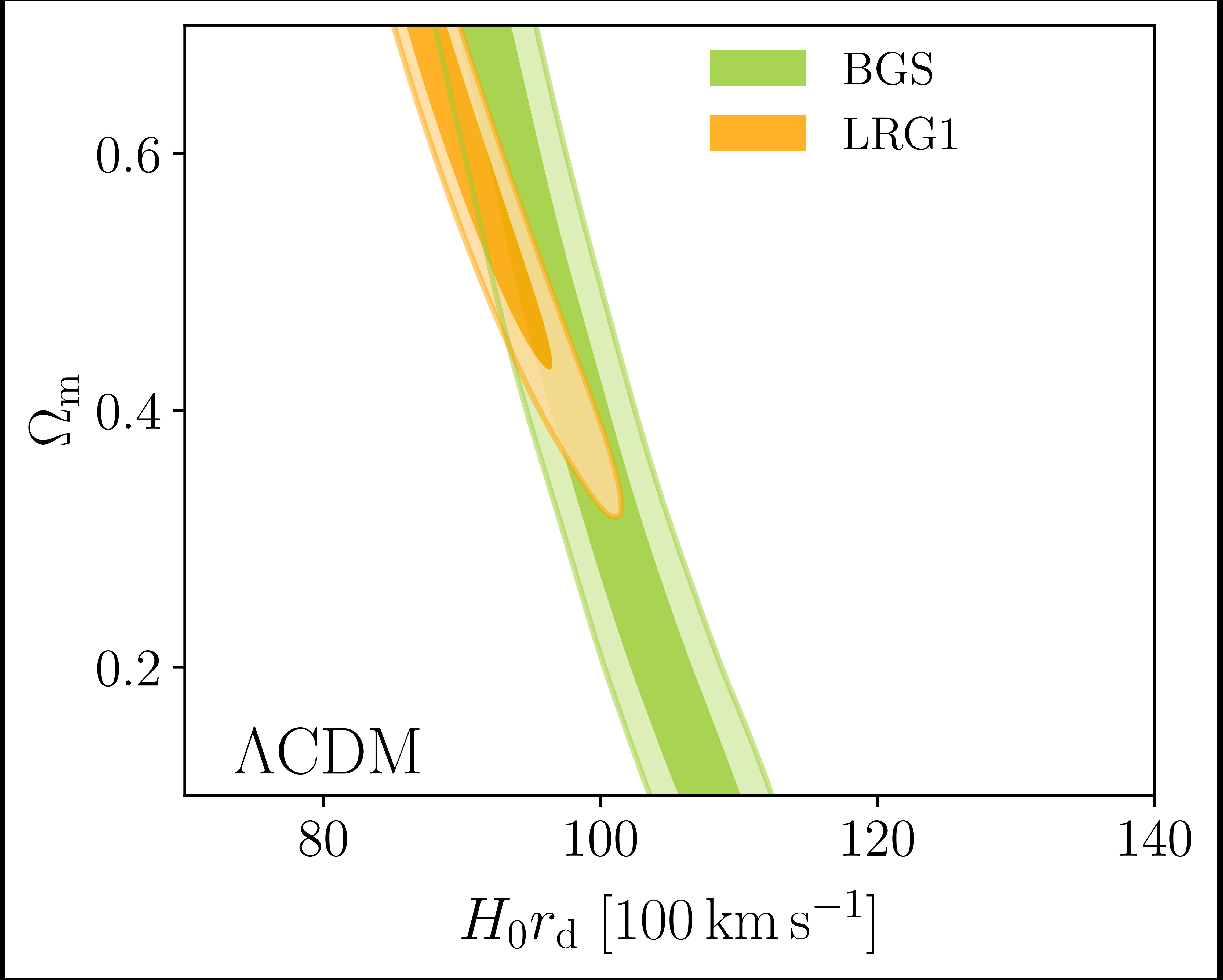

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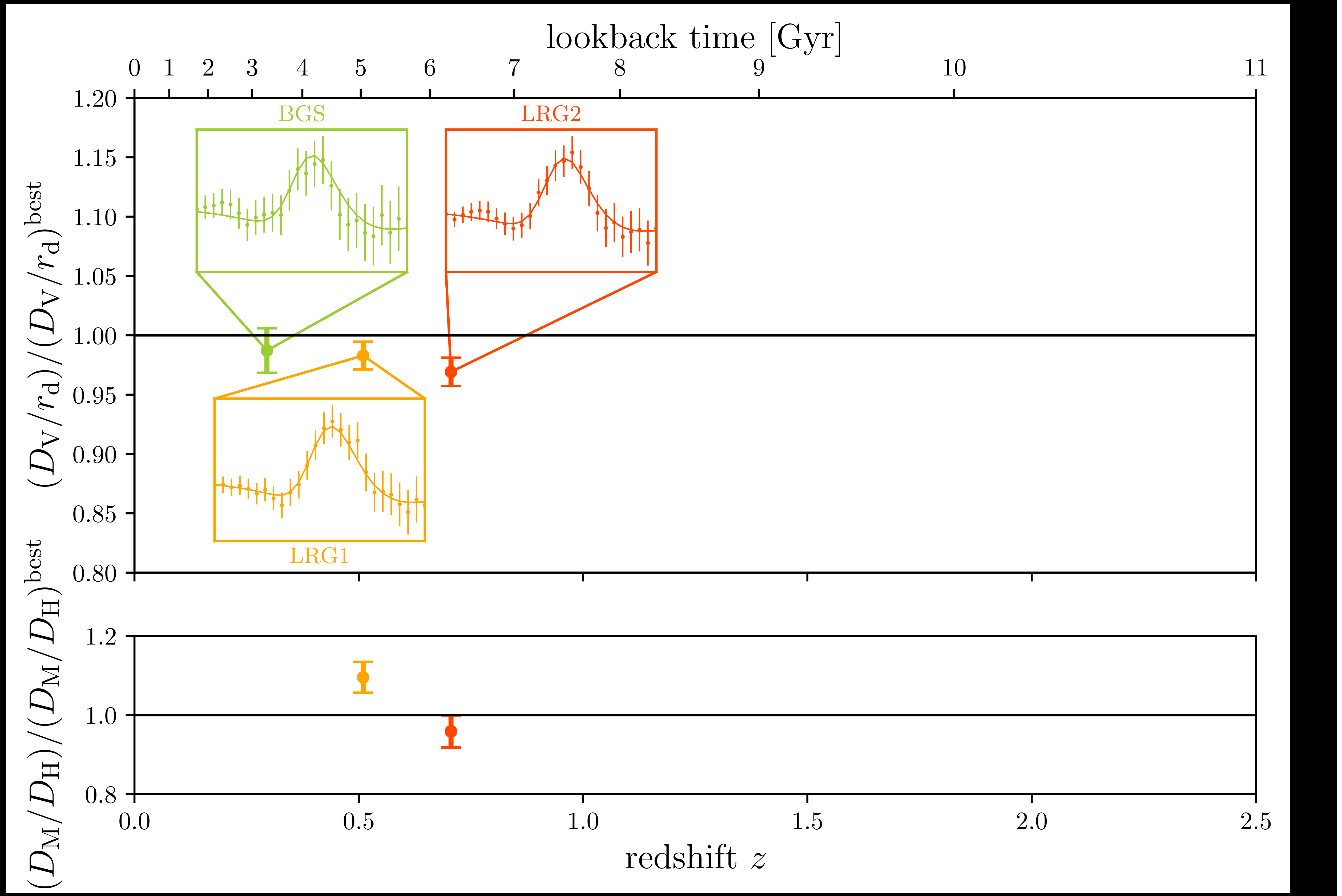

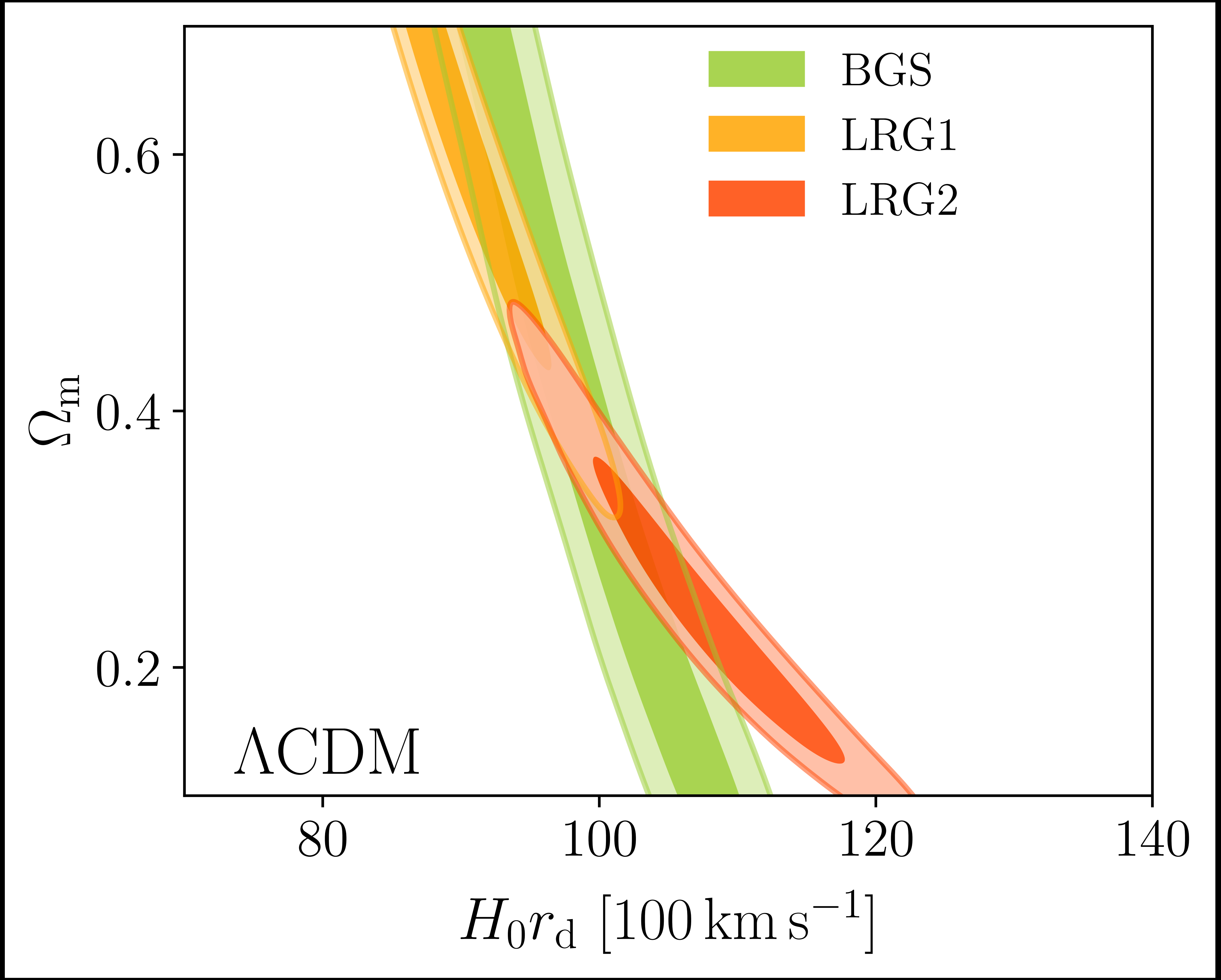

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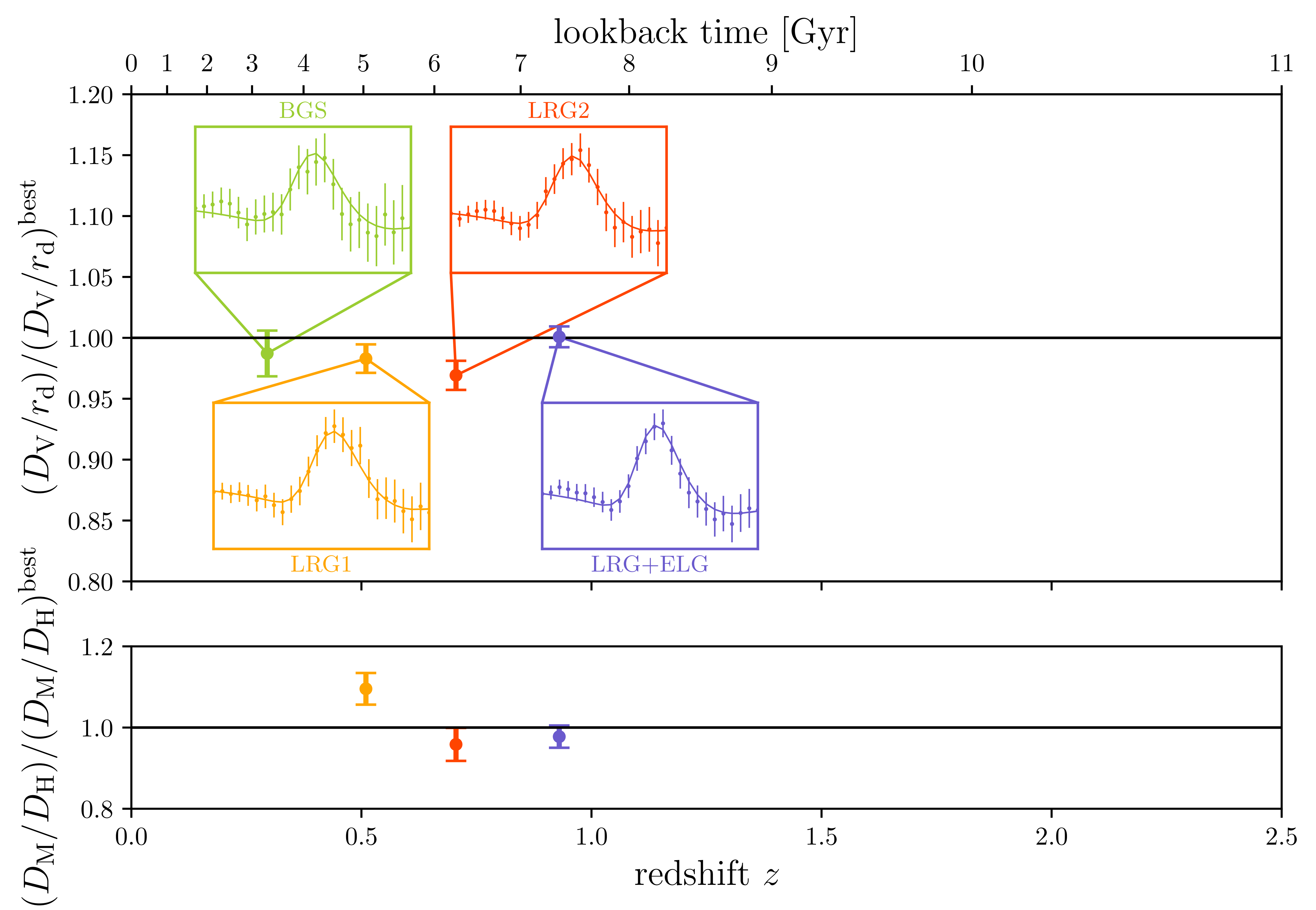

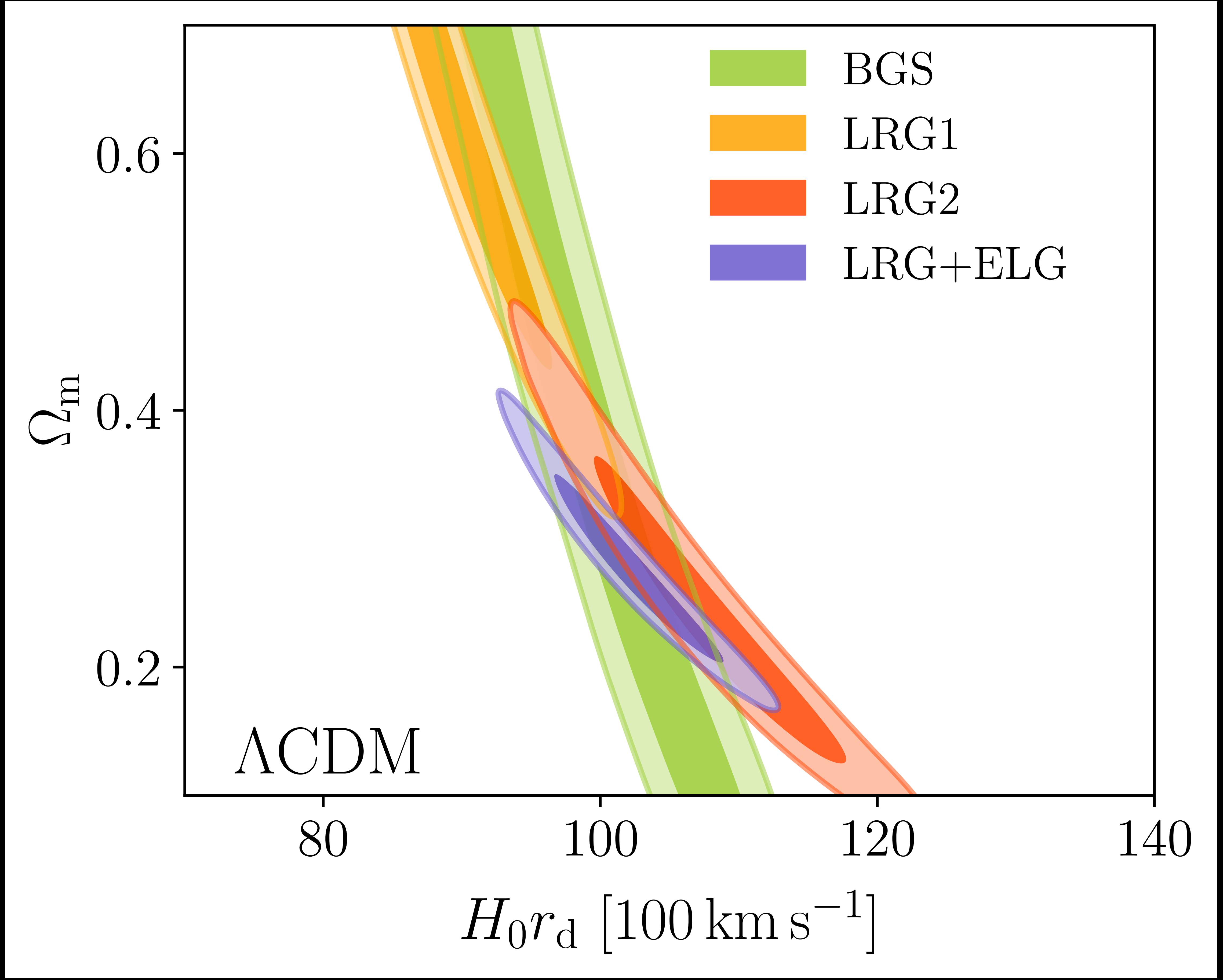

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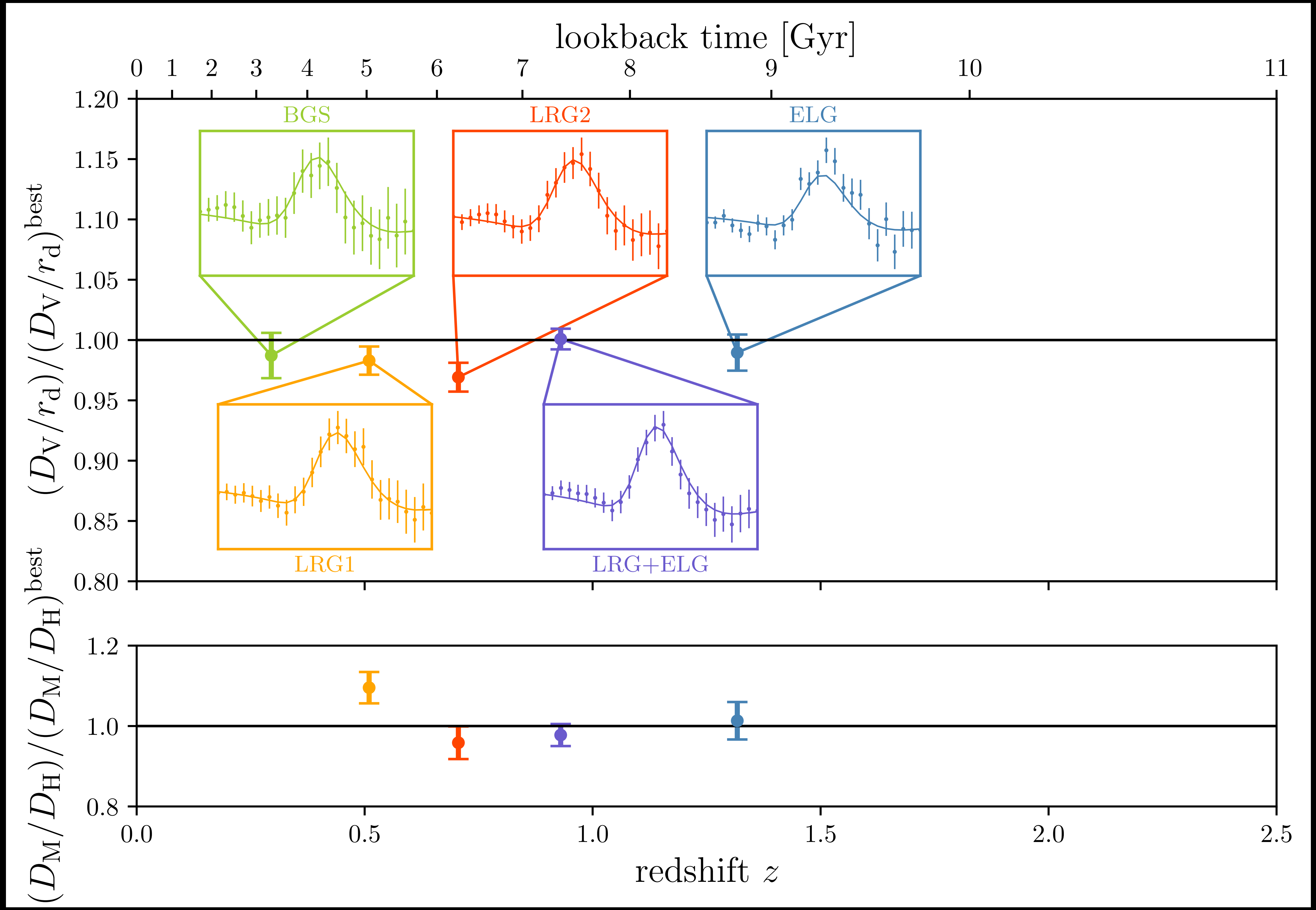

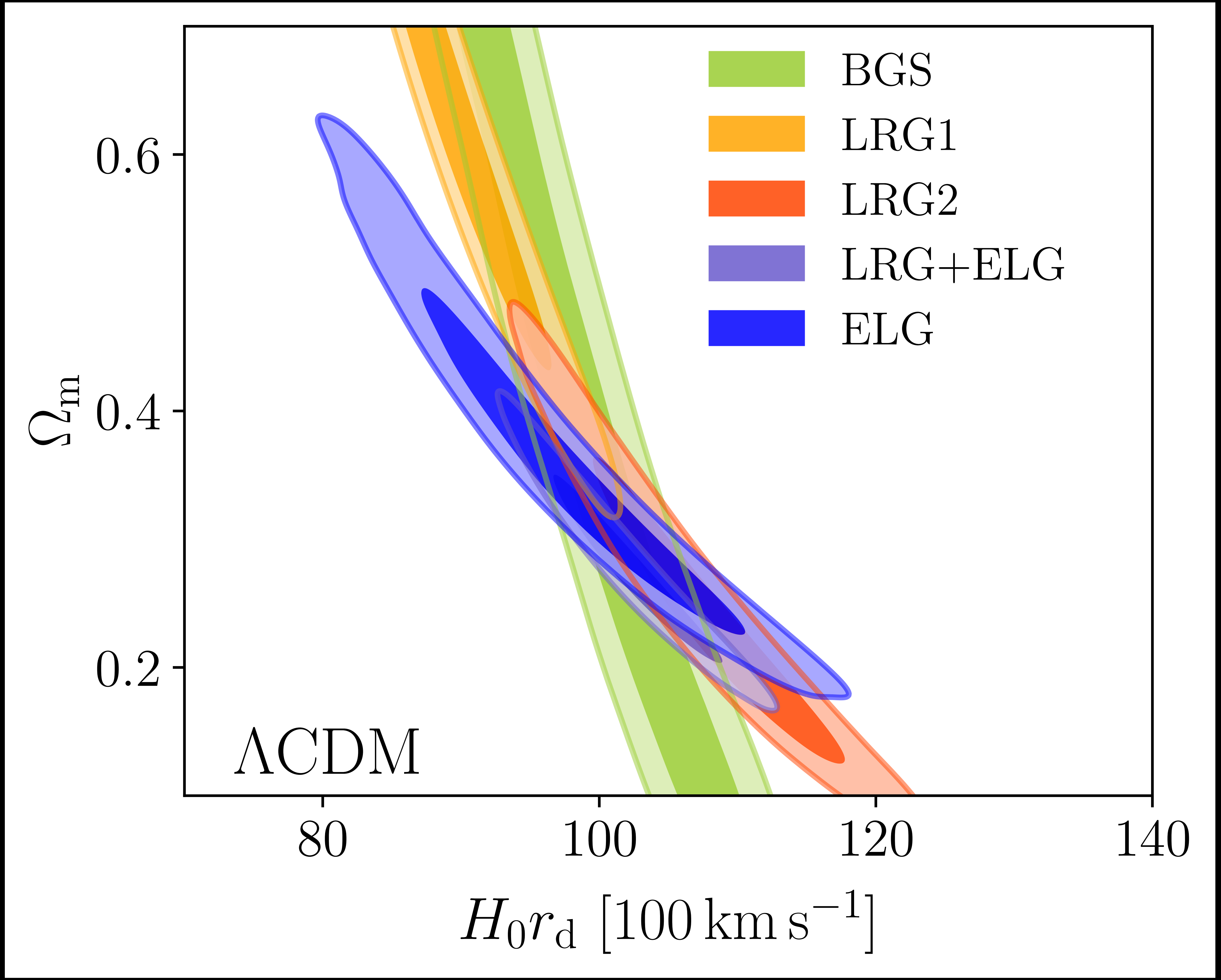

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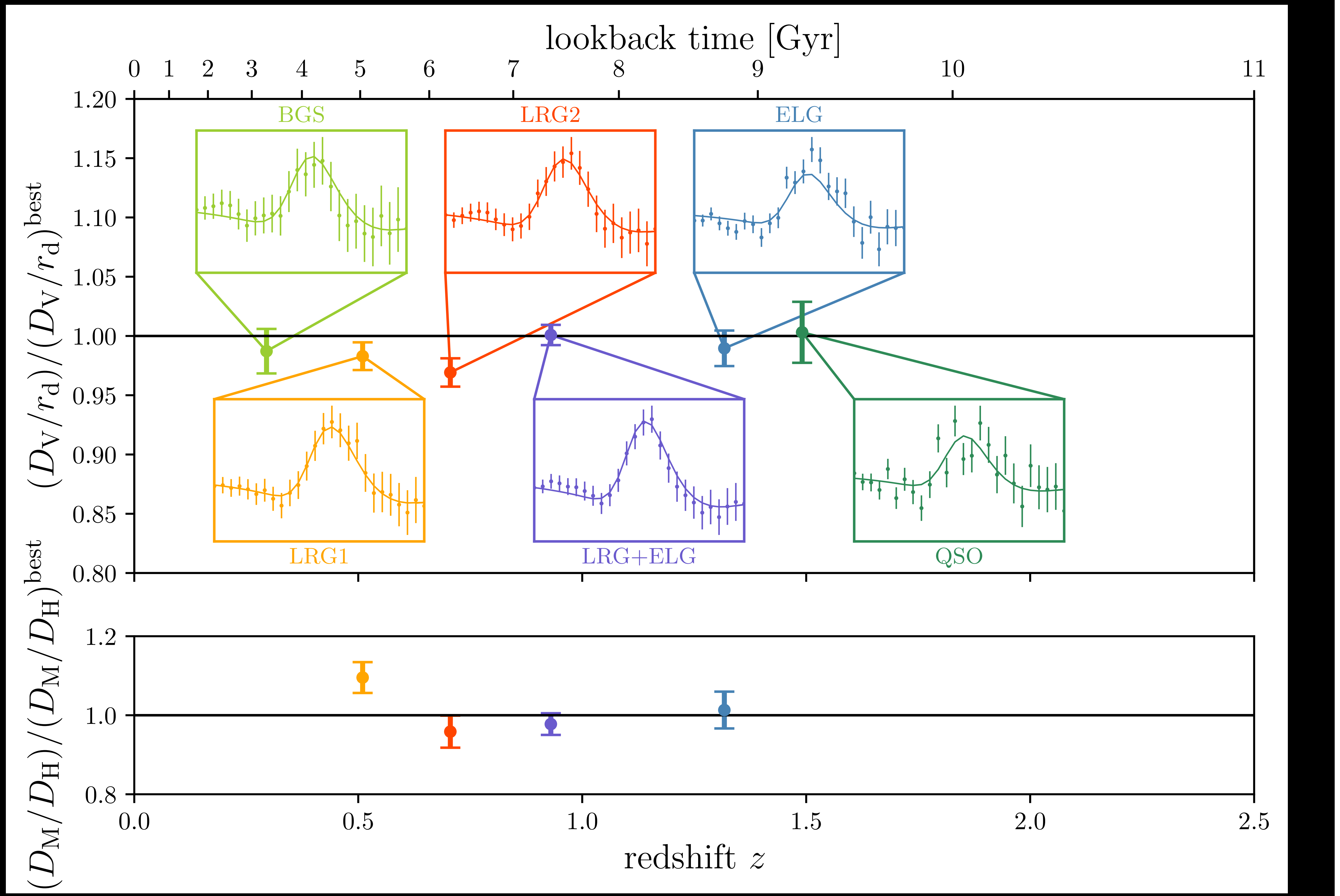

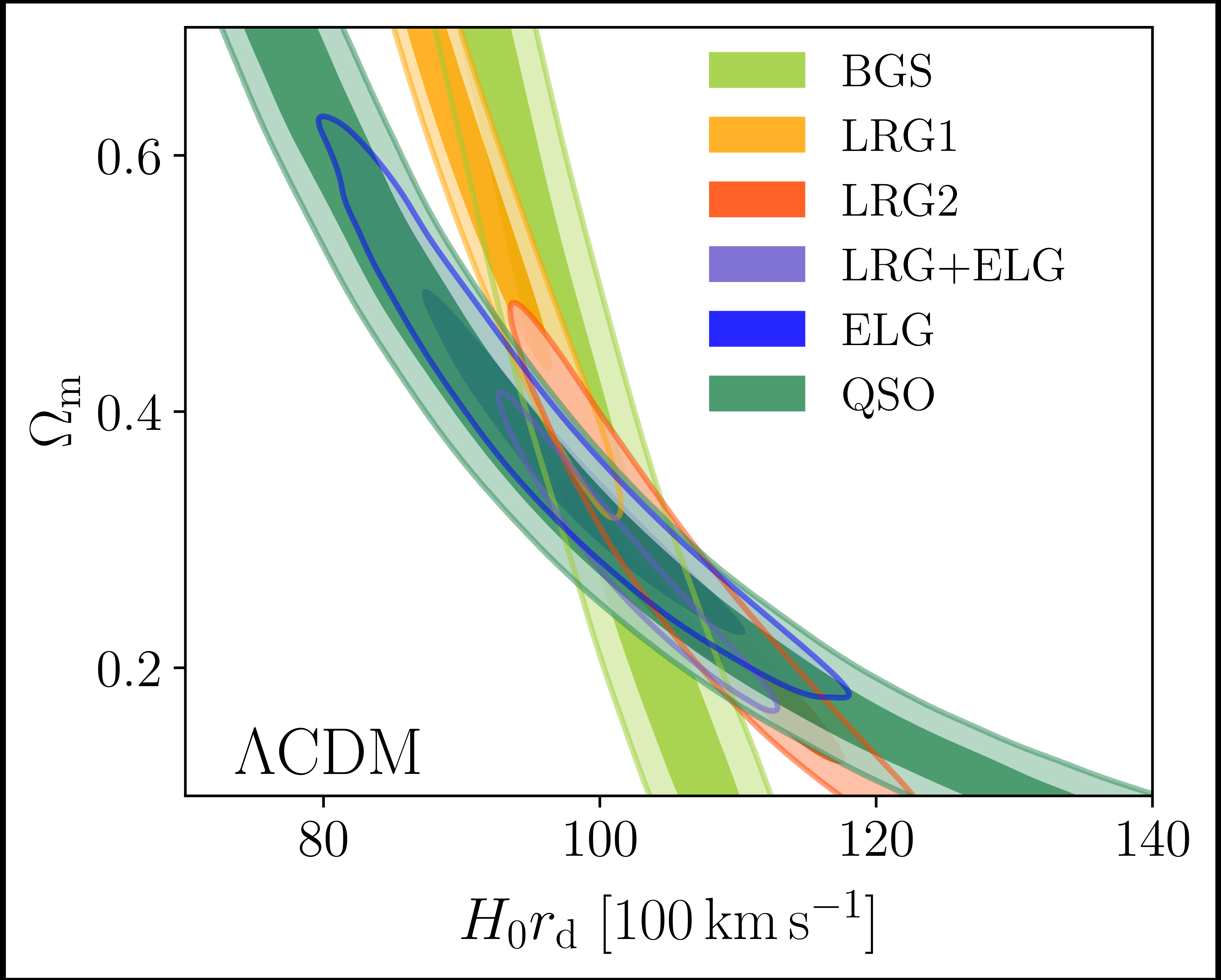

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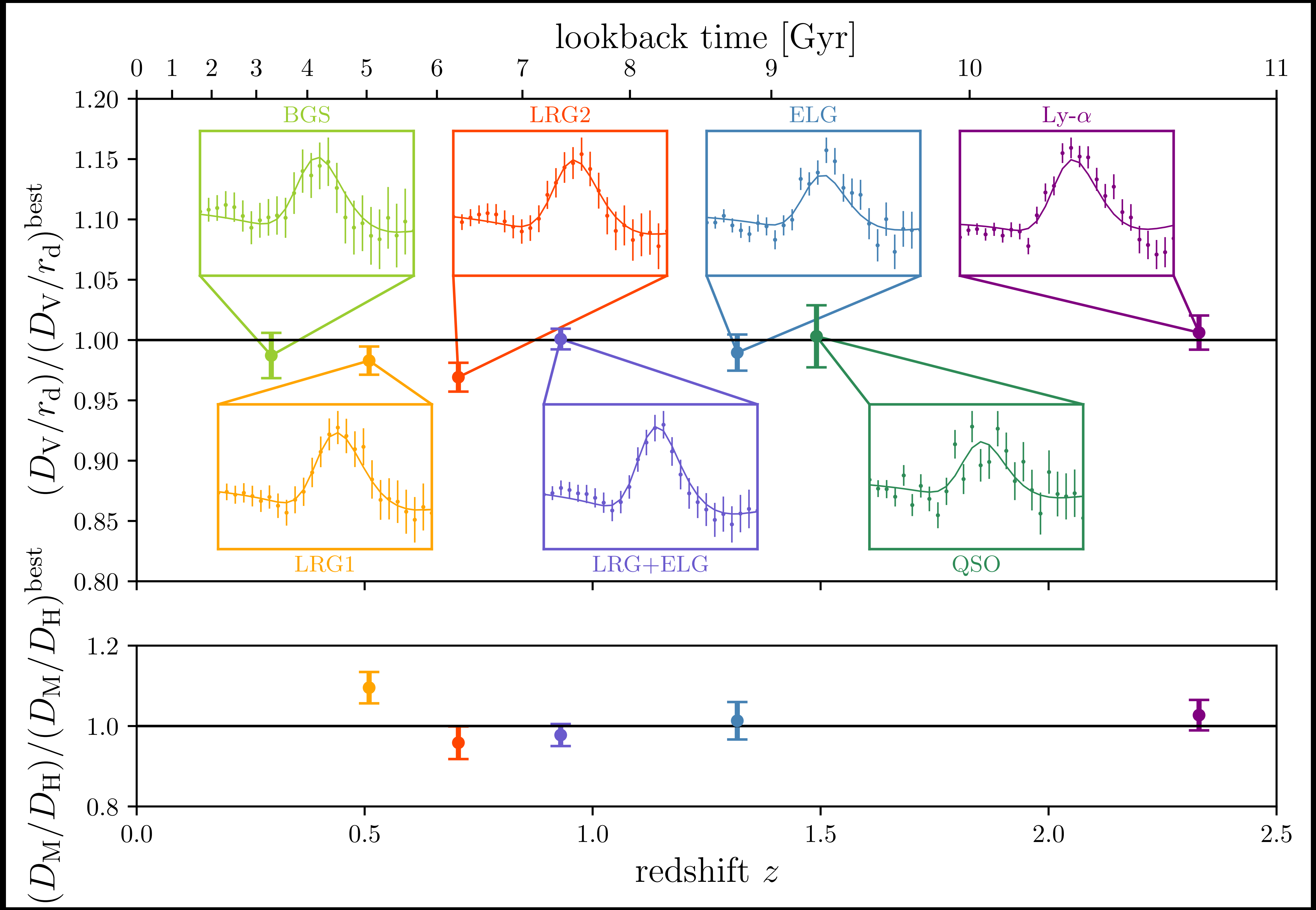
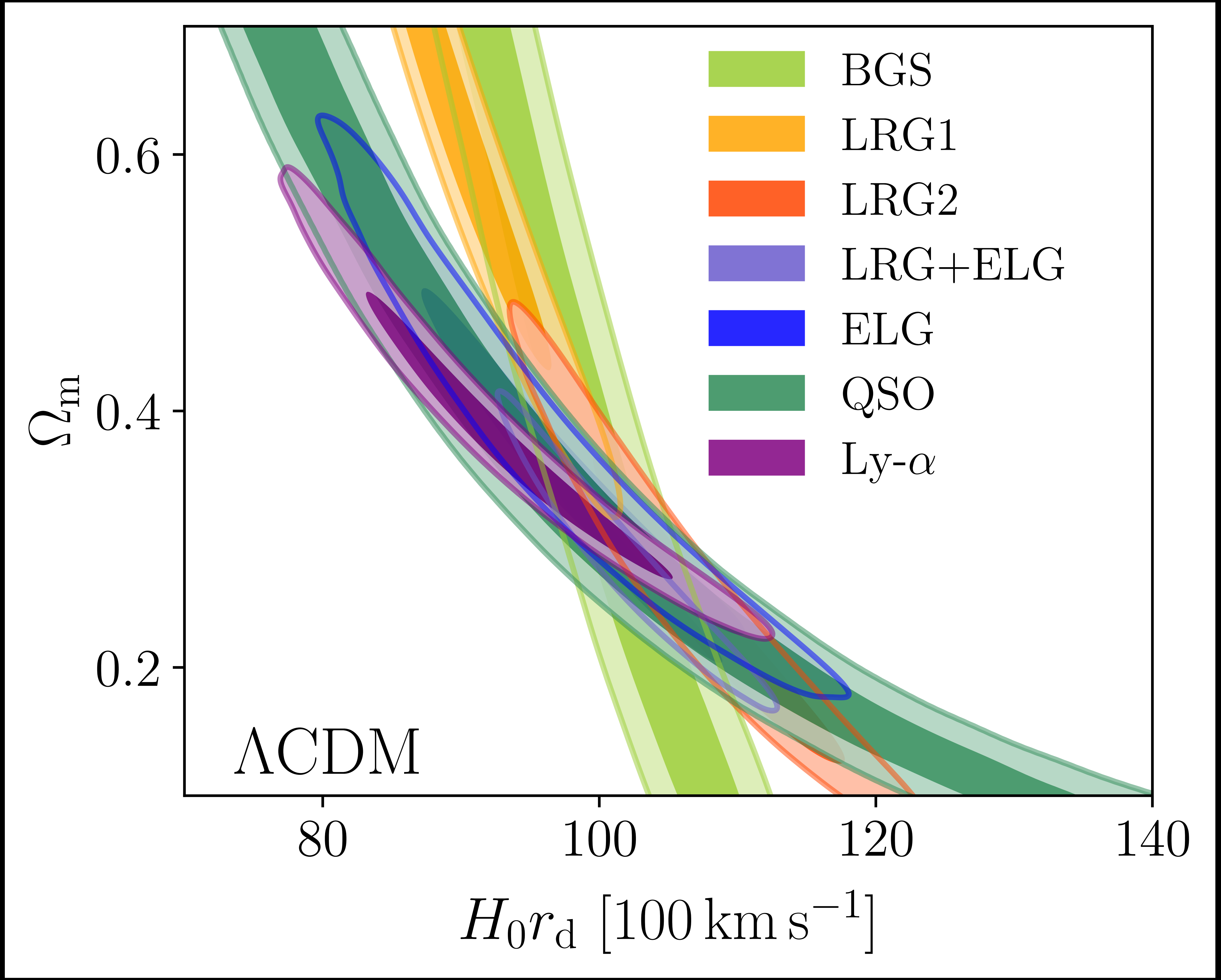




Internal consistency of DESI results

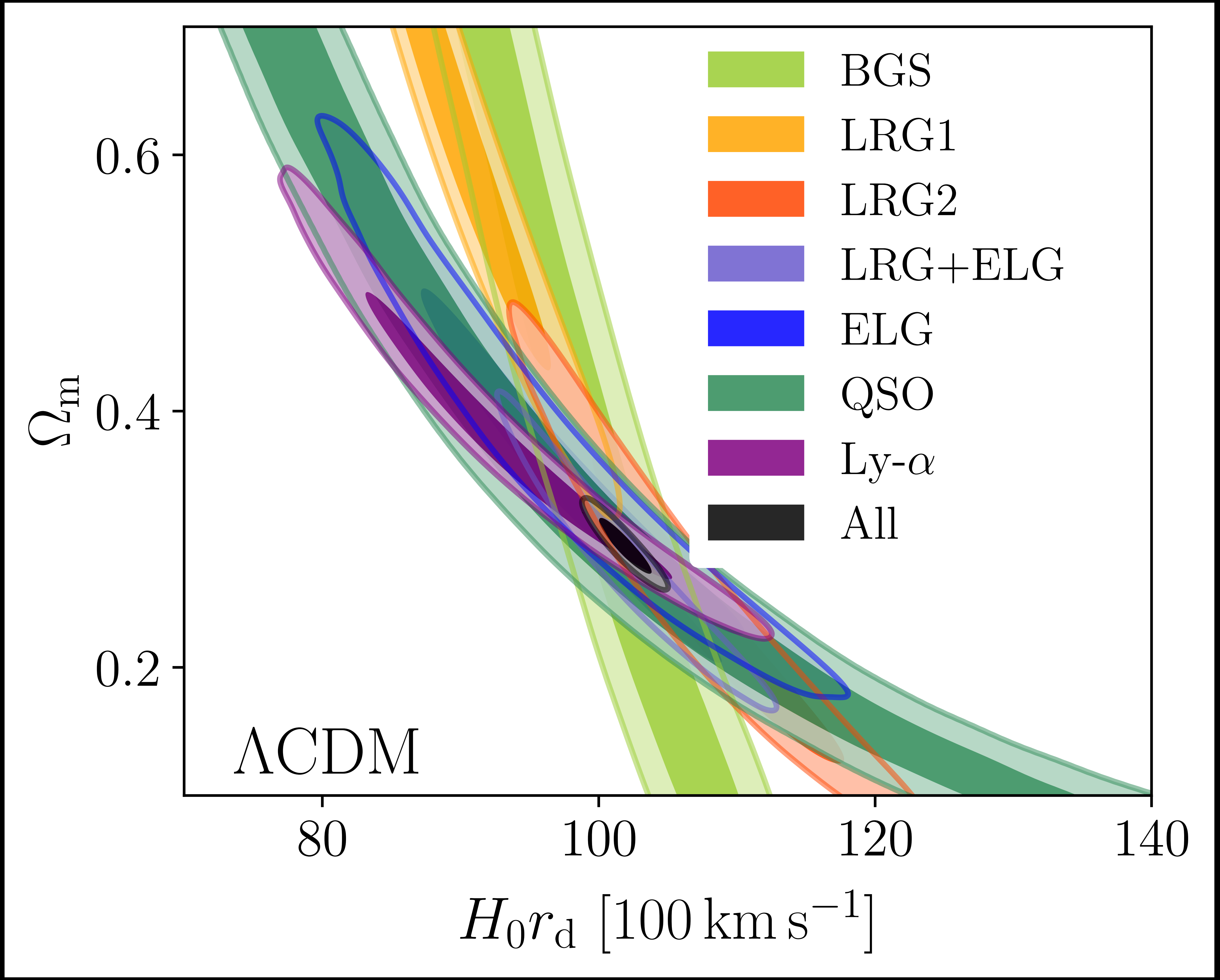
Consistent with each other —

and complementary

$$\Omega_m = 0.295 \pm 0.15 \qquad (5.1\%)$$

$$H_0 r_d = (101.8 \pm 1.3)\ [100\ \mathrm{kms}^{-1}] \qquad (1.3\%)$$

DESI



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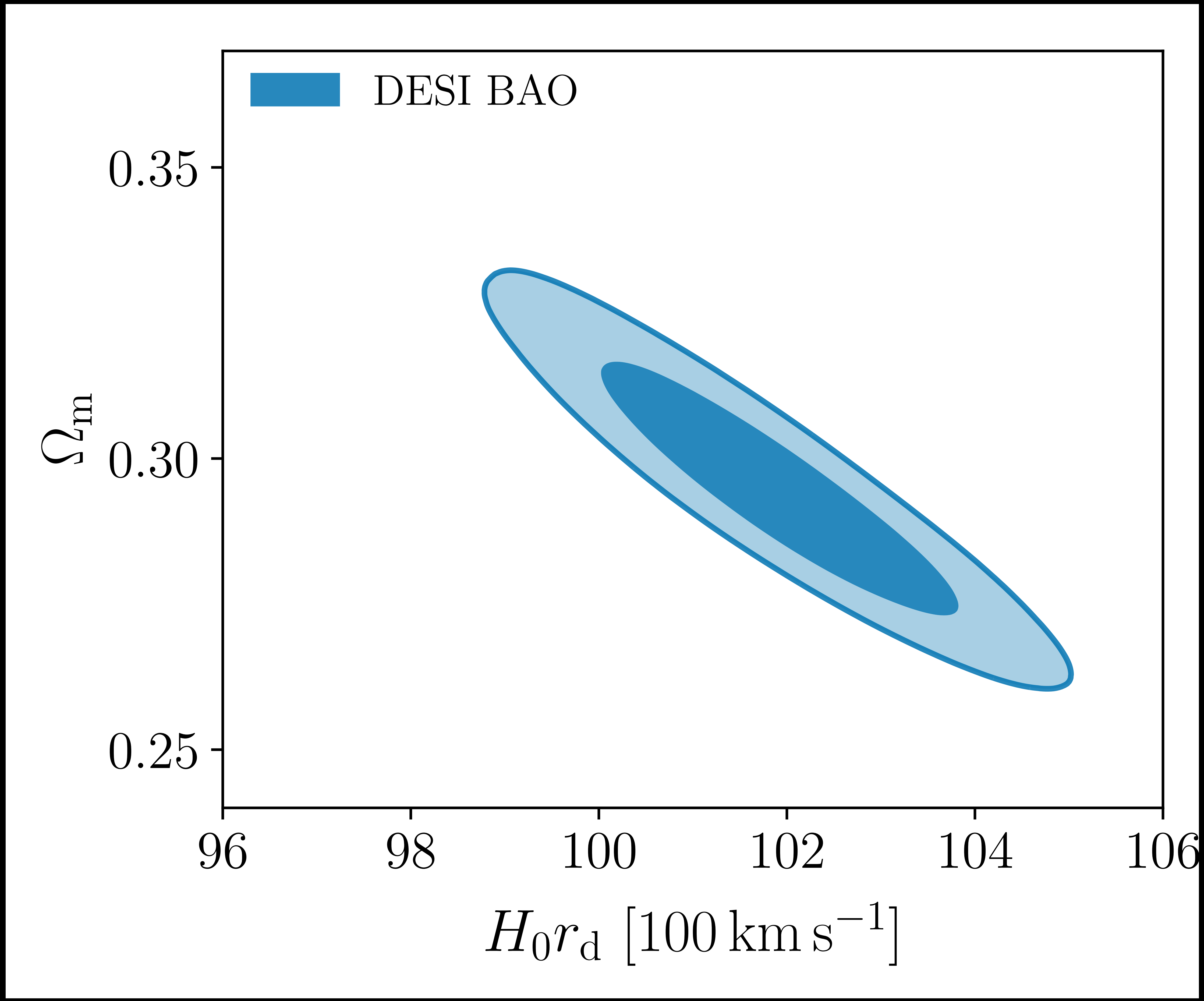
DESI vs. external probes



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DESI Y1 BAO consistent with:

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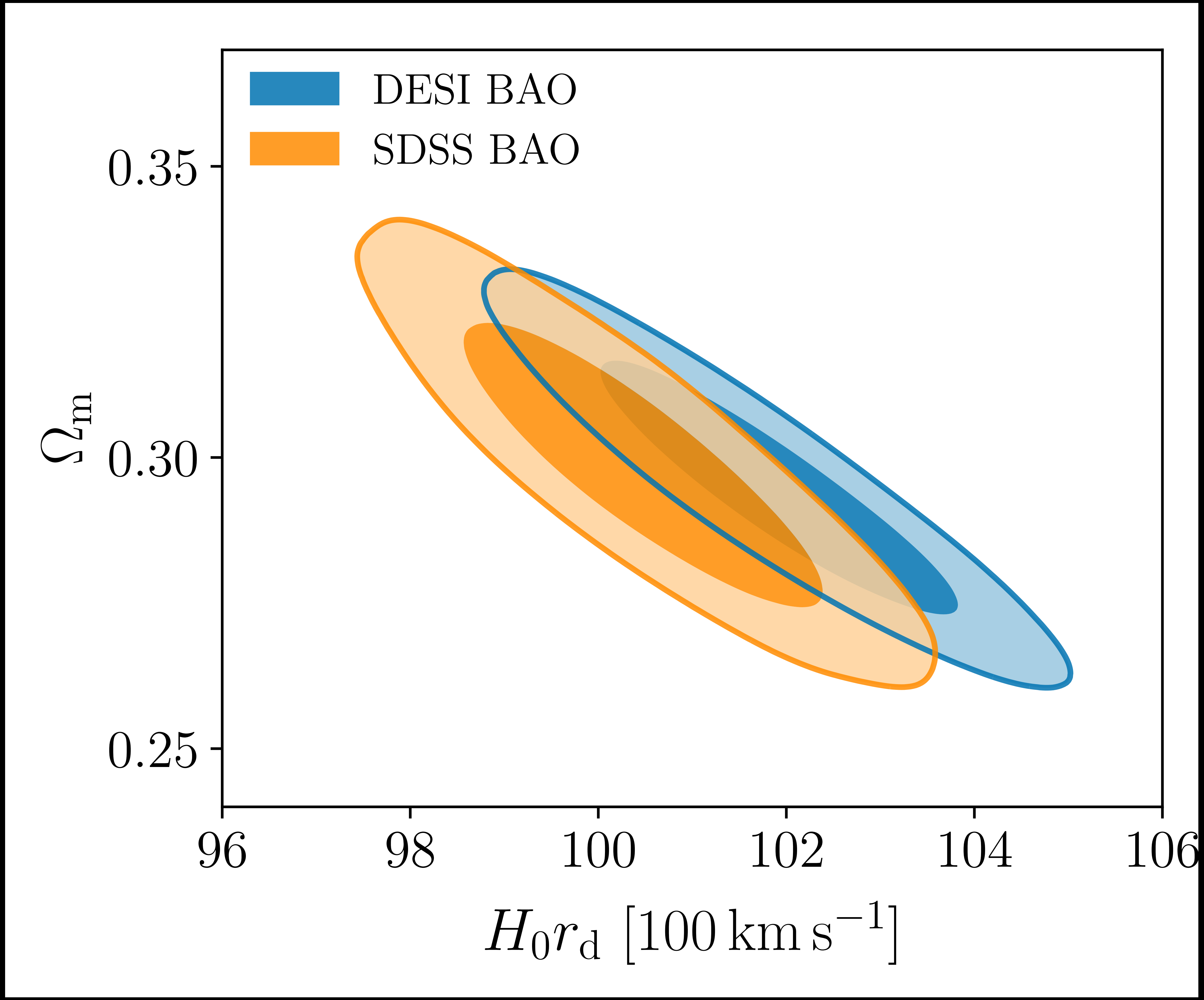

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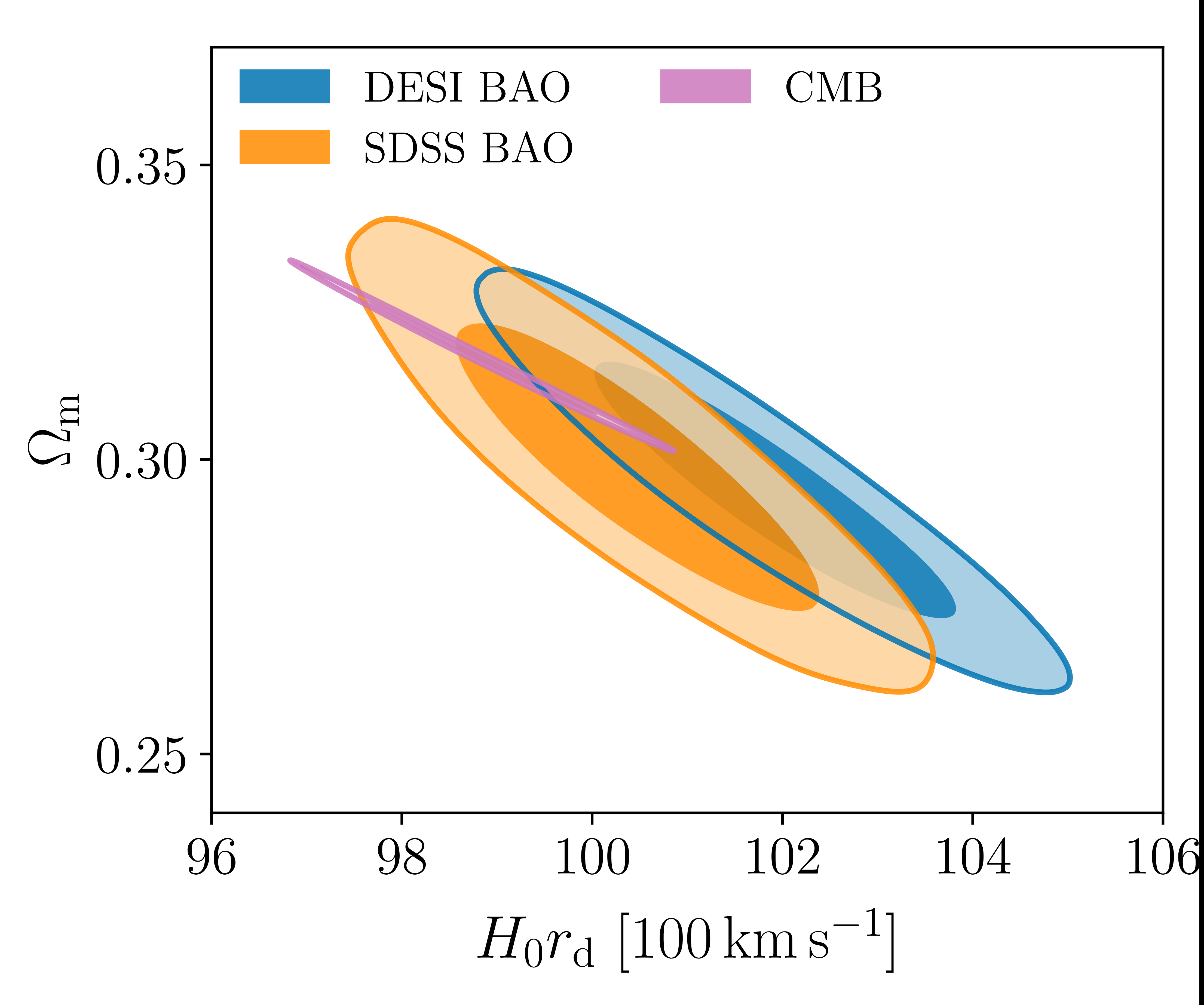

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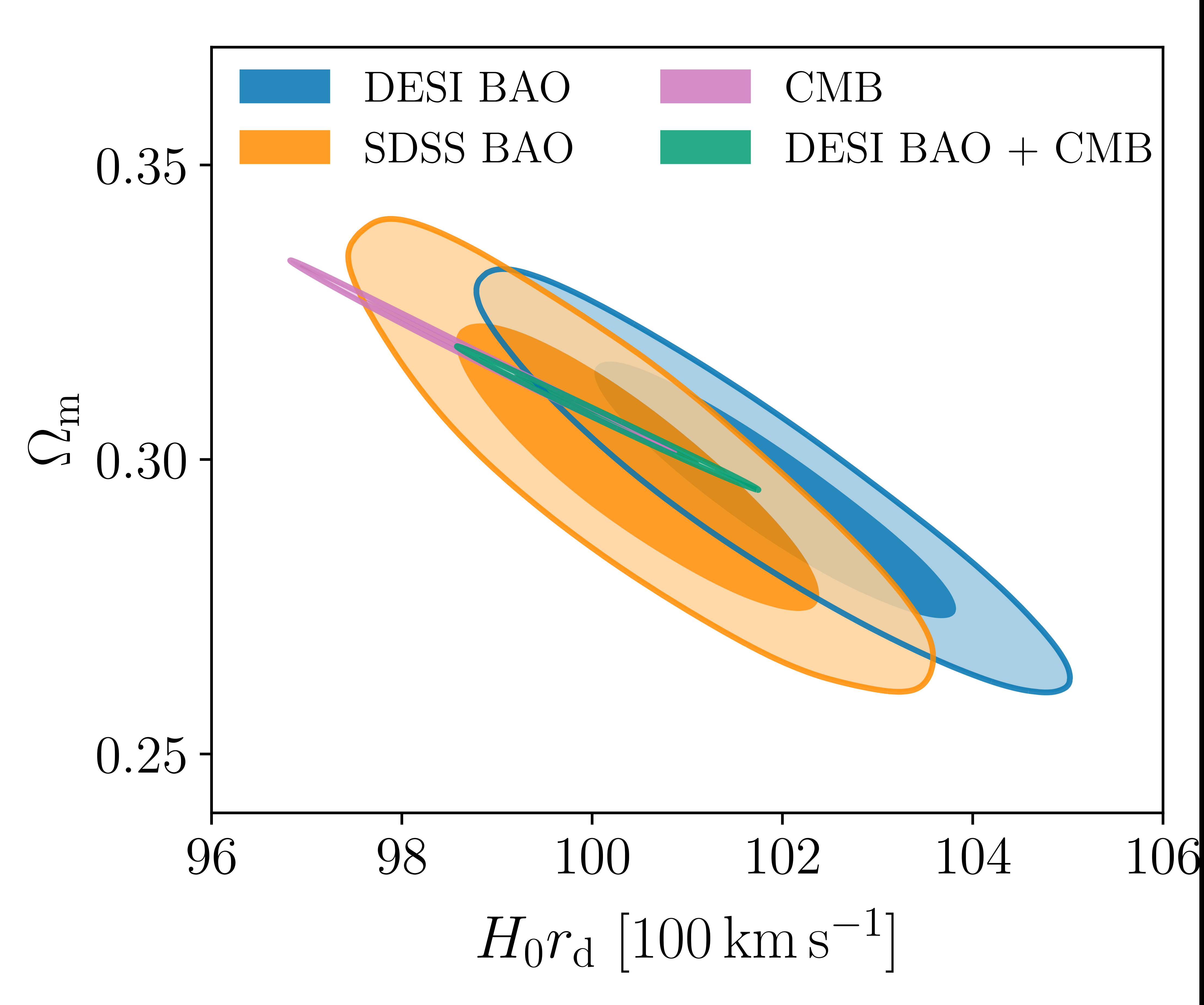
$$\Omega_\mathrm{m} = 0.3069 \pm 0.0050 \qquad (1.6\%)$$

DESI + CMB



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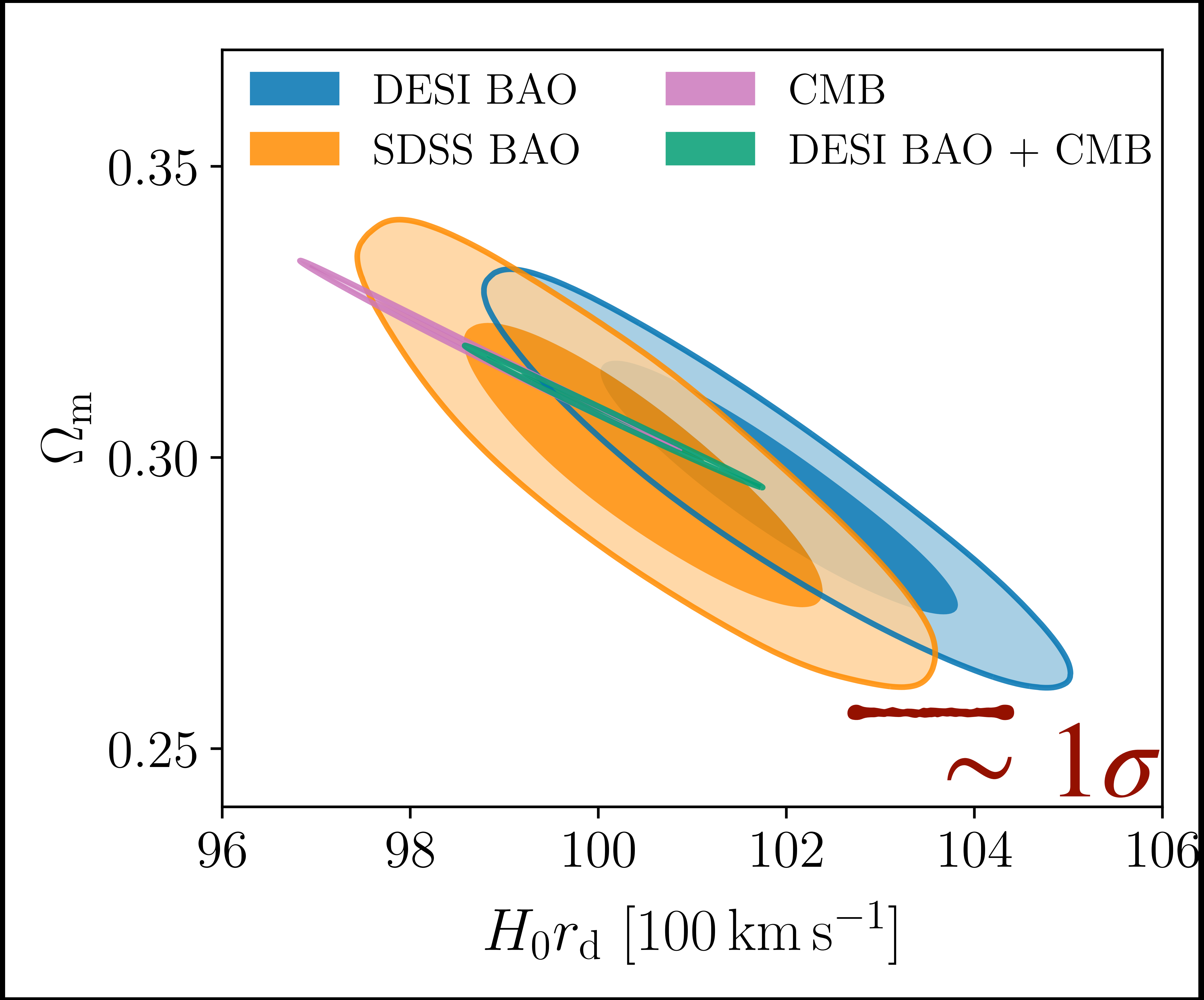

Hubble constant

- BAO constraints $r_{\mathrm{d}}(\Omega_{\mathrm{m}}h^2, \Omega_{\mathrm{b}}h^2)\ h$

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$$\Longrightarrow \mathrm{constrains\ \ on}\ \ h\ \ \mathrm{i.e.}\, H_0$$

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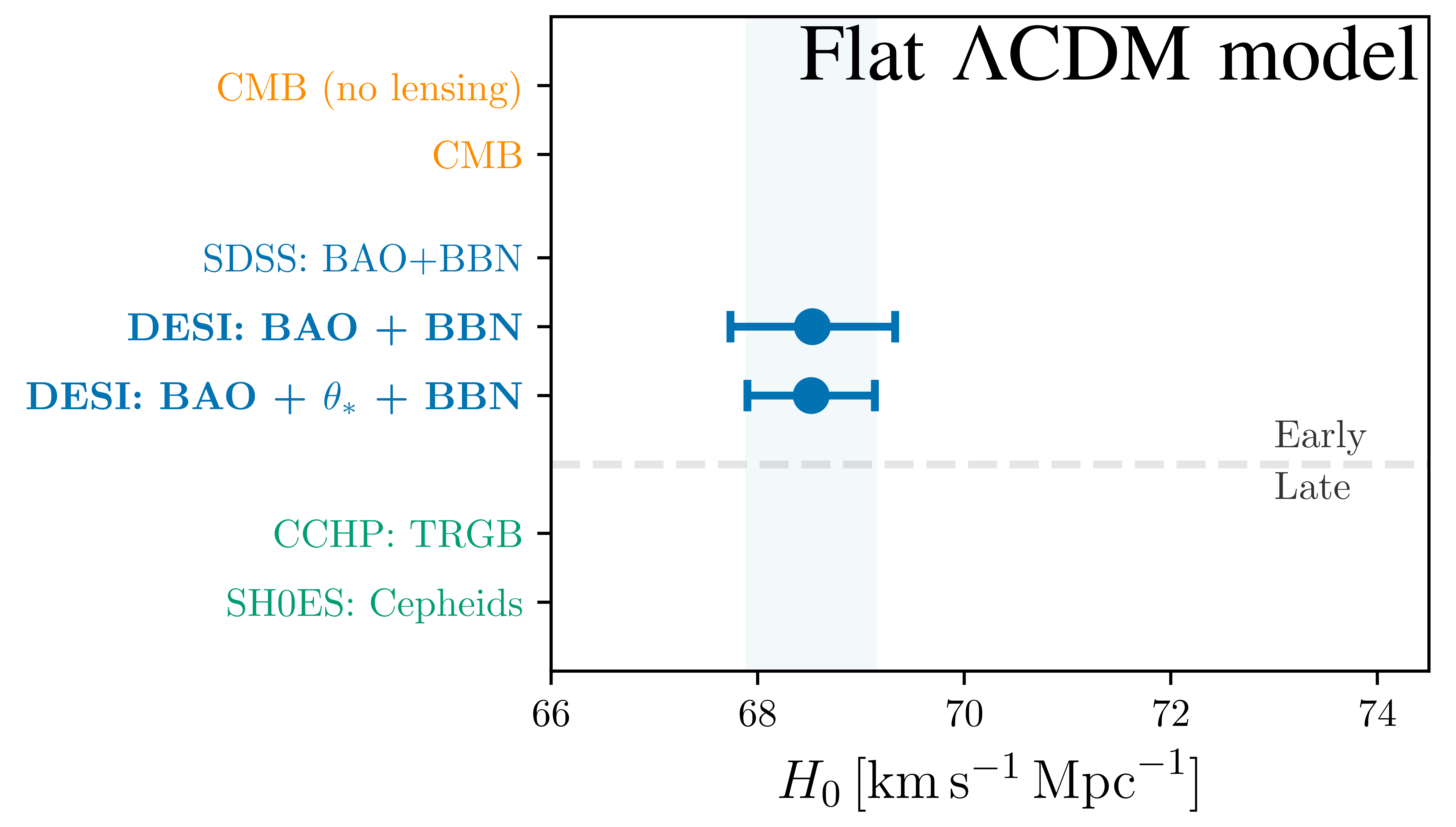
Hubble constant

$$H_0 = (68.53 \pm 0.80)\ \mathrm{kms^{-1}\ Mpc^{-1}}$$

DESI + BBN

$$H_0 = (68.52 \pm 0.62)\ \mathrm{kms^{-1}\ Mpc^{-1}}$$

DESI + θ_* + BBN



θ_* → CMB angular acoustic scale

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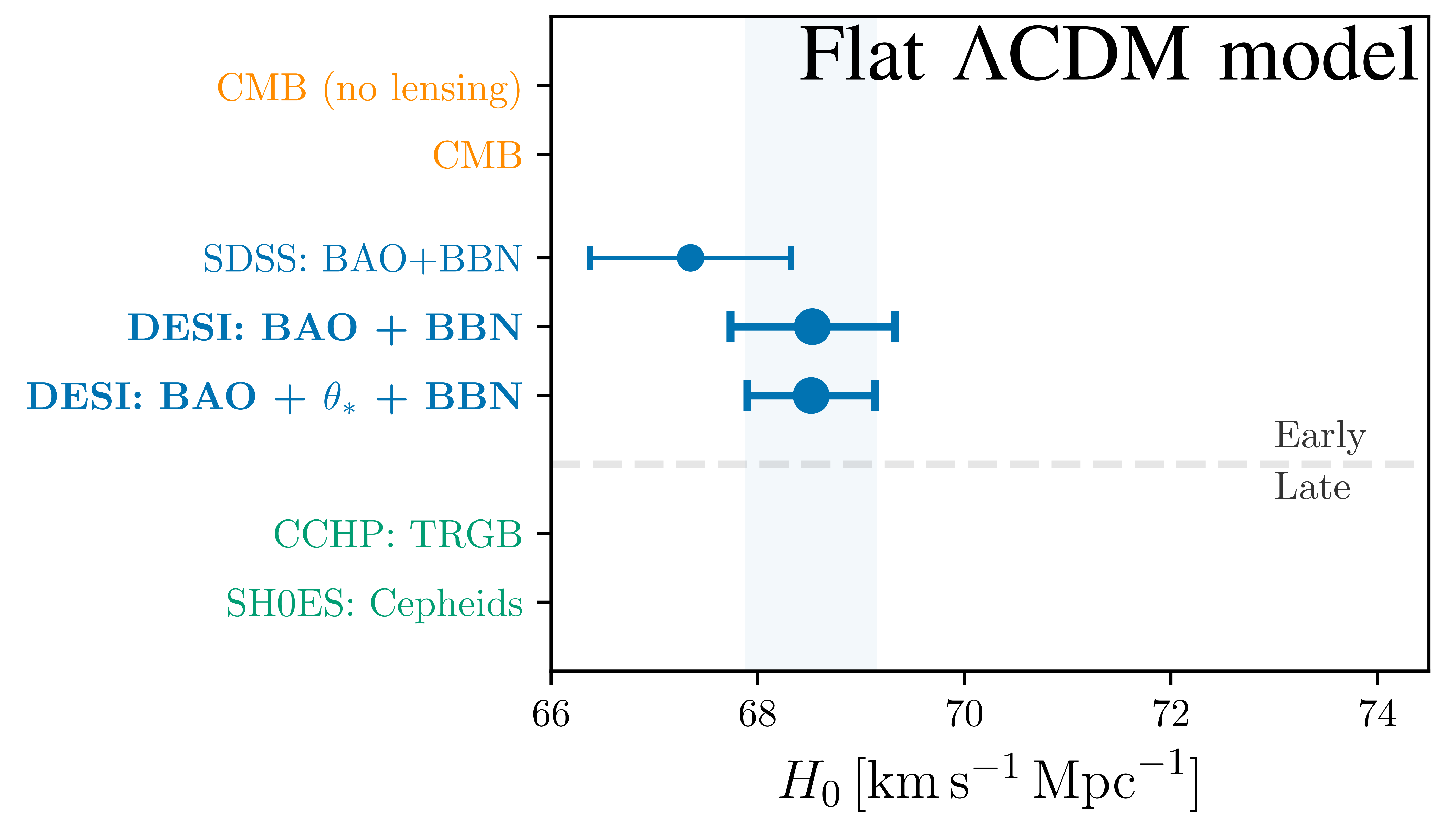
- Consistency with SDSS



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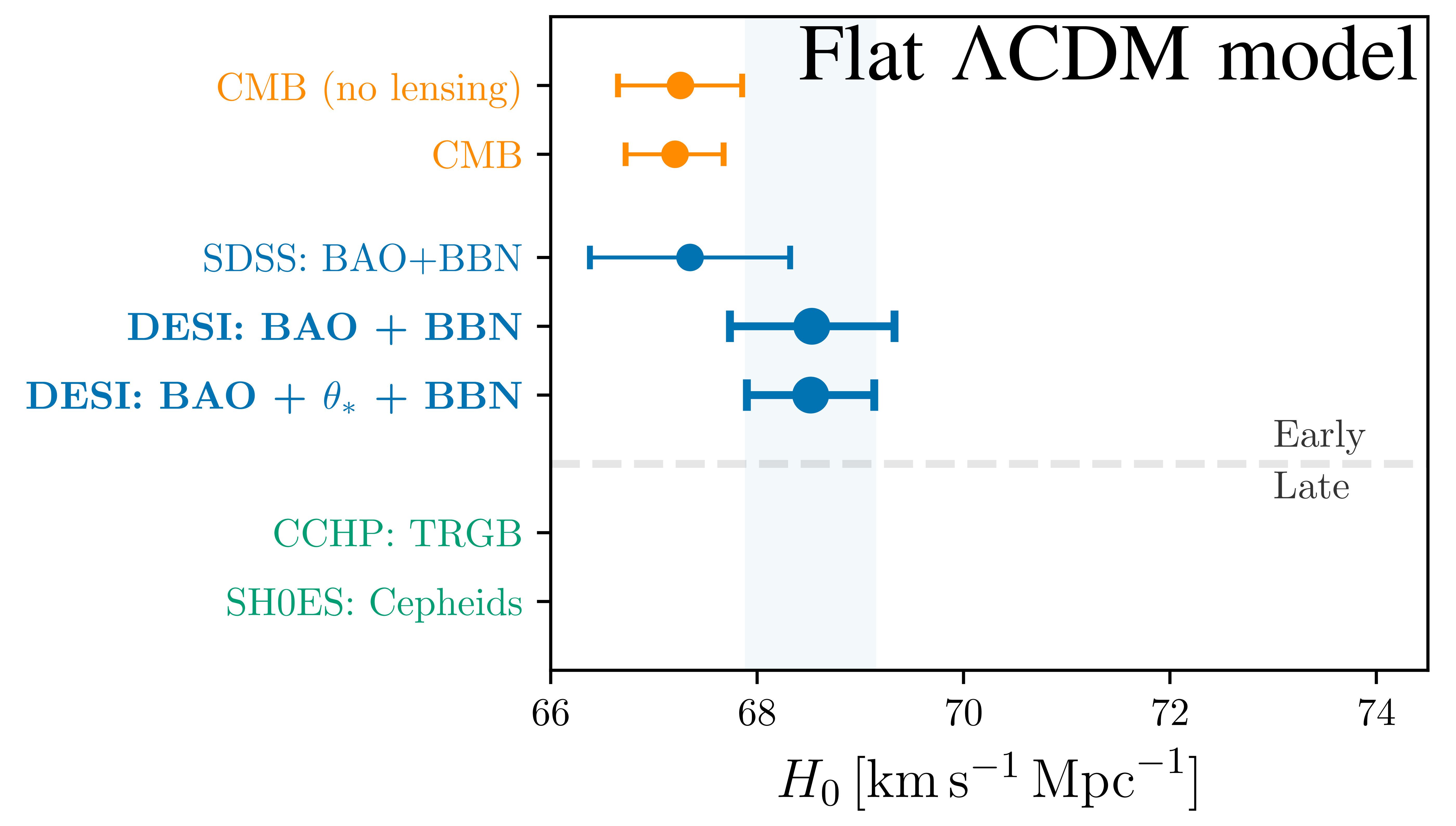
- Consistency with SDSS
- In agreement with CMB



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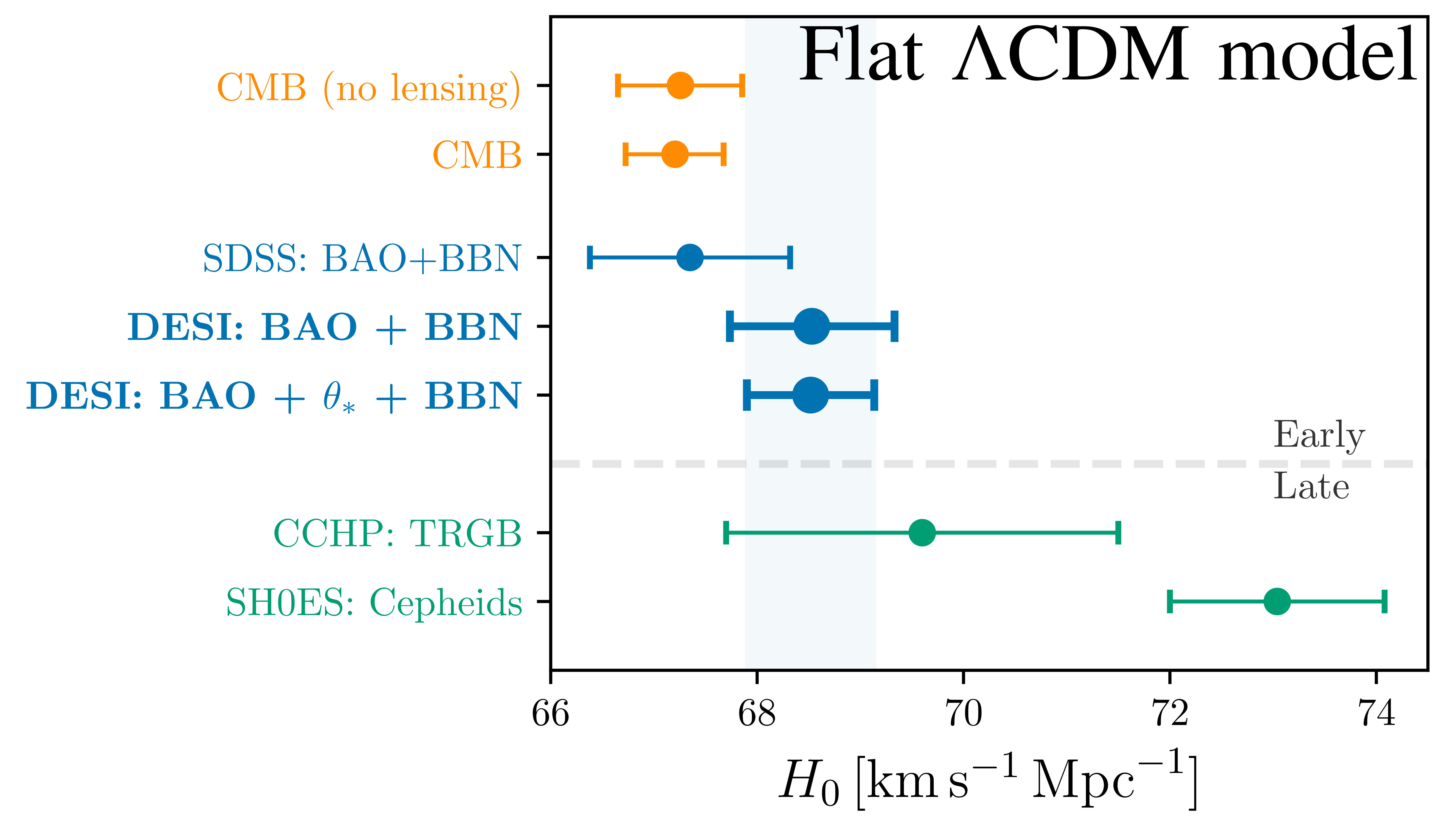
DESI + θ_* + BBN

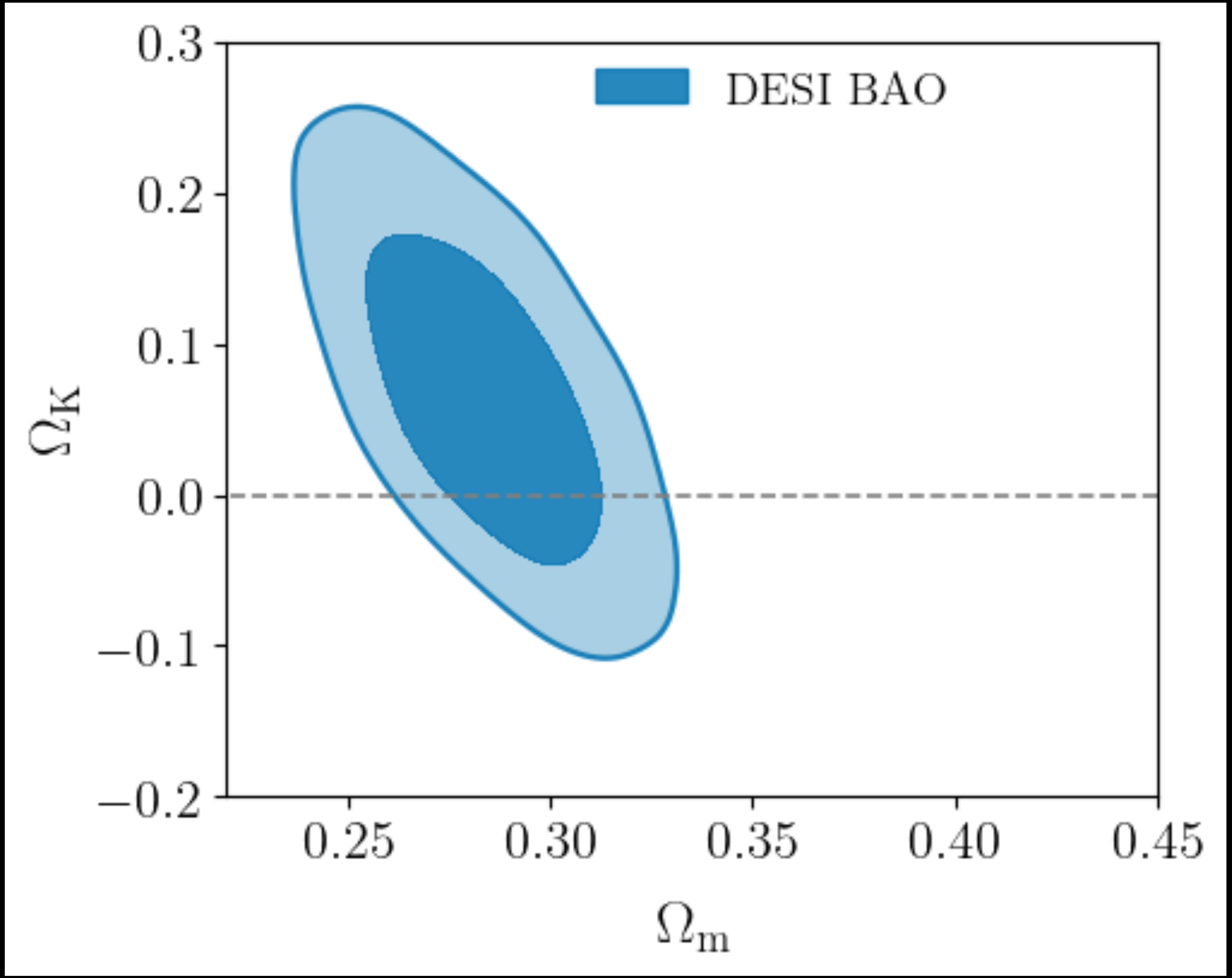
- Consistency with SDSS
- In agreement with CMB
- In 3.7σ tension with SHOES



$\theta_* \rightarrow$ CMB angular acoustic scale

Spatial curvature

DESI + CMB measurements favor a flat Universe



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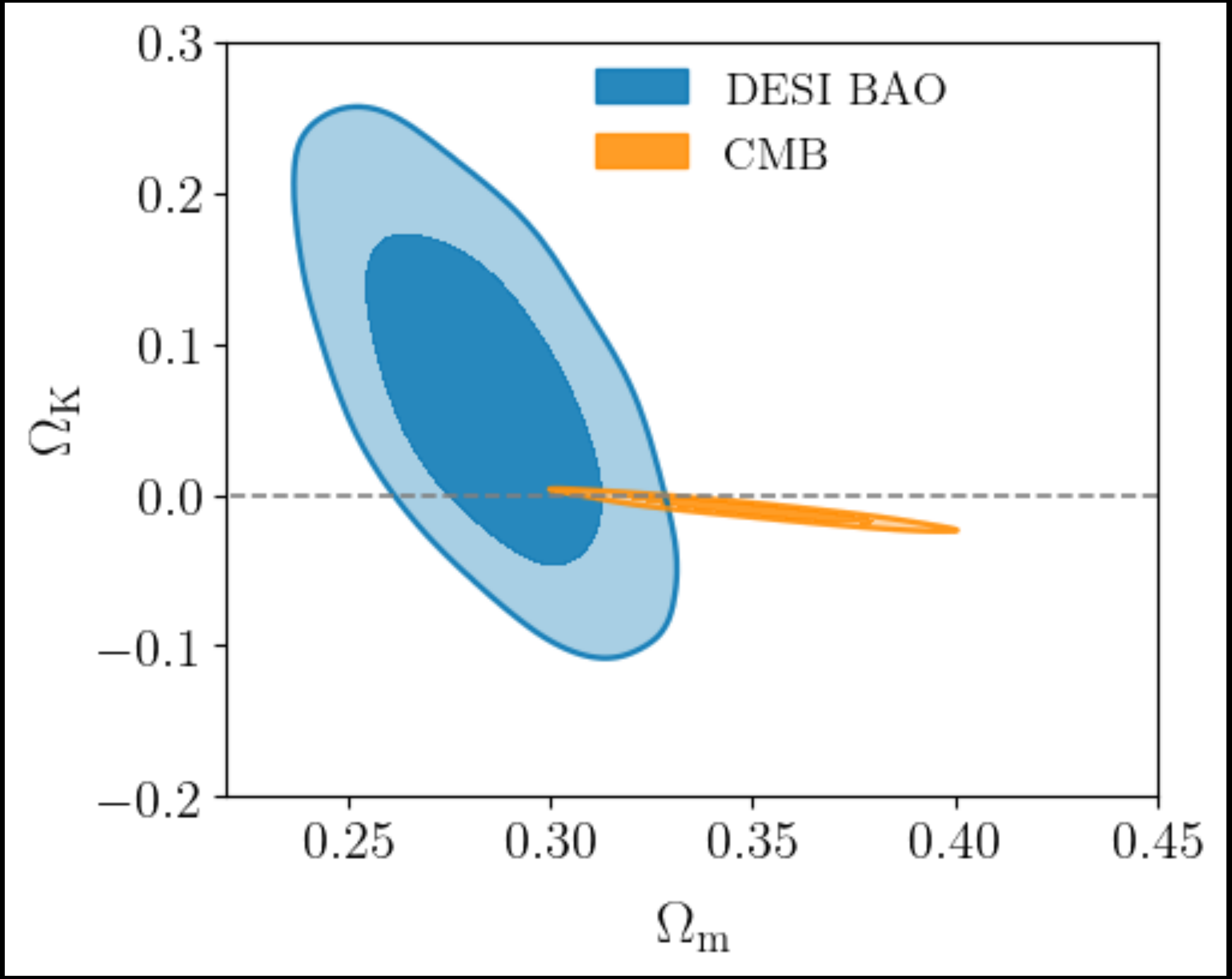

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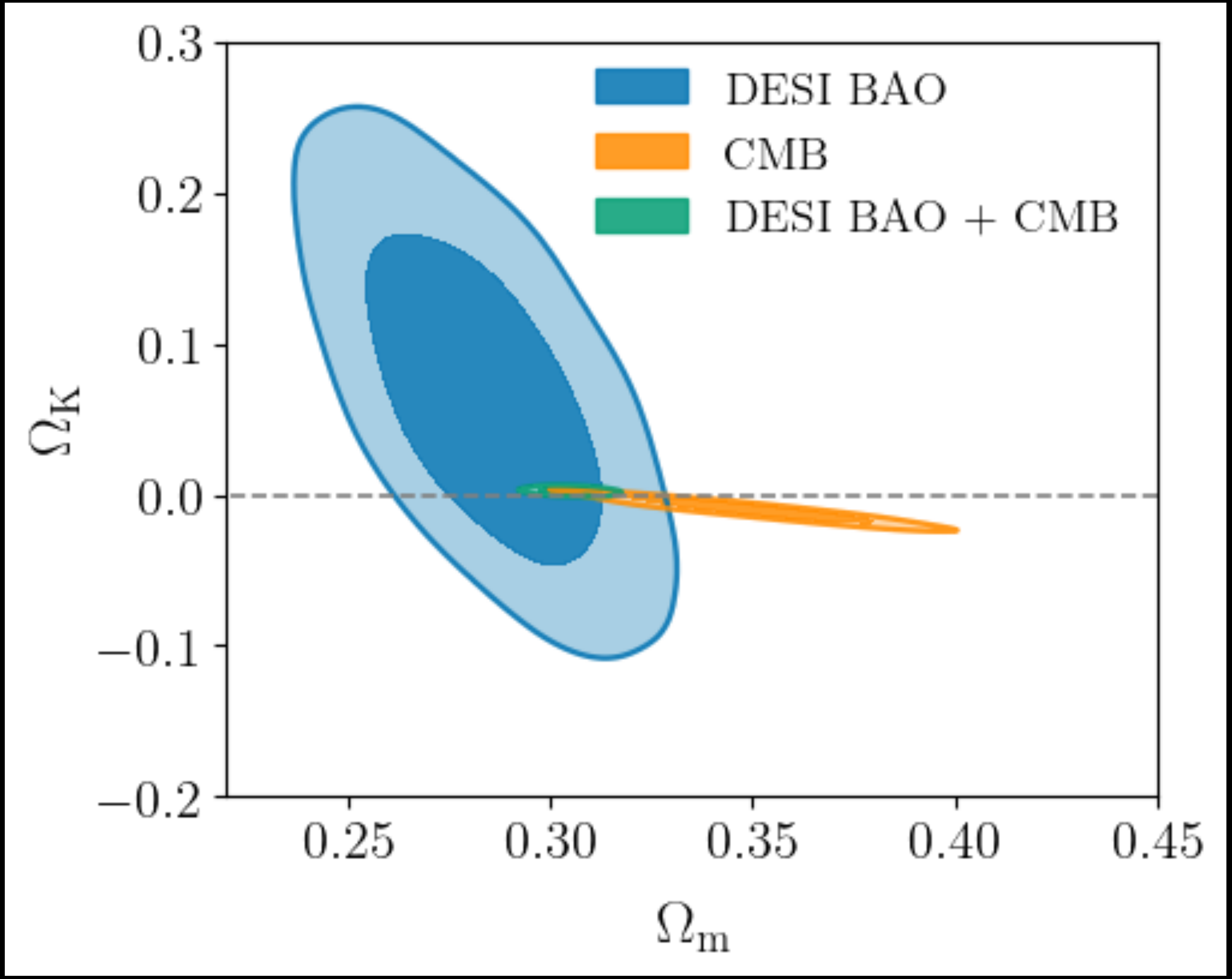
$$\Omega_K = 0.0024 \pm 0.0016$$

DESI + CMB



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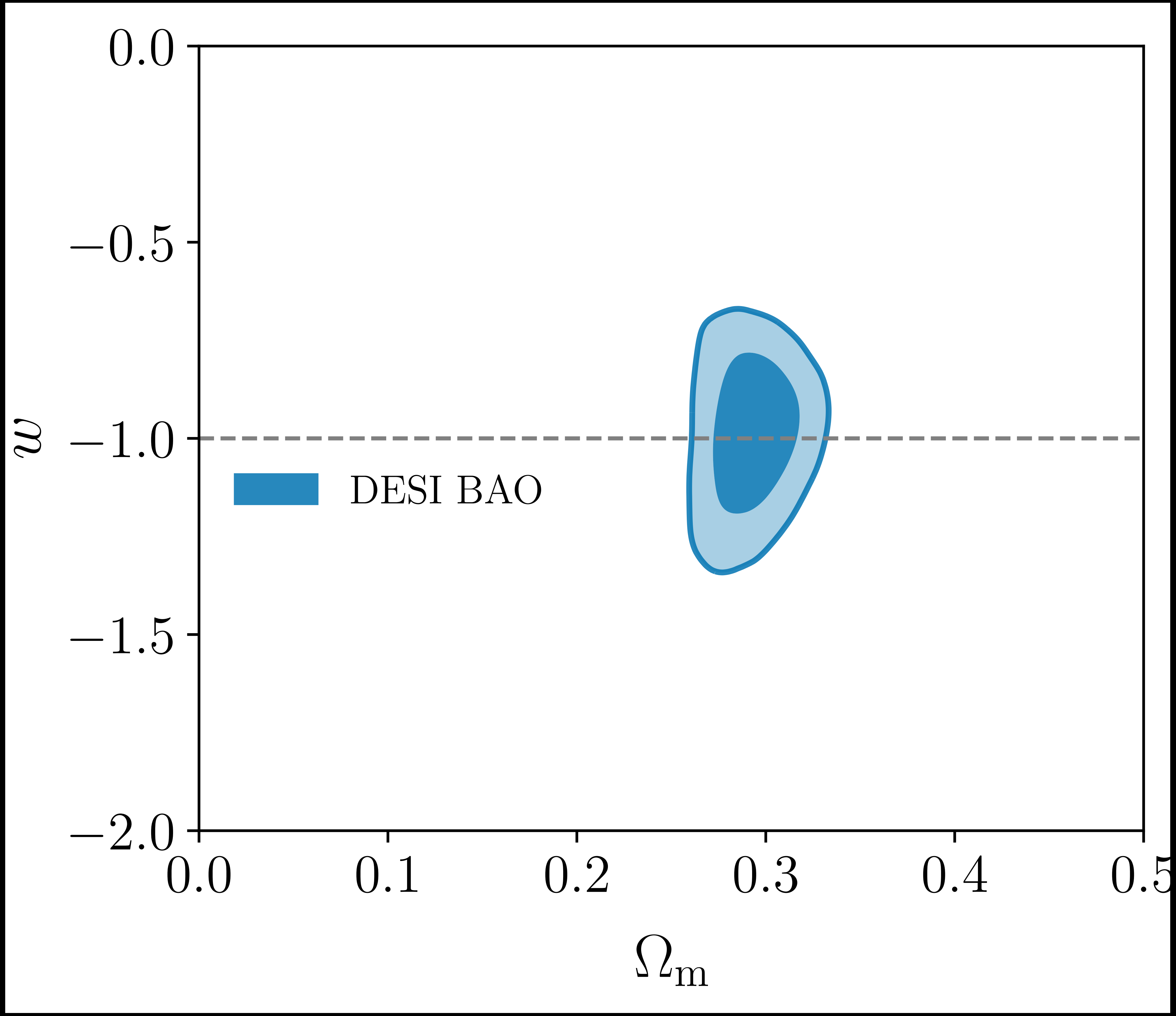
Dark Energy Equation of State

Constant EoS parameter w

$\Omega_{\rm m} = 0.295 \pm 0.15$ (5.1%)

$w = -0.99^{+0.15}_{-0.13}$ (15%)

DESI



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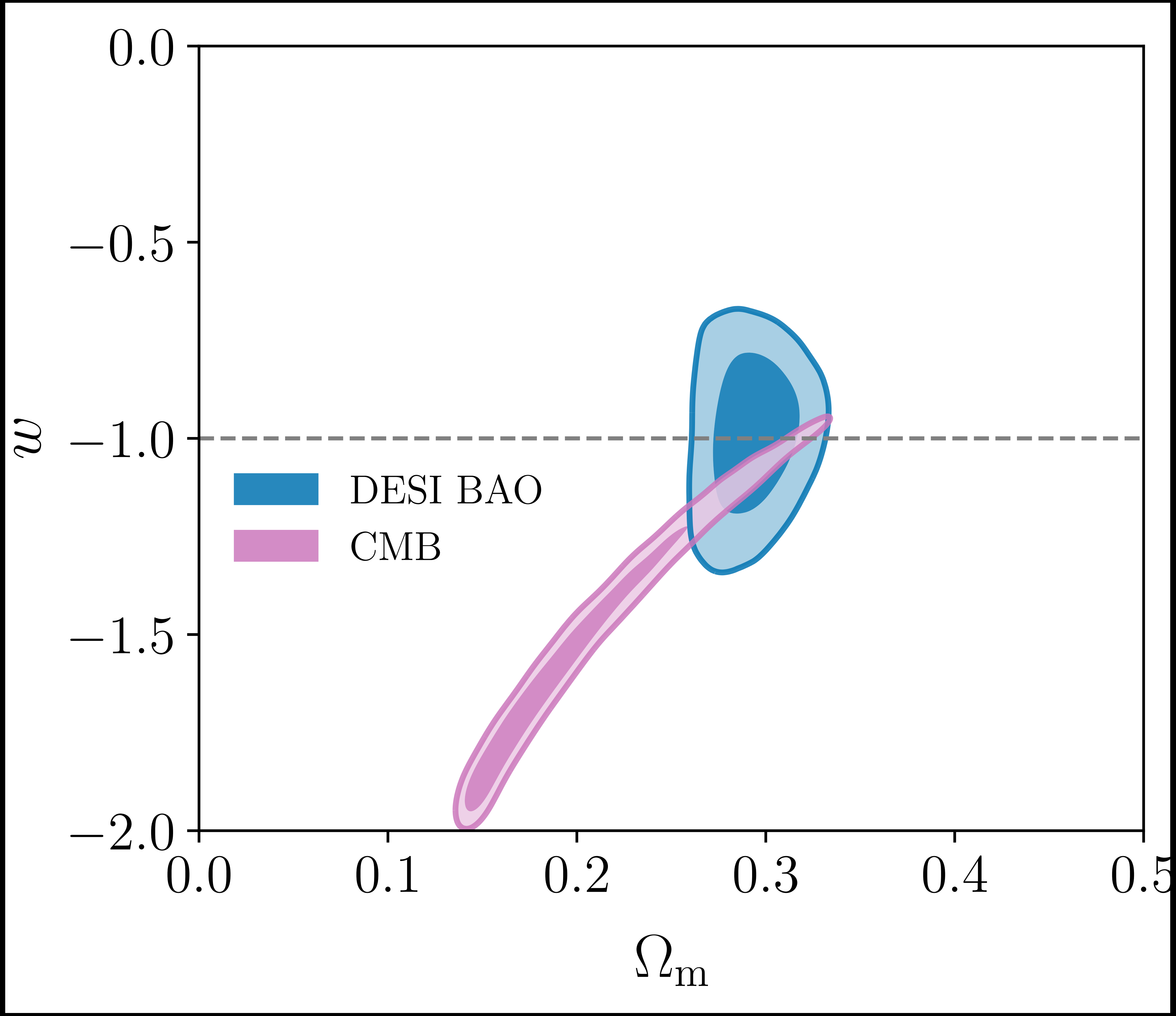

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DESI

SNe:

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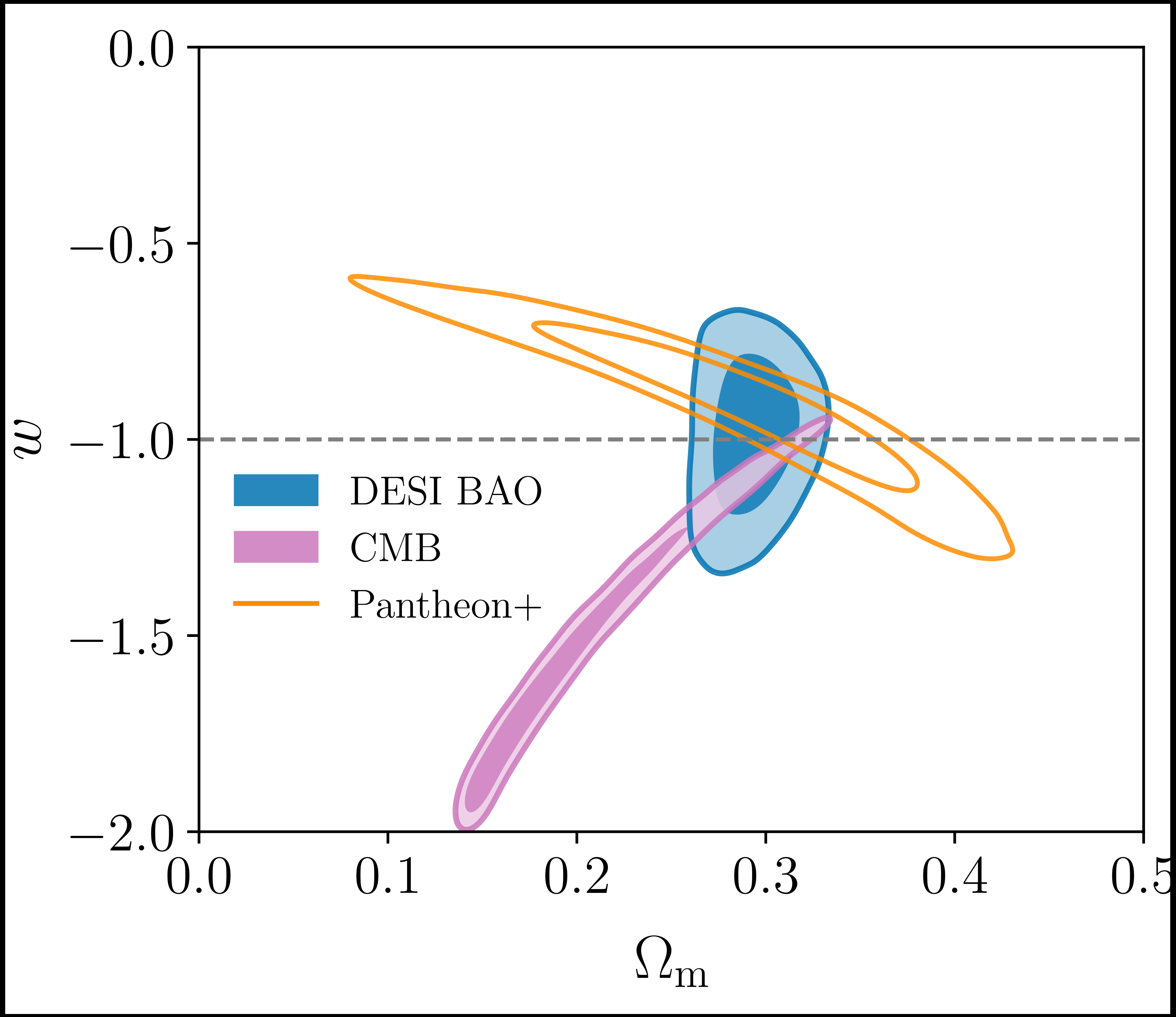

Dark Energy Equation of State

Constant EoS parameter w

$\Omega_{\rm m} = 0.295 \pm 0.15$ (5.1%)

$w = -0.99^{+0.15}_{-0.13}$ (15%)

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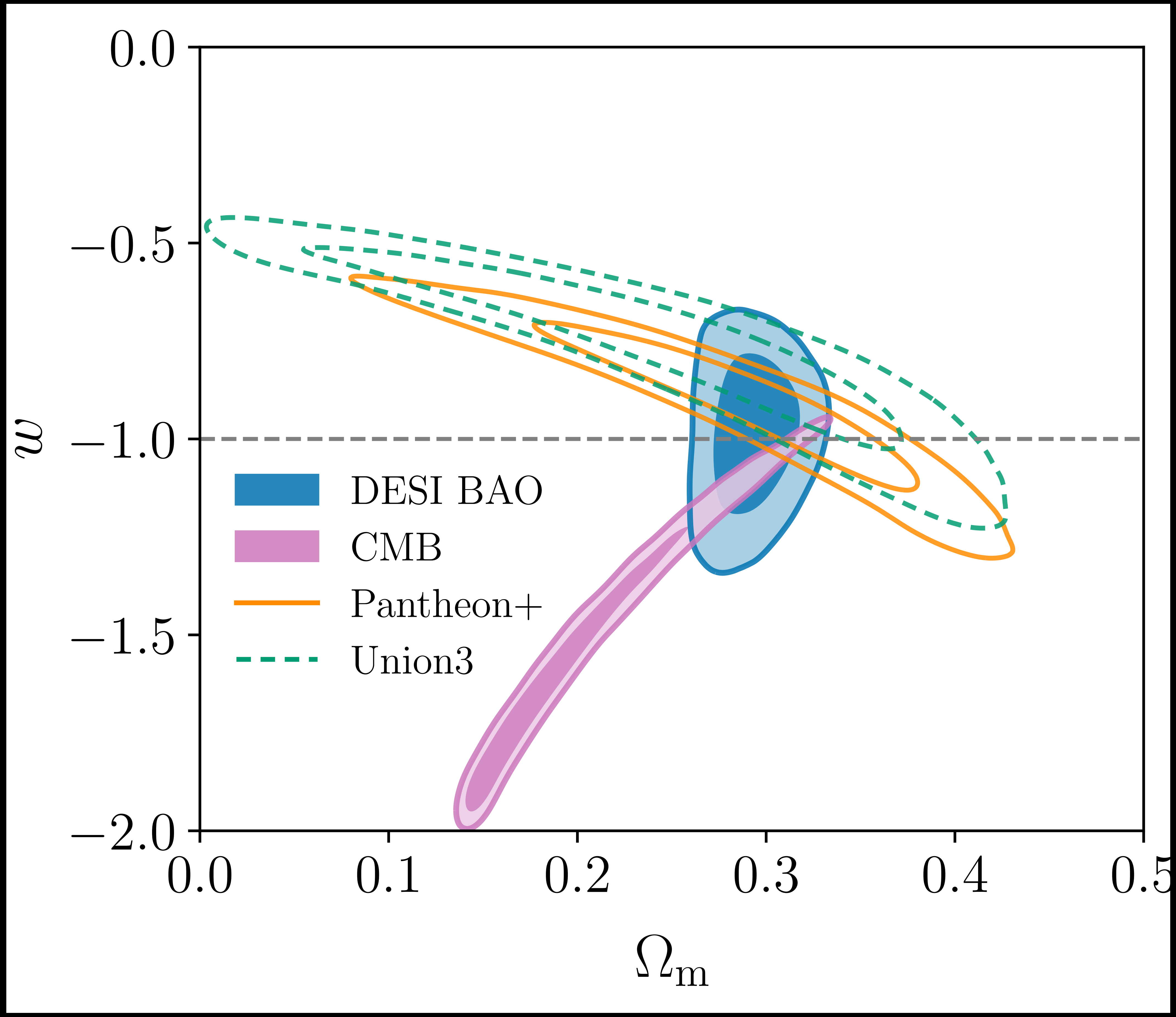

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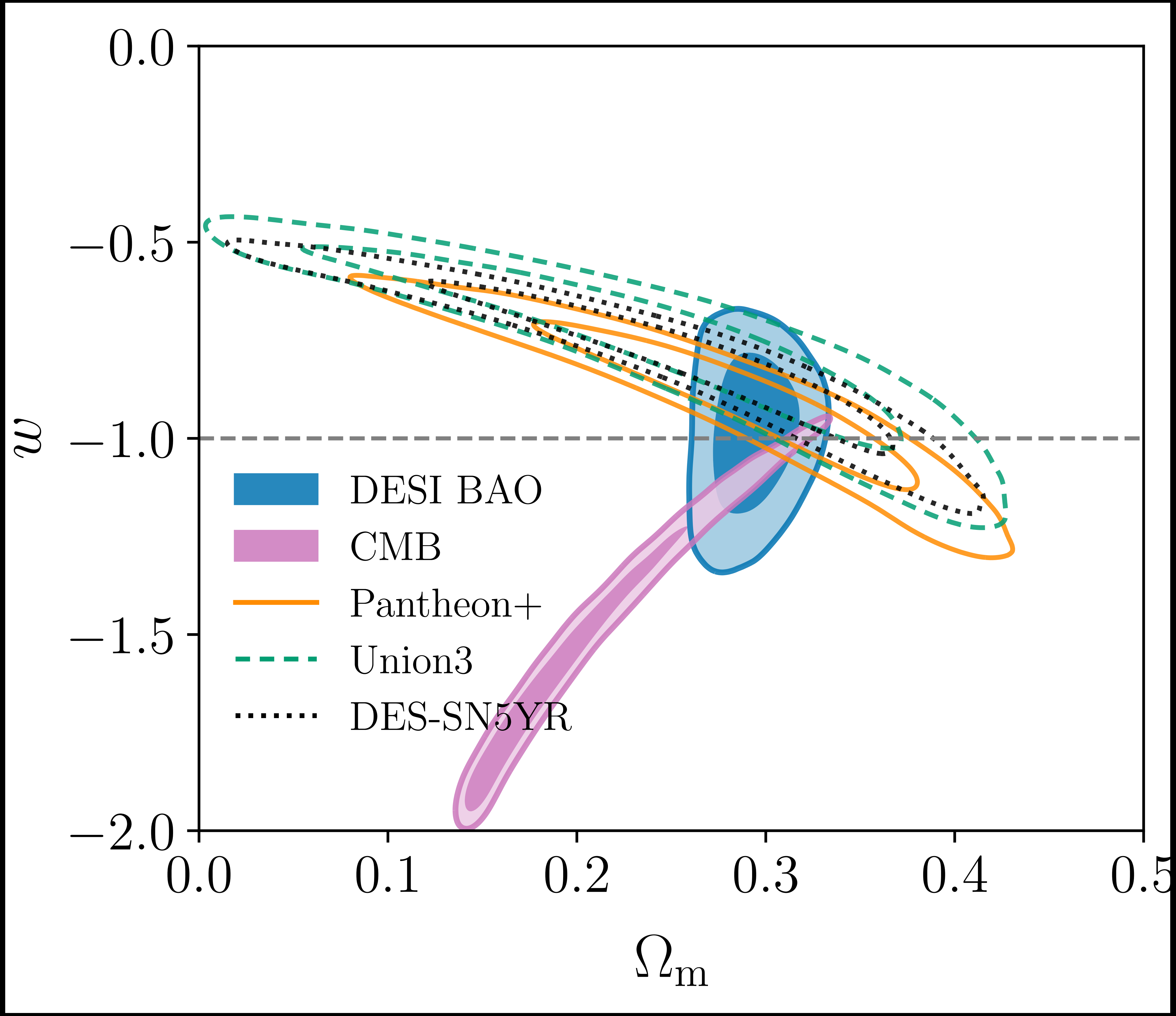

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DESI

$$\Omega_\mathrm{m} = 0.295 \pm 0.15 \qquad (2.1\%)$$

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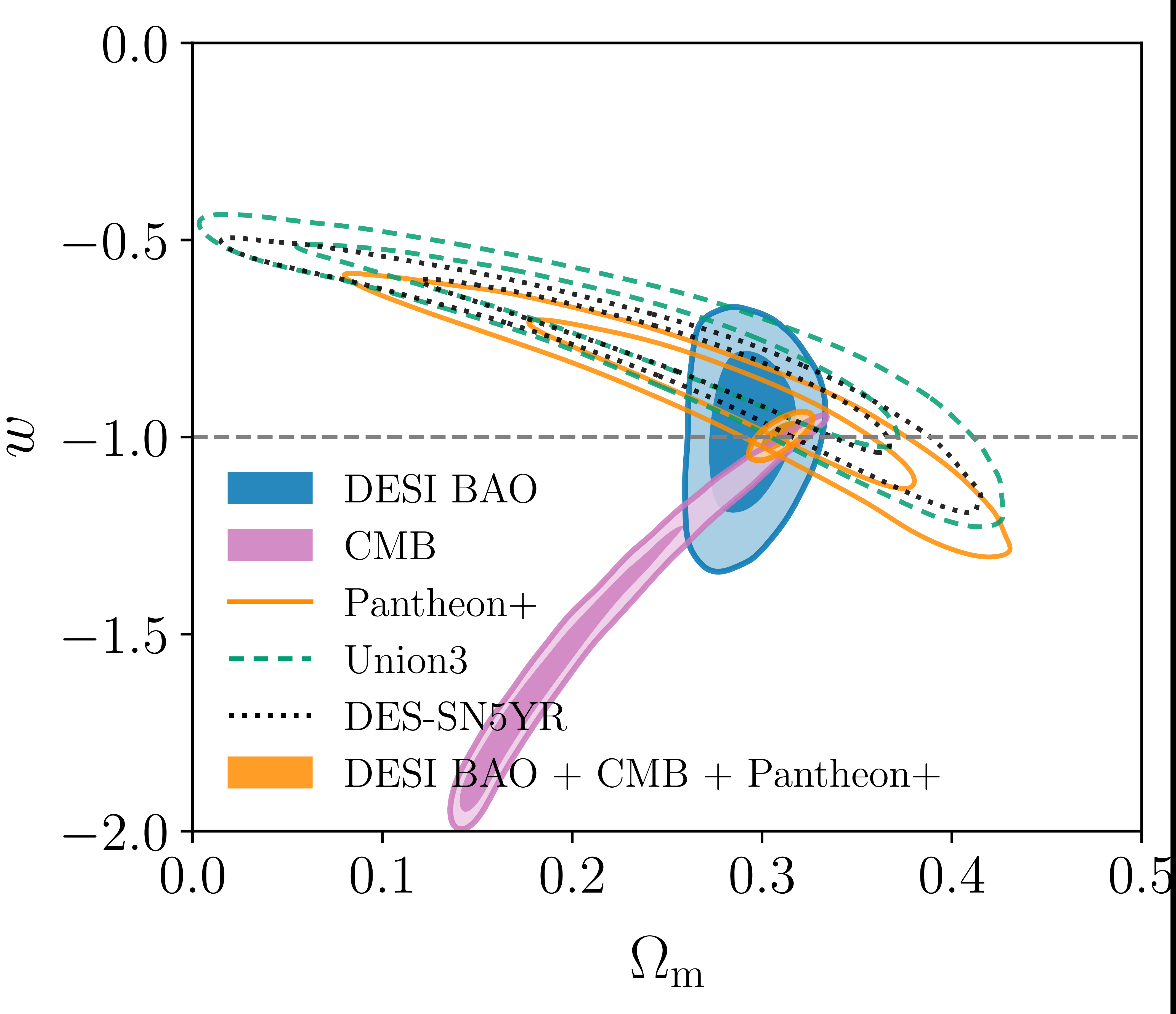
DESI+CMB+PantheonPlus



Dark Energy Equation of State

Varying EoS

$$w(a) = w_0 + (1 - a)w_a \qquad \text{(CPL)}$$

$$w_0 = -0.45^{+0.34}_{-0.21}, \qquad w_a = -1.79^{+0.48}_{-1.00}$$

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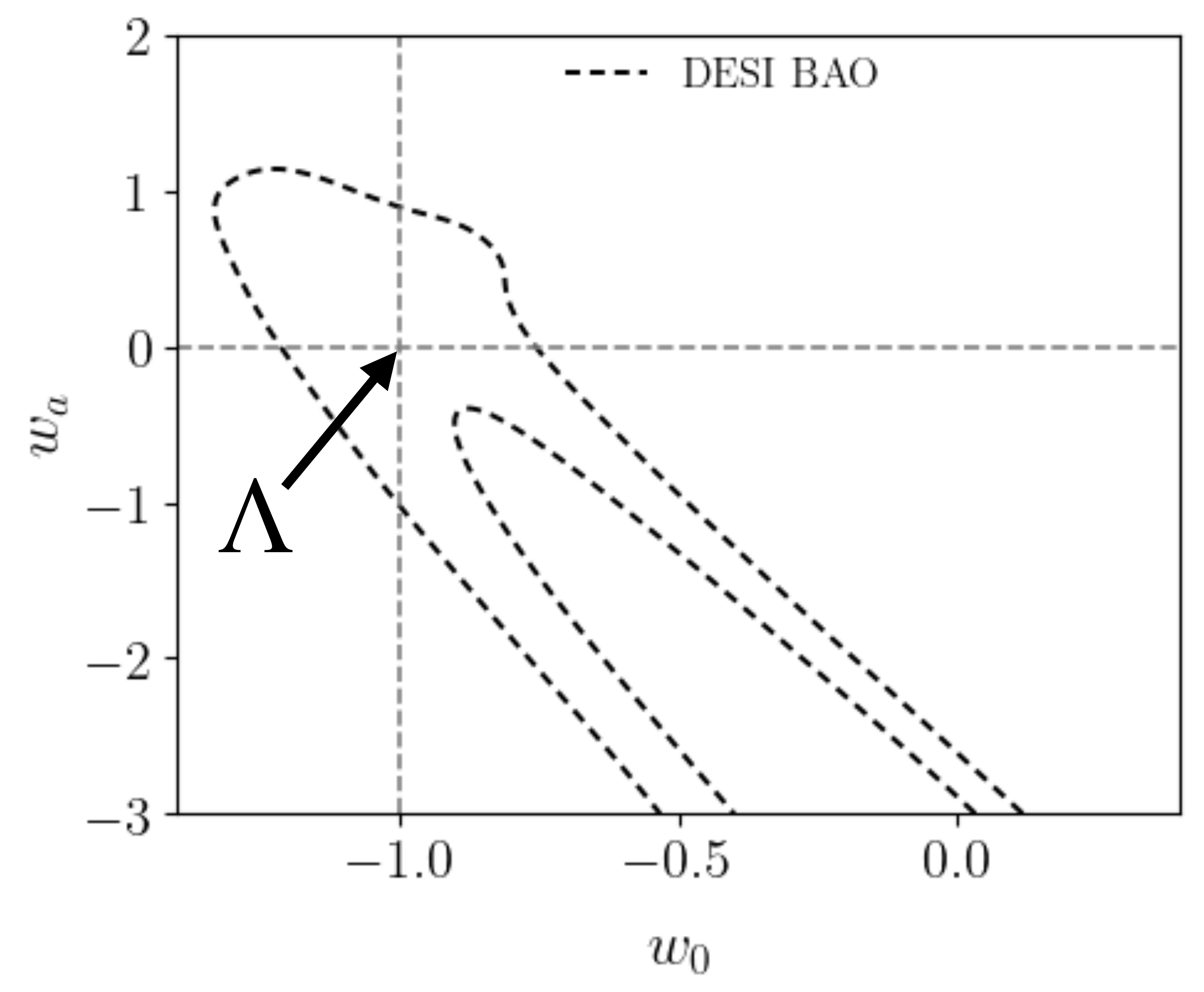

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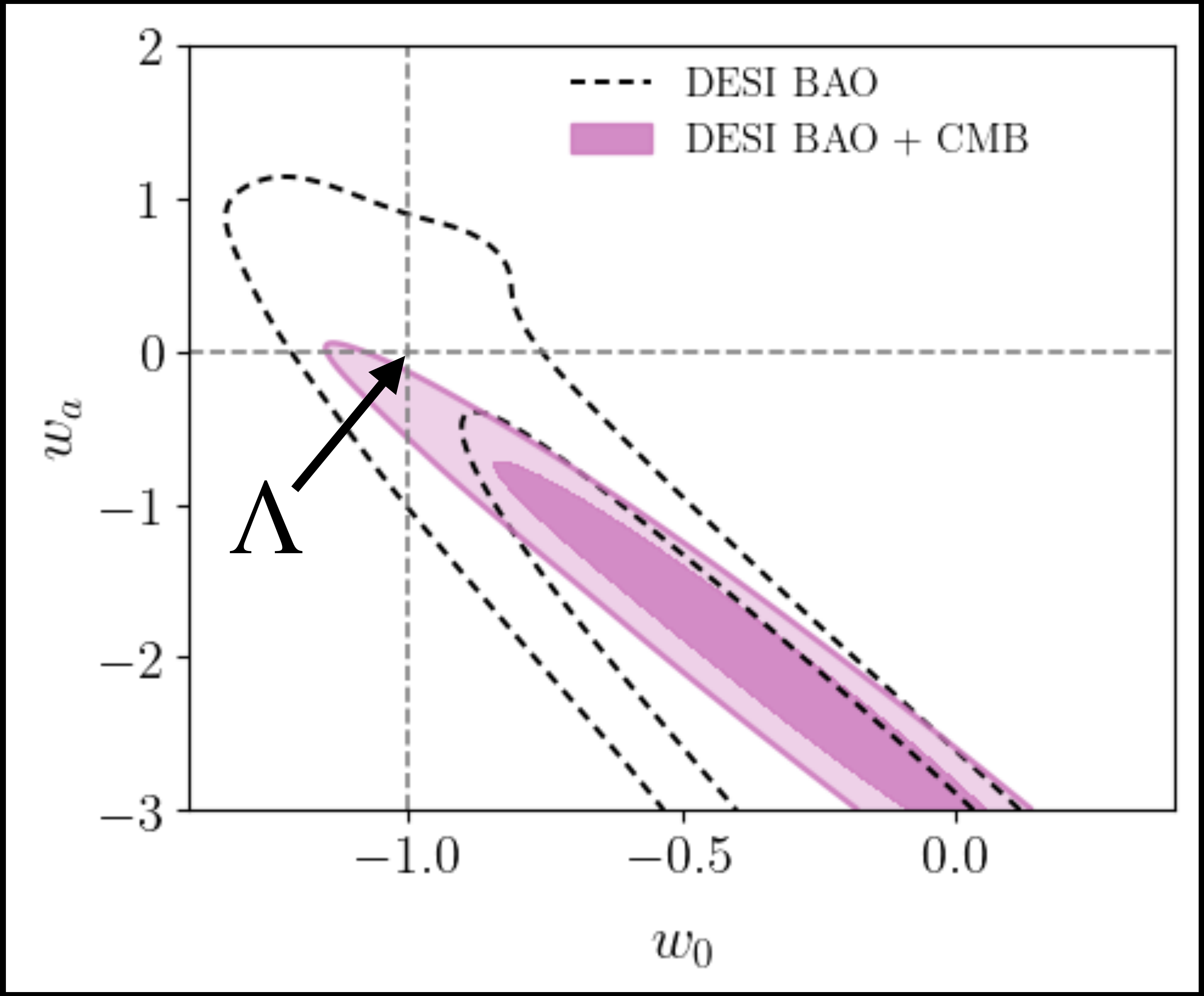

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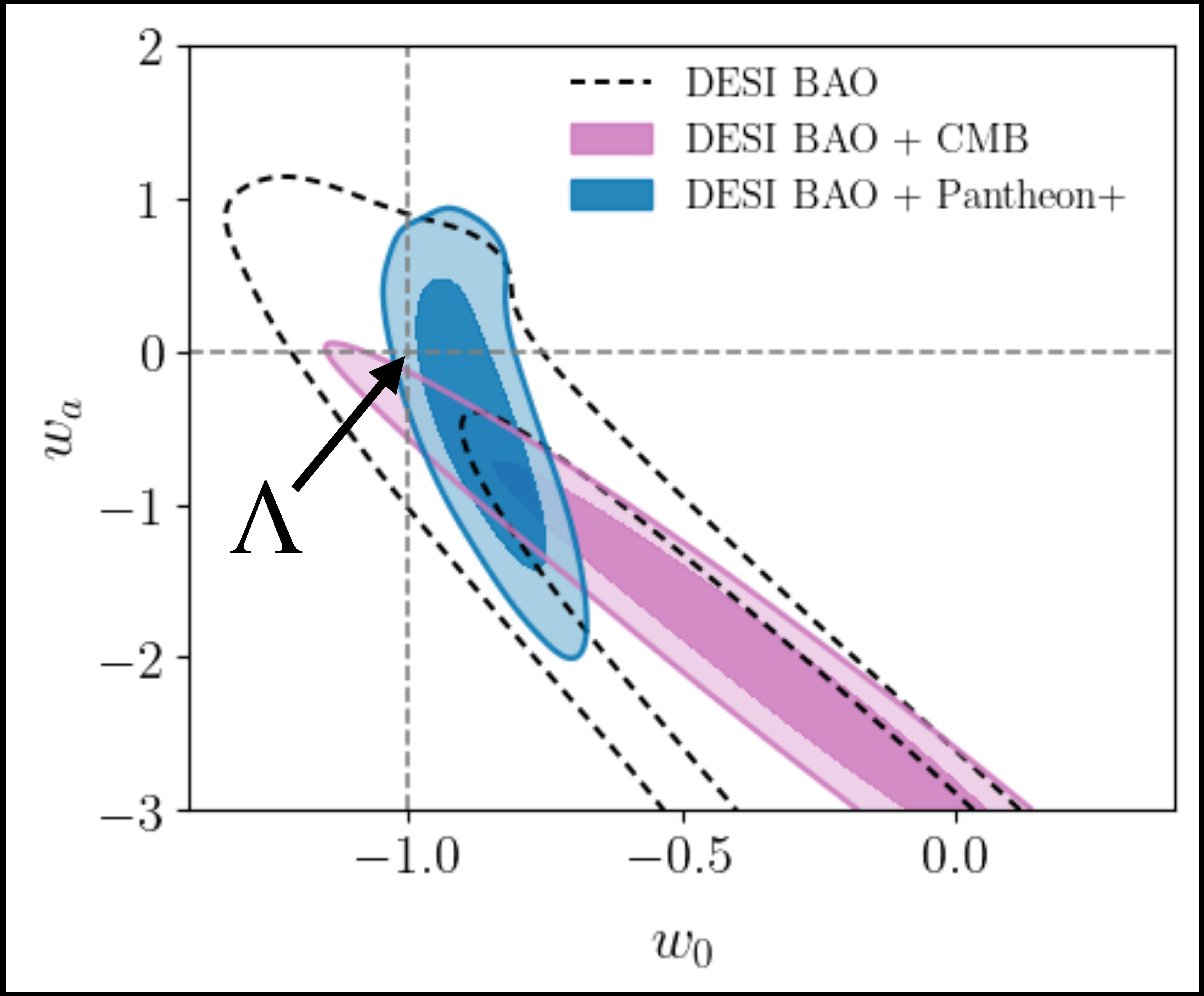

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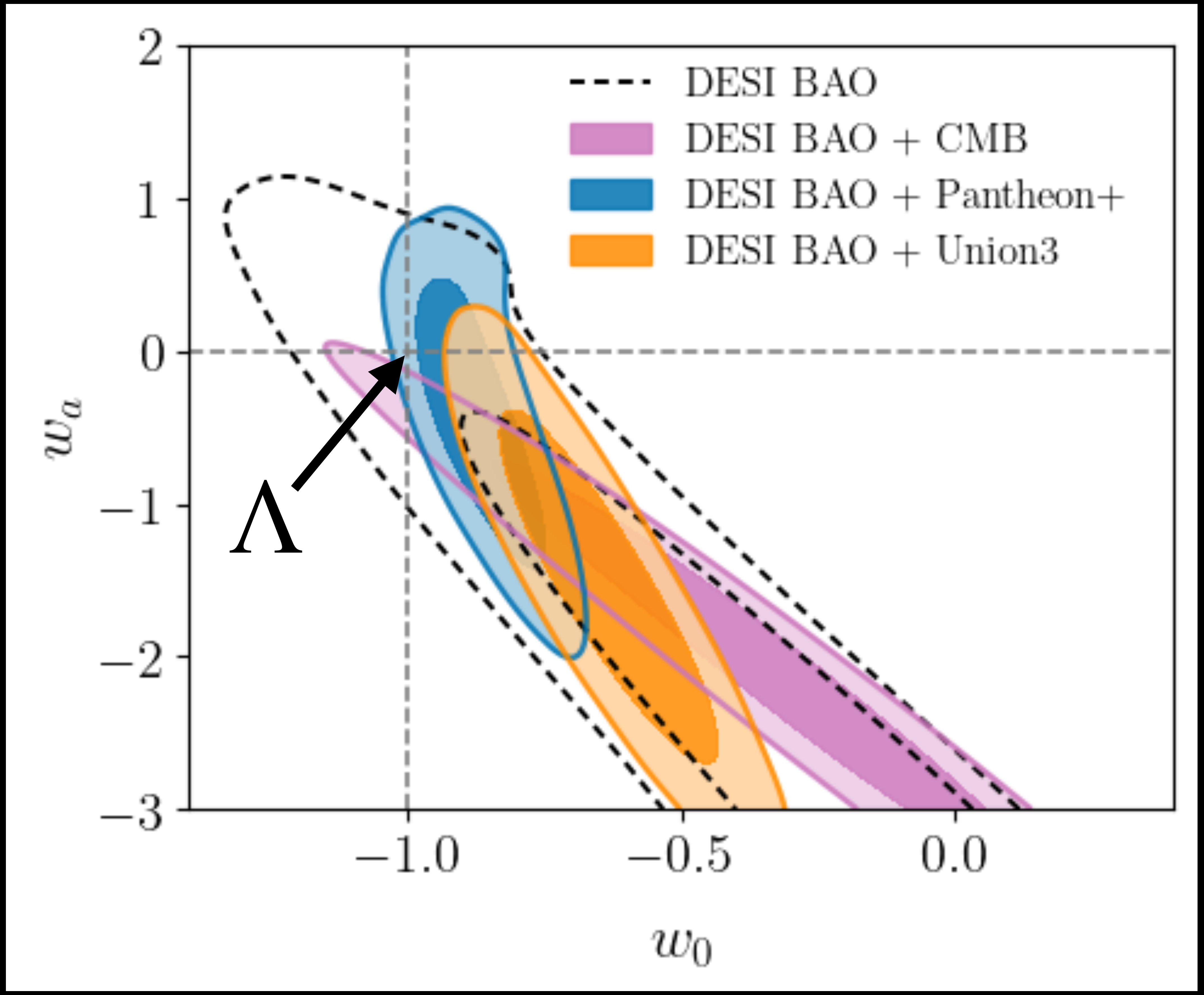

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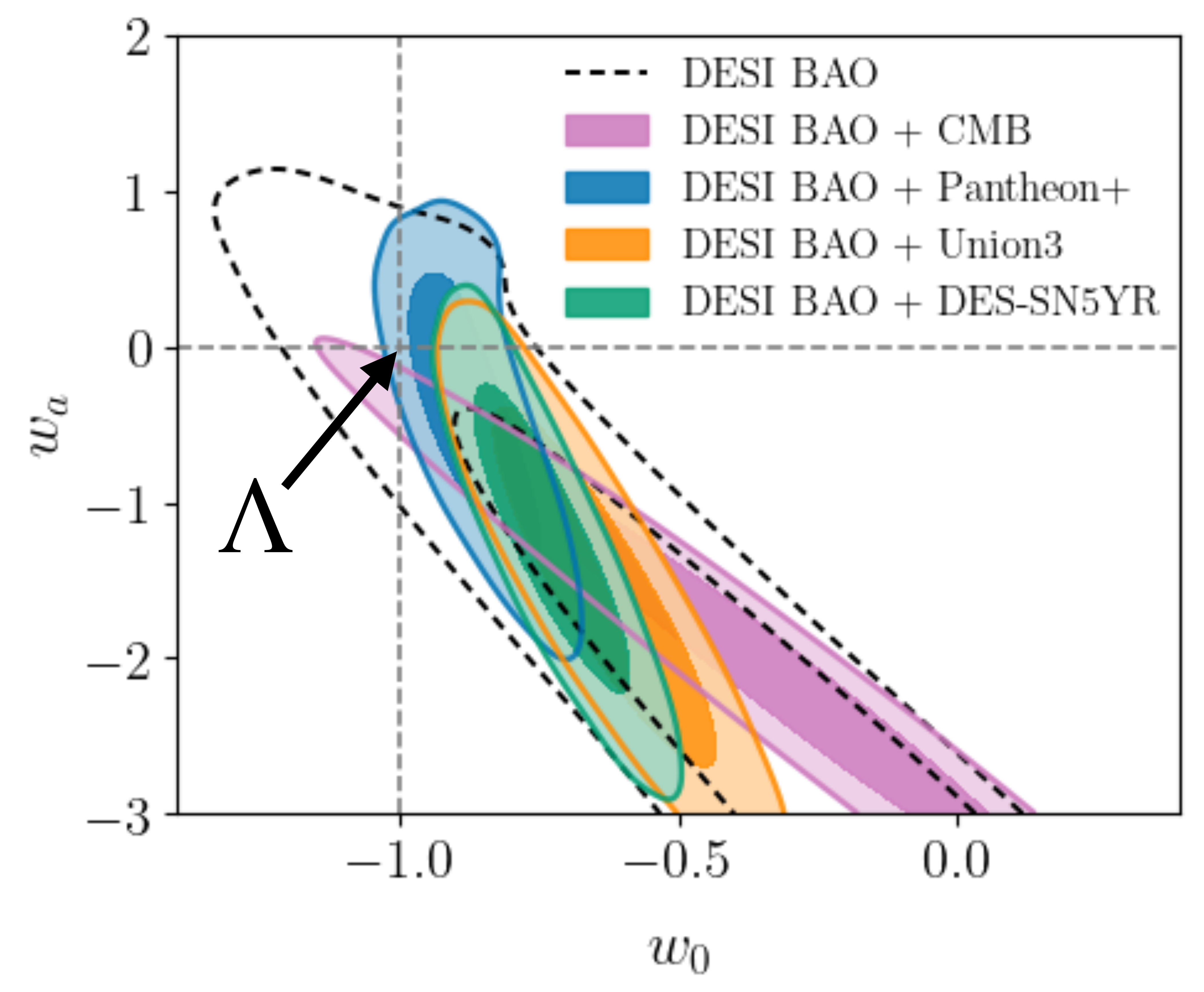

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Combining all DESI + CMB + SN

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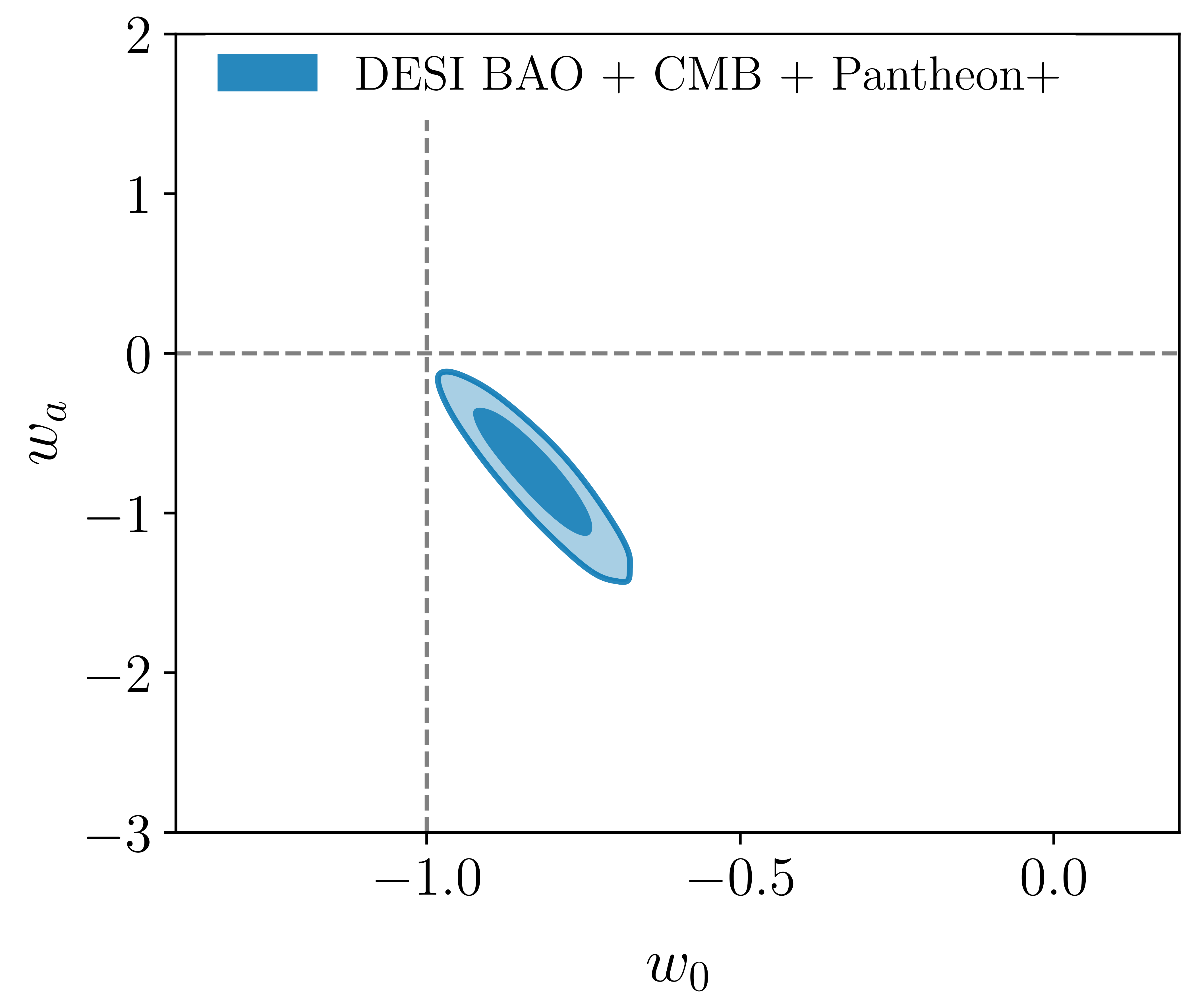
DESI + CMB + PantheonPlus $\Longrightarrow 2.5\sigma$



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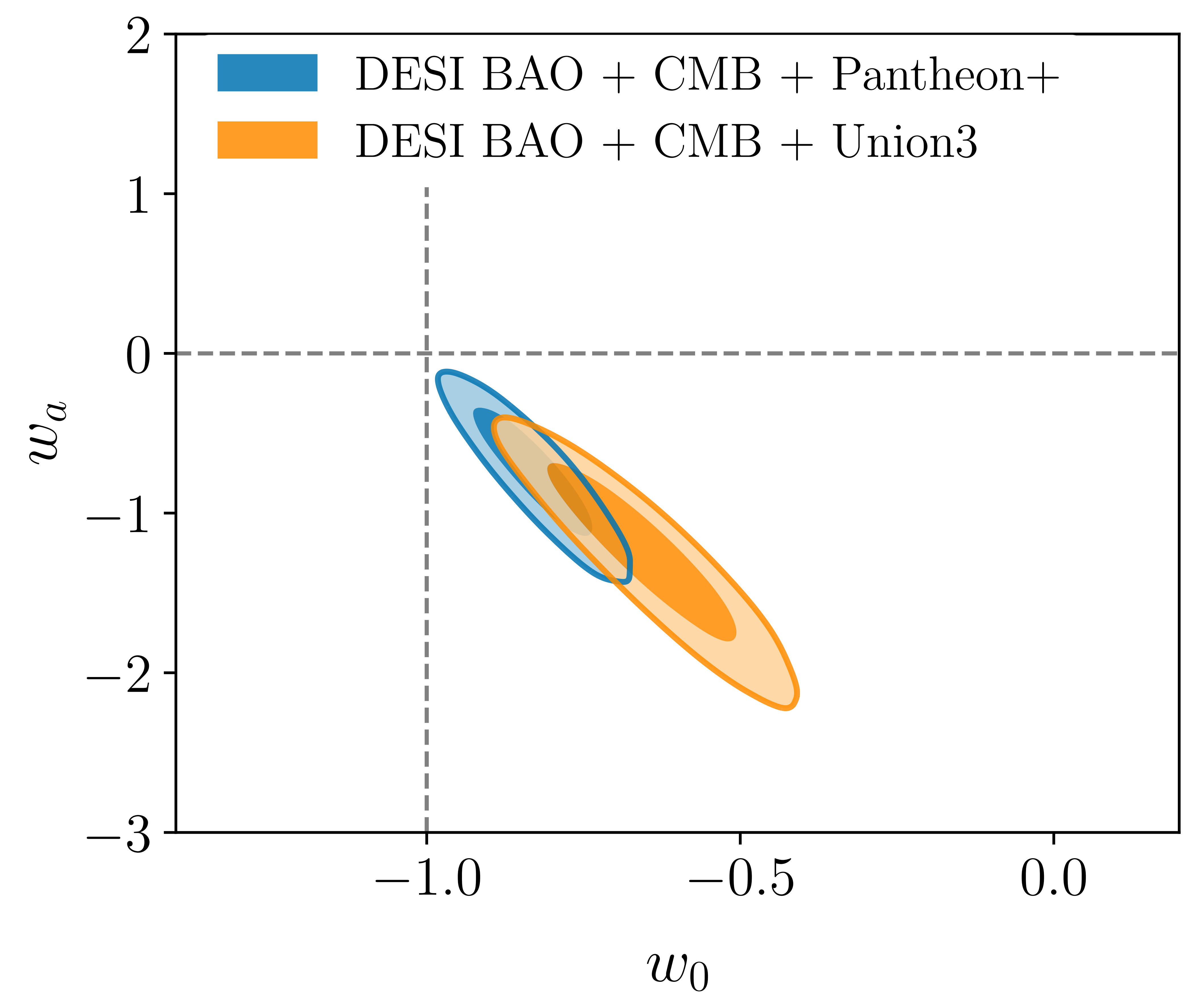

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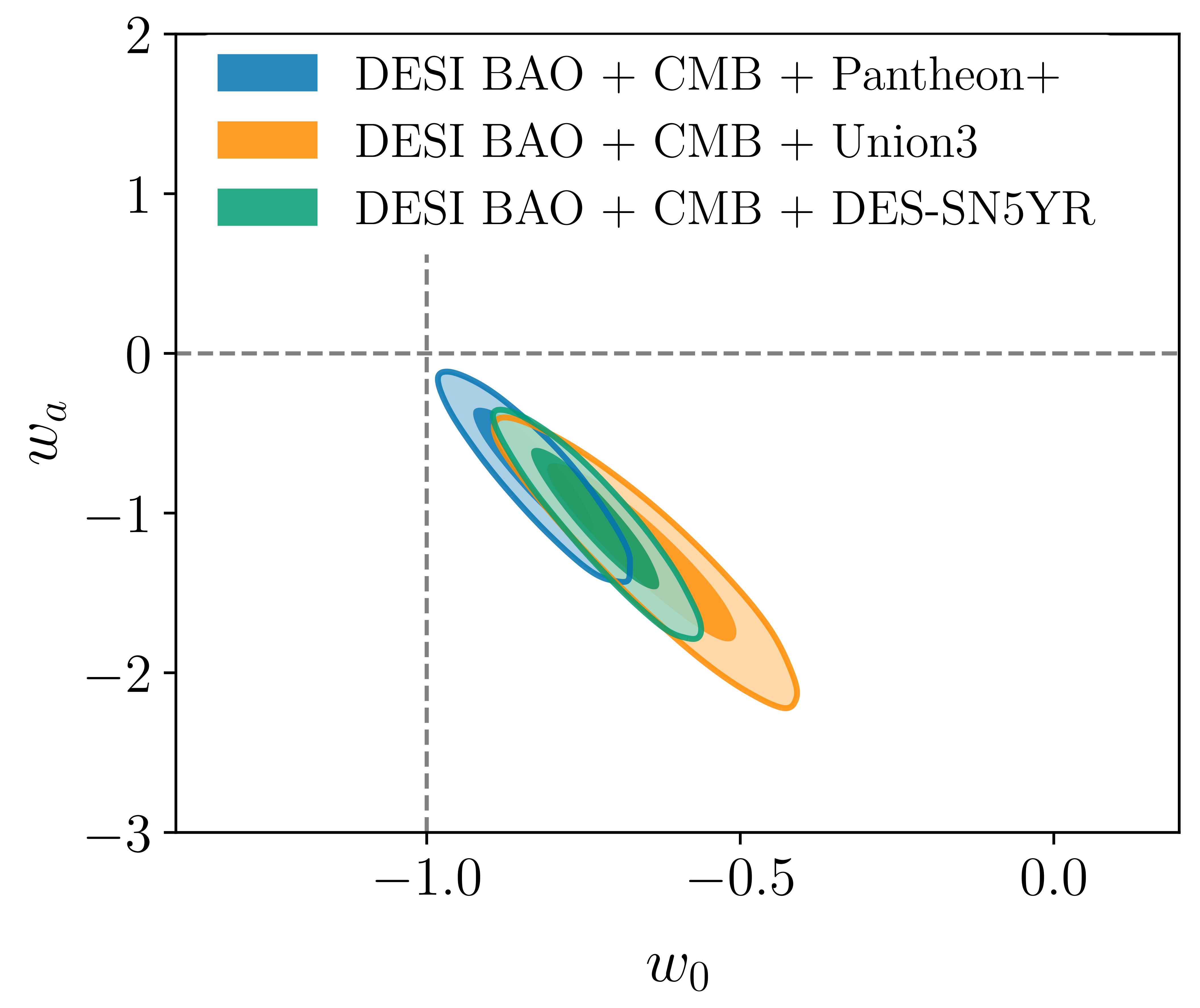

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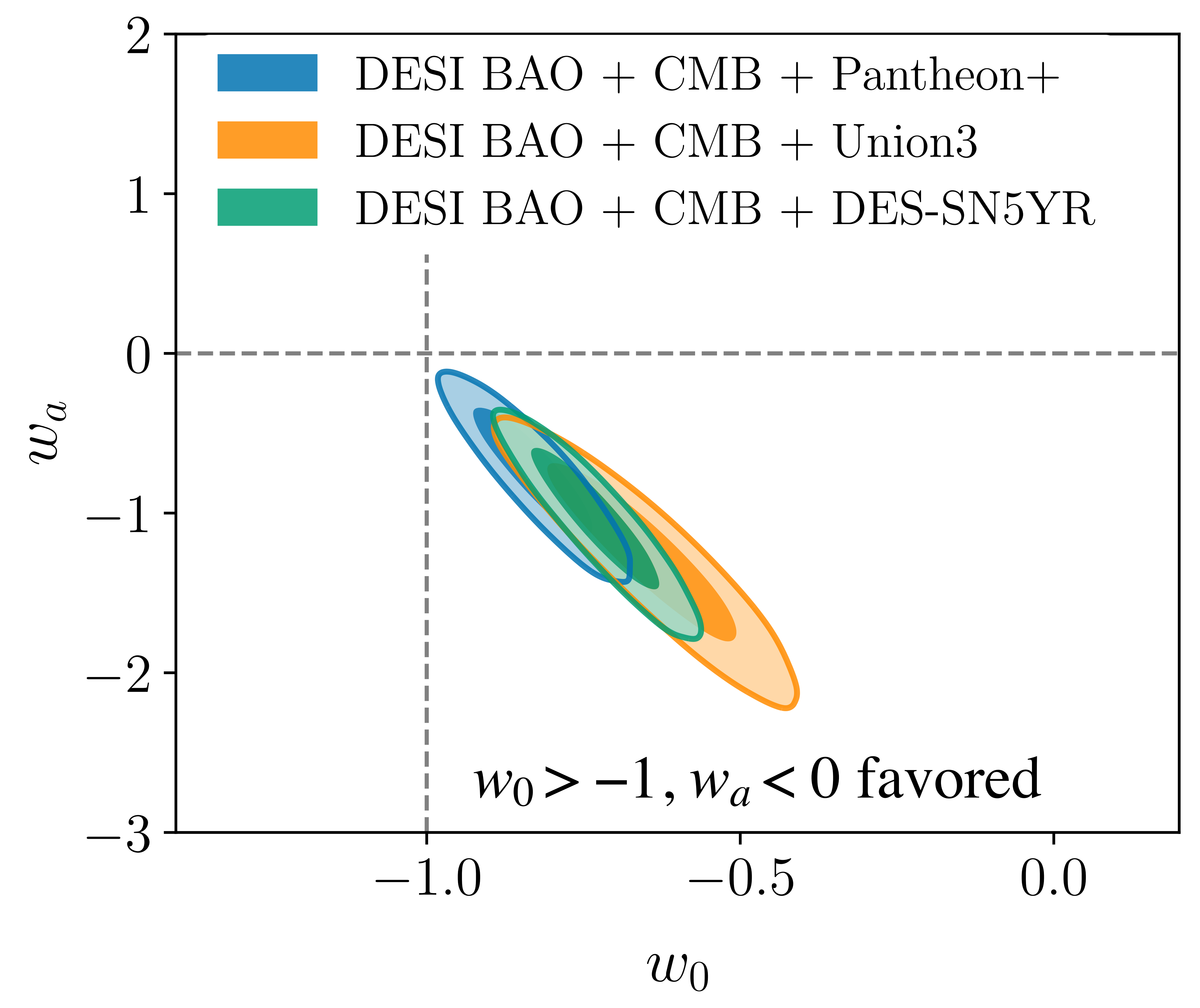

Neutrinos in cosmology

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Both the *acoustic oscillations* in the primordial plasma as well as the *background evolution* and structure formation

Cosmological observations are sensitive to both the **number of neutrino species** and their **total mass**

Sum of neutrino masses

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Sum of neutrino masses: DESI constrains

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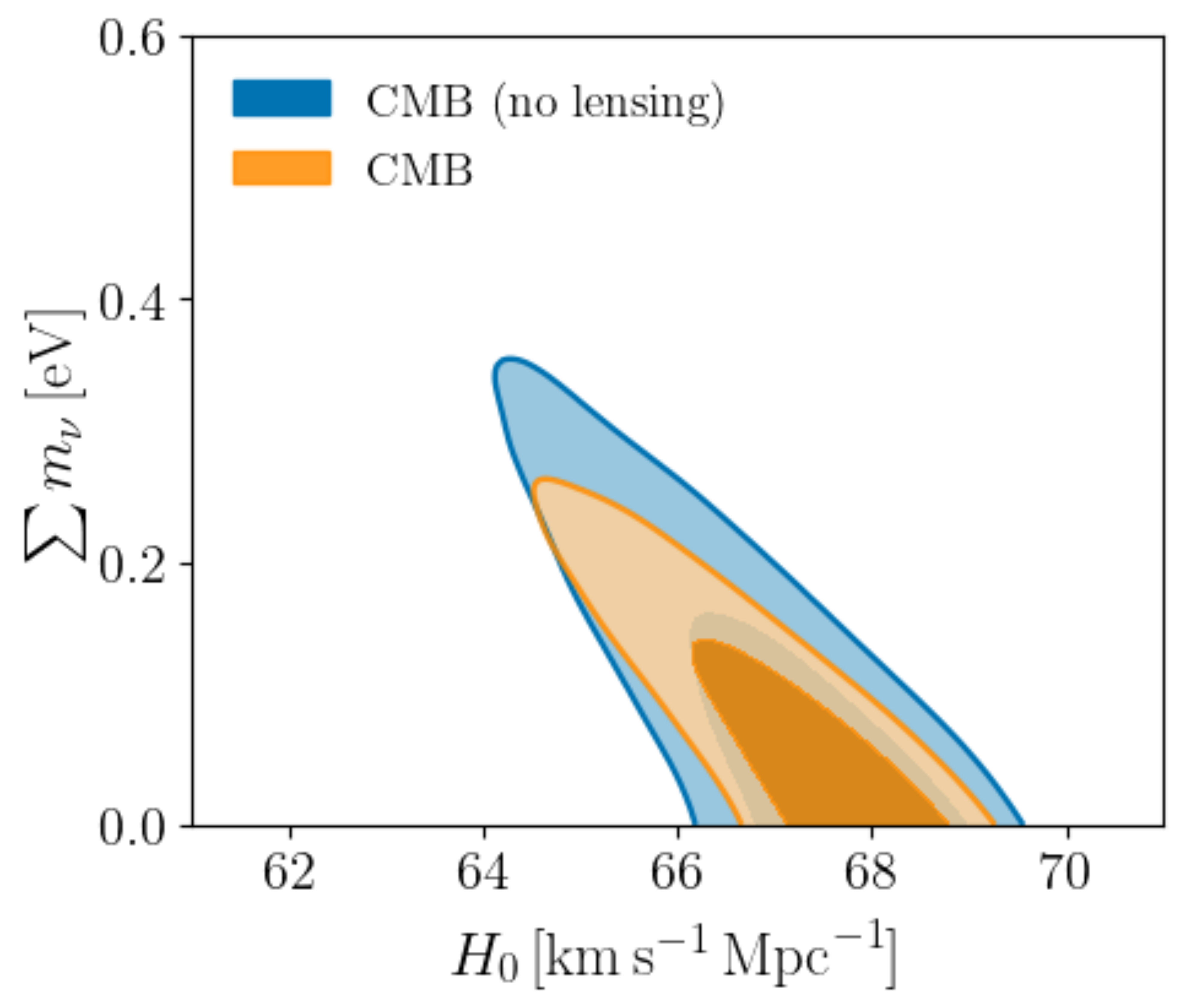
Internal CMB degeneracies limiting precision on the sum of neutrino masses



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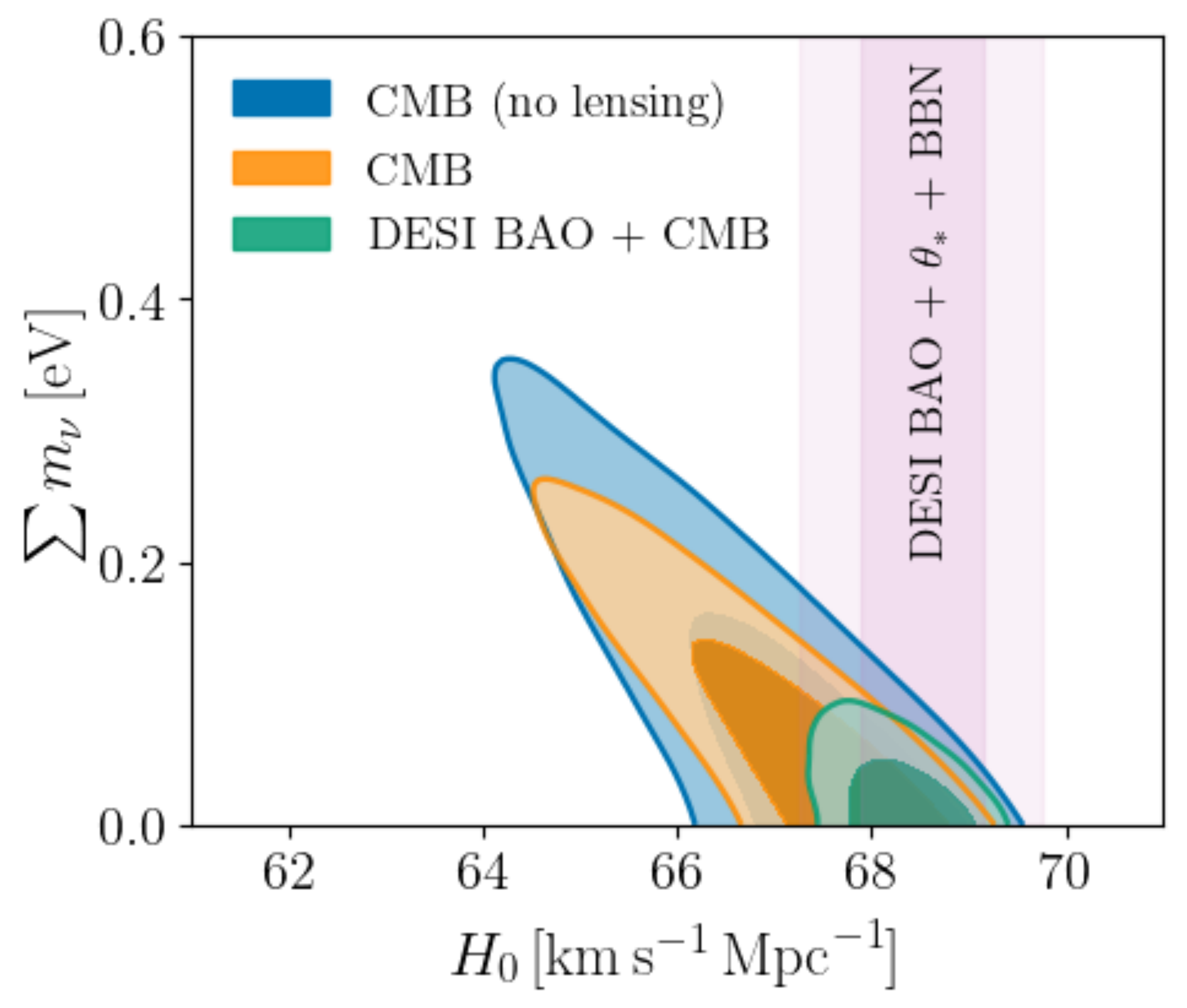

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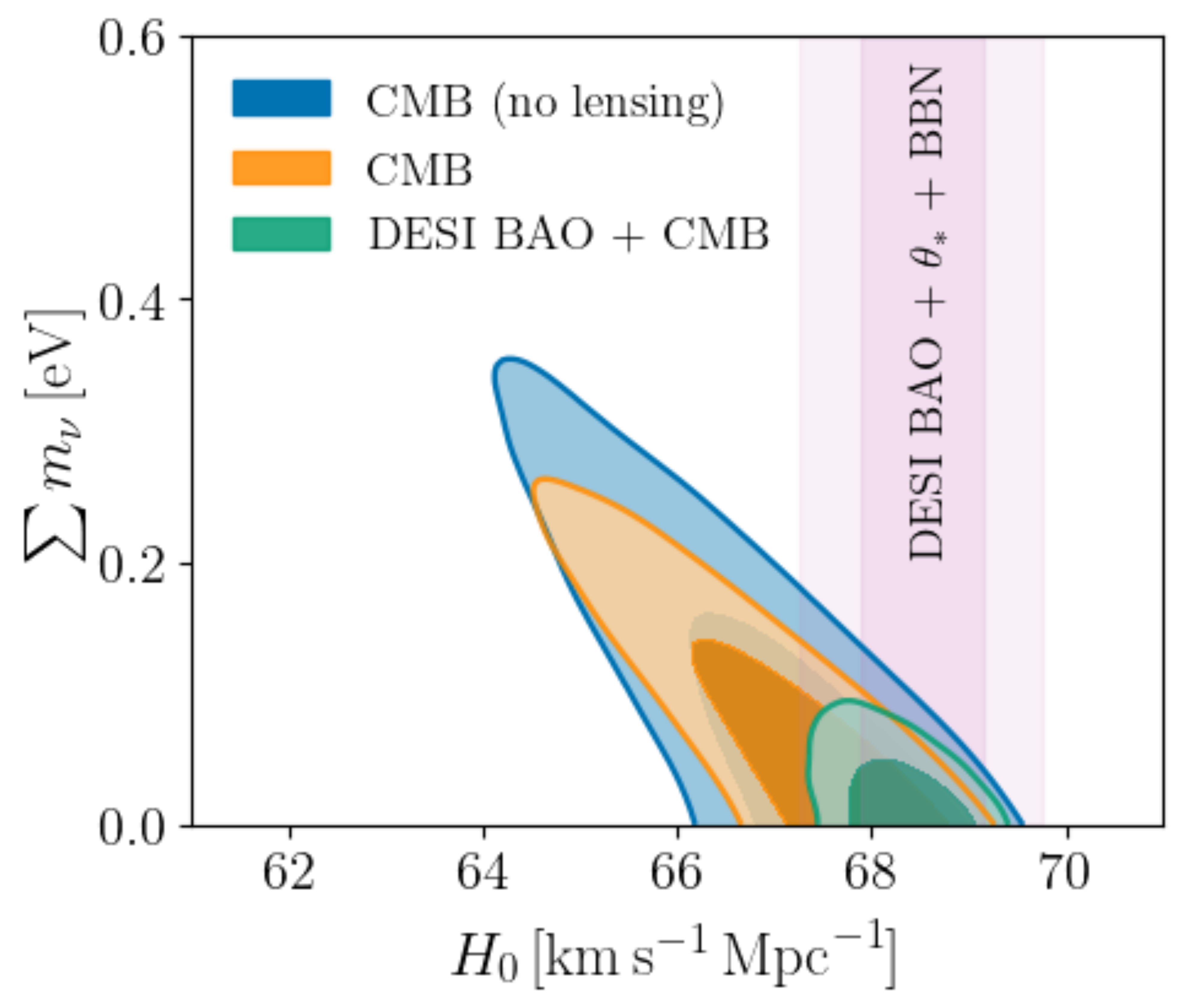

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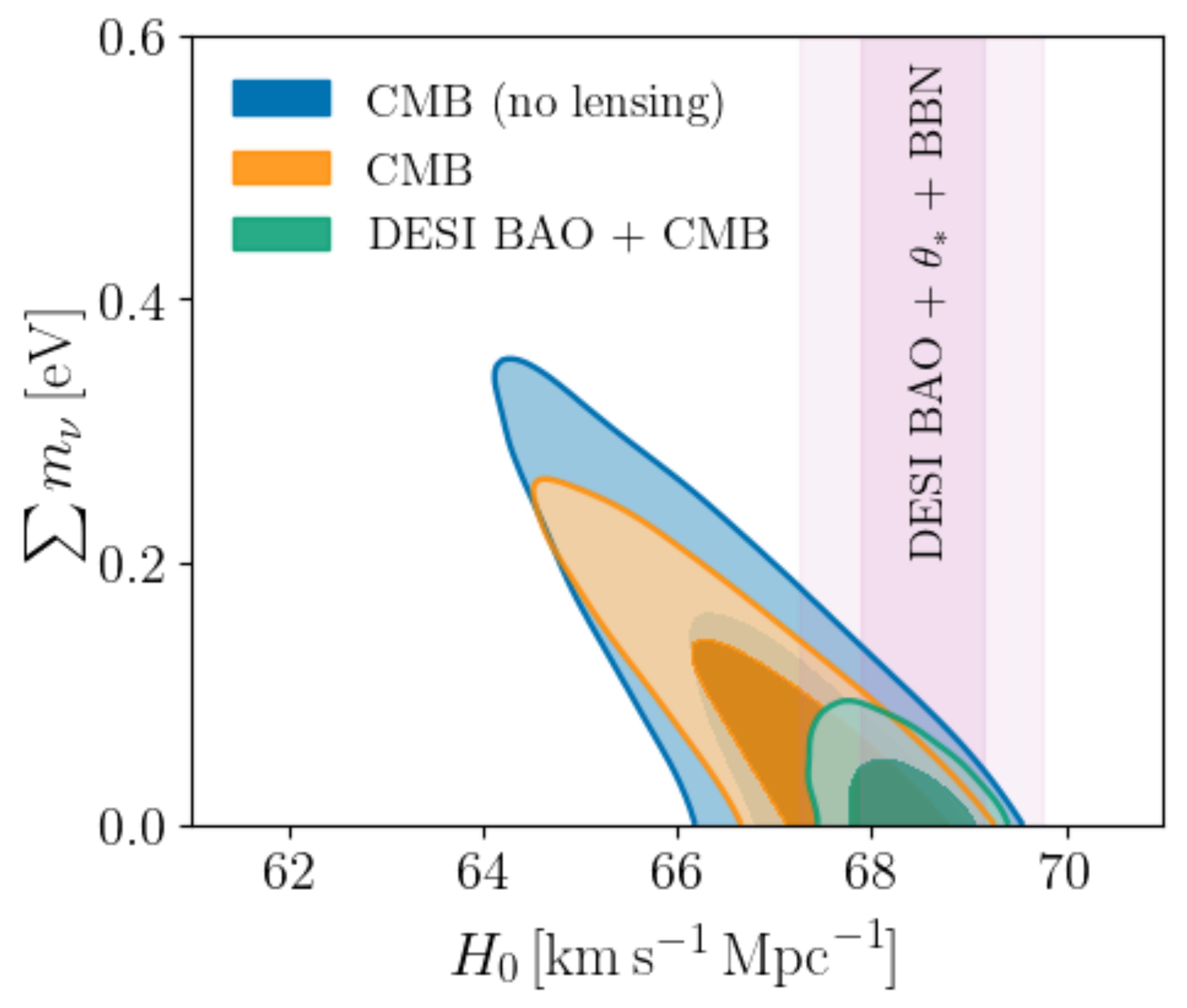
Limit relaxed for extensions to ΛCDM

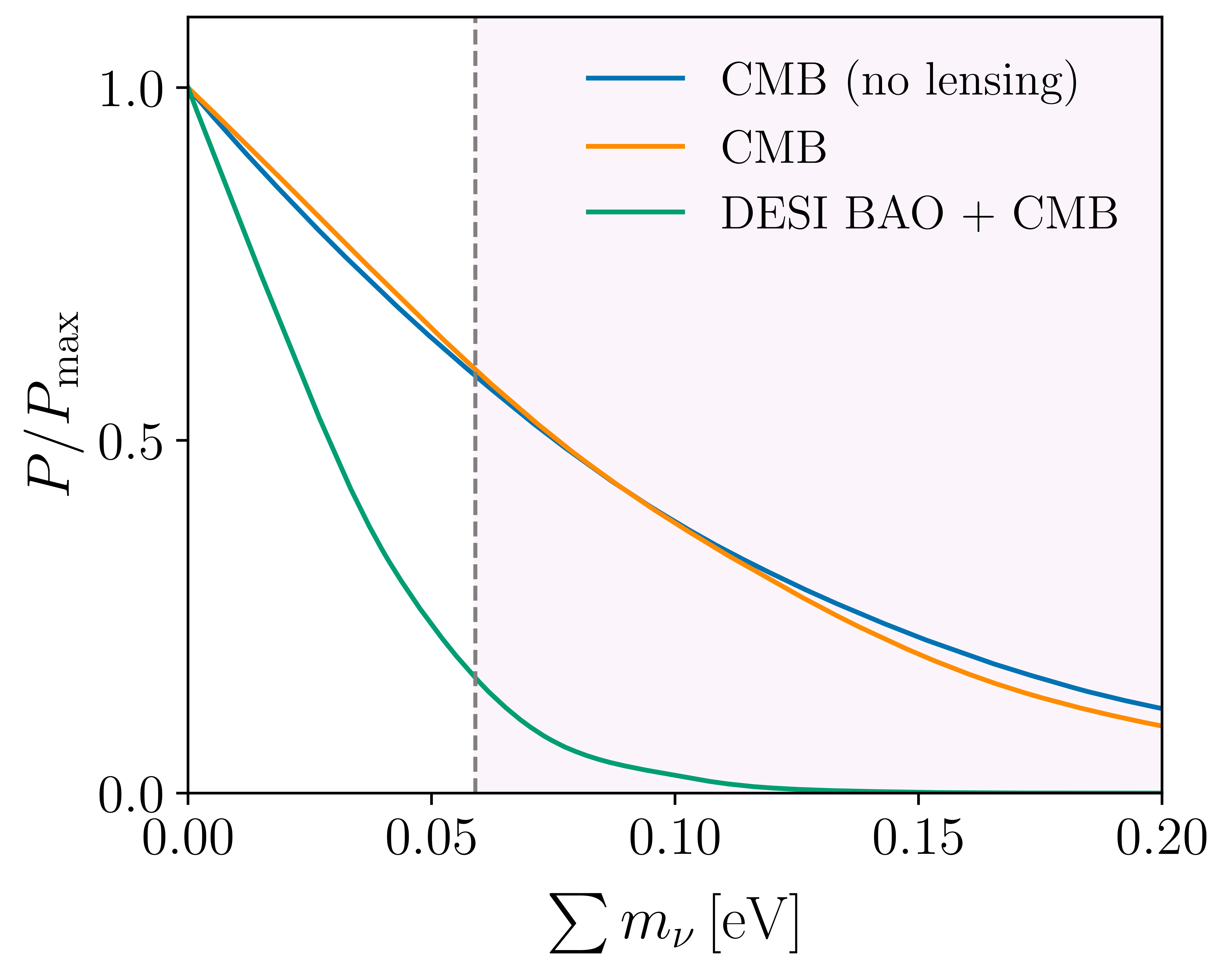
$\sum m_\nu < 0.195$ eV for $w_0 w_a$CDM



Neutrino mass hierarchies

With > 0.059 eV prior (NH)

$\sum m_\nu < 0.113$ eV (95%, DESI + CMB)



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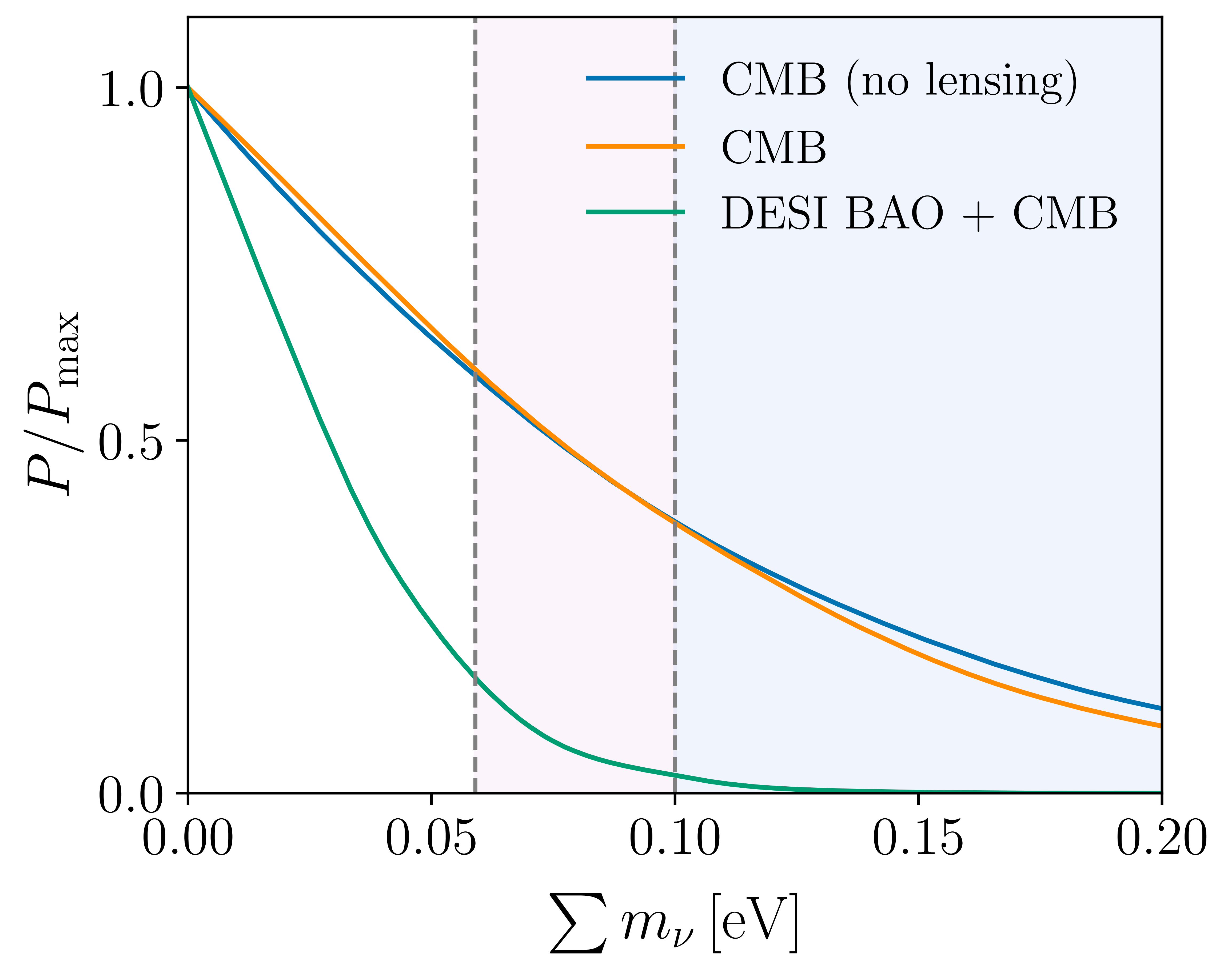

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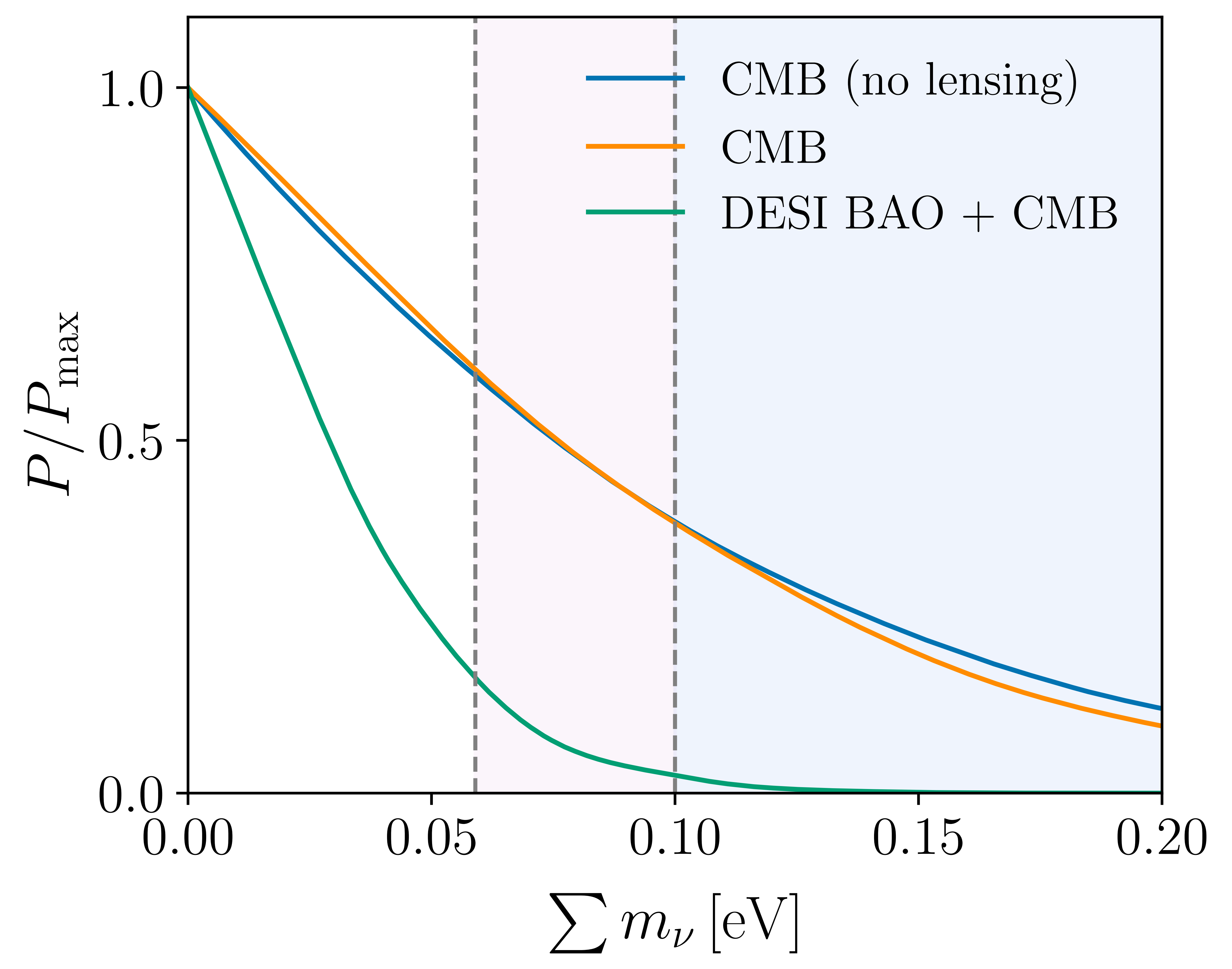

Current constraints do not strongly favor normal over inverted hierarchy ($\simeq 2\sigma$)

Hubble tension?

- Extension models: modify the background geometry or late-time expansion history
- The calibration of the sound horizon using BBN relies on assumptions about the physics at the time of BBN: effective number of relativistic degrees of freedom, N_{eff}

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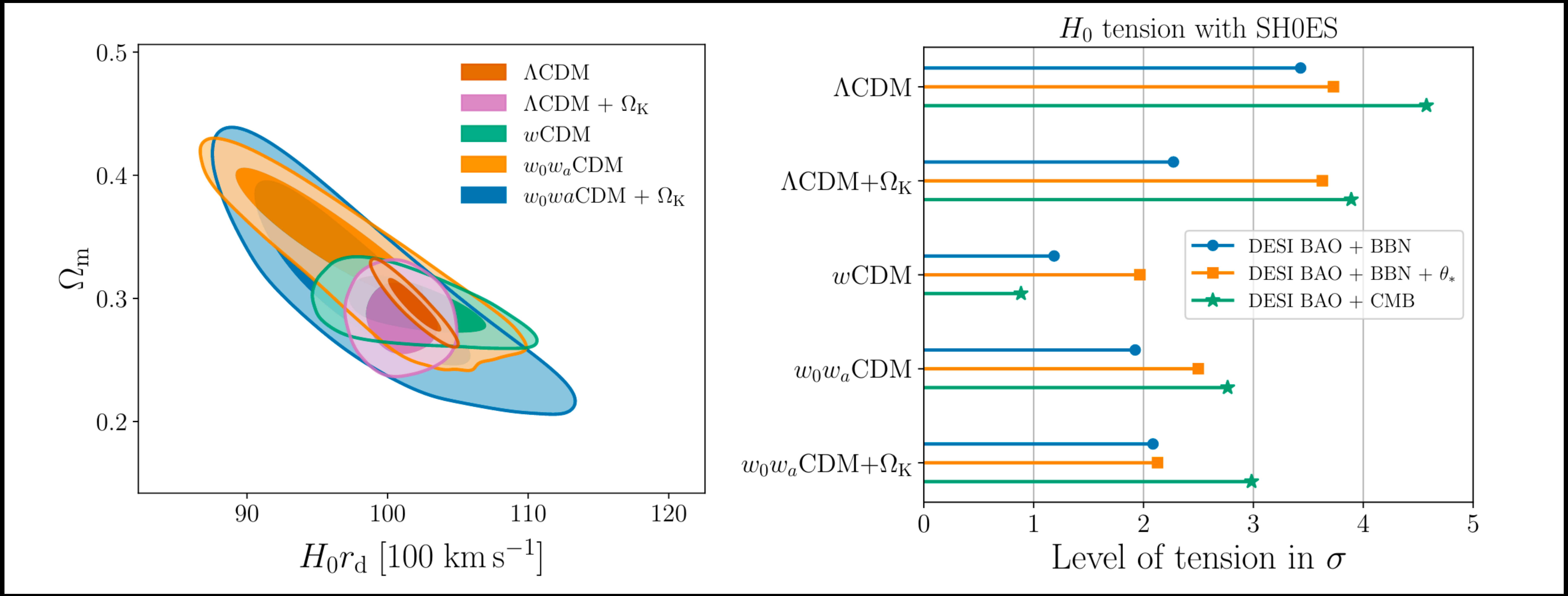

Summary

- DESI + BBN (+ θ_*) constrains H_0 to $\sim 1\,\%$; 3.7σ tension w/ SH0ES
- DESI, in combination with CMB data, favors zero spatial curvature
- DESI is consistent with $w = -1$ when w assumed constant
- When w allowed to vary with time:
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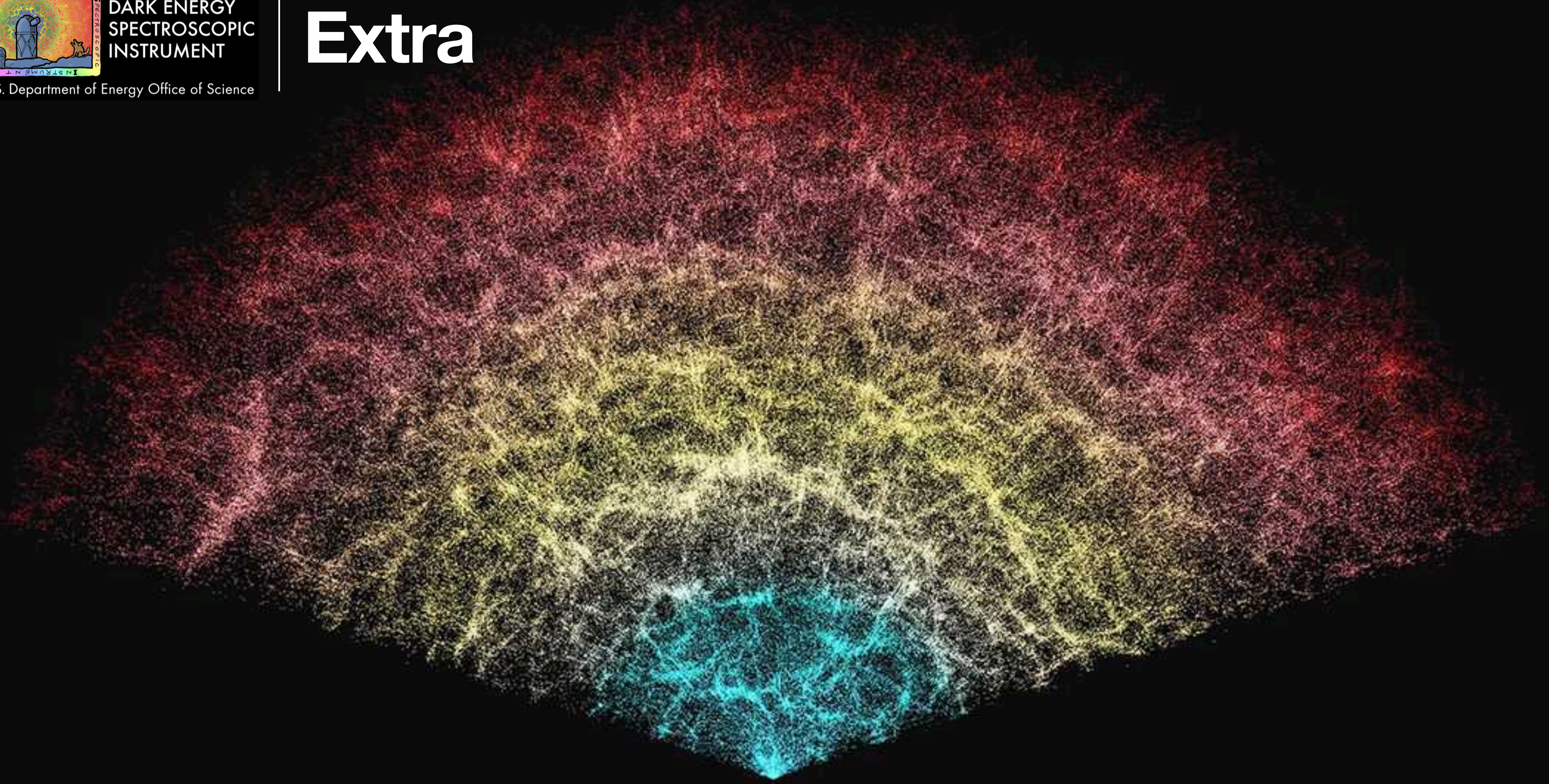
Extra



DESI cosmology from Full-Shape

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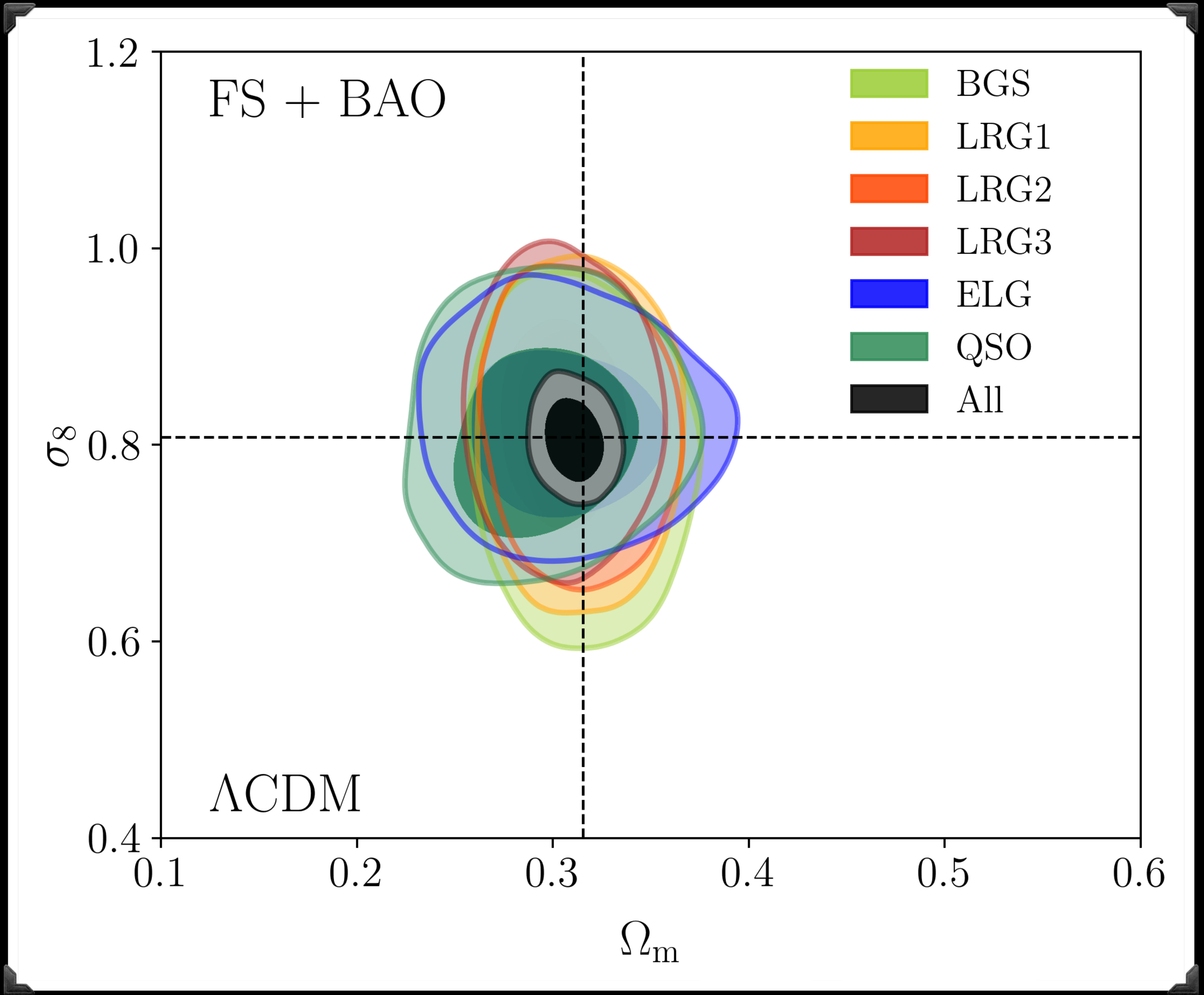

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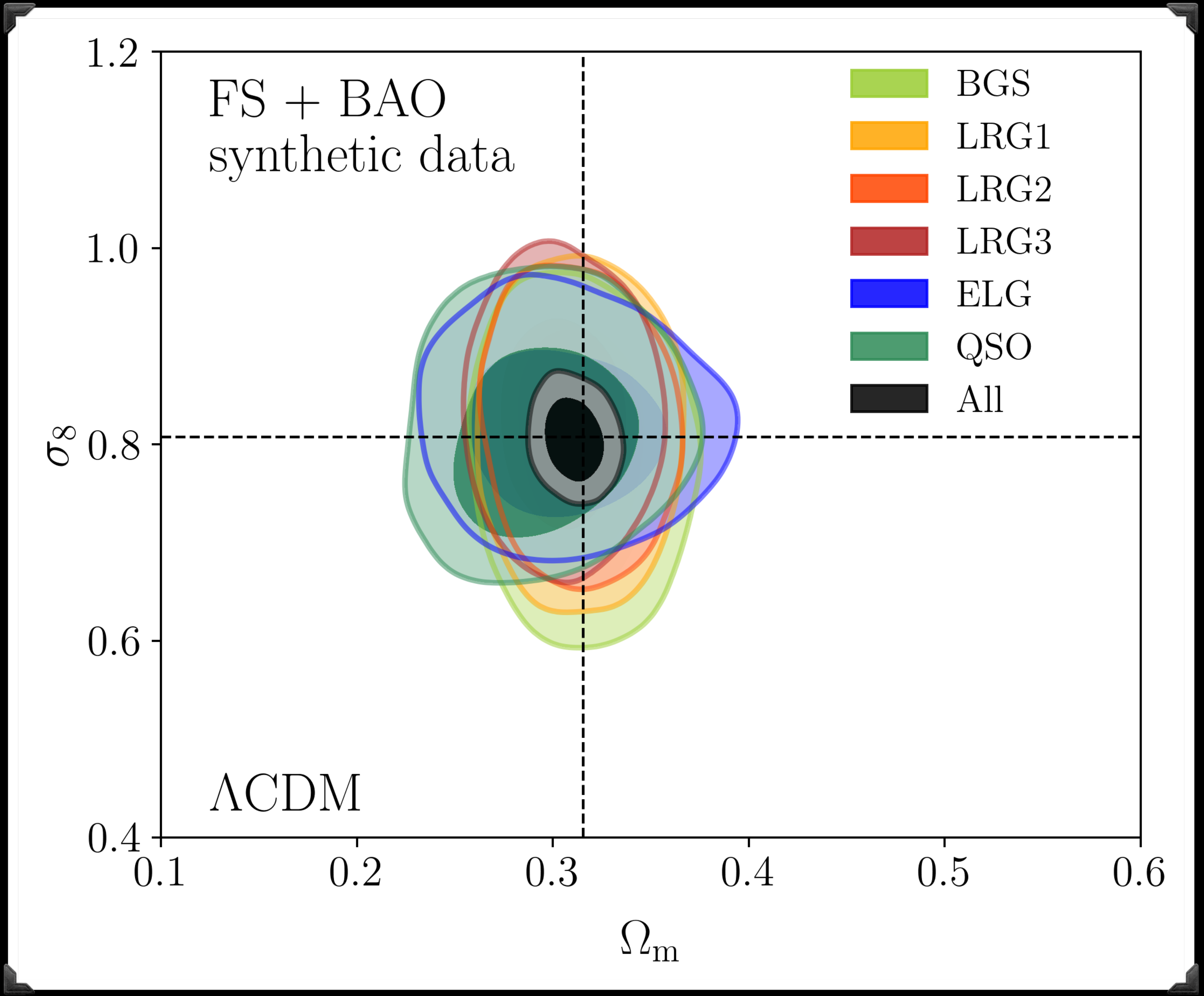
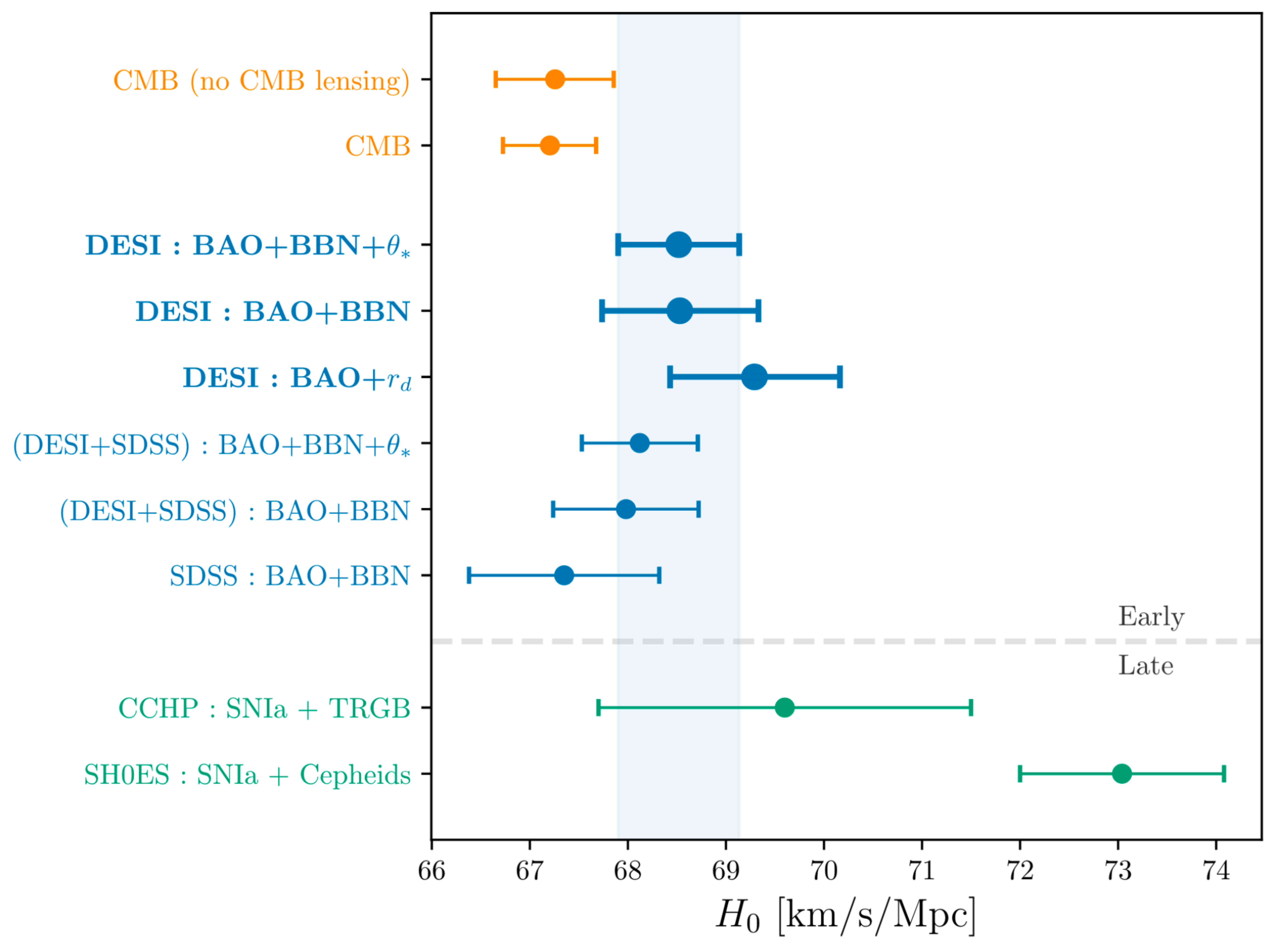


Hubble tension

Combination with an external prior:

- CMB measurement of the sound horizon
- CMB measurement of the acoustic angular scale
- BBN



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How is the DESI BAO analysis different?

- The data! – already **the biggest ever BAO dataset** (both in and volume)
- **Blind analysis** to mitigate observer/confirmation biases (catalogue-level blinding)
- Theory developments in BAO fitting procedure
- New and improved reconstruction methods
- **Unified BAO pipeline** applied to all tracers/redshifts consistently
- Wide-ranging tests of systematic errors, done before unblinding
- New combined tracer method used for overlapping galaxy samples (LRG and ELG in $0.8 < z < 1.1$)

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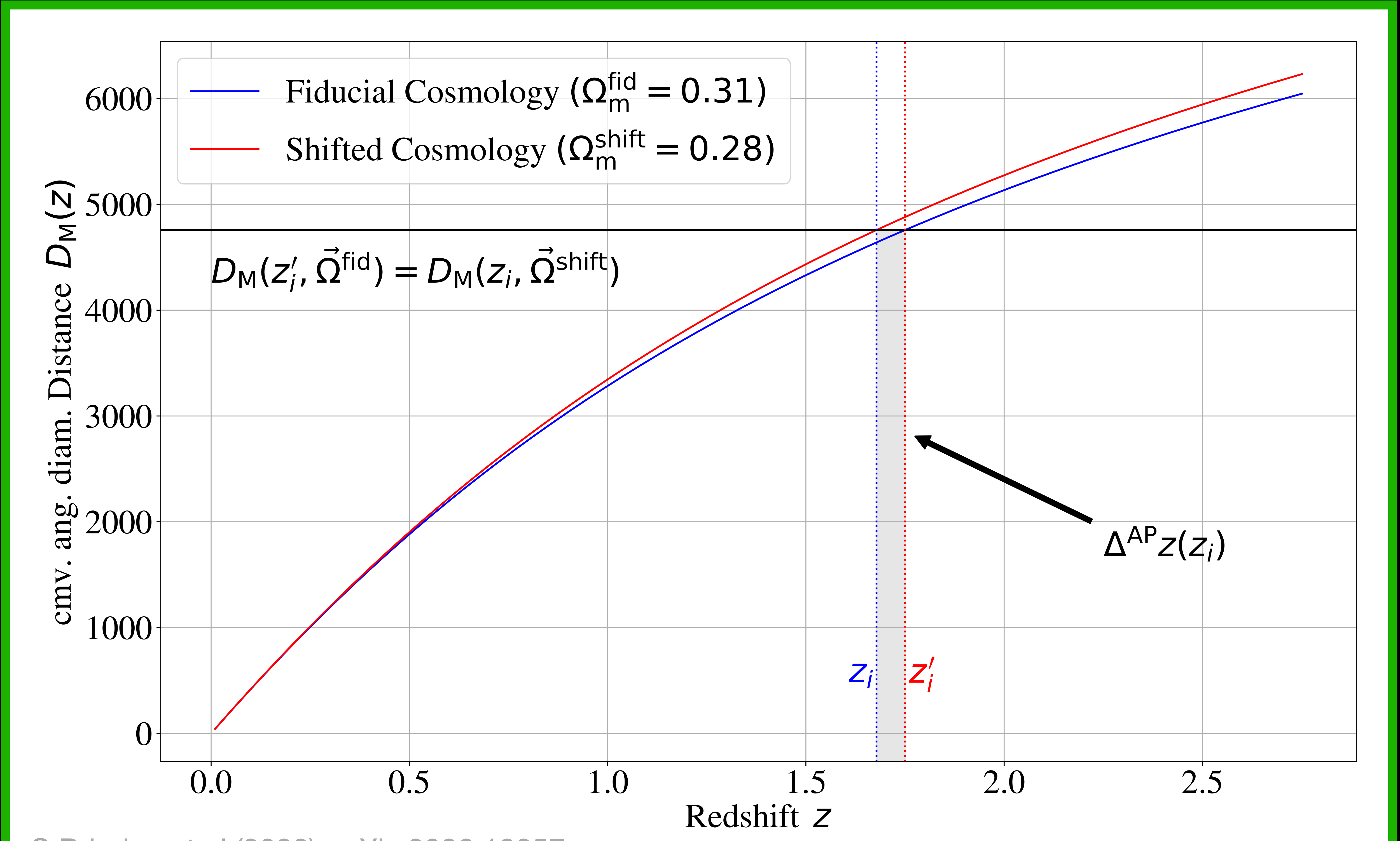
Blinding happens in three steps:

1. Blinding for BAO;
2. Blinding for RSD;
3. Blinding for primordial non-Gaussianity $f_{\rm NL}$.

How is the DESI BAO analysis different?

- **First step**: AP-like shift



S Brieden et al (2020): arXiv:2006.10857

blind cosmology w_0, w_a, Ω_m (not revealed!)

$$(\text{ra}, \text{dec}, z) \longrightarrow (X, Y, Z)$$

fiducial cosmology

$$(\text{ra}, \text{dec}, z') \longleftarrow (X, Y, Z)$$

$$z_i\,(\mathbf{\Omega}_{\rm true}) \xrightarrow{\mathbf{\Omega}_{\rm blind}} D_{\rm M}(z_i, \mathbf{\Omega}_{\rm blind}) = D_{\rm M}(z_i', \mathbf{\Omega}_{\rm fid}) \xrightarrow{\mathbf{\Omega}_{\rm fid}} z_i'\,(\mathbf{\Omega}_{\rm blind})$$

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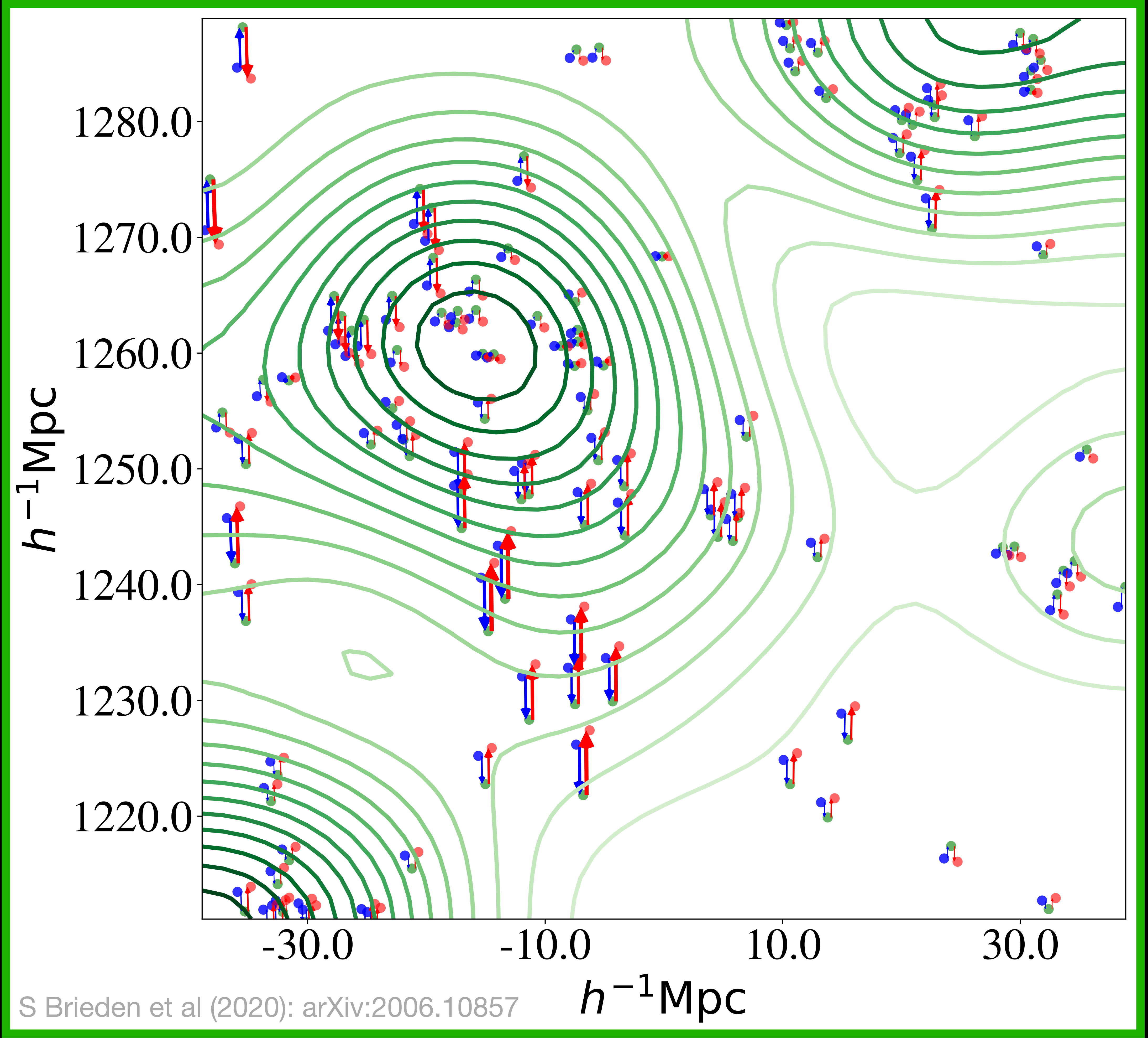
How is the DESI BAO analysis different?

- **Second step**: RSD shift



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The so-called displacement field: $\mathbf{\Psi} = \nabla \phi$

$$\nabla \cdot \mathbf{\Psi} = -\frac{\delta_g}{b_1}, \qquad \vec{r} = \vec{x} + f\left(\mathbf{\Psi} \cdot \hat{\mathbf{r}}\right)\hat{\mathbf{r}}$$

$$\mathbf{r}' = \mathbf{r} - f^{\mathrm{fid}}(\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} + f^{\mathrm{blind}}(\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$$

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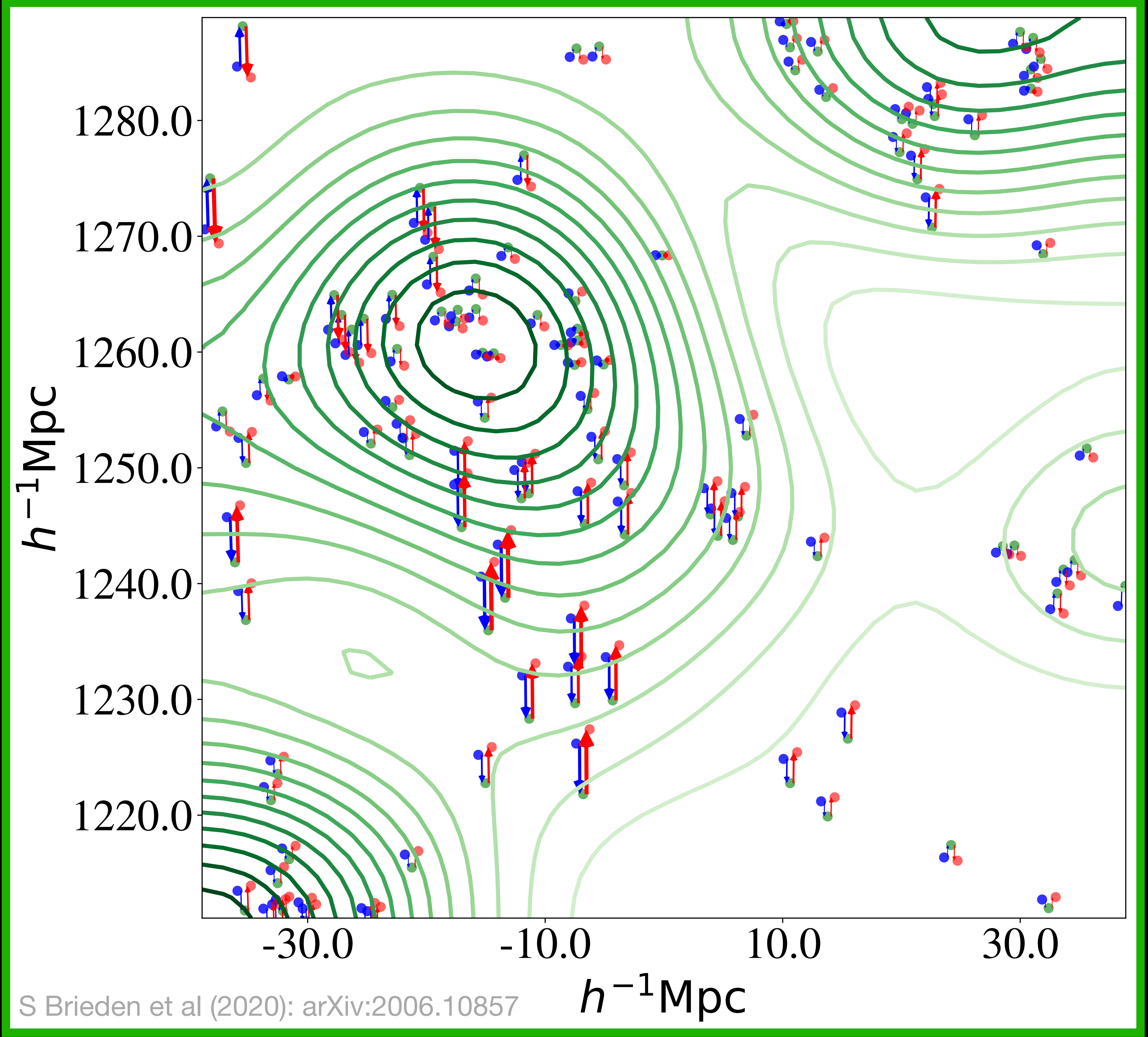

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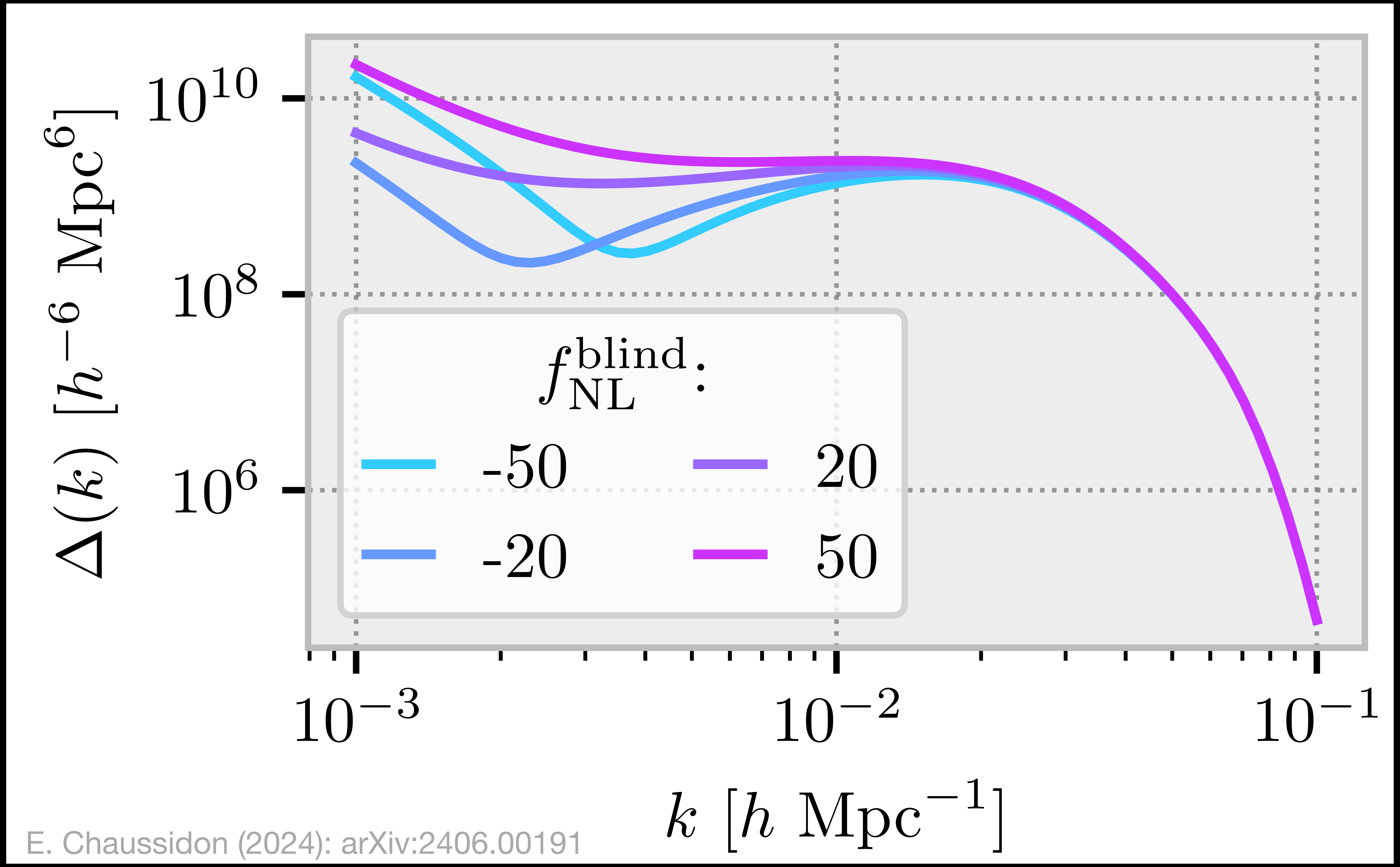
How is the DESI BAO analysis different?

- **Third step**: weights-based blinding $f_{\rm NL}$



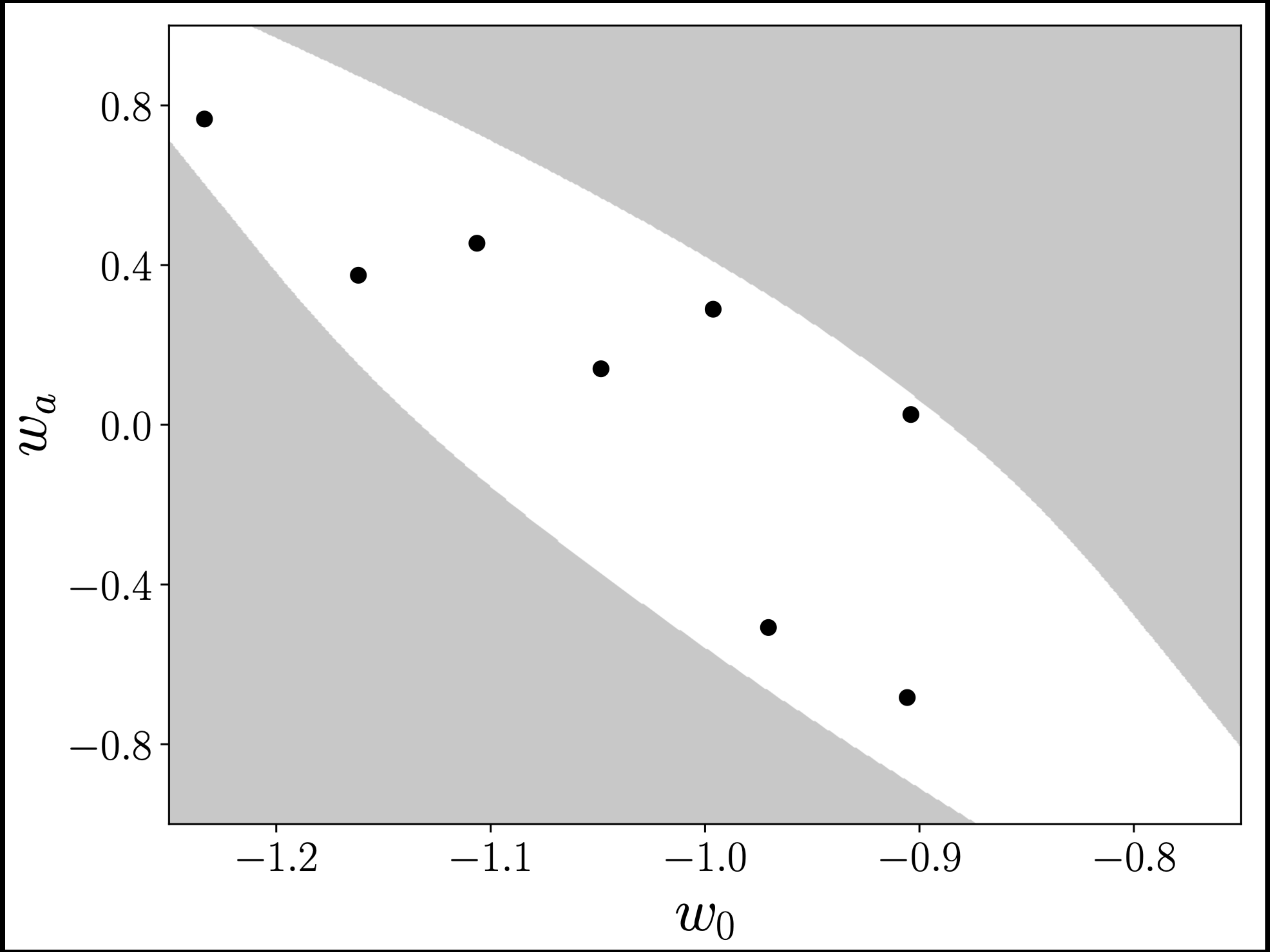
E. Chaussidon (2024): arXiv:2406.00191

$$P(k,z) = \left(b(z) + \frac{b_\Phi(z)}{\alpha(k,z)} f_{\rm NL}^{\rm loc} \right)^2 P_{\rm lin}(k,z)$$

$$w_{\rm blind}(k) = \frac{b_\Phi f_{\rm NL}^{\rm blind}}{b\alpha(k)} \times \hat{\delta}^r(k)$$

Alters the measured power spectrum at large scales by including in the catalog an *additional set of* ***weights***, multiplied by the traditional ones.

How is the DESI BAO analysis different?



- Additional requirement: shifts in the blinded cosmology to specific regions within the (w_0, w_a) parameter space
- shifts in f do not exceed $10\,\%$ of the fiducial value, $f_{\text{fid}} = 0.8$
- $3\,\%$ for $\alpha_\perp, \alpha_\parallel$ from unity

Validating the Galaxy and Quasar Catalog-Level Blinding Scheme for the DESI 2024 analysis: U. Andrade et al (2024): arXiv:2404.07282

DESI Y1 Results

First batch of DESI DR1 cosmological analyses are out: 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**
- **DESI 2024 IV: BAO from Lyman-α Forest at z > 2**
- **DESI 2024 V: Galaxies and Quasars at z < 2**
- **DESI 2024 VI: Cosmological constraints from BAO measurements**
- DESI 2024 VII: Cosmological constraint from RSD measurements